Molten Salt Reactor Fuel Cycle

ESFR-SMART Spring School

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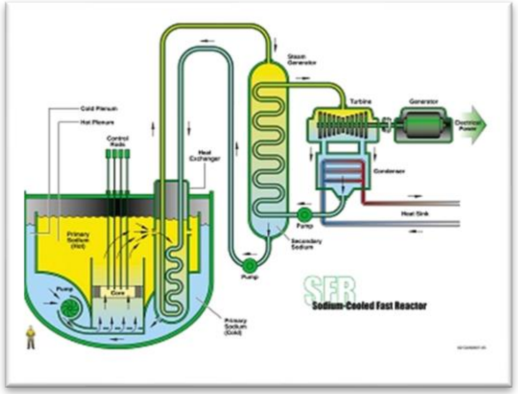
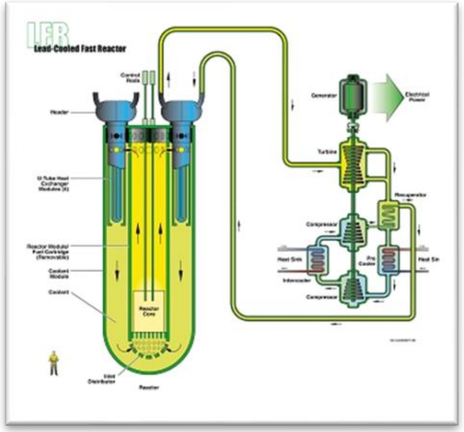
31.03.2021

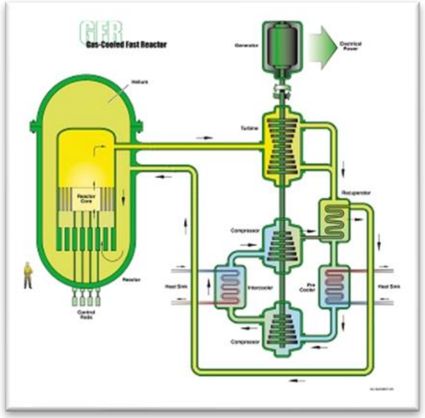
CHAPTER 1: **MSR Concept**



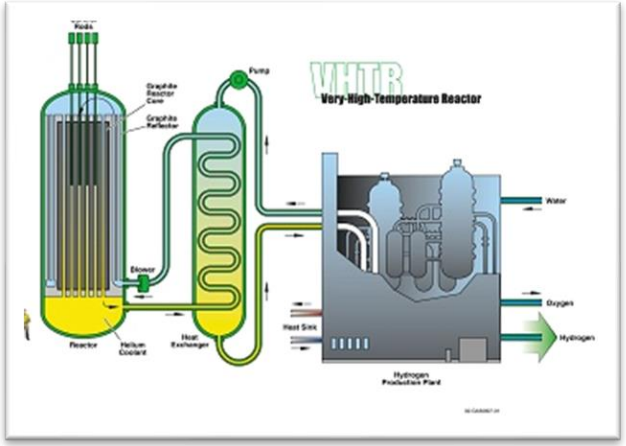


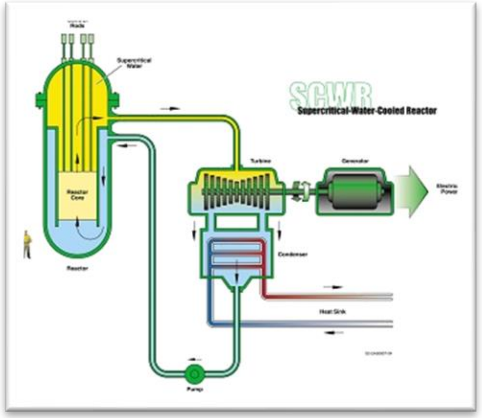
Advanced Reactor Concept

Generation IV family



- Sodium Cooled Fast Reactor
- Lead Cooled Fast Reactor
- Gas Cooled Fast Reactor
- Very High Temperature Reactor
- Supercritical Water Cooled Reactor
- **Molten Salt Reactor**





GEN IV International Forum
Expertise | Collaboration | Excellence

MSR Nowadays

- After 2001: MSR included in Gen IV initiative

MSR SSC Chair: Dr. Stephane Bourg, CEA

2010 - MoU signed between **France** & **Euratom**
(since then 2 regular annual PSSC meetings)

2013 - **Russian Federation** signed MoU

2015 - **Switzerland** signed MoU

2016 – **USA** signed MoU

2017 – **Australia** signed MoU

2019 – **Canada** signed MoU

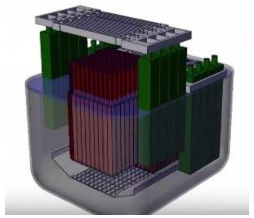
China & Japan – permanent Observers

2019-2021 – Transition of MoU to SA (with 1/3 PA lead by JRC)

MSR Nowadays - Vendors

Start-up companies (within last 5 years – mostly private investors)

moltex energy
safer, cheaper, nuclear



COPENHAGEN ATOMICS

SEABORG

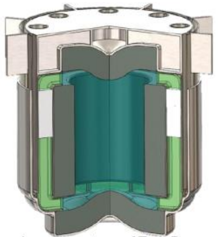


Image courtesy of TerraPower

ONE
TerraPower
Fast
Breeder
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

TWO
Thorcon
Thermal
Burner
Liquid Fuel
Salt Cooled
Thorium

THREE
Terrestrial Energy
Thermal
Burner
Liquid Fuel
Salt Cooled
Uranium
(Could use Th)

FOUR
Flibe Energy
Thermal
Breeder
Liquid Fuel
Salt Cooled
Thorium

FIVE
Transatomic Power
Hybrid
Burner
Liquid Fuel
Salt Cooled
Uranium

$68M funding
(B. Gates)
(~100 staff)

est. $10sM funding
(~60 staff)
Contracts with JRC

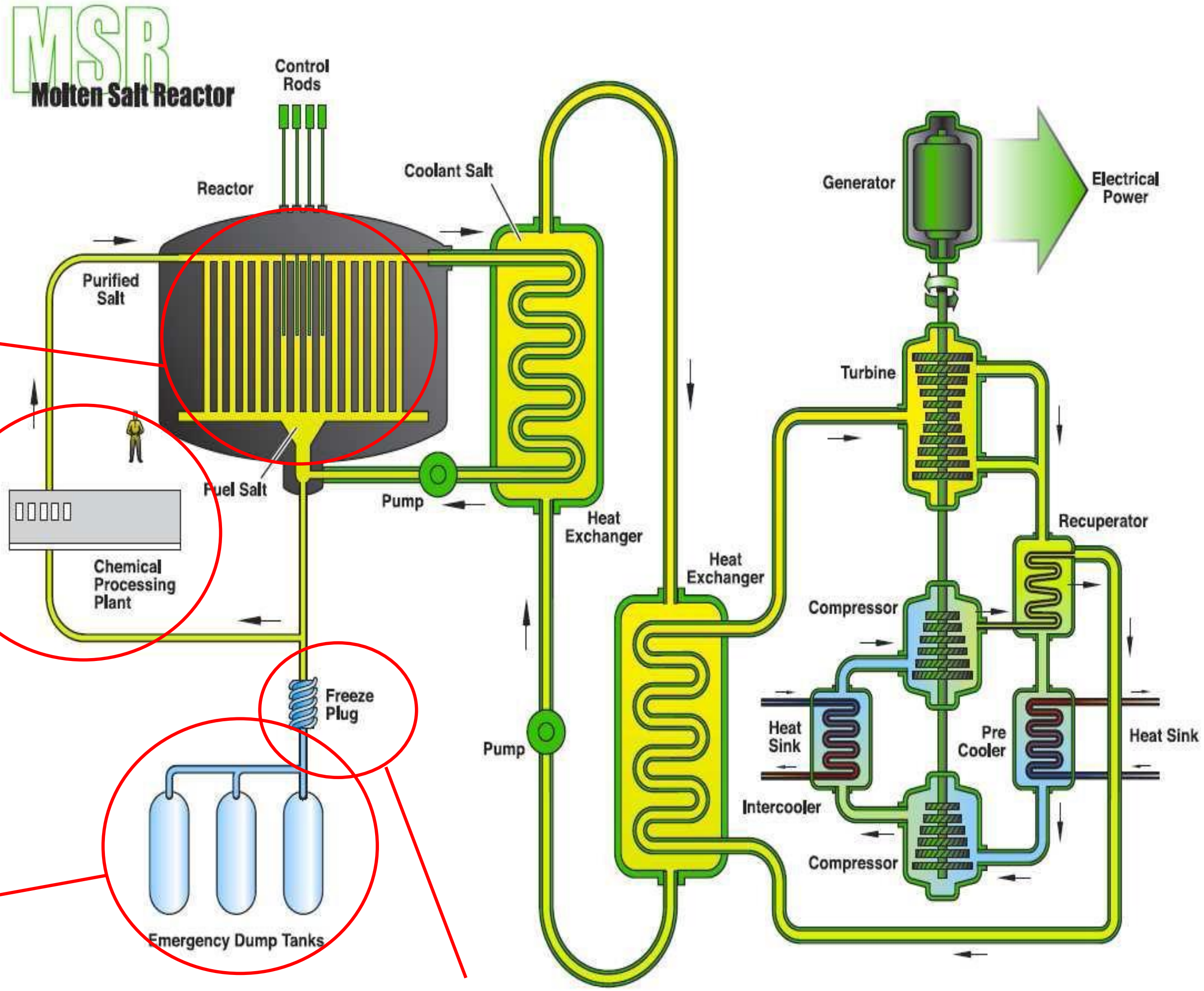
MSR Concept

Core:
Moderator replacement

Clean-up:
Safeguarding

Dump tanks:
cooling

Freeze plug:



Taken from the GIF platform

LiF-BeF$_2$ eutectic mixture, ORNL, 1960's

LiCl-KCl eutectic melt, JRC, Dec. 2020

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MSR Fuel Requirements

Only a limited number of metals is suitable from neutronic considerations

- ✓ Wide range of solubility for actinides
- ✓ Thermodynamically stable up to high temperatures
- ✓ Stable to radiation (no radiolytic decomposition)
- ✓ Low vapour pressure at the operating temperature of the reactor
- ✓ Compatible with nickel-based structural materials
- ✓ Compatible with the reprocessing technology

MSR Fuel

Mixture of Fluorides or Chlorides with dissolved fissile material

US Historic concepts

Solvent — Fissile Material — Oxygen getter — Fertile Material

ARE	$NaF - ZrF_4$	$- UF_4$		
MSRE	$^7LiF - BeF_2$	$- ZrF_4$	$- UF_4$	
MSBR	$^7LiF - BeF_2$	$- ThF_4$	$- UF_4$	

Selected nowadays concepts

MOSART	$^7LiF - BeF_2 - PuF_3$
TMSR	$^7LiF - BeF_2 - ThF_4 - UF_4$
MCRE	$NaCl – UCl_3 – PuCl_3$
MCFR	$NaCl – (MgCl_2) – PuCl_3$

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MSR Breeder Design

Thorium Utilization

$$^{232}\mathrm{Th} + {}^{1}\mathrm{n} \rightarrow {}^{233}\mathrm{Th} \xrightarrow{22\ \mathrm{min}} {}^{233}\mathrm{Pa} \xrightarrow{27\ \mathrm{days}} {}^{233}\mathrm{U}$$

Non-fissile (^{232}Th) — Fissile (^{233}U)

- ^{233}U is an exellent fissile material
- Strongly reduced transuranium element production (Pu,Np,Am)
- The Th/U cycle needs start-up (U, Pu)
- Breeder can be 238U to 239Pu

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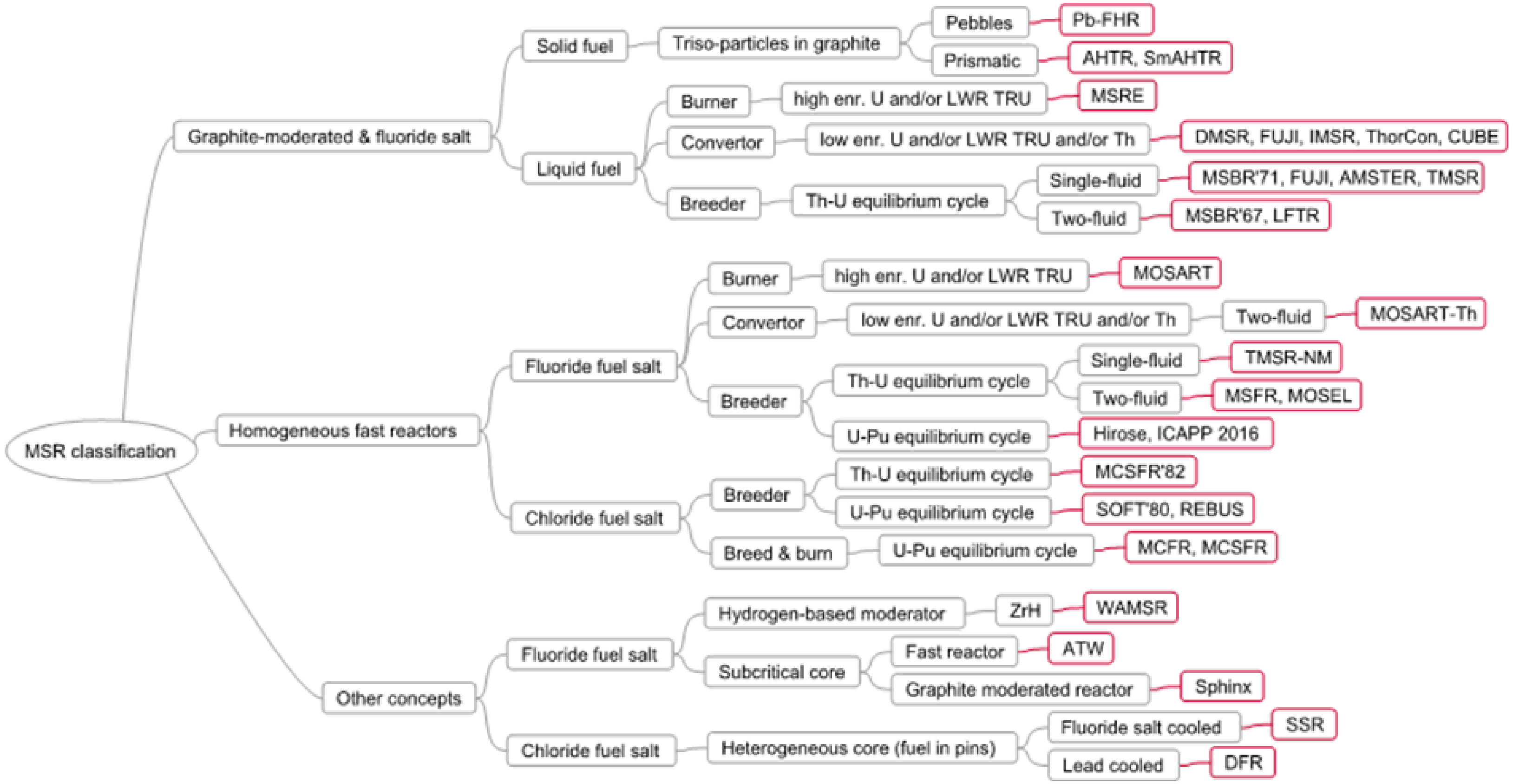
MSR Concepts

General overview of ~95% of MRS concepts



Courtesy from MSR SSC PA description, J. Krepel, PSI, Switzerland

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Highlights of MSR concept

High Safety

- Atmospheric pressure operation
- Retention capacity of volatilie fission products
- No H_2 production at high T
- High boiling point ~1800 °C (>1000 °C buffer)
- Passive safety – thermal expansion
- Dump tanks in case of emergency
- No radiation damage – fuel is homogeneous
- Thermodynamic stability to high T
- *Possibility to remove fission products ???*

Design variability

- Fuel mixture selection
- Fast or Thermal concept
- Burner design, as well Breeder design (U-Pu cycle or Th-U cycle)
- Power window ~MSR can be BIG but SMR too! (ship propulsion)

Application variability

- Electricity production
- High T operation (up to 750 °C) – Hydrogen production
- Pu management (burning)
- Water desalination

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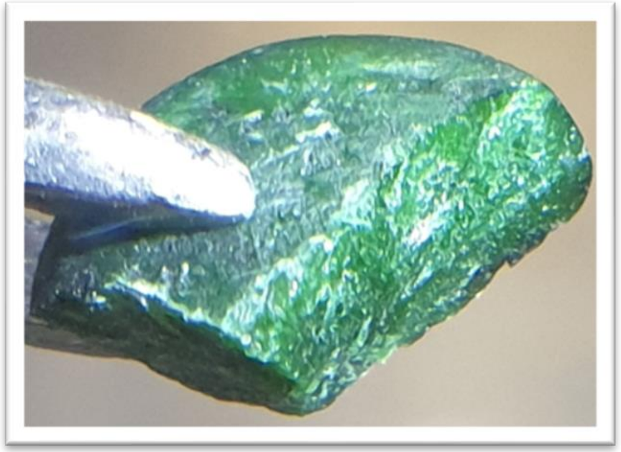
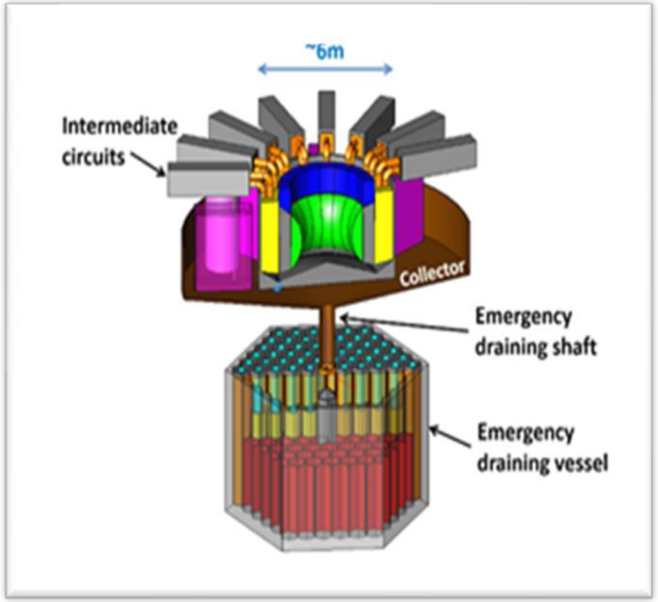
MSR Fuel Cycle



SALIENT03 fuel synthesised at JRC

- Fresh fuel
- During operation
- Waste storage and form



French MSFR concept studied in SAMOFAR EU project

MSR Fuel Cycle - Fresh Fuel

- **Fuel composition that meets needed neutronics + suitable properties**

- **Neutronics defined by reactor design (neutron specra, fuel concept)**

- **Properties must meet other relevant criteria:**
  - Low melting point
  - High boiling point (low pressure)
  - Sufficient solubility of actinides
  - Thermodynamic Stability at high T

- **For reactor design**
  - Heat capacity
  - Thermal conductivity
  - Density
  - Viscosity

One needs all these properties vs. neutronics to design MSR

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MSR Fuel Cycle – During operation

- **Fission product accumulate and change Fuel properties**
- **Identification of those properties that are of concern**
- **Address influence of FP**
- **Control redox potential of salt (corrosion relevant)**
- **Behaviour during off-normal conditions**
  - Overheating (vaporization of FP and of Fuel)
  - Under-cooling (what are first precipitates?)
- **Clean-up scheme**
  - Is it in place
  - Online processing (He bubbling for FG and metallic precipitates)
  - Online with out-of-pile chemical plant

Online Monitoring

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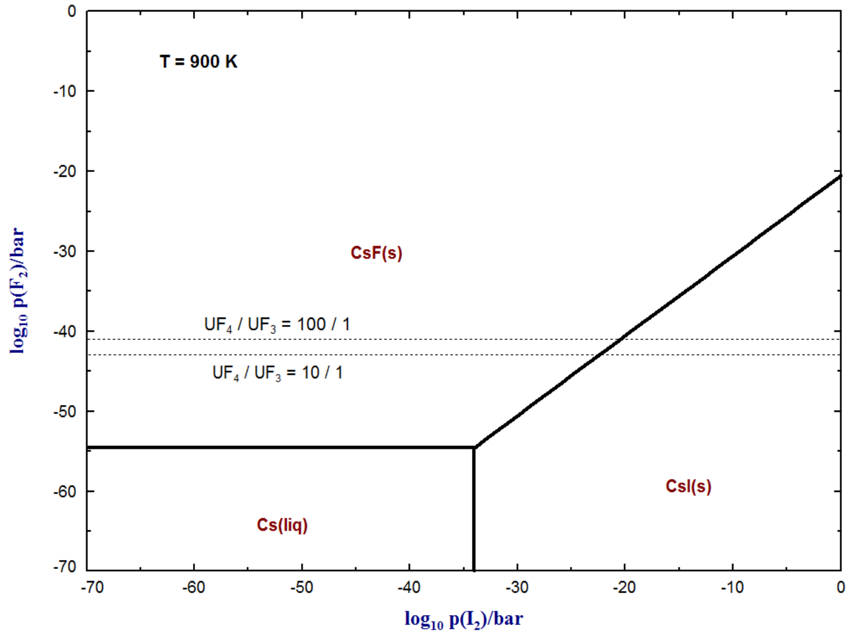
MSR Fuel Cycle – During operation

- **Which Properties are of concern with respect to FP accumulation?**
  - For licensing Authorities All (at least at early stage of MSR licensing)
  - But only some may be of concern (low FP yield compared to mass of fuel)
  - Chemistry of FP plays important role !!!
    - Dissolved in the fuel
    - As precipitate (low soluble FP chemical species)

Example: Cs and I in fluoride based reactor



- CsF and CsI can formed

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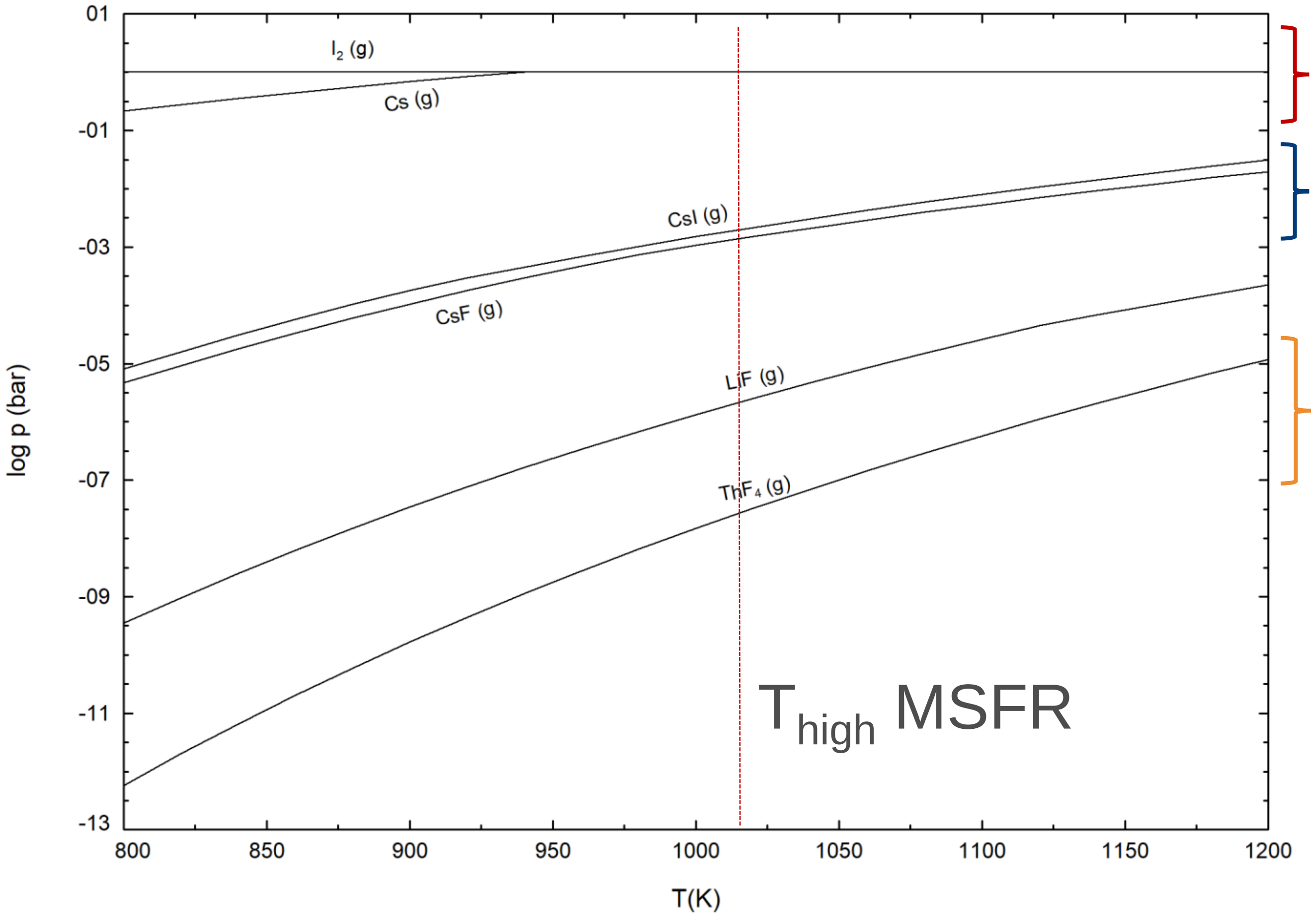
Volatility

Volatility of pure chemical species



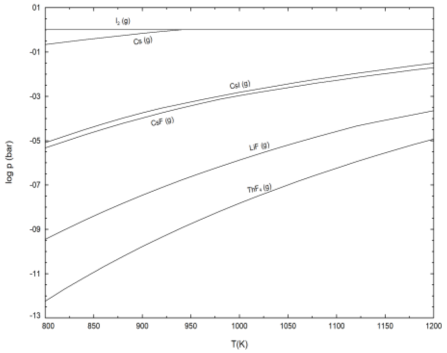
Highly volatile in Elemental form

Moderately volatile CsF and CsI

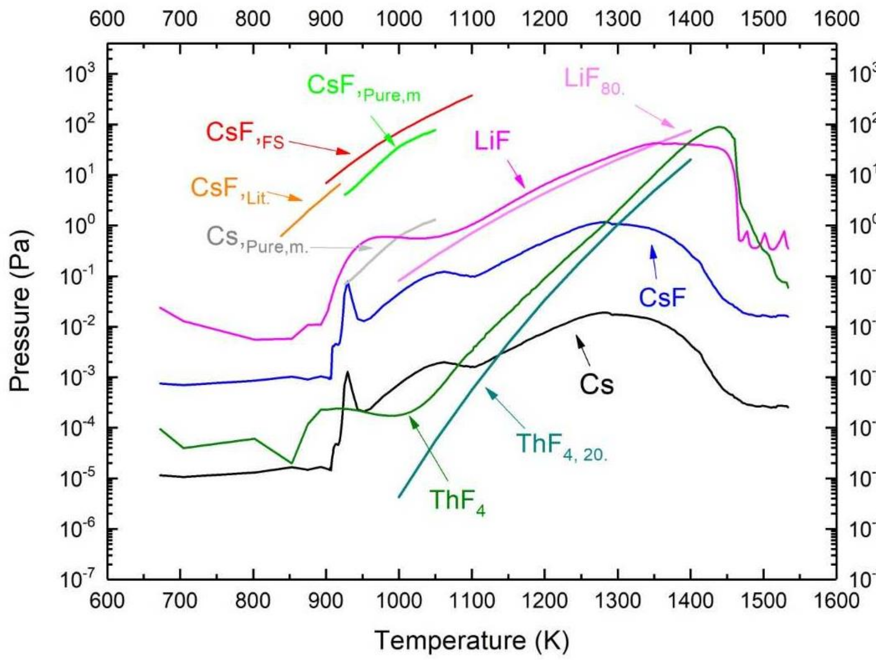
Low volatility of matrix components

Volatility effected by solubility

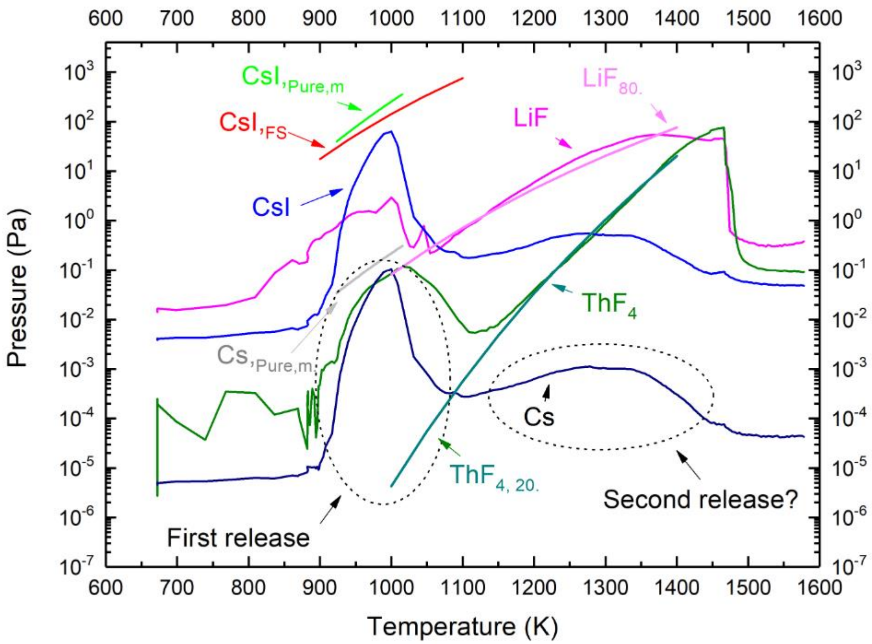
Frame: HORIZON2020 Project SAMOFAR (2015-2019)



CsF release from LiF-ThF4



CsI release from LiF-ThF4



Conclusions:

- CsF dissolves and as consequnce decreases volatility of Cs >100000x (ref. Elemental form)
- CsI is highly immiscible, but formation of CsI compound causes ~3000x lower volatility (ref. Elemental form)

During Operation - Fuel Stability

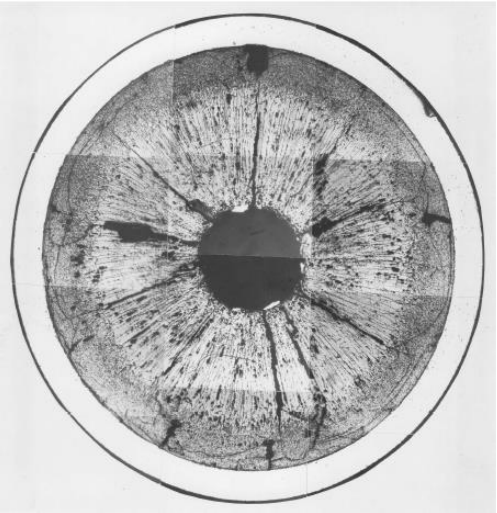
- Fuel remain homogeneous during MSR operation
- No radiation damage
- Radiolysis occurs (but also recombination)

Radiolysis:

$$UF_4 \xrightarrow{\gamma} UF_3 + \frac{1}{2}F_2$$

Recombination:

$$UF_3 + \frac{1}{2}F_2 \rightarrow UF_4$$



Fast Reactor MOX fuel after irradiation – JRC image

LiCl-KCl eutectic melt, JRC, Dec. 2020

- Radiolysis starts dominanting below 150 °C

WASTE STORAGE RELEVANT

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Conclusions

- MSR certainly offers interesting option for future Nuclear fleet
- It has high safety standards
- Chemistry of FP plays key role for performance of MSR
- Lots of R&D needed

Thank you

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