Safe, High Power / Voltage Battery Module Design Challenges

By

Eric Darcy/NASA, Houston, TX USA
with contributions from and collaborations with

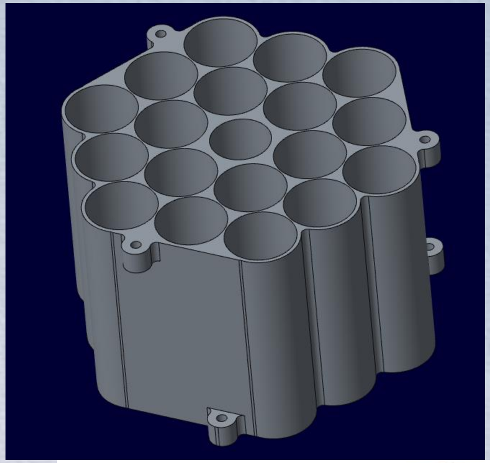
Jacob Darst, Will Walker, Sean Nogrady, Jim Rogers, Minh Tran, Sam Russell, and Alex Quinn/NASA, Houston, TX USA
Paul Coman & Ralph White/White & Associates, Columbia, SC USA
Gary Bayles/SAIC, Baltimore, MD USA
Brad Strangways/SRI, Arab, AL USA
Dan Pounds & Ben Alexander, ThermAvant Technologies/Columbia, MO USA

Battery Show Europe
Stuttgart, Germany
7-9 May 2019

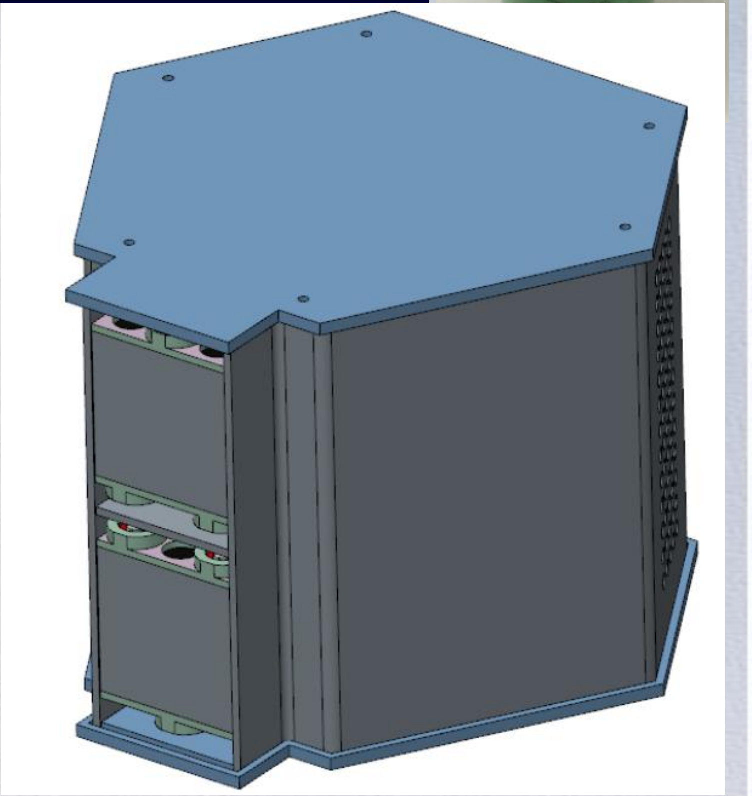
Outline

- Goals of Safe, High Power Battery Task
- Major Challenges Driving Designs
  - Thermal management – Interstitial Al heat sink
  - Cell design selection for 3C discharge
  - Performance analysis on heat sink spine approach
    - Impact of epoxy, contact area, and conductivity of spine
    - Oscillating heat pipe spine
  - Risk of side wall breaches
- Summary

Safe, High Power Battery Task Top Level Reqts



- 100V, 2 kWh Battery Module
- Capable of 3C discharge continuous (20 minutes)
  - 100 cycles, 5 year storage life
- Capable of being connected in series and parallel as building block
- Safe
  - Resistant to single cell TR propagation
  - No flames exiting the module enclosure
  - Dead-face power connectors for electrocution hazard mitigation
  - Resistant to corona discharge hazard
- High performance (>160 Wh/kg, 200 Wh/L)
  - Using Li-ion commercial cylindrical cell technology that achieves 225 Wh/kg, 650 Wh/L at 3C



Credits: J. Darst, J. Rogers/JSC

Latest High Power/Energy 18650 Cell Designs

- Specific Energy Range 259-276 Wh/kg
- Energy Density Range 704-735 Wh/L

Panasonic NCR18650GA

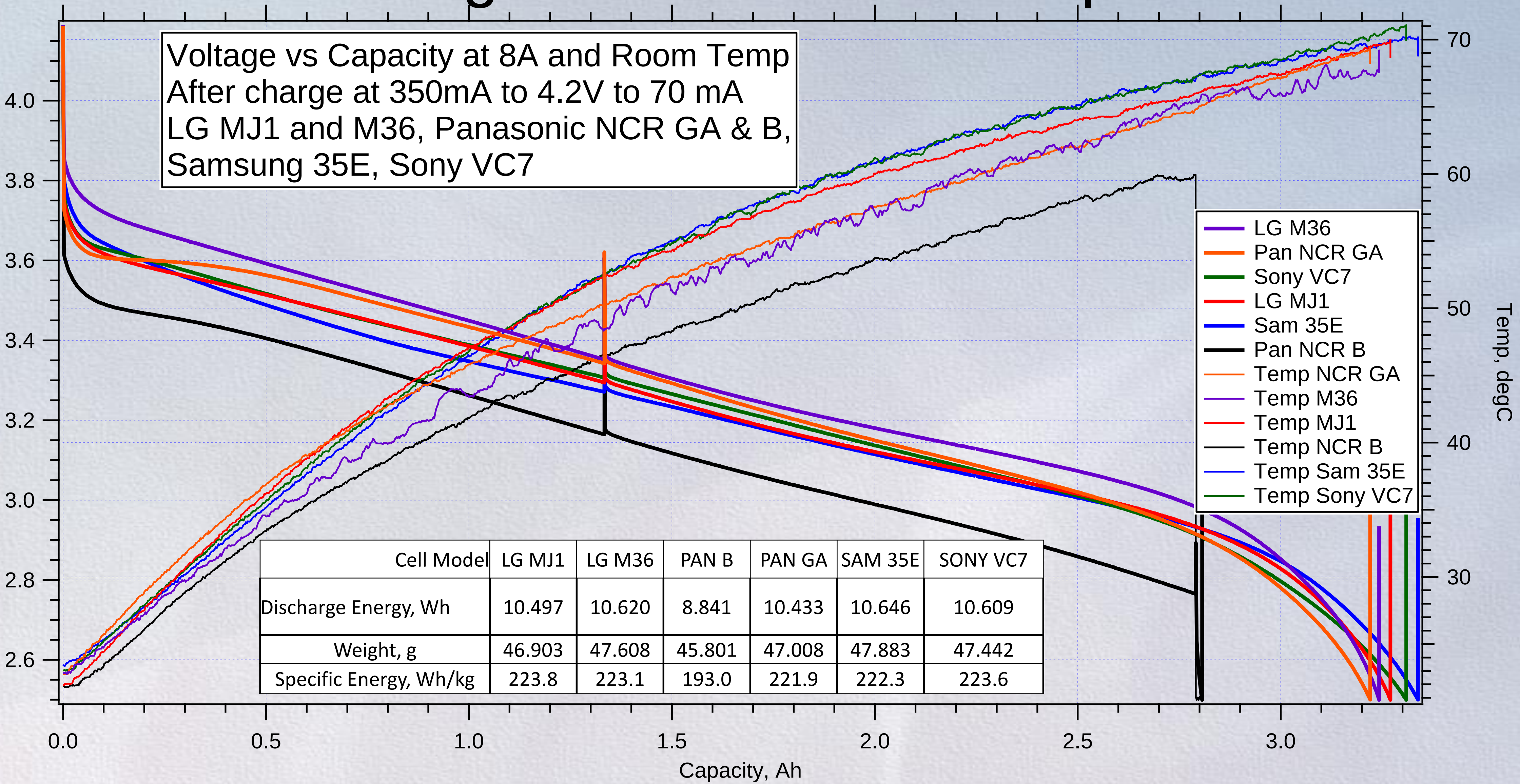
LG INR18650 MJ1

Samsung INR18650-35E

Sony US18650VC7

C/10 at RT	Panasonic NCR GA	Samsung 3.5E	Sony VC7	LG MJ1
Discharge Capacity (Ah)	3.34	3.49	3.5	3.41
Discharge Energy (Wh)	12.16	12.7	12.72	12.46
DC Internal Resistance (mohm)	38	35	31	33
Average Mass (g)	47	46	47.4	46.9
Average Volume (L)	0.0173	0.0173	0.0173	0.0173
Specific Energy (Wh/kg)	259	276	269	266
Energy Density (Wh/L)	704	733	735	720

~3C Discharge Performance Comparison

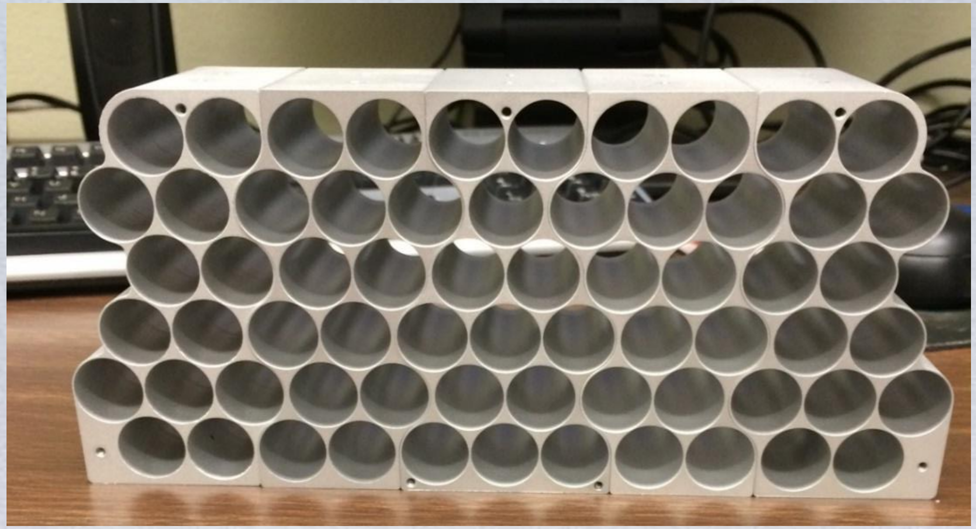


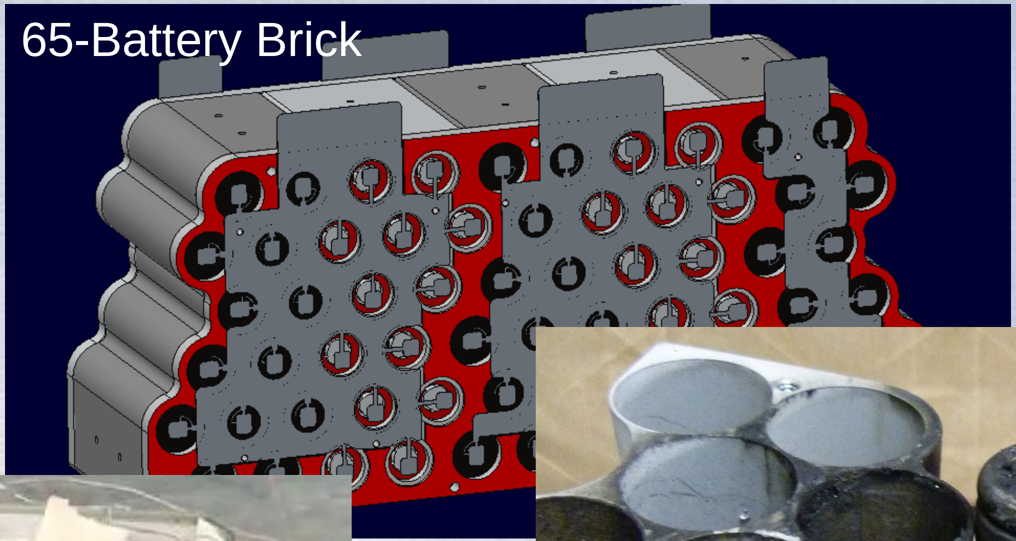
Cell Model	LG MJ1	LG M36	PAN B	PAN GA	SAM 35E	SONY VC7
Discharge Energy, Wh	10.497	10.620	8.841	10.433	10.646	10.609
Weight, g	46.903	47.608	45.801	47.008	47.883	47.442
Specific Energy, Wh/kg	223.8	223.1	193.0	221.9	222.3	223.6

Panasonic NCR18650B has a current limiting PTC switch, adding ~10 mohms to cell resistance and trips
Note cell skins temp reaching 70°C and specific energy drops to ~223 Wh/kg

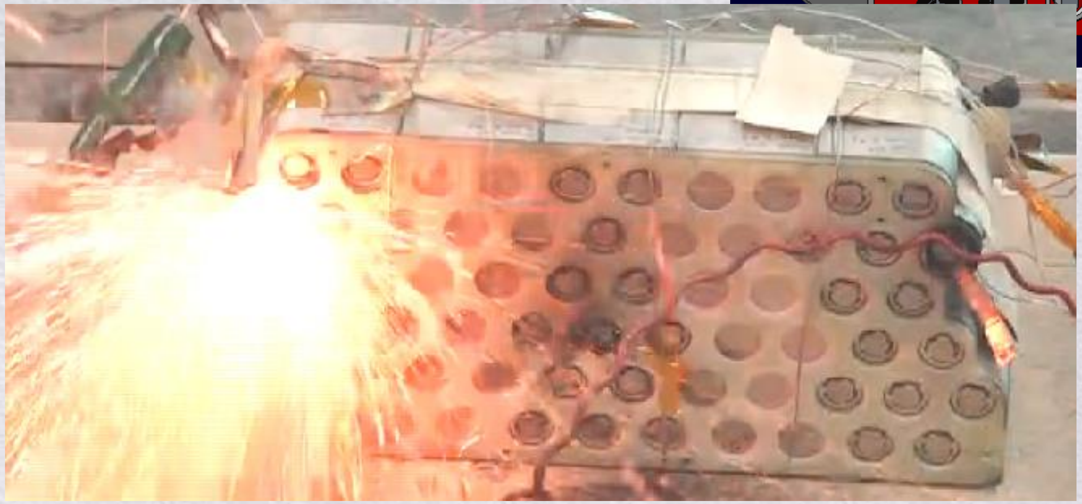
Safer, Higher Performing Spacesuit Battery Design

Features
- 65 High Specific Energy Cell Design 3.4Ah (13P-5S)
- 37Ah and 686 Wh at BOL (in 16-20.5V window)
- Cell design likely to side wall rupture, but supported





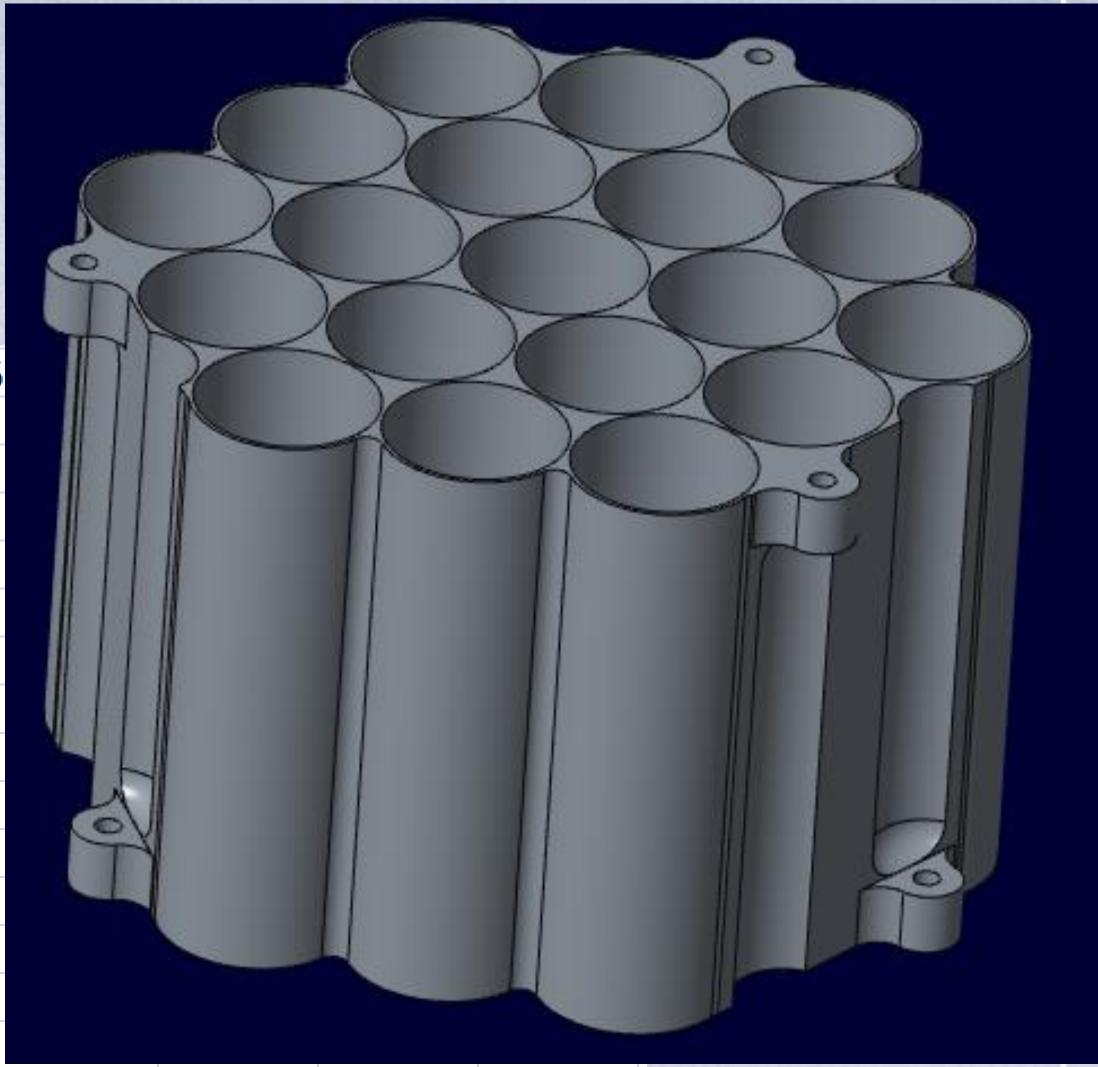
Aluminum interstitial heat sink protects adjacent cells from side wall ruptures during TR and dissipates heat very effectively



Aluminum Interstitial Heat Sink

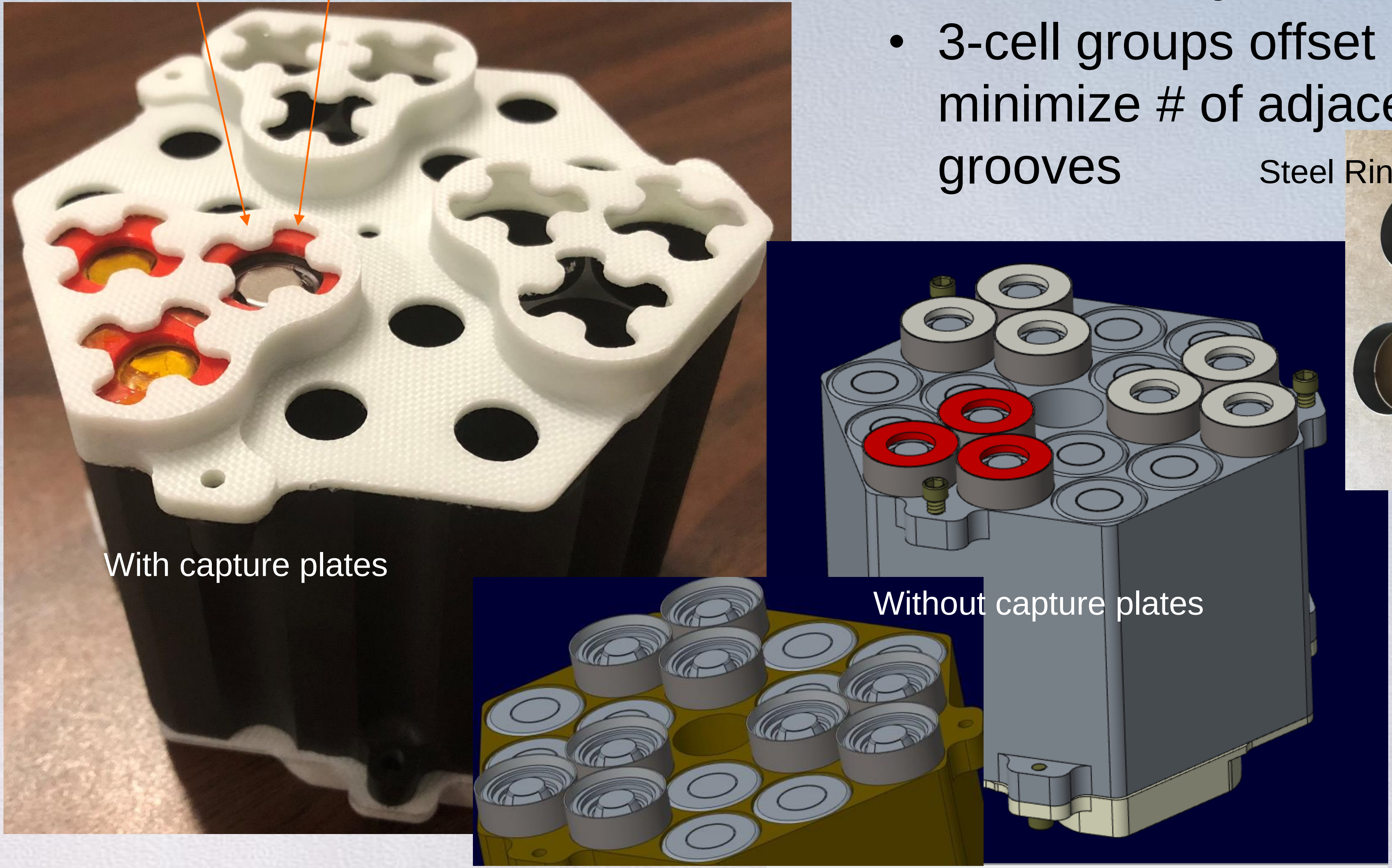
- With wire EDM, intercell webbing can be narrowed to 250µm ± 25µm
- All surfaces hard anodized for electrical isolation
- Provides for heat transfer & protects adjacent cells from breaches, except for spin groove area

Part	Volume (in^3)	volume (cm^3)	mass (g)	QTY	total mass	Mass frac (%
Cell	1.01100	16.567	46.00	18	828.00	79.59
Heatsink	3.13800	51.423	139.36	1	139.36	13.39
Top Cap plate	0.75300	12.339	22.21	1	22.21	2.13
bot cap plate	0.76200	12.487	22.48	1	22.48	2.16
steel sleeve	0.00601	0.098	0.78	18	14.00	1.35
fasteners	0.00598	0.098	0.77	6	4.64	0.45
mica wrap	0.00524	0.086	0.18	18	3.32	0.32
plastic button	0.01869	0.306	0.35	18	6.34	0.61
paraxylene					0.00	0.00
bus plates					0.00	0.00
				Total Volu	Total mass	wh/kg
				383.881	1040.35592	179.07333
				paras Vol	Paras Mass	
				27.57822	20.41	



18-Cell Subscale Assembly

Breakable tabs and washer



With capture plates

Without capture plates

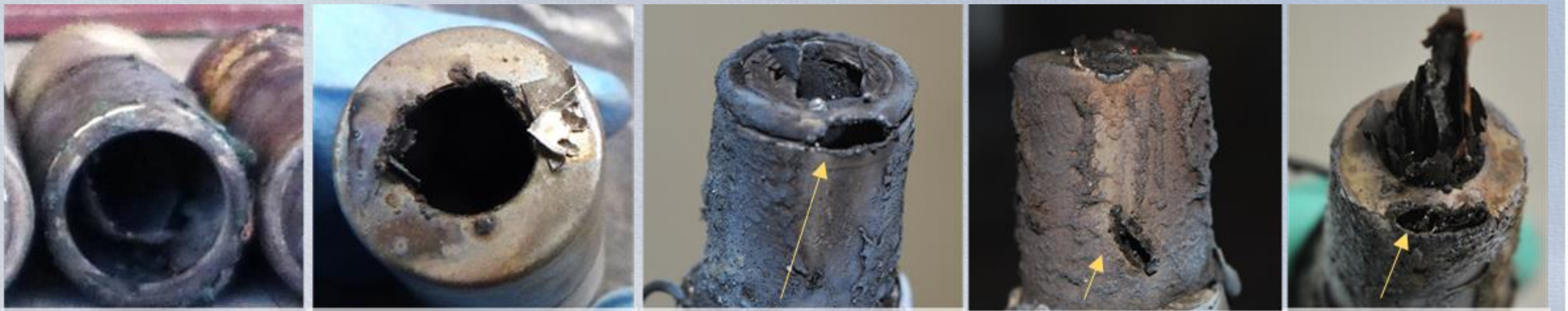
- 3-cell groups offset (raise) to minimize # of adjacent spin grooves

Steel Rings

18.33mm ID
0.125mm thick
0.39g

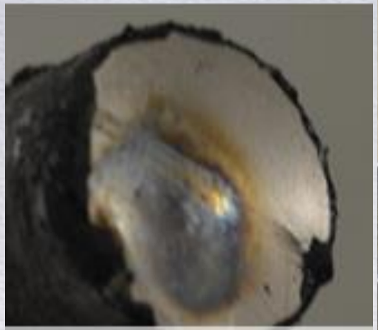
vs

Full length
60mm tube
weighs 3.2g



Bursting: Top | Bursting: Bottom | Breach: Top | Breach: Side | Breach: Bottom

Types of Cell Enclosure Failures and Damage Conditions



Discoloration

Spin groove breach

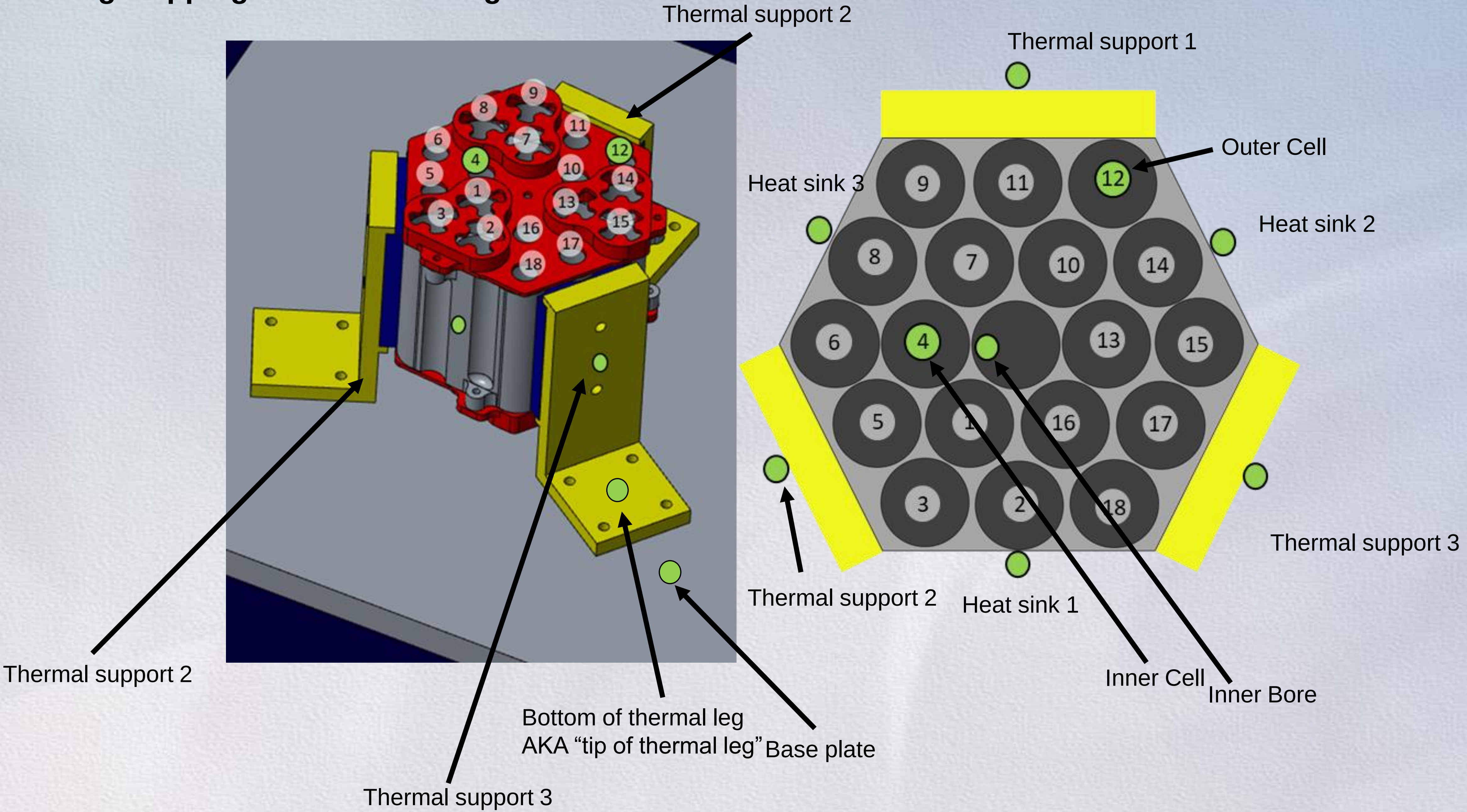
Example of Spin Groove Breach

Cell type: Li-ion 18650
Capacity: 3.5 Ah
State of Charge: 100 % (4.2 V)
Bottom vent: No
Wall thickness: Not known
Separator: Polymer
Orientation of cell: Positive end up
Location of ISCD radially: N/A
Location of ISCD longitudinally: N/A
Side of ISCD in image: N/A

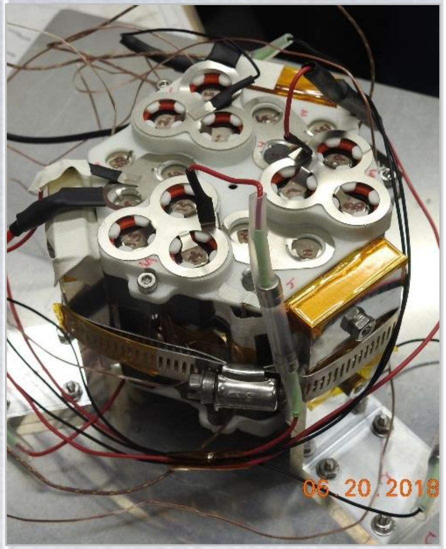
Location of FOV longitudinally: Top
Frame rate: 2000 Hz
Frame dimension (Hor x Ver): 1280 x 800 pixels
Pixel size: 17.8 µm

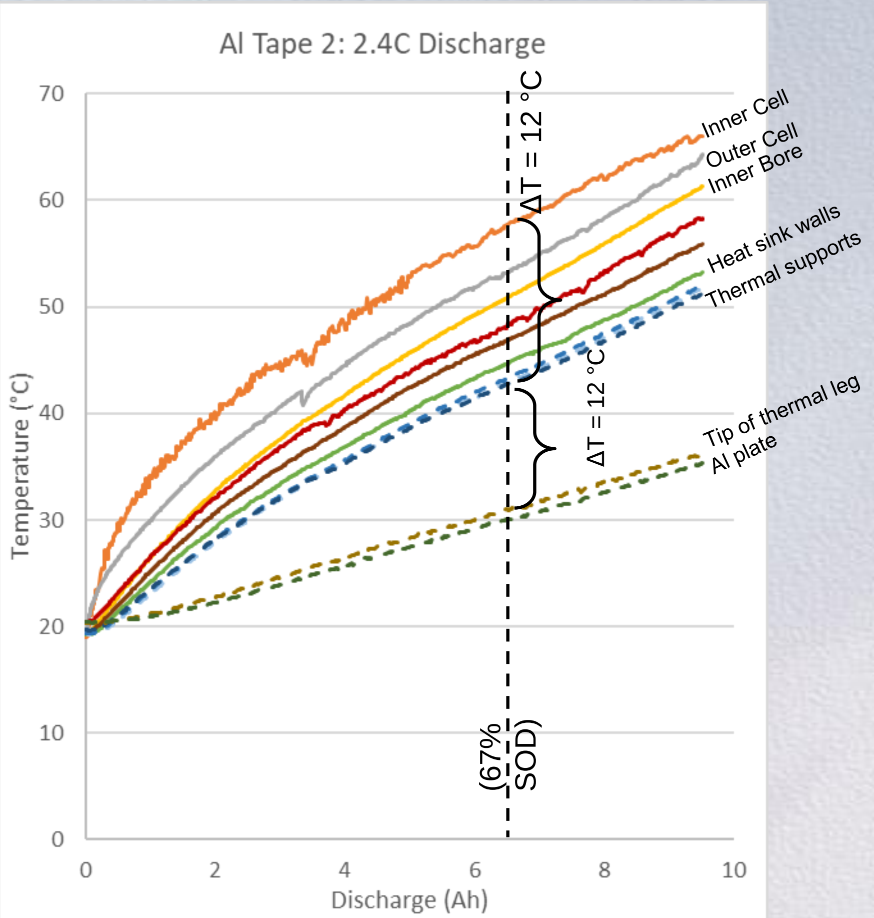
Credit: Donal Finegan/NREL

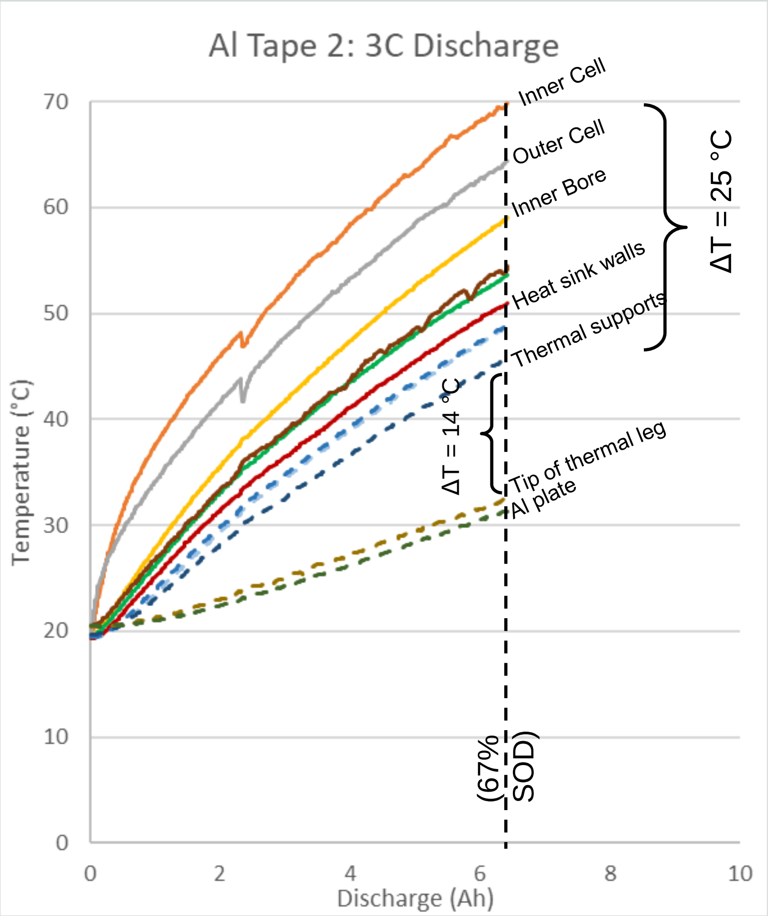
TC Naming/Mapping: L-bracket configurations



2.4C (24A) vs 3C (28.8A) discharge



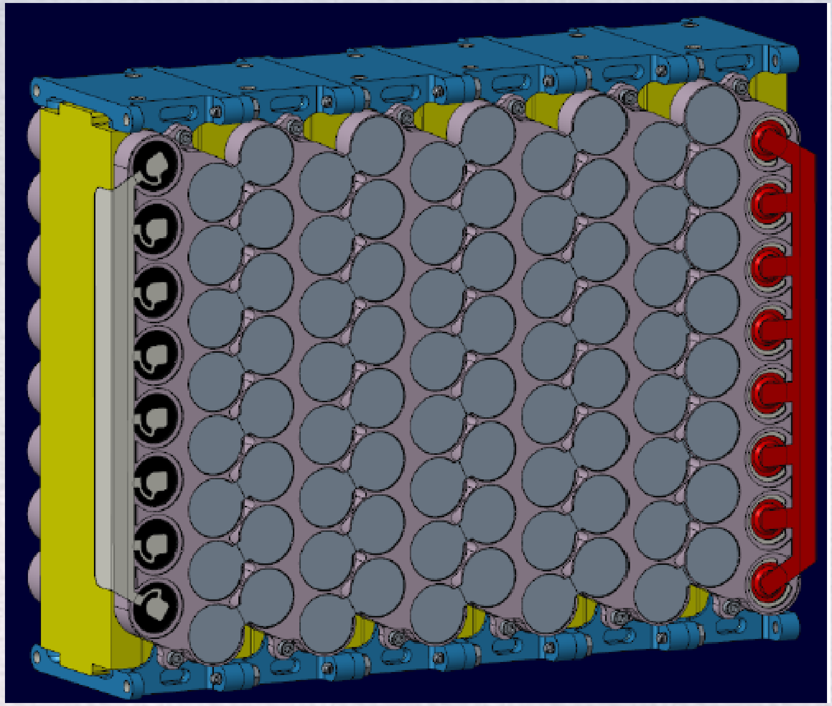




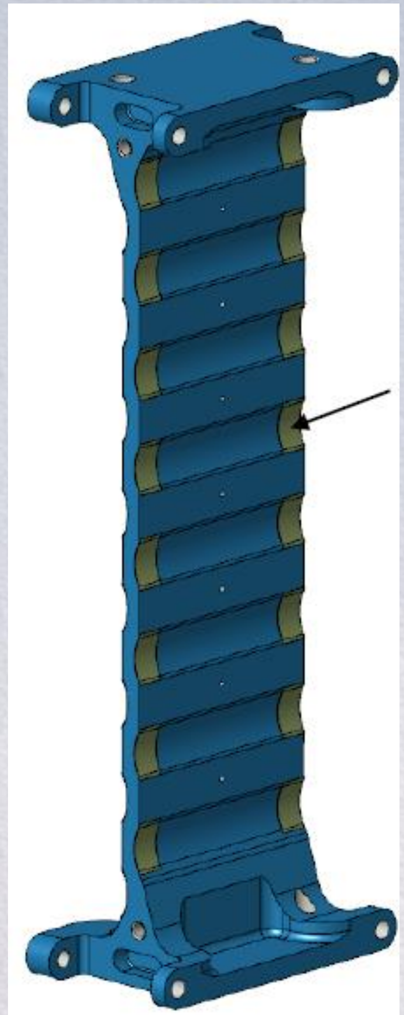
- Can’t fully discharge at 3C rate before inner ring of cells reach 70ºC
- ΔT between inner and outer ring of cells is alarming for 96-cell deck
- Lightweight Al interstitial heat sink with 0.5mm cell spacing is inadequate
- Need to improve heat dissipation from cells to battery housing surfaces

New Approach to Improve Heat Dissipation

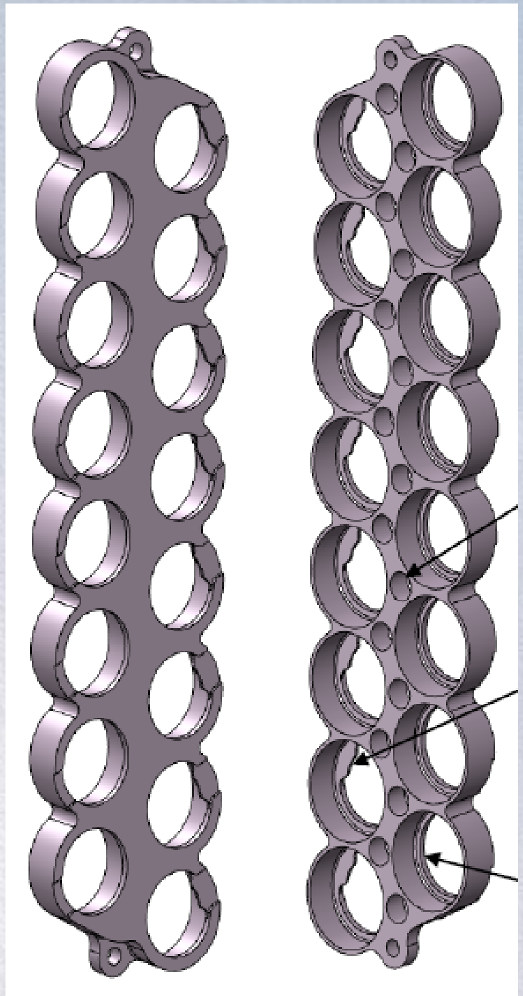
- Introduce a conductive spine to heat sink each cell and insulating gaps between pairs of vertical rows of cells
  - Improve heat dissipation to top and bottom



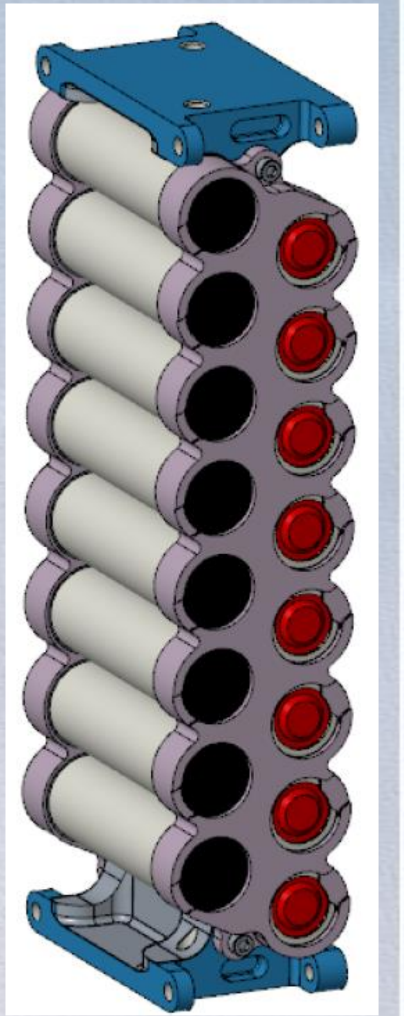
96-cell deck (1 kWh)



Al or OHP spine



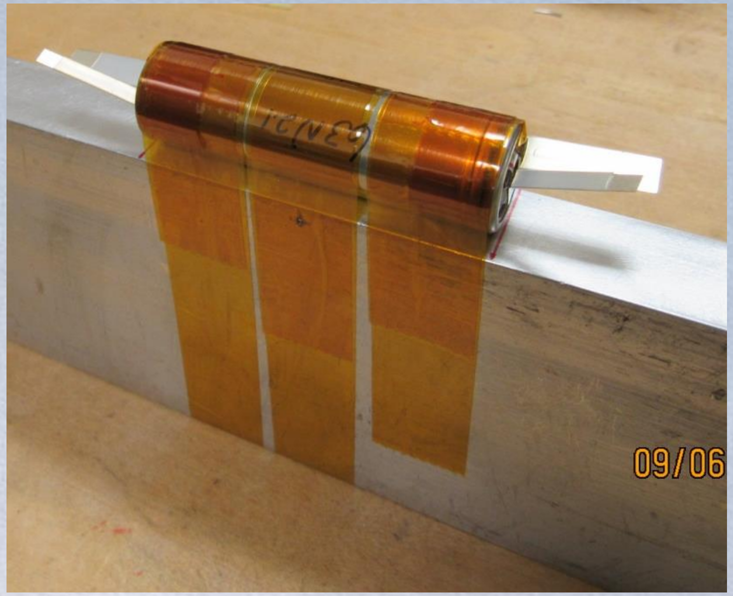
G10 capture plates

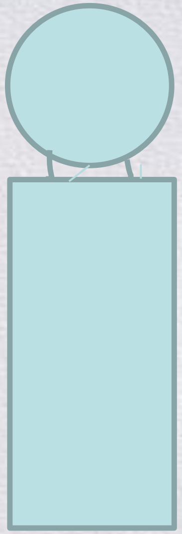


16-cell assembly

How much of cell surface is needed to dissipate needed flux?

- LG MJ1 cell with radial kapton tape at top and bottom of cylindrical wall
  - Several winds to get 0.006” thick
  - Provide gap between can wall and heat sink block
- Thermal paste (2-3 W/mK) bond between cell and block of Al
  - 3/16” wide along curved cell surface
  - 0.006” at thinnest point
  - 1.5” along axial cell length
- Insulate rest of cell with Nomex felt
- 12AWG power wires and 4-wire sensing





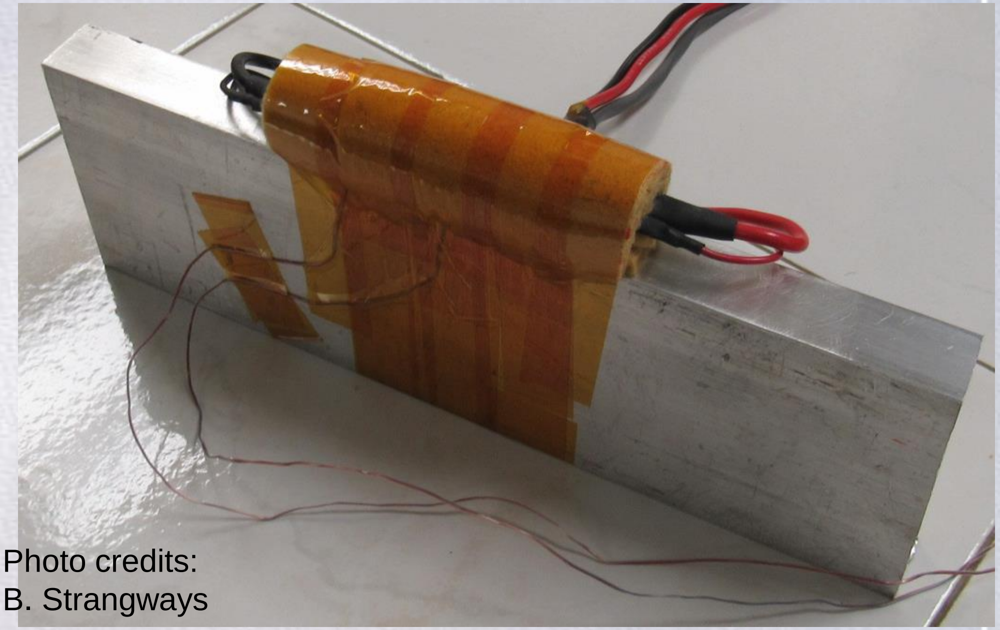
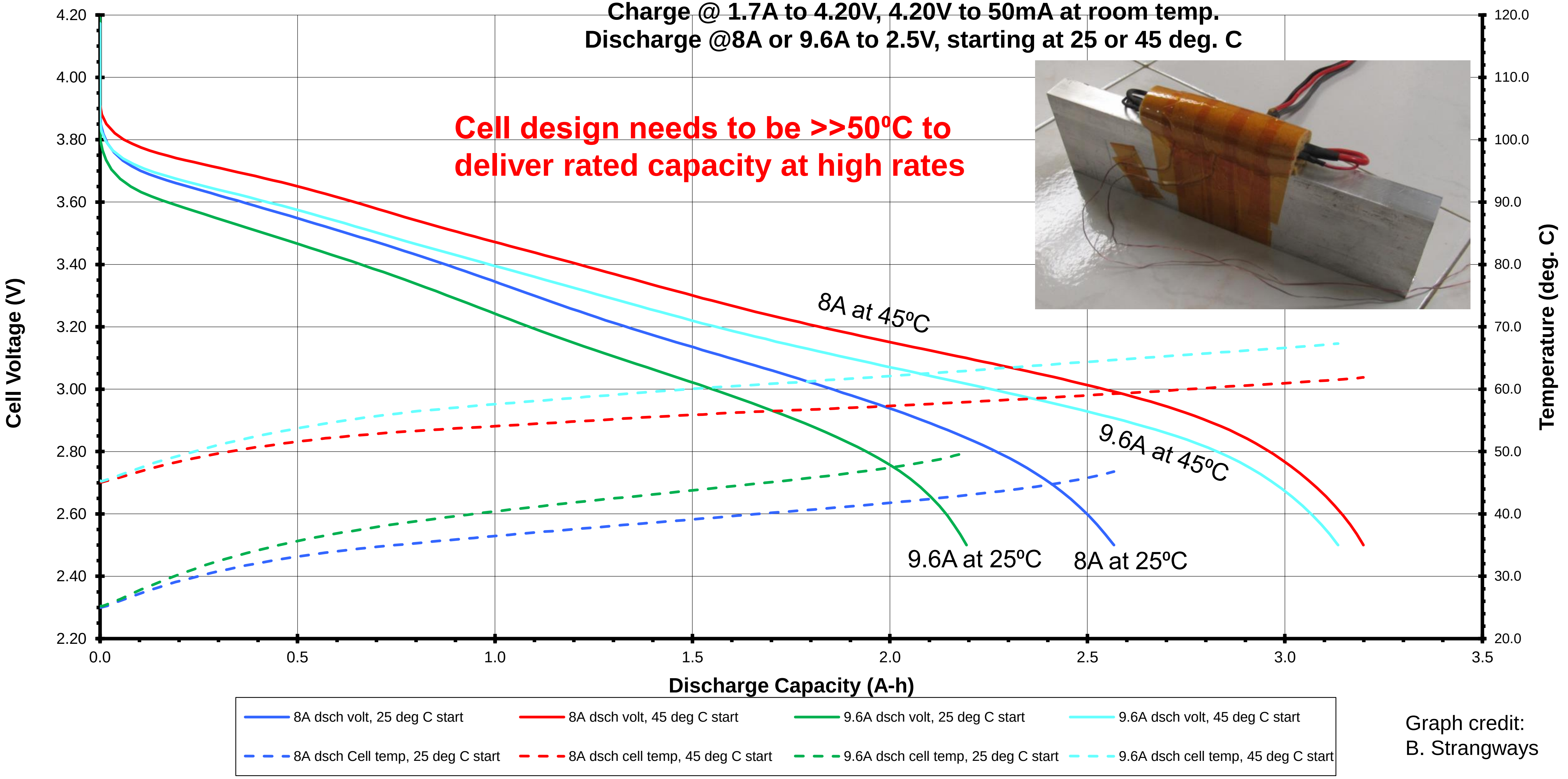


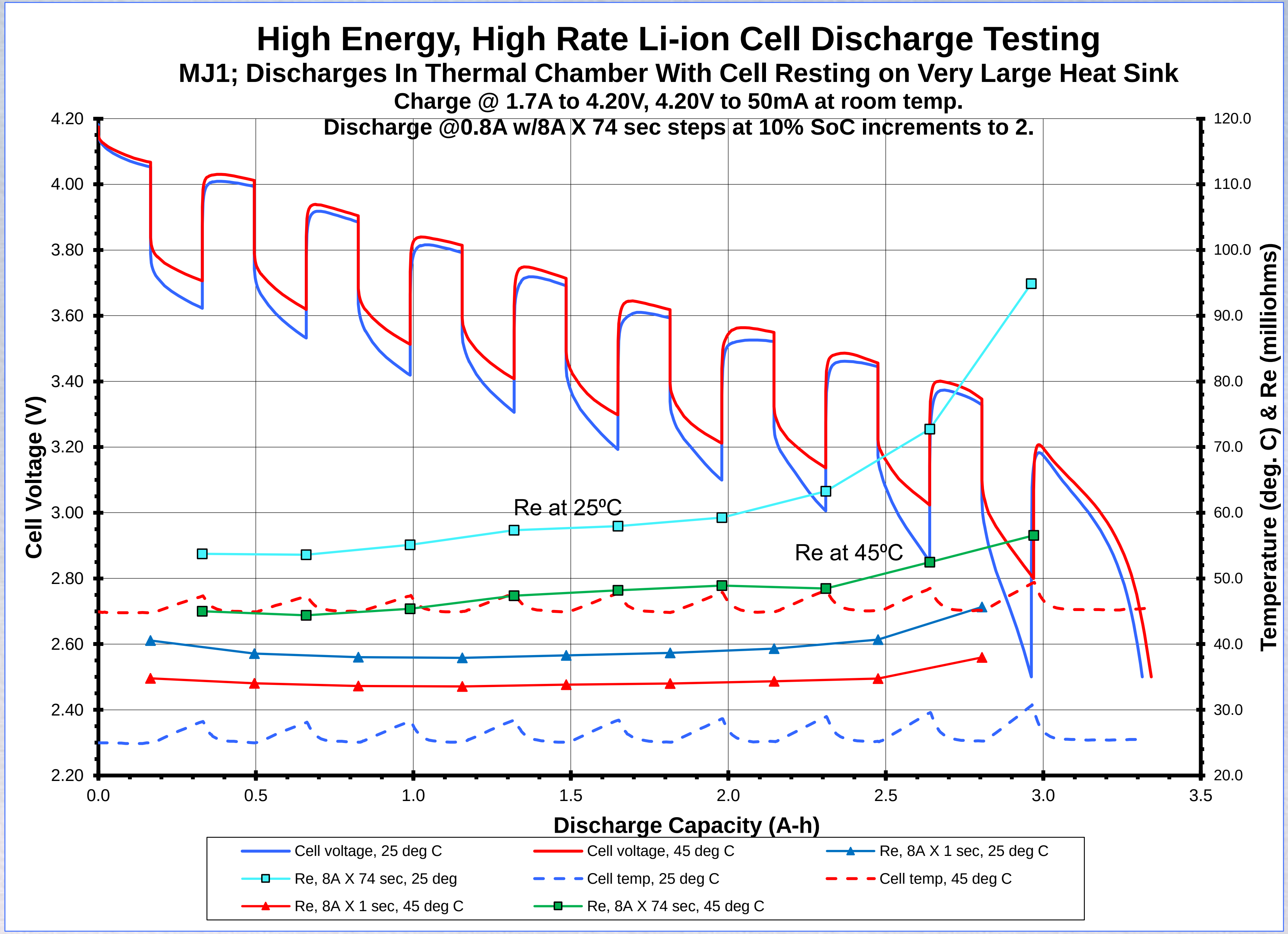
Photo credits:
B. Strangways

High Energy, High Rate Li-ion Cell Discharge Testing

LG INR18650 MJ1; Discharges With Cell Insulated and Resting on Very Large Heat Sink



Graph credit:
B. Strangways



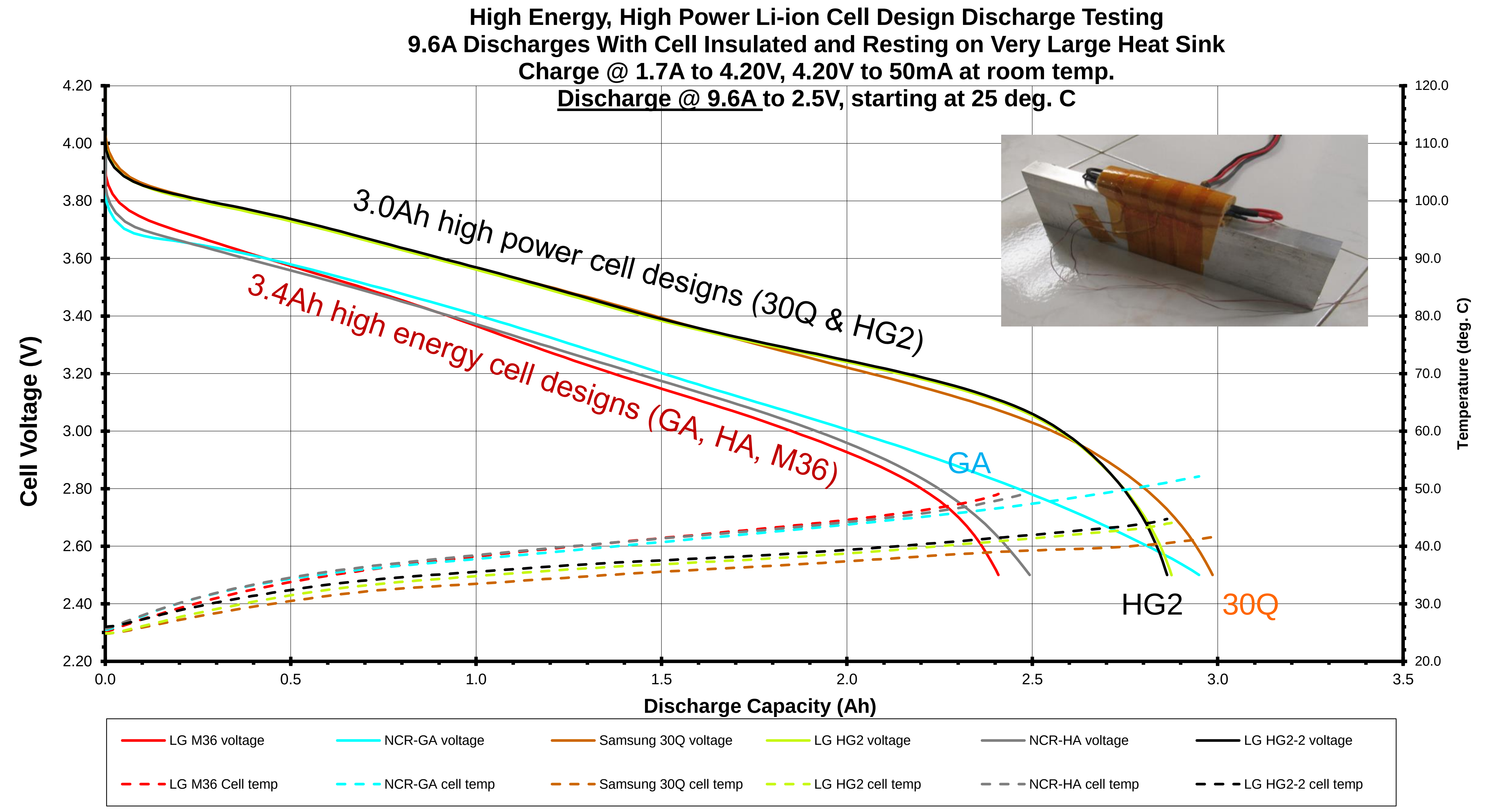
Effective Cell Internal Resistance, Re, ***significantly reduced at higher temperatures***

- Re with 1s pulses
- Re with 74s pulses

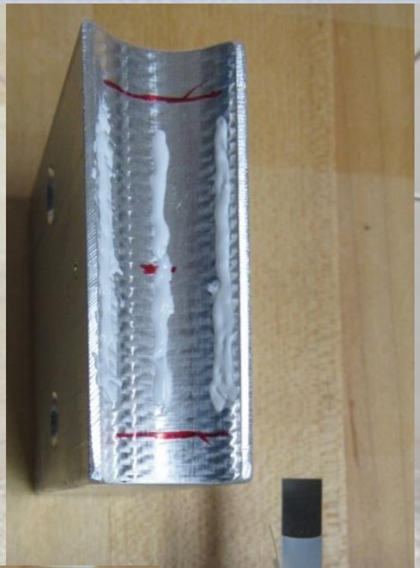
High Power Cell Designs: LG HG2, Samsung 30Q

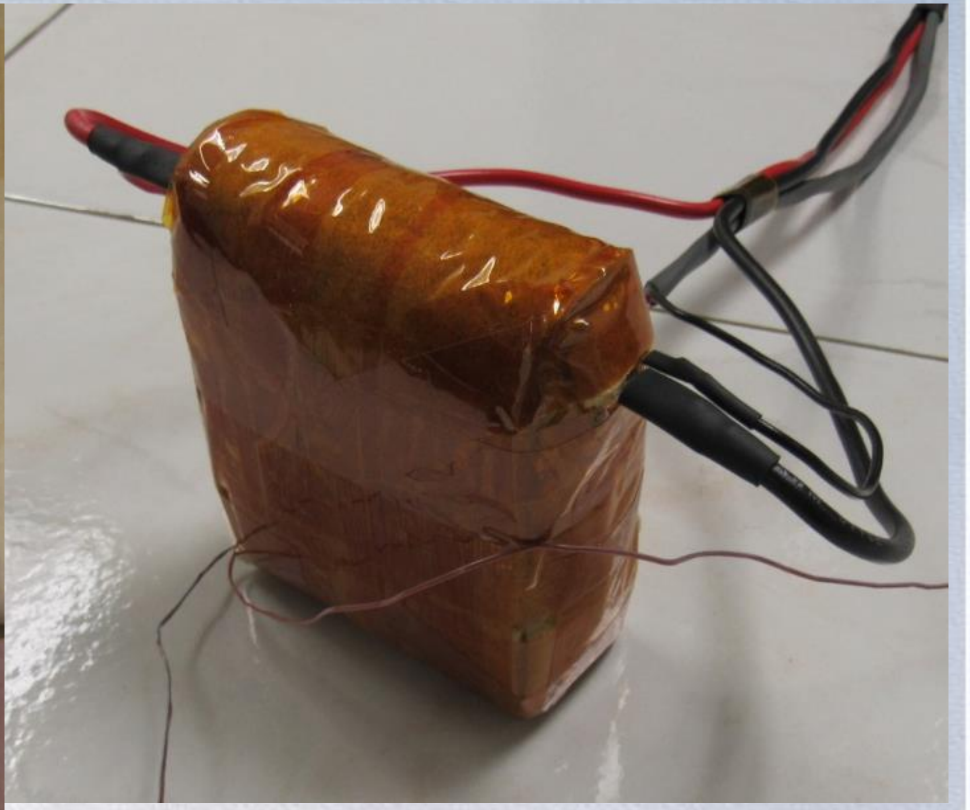
Model 18650HG2		
Nominal Capacity*(Ah, C_N)		3.0
Energy (Wh)		10.8
Dimensions	Diameter	18.3 + 0.2/-0.3mm
	Height	65.2 ±0.2 mm
Nominal Voltage*(V)		3.6
Internal Impedance**(mOhm)		14 (ave.)
DCIR(mOhm)		24 (ave.)
Designed charge current		4A

Type		
Chemistry		NCA
Dimension (mm)	Diameter	18.33 ± 0.07
	Height	64.85 ± 0.15
Weight (g)		45.6
Initial IR (mΩ AC 1kHz)		13.13 ± 2
Initial IR (mΩ DC (10A-1A))		19.94 ± 2
Nominal Voltage (V)		3.61
Charge Method (100mA cut-off)		CC-CV (4.2±0.05V)
Charge Time	Standard (min), 0.5C	134min
	Rapid (min), 4A	68min
Charge Current	Standard current (A)	1.5
	Max. current (A)	4.0
Discharge	End voltage (V)	2.5
	Max. cont. current (A)	15
ed discharge Capacity	Standard (mAh) (0.2C)	3,040
	rated (mAh) (10A)	2,983


High Energy, High Power Li-ion Cell Design Discharge Testing
9.6A Discharges With Cell Insulated and Resting on Very Large Heat Sink
Charge @ 1.7A to 4.20V, 4.20V to 50mA at room temp.
Discharge @ 9.6A to 2.5V, starting at 25 deg. C
Cell Voltage (V)
Temperature (deg. C)
Discharge Capacity (Ah)
4.20
4.00
3.80
3.60
3.40
3.20
3.00
2.80
2.60
2.40
2.20
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
3.0Ah high power cell designs (30Q & HG2)
3.4Ah high energy cell designs (GA, HA, M36)
GA
HG2
30Q
LG M36 voltage
NCR-GA voltage
Samsung 30Q voltage
LG HG2 voltage
NCR-HA voltage
LG HG2-2 voltage
LG M36 Cell temp
NCR-GA cell temp
Samsung 30Q cell temp
LG HG2 cell temp
NCR-HA cell temp
LG HG2-2 cell temp

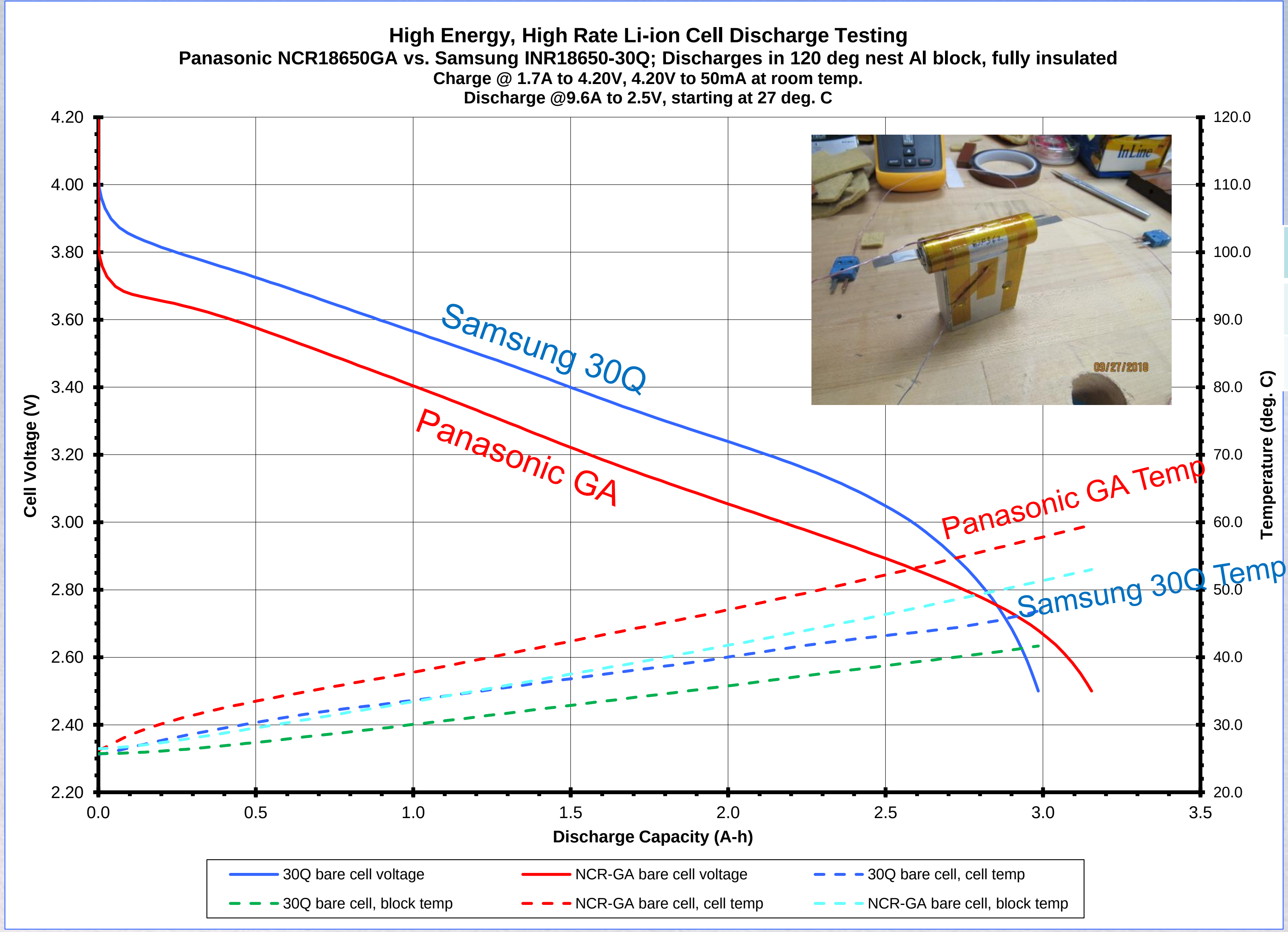
Adiabatic Cell & Al 120º Heat Sink Test





Al Block 2.0” wide X 0.75” thick X 2.28” long. There is also a small 0.04” dia hole 0.375” deep located 0.065” below the center of the nest for the Al block T/C. The nest radius providea a 120º contact. Block mass is 140.2g.

Cell to block interface = Omega thermal paste with κ = 2.3W/m°K. Nominal film thickness is 0.003” for the mica-wrapped GA cell and 0.009” for the bare cells. The mica wrapped cell has 0.004” thk mica with 0.002” thk acrylic adhesive layer between the mica and can wall.



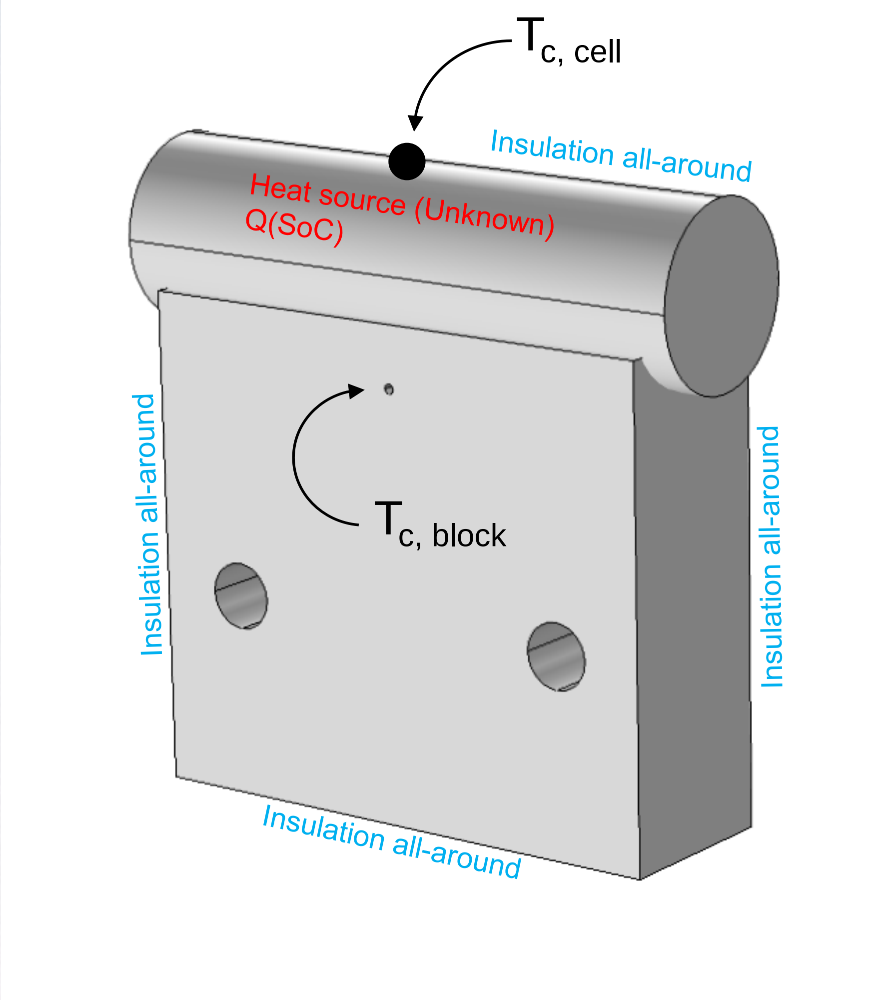
Bare cell (no mica) comparison at RT and 9.6A

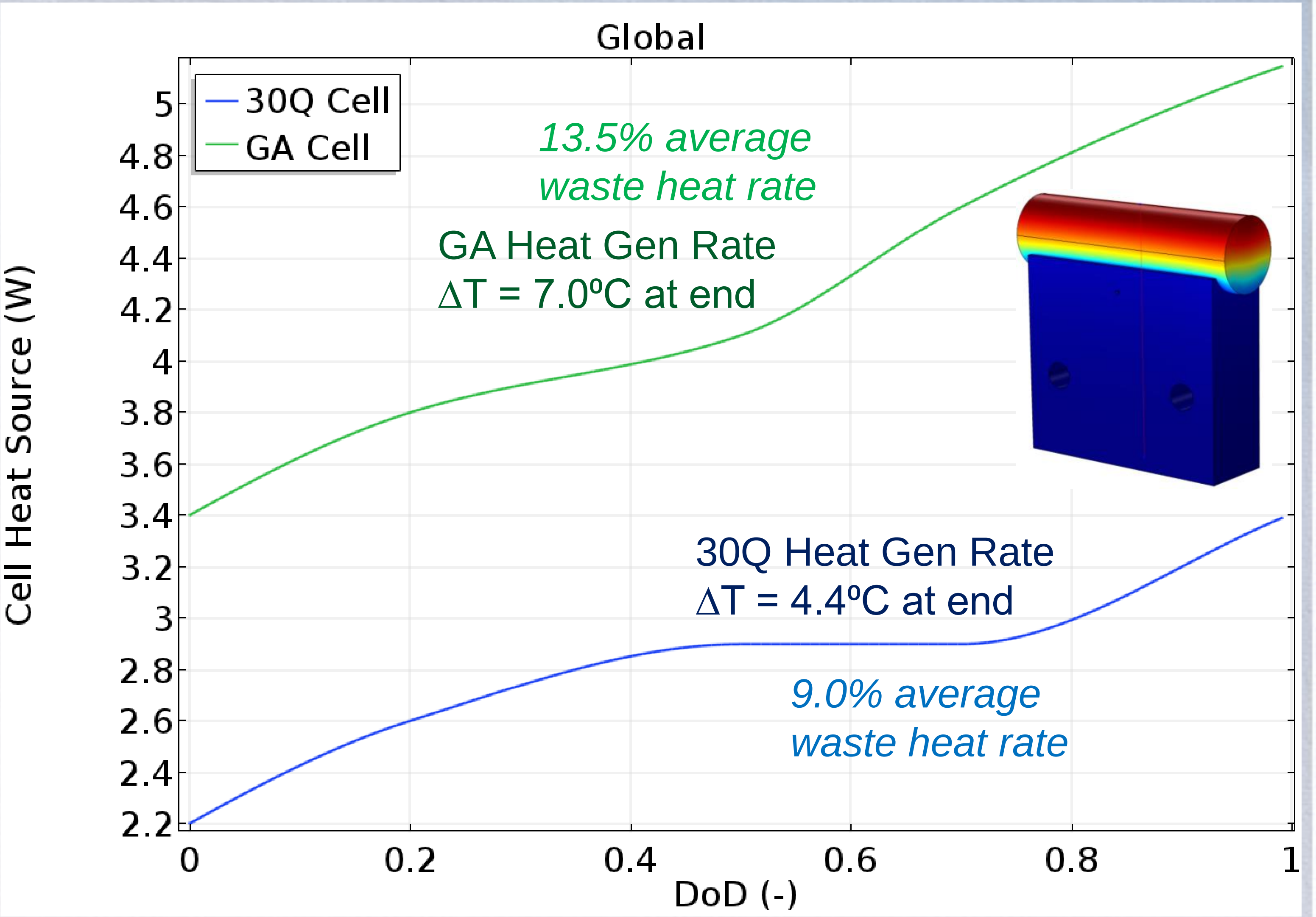
Cell Design	Ah	Wh
NCR GA	3.154	10.08
Sam 30Q	3.029	10.73

At > 3C, high power cell design (30Q) provides more Wh and less heat than higher capacity cell design (GA)

Analysis to Extract Cell Heat Generation Rate at 9.6A

Paul Coman & Ralph White





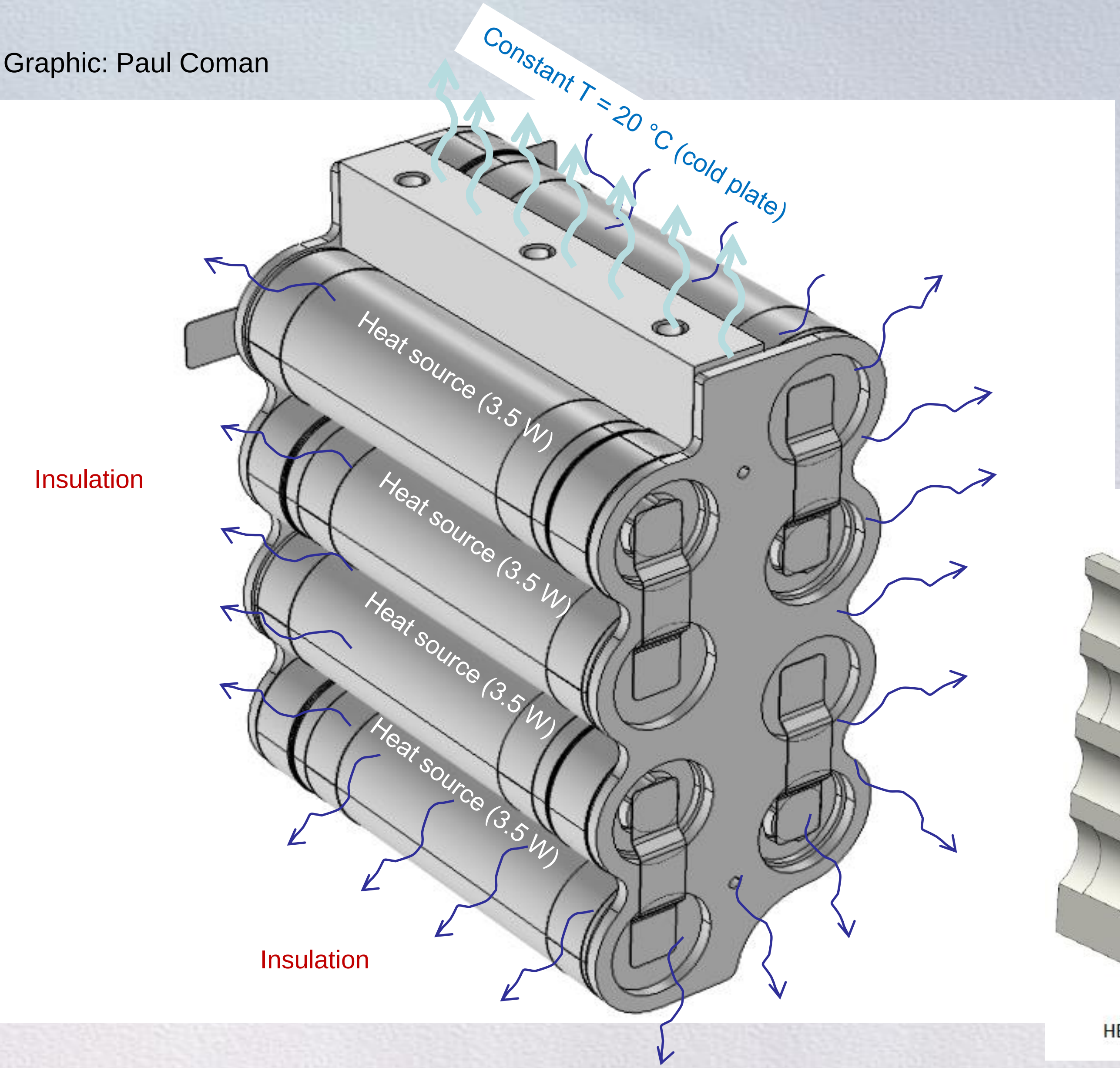
Graphics: Paul Coman

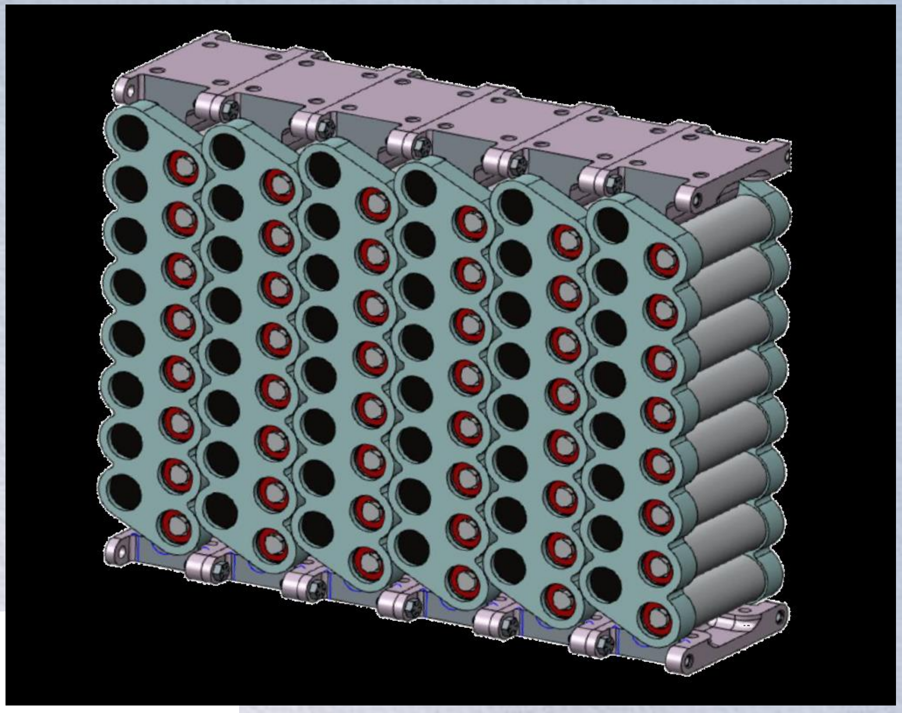
Recap of Test Findings

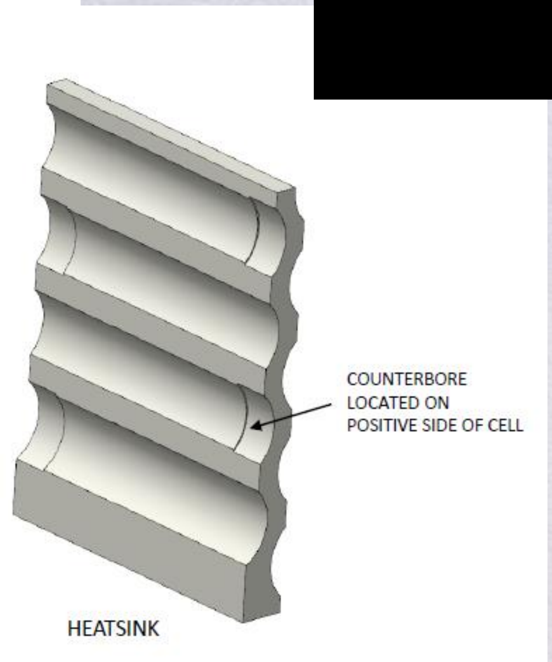
- Thin webbing, tight nesting heat sink with circumferential cylindrical interface with cells provides inadequate heat rejection path at 3C rates
  - *Even with the best thermal bond between cell and heat sink*
- If we improve the heat dissipation path too much and keep cells < 50ºC, cell high rate performance of high energy cell designs will suffer greatly
  - *Confirmed on MJ1, M36, VC7, GA, and 35E*
- However, temperature impact on 3C performance is much less with higher power cell designs
  - *Confirmed on 30Q and HG2*
- If cell has short path to heat sink, only small amount of cell surface area is needed for adequate heat dissipation
  - *This approach is more likely to prevent TR propagation*
- **We need to keep high energy cell designs in 50-70ºC range to beat capacity performance of high power cell designs**
  - *However, energy deliver is nearly equivalent between 30Q and GA > 9A, 45ºC*
- Regardless, battery pack design will need to minimize ΔT between cells to keep them balanced

Solid Al Thermal Path 90º interface

Graphic: Paul Coman



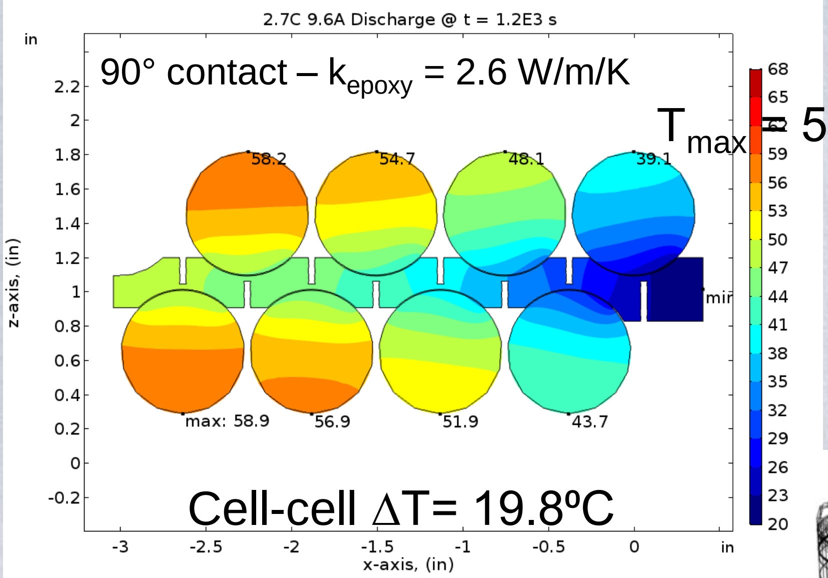


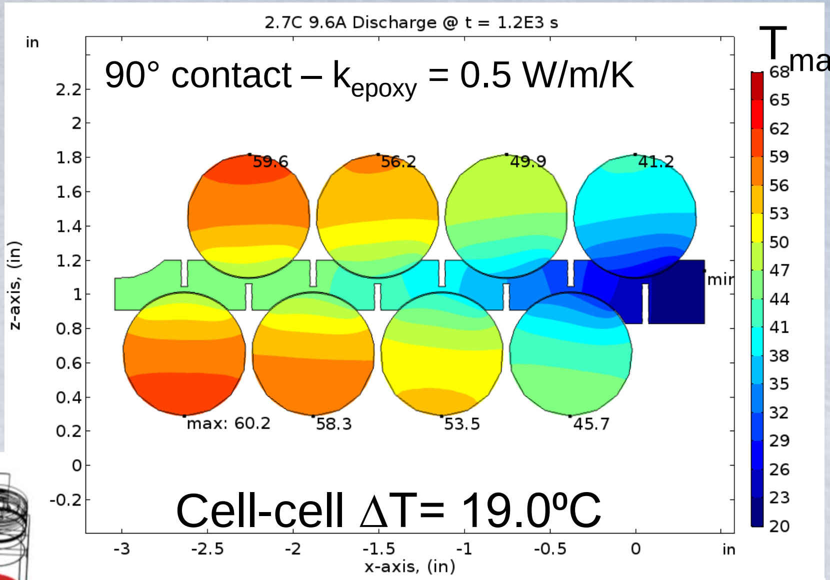


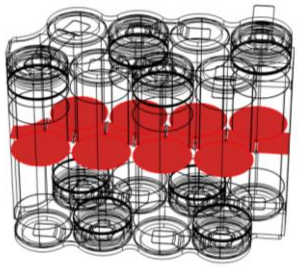
- 90º interface with cell can wall
- Epoxy bonded interface
- With interface to battery bottom plate or cold plate
- What ΔT cell to cell will we get?

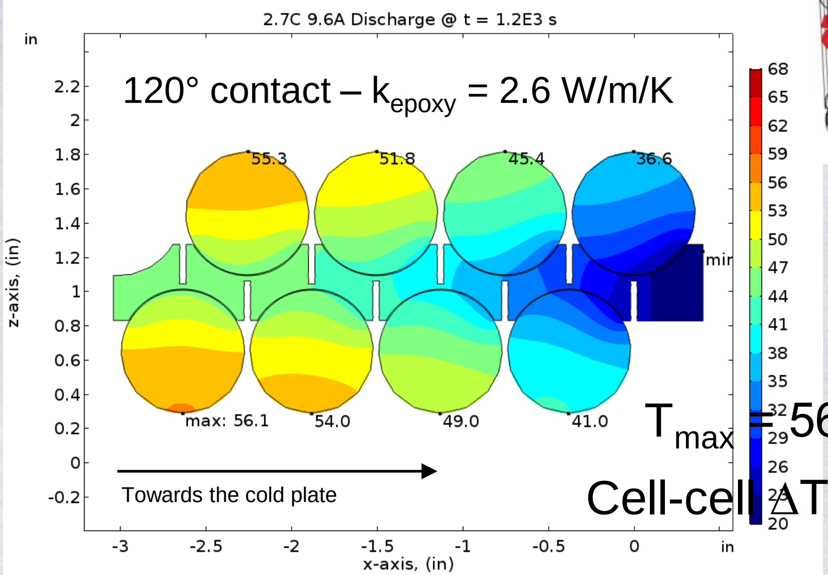
ΔT differences – mid-plane cross-section

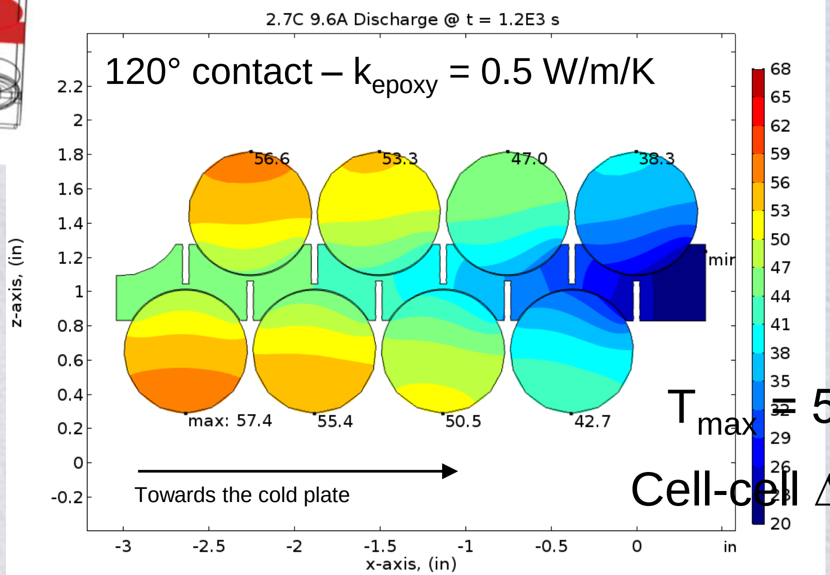
(Adiabatic case, GA cell heat gen rate – different epoxies & cell contact areas)





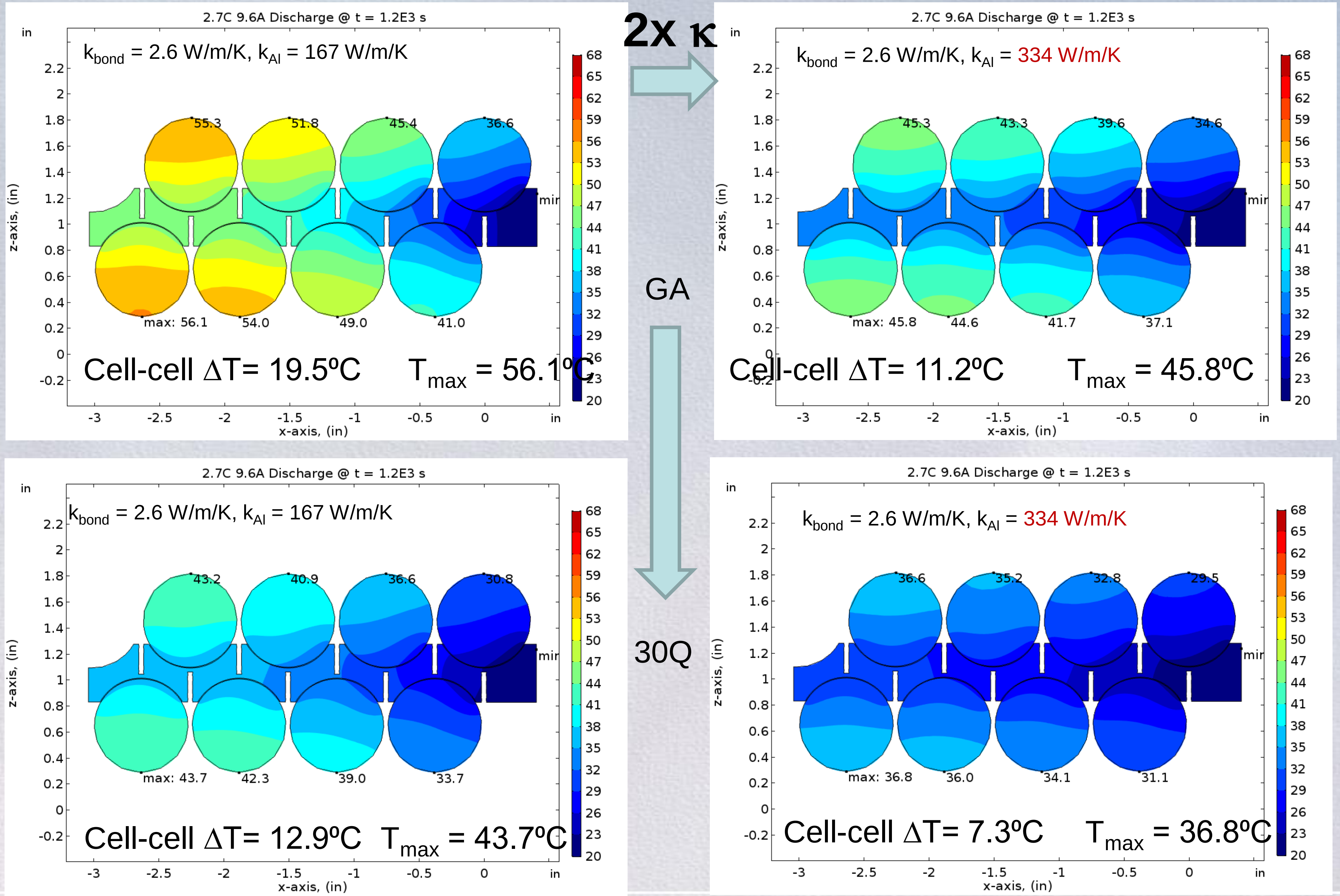






Improving thermal conductivity of epoxy or cell contact area provides little impact to cell-cell ΔT or T_{max}

Graphs: Paul Coman



- Doubling thermal conductivity of spine reduces ΔT by 43%
- Replacing GA with 30Q cell design reduces ΔT by 33%
- Very significant improvements in both cases

Graphs: Paul Coman

Recap of Analysis Findings

Oscillating Heat Pipes

- Heat transfer fluid encapsulated in microchannels
- Very efficient, high flux heat transfer from hot middle to cooled ends of pipe
- Greatly reduces ∆T between cells vs solid Al spines
- Significantly expands range of initial temperature operating conditions vs solid Al spines

Insignificant design factors

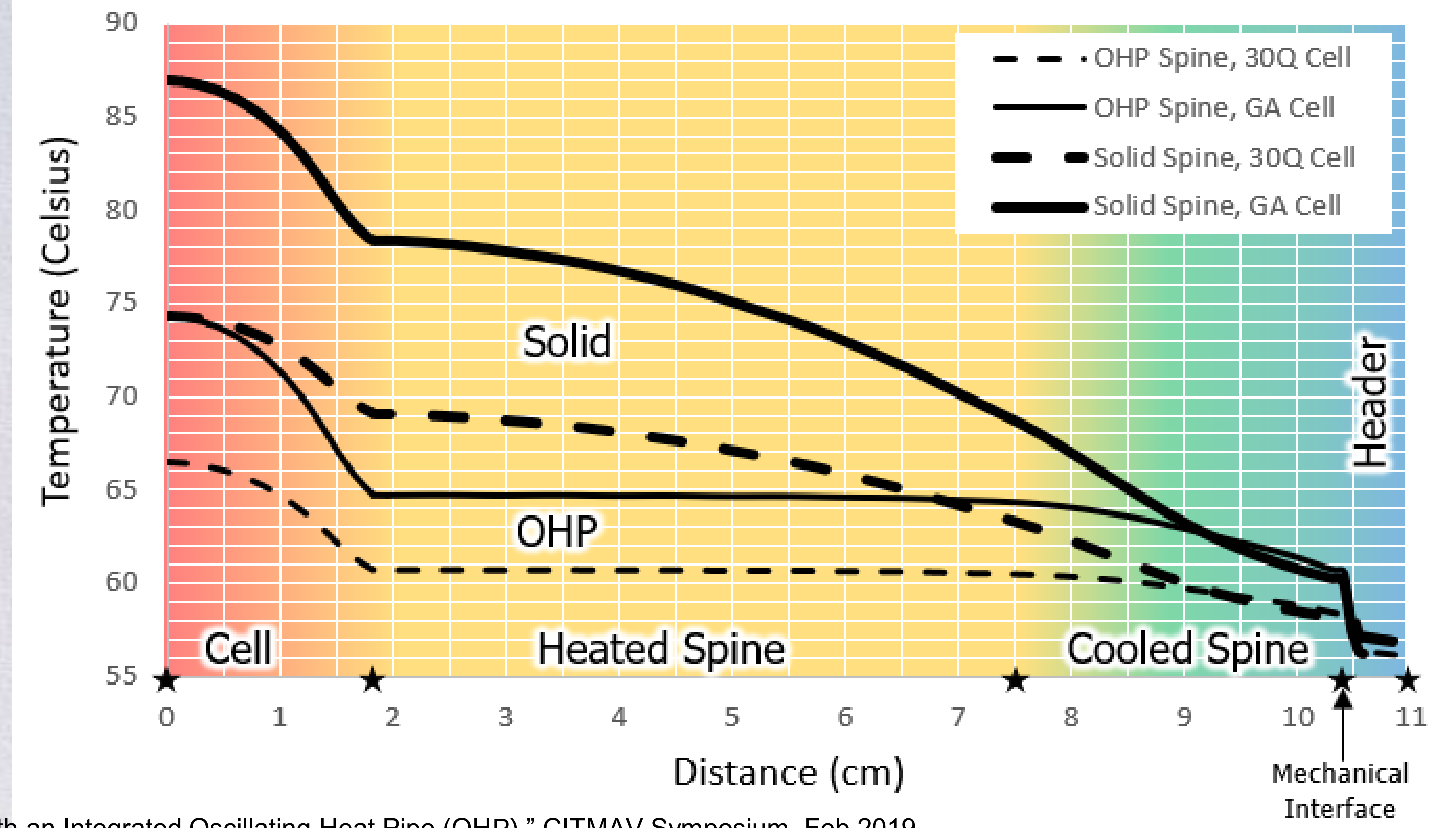
- Thermal conductivity of epoxy for cell bond
- Cell to heat sink interface area

Significant design factors

- Thermal conductivity of heat sink spine
- Reducing cell heat generation

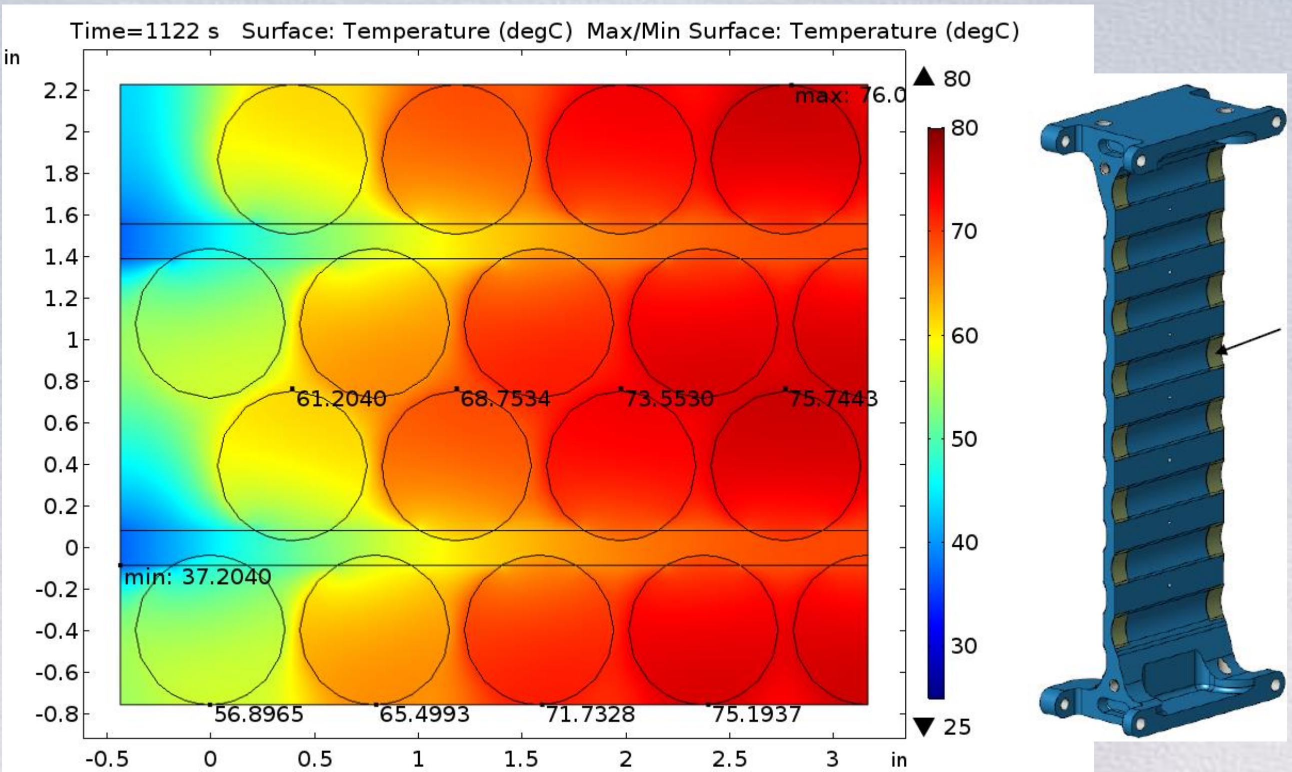
How to improve κ of heat sink spine

- ***Oscillating heat pipes***

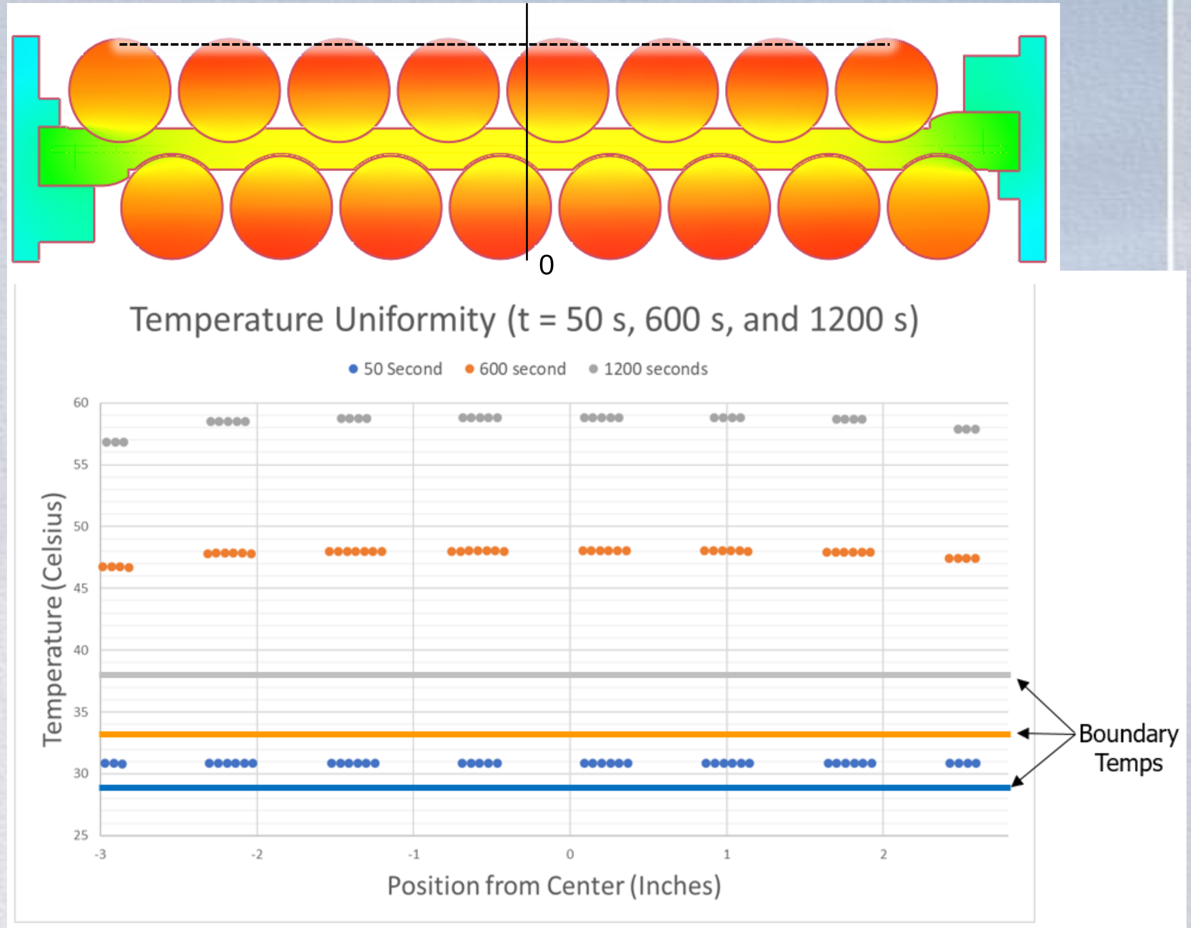


*J. Boswell, D. Pounds, B. Alexander and E. Darcy, “High Power Battery Heat Sink with an Integrated Oscillating Heat Pipe (OHP),” CITMAV Symposium, Feb 2019

Solid Al vs OHP Spine Performance



T_{max} = 76.1 °C
ΔT_{max} = 19.1 °C



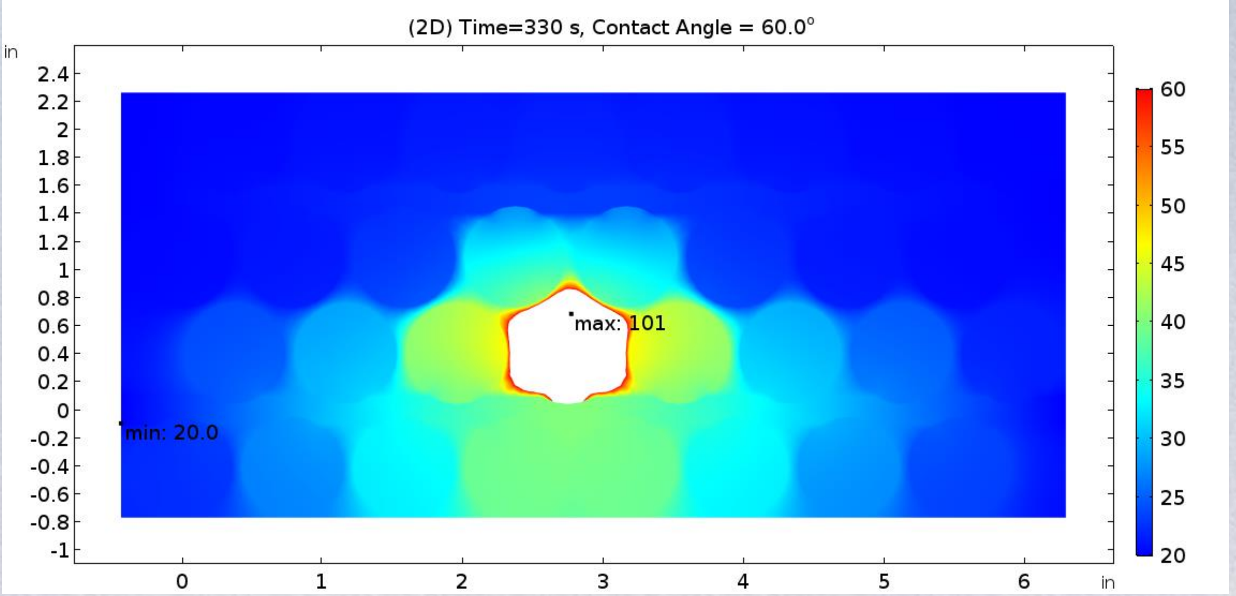
T_{max} = 59 °C
ΔT_{max} = 2.0 °C

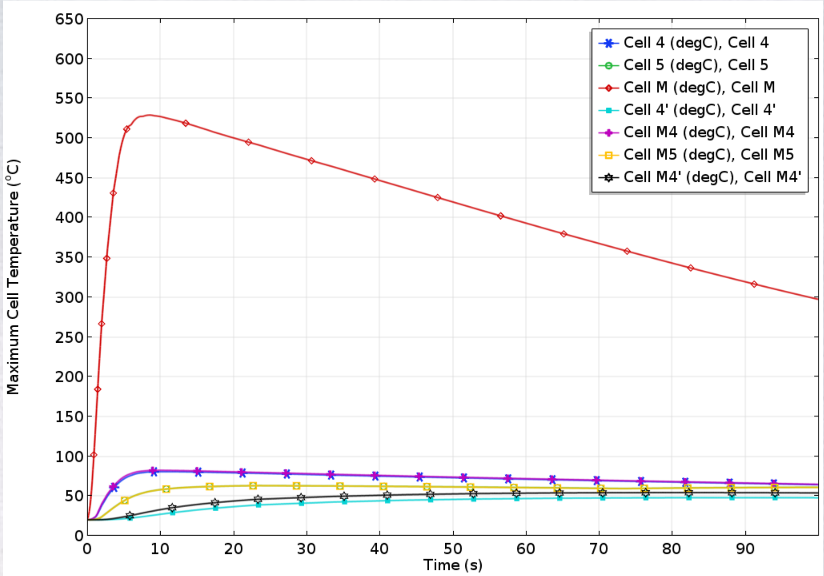
Credit: P. Coman, White & Associates

Credit: J. Boswell, D. Pounds, B. Alexander and E. Darcy, “High Power Battery Heat Sink with an Integrated Oscillating Heat Pipe (OHP),” CITMAV Symposium, Feb 2019

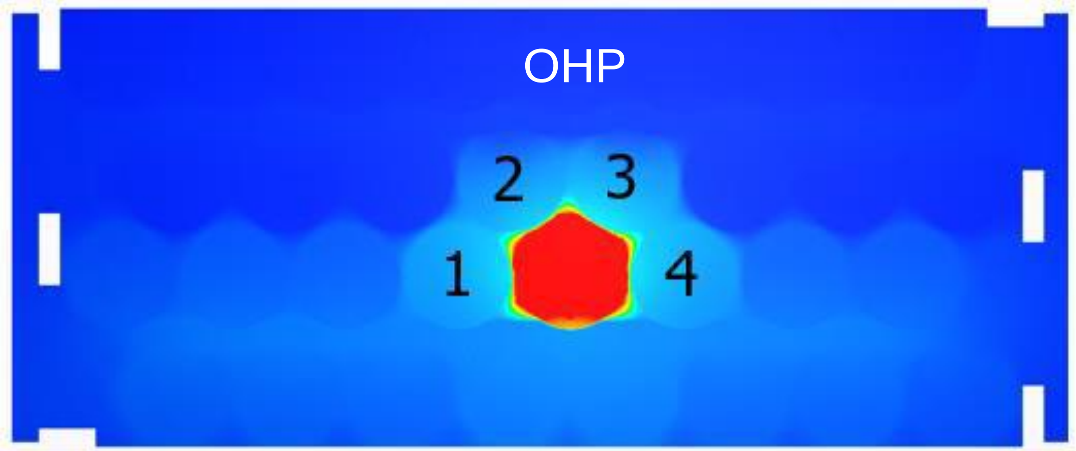
Both Are Predicted to Protect Adjacent Cells from Propagating TR

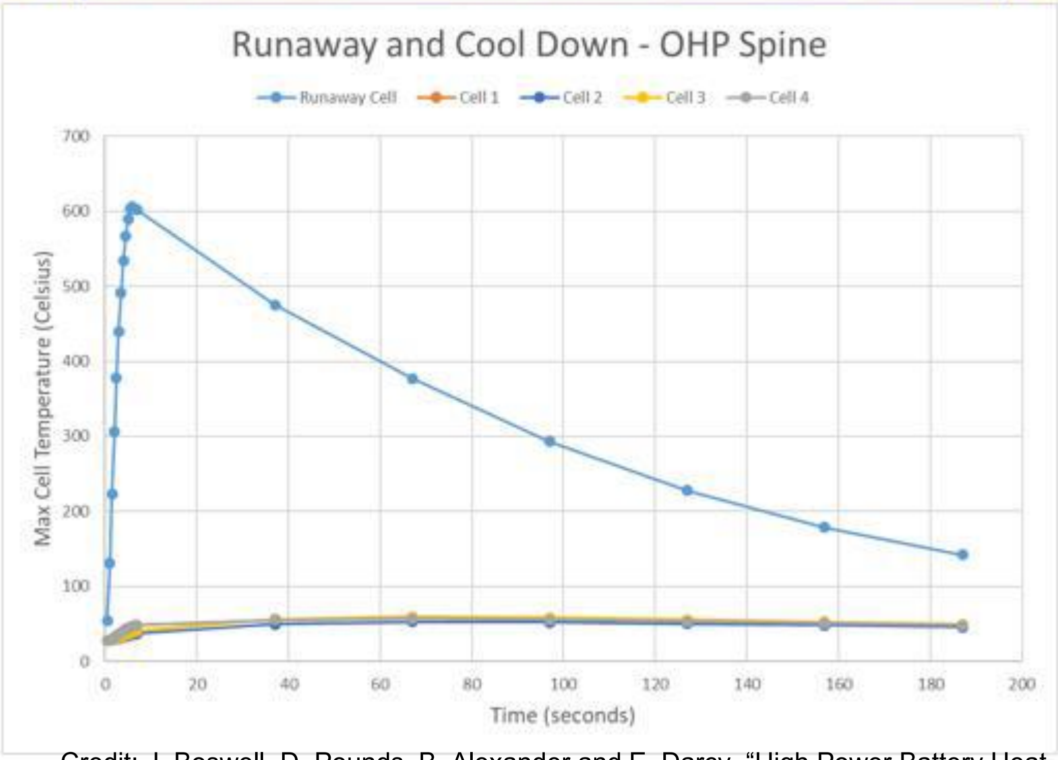
Solid Al Spine





Credit: P. Coman, White & Associates





Credit: J. Boswell, D. Pounds, B. Alexander and E. Darcy, “High Power Battery Heat Sink with an Integrated Oscillating Heat Pipe (OHP),” CITMAV Symposium, Feb 2019

Final Chart

- Take Away Messages
  - Safe, high power battery designs that achieve > 160 Wh/kg are predicted with
    - A high performing commercial high power 18650 cell design
    - A high flux, lightweight oscillating heat pipe technology
  - Verification will be complete this summer

- Acknowledgements
  - C. Iannello, NASA-NESC for funding the task