ThermAvant™
TECHNOLOGIES

Oscillating Heat Pipes for Thermal Management of Li-ion Batteries

NASA Aerospace Battery Workshop

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Executive Summary

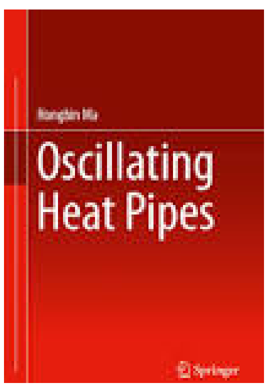
- **Goal:** Enable safe, high power discharges (up to 3C) of a 2 kWh Li-ion battery by limiting peak cell temperatures, maintaining <2 °C cell uniformity, and providing resistance to thermal runaway propagation.
- **Approach:** Embed Oscillating Heat Pipes (OHPs) within the structural heat sinks to increase conductance and reduce overall system mass.
- **Result:** Experimental results with a 16-cell subunit utilizing electric heaters to simulate cells show steady-state conductance 8-16x higher than solid aluminum and uniformity between cells of around 1 °C. Analysis also predicts the design to be passively resistant to thermal runaway propagation

ThermAvant at a glance

- **2007** Filed initial patent w. Univ. of Missouri
- **2009** Awarded first NSF and DoD SBIRs

6+ years demonstrating OHP feasibility (mostly with DoD SBIR funding)

- **2015** OHP pilots and MRL matures with AS9100D processes, supply chain
- **2017** **First on-orbit flight and commercial adoption of OHPs**
- **2019** Quadrupled capacity for growing Aero-Def-Tech customers' demand

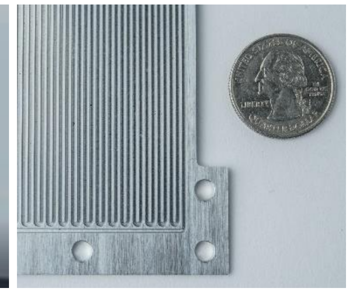


Oscillating Heat Pipes text-book by Dr. Ma (2015)

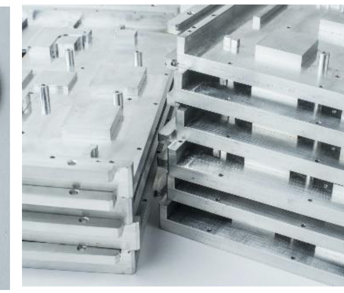
Winner of 2018 R&D 100
Most Technologically Significant New Product in Mechanical-Materials

- World-leader in **Oscillating Heat Pipes (OHPs)**
- 2- and 3-D **thermal-mechanical** solutions
- Blue chip **Aero-Defense** customer base
- 40k ft^2 of **ISO9000/AS9100D certified** facilities
- Awarded **$20M in government R&D** since 2009

ASETS-II launch of OHPs



Cut away of ASETS-II OHP



Complex OHP heat sinks

Management team

Joe Boswell (CEO, co-Founder) Director, ISC; CFO, InsideTrack; JPMorgan M&A; UPenn Engr & Wharton

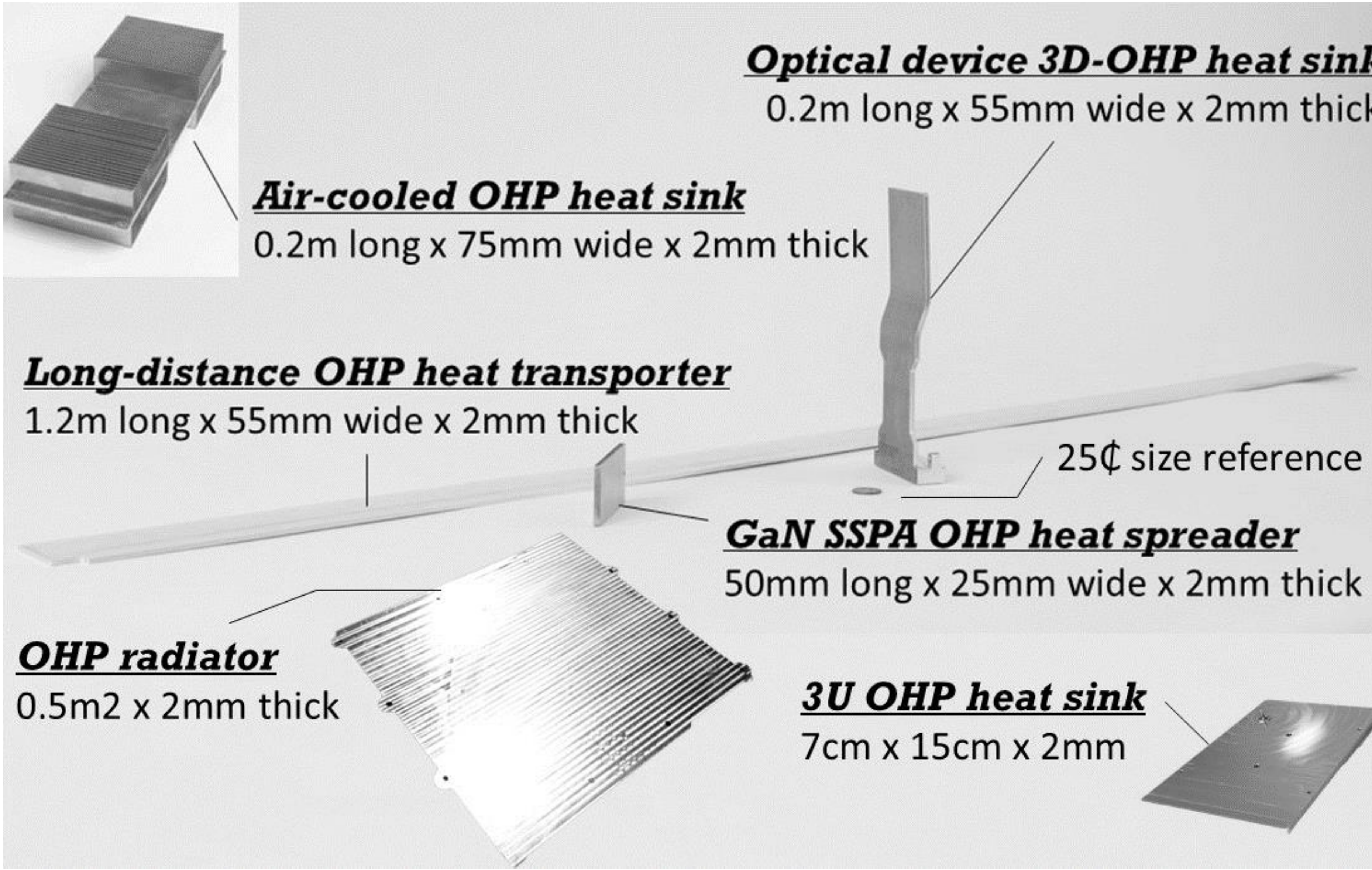
Dr. Hongbin Ma (co-Founder) La Pierre Prof. & Ctr Thermal Mgt MU; PhD Texas A&M

Matt Steele (VP Operations) 20-years metals & mfg. experience; VP, Van Am Custom; Engr., EPT; BS MWSU

Daniel Pounds (VP Engineering) Prod Dev Engr, Advanced Cooling Technologies; BS/MS MU under Ma

Soo Lee (VP Finance) GM Greenwave Foods, Associate Director, UBS BS Barnard, MBA Columbia Univ.

Example OHP products from 1cm to +1m



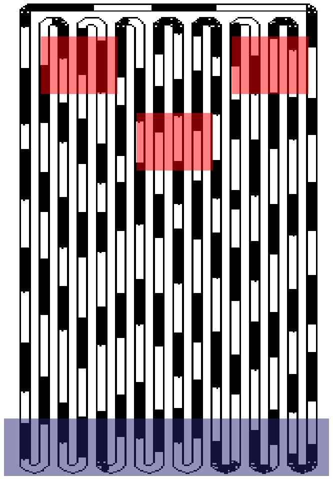
Agenda

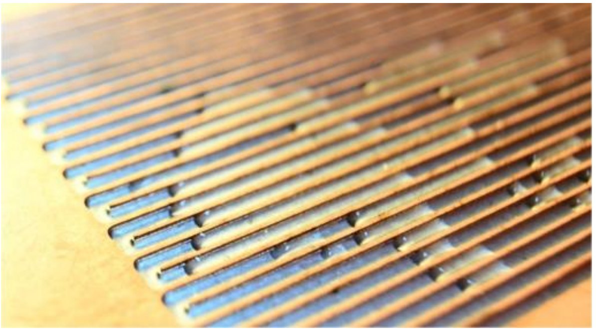
- Introduction to Oscillating Heat Pipes
- Problem Background
- The Proposed Solution
- Design & Analysis Results
- Experimental Results
- Conclusions & Questions

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 due to axial expansion and contraction caused by evaporation and condensation



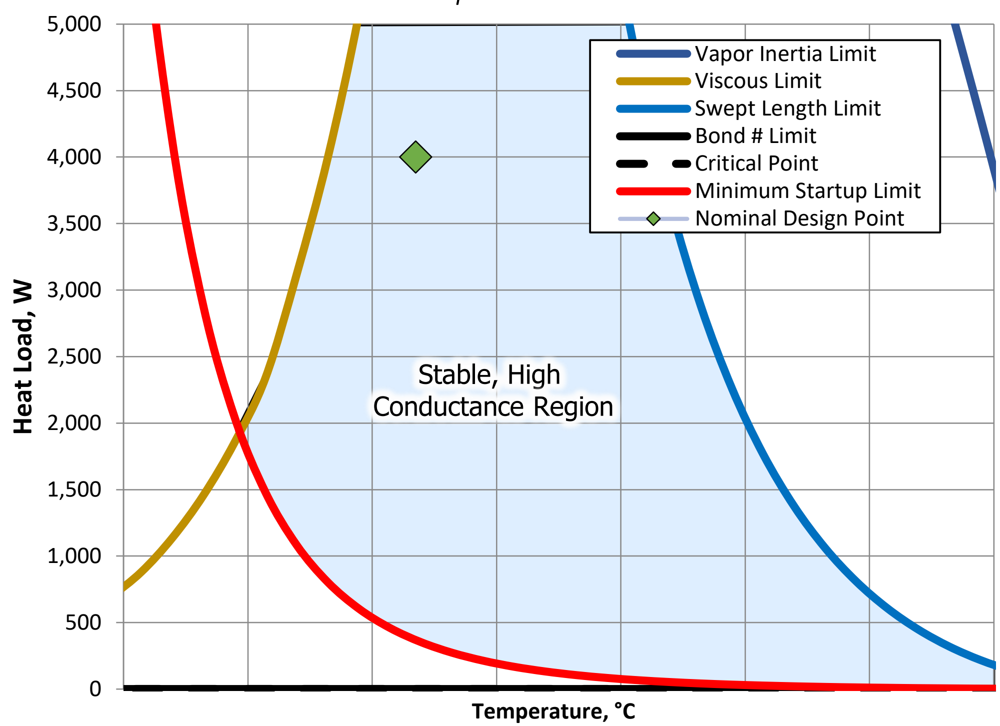


Introduction to OHPs

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)

Agenda

- Introduction to Oscillating Heat Pipes
- **Problem Background**
- The Proposed Solution
- Design & Analysis Results
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Problem Background

Guidelines for Safe, High-Performing Li-Ion Batteries

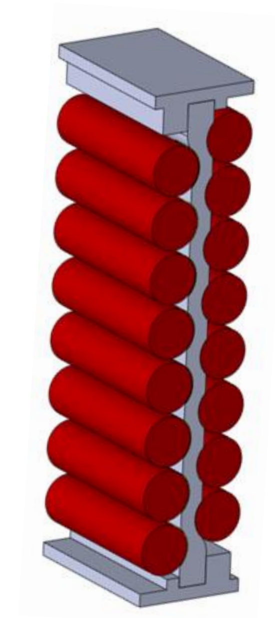
- Overall Program Objectives:
  - Minimize mass and volume of battery components to achieve specific power and energy targets
  - Develop methods for achieving passive thermal runaway propagation resistance utilizing commercial Li-ion cells

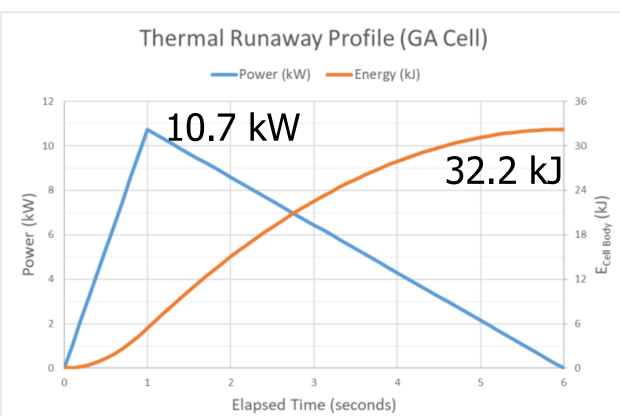
- ThermAvant Specific Objective:
  - Demonstrate how high-conductance, embedded OHPs can provide a significant thermal performance benefit while reducing size and weight.

Problem Background

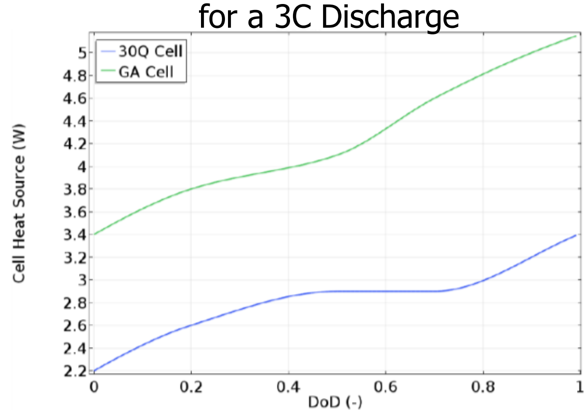
Scope of Investigation

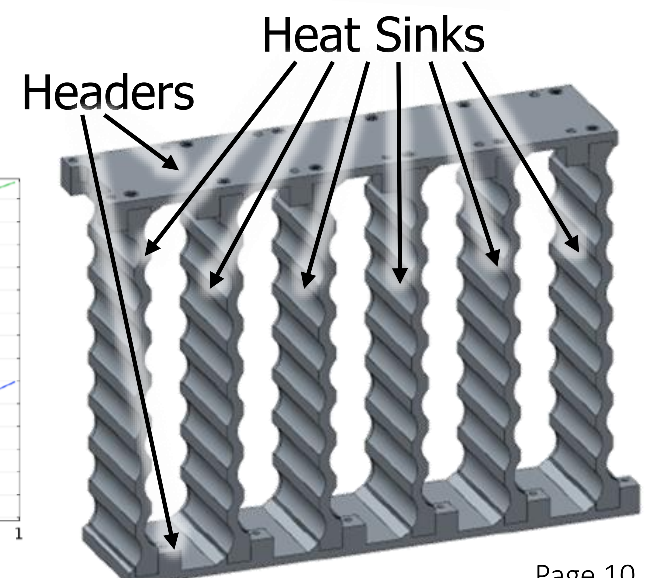
- Design scope limited to the structural heat sink "spines" and headers
- Defined cell-to-spine and spine-to-header interfaces
- 16 x 18650 Li-ion cells per heat sink
    - Two cells considered: 30Q and GA
- Transient boundary condition with a starting temperature of either 25 or 45 °C and rising 10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





Heat Generating Rates
for a 3C Discharge





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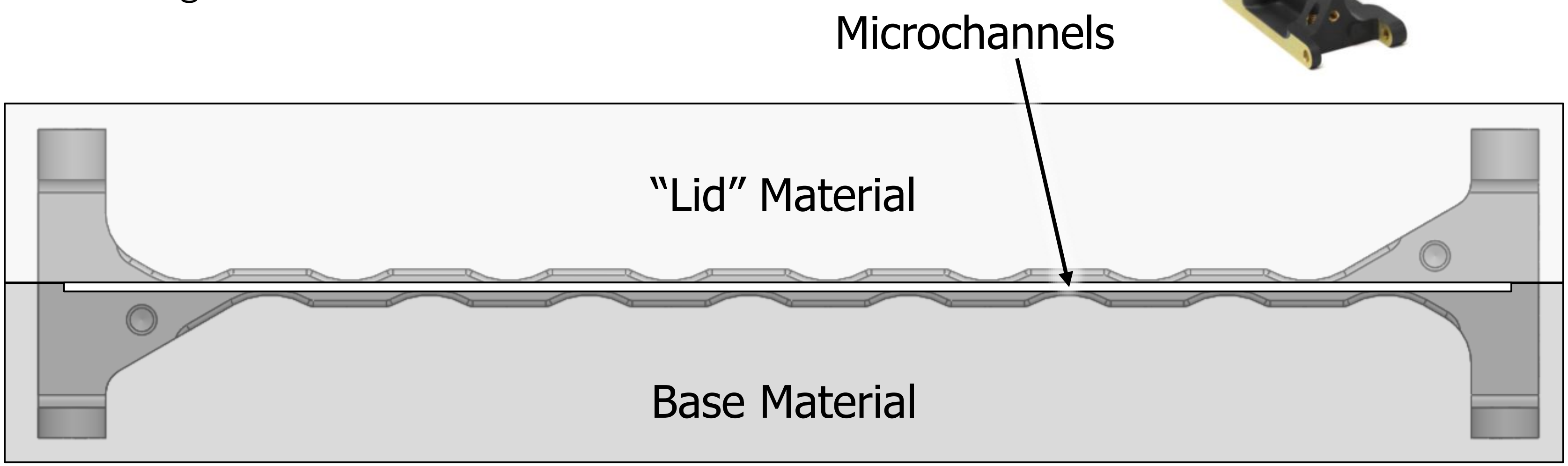
The Proposed Solution

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

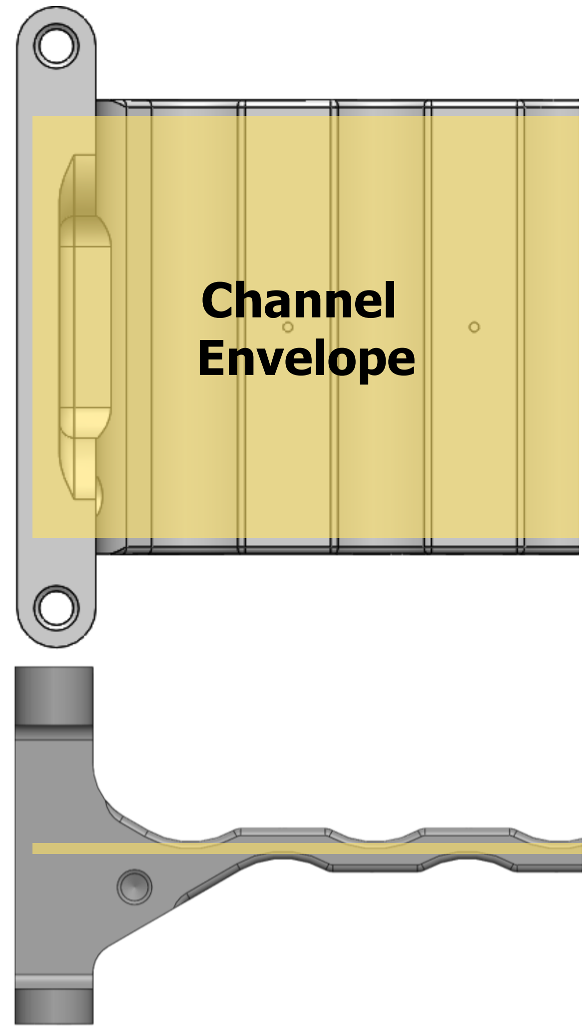
Heat Sink w/ Integrated Headers



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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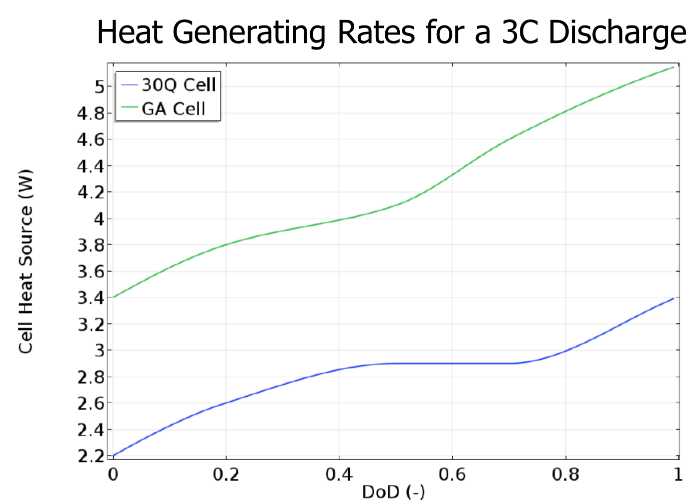
OHP Heat Sink Design & Analysis

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



OHP Heat Sink Design & Analysis

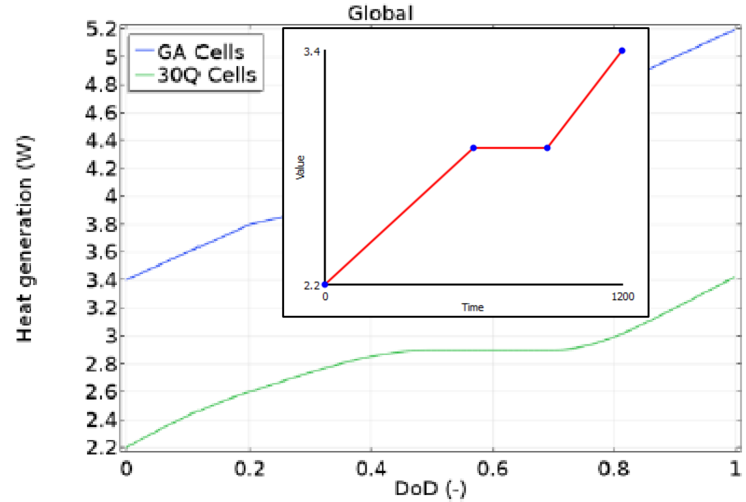
Model Setup

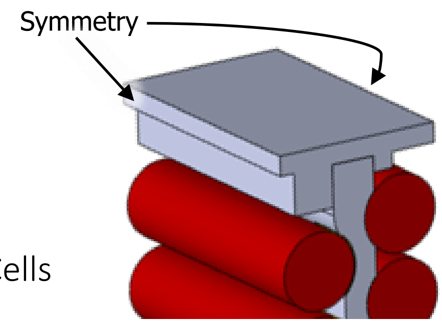
Material and interface properties

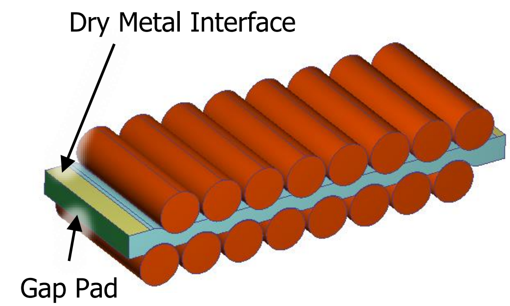
- Spine-to-Header Interface
  - Dry metal interface: $3.2\ {}^{W}/_{in^2\ ^\circ C}$
  - Gap pad on end: $5.0\ {}^{W}/_{in^2\ ^\circ C}$
- Simplified Model
  - Cells (w/ anisotropic conductivity)
  - Kapton Tape
  - Epoxy TIM
  - Spine

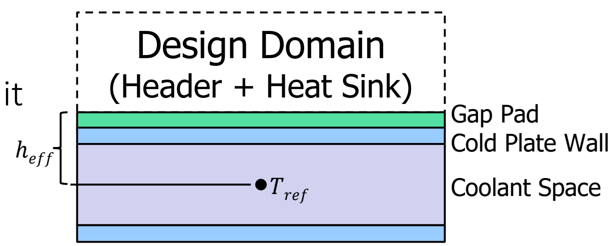
Boundary conditions

- Heat Generation
  - Piecewise-linear approx. of 30Q and GA Cells
- Heat Rejection
  - $h_{eff}\ (5\ {}^{W}/_{in^2\ K})$ w/ transient T_{ref}
  - T_{ref} of 45-55 °C to being; reduced as needed to limit max cell temperatures
- Other Boundaries
  - Symmetric on header ends
  - Adiabatic everywhere else







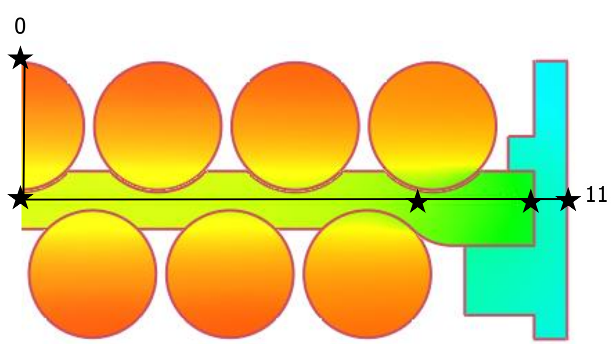


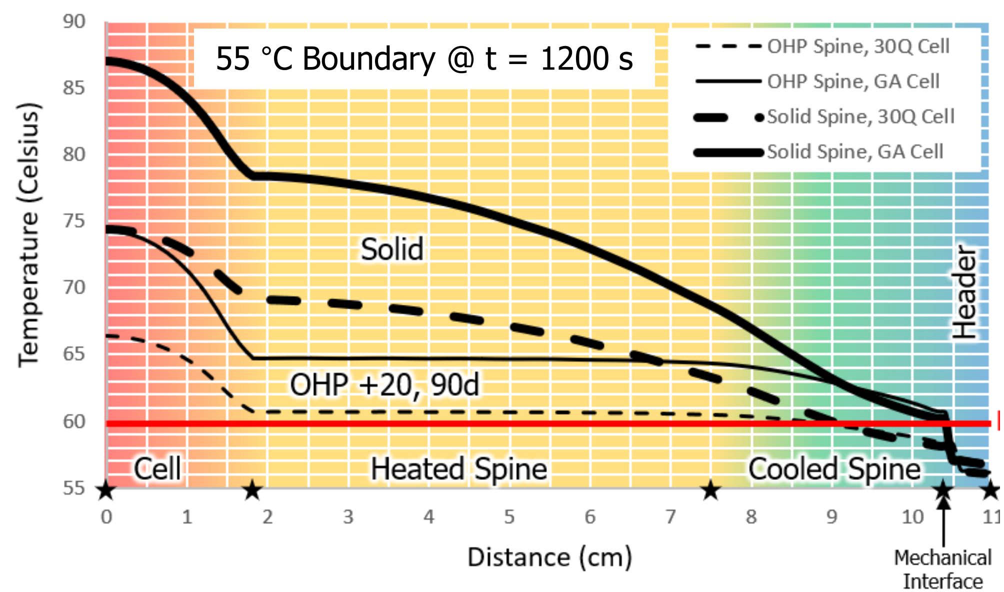
$$T_{ref}(t) = 25\ ^\circ C + \frac{(10\ ^\circ C)t}{1200\ s}$$

OHP Heat Sink Design & Analysis

Transient Analysis

- 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

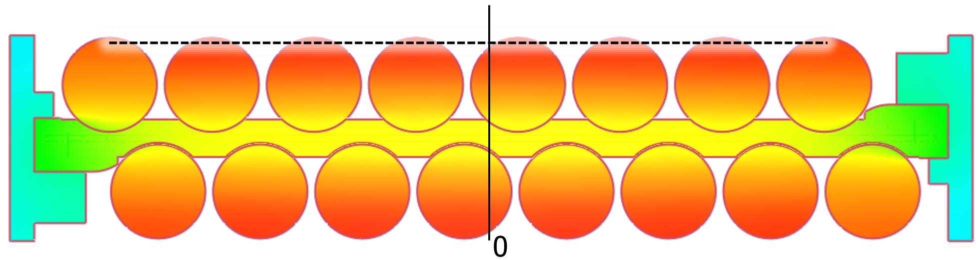


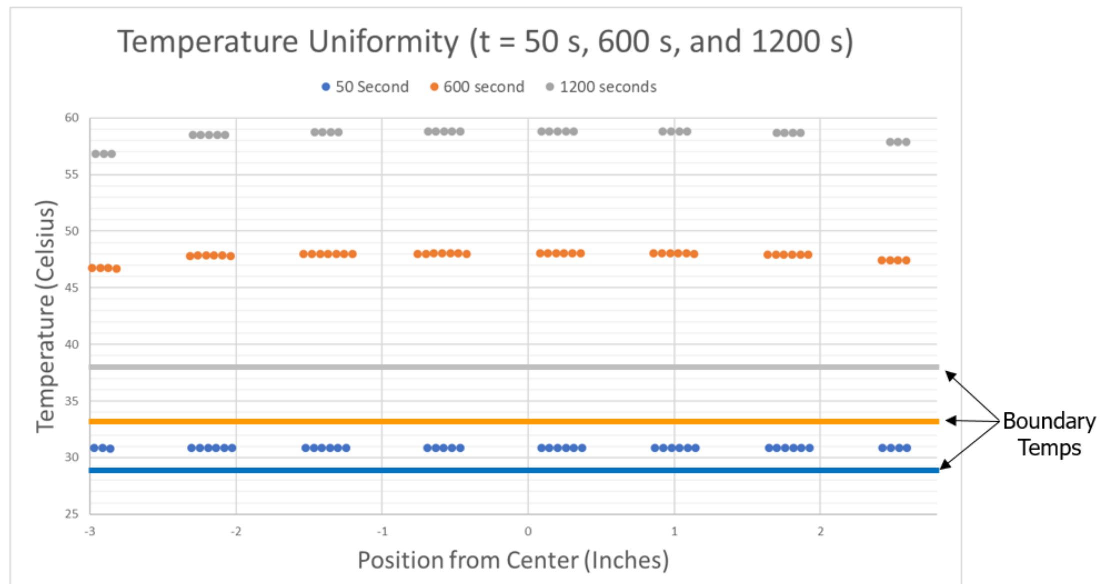


OHP Heat Sink Design & Analysis

Transient Analysis

- Uniformity of peak cell wall temperatures predicted to be 1-2 °C
- Edge cells are primary contributors to the ΔT
  - Additional envelope material sinks more heat from cells



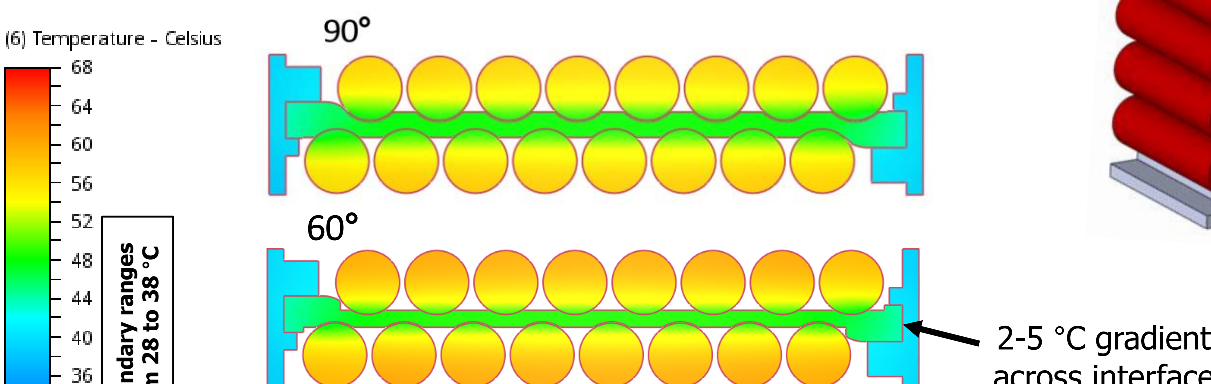


Results shown are for GA cells with a boundary temperate varying from 28 to 38 °C.

OHP Heat Sink Design & Analysis

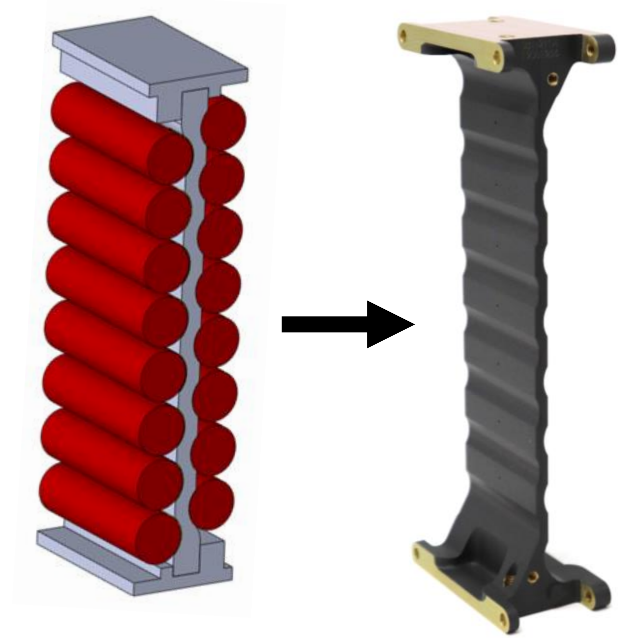
Mass Reduction and Header Integration

- 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



Separate Header

Integrated Header

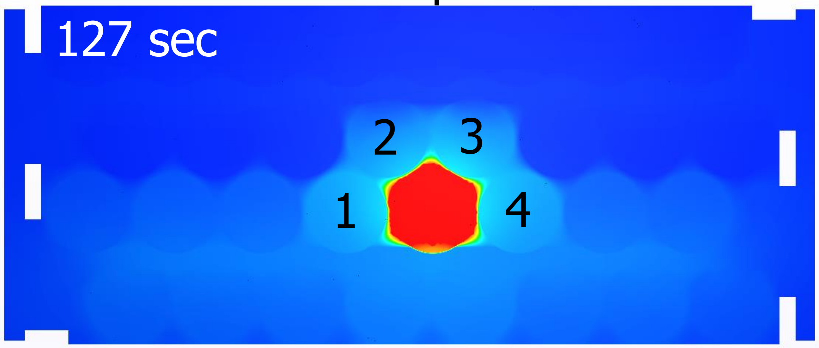


	Maximum Cell Temperatures (°C)									Max Mid-Plane Temperature (°C)	Temperature Spread (°C)
GA Cell, 90 degree contact angle		56.7	57.4	57.5	57.5	57.5	57.5	57.2	55.9	57.5	1.6
	55.9	57.2	57.5	57.5	57.5	57.5	57.4	56.7			
GA Cell, 60 degree contact angle		60.1	60.7	60.8	60.8	60.8	60.7	60.6	58.9	60.8	1.9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

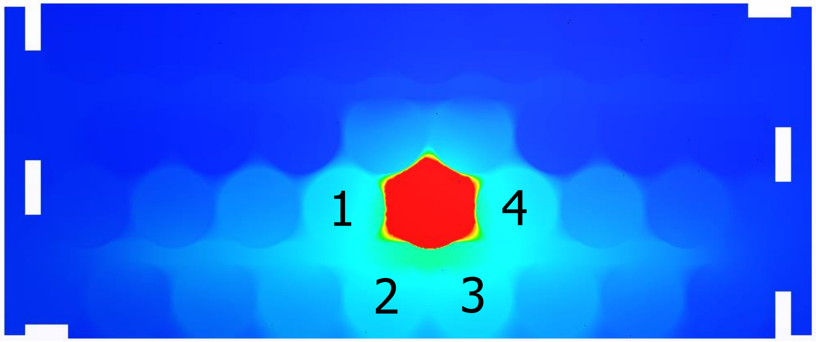
OHP Heat Sink Design & Analysis

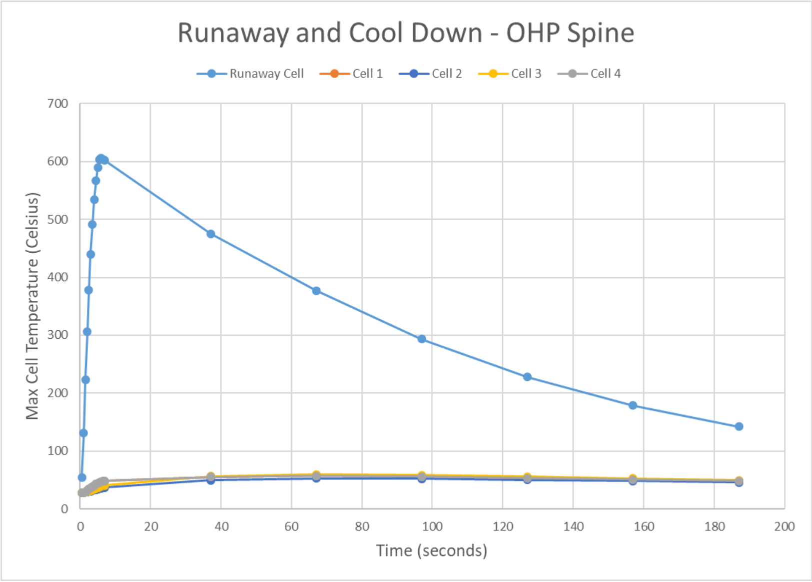
Thermal Runaway Analysis

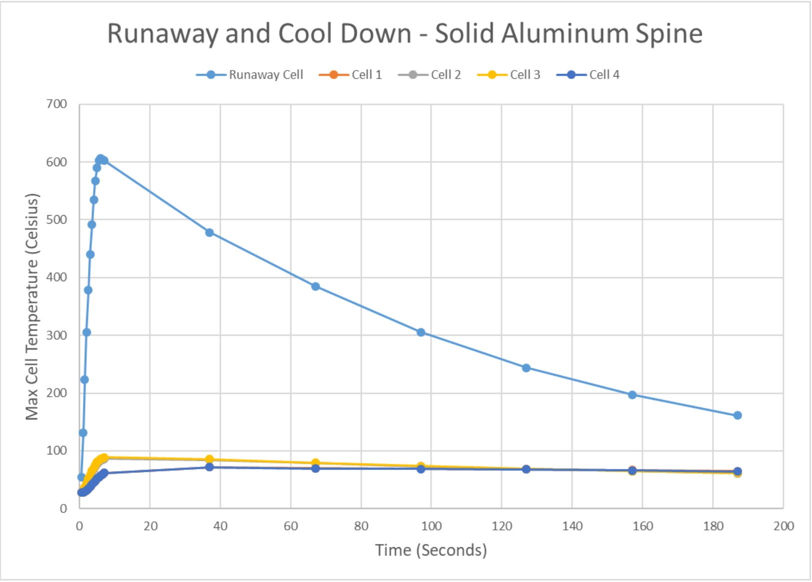
OHP Spine



Solid Al Spine

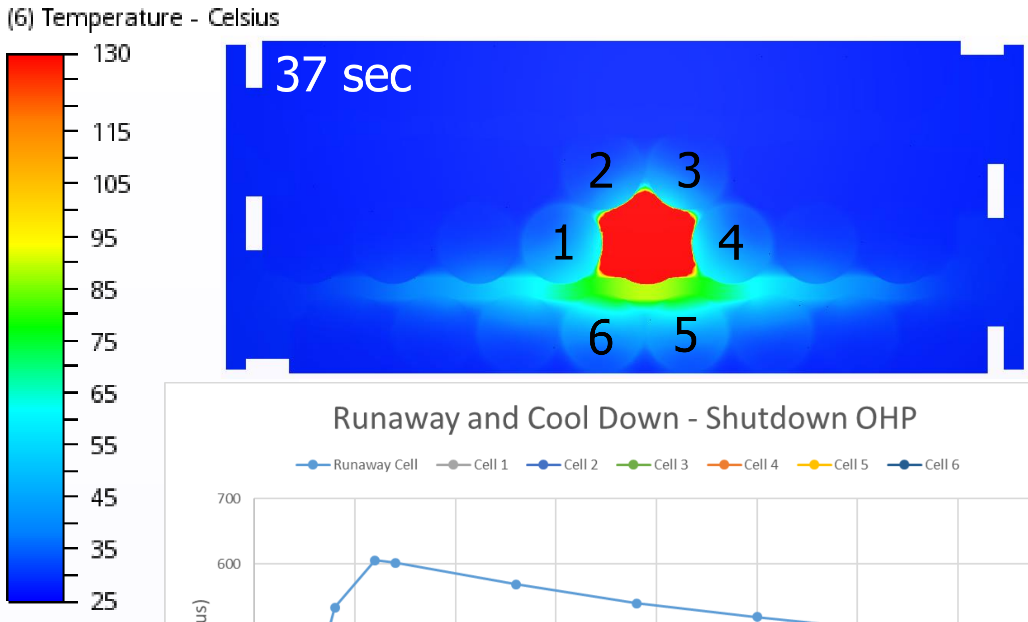


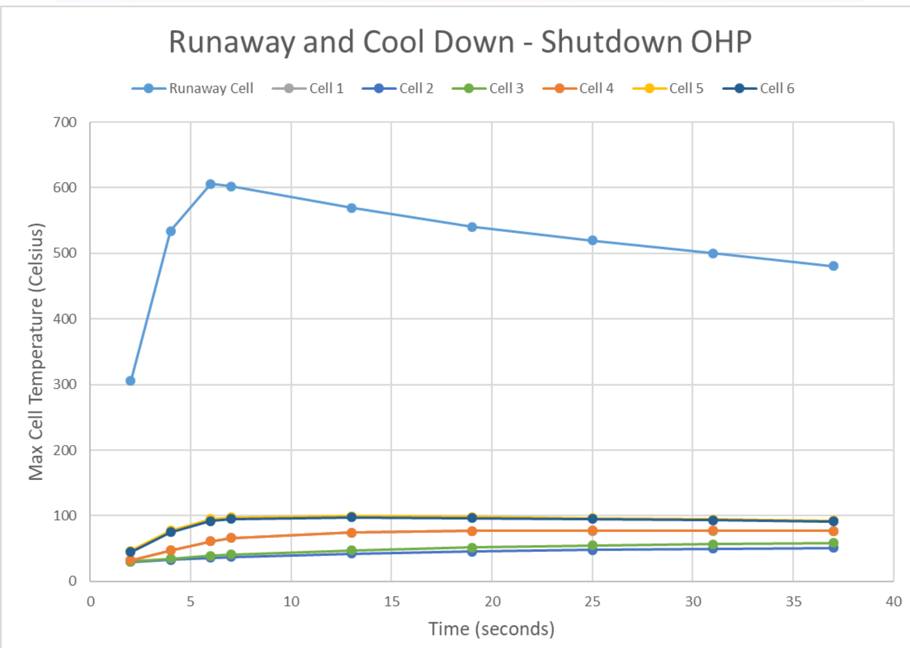




OHP Heat Sink Design & Analysis

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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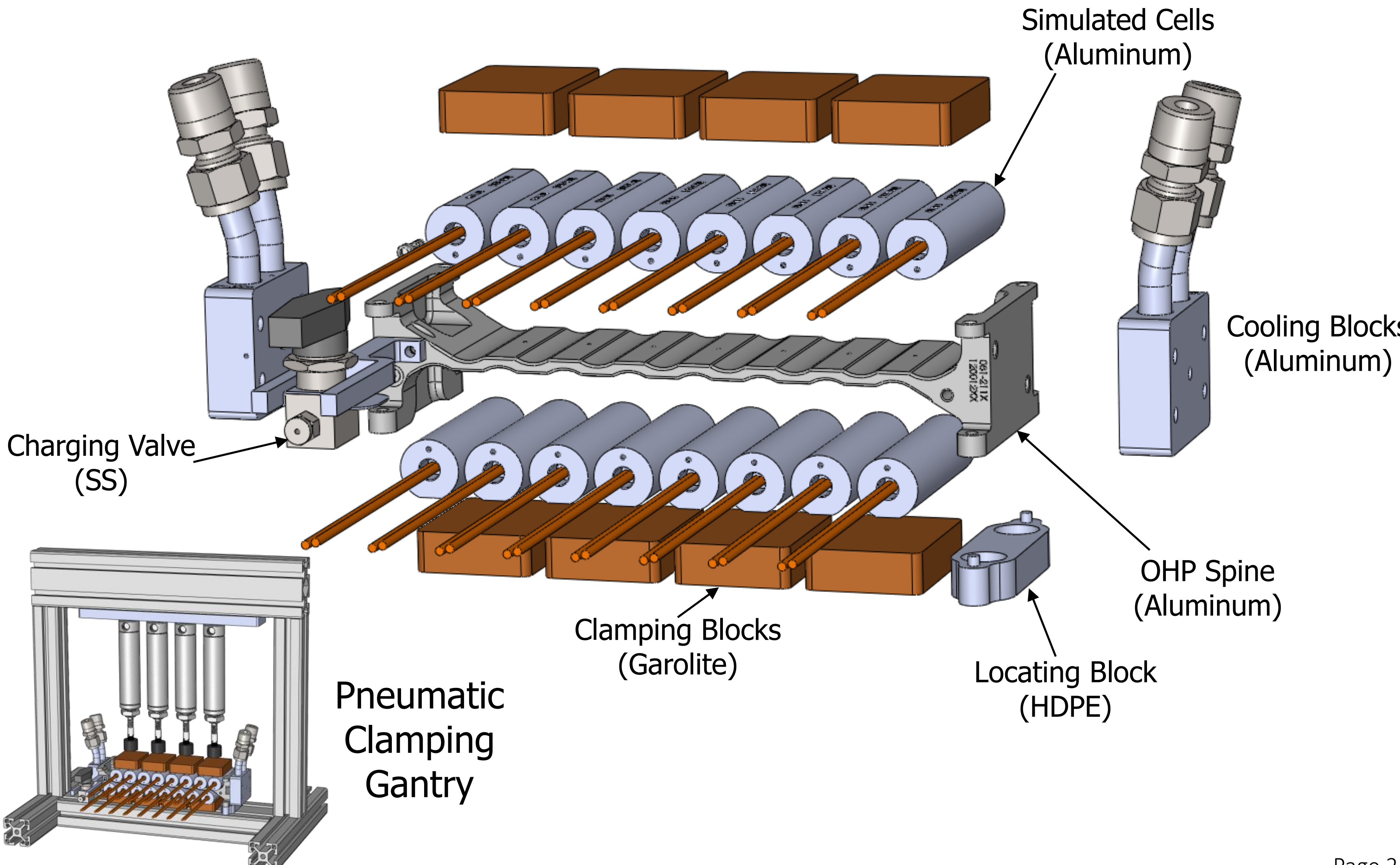
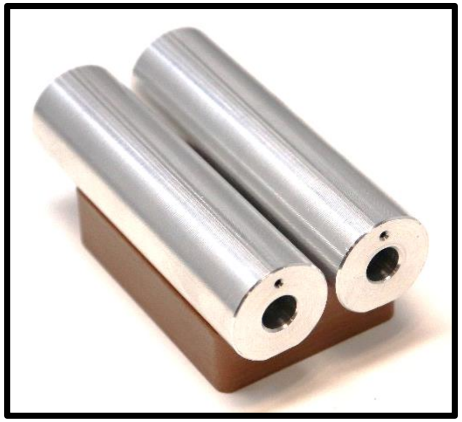
Experimental Results

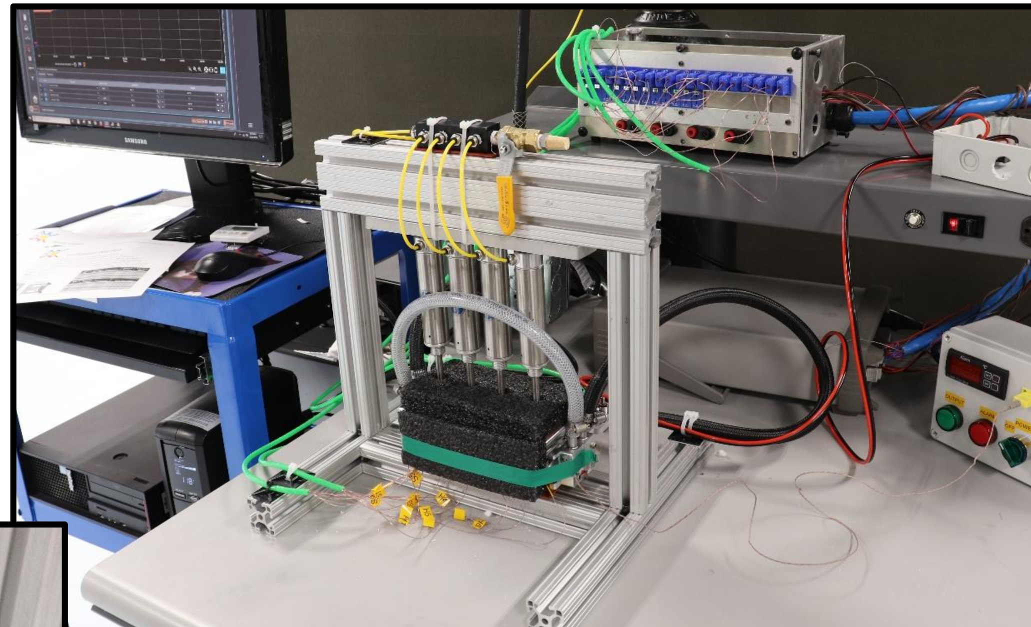
Thermal Test Vehicle

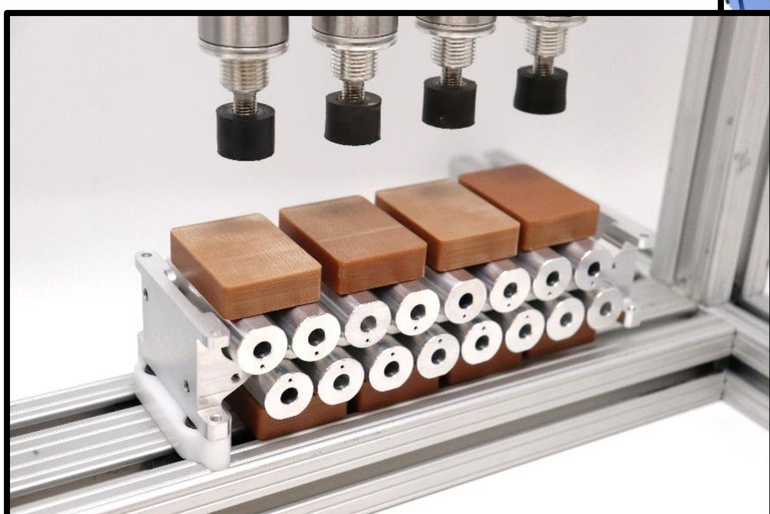


Experimental Results

Thermal Test Vehicle

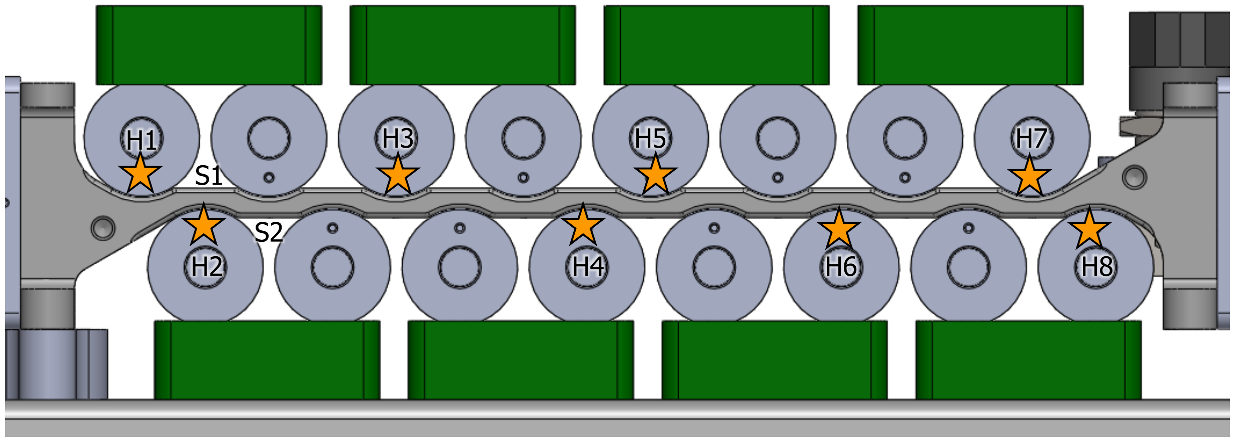


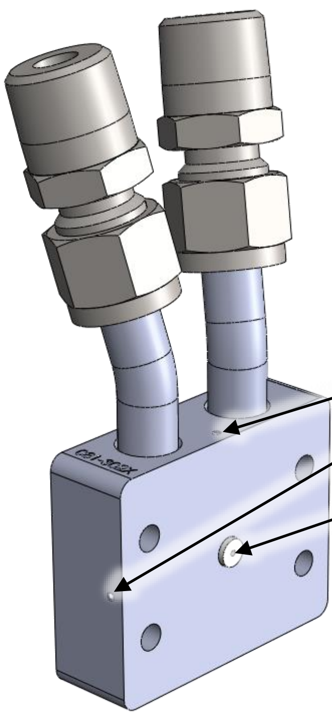




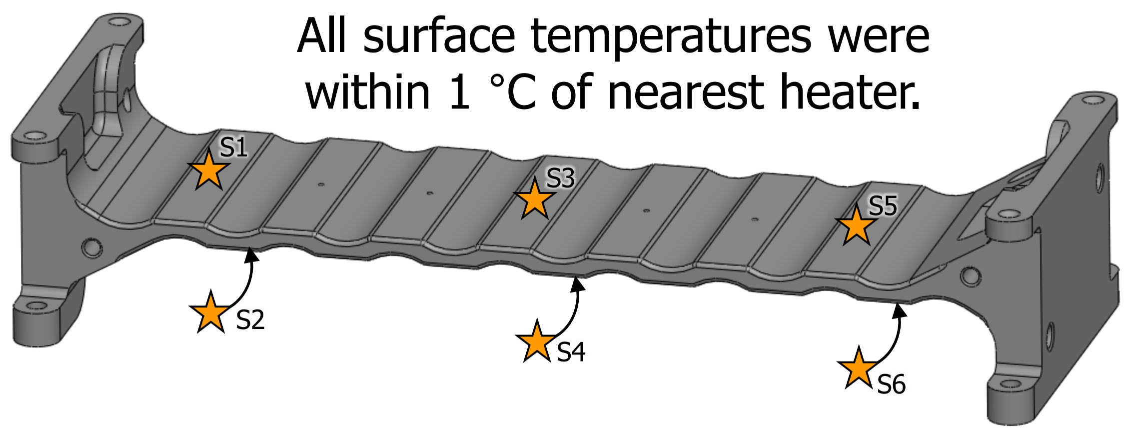
Experimental Results

Thermal Test Vehicle – Sensor Locations





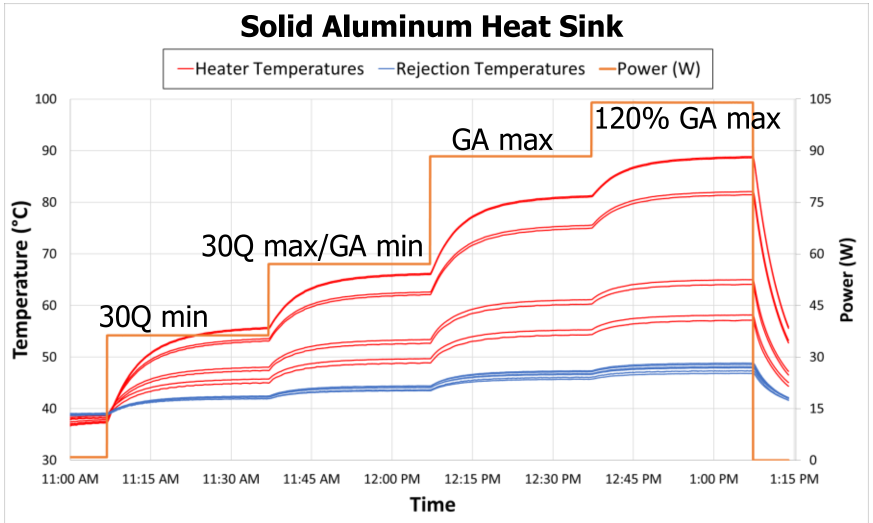
All surface temperatures were within 1 °C of nearest heater.

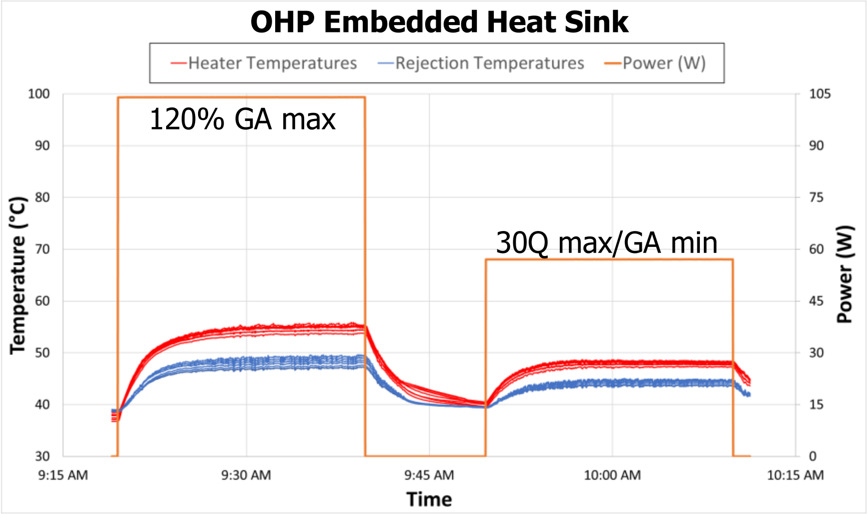


Experimental Results

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)	ΔT_{OHP} (°C)	Boundary Temp (°C)	ΔT_{OHP} (°C)	Boundary Temp (°C)	ΔT_{OHP} (°C)	Boundary Temp (°C)	ΔT_{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**

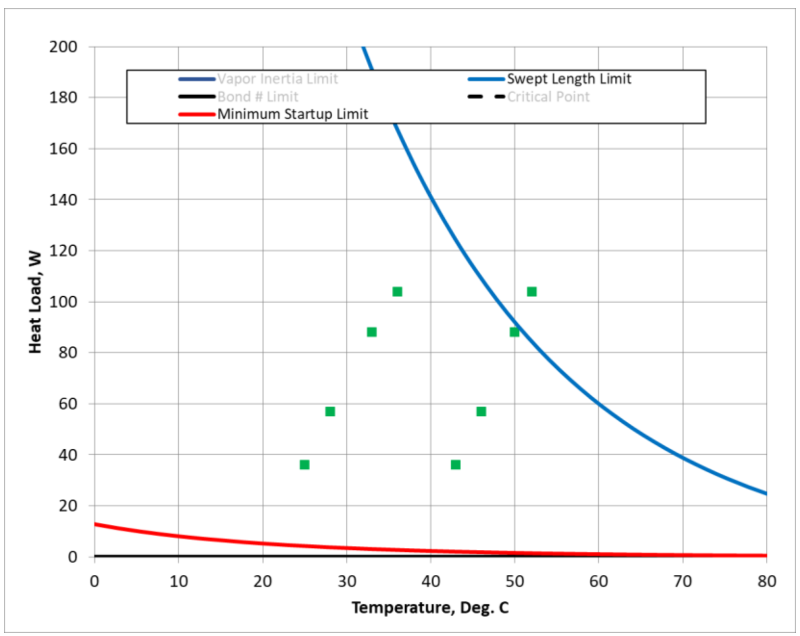
Cell-to-Cell dT (*1-2 °C predicted*)

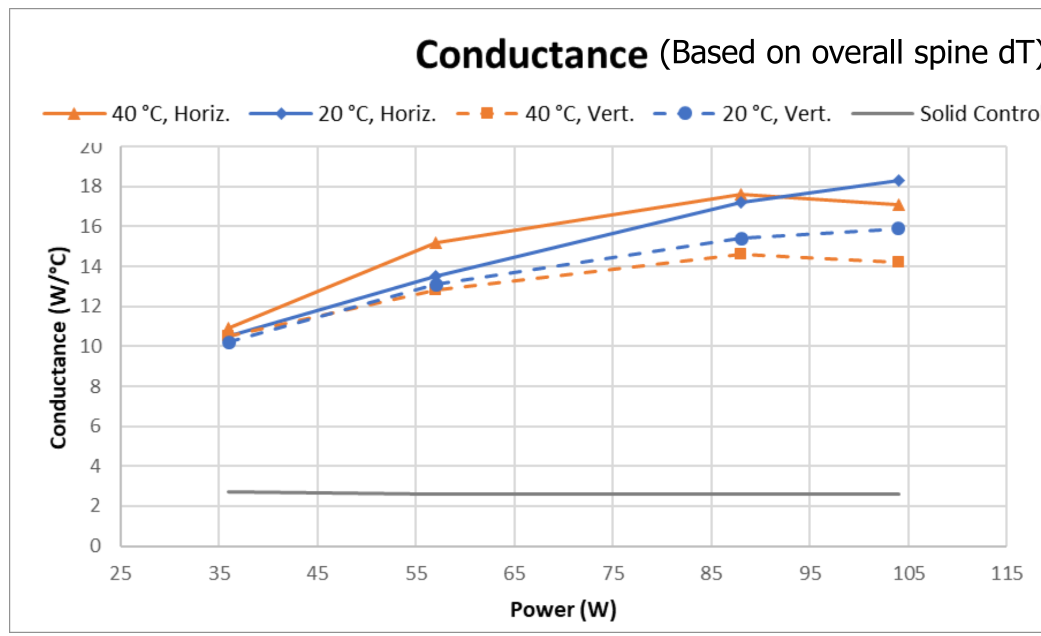
Test No.	Orient.	36 W Boundary Temp (°C)	36 W ΔT_{cells} (°C)	57 W Boundary Temp (°C)	57 W ΔT_{cells} (°C)	88 W Boundary Temp (°C)	88 W ΔT_{cells} (°C)	104 W Boundary Temp (°C)	104 W ΔT_{cells} (°C)
B1	Horiz.	42.0	**1.5**	44.4	**1.2**	47.3	**1.4**	48.9	**1.8**
B2		23.8	**1.8**	26.5	**1.7**	30.9	**1.4**	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.

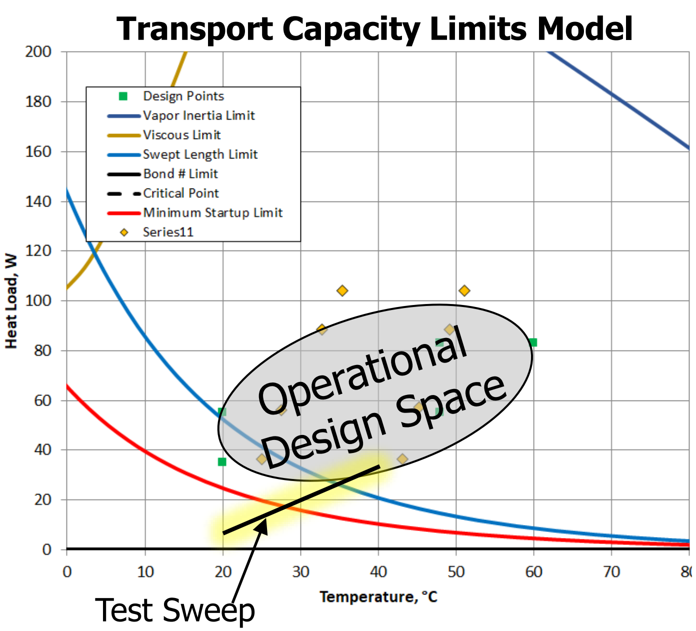


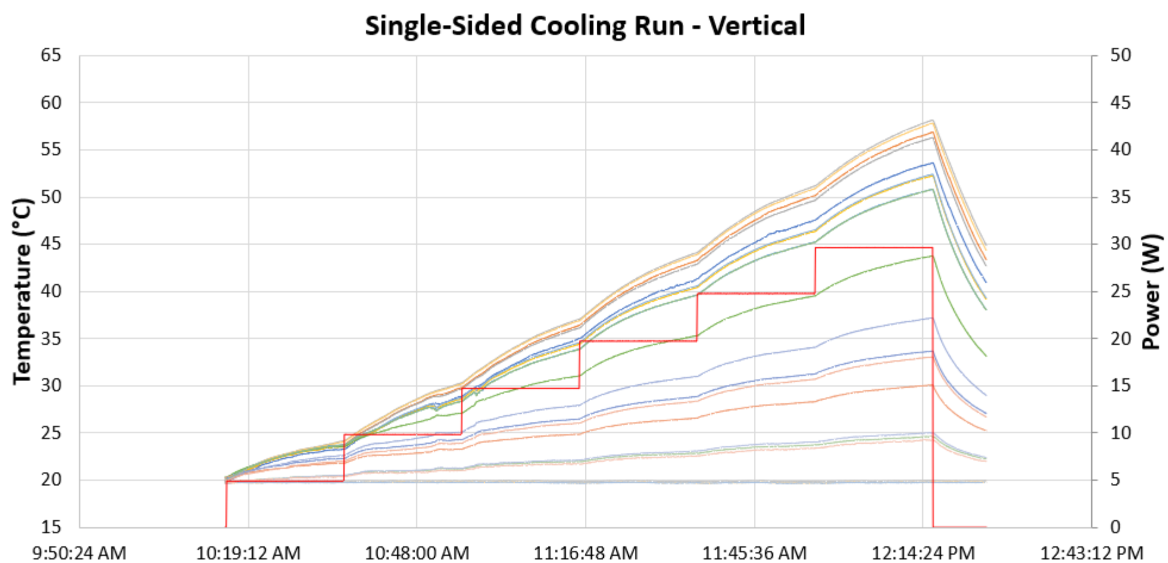


Experimental Results

Single Ended Cooling

- Cooling just one end of the OHP shifts the Swept Length Curve far left, leaving little overlap with the design space.

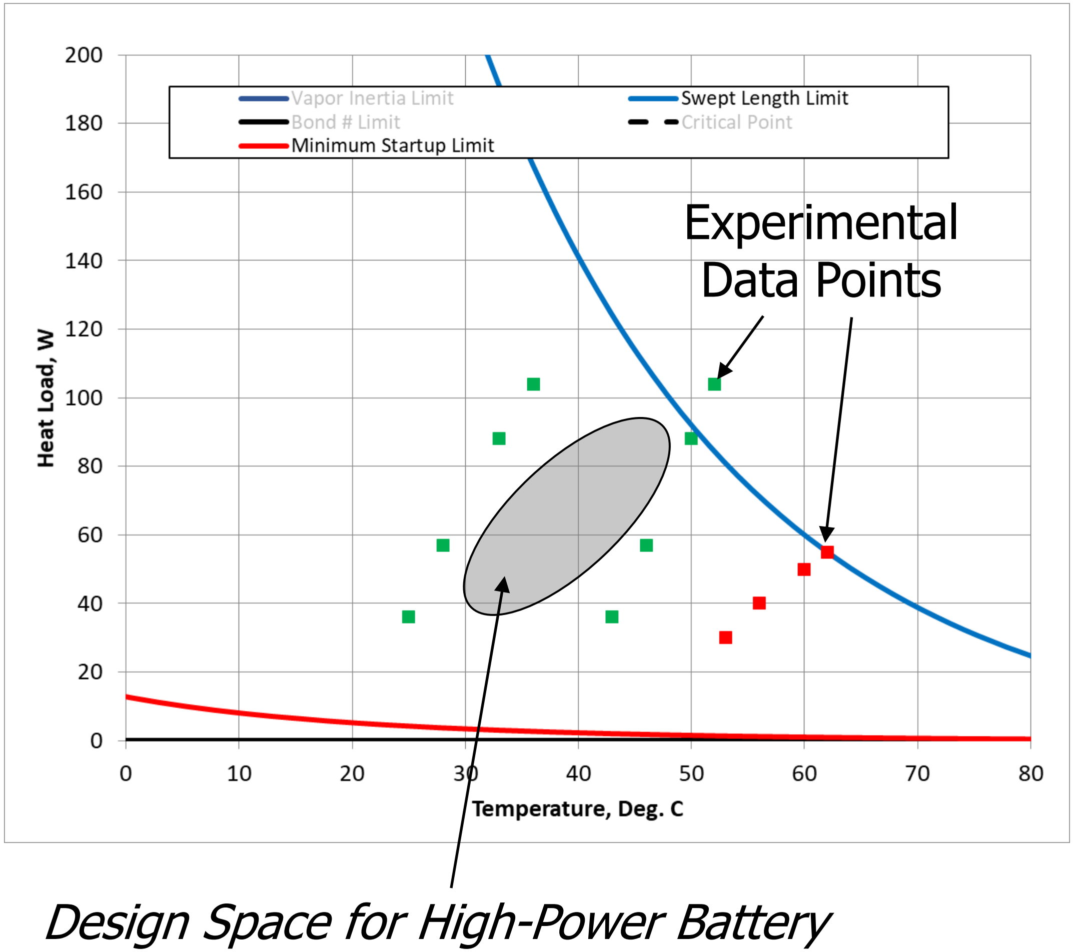




Experimental Results

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



Agenda

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

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.
- 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

- Testing confirms the requirement for cooling of both ends of the spine

- Testing shows the heat sink to function well at boundary temperatures less than 50 °C;
  - Heat sink performance drops significantly above this temperature

- ***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***

QUESTIONS?