INL/MIS-21-62139-Revision-0

Molten-salt Research Temperature-controlled Irradiation (MRTI) Conceptual Design Review

March 2021

Changing the World's Energy Future

Abdalla Abou Jaoude, Kim B Davies, Stacey M Wilson, Calvin Myer Downey, Gregory M Core

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-21-62139-Revision-0

Molten-salt Research Temperature-controlled Irradiation (MRTI) Conceptual Design Review

Abdalla Abou Jaoude, Kim B Davies, Stacey M Wilson, Calvin Myer Downey, Gregory M Core

March 2021

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

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

March 24, 2021

Abdalla Abou-Jaoude, Gregory Core, Kim Davies, Calvin Downey, Stacey Wilson

Molten-salt Research Temperature-controlled Irradiation (MRTI)

Conceptual Design Review

Idaho National Laboratory

Introduction & Overview

Greg Core

Design Team

Abdalla Abou-Jaoude
Neutronics

Kim Davies
Mechanical and Electrical Design

Calvin Downey
Mechanical Design

Stacey Wilson
Thermal Hydraulics

Bill Phillips
Materials & Chemistry Advisor

Greg Core
Project Manager

Experiment Overview & Goals

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

Design Review Objectives

Purpose of Conceptual Design

Generate options that satisfy the project's requirements

Purpose of the Conceptual Design Review

Present the engineering design team's solutions and recommendations to the sponsor

Primary Objective of the Conceptual Design Review

Obtain agreement from sponsor to proceed with preliminary design using recommended design solution

- All attendees are asked to provide input and feedback
- The LDRD PI team will develop a consensus decision supporting further design activities

Design Figures of Merit

Rank	Figure	Characteristic	Value
1	**Burnup** (highest concentration of fission products)	Maximize	N/A
2	**Salt Temperature**	Target	600 deg-C
3	**Experiment-Pool Interface Temperature**	Target	70 deg-C
4	**Power Density**	Target	20 W/cc
5	**Volume of Salt** (cc)	Maximize	$\geq$ 5 cc
6	**Radial and Axial Salt Temperature Gradients**	Minimize	N/A
7	**Surface Area-to-Volume Ratio** (Capsule wall to salt volume)	Minimize	N/A

Requirements Documents

FOR-584, Experimenter's Requirements (PI Team's Requirements)
FOR-585, Mechanical and Interface Requirements

Mechanical Design

Kim Davies and Calvin Downey

Mechanical/Physical System Internal & External Interfaces

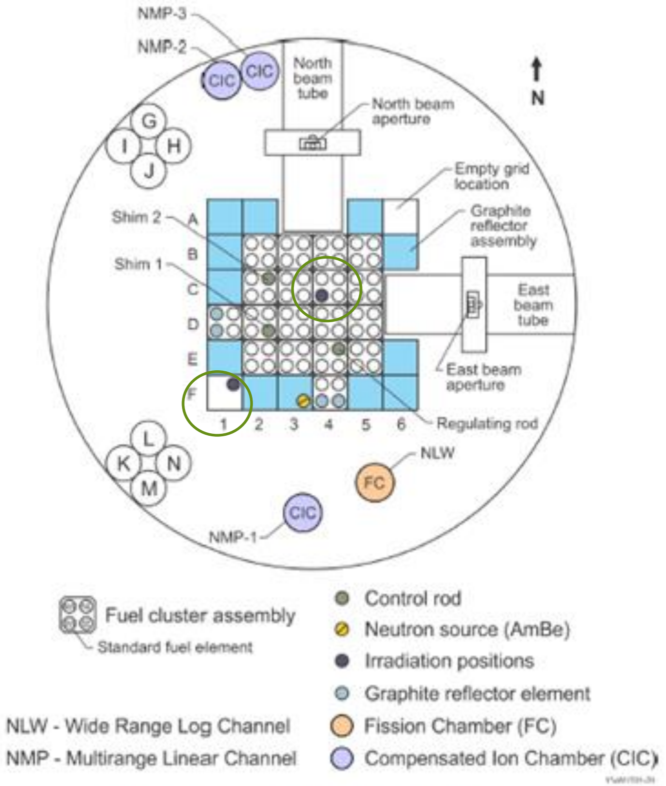
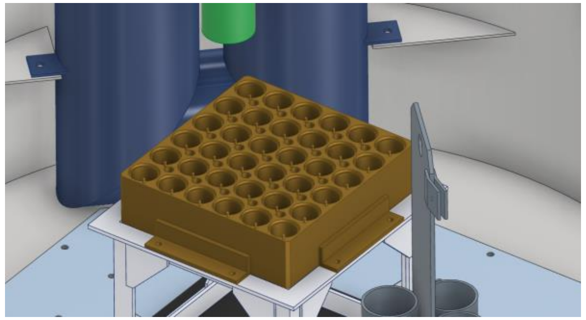


Figure 1. Sixty-four-element core and tank layout.

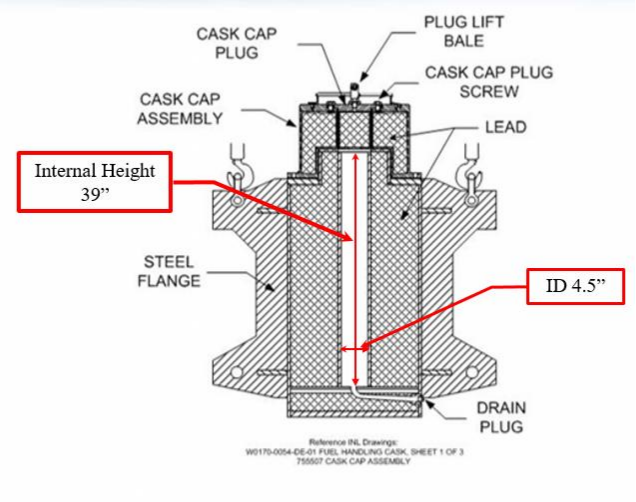
NRAD Core Grid Plate



Cluster End Grid Plate Fitting

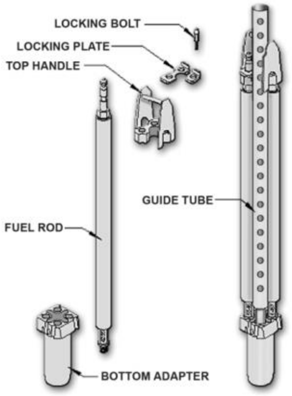
Pin Fitting into Cluster End Fitting

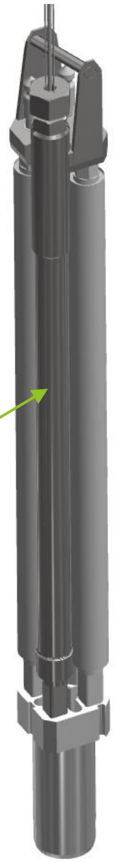
NRAD Transport Cask



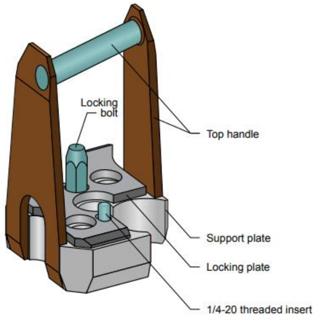
Graphic Overview of Design Options

- Design 1&2: MRTI Immersion Design
  - Largely designed to match NRAD fuel cluster guide tube assembly
  - Interfaces with grid plate
  - Traditional fuel cluster top 45° bail for handling
  - Pre-assembled with 3 pins into a cluster (F1)
  - Singular salt capsule within outer can, separated by gas gap

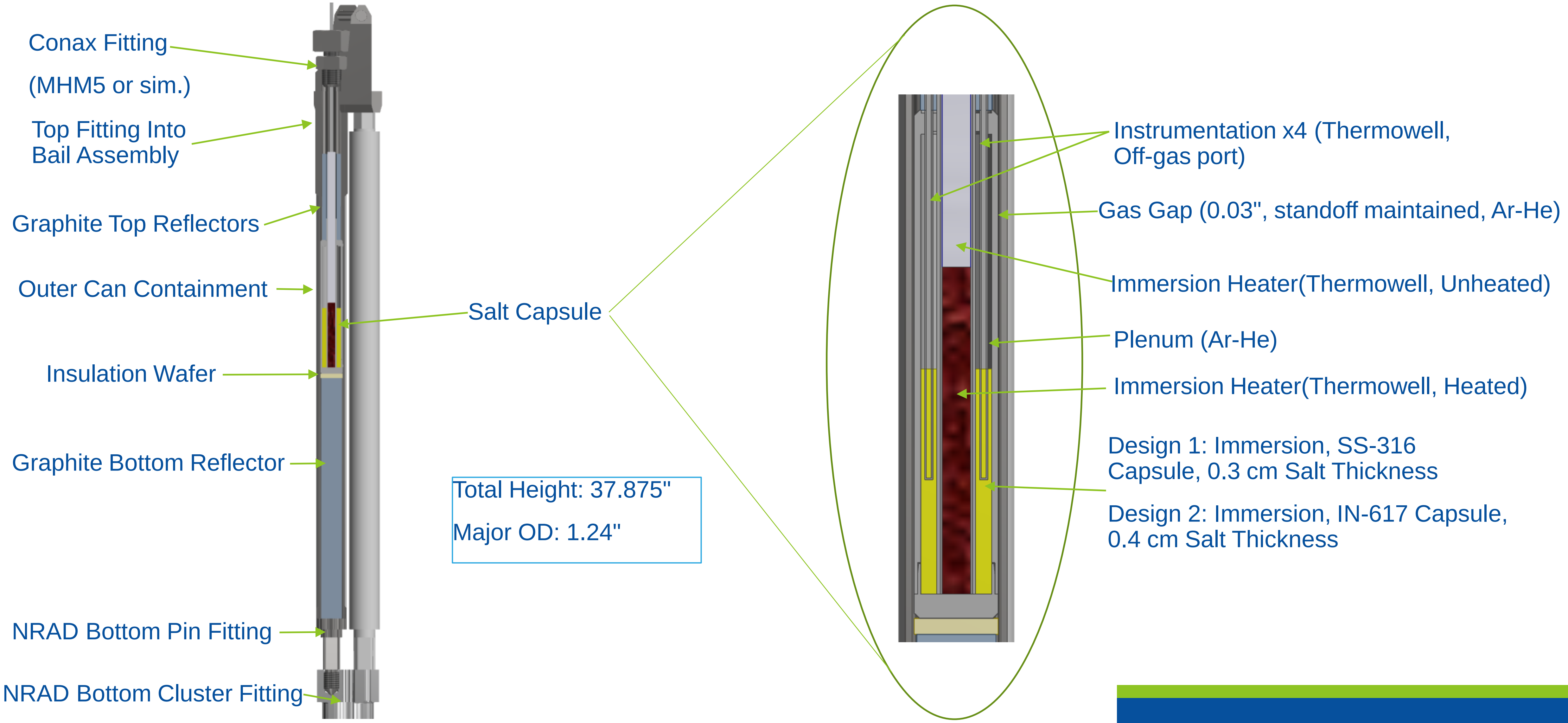




- Design 3: MRTI Monolith Design
  - Outer dimensions of NRAD CHARIN design
  - Interfaces with grid plate
  - Configured fuel cluster top 45° bail for handling
  - Internal graphite monolith with 4 inserted salt capsules within outer can, separated by gas gap
  - Perforated bottom places salt midplane



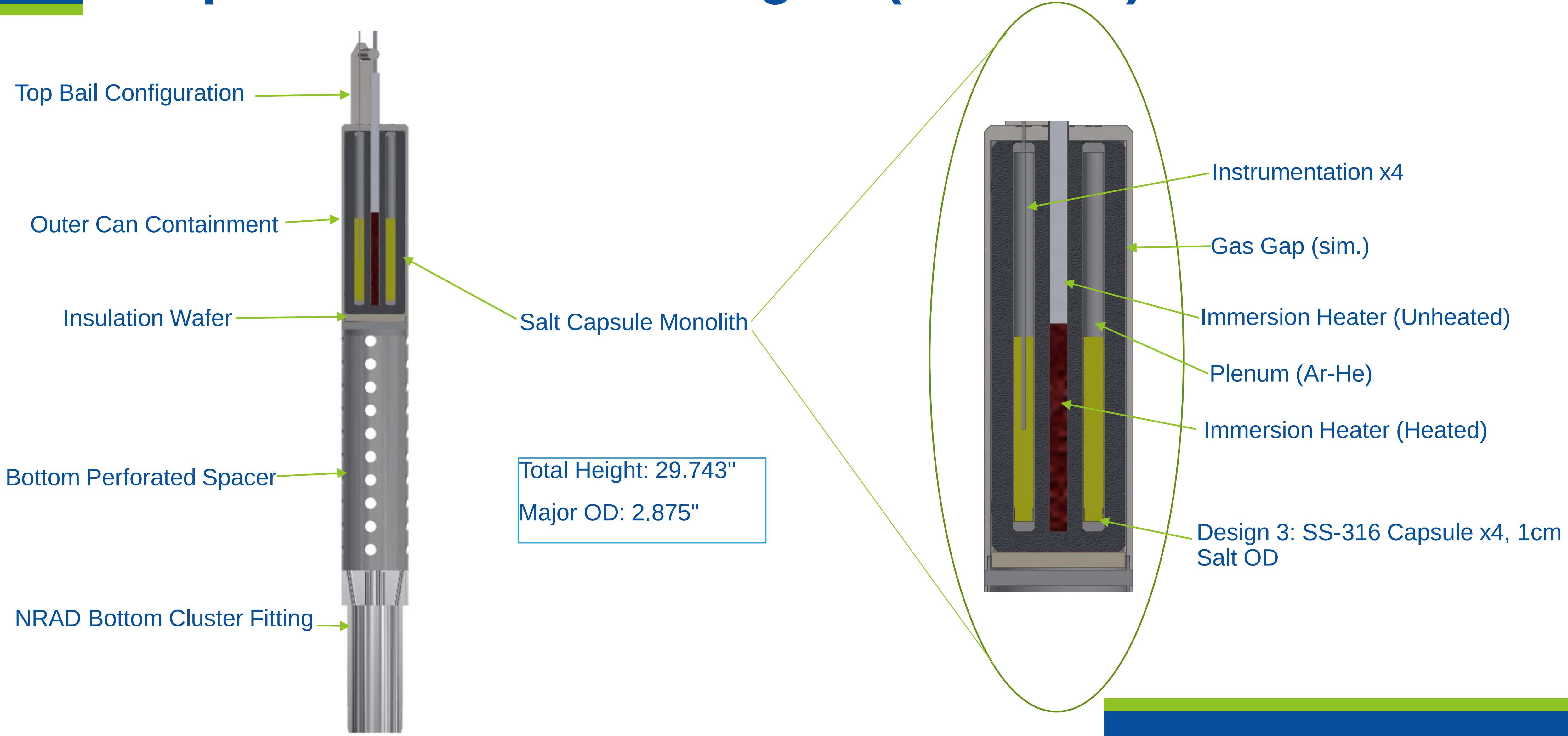
Graphic Overview of Design 1 & 2 (Immersion)



Total Height: 37.875"

Major OD: 1.24"

Graphic Overview of Design 3 (Monolith)



Total Height: 29.743"

Major OD: 2.875"

Nuclear Safety Requirements

- Containment
  - Material choices
    - Salt facing materials should be compatible with molten salt (corrosion and temp.)
    - Containment material will be QL-1 (QV, green tagged, CMTRs, inspection)
  - # of Boundaries
    - It is preferred to maintain two sealed environments, with one claimed as the primary containment vessel
  - Sealing options
    - Primary containment vessel must be QL-1, standard weld/braze procedures and inspections required, potential testing on Conax fitting
  - Internal Pressure Generation
    - At least standard cladding thickness SS, high plenum volume

Operational Requirements

- Requirements per FOR-585

Operational	Value	System
Containment Compatible with Water, 12ft Submerged Depth	Provide	Assembly
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-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

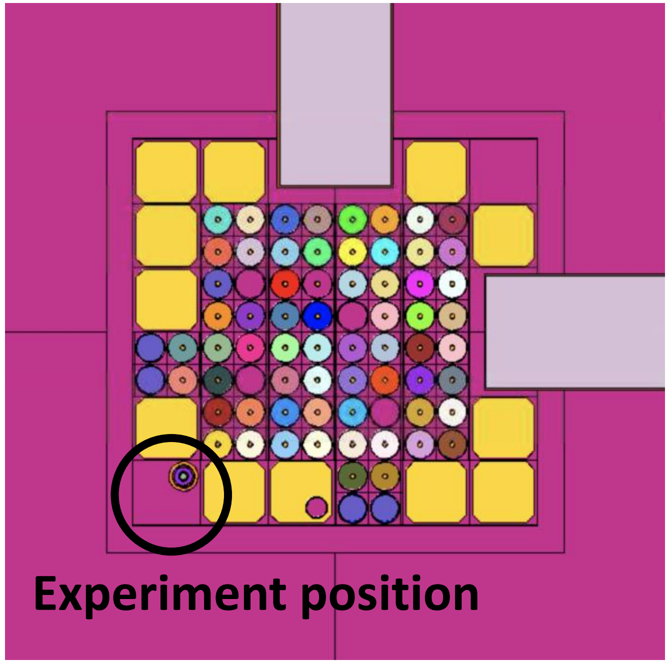
Neutronics Analysis

Abdalla Abou-Jaoude

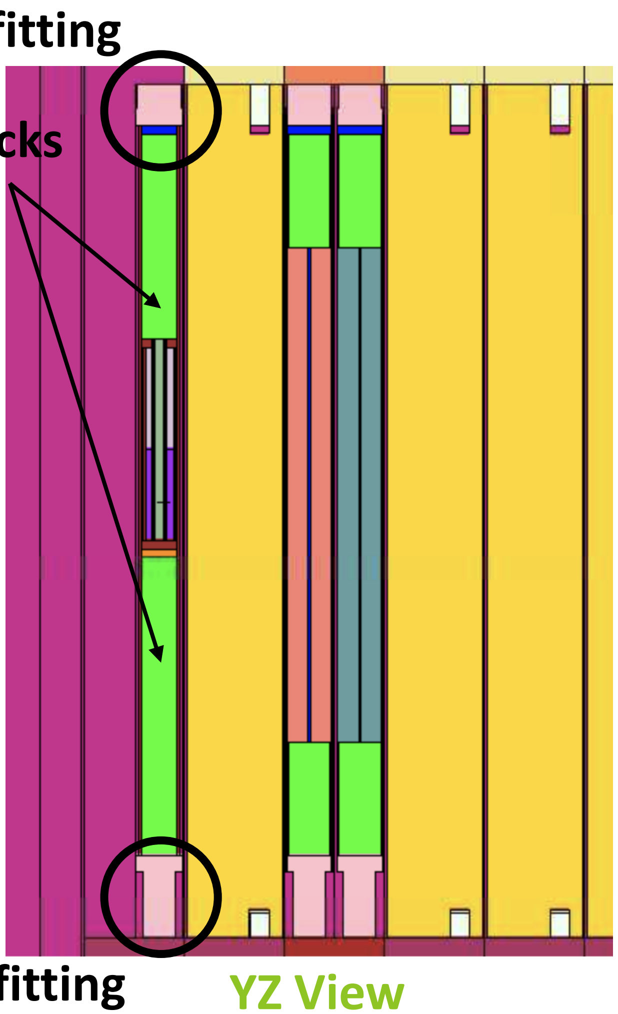
Reactor Physics Requirements

- 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.

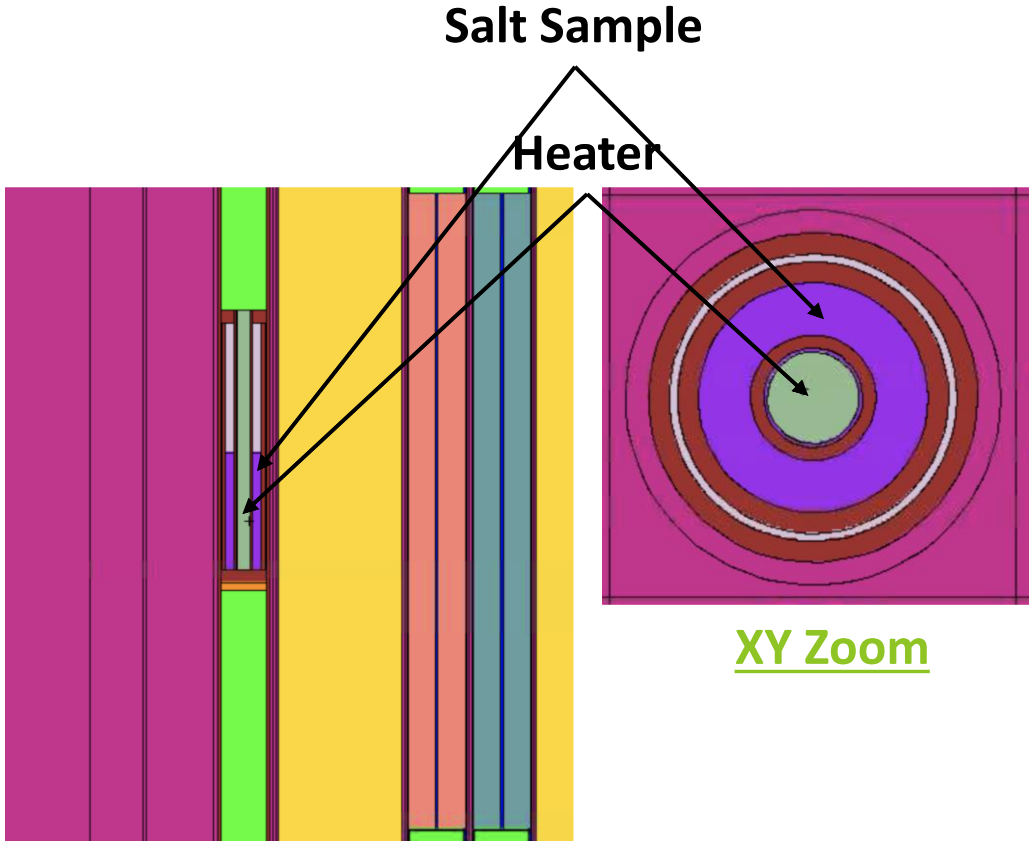
Design 1 & 2: Immersion Heater



XY View



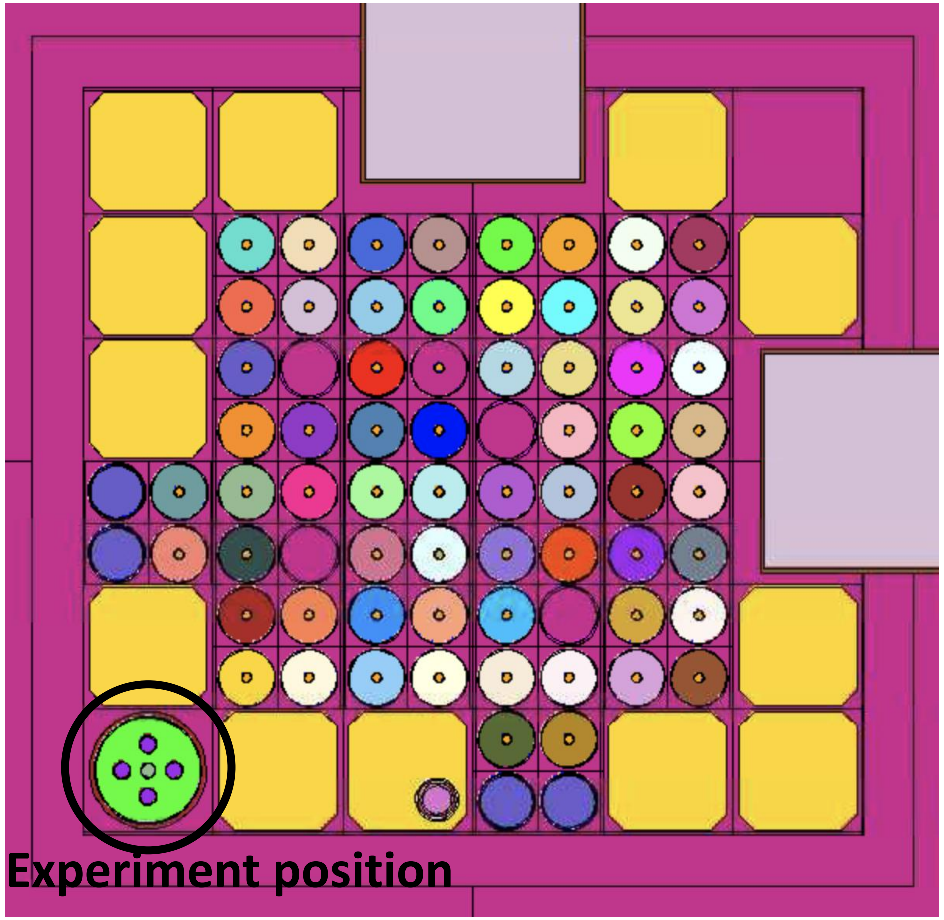
YZ View



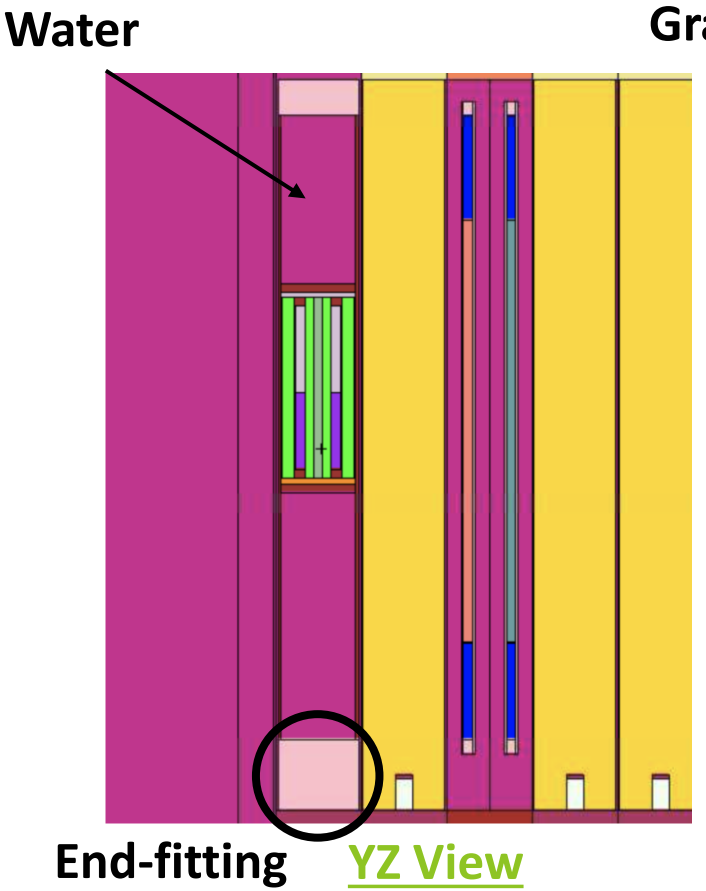
YZ Zoom

XY Zoom

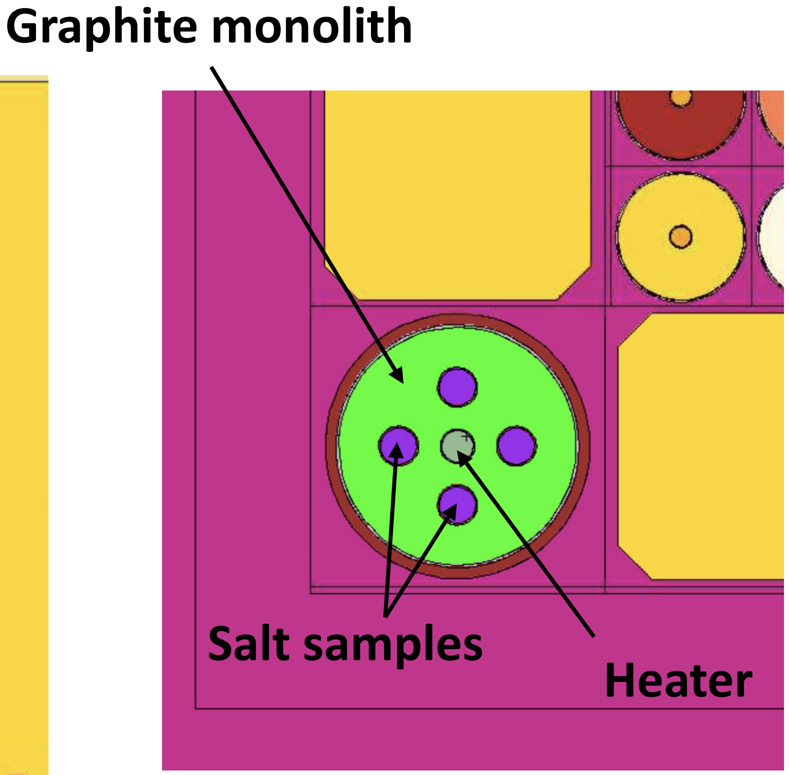
Design 3: Graphite Monolith



XY View



YZ View



XY Zoom

Immersion Option: Design Matrix

- **Design 1** = SS-316 / SS-316 / F-1/ 0.3 cm / HEU
- **Design 2** = SS-316 / IN-617 / F-1 / 0.4 cm / HEU

	Options		Considerations
Outer Can Material	Al	SS-316	Temperature & manufacturing
Capsule Material	SS-316	IN-617	Temperature & corrosion
NRAD Position	F-1	C-4	Power density & temperature
Salt thickness	0.4 cm	0.3 cm	PIE & temperature
^{235}U enrichment	HALEU	HEU	Power density & temperature

Neutronic Performances: Heat Generation Rates (1)

Sensitivity: outer can, enrichment, and position

Outer can	Al	Al	Al	Al	SS-316	SS-316	SS-316
Inner capsule	SS-316	SS-316	SS-316	SS-316	SS-316	SS-316	SS-316
NRAD Position	F-1	F-1	C-4	C-4	C-4	C-4	F-1
Salt thickness	0.5 cm	0.5 cm	0.5 cm	0.5 cm	0.5 cm	0.5 cm	0.5 cm
Enrichment	19.75%	93.20%	19.75%	93.20%	19.75%	93.20%	93.20%
Salt volume (cc)	18.7	18.7	18.7	18.7	18.7	18.7	18.7
Flux (n/cm^2-s)	3.47×10^{12}	4.43×10^{12}	1.61×10^{13}	1.76×10^{13}	1.58×10^{13}	1.72×10^{13}	4.00×10^{12}
Fission power (W/cc)	8.78	29.07	13.09	50.23	12.81	49.10	24.63

- Main findings:
  - LEU fuel not feasible from a power density standpoint
  - Limited penalty with opting for SS-316 outer can
  - C-4 can contribute to x2 increase in W/cc

Neutronic Performances: Heat Generation Rates (2)

Sensitivity: outer can, inner capsule, and salt thickness

	(from before)					
Outer can	SS-316	SS-316	SS-316	IN-617	SS-316	SS-316
Inner capsule	SS-316	SS-316	IN-617	IN-617	IN-617	IN-617
NRAD Position	F-1	F-1	F-1	F-1	F-1	F-1
Salt thickness	0.5 cm	0.3 cm	0.5 cm	0.5 cm	0.3 cm	0.4 cm
Enrichment	93.20%	93.20%	93.20%	93.20%	93.20%	93.20%
Salt volume (cc)	18.7	9.9	18.7	18.7	9.90	14.07
Flux (n/cm^2-s)	4.00×10^{12}	4.12×10^{12}	3.60×10^{12}	3.27×10^{12}	3.68×10^{12}	3.64×10^{12}
Fission power (W/cc)	24.63	35.73	20.39	17.08	29.15	23.99

- Main findings:
  - IN-617 in inner capsule contributes to limited penalty in W/cc
  - IN-617 in outer can discouraged
  - Reducing salt thickness by 0.1 cm can increase ~ +10 W/cc

Reactivity Margin Considerations

	Base	Voided							(10 cm salt)
Outer can	N/A	Al	SS-316	SS-316	SS-316	SS-316	SS-316	SS-316	SS-316
Inner capsule	N/A	void	SS-316	SS-316	SS-316	SS-316	SS-316	SS-316	SS-316
NRAD Position	N/A	C-4	C-4	F-1	C-4	C-4	C-4	C-4	C-4
Salt thickness	N/A	N/A	0.5 cm	0.5 cm	0.5 cm	0.5 cm	0.5 cm	0.5 cm	0.5 cm
Enrichment	N/A	N/A	93.20%	93.20%	93.20%	93.20%	93.20%	93.20%	93.20%
Axial material	N/A	N/A	Graph.	Graph.	ZrH	Be	BeO	Graph/H_2O	Graph.
Salt volume	N/A	N/A	18.7	18.7	18.7	18.7	18.7	18.7	26.7
Reactivity (cents)	-	-66.71	-56.54	1.86	-54.79	-47.90	-47.52	-63.19	-49.28

- Main findings:
  - Very challenging for C-4 configuration to meet reactivity target of < 40 cents
  - Can reduce operating power to compensate
  - Almost no impact in F-1

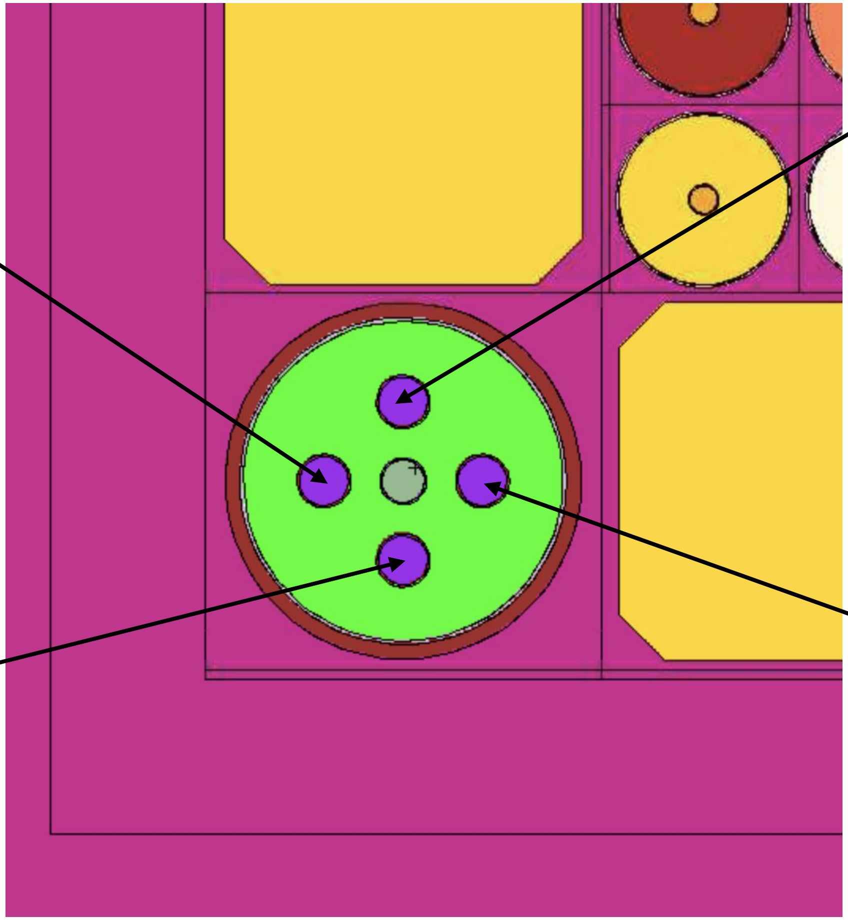
Evaluation of Graphite Monolith Design

West Position

- Fission heat = 17.1 W/cc
- Flux = 2.37×10^{12} n/cm^2-s
- Salt volume = 5.5 cc

South Position

- Fission heat = 17.1 W/cc
- Flux = 2.34×10^{12} n/cm^2-s
- Salt volume = 5.5 cc



North Position

- Fission heat = 24.1 W/cc
- Flux = 3.35×10^{12} n/cm^2-s
- Salt volume = 5.5 cc

East Position

- Fission heat = 24.6 W/cc
- Flux = 3.32×10^{12} n/cm^2-s
- Salt volume = 5.5 cc

Hand-off to Thermal Analysis: Heat Generation

(Includes both neutron & gamma heat contribution)

Immersion Designs

	Design 1	Design 2
Salt (W/cc)	33.698	22.693
Heater (W/cc)	0.160	0.172
Capsule wall (W/cc)	0.217	0.254
Outer can (W/cc)	0.142	0.142
Graphite low (W/cc)	0.024	0.024
Insulating disk (W/cc)	0.005	0.006
Capsule low (W/cc)	0.235	0.289
Capsule up (W/cc)	0.108	0.148
Graphite up (W/cc)	0.015	0.015

Monolith Design

	Design 3
Salt E/N/W/S (W/cc)	23/23/16/16
Capsule E/N/W/S (W/cc)	0.2/0.2/0.1/0.1
Heater (W/cc)	0.07
Insulating disk (W/cc)	0.00
Graphite monolith (W/cc)	0.03
Outer wall (W/cc)	0.11
Outer low (W/cc)	0.15
Outer up (W/cc)	0.10

Challenges, Limitations, and Future Improvements

- Axially and radially-graded power density tally in salt
  - Temperature gradients found to be driven by both axial and radial heat transfer
- 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
- ORIGEN depletion/activation analysis for dose calculations
  - Dose from fission products, capsule wall material, and Ar gas

Most of these improvements are expected to be minor and are not anticipated to impact the overall conclusions thus far

Thermal Hydraulics Analysis

Stacey Wilson

Thermal Hydraulics Requirements

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

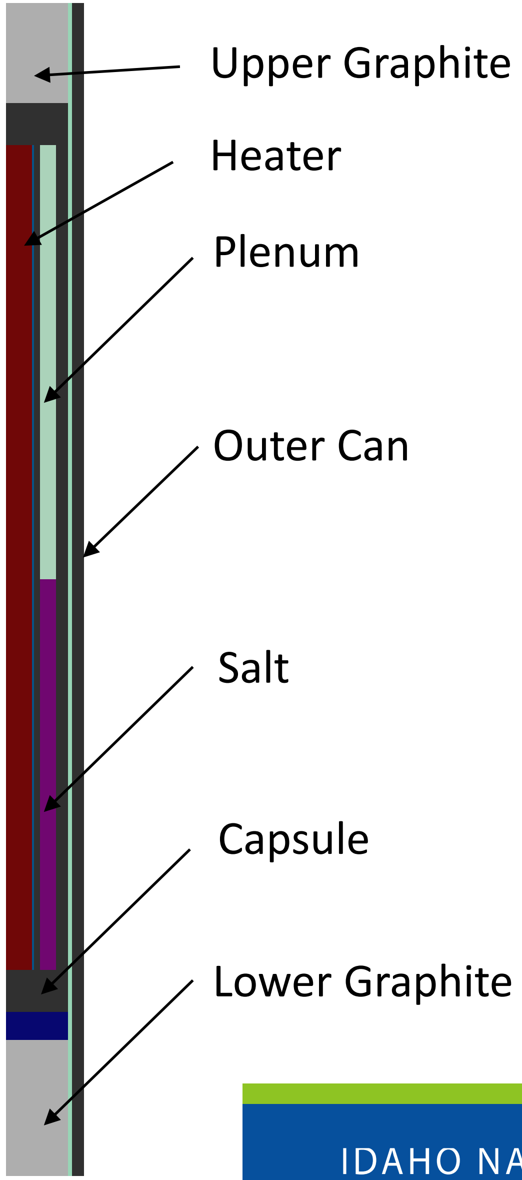
- Programmatic Requirements from FOR-584
  - 3.1.1.3: Salt Average Temperature = 600°C
  - 3.1.1.3: Salt Temperature > 523°C
  - 3.1.1.3: Radial and Axial Salt Temperature Gradients = Minimized
  - 3.1.7.3: Time for Salt to Freeze After Irradiation = Maximized

Thermal Hydraulics Model Setup

- ABAQUS 6.14-2
  - Design Options 1 and 2 are axisymmetric
  - Design Option 3 is 2D planar
- Simplifications
  - Material properties are constant with temperature
  - No natural convection of salt
  - Geometry
- NRAD Flow = 2 gpm and T_{inlet} = 40°C

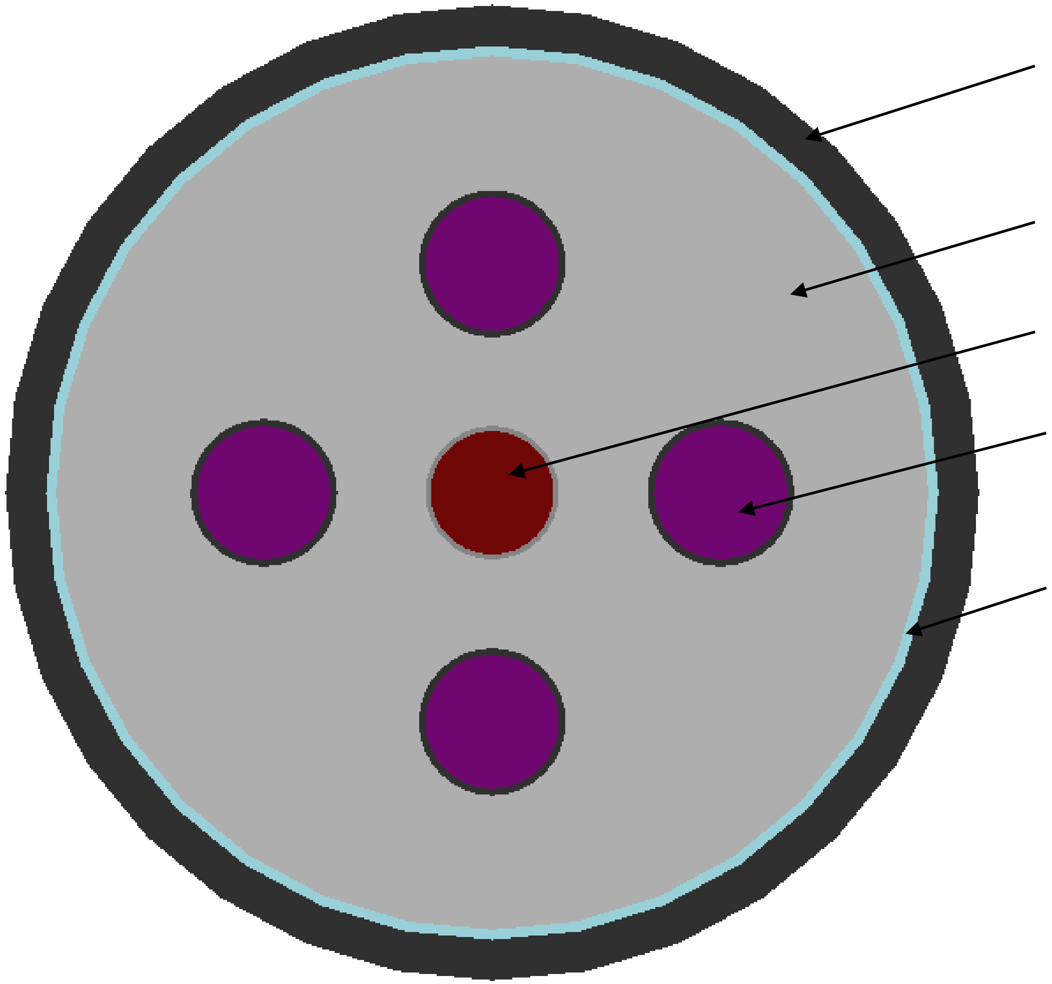
Thermal Hydraulics Model Setup (cont.)

- Design 1 and 2
  - Axisymmetric ABAQUS model
  - Left boundary is center of experiment
  - Right boundary is interface between experiment can and coolant
- Differences between Design 1 and 2
  - Salt thickness (and dependent experiment dimensions)
  - Capsule material
- Analysis Options
  - Gas gap between capsule and can
  - Heater off and on



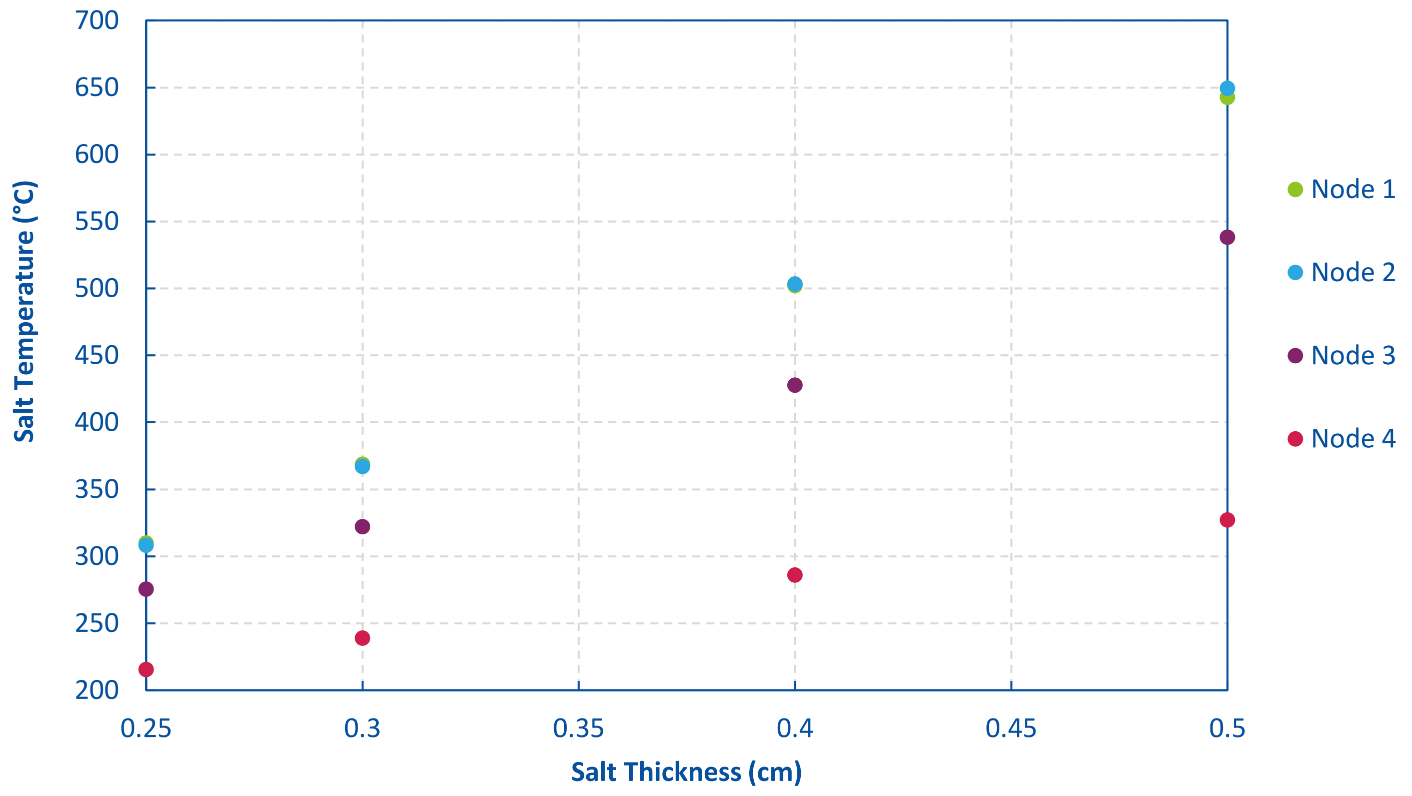
Thermal Hydraulics Model Setup (cont.)

- Design 3
  - 2D planar ABAQUS model
  - XY Plane
- Analysis Options
  - Gas gap between graphite monolith and can
  - Heater off and on



Design Analysis and Outcomes

Salt Thickness Scoping Study



- Main findings:
  - The 0.5 cm salt temperature gradient was too extreme
  - To maximize the salt volume, design options with 0.3 cm and 0.4 cm thick salt were explored

Design Analysis and Outcomes

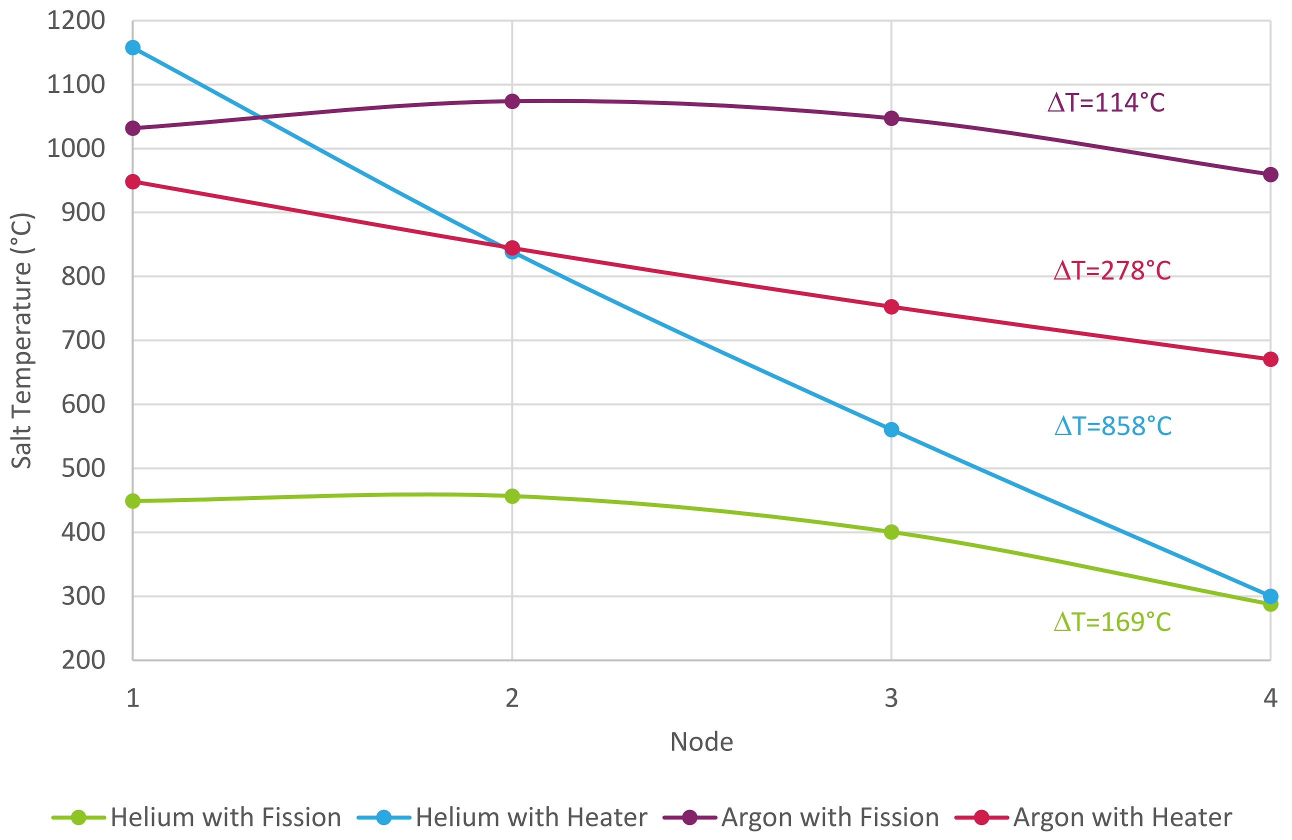
Design 1 - *Salt thickness of 0.3cm*

Gas Gap Gas	Fission Heat	Heater Output (W)	Salt Tmax (degC)	Salt Tmin (degC)	Salt ΔT (ΔdegC)	Salt Tavg (degC)	Can Tmax (degC)
He	On	0	457	192	264	324	69
He	Off	400	1158	260	898	709	72
Ar	On	0	1074	712	362	893	62
Ar	Off	~225	948	553	396	751	54

- Main findings:
  - Temp. outer surface < 70°C except for He case with heater on
  - Pure Ar case meets min temp. requirements while pure He does not
  - Ar + He mixture will reduce the temp. of the pure Ar case, meet requirements, and provide more operational flexibility with the heater

Design Analysis and Outcomes

Design 1 - *Salt thickness of 0.3cm*



Note that gradients are presented along a radial line of nodes containing the maximum salt temperature. They do not contain the minimum salt temperature in the entire capsule. For the true minimum, maximum, and delta in salt temperatures, see previous slide.

Node 1 is next to the heater and Node 4 is next to the outer capsule wall.

Design Analysis and Outcomes

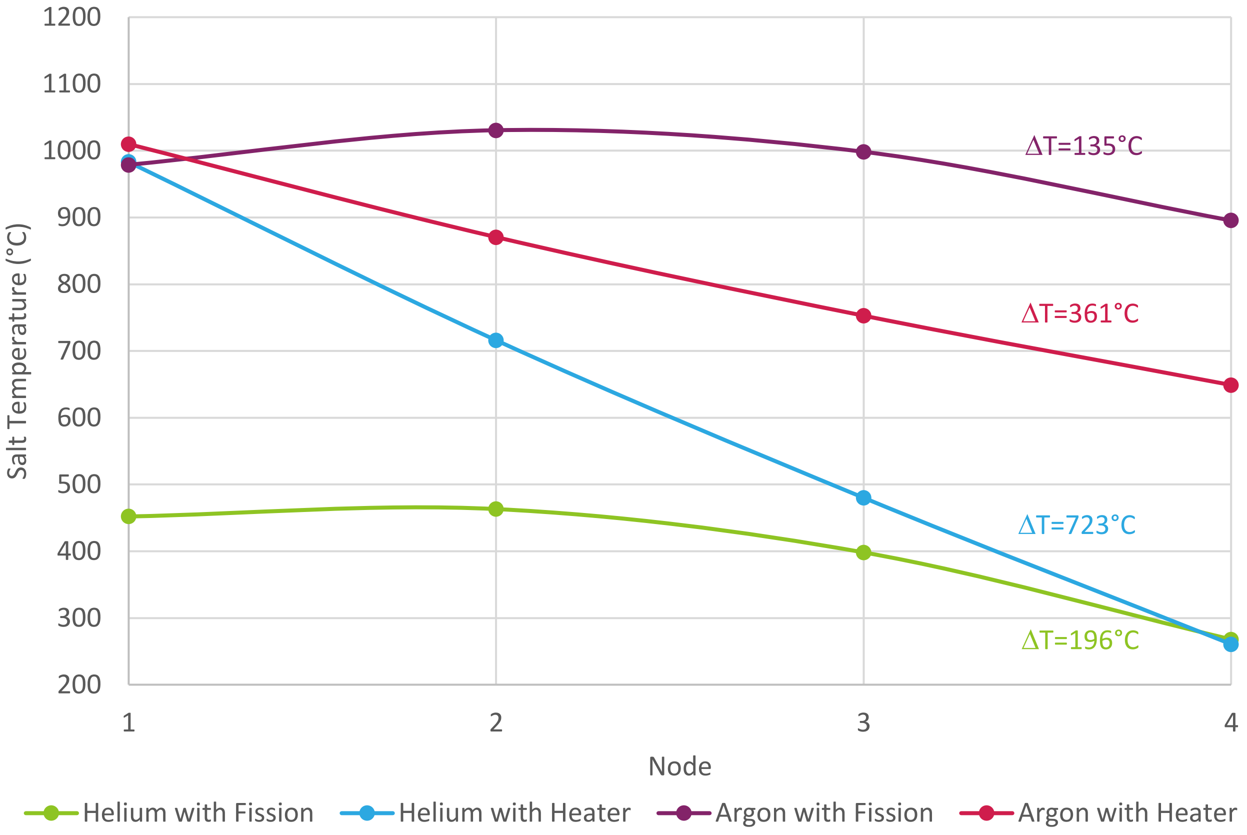
Design 2 – *Salt thickness of 0.4cm*

Gas Gap Gas	Fission Heat	Heater Output (W)	Salt Tmax (degC)	Salt Tmin (degC)	Salt ΔT (ΔdegC)	Salt Tavg (degC)	Can Tmax (degC)
He	On	0	463	178	286	321	67
He	Off	400	983	228	756	606	67
Ar	On	0	1031	657	374	844	61
Ar	Off	~230	1010	543	467	776	54

- Main findings:
  - Temp. outer surface < 70°C for all cases
  - Pure Ar case meets min temp. requirements while pure He does not
  - Ar + He mixture will reduce the temp. of the pure Ar case, meet requirements, and provide more operational flexibility with the heater

Design Analysis and Outcomes

Design 2 – *Salt thickness of 0.4cm*

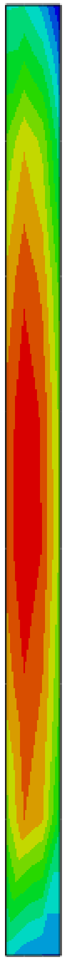


Note that gradients are presented along a radial line of nodes containing the maximum salt temperature. They do not contain the minimum salt temperature in the entire capsule. For the true minimum, maximum, and delta in salt temperatures, see previous slide.

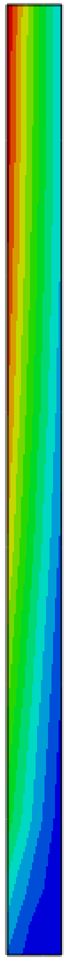
Node 1 is next to the heater and Node 4 is next to the outer capsule wall.

Design Analysis and Outcomes

Design 1 and 2 Temperature Distributions



Representative temperature distribution with just fission heat



Representative temperature distribution with just heater output

Design Analysis and Outcomes

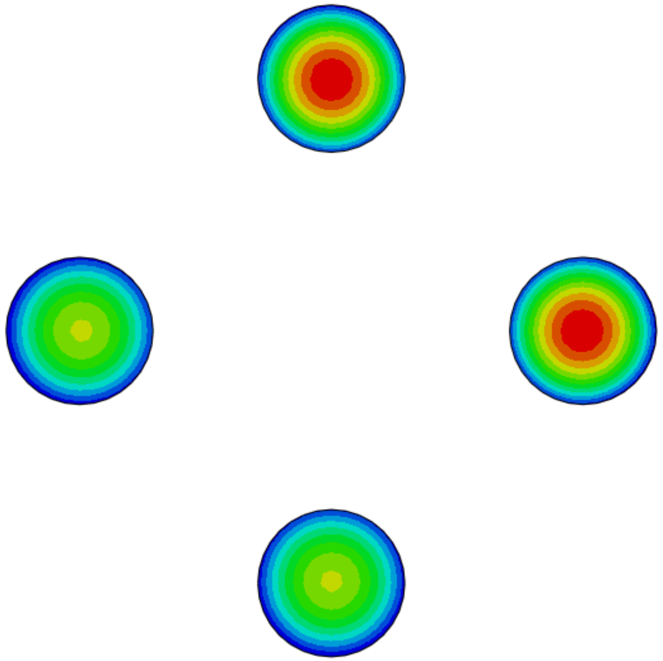
Design 3

Gas Gap Gas	Fission Heat	Heater Output (W)	Salt Tmax (degC)	Salt Tmin (degC)	Salt ΔT (ΔdegC)	Salt Tavg (degC)	Can Tmax (degC)
He	On	0	512	202	309	357	62
He	Off	~800	211	167	44	189	57
Ar	On	0	1102	792	311	947	61
Ar	Off	~630	582	547	35	565	53

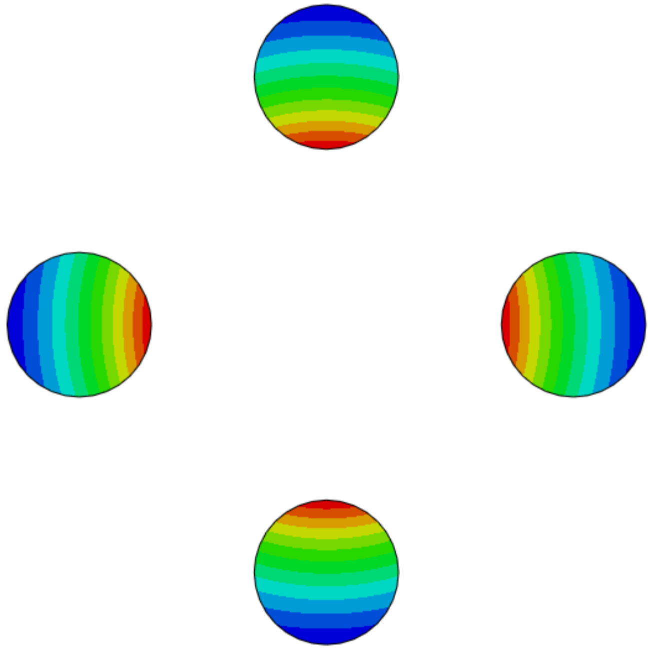
Safety Requirement FOR-585 3.3.1.3: Maximum Temperature of Outer Surface of In-Tank Assembly = 70°C is met for all cases. Note that a different heater than what was assumed for Designs 1 and 2 was used for Design 3.

Design Analysis and Outcomes

Design 3 Temperature Distributions



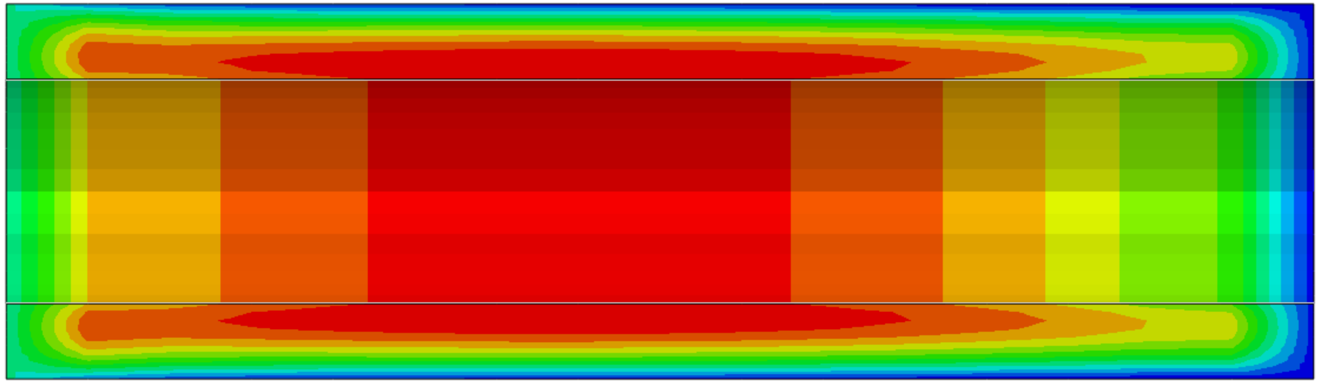
Representative temperature distribution with just fission heat



Representative temperature distribution with just heater output

Design Analysis and Outcomes

- Challenges
  - Initial design using furnace-type heater (CHARIN)
  - Temperature limits of salt facing materials
  - Salt temperature gradient
  - ABAQUS does not compute natural convection of molten salt



Temperature gradient in salt with a previously determined natural convection velocity profile manually applied in ABAQUS. Similar to gradient seen in axisymmetric models with no salt flow with slight improvement on magnitude of gradient.

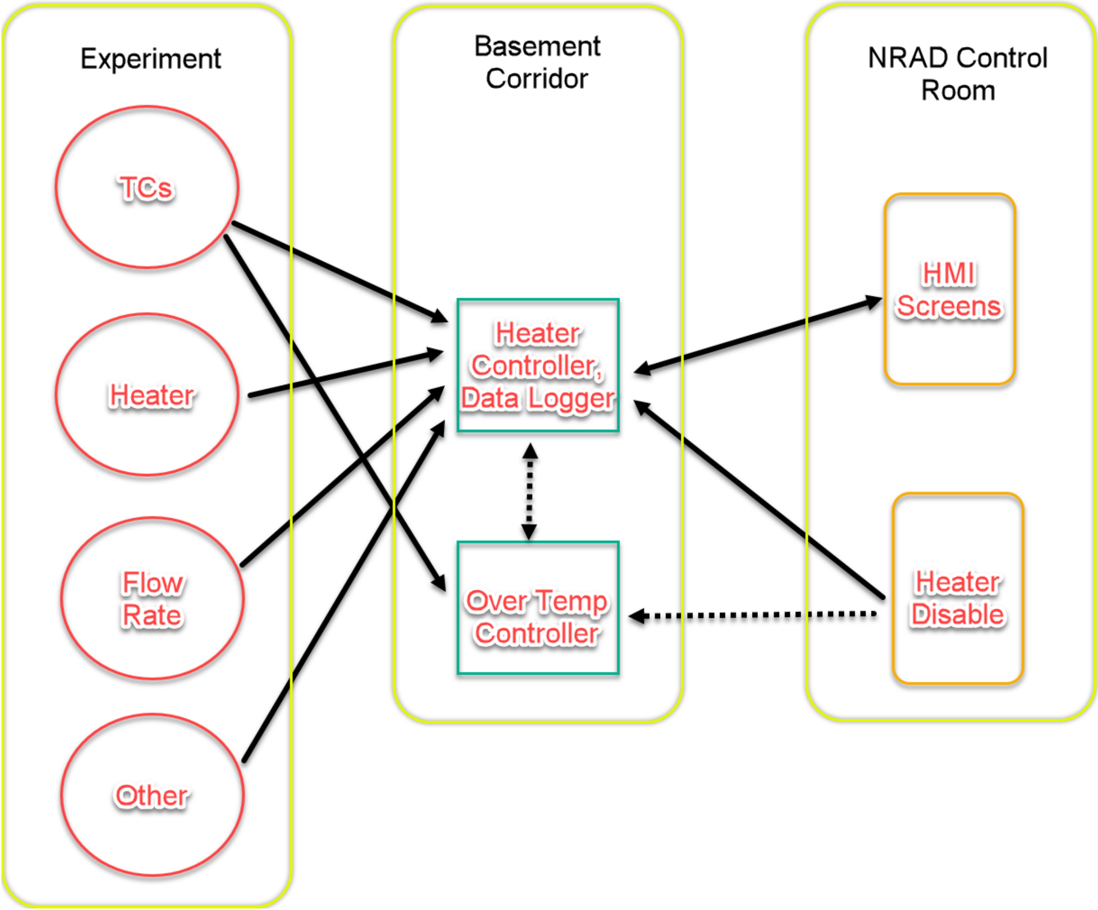
Systems Control & Electrical Design

K. Davies & J. Chandler

Control System Interfaces

ID	Source	Description	Details
MRTI-R-22 & 23 & 24 & 47 & 52	FOR-585, 3.2.1.6 to 3.2.1.10 FOR-584, 3.1.4.1 to 3.1.4.3	Data recording, including: Temperature Heater Power Reactor Power Neutron Detectors	Continuous >30 days & expandable Every Minute (+/- 10 degrees) Every Minute Every Hour None provided
MRTI-R-25 & 40 & 41 &43 & 44 & 46	FOR-585, 3.2.1.2 to 3.2.1.5.2 FOR-584, 3.1.4.4	NRAD Control Room Console: HMI screens Auto control loop Manual temp set	Display op, over, & current temps ≥ 1 Hz, target +/- 10 deg-C within 10 mins Op & over temp
MRTI-R-50 & 51	FOR-585, 3.2.1.9	Auto Over-temp shutdown compliant with NFPA-70E	
MRTI-R-54	FOR-585, 3.2.2.2	Connection plug at heater	Continuous wires, cut for transfer
MRTI-R-55 & 68	FOR-585, 3.2.2.2.1 & 3.3.2.6	Watertight Submerged Electrical Connections	

Control System Interfaces



- Shared CHARIN design
- 120-volt power access
- Requires wall feedthrough to exit reactor room
- Prove design with prototype test unit
- Compac Logix controller (pulse width modulated)
- Wattlow limit controller (over temp shutdown)

Control of Temperature in Reactor

Design Goal:
Require some supplemental heat input to maintain operating temperature for duration of experiment

- Internal heater melts salt in capsule and reach operating temperature
- Reactor is started and power increased to desired level
- Internal heater provides supplemental power as needed

Prototype Experiment Objectives

Role:

- Prove capsule design
- Characterize insulation performance
- Optimize control performance
- Verify thermal calculations & assumptions

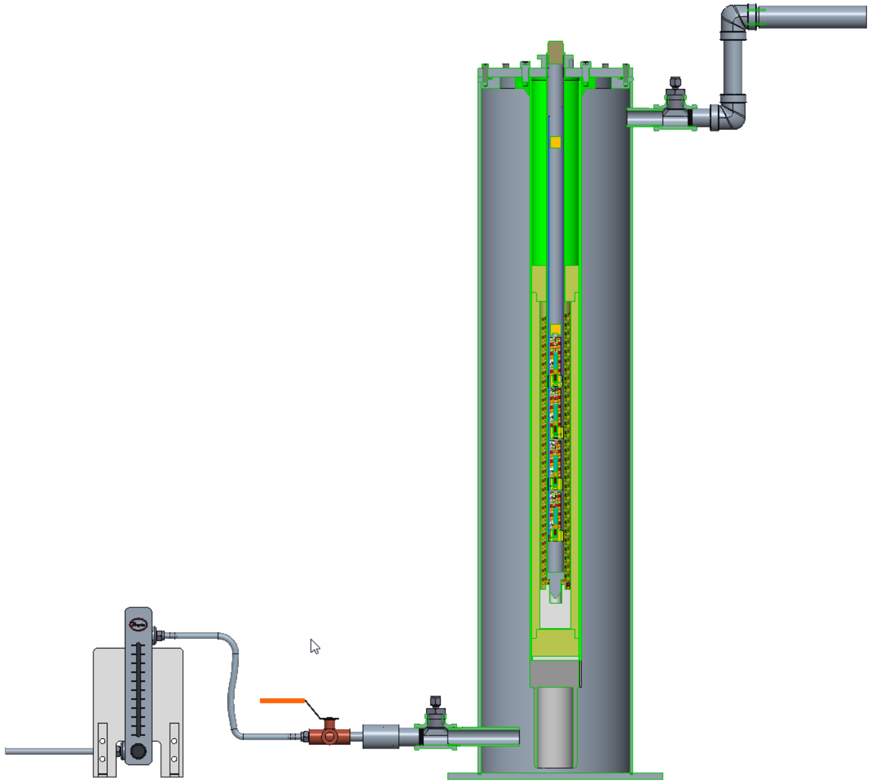


Illustration of the CHARIN prototype

Summary & Conclusions

G. Core & A. Abou-Jaoude

Figure of Merit Comparison

Best	Better	Acceptable

#	Figure	Charact.	Value	Design Option 1	Design Option 2	Design Option 3
1	**Burnup** (GWd/MTU - assuming 30 days ops)	Maximize	N/A	0.665	0.446	0.388
2	**Salt Temperature***	Target	600 deg-C	324-893 deg-C	321-844 deg-C	357-947 deg-C
3	**Experiment-Pool Interface Temperature**	Target	70 deg-C	*No difference*		
4	**Power Density**	Maximize	20 W/cc	35.73	23.99	20.8 (avg)
5	**Volume of Salt** (cc)	Maximize	$\geq$ 5 cc	9.9	14.1	22
6	**Radial and Axial Salt Temperature Gradients****	Minimize	N/A	**Ar:** 362/396 deg-C **He:**264/898 deg-C	**Ar:** 374/467 deg-C **He:** 286/756 deg-C	**Ar:** 311/35 deg-C **He:** 309/44 deg-C
7	**Surface Area-to-Volume Ratio** (1/cm)	Minimize	N/A	6.81	5.14	4.14

*Based on heater off, fission on, and min/max correspond to He/Ar range
**Values are provided in ranges (fission heat only / heater input only) for each insulating gas.

Concluding Discussion and Recommendation

Other Considerations

- **Remote Disassembly:** Easier in Design 2 than Design 1 due to thicker salt ring
- **PIE Instrument Interfaces:** Design 2 may pose a challenge for corrosion studies due to Co activation
- **Salt Removal:** Design 1 creates largest challenge to removing salt
- **Multiple Capsules:** Design 3 provides four unique irradiated salts
- **Instrumentation:** Design 1 will be most challenging to fit instrumentation in salt bath
- **Fabrication:** Unique challenges present in all, but shouldn't prevent overall success

Figures of Merit Performance

- Design 1 provides the highest fission power and burnup
- All designs acceptably perform thermally with Design 3 providing a lower maximum temperature
- Design 3 can provide highest volume of salt

Recommendation

- Design 2 is recommended to be refined further due to FOM performance and other considerations