INL/CON-23-72200-Revision-0

ENYGF 2023 - Design of Temperature-controlledFuel-salt Irradiation Experiment

May 2023

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Changing the World's Energy Future

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Design of Temperature-controlled Fuel-salt Irradiation Experiment

Idaho National Laboratory

Molten-salt Research Temperature-controlled Irradiation (MRTI) Experiment Overview & Goals

Mission Statement

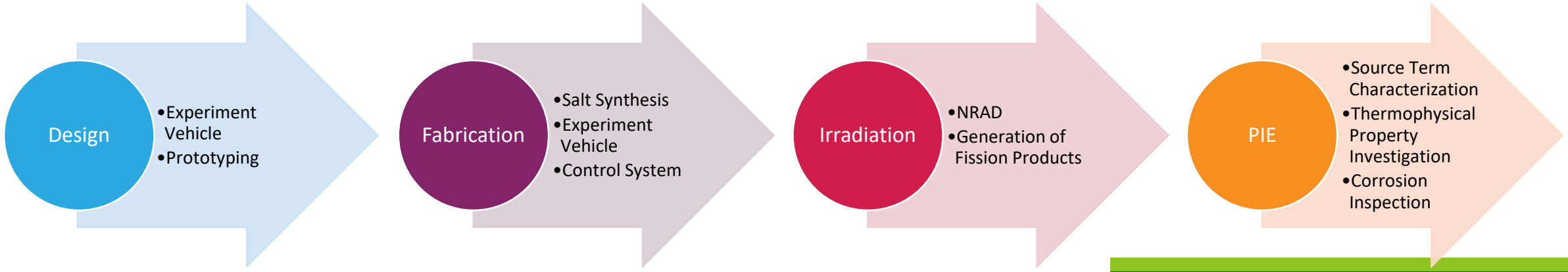
Establishment of a domestic neutron irradiation capability for fissile material-bearing salts at INL for Molten Salt Reactor (MSR) R&D.

Executing Research in Three Primary Areas

1. Radioactive Source Term Quantification
2. Thermophysical Property Evolution
3. Salt-facing Materials Corrosion

Mission Realization

Utilize the Neutron Radiography Reactor (NRAD) to irradiate molten fissile material-bearing chloride salt with salt-facing materials relevant to MSR development



Neutron Radiography (NRAD) Reactor

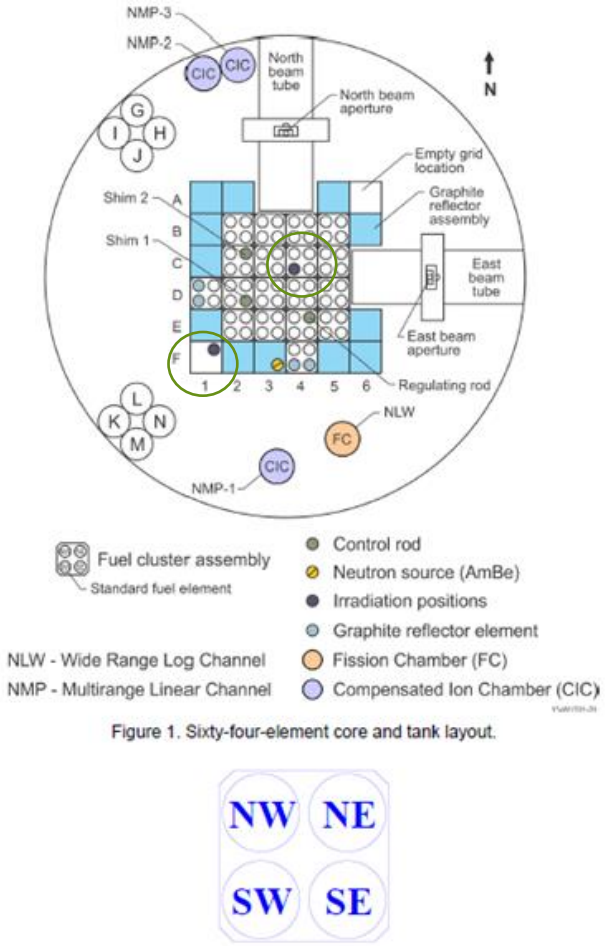
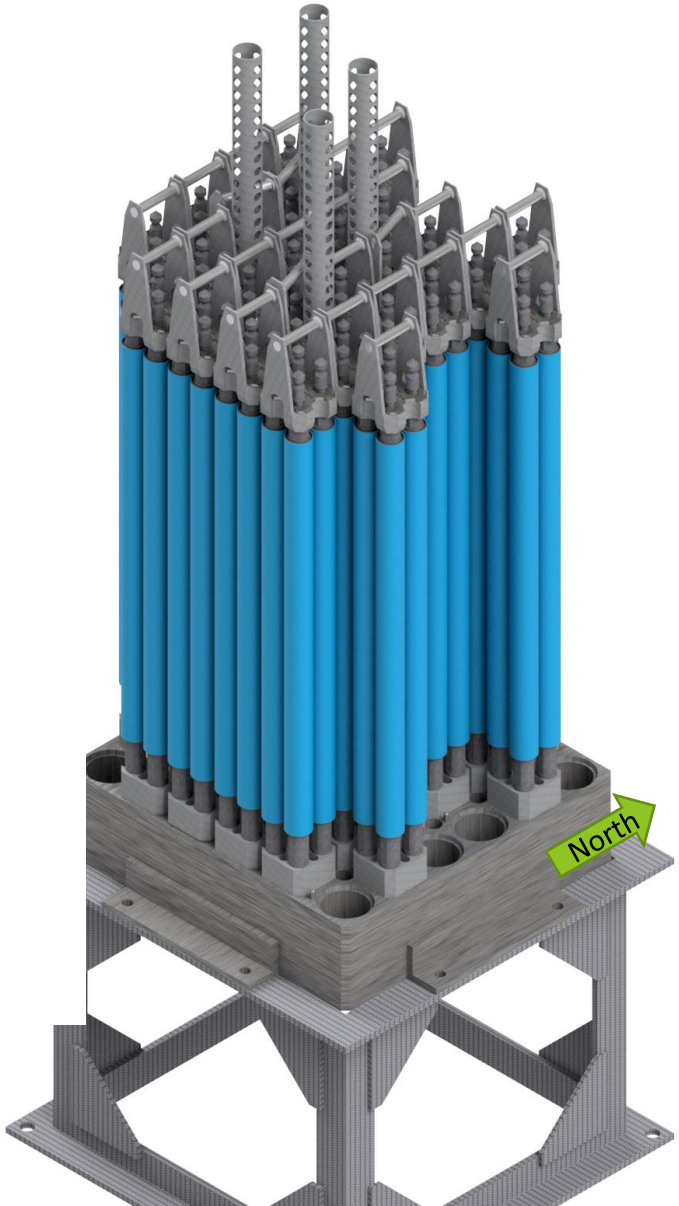


Figure 1. Sixty-four-element core and tank layout.



- TRIGA-fuel MTR-grid pool reactor for neutron radiography PIE
- Why NRAD?
  - Basement of Hot Fuels Examination Facility (HFEF)
  - Only experiment in core
  - Pool type → no pressure
- NRAD 4-pin fuel cluster design with various top bail configurations
- F1 and C4 position available for experiments
- 2.1E+12 $\frac{n}{cm^2-s}$ in F1 Position & 5.2E+12 $\frac{n}{cm^2-s}$ in C4 Position
  - C4 comes with the downside of more reactivity effects on core

MRTI Inner Capsule Mechanical Design

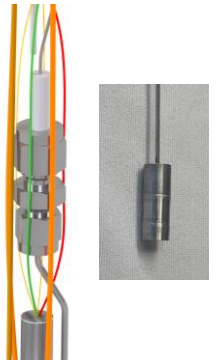
800W immersion heater, heated in bottom 3” section only, integrated Type-K TC

Large plenum (Argon) to reduce pressure and account for packing factor of powder salt

SS316 Radiative heat shield reduces heat loss at high temperature section of capsule

Molten salt (UCl_3-NaCl)

Bottom centering feature



INL-developed Optical Fiber Pressure Sensor, extended to capsule plenum with Swagelok and extension tube

3X Type-N TCs, IN625 sheath, axially placed

1X Pressure sensor extension tube

1X IN625 thermowell

→ BNi-5 sealed braze into capsule

Standoffs create nominal .030” gas-gap (85Ar15He)

MRTI Outer Can and Cluster Mechanical Design

NRAD bail assembly for dry tube assemblies

Leadout compression fitting

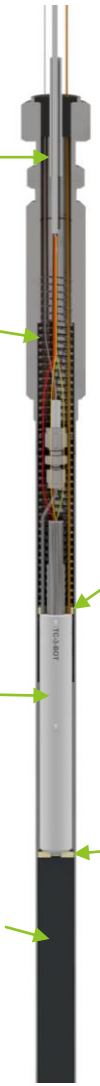
Top fitting into cluster bail assembly

SS316 Outer can

Al6061-T6 surrogate pins

Bottom threaded pin fitting into bottom cluster end fitting

NRAD Bottom cluster end fitting



Compression internals, potted leadout tube for power cabling

Compression springs hold capsule in axial position

Self-powered Neutron Detector (optional)

MRTI capsule

Graphite bottom reflector and spacer

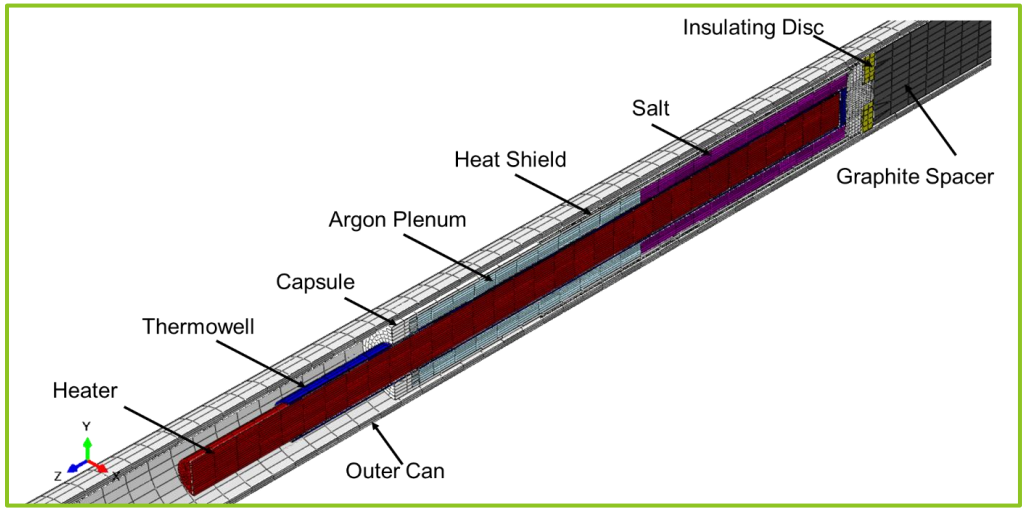
Top insulation wafer (alumina) reduces heat transfer to compression springs

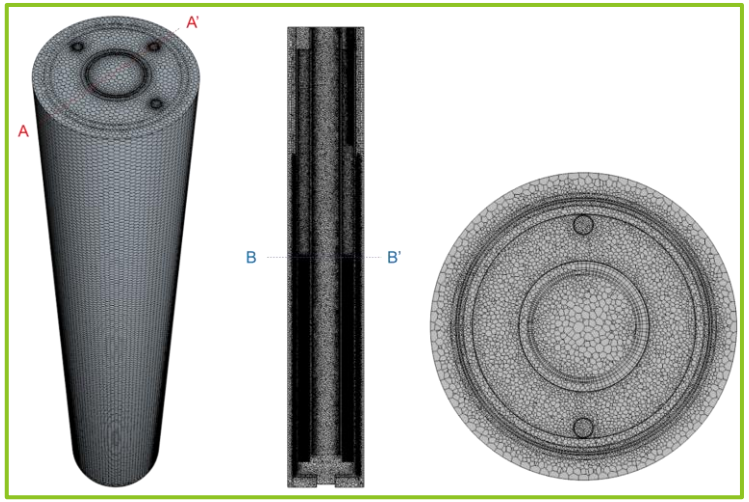
Bottom insulation wafer (alumina) reduces thermal losses out of bottom of capsule

Thermal Analysis Models

ABAQUS

- Assumptions
  - Salt material properties are assumed
  - No natural convection of salt
  - Thermocouples not modeled
  - Full thermal contact
  - Capsule standoff not modeled
- NRAD Flow = 2 gpm and T_{inlet} = 40°C





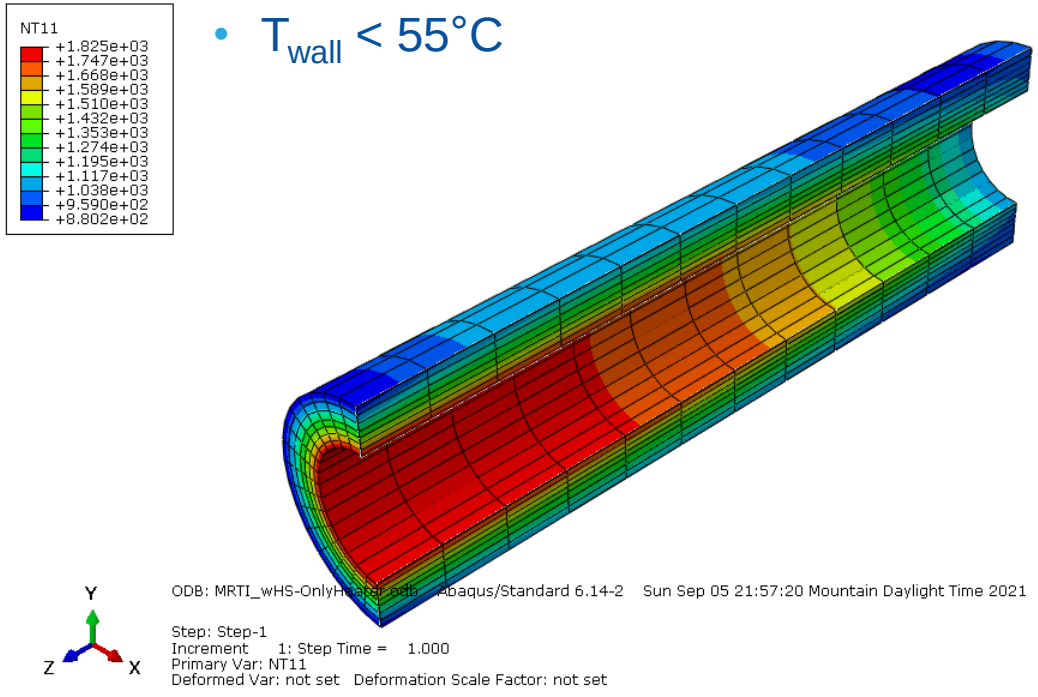
STAR-CCM+

- Fluid region:
  - Segregated flow and temperature, turbulence model
  - Temperature-dependent density and viscosity, constant specific heat and thermal conductivity.
- Gas gap region:
  - Conduction, convection and radiation heat transfers
- Solid region:
  - Segregated Solid energy solver, constant properties, no standoff assumed

ABAQUS Simulation Outcomes

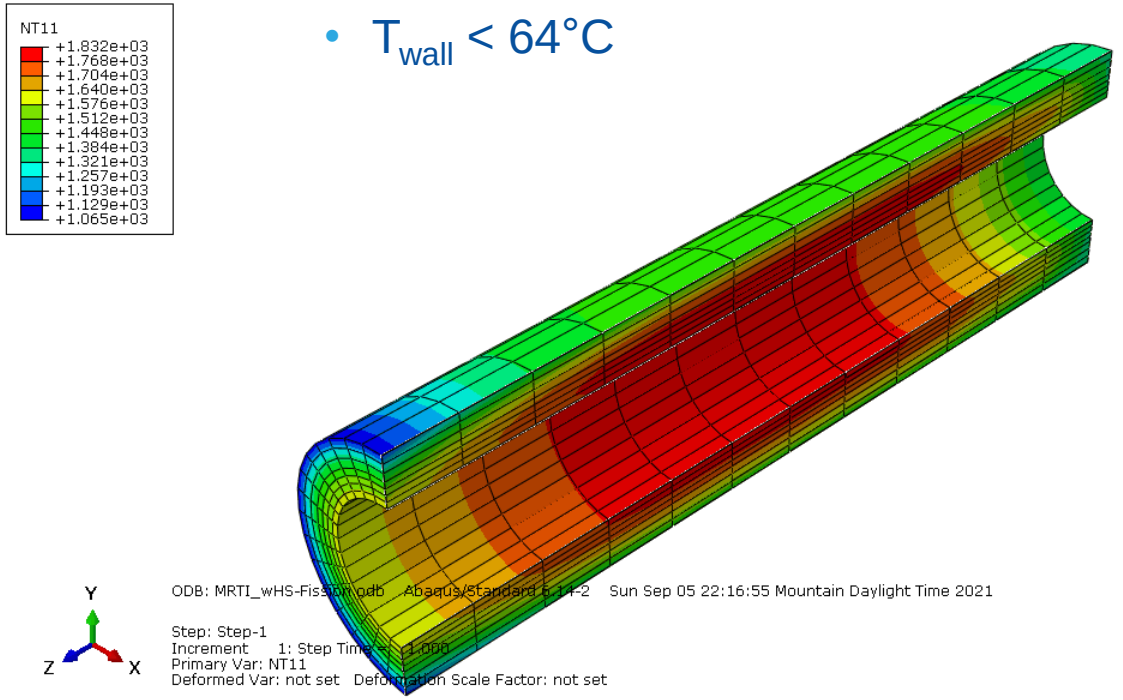
Pre-Irradiation (Heater Only)

- Heater ~150 W
- Salt T_{max}/T_{min} = 996/471°C
- 88% salt melted
- T_{wall} < 55°C



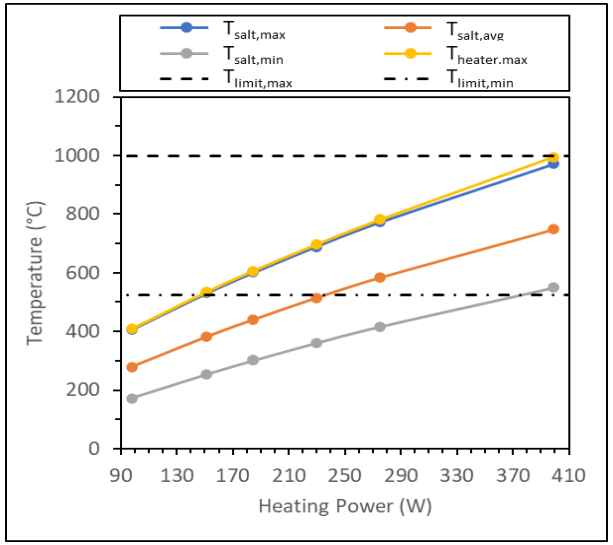
Irradiation (Heater+Fission)

- Heater ~10 W
- Salt T_{max}/T_{min} = 1,000/574°C
- 100% salt melted
- T_{wall} < 64°C

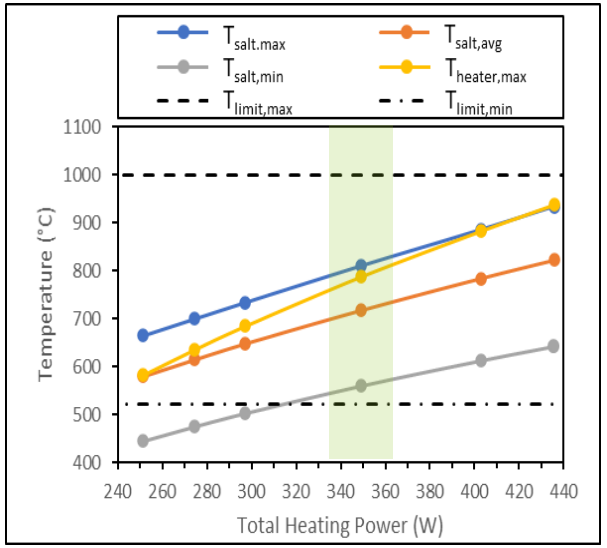


CFD Analysis Results

Heater Only



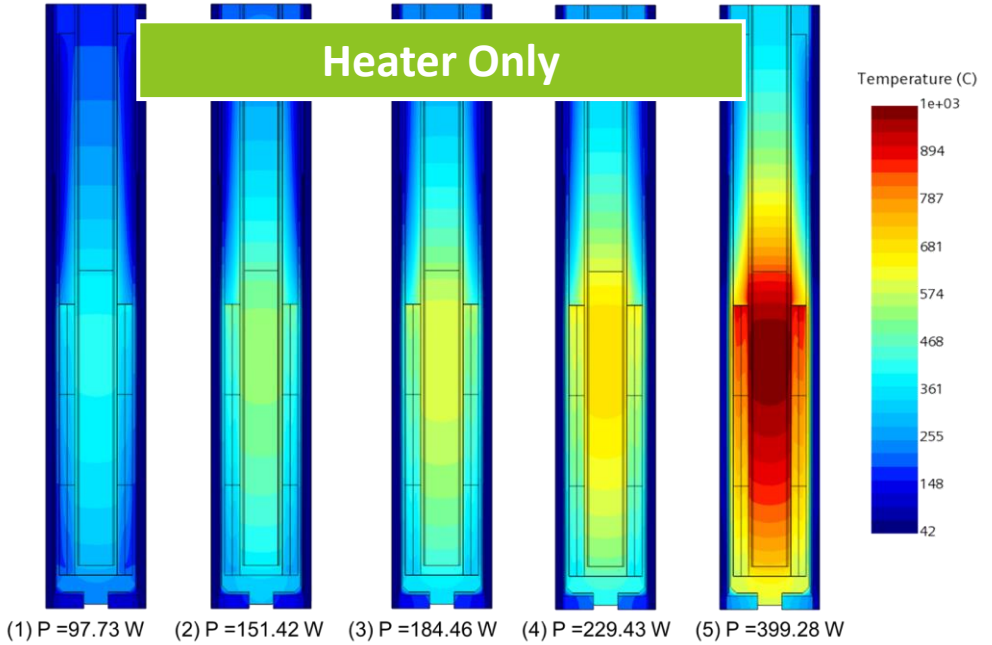
Fission + Heater



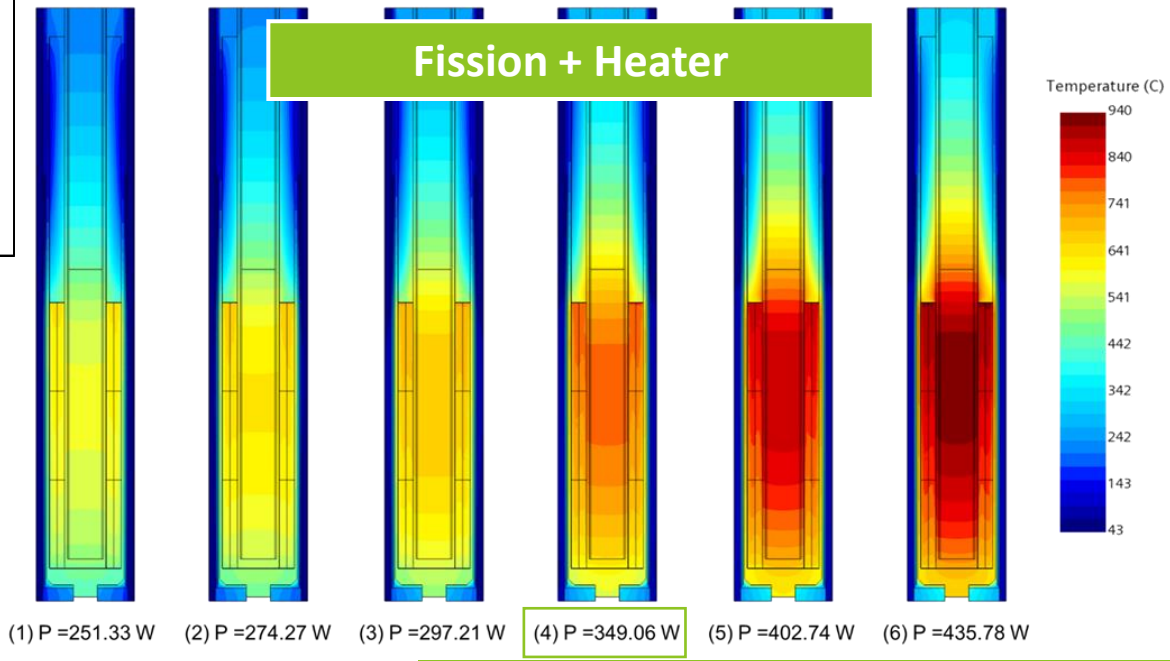
Main Outcomes:

- Natural circulations of salt, cover gas are clearly observed.
- The peak and minimum temperatures of salt can be within the temperature limits with the heater input.
- Heater only: ~400 W output target
- Fission + Heater: ~100 W heater output target

Heater Only



Fission + Heater



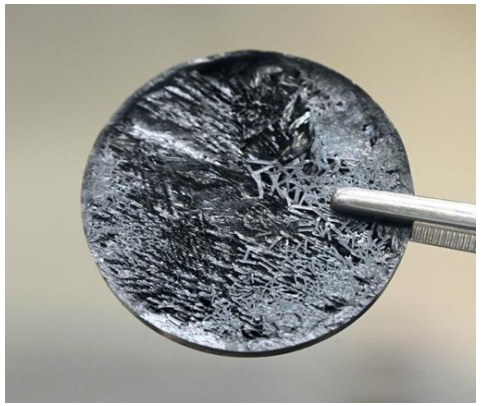
Testing and Preparations

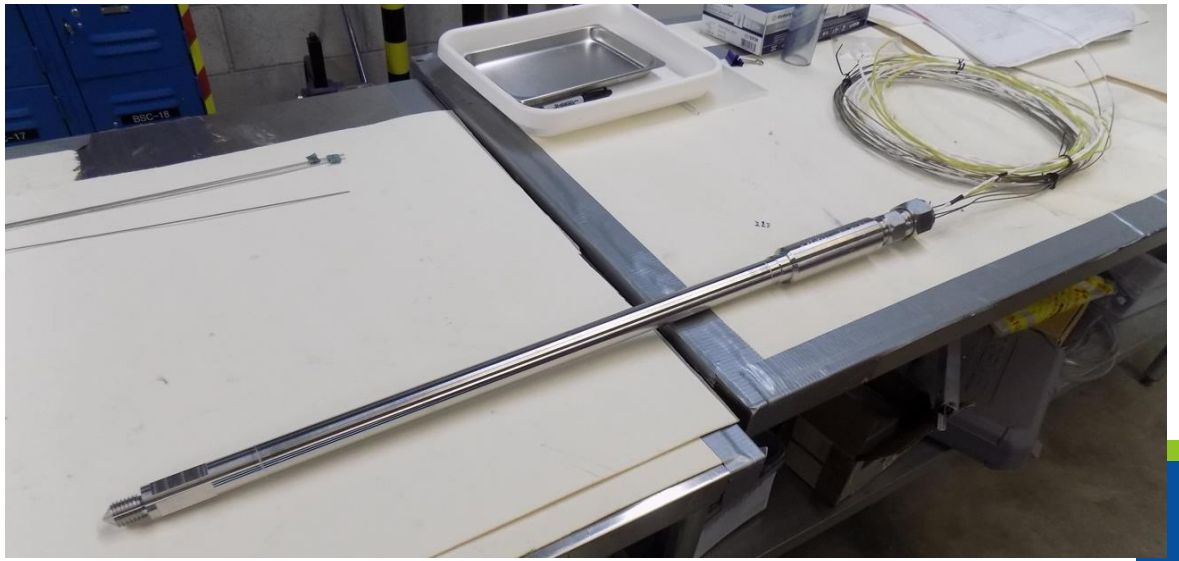
Full-Scale Prototype Testing

- Evaluate manufacturability & integrated system response

Synthesized Fuel Salt

66NaCl-33UCl_3 (mol%), 93 wt% ^{235}U



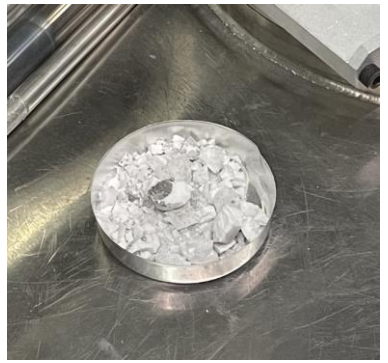


Salt Removal Mock-up Experiment

- Recovery of ~90% is achievable
- Existing tools at PIE facilities are adequate

Before test

After test



Extracted salt

Long-Term Vision

- Versatile salt & capsule
  - New novel salts being proposed from industry that have never been irradiated (fluoride and chloride based)
  - Novel salt-wall materials being proposed (including using novel manufacturing techniques)
  - Provide the infrastructure for qualification of novel salt/material combinations
- Sensor testing
  - Provide testbeds for up to 3 (maybe even 4) in-salt and in-pile sensor testing (e.g., thermocouple needle probes)
- Potential future modifications
  - More than one experiment at a time (currently have 3 dummy pins)
  - Higher flux locations (e.g., C1) - note that will need changes to NRAD SAR
  - Fine tune gas/gap + heat shield for specific use case
- Steppingstone to other experiments
  - Higher burnup irradiation in ATR
  - In-pile natural circulation loop

Summary

- MRTI fueled salt irradiation experiment for NRAD reactor at INL - planned for Summer 2023.
- Immersion heater to control temperature before/during/after irradiation
- Salt sample: 0.66UCl_4-NaCl (93wt% 235U), 40g, 13 cm^3 (molten)
- 3-D printed prototype, tested salt removal, tested heater, PIE equipment preparation (GASR handling, laser flash), assembly development completed
- Power density of 20 W/cc can be reached in F1 position according to neutron transport simulation
- Thin salt annulus with temperatures above salt melting (520°C) and below material limits (1,000°C) according to CFD and FEA
- Project currently in final design review stage with fabrication already underway
- *Funding*: INL Laboratory Directed Research & Development (LDRD) Award

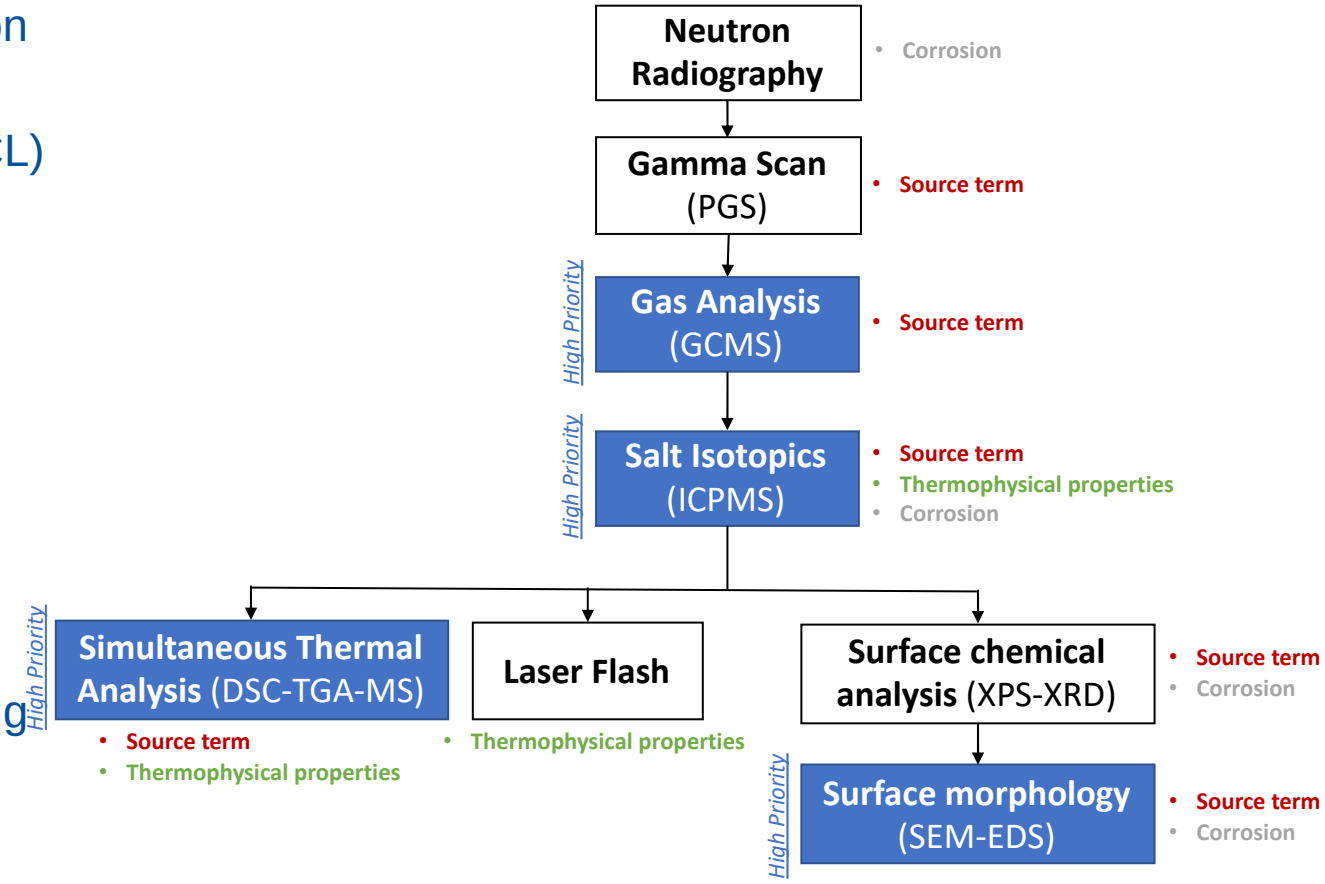
Thank you!

Questions?

Backup Slides

Planned PIE Activities

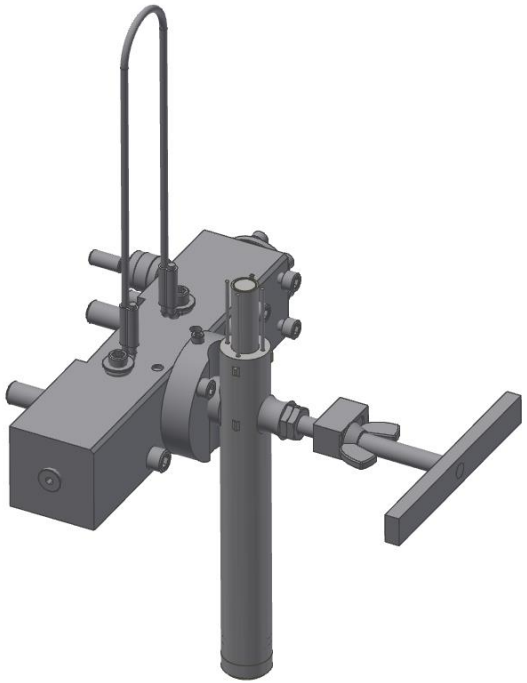
- Hot Fuel Examination Facility (HFEF)
  - Salt removal, Precision gamma scanning, neutron radiography, plenum gas capture, Disassembly
- Irradiated Materials Characterization Laboratory (IMCL)
  - Sample prep, Thermal property measurements, TEM, XRD, SEM, FIB
- Molten Salt Thermophysical properties Examination Capability (MSTEC)
  - Thermal property measurements
- Preparatory/Interfacing activities:
  - Plenum Gas Capture System interface
  - IMCL salt sample handling
  - Thermal property measurements sample handling (Laser Flash Analyzer)



PIE Preparation Activities

Gas Assay, Sample and Refill (GASR)

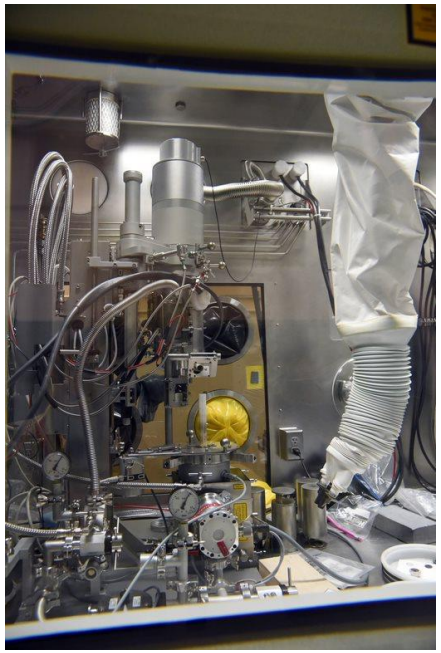
- Purpose: off-gas extraction & analysis
- Capsule OD (.805”) interfaces with GASR seal assembly
- Laser pinpointed on plenum region of capsule



Fuel salt thermal property measurement in TPC

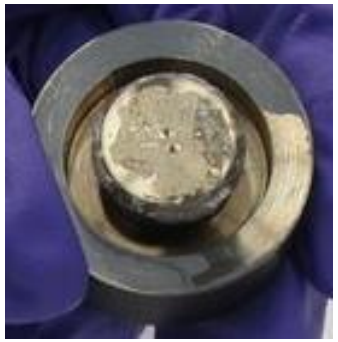
- Irradiated fuel salt thermal property measurement in shielded glovebox
- Avoid moisture/air exposure during handling

LFA



Laser Flash Analyzer (LFA) Crucible Design

- Good bonding between salt and wall
- Recommended design changes to tested crucible: increase salt thickness, change crucible material, increase wall gap etc.
- Test measurements with water, sodium nitrate, sodium chloride



Salt loaded into crucible

↓

Salt and crucible degas in vacuum furnace just over melting temperature

↓

Cooled salt and crucible loaded into LFA for measurement