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Molten-salt Research Temperature-controlled Irradiation (MRTI)

2021 MSR Workshop

Idaho National Laboratory

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

Design
- Experiment Vehicle
- Control Console
- Prototyping

Fabrication
- Salt Synthesis
- Experiment Vehicle
- Control Console

Irradiation
- NRAD
- Generation of Fission Products

PIE
- Source Term Characterization
- Thermophysical Property Investigation
- Corrosion Inspection

NRAD Reactor and Cluster

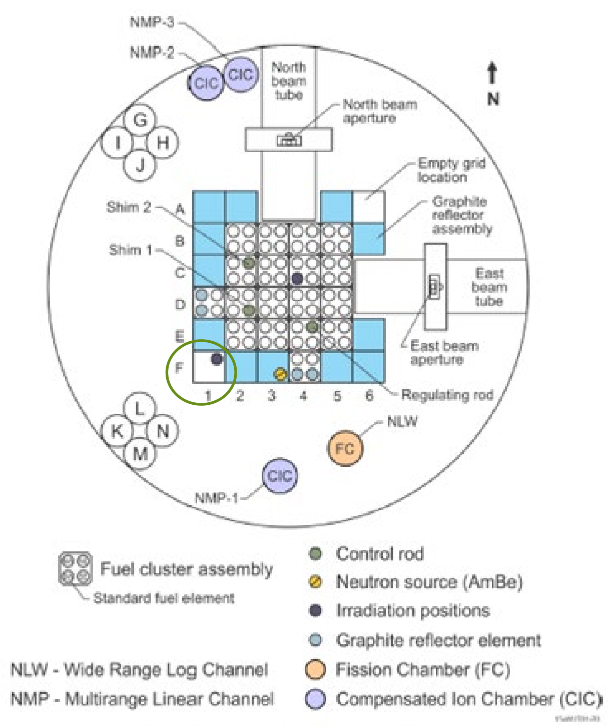
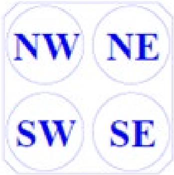
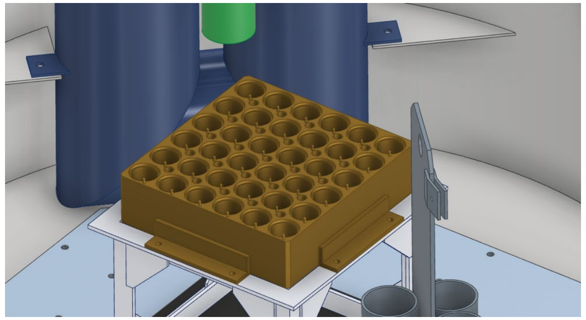


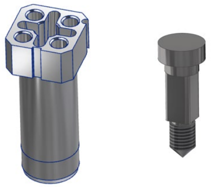
Figure 1. Sixty-four-element core and tank layout.

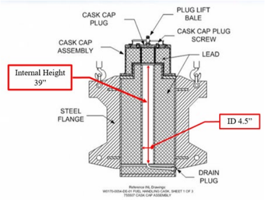


NRAD Core Grid Plate



Assembly Fittings

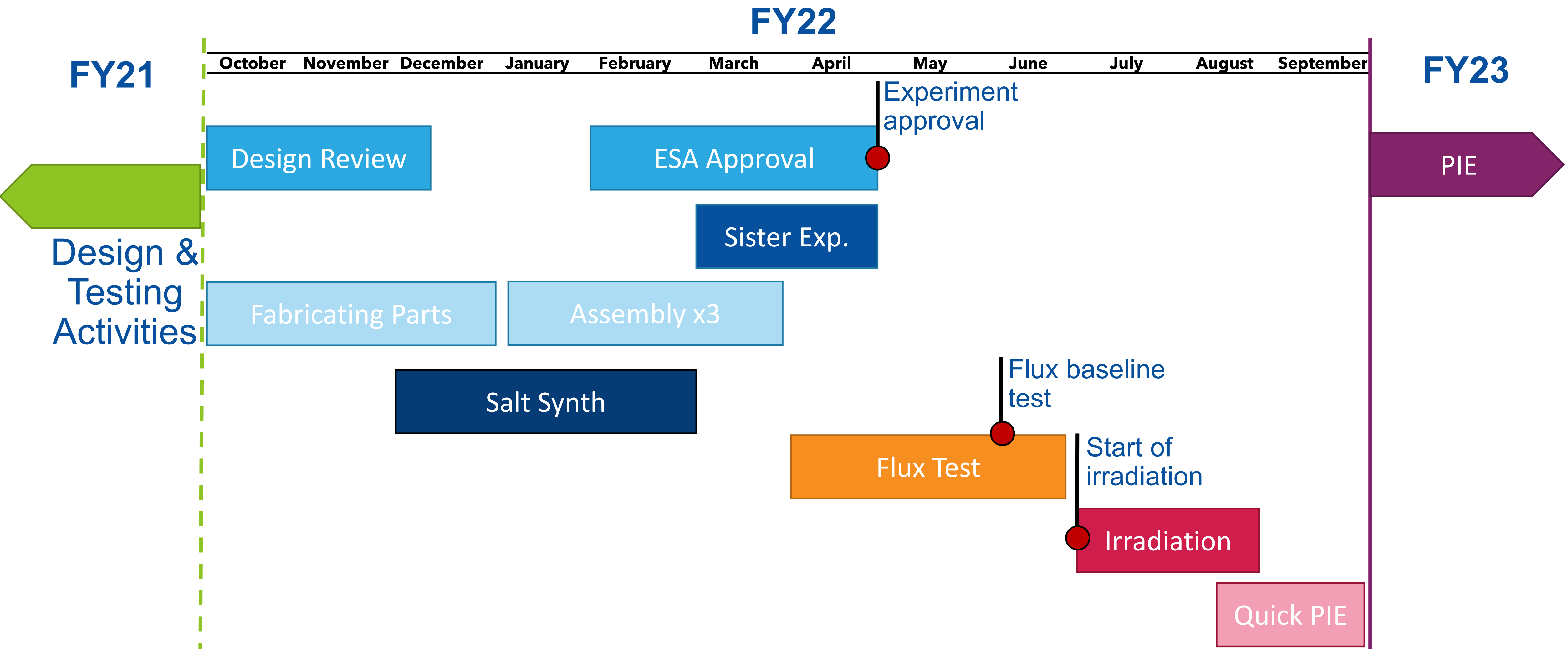




NRAD Transport Cask

- TRIGA type reactor
- NRAD fuel cluster design with wet tube top bail configuration
- Internal salt containing capsule (Inconel 625)
- Graphite bottom reflector/spacer
- Axial immersion heater for pre-melting and supplemental heat
- NRAD C4 position

MRTI Experiment Timeline



MRTI Design Requirement

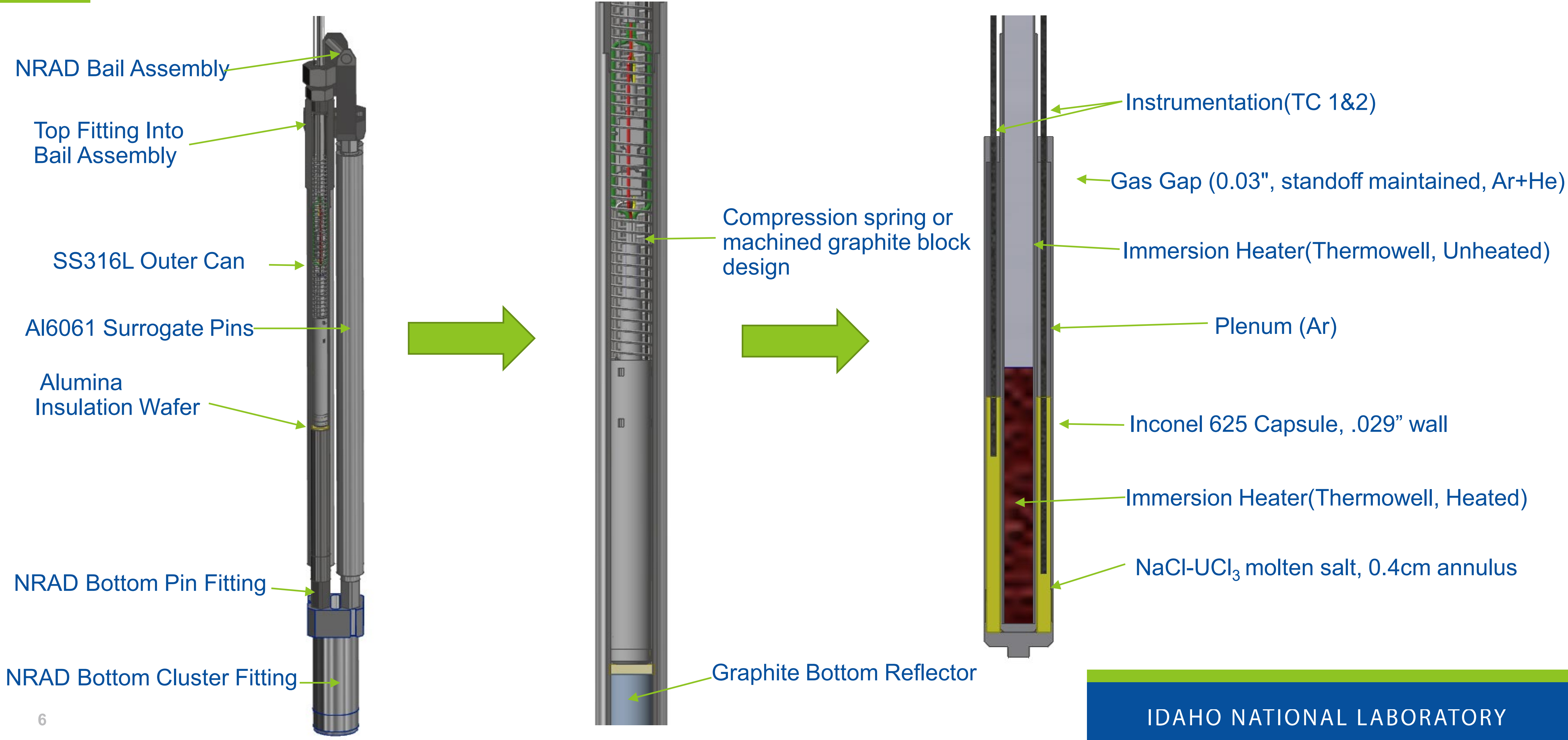
Programmatic Requirements

- Target power density: 20 W/cc
- Salt temperature kept > 525ºC (avoid freezing and possible undesirable radiolysis)
- Irradiated salt volume > 5 cc (for PIE activities)

Facility/Safety Requirements

- Outside capsule temperature below 100ºC (target 70ºC)
- < 45 ¢ of reactivity worth
- < 50 lbs weight
- Maintain integrity due to pressure increase

Overview of MRTI Design

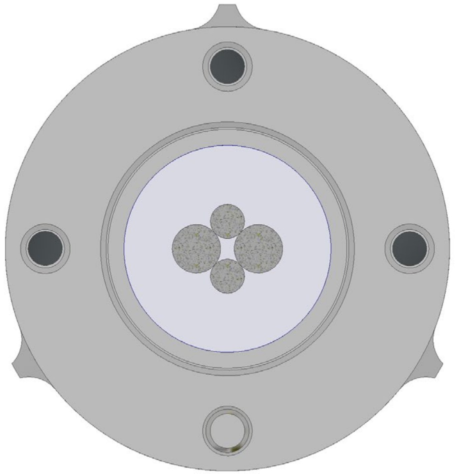


MRTI Instrumentation

3x Type N Thermocouples

- INC625 Sheath, 0.062”

Capsule Top Down



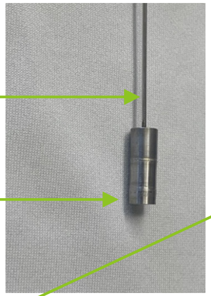
Optical Fiber Pressure Sensor

- 2mm tube outlet, 0.062” lead

Wire Leadout

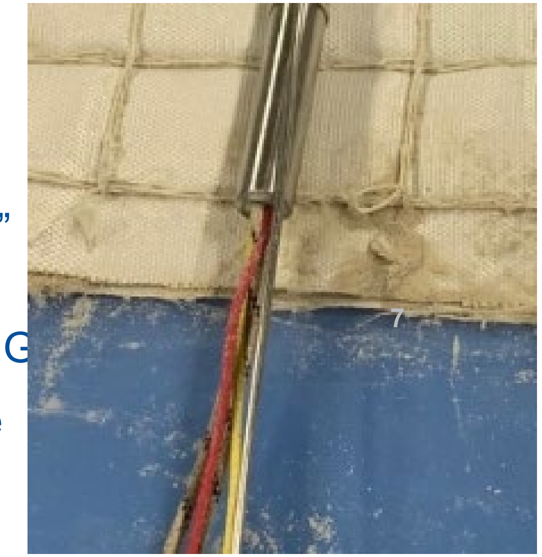
Protective Tube

(Connected to tube extension on Swagelok)



Heater Leadouts:

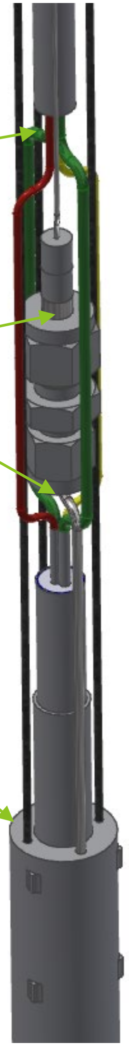
- Power to 800W, 3” section
- 0.080” Power + & G
- 1/16” TC separate leads



Heater Leadouts potted into .3125” tube, Stycast Epoxy

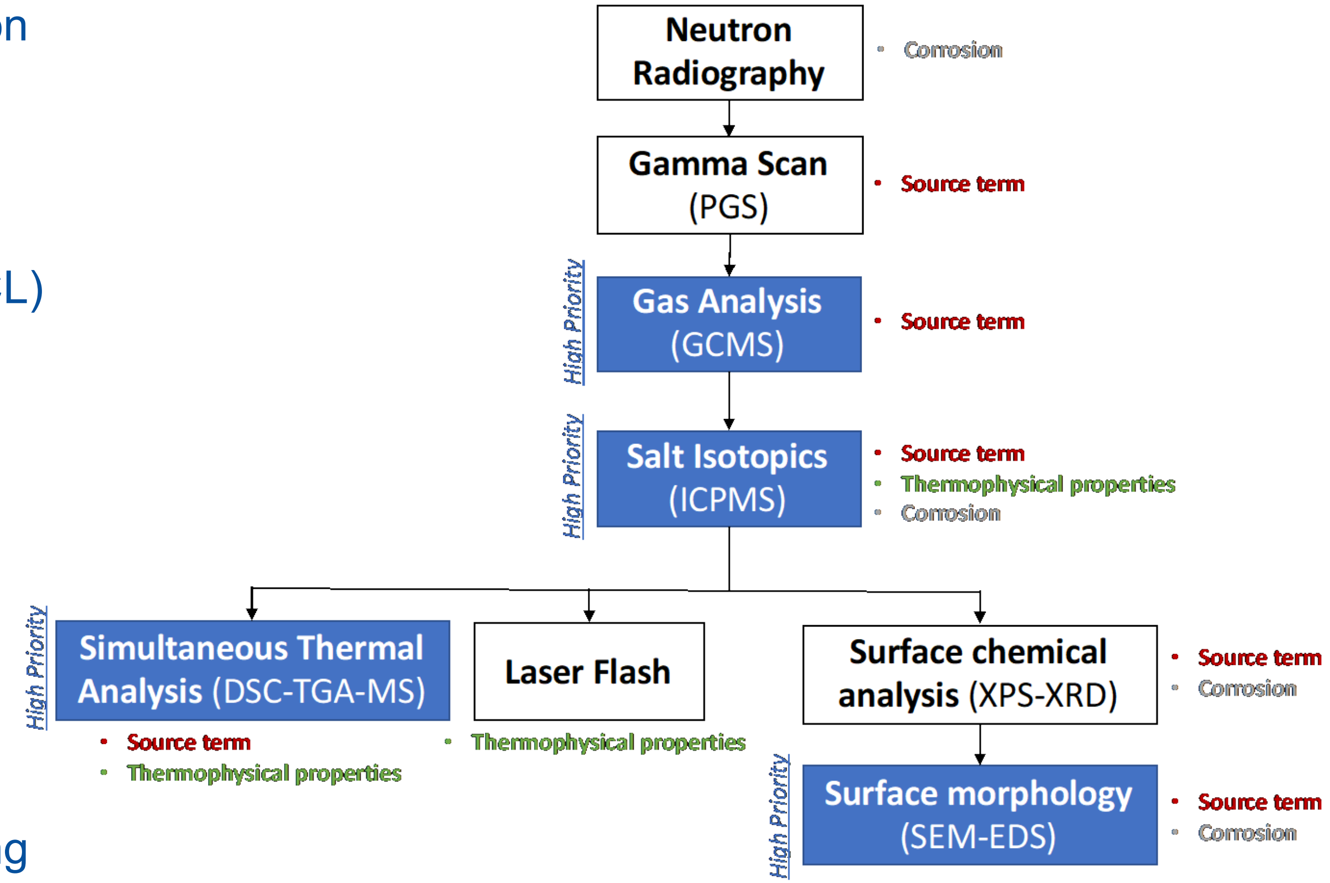
Pressure Sensor sealed via Swagelok to Pressure Tube

TCs, Pressure Tube, Heater Thermowell brazed at Capsule Top Cap, BNi-5



Planned PIE Activities

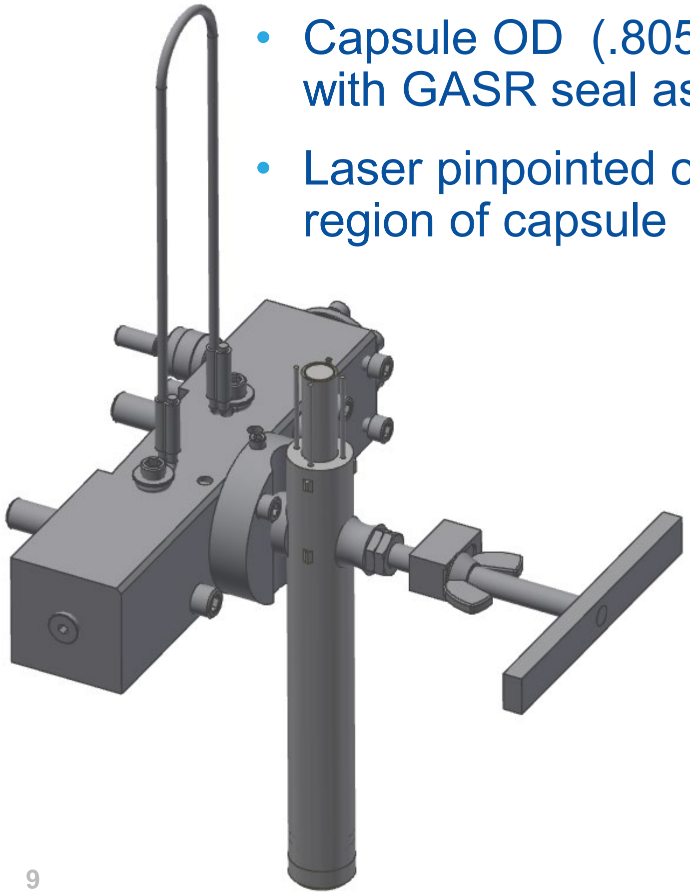
- Hot Fuel Examination Facility (HFEF)
  - Salt removal, Precision gamma scanning, neutron radiography, plenum gas capture, Disassembly
- Analytical Lab
  - ICP-MS, DSC, Dissolutions
- Irradiated Materials Characterization Laboratory (IMCL)
  - Sample prep, Thermal property measurements, TEM, XRD, SEM, 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 (1)

Gas Assay, Sample and Refill (GASR)

- Capsule OD (.805”) interfaces with GASR seal assembly
- Laser pinpointed on plenum region of capsule



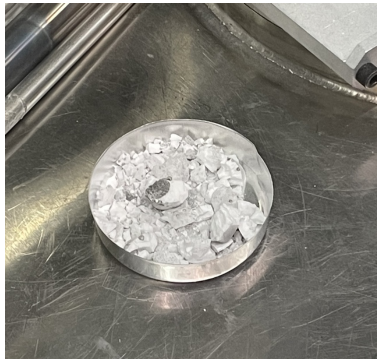
Salt Removal Mock-up Experiment

- LiCl-KCl used as surrogate in different annuli thicknesses
- Recovery of ~90% is achievable
- Existing tools at HFEF are adequate

Annulus Thickness	Initial Salt Mass	Recovered Salt Mass	Recovered Fraction
0.3 cm	15.000 g	13.892 g	0.926
0.4 cm	20.001 g	15.908 g	0.795
0.5 cm	25.002 g	24.804 g	0.992

Before test

After test



Extracted salt

PIE Preparation Activities (2)

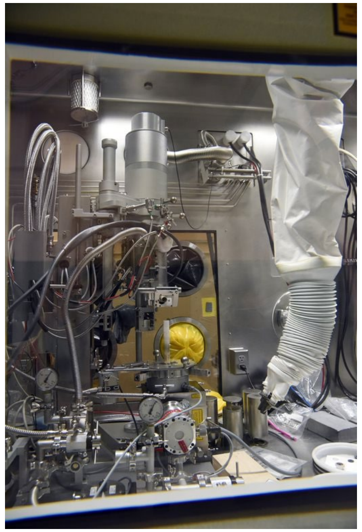
Fuel salt thermal property measurement

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

Salt transfer to IMCL or MSTEC → Salt loaded into crucible in SSPA → Salt and crucible transfer to the TPC → Crucible loaded into instrument

Thermal Property Cell (TPC)

LFA



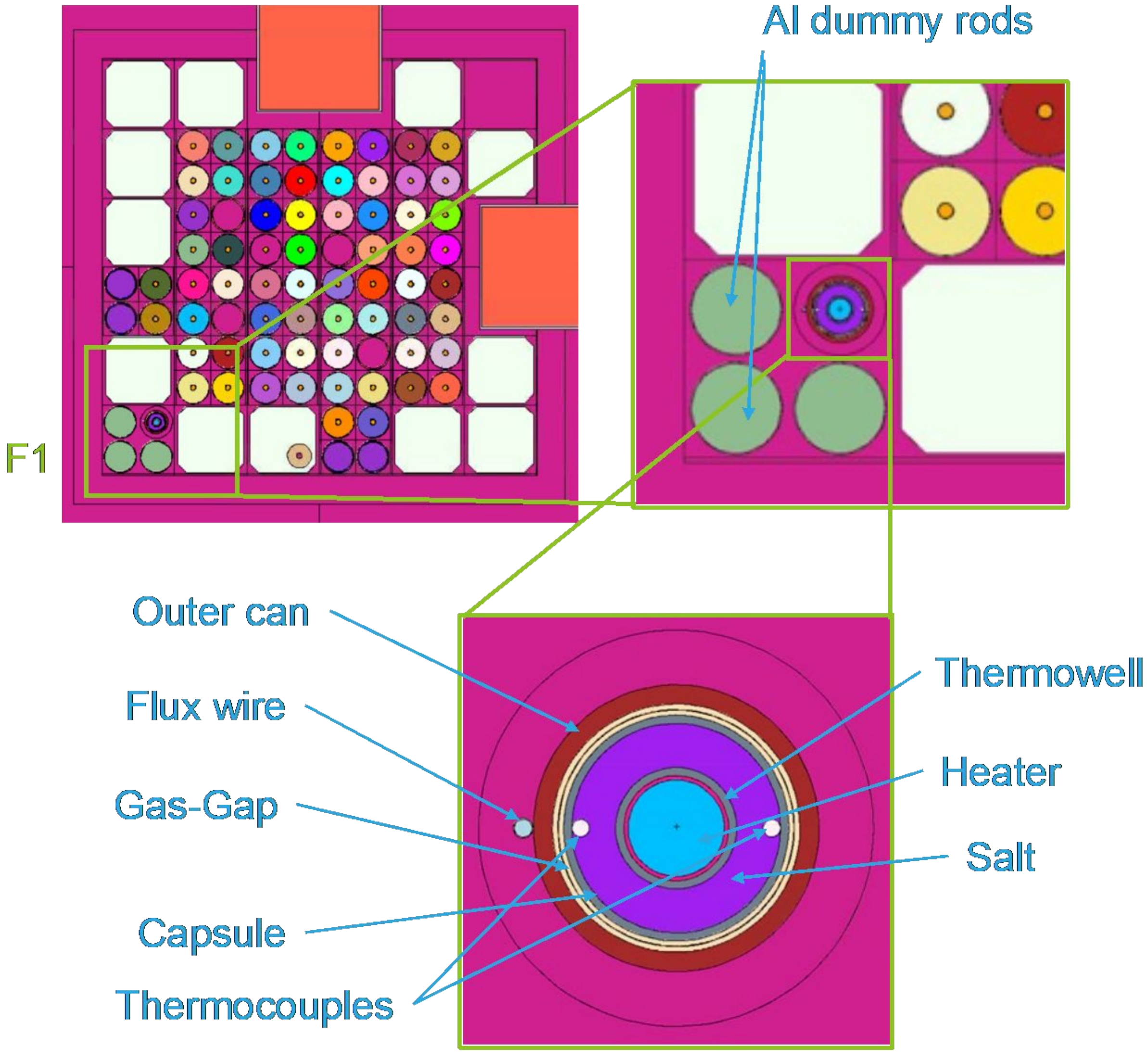
DSC-TGA-MS

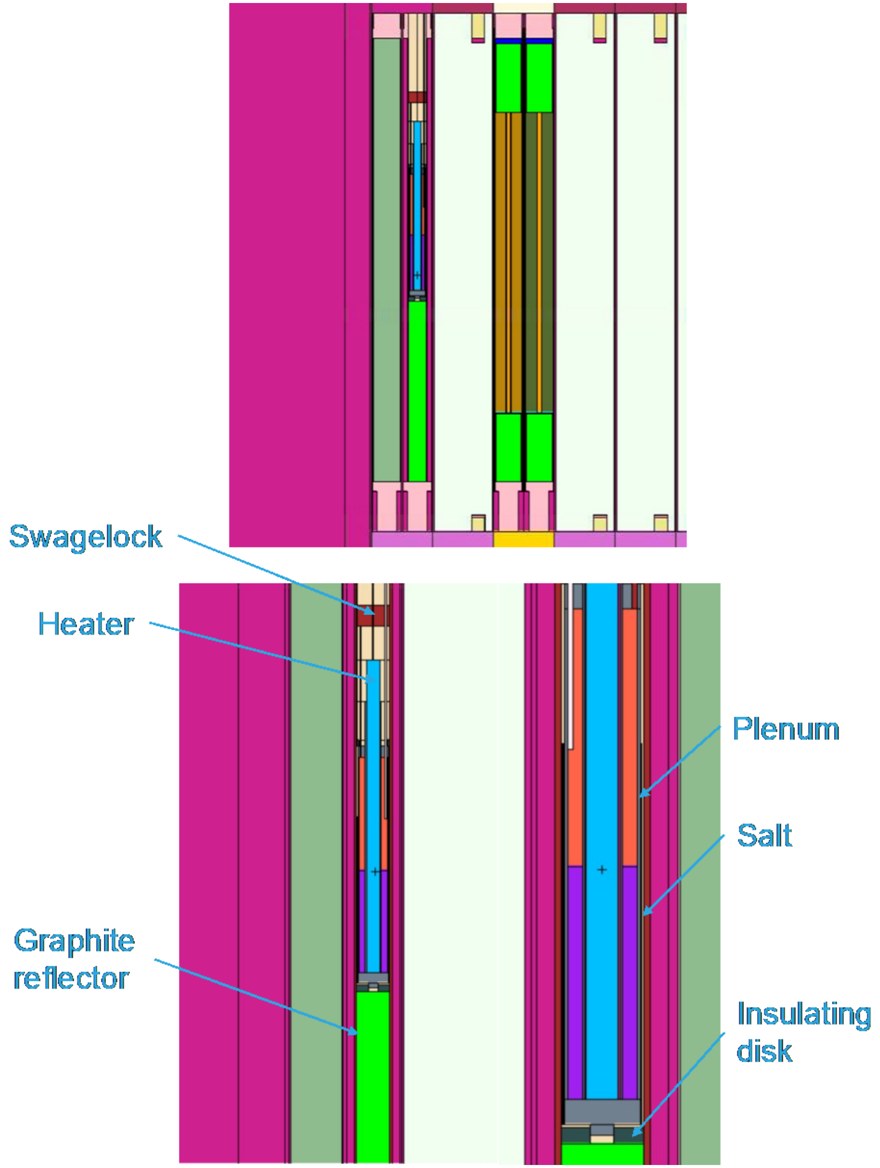
LFA Crucible Design

- Good bonding between salt and wall
- Recommended design changes to tested crucible: increase salt thickness, change crucible material, increase wall gap etc.

Salt loaded into crucible → Salt and crucible degas in vacuum furnace just over melting temperature → Cooled salt and crucible loaded into LFA for measurement

MRTI Neutronics Model (MCNP)





MRTI Heat Generation and Reactivity Impact

- Salt fission heat generation of 20.09 W/cc

  → **Experiment objective met**

- Component heat generation tabulated for thermal analysis handoff

Component	Volume (cc)	Total Power (W)	Power Density (W/cc)
MRTI Salt Sample	13.054	247.687	18.974
Capsule Radial	6.737	1.586	0.235
Heater Thermowell	4.422	0.972	0.220
Bottom + Slot	2.570	0.649	0.253
Capsule top	1.699	0.275	0.162
Outer Shell	74.476	10.046	0.135
Hot TC	0.577613	0.048	0.084
Plenum TC	0.494349	0.035	0.070
Cold TC	0.693059	0.067	0.096
Pressure tube	0.124348	0.013	0.102
Cu	0.068296	0.004	0.065
Bottom Graphite Reflector	91.29308	2.126	0.023
Lower Insulator disk	1.830612	0.009	0.005
Upper Insulator disk	0.442517	0.001	0.003
Spring	0.45292	0.032	0.071
Swagelock	5.398074	0.023	0.004
Heat Shield	0.384924	0.084	0.218

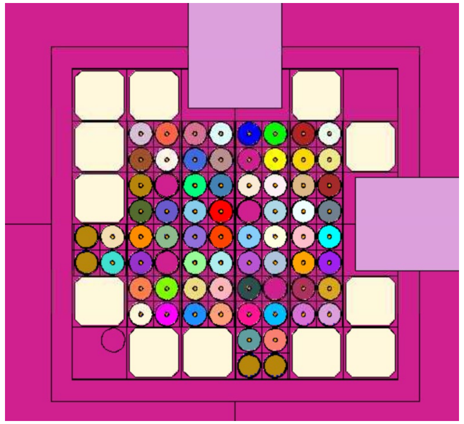
- Evaluating impact of experiment against base design (i.e., water in F1 position)
- Reactivity impact estimated using:

$$\Delta\rho(\text{pcm}) = \frac{k_{MRTI} - k_{base}}{k_{MRTI} \times k_{base}}$$

$$cents = \frac{\Delta\rho(\text{pcm})}{\beta}$$

- Resulting impact of MRTI = -1.24 ± 1.07 ¢ (in the noise essentially) << 45 ¢ limit

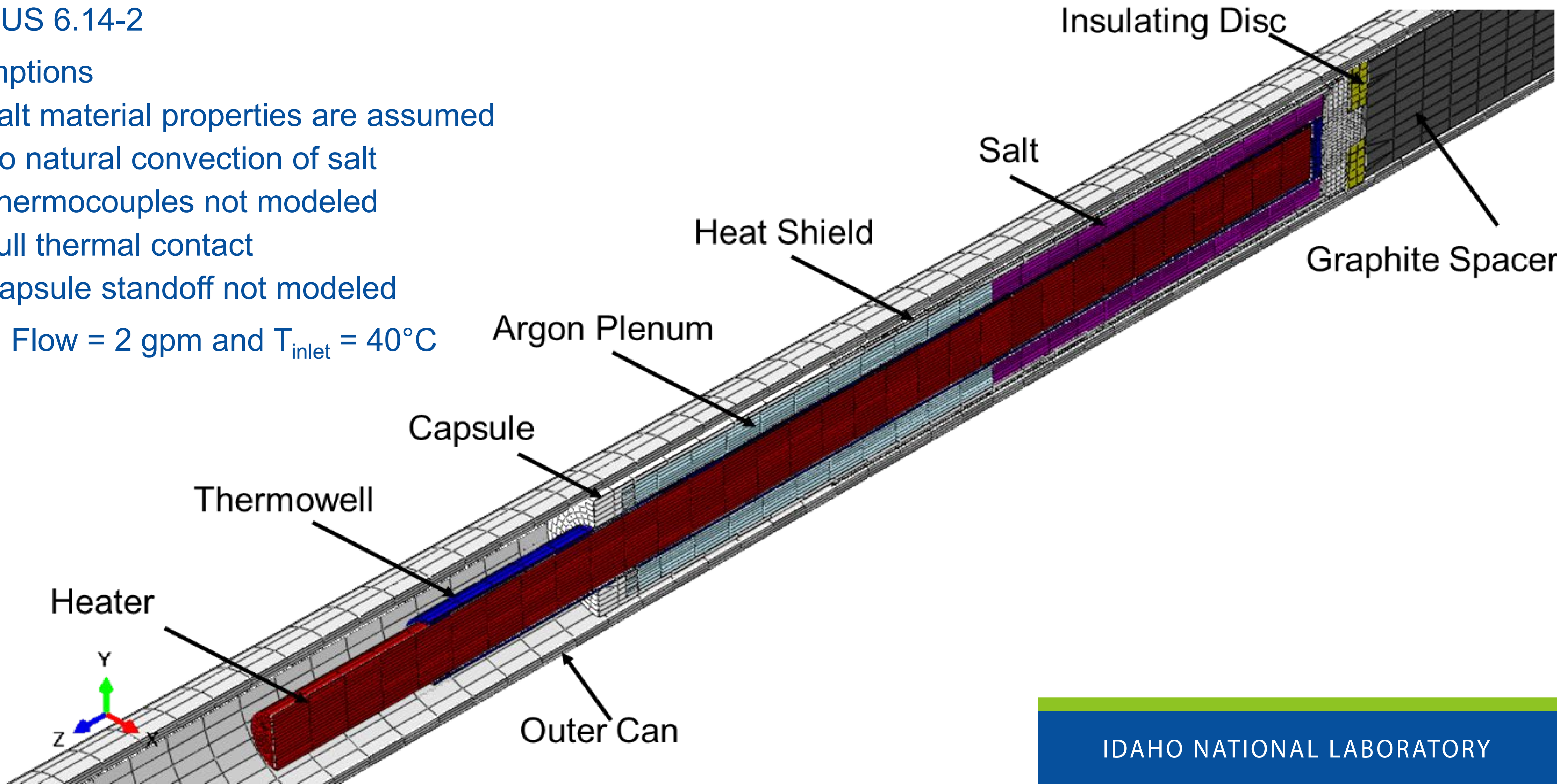
  → **NRAD operational requirement met**



Base model with no experiment

ABAQUS Thermal Hydraulics Model Setup

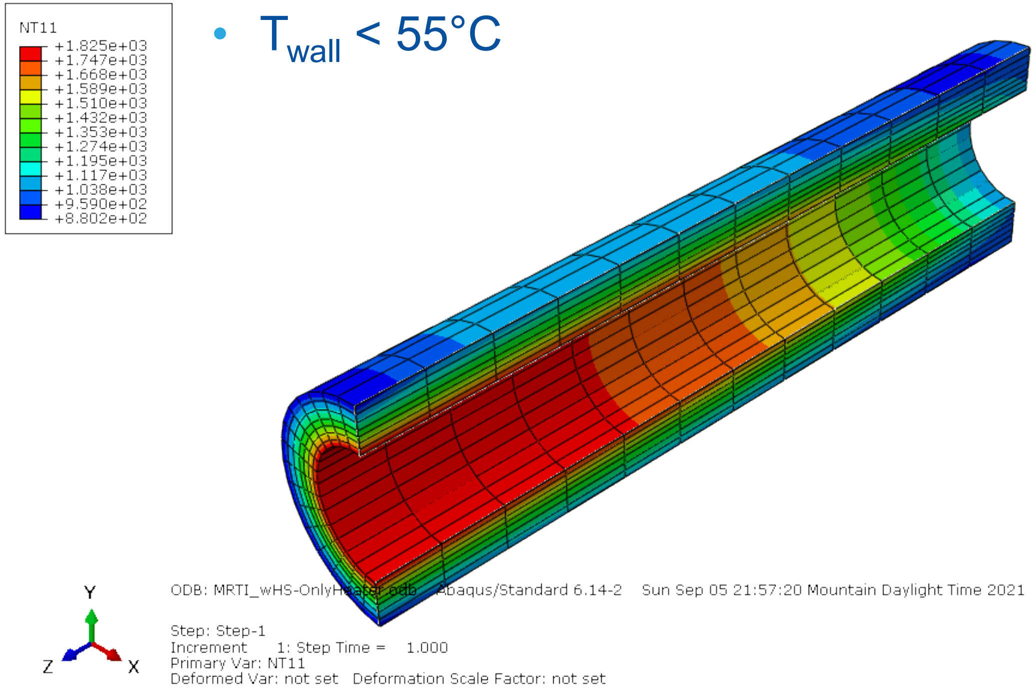
- ABAQUS 6.14-2
- Assumptions
  - Salt material properties are assumed
  - No natural convection of salt
  - Thermocouples not modeled
  - Full thermal contact
  - Capsule standoff not modeled
- NRAD Flow = 2 gpm and T_{inlet} = 40°C



ABAQUS Simulation Outcomes

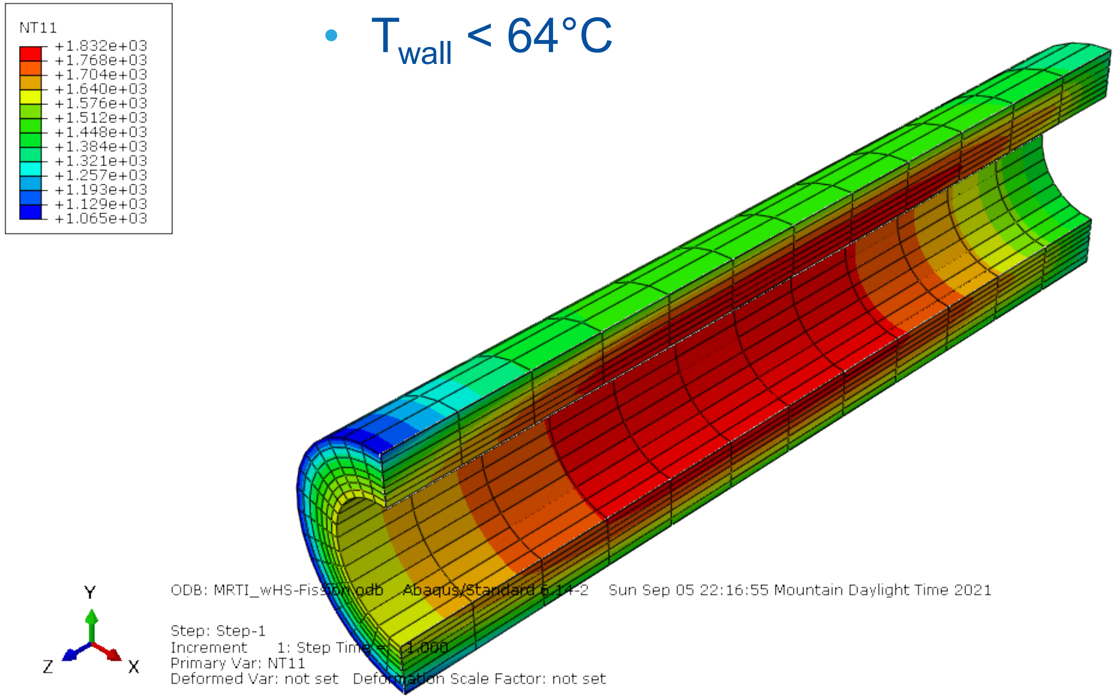
Pre-Irradiation (Heater Only)

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



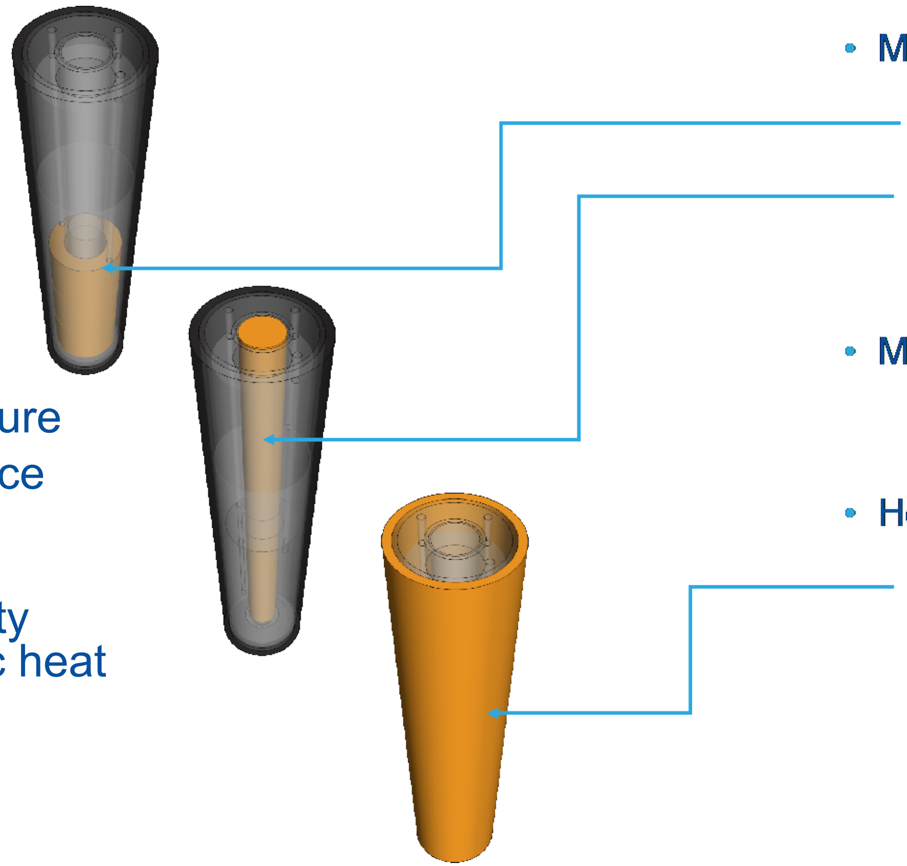
Irradiation (Heater+Fission)

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



Computational Fluid Dynamics (CFD) Model

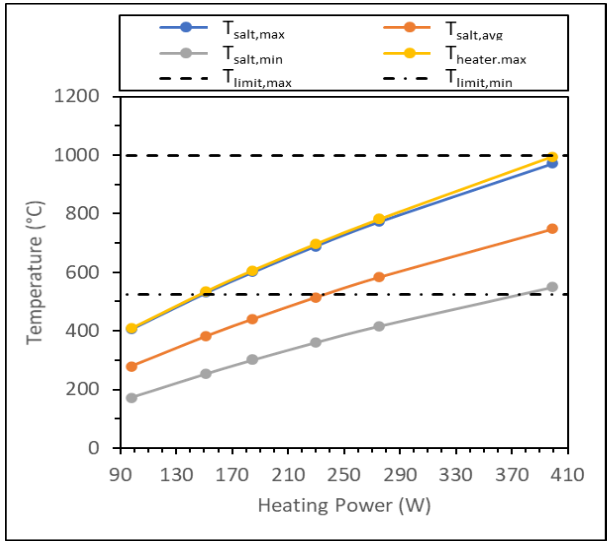
- STAR-CCM+ Simulation
- Fluid region:
  - Segregated flow and temperature
  - RANS solver with k-ω turbulence model. Note that calculated Ra(=Gr*Pr) > 10^9.
  - Temperature-dependent density and viscosity, constant specific heat and thermal conductivity.
- Gas gap region:
  - Conduction, convection and radiation heat transfers
- Solid region:
  - Segregated Solid energy solver
  - Constant properties
  - No Standoff assumed

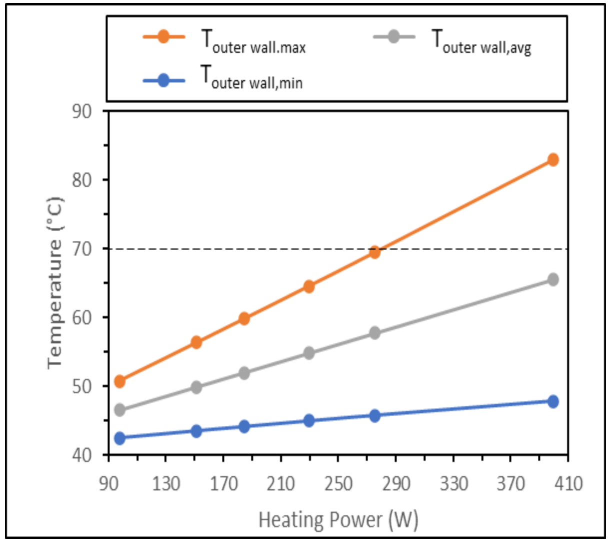


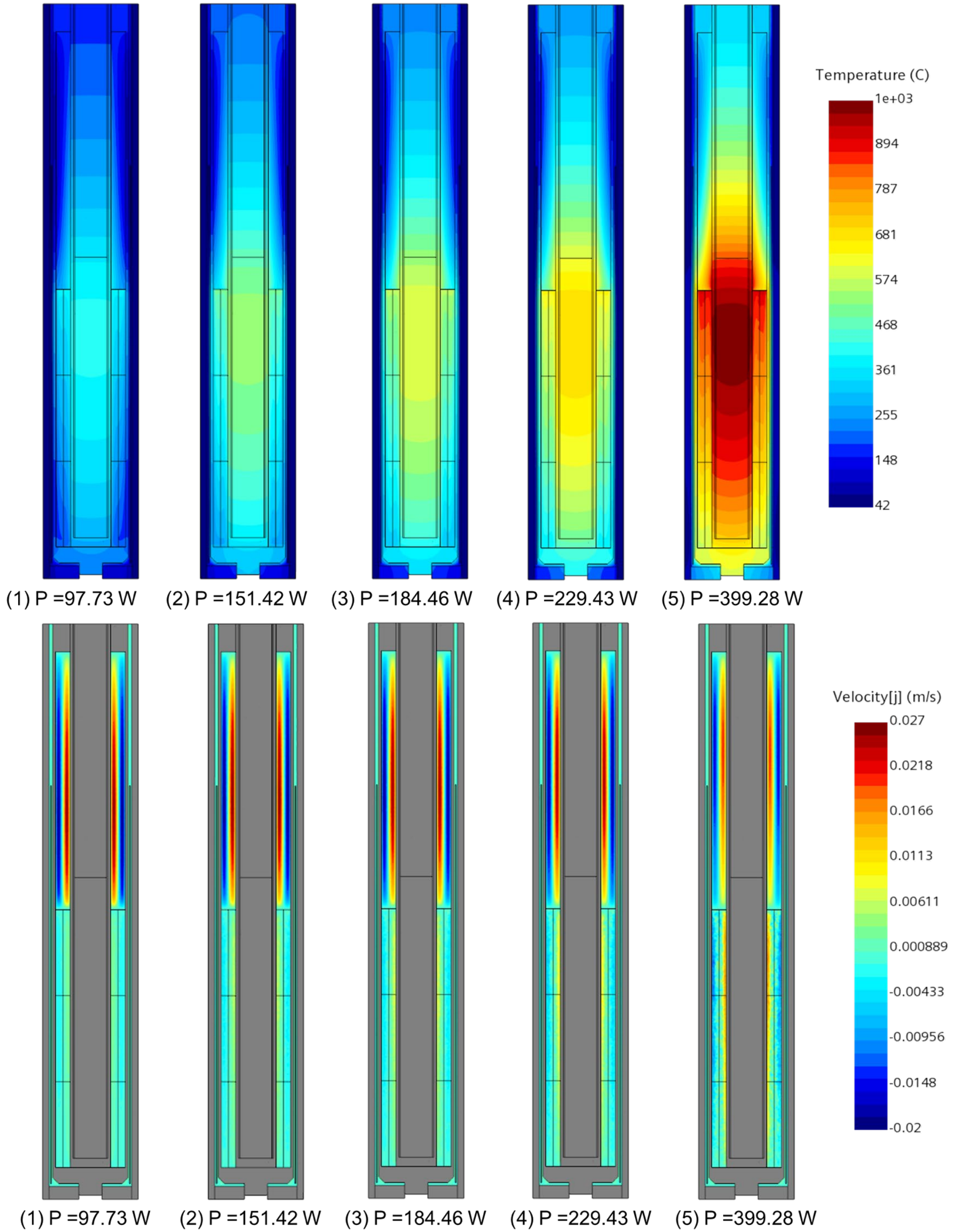
- Major Heat Sources
  - Salt fission heating based on neutronics calculation
  - Heater
    - programmatic test ($5 MW/m^3$ – $87 MW/m^3$)
- Minor Heat Sources
  - Fission heating of solid components
- Heat Sink
  - External convection on outer surface of outer wall
    - Ambient temp.: 40°C
    - HTC: $1250 W/m^2$-K

CFD Analysis Results

Heater Test Results





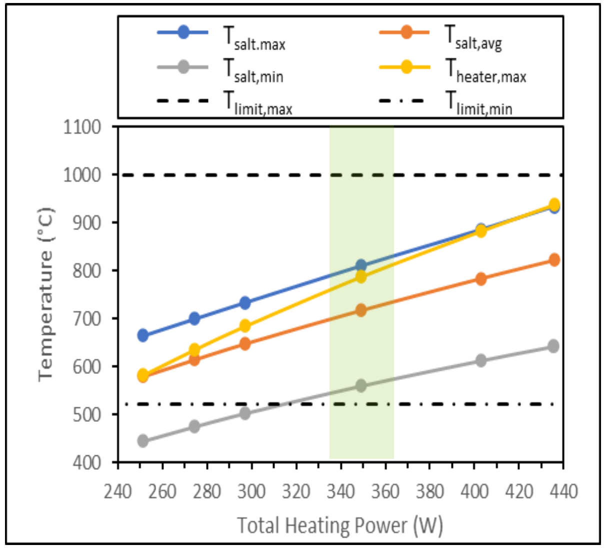


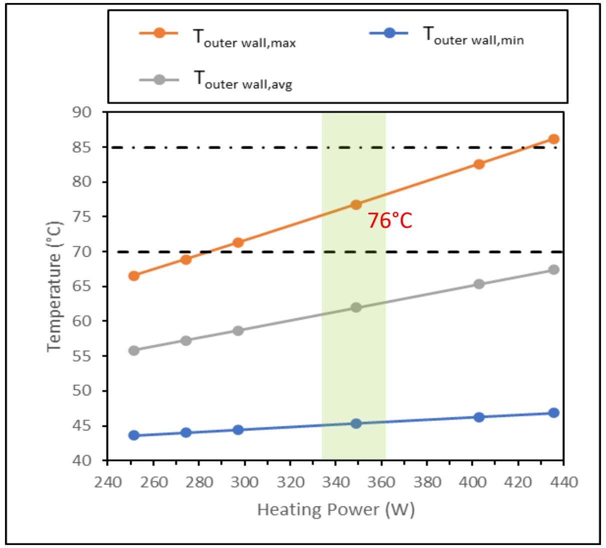
Main Outcomes:

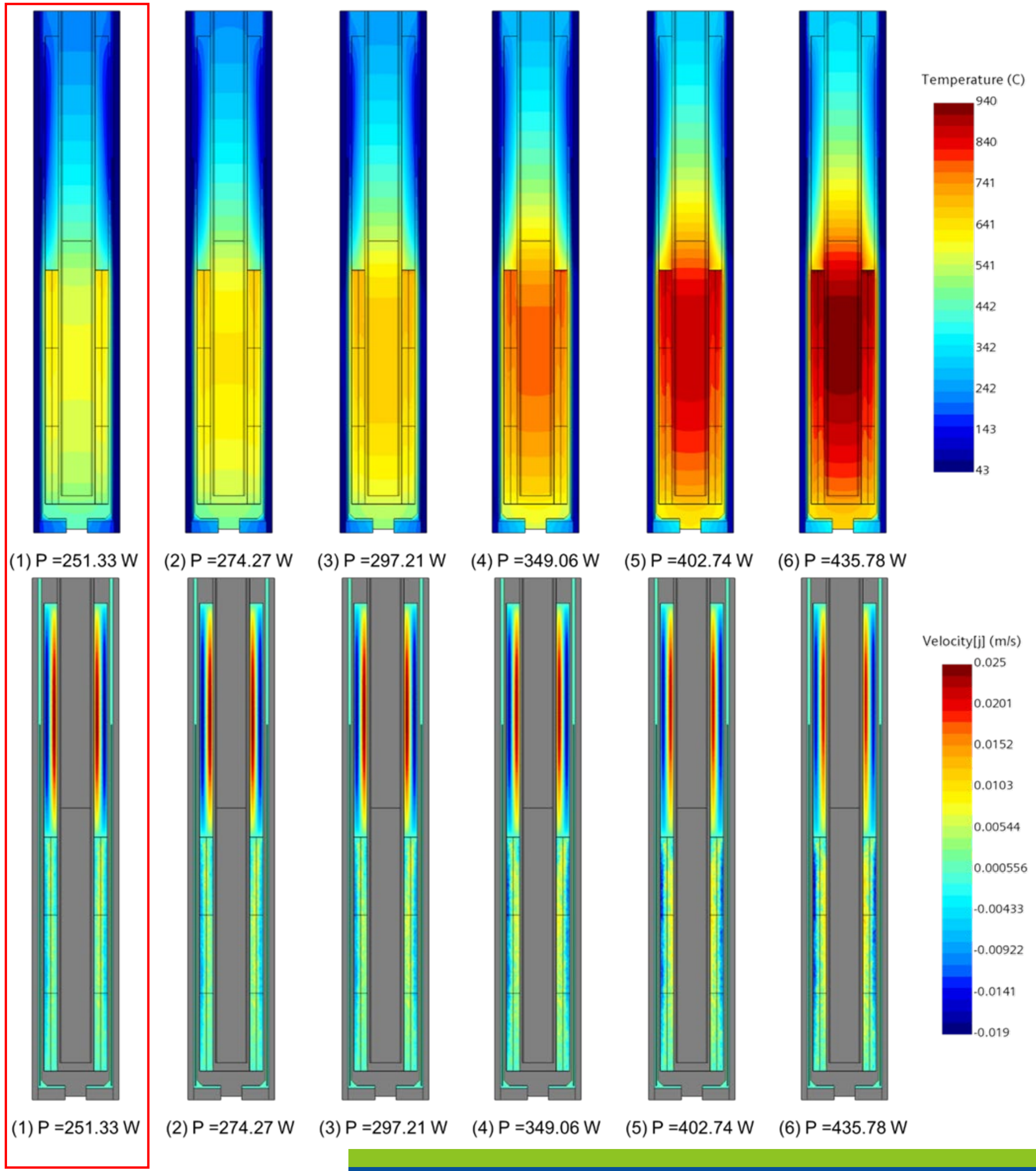
- Natural circulations of salt, cover gas are clearly observed.
- The peak and minimum temperatures of salt can be within the temperature limits with the heater input.
- For the heater power of 400 W, the average temperature on the outer surface is calculated to be 65.48°C with a local maximum of 82.89°C.

CFD Analysis Results

Fission Heat Test Results







Heater off

Main Outcomes:

- Programmatic requirements for the salt temperature can be met with a combination of fission heating and heater input. The salt temperatures meet the requirements by the heater input of 97W (total heating power=349W) while a maximum temperature on the outer surface slightly exceeds 70°C.
- For the maximum heating power tested, the average temperature on the outer surface is calculated to be 67.41°C with a local maximum of 86.17°C.

Summary

- MRTI fueled salt irradiation experiment for NRAD reactor at INL - planned for Summer 2022.
- Comprehensive PIE planned as part of project including gamma scan, mass spec, corrosion study, salt thermophysical properties.
- Immersion heater to control temperature before/during/after irradiation
- Power density of 20 W/cc was reached
- Thin salt annulus with temperatures above salt melting (520°C) and below material limits (1,000°C)
- Initial PIE exercises conducted to ensure adequate interfacing with tooling after irradiation
- Project currently in final design review stage with fabrication already underway

Questions?

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Supplementary Slides

3D Printed Mockup

- 3D Printed mockup for visual representation of experiment
  - Assists in presenting to-scale MRTI pin assembly to key players in reactor operations and PIE
  - Did not include radiative heat shield due to resolution of 3D printer

Model and Assumptions

Codes and Models Used

- MCNP6.1 of NRAD core provided by Kyrone Riley – Aug. 02, 2020.
  - Nuclear data uncertainties ignored
  - Geometry simplifications for MRTI (e.g., homogenization)
  - 200,000 virtual particles with 800 cycles: k_{eff} sd of 7 pcm, and salt heat generation uncertainty of 0.31%
- ORIGEN-6.2 with COUPLE: 44-group structure obtained from MCNP to generate cross-section libraries.

Important Specifications

- Salt density obtained from Desyatnik et al.

$$\rho(T) = 3.8604 - 8.37 \times 10^{-4} \times T$$

- HEU enrichment vector:

^{232}U	^{234}U	^{235}U	^{236}U	^{238}U
0.0%	1.0%	93.2%	0.3%	5.6%

- Resulting salt composition:

Salt density	3.13 g/cc
Salt volume	13.05 cc
Salt mass	40.85 g
U mass in salt	20.95 g
^{235}U mass in salt	19.52 g

MRTI Flux Predictions

- Normalized against the total power of the core (F6 tally):

$$\phi = F4 \times \frac{F6_t}{250\ \text{kW}} \times \frac{1}{1.60218 \times 10^{-13}}$$

- Spectrum is harder in salt, and surrounding capsule compared due to fission neutrons

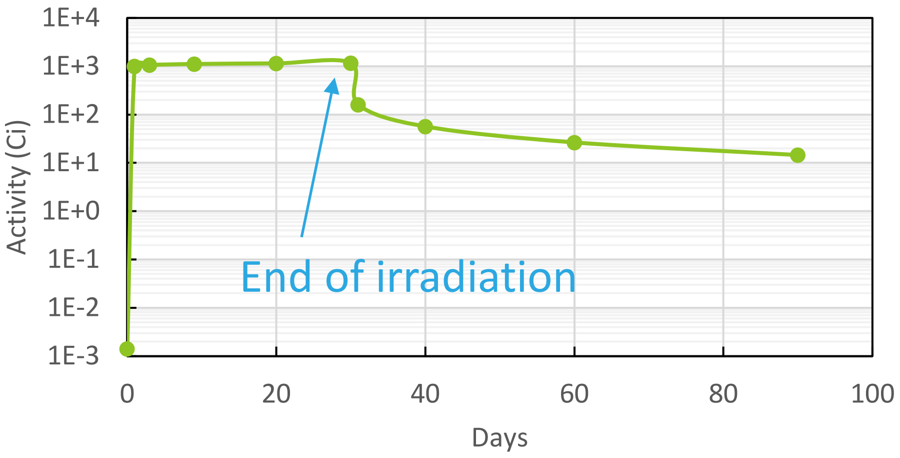
Component	Total Flux (n/cm^2-s)	Fast Flux (> 100 keV)	Fast Flux (n/cm^2-s)
MRTI Salt Sample	3.49×10^{12}	64%	2.23×10^{12}
Capsule Radial	3.29×10^{12}	43%	1.40×10^{12}
Heater Thermowell	2.93×10^{12}	44%	1.28×10^{12}
Gas total	1.31×10^{12}	29%	3.81×10^{12}
Bottom + Slot	3.54×10^{12}	41%	1.45×10^{12}
Capsule top	2.34×10^{12}	29%	6.74×10^{12}
Outer Shell	2.40×10^{12}	29%	6.98×10^{12}
Flux wire	2.05×10^{12}	27%	5.51×10^{12}

MRTI Depletion/Activation Analysis

- Noble gas generation after 30-day irradiation (for pressure analysis):

	Mass (g)
Ar	1.30E-06
Kr	1.10E-04
Xe	9.78E-04

- Evolution of salt activity after irradiation



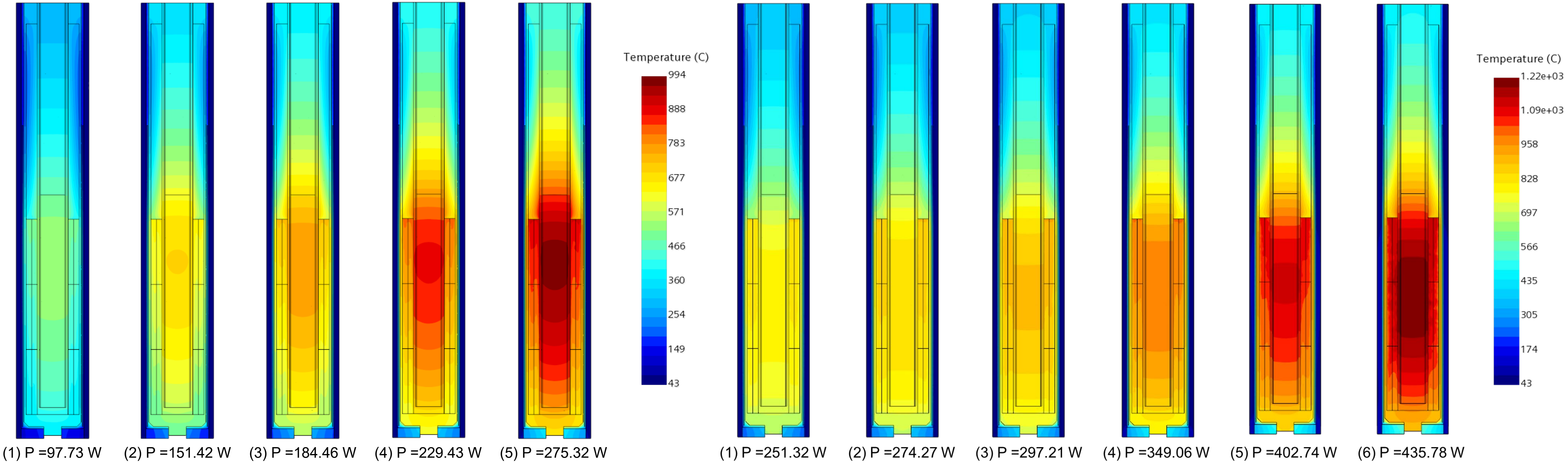
- Ar-41 gas peak activation in MRTI of 2.75×10^{-2} Ci (109 mins half-life)

Grams of FPs produced:

	Before	Irradiation					Post Irradiation			
days:	0	1	3	9	20	30	31	40	60	90
na	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00	4.10E+00
mg	0.00E+00	2.26E-08	1.21E-07	4.61E-07	1.09E-06	1.66E-06	1.69E-06	1.71E-06	1.71E-06	1.71E-06
s	0.00E+00	2.99E-07	8.96E-07	2.66E-06	5.79E-06	8.49E-06	8.46E-06	8.09E-06	7.22E-06	5.98E-06
cl	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01	1.58E+01
ar	0.00E+00	4.18E-08	1.29E-07	3.89E-07	8.67E-07	1.30E-06	1.30E-06	1.30E-06	1.30E-06	1.30E-06
se	0.00E+00	4.90E-07	1.45E-06	4.34E-06	9.65E-06	1.45E-05	1.45E-05	1.45E-05	1.45E-05	1.45E-05
br	0.00E+00	2.90E-07	6.64E-07	1.78E-06	3.83E-06	5.69E-06	5.59E-06	5.59E-06	5.59E-06	5.59E-06
kr	0.00E+00	4.62E-06	1.19E-05	3.36E-05	7.33E-05	1.10E-04	1.09E-04	1.09E-04	1.09E-04	1.08E-04
rb	0.00E+00	3.20E-06	1.02E-05	3.11E-05	6.96E-05	1.05E-04	1.05E-04	1.05E-04	1.05E-04	1.05E-04
sr	0.00E+00	1.73E-05	4.59E-05	1.28E-04	2.75E-04	4.02E-04	3.97E-04	3.83E-04	3.59E-04	3.32E-04
y	0.00E+00	7.97E-06	2.03E-05	5.61E-05	1.21E-04	1.79E-04	1.77E-04	1.75E-04	1.71E-04	1.66E-04
zr	0.00E+00	3.19E-05	1.00E-04	3.01E-04	6.69E-04	1.00E-03	1.00E-03	1.00E-03	9.99E-04	9.96E-04
nb	0.00E+00	3.51E-07	7.94E-07	3.27E-06	1.28E-05	2.56E-05	2.67E-05	3.71E-05	5.05E-05	5.43E-05
mo	0.00E+00	2.19E-05	6.83E-05	1.99E-04	4.23E-04	6.27E-04	6.26E-04	6.15E-04	6.31E-04	6.63E-04
tc	0.00E+00	9.26E-07	6.22E-06	3.83E-05	1.12E-04	1.82E-04	1.88E-04	2.06E-04	2.09E-04	2.09E-04
ru	0.00E+00	1.70E-05	5.08E-05	1.51E-04	3.29E-04	4.87E-04	4.85E-04	4.73E-04	4.52E-04	4.32E-04
rh	0.00E+00	7.33E-07	1.97E-06	4.71E-06	1.35E-05	2.60E-05	2.68E-05	3.70E-05	5.74E-05	7.72E-05
pd	0.00E+00	4.50E-07	2.31E-06	1.03E-05	2.60E-05	4.04E-05	4.14E-05	4.33E-05	4.38E-05	4.45E-05
ag	0.00E+00	4.26E-08	1.50E-07	4.61E-07	9.57E-07	1.37E-06	1.37E-06	1.26E-06	1.19E-06	1.17E-06
cd	0.00E+00	7.04E-08	2.27E-07	7.17E-07	1.66E-06	2.55E-06	2.57E-06	2.66E-06	2.73E-06	2.74E-06
sn	0.00E+00	2.95E-07	7.61E-07	2.11E-06	4.51E-06	6.66E-06	6.58E-06	6.46E-06	6.37E-06	6.34E-06
sb	0.00E+00	6.28E-07	1.09E-06	2.02E-06	3.11E-06	3.96E-06	3.42E-06	2.67E-06	2.53E-06	2.52E-06
te	0.00E+00	1.03E-05	2.58E-05	5.71E-05	9.72E-05	1.30E-04	1.23E-04	1.02E-04	9.74E-05	9.65E-05
i	0.00E+00	1.49E-05	2.83E-05	5.02E-05	7.44E-05	8.88E-05	7.52E-05	4.73E-05	3.20E-05	2.96E-05
xe	0.00E+00	2.78E-05	9.20E-05	2.93E-04	6.53E-04	9.78E-04	9.83E-04	9.80E-04	9.78E-04	9.80E-04
cs	0.00E+00	1.30E-05	5.16E-05	1.92E-04	4.94E-04	7.81E-04	7.96E-04	8.50E-04	8.71E-04	8.72E-04
ba	0.00E+00	2.06E-05	5.92E-05	1.65E-04	3.30E-04	4.61E-04	4.53E-04	4.00E-04	3.45E-04	3.22E-04
la	0.00E+00	1.25E-05	3.39E-05	9.96E-05	2.17E-04	3.22E-04	3.20E-04	3.14E-04	3.05E-04	3.02E-04
ce	0.00E+00	3.18E-05	9.41E-05	2.67E-04	5.91E-04	8.91E-04	8.90E-04	8.96E-04	8.90E-04	8.48E-04
pr	0.00E+00	4.39E-06	1.64E-05	6.58E-05	1.49E-04	2.17E-04	2.20E-04	2.10E-04	2.05E-04	2.29E-04
nd	0.00E+00	1.67E-05	5.44E-05	1.73E-04	4.09E-04	6.40E-04	6.48E-04	6.89E-04	7.45E-04	7.83E-04
pm	0.00E+00	2.04E-06	5.39E-06	1.45E-05	3.89E-05	6.79E-05	6.90E-05	8.41E-05	1.02E-04	1.06E-04
sm	0.00E+00	1.22E-06	5.24E-06	2.20E-05	5.60E-05	8.75E-05	8.94E-05	9.41E-05	9.57E-05	9.80E-05
eu	0.00E+00	1.19E-07	5.54E-07	2.42E-06	6.16E-06	9.54E-06	9.76E-06	1.01E-05	9.98E-06	9.89E-06
gd	0.00E+00	1.19E-08	4.81E-08	1.89E-07	5.22E-07	8.80E-07	9.06E-07	1.06E-06	1.24E-06	1.34E-06
u	2.09E+01	2.09E+01	2.09E+01	2.09E+01	2.09E+01	2.09E+01	2.09E+01	2.09E+01	2.09E+01	2.09E+01
np	0.00E+00	1.41E-06	3.34E-06	5.57E-06	6.84E-06	7.83E-06	6.51E-06	3.11E-06	3.12E-06	3.16E-06
pu	0.00E+00	2.17E-07	1.66E-06	9.70E-06	2.76E-05	4.43E-05	4.57E-05	4.96E-05	4.99E-05	4.99E-05

CFD Simulation with Pure Argon Gas in Gas Gap Region

Heater Only	Heater + Fission Heat (251W)



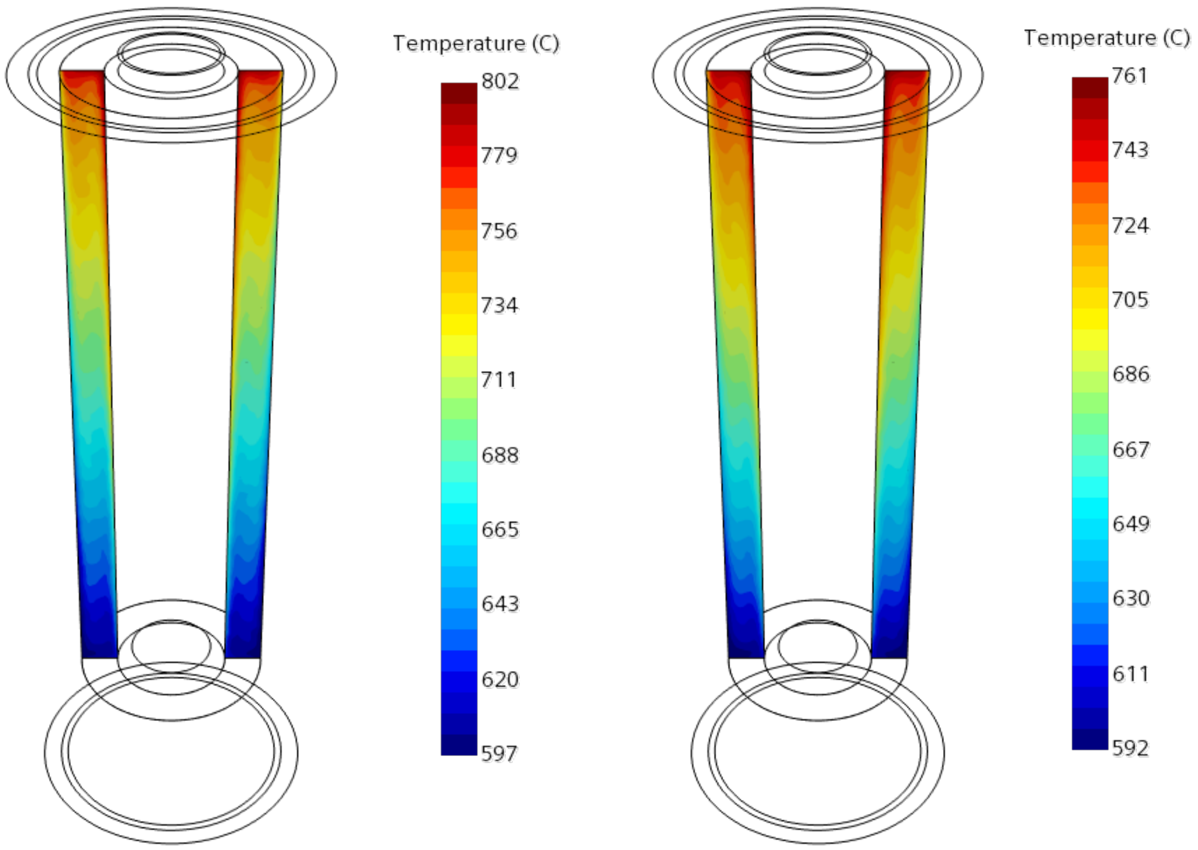
Main Outcomes:

- Overall temperatures were higher than those of the model with Argon-Helium gas mixture due to the lower thermal conductivity of pure argon gas.

CFD Salt Property Sensitivity Analysis (Preliminary Design)

Thermal Conductivity

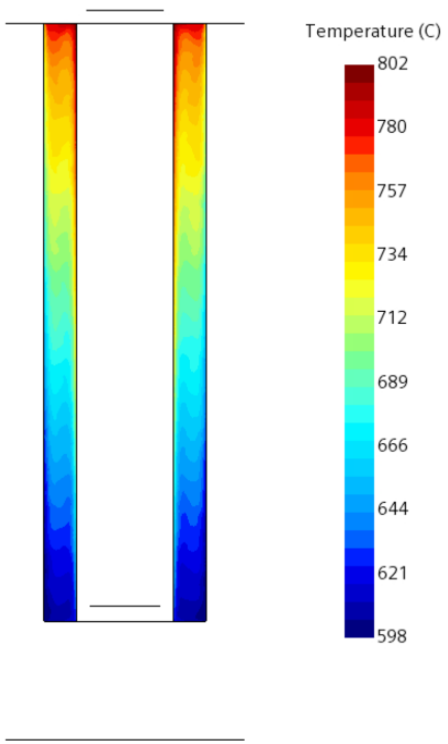
- Uncertainty in thermal conductivity of molten salt:
  - Range: 0.2 ~ 0.5W/m-K.
- Peak Temperature of molten salt:
  - k=0.2 W/m-K: 802°C
  - k=0.5 W/m-K: 761°C



k = 0.2 W/m-K

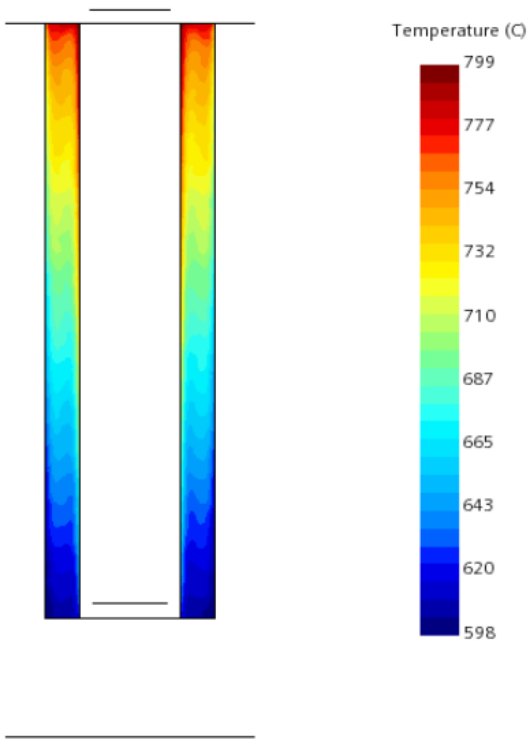
k = 0.5 W/m-K

Impact of Turbulence and Mesh Size (Preliminary Design)



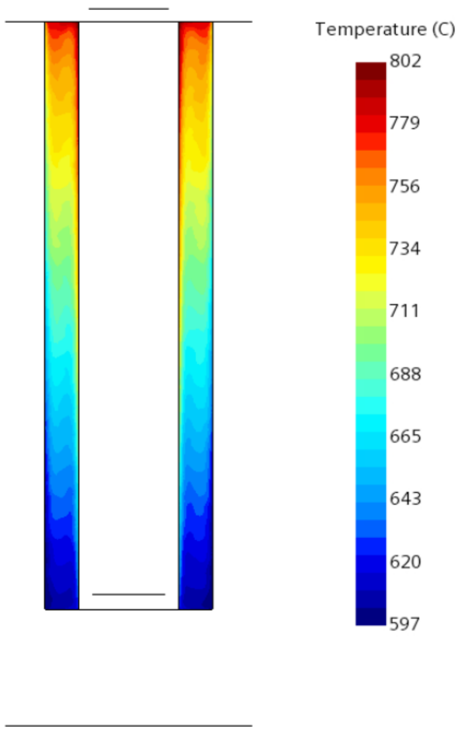
Laminar

T_{max} = 802ºC



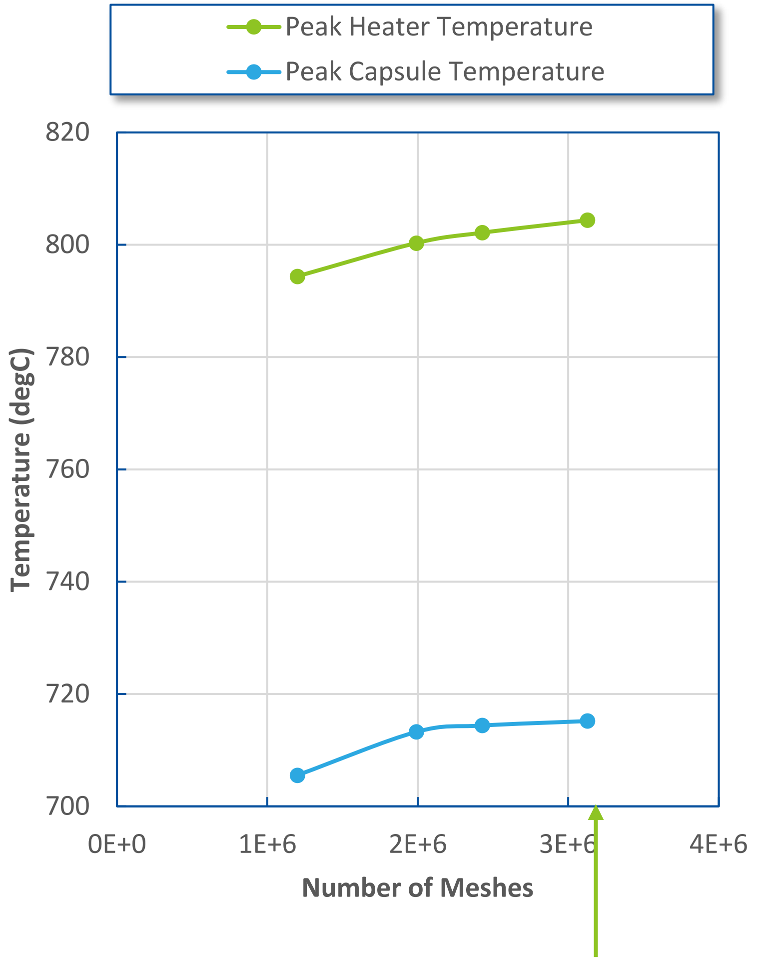
Realizable k-ε two-layer

T_{max} = 799ºC



SST k-ω

T_{max} = 802ºC



Chosen mesh size