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 CO₂-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
# ROADMAP MSR PROGRAM

<table>
<thead>
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<th>Projects</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
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<tr>
<td>SALIENT-01 (FP/graphite)</td>
<td>IRRADIATION</td>
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<td>PIE</td>
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<tr>
<td>ENICKMA-01 (He embr.)</td>
<td>DESIGN / BUILD</td>
<td>IRRADIATION</td>
<td>PIE</td>
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<tr>
<td>MSR Waste</td>
<td>DEVELOPING MSR WASTE HANDLING – CONTINUOUS EFFORT</td>
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<tr>
<td>MSR Loop</td>
<td>BASIC DESIGN</td>
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<tr>
<td>SAGA (F$_2$/UF$_6$ production)</td>
<td>DESIGN / BUILD</td>
<td>IRRADIATION</td>
<td>PIE</td>
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<tr>
<td>SALIENT-03 (Corrosion)</td>
<td>DESIGN / BUILD</td>
<td>IRRADIATION</td>
<td>PIE</td>
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<tr>
<td>He-Bubbling (out-of-pile)</td>
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<td>MOCK-UP FOR SALIENT-04</td>
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<tr>
<td>Corrosion (out-of-pile)</td>
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<td>TEST</td>
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<td>Dreams</td>
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<tr>
<td>SALIENT-04 (purification)</td>
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<td>DESIGN</td>
<td>BUILD</td>
<td>IRRADIATION</td>
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</tr>
<tr>
<td>ENICKMA-02 (creep ????)</td>
<td></td>
<td>DESIGN / BUILD</td>
<td>IRRADIATION</td>
<td>PIE</td>
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</tbody>
</table>
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)

<table>
<thead>
<tr>
<th>Ex-core region, flux control by displacement</th>
<th>0-3, location dependent</th>
<th>0-700, displacement controlled</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-7, 2.5 - 5, 1 - 2.5</td>
<td>5-8, 3-5, 1-3</td>
<td>n/a, 500-700, 300-400</td>
</tr>
</tbody>
</table>

- **Fast fluence $E > 1$ MeV ($10^{21}$ n/cm$^2$ per year)**
- **Material DPA rate (DPA/year)**
- **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: \(78\text{LiF}-22\text{ThF}_4\)
- Nuclear-grade graphite
- Fuel power rises during irradiation due to production of U-233
- Fixed crucible temperature (\(\sim 600 \, ^\circ\text{C}\))
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**

Weights 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
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’ (UF₄/UF₃)
- 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 °C
  - Up to 1E21 n/cm² thermal, 3E21 n/cm² fast (up to 50 appm helium, >1 dpa expected)

- Oven anneal test at same temperatures for comparison
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

FLUID INLET (liquid + particles)

HALLIMOND TUBE

PARTICLES COLLECTOR

BUBBLE COLUMN

CAMERA with High frame rate (120fps HR-1200 fps LR)

METAL MEMBRANE/FILTER

AIR INJECTION / MASS FLOW CONTROLLER

LIQUID OUTLET

Noble metal removal:
- Thermochemistry
- Particle growth
- Flotation

Setup Elisa Capelli (TU Delft)
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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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)
THE HIGH FLUX REACTOR (HFR)

- 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
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