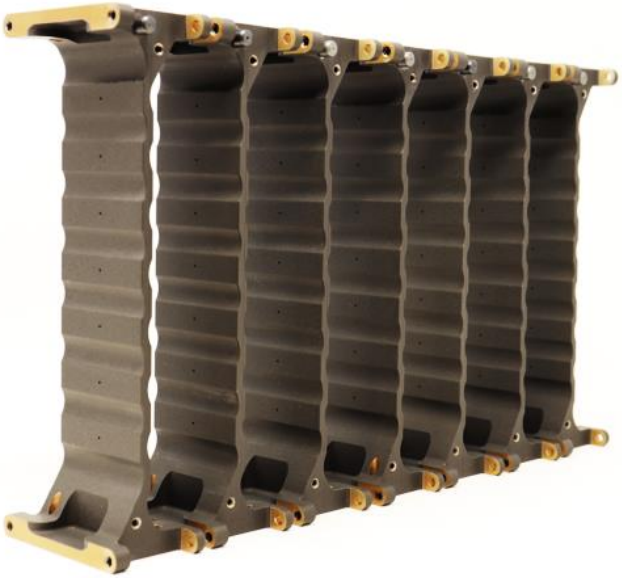
# Oscillating Heat Pipes for Thermal Management of Li-ion Batteries

## Space Power Workshop 2021

April 19-22, 2021



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# Executive Summary

- **Goal:** Enable safe, high power discharges (up to 3C) of a 2 kWh Li-ion battery by limiting peak cell temperatures, maintaining <2 °C cell uniformity, and providing resistance to thermal runaway propagation.

- **Approach:** Embed Oscillating Heat Pipes (OHPs) within the structural heat sinks to increase conductance and reduce overall system mass.

- **Result:** Experimental results with a 16-cell subunit utilizing simulated cells show steady-state conductance 8-16x higher than solid aluminum and uniformity between cells of around 1 °C. The design was also shown analytically and experimentally to demonstrate passive propagation resistance.

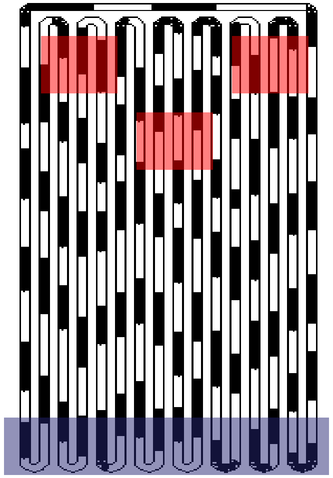
# Agenda

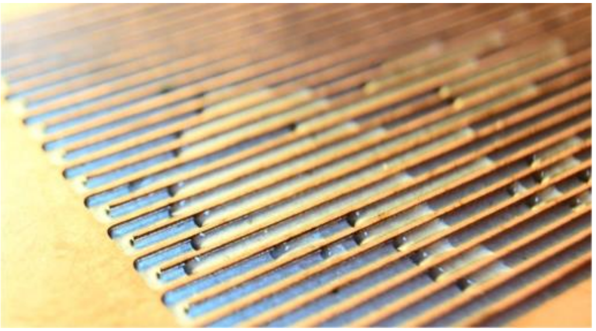
- Introduction to Oscillating Heat Pipes
- Problem Background
- The Proposed Solution
- Design & Analysis Results
- Experimental Results
- Conclusions & Questions

# Introduction to OHPs

*Structurally Embedded Oscillating Heat Pipes (OHPs)*

- OHPs are passive, thermally pumped, two-phase heat transfer devices.
- Principle of Operation:
    - A microchannel circuit within a hermetic envelope is charged with a saturated refrigerant to form a chain of liquid slugs and vapor bubbles.
    - This liquid and vapor is pumped between heat input and heat rejection regions by axial expansion and contraction caused by evaporation and condensation events.



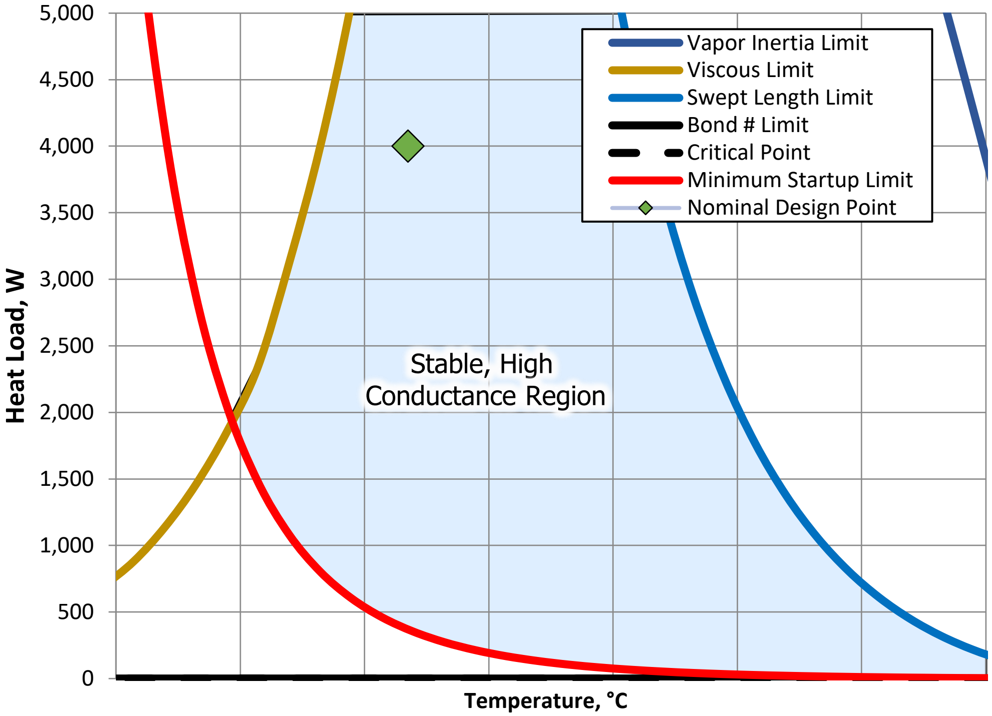


# Introduction to OHPs

## *OHP Transport Capacity Limits Model*

- Used to define OHP configuration
- Viscous Limit
  - *Due to viscous loss, temperature rise will increase until the viscous drag is overcome by ΔP to create fluid movement*
- Minimum Startup Limit
  - *Incident heat flux must be sufficiently high to create a large enough superheat at the wall to begin nucleation*
- Swept Length Limit
  - *Nucleation frequency becomes sufficiently high enough to prevent full liquid return*
- Vapor inertia limits high temperature operation
  - *Vapor generation rate is high enough to allow vapor to penetrate liquid plugs*
- Bond number also limits high temperature limit
  - *Surface tension decreases and can no longer span the capillary channel, and fluid movement ceases*

*Example limits chart*



Reference: B.L. Drolen and C.D. Smoot, "The Performance Limits of Oscillating Heat Pipes: Theory and Validation," Journal of Thermophysics and Heat Transfer, 31, 4, pp. 920-936 (2017)

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# Problem Background

*Guidelines for Safe, High-Performing Li-Ion Batteries*

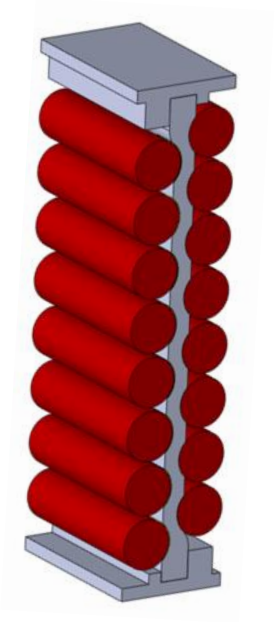
- Overall Program Objectives:
    - Minimize mass and volume of battery components to achieve specific power and energy targets
    - Develop methods for achieving passive thermal runaway propagation resistance utilizing commercial Li-ion cells

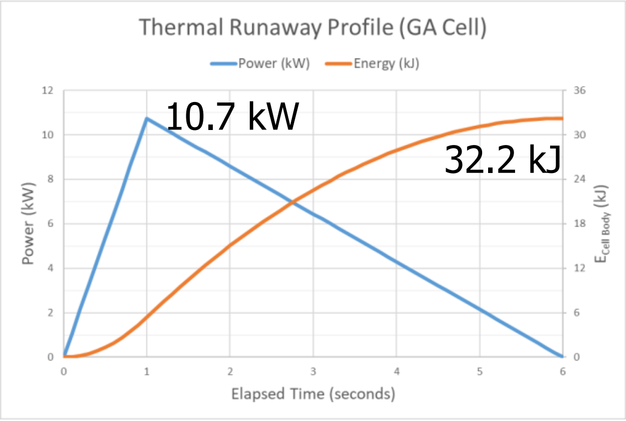
- ThermAvant Specific Objective:
    - Demonstrate how high-conductance, embedded OHPs can provide a significant thermal performance benefit while reducing size and weight.

# Problem Background

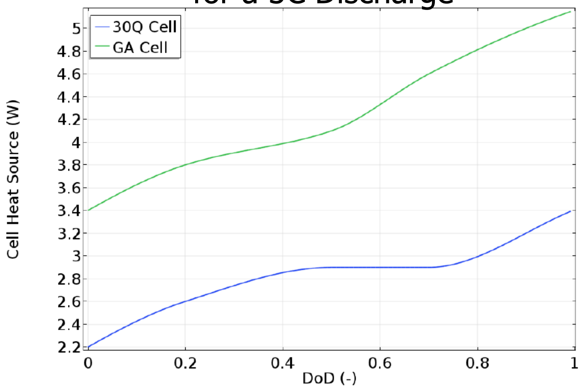
*Scope of Investigation*

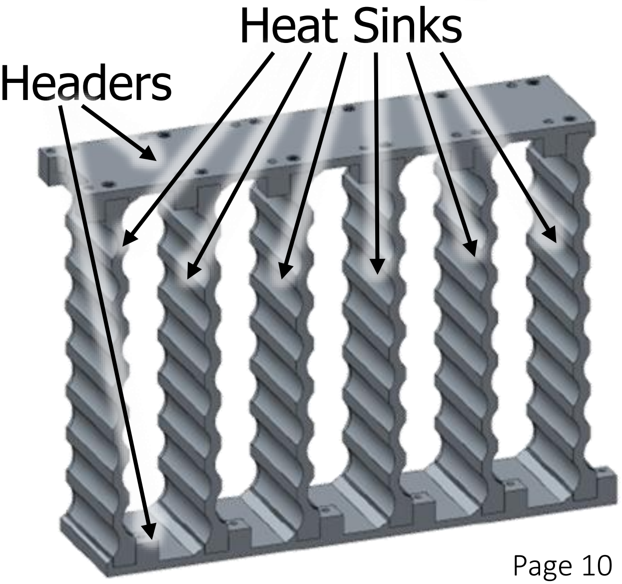
- Design scope limited to the structural heat sink “spines” and headers
- Defined cell-to-spine and spine-to-header interfaces
- 16 x 18650 Li-ion cells per heat sink
    - Two cells considered: 30Q and GA
- Transient boundary condition with a starting temperature of either 25 or 45 °C and rising 10 °C over the course of the discharge





Heat Generating Rates for a 3C Discharge





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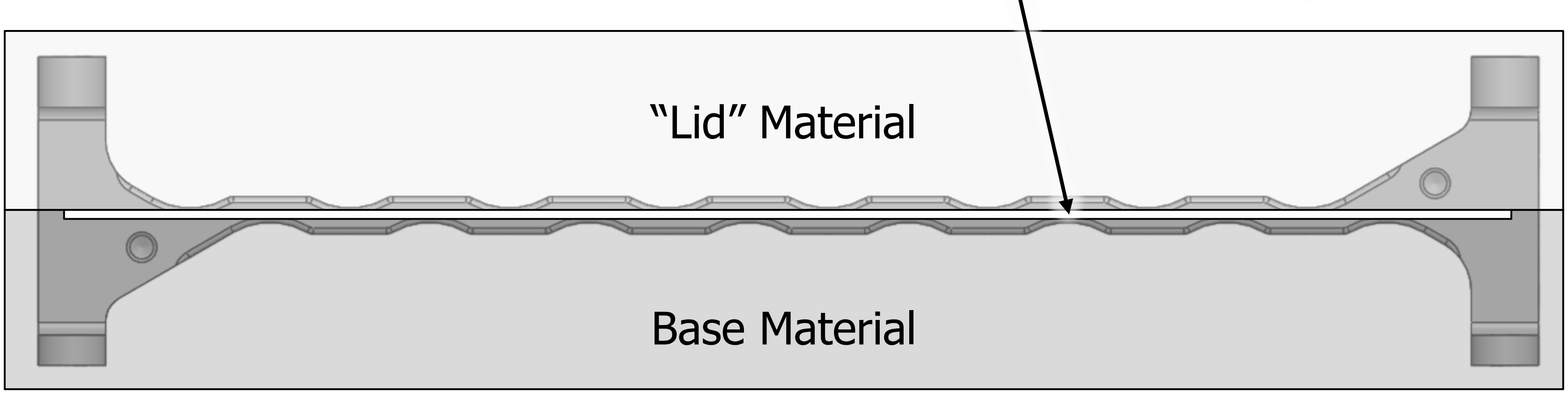
# The Proposed Solution

*Structurally Embedded Oscillating Heat Pipe (OHP)*

- Microchannels may be embedded within structural components:
    - Channels CNC machined onto base material (can be routed 3-dimensionally, if needed)
    - Lid hermetically bonded to base material sealing channels within the part
    - Part machined to final profile and channels charged with refrigerant

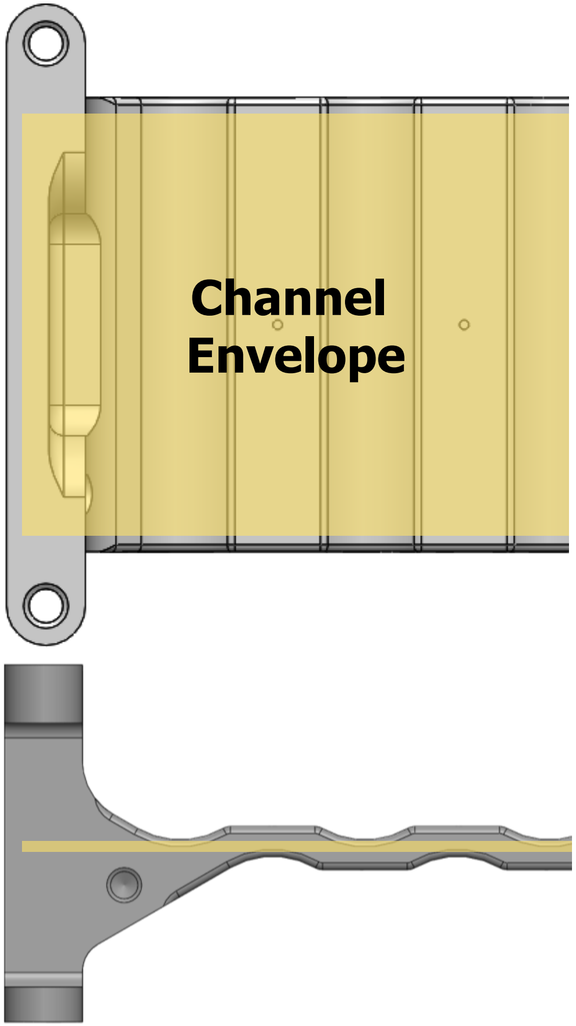
Heat Sink w/ Integrated Headers



# The Proposed Solution

*Structurally Embedded Oscillating Heat Pipe (OHP)*

- The addition of a 2-phase heat transfer mechanism was expected to:
    - Provide significant improvement to heat sink conductance
    - Provide around 10% mass reduction over a solid part ***of the same exterior dimensions***
        - Significantly higher reduction compared to a solid component with comparable thermal properties



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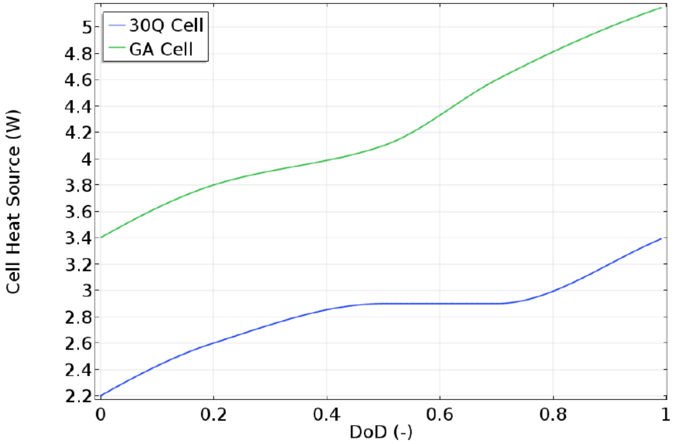
# OHP Heat Sink Design & Analysis

*Design Factors*

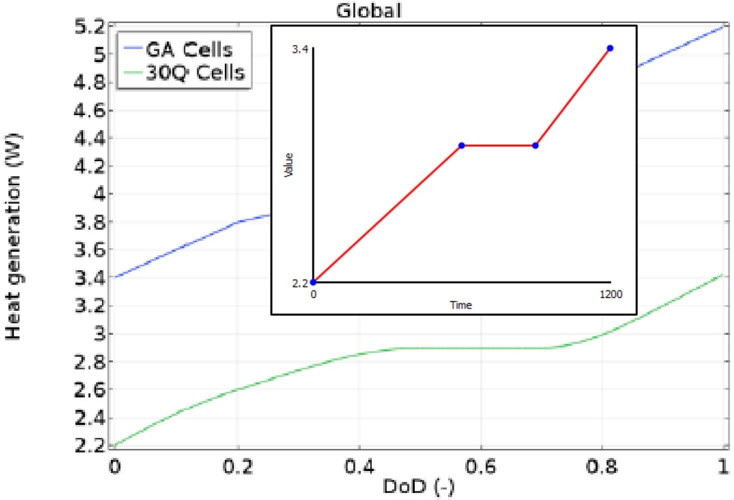
- 30Q vs GA cell performance
- Boundary conditions
  - Determine maximum acceptable operating temperatures for each cell based on maximum cell temperatures
- Evaluate effect of cell contact angle
- Evaluate the OHPs passive propagation resistance
- Heat sink designed to be cooled on both ends to allow for the most compact design

Heat Generating Rates for a 3C Discharge



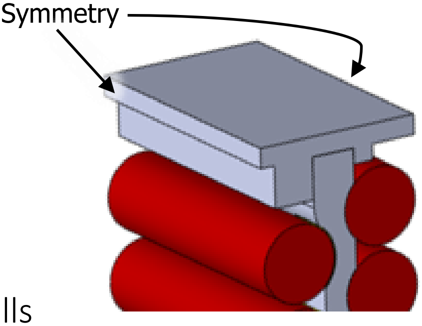
# OHP Heat Sink Design & Analysis

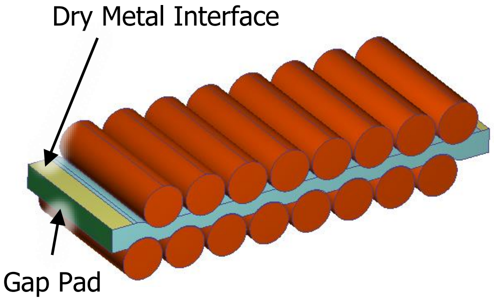
## *Model Setup*



### Material and interface properties

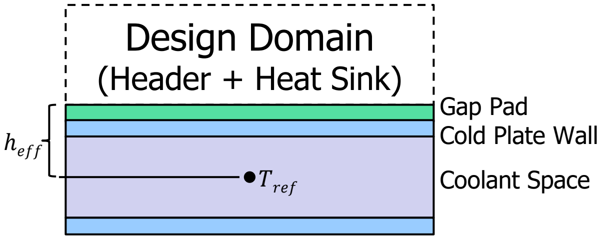
- Simplified Model
  - Cells (w/ anisotropic conductivity)
  - Kapton Tape
  - Epoxy TIM
  - Spine
- Spine-to-Header Interface
  - Dry metal interface: $3.2\ {}^{W}/_{in^{2}\,{}^{\circ}C}$
  - Gap pad on end: $5.0\ {}^{W}/_{in^{2}\,{}^{\circ}C}$





### Boundary conditions

- Heat Generation
  - Piecewise-linear approx. of 30Q and GA Cells
- Heat Rejection
  - $h_{eff}\ \left(5\ {}^{W}/_{in^{2}\,K}\right)$ w/ transient $T_{ref}$
  - $T_{ref}$ of 45-55 °C; reduced as needed to limit max cell temperatures



Design Domain
(Header + Heat Sink)

Gap Pad
Cold Plate Wall
Coolant Space

$h_{eff}$

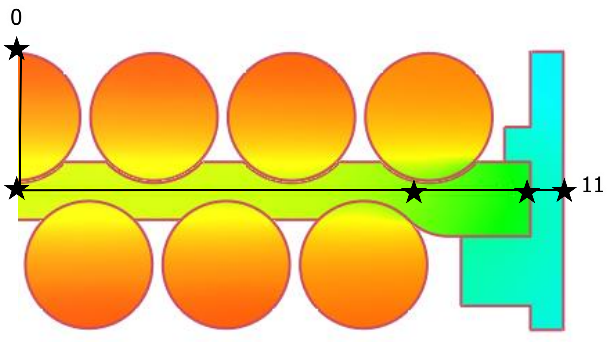
$T_{ref}$

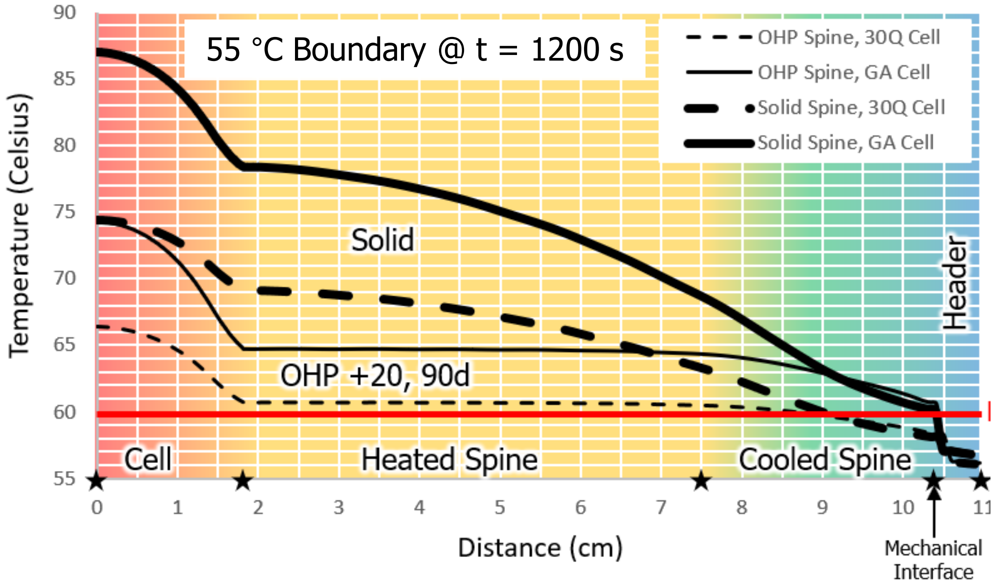
$$T_{ref}(t) = 25\,{}^{\circ}C + \frac{(10\,{}^{\circ}C)t}{1200\ s}$$

# OHP Heat Sink Design & Analysis

*Transient Analysis – Overall Thermal Gradients*

- 45-55 °C transient boundary temperature results in excessive cell temperature, primarily due to gradients within the cells
- GA and 30Q cells produce a 2 to 4 °C gradient, respectively, across the interface with the header
- Maximum allowable transient boundary temperatures
  - ○ **GA Cell**: 28-38 °C
  - ○ **30Q Cell:** 37-47 °C



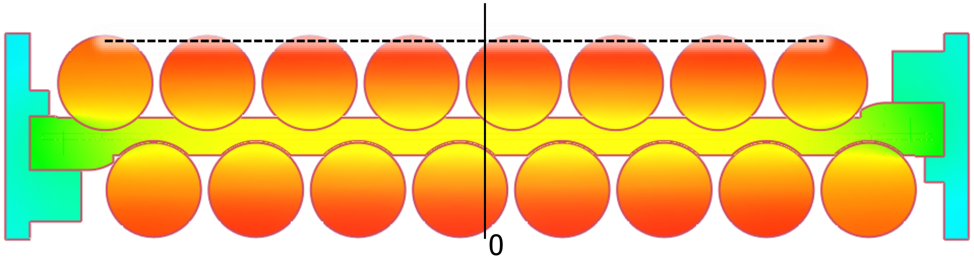


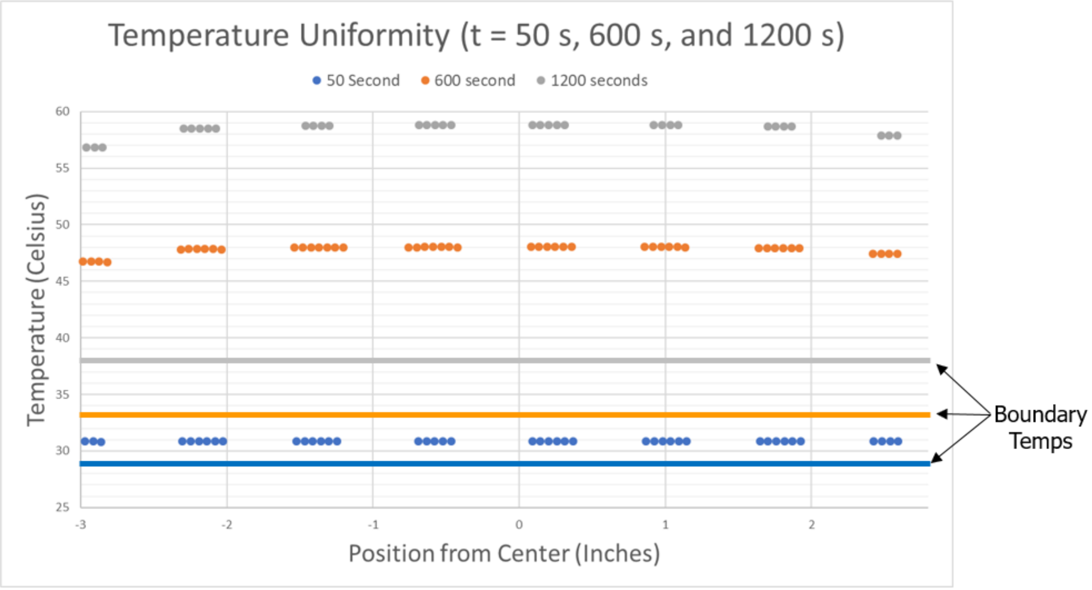
# OHP Heat Sink Design & Analysis

*Transient Analysis – Cell-to-Cell Uniformity*

- Uniformity of peak cell wall temperatures predicted to be 1-2 °C

- Edge cells are primary contributors to the $\Delta T$
  - Additional envelope material sinks more heat from cells



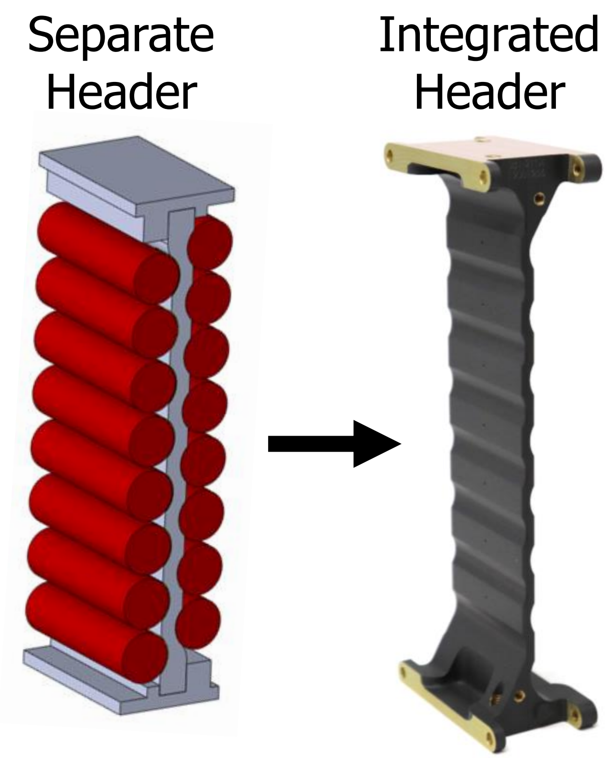


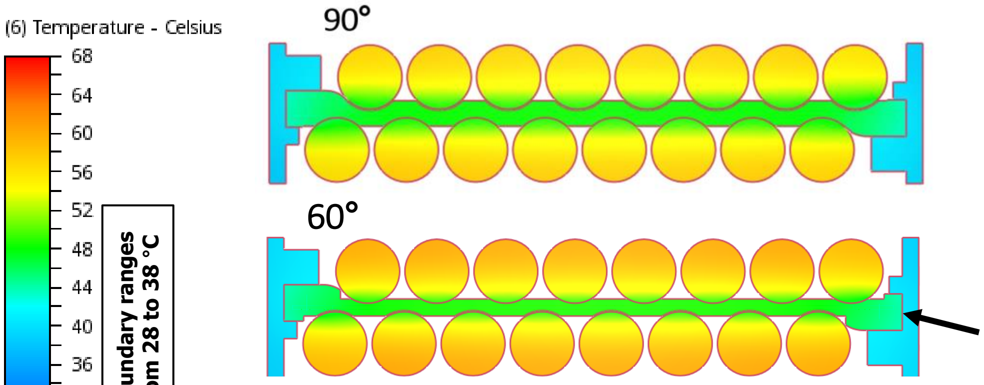
Results shown are for GA cells with a boundary temperate varying from 28 to 38 °C.

# OHP Heat Sink Design & Analysis

*Mass Reduction and Header Integration*

- The thermal penalty of going to a 60° contact angle (vs 90°) can be offset by integrating the header into the spine
    - Shifts the thermal interface into a low flux region between adjacent spines
    - Allows for around 20% mass savings with no thermal penalty





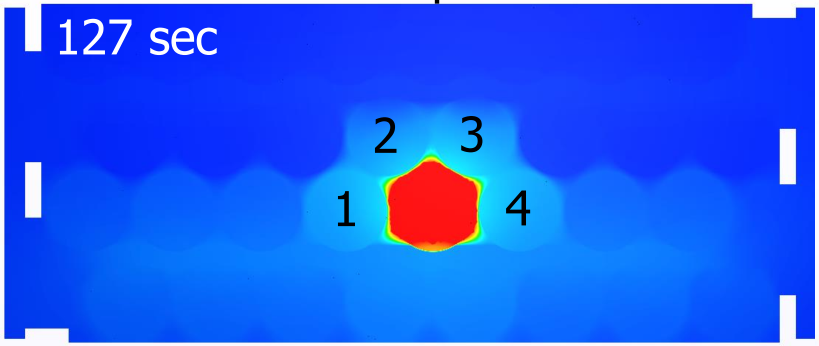
2-5 °C gradient across interface

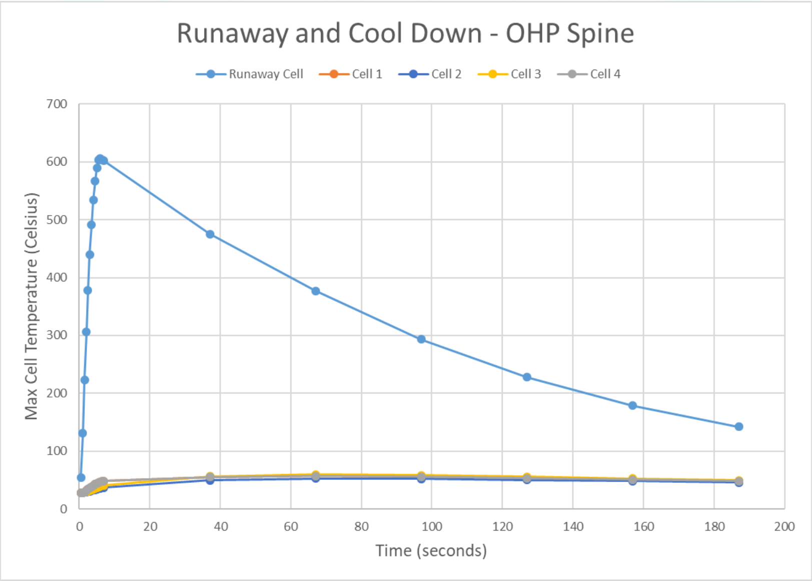
| | Maximum Cell Temperatures (°C) | | | | | | | | | Max Mid-Plane Temperature (°C) | Temperature Spread (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GA Cell, 90 degree contact angle | | 56.7 | 57.4 | 57.5 | 57.5 | 57.5 | 57.5 | 57.2 | 55.9 | 57.5 | 1.6 |
| | 55.9 | 57.2 | 57.5 | 57.5 | 57.5 | 57.5 | 57.4 | 56.7 | | | |
| GA Cell, 60 degree contact angle | | 60.1 | 60.7 | 60.8 | 60.8 | 60.8 | 60.7 | 60.6 | 58.9 | 60.8 | 1.9 |
| | 58.9 | 60.6 | 60.8 | 60.8 | 60.8 | 60.8 | 60.7 | 60.1 | | | |

# OHP Heat Sink Design & Analysis

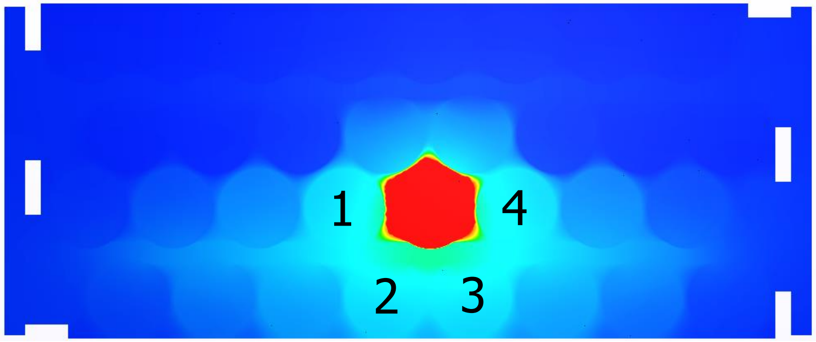
*Thermal Runaway Analysis*

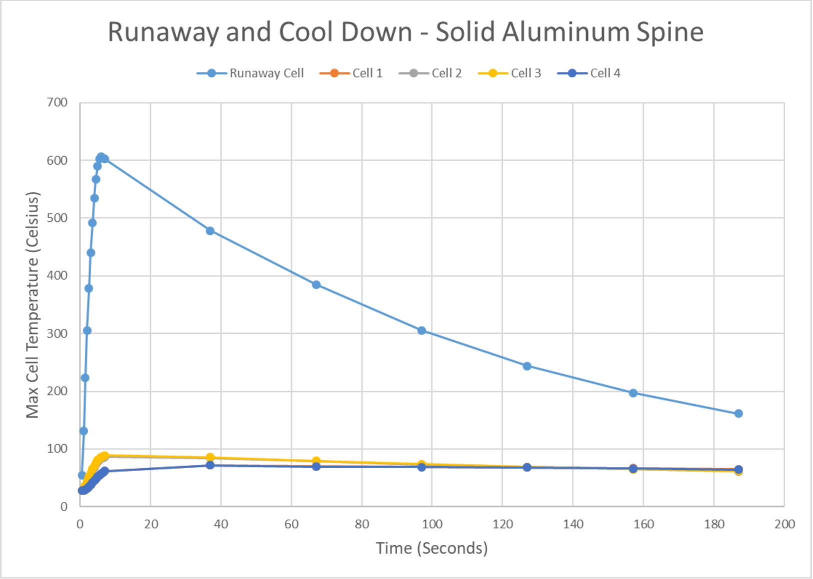
## OHP Spine





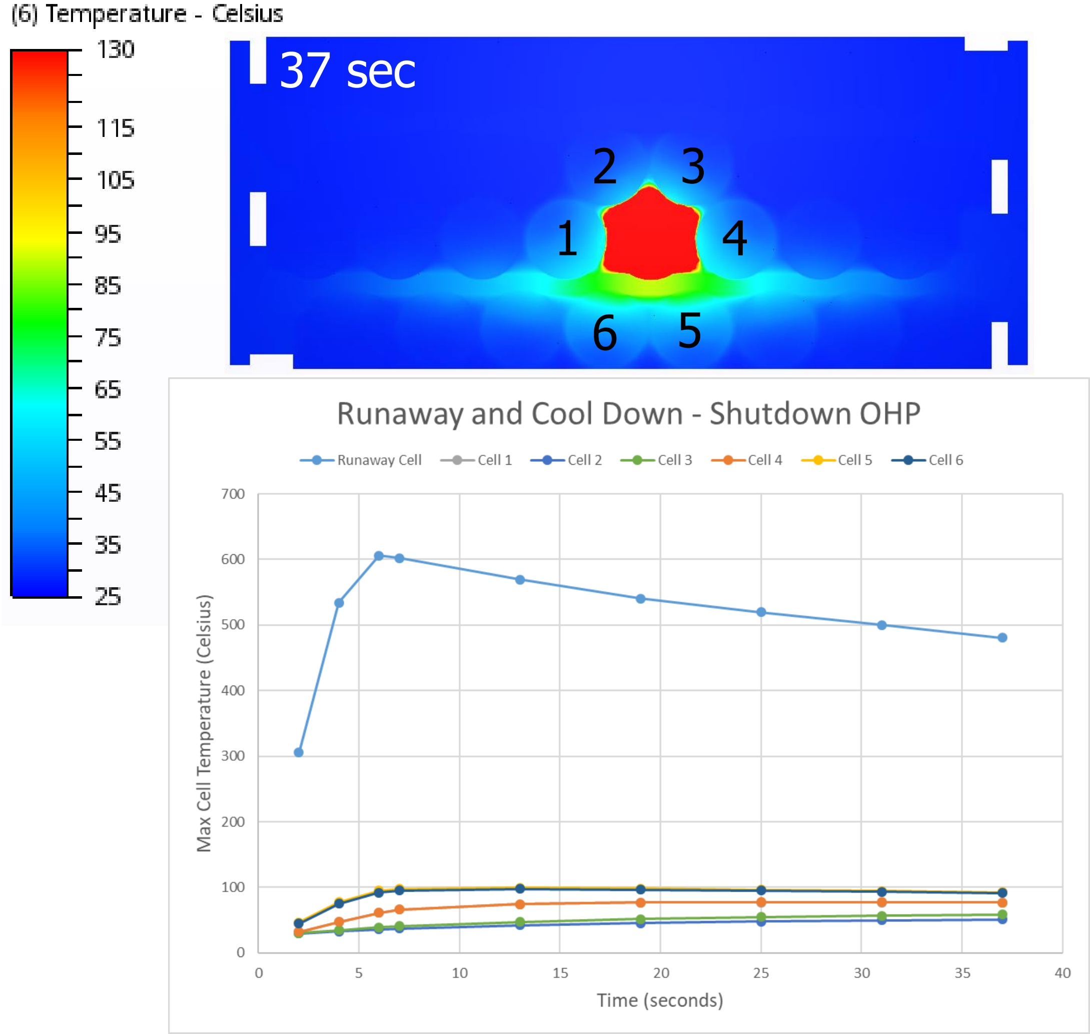
## Solid Al Spine





# OHP Heat Sink Design & Analysis

## *Thermal Runaway Analysis – Worst Case Scenario*



This scenario represents the worst case condition in which the OHP is *completely non-functioning* during the *entire* thermal runaway and cooldown event.

In this case, the only cooling path within the heat sink is the aluminum envelope of the OHP.

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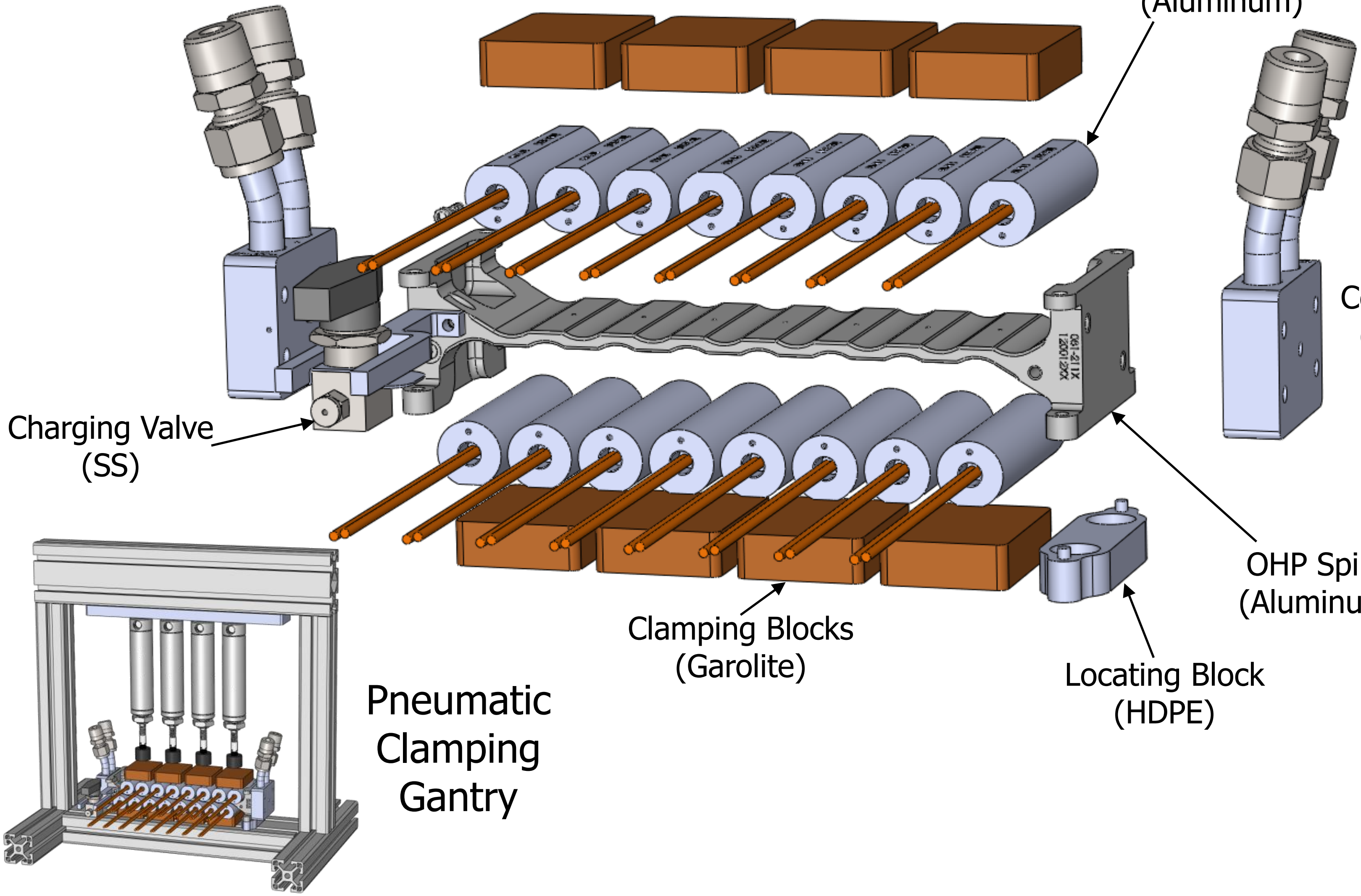
# Experimental Results

*Thermal Test Vehicle*



Simulated Cells
(Aluminum)

Cooling Blocks
(Aluminum)

Charging Valve
(SS)

OHP Spine
(Aluminum)

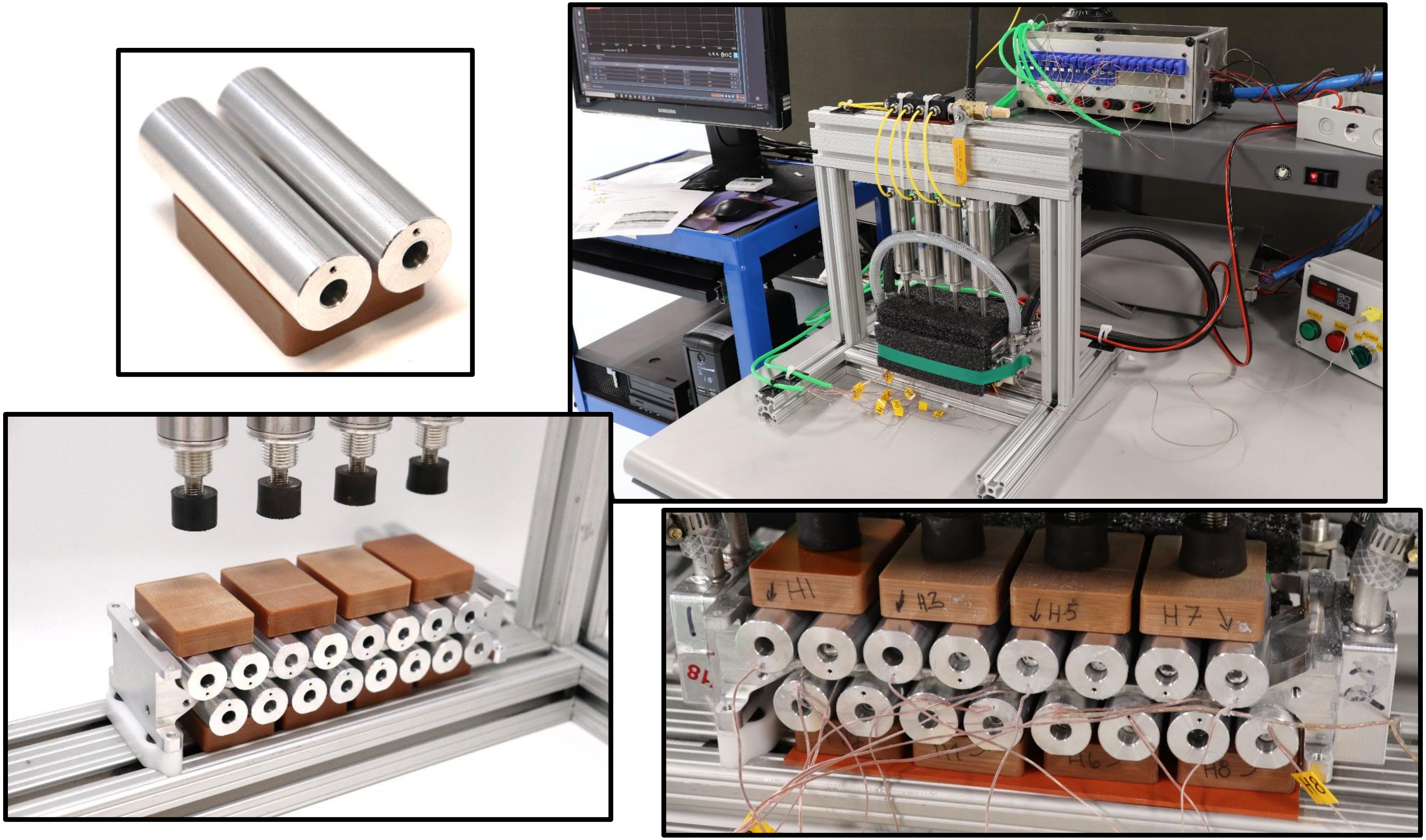
Clamping Blocks
(Garolite)

Locating Block
(HDPE)

Pneumatic
Clamping
Gantry

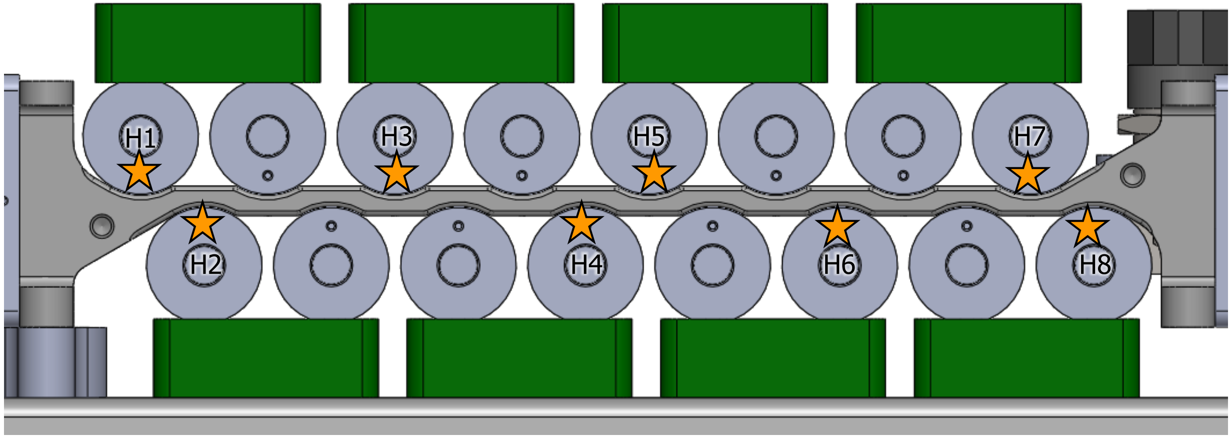
# Experimental Results

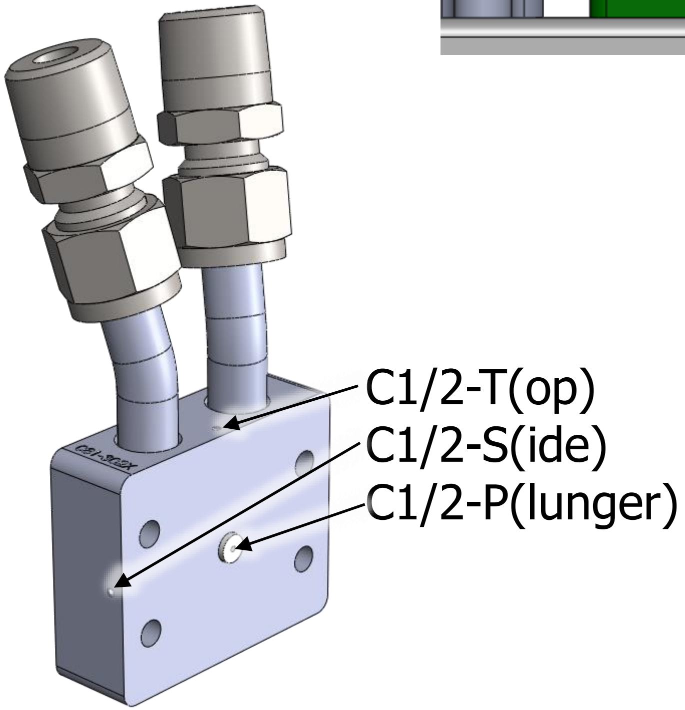
## *Thermal Test Vehicle*



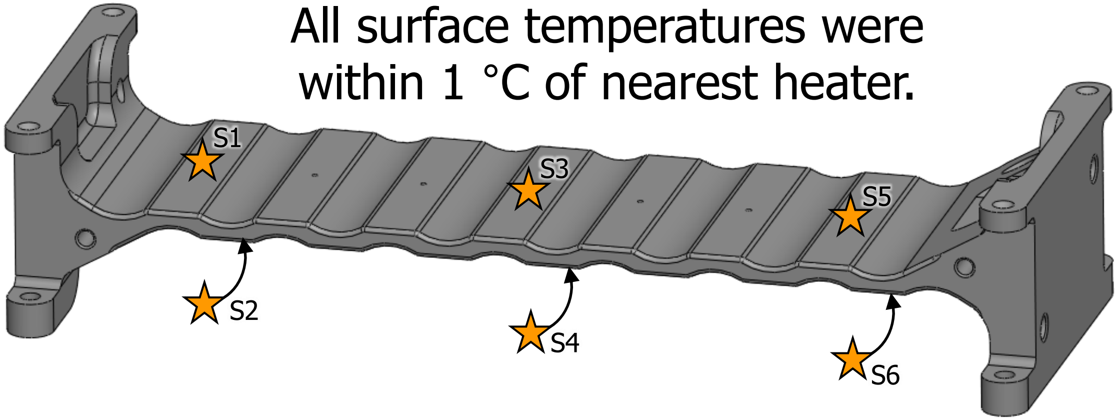
# Experimental Results

*Thermal Test Vehicle – Sensor Locations*





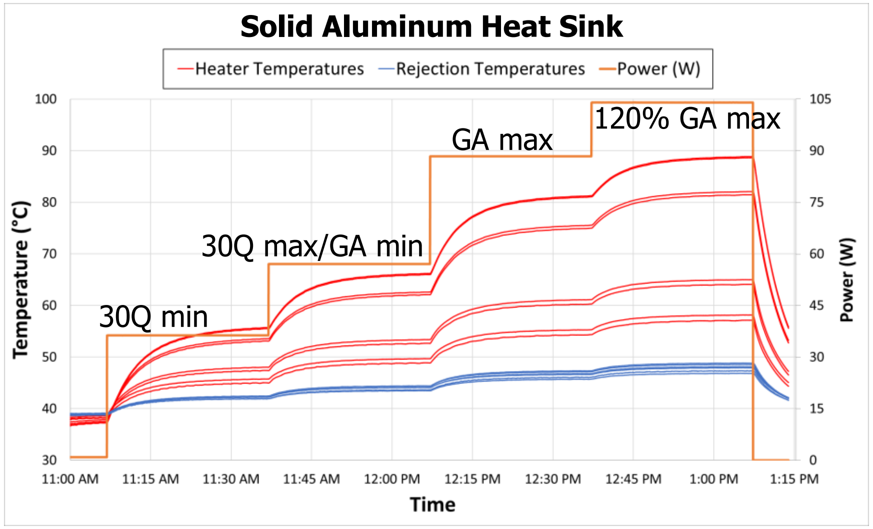
All surface temperatures were within 1 °C of nearest heater.

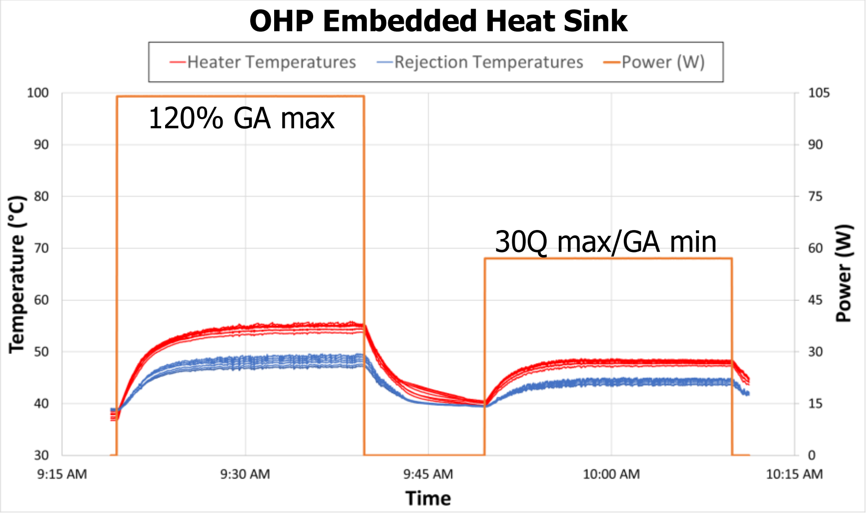


# Experimental Results

*Solid Aluminum vs OHP*

- Tested at a range of powers representative of the cell heat loads
  - Tests allowed to reach equilibrium at each power level
- Baseline test with solid aluminum heat sink
  - Produces large gradients across heat sink and between central and outermost cells
- Performance verification with OHP heat sink
  - Two-phase cooling produces extremely low gradients between cells (evaporators), and much lower gradients across the heat sink (evaporator to condenser).





# Experimental Results

## *Steady-State Performance Verification*

- OHP tested at powers between 36 W (minimum 30Q rate) and 104 W (120% of maximum GA rate)
- OHP tested with boundary temperatures (OHP surface) between 23.7-48.9 °C
- OHP tested in horizontal (analogous to zero-g) and vertical orientations

Overall Spine dT (*3-5 °C predicted*)

| | | 36 W | | 57 W | | 88 W | | 104 W | |
|---|---|---|---|---|---|---|---|---|---|
| **Test No.** | **Orient.** | **Boundary Temp (°C)** | **$\Delta T_{OHP}$ (°C)** | **Boundary Temp (°C)** | **$\Delta T_{OHP}$ (°C)** | **Boundary Temp (°C)** | **$\Delta T_{OHP}$ (°C)** | **Boundary Temp (°C)** | **$\Delta T_{OHP}$ (°C)** |
| B1 | Horiz. | 42.0 | **3.3** | 44.4 | **3.8** | 47.3 | **5.0** | 48.9 | **6.1** |
| B2 | | 23.8 | **3.5** | 26.5 | **4.2** | 30.9 | **5.1** | 33.1 | **5.7** |
| B3 | Vert. | 41.8 | **3.5** | 43.8 | **4.5** | 47.2 | **6.1** | 48.6 | **7.4** |
| B4 | | 23.7 | **3.6** | 26.4 | **4.4** | 30.9 | **5.7** | 33.1 | **6.5** |

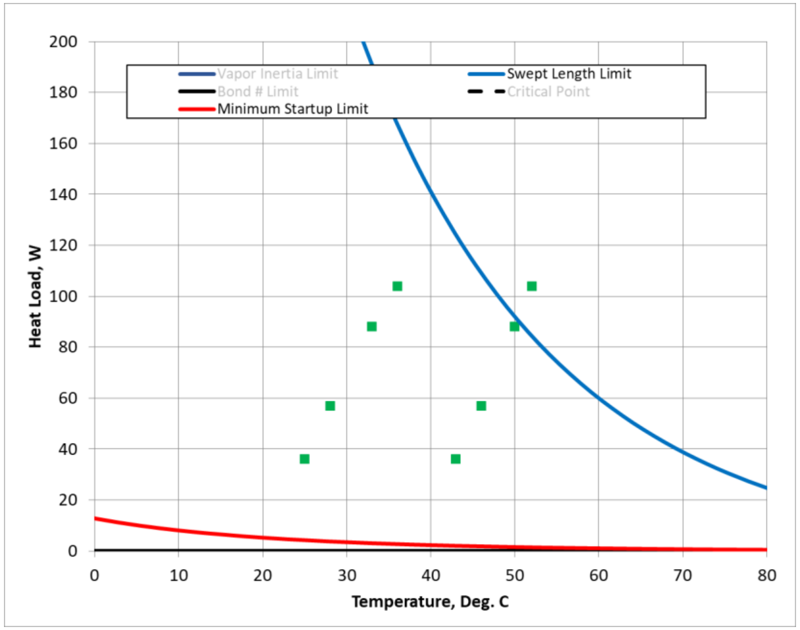
Cell-to-Cell dT (*1-2 °C predicted*)

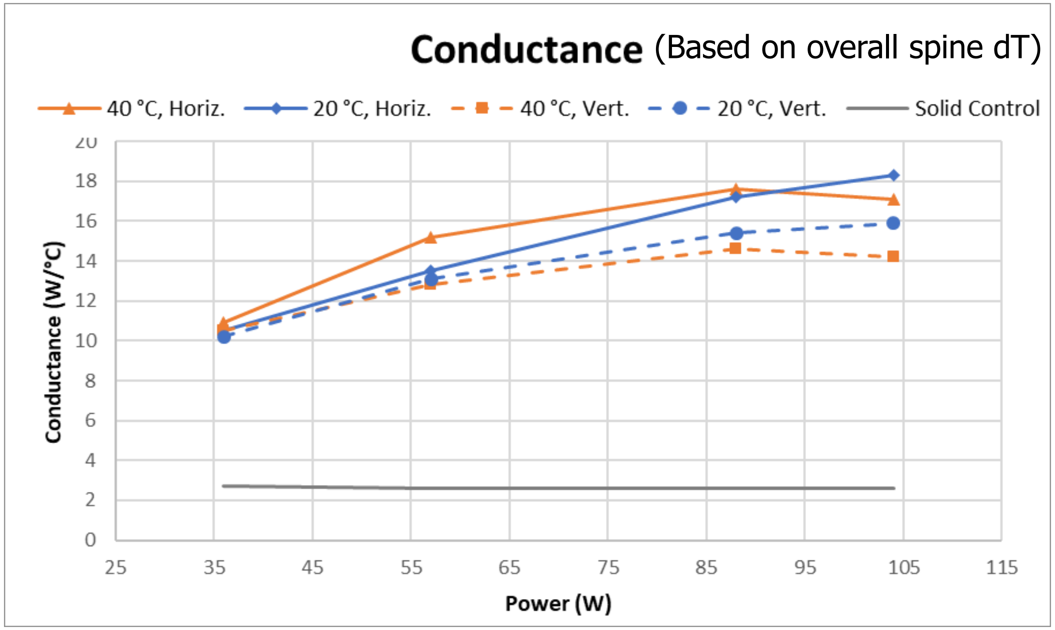
| **Test No.** | **Orient.** | **Boundary Temp (°C)** | **$\Delta T_{cells}$ (°C)** | **Boundary Temp (°C)** | **$\Delta T_{cells}$ (°C)** | **Boundary Temp (°C)** | **$\Delta T_{cells}$ (°C)** | **Boundary Temp (°C)** | **$\Delta T_{cells}$ (°C)** |
|---|---|---|---|---|---|---|---|---|---|
| B1 | Horiz. | 42.0 | **1.5** | 44.4 | **1.2** | 47.3 | **1.4** | 48.9 | **1.8** |
| B2 | | 23.8 | **1.8** | 26.5 | **1.7** | 30.9 | **1.4** | 33.1 | **1.5** |
| B3 | Vert. | 41.8 | **1.6** | 43.8 | **1.4** | 47.2 | **1.8** | 48.6 | **2.5** |
| B4 | | 23.7 | **1.4** | 26.4 | **1.4** | 30.9 | **1.3** | 33.1 | **1.4** |

# Experimental Results

*Variable Conductance*

- OHP conductance varies with temperature and power
- Low sensitivity to gravity and boundary temperature
- At boundary temperatures above 50 °C, the device encounters the Swept Length Limit resulting in a decrease in conductance
  - ○ Conductance is restored once temperature is reduced.

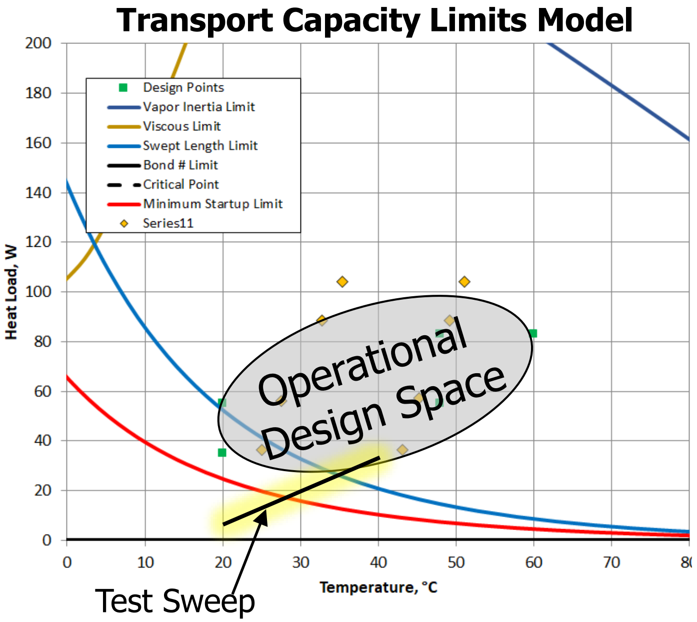




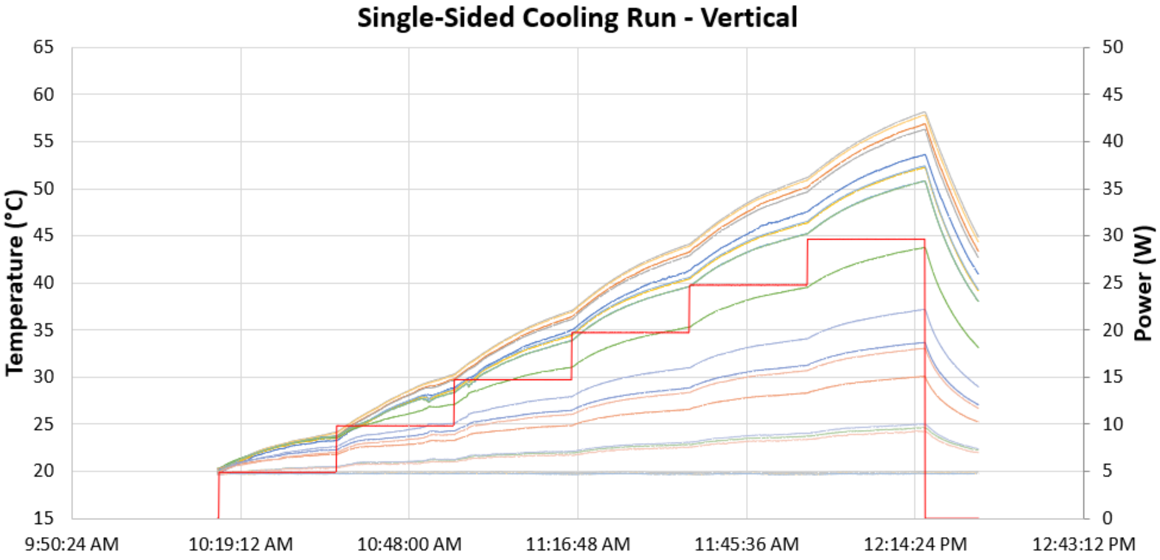
# Experimental Results

*Single Ended Cooling*

- Cooling just one end of the OHP shifts the Swept Length Curve far left, leaving little overlap with the design space.
- Design-dependent characteristic – measures can be taken to better accommodate single-ended cooling, where required.
    - Various trade-offs (e.g., size, weight, etc.) may apply



**Transport Capacity Limits Model**

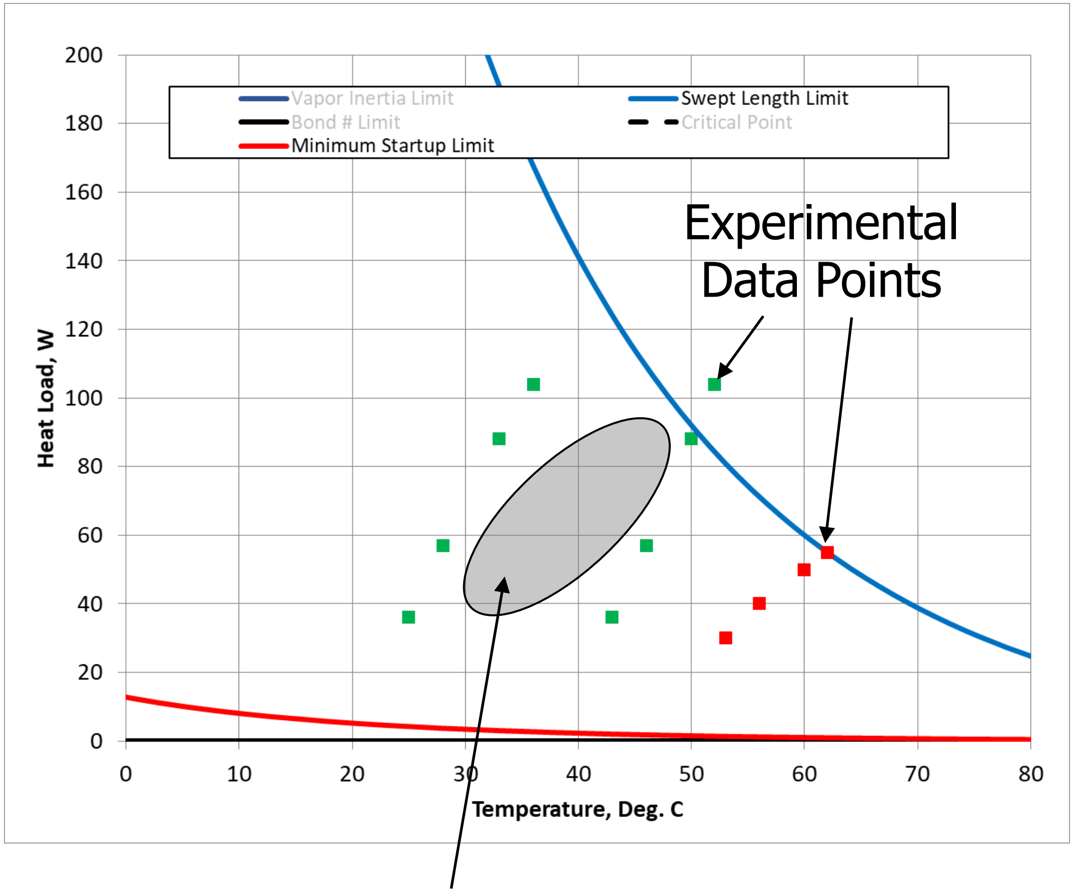


**Single-Sided Cooling Run - Vertical**

# Experimental Results

## *High-Temperature Operation*

- OHP continues to experience stable operation over the entire application design space
- With temperatures above 50 °C, OHP transport capacity is reduced (must run at lower power) and operation becomes less stable
- This is also a design-dependent characteristic
    - Alternative designs can accommodate higher temperature operation; again, trade-offs likely apply



*Design Space for High-Power Battery*

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# Conclusions from Modeling

- The OHP spine is predicted to achieve the uniformity targets with the cell-to-cell dT being dominated by the cells nearest the ends
  - Enabled by the two-phase nature of the OHP

- The dT within the spine (3-5 °C) is around half of the dT expected within each cell (5-10 °C)
  - Cell internals and interfaces are primary contributors to overall gradient.

- Use of an integrated header provides mass savings and temperature reduction, offsetting the thermal impact of using a 60° cell contact angle. (Trades with machining complexity.)

- OHP heat sink predicted to provide around 2x the margin of a solid aluminum heat sink during a thermal runaway event
  - High conductance spine carries heat to cells throughout the spine, reducing the heat load on neighboring cells.

# Conclusions from Testing

- ***Experimental results match the modeling predictions*** for both overall heat sink gradient as well as cell-to-cell uniformity
- Results show very ***little sensitivity to boundary temperatures in the 20-45 °C range*** and to ***gravitational orientation***
- Testing shows the heat sink to meet performance targets at boundary temperatures less than 50 °C
  - Performance drops significantly above this temperature
- Testing confirms the requirement for cooling of both ends of the spine
- Boundary temperature and dual-sided cooling requirements are design-dependent – alternative OHP designs may be conceived which allow for higher temperature operation and single-sided cooling.
  - ***Boundary conditions are a key input to the OHP design process***
- Thermal Runaway testing at NASA-JSC verified propagation resistance of this battery design

# Acknowledgements

Dr. Eric Darcy and team at NASA for their support and on-going efforts to characterize and verify these OHPs for thermal management of Li-ion batteries.

Dr. Paul Coman at Univ. of South Carolina for his excellent modeling contributions which served as the starting point for our analysis.

# QUESTIONS?