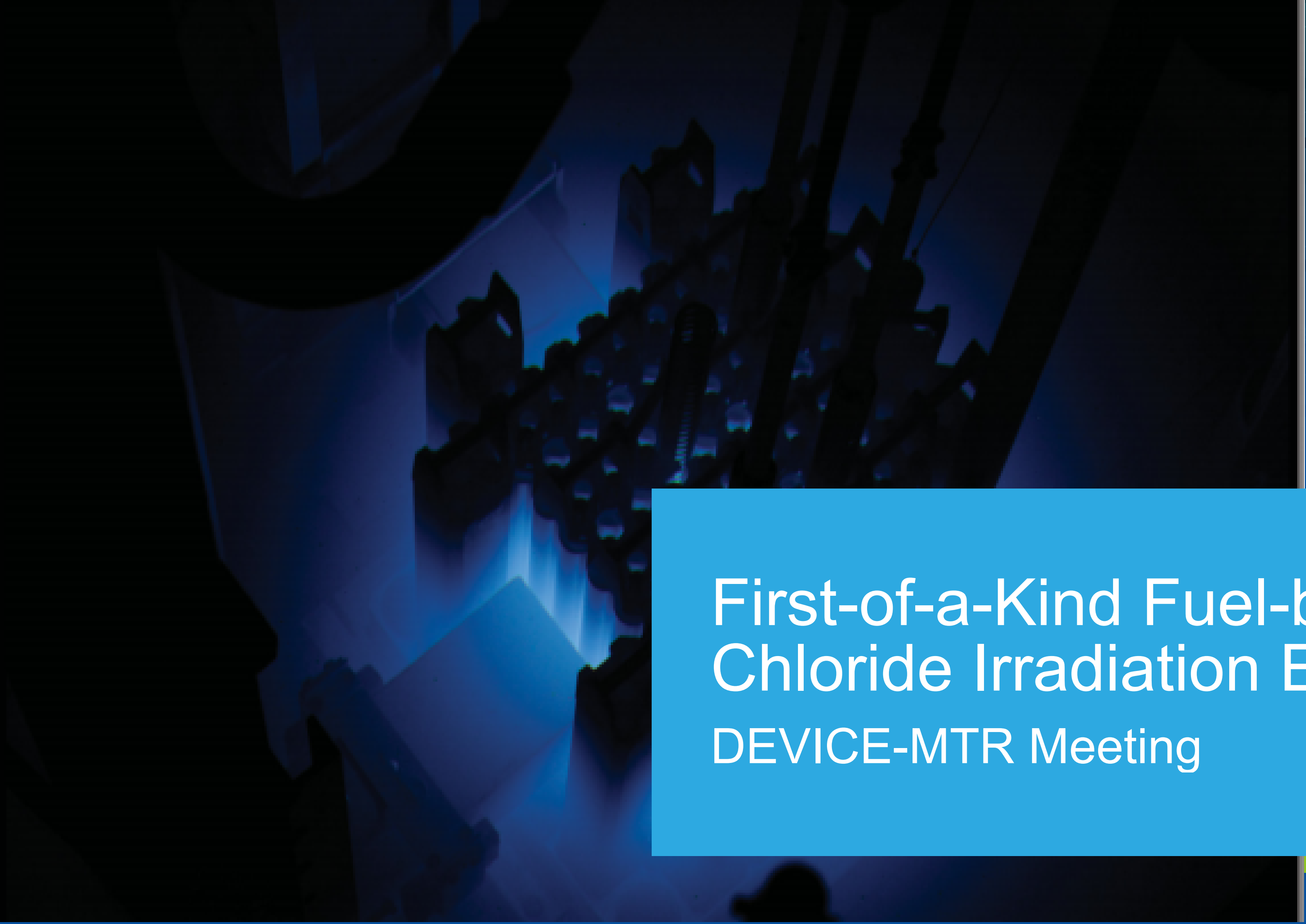


December 4-10, 2023

Calvin Downey, **Abdalla Abou-Jaoude**, Gregory Core, Kim Davies, Bill Phillips, Chuting Tan, SuJong Yoon, and Stacey Wilson

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

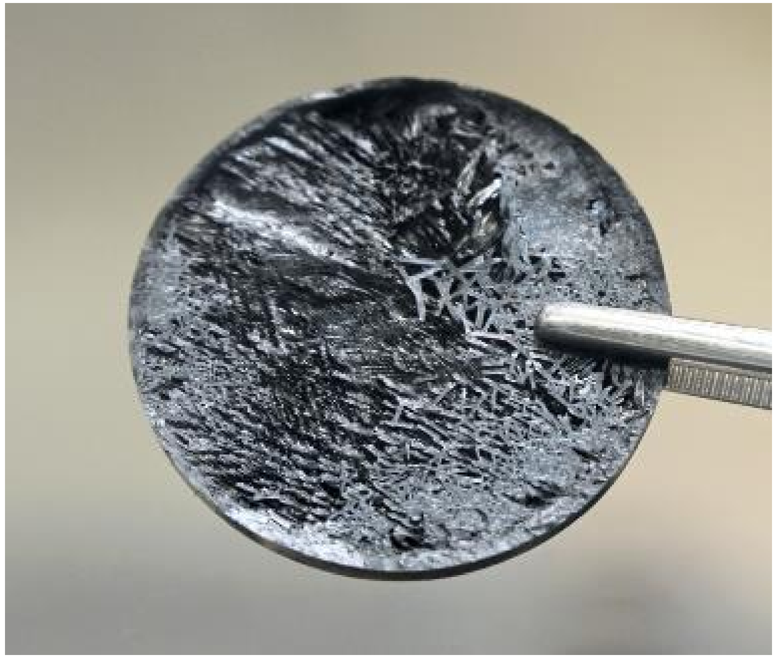
DEVICE-MTR Meeting

Idaho National Laboratory

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

Mission Statement

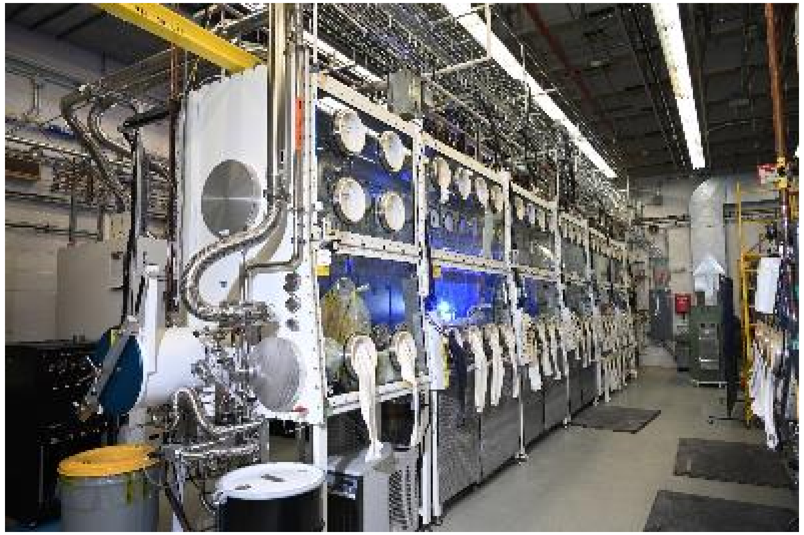
Establishment of a domestic neutron irradiation capability for fissile material-bearing salts at INL for Molten Salt Reactor (MSR) R&D.



Research in Three Primary Areas

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

- Molten salt (UCl_3-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 W/cc (~60W/cm)
- Interface with Post-irradiation Examination (PIE) equipment
- Capsule material must retain strength at temperature

Operational Requirements

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

Neutron Radiography (NRAD) Reactor

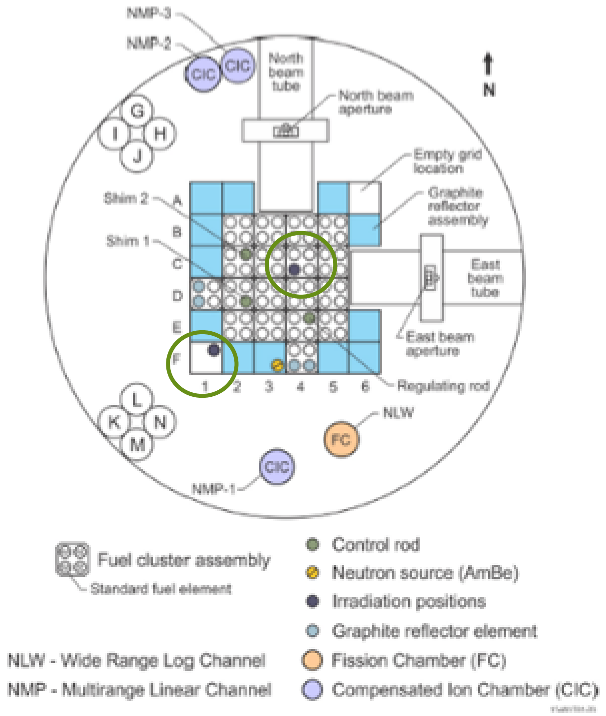
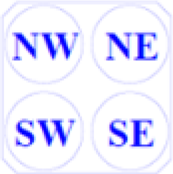
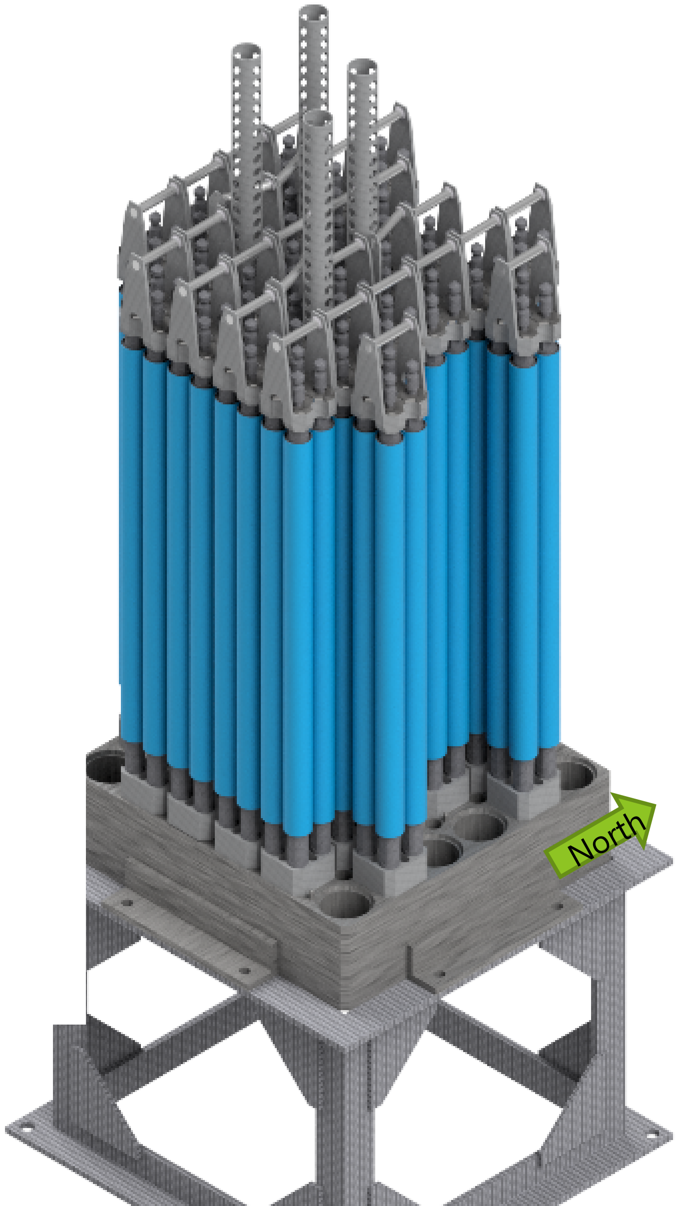


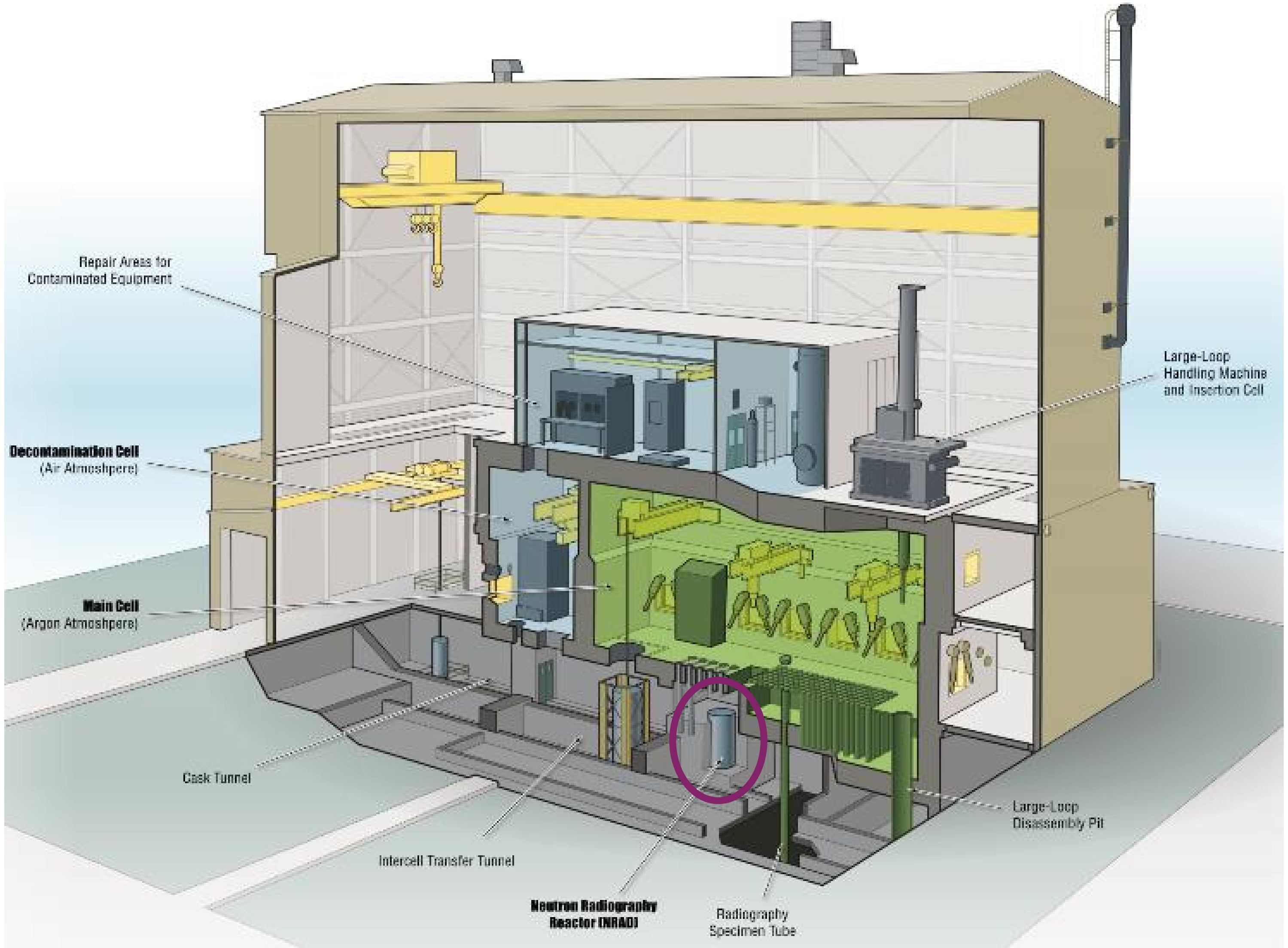
Figure 1. Sixty-four-element core and tank layout.





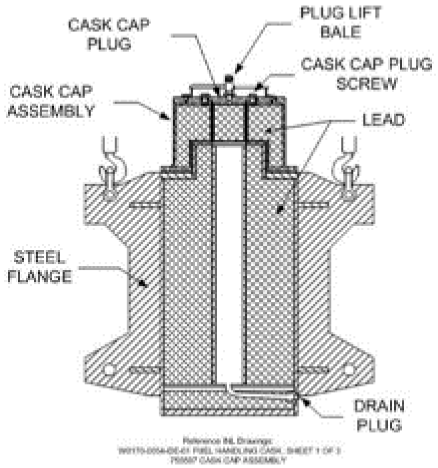
- TRIGA-fuel MTR-grid pool reactor for neutron radiography PIE
- NRAD 4-pin fuel cluster design with various top bail configurations
- F1 and C4 position available for experiments
- 2.1E+12 in F1 Position & 5.2E+12 in C4 Position
  - C4 comes with the downside of more reactivity effects on core

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

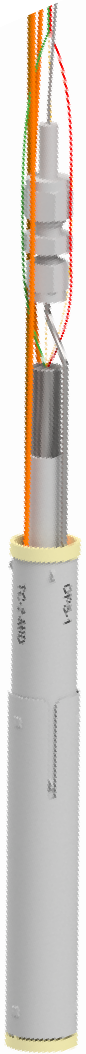
Outer contain.	SS-316	SS-316	SS-316	SS-316
Inner capsule	SS-316	IN-617	IN-625(Nb)	IN-625(Ta)
NRAD Position	F-1	F-1	F-1	F-1
Salt thickness	0.4 cm	0.4 cm	0.4 cm	0.4 cm
Enrichment	93.0%	93.0%	93.0%	93.0%
Salt volume (cc)	14.07	14.07	14.07	14.07
Flux (n/cm^2-s)	3.68×10^{12}	3.32×10^{12}	3.58×10^{12}	3.51×10^{12}
Fission power (W/cc)	21.32	17.35	20.09	19.73

Reactivity (¢)	0.62	-1.62	0.62	-0.37

- 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

MRTI Inner Capsule Design



3X Type-N TCs, IN625 sheath

Plenum, Top, Bottom

1X IN625 thermowell

1X Pressure sensor tube (planned)

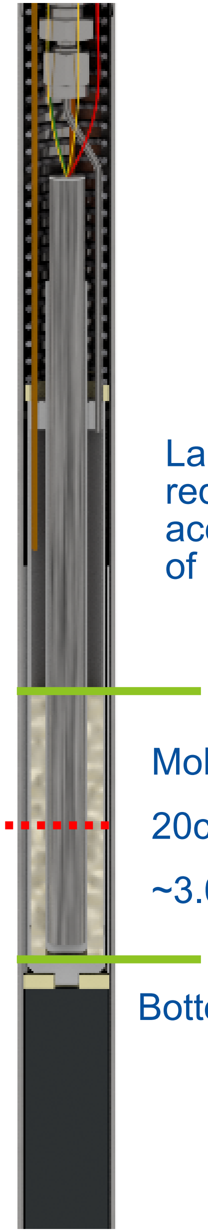
BNi-5 sealed braze into capsule

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

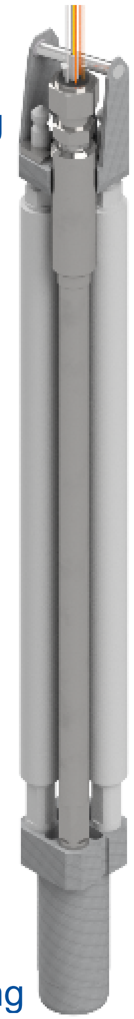
Molten salt (UCl_3-NaCl)

20cc

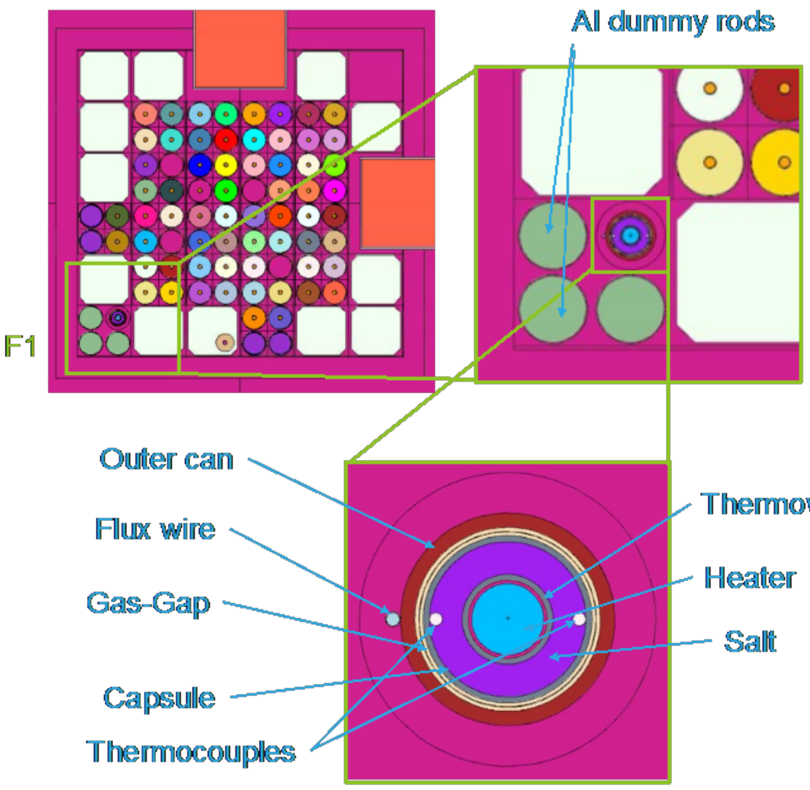
~3.0” height

Bottom centering feature

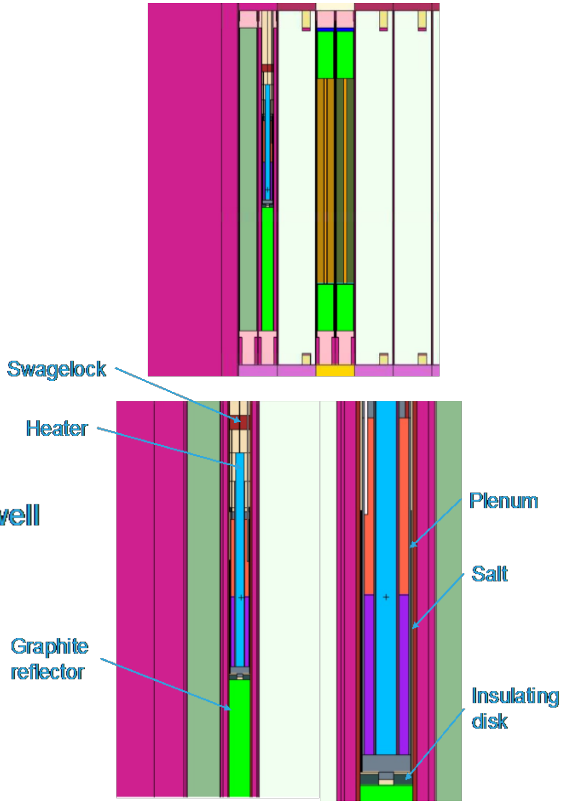
MRTI Outer Containment and Cluster Design



Neutronics, Thermal, and Structural Analysis

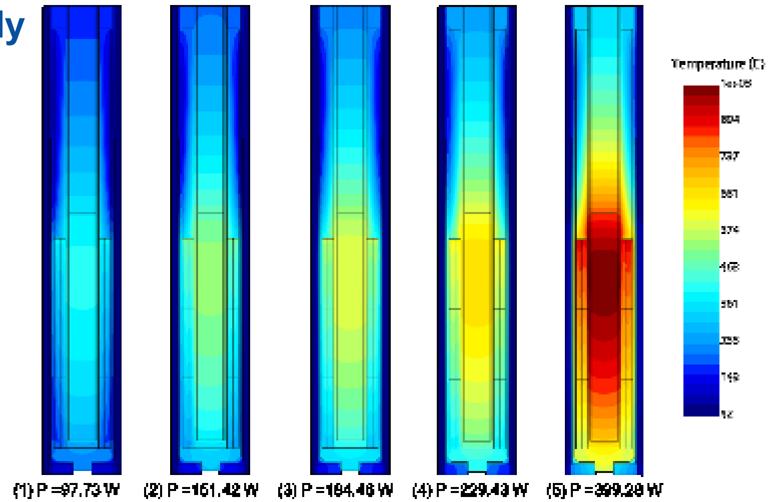


XY View

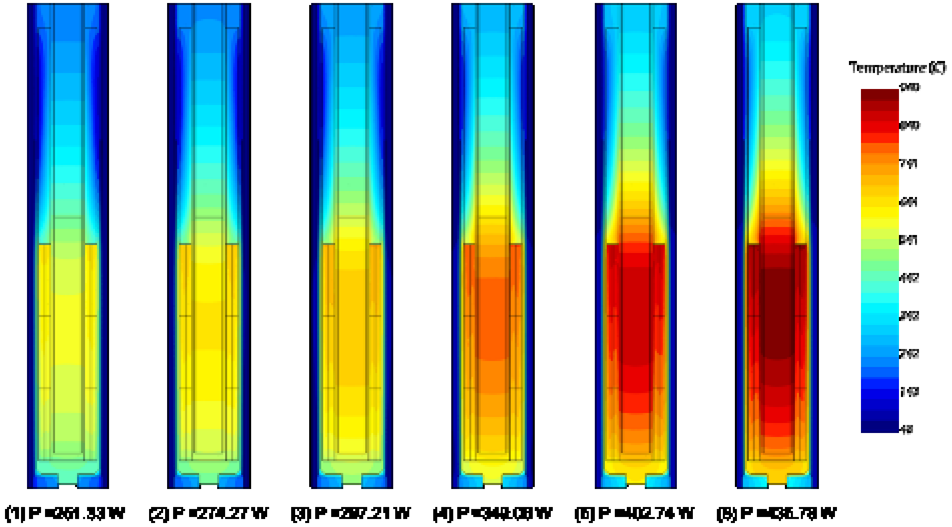


YZ View

Heater Only



Heater + Fission



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

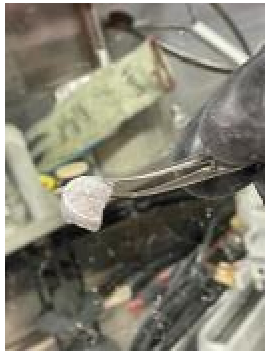
Salt Removal Mockup

- 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

Before test

After test

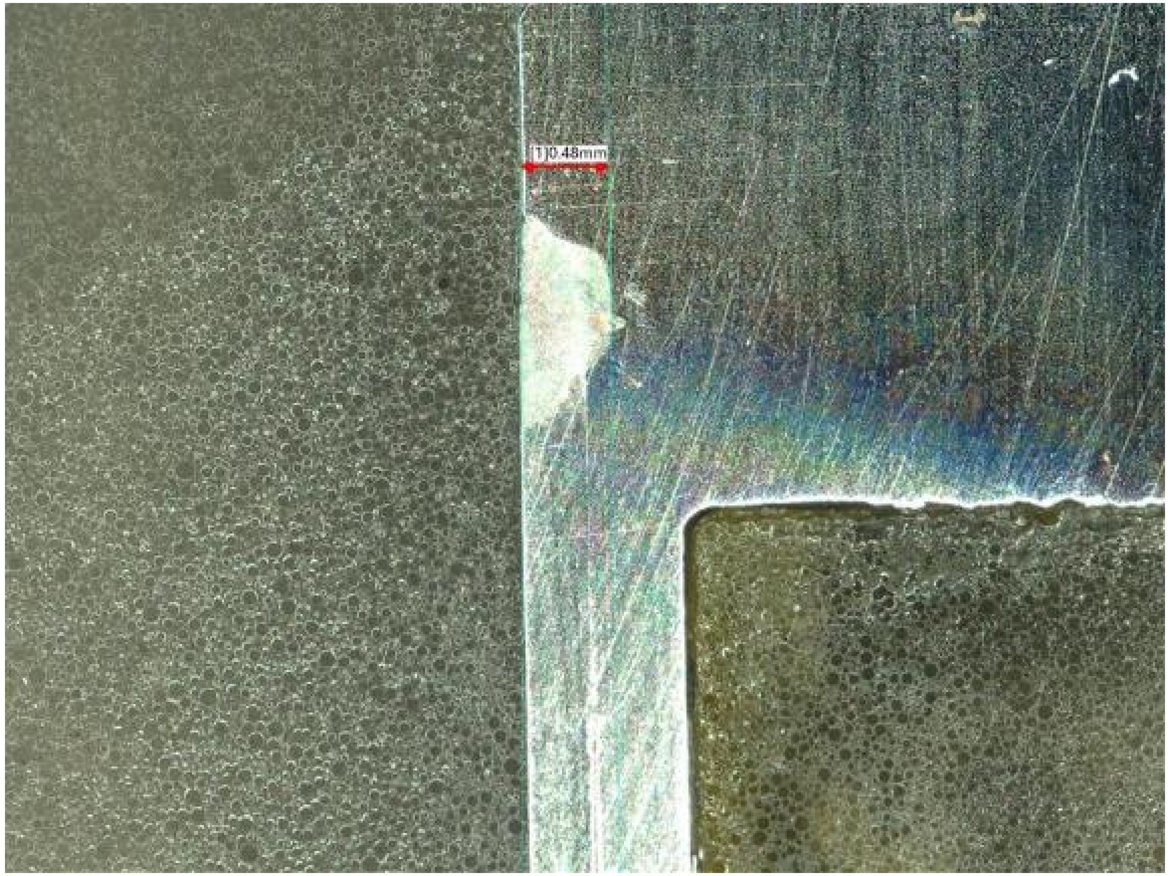


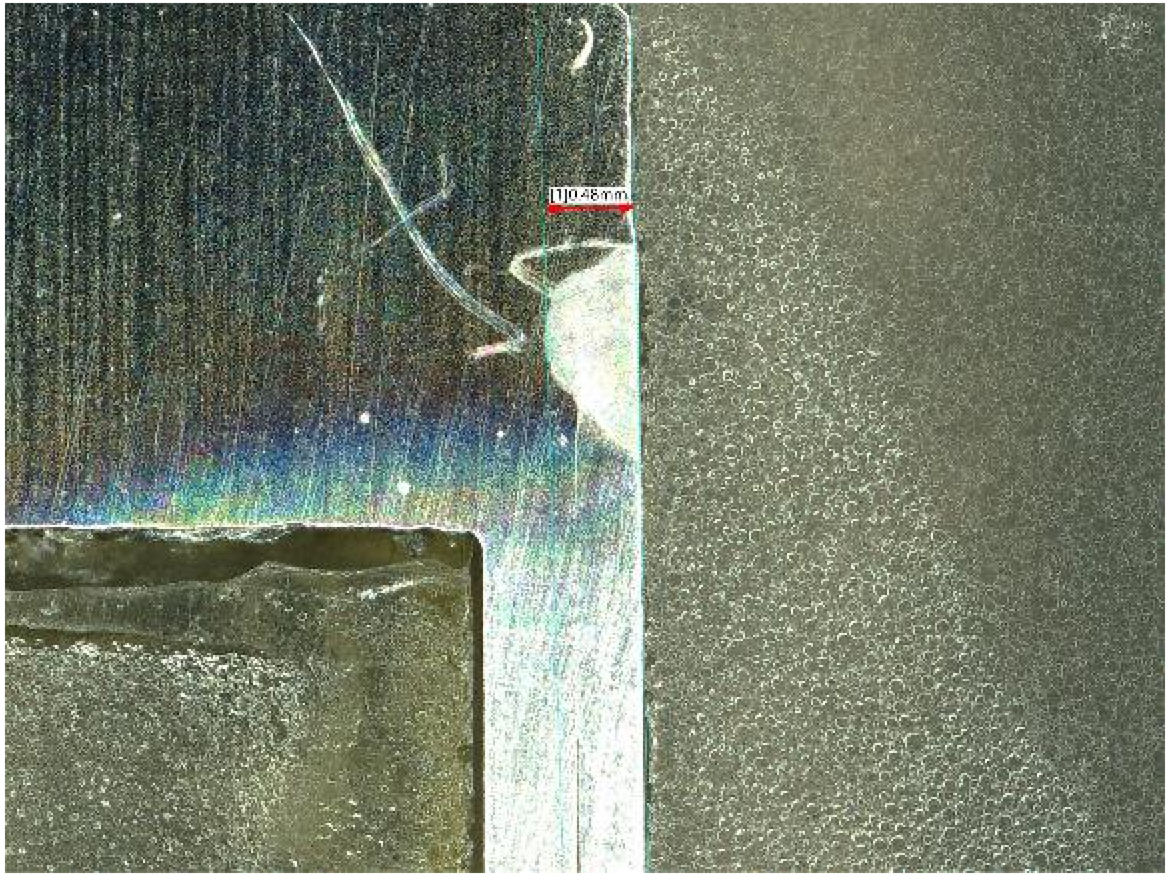
Extracted salt

Heater testing

Heater w/ T99 compound

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_{melt} = 1080°C

3 geometries, 2 materials

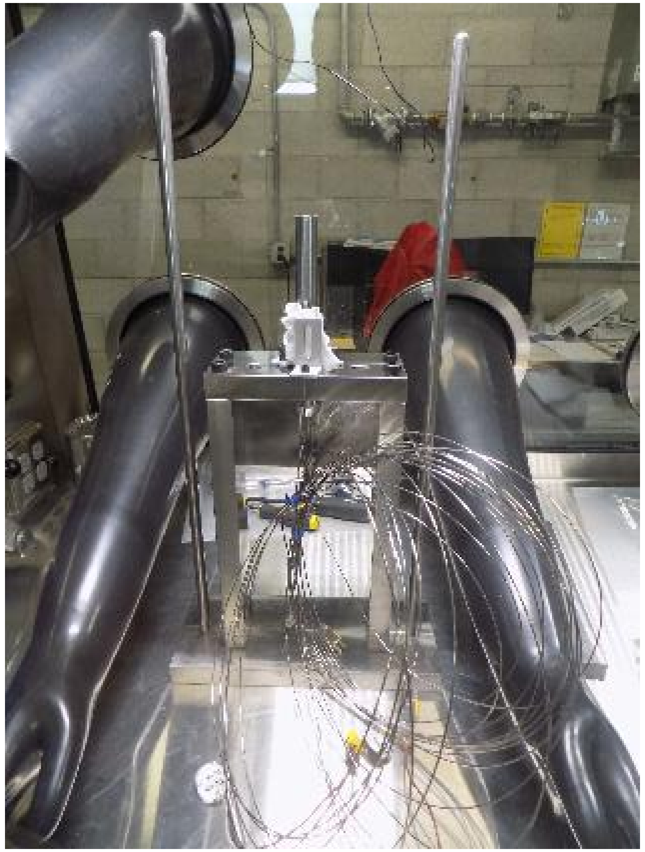
Braze mockup

INL BPS IS12.4 and I12.0

Capsule braze

Capsule Loading (Surrogate Commissioning Testing)

Capsule Mount



Salt Fill w/ Funnel

Bottom Cap Press

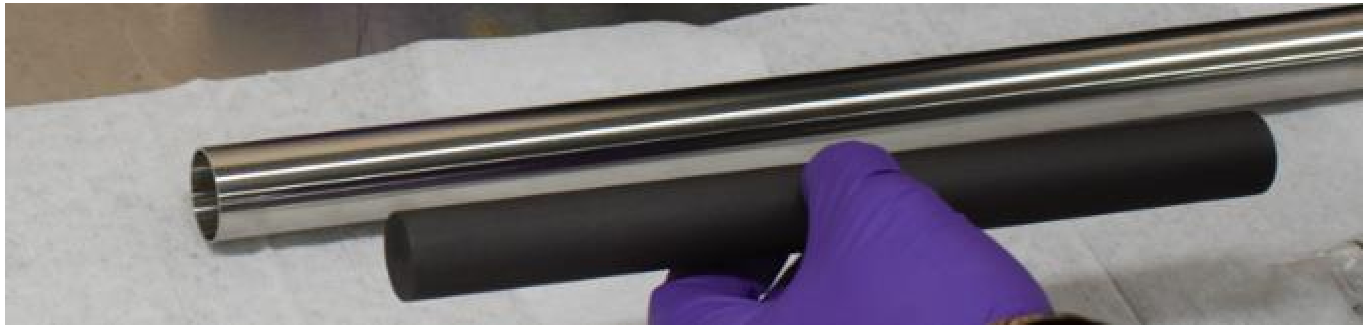
DSC_0003.NEF

MRTI Assembly (Surrogate Commissioning Testing)

MRTI Inner Capsule

MRTI Inner Capsule w/ Heat Shield and Insulation

MRTI Inner Capsule w/ Springs and Top Fitting



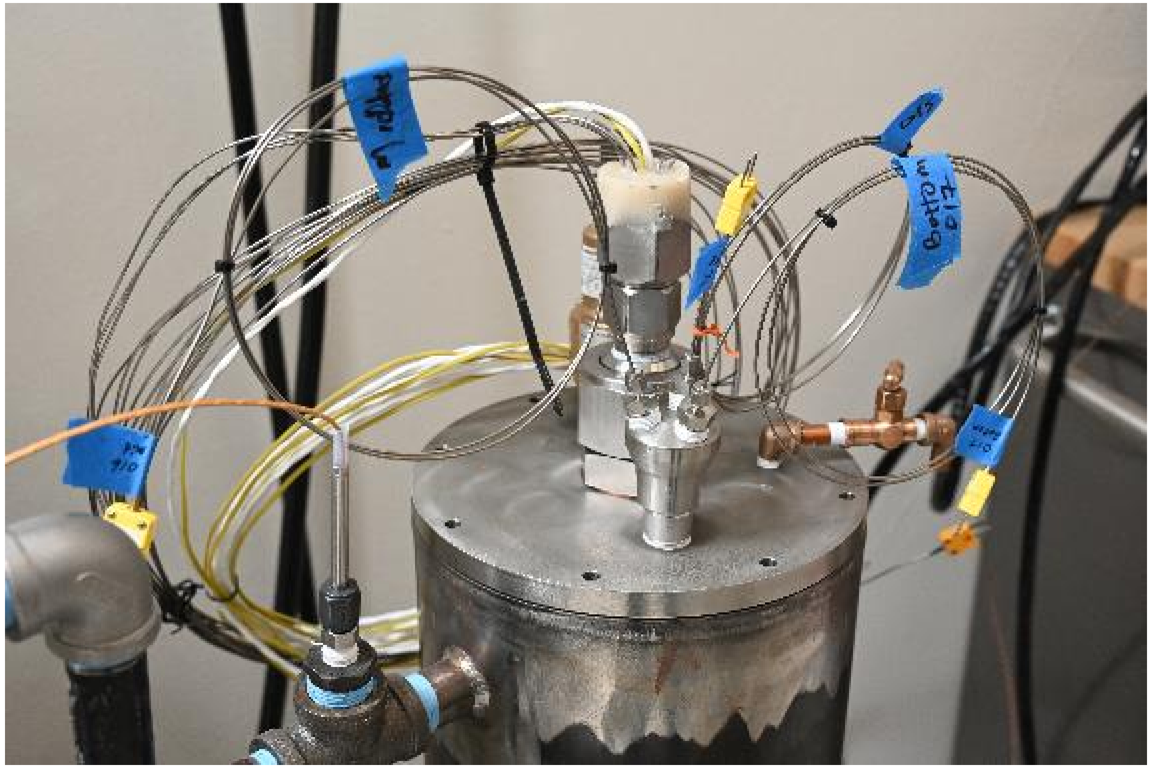
MRTI Outer Containment and Graphite Spacer

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



MRTI Test Rig Installation

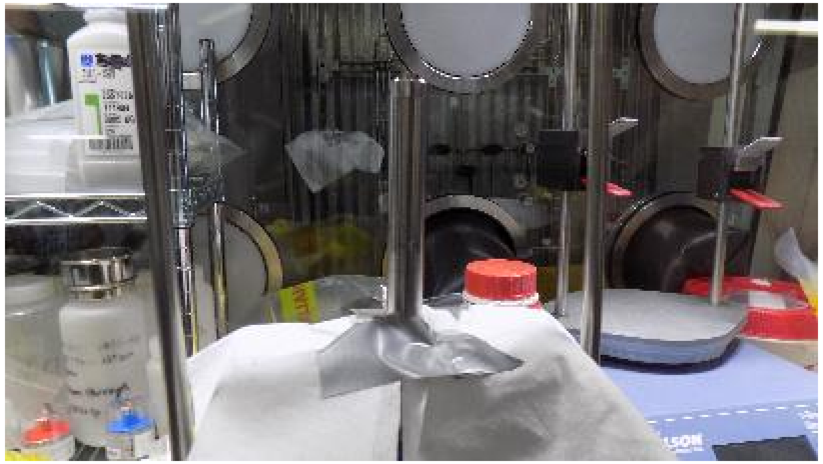
0.2-0.5 GPM water flow, outer containment Type-K thermocouples

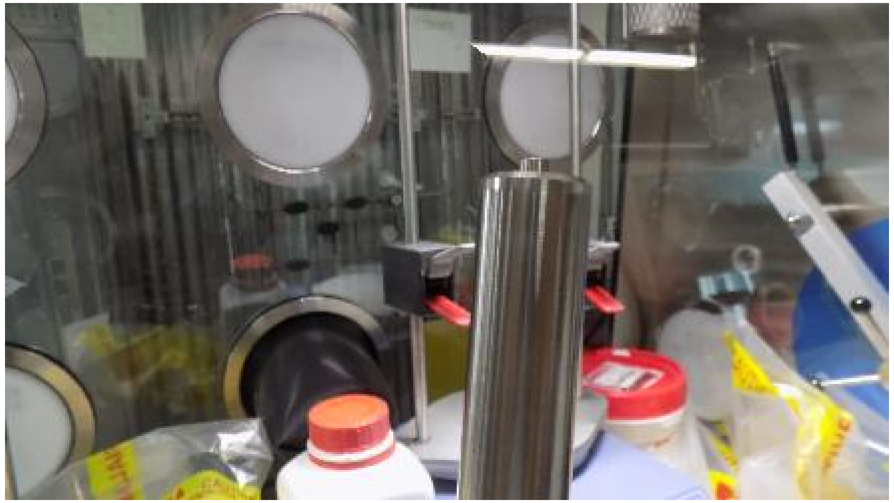
Test salt temperature >700°C, determine control scheme, heater performance

Capsule Loading (Fueled Experiment)

MRTI Salt Fill

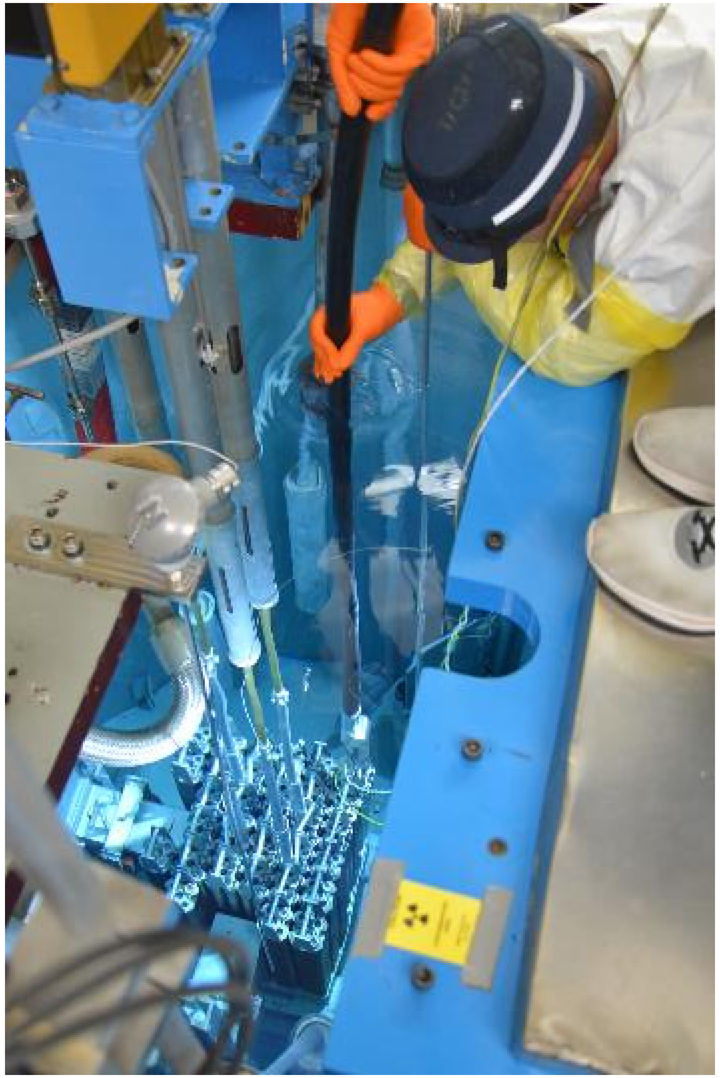
MRTI End Cap Press





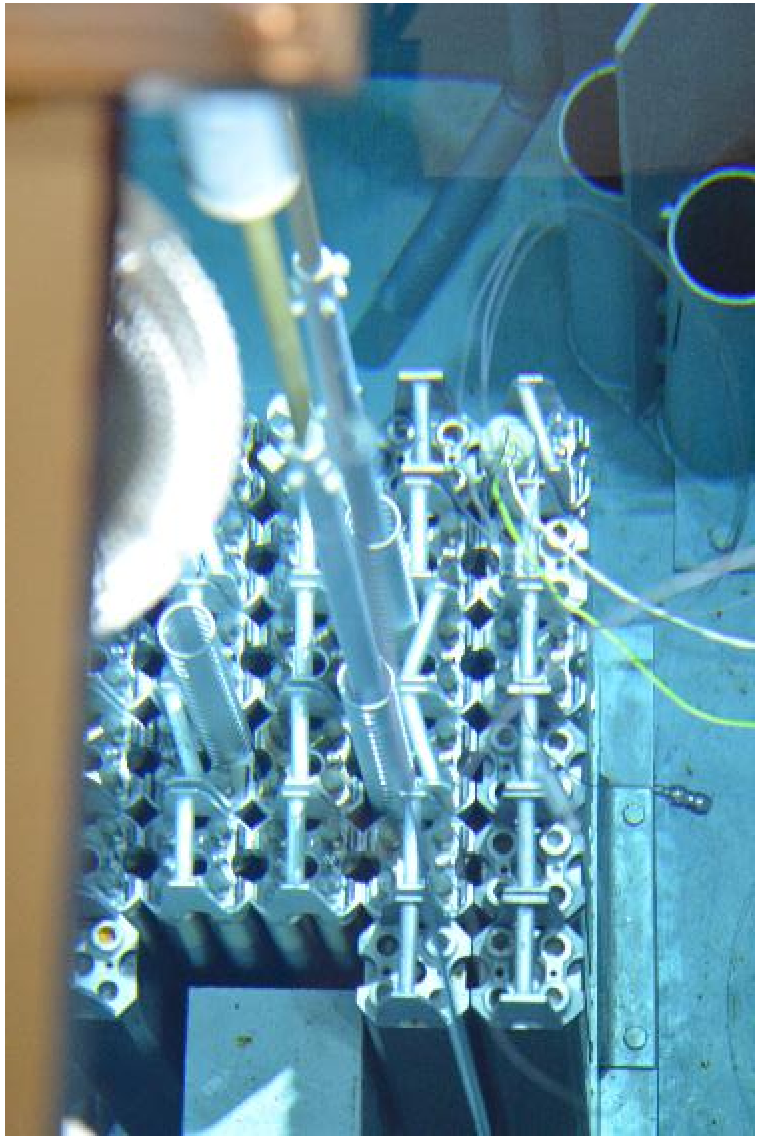
MRTI NRAD Installation

MRTI Cluster



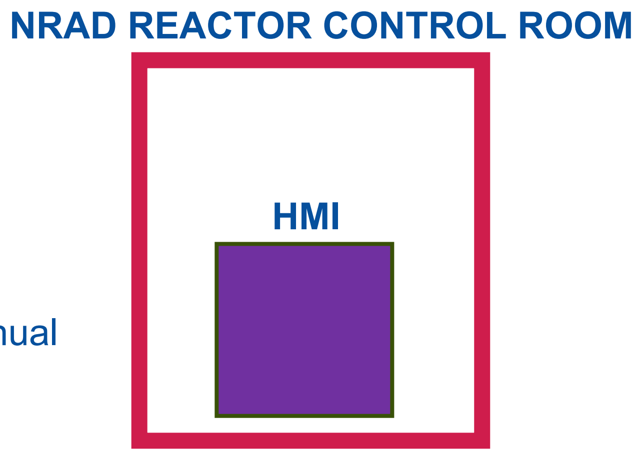
MRTI Handling

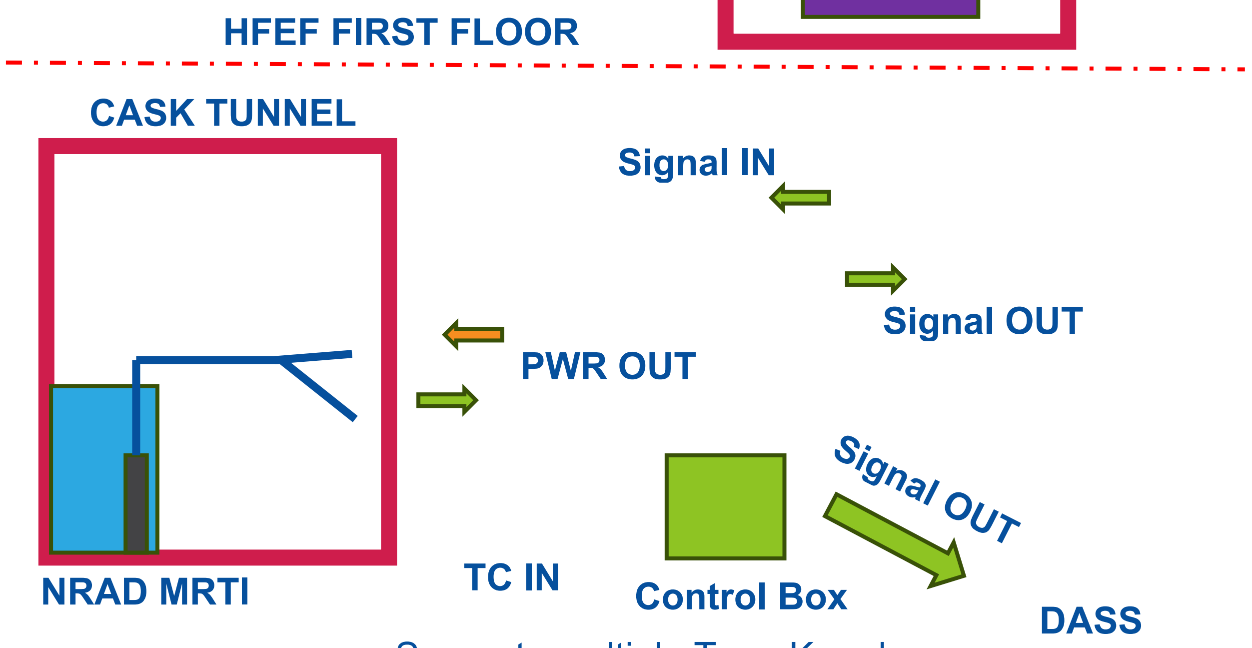
MRTI Installed



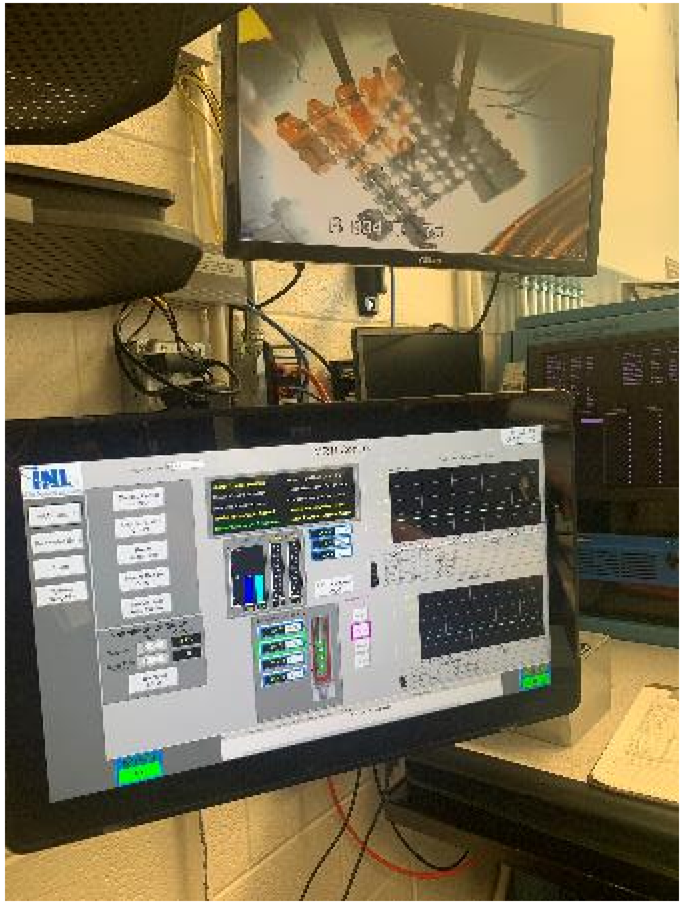
MRTI Heater Control System and Data Acquisition

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





Supports multiple Type-K and Type-N TC connections and up to three heater outputs

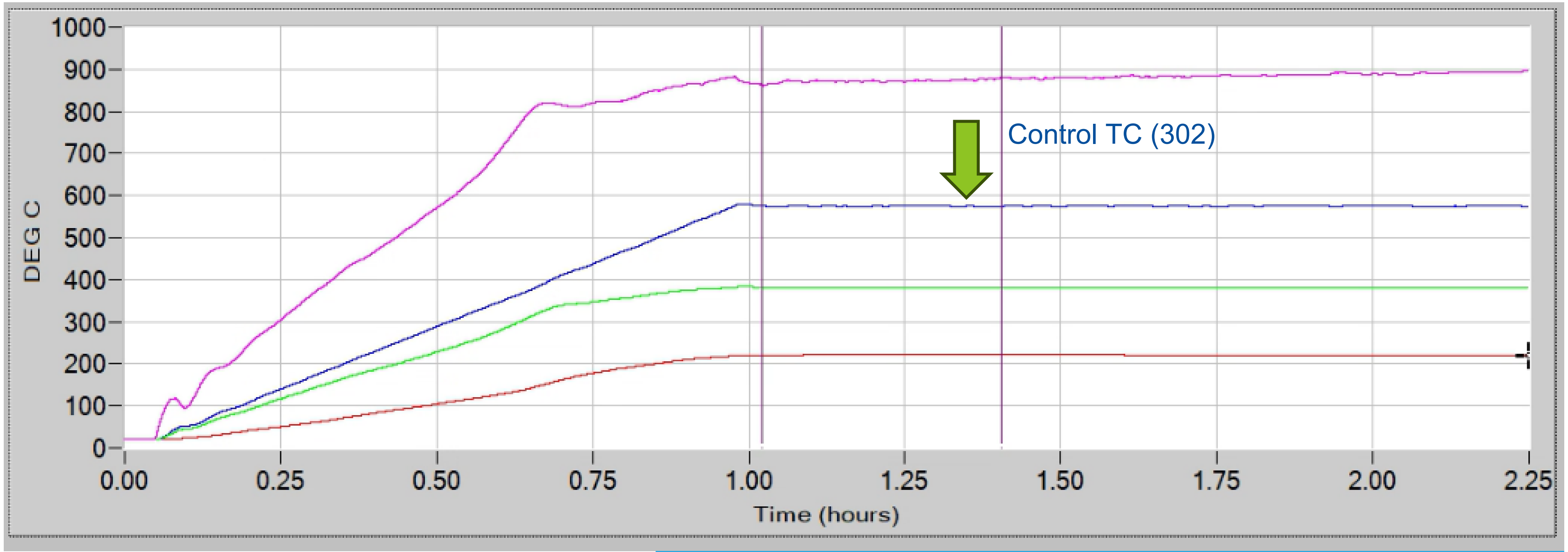


MRTI HMI

REACTOR ON

MRTI Irradiation Heater Startup

DASS



10°C/min ramp, 575°C set temp, TC_302 control

Hold temperature pre-irradiation

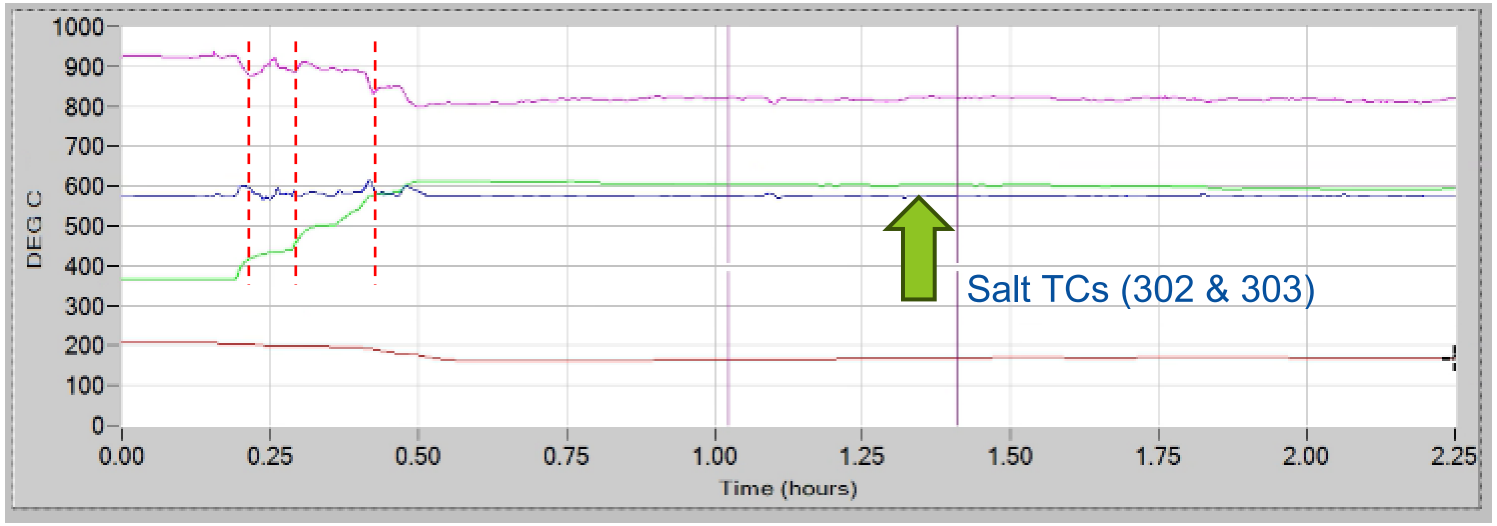
Bottom salt frozen (no radiolysis) due to set temp

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

MRTI Irradiation

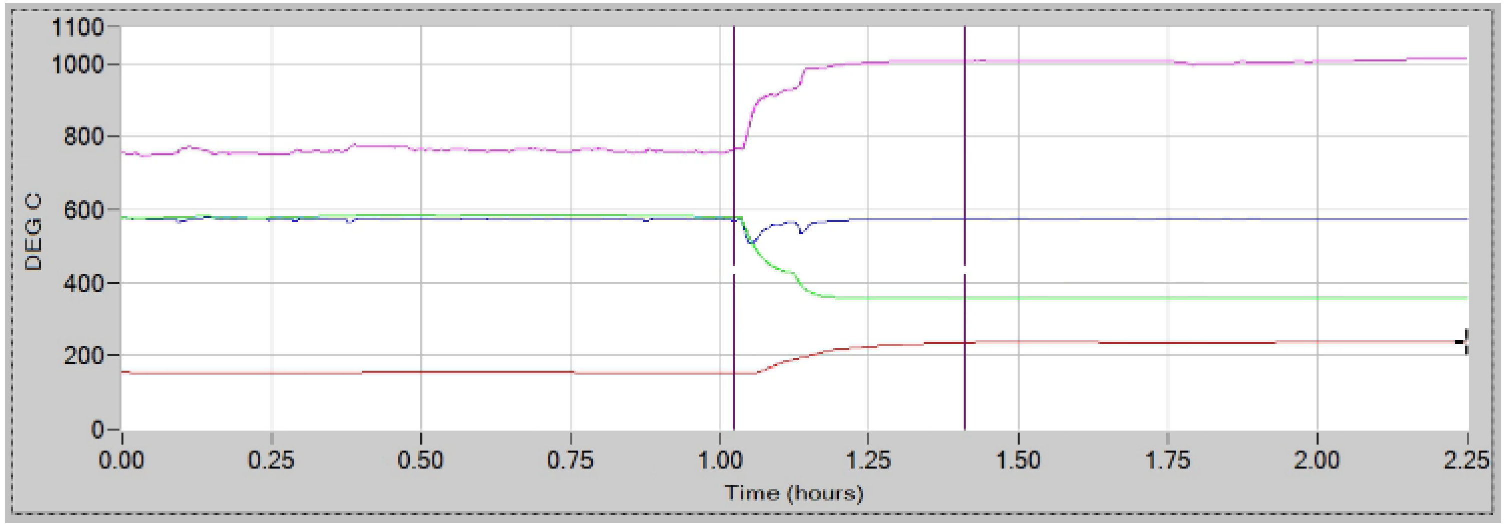
Reactor Startup

50kW step-wise startup



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

Reactor Shutdown



- Heater response
- Cyclic irradiation
- Higher gradient

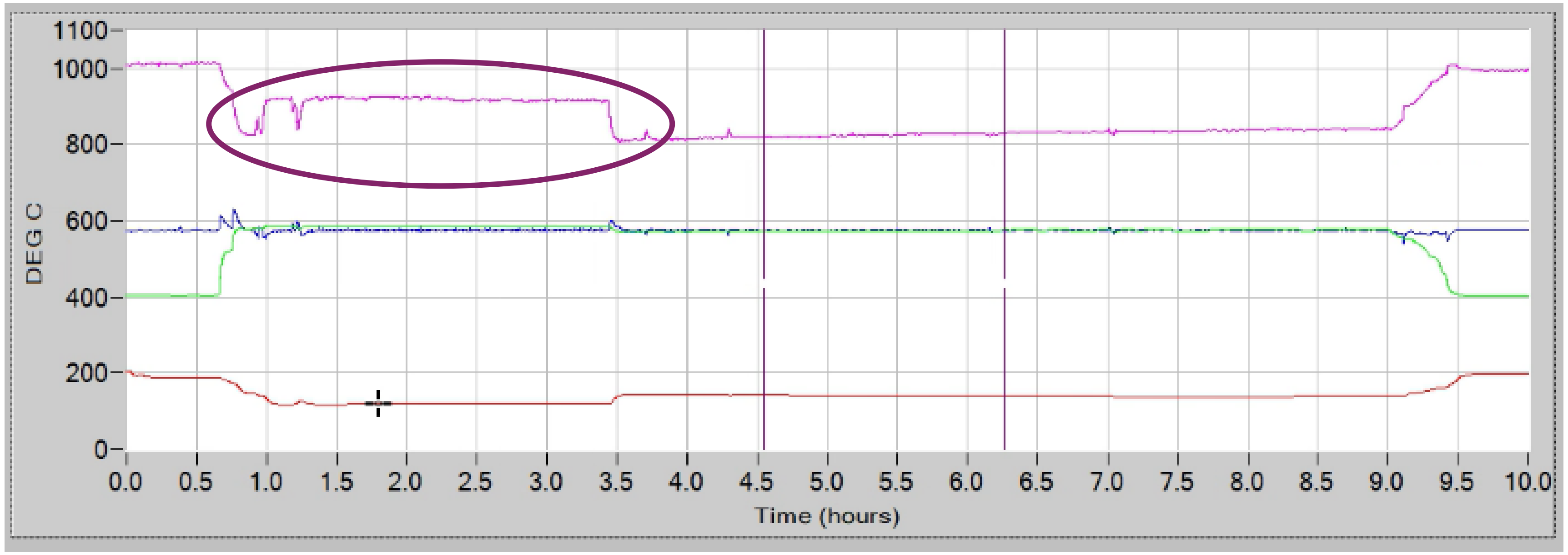
Day 1

TC_301	TC_302	TC_303	TC_304
Plenum	Top Salt	Bottom Salt	Heater

MRTI Irradiation

Reactor Startup

Reactor Shutdown



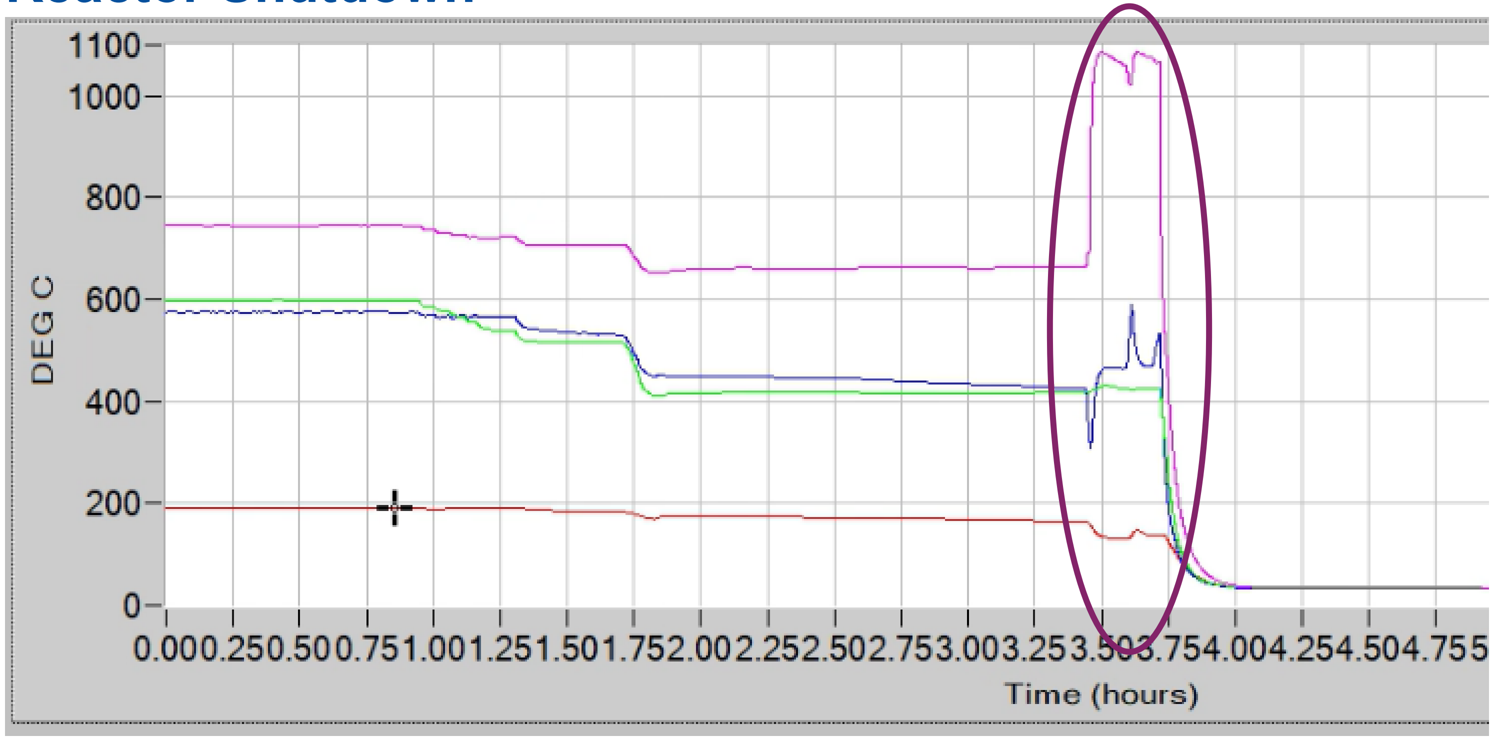
Day 20

MRTI HMI

IDAHO NATIONAL LABORATORY

MRTI Irradiation

Reactor Shutdown



Day 30 (Day 29 Midnight)

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

MRTI Heater Failure (Lessons Learned)

In-tank Video Camera

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

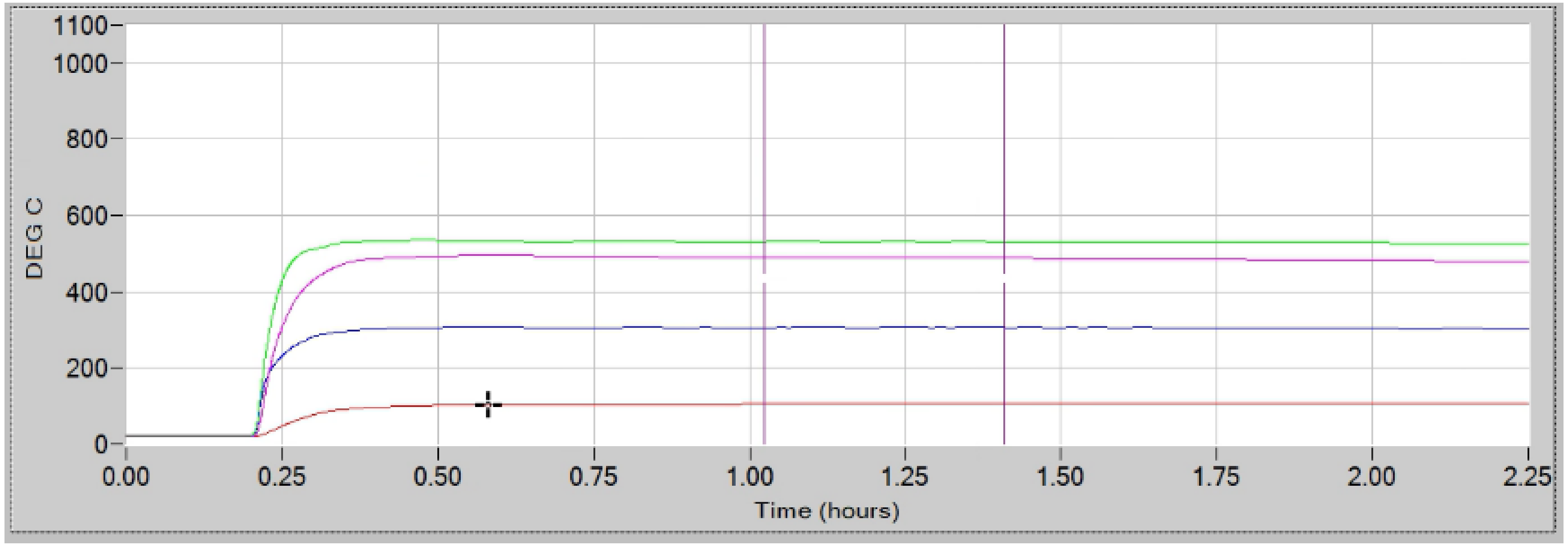
Plastic embrittlement & water flow erosion

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: $0.66UCl_4$-$0.33NaCl$ (93wt% U235), 40g, 13 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?

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