Salt Irradiations at the Nuclear Research and Consultancy Group

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Dutch program overview

- **Sponsored by the Dutch Ministry of Economic Affairs as part of a broader Nuclear Energy R&D program.**
- **Collaborations with JRC, TU Delft and CV Rez**
- **Program objective: contribute to MSR technology development and realization**
  - Obtain **operational experience** (salt handling, liquid fuel irradiation)
  - **Qualify materials (alloys, graphite) and fuels (fluoride, chloride)**
  - Study **fission product behavior** (normal and accident conditions)
  - Tackle **waste issues**
  - Work towards **Integral Demonstration**

High Flux Reactor Petten

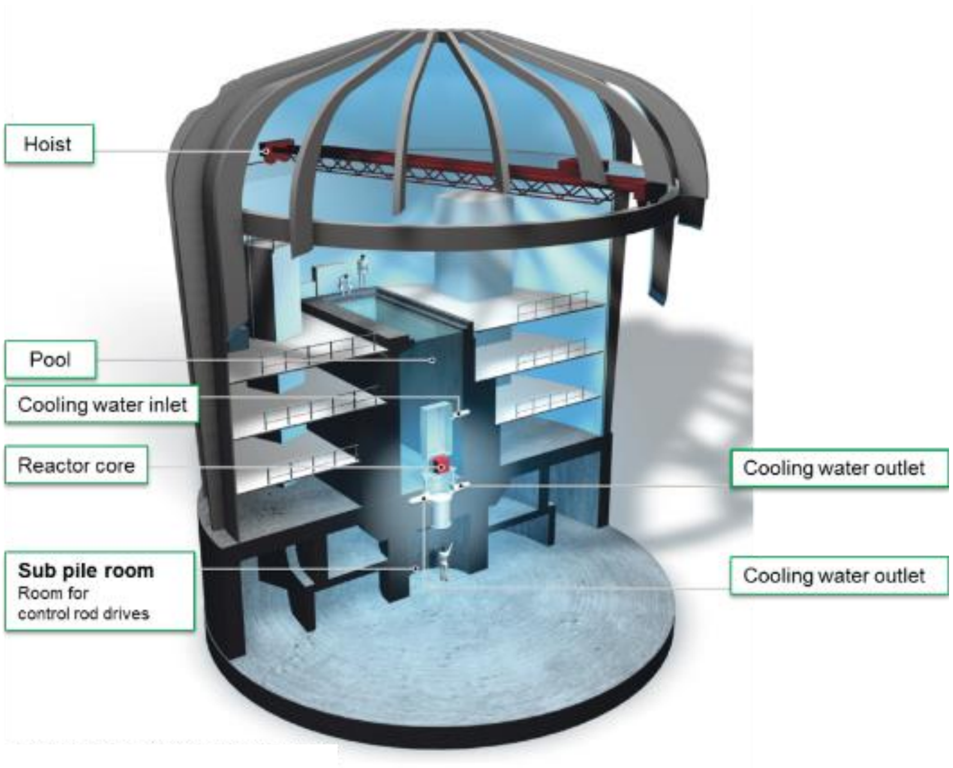
Nickel-based Alloy Irradiation & Mechanical Testing (ENICKMA and ENICKMA-HTC)

In-pile Hastelloy N corrosion by fluoride fuel salt

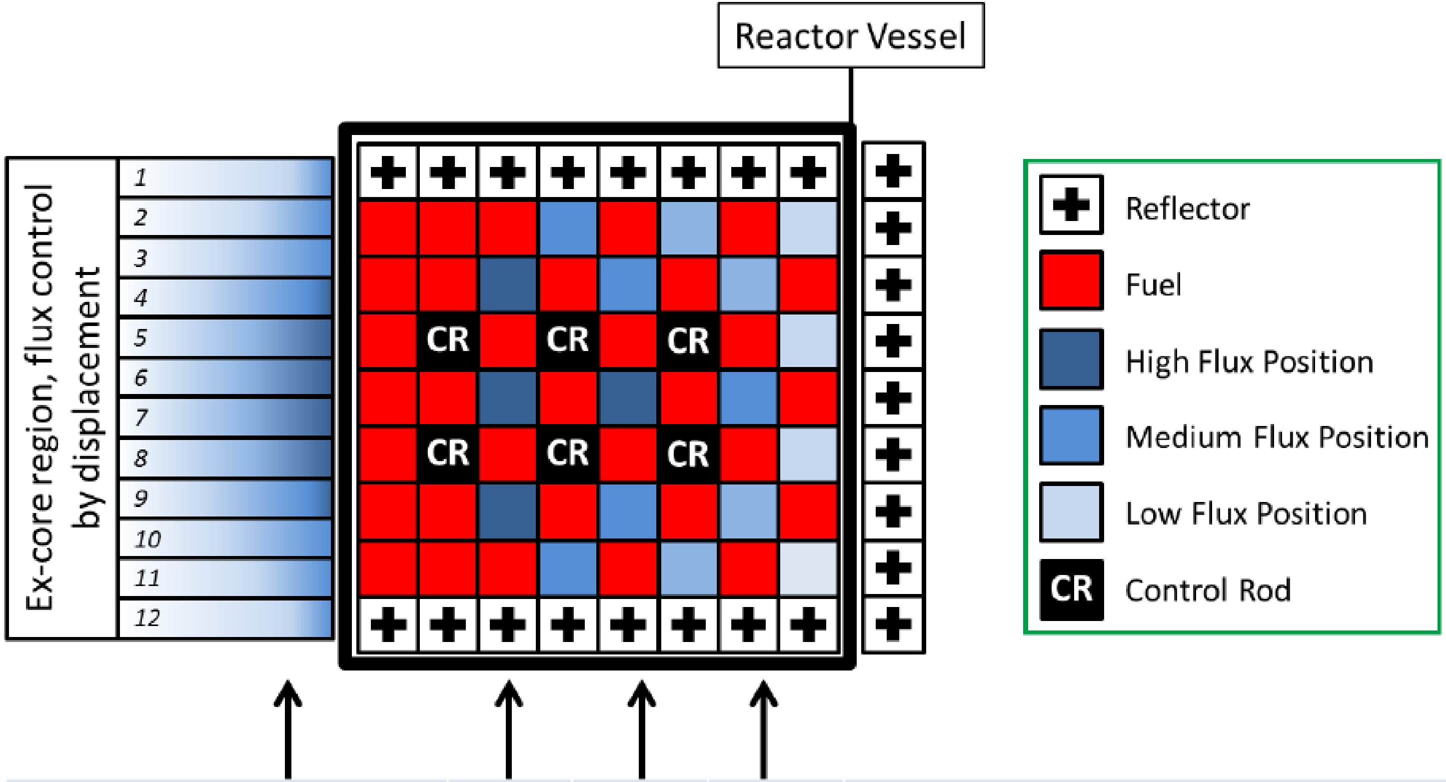
LiF-ThF_4 irradiation in graphite crucibles & graphite qualification

Ensuring Nuclear Performance

The High Flux Reactor



- **High flux**
- **45 MW thermal power**
- **Stable and constant flux profile in each irradiation position**
- **Main applications**
  - Isotope production
  - Nuclear energy irradiation services
  - R&D
- **31 operation days per irradiation cycle, 9 cycles a year**



0-3, location dependent	5-8	3-5	1-3	Material DPA rate (DPA/year)
0-700, displacement controlled	n/a	500-700	300-400	Linear heat rate (W/cm fresh LWR fuel)

The stable and constant flux profile in each irradiation position is a unique HFR feature

ENICKMA project

Helium embrittlement
Thermal embrittlement

- **Goal:** Study material degradation behavior under neutron irradiation at high temperature + investigate underlying mechanism

- **Materials:** Nickel alloys with compositions close to Hastelloy N

ENICKMA materials

- Hastelloy N (Haynes)
- MONICR (CV Rez)
- HN80MTY (COMTES FHT)
- GH3535 (SINAP)

- Hastelloy 242 (Haynes)

- 316 L(N) (CEA)

	Weight % Main Alloying Elements											
Alloy	Al	Co	Cr	Fe	Mn	Mo	Nb	Ni	Si	Ti	V	C
Hastelloy N	0.29	0.078	7.10	3.60	0.46	17.10	0.070	Bal.	0.31	0.002	0.005	0.059
Hastelloy 242	0.17	0.026	8.00	1.16	0.26	25.80	<0.001	Bal.	<0.02	0.001	0.002	0.002

High-Temperature embrittlement

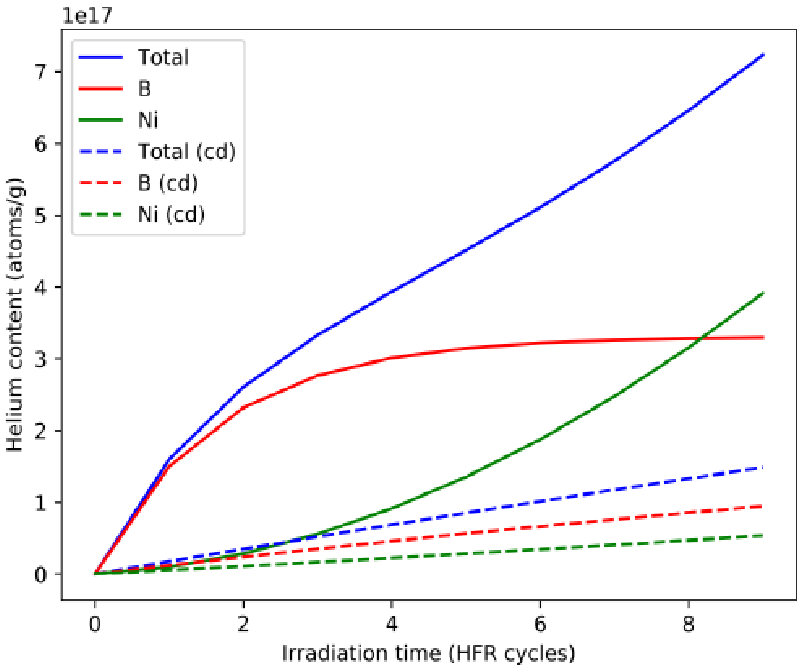
Helium embrittlement in nickel based alloys

- (n,α) reactions in ^{10}B (fast burn-out) and $^{58,59}Ni$ (slow but steady)
- He-production from fast neutron (n,α) reactions
  $^{58}Ni + n_f \rightarrow {}^{55}Fe + {}^{4}He$, $^{60}Ni + n_f \rightarrow {}^{57}Fe + {}^{4}He$
- For thermal neutrons
  $^{10}B + n \rightarrow {}^{7}Li + {}^{4}He$
  $^{58}Ni + n \rightarrow {}^{59}Ni + \gamma$, $^{59}Ni + n \rightarrow {}^{56}Fe + {}^{4}He$

Target fluence: Up to **1E21 n/cm² thermal**, **3E21 n/cm² fast** (up to 50 appm helium, >1 dpa)

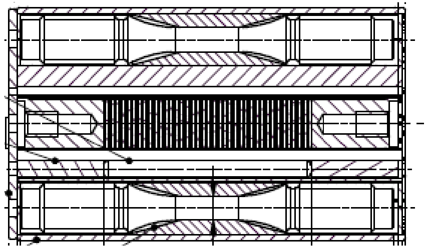
Sample temperatures 650 °C and 700/730 °C

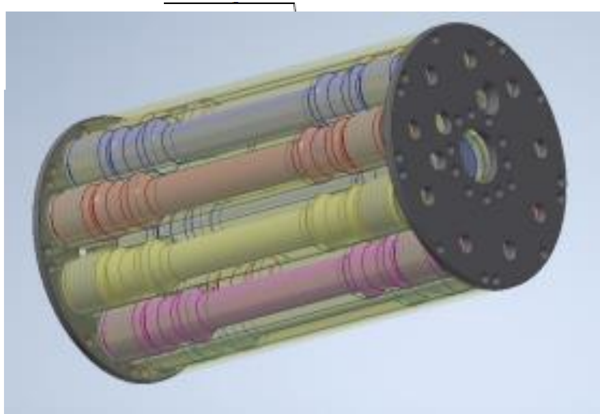
- Oven anneal test at same temperatures for comparison with pure thermal embrittlement

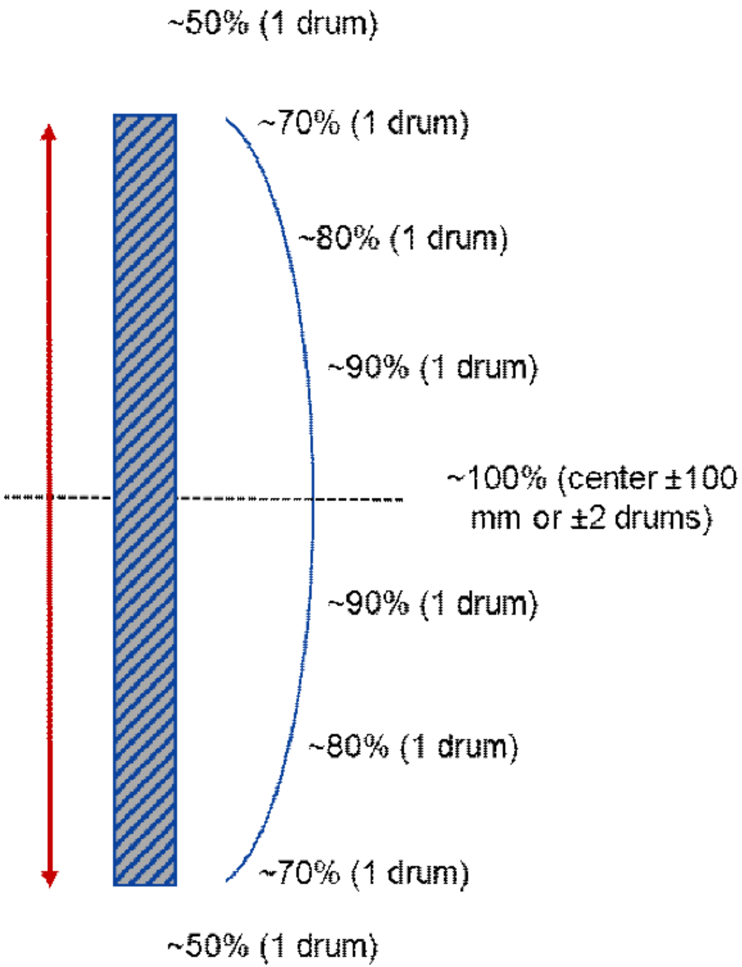


ENICKMA irradiation capsule

- Welded capsule with inert gas plenum
- 10 drums each containing 10 specimens (tensile, LCF)
- Sample temperatures 650 and 700-730 ºC
- Irradiation for 9 months (9 HFR cycles)





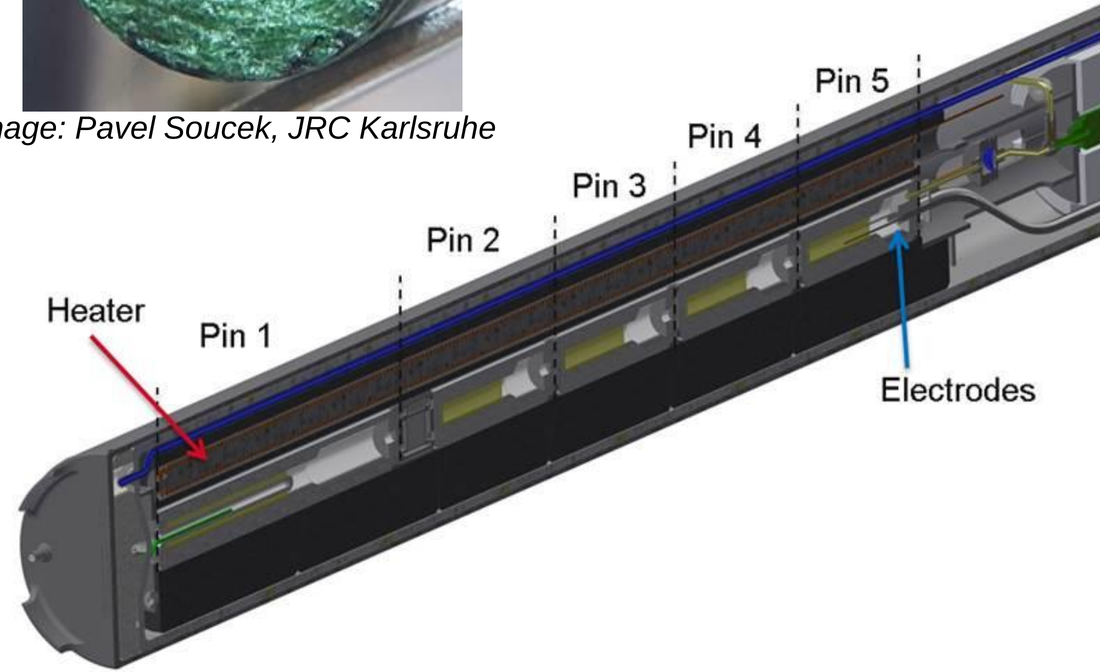


Corrosive salt
Burn-up / fission products

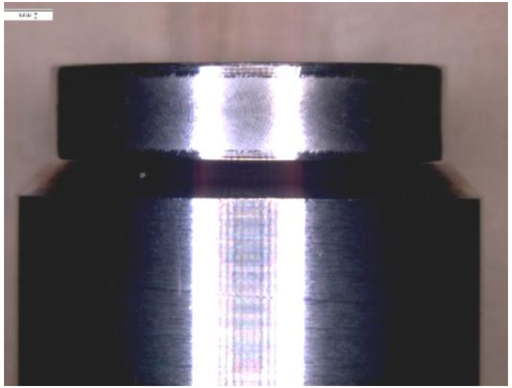
SALIENT-03

- Irradiation of 5 salt-filled capsules
- Investigates **in-pile corrosion** of **Hastelloy N** for different salt chemistry:
  - $LiF\text{-}ThF_4\text{-}\mathbf{UF_4}\text{-}PuF_3$
  - $LiF\text{-}ThF_4\text{-}\mathbf{UF_4}\text{-}\mathbf{UF_3}\text{-}PuF_3$ (UF_4/UF_3 = 20-50)
  - $LiF\text{-}ThF_4\text{-}\mathbf{UF_4}\text{-}PuF_3 + CrF_x$
- Additional focus on behavior/migration of non-soluble and volatile **fission products**
- Attempt to measure redox potential and FGR in-pile
- Use of **heaters** to avoid radiolysis during downtime (T ~150 °C)

Image: Pavel Soucek, JRC Karlsruhe



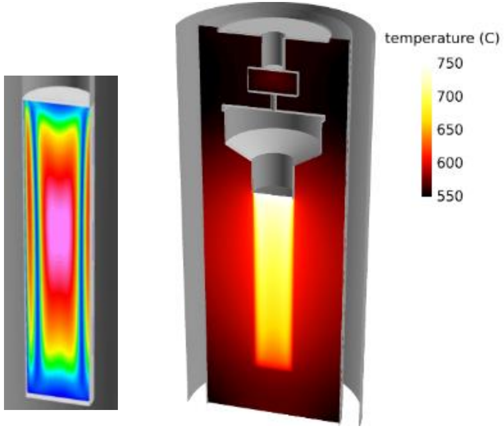
SALIENT-03 - Assembly

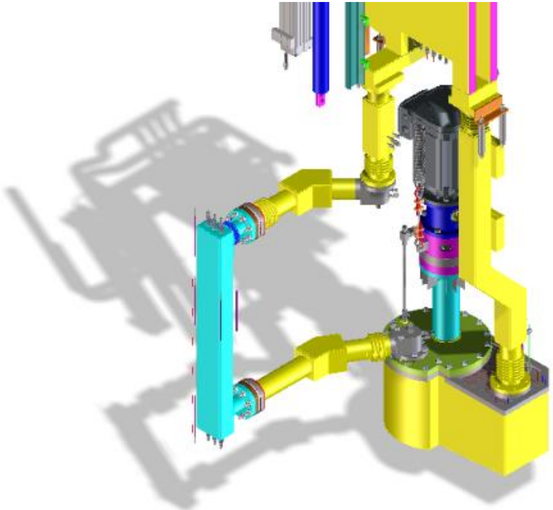


In-pile capsule corrosion tests vs. molten salt loops

- **Convective flow at a rate of 1-2 cm/s creates an axial temperature gradient**
- **The axial gradient is of interest in relation to corrosion testing, creating conditions similar to convective flow loops.**

	Capsule	Loop
Salt flow?	1-2 cm/second	meters/second
Temperature gradient	yes (less control)	yes (good control)
FP build-up	fast	slow
Volume to Area ratio	very low	low





Status and Outlook

ENICKMA

- Irradiation near completion (1 30-day cycle to go)
- 9-month oven anneal at 650 ^{o}C nearly completed
- **Next steps:** post-irradiation mechanical testing and microscopy (SEM/TEM)
- **Follow-up:** In-pile (tensile) creep experiment at 700 ^{o}C

SALIENT-03

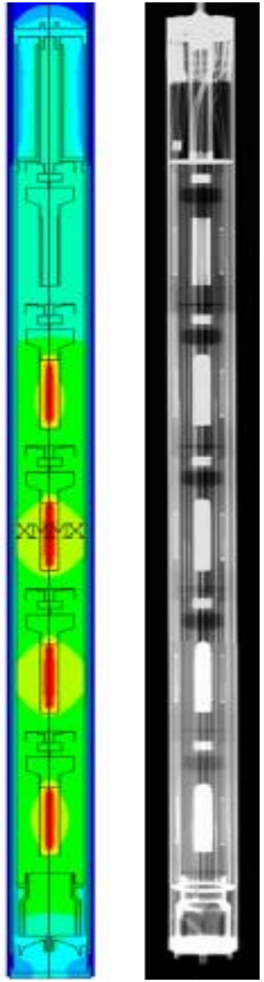
- Salt samples received from JRC Karlsruhe
- Fabrication & Assembly of the irradiation capsule ongoing
- Start of Irradiation expected Q1 2023

MIMOSA (EU HORIZON project)

- Similar studies in relation to chloride salt reactor

SALIENT-01

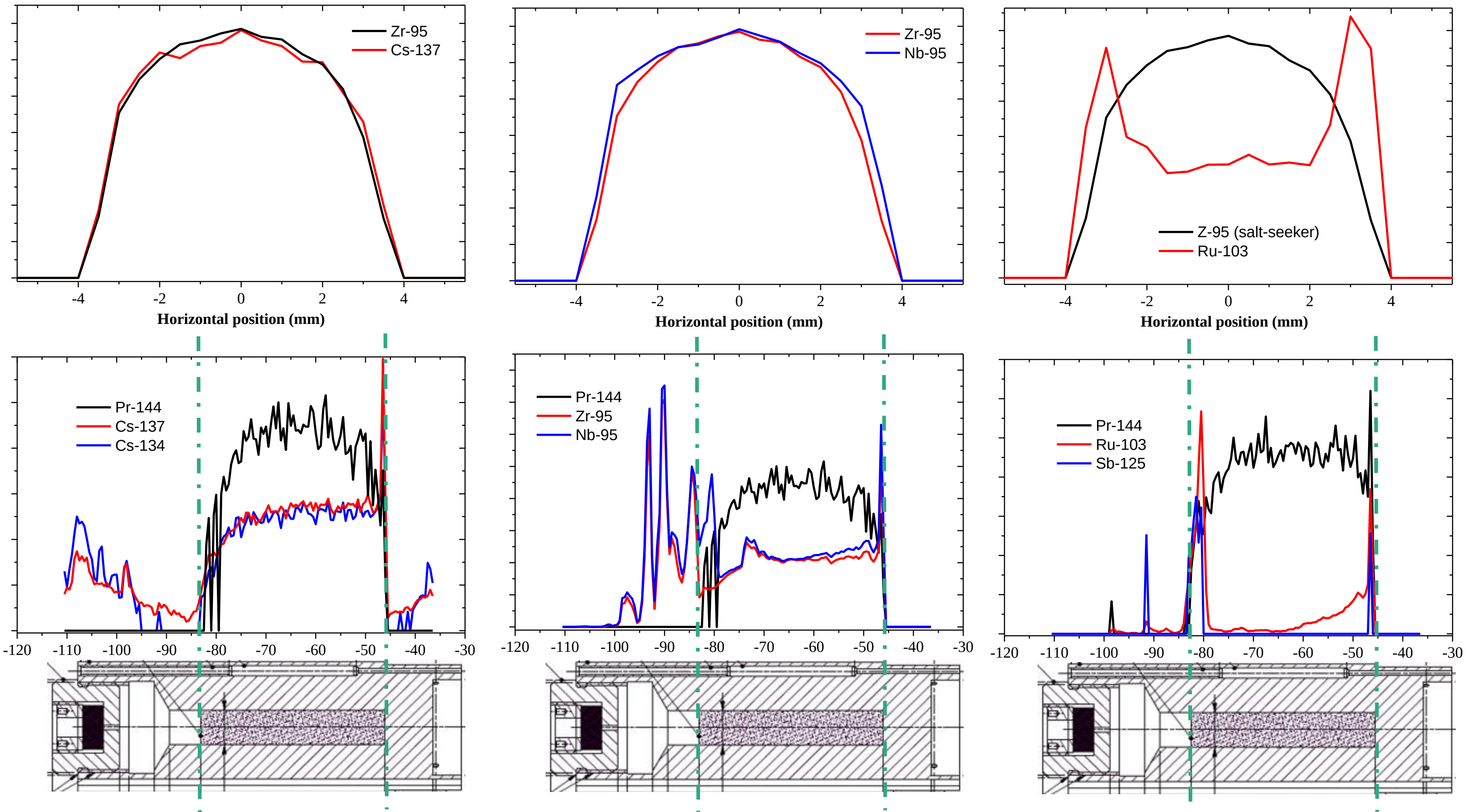
- Irradiation of 78LiF-22ThF_4 salt
- 5 open capsules fabricated from nuclear-grade graphite (4 loaded) in containment with He-Ne mixture
- Fuel power rises during irradiation due to production of U-233
- Fixed crucible temperature (~600 ^{o}C) actively maintained during irradiation



Results gamma spectroscopy

Radial scan (ID crucible 7.6mm)

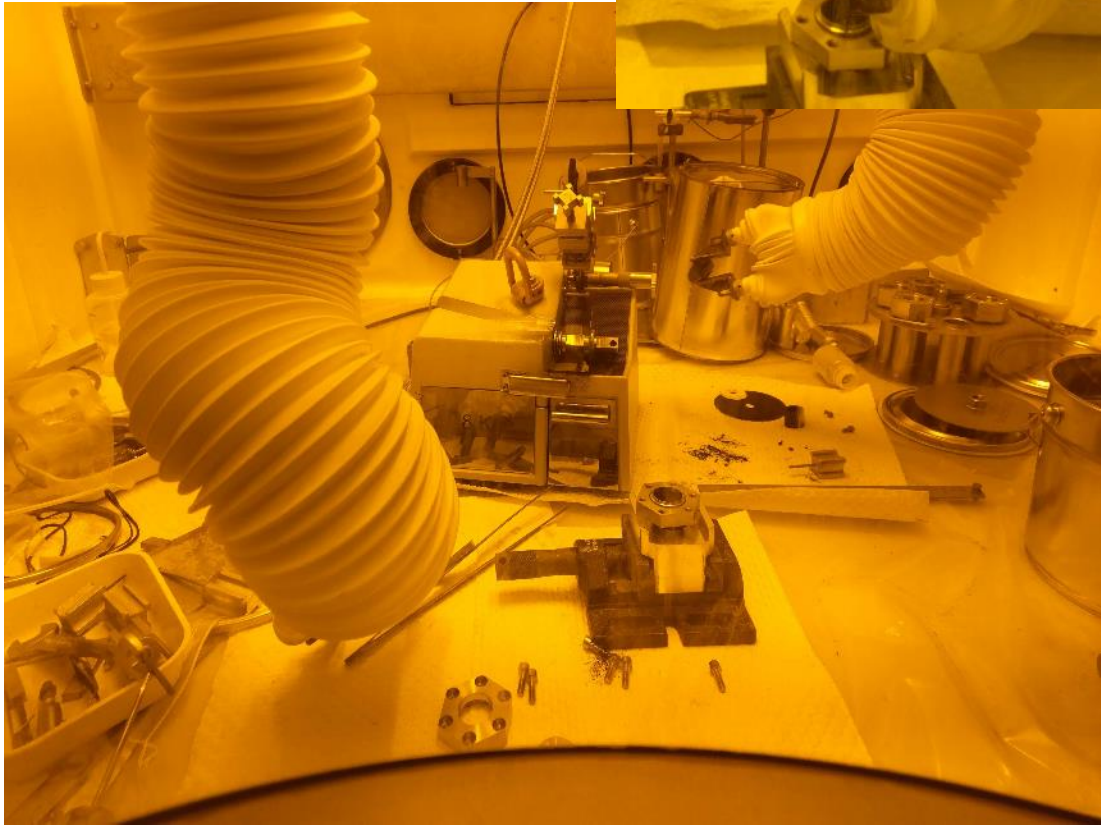
Axial scan (L crucible 80mm)



Dismantling of graphite crucibles

- Alpha hot cell, nitrogen-flushed (O_2 <0.4%, H_2O <200 ppm) for
  - dismantling
  - aqueous chemistry/sampling
    - ICP-MS / ICP-OES
    - Gamma spectrometric analysis
  - high-temperature oven testing (oven in test phase)

- Alpha hot cell, nitrogen-flushed (O_2 ~1%) for electron microscopy (SEM/EDS/WDS/EBSD)



SALIENT-01 - Conclusions and next steps

Conclusions

- Successful irradiation of fuel salts in graphite crucibles
- First PIE results available give information on distribution and retention of fission elements

Next steps

- Continue preparation of samples for in-cell microscopy (light microscopy and SEM/EDS/WDS)
- Send samples to JRC Karlsruhe for TEM and Knudsen Cell tests

Acknowledgements

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