INL/MIS-21-63218-Revision-0

Molten salt Research Temperature controlled Irradiation (MRTI) Preliminary Design Review

June 2021

Changing the World's Energy Future

Abdalla Abou Jaoude, James Loren Chandler, Stacey M Wilson, Kim B Davies, Calvin Myer Downey, Chuting Tan, William C Phillips, Gregory M Core

Idaho National Laboratory

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

June 16, 2021

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Molten-salt Research Temperature-controlled Irradiation (MRTI)

Preliminary Design Review

Idaho National Laboratory

Introduction & Overview

Greg Core

Design Team

Abdalla Abou-Jaoude
Neutronics

James Chandler
Control Systems Design

Greg Core
Project Manager

Kim Davies
Mechanical and Electrical Design

Calvin Downey
Mechanical Design

Bill Phillips
Materials & Chemistry Advisor

Chuting Tan
Post-Irradiation Examination Planning

Stacey Wilson
Thermal Hydraulics

SuJong Yoon
Thermal Hydraulics

Experiment Overview & Goals (Refresher from Conceptual Design)

Mission Statement

Substantially increase INL's visibility in Molten Salt Reactor (MSR) R&D through the establishment of a domestic neutron irradiation capability for fissile material-bearing salts

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
- Final Outcomes
  - 2 Conference Presentations
  - 4 Journal Papers
  - Proven Domestic Irradiation Source

Preliminary Design Review Objectives

Purpose of Preliminary Design

Advance the detail and rigor of the design solution

Purpose of the Preliminary Design Review

Present current design details while discussing the design's ability to meet given requirements

Primary Objective of the Preliminary Design Review

Obtain agreement from design authority and cognizant engineer to proceed with final design activities

- All attendees of the review are asked to provide input and feedback

Overview to MRTI Design

Kim Davies & Calvin Downey

Operational Requirements

- Requirements per FOR-584 & 585

Operational	Value	System
Containment Compatible with Water, 12ft Submerged Depth	Provide	Assembly
FOR-585 1.12 Maximum Outer Diameter	2.9in	Assembly
Assembly Interfaces with NRAD Grid Plate	Allow	Assembly
NRAD Cask Fitment	<4.5in OD, <39in Tall	Assembly
Sufficient Temperature Monitoring (# of TCs)	Provide	Assembly
Assembly Weight	<50lbs	Assembly
Connection to GASR	See FOR	GASR
Corrosion Samples Interface with Existing Tools	Provide	Assembly

Programmatic Requirements

- Requirements per FOR-584 & 585

Programmatic	Value	System
Molten Salt Volume	>5cc	Capsule
Volume to Surface Area Ratio	Max.	Capsule
Off-gas Capability and Additional Inst.	Provide	Assembly
Multiple Capsules	Target	Assembly
Characterization Prototype Capsule	Provide	Capsule
Capsule(s) to Withstand FG Pressure	Allow	Capsule
Heating Margin from Heater	Allow	Assembly
Heater	Provide	Assembly
Certified Material Test for Salt facing Materials	Obtain	Capsule
High Neutron Absorption Materials	Minimize	Assembly
Rapid Disassembly and FG Collection	Allow	Assembly

Preliminary Mechanical Design

Kim Davies & Calvin Downey

Input from Conceptual Design

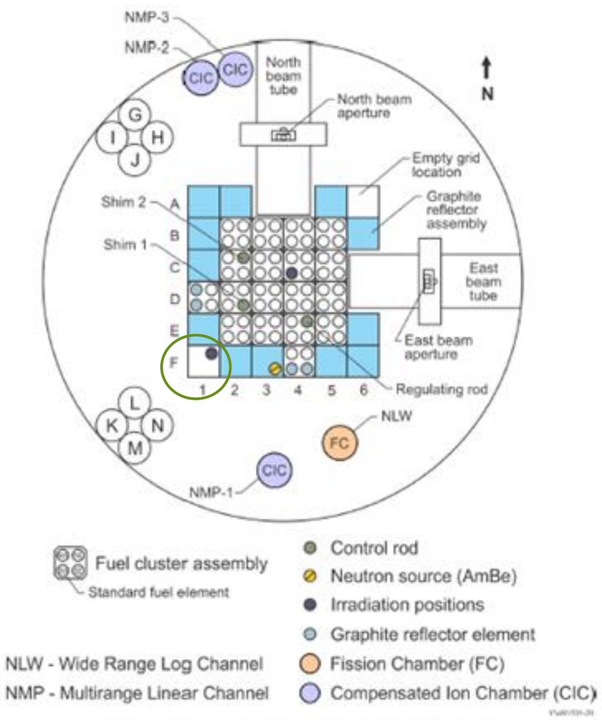
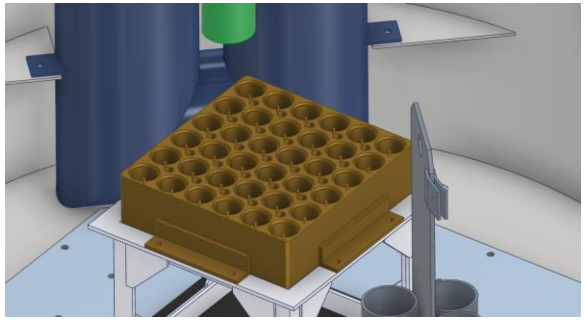
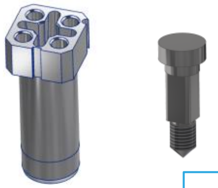


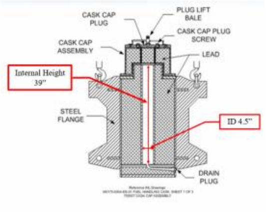
Figure 1. Sixty-four-element core and tank layout.

NRAD Core Grid Plate



Assembly Fittings





NRAD Transport Cask

- NRAD fuel cluster design with dry 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

Preliminary Mechanical Design Focuses

- Preliminary analysis of thermomechanical stresses in the system
  - Thermal expansion and fission gas buildup in capsule plenum
  - Potentially affects material choices, wall thicknesses
- Identifying and finalizing instrumentation included in experiment
  - Limitations in capsules space and sensor fabrication/availability
- Defining QLDs and relevant inspections

- Iterations on experiment geometries
  - Inputs from PIE, as well as thermal hydraulic and neutronics model needs
  - Based on manufacturability and available parts/raw material
- Investigation of heater placement, performance, and thermocouple output relations
  - Based on thermal model and PIE inputs
  - Affects final thermal model iterations and control calibrations

Internal Capsule Pressure

- Estimate maximum internal pressure for structural integrity of materials and welds
- Capsule loaded and sealed at ambient temperature and pressure
- Pressure increase is estimated from ideal gas law

$$\frac{PV}{T} = Constant$$

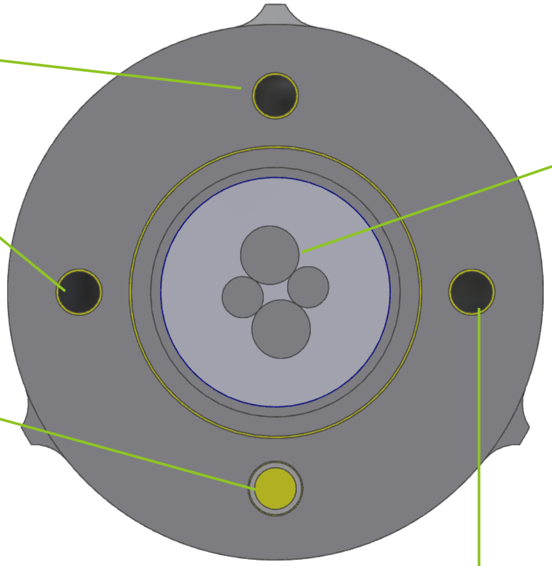
- Two significant contributors; 1) temperature increase and 2) decrease in free volume from salt density decrease
- Maximum pressure estimate is < 75 psi
- Allowable pressure estimate is >900 psi (per ASME B31.1 for Inconel 625 tube with .805" OD at 600 C)

MRTI Instrumentation Considerations

Type K Thermocouples

- INC625 Sheath, 1/16”

Capsule Top Down

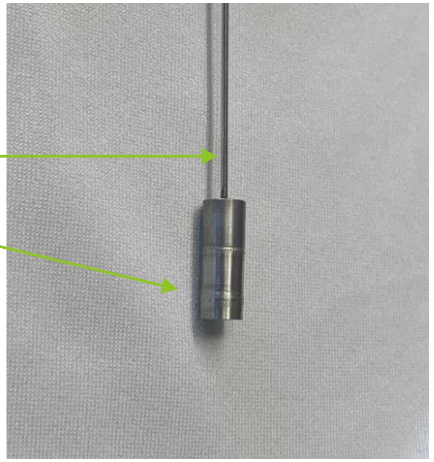


Heater Leadouts

- .080” Power + & G
- 1/16” TC separate leads

Optical Fiber Pressure Sensor

- 2mm tube outlet, 1/16” lead



Instrument Options:

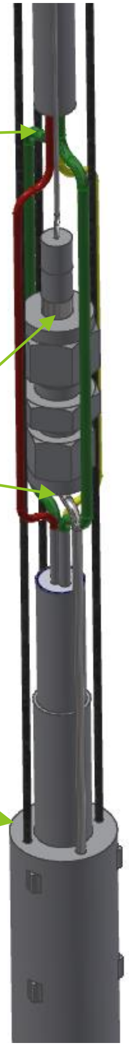
- INC625 SPND
- Flux Wire Wand
- Additional TC

MRTI Instrumentation Considerations

Heater Leadouts potted into ½ ” tube

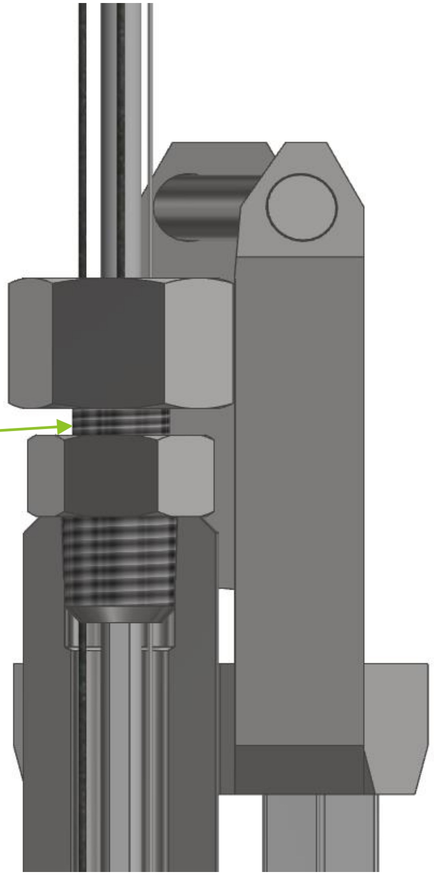
Pressure Sensor sealed via Swagelok to Pressure Tube

TCs, Pressure Tube, Heater Thermowell brazed at Capsule Top Cap



Instrument Sealing

Leadout tube, 2-3TCs, Optical Fiber MIC leadout sealed out of Outer Can by MHM5 Conax compression fitting

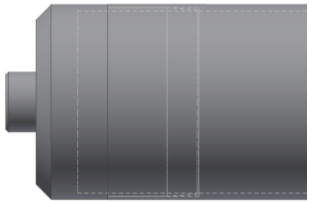


Assembly Quality Level Designations and Inspections

- NRAD Quality Level Designations:
  - QLD MFC-001608: QL3 components, commercial grade designation for sealing boundaries in experiment assembly
  - QLD MFC-001611: QL4 components for general use
- Weld and braze efforts will include qualifications and inspections for all QL3 sealing components in assembly
- Inspections:
  - Visual inspection (TPR-13442, specified criteria)
  - Helium leak check (TPR-13438)
  - Dye penetrant (considered, based on final thermomechanical analysis)
  - Radiography (considered, based on final thermomechanical analysis)

Brazed Capsule Top Cap

Welded Capsule Bottom Cap



Post-Irradiation Examination Considerations

Chuting Tan & Bill Phillips

PIE Facilities Coordination Initiated

- HFEF
  - Salt removal, Precision gamma scanning, GASR, Disassembly
- AL
  - ICP-MS, DSC, Dissolutions
- IMCL
  - Sample prep, Thermal property measurements, TEM, XRD, SEM, FIB
- Action list
  - GASR MRTI interface
  - IMCL salt sample handling
  - Thermal property measurements sample handling (Laser Flash Analyzer)

Capsule Interface with GASR

- The use of the Gas Assay, Sample and Refill (GASR) system is needed to collect the fission and radiolysis gasses generated during irradiation
- This system uses a laser to bore a small hole in the side of the capsule and subsequently collect the gasses in the capsule headspace
- A gasket is required that is able to seal to the capsule outer diameter
  - Needs to be able to seal directly to the capsule to prevent contamination of the gas sample
- Key design outcomes:
  - Wall thickness needs to be decreased to 0.029” in at least one section of the tube
  - Desirable to keep OD within range of existing gasket designs to allow for easier interface with GASR

Salt Removal Mock-up Experiment - Details

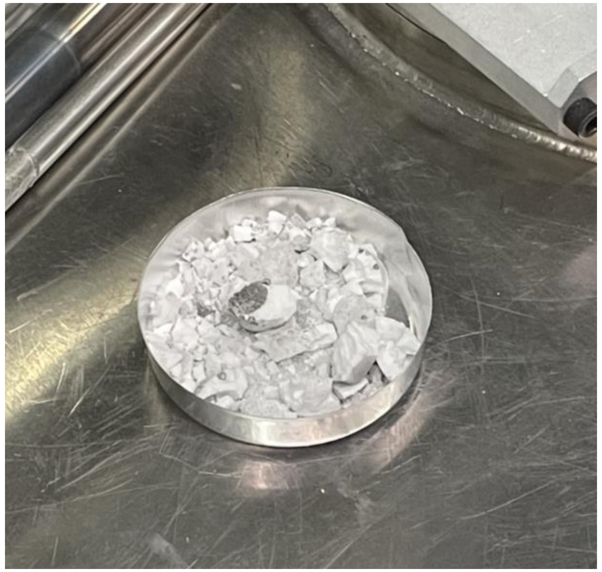
- **Purpose:** Determine ability to recover salt from capsule following irradiation
- **Goal:** greater than 33% recovery
- LiCl-KCl eutectic was used as a non-rad surrogate salt
  - Salt annulus thickness and salt mass variations tested:
    - 0.3cm thickness = 15g LiCl-KCl
    - 0.4cm thickness = 20g LiCl-KCl
    - 0.5cm thickness = 25g LiCl-KCl
- Salt was melted within capsules with rods inserted into salt at 500°C
- After cooling overnight, the top collars were removed and capsules disassembled
  - Simulated heater and thermocouple thermowells remained stuck in salt, as anticipated
- Salt was removed from capsules using an electric impact nail driver to break up salt

Before test

After test

Salt Removal Mock-up Experiment - Results

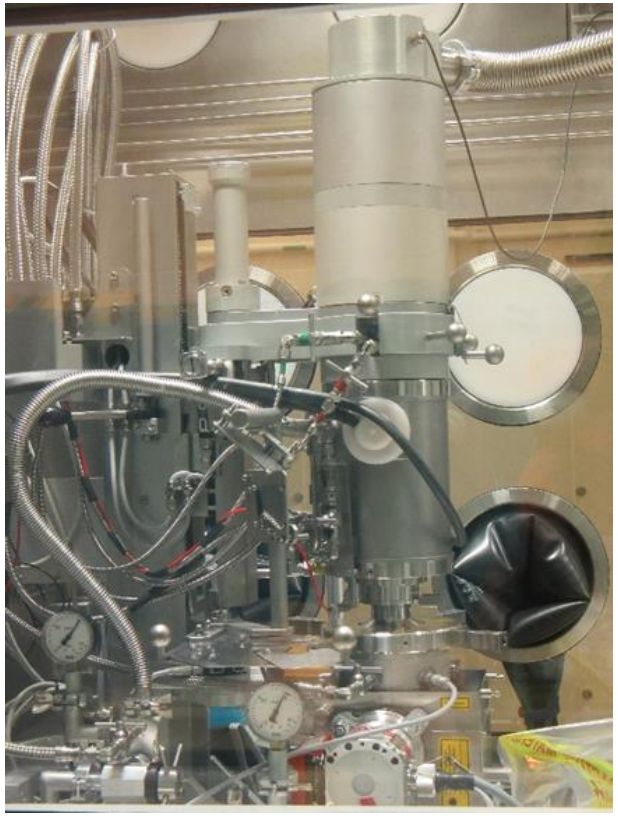
- **Results**
  - Recovery of up to 99.2% of loaded amount was achieved (full results in table)
  - Salt located below the heater thermowell was more difficult to remove
    - Caused relatively low recovery on 0.4cm test
    - Should minimize salt layer thickness below thermowell
- **Design Outcomes:**
  - Capsule thickness can be decreased throughout length to 0.029”, which will facilitate easier salt removal and interfacing with GASR
  - Existing impact hammer techniques developed for de-cladding operations in HFEF can be easily adapted to the salt irradiation capsules
    - Will need to design fixturing due to capsule O.D.

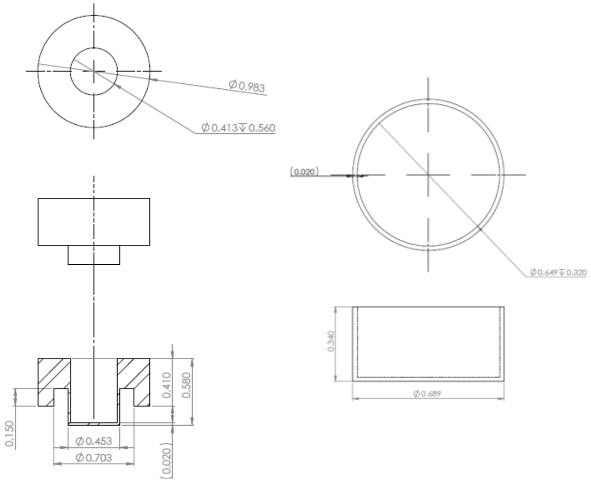


Annulus Thickness	Initial Salt Mass	Recovered Salt Mass	Recovered Fraction
0.3 cm	15.000 g	13.892 g	0.926
0.4 cm	20.001 g	15.908 g	0.795
0.5 cm	25.002 g	24.804 g	0.992

Laser Flash Analyzer Sample Handling Method Development

- Laser flash analyzer in IMCL will be used for measure irradiated salt thermal diffusivity
- Method development includes design, fabrication, and testing of a SS 316 sample crucible for irradiated salt samples
- LFA is located in IMCL's thermal property cell, capable of handling highly irradiated samples





Neutronics Analysis

Abdalla Abou-Jaoude

Updates Since the Conceptual Design

Added Features

- Zeroed in on ‘Design Option 2’
- ^{235}U vector from mean of feed

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

- Updated material: IN-625
- Granular power distribution for axial/radial/azimuthal power variation

Features still Missing

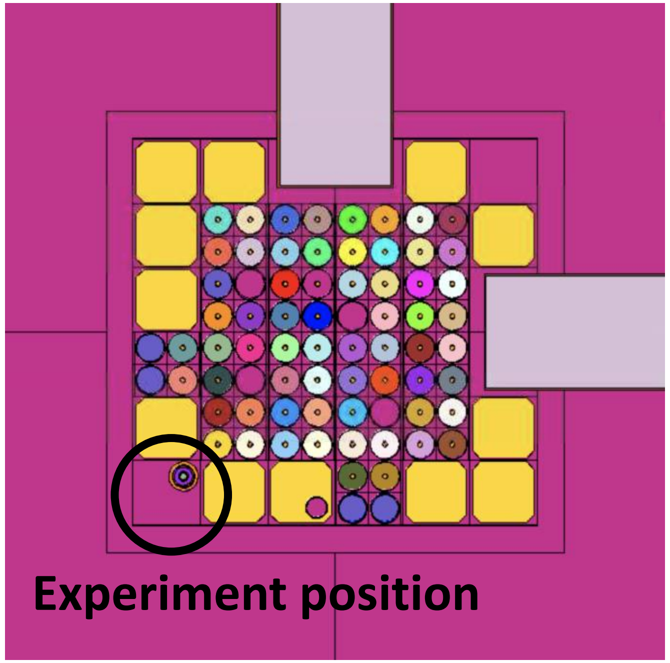
- Minor geometric mismatches with mechanical design
  - E.g., graphite height, capsule thickness
- F-1 fuel cluster dummies
  - 3 additional elements filled with Al/graphite
- Explicit model of instrumentation
  - Will cause minor variation in power generation profile

Missing features are not expected to impact the overall conclusions in the analysis

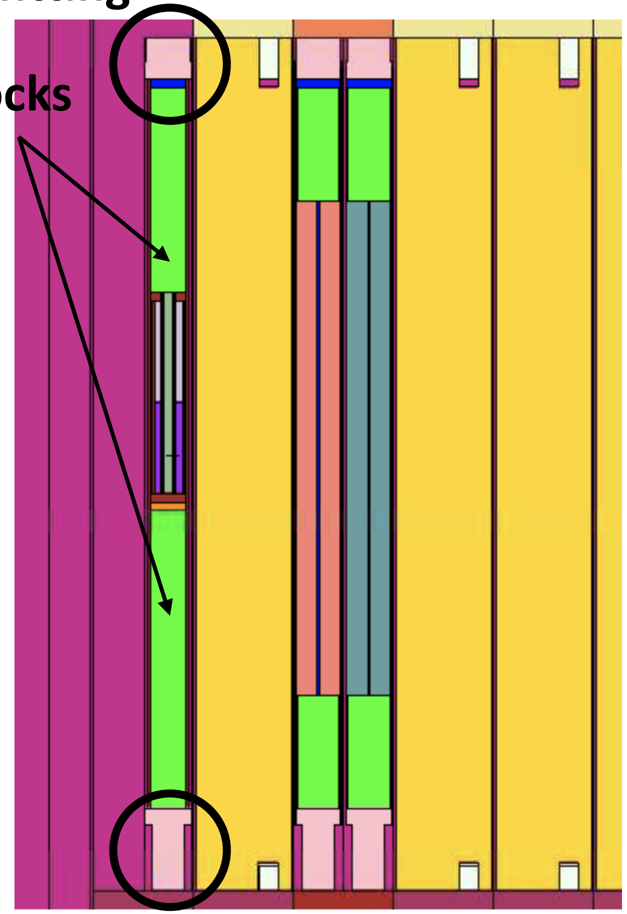
Reactor Physics Requirements

- Programmatic requirements:
  - Maximize flux/power/burnup in salt: Target of > 20 W/cc
  - Maximum feed ^{235}U enrichment = 93 wt%
- Operational/safety requirements
  - Reactivity worth of experiments must be < $\pm$40 cents (45 cent limit with 5 cents for conservatism)
  - Pu-equivalent Grams (PEG): consideration for the preliminary design
- Analysis conducted using MCNP6.1.0 on HPC using NRAD 11/07/2020 model
  - 100,000 virtual particles with 1000 cycles (100 inactive)
  - keff standard deviation of around 9 pcm.

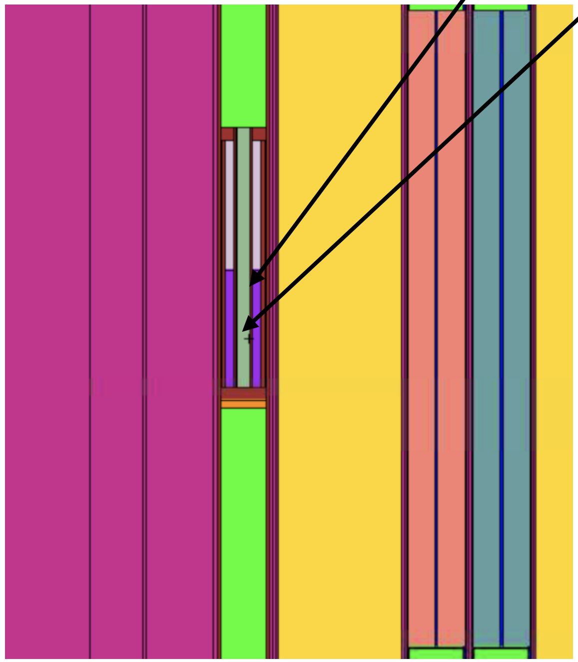
MCNP Model Visualization



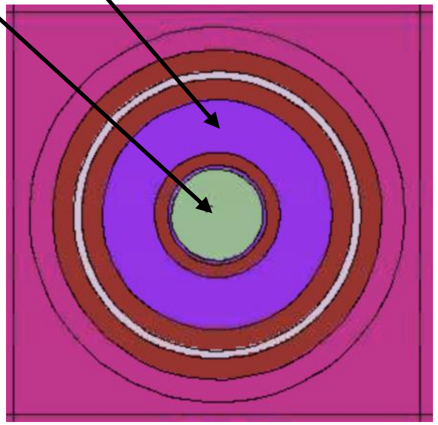
XY View



YZ View



YZ Zoom



XY Zoom

Impact of variations in Inconel composition on Heat Generation & Reactivity

Outer can	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	93.20%	93.20%	93.20%	93.20%
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

Note1:

Two variants of IN-625 considered, with all Nb/Ta based on ASME specs

Note2:

Reactivity standard deviation is ~1 ¢

- Main findings:
  - Heat generation of 20 W/cc requirement can be met
  - All cases satisfy reactivity requirement of < 40 ¢
  - IN-625(Nb) selected moving forward for conservatism

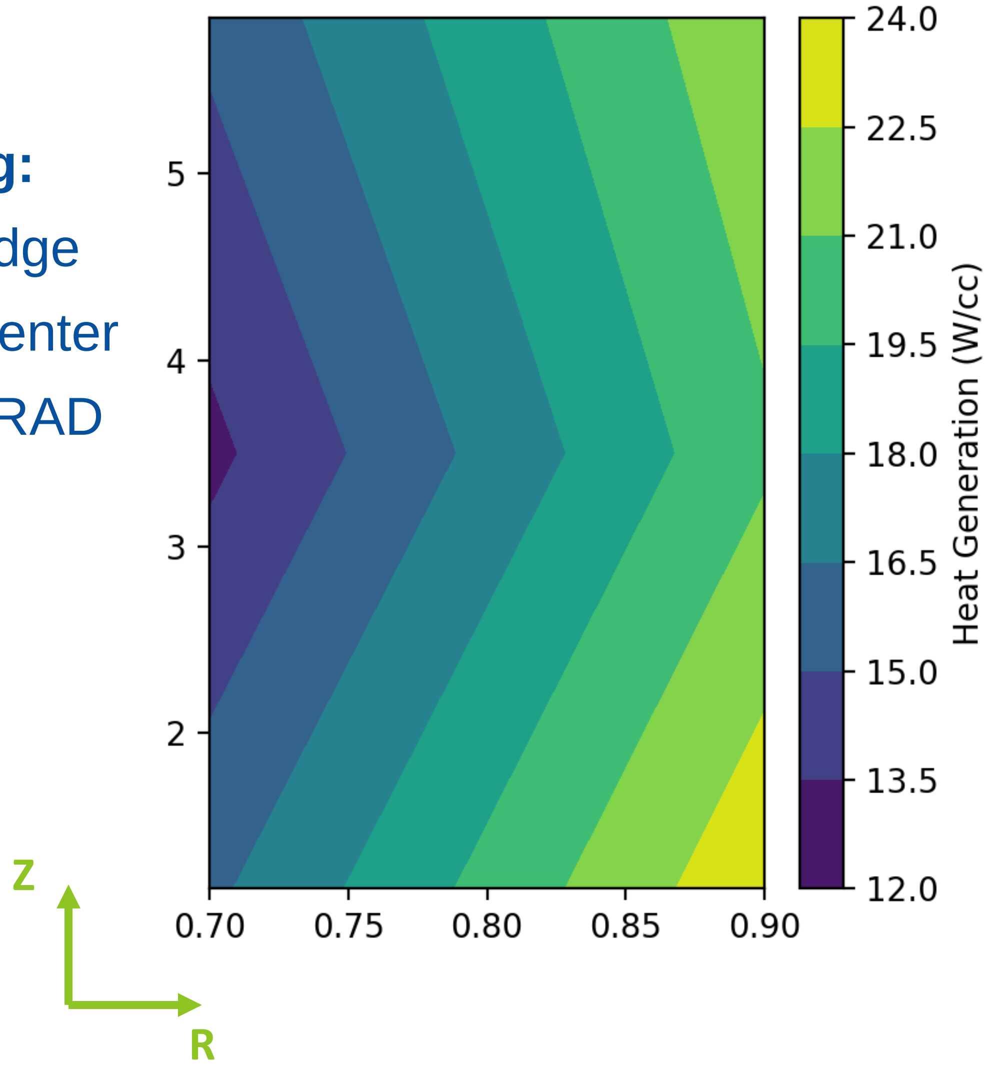
Granular Power Distribution in Salt

Impact of self-shielding effect

Impact of self-shielding:

- More peaked at wall edge
- Less peaked at axial center
- More peaked facing NRAD center

Azimuthally Averaged



- Average: 18.54 W/cc
- Max/min ratio: 2.39

R	Z	Th	W/cc
0.7	1.167	0.125	**17.83**
0.7	1.167	0.375	**16.20**
0.7	1.167	0.625	**14.56**
0.7	1.167	0.875	**16.12**
0.7	3.5	0.125	**14.55**
0.7	3.5	0.375	**13.81**
0.7	3.5	0.625	**11.11**
0.7	3.5	0.875	**12.97**
0.7	5.833	0.125	**16.36**
0.7	5.833	0.375	**15.49**
0.7	5.833	0.625	**13.74**
0.7	5.833	0.875	**15.82**
0.9	1.167	0.125	**26.54**
0.9	1.167	0.375	**23.75**
0.9	1.167	0.625	**20.26**
0.9	1.167	0.875	**24.26**
0.9	3.5	0.125	**23.28**
0.9	3.5	0.375	**21.37**
0.9	3.5	0.625	**17.26**
0.9	3.5	0.875	**20.98**
0.9	5.833	0.125	**24.70**
0.9	5.833	0.375	**22.27**
0.9	5.833	0.625	**19.01**
0.9	5.833	0.875	**22.80**

Hand-off to Thermal Analysis: Heat Generation
(Includes both neutron & gamma heat contribution)

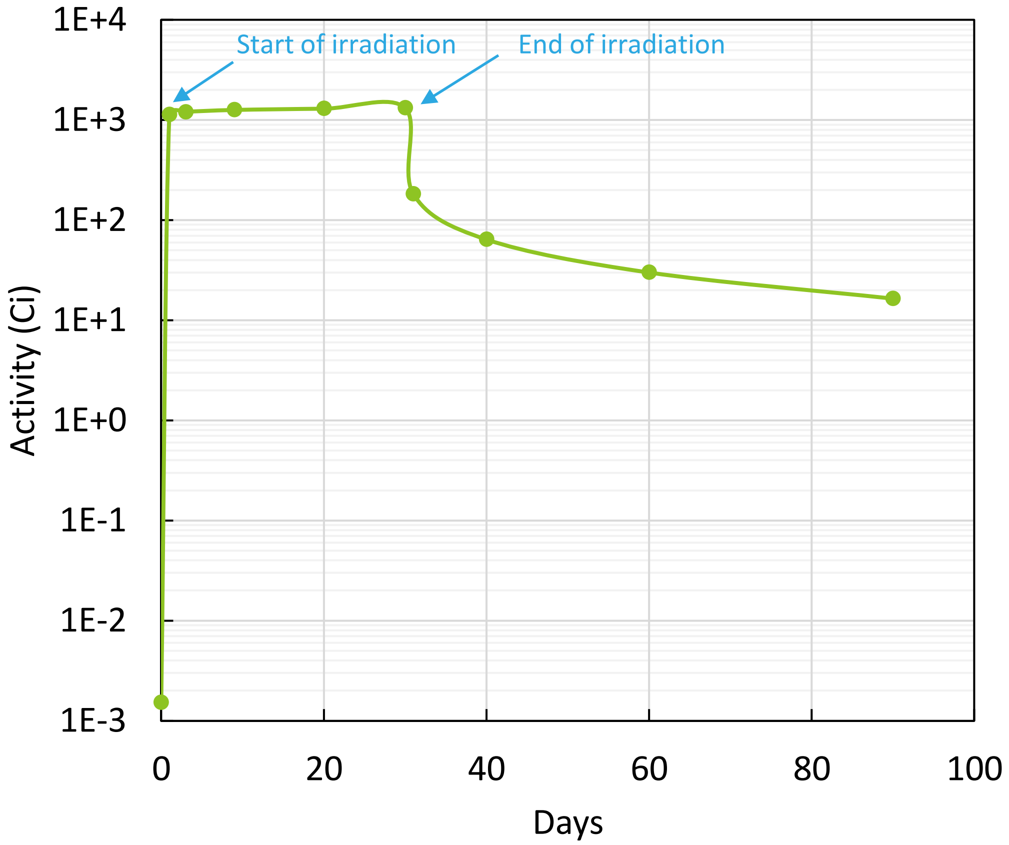
Heat Generation Rates

Inner capsule	IN625-Nb
Enrichment (w%)	0.9320
Salt thickness (cm)	0.4
Salt volume (cc)	14.07
W/cc fission	20.09
W/cc salt	18.993
W/cc heater	0.168
W/cc inner capsule	0.240
W/cc outer can	0.141
W/cc graphite low	0.024
W/cc insulator disk	0.005
W/cc capsule low	0.271
W/cc capsule up	0.135
W/cc graphite up	0.015

- Estimated heating rates in all relevant components to bound ABAQUS analysis
- Handed off values to ABAQUS simulation (and later STAR-CCM+) to inform heat transfer calculations
- Values are expected to vary slightly with updated final design

Source Term Calculations

- Salt activity level:
  - 1 day later = 183 Ci
  - 10 days later = 64 Ci
  - 30 days later = 30 Ci
- Fission production total = 9.0 mg
  - 0.1 mg of I
  - 0.01 mg of Eu
  - 0.05 mg of Pu
- Off-gas generation:
  - Summing up Ar+Kr+Xe
  - 15% increase in plenum mass and therefore pressure



Remaining Tasks for Final Design

1. Update neutronic model to capture final design features
2. Tech check final neutronic model
3. ORIGEN depletion + Microshield dose calculation
   a. Dose of entire assembly with shielding
   b. Ar-41 buildup in experiment
   c. Salt dose rate for PIE analysis (contact dose)
   d. Wall dose rate for PIE (contact dose)
   e. Plenum isotopics
4. Final PEG assessment
5. Sensitivity analysis
   a. Min/max ^{235}U vector
   b. Min/max UCl_3-NaCl density ranges

Thermal Hydraulics Analysis

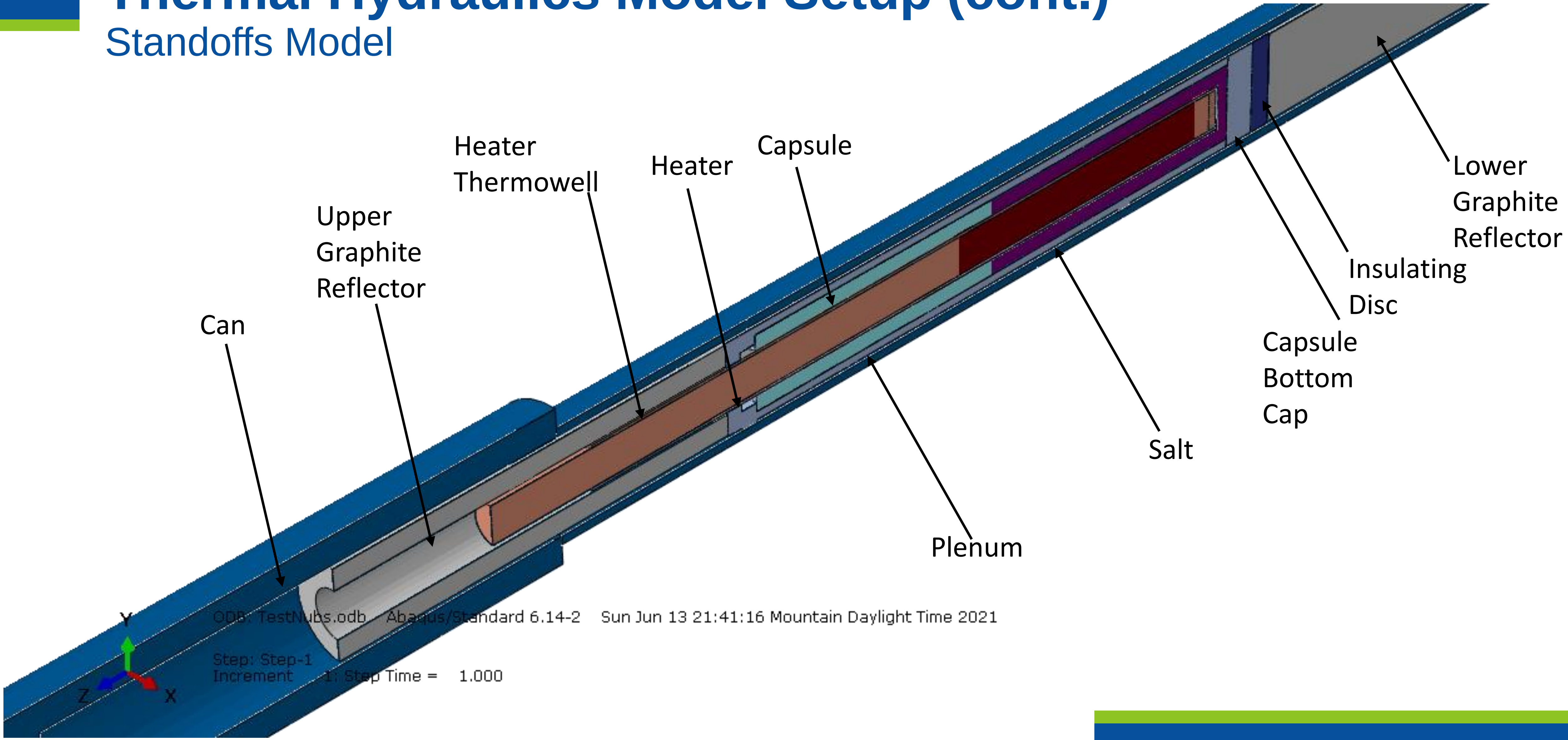
Stacey Wilson, SuJong Yoon

Thermal Hydraulics Model Setup

- ABAQUS 6.14-2
  - Three dimensional
  - 8 node linear heat transfer bricks
- Assumptions
  - Material properties are constant with temperature
  - No natural convection of salt
  - Thermocouples not explicitly modeled
  - Heater and heater thermowell have full thermal contact, attained in ABAQUS by adjusting the geometry
- NRAD Flow = 2 gpm and T_{inlet} = 40°C

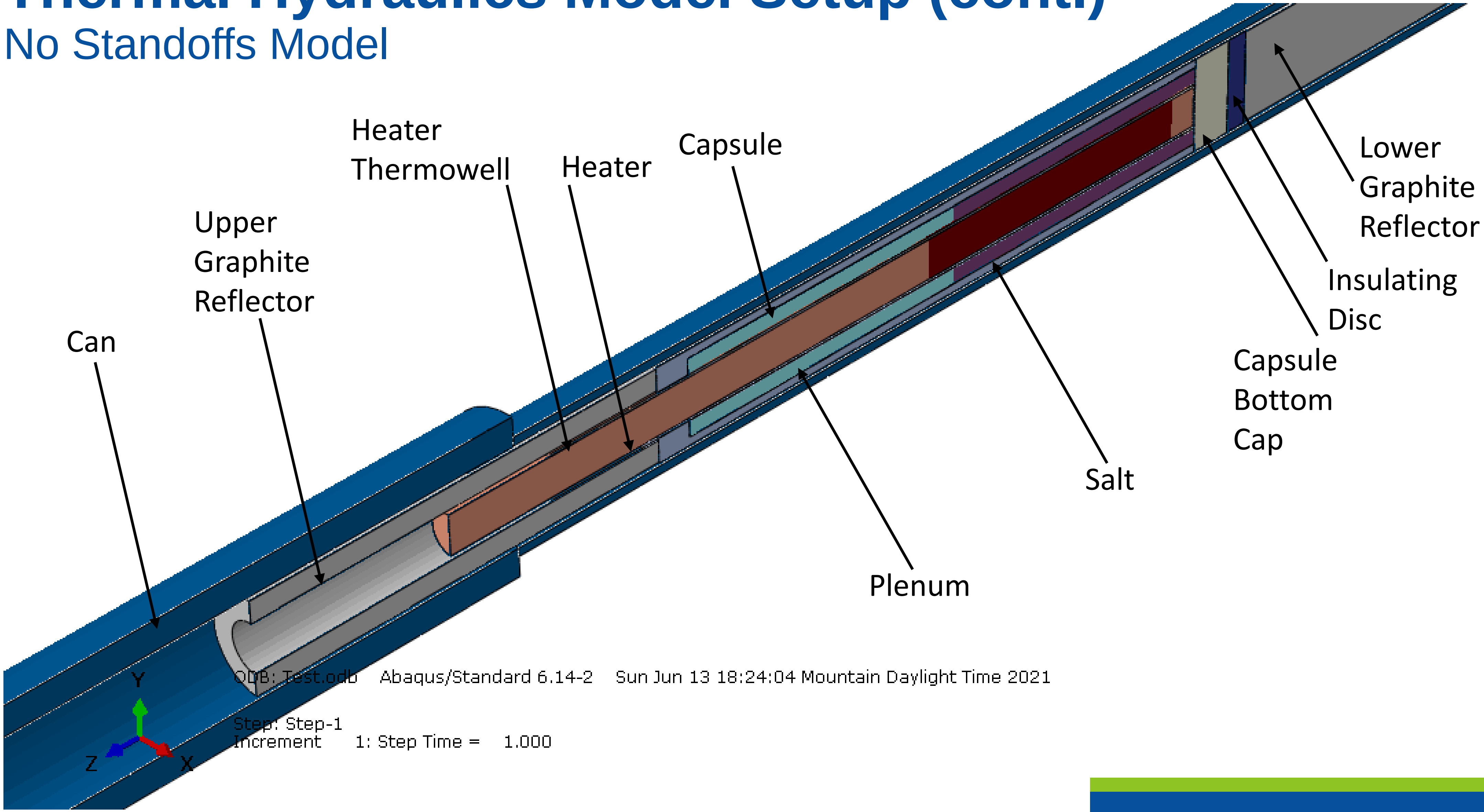
Thermal Hydraulics Model Setup (cont.)

Standoffs Model



Thermal Hydraulics Model Setup (cont.)

No Standoffs Model



Design Analysis and Outcomes

Standoff Model

Fission Heat	Heater Output (W)	Salt Tmax (degC)	Salt Tmin (degC)	Salt ΔT (ΔdegC)	Salt Tavg (degC)	Can Tmax (degC)	Percentage of Salt Melted
No	188	995	459	536	727	66	90.6%

- Main findings:
  - Standoffs in their current location cause an increase in salt temperature gradient and a decrease in percentage of salt melted during initial melting before irradiation begins
  - Standoffs cause an increase in the maximum can temperature as a localized hot spot

Design Analysis and Outcomes

No Standoffs Model

Fission Heat	Heater Output (W)	Salt Tmax (degC)	Salt Tmin (degC)	Salt ΔT (ΔdegC)	Salt Tavg (degC)	Can Tmax (degC)	Percentage of Salt Melted
No	216	990	483	507	736	53	97.5%
Yes	83	996	589	407	792	59	100%
Yes	0	726	464	262	595	54	94.7%

- Main findings:
  - Necessary to use heating during irradiation to ensure all salt is melted
  - More margin to material temperature limits may be required, which could result in frozen salt

Thermal Hydraulics Requirements with ABAQUS Results

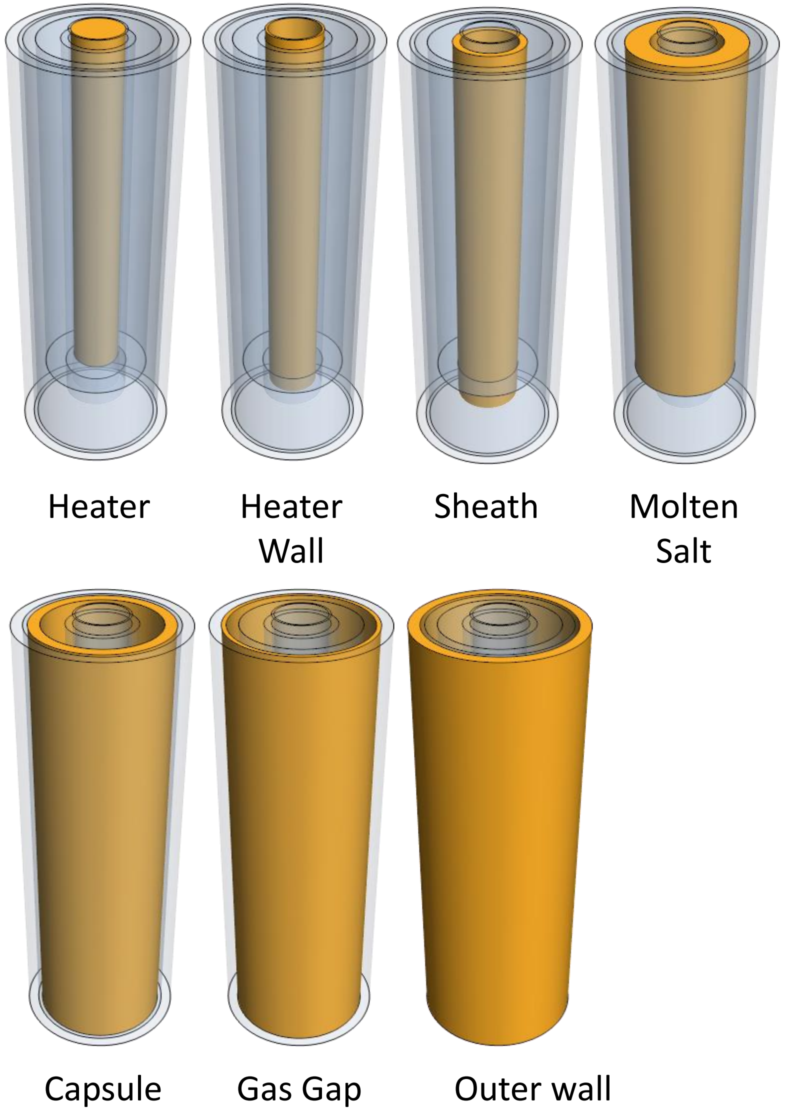
- Structural Requirements
  - Maximum heater temperature less than 1000°C
    - The analysis purposefully calculated maximum results, so heater output less than the reported values will ensure this requirement is met ✓

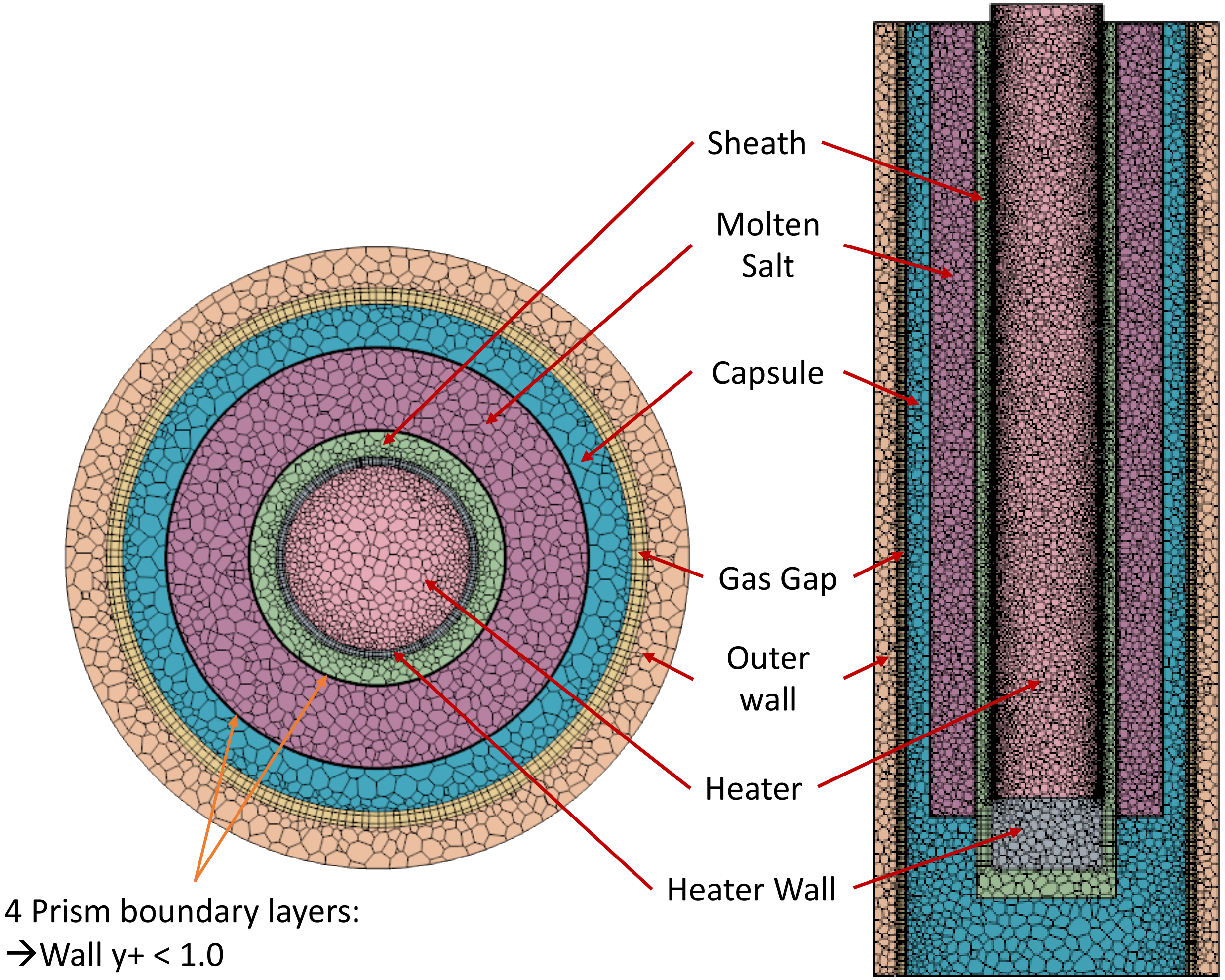
- Safety Requirements from FOR-585
  - 3.3.1.3: Maximum Temperature of Outer Surface of In-Tank Assembly = 70°C
    - Met in all cases ✓

Thermal Hydraulics Requirements with ABAQUS Results (cont.)

- Programmatic Requirements from FOR-584
  - 3.1.1.3: Salt Average Temperature = 600°C
    - Can be met with a combination of fission heating and heater input ✓
  - 3.1.1.3: Salt Temperature > 523°C
    - Can be met with a combination of fission heating and heater input ✓
  - 3.1.1.3: Radial and Axial Salt Temperature Gradients = Minimized
    - Gas gap of 100% argon helps to reduce the gradient ✓
  - 3.1.7.3: Time for Salt to Freeze After Irradiation = Maximized
    - Met by choosing appropriate insulating gas mixture ✓

Computational Fluid Dynamics (CFD) Model

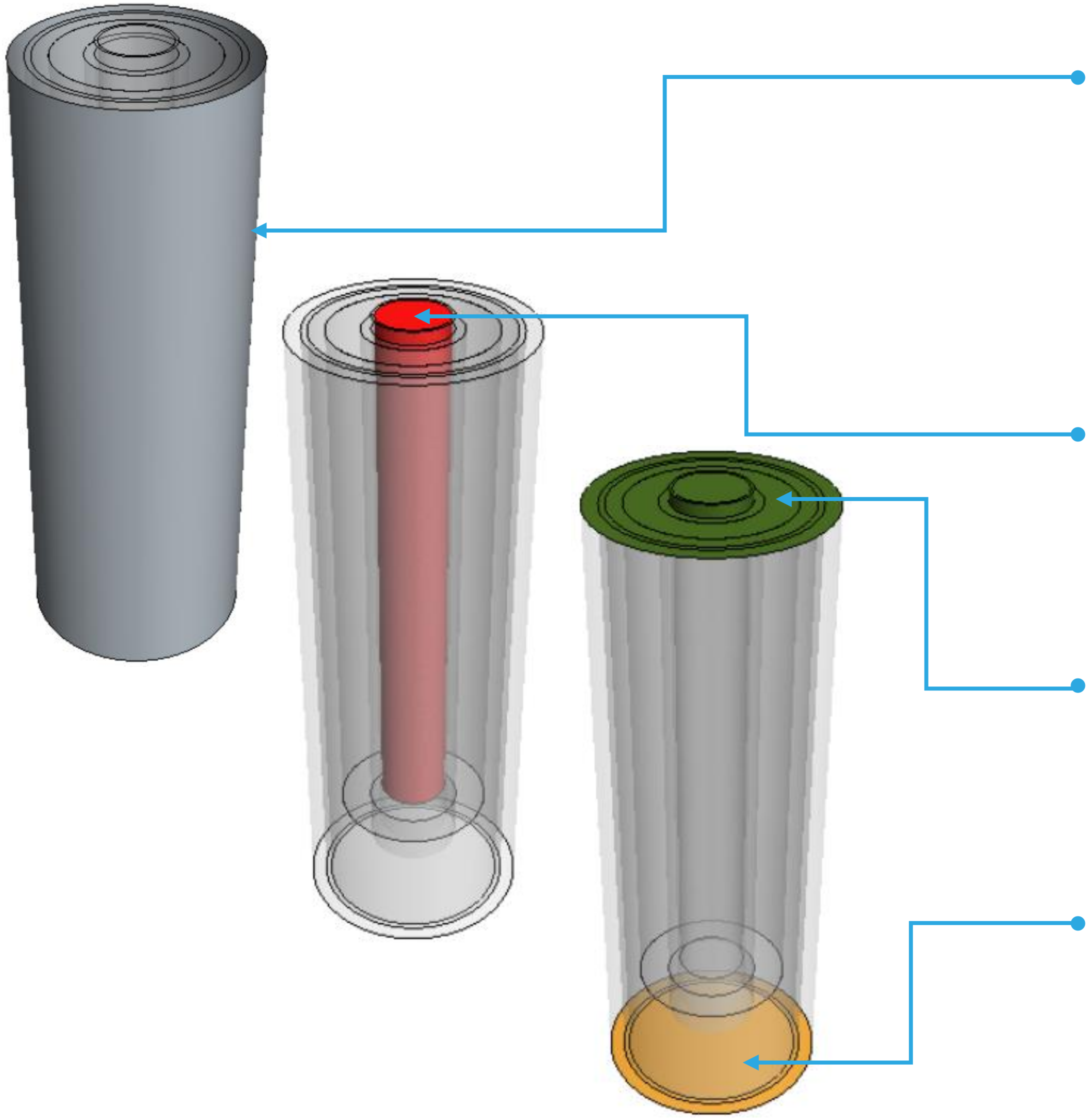




CFD Problem Setup

- Fluid region:
  - Segregated flow and segregated fluid temperature solvers
  - Gravity model
  - Reynolds-Averaged Navier-Stokes (RANS) equations-based solver with Shear Stress Transport (SST) k-ω turbulence model.
    Note that calculated Ra(=Gr*Pr) > 10^9.
  - Temperature-dependent density and dynamic viscosity, constant specific heat and thermal conductivity.
- Gas gap region:
  - Gap conductance only
  - Constant properties
- Solid region:
  - Segregated Solid energy solver
  - Constant properties

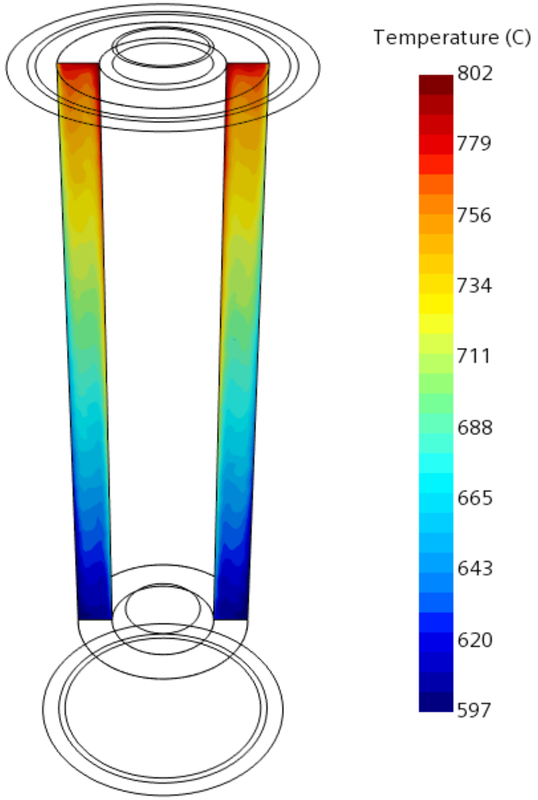
CFD Model Boundary Conditions



- Outer wall surface: convective cooling
  - Ambient temperature: 40°C, HTC:1250W/m^2-K
- Heater: volumetric heat generation
  - 21.3 MW/m^3, Total heater power: 89.6 W
- Top surface: adiabatic (Argon gas works as insulation)
- Bottom walls: adiabatic (insulated)

CFD Analysis Results

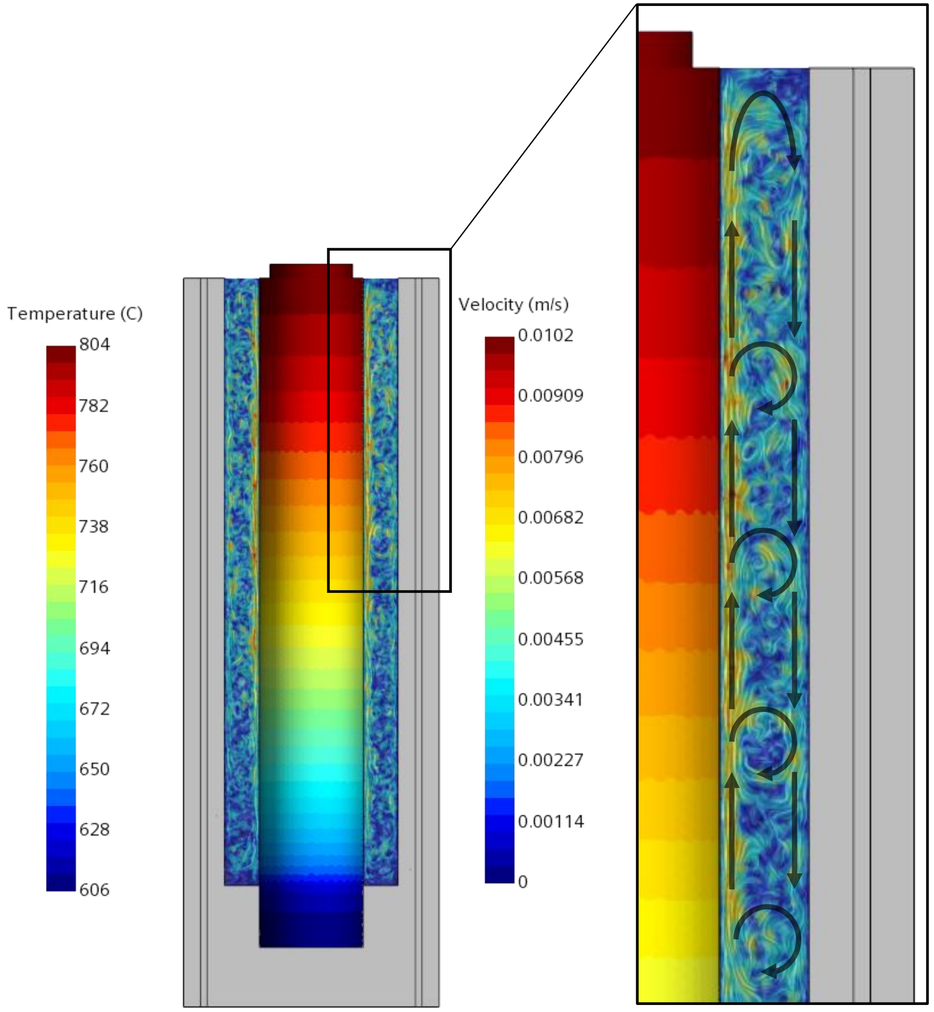
Molten Salt Temperature



Main Outcomes:

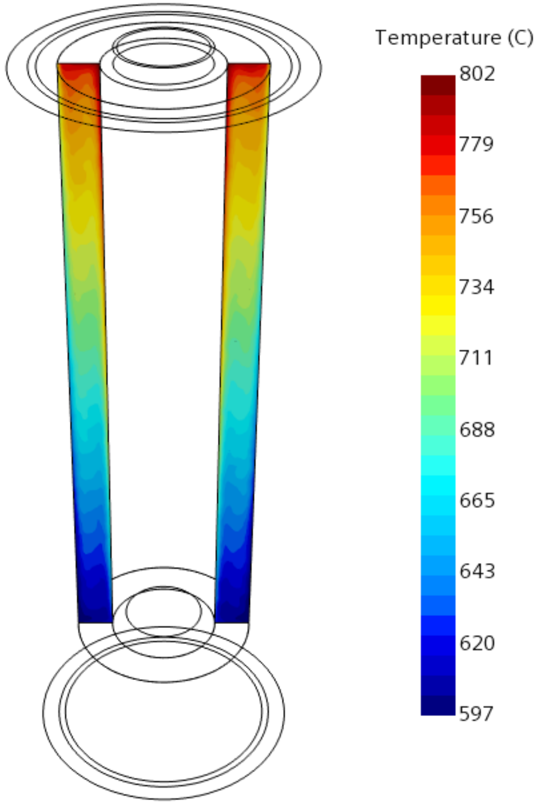
- Wall/salt temperatures within allowable ranges: no IN-625 melting or salt freezing
- Assumed salt conductivity of 0.2 W/m-K
- Noticeable natural circulation in salt with formation of vortices
- Peak velocity of 0.01 m/s

Wall Temperature + Fluid Velocity

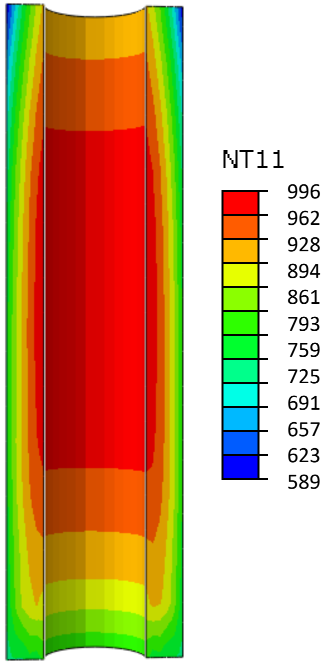


Comparison between ABAQUS & STAR CCM+

STAR-CCM+



ABAQUS



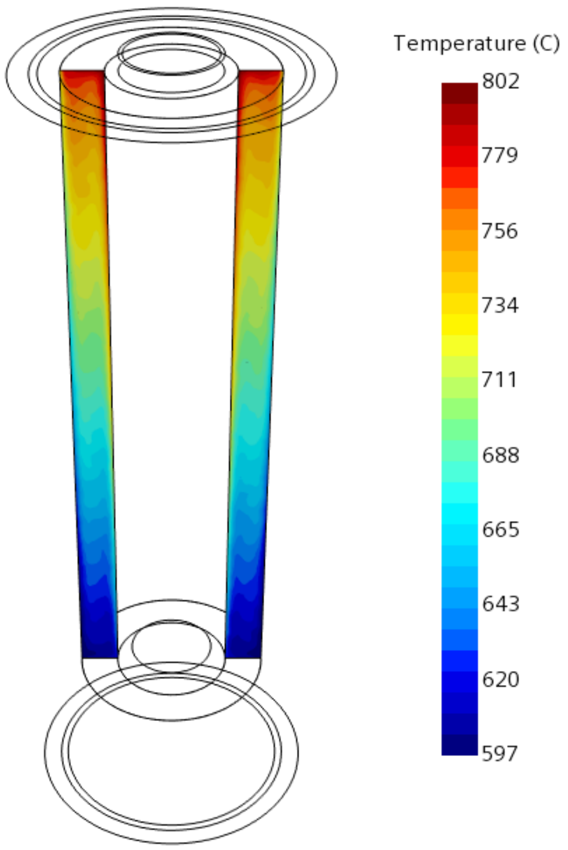
Main Findings:

- Delta T in salt:
  - STAR-CCM+ = 205°C
  - ABAQUS = 407°C
- Heat conduction-only model: overly conservative

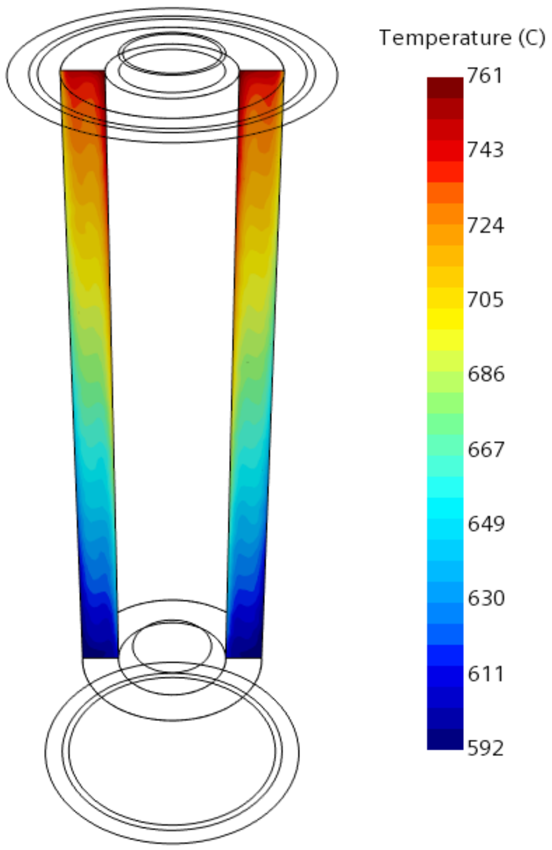
CFD Salt Property Sensitivity Analysis

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

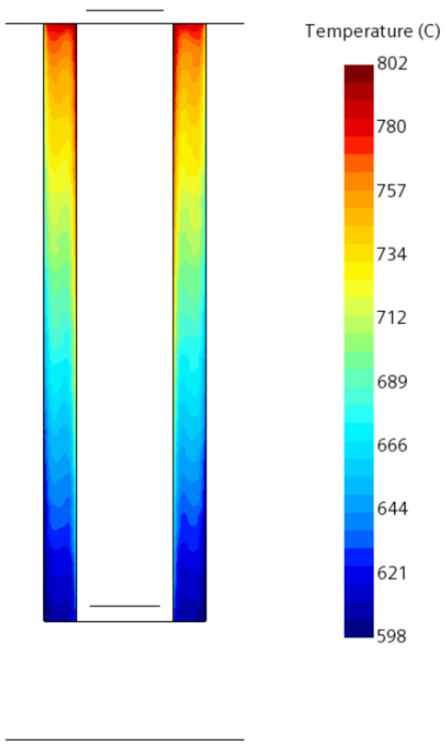


k = 0.2 W/m-K



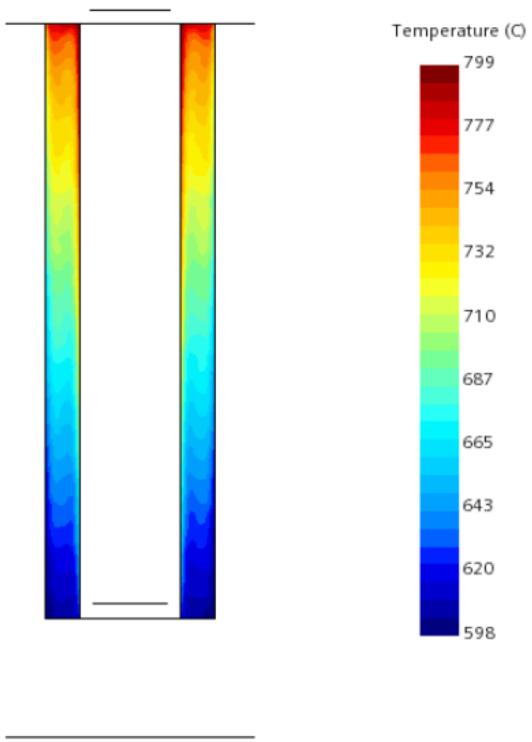
k = 0.5 W/m-K

Impact of Turbulence and Mesh Size



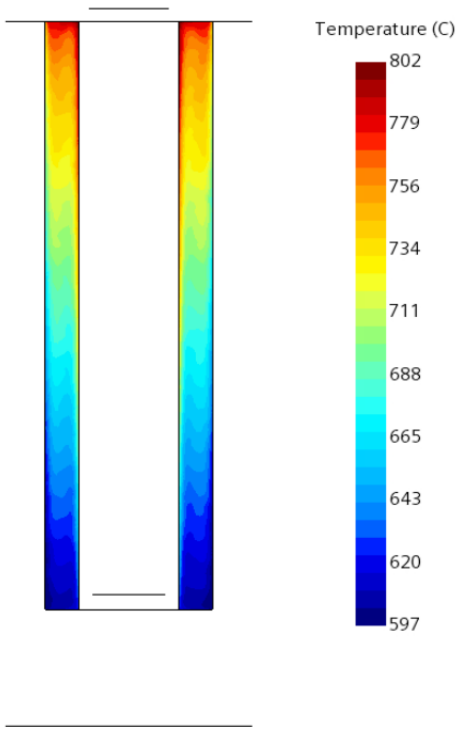
Laminar

T_{max} = 802ºC



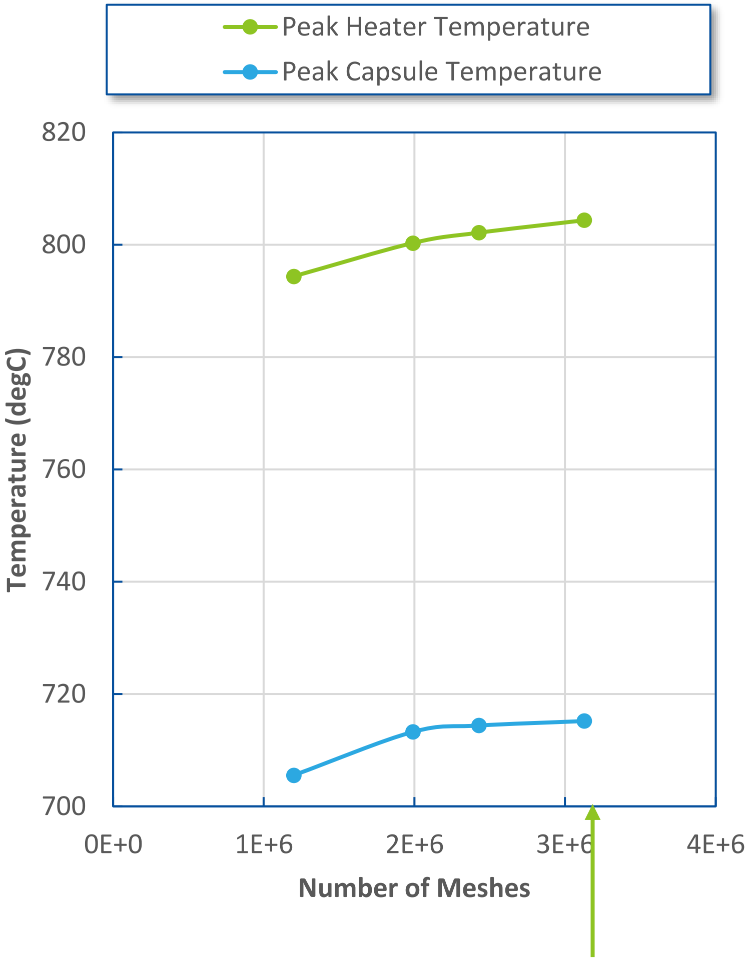
Realizable k-ε two-layer

T_{max} = 799ºC



SST k-ω

T_{max} = 802ºC



Chosen mesh size

Thermal Hydraulics Actions into Final Design

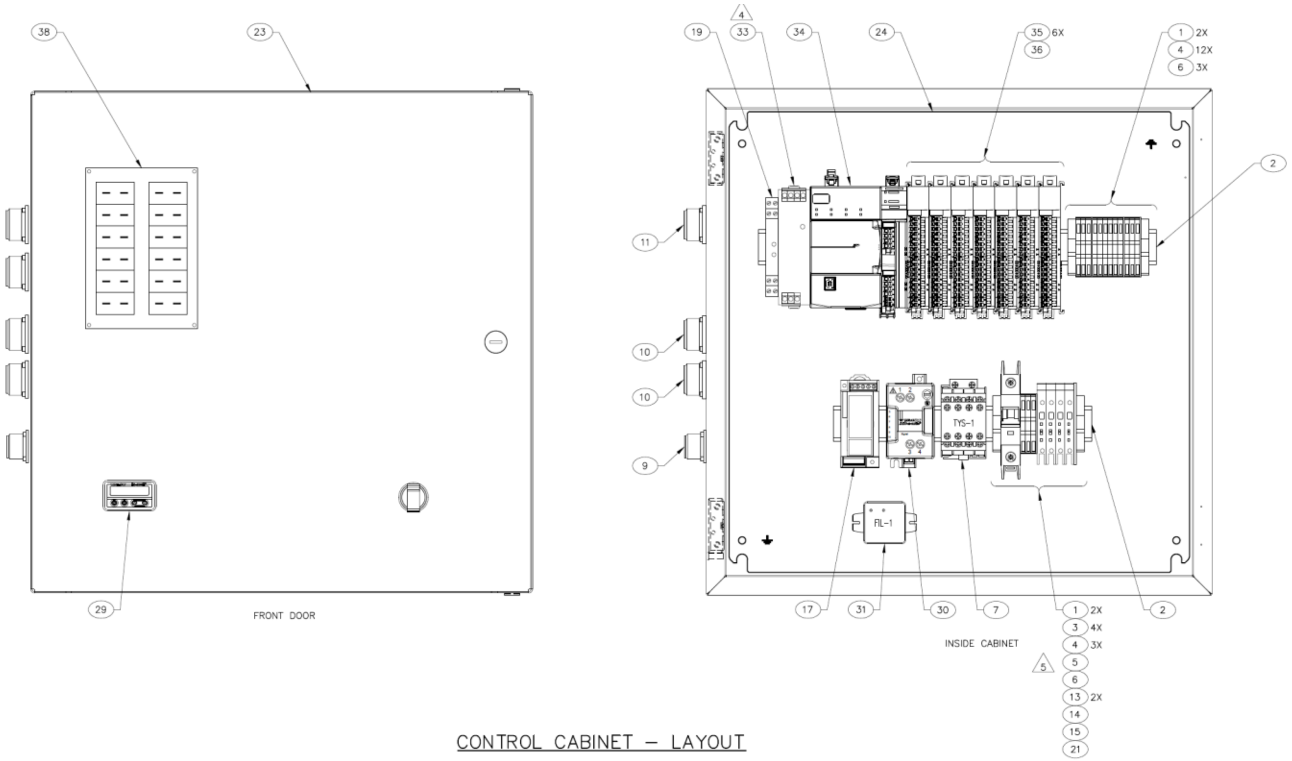
1. Update geometry to reflect most current design
2. Update heating rates to reflect appropriate material and geometry (namely stand off locations)

Systems Control & Electrical Design

J. Chandler (presented by K. Davies)

Control System Status

- Design relies heavily (~80%) on a design in-progress used by another experiment in NRAD (CHARIN)
- Equipment and parts list complete
- Draft drawings complete
- Majority of components have been ordered
- All requirements expected to be met
- Facility mods to support experiment monitoring and controlling underway and ongoing
- Review and assembly still to complete

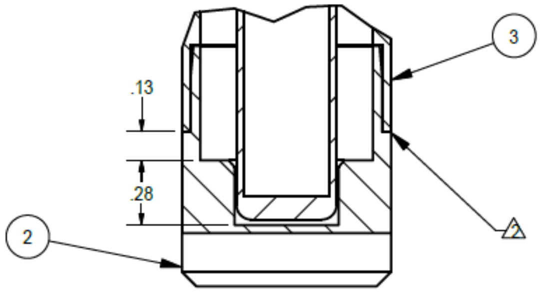


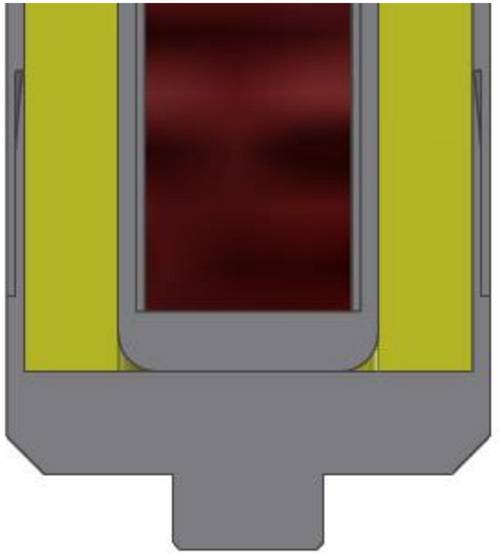
Resulting Mechanical Design from Preliminary Design Activities

Calvin Downey

MRTI Heater Considerations going into Final Design

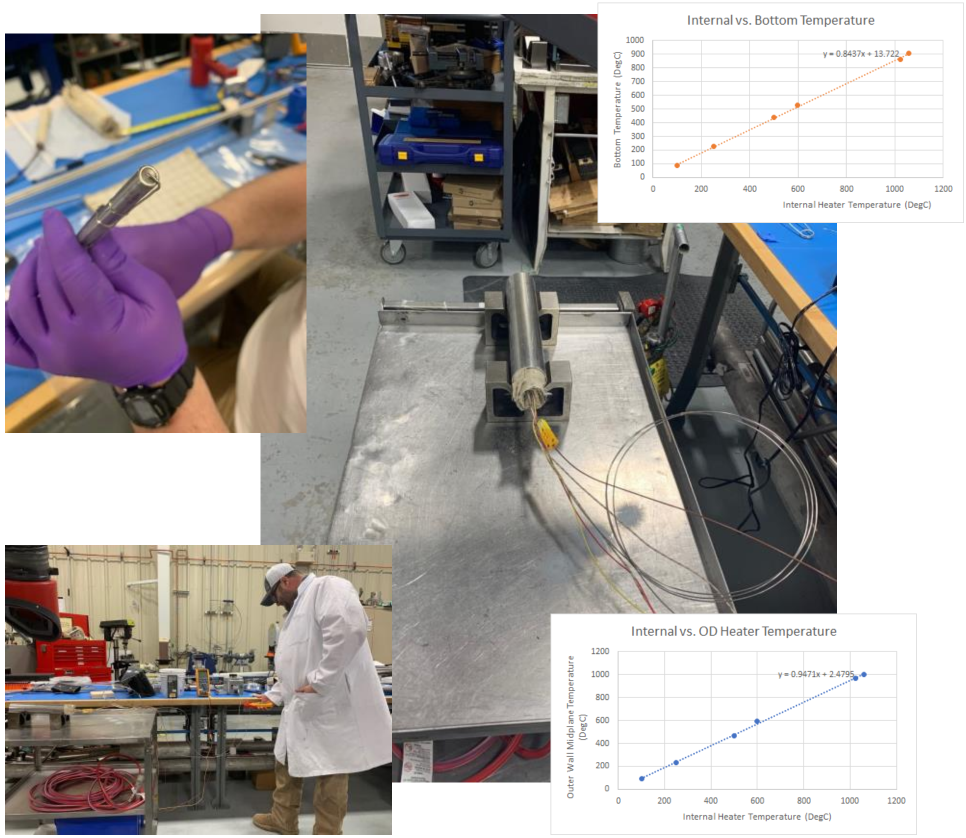
- Bottom 0.25" cap of heater is unheated and could freeze salt
- Iterated design aimed at keep salt within only heated region:





- Remove pocket
- Heater flush or slightly offset from bottom of capsule

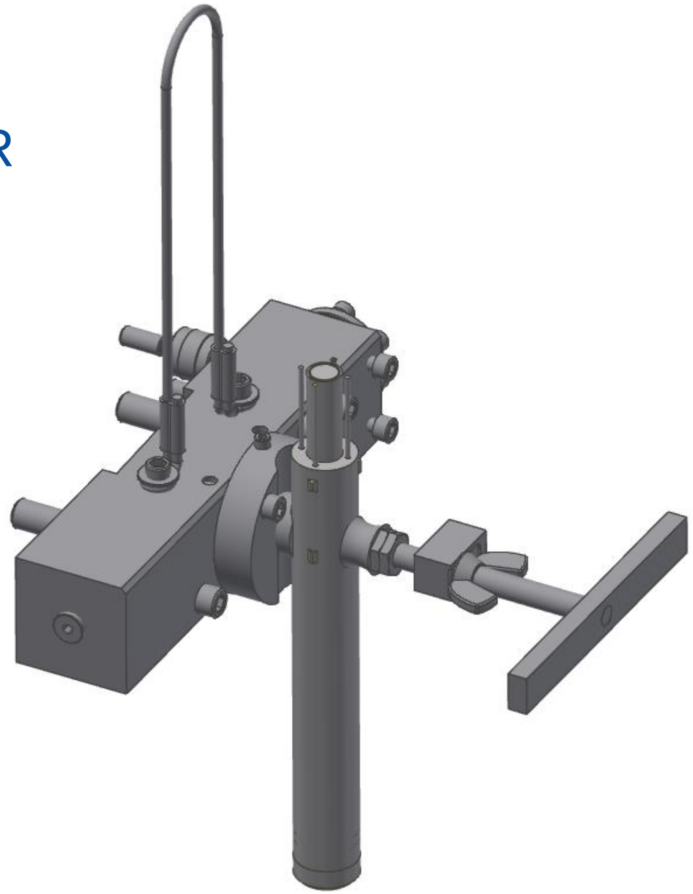
- Test to empirically confirm sufficient heat transfer into bottom unheated section



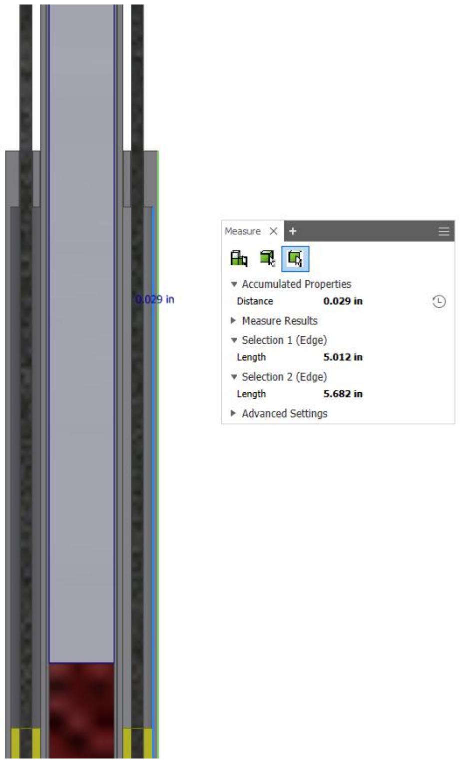
- Potential issues with PIE with salt capillary into pocket, or with major heater offset from bottom

MRTI PIE Considerations going into Final Design

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



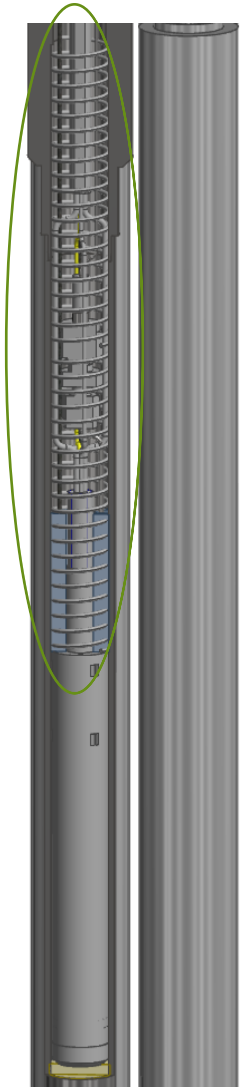
- Revised wall thickness of .029" allows for GASR laser to more easily penetrate into plenum
- Reduced wall may also increase reliability of frozen salt recovery



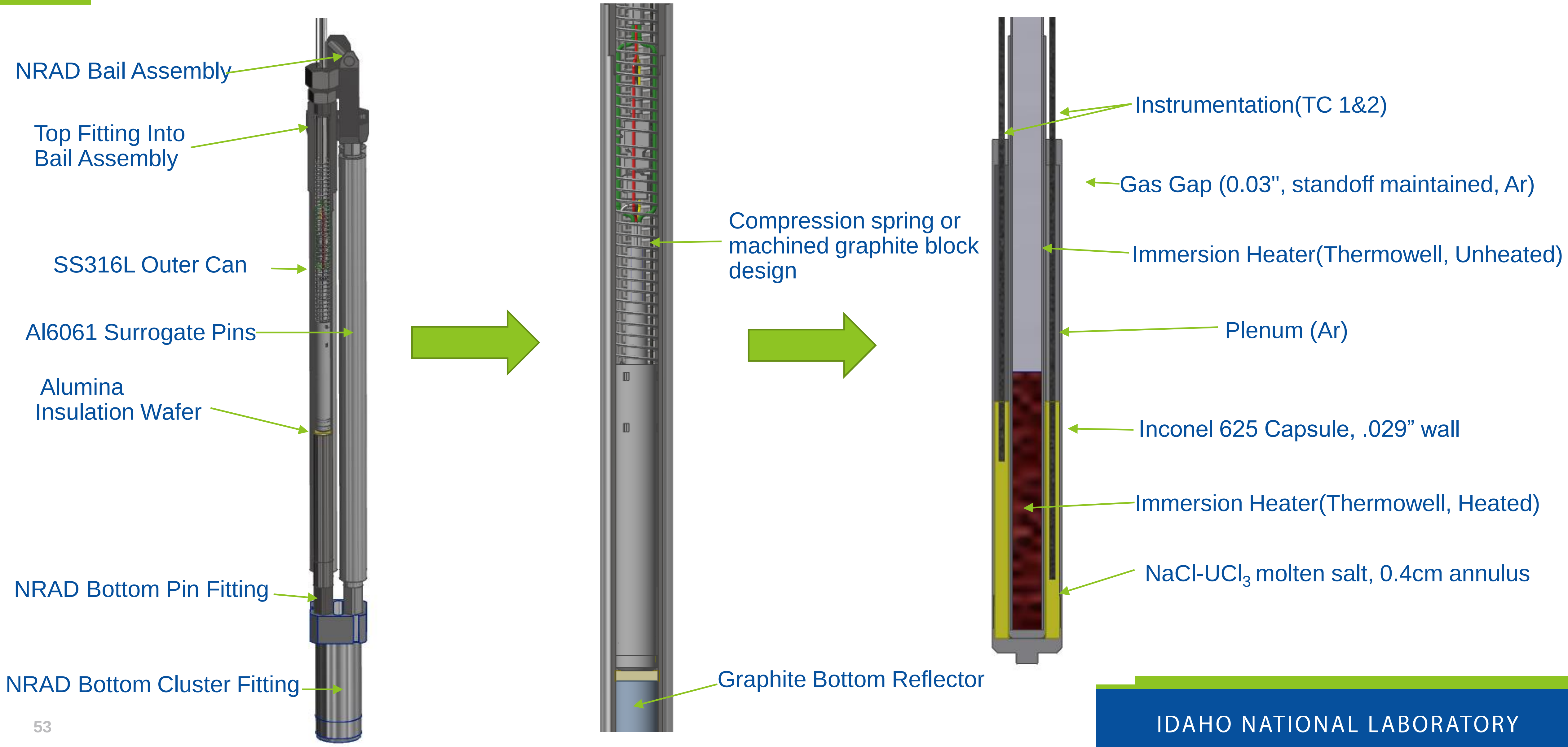
- Sample tubing in process of procurement to test MRTI capsule wall thickness and fitment into GASR system

MRTI Internal Supports Considerations going into Final Design

- Gas gap standoffs (.03”) moved into plenum region to not affect radial conductive heat transfer from salt
- Bottom slot geometry into Alumina insultation ensures that bottom of assembly remains coaxial and does not create thermal contact with Outer Can wall
- Compression springs under consideration to solidify capsule into insulation wafer and alleviate capsule shifting during post-irradiation handling; will affect neutronics slightly in final design versus graphite top reflectors



MRTI Current Preliminary Design



Questions?