# MSR IRRADIATION PROGRAM AT NRG PETTEN

MSR Workshop 2018, ORNL, US

P.R. Hania

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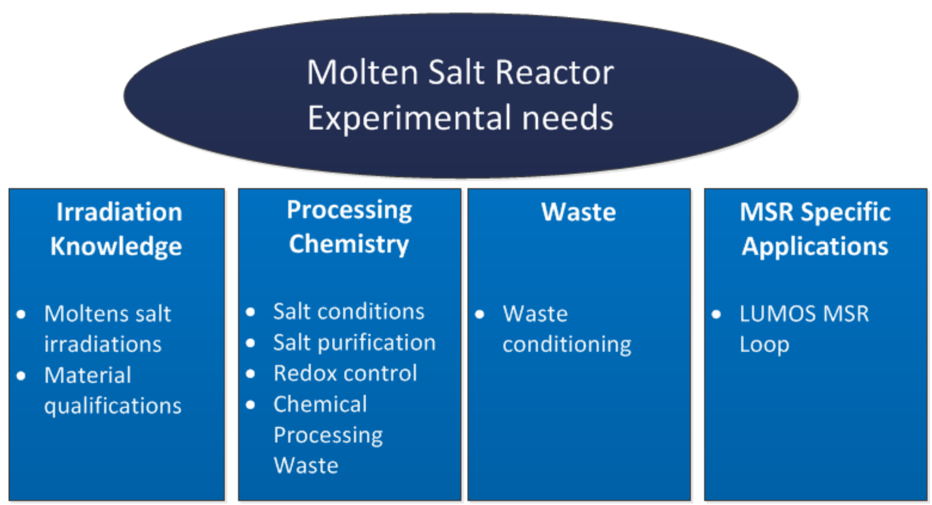
# MOLTEN SALT REACTOR CHALLENGES

- MSRs are complex, and difficulties are multidisciplinary
- Technological challenges need to be solved for a safe and economic MSR.
- Time-consuming and costly experiments are required, to tackle these challenges and provide a basis to license MSR designs

- ***With its experience and facilities available, NRG can provide a significant contribution to MSR research. In view of the large perspective of MSR technology for the (longer term) future, NRG has embarked on MSR R&D based on a government supported program.***



# THE DUTCH MOLTEN SALT PROGRAM

**Molten Salt Technology fits well within the goals of the Dutch nuclear energy R&D program:**

- Improve safety
- Reduce resource consumption / waste
- Contribute to $CO_2$-free energy market

**Collaboration between NRG, JRC, TU Delft and CV Rez**

- Complementary competences

**Objective: to contribute to molten salt technology development:**

1. **Obtain operational experience**
2. **Safety**
   - Confirm Fission Products (FP) stability in the salt and FP migration
   - Investigate FP management methods
3. **Material qualification:**
   - Material properties of irradiated containment materials
   - In-pile corrosion / deposition of suitable alloys and SiC
4. **Waste:**
   - Provide a waste route for spent molten salt fuel
5. **Integral Demonstration:**
   - Feasibility of experimental Molten Salt loop for the HFR Petten

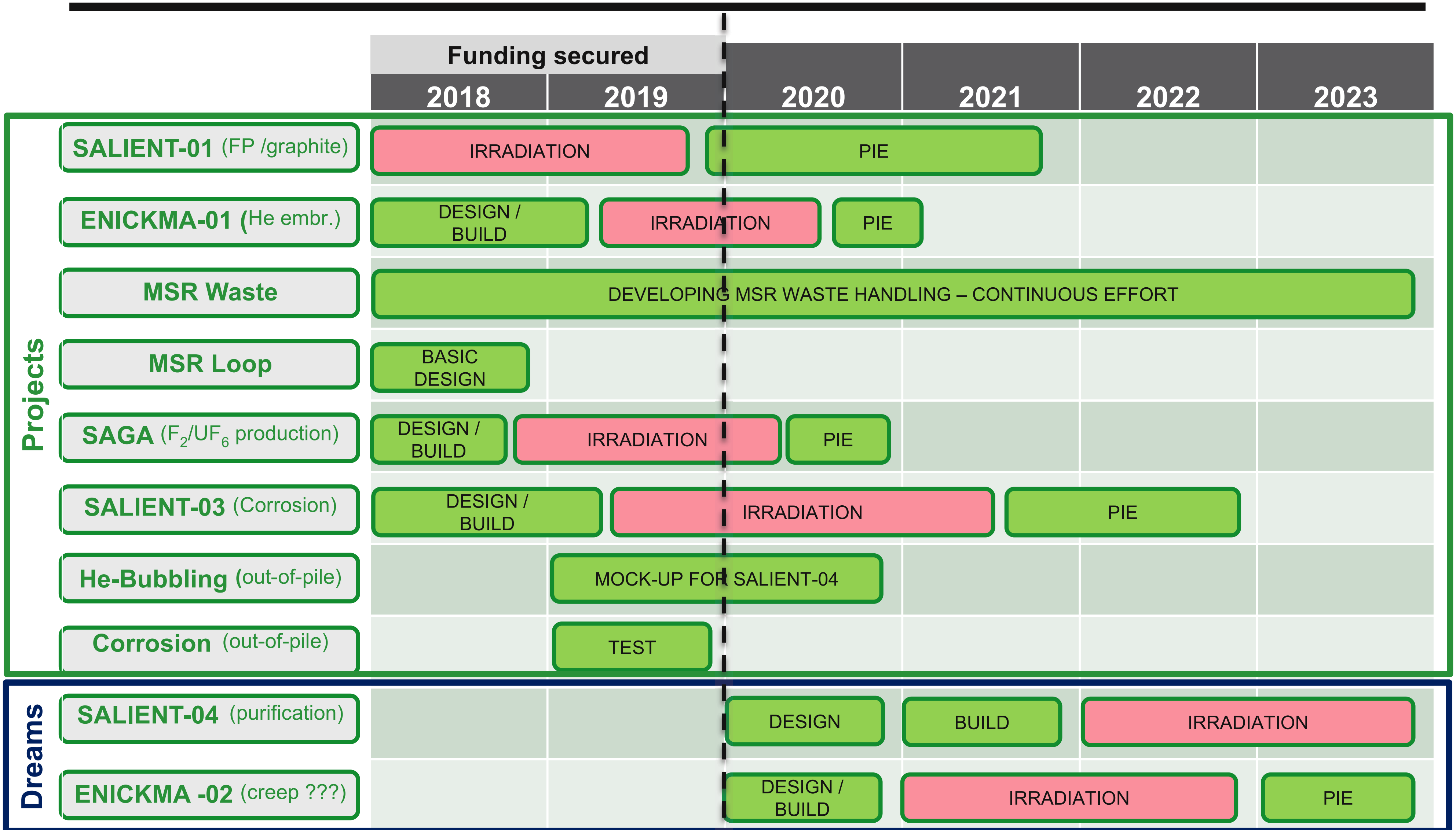
JRC EUROPEAN COMMISSION

TU Delft Technische Universiteit Delft

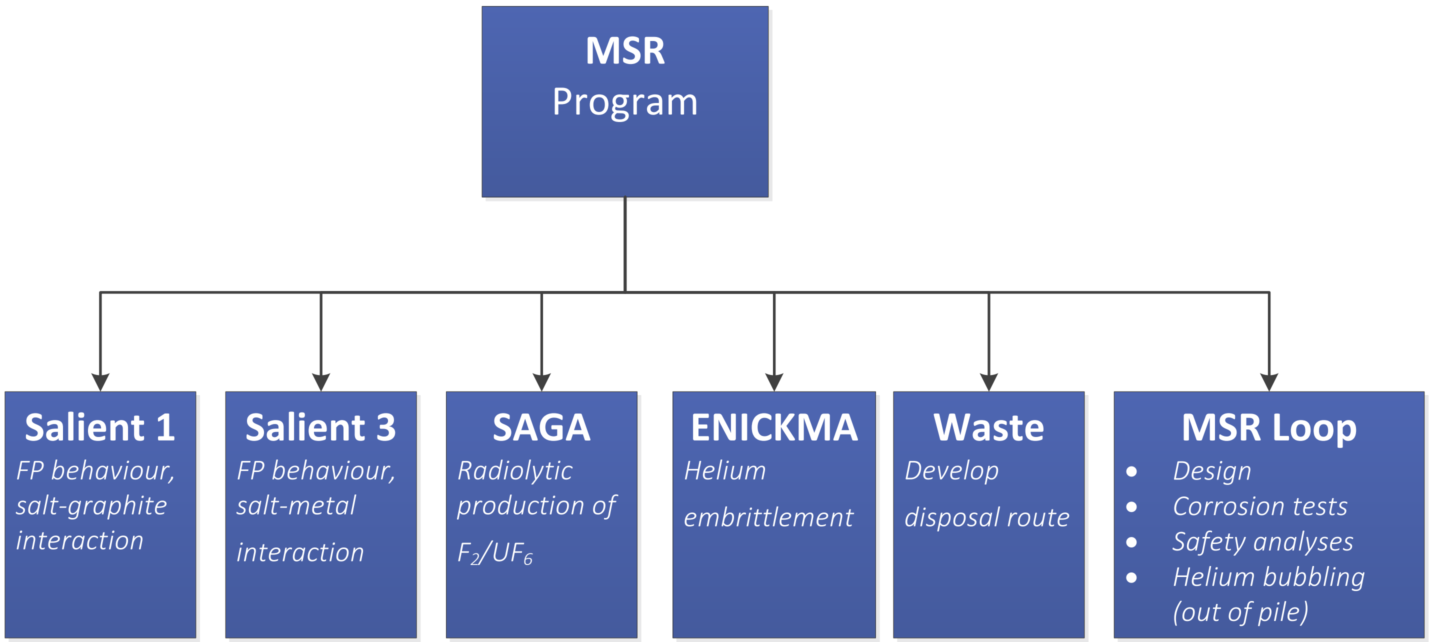
Centrum výzkumu Řež s.r.o.
Research Centre Řež

Ministry of Economic Affairs of the Netherlands

# ROADMAP MSR PROGRAM



# NRG MSR PROGRAM AT NRG



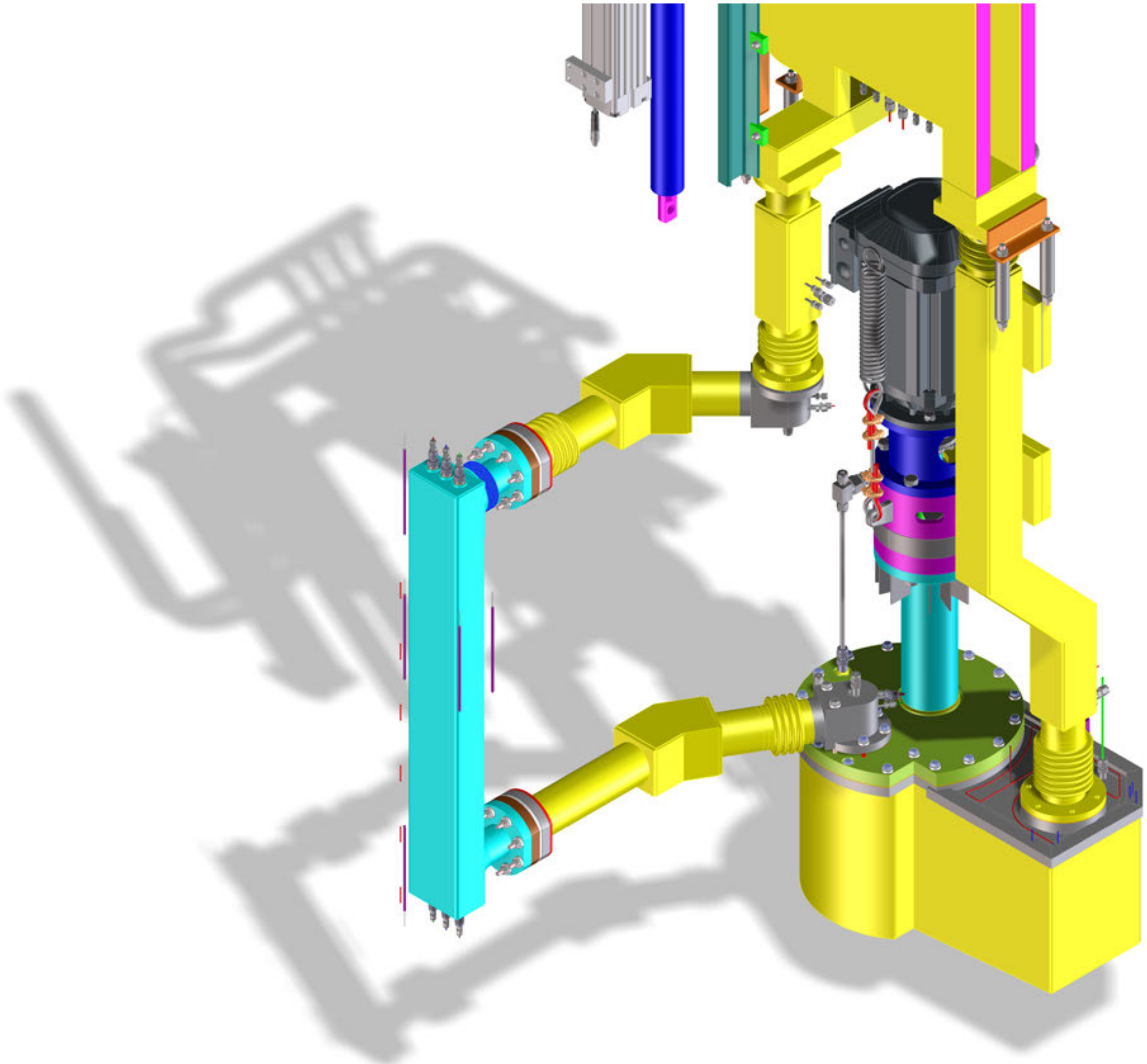

- Focus on irradiation technology
- Focus on generic topics (not specific for certain concepts)
- Ambitious program with limited funding, program open for partnering

# LUMOS LOOP CONCEPT DESIGN

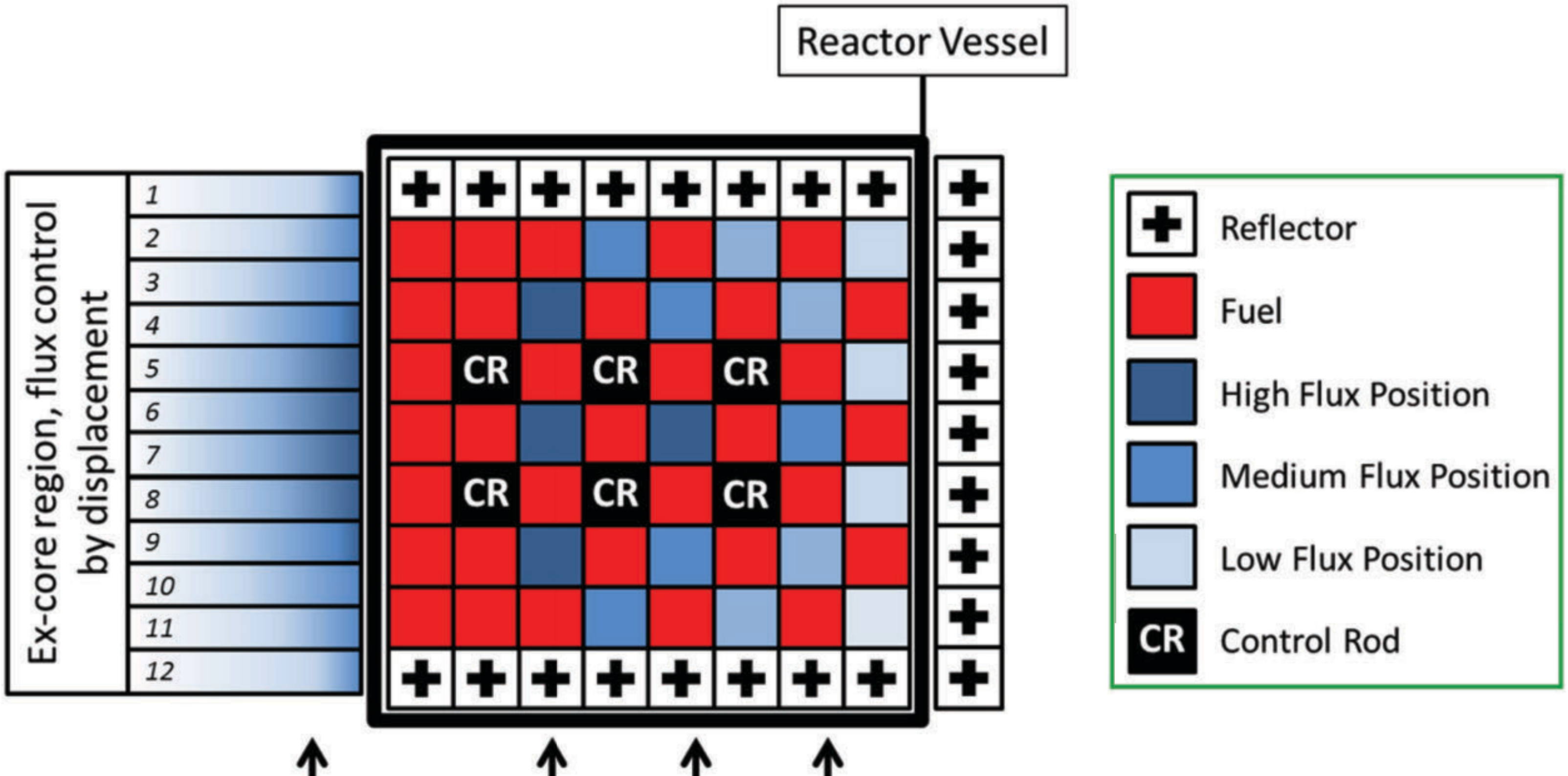
**In-pool loop positioned directly next to HFR core wall**

**Main parameters:**

- Actinide bearing FLIBE salt (20-25 L)
- Alloy N first containment
- Power: 125 kW
- Power density: 100-150 W/cc
- Flow rate: ≤3 m/s
- ΔT: ≤100 °C
- 5-6 operational years targeted



# THE HIGH FLUX REACTOR (HFR)




| | | | | |
|---|---|---|---|---|
| | 5-7 | 2.5 - 5 | 1 - 2.5 | Fast fluence E > 1 MeV ($10^{21}$ n/cm$^2$ per 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) |

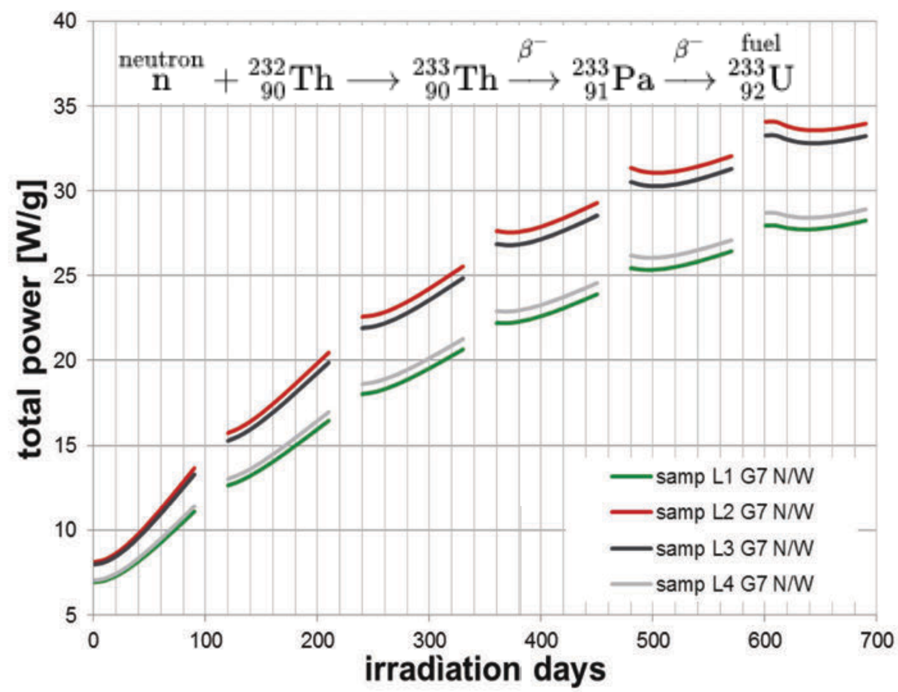
The stable and constant flux profile in each irradiation position is a unique HFR feature

# CURRENT IRRADIATION ACTIVITIES

1. **SALIENT-01:** LiF-$ThF_4$ in graphite crucibles
2. **SALIENT-03:** LiF-$ThF_4$-$UF_x$-$PuF_3$ in Alloy N crucibles
3. **ENICKMA:** tensile and low-cycle fatigue samples of nickel based alloys

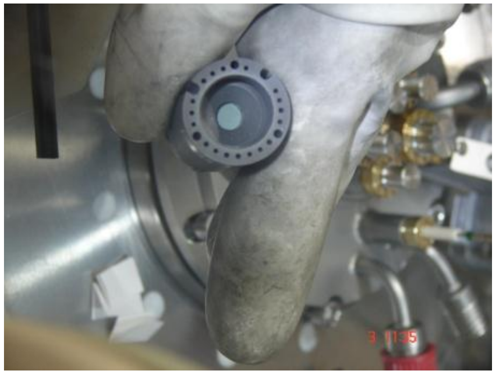
# SALIENT-01 DESIGN

- Salt composition: **78LiF-22ThF$_4$**
- Nuclear-grade graphite
- Fuel power rises during irradiation due to production of U-233
- Fixed crucible temperature (~600 $^{o}$C)

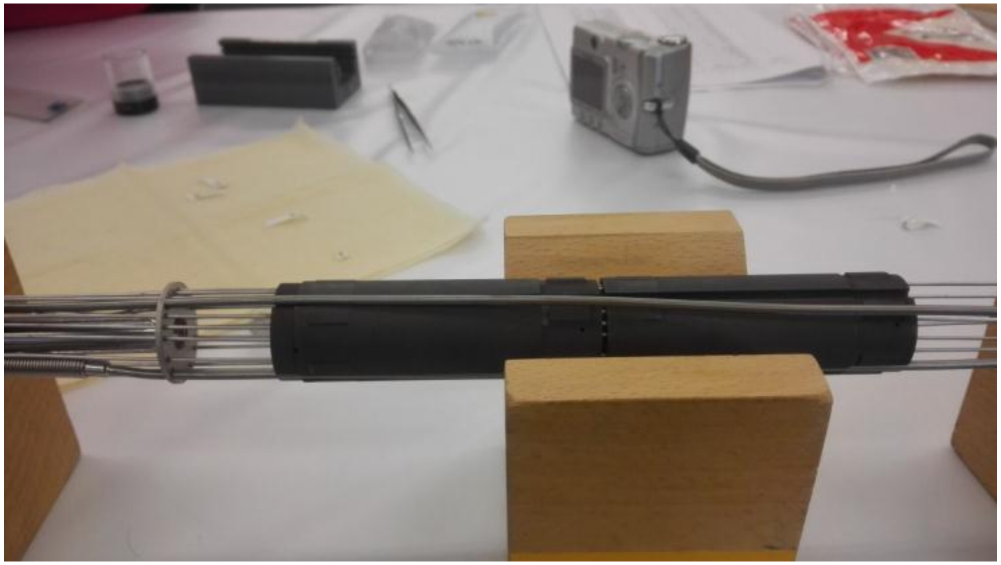



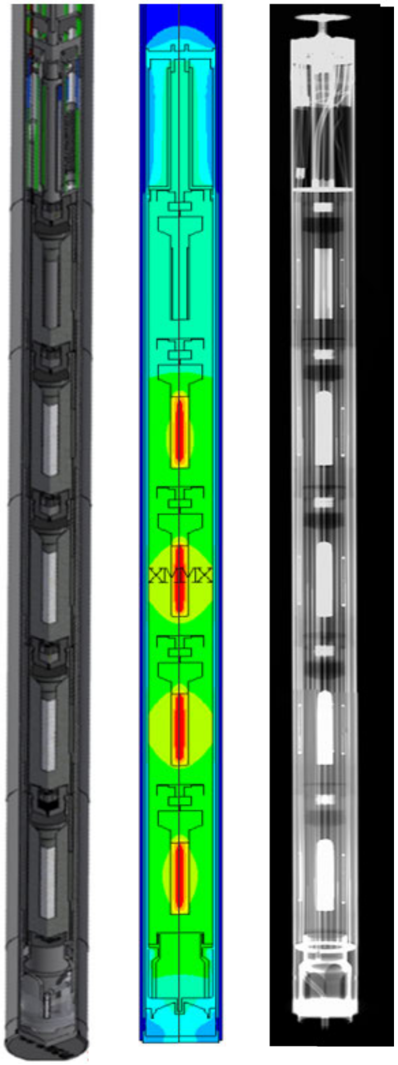
# SALIENT-01 ASSEMBLY

Synthesis and crucible loading at JRC Karlsruhe



Assembly of sample holder at NRG

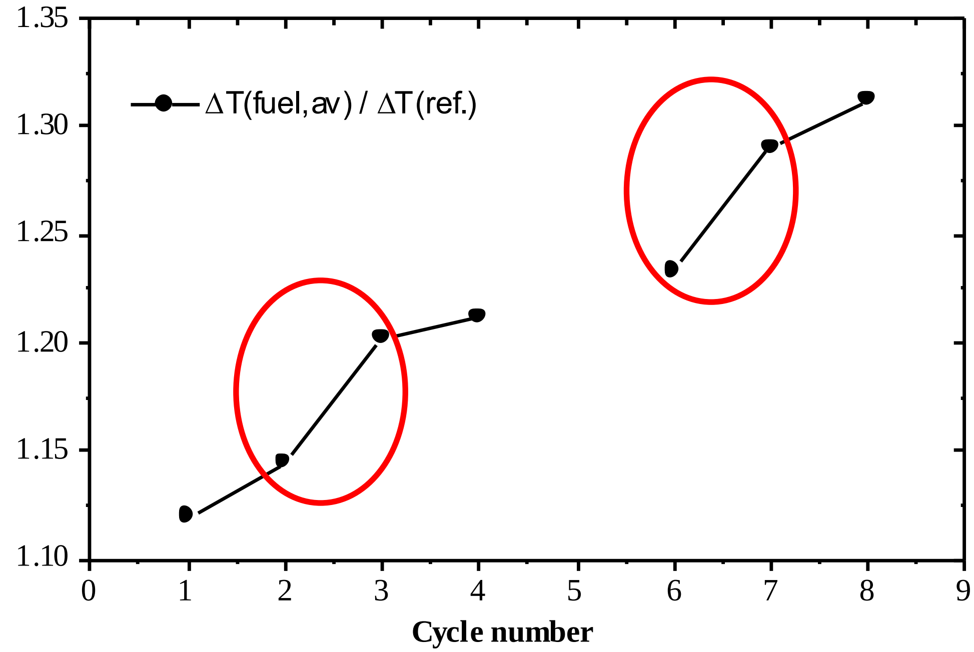




# SALIENT-01 STATUS

- **Start of irradiation:**
  August 10, 2017
- **9 out of 18 cycles completed according to specifications**
  - 273 Full Power Days
  - Temperatures on target:
    - 595 °C (L1, L4)
    - 634 °C (L2, L3)
- **Experiment was moved to lower-flux position (G7-> H4) after cycle 8**

**Experimental power increase**




*Temperatures at 100% neon in gas gaps (measured at cycle start-up)*

# SALIENT-03: GOALS

**Investigate in-pile corrosion of Hastelloy N by fluoride fuel salt**

- Determine whether corrosion is irradiation-enhanced
- Determine the influence of fission products and redox buffering on the corrosion rate
- Compare experimental mass transport in a non-isothermal salt column to CFD simulations

**Investigate fission product behavior**

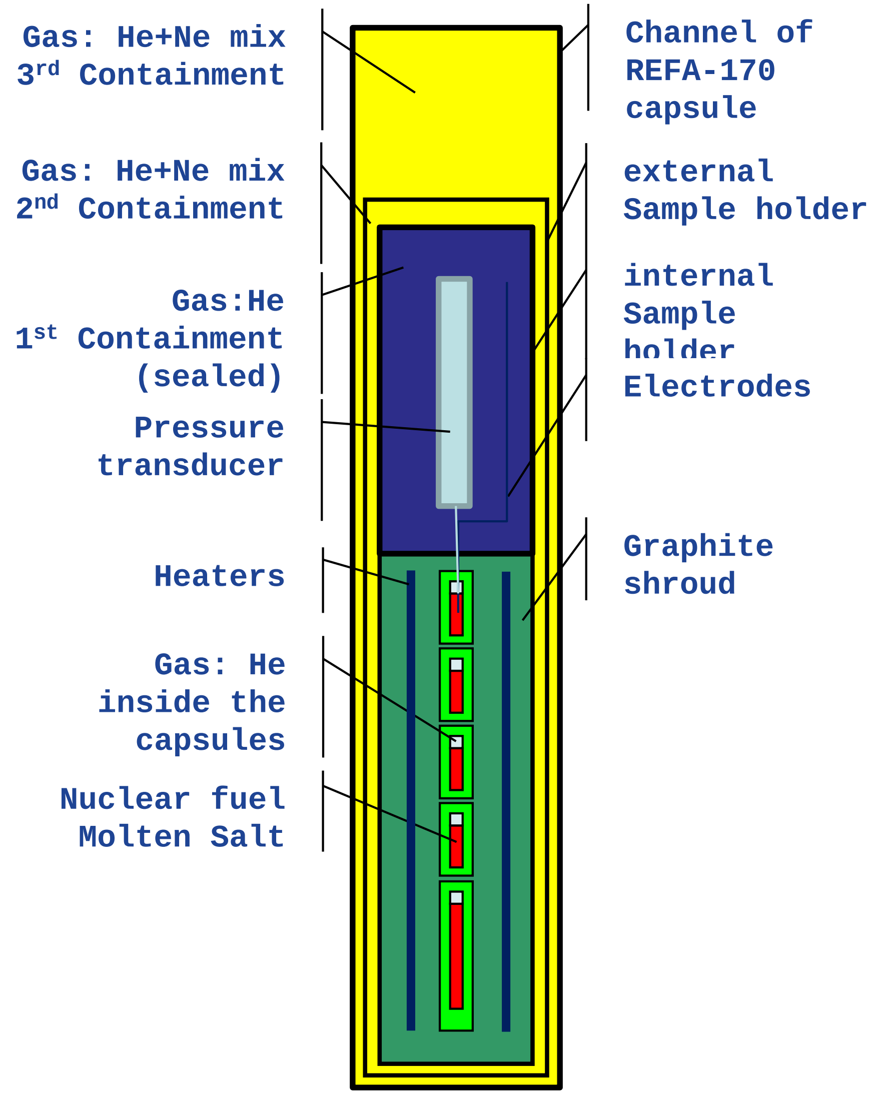
- Determine in-pile fission gas release
- Establish which fission products/species relocate to 'cold spots' during irradiation
- Determine post-irradiation fission product release temperatures (Knudsen Cell Effusion test at JRC Karlsruhe)

**Start of irradiation in 2019**

# SALIENT-03 DESIGN

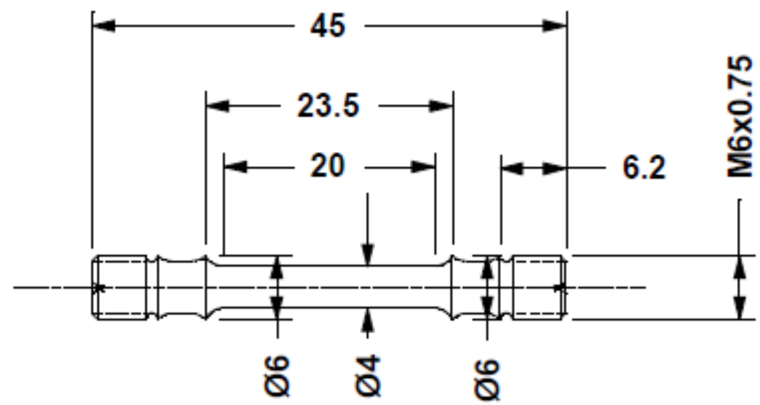
**Changes with respect to SALIENT-01:**

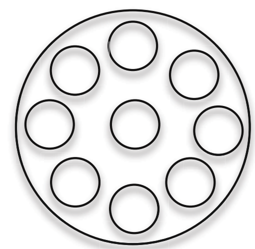
- **Heaters** to avoid radiolysis during HFR downtime
- Addition of Pu for fission power at start of irradiation
- Addition of U for **'salt buffering'** ($UF_4/UF_3$)
- Welded Alloy N capsules:
  - **Corrosion test**
  - **Pressure** measurement
  - Inclusion of 3 inert **electrodes**
- Large measurable **temperature gradients**:
  - Transport phenomena



# ENICKMA IRRADIATION

- Irradiation of Alloy N based material specimens for post-irradiation mechanical testing:
  - Tensile testing
  - Low Cycle Fatigue
  - Small Punch testing
  - Microstructure analysis
- Irradiation parameters:
  - Temperature: 650 and 750 $^{o}$C
  - Up to 1E21 n/cm$^2$ thermal, 3E21 n/cm$^2$ fast (up to 50 appm helium, >1 dpa expected)
- Oven anneal test at same temperatures for comparison



Sample number ~ 100

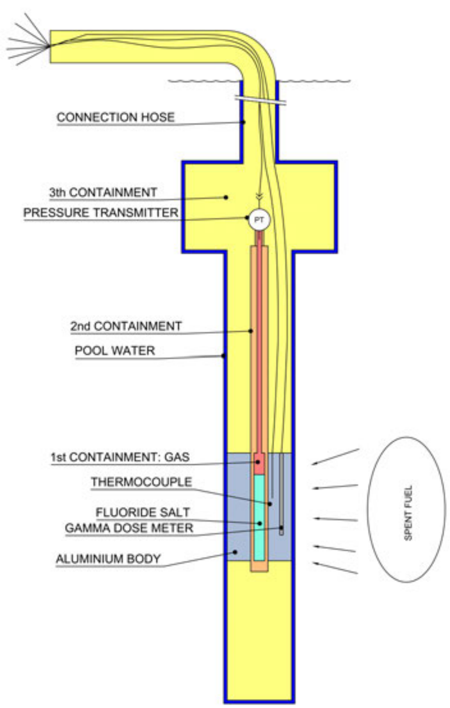
COMTES FHT
SINAP
HAYNES International

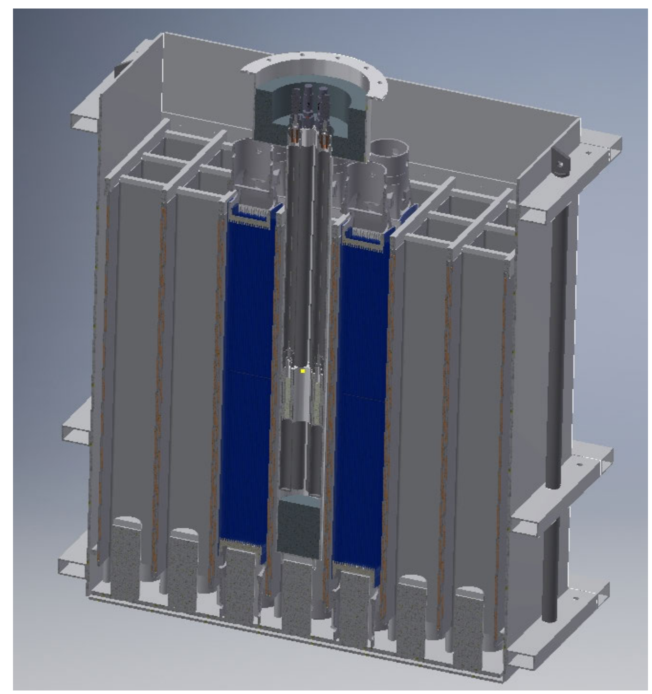
# OTHER ACTIVITIES

1. Gamma irradiation near RT
2. Waste treatment
3. Lab-scale helium bubbling

# SAGA: SALT RADIOLYSIS TEST

- HFR Spent fuel is used as the gamma source
- ~50 °C base irradiation (solid salt samples)
- Monitoring of pressure, dose and temperature
- 5 salts investigated, Salt samples provided by CV Rez
- Start Q4 2018



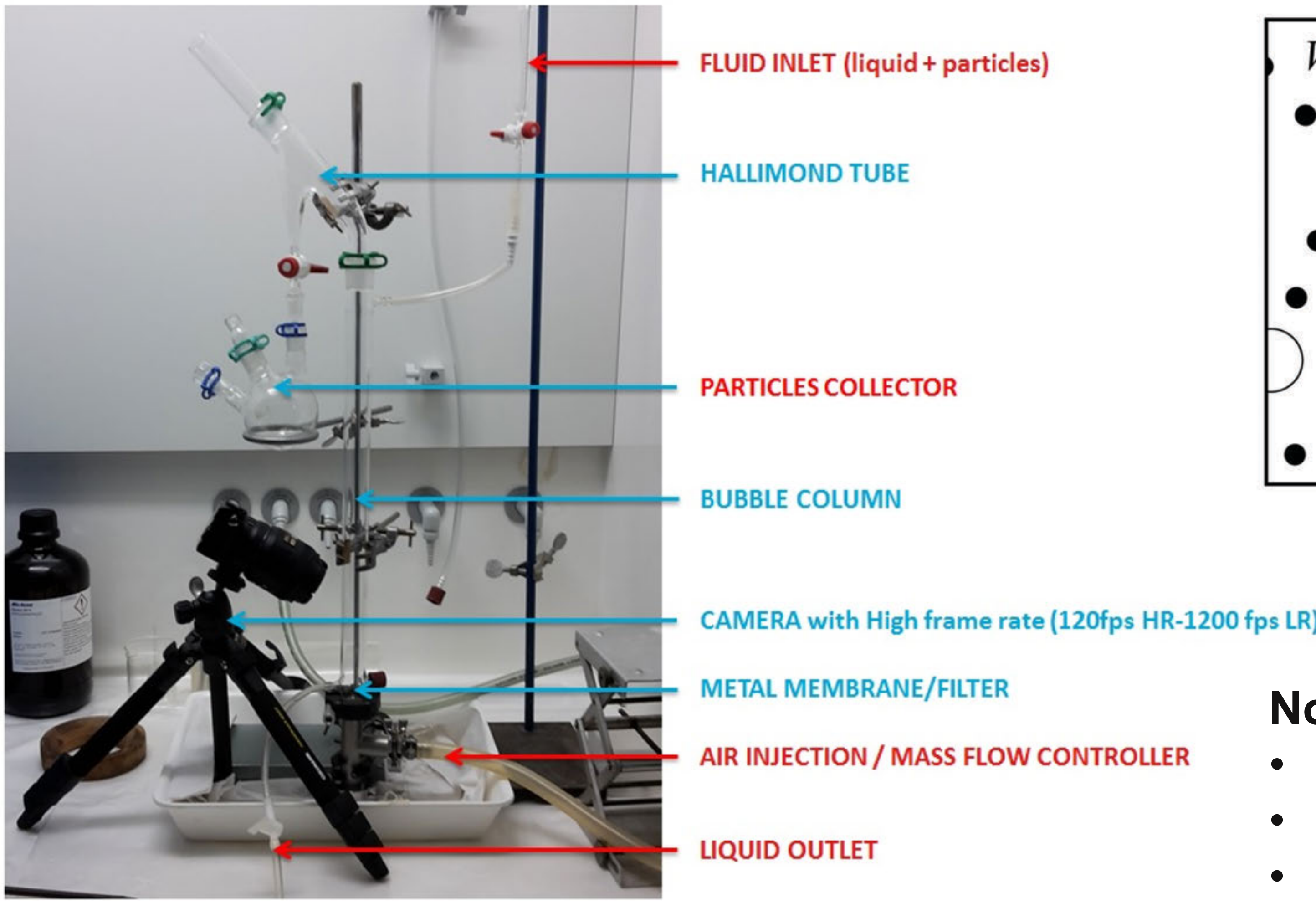



# WASTE PROJECT

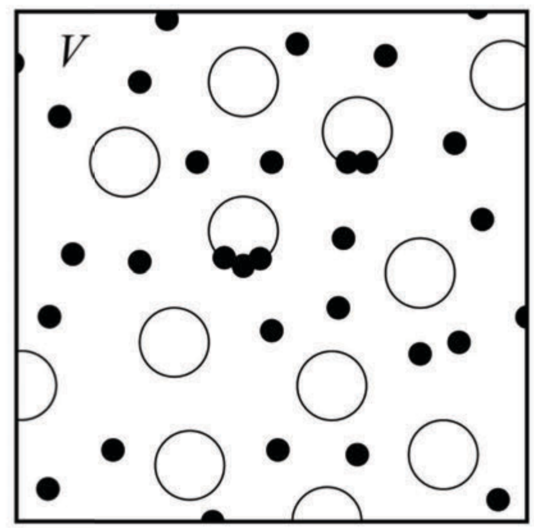
- Commitment to convert the waste produced by the MSR irradiations to a chemical form to be transported to Dutch center for interim storage (COVRA)
- Actinide- and fission product bearing fluoride salt samples are not an acceptable waste form by COVRA
- Fuel waste (containing actinides and fission products) can be accepted only in chemically stable forms
- Irradiated fuel salts release the corrosive fluorine gas following radiolysis at near room temperature, reduced salt is itself corrosive

→ **conversion to well-known stable matrices**

# LAB-SCALE HELIUM BUBBLING




*Setup Elisa Capelli (TU Delft)*

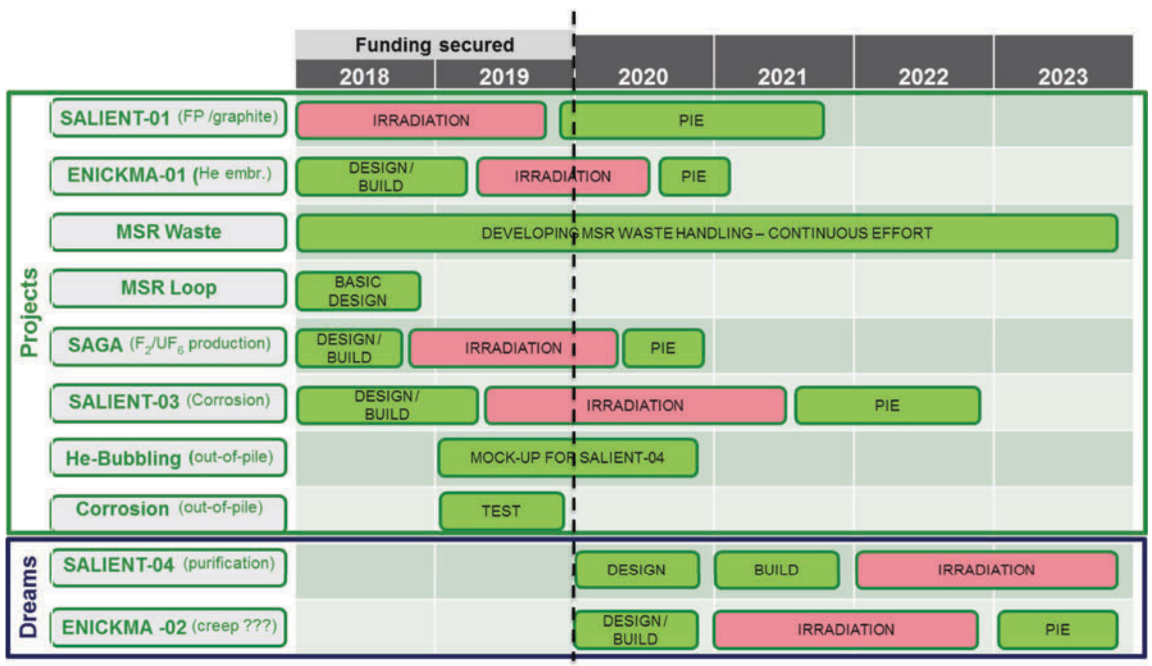



**Noble metal removal:**

- Thermochemistry
- Particle growth
- Flotation

# SUMMARY

- NRG develops irradiation capabilities, provides information to mitigate risks and increases knowledge on Molten Salt Reactor Technology
- NRG seeks to collaborate with (support) MSR developers to accelerate their path towards MSR technology



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Ministry of Economic Affairs of the Netherlands

# PETTEN NUCLEAR INFRASTRUCTURE

**HIGH FLUX REACTOR**

**HOT CELL LABORATORIES**

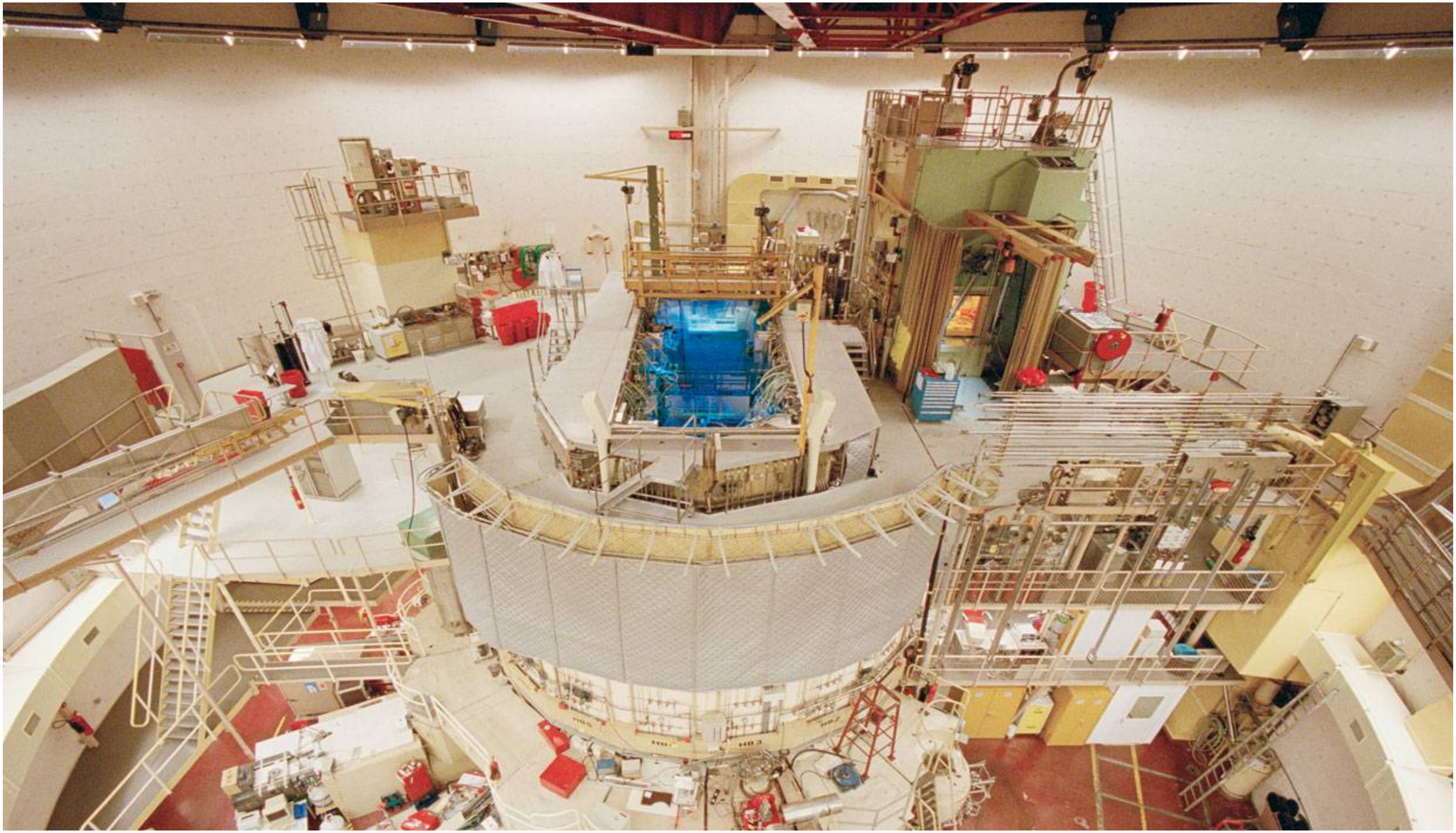
**MOLYBDENUM PRODUCTION FACILITY**

**DECONTAMINATION & WASTE TREATMENT**

**ACTINIDE & RADIOLOGICAL LABORATORIES**

**WORLDWIDE LOGISTICS**

# THE HIGH FLUX REACTOR (HFR)



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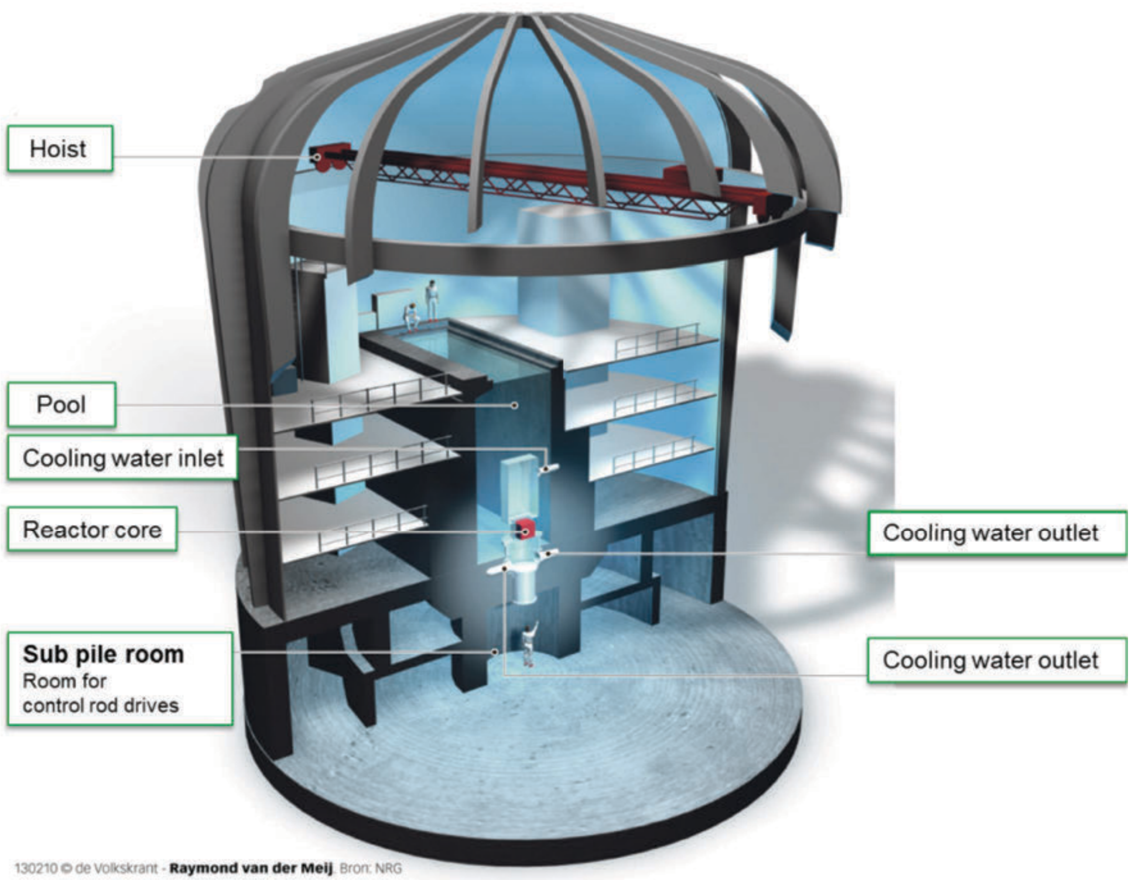
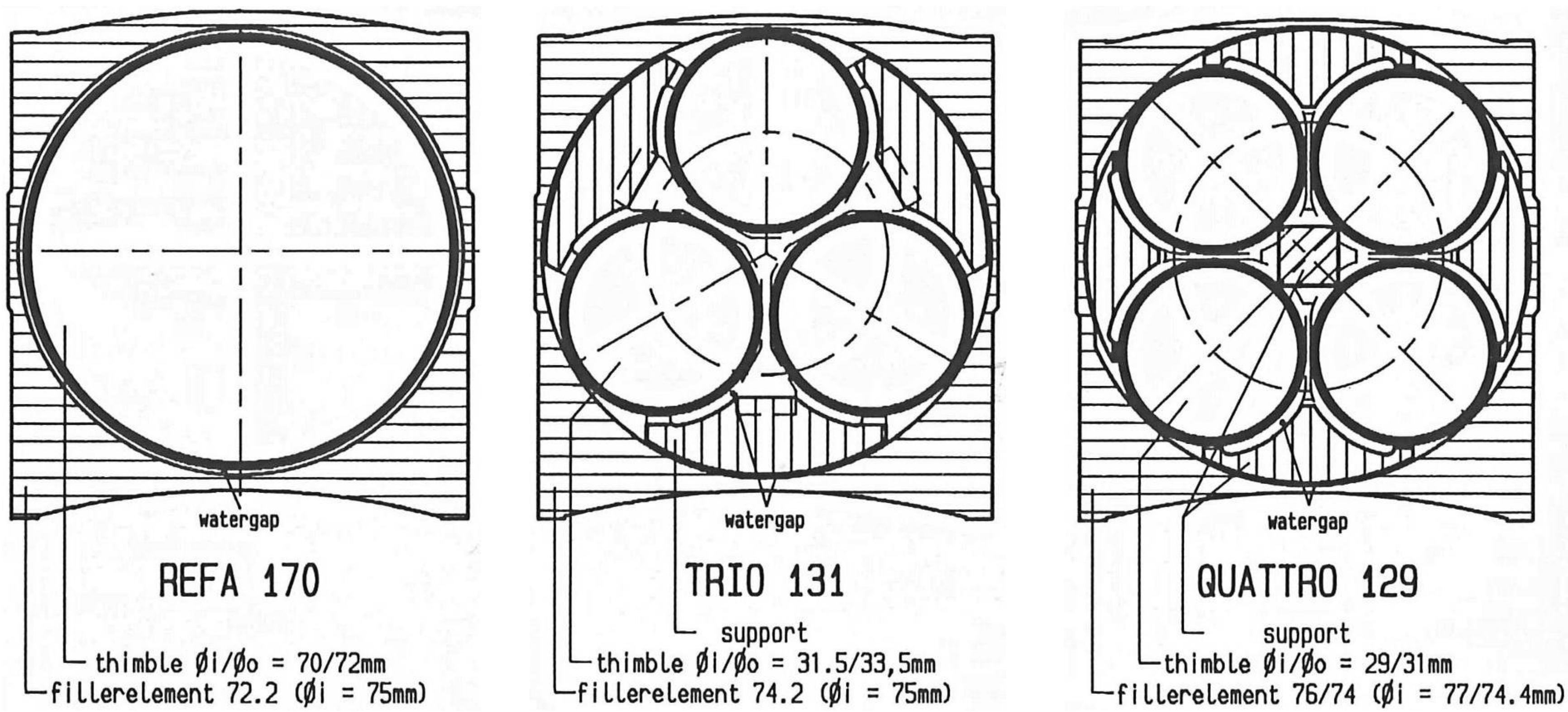



- High flux
- 45 MW thermal power
- Stable and constant flux profile in each irradiation position
- Main applications
  - Isotope production
  - Nuclear energy irradiation services
  - R&D
- 31 operation days per irradiation cycle, 9 cycles a year

# HFR IRRADIATION RIGS



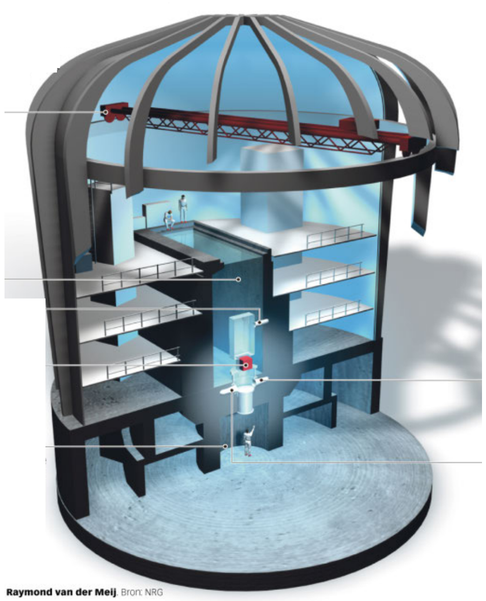

- Standard irradiation rigs (TETRA and TRIO 129 not shown)
- Outside water cooled, inside gas swept (mixtures of helium, neon, nitrogen)
- Customisation possible

# POSSIBILITIES AT NRG

- **Capsule irradiations, inert gas or sodium filled**
  - Rodlets, fuel discs, cladding tubes, material samples
- **Extensive experience with instrumentation**
  - thermocouples, Halden LVDT-based, SPNDs, activation monitors, capacitive dimension change, off-gas monitoring, ...
- **(Re)fabrication of rods in collaboration**
  - Example: rods can be (re)fabricated at IFE and irradiated in HFR
- **Extensive on-site PIE**
  - Neutron radiography in-pool (transfer between HFR cycles)
  - Non-destructive examination (visual, profile, gamma, Eddy current)
  - Rod puncture + mass spectrometry for fission gas analysis
  - Light and electron microscopy in alpha-tight hot cell (SEM/EDS/WDS/EBSD)
- **Experience with international fuel transports**

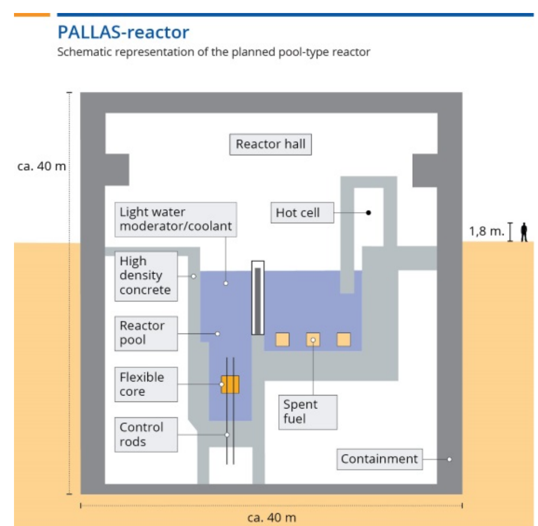
# FROM HFR TO PALLAS

- HFR is projected to operate until 2025, but has no fixed end-of-life date
- PALLAS is taking over the roles of HFR from ~2025 in a seamless cross-over




< 2025

PALLAS




> 2025

# WASTE STRATEGY

- **Conversion of salt to recognizable, acceptable chemical forms:**
  - Oxide high level waste
  - Cemented intermediate level waste
  - Fluoride intermediate level waste ($CaF_2$ or fluorapatite)

- **Route: aqueous processing**
  - Can be performed at NRG hot cells with relatively little infrastructure changes
  - No complicated gas streams
  - Limited spreading of dust