Oscillating heat pipe thermal management for battery packages

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Thermal Management of Li-Ion Cells

Overview

- ThermAvant is the leading developer of **Oscillating Heat Pipes** (OHP), a **passive** heat transfer technology that is manufacturable in a wide variety of geometric shapes
  - Primarily used in the Aerospace & Defense industry
- ThermAvant has developed OHPs for cylindrical and prismatic Li-ion cells
  - Enabling high C-rate discharge
  - Minimizing cell-to-cell temperature gradients
  - Minimizing runaway propagation to adjacent cells
- Development of OHPs for electric vehicle (EV) battery cooling is already occurring in the automotive industry by Hyundai Mobis[1]
  - Also referred to as Pulsating Heat Pipes (PHPs)
- Today's presentation is on the development of OHPs to maximize cylindrical cell packing density
  - Other cell form factors (prismatic, pouch, etc.) are also possible but not presented today

OHP for 18650 Battery Module

[1] https://www.hyundaimotorgroup.com/story/CONT0000000000173684

OHP Operating Characteristics

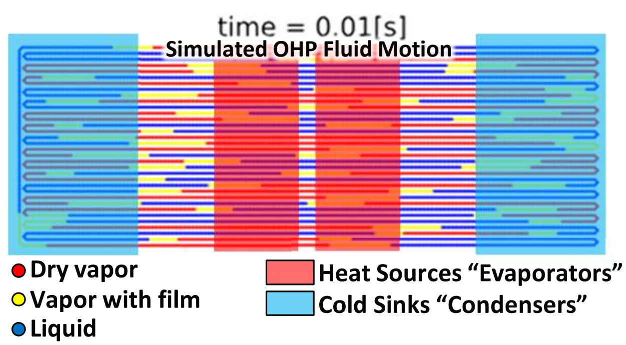
Key design requirements

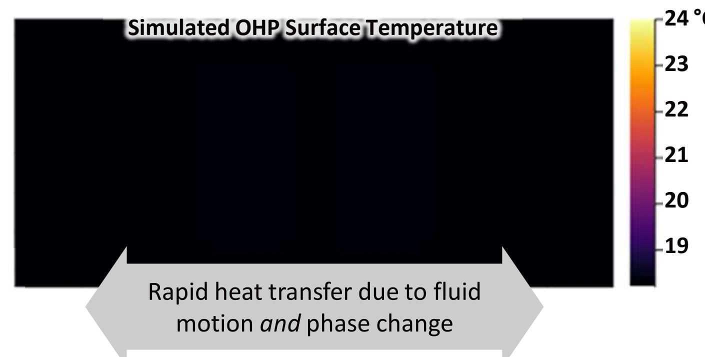
- Pressure-driven liquid flow rather than capillary-driven wicked flow (Conventional Heat Pipe)
  - OHPs are wickless structures
- Channel crosses between heat source(s) and cold sink(s) multiple times
- Channel is filled with a saturated working fluid
- Channel size must be capillary. I.e., bridged by the working fluid at a given operating temperature and gravity

Thermal transport mechanism

- Pressure difference source
  - Heat source(s) cause liquid to evaporate, bubble nucleation, and vapor expansion
  - Cold sink(s) cause vapor to condense, bubbles to collapse, and vapor contraction
- Generated motion
  - Resulting pressure gradients and waves push the fluid in a rapid oscillating/ pulsating motion
- Heat transport
  - Rapid fluid motion moves heat from heat source(s) to cold sink(s)

Photograph of OHP channels in an aluminum plate before brazing. Optimal performance requires custom channel routing for each heat map

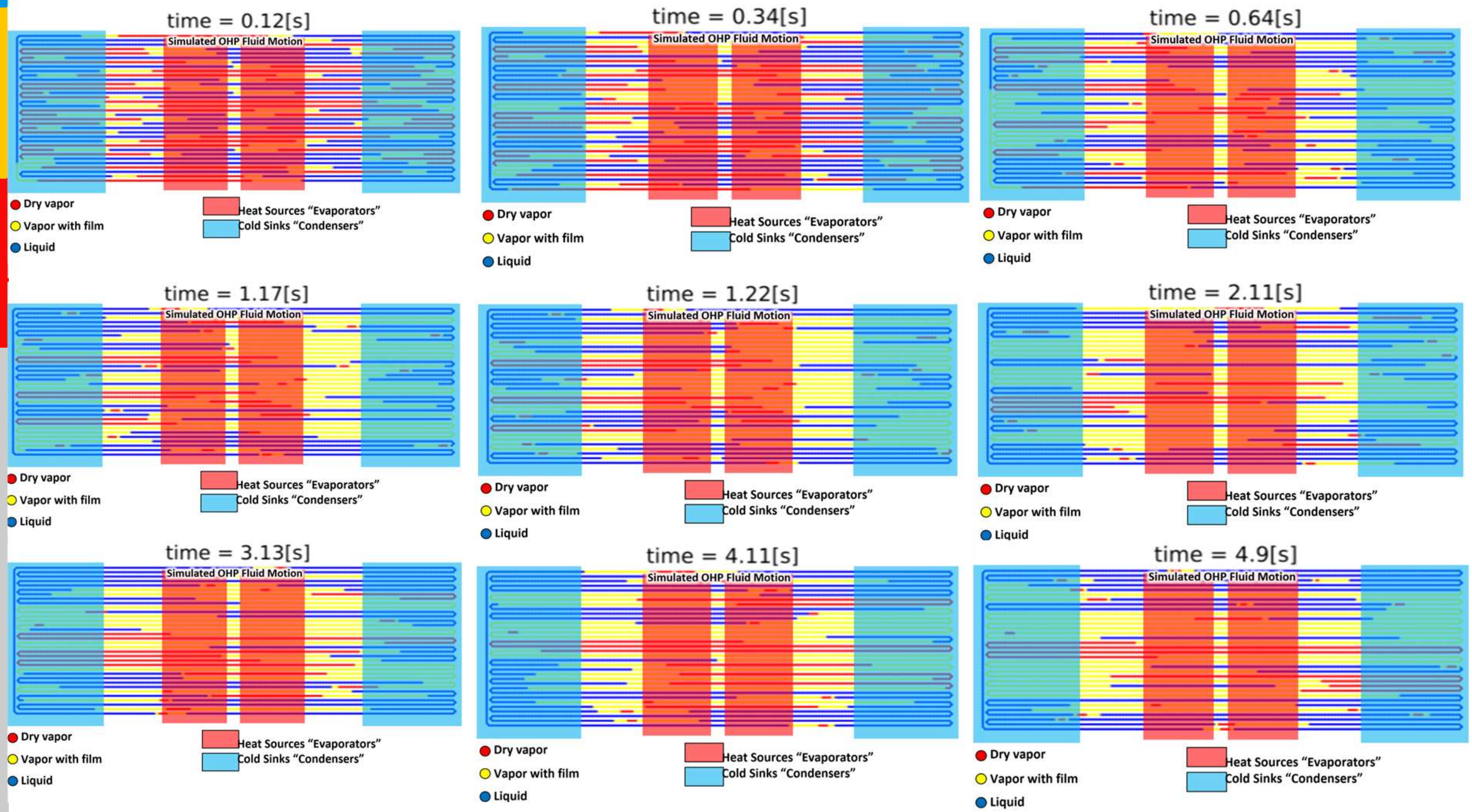




Note: Simulation of ASETS-II OHP 2 Large Heater; Q=40 W; Overall steady-state dT <5 °C

Simulation Stills

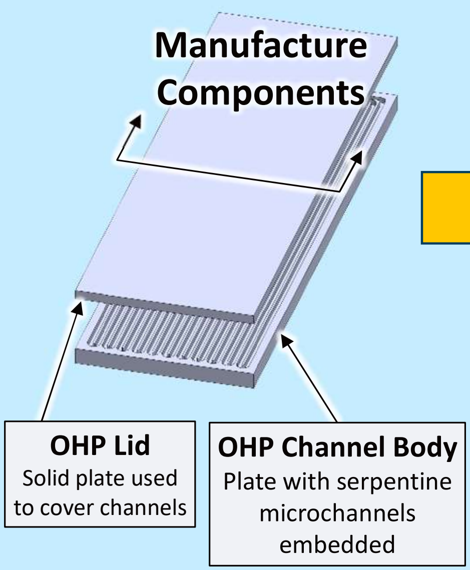
Note: Simulation of ASETS-II OHP 2 Large Heater; Q=40 W; Overall steady-state dT <5 °C



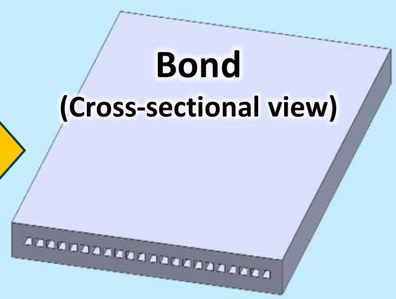
OHP Manufacturing

Simplified steps

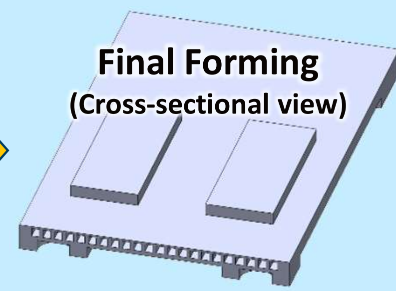
1. Manufacture layers



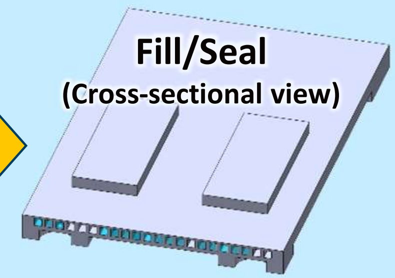
2. Hermetically seal OHP lid to OHP channel body



3. Remove material to form OHP final shape (skyline)

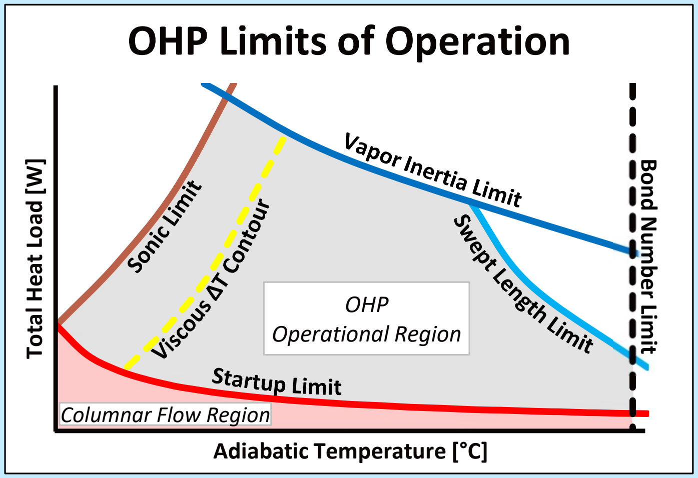


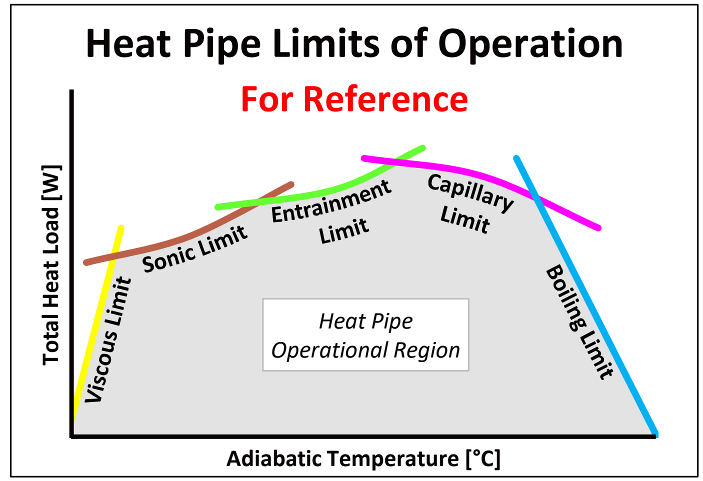
4. Fill with working fluid and hermetically seal



OHP Limits of Operation Overview

Limits model developed by ThermAvant





Bond Number

- *Surface tension decreases and can no longer span the capillary channel, and fluid movement cease*

Sonic Limit

- *Fluid velocity is choked at the speed of sound for the two-phase mixture*

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 Limit

- *Vapor generation rate is high enough to allow vapor to penetrate liquid plugs*

Viscous Contours

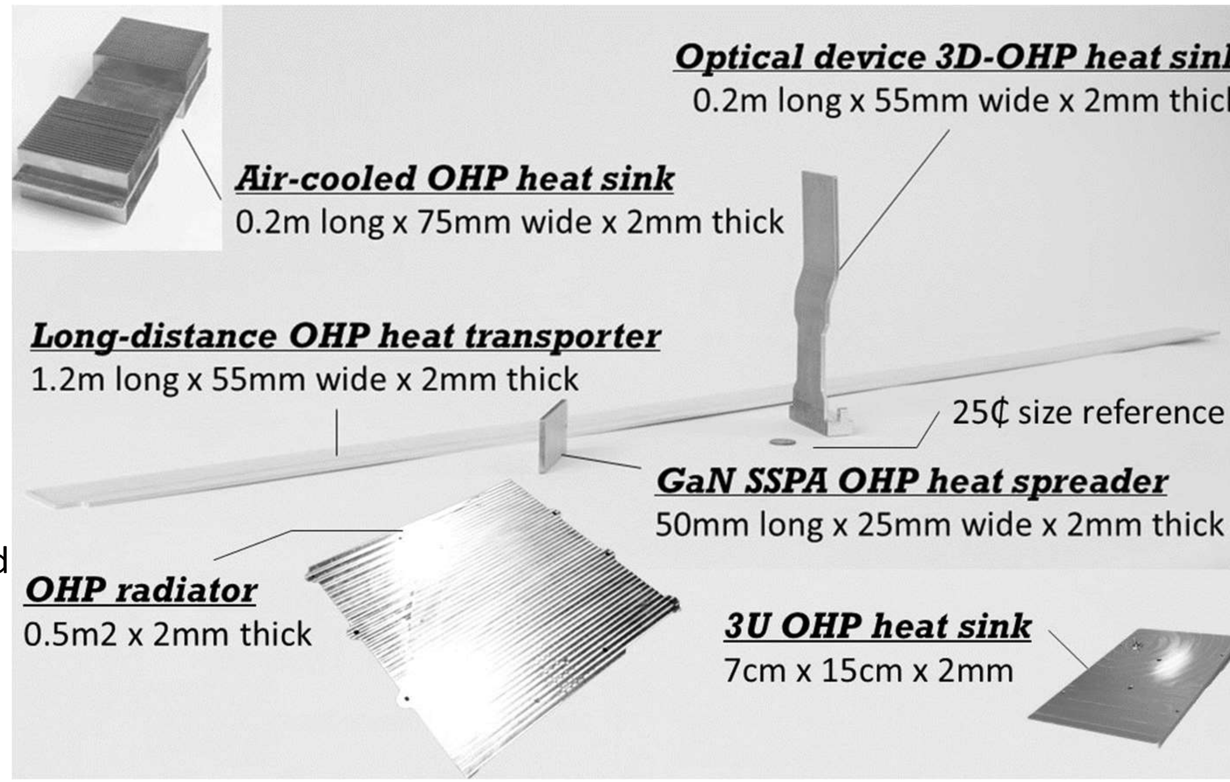
- *Due to viscous loss, temperature rise will increase until the viscous drag is overcome by ΔP to create fluid movement – contours show isotherm lines, e.g. 5 °C ΔT (within fluid space) along this line*

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); Start up minimum presented at Spacecraft Thermal Control Workshop (2018)

Used to design thousands of commercial OHPs

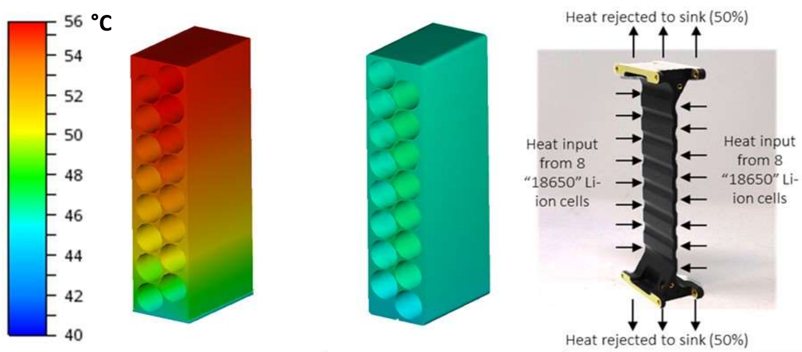
OHP Capabilities

- Producible in virtually any 3D shape or size
  - Thickness: <1 mm to >30 cm
  - Lengths: <1 cm to >1 m
- High performance:
  - <10 to >100s W/K
  - Heat transfer rates at 5-500x higher than solid material equivalent
- Heat loads per OHP
  - <1 to >300 W/cm^2
  - <1 to >1000 W
- Structural
  - Typ. stiffness ~94% of solid
  - Typ. modal frequencies ~104% of solid
- Lightweight
  - Typ. effective density 10-30% lower than solid
- Proven heritage with +5M hours of on-orbit, fielded operation
- Gravity independence



Prior Work – High C-rate OHP

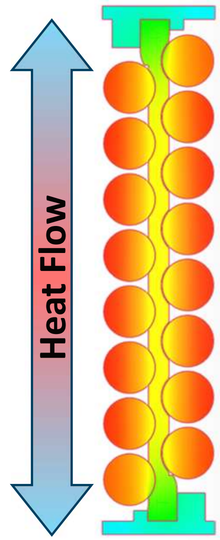
NASA electric aircraft application

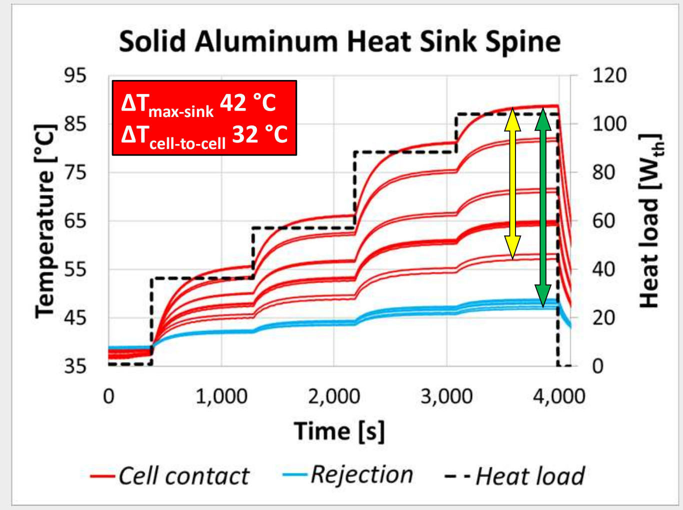


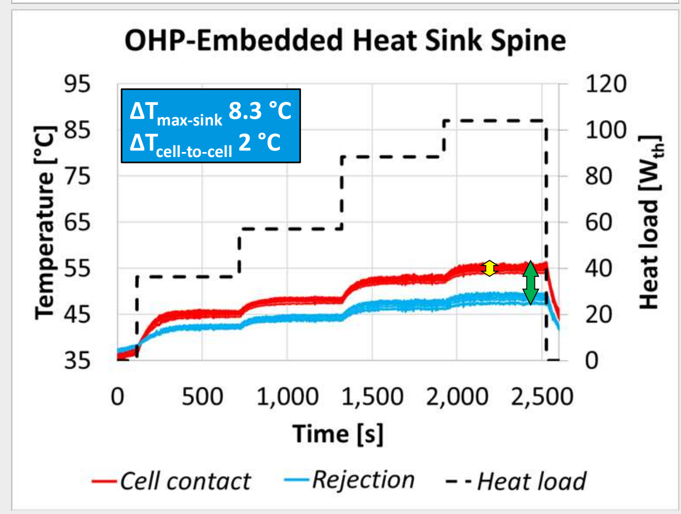
Annealed Pyrolytic Graphite Model
2.9 W/K (>7K cell-cell)

Aluminum OHP Model
16 W/K (<2K cell-cell)

Actual Al OHP Test Data
15 W/K (<2K cell-cell)







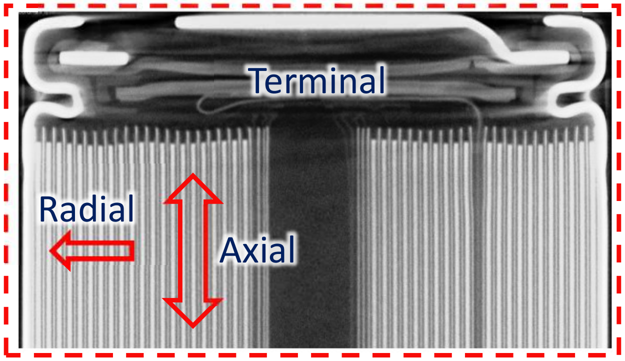
OHP solution presented herein based upon work supported by Contract Nos. 80NSSC19P1055 and 80NSSC19P0129

Honeycomb OHP

Design optimization

- **Purpose:** Demonstrate an OHP design to remove heat from Li-ion 18650 cylindrical cells at maximum packing density
- 18650 cell internal thermal properties
  - Radial: 0.4 W/mK[2]
  - Axial: 16.5 W/mK[2]
  - Terminal: Very high thermal resistance due to gap between jelly roll and end surface
  - Ratio Axial/Radial: 41x
- OHP design
  - Remove heat from vertically aligned, hexagonally packed cells and reject to base plate
  - **Minimize ΔT** from cell surface to base plate
  - **Maximize** cylindrical cell **packing density**
  - **Minimize** added **mass & volume**

Internal View of 18650 [3]



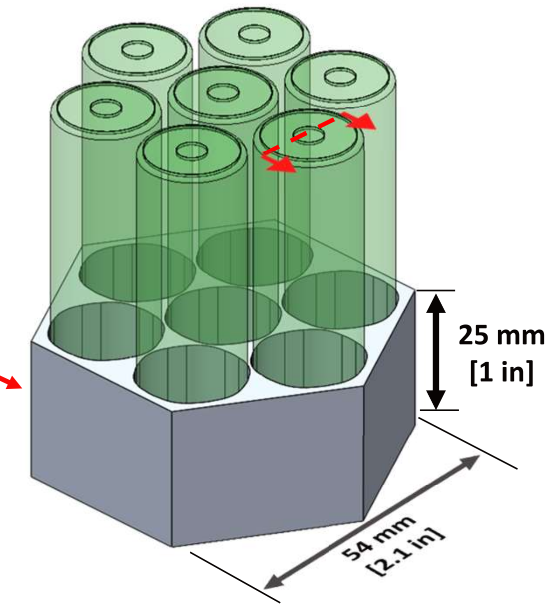
18650 Cell

[2] N. S. Spinner, K. M. Hinnant, R. Mazurick, A. Brandon, S. L. Rose-Pehrsson, and S. G. Tuttle, “Novel 18650 lithium-ion battery surrogate cell design with anisotropic thermophysical properties for studying failure events,” *Journal of Power Sources*, vol. 312, pp. 1–11, Apr. 2016, doi: 10.1016/j.jpowsour.2016.01.107.
[3] J. E. Trillo, D. Petrushenko, Z. Bilc, and E. Darcy, “Sidewall Rupture Characterization: 21700 Cell Format,” Nov. 18, 2024. Accessed: May 16, 2025. [Online]. Available: https://ntrs.nasa.gov/citations/20240012828

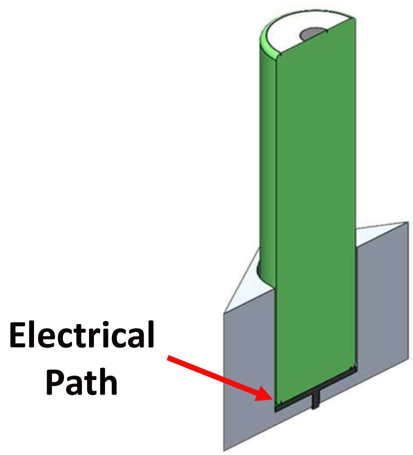
Honeycomb OHP

Design

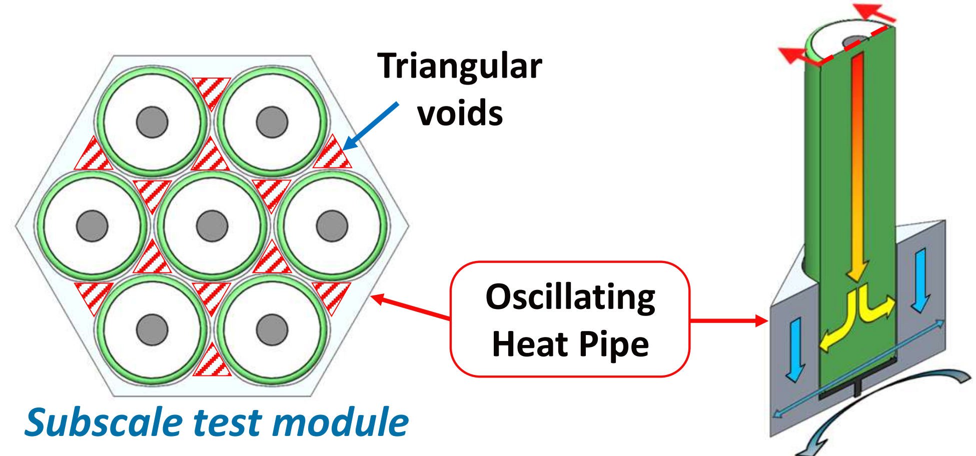
- A **modular** “honeycomb” OHP was designed to remove heat from **25% of the cell length** and **reject to the bottom**
- Hexagonal packing minimizes battery module size
  - Up to 91% of volume is occupied by Li-ion cells
- The OHP channels fit in the **triangular void** between cells and route to bottom surface
- Design integrates electrical pathway at bottom of cell
  - Other electrical integrations are possible



Subscale test module



Electrical Integration



Subscale test module (Top View)

Heat flow path

Honeycomb OHP

Module design

Design

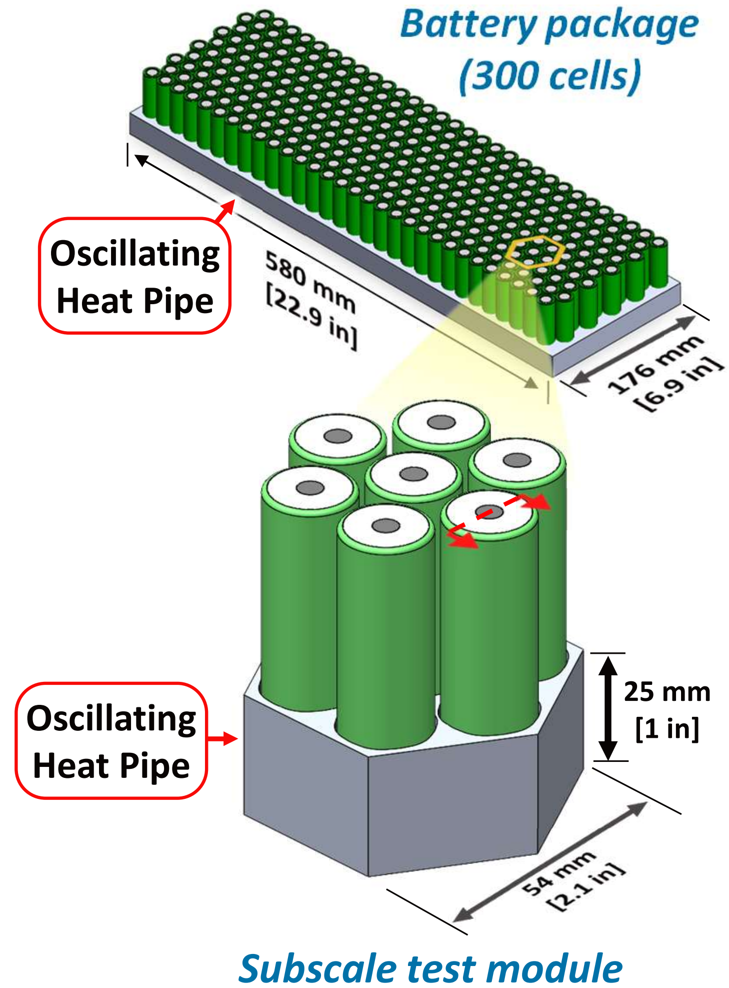
- Module is central cell with one layer of cells around to ensure the central cell sees a uniform thermal profile
- Single module is hexagonal
- Width: 2.1” [54 mm]
- Height: 1” [25 mm]

Mass analysis

- OHP mass: 54 g (OHP mass per cell: 7.7 g)
- 18650 cell mass: 49 g (12% reduction in mass vs. solid control)
- OHP added mass per cell: 15.7%
  - OHP is structural and can replace existing structural elements

Heat flux analysis

- Heat acquisition area per cell: 4.4 cm^2
- Heat rejection area per cell: 3.4 cm^2
- Flux transformation: 1.3x heat concentration



Honeycomb OHP

Experimental setup

Heat Source

- Simulated 18650 cells – Custom aluminum cylinders with cartridge heaters and thermocouple (TC) locations
- Shim on bottom of simulated cell to match Li-ion cell transport

Heat Sink

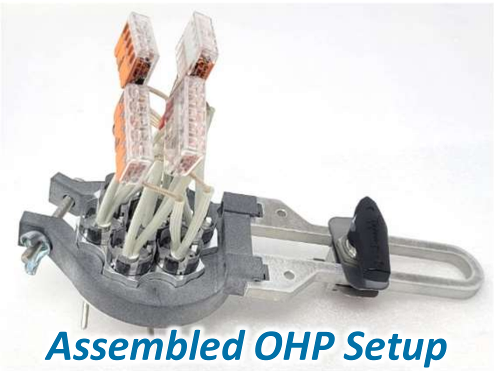
- Cold plate with copper spacer to allow integration of thermocouple plungers

OHP

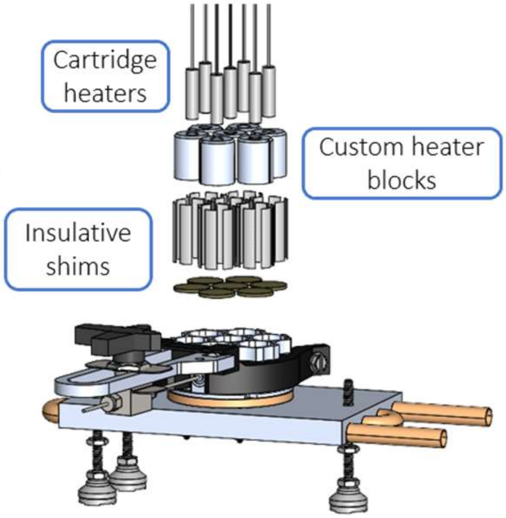
- OHP had integrated fluid charging valve for optimization purposes for in lab testing – is removed and sealed in production
- Shin Etsu X23D thermal grease used for thermal contacts

Measurements

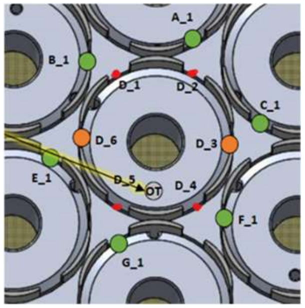
- TCs are positioned between simulated central cell and OHP
- TCs at heat rejection surface of OHP



Assembled OHP Setup

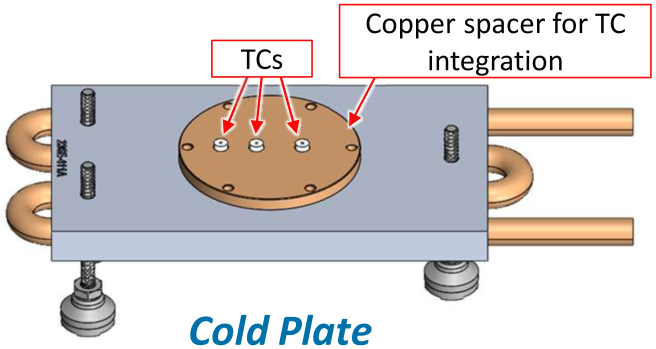


Test Bed



TC Locations around cell (top View)

Simulated Cell



Cold Plate

Honeycomb OHP

Test plan

Li-ion cell parameters

- The operational requirements for the LG MH1 18650 cell was used
- Maximum temperature
  - Charge: 45 °C
  - Discharge: 60 °C
  - Assumed external surface temperature

Two devices tested

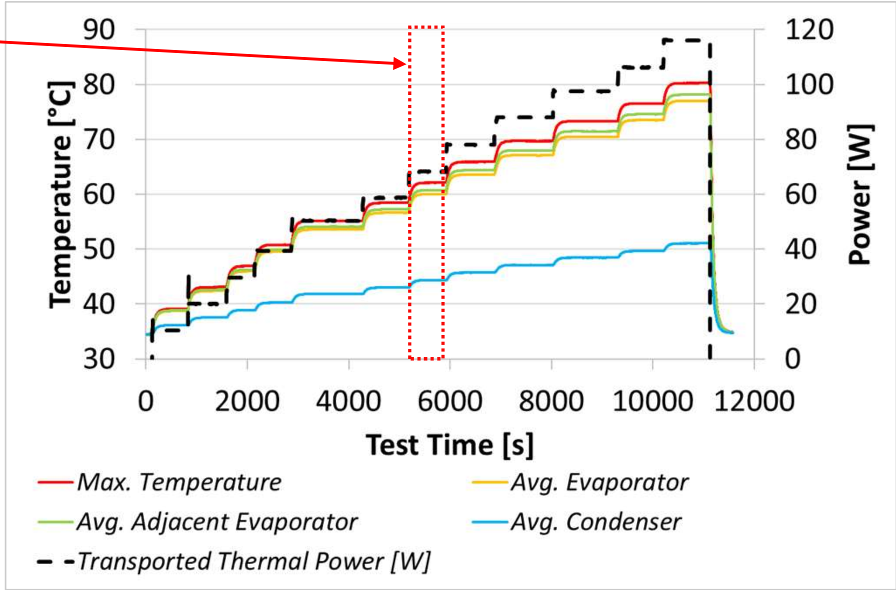
- Solid control
  - Incremented power levels
- OHP
  - Evaluated at two points

Item	Condition / Note	Specification
2.1 Energy (Power)	Std. charge / discharge	Nominal 3200 mAh Minimum 3100 mAh
2.2 Nominal Voltage	Average	3.67V
2.3 Standard Charge (Refer to 4.1.1)	Constant current Constant voltage End current(Cut off)	0.5C (1550mA) 4.2V 50mA
2.4 Max. Charge Voltage		4.2 ± 0.05V
2.5 Max. Charge Current		1.0 C (3100mA)
2.6 Standard Discharge (Refer to 4.1.2)	Constant current End voltage(Cut off)	0.2C (620mA) 2.5V
2.7 Max. Discharge Current		10A
2.8 Weight	Approx.	Max. 49.0 g
2.9 Operating Temperature	Charge Discharge	0 ~ 45℃ -20 ~ 60℃
2.10 Storage Temperature (for shipping state)	1 month 3 month 1 year	-20 ~ 60℃ -20 ~ 45℃ -20 ~ 20℃

Honeycomb OHP

Experimental results – solid conductor

- A solid version of the Honeycomb module was tested to establish a baseline
- Heat load matching maximum discharge temperature
- Condenser: 22 °C
- Heat load: 68 W (9.7 W/cell)
- Average heat input surface temperature: 59.2 °C
- Temperature difference: **14.9 °C**
- Conductance: **4.6 W/K**
- Equivalent C-rate for 18650 cell*: **4.5**



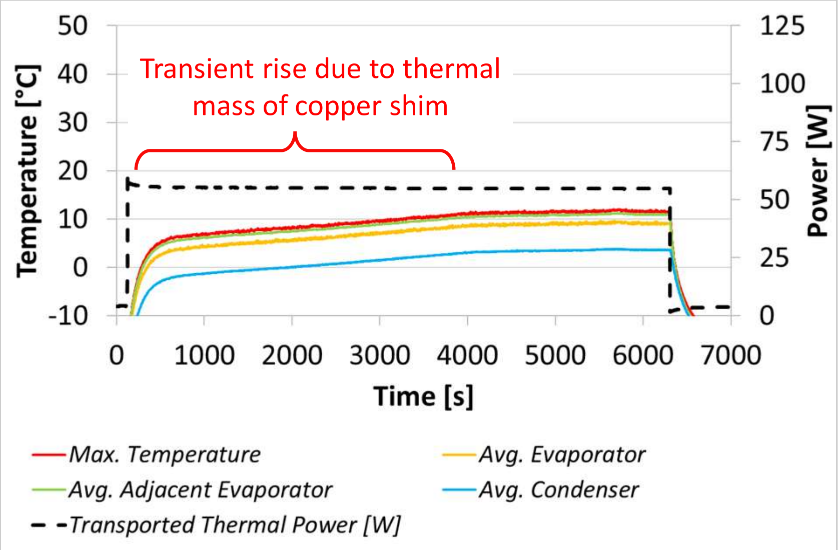
*R_{int}: 48 mΩ & Q_{nom}: 3200 mAh

Honeycomb OHP

Experimental results - OHP

Low Temperature Test

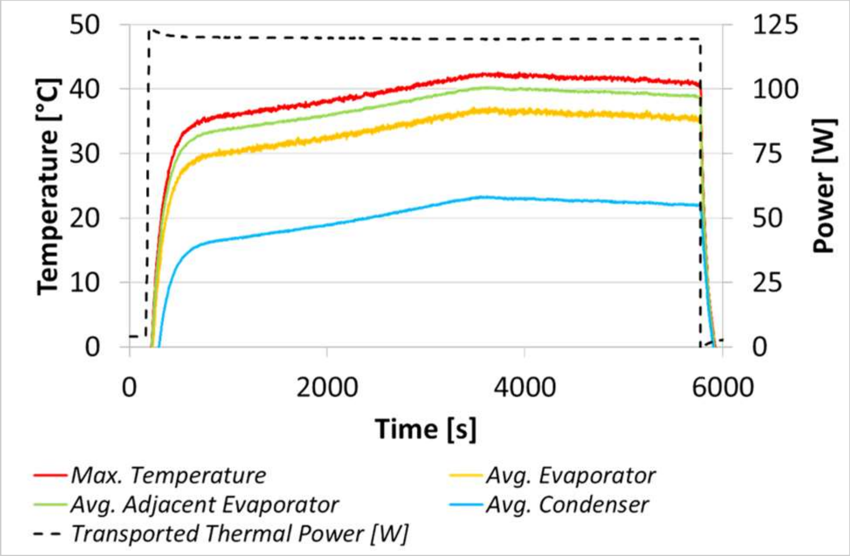
- Rejection temperature: 4 °C
- Heat load: 54.7 W (7.8 W/cell)
- Average heat input surface temperature: 11.6 °C
- Temperature difference: **5.5 °C**
- Conductance: **10 W/K**
- Equivalent C-rate for 18650 cell*: **4.0**



*R_{int}: 48 mΩ & Q_{nom}: 3200 mAh

High Temperature Test

- Rejection temperature: 22 °C
- Heat load: 119.4 W (17.1 W/cell)
- Average heat input surface temperature: 41.0 °C
- Temperature difference: **13.5 °C**
- Conductance: **8.9 W/K**
- Equivalent C-rate for 18650 cell*: **5.9**



Honeycomb OHP

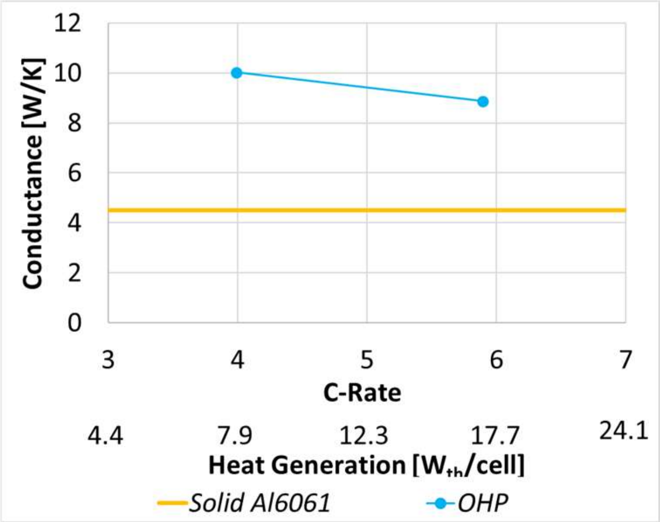
Experimental results – analysis

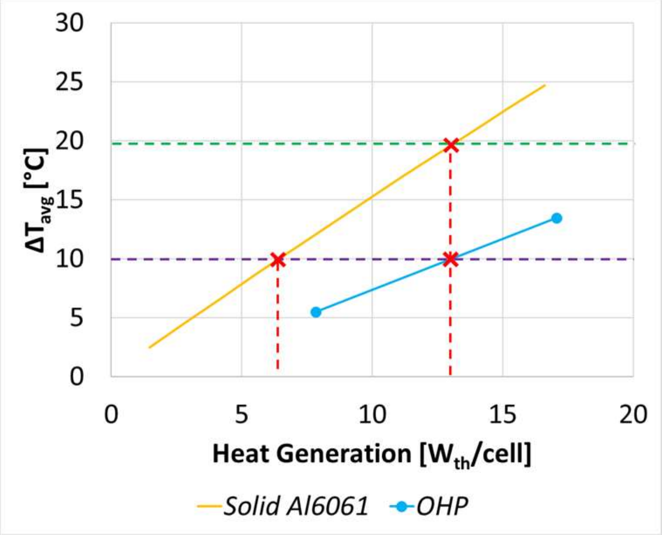
Performance

- Honeycomb OHP average conductance: 9.5 W/K
- Solid Al6061 honeycomb average conductance: 4.5 W/K
- OHP conductance 2.1X greater than solid Al6061

System

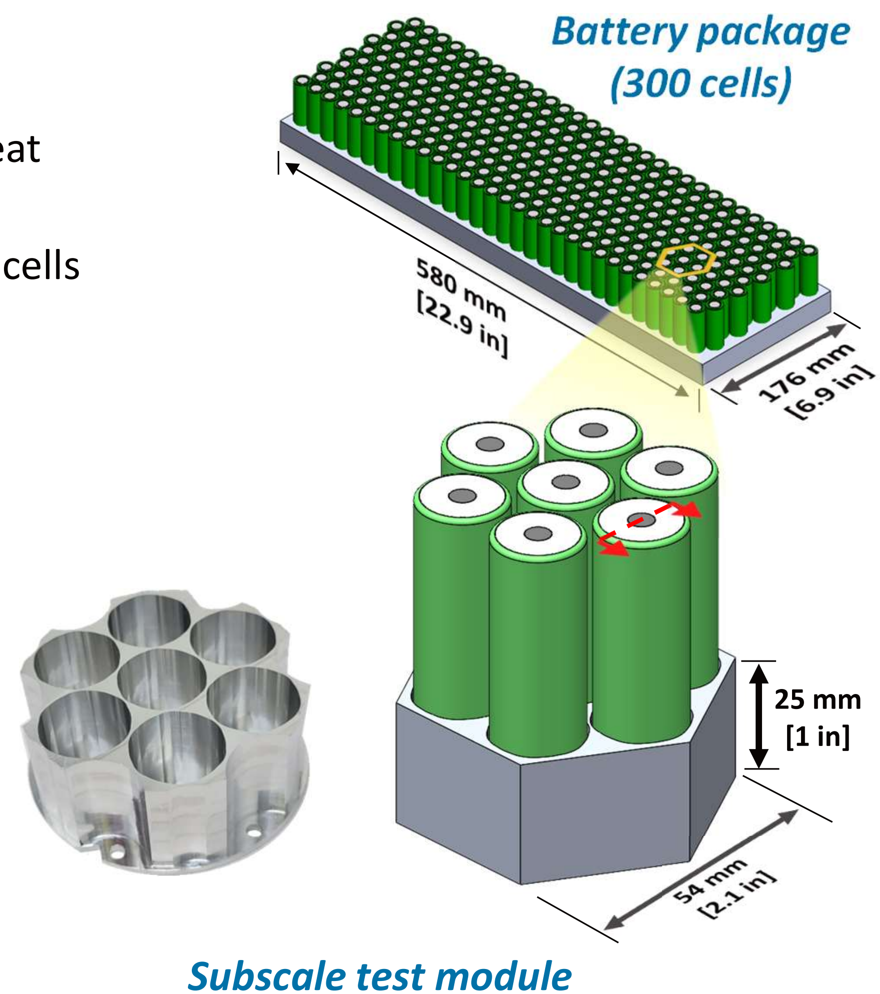
- System requirements may target maximum heat generation or allowable ΔT
- Assuming ΔT_{max} for battery pack is 10 °C
  - Solid Al6061 Q_{cell}: 6.5 W
  - OHP Q_{cell}: 13.1 W
- Assuming Q_{max} for battery pack is 13.1 W/cell
  - Solid Al6061 ΔT: 19.6 °C
  - OHP ΔT: 10 °C





Conclusions

- A **passive** OHP based heat sink was designed to remove heat from cylindrical Li-ion cells
- The **OHP enables maximum packing density** of cylindrical cells
- The resulting OHP based honeycomb heat spreader had a conductance of **2x** the solid equivalent with a reduction in mass of **12%**
- This solution allows the active cooling solution to remain outside of the battery package
  - Reducing power requirements
  - Reducing points of failure



Questions

- Special thanks to: Dr. Corey Wilson, Sam Lohman, Lily Ellebracht, Derrik Roll, & Jeff Akers