

Molten Salt Reactors

Technology and Safety considerations

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Training Course on Safety Aspects of Small Modular Reactors and
Other Innovative Reactor Technologies

November 4-8, 2024
Fukui, Japan



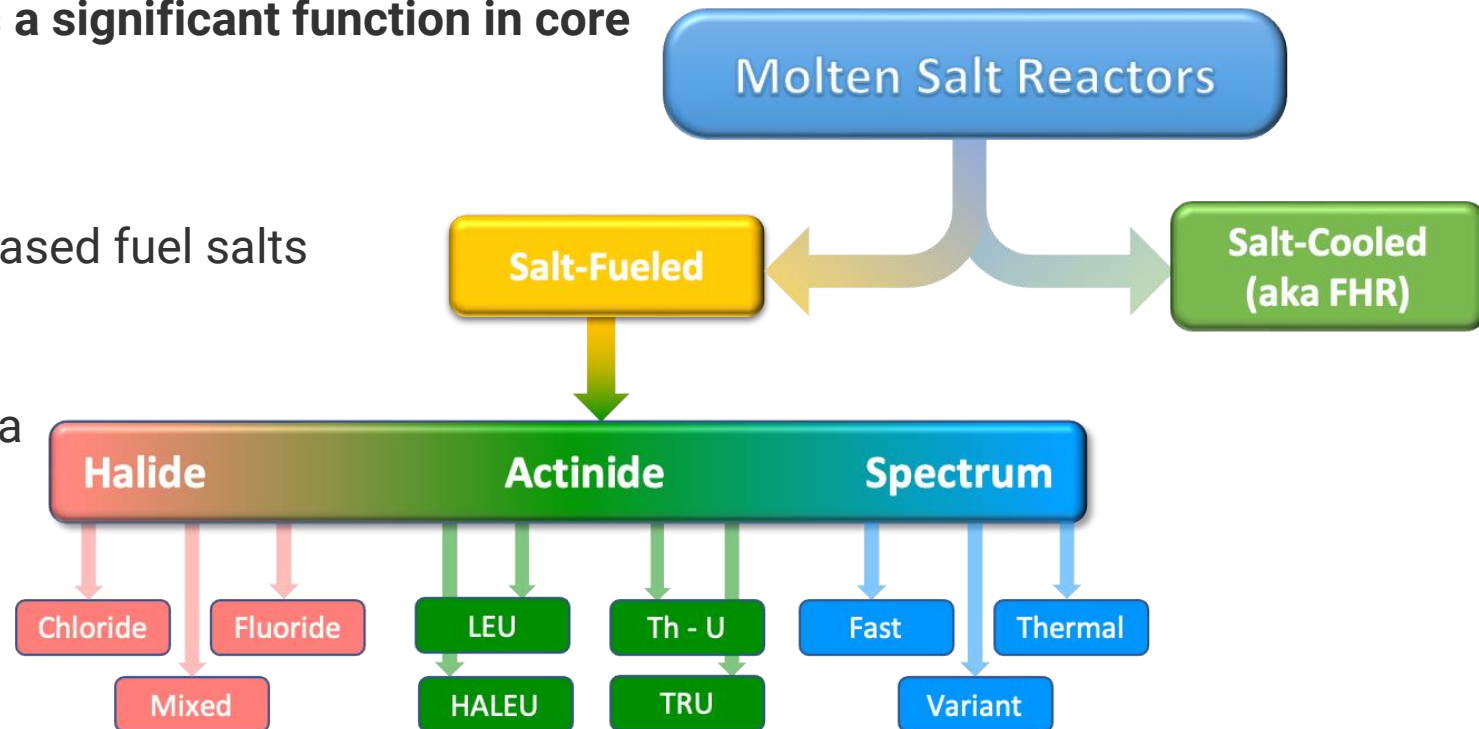
MSR Technology considerations

Boris Hombourger, Ph.D.

What are Molten Salt Reactors (MSRs) ?

Reactors in which a molten salt performs a significant function in core

- Liquid- and solid-fueled variants
- Chloride-, fluoride-, and mixed halide-based fuel salts
- Salt and liquid-metal coolants
- Thermal, fast, or mixed neutron spectra
- Wide range of power levels
- With or without fuel processing
- Nearly all fuel cycles
- Multiple different primary system configurations
- Etc. !

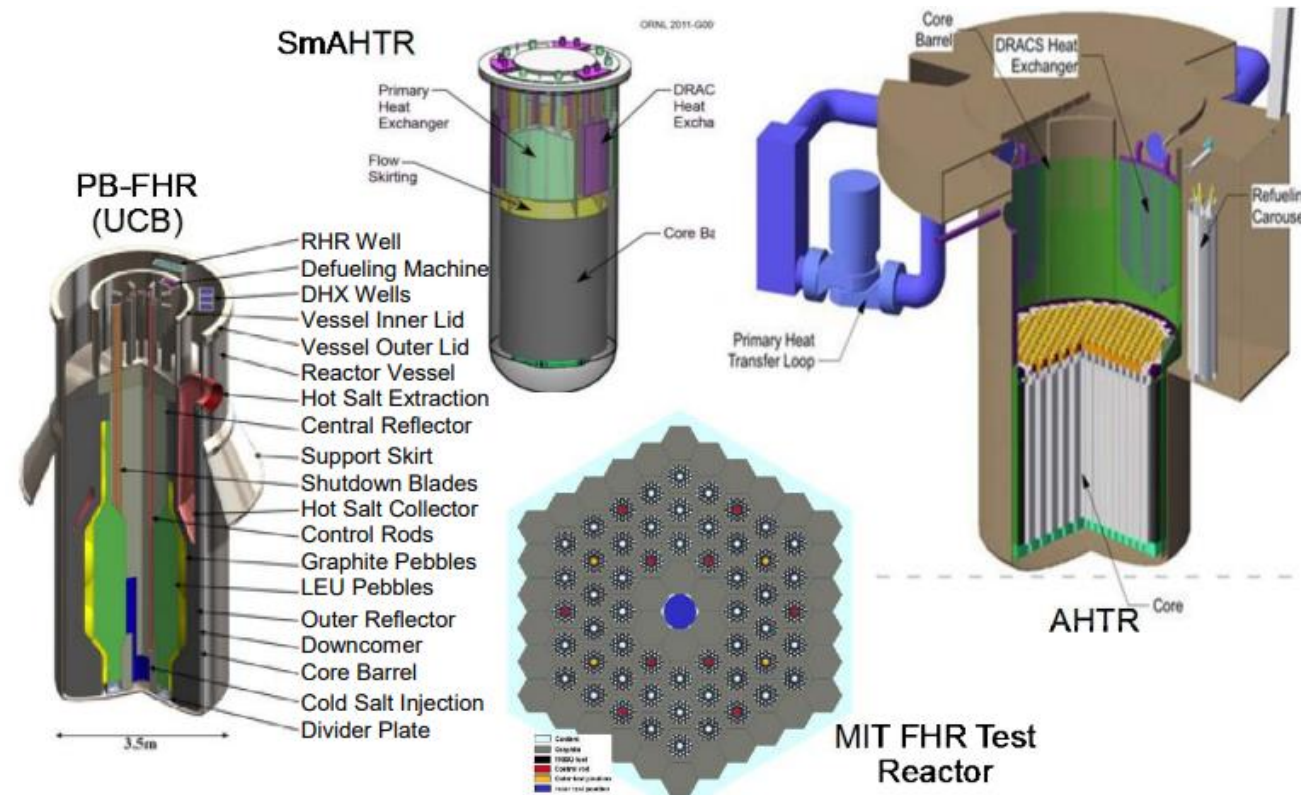


This diversity of characteristics should incite to **caution** when making **generic statements**

Salt-cooled, solid-fueled MSR

- Sometimes called **Fluoride High-temperature Reactors (FHR)**.
- Designs have been proposed in which the **fuel is solid**, e.g., TRISO fuel used in High-temperature gas-cooled reactors (HTGRs) and in which the salt serves as a **high-temperature, low-pressure coolant**.
- These designs **share a lot of their safety-related characteristics with HTGRs and LMRs**, sometimes more than with liquid-fueled MSRs.
- The focus of this presentation will be **liquid-fueled MSRs**.

Illustration from ORNL/TM-2015/700



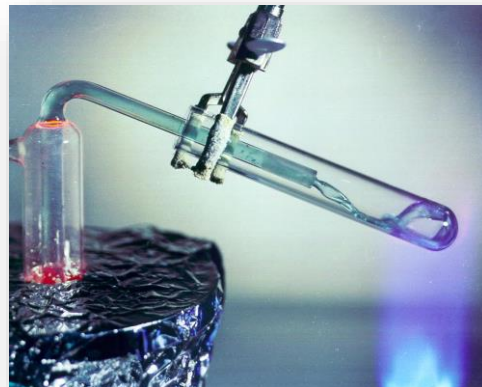
What are “Molten Salts”, actually?

Salts are **ionic compounds** formed from a combination of **electronegative** and **electropositive** elements

At elevated temperatures salts **liquefy** and are termed “molten salts”

Halide salts are ionic compounds formed from the combination of a **halogen** (electronegative) and another electropositive element – commonly, but not exclusively, **alkali metals** or **alkaline earths**

Examples: LiF , BeF_2 , MgCl_2 , NaCl (table salt), ZrF_4 , RbF , UF_4 , UCl_3



(left) Solid “Frozen” and (right) Liquid “Molten” $2\text{LiF}\text{-BeF}_2$ salt

Halogens

9	F
	Fluorine
	18.998...
17	Cl
	Chlorine
	35.45
35	Br
	Bromine
	79.904
53	I
	Iodine
	126.90...
85	At
	Astatine
	(210)
117	Ts
	Tennesine
	(294)

Alkali Metals

3	Li
	Lithium
	6.94
11	Na
	Sodium
	22.989...
19	K
	Potassium
	39.0983
37	Rb
	Rubidium
	85.4678
55	Cs
	Caesium
	132.90...
87	Fr
	Francium
	(223)

Alkaline Earths

4	Be
	Beryllium
	9.0121...
12	Mg
	Magnesium
	24.305
20	Ca
	Calcium
	40.078
38	Sr
	Strontium
	87.62
56	Ba
	Barium
	137.327
88	Ra
	Radium
	(226)

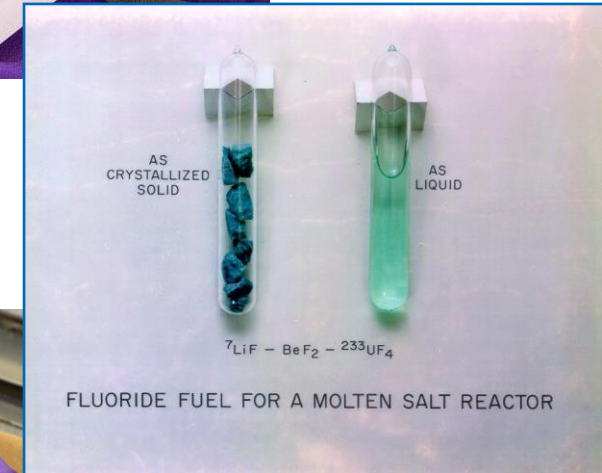
What is so special about salts ?

Compared to water, liquid metals, or gas ?

- High solubilities for Th, U and Pu
(= we can make nuclear fuel out of them !)
- High melting point and high boiling points
(= Low vapor pressure at operating temperatures)
- Low chemical potential energy
(= no vigorous reactions with air or water)
- Large heat capacity, low conductivity, relatively high viscosity
- Compatible with Ni-base alloys and graphite
- Stable thermodynamically, no radiolysis at high temperature
- May be transparent when free of fission products
(important for solid-fuel MSR)
- Compatible with chemical processing
(= MSR can have “native” fuel reprocessing)



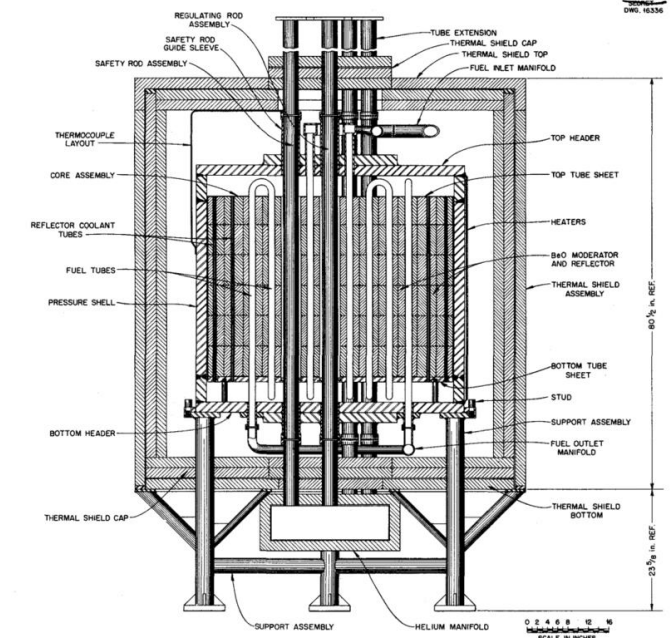
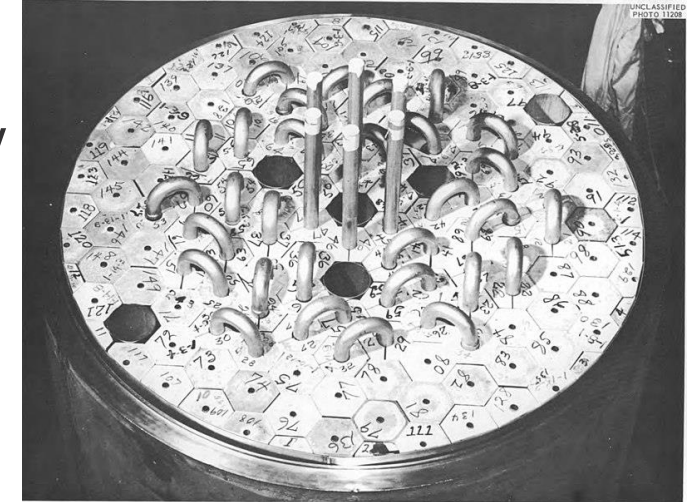
FLiBe Salt



Plutonium Chloride

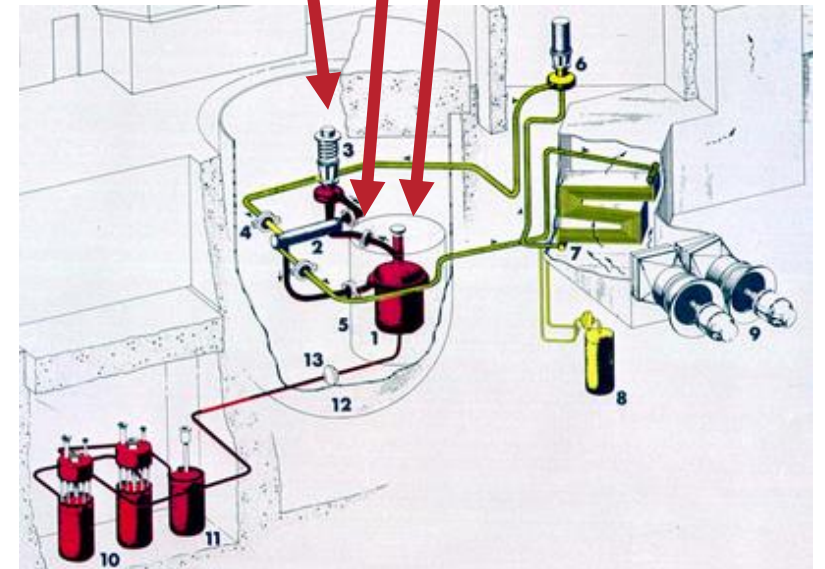
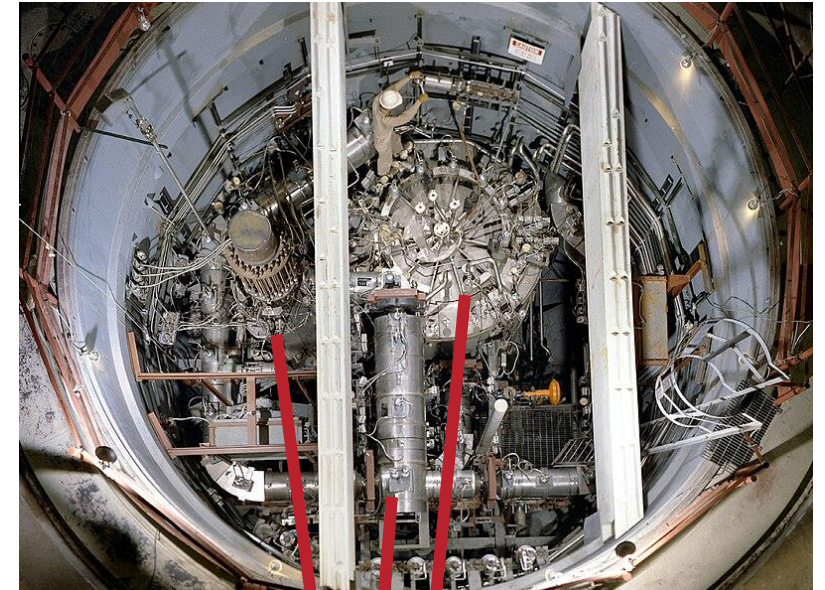
History: Aircraft Reactor Experiment (ARE)

- **First** molten salt reactor built (1954) for military purposes (aircraft nuclear propulsion) at Oak Ridge National Laboratory
- Beryllium Oxide (BeO) moderated, $\text{NaF-ZrF}_4\text{-UF}_4$ fueled
- Liquid sodium (Na) and helium (He) cooled
- Structural material was Inconel 600
- Operated for 10 days (3 EFPD) up to $2.5 \text{ MW}_{\text{th}}$ power
- Reached temperatures of $\sim 800^\circ\text{C}$, a record at the time
- Demonstrated the feasibility of operating a MSR
- Exhibited no measurable Xenon reactivity effect !
- Demonstrated the practicality of **load-following** by **varying heat extraction on the secondary side**



History: Molten Salt Reactor Experiment (MSRE)

- **Second** molten salt reactor built (1965) at ORNL
- Graphite moderated, $\text{LiF-BeF}_2\text{-ZrF}_4\text{-UF}_4$ fueled
- LiF-BeF_2 and air-cooled
- Structural material was INOR-8/Hastelloy N
- Operated for 4 years up to $7.4 \text{ MW}_{\text{th}}$ power
- Operated at a max. nominal fuel temperature of 650°C
- Demonstrated the use of **drain tanks, off-gas system**
- Demonstrated corrosion management by **redox control**
- Demonstrated relatively good behavior of Hastelloy N
- Produced **precious experimental data for validation**



History: Molten Salt Reactor Experiment (MSRE)

MSRE successfully demonstrated key MSR technologies

Salt chemistry was well-behaved

Almost no corrosion

UF_4 to UF_3 ratio maintained

Molten salts are stable under reactor conditions

Alloy N performed adequately

Little change: ultimate strength, yield strength, creep rate

Rupture ductility and creep rupture life in specimens reduced

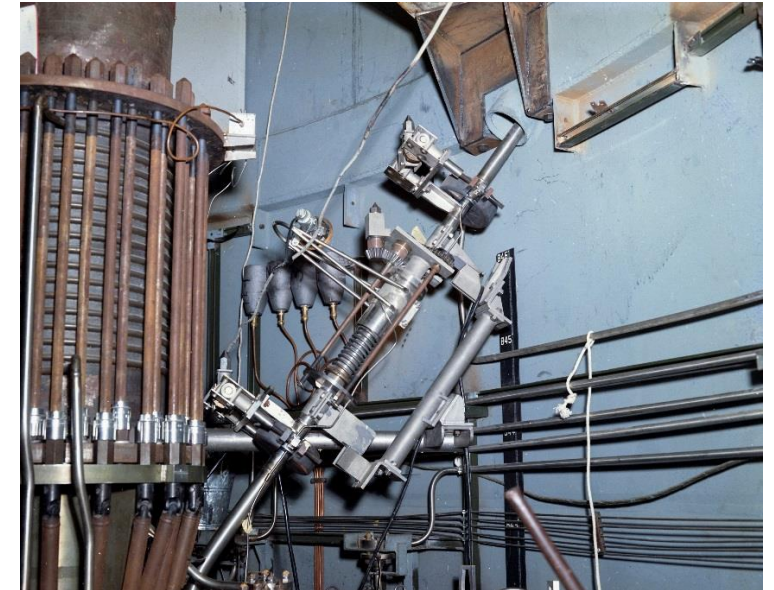
Nuclear performance closely paralleled predictions

Fission products behaved as anticipated

Noble gases Xe and Kr efficiently stripped out in off-gas system

Most other FPs remained in fuel salt

On-line and chemistry adjustment performed well



MSRE Sampler-Enricher Mechanism



MSRE Sample, Enricher Capsules

History: Molten Salt Reactor Experiment (MSRE)

MSRE *did* encounter issues during operation

Reactor vessel progressively embrittled due to neutron damage

Drain tank isolation freeze valve cracked during its final cycle due to a field modification

Stiffening the air-cooling housing prevented pipe flexing

Xenon, iodine, krypton, and noble metals detected in reactor cell

Small, continuous leak of oil into fuel pump caused foaming

Periodic plugging of off-gas system

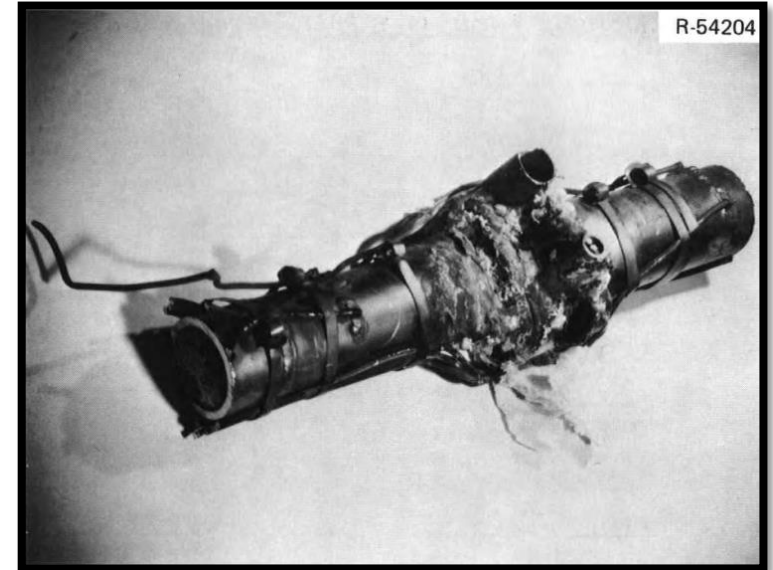
Fixed with larger filter

Pump-entrained gas caused sporadic (about 10 times/h) increases in reactor power (~5–10%) for a few seconds

Control rod failed scram test due to snagging on thimble

Experimental 'rod-jogger' stuck control rod in out position during a pseudo random binary sequence test

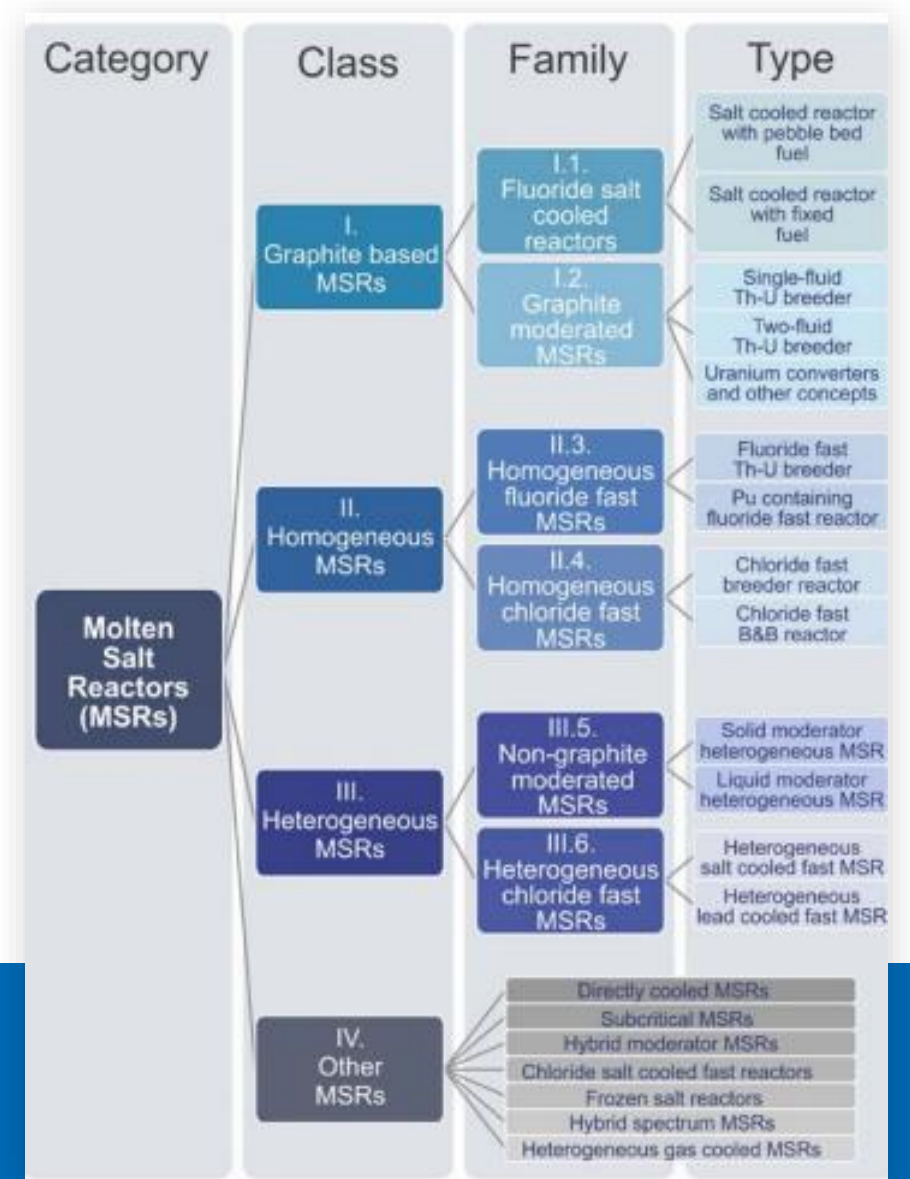
Power level ramped up then decreased without intervention



Bottom of cracked freeze valve

There are many types of MSR

- They can be **graphite-moderated, fluoride-fueled**, with either solid or liquid fuel;
- They can be **homogeneous** (only salt in the core) fast reactors, using fluoride or chloride salts; or **heterogeneous** (e.g., with coolant in the core);
- They can be moderated by **other moderator** than graphite;
- ... or even “something else” !



See “*Status of Molten Salt Reactor Technology*”,
IAEA Technical Report Series 489

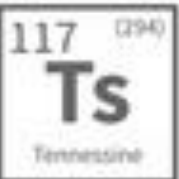
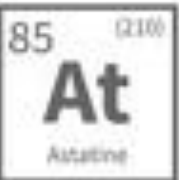
Fluoride salts vs. Chloride salts

Fluoride salts

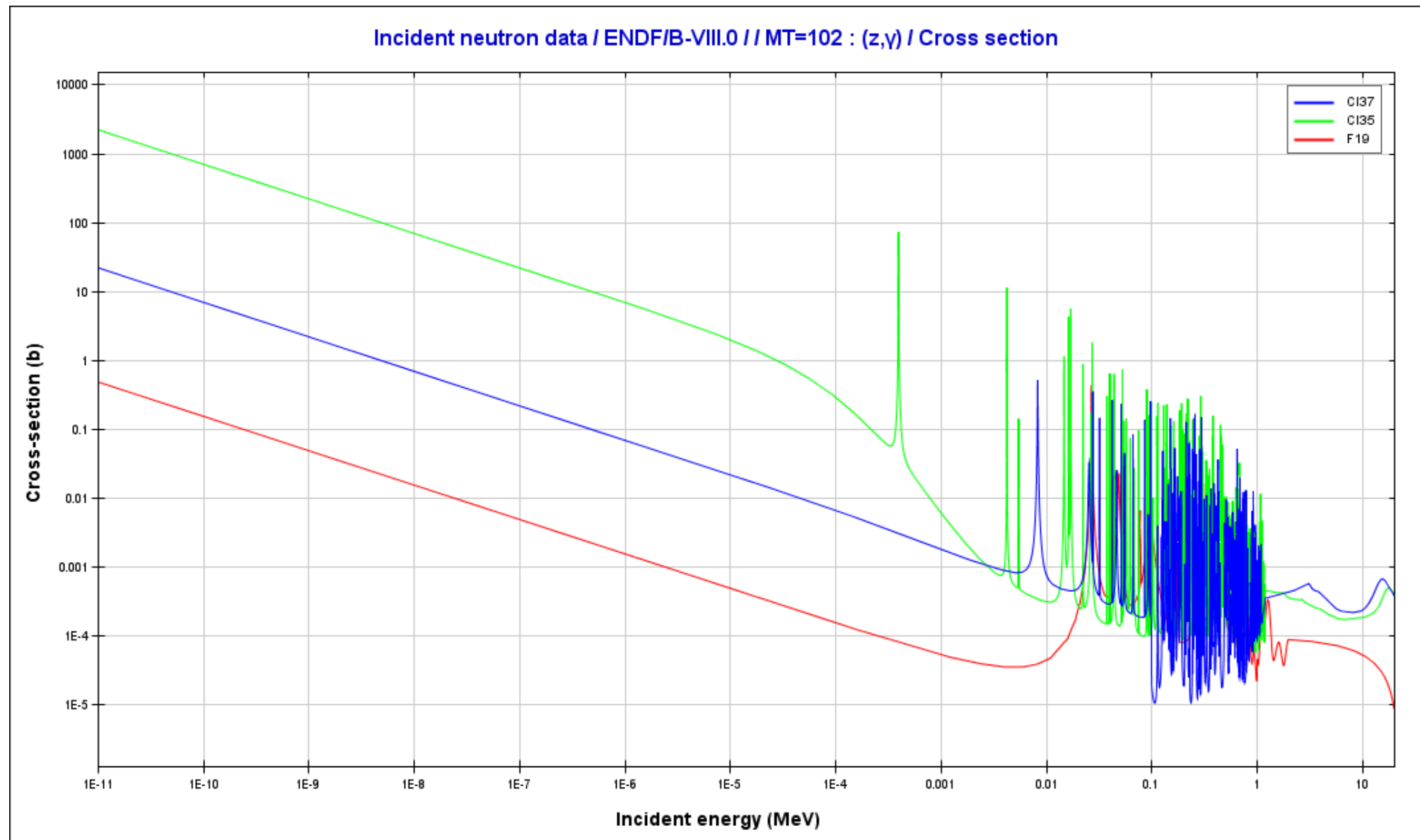
- Higher melting/boiling points;
- Higher heat capacities and densities;
- Low capture cross-section of F allows thermal spectrum;
- “Soft” fast-spectrum if unmoderated;
- Low plutonium fluoride solubility
- Good compatibility with Th-U cycle
- Generally lower activation

Chloride salts

- Lower melting/boiling points;
- Lower heat capacities and densities;
- High capture cross-section precludes thermal spectrum;
- “Hard” fast spectrum;
- High plutonium chloride solubility;
- Good compatibility with U-Pu cycle
- Higher activation (^{36}Cl)

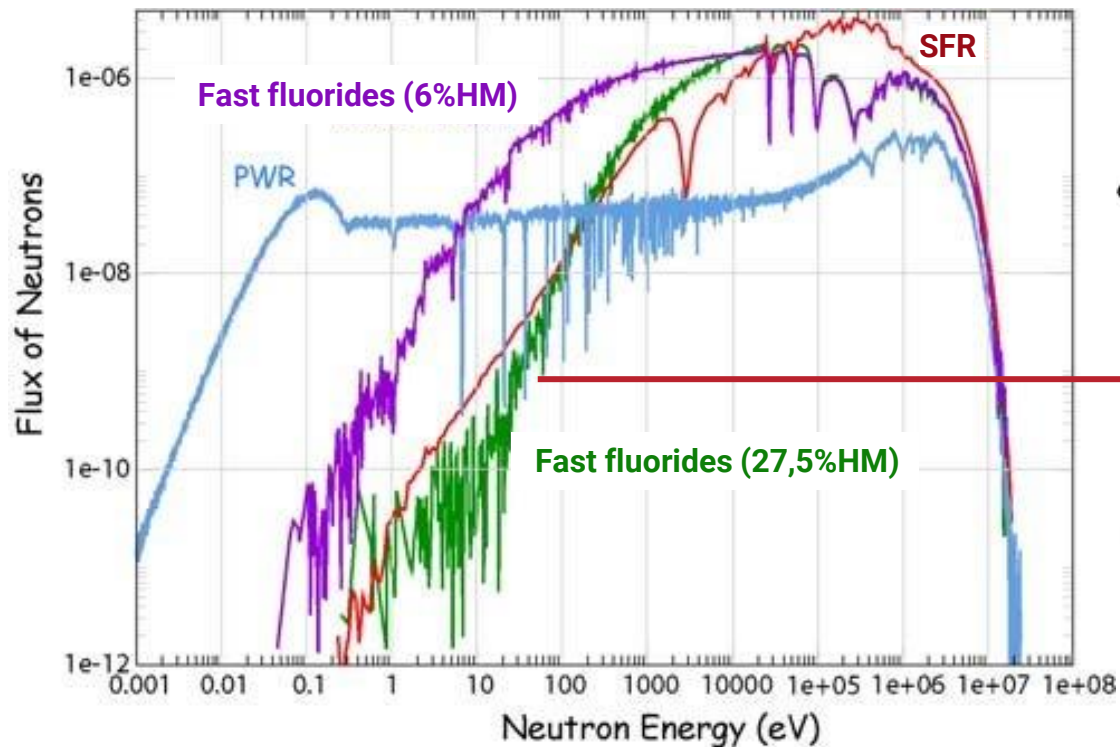


^{19}F , ^{35}Cl and ^{37}Cl cross-sections

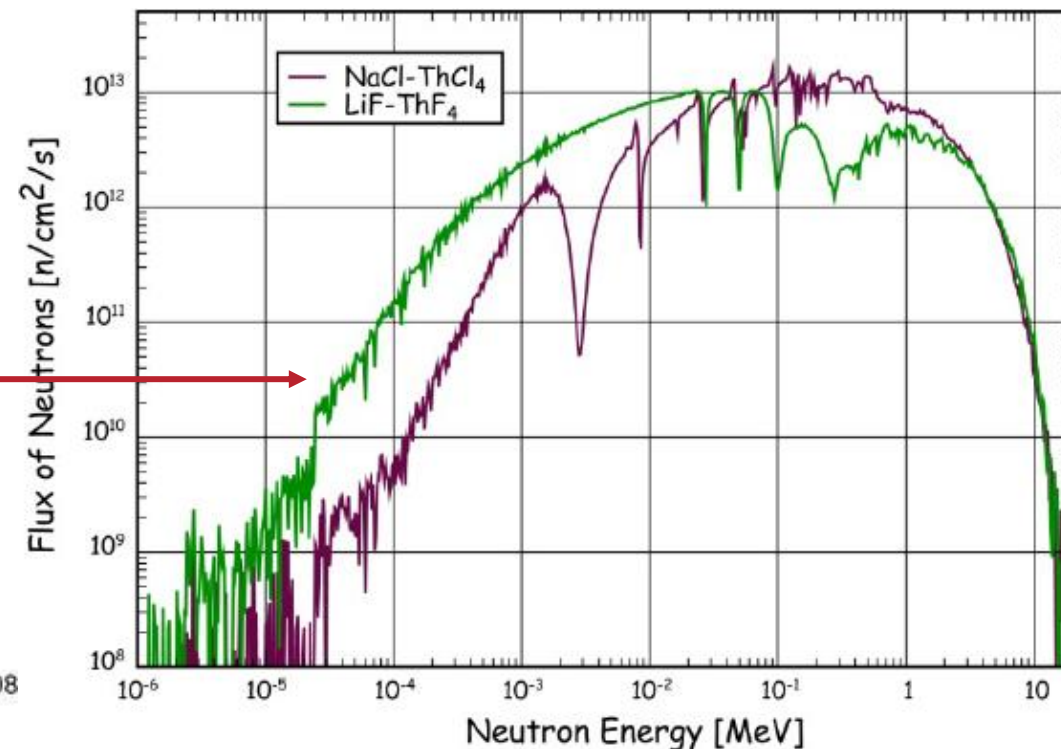


Typical neutron spectra in MSRs

Fast and thermal fluoride MSRs



Fast, homogeneous MSRs



Thermal spectrum vs. Fast spectrum

Thermal spectrum

- Lower fissile load needed
- Higher impact of fission products
- Higher beta-effective, higher neutron lifetime
- Tends to accumulate minor actinides
- Can be a breeder reactor but only in the Th-U cycle

Fast spectrum

- Higher fissile load needed
- Much lower impact of fission products
- Lower beta-effective, lower neutron lifetime
- Large neutron budget for actinide burning or breeding
- Can be a breeder reactor in both Th-U and U-Pu cycles



Graphite moderator vs. other moderators

Graphite moderator

- Chemically compatible with the salt – **no need for cladding**;
- **Limited lifetime under irradiation** (effect is temperature and flux dependent);
- Takes substantial amounts of space;
- Waste may be difficult to deal with.

Other moderators

- Solid moderators, e.g., beryllium (metal or oxide) and metal hydrides; **subject to lifetime limits due to irradiation**;
- Liquid moderators, e.g., heavy water, hydroxide salts; **not subject to lifetime limits** due to irradiation but **may interact violently with hot salt**;
- Generally, all need a **cladding material because they are incompatible with salt**.

Homogeneous vs. Heterogeneous cores

Homogeneous cores

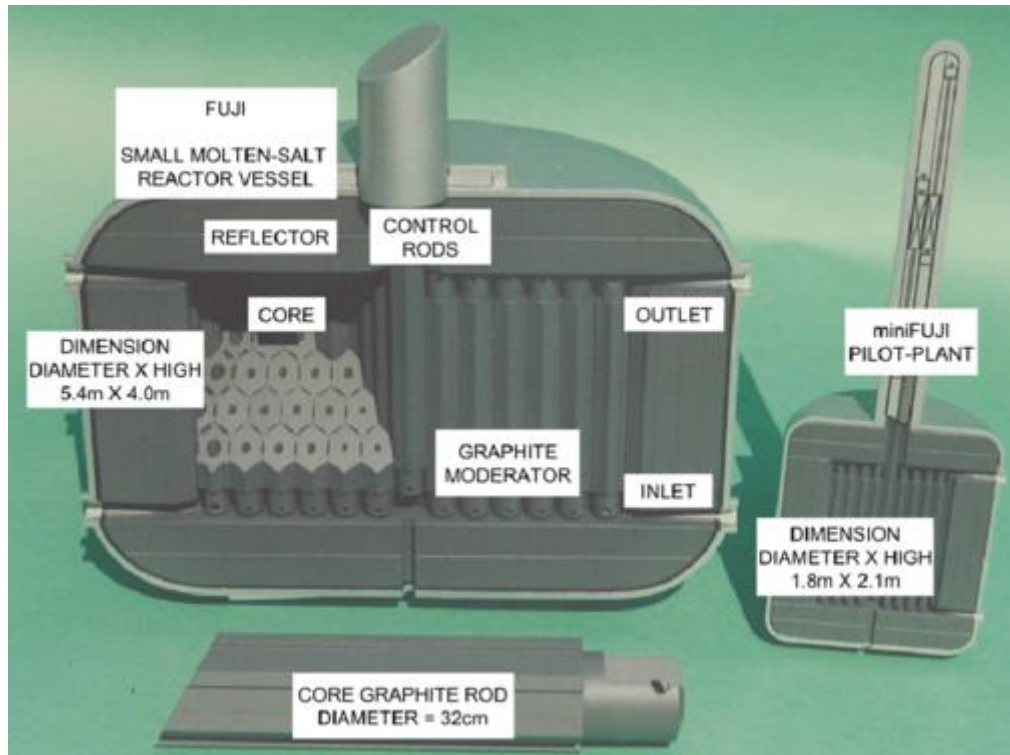
- Simple neutronics, reactivity feedback coefficients **naturally negative**
- **Low neutron absorption**, improves neutron economy, e.g., for breeding
- Potentially **more complicated thermal-hydraulics** due to 2D or 3D flow field effects

Heterogeneous cores

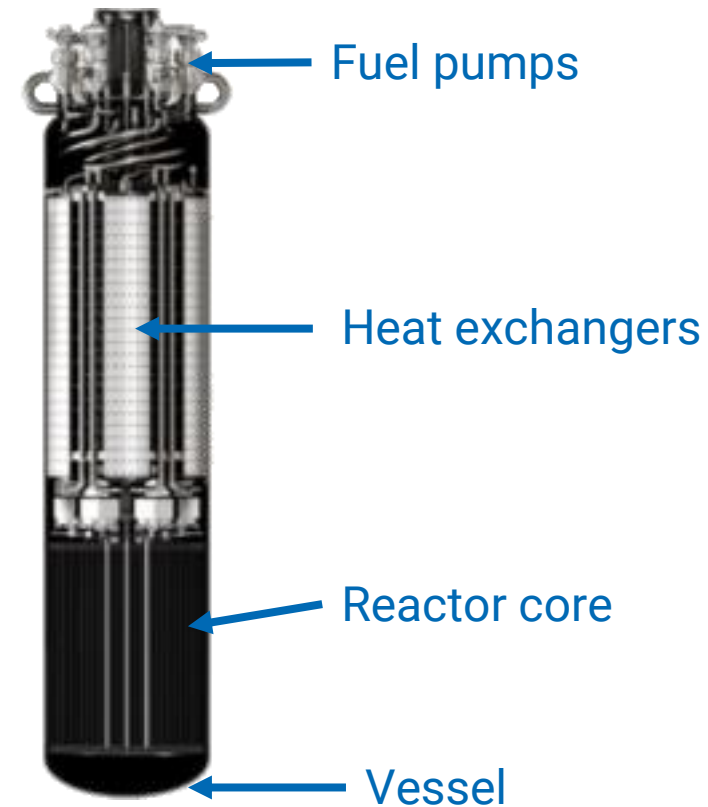
- Moderated cores are **by definition** heterogeneous ;
- Other reasons to have heterogeneity **include in-core cooling of the fuel to minimize out-of-core inventories** ;
- Heterogeneity impacts neutronics : **special attention should be paid to reactivity feedbacks**

Examples : Graphite-moderated MSR

FUJI reactor (Japan)

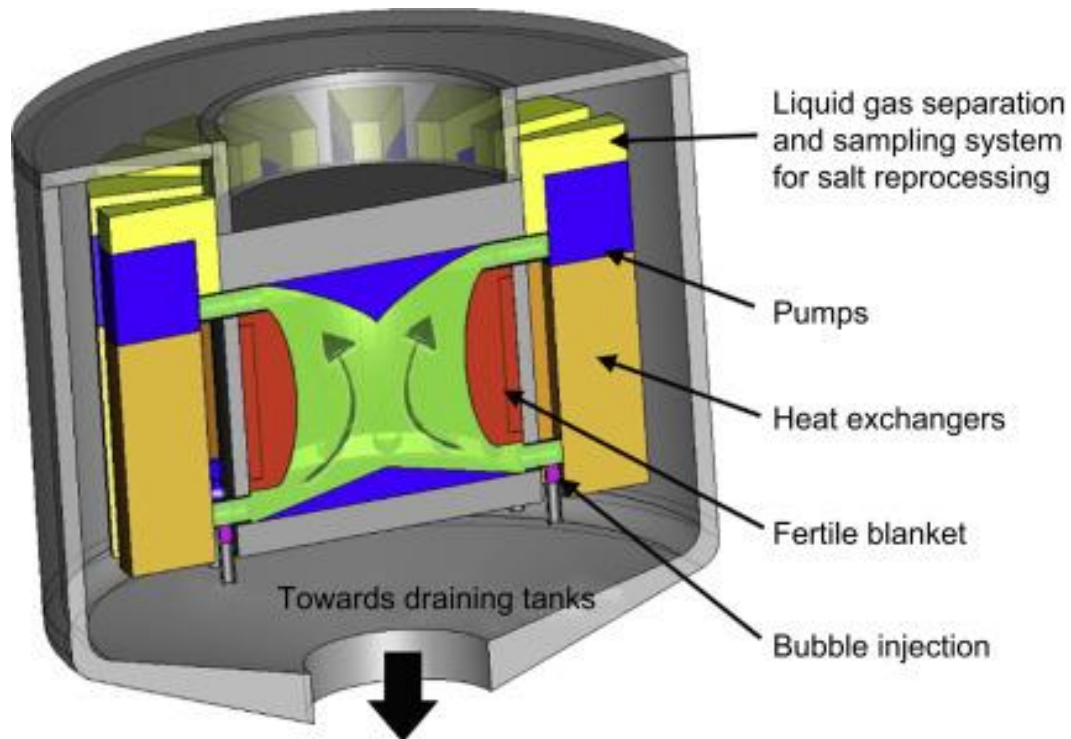


Terrestrial Energy IMSR (Canada)

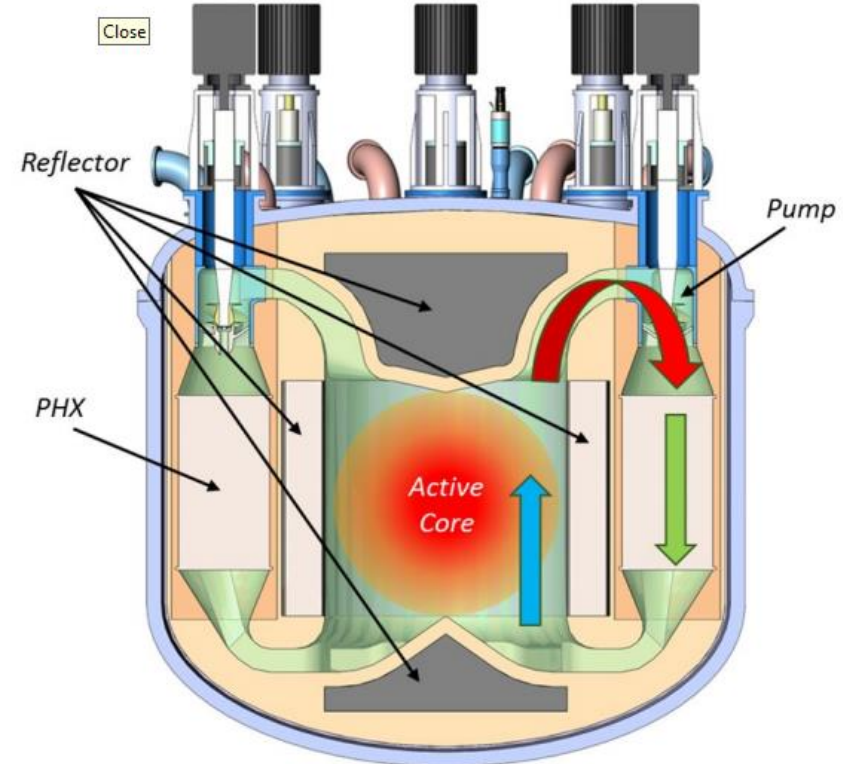


Examples : Homogeneous fast spectrum

MSFR (France, EU)

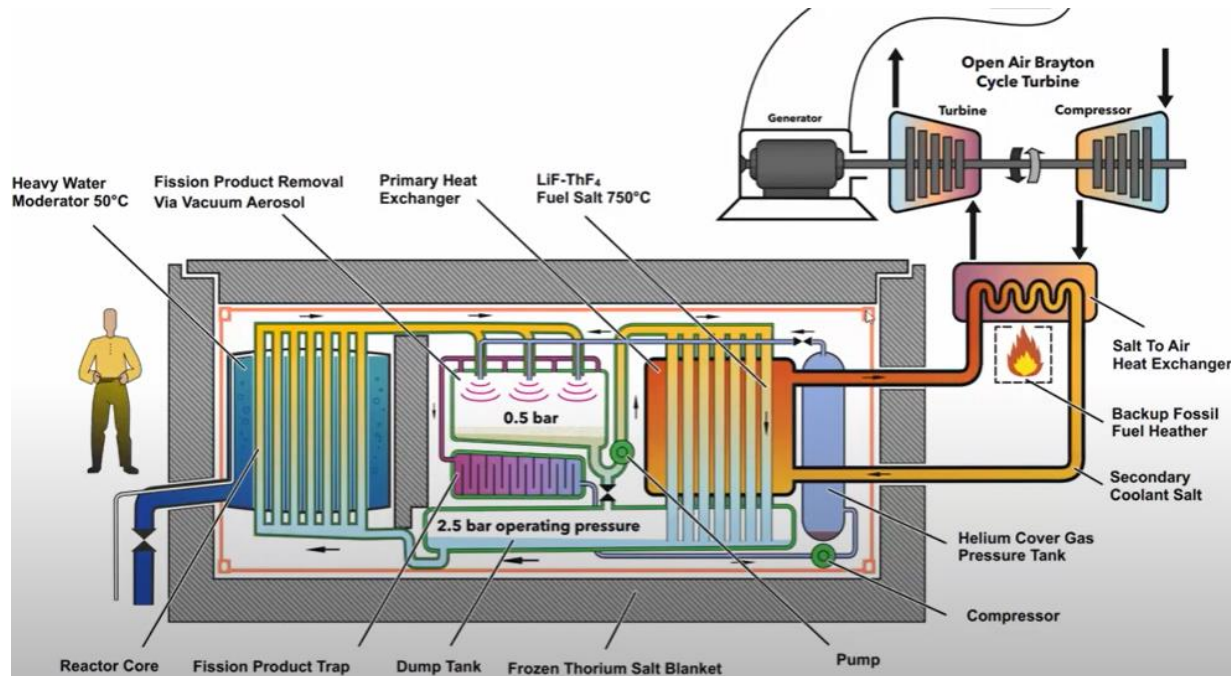


TerraPower MCFR (USA)

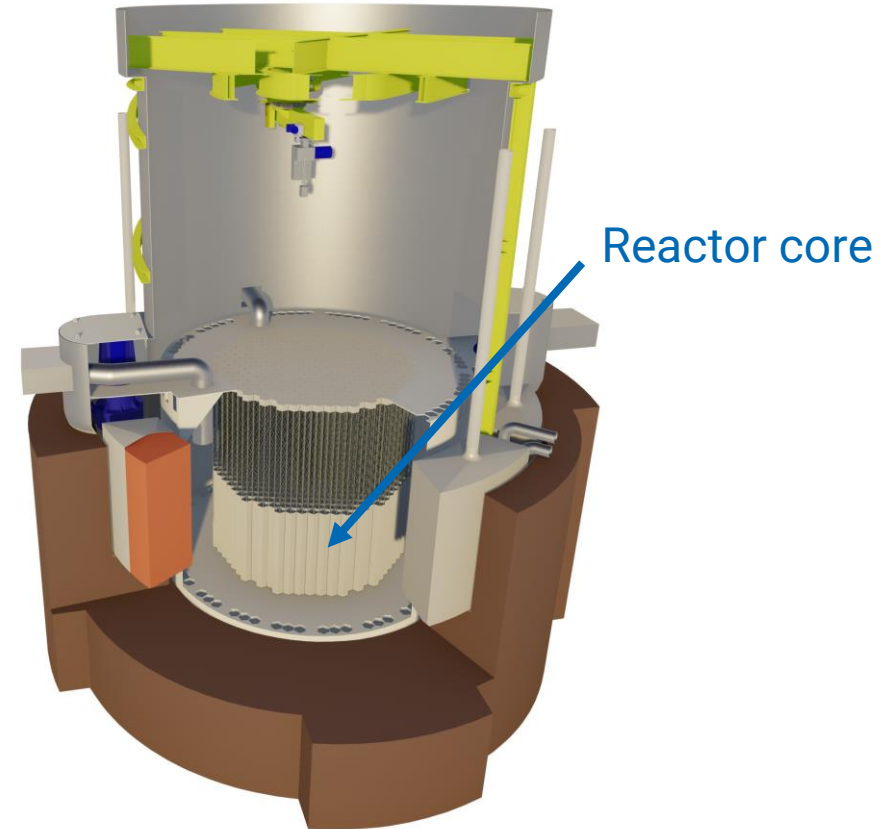


Examples : Heterogeneous MSR

Copenhagen Atomics Wasteburner (Denmark)



Moltex Energy SSR-W (UK)



Molten salt physics and chemistry

Choosing a salt mixture

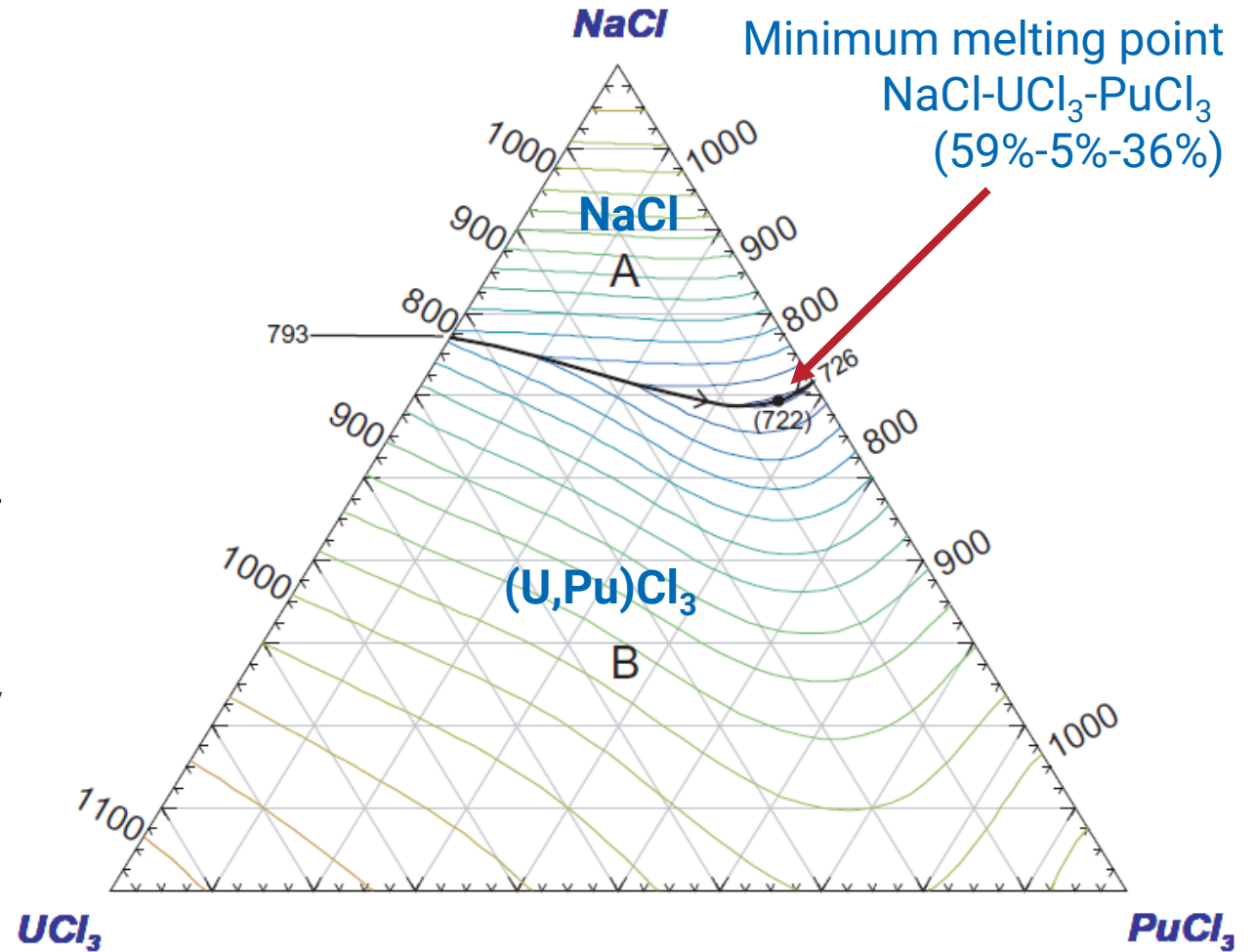
- Choose the halide (F or Cl)
- Choose diluting elements (usually, alkali or alkali-earth metals)
 - Does the element **activate** ?
 - Is it stable in salt in temperature ?
 - Does it produce a **low-melting mixture** ?
 - Is it **electrochemically compatible** with the container material ?

H hydrogen																	He helium						
Li lithium	Be beryllium																	B boron	C carbon	N nitrogen	O oxygen	F fluorine	Ne neon
Na sodium	Mg magnesium																	Al aluminium	Si silicon	P phosphorus	S sulphur	Cl chlorine	Ar argon
K potassium	Ca calcium	Sc scandium	Ti titanium	V vanadium	Cr chromium	Mn manganese	Fe iron	Co cobalt	Ni nickel	Cu copper	Zn zinc	Ga gallium	Ge germanium	As arsenic	Se selenium	Br bromine	Kr krypton						
Rb rubidium	Sr strontium	Y yttrium	Zr zirconium	Nb niobium	Mo molybdenum	Tc technetium	Ru ruthenium	Rh rhodium	Pd palladium	Ag silver	Cd cadmium	In indium	Sn tin	Sb antimony	Te tellurium	I iodine	Xe xenon						
Cs caesium	Ba barium		Hf hafnium	Ta tantalum	W tungsten	Re rhenium	Os osmium	Ir iridium	Pt platinum	Au gold	Hg mercury	Tl thallium	Pb lead	Bi bismuth	Po polonium	At astatine	Rn radon						
Fr francium	Ra radium																						
			La lanthanum	Ce cerium	Pr praseodymium	Nd neodymium	Pm promethium	Sm samarium	Eu europium	Gd gadolinium	Tb terbium	Dy dysprosium	Ho holmium	Er erbium	Tm thulium	Yb ytterbium	Lu lutetium						
			Ac actinium	Th thorium	Pa protactinium	U uranium	Np neptunium	Pu plutonium	Am americium	Cm curium	Bk berkelium	Cf californium	Es einsteinium	Fm fermium	Md mendelevium	No nobelium	Lr lawrencium						

Molten salt physics and chemistry

Phase diagrams

- Mixtures are generally chosen to have a **low melting point**.
- Phase diagrams are used to determine the **behavior of the mixtures** in terms of melting, boiling, etc.
- Phase diagrams can also **give solubility limits as function of the temperature**.
- Cooling **above the solubility limit** may lead to **precipitation of species**



Phase diagram of the NaCl-UCl₃-PuCl₃ ternary system with isotherms in Kelvins. From doi:10.1016/j.jnucmat.2008.01.007

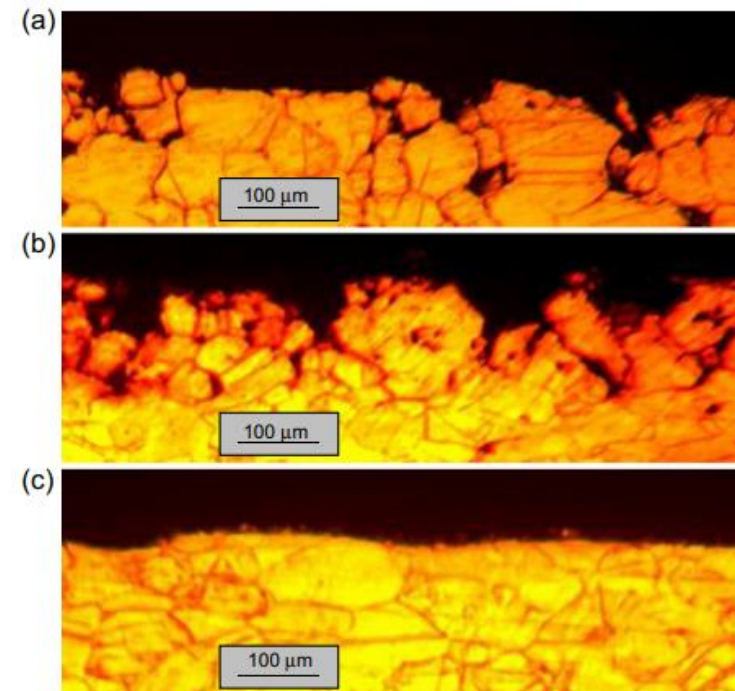
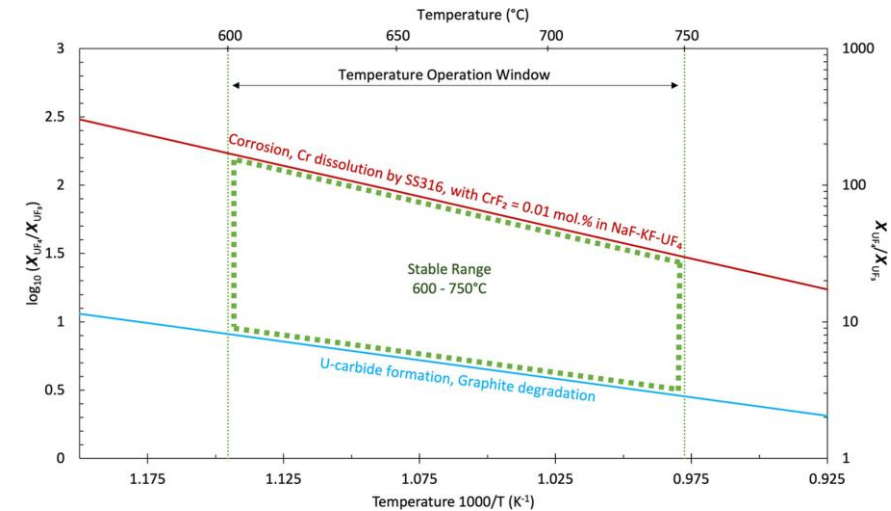
Molten salt physics and chemistry

Redox potential control

- Electrical potential in the cell formed by the salt and the container material follows the **Nernst equation**
- Influences **corrosion rates** and **what types of materials** will be stable in or in contact with the salt
- In particular, it influences the **behavior of salt components**, in particular fission products

Source (1) : doi.org/10.1016/j.electacta.2024.144647

Source (2) : doi.org/10.1016/B978-0-08-100906-2.00005-7



No load
 $U(4)/U(3) = 500$

Loaded
 $U(4)/U(3) = 500$

Loaded
 $U(4)/U(3) = 100$

Fission product behavior in salt

Physical behavior of elements

- Depending on the redox potential of the salt, elements will have different valences states
- Depending on the **temperature**, **pressure**, and **valence state**, an element will behave **differently**
- This means that there is an **additional variable to take into account** in the safety assessment

+1 H																		0 He					
+1 Li	+2 Be																	B	C	N	O	-1 F	0 Ne
+1 Na	+2 Mg																	Al	Si	P	S	-1 Cl	0 Ar
+1 K	+2 Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	0 Zn	0 Ga	0 Ge	0 As	0 Se	-1 Br	0 Kr						
+1 Rb	+2 Sr	+3 Y	+4 Zr	0 Nb	0 Mo	0 Tc	0 Ru	0 Rh	0 Pd	0 Ag	0 Cd	0 In	0 Sn	0 Sb	0 Te	-1 I	0 Xe						
+1 Cs	+2 Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	0 Rn						
Fr	Ra																						
		+3 La	+3 Ce	+3 Pr	+3 Nd	+3 Pm	+3 Sm	+3 Eu	+3 Gd	+3 Tb	+3 Dy	+3 Ho	+3 Er	+3 Tm	+3 Yb	+3 Lu							
		Ac	+4 Th	+4 Pa	+4 U	+3 Np	+3 Pu	+3 Am	+3 Cm	Bk	Cf	Es	Fm	Md	No	Lr							

Insoluble

Soluble

Sometimes soluble

Expected nominal elements behavior in a typical fluoride salt

Fission product behavior in salt

Depends on the element, redox potential, temperature...

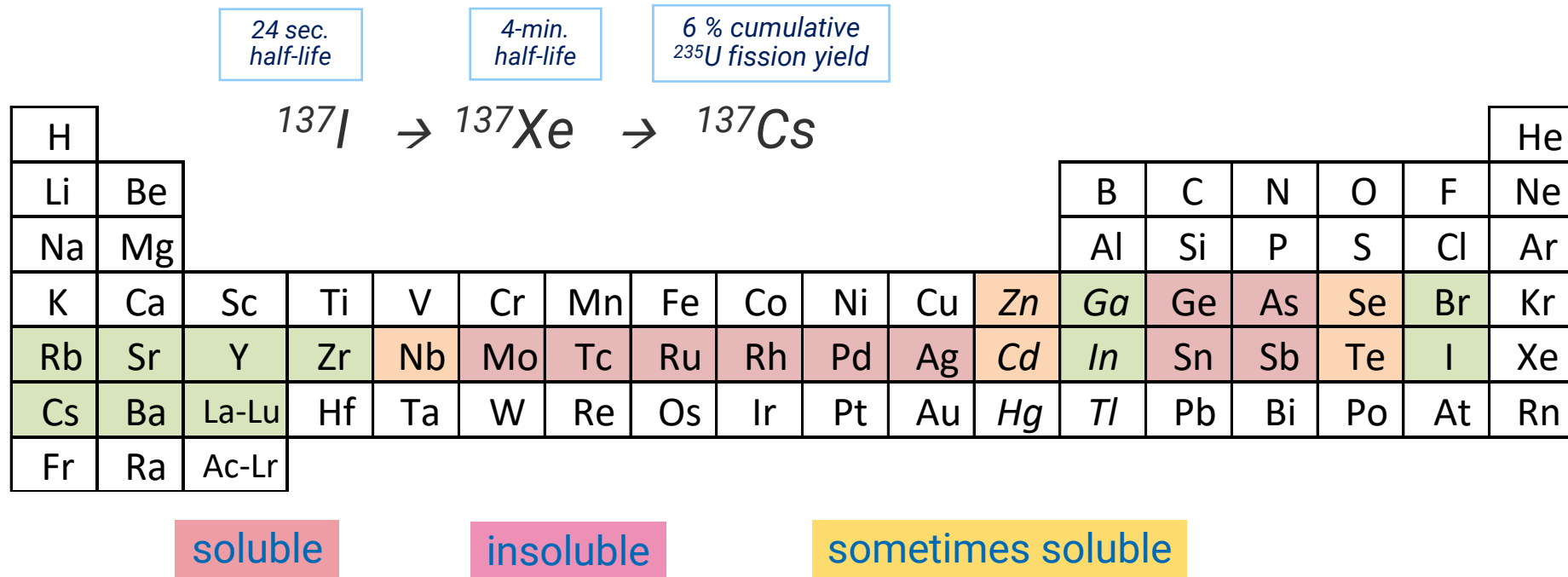
- Some elements are **gaseous** and **insoluble** in the salt : they will leave the salt naturally (e.g., Xenon, Krypton, etc.);
- Some elements are **gaseous with a small partial pressure** : part of them will be found in the cover gas (e.g., ZrCl_4), part of them in the salt.
- Some elements are **solid** and **insoluble** (electrochemically noble) : they will likely deposit (plate out) in the fuel circuit (e.g., Mo, Nb, etc.);
- Some elements are **liquid** and **insoluble** (electrochemically noble) : they will likely travel with the salt as droplets or deposit in the circuit (e.g., Sb);
- Other elements form halides and will **remain in the salt** (e.g., lanthanides).

100

A few elements are very sensitive to redox changes:

Nb behavior changed during MSRE operation after addition of Be°

Transitional (*soluble* $\rightarrow$ *gas* $\rightarrow$ *soluble*) decay example:



Fission continuously alters redox conditions

When a U or Pu ion fissions, the available electrons will rearrange on each fission product to satisfy its valence requirements and produce either net oxidizing or reducing conditions in the melt :

- For ^{235}U (as UF_4) **four** F ions are released.
FPs require <4 and thus there will be an **excess** of F ions with **net oxidizing conditions**
- For ^{239}Pu (as PuF_3) **three** F ions are released.
FPs require >3 and thus there will be a F ion **deficit** with **net reducing conditions**

MSRE periodically added metallic Be (strong reducing agent) to maintain UF_4/UF_3 ratio

- Fuel salt redox changes with decay of retained fission products and escape of gaseous fission products

Salt Type	Fission Product	Oxidation State (Z)	Yield (Y) [atoms]	Cl atoms reacted (Y*Z)
Chloride Salt (UCl_3)	Kr, Xe	0	25	0
	Rb, Cs	1	19	19
	Sr, Ba	2	10	20
	Rare Earths	3	46	138
	Zr	3	22	66
	Nb, Mo	0	2	0
	Te, I	0	6	0
	Pd, Re, Rh			
	Ag, Cd	0	61	0
	Total Cl atoms reacted out of 300 available			243
	Br, I	-1	1.5	-1.5
	Kr, Xe	0	60.6	0
	Rb, Cs	1	0.4	0.4
Fluoride Salt (UF_4)	Sr, Ba	2	7.2	14.4
	Lanthanides, Y	3	53.8	161.4
	Zr	4	31.8	127.2
	Nb	0	1.4	0
	Mo	0	20.1	0
	Tc	0	5.9	0
	Ru	0	12.6	0
	Total F atoms reacted out of 400 available			301.9

Sources: Baes (fluoride salts), Harder (chloride salts)

Maintaining mildly reducing redox conditions

Key to enabling use of engineered alloys

Use of a circulating redox buffer provides means to maintain redox condition

Fission changes oxidation state of salts

Ratio of U^{4+}/U^{3+} serves as a measure of the redox potential of the salt

Applicable to both fluoride and chloride salts

Be active metal reductant in fluorides, Mg or Zr in chlorides

Combination of active metal redox control and cathodic protection recently demonstrated to minimize chloride salt corrosion

Fluoride salts will likely have an ideal ratio of ~10–100

Uranium carbide formed when fuel salt becomes too reducing

Structural metal fluorides formed when too oxidizing

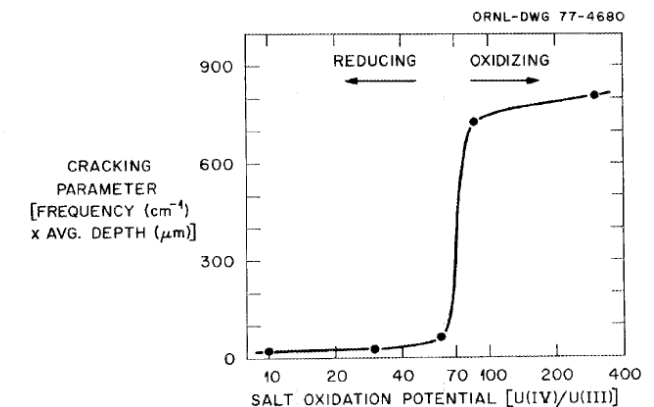
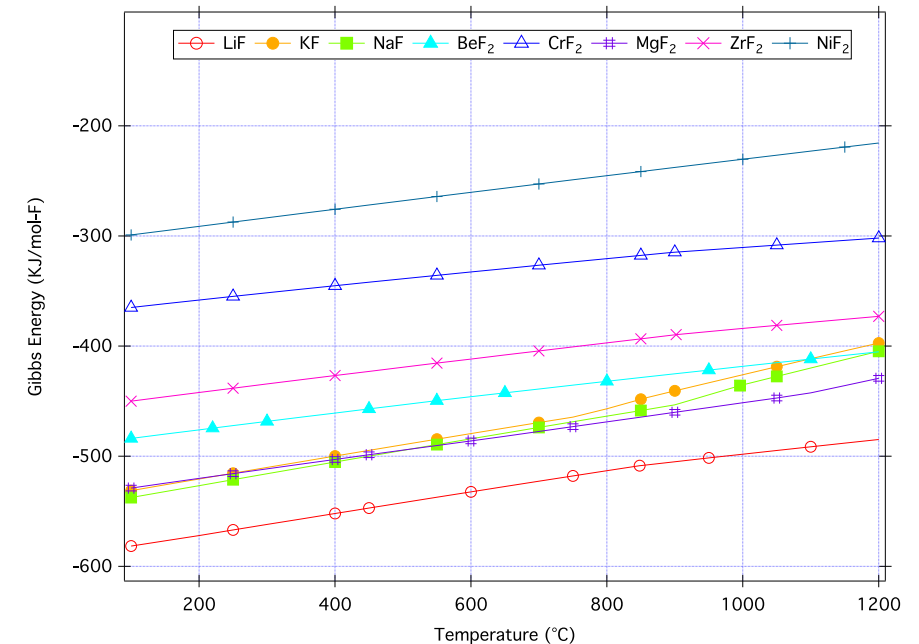


Fig. 12. Cracking Behavior of Hastelloy N Exposed 260 hr at 700°C to MSBR Fuel Salt Containing CrTe_{1.266}.

Keiser, ORNL/TM-6002

MSRE demonstrated corrosion control via redox

Source: ORNL/TM-4174

- Surveillance specimen of graphite and Hastelloy-N were introduced in MSRE
- As can be seen on the picture, numbers scratched on the surface are **still visible**
- And this after 15300 hours in salt at 650°C !
- **Corrosion control by redox control** is demonstrated, but it needs to be implemented **practically** for a reactor

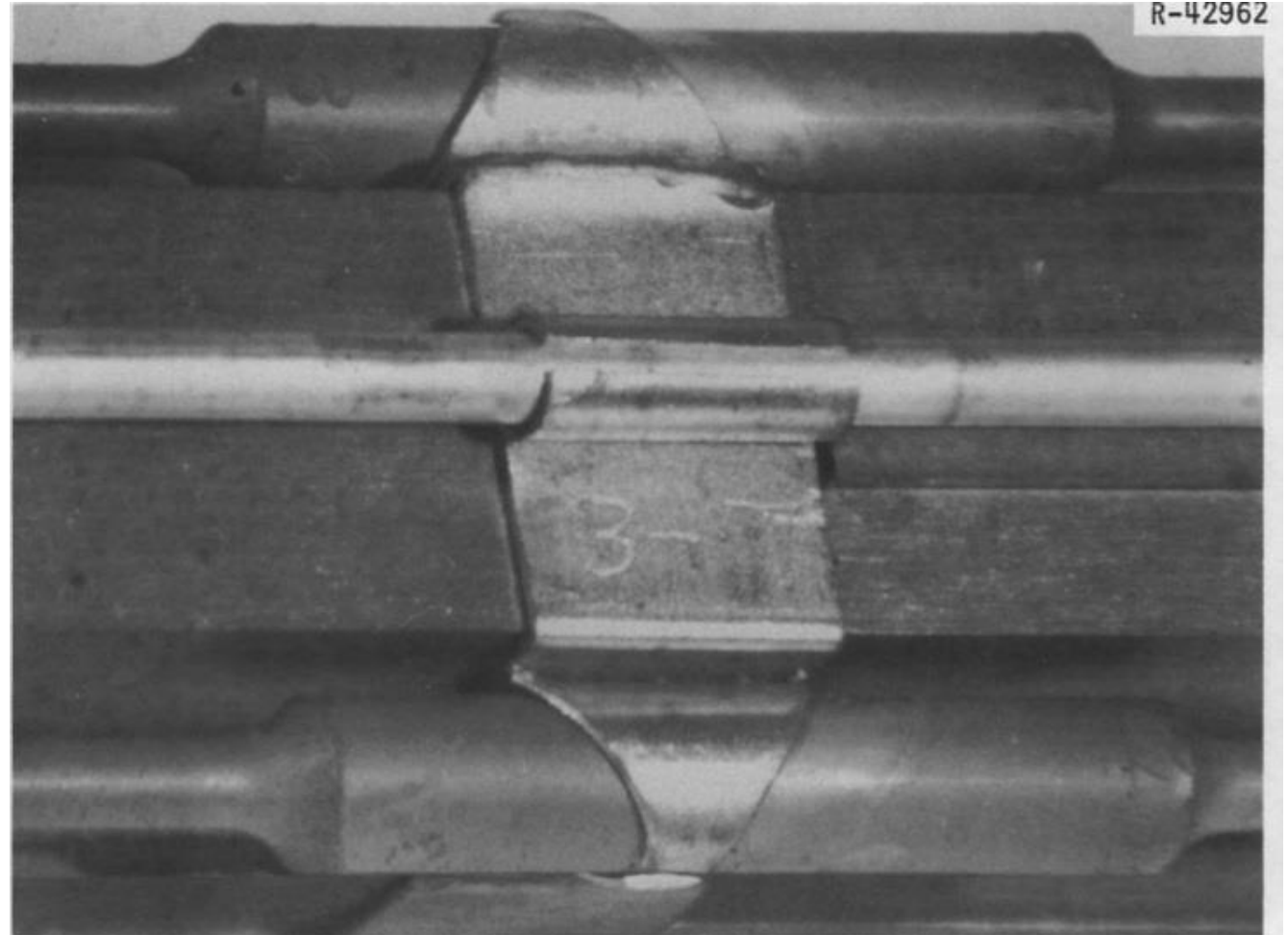


Fig. 1. Graphite and Hastelloy N Surveillance Assembly Removed from the Core of the MSRE After 72,400 Mwhr of Operation. Exposed to flowing salt for 15,300 hr at 650°C.

Fuel off-gas system

MSRE example

- Salt circuits need to be **inertized** to avoid **air** or **water ingress**
- Gaseous/volatile compounds must be handled
- Many MSRs use an off-gas system dedicated to this task

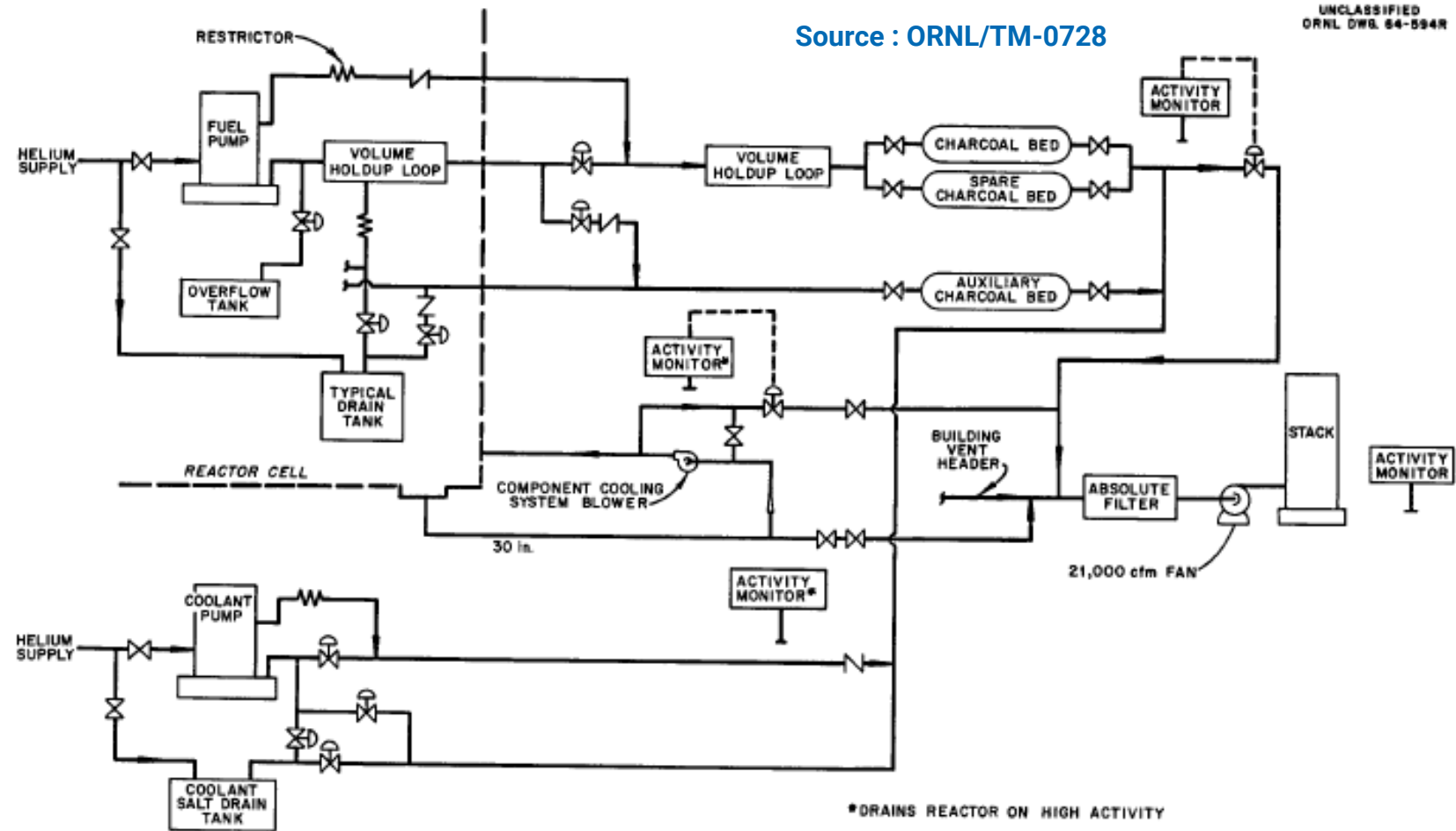
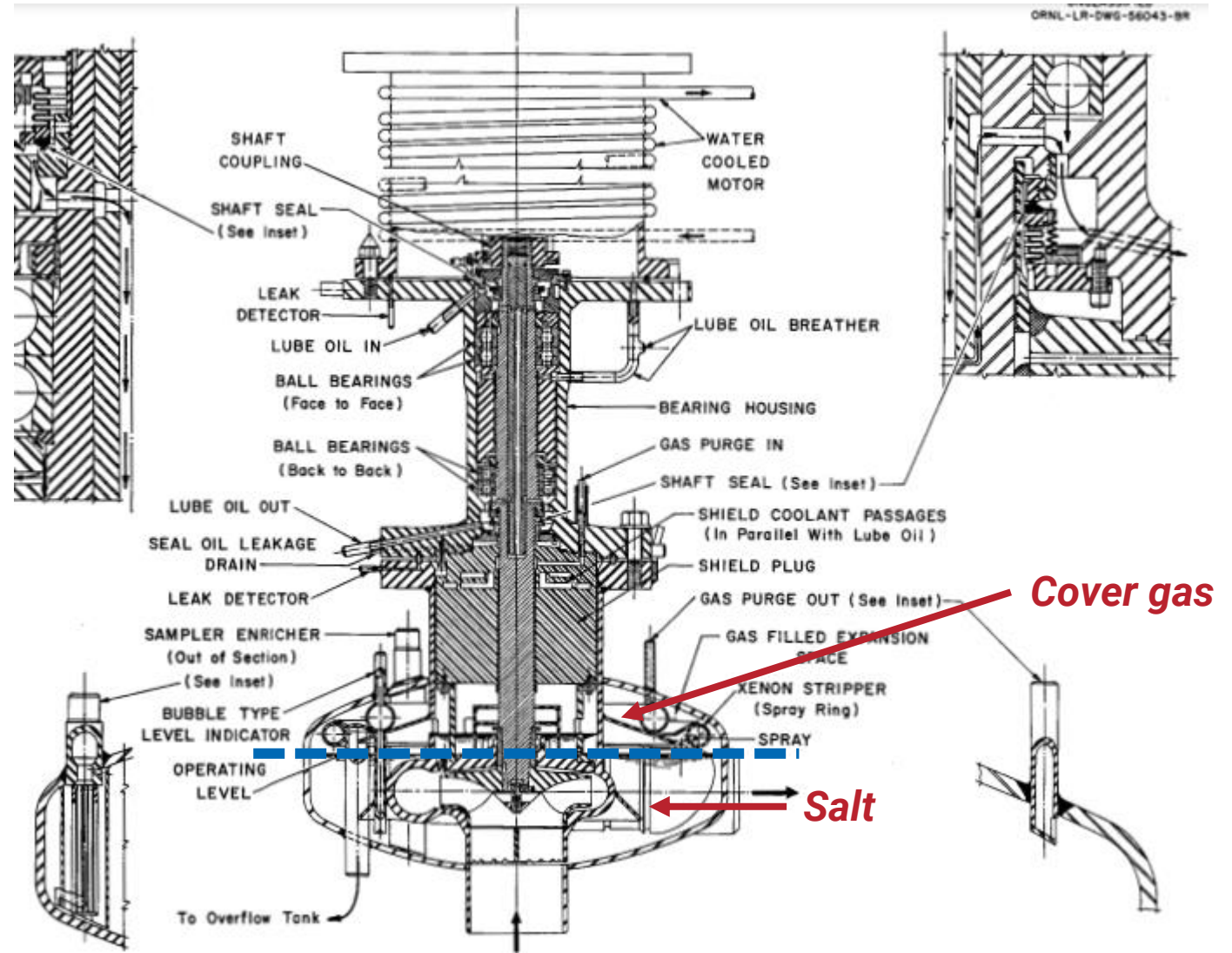


Fig. 12.1. Schematic Diagram of Off-Gas System.

Fuel off-gas system and pump bowl

MSRE example

- The MSRE pump also plays the role of **expansion tank**
 - Like the PZR in a PWR, accommodates for **changes in volume** of the fuel with temperature
- Provides the fuel circuit with cover gas for inertizing
- Provides free surface for removal of gaseous FP



Fuel salt drain tanks

MSRE example

- You generally need a place to **remove your salt to** for **operational** reasons (e.g., maintenance).
- Such drain tanks can also be used as **safety systems**, as the **fuel can be drained by gravity** from the core into the tank.
- This can be used as a **reactivity control method** and/or alternate **decay heat removal method**.
- Ways of draining include pumping stoppage, frozen valves, siphons, active valves...

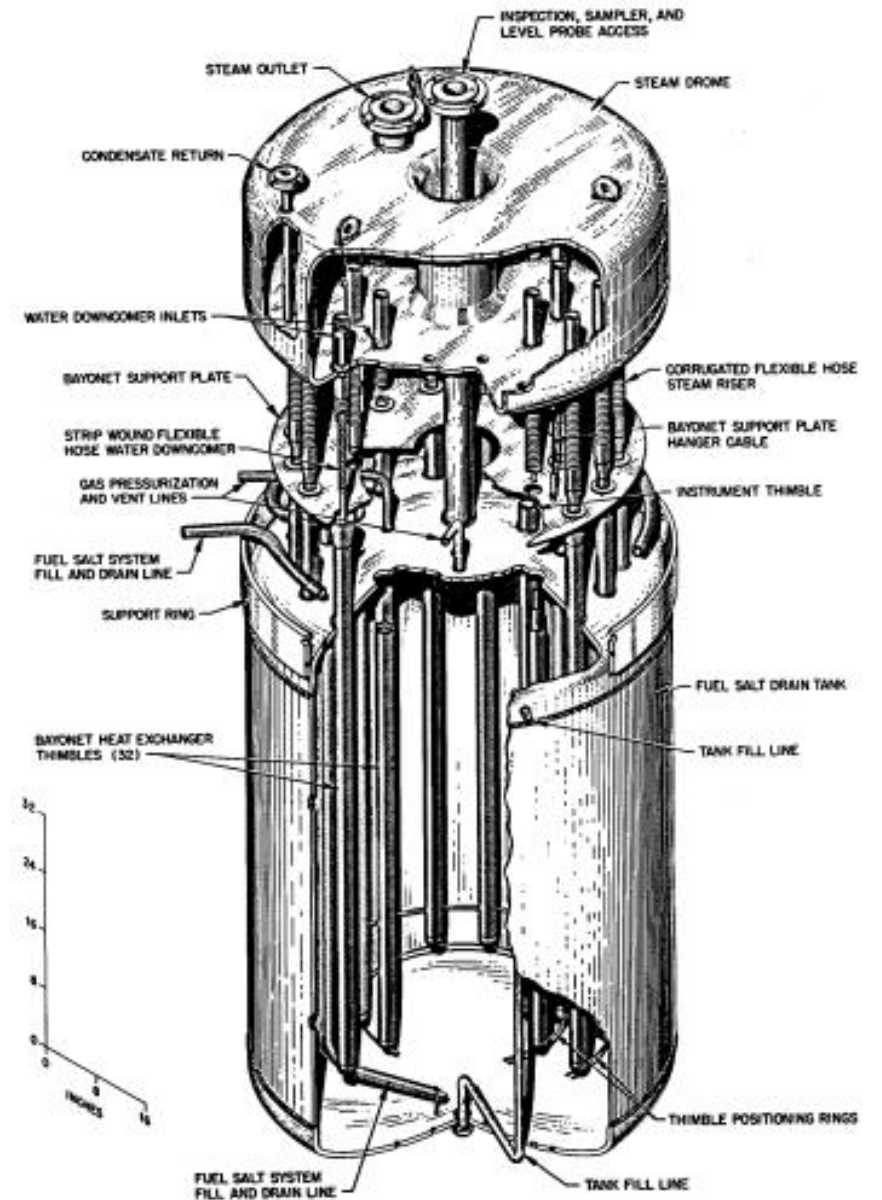


Fig. 2.6. Fuel-Salt Drain Tank.

Source : ORNL/TM-0728

Distributed source term & decay heat

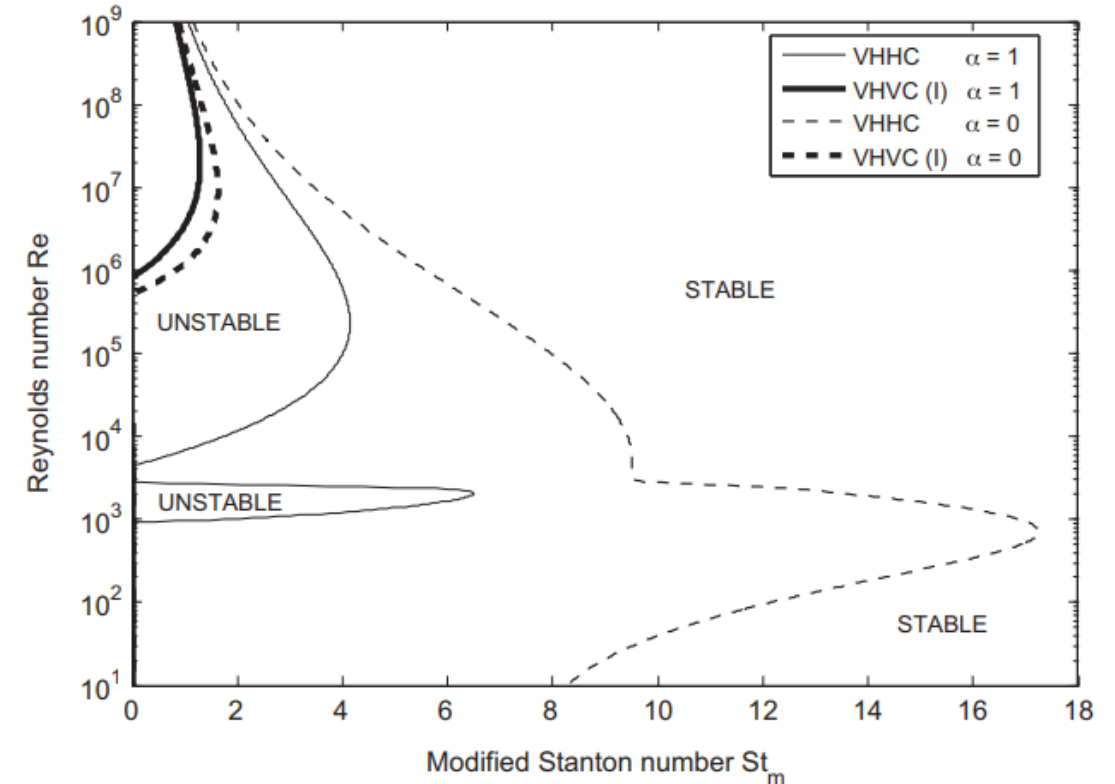
A unique aspect of MSR's

- Some elements will **leave the salt to the cover gas** or **deposit in the fuel circuit**
- This means that both the **source term** and the **decay heat** will be **distributed** (not “all in one place”)
 - Specific **challenge to decay heat removal** fundamental safety function;
 - Specific **challenge to the confinement of radionuclides** fundamental safety function;
 - Specific challenge for **maintenance, in-service inspection, and decommissioning**.
- Not only does it need a dedicated safety approach, but also:
 - **Specific physico-chemical models for codes** (including severe accidents)
 - **Experimental data to validate the models** (which may be difficult to obtain!)

Natural circulation & stability

Impact of internal heat generation

- It is known that **natural circulation** can be **unstable** in certain situations ;
- Internal heat generation (for example in a **liquid fuel with decay heat**) tends to **increase the size of the unstable domains**;
- **Particular attention should be paid to the physics of such systems**, as well as experimental and code validation.



Stability maps for loops with vertical heaters and horizontal (VHHC) or vertical (VHVC) cooler and without ($\alpha=1$) or with ($\alpha=0$) internal heat generation

Source : doi.org/10.1016/j.ces.2014.12.050

Delayed neutrons precursors (DNP) drift

Reduced effective delayed neutron fraction

- Most MSRs are **circulating-fuel reactors**;
- Fuel circulation leads to **part of the delayed neutron precursors decaying outside of the active region**;
- This **reduces the effective delayed neutron fraction**, and thus, the **margin to prompt criticality**;
- Moreover, **variations in the circulation of fuel lead to reactivity transients**

Classical point kinetics equations

$$\frac{d}{dt}N(t) = \frac{\rho(t) - \beta}{\Lambda_{\text{eff}}}N(t) + \sum_{i=1}^G \lambda_i \mathbf{C}_i(t)$$

$$\frac{d}{dt}\mathbf{C}_i(t) = \frac{\beta_i}{\Lambda_{\text{eff}}}N(t) - \lambda_i \mathbf{C}_i(t)$$

Modified point kinetics equations

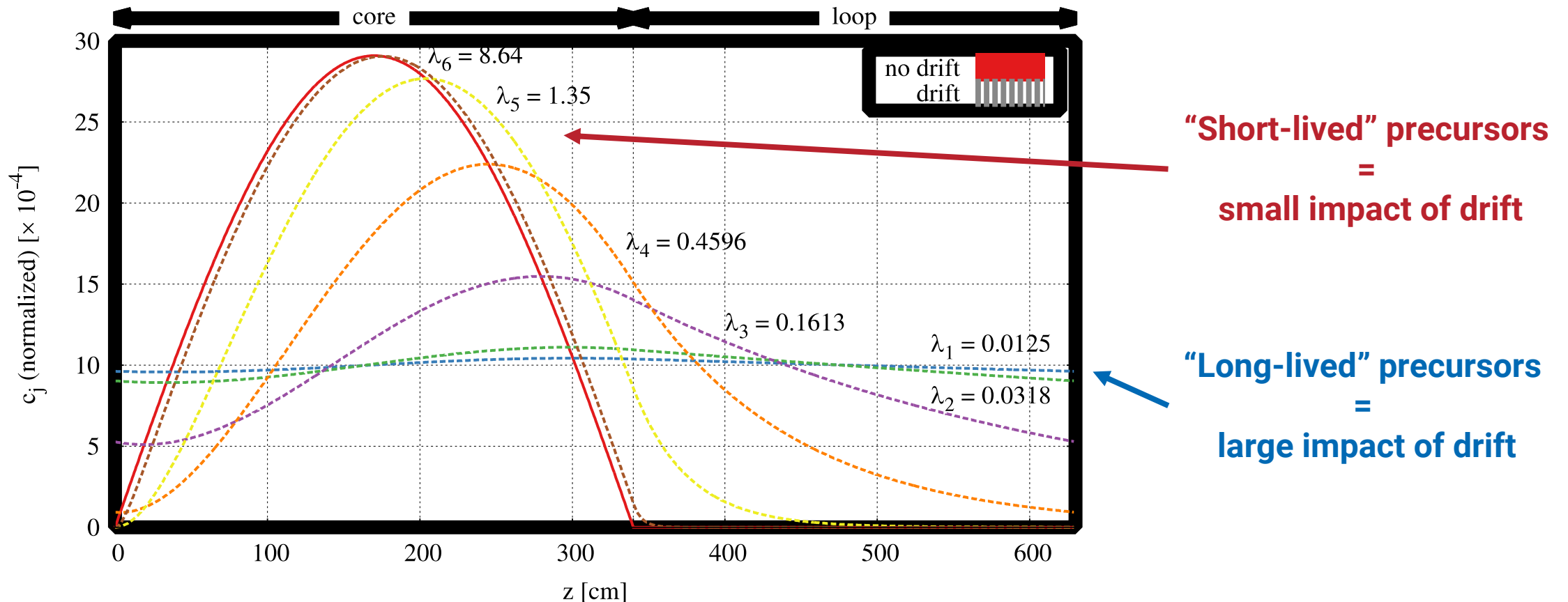
$$\frac{d}{dt}N(t) = \frac{\rho(t) - \beta}{\Lambda_{\text{eff}}}N(t) + \sum_{k=1}^K w_k \sum_{i=1}^G \lambda_i \mathbf{C}_i^k(t)$$

$$\frac{d}{dt}\mathbf{C}_i^k(t) = \frac{\beta_i}{\Lambda_{\text{eff}}}N(t) - \lambda_i \mathbf{C}_i^k(t) + \dot{\mathbf{C}}_i^{k,\text{in}}(t) - \dot{\mathbf{C}}_i^{k,\text{out}}(t)$$

To take delayed neutron precursor (DNP) movement into account

Delayed neutrons precursors (DNP) drift

An example of DNP distribution



Source: B. Ade, B. Betzler, et. al., *MSR Modeling Tools: Past, Present and Future*, presented at the Advanced Reactor Working Group Modeling & Simulation Workshop, EPRI, Charlotte, NC, January 24-25, 2017.

Examples of DNP movement-mediated transients

Pump flowrate variations

- Experiments were conducted in MSRE with an initial critical state and the reactivity change during the transient would be compensated by control rod movement.
- Two situations : initially **critical at full flowrate** and **pump coast-down transient**, and initially **critical at zero flowrate** and **pump start-up**.

Source : ORNL-4233

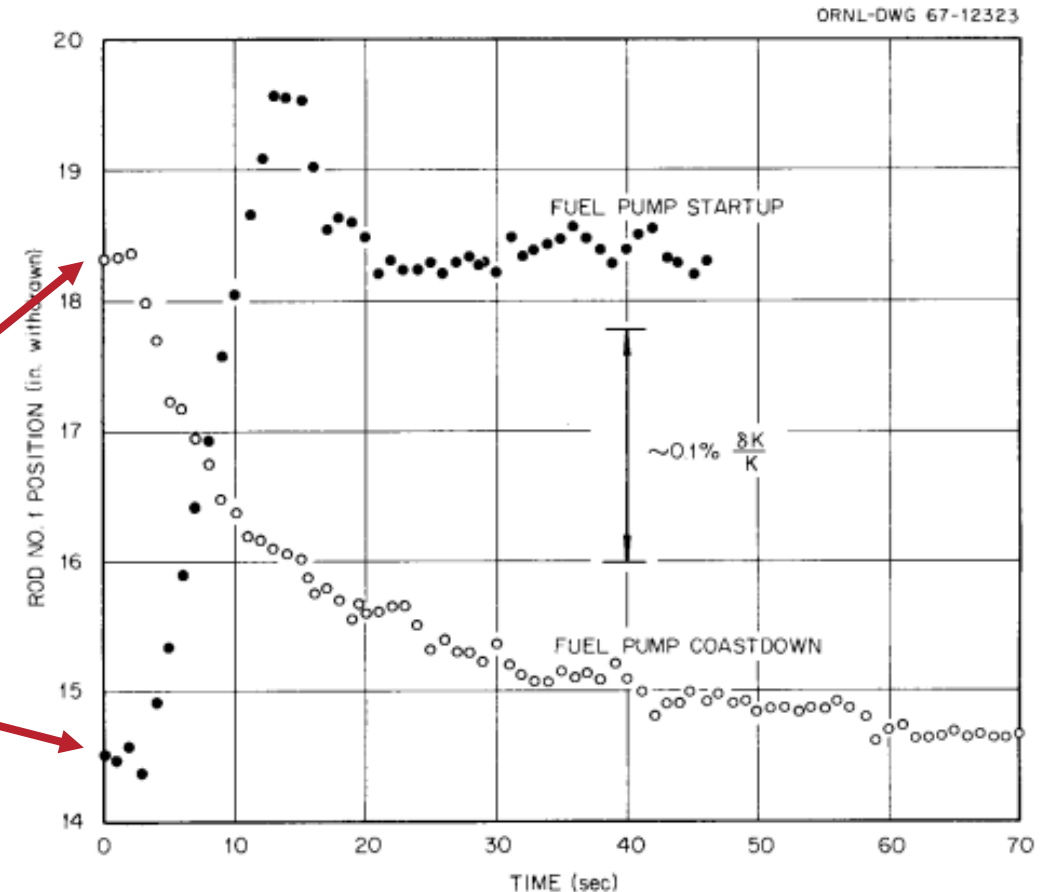


Fig. 24. Control-Rod Response to Fuel-Pump Startup and Coastdown.

Fuel density reactivity feedback

Reactivity effect of fuel dilatation

- The fuel being **liquid**, it dilates **more** with temperature than a solid (approx. **by a factor of 10**);
- Provided the fuel can expand **freely**, fuel expansion **reduces the fuel density in the core**;
- The **reactivity effect** is thus strongly **negative**;
- Moreover, the power is deposited mostly **directly in the fluid** (because it is fuel), and thus the feedback is **fast** (but **not instantaneous**);
- In many MSR designs, it plays a **central role** in the safety of the core design.

MSR Safety considerations

Boris Hombourger, Ph.D.

Safety considerations

It is not straightforward to adapt the usual approach

- What is **fuel** or **core damage** in a liquid-fuel Molten Salt Reactor ?
 - Could be interpreted as the **loss of the first barrier**
- How many and what are the **barriers** in MSR ?
 - The fuel circuit may be the obvious one, but which others ?
- How do you apply **defense-in-depth** in MSR ?
 - Dispersed radioactive material
 - Fuel in many places of the installation
- To date there is no consensus for MSR, but a IAEA TECDOC in preparation

Fundamental safety functions (FSFs)

From SSR-2/1 rev. 1 :

Fulfilment of the following **fundamental safety functions** for a nuclear power plant **shall be ensured for all plant states**:

1. Control of reactivity

- In MSRs there may be fuel outside of the core and fuel store !

2. Removal of heat from the fuel and the fuel store

- In MSRs there may be decay heat outside of the core and fuel store !

3. Confinement of radioactive material, shielding against radiation and control of planned radioactive releases, as well as limitation of accidental radioactive releases

- In MSRs there may be radioactive material in several locations !

FSFs : Control of reactivity & Heat removal

Example of design choice : Drain tanks

- Many designs foresee the use of drain tanks like MSRE
- Drain tanks may be designed to remain subcritical, even after fuel salt solidification
- Drain tanks may be used as a **diverse reactivity control mechanism**
 - If primary reactivity control systems fail, drain the salt
- Drain tanks may be used a **diverse decay heat removal mechanism**
 - If heat cannot be removed in the core, drain the salt
- Alternatives for **fast negative reactivity insertion** may include e.g. control rods
- Fuel drainage may be design to happen passively (freeze valves, siphons, etc.)

FSFs : Control of reactivity

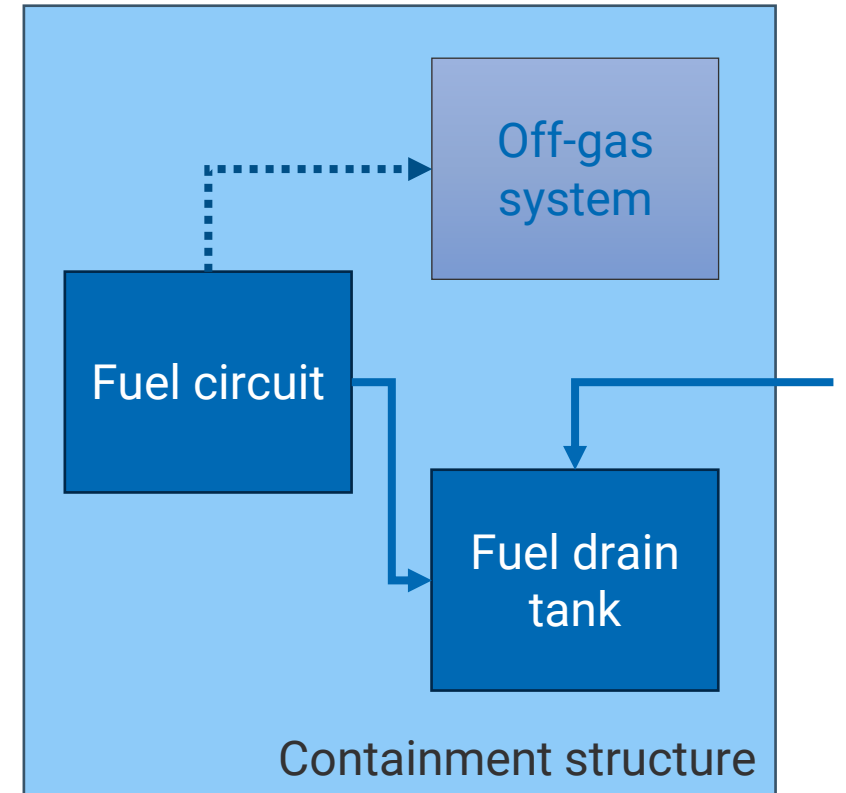
Example of design choice : Low excess reactivity

- Due to the ease of refueling a MSR, one could choose to have **low excess reactivity**:
 - In a breeder reactor, reactivity swing can be minimized by breeding
 - In other reactors, the salt can be refueled or topped-up (adding more salt)
- Having low excess reactivity *may* make possible to “survive” the most envelope reactivity insertion transient and reaching a non-hazardous stable state.
- For example, with **+1000 pcm** reactivity insertion and **-10 pcm/°C** fuel temperature reactivity feedback coefficient, the asymptotic fuel temperature increase would be limited to **+100°C**.

FSFs : Confinement of radioactive materials

With dispersed radioactive materials

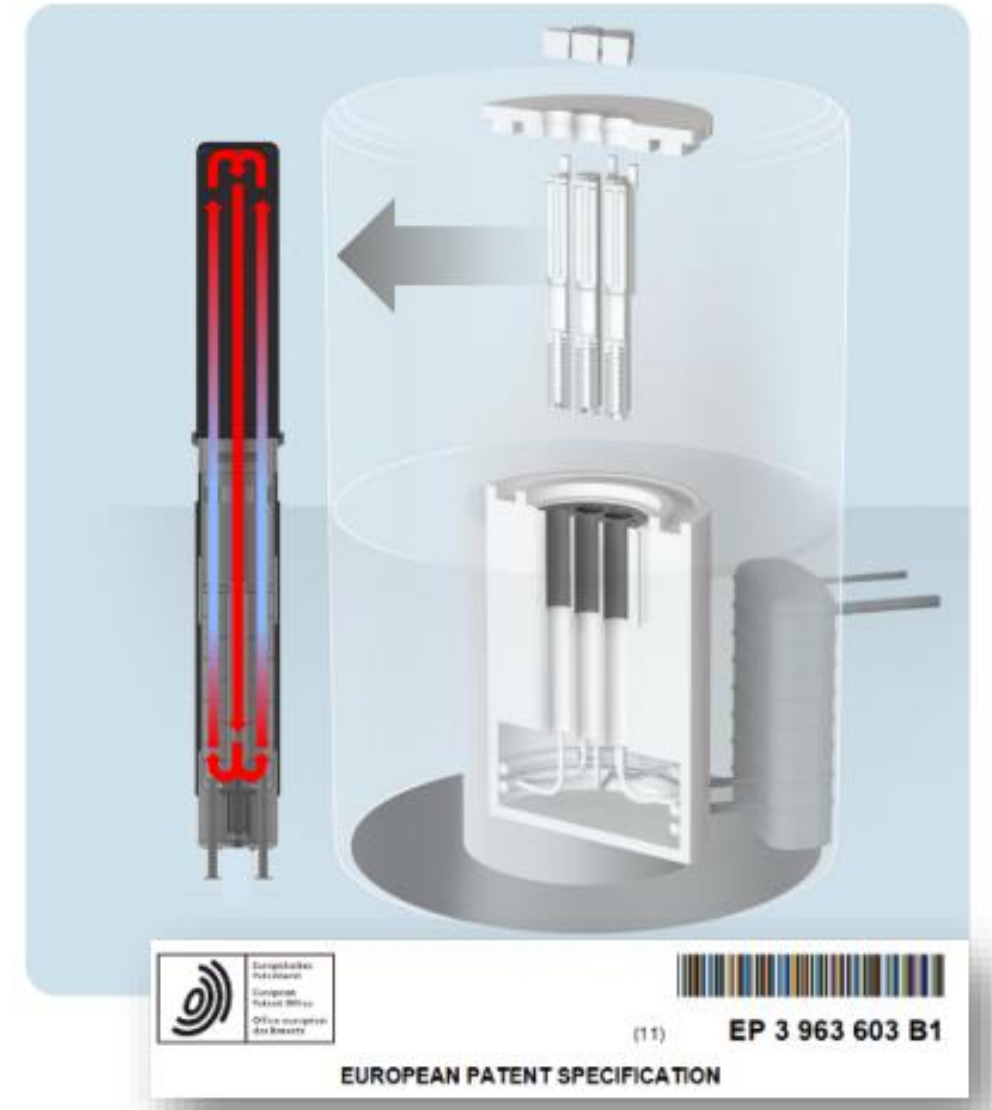
- In a liquid-fuel MSR the **fuel circuit is the first physical barrier to the release of radionuclides**
 - **Any leak of fuel** (flange leakage, pipe break, etc.) outside of the circuit **would lead to a release**.
- Defense-in-depth requires **multiple barriers**.
- Many designs therefore foresee the use of **at least one containment structure**.
- For designs **foreseeing the use of an off-gas system**, it is likely necessary to **include the system in the containment structure**.



An alternative approach to confinement

Thorizon (Netherlands) design

- Reactor is made of several “**cartridges**”
- Each **cartridge** is its **own fuel circuit**
- Including **pumps, intermediate heat exchangers**
- Fuel is kept in the top part (the core) by pumping, a stop shuts the reactor down
- **Fuel and gaseous FPs never leave the cartridge** during normal operation



Specific safety functions in MSR

Fuel properties control : composition

- Water, oxygen (for example from impurities in cover gas) or air ingress can lead to oxidation of salt components by oxygen.

- Which can lead to their **precipitation in the form of oxides, e.g. :**



- This **could happen to fissile material** and present :
 - **A criticality risk** : accumulation of denser fissile material in some part of the installation
 - **A plugging risk** : risk of flow blockage or **off-gas system** line plugging
- Therefore, fuel composition and purity control plays a particular safety role.

Specific safety functions in MSRs

Fuel properties control : vapor pressure

- Vapor pressure **increases** with increasing temperature.
- A positive vapor pressure implies **some elements are in the cover gas**.
- For fuel salt, this means a certain quantity of **fuel salt vapors are in the gas phase**.
- Cover gas flow rate could **carry these elements away in the off-gas system**.
- It may lead to **accumulation of fissile material** in a part of the installation **not designed for it**.
- Therefore, **particular attention** should be paid to this phenomenon.

Specific safety functions in MSR

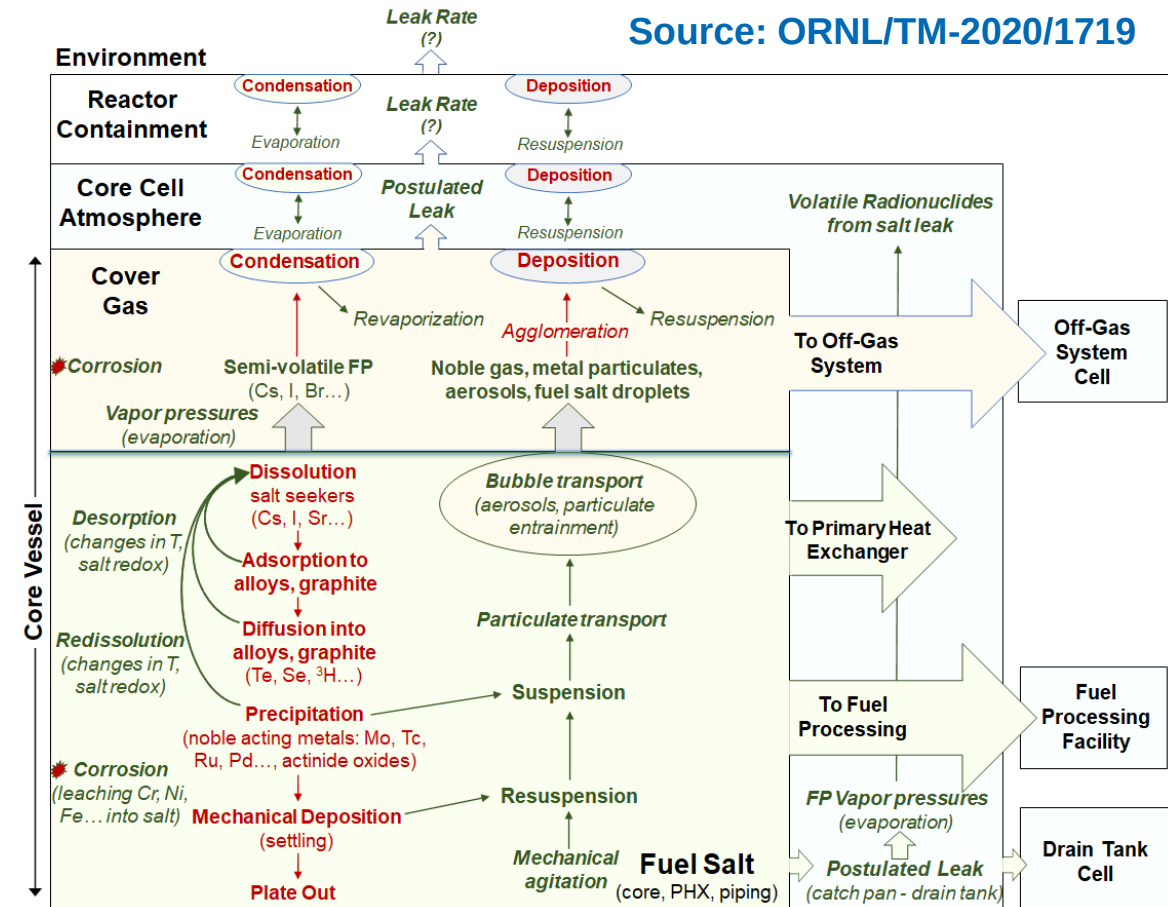
Fuel properties control : salt solidification

- The melting points of molten salts are **high** (generally $> 450^{\circ}\text{C}$) and **much higher than ambient temperature**.
- **Sudden overcooling** or **increase in thermal losses** could lead to a temperature drop in the fuel.
- If the temperature drops low enough, it could lead to **salt solidification**, which may lead to:
 - Flow blockage;
 - Selective precipitation of salt species (potentially, fissile material) and Criticality risk (higher local density).
- Salt solidification is to be avoided by **trace heating (which may have to be safety grade)** and adequate **thermal insulation**.

Specific safety functions in MSRs

Fuel properties control : fission product behavior

- Redox potential has a substantial impact on fission product behavior
- It may change during operation and should thus be monitored.
- It may also change during accidents and may thus impact accident progression and nature and quantity of the radioactive releases
 - It is essential to understand the physics and chemistry to predict severe accident behavior



Defense-in-depth – Level 1 – Examples

Prevent abnormal operation and failures

- Inherent neutronic characteristics of the core
- Corrosion control and monitoring via redox
- Control and monitoring of salt temperature to avoid fissile material precipitation
- Chemically inert cover gas
- Maintaining salt molten via trace heating to avoid freezing
- Subcritical design of piping of the fuel circuit
- Low chemical reactivity and stored energy of fuel salt

Defense-in-depth – Level 2 – Examples

Detect and intercept deviations from normal operation

- Redundant off-gas system trains in case of failure
- Oxygen “getters” in salts to prevent precipitation of fissile material by air or water vapor ingress in the off-gas system
- Automatic reactivity control systems (via absorbers, pumps, etc.)
- Fuel piping leak monitoring
- Prevent operation with inactive fuel pump to avoid spurious start-up
- Self-draining systems on pump stop

Defense-in-depth – Level 3 – Examples

Control accidents and prevent progression

- Fuel salt drainage in drain tanks
- Shutdown systems with absorbers
- Double-envelope piping for the off-gas system
- Minimization of excess reactivity
- Subcritical design of environment of potential leaks
- “Core catchers” to recover salt leakages
- Passive cooling systems (natural circulation, radiative heat transfer, etc.)

MSR-specific accidental sequences

Fuel overcooling

- Peculiar physics in MSRs with low β (prompt criticality risk) and risk of salt freezing.

Loss of fuel flow/Uncontrolled increases in fuel flow

- Peculiar

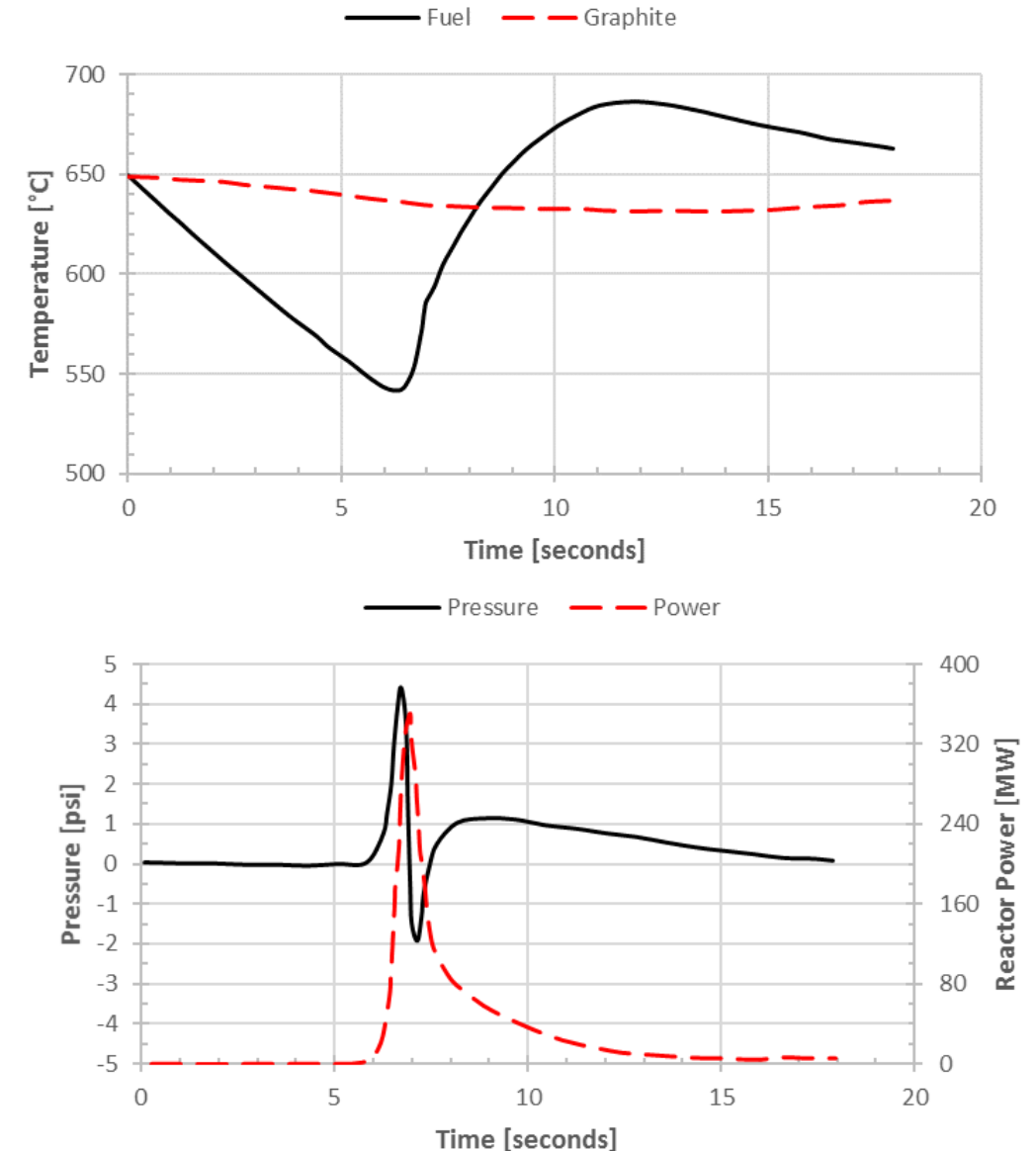
Fuel circuit leaks and off-gas/cover gas leaks

- Release of salt to containment, uncontrolled criticality risk, decay heat to be removed, potential interactions of fuel salt with containment structures (including concrete).
- Potential for substantial releases of highly volatile and high activity nuclides.
- **Reactivity insertions**
- Fuel loading errors in systems with on-line refueling systems.
- Core disruptive accidents in fast heterogeneous systems (analogous to LMRs).

Simulation of accident scenarios - MSRE

Cold slug in the fuel

- Worst case scenario for cold slug of 20 ft³ at 480°C
- Core initially critical at 650°C with 10 kW of power and no circulating fuel
- Demonstrates inherently safe feedback of the reactor
- Similar tests with control rod action limited peak power to only 0.66 MW

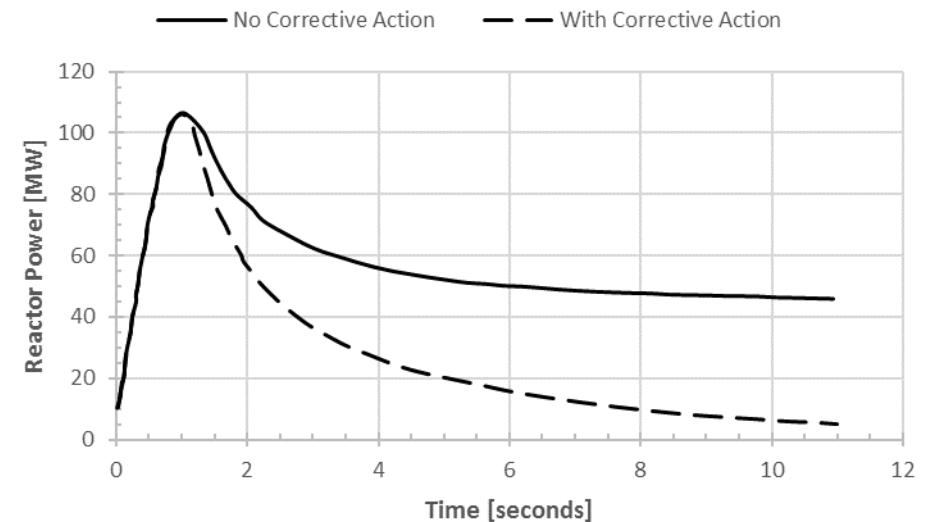
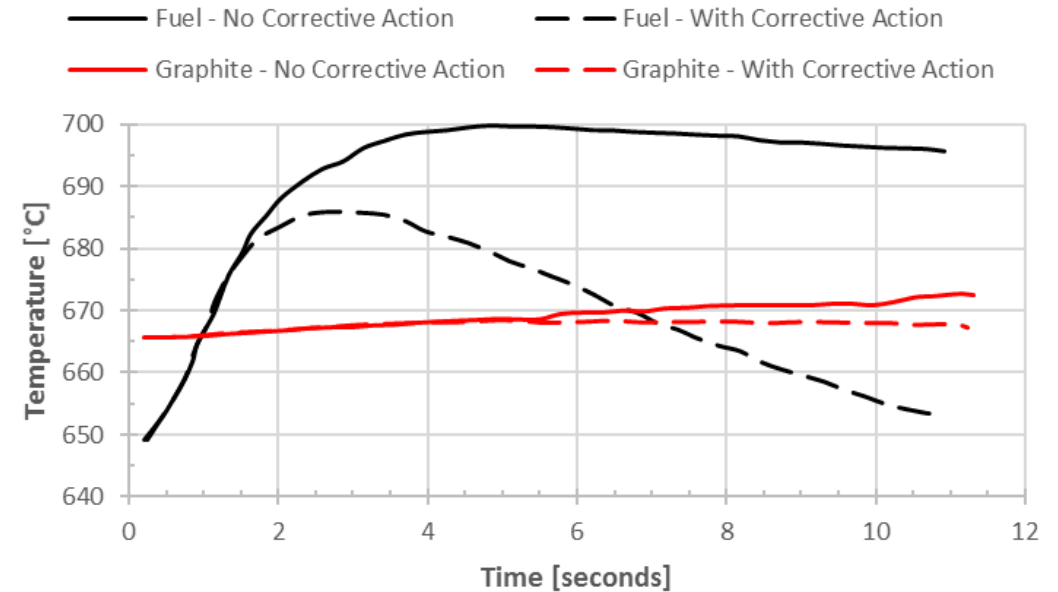


Source: ORNL-TM-251

Simulation of accident scenarios - MSRE

Reactivity insertion

- Reactivity insertion of 0.338% $\Delta k/k$ which makes the reactor exactly prompt critical
- Corrective action is -0.075% $\Delta k/k$ per second beginning at $t=1$ s
- Demonstration with and without corrective action illustrates inherent safety of the reactor



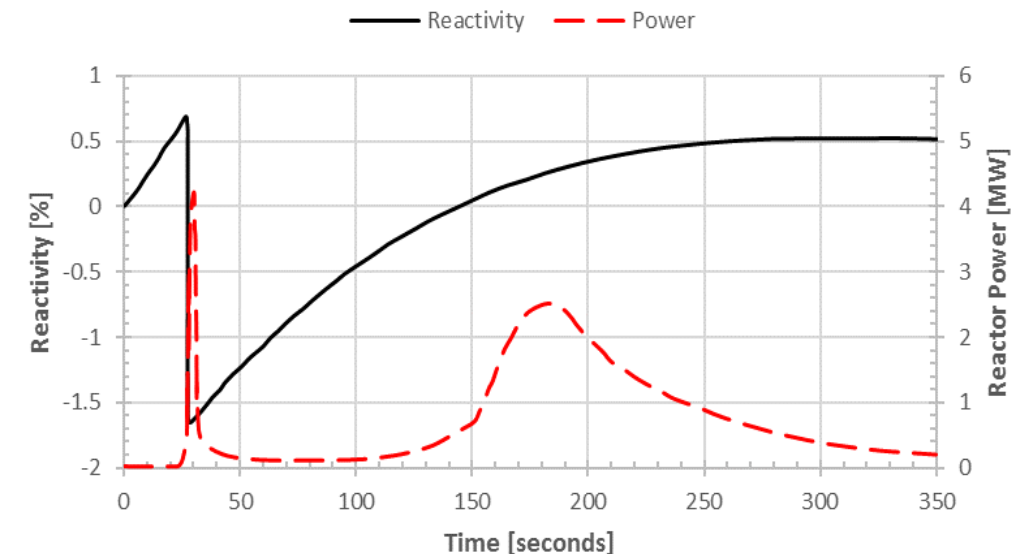
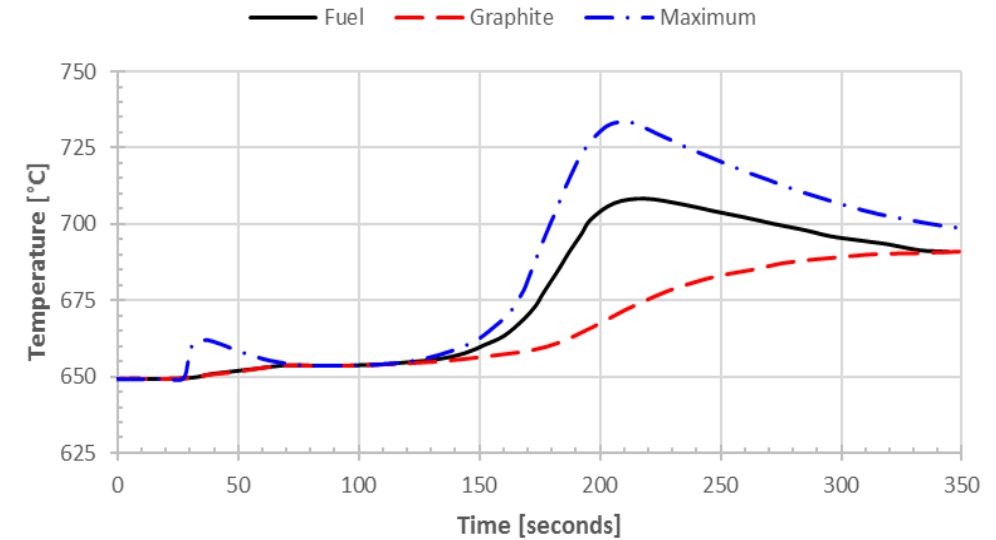
Source: ORNL-TM-251

Simulation of accident scenarios - MSRE

Source: ORNL-TM-497

Fuel filling accident

- Maximum reasonable filling accident
 - Fuel composition is least favorable for safe filling (most excess reactivity)
 - Gas supply over pressured from 40 psig to 50 psig (increases salt addition rate)
 - 1/3 control rods fails to insert. Other 2 rods automatically insert when power reaches 150% of design power (see transient at ~30 seconds)
 - Only 1 of 3 valves (the gas addition valve) functioned properly
- Maximum temperature safely within tolerated range



Many challenges are left

Radiation protection, maintenance, decommissioning

- **Radionuclides distributed in several systems** in the plant make **radioprotection complex**.
- Moreover, certain parts of the plant (e.g., the fuel circuit) will be **inaccessible to humans** even shutdown due to activation and **substantial contamination from the fuel** and thus **remote maintenance must be foreseen**, which is particularly challenging.
- Many MSR designers foresee the use of technologies such as **compact heat exchangers**, for example, to minimize out-of-core fuel volumes. These technologies lead to substantial **challenges for in-service inspection** due to **the lack of ease of access**.
- For **decommissioning and waste disposal**, acceptable **waste forms** must be developed and qualified for activated salt and its components, **decontamination processes** for structural components.

Conclusions

- Liquid-fuel MSR have unique but promising safety characteristics.
- Many **very different designs** have been proposed : one should be careful before making generic statements or assumptions.
- The “usual” safety approach is not straightforward to apply in MSRs, but it can be done.
- To this date, there is no consensus on the definition of a severe accident in MSRs.
- Defense-in-depth *starts* at the first levels (including monitoring and prevention), for which **a thorough understanding of fuel salt physics and chemistry is necessary**.
- Moreover, there remains substantial challenges in terms of **radiation protection**, **maintenance** and **in-service inspection**, reliability and performance of the fuel salt draining systems, and waste management and decommissioning.



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