MSR R&D at JRC and in Europe

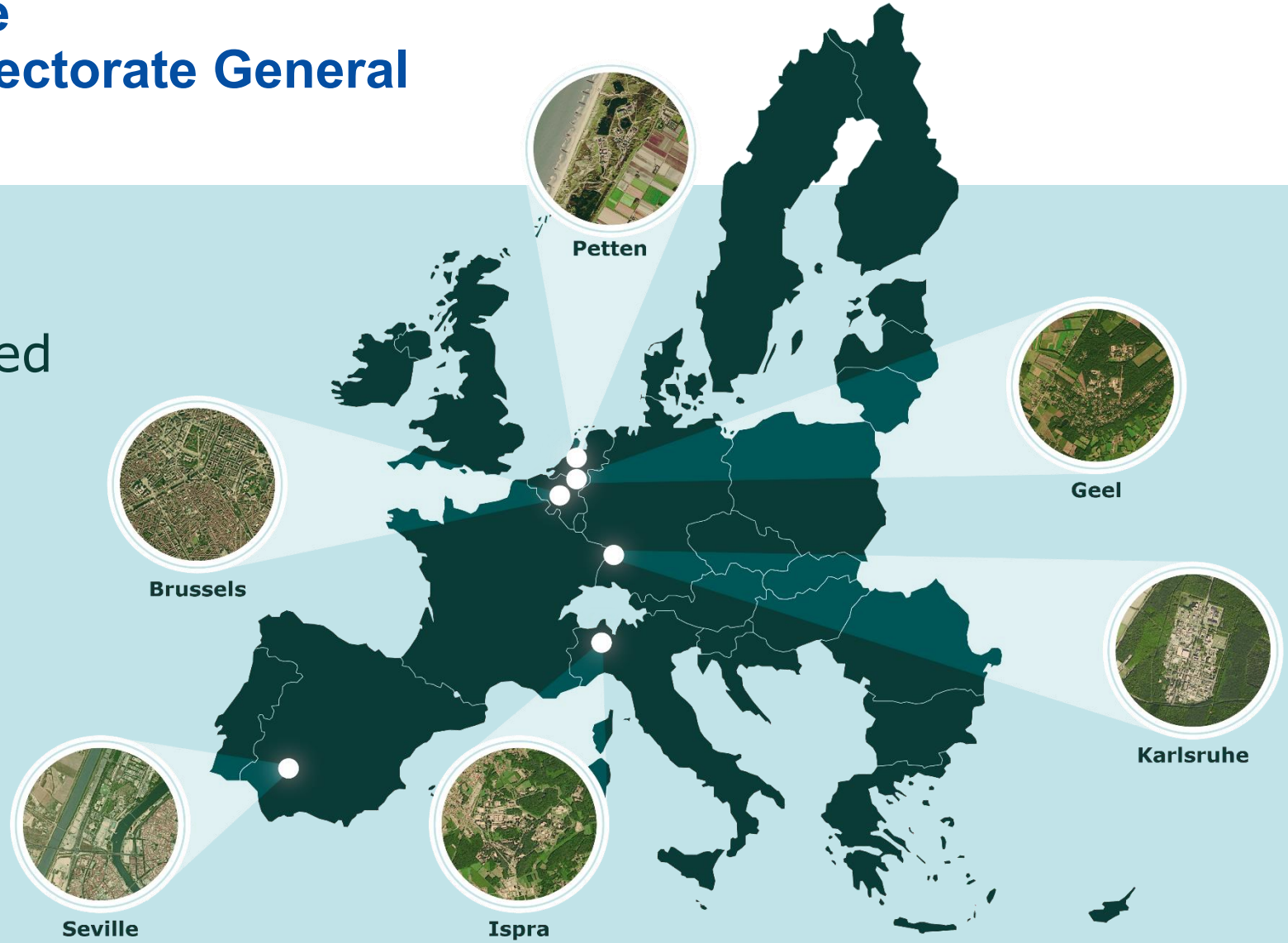
Ondrej Benes, Joint Research Centre, Karlsruhe, Germany

MSR workshop at PSI, 10.12.2025, PSI, Switzerland

JRC – Joint Research Centre
European Commission‘s Directorate General

Headquarters in Brussels
and research facilities located
in **5 Member States:**

- Belgium (Geel)
- Germany (Karlsruhe)
- Italy (Ispra)
- The Netherlands (Petten)
- Spain (Seville)



~ 3000 employees

European Commission

JRC Directorate G - Nuclear Safety and Security

Petten
- Reactor Safety and Components

Karlsruhe
- Safety of the Nuclear Fuel Cycle
- Nuclear Science and Innovation for Energy and Health
- Nuclear Safeguards and Security

Geel
- Nuclear Data and Measurement Standards

Ispra
- Digital Systems for Safeguards and Non-proliferation
- Nuclear Facilities Management and Safe Conservation

MSR Collaborations

Framework Projects

- MIMOSA (Orano lead)
- ENDURANCE (Polimi lead)
- In the past: e.g. SAMOSAFER

Industry & SME

- Orano Group
- NAAREA, Thorizon, Stellaria
- SALTFOSS, Copenhagen Atomics

Member States

- NRG, TUD (NL)
- CNRS, CEA (France)
- DTU (DK)
- CIRTEN (IT)
- CVR (CZ)
- others

Licensing Authorities & TSO

- ASNR

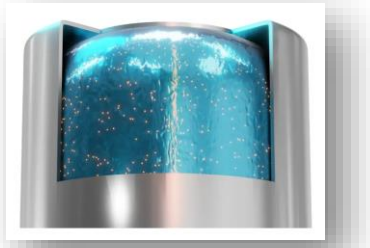
International Collaborations

- GIF
- IAEA
- NEA / OECD

- JRC support EU MSR programme through:
  - Access to their unique nuclear infrastructure
  - Consultations / coordination / collaborations

MSR Reactor Designs Across Europe

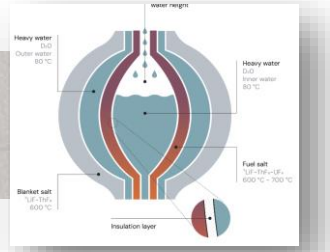
STELLARIA



naarea

THORIZON

copenhagen atomics

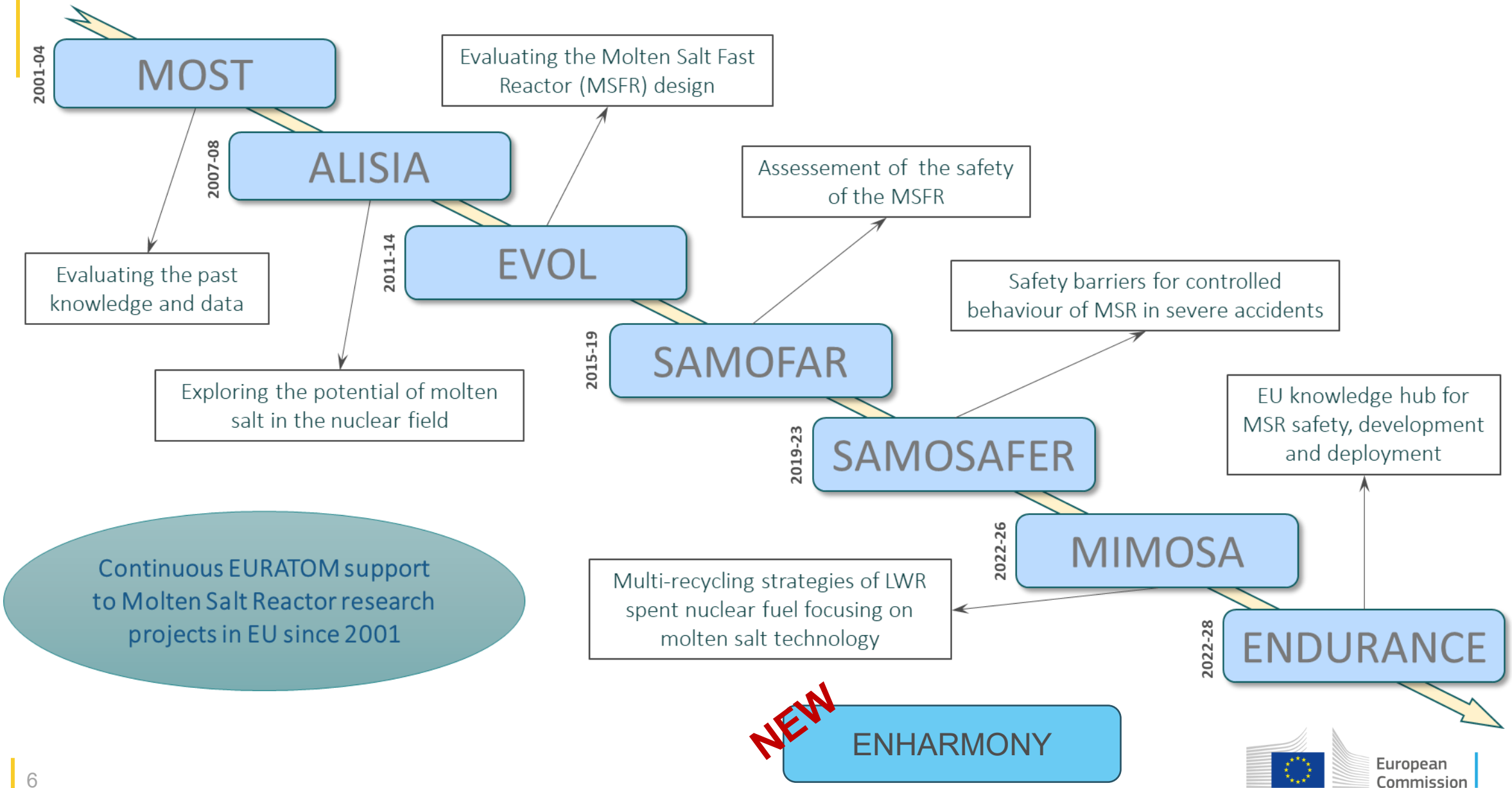


SALTFOSS

European Industrial Alliance on SMALL MODULAR REACTORS

European Commission

EU MSR Framework projects overview



European Commission

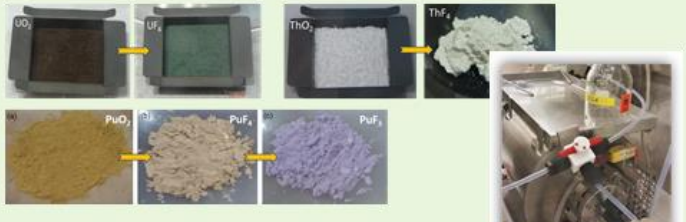
JRC Expertise

SALIENT03 irradiation at NRG Petten
MOCHA irradiation – Cl-based salt - 2026

Oxygen analysis in process

Karlsruhe

Synthesis & Electrochemistry



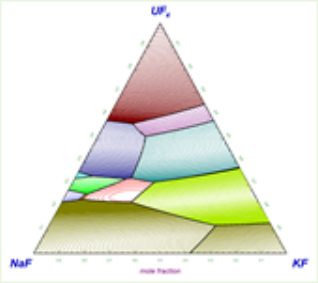
UF_4, UF_3, PuF_3, ThF_4, $PuCl_3$
Ongoing: UCl_3, NpF_3

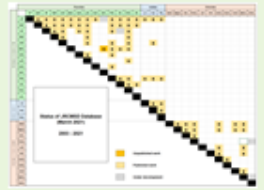
Karlsruhe

Irradiation of MS & PIE MS

Karlsruhe

Thermodynamic Database development





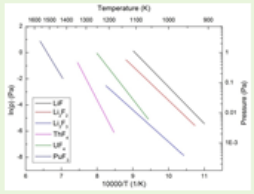
~120 binary systems

JRCMSD

JRC Competences in MSR R&D Safety Studies

Thermo-physical Properties

- Melting point
- Thermal conductivity
- Heat capacity
- Fission product behaviour
- Vapour pressure
- Transition enthalpy
- Phase diagrams
- Density, Viscosity
- Corrosion studies

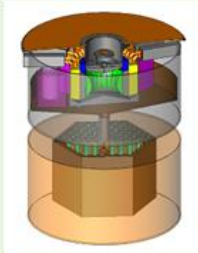


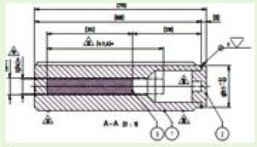
Quality – Assurance towards ISO 17025

Karlsruhe

Petten

Reactor Safety





Petten

Material Testing

Safeguards

Ispra

JRC is on of the Reference Centres for Properties Determination

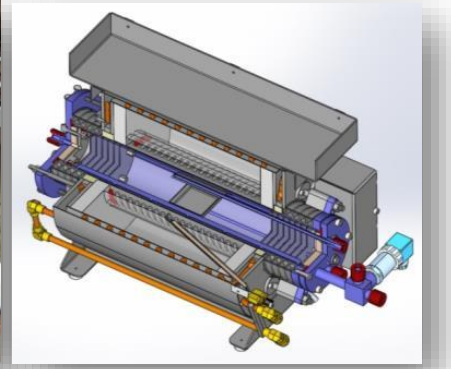
Synthesis of An halides

Synthesis of actinide halides

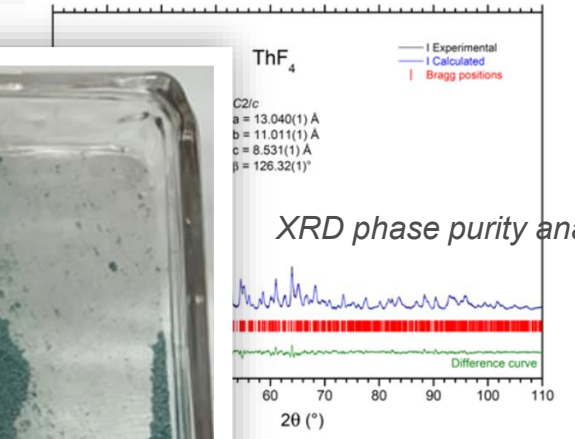
Synthesis of UF_4, ThF_4 and PuF_3 from oxides using HF

Synthesis of $PuCl_3$ from precursors by chlorination (HCl)

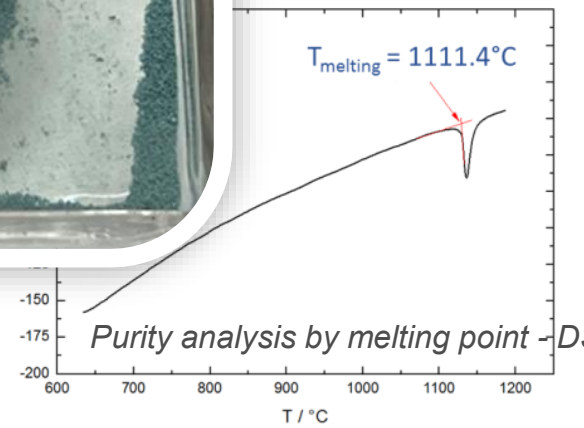
Confirmation of purity by XRD, melting point, ICP-MS



- colours agree to published appearance



XRD phase purity analysis



Purity analysis by melting point - DSC

European Commission

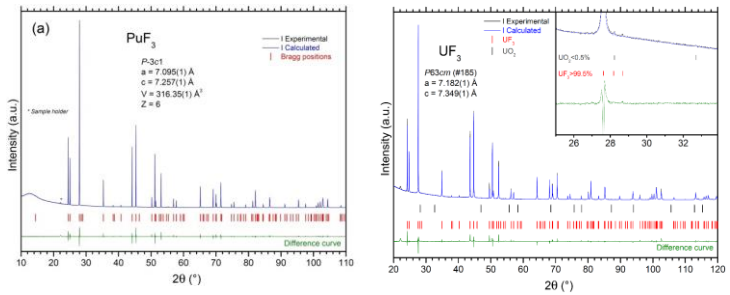
Irradiations

SALIENT-03 project (follow-up of SALIENT-01)

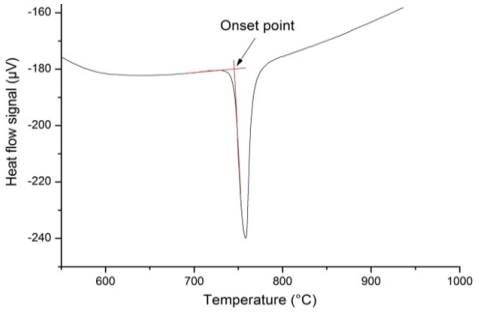
- 2nd European irradiation of molten salts at HFR, NRG, Petten (~5M€ project)
- Collaboration between JRC (KA, PT) and NRG
- Very challenging task (demand on purity, Quality control, ~100g of fuel mixture, encapsulation of plutonium fuel with no surface contamination)
- 4 different fuels (6 welded capsules) (^{7}LiF-ThF_4-UF_4-UF_3-PuF_3-(CrF_3) composition)

At JRC:

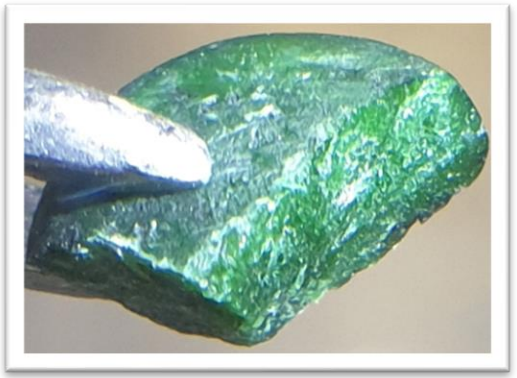
- Fuel synthesis and Encapsulation
- Safety analysis for HFR
- Post Irradiation Examination



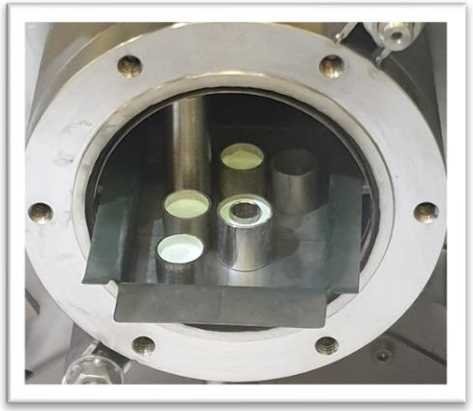
Purity analysis of all end-members



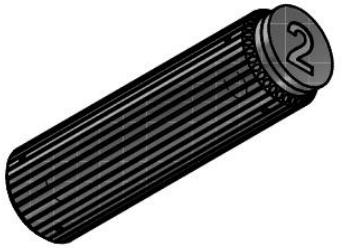
Melting point verification – Fuel 01



Solid ingots of frozen fuel of ~100% th. density



Densification of fuel by melting



Capsule 2 design (~6.5g fuel)

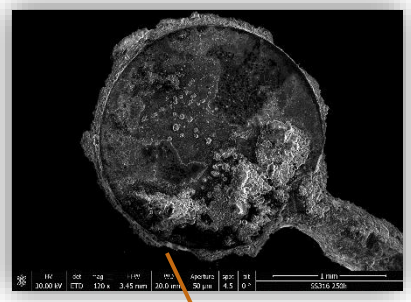
Optimized test weld

MSR Fuel Properties at JRC

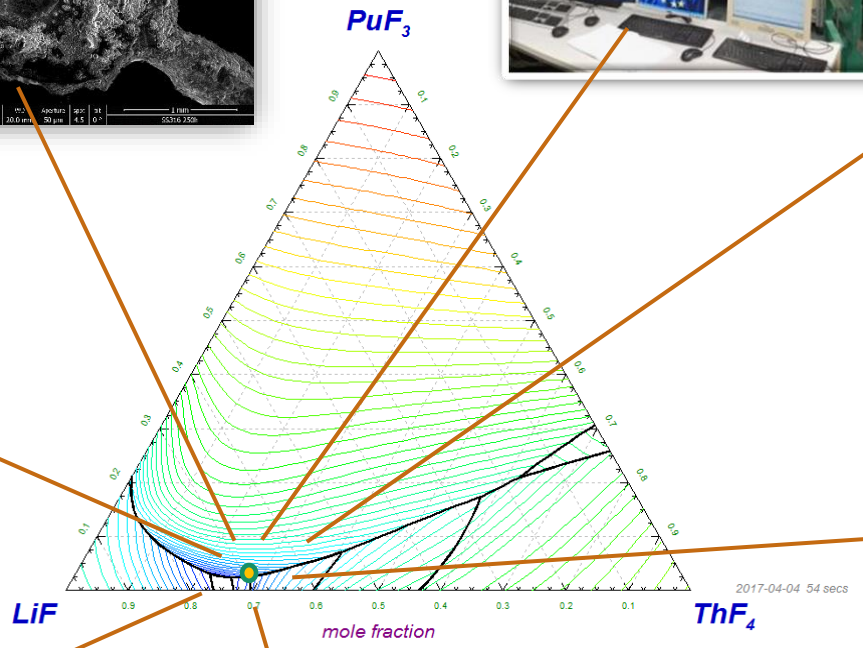
Vapour pressure (Boiling point)

Heat capacity

Corrosion studies

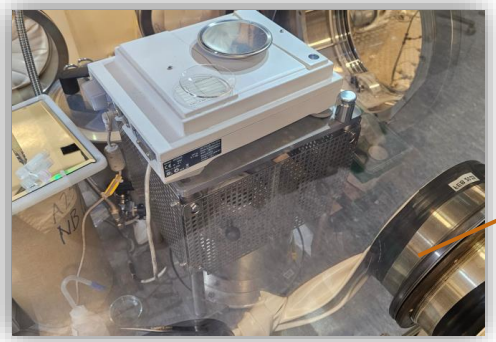


Thermal conductivity



Melting point (Heat of fusion)

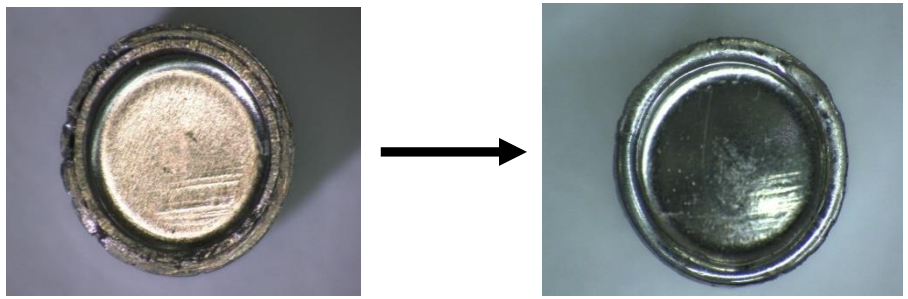
Density



Electrochemistry

Salt Handling

- Proper handling in place



✓ *Purity of the materials*

✓ *How to avoid O_2 and H_2O*

→

- Treatment with HF(g) or Cl_2,
- Handling only in Ar glove boxes

✓ *How to contain the liquid?*

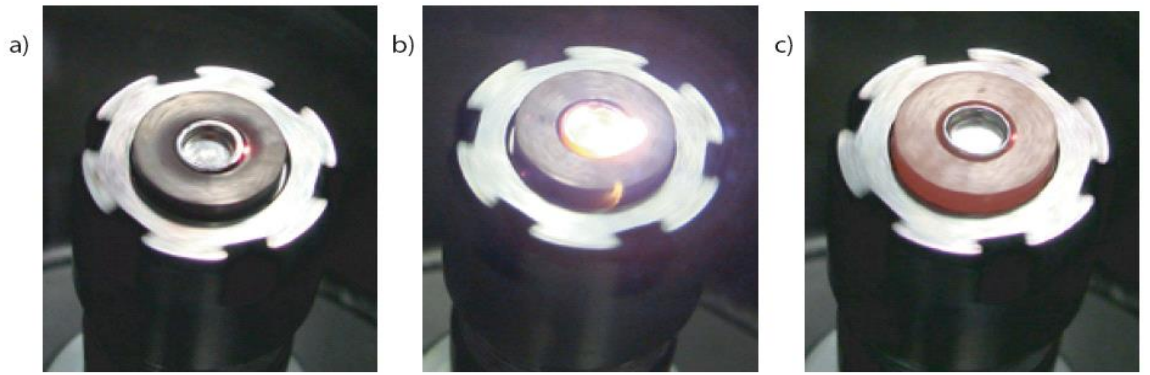
✓ *How to avoid corrosion ?*

✓ *How to avoid vaporisation ?*

↓

- Ni-based, C or BN container materials
- Encapsulation

Up to 6 years to
set-up the facilities



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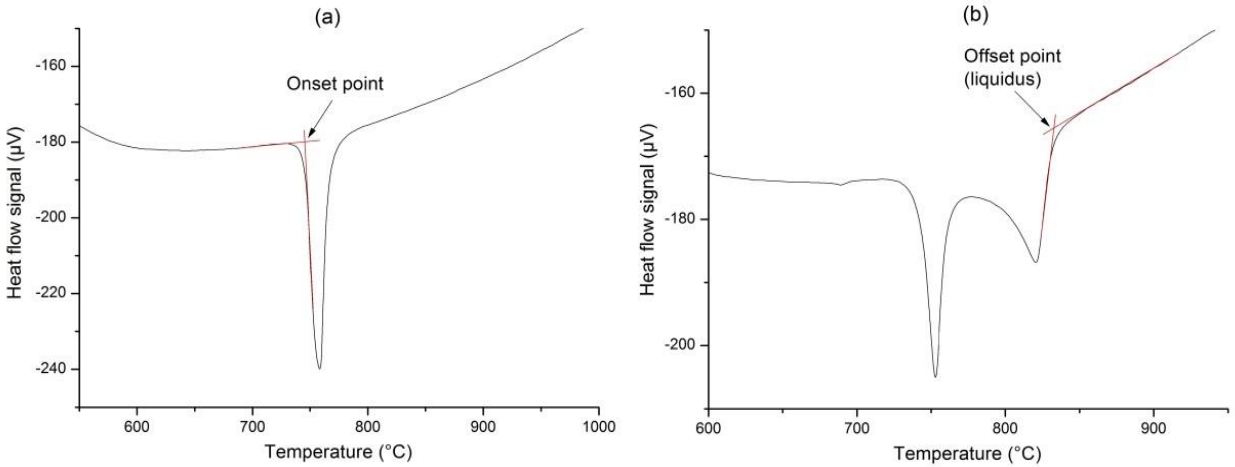
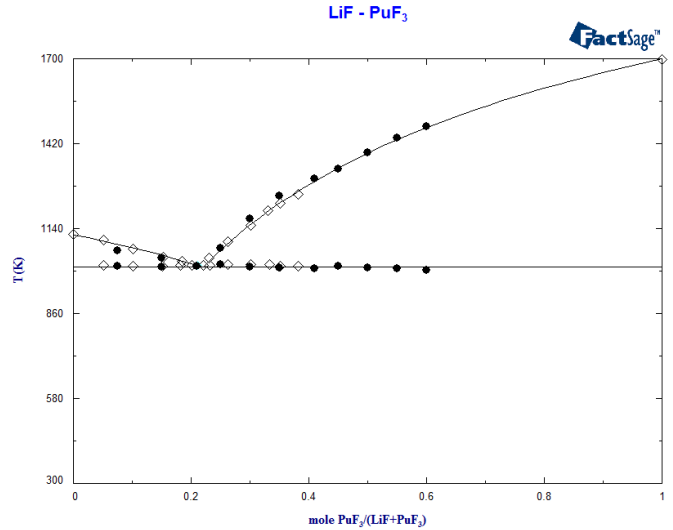
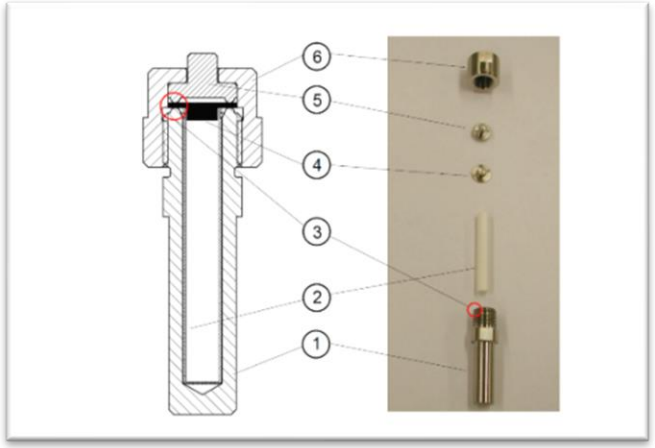
Phase diagrams

Differential Scanning Calorimetry (DSC) for phase transitions, e.g. melting

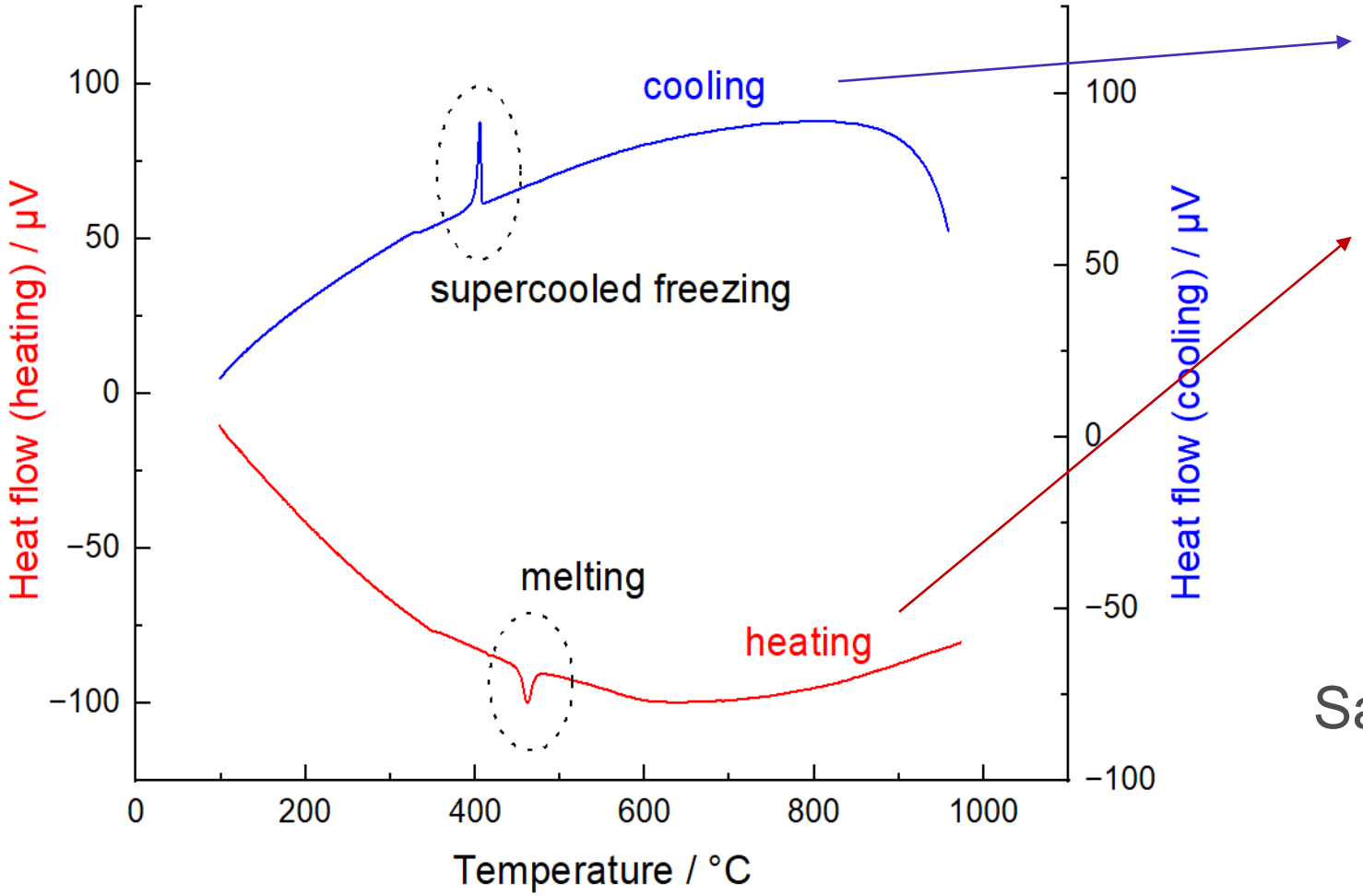






Adopted encapsulation technique

Supercooling



Cooling: 390 °C

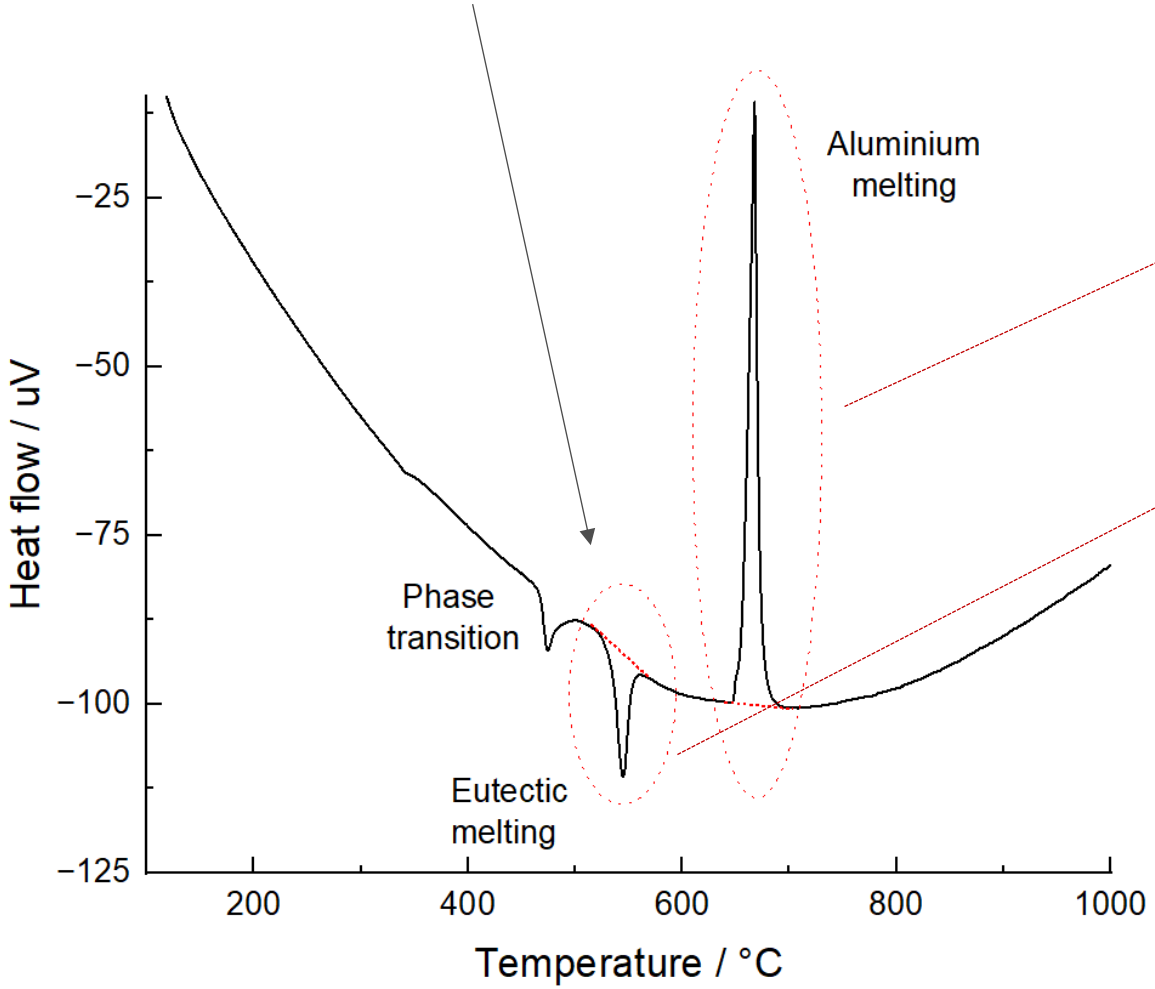
Heating: 445 °C (equilibrium)

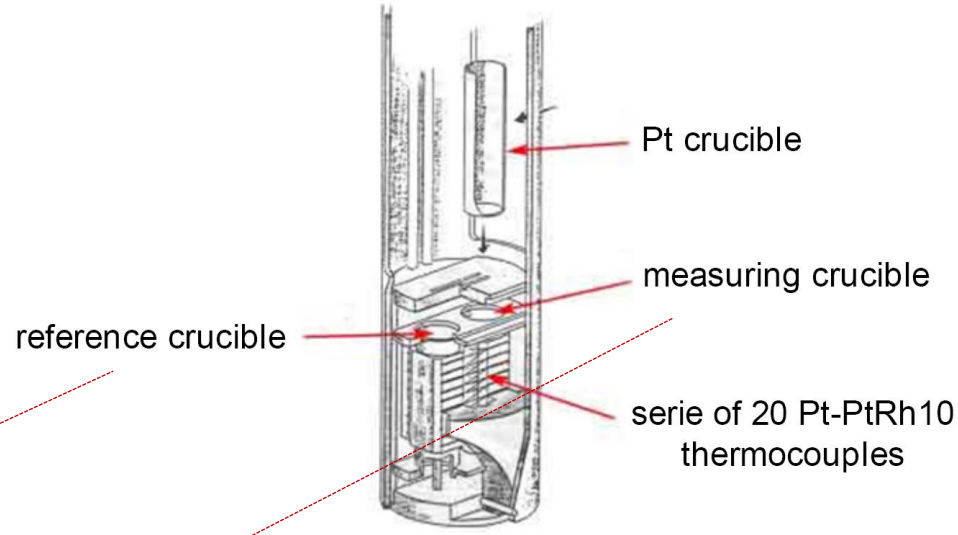
△ T = -55 °C

Salt and geometry specific !

Fusion Enthalpy

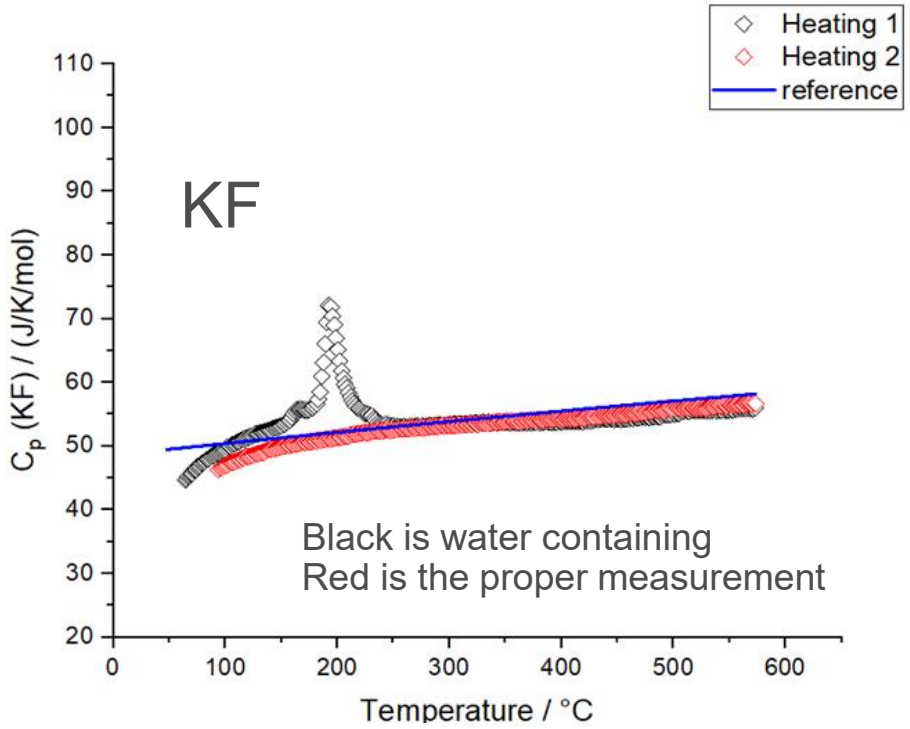
Funak Eutectic (NaF-KF-UF_4)



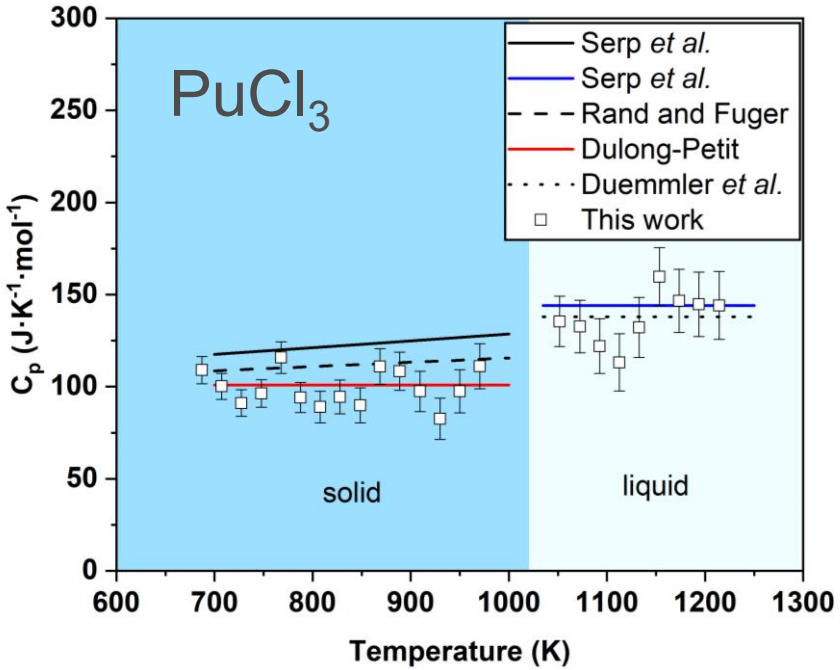


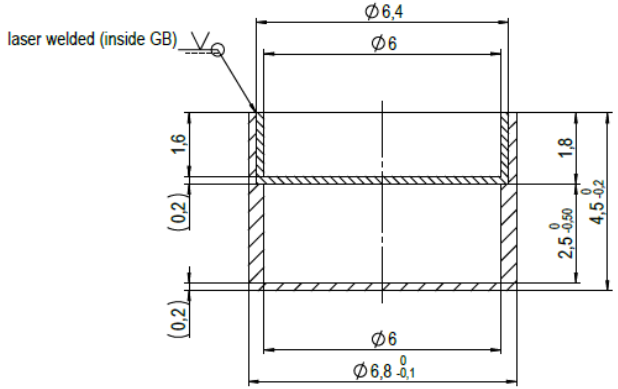
- Al reference gives sensitivity
- Correction factor for T shift

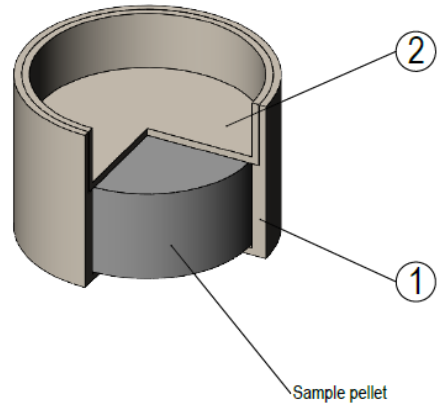
Heat Capacity



Netzsch STA DSC



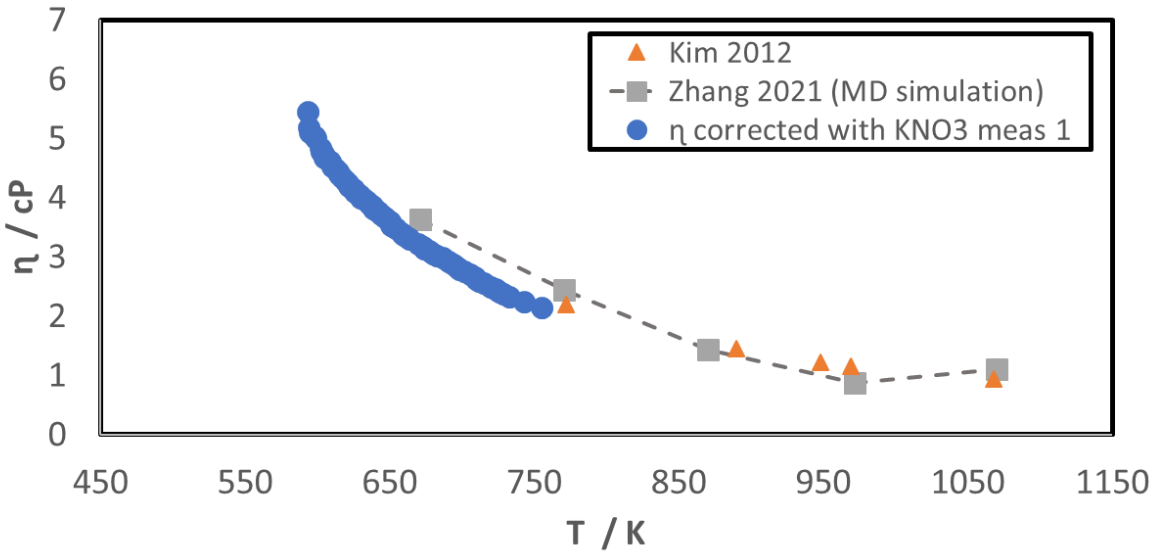


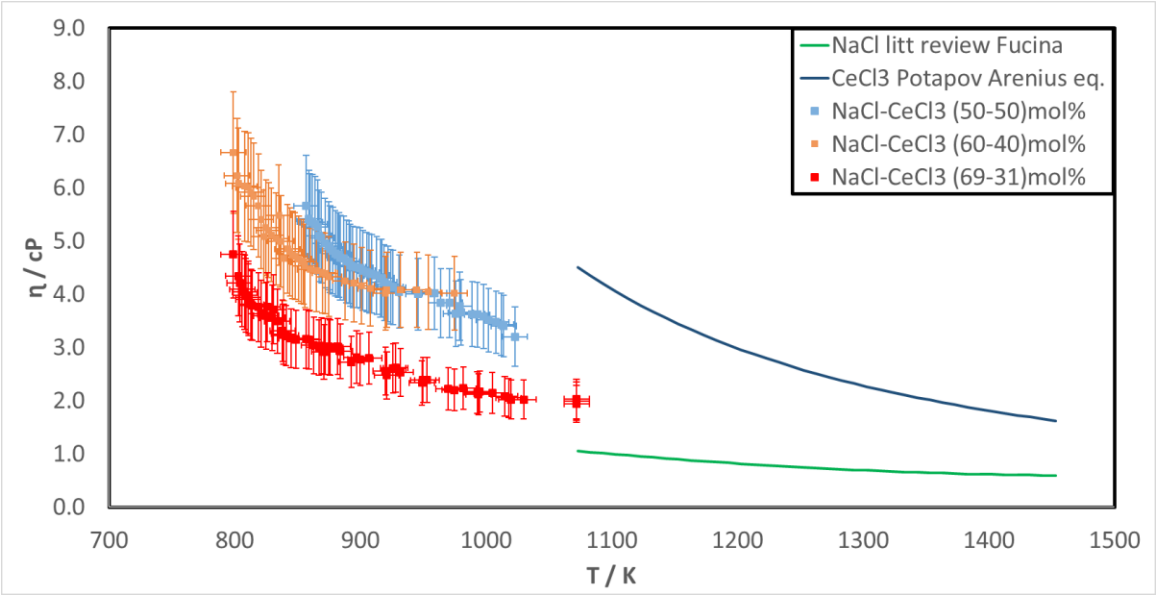


European Commission

Viscosity

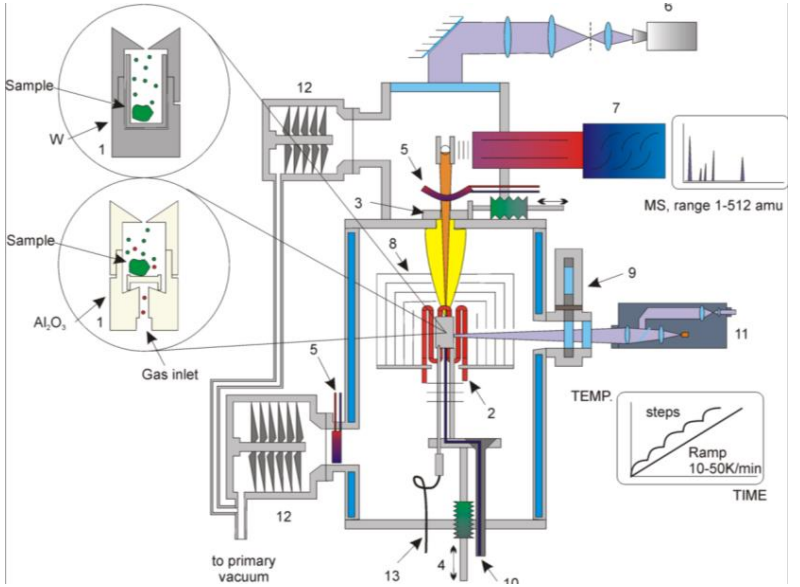
- Method improved
- High temperature viscosity of molten salts measured – inactive salts
- Follow up to active glove box

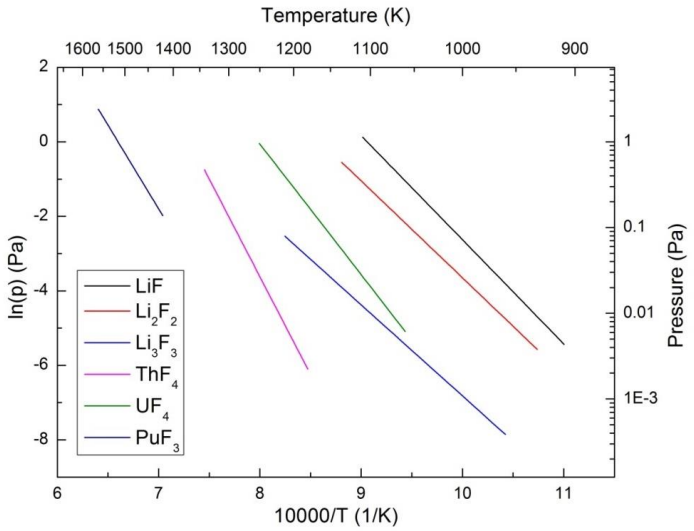




Vapour Pressure

- In house development with key commercial parts
- Measured using Knudsen Effusion cell – Mass Spectrometry (KEMS)
- Complete vaporization of the fuel
- At vacuum conditions





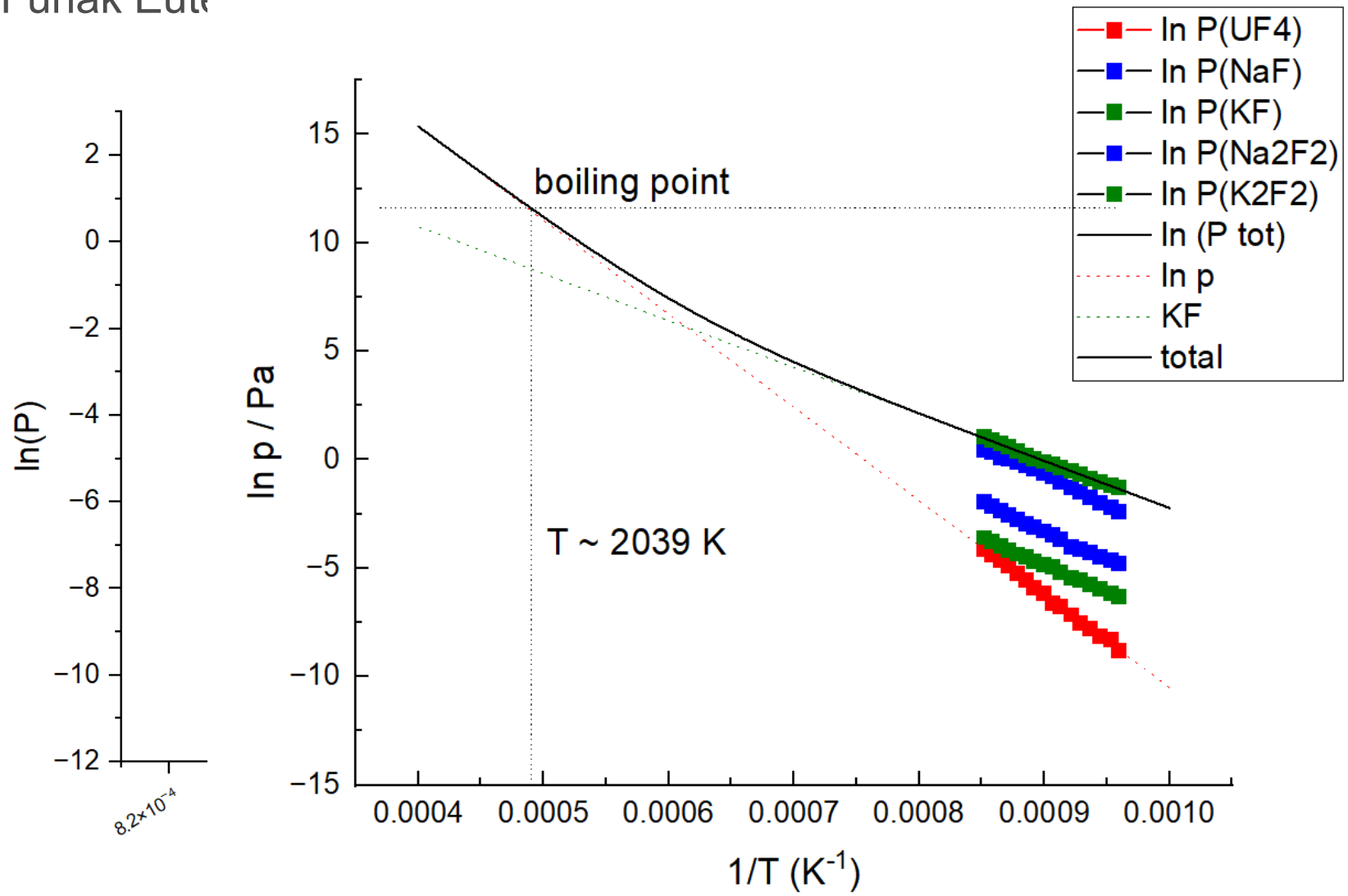
Partial and total vapour pressures for the mixture $LiF\text{-}ThF_4\text{-}UF_4\text{-}PuF_3$ (77.5-6.6-12.3-3.6 mol%)

- Boiling point never reached (due to vacuum)
- Boiling point is very well extrapolated
- ... and correlated with JRCMSD database

B.p. = 1896 ± 20 K

Boiling Point

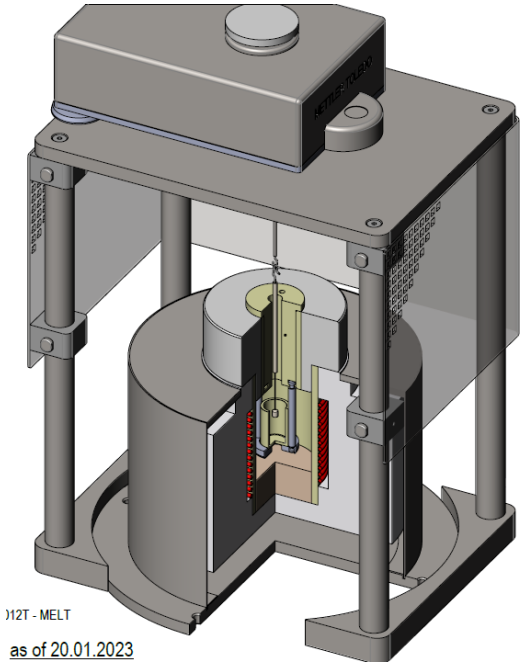
Funak Eutectic (NaF-KF-UF$_4$)

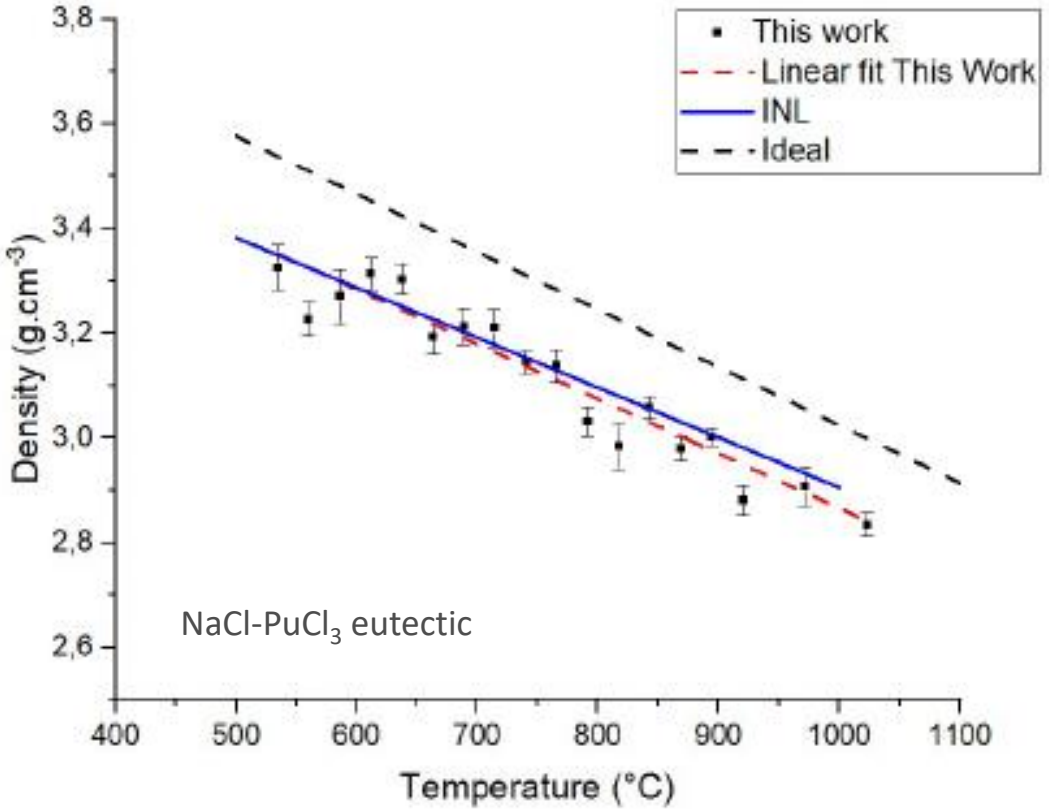


- K - species
- Na - species
- U - species

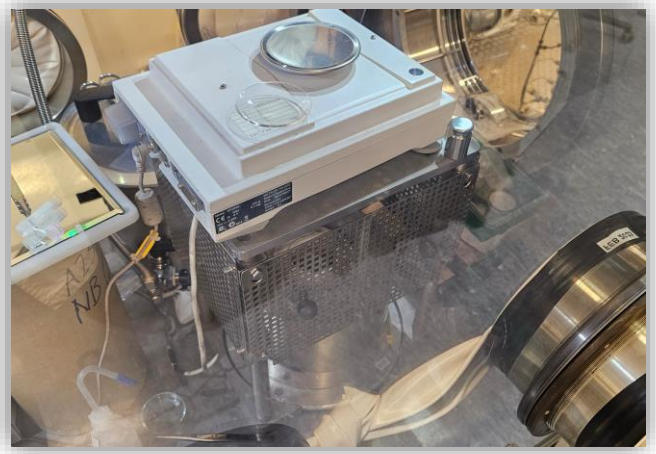
Density

- Completely novel set-up developed
- Based on Archimedean method
- High temperature measurements of fluoride and chloride salts as T function up to 950 °C.
- Very recent measurements on $NaCl\text{-}PuCl_3$ system





$NaCl\text{-}PuCl_3$ eutectic



High T test with (Li,K)Cl eut. melt

European Commission

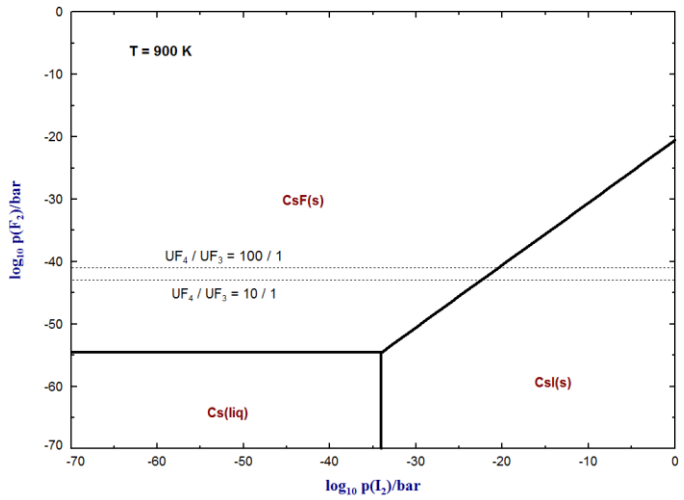
Fission Product Retention

Fission Product retention of the MSR fuel

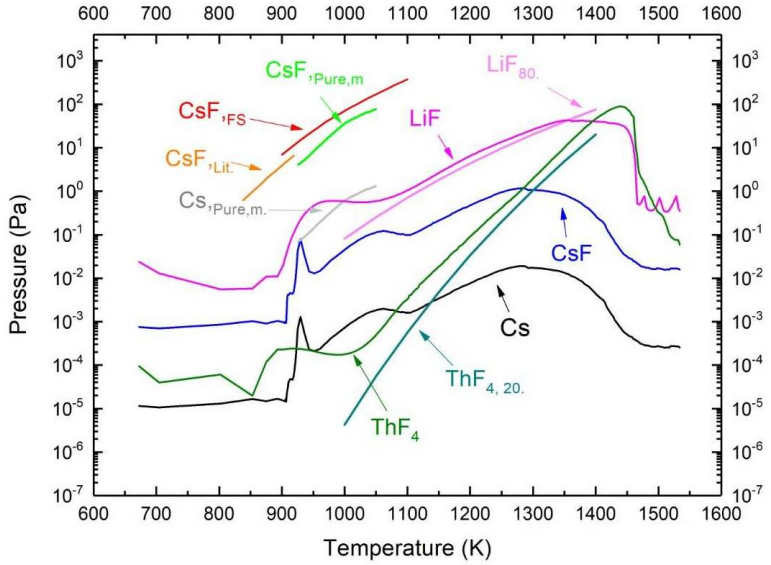
- 1 Determination of Fission product chemistry by simulation
- 2 Sim-fuel synthesis (CsI and CsF additives)
- 3 Measurement of CsF/CsI volatility using KEMS

Frame: HORIZON2020 Project SAMOFAR (2015-2019)

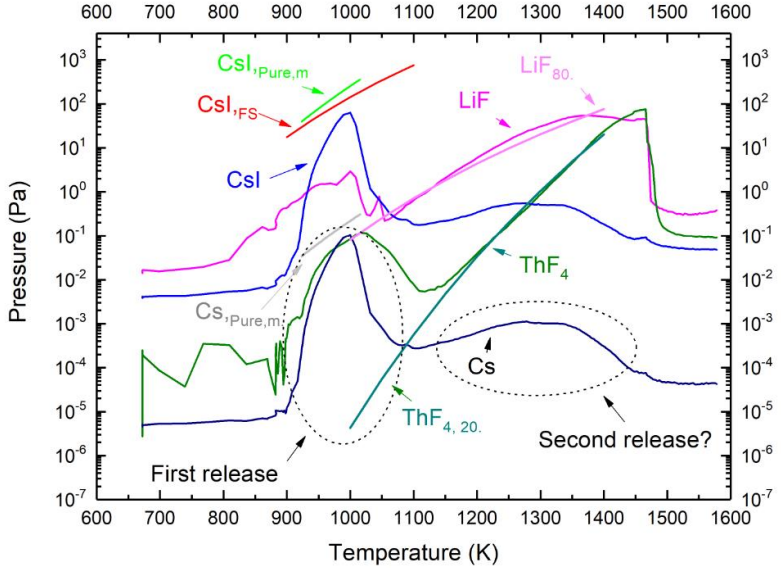
Calculation of Cs- and I- chemical forms



CsF release from LiF-ThF4



CsI release from LiF-ThF4



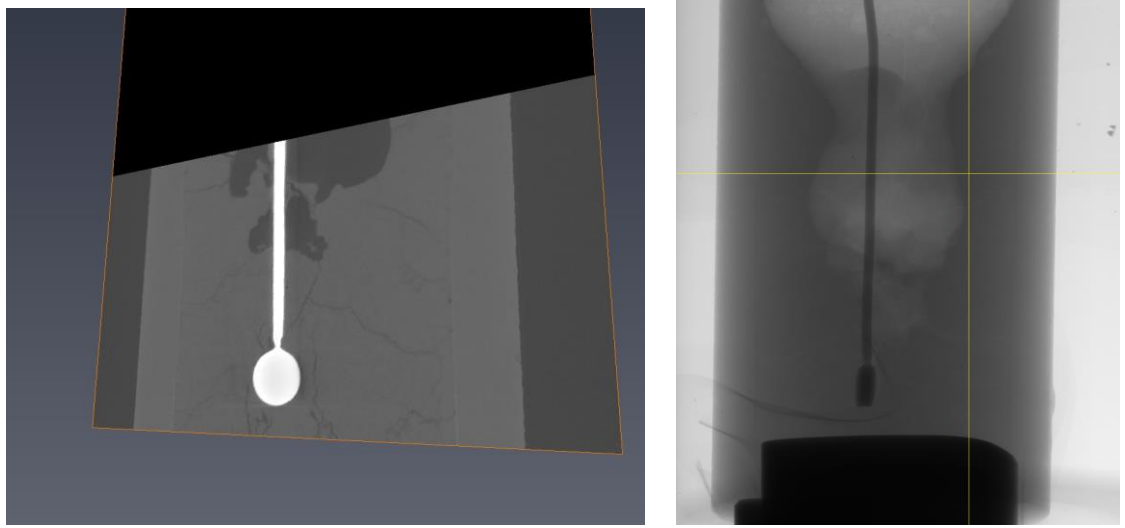
Conclusions:

- 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)

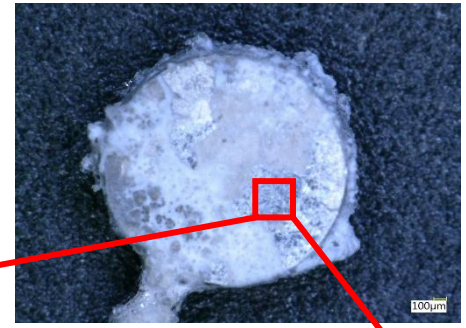
European Commission

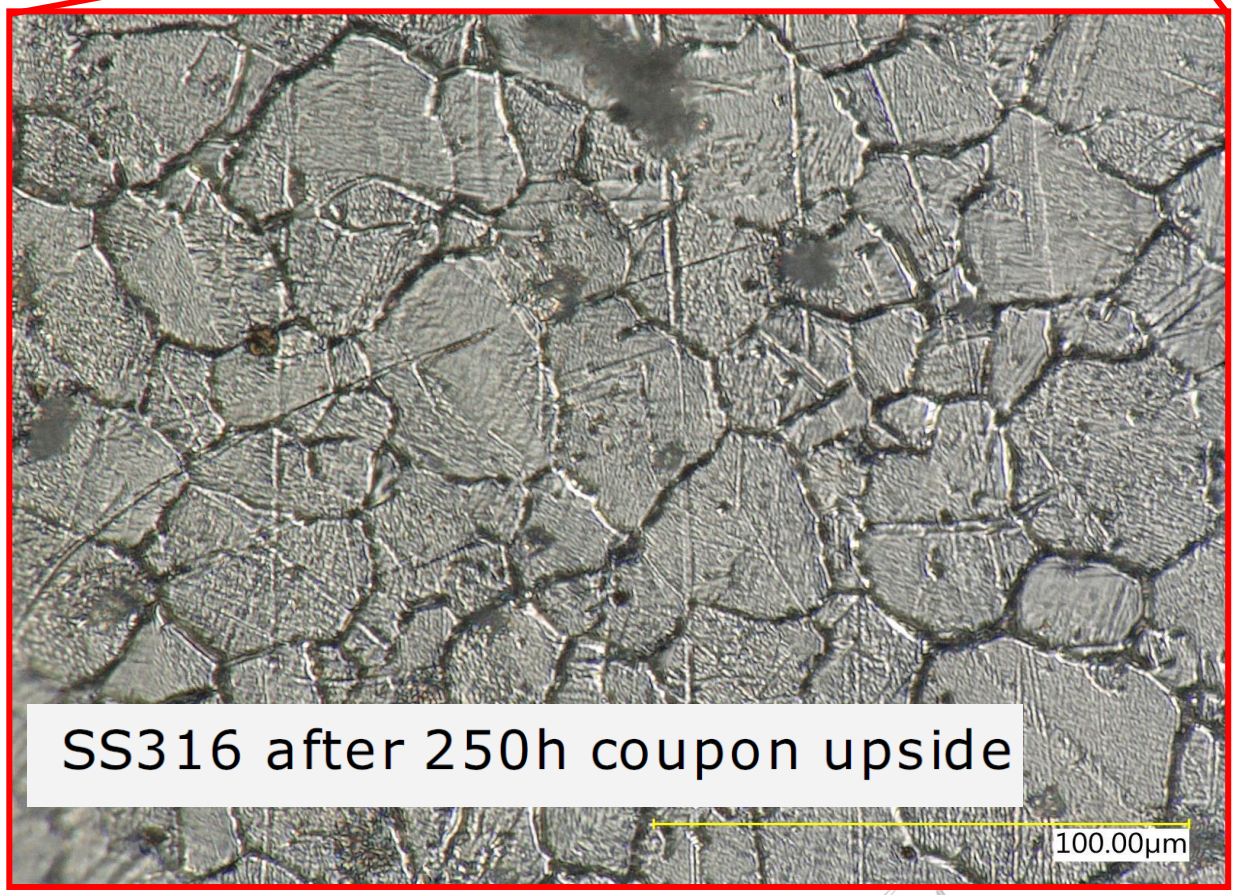
Corrosion Studies

- First test conducted on 316 steel + Flinak for 250h at 700 °C



X-ray tomography before the experiment





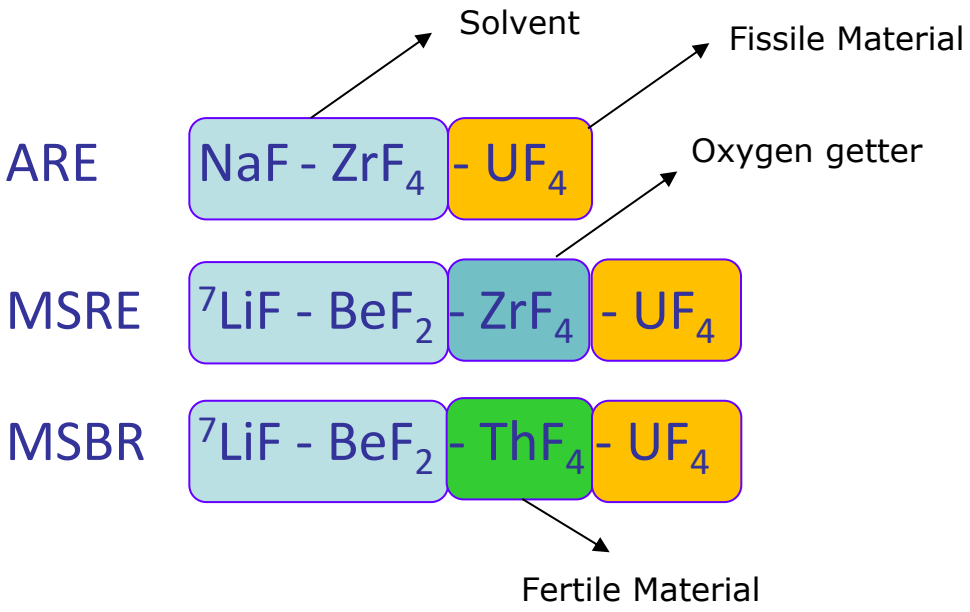
European Commission

Thermodynamic Database

The Fuel

Mixture of Fluorides or Chlorides with dissolved fissile material

US Historic concepts



Selected nowadays concepts

MOSART	$^{7}LiF - BeF_2 - PuF_3$
TMSR	$^{7}LiF - BeF_2 - ThF_4 - UF_4$
MCRE	$NaCl - UCl_3 - PuCl_3$
MCFR	$NaCl - (MgCl_2) - PuCl_3$
CMSR	$NaF - KF - UF_4$

Database Properties

Need for Thermodynamic database

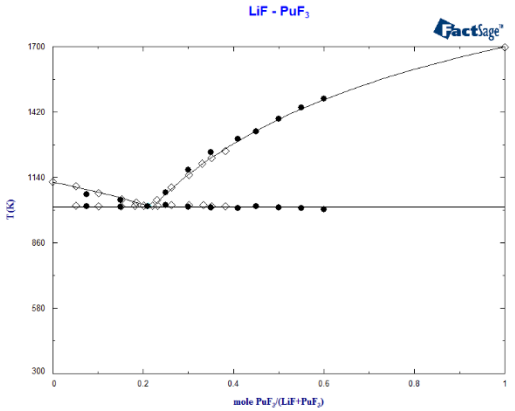
For reactor concept

- **Neutronic properties**
- **Melting temperature**
- **Heat capacity**
- **Vapour pressure**
- **Actinide solubility**
- **Chemical stability to high T**
- **Density and Viscosity**
- **Thermal conductivity**
- **Stability to radiation**

Thermochemistry

MSR fuel is multi-component system
e.g. $NaCl$-UCl_3-$PuCl_3$

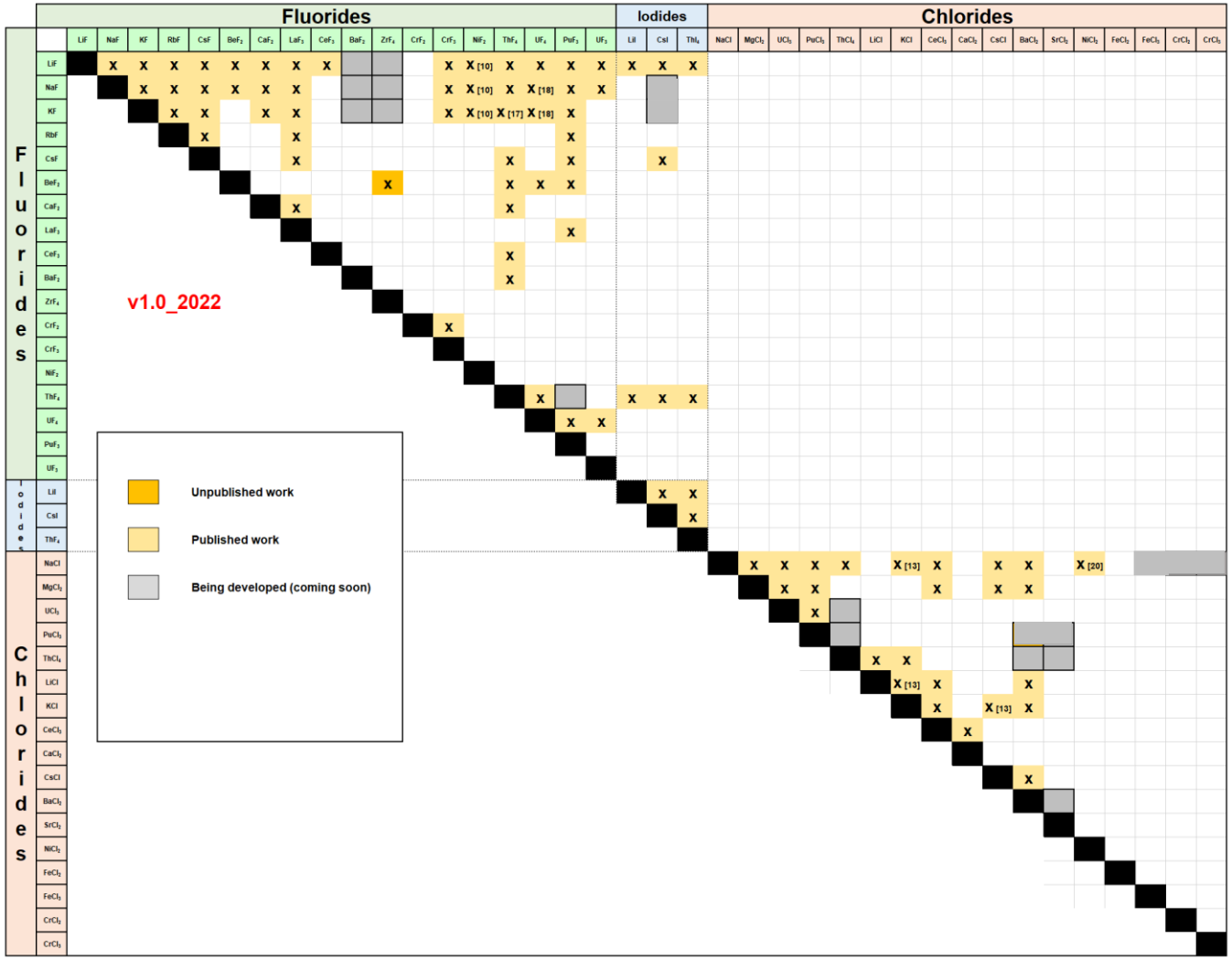
- Finding optimal composition
- Trial-Error method is not efficient
- Having model is the solution

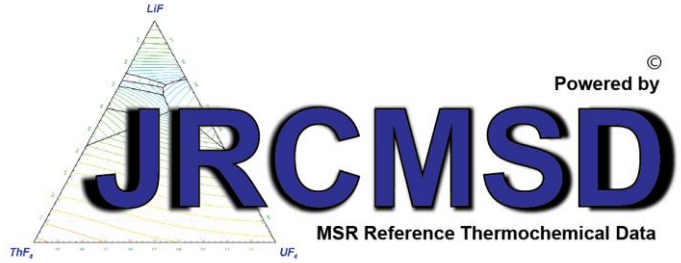


Points – Experimental input

Line – Thermodynamic model

JRC Thermodynamic database - JRCMSD





- Started by JRC in 2002
- >130 pseudo-binary systems included
- Multi-lateral collaboration TEMOSA Project
  - (CEA, JRC, Orano, TU Delft)
  - Open for other partners
- Distribution through FactSage and Thermochimica ongoing
- Describes all key MSR fuels (chlorides, fluorides)
- Extension by corrosion and fission products
- Validation through experiments

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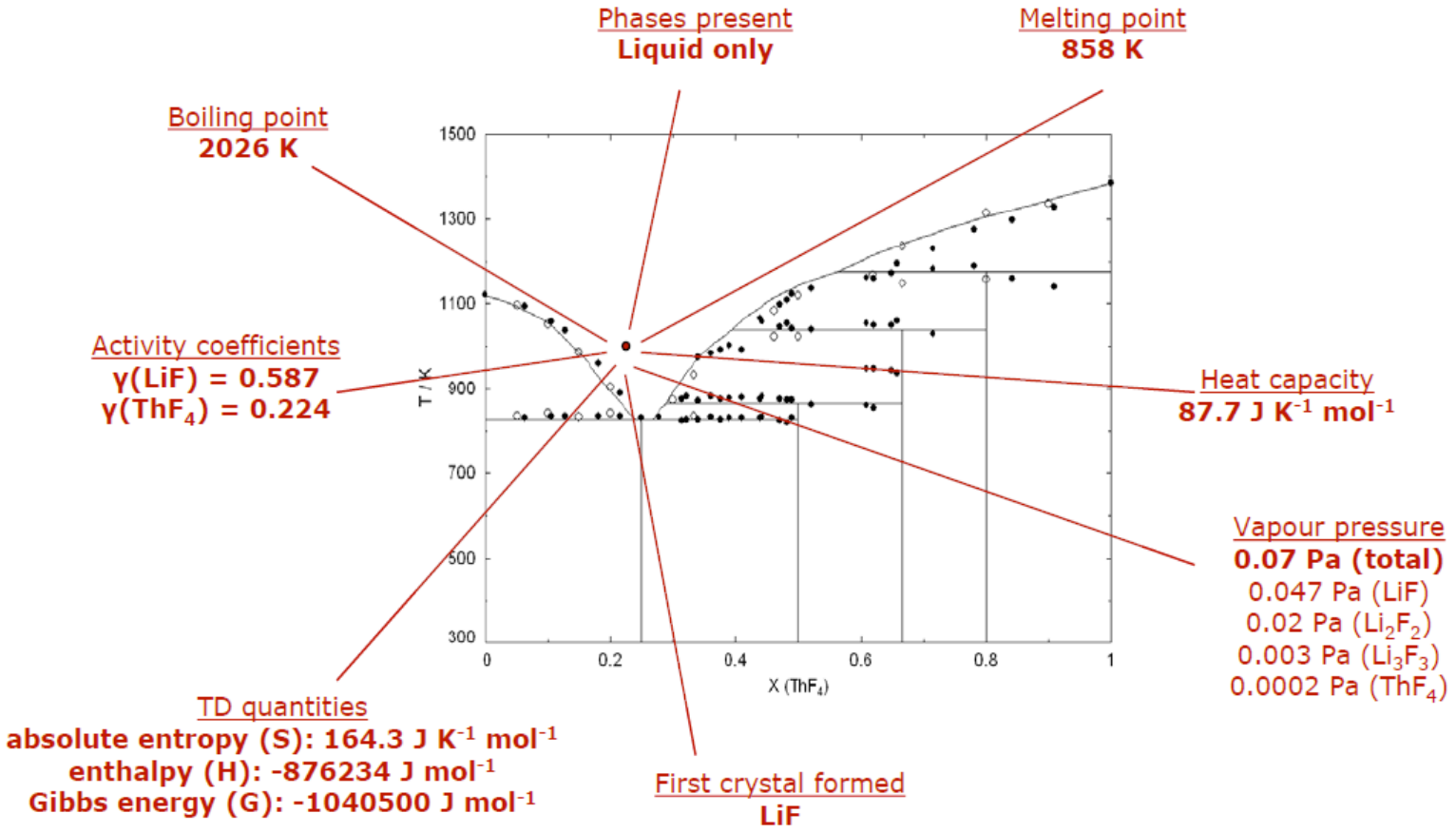
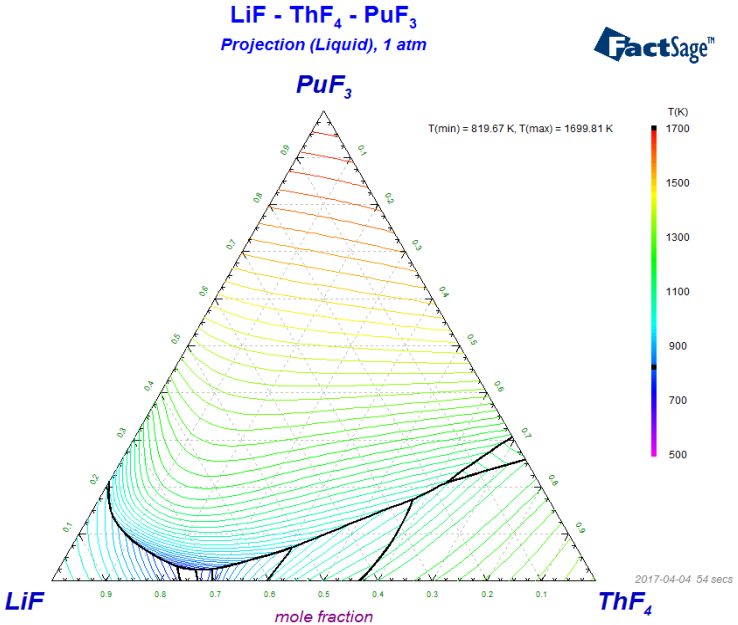
Thermodynamic Database

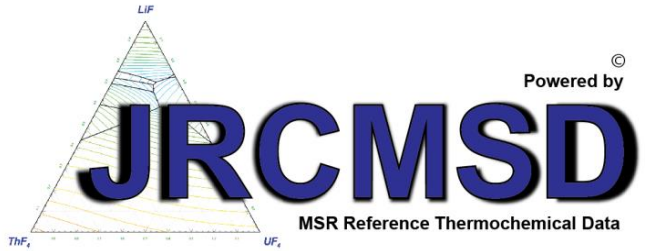
Simple example what we can quickly determine from the database

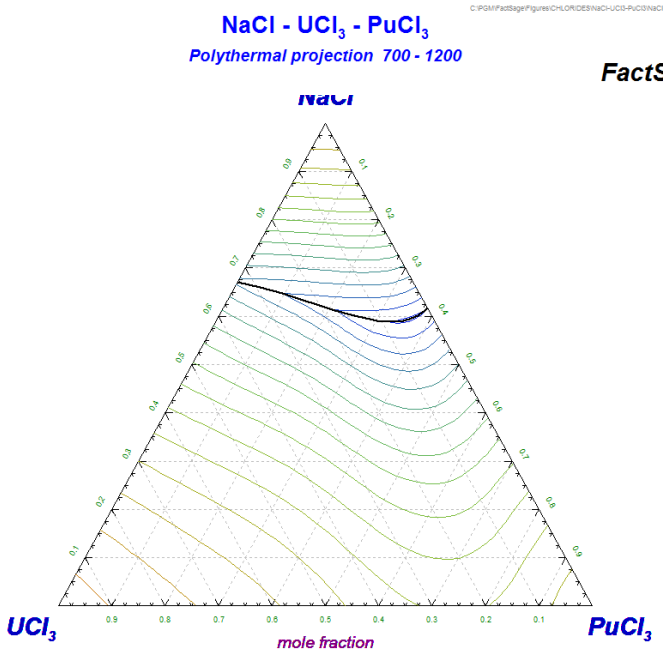
Example is the LiF-ThF_4 (78-22 mol%) composition – The red dot

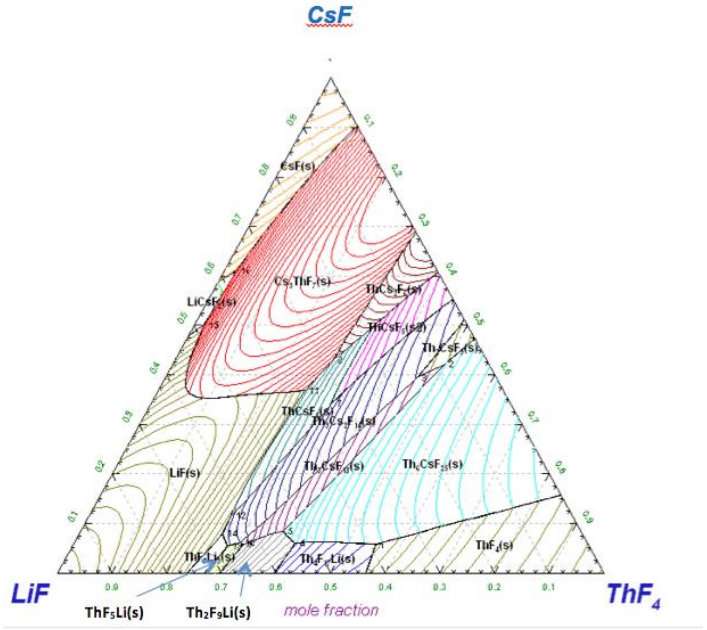


Thermodynamic Database









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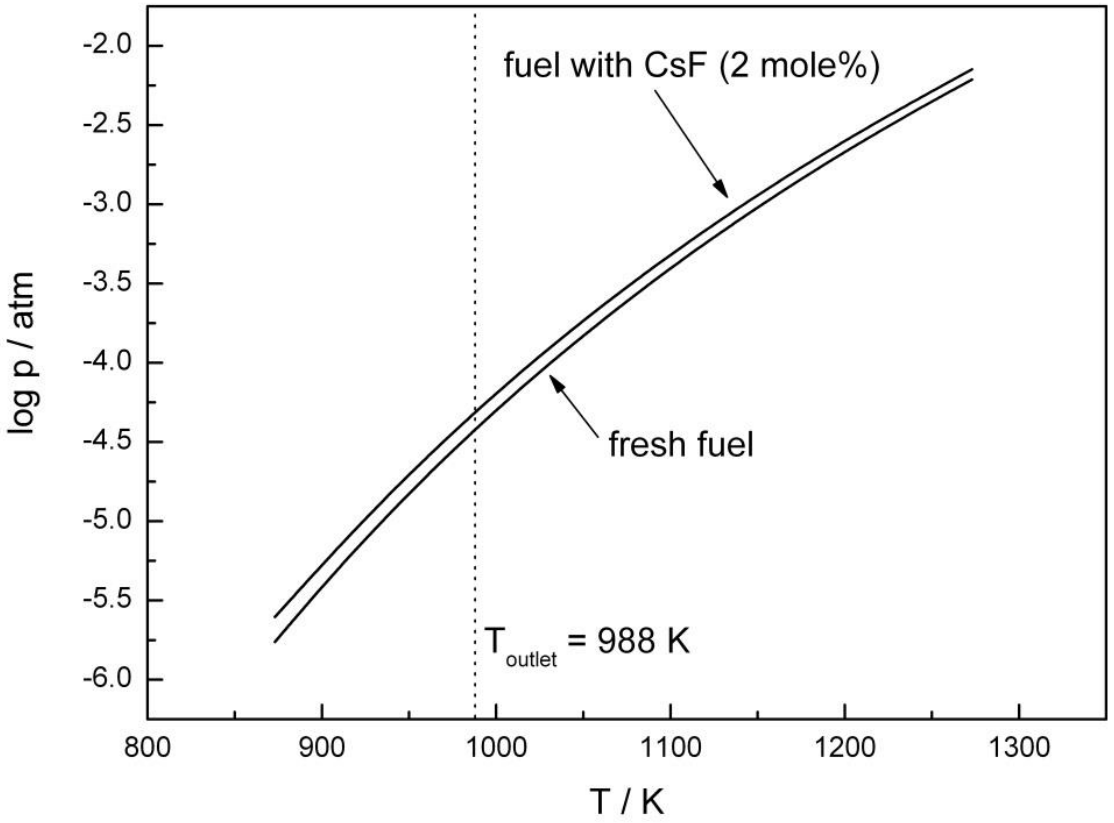
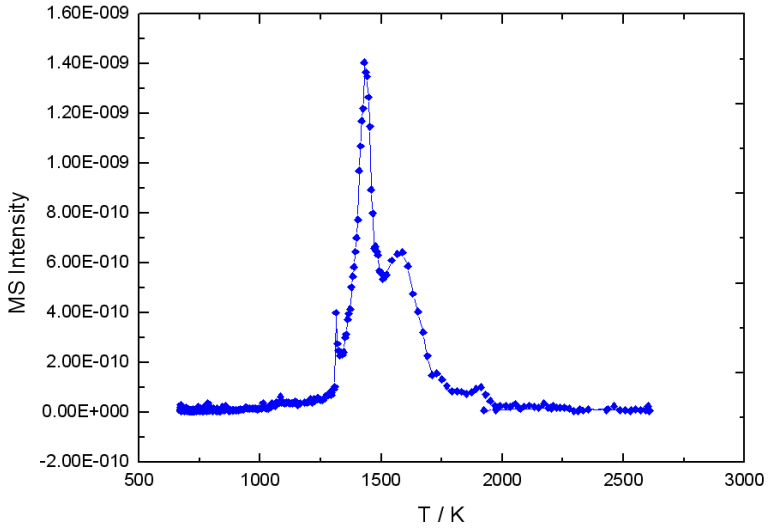
Thermodynamic Databae

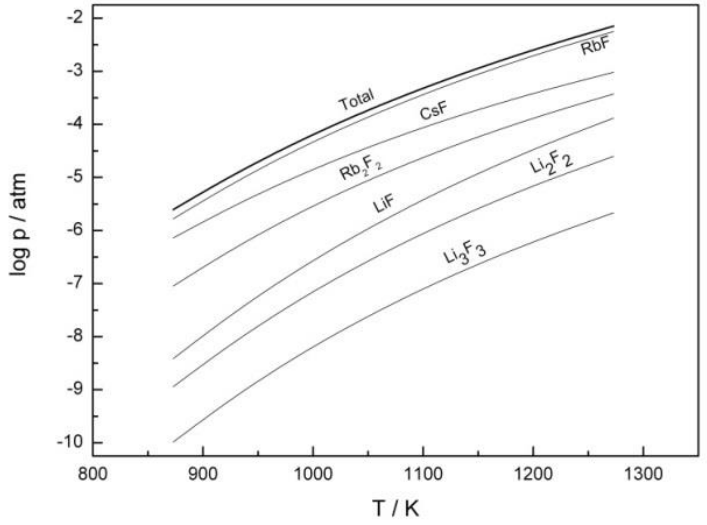
Example 1: Fission product influence on MOSART fuel

Case of LiF-RbF-PuF_3 (43.9-54.8-1.3) fuel
(alternative of MOSART fuel, m.p. 744 K)



Cs realease from MOX





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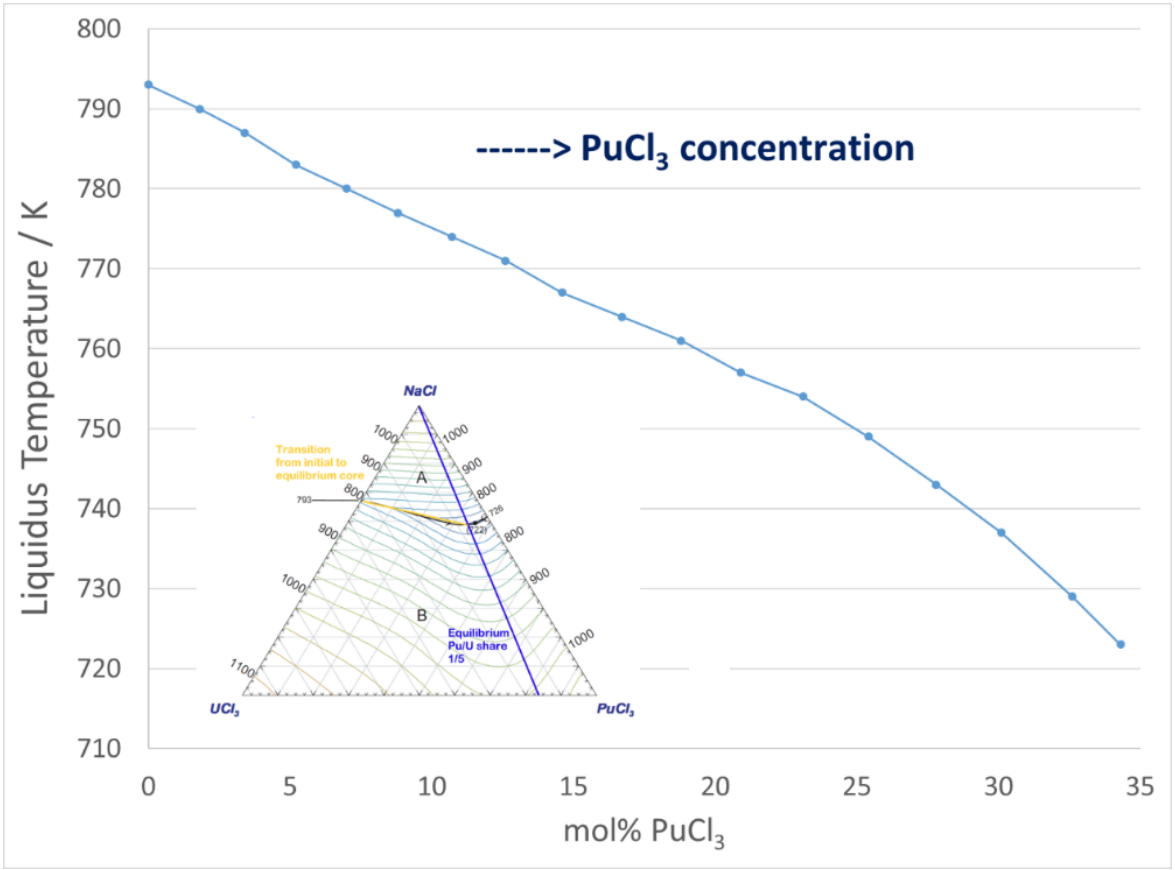
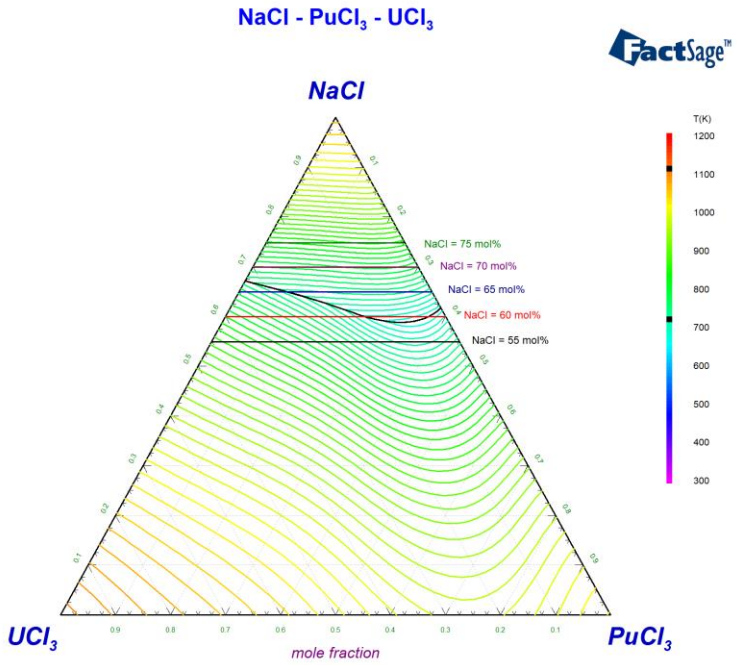
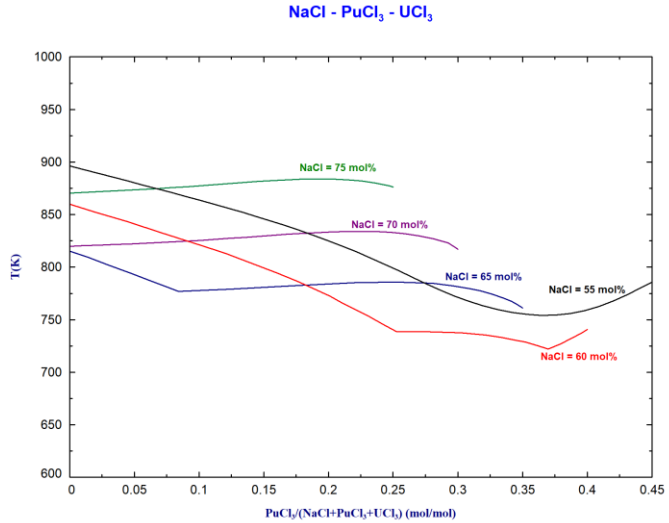
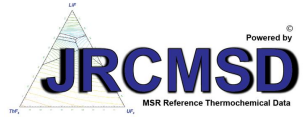
Thermodynamic Databae

Example 2: Melting point determination With fuel burn-up









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EUROMOST 26’

- Organized by JRC
- Panels based on invitations
- Call for Abstracts for Posters coming
- JRC-EUROMOST@ec.europa.eu

- Conference Chair: O. Benes
- Scientific Committee:
  - P. Soucek (JRC)
  - E. Capelli (Orano)
  - J. Krepel (PSI)
  - S. Lorenzi (Polimi)

- International format (invitations coming)

Conclusions

Thank you

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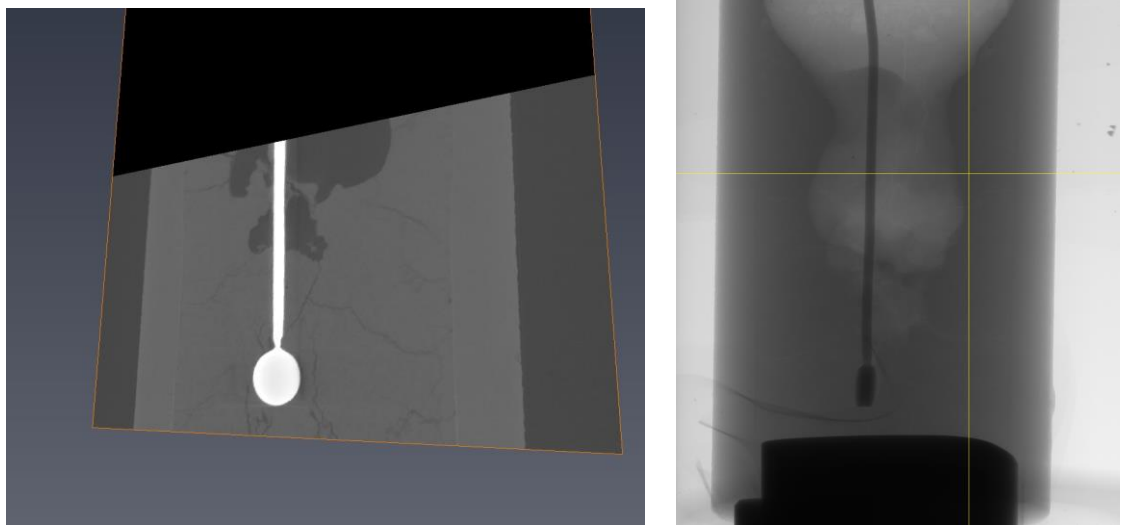
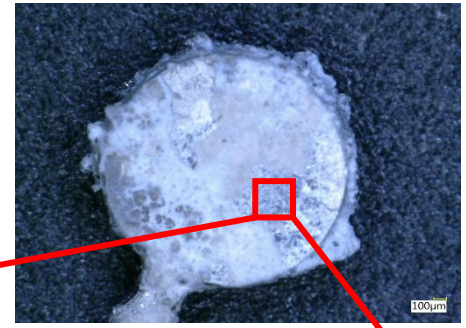
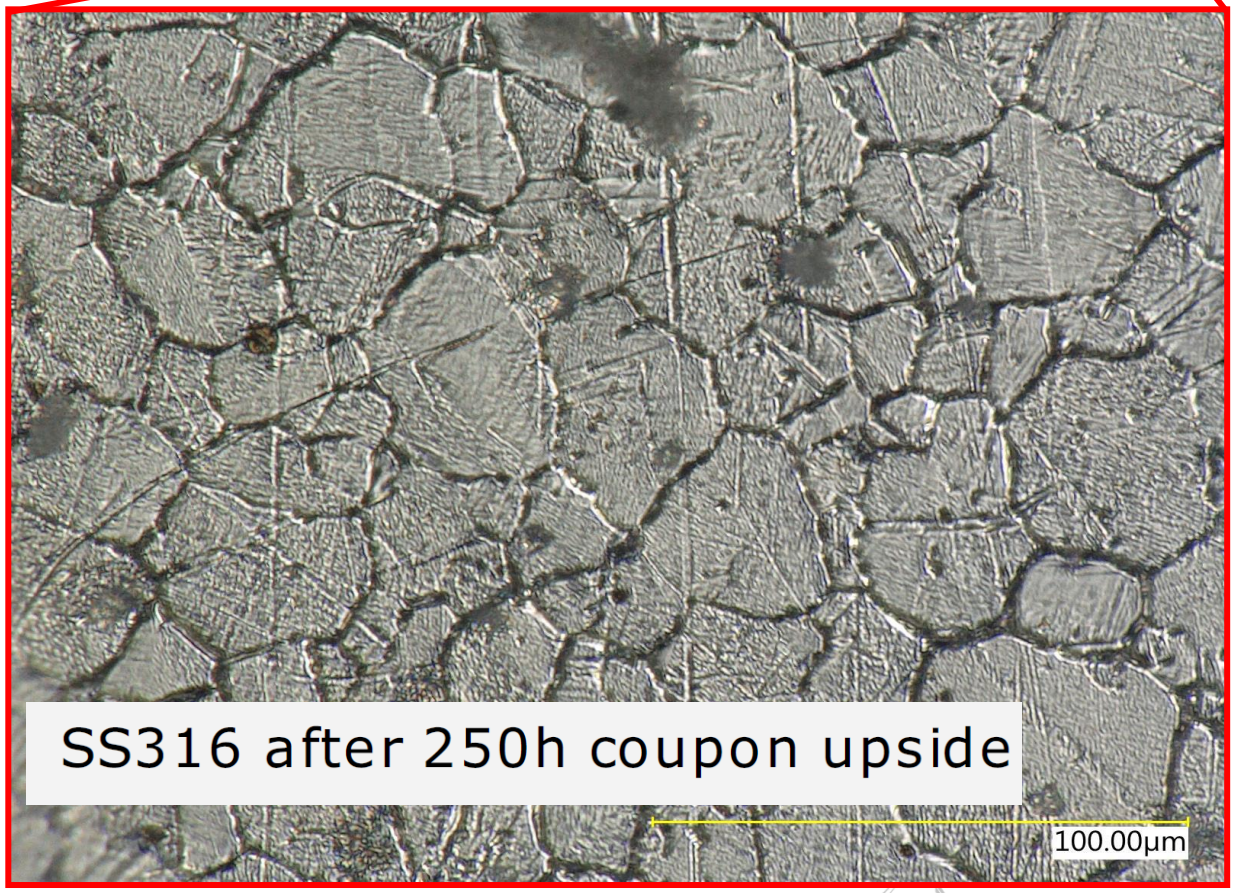
Corrosion Studies

- First test conducted on 316 steel + Flinak for 250h at 700 °C



X-ray tomography before the experiment





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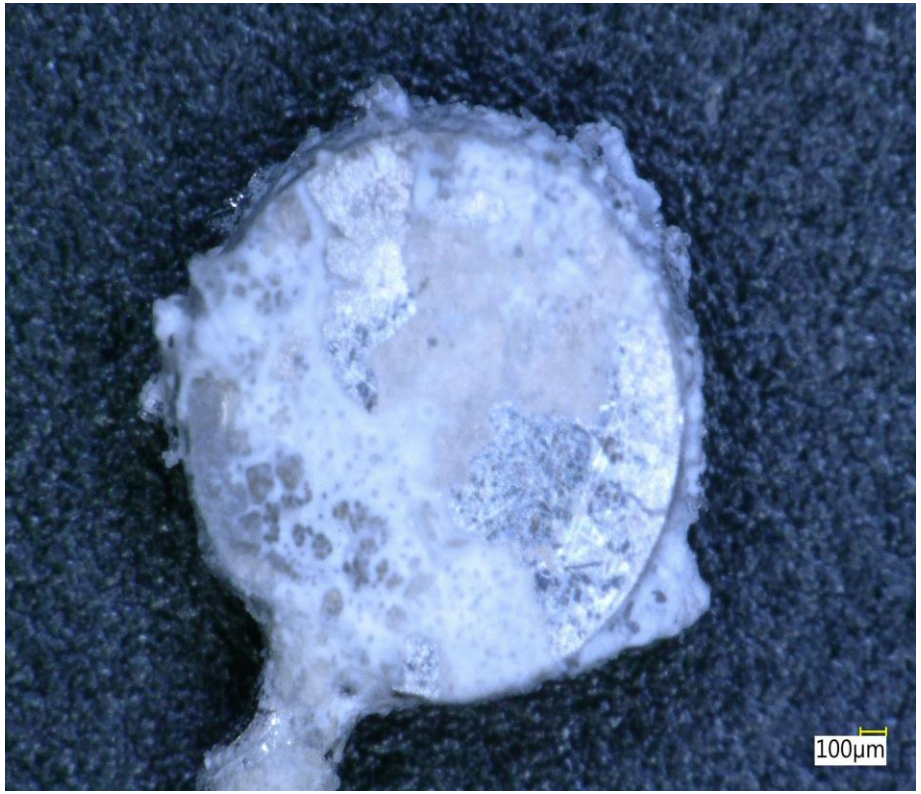
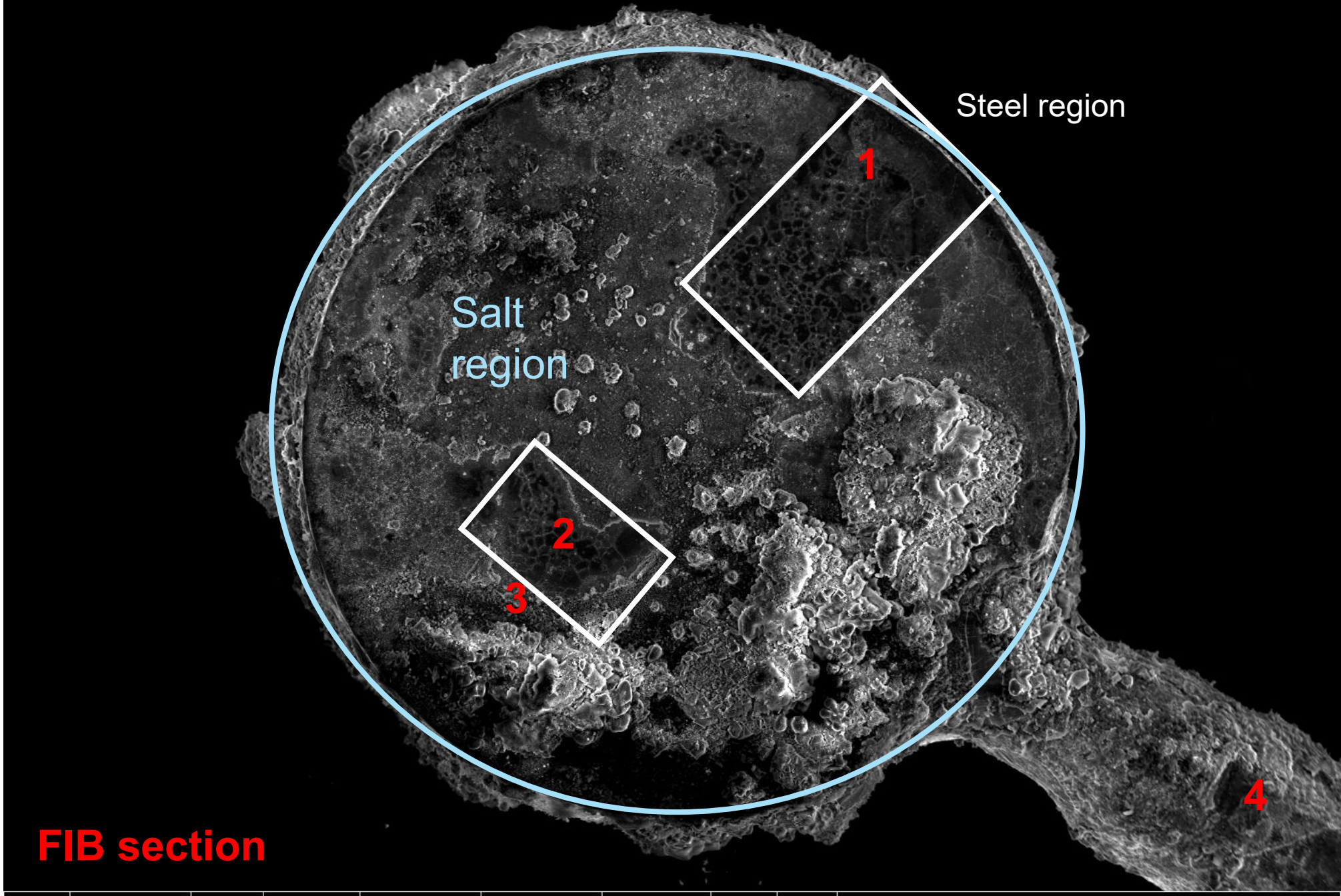
Before experiment

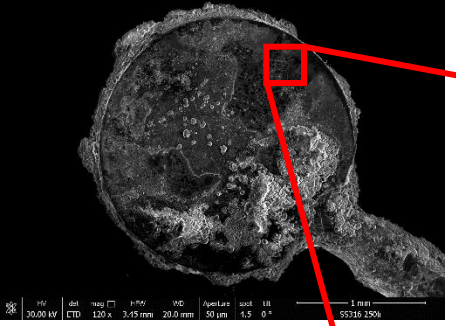
After experiment



FIB/SEM investigation

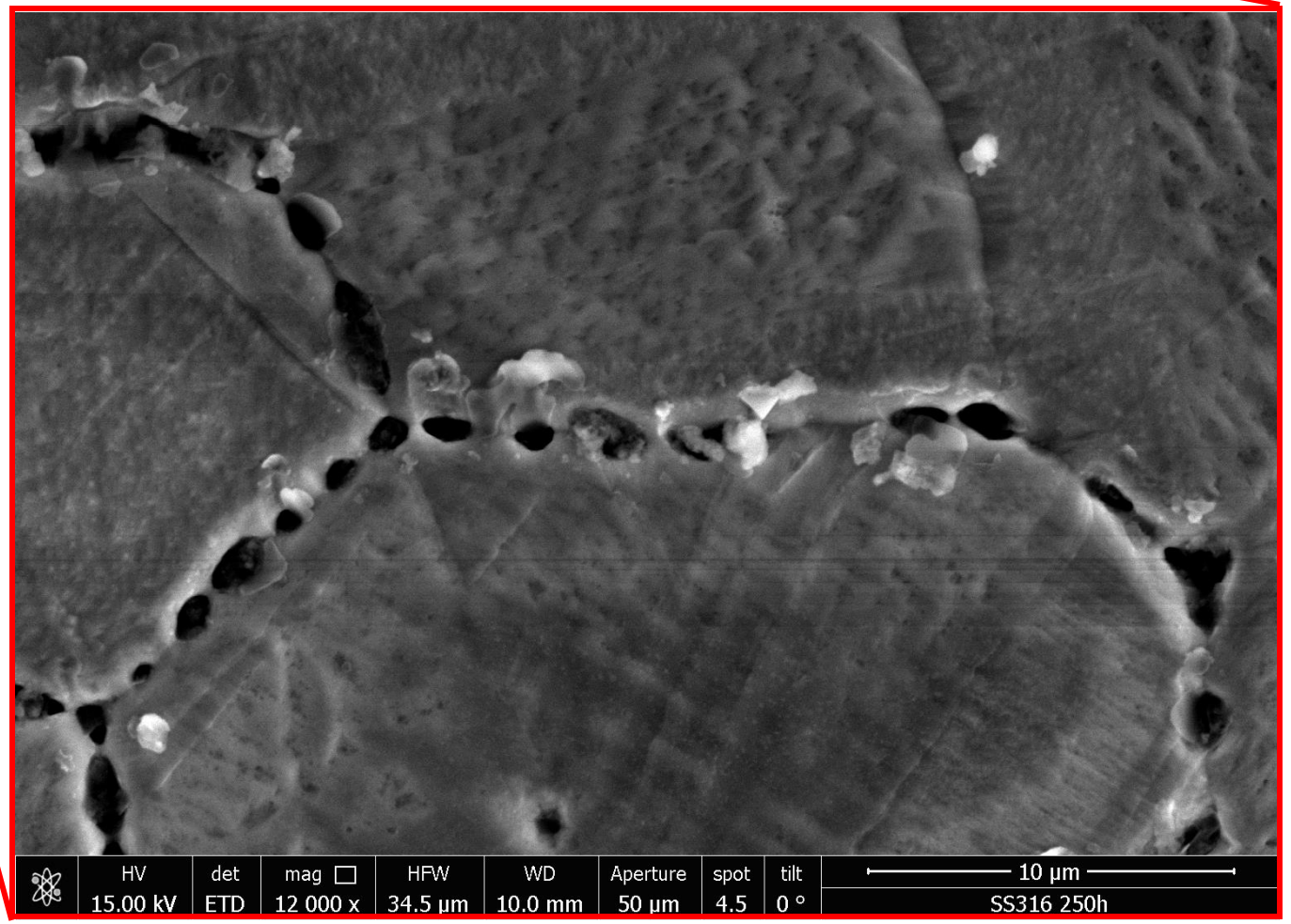


	HV	det	mag	HFW	WD	Aperture	spot	tilt	1 mm
	30.00 kV	ETD	120 x	3.45 mm	20.0 mm	50 µm	4.5	0 °	SS316 250h

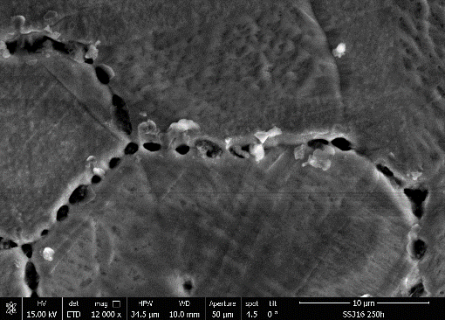


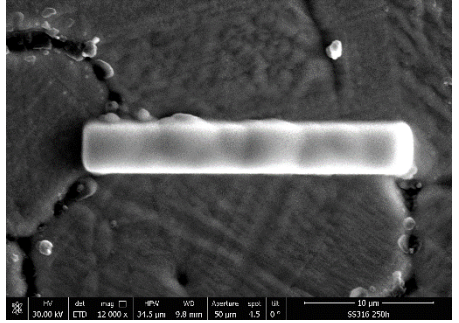
Steel region

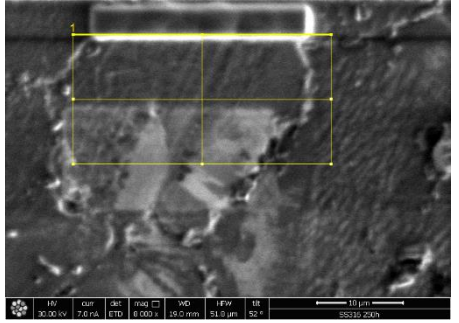
FIB section 1 investigation

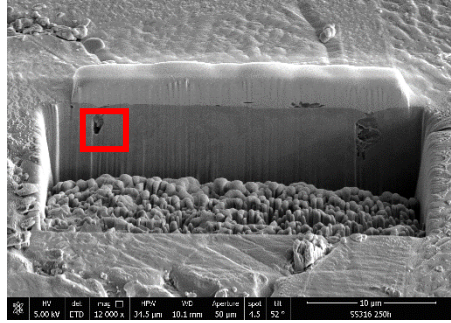


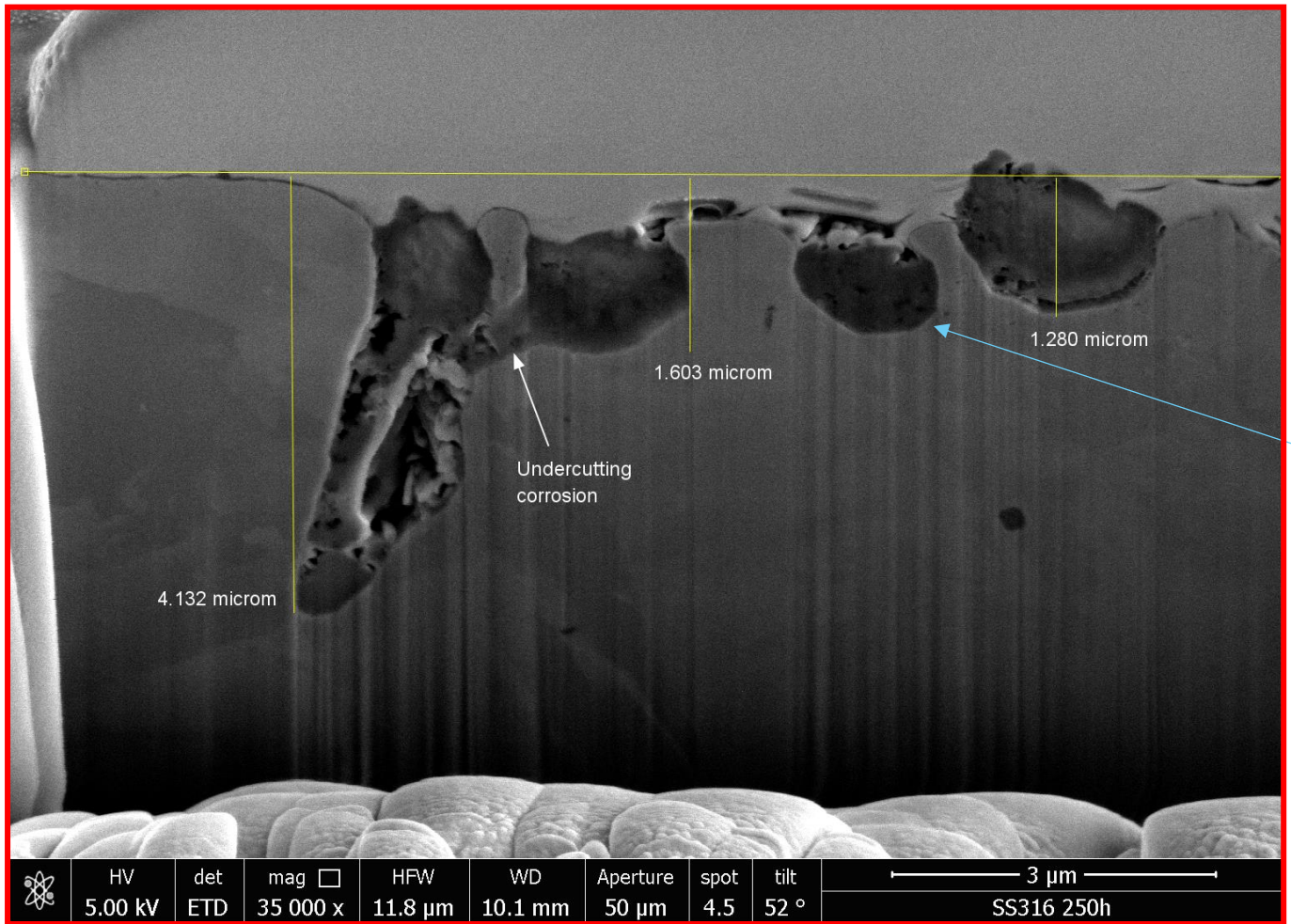
Essentially pitting corrosion



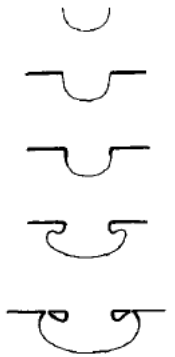








Characteristic lacy formation



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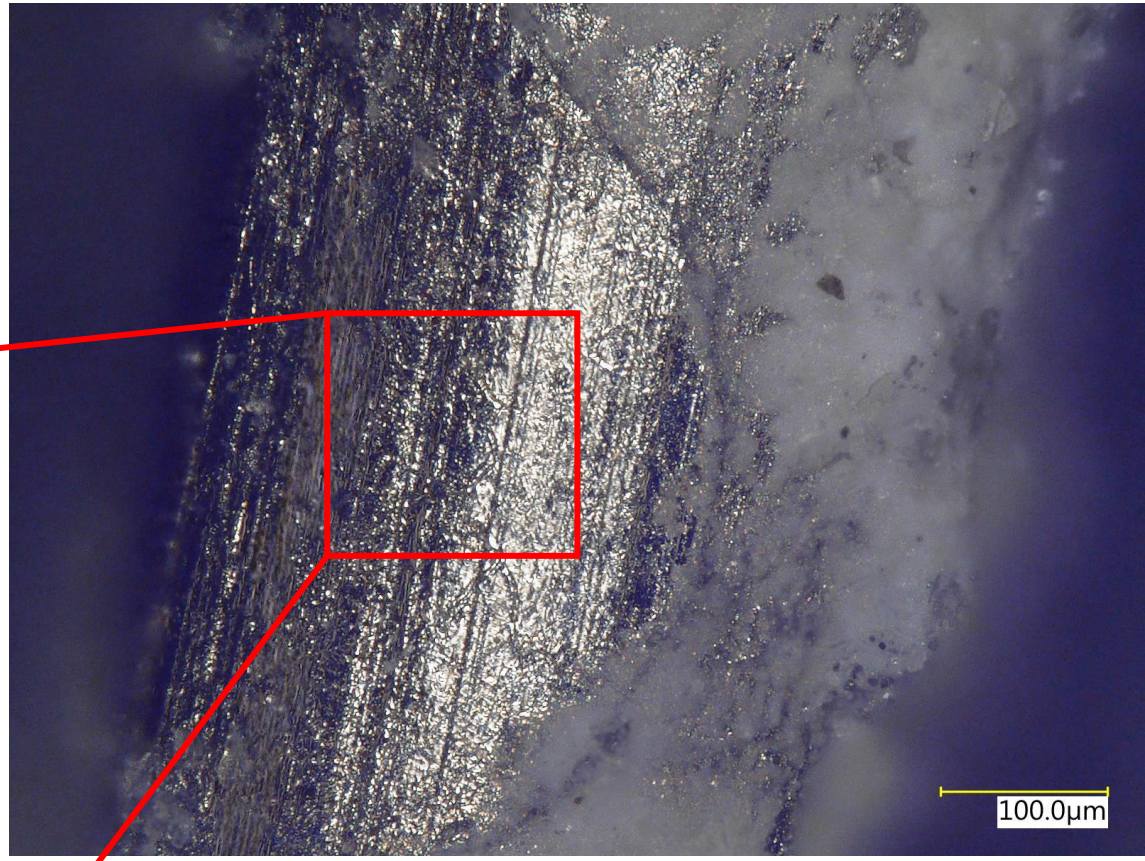
Optical Microscope: Ni wire

None or almost no effect after 250h



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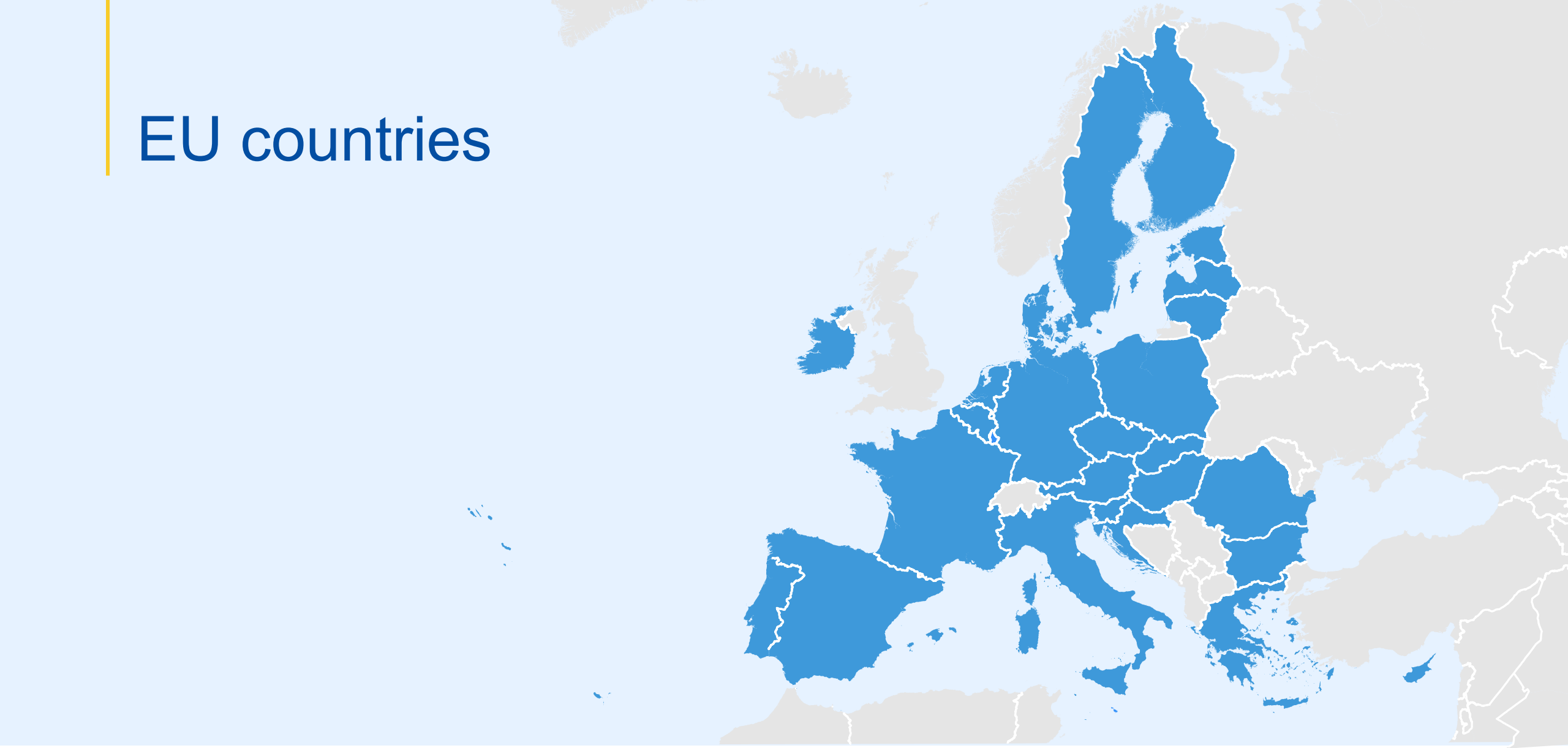
EU countries



0 250 500 1,000 Km

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