



# First-of-a-Kind Fuel-bearing Molten Chloride Irradiation Experiment

December 2023

*Changing the World's Energy Future*

Calvin Myer Downey, Abdalla Abou Jaoude, William C Phillips, Chuting Tan Tsai, SuJong Yoon, Gregory M Core, Stacey M Wilson, Kim B Davies



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**December 2023**

**Idaho National Laboratory  
Idaho Falls, Idaho 83415**

**<http://www.inl.gov>**

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# First-of-a-Kind Fuel-bearing Molten Chloride Irradiation Experiment

DEVICE-MTR Meeting

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

## Mission Statement

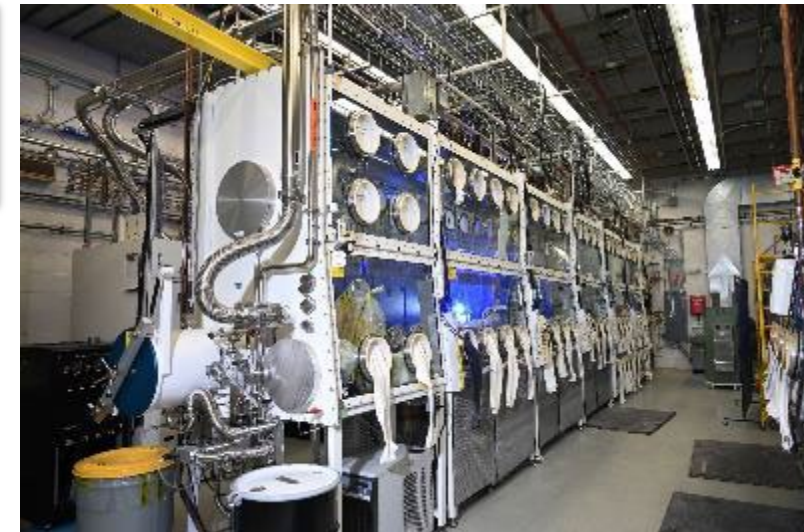
Establishment of a domestic neutron irradiation capability for fissile material-bearing salts at INL for Molten Salt Reactor (MSR) R&D.



### Research in Three Primary Areas

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

- Molten salt (UCl<sub>3</sub>-NaCl)
- Eutectic @523°C
- 93% U235 Enriched
- 20cc volume



# MRTI Design Requirement

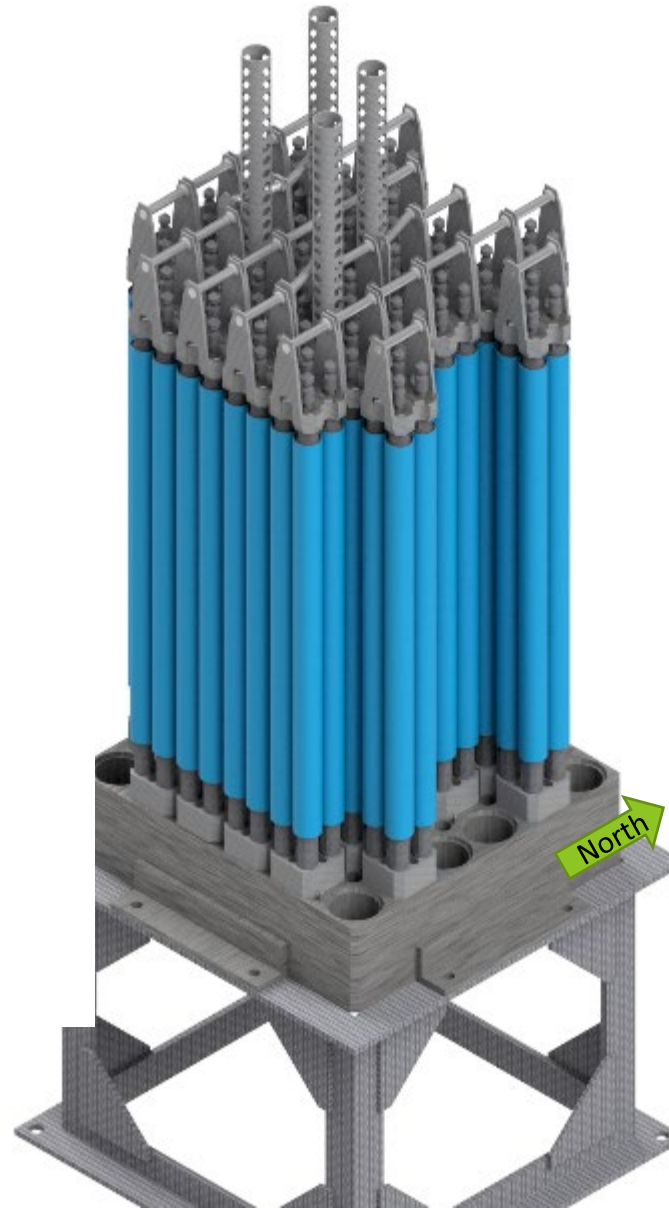
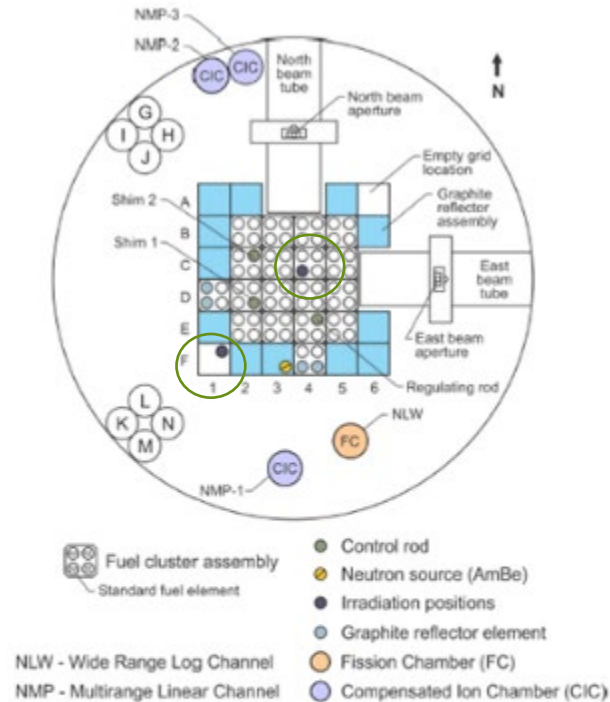
## Functional Requirements

- Integrate with current reactor geometries and cask requirements
- Retain fission gas/off-gas pressure during irradiation
- In-situ adjustment of salt temperature
- Maximize flux/power/burnup in salt: Target of  $> 20 \text{ W/cc}$  ( $\sim 60 \text{ W/cm}$ )
- Interface with Post-irradiation Examination (PIE) equipment
- Capsule material must retain strength at temperature

## Operational Requirements

- Reactivity worth of experiments must be  $< \pm 40$  cents (45 cent limit with 5 cents for conservatism)
- Salt Temperature  $\sim 600^\circ\text{C}$ 
  - Can be met with a combination of fission heating and heater input
- Salt Temperature  $> 523^\circ\text{C}$ 
  - Can be met with a combination of fission heating and heater input
- Radial and Axial Salt Temperature Gradients = Minimized
- Maximum feed  $^{235}\text{U}$  enrichment = 93 wt%

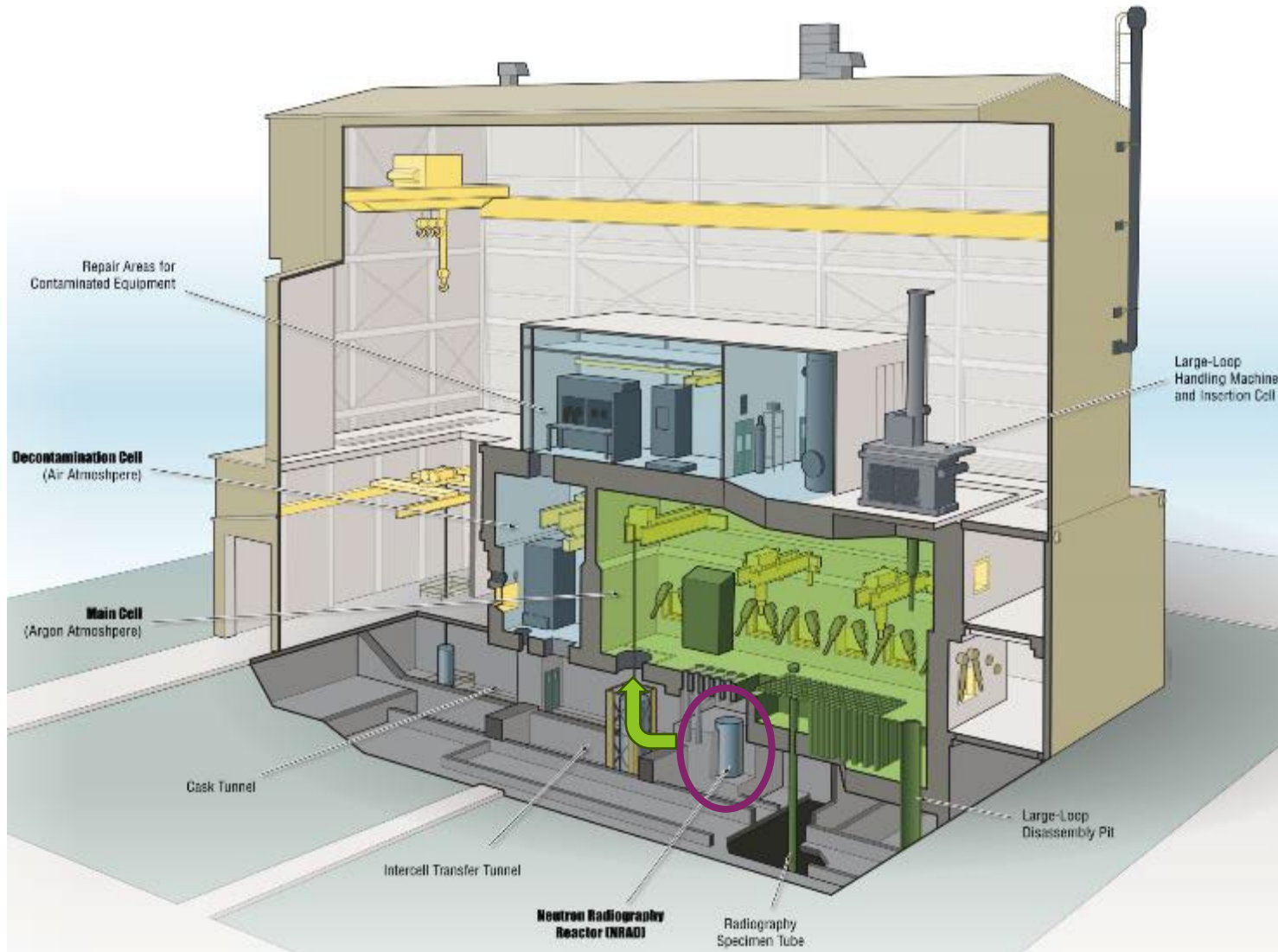
# Neutron Radiography (NRAD) Reactor



- TRIGA-fuel MTR-grid pool reactor for neutron radiography PIE
- NRAD 4-pin fuel cluster design with various top bail configurations
- F1 and C4 position available for experiments
- $2.1\text{E}+12 \frac{n}{\text{cm}^2\text{-s}}$  in F1 Position &  $5.2\text{E}+12 \frac{n}{\text{cm}^2\text{-s}}$  in C4 Position
  - C4 comes with the downside of more reactivity effects on core

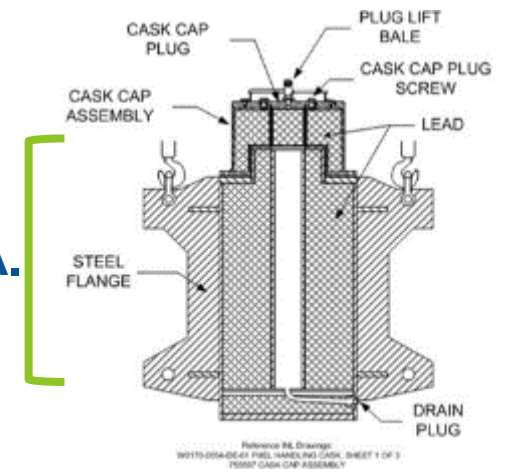


# Why NRAD?



- 250kW power, adjustable
- Pool reactor (no pressure)
- Only TRIGA that handles HEU
- No experiment traffic/schedule, irradiate by request
- Immediate access to HFEF for quick turnaround PIE

39"H X 4" DIA.





# Salt Retaining Capsule Material

- Stainless Steel 316/316L
  - Strength drastically affected around 650°C
  - Highly corroded in high temperature salts
- Inconel 617
  - Supply chain limited
- Inconel 625
  - High strength at temperature
  - Lower corrosion
  - Lower affect on fission power

Minimize Tantalum in IN625

<b>Outer contain.</b>	SS-316	SS-316	SS-316	SS-316
<b>Inner capsule</b>	SS-316	IN-617	IN-625(Nb)	IN-625(Ta)
<b>NRAD Position</b>	F-1	F-1	F-1	F-1
<b>Salt thickness</b>	0.4 cm	0.4 cm	0.4 cm	0.4 cm
<b>Enrichment</b>	93.0%	93.0%	93.0%	93.0%
Salt volume (cc)	14.07	14.07	14.07	14.07
Flux (n/cm <sup>2</sup> -s)	3.68x10 <sup>12</sup>	3.32x10 <sup>12</sup>	3.58x10 <sup>12</sup>	3.51x10 <sup>12</sup>
Fission power (W/cc)	21.32	17.35	20.09	19.73
Reactivity (¢)	0.62	-1.62	0.62	-0.37

# MRTI Inner Capsule Design



3X Type-N TCs, IN625 sheath

Plenum, Top, Bottom

1X IN625 thermowell

1X Pressure sensor tube (planned)

BNi-5 sealed braze into capsule

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



800W immersion heater,  
heated in bottom 3" section  
only, 1X Type-K TC



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

Core midplane



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

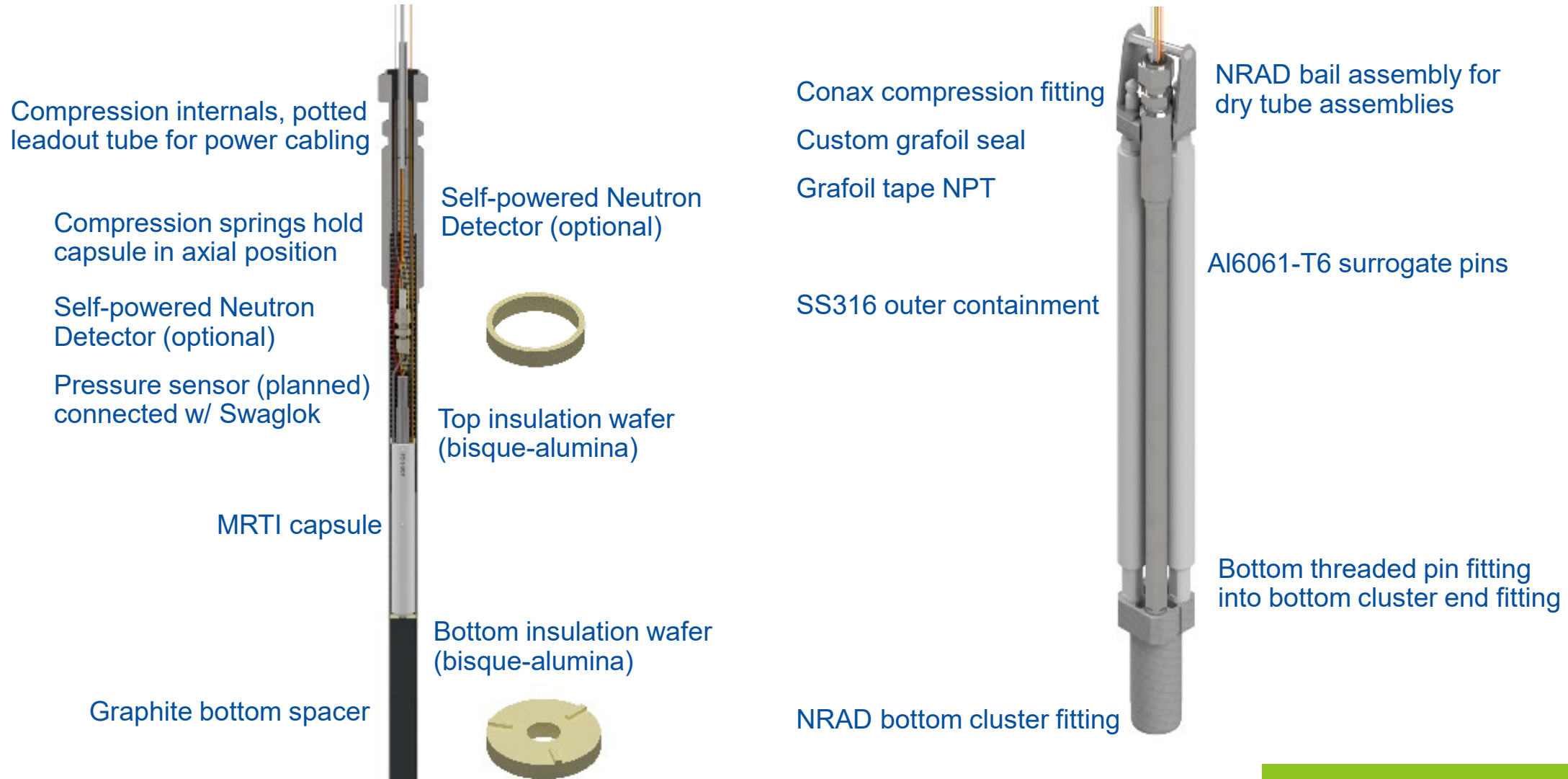
Molten salt ( $\text{UCl}_3\text{-NaCl}$ )

20cc

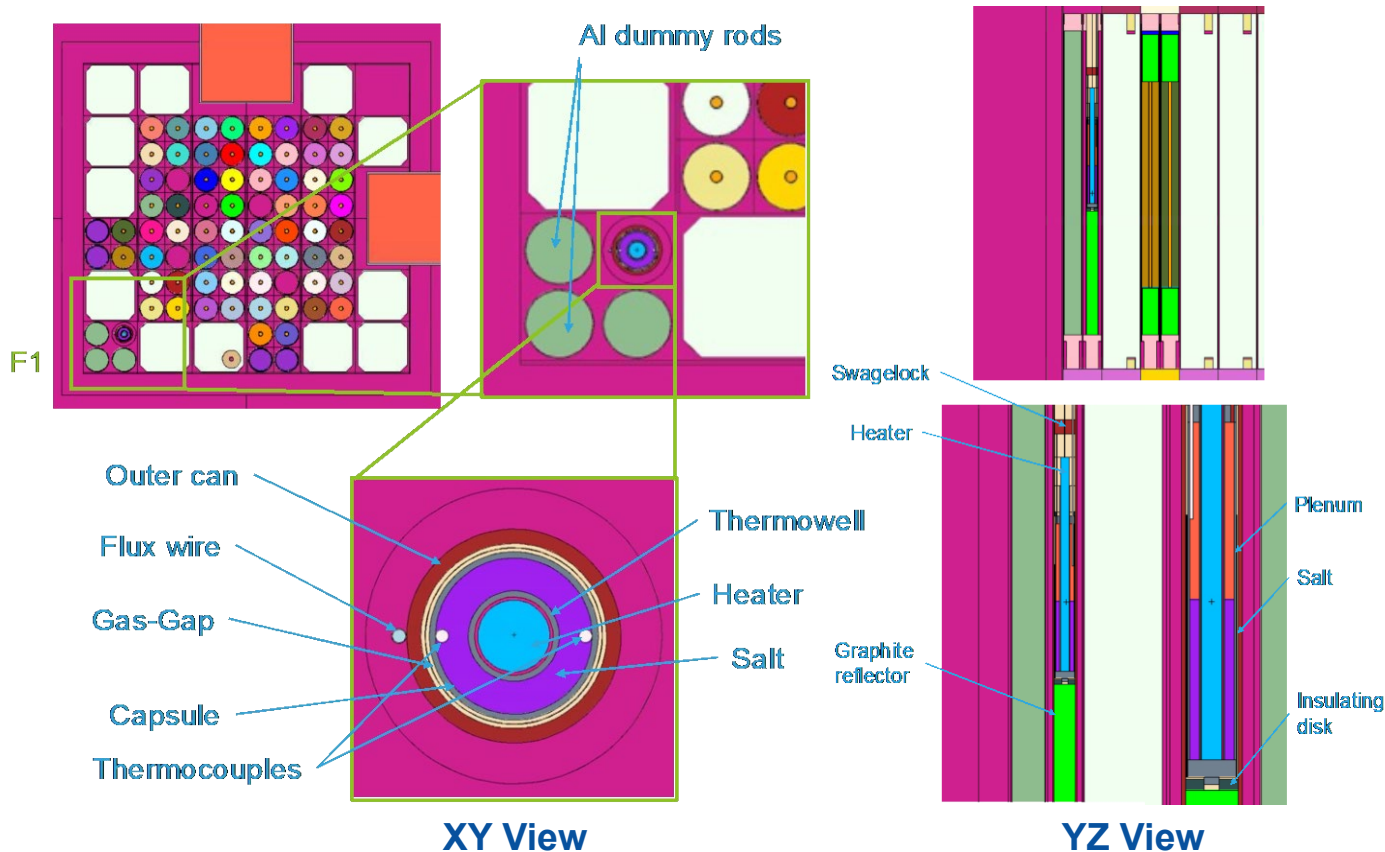
~3.0" height

Bottom centering feature

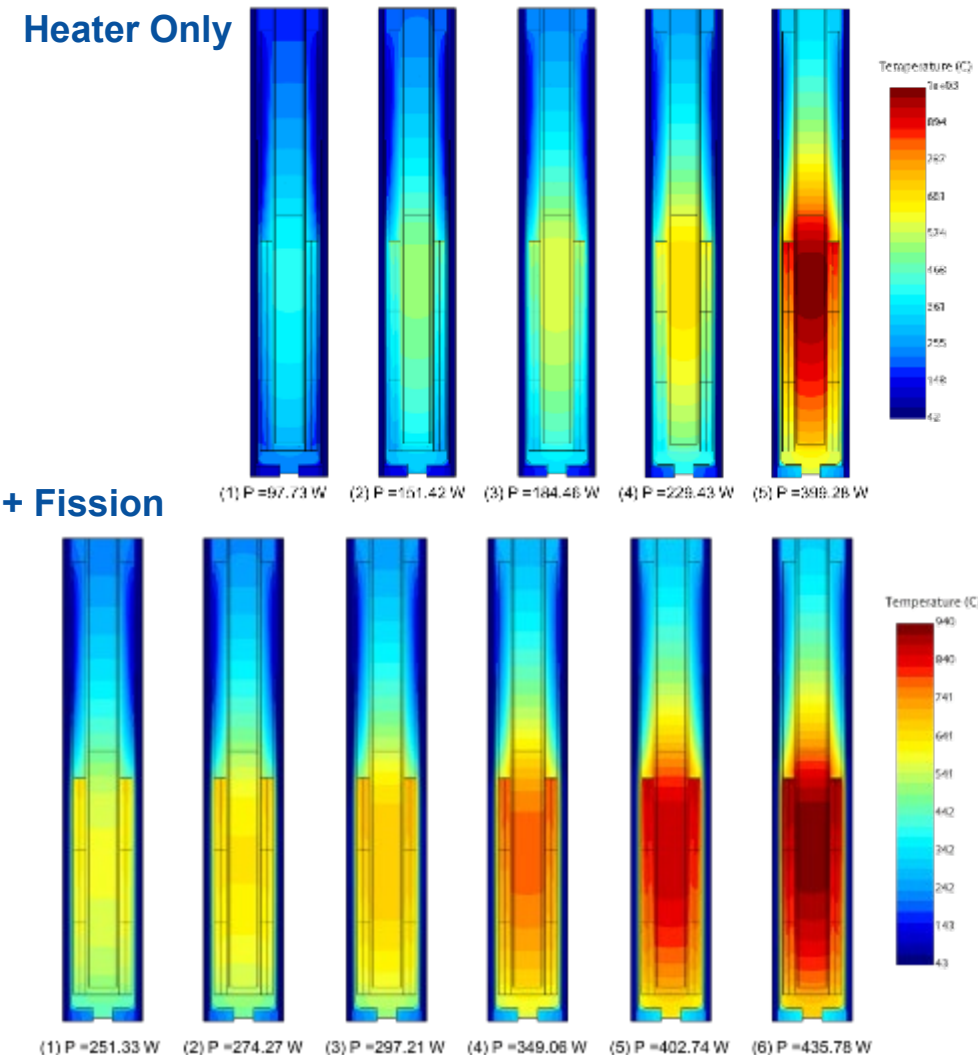
# MRTI Outer Containment and Cluster Design



# Neutronics, Thermal, and Structural Analysis



Final pressure based on 1.) change in temperature, 2.) change in free gas volume, and 3.) generation of fission gases results in 71.5 psi, and the total stored energy in the system is 6.1J  
Calculated hoop stress is 1.9ksi, safety factor of 7 in comparison to strength of IN625 @ 1000°C.



# Preliminary Mockup Testing

## Salt Removal Mockup

- LiCl-KCl 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

## Heater testing



Heater w/ T99 compound



Before test



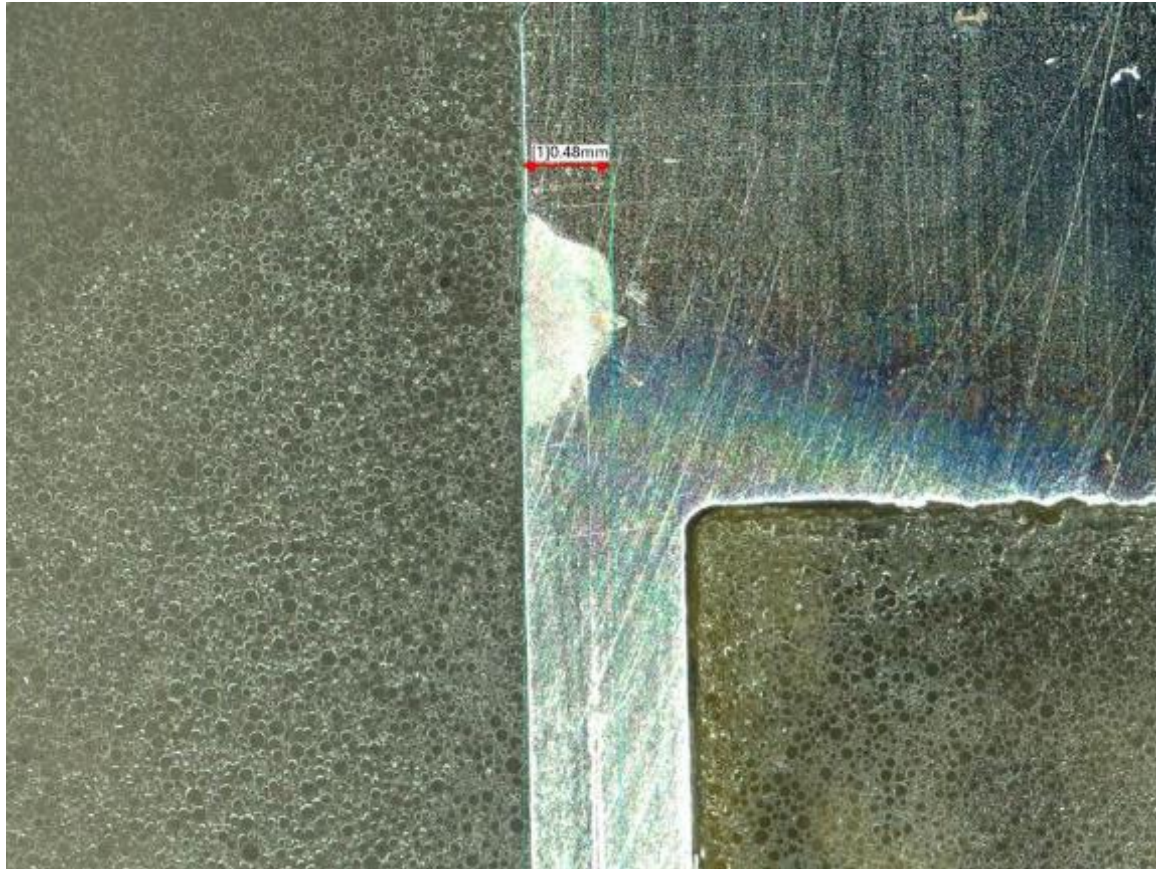
After test



Extracted salt



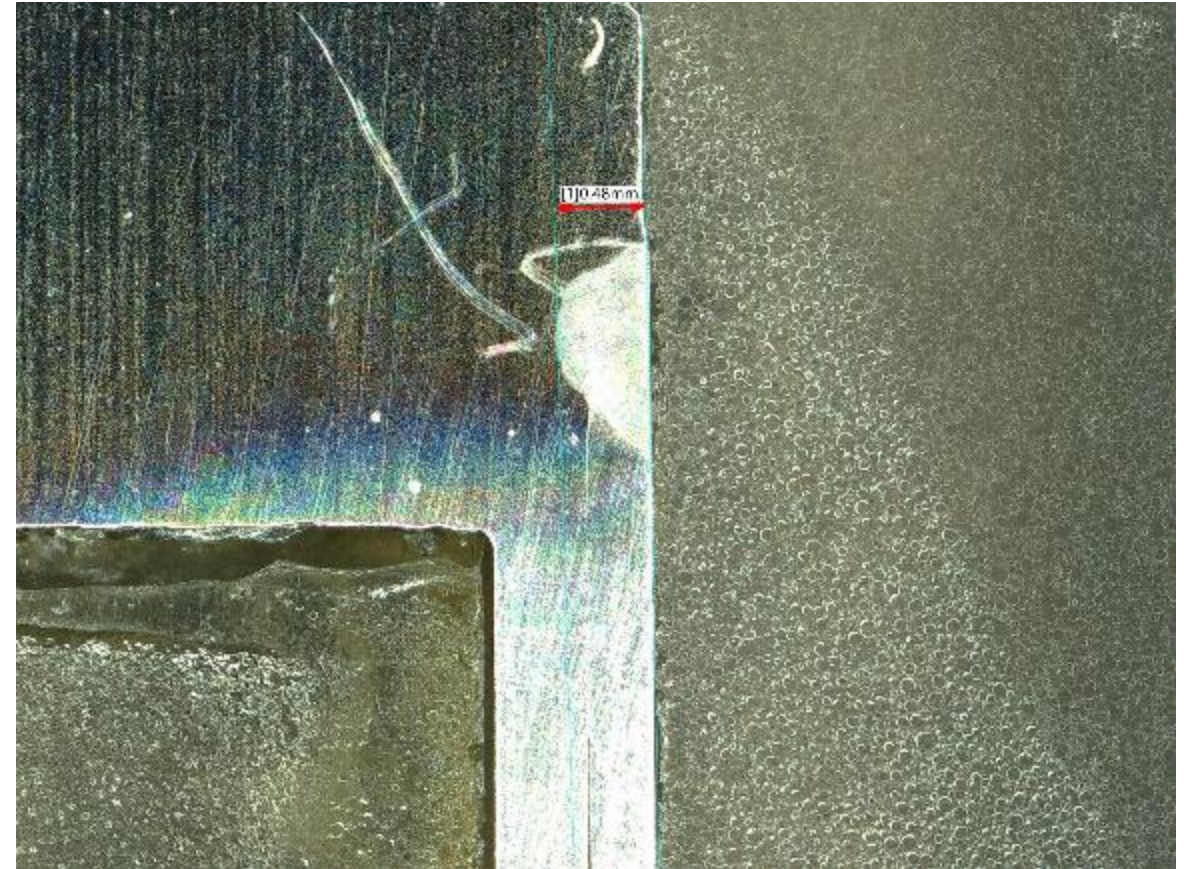
# Laser Weld Development



**Weld Coupon**

Laser weld in AFF glovebox  
under argon atmosphere

2 geometries, 2 materials



INL WPS I13.1 and S13.13



# Induction Braze Development



**Single TC Coupon**

BNi-5 braze,  $T_{\text{melt}} = 1080^{\circ}\text{C}$

3 geometries, 2 materials



**Braze mockup**

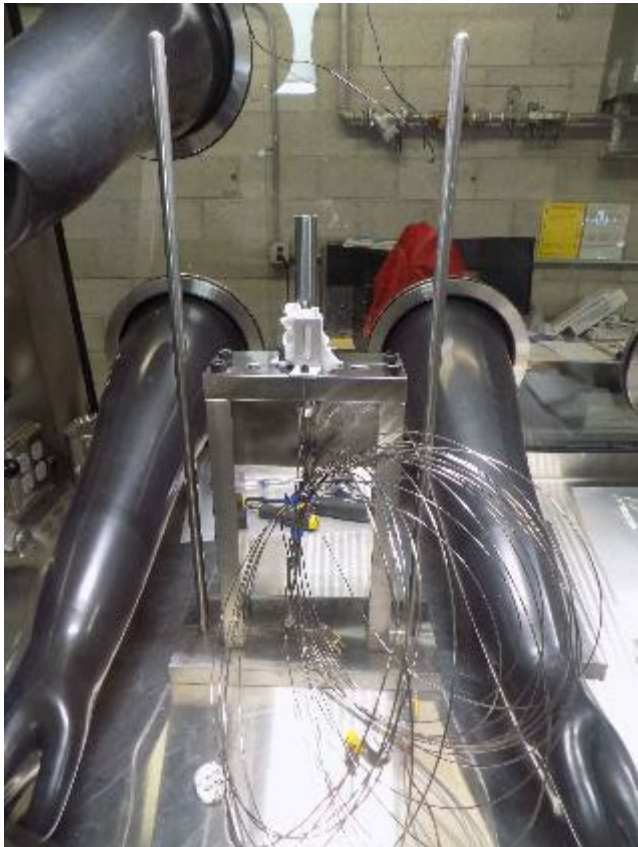
INL BPS IS12.4 and I12.0



**Capsule braze**

# Capsule Loading (Surrogate Commissioning Testing)

**Capsule Mount**



**Salt Fill w/ Funnel**

**Bottom Cap Press**







DSC\_0003.NEF

# MRTI Assembly (Surrogate Commissioning Testing)

**MRTI Inner Capsule**



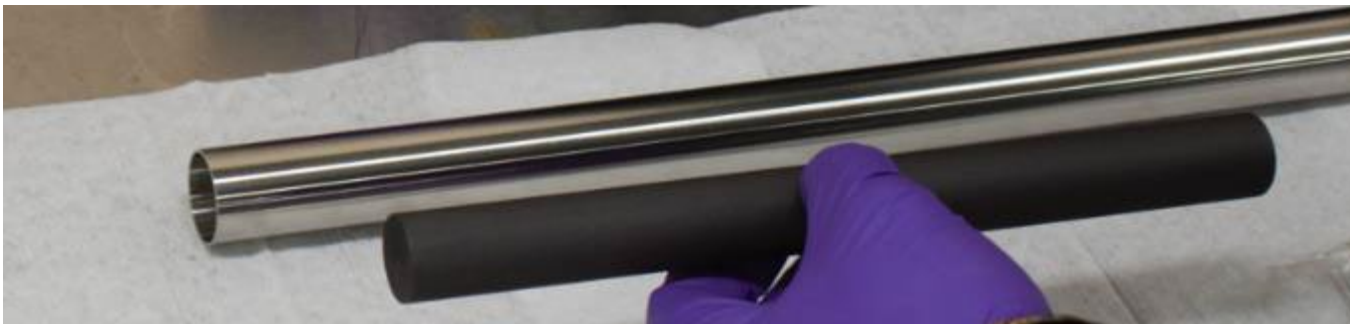
**MRTI Inner Capsule w/ Heat Shield and Insulation**



**MRTI Inner Capsule w/ Springs and Top Fitting**



**MRTI Outer Containment and Graphite Spacer**



# MRTI Surrogate Commissioning Testing Assembly



- LiCl-KCl surrogate salt
- 1:1 scale, Type-K TCs
- Axial Type-K TCs installed on outer containment at capsule
- Followed exact fabrication control plan (FCP) to fueled MRTI capsule
  - Lessons learned
  - Process improvement
- Used for control system qualification commissioning testing



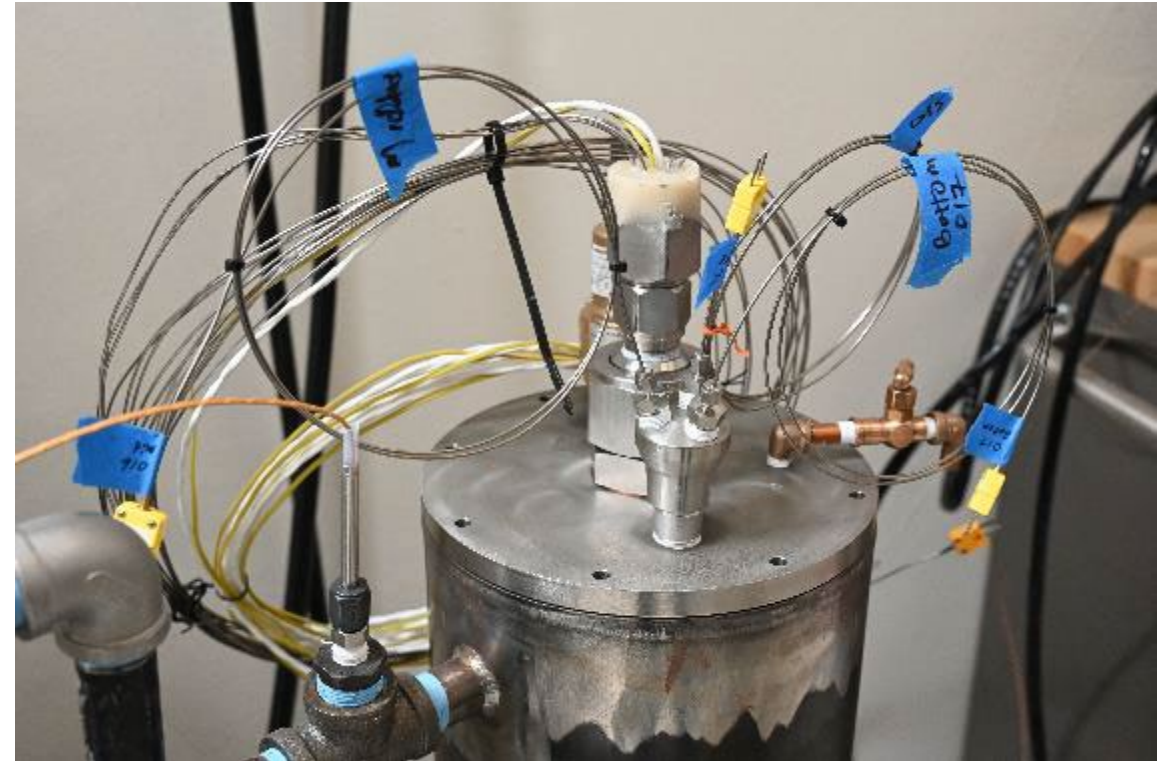
# MRTI Commissioning Test



**MRTI Flange Installation**

0.2-0.5 GPM water flow, outer containment Type-K thermocouples

Test salt temperature  $>700^{\circ}\text{C}$ , determine control scheme, heater performance



**MRTI Test Rig Installation**

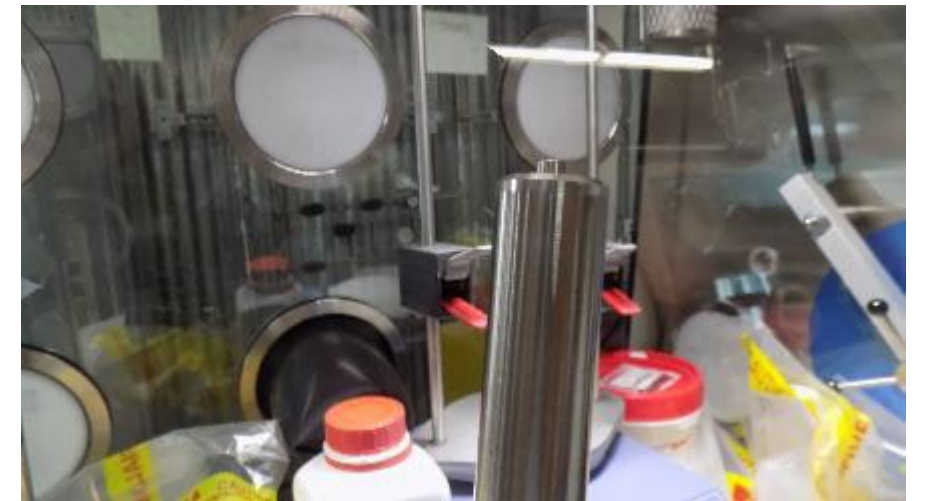
# Capsule Loading (Fueled Experiment)



**MRTI Salt Fill**



**MRTI End Cap Press**

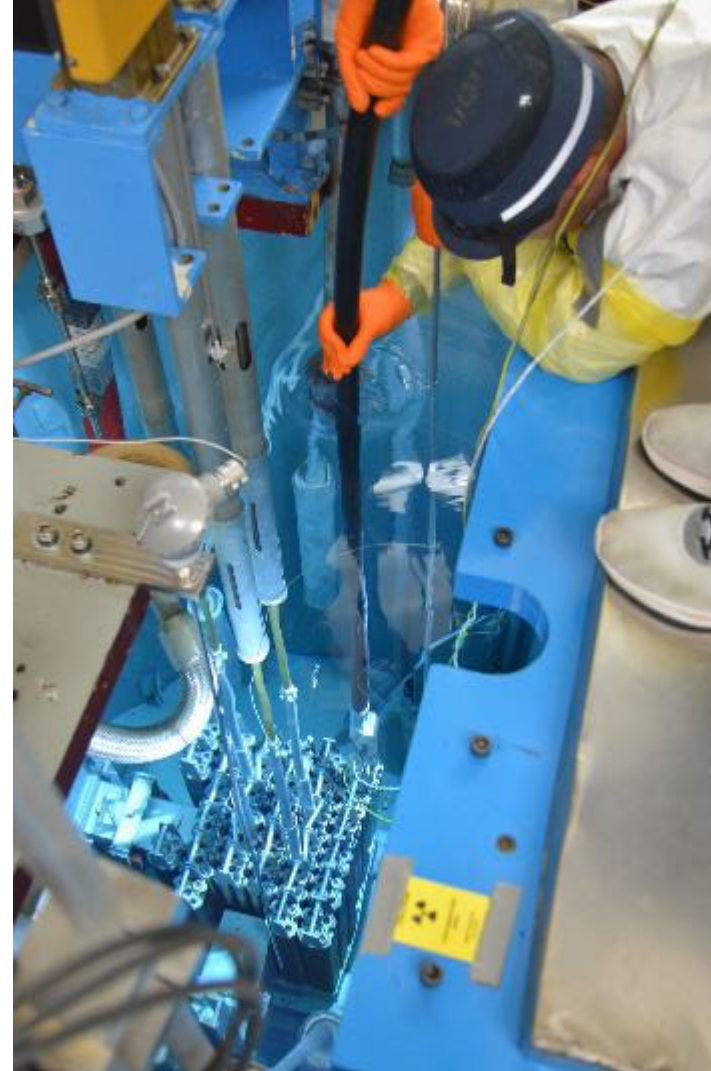




# MRTI NRAD Installation

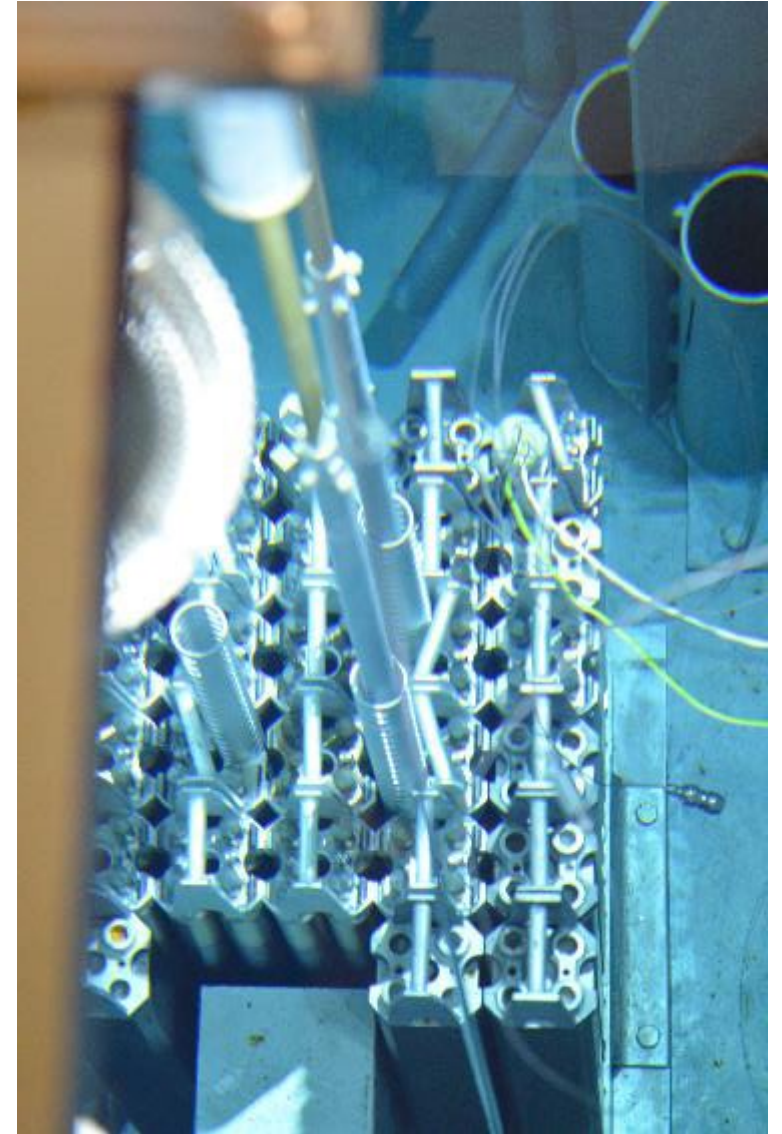


**MRTI Cluster**



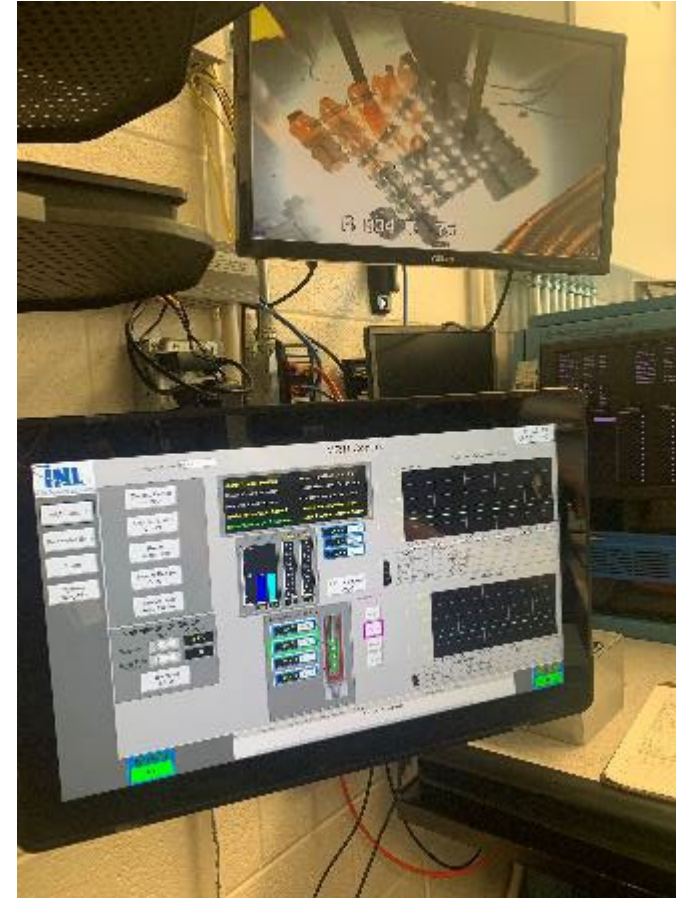
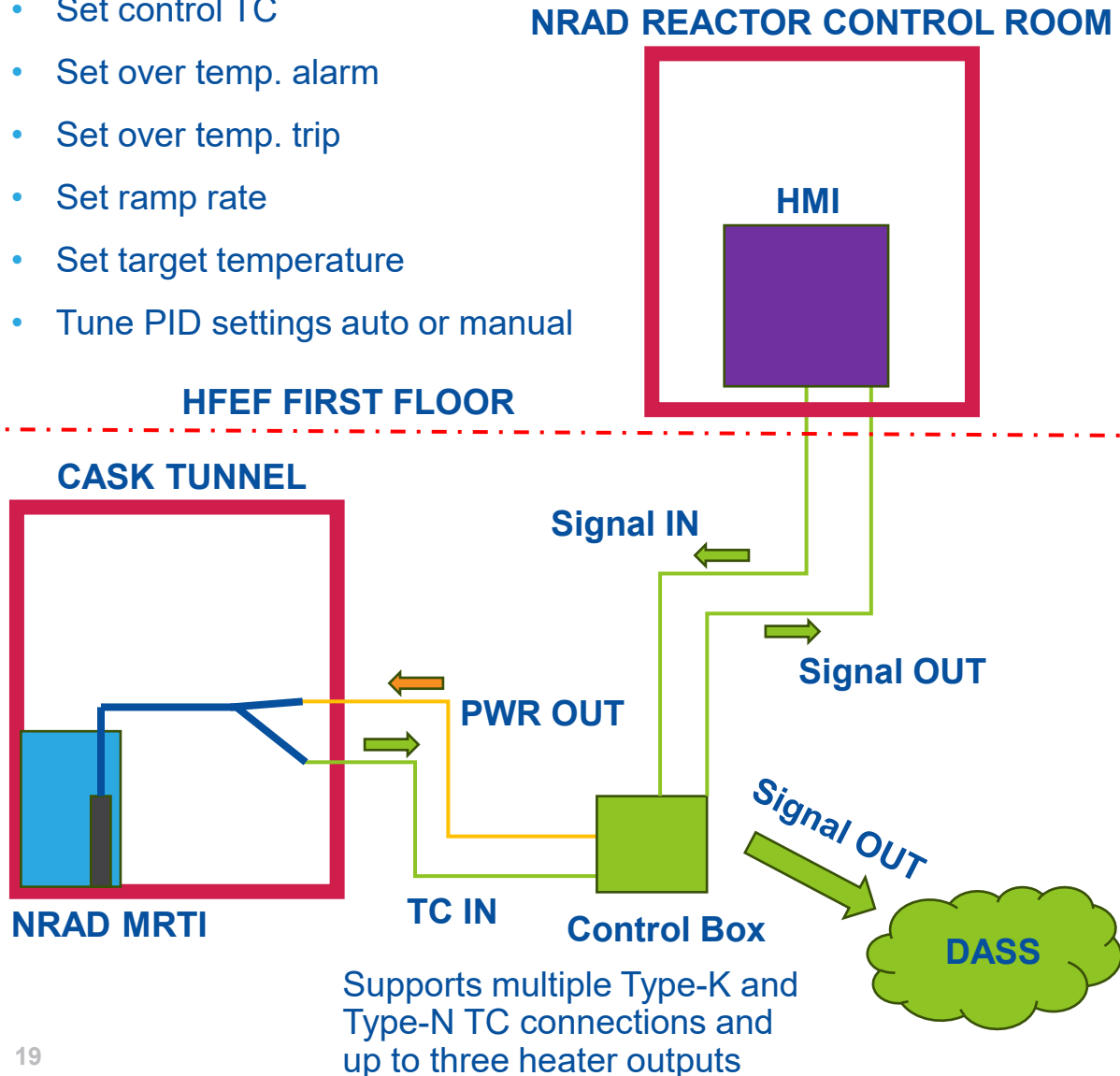
**MRTI Handling**

**MRTI Installed**



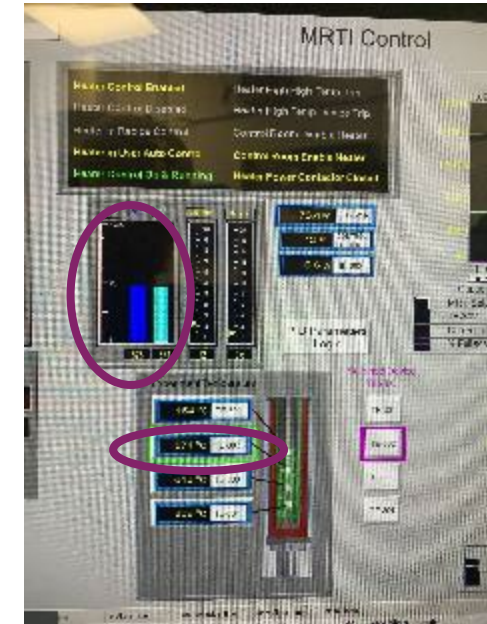
# MRTI Heater Control System and Data Acquisition

- Set control TC
- Set over temp. alarm
- Set over temp. trip
- Set ramp rate
- Set target temperature
- Tune PID settings auto or manual



**MRTI HMI**

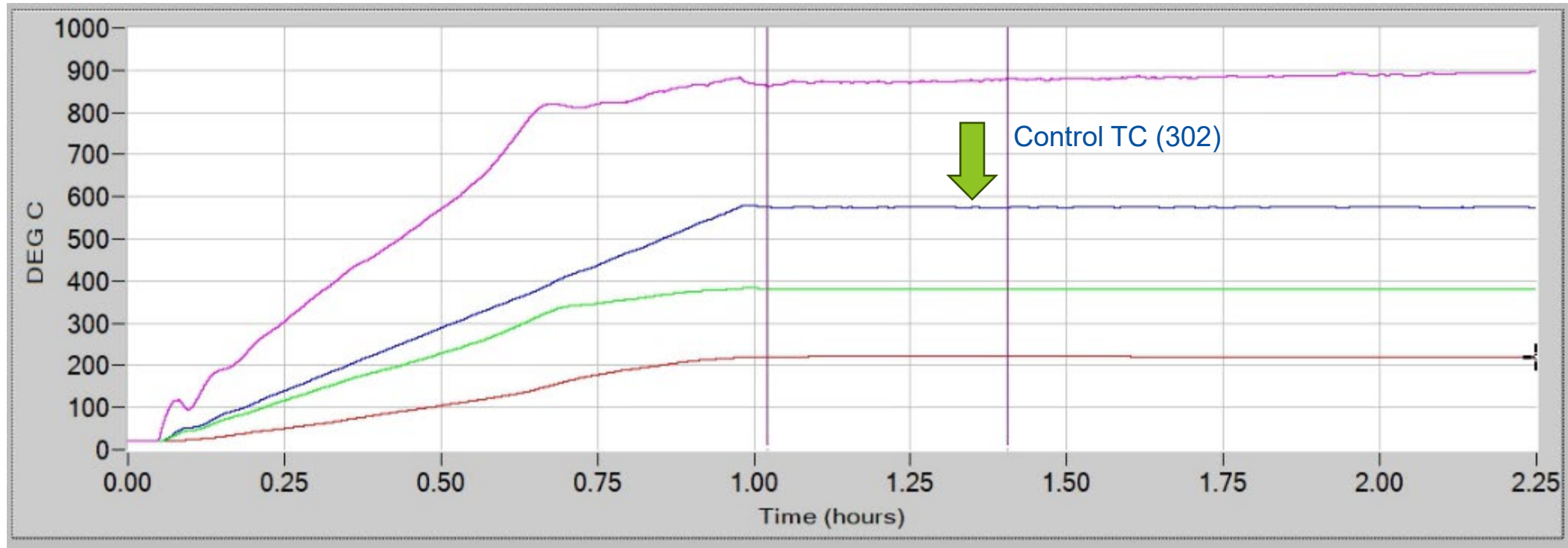
**REACTOR ON**





# MRTI Irradiation Heater Startup

DASS



10°C/min ramp, 575°C set temp, TC\_302 control

Hold temperature pre-irradiation

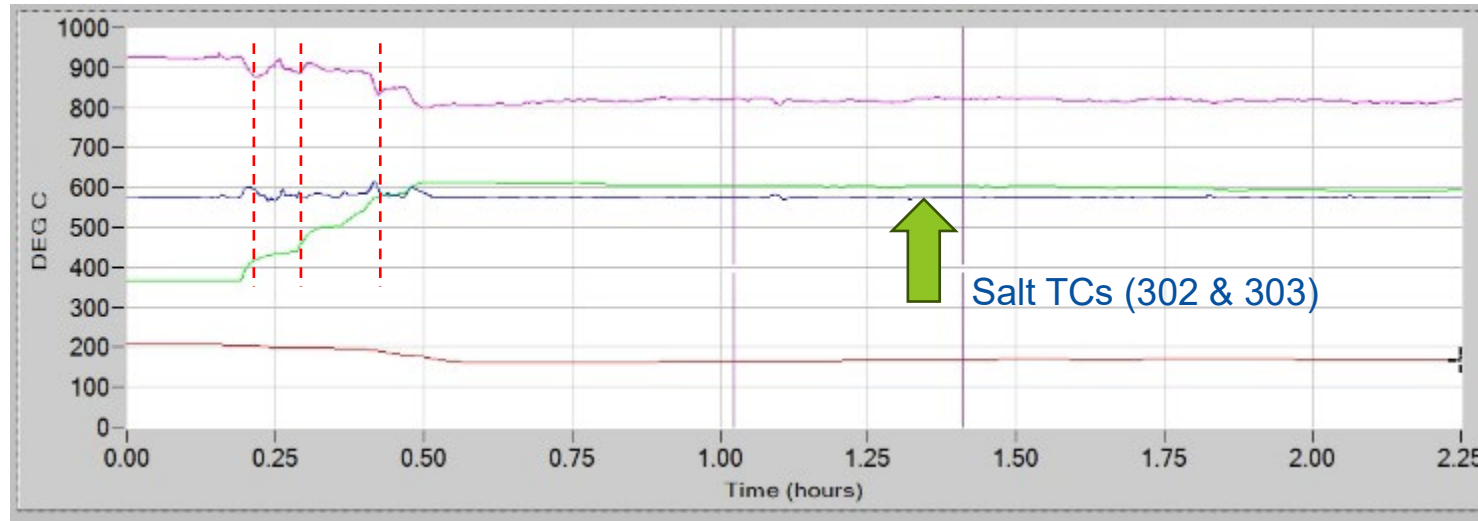
Bottom salt frozen (no radiolysis) due to set temp

TC_301	TC_302	TC_303	TC_304
Plenum	Top Salt	Bottom Salt	Heater
Type N	Type N	Type N	Type K

# MRTI Irradiation

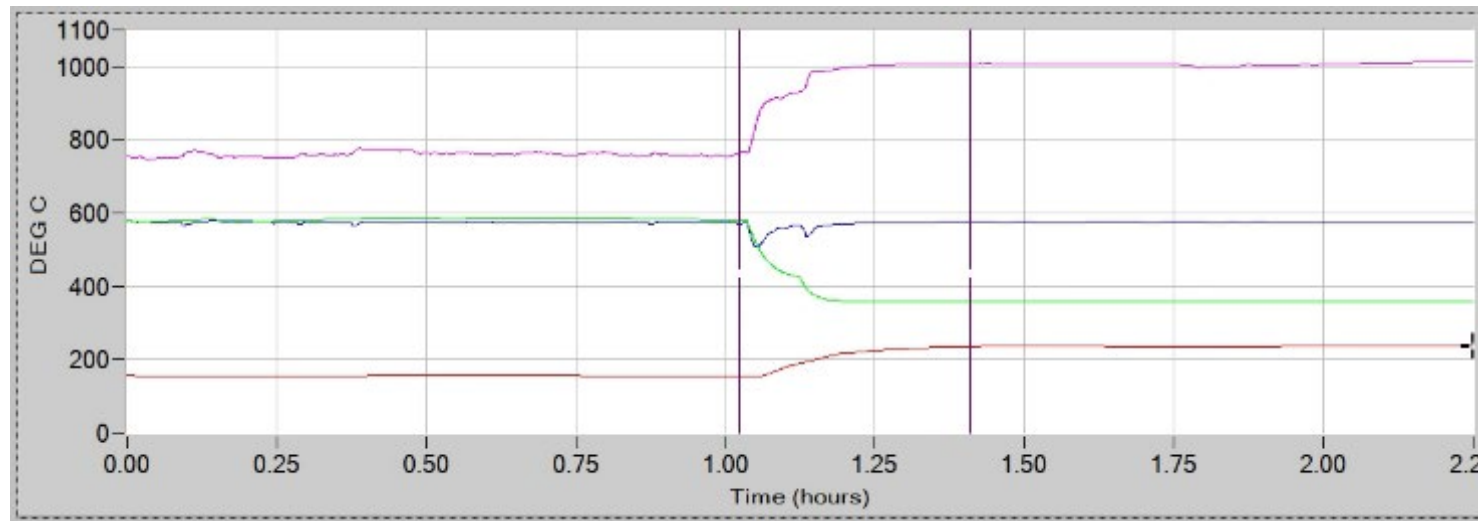
## Reactor Startup

50kW step-wise startup



- Heater response
- Steady-state operation
- 575-600°C temperature
- Low gradient

## Reactor Shutdown



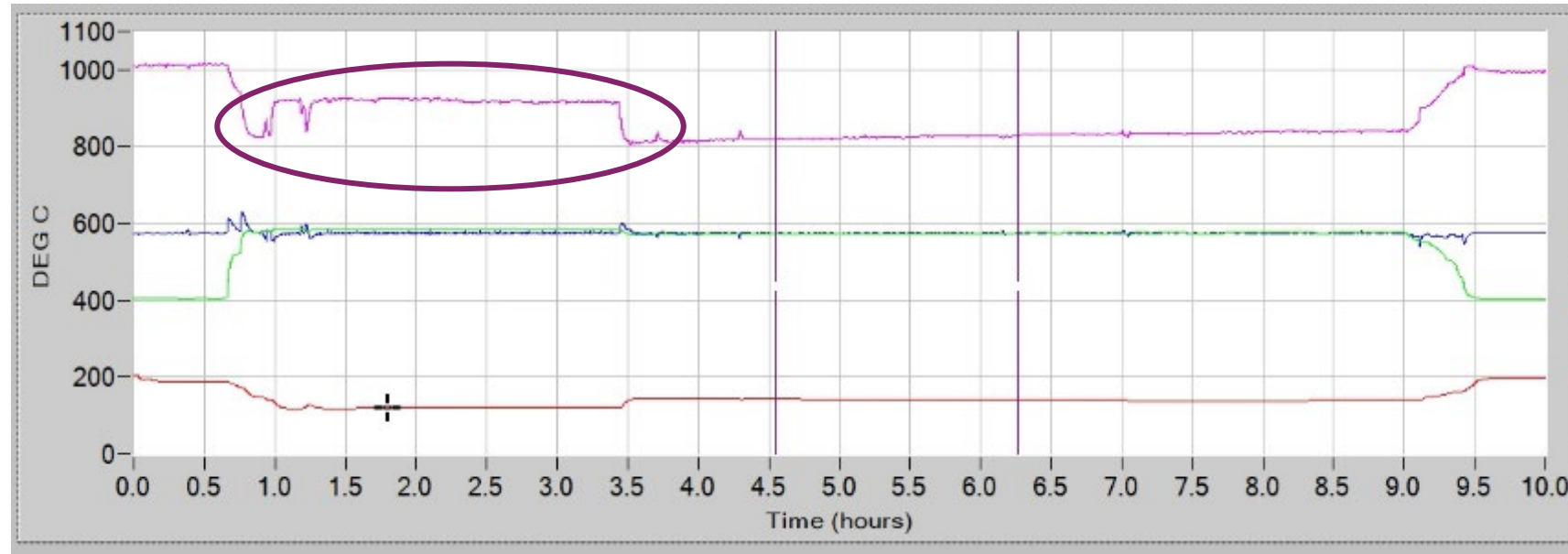
- Heater response
- Cyclic irradiation
- Higher gradient

Day 1

TC_301	TC_302	TC_303	TC_304
Plenum	Top Salt	Bottom Salt	Heater

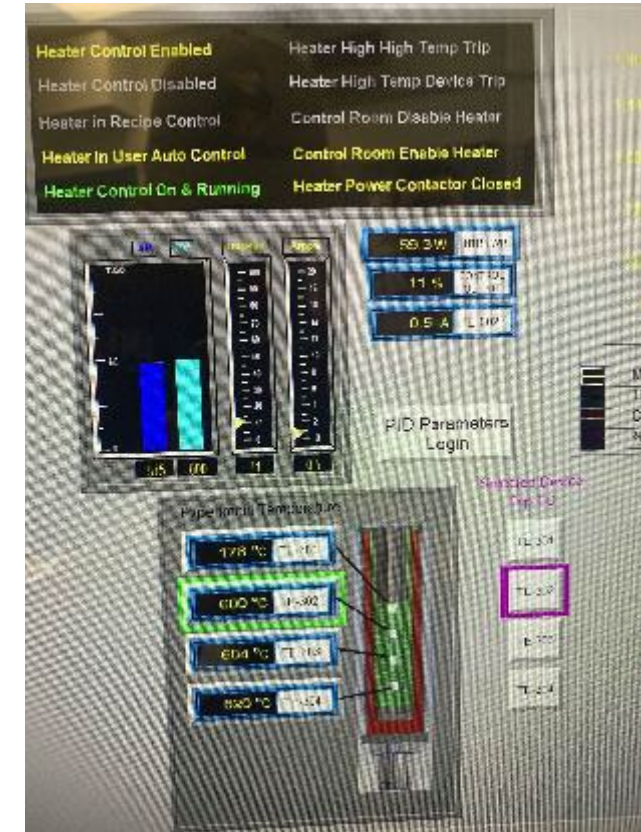
# MRTI Irradiation

## Reactor Startup



Day 20

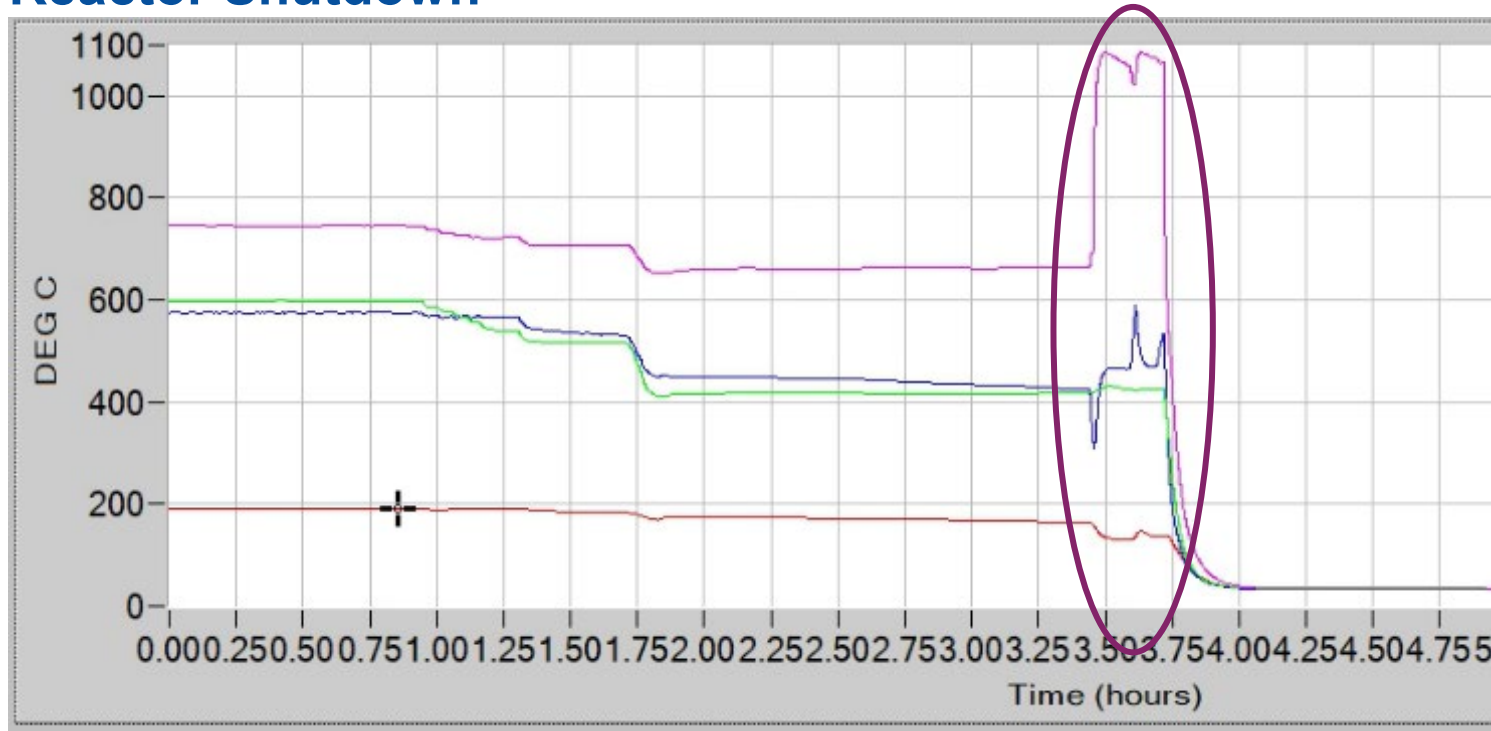
## Reactor Shutdown



MRTI HMI

# MRTI Irradiation

## Reactor Shutdown



- Heater failure
- Cabling degradation
- Salt at room temperature when reactor is off

Day 30 (Day 29 Midnight)



# MRTI Heater Failure (Lessons Learned)

## In-tank Video Camera



PTFE (Teflon) insulation, high temperature, water-proof, not irradiation tolerant

Plastic embrittlement & water flow erosion

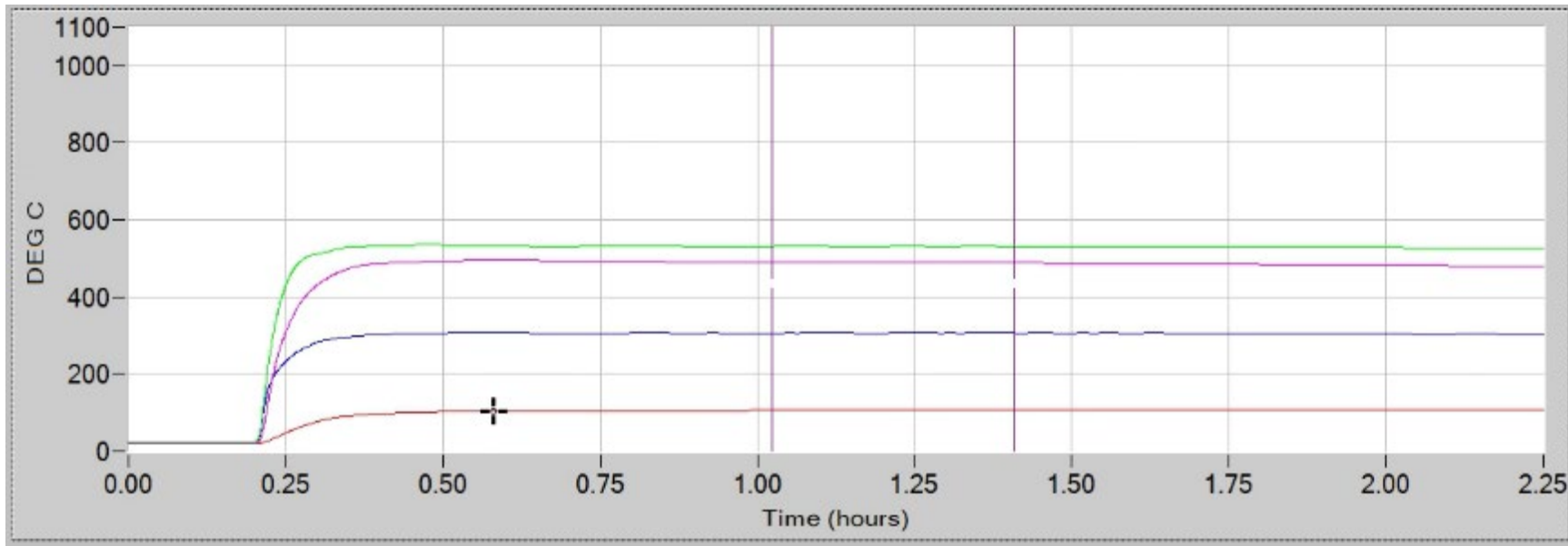


Gamma dose in core not well characterized, assumption: low power core outer position = low gamma dose, off-the shelf heater design (no MIC offered), potting into soft cabling instead of MIC. Suggested SST conduit to compile cabling and reduce some dose.

Need custom MIC heater solutions.

# MRTI Future Irradiation

## Reactor Startup



- No heater
- Achieved molten salt
- 480-530°C
- ATR gamma tube experiments show no concerns of radiolysis when shutdown
- Fission product accumulation

# Summary

- Demonstration of temperature controlled molten salt irradiation capabilities @INL
- MRTI fueled salt irradiation experiment for NRAD reactor @INL: first-of-a kind
- Immersion heater to control temperature before/during irradiation, lessons learned
- Salt sample:  $0.66\text{UCl}_4\text{-}0.33\text{NaCl}$  (93wt% U235), 40g,  $13\text{ cm}^3$  (molten)
- Power density of 20 W/cc reached (~400W)
- Continued irradiation efforts with MRTI capsule
  - KAERI and Seaborg molten salt irradiations planned using MRTI
- Patent of MRTI capsule design, INL Internal BA-1451 (pending)
- *Funding*: INL Laboratory Directed Research & Development (LDRD) Award



# Questions?

[Calvin.downey@inl.gov](mailto:Calvin.downey@inl.gov)