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PBNC Presentation: Dynamic Modeling of a Latent Heat Thermal Battery

October 2024

Changing the World's Energy Future

Daniel Mark Mikkelson, Jun Soo Yoo, Sunming Qin

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Dynamic Modeling of a Latent Heat Thermal Battery

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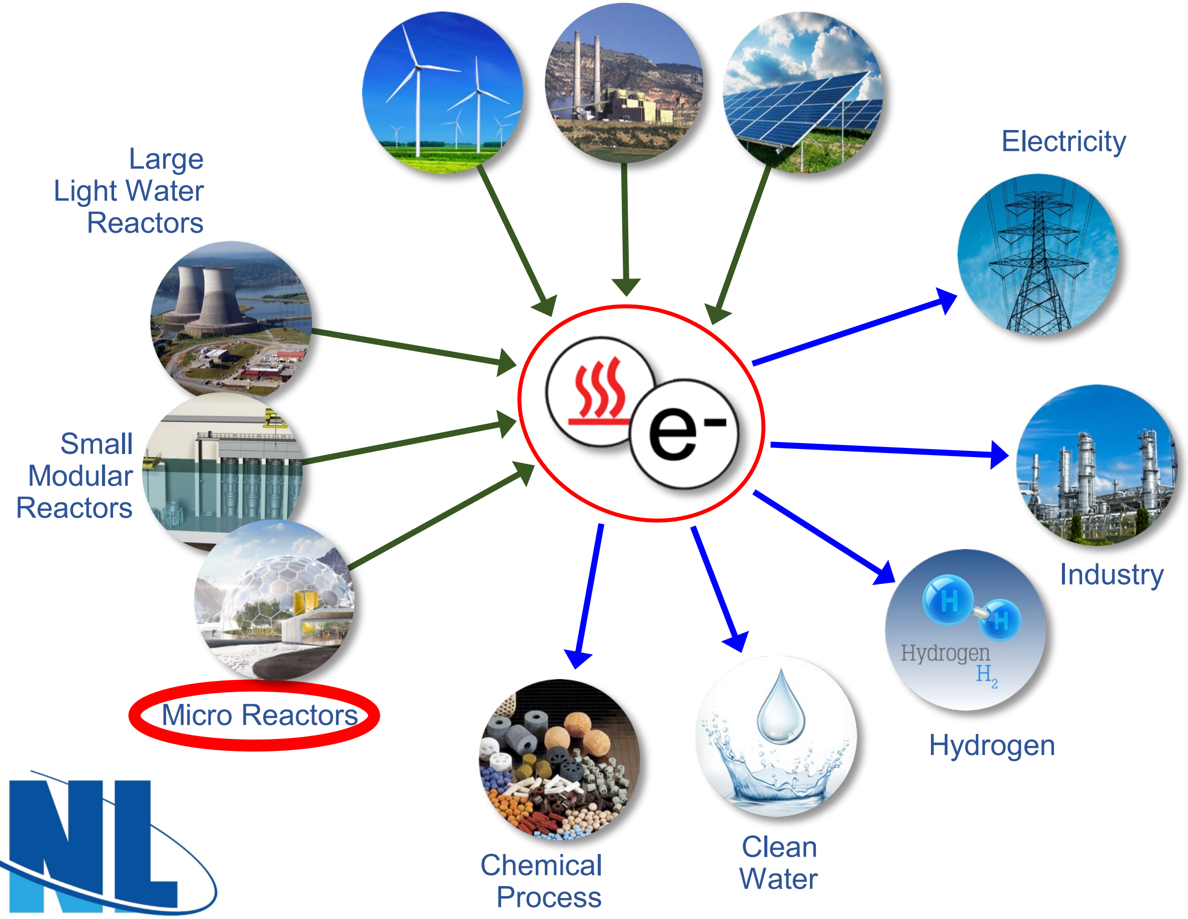
ANS American Nuclear Society

Why Thermal Energy Storage (TES)? What Needs Exist? What Innovations Needed?

TES in Integrated Energy Systems (IES)



IES Objectives

1. "Multiple" clean energy streams within "one" integrated system
2. Maximize energy efficiency & achieve decarbonization
3. Expand the role of nuclear energy beyond electricity

What are the Challenges of Integrating TES with Nuclear?

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Why Thermal Energy Storage (TES)? What Needs Exist? What Innovations Needed?

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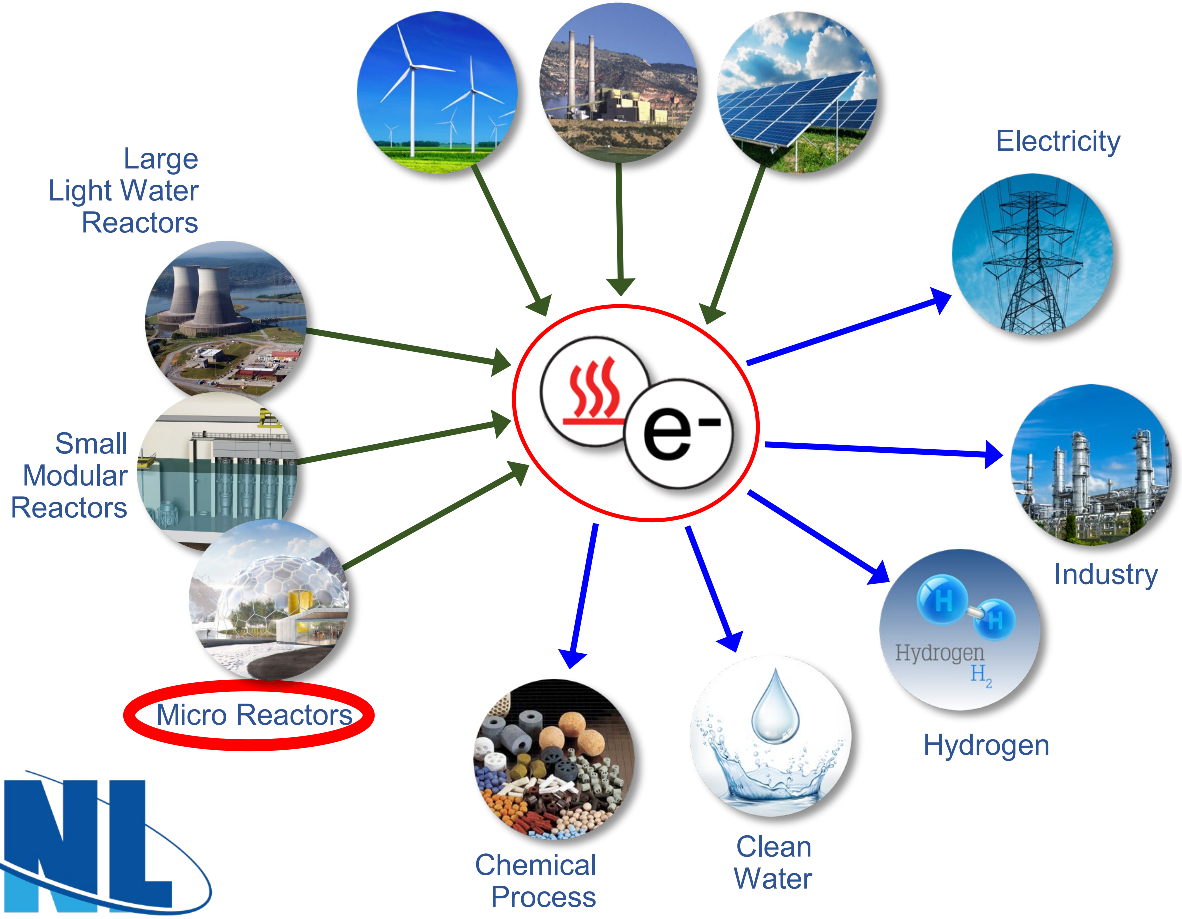

Key Challenges

1. Thermal Interface Challenge

- Safety (e.g., cross-contamination)
- Cost (e.g., additional installation, O&M, regulation)
- Functional and structural reliability under dynamic conditions (especially, at high-temperature)

2. Heat Storage Challenge

- Limited energy density (=> large space & cost)
- Poor thermal conductivity (=> large surface & cost)
- Material compatibility (e.g., hot corrosion)
- Recyclability
- Material cost (storage medium, container)

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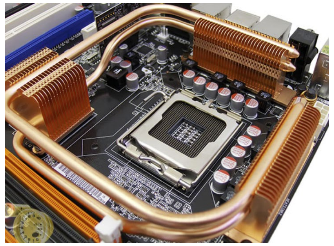
Thermal Interface Challenge:
How to Make "Integration" Safe and Efficient?

- ***Heat pipe*** can be a promising option

- Passive heat transfer device
- Highly efficient (super-conductor)
- Flexibility in design
- Low maintenance
- Isothermal operation
- Proven technology (> 70 years)

$$K_{\text{heat pipe}} = 4{,}000\text{-}100{,}000 \text{ W/m-k} \gg K_{\text{copper}} = 385 \text{ W/m-k}$$

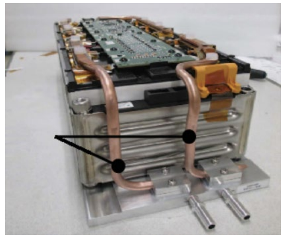
Heat Pipe Applications



Computers
Cell phones
⋮

HVAC

Space application



Battery cooling

Nuclear microreactor (INL)

…

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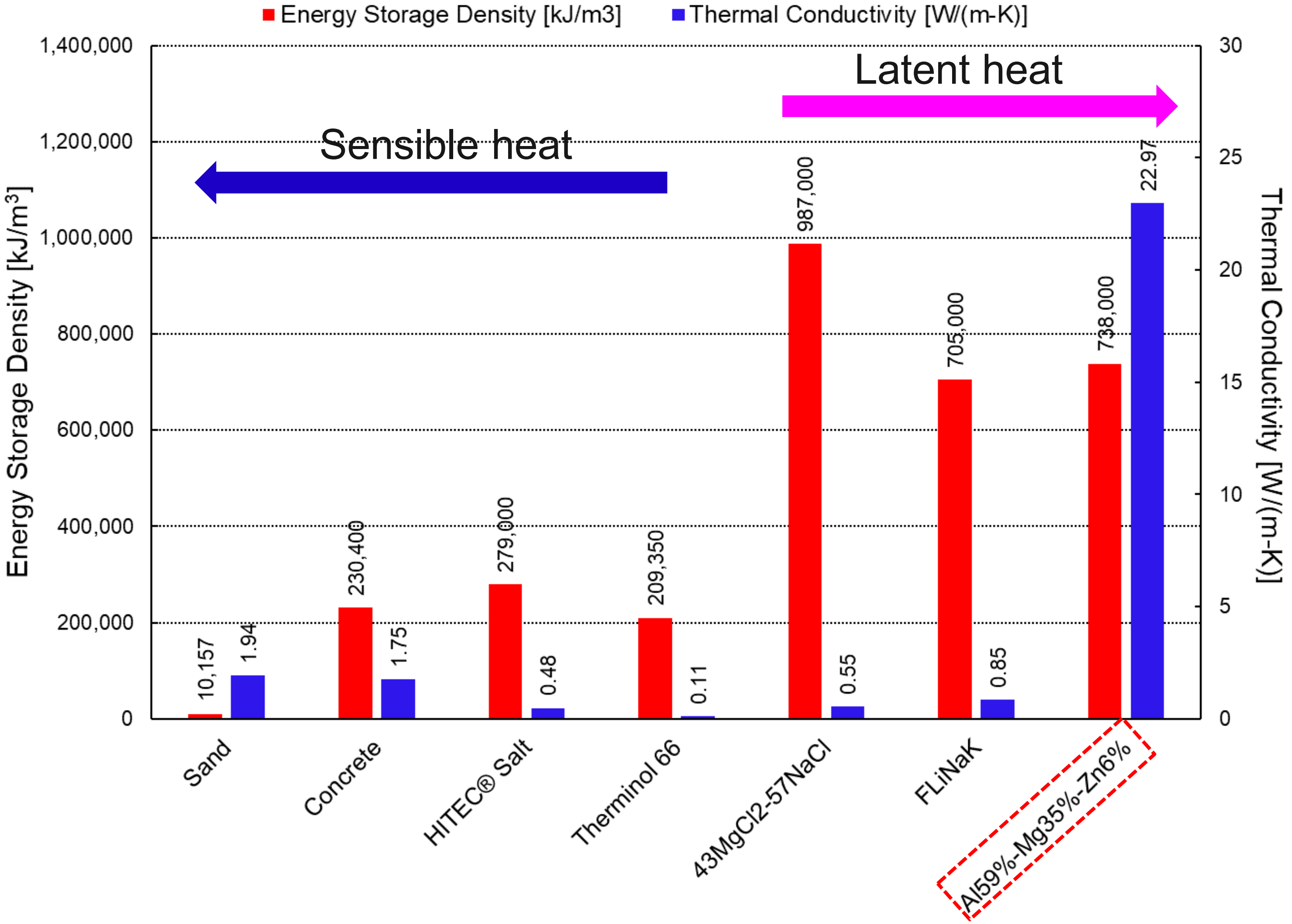
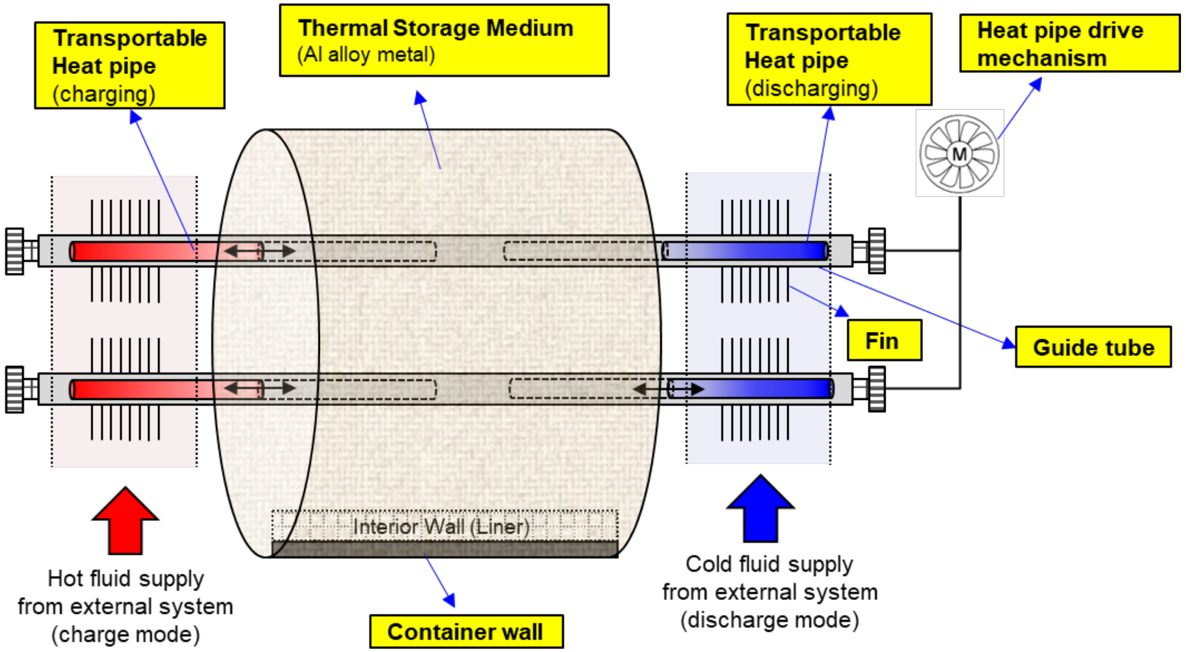
Heat Storage Challenge: How to Store & Release Heat Cost-Effectively?



Heat pipe-Integrated Thermal Battery (HITB)



Major Components

1. TES container
2. TES medium (Al alloy)
3. Heat pipe
4. Guide tube
5. Heat pipe drive mechanism

- Simplified design (no pump, no complex structure)
- Minimal safety concern
- Easy coupling
- Low integration cost

- **Key Design Features**
  1) High-temperature Liquid Metal Heat Pipe (LMHP) (passive heat transfer device)
  2) Heat pipe (HP) drive mechanism (transportable HP allows for flexible and dynamic thermal connection)
  3) Guide tube (additional barrier to prevent cross-leakage and high-temperature oxidation)
  4) TES medium with high thermal conductivity does not require additional installation for heat transfer enhancement (=> cost benefit)

Modelica Model of HITB

Model Requirements:

- Exhibit phase change phenomena
- Account for liquid-phase specific convection
- Account for heat pipe movement
- Calculate heat losses to environment
- Determine controlled behavior

Model Preferences:

- Use modular construction to allow for future model expansion
- Simultaneously economically use equations for faster simulation

Why Modelica?

- INL has a library of various other physical models constructed in Modelica, allowing for integration
- Modelica is acausal equation writing, allowing for diverse equation sets to be readily understood
- Inherent time-dependent solvers are ideal for experiment design
- User-specified level of control of equations: impose relationships necessary but allow for simplifying assumptions on an as-needed basis

Model Construction: Three Main Subsystems

1) Thermal Battery

- 3D conduction model with a phase change material medium, allowing for state calculations across solid and liquid states
- “Deficit” method applied to allow for heat pipe and thermocouple penetrations: calculating missing volume and reduced interaction area in 3D conduction matrix
- Vertical symmetry applied, allowing for equation reduction and for one of three heat pipes to be operated independently of the others

2) Heat Pipe

- Enhanced conduction model that leverages small-scale data of heat pipe to calculate a thermal conductivity multiplier on the heat pipe for axial heat transfer
- Radial conduction through heat pipe layers: core, wick, and wall, to calculate heat dissipation
- Interaction terms between heat pipe and outside space: heat exchanger, thermal battery, or air is dynamically determined based on position
- Potential for improved heat pipe model in the future

3) Control and Boundary Conditions

- Preliminary control system takes in charge and discharge demand (0-3kW each) and determines heat pipe position; if the net charge and discharge exceeds 3kW, discharge is preferred
- Heat exchangers treated in current model as boundary conditions allowing for heat transfer if heat pipe is in location
- In space between heat exchangers and thermal battery, a high value of air convection is used assuming a temperature controlled environment

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Phase Change Material Calculations

$$cp_{solid}(T_{m-}) = aT_{m-}{}^2 + bT_{m-} + c * \sin\left({}^{\pi}/_{\Delta T} * T_{m-}\right) + d * \cos\left({}^{\pi}/_{\Delta T} * T_{m-}\right) + e$$

$$cp_{liquid}(T_{m+}) = aT_{m+}{}^2 + bT_{m+} + c * \sin\left({}^{\pi}/_{\Delta T} * T_{m+}\right) + d * \cos\left({}^{\pi}/_{\Delta T} * T_{m+}\right) + e$$

$$\frac{\partial cp_{solid}(T_{m-})}{\partial T} = 2aT_{m-} + b + c\frac{\pi}{\Delta T}\cos\left({}^{\pi}/_{\Delta T} * T_{m-}\right) - d\frac{\pi}{\Delta T}\sin\left({}^{\pi}/_{\Delta T} * T_{m-}\right)$$

$$\frac{\partial cp_{liquid}(T_{m+})}{\partial T} = 2aT_{m+} + b + c\frac{\pi}{\Delta T}\cos\left({}^{\pi}/_{\Delta T} * T_{m+}\right) - d\frac{\pi}{\Delta T}\sin\left({}^{\pi}/_{\Delta T} * T_{m+}\right)$$

$$\int_{T_{m-}}^{T_{melt}} cp_{solid}(T) + \int_{T_{melt}}^{T_{m+}} cp_{liquid}(T) + \Delta h_{fusion} =$$

$$\left(a\frac{T^3}{3} + b\frac{T^2}{2} - c\frac{\Delta T}{\pi}\cos\left({}^{\pi}/_{\Delta T} * T\right) + d\frac{\Delta T}{\pi}\sin\left({}^{\pi}/_{\Delta T} * T\right) + eT\right)\Bigg|_{T_{m-}}^{T_{m+}}$$

$$\theta(T) = \frac{\left(\tanh\left(\frac{2\pi(T - T_{melt})}{2\Delta T}\right) + 1\right)\theta_{solid}(T) + \left(\tanh\left(\frac{-2\pi(T - T_{melt})}{2\Delta T}\right) + 1\right)\theta_{liquid}(T)}{2}$$

The model does not track physical movement of the phase change material in the HITB. At both solid and liquid states, properties are linear functions of temperature.

Latent heat is modeled using a local increase in heat capacity.

Density and thermal conductivity (bottom equation) are smoothly transition between solid and liquid correlations.

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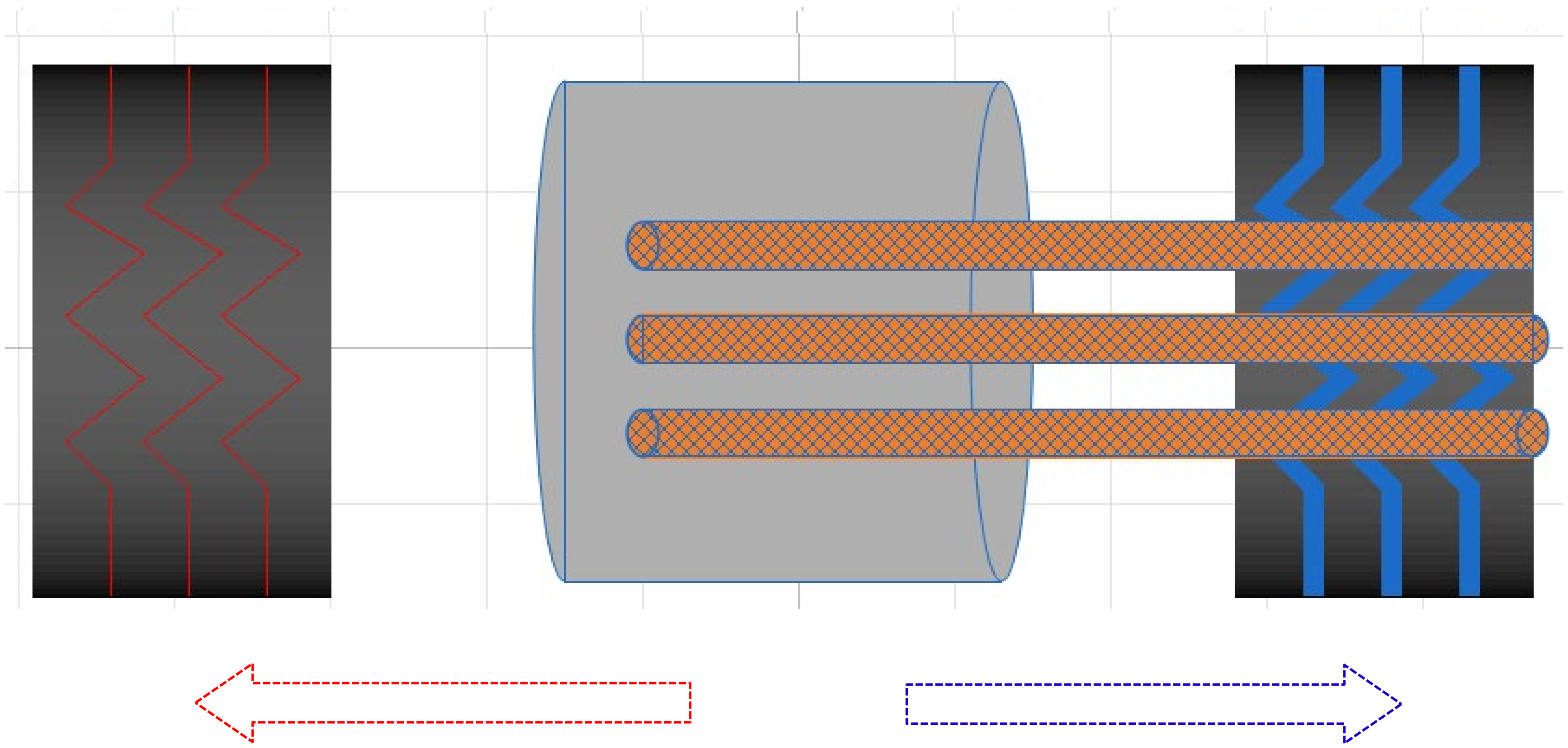
Dynamic Modeling

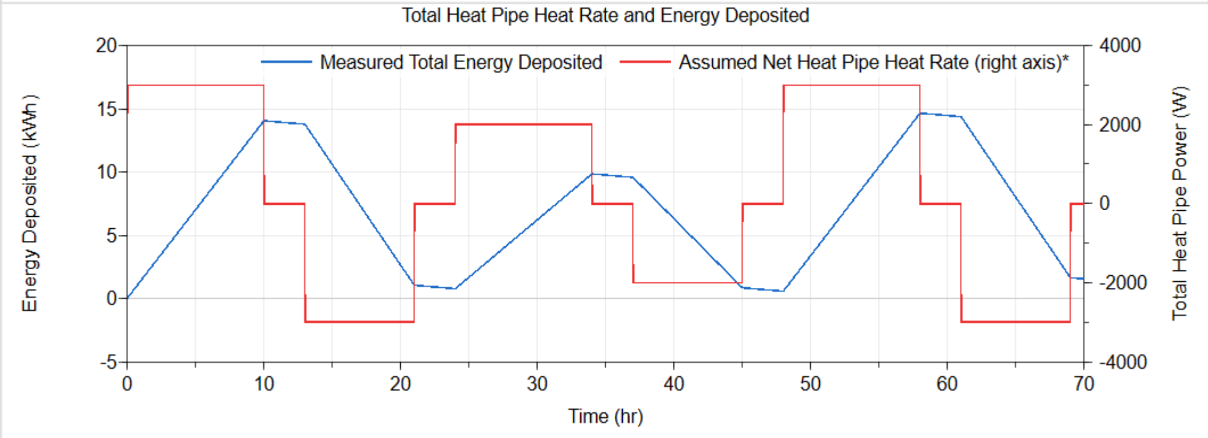
- HITB system is designed to shift the positions of the heat pipes depending on the operating mode.
- This operational characteristic is modeled in Modelica.

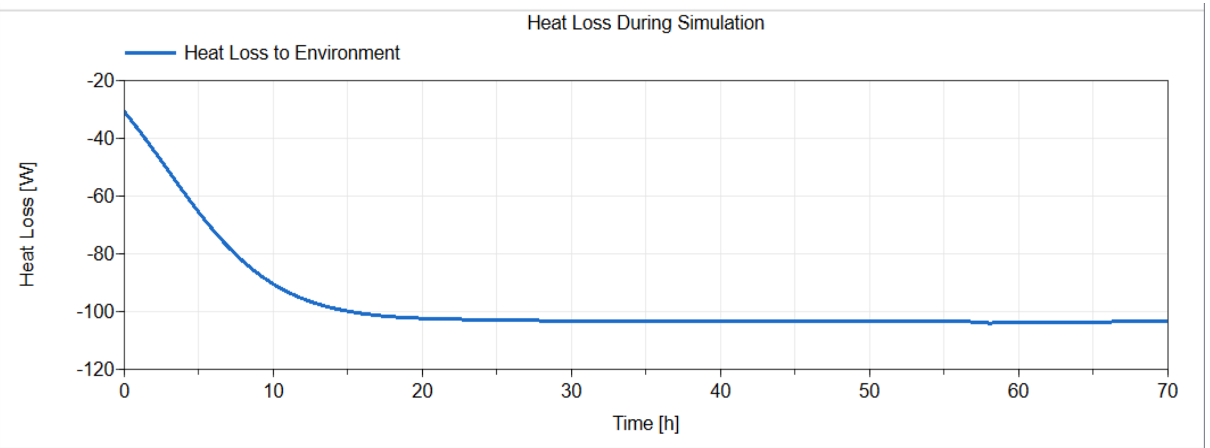


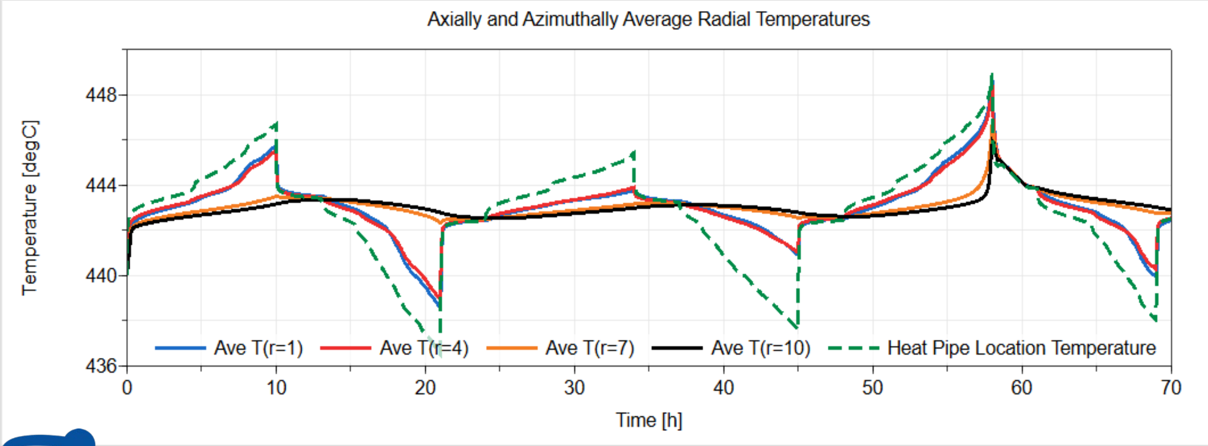
Heat pipes move to the left for charging heat

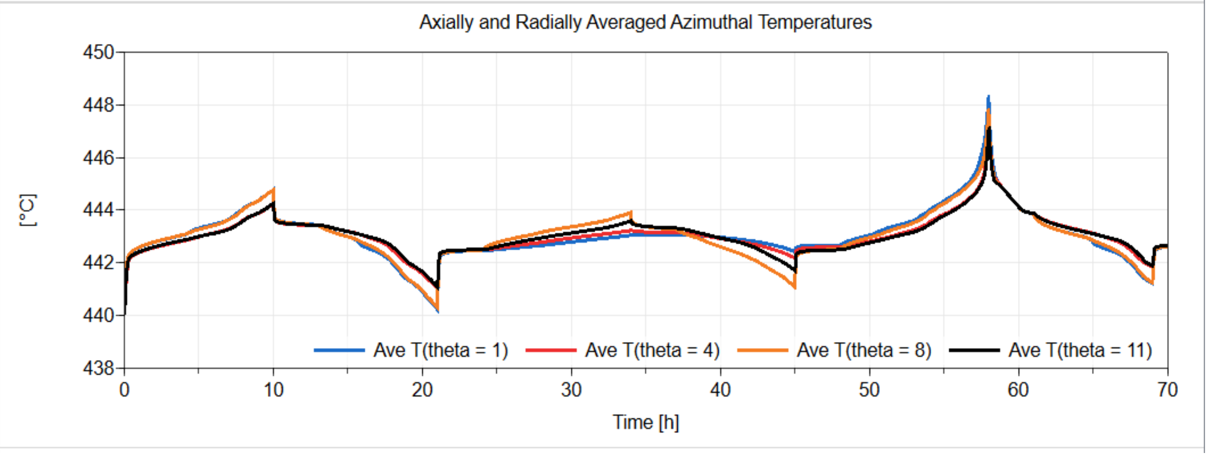
Heat pipes move to the right to discharge heat

Initial Results – Thermal Battery Response to Periodic Charge and Discharge









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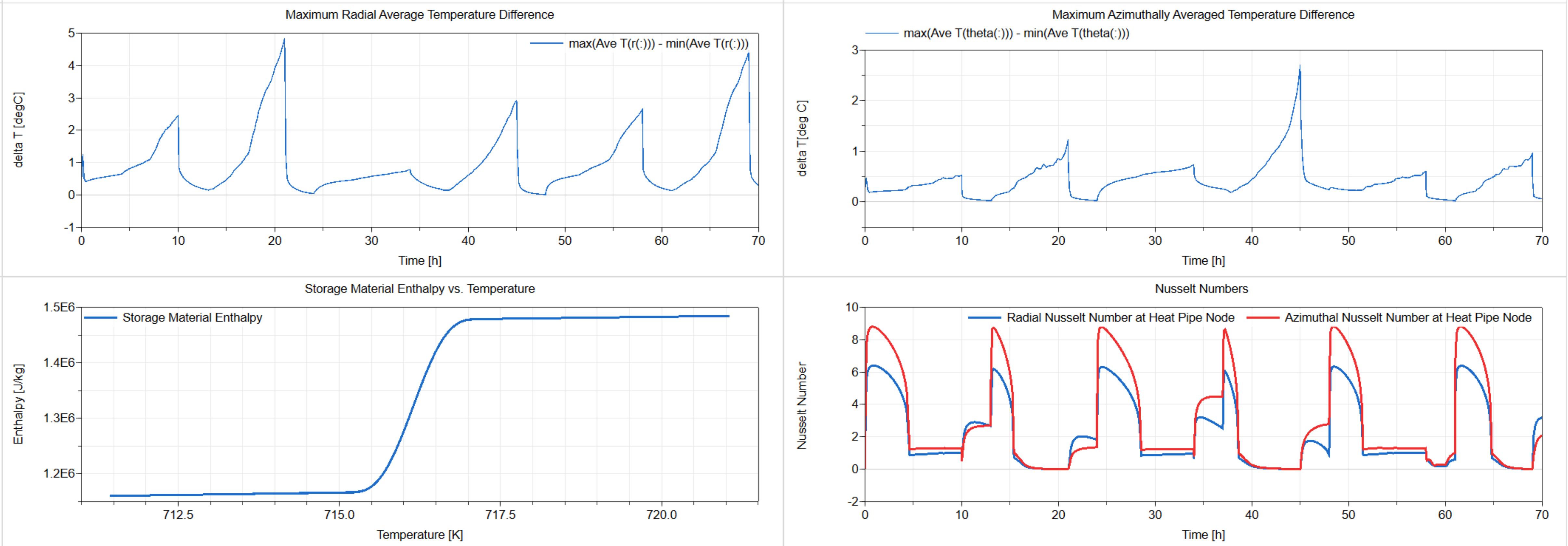
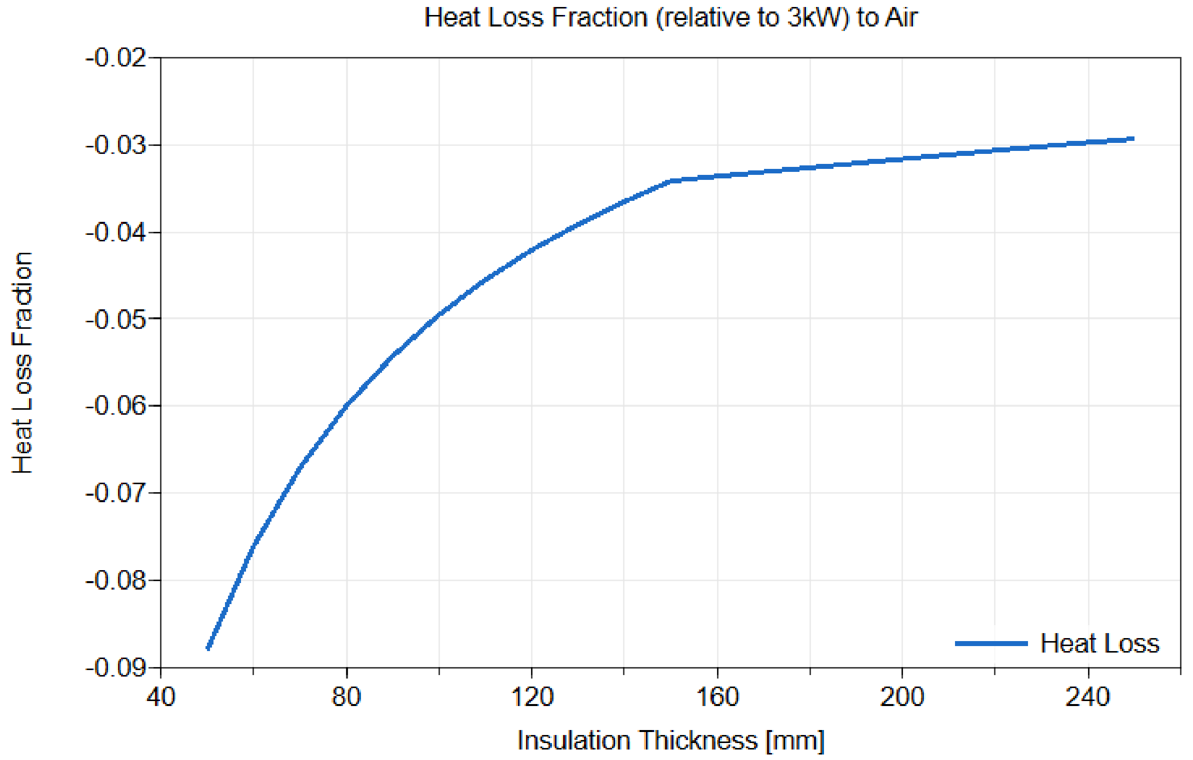
Initial Results – Thermal Battery Response to Periodic Charge and Discharge



- Top: temperature differences are expected to be small in this system
- Nusselt numbers should be very small in this system

Initial Results Measuring Heat Loss Changes with Insulation

- Insulation material is foam glass, with thermal conductivity in the 0.05-0.15 range across operating temperature
- Due to anticipated experiment geometry, initial insulation maximum thickness was set to be 15 cm at the axial ends of the battery, which causes clear inflection point in heat loss
- Desired heat loss of 3% requires very thick insulation around thermal battery main cylinder



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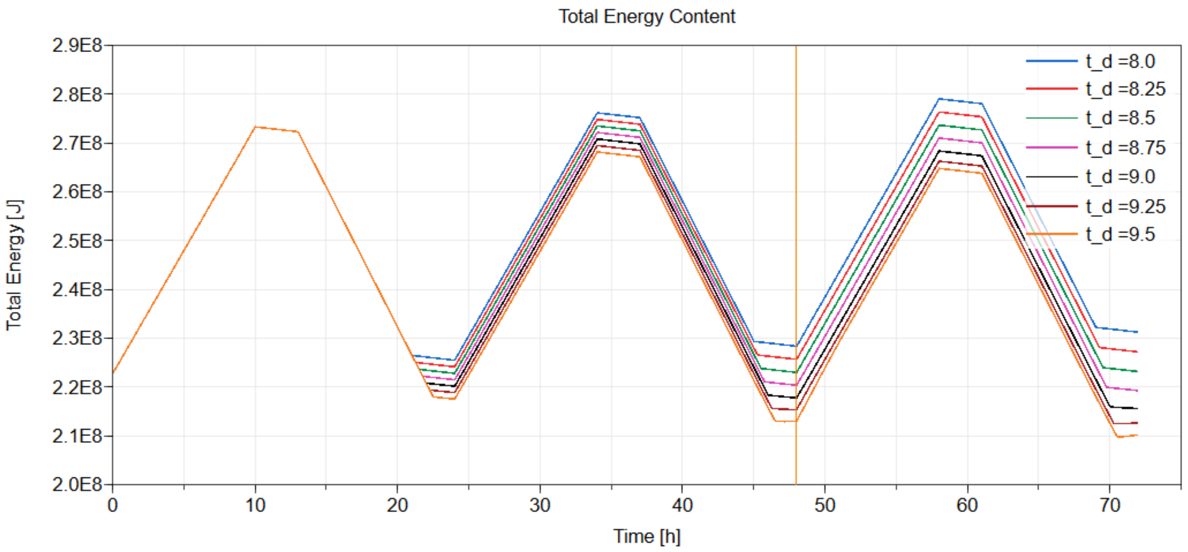
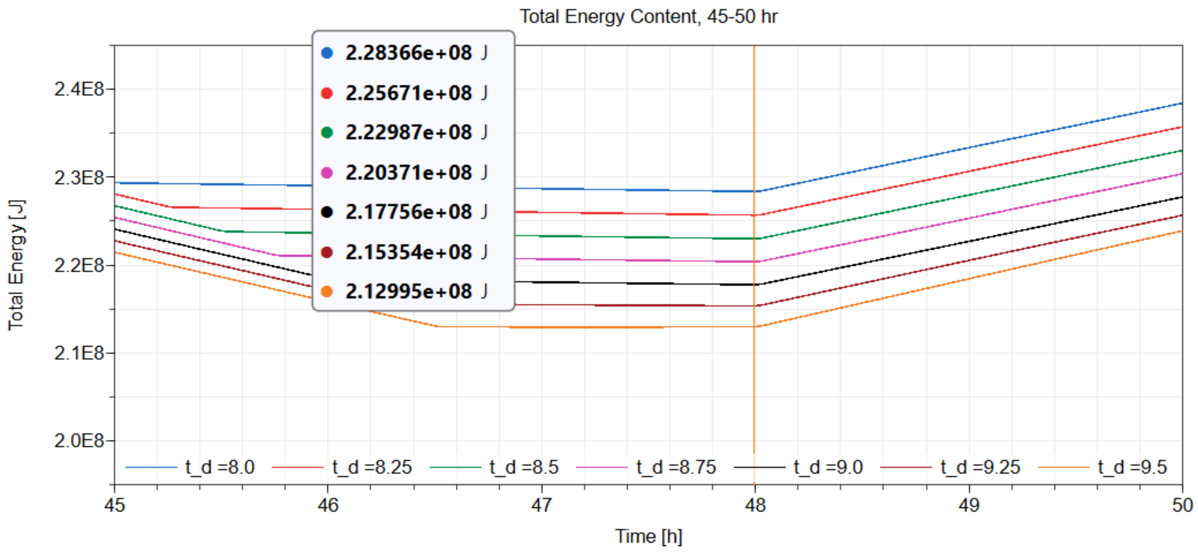
Other Initial Results

- Using 440℃ (3℃ below melting) as target temperature, system requires 7.27 days to heat from 20℃

- Round trip efficiency using 10 hour charging cycles indicates that the battery should have around an 85% discharge capability in a 10-8.5-5.5 charge-discharge-standby cycle.





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Transition to Experiments

- Model calculations will be used to plan experiment operation at INL starting this fall
- Experimental data will be used for validation and verification of the model
- Iterative experiment results and model updates will tune model to physical system and then allow for prediction of deployment-scale systems (30 kWh to MWh-scale).

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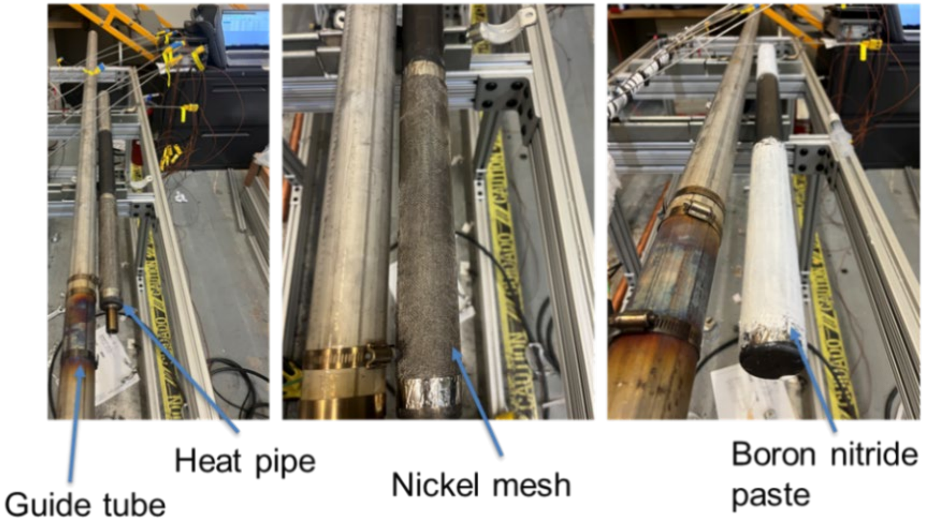
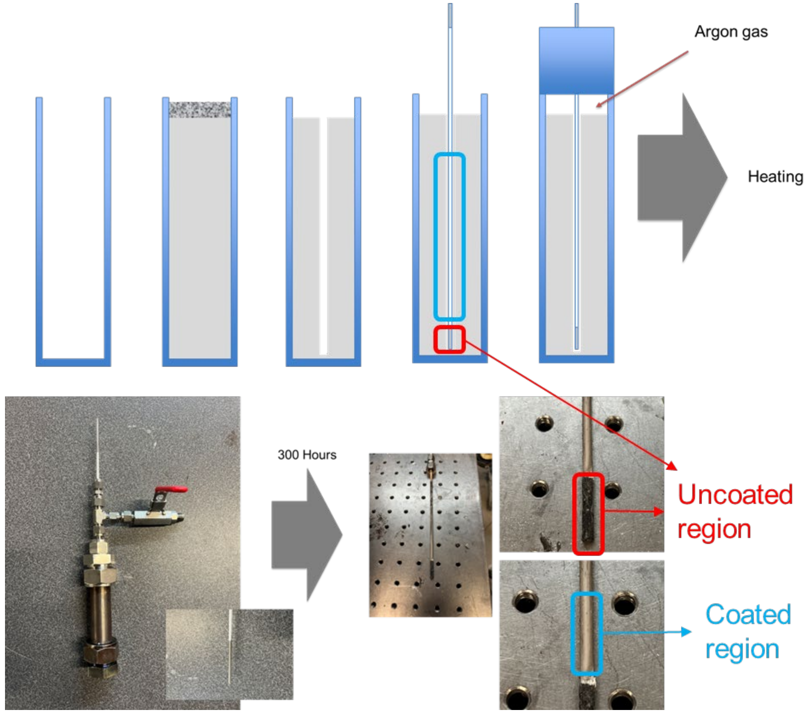
Component-scale Experimental Demonstrations

Thermal Interface & Compatibility Testing



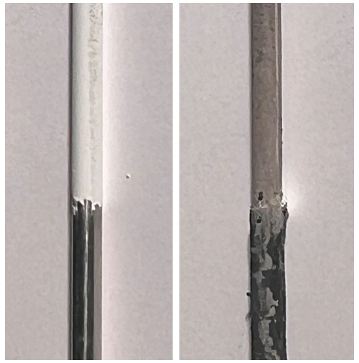
Thermal interface testing
(for gap conductivity improvement)



High-temperature corrosion test with and without BN coating, using SS-316 sample

Courtesy of Texas A&M Univ.

Heat pipe performance test with guide tube



Test result of immersion in a liquid aluminum alloy at 600 ℃ temperature for 300 hours.

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Current Status of HITB Project

Development and Demonstration of Versatile Modular HITB at INL

Completed fabrication of HITB thermal energy storage container

Connex box is placed where HITB's demonstration will be performed.

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Thank You
for Your Attention!

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