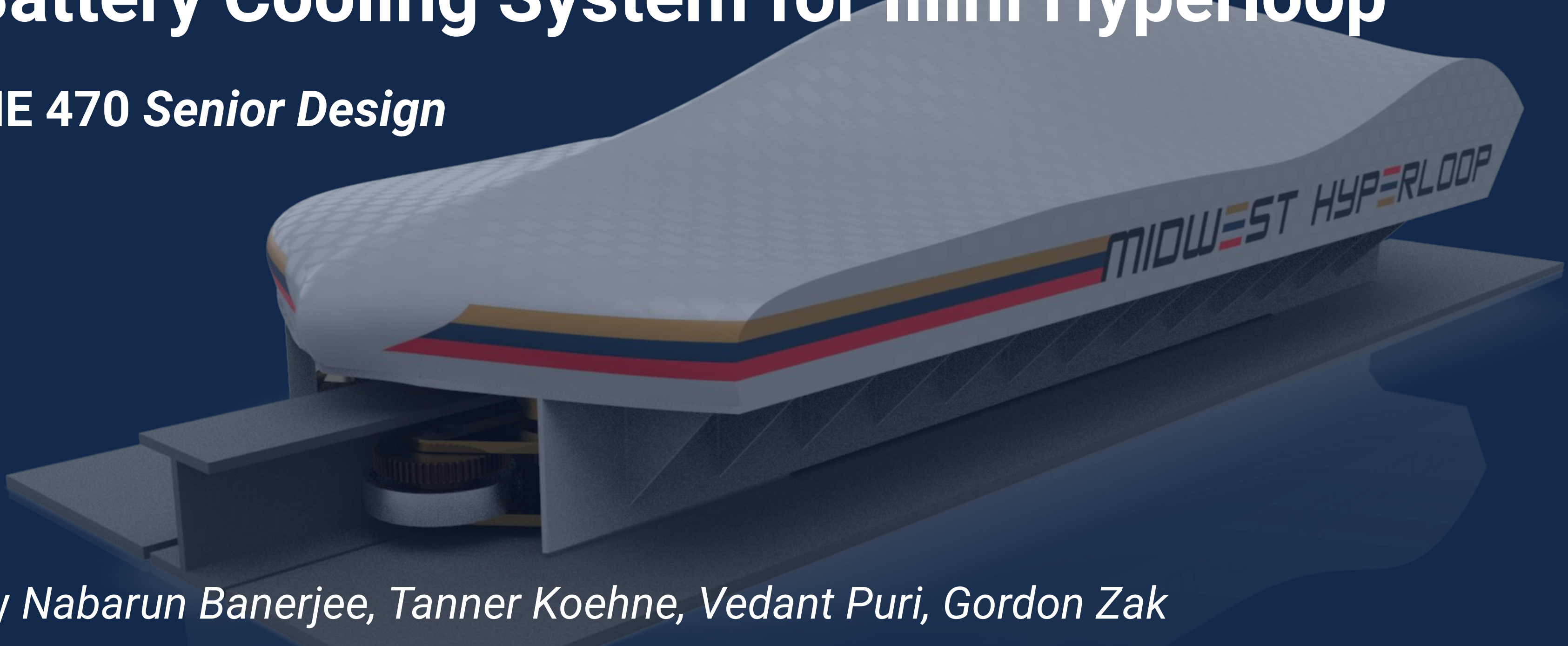
Battery Cooling System for Illini Hyperloop

ME 470 *Senior Design*



By *Nabarun Banerjee, Tanner Koehne, Vedant Puri, Gordon Zak*

ILLINOIS
Mechanical Science & Engineering
COLLEGE OF ENGINEERING

Sponsor

Sponsor - Novark Technologies

- Thermal solutions company serving a variety of industries
- Consulted on design
- Handled prototype fabrication

Client - Illini Hyperloop RSO

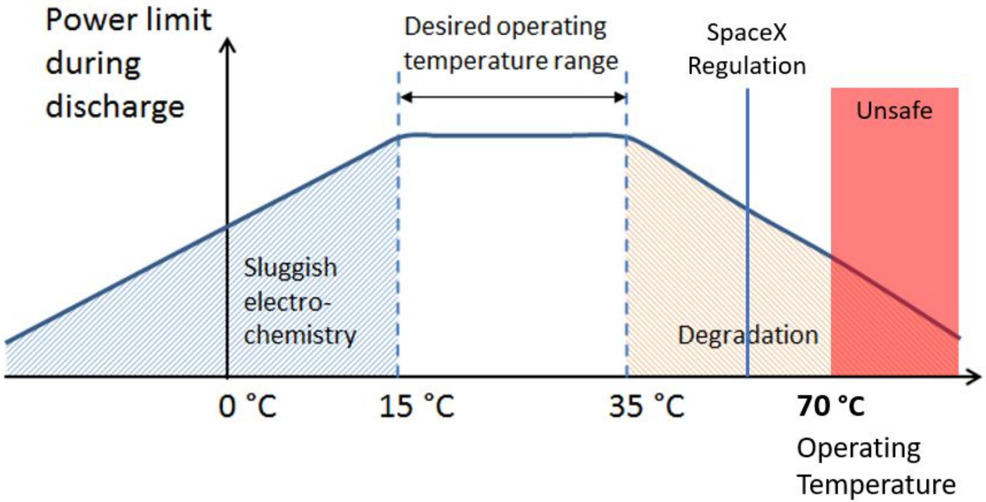
- Constituent member of Midwest Hyperloop
- Designing a pod to compete in SpaceX 2019 Hyperloop Competition

Overview

- Introduction
  - Problem Statement
  - Design Constraints
- Power Modelling
- Cooling Solution
- Battery Testing
- Design
  - Cooling Plate Design
  - Battery Box
  - Finite Element Analysis
  - Fabrication
- Summary & Recommendations

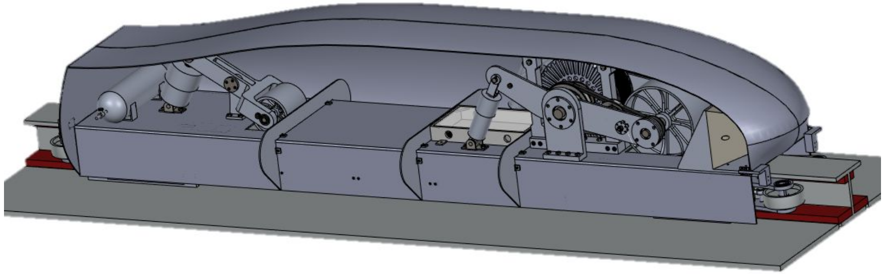
Problem Statement

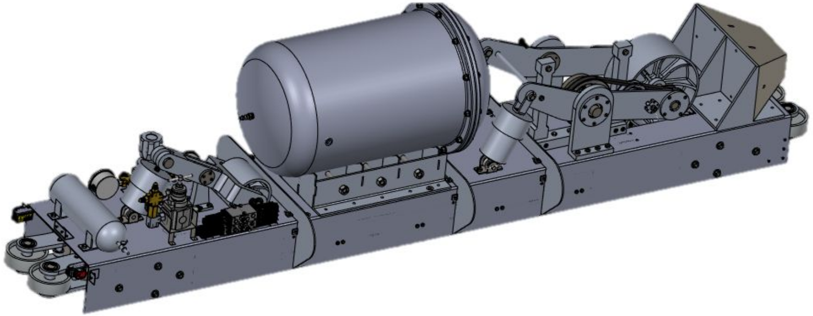
- Pod propulsion system runs at 111V, 800A
  - 5 Lithium Polymer (Li-Po) batteries in series power an electric motor
- Excessive heating may produce unsafe operating conditions, risk thermal runaway
- SpaceX regulation: battery temperature not to exceed 50°C (122°F)
- Project objective: maintain temperature as close to 35°C (95°F) as possible



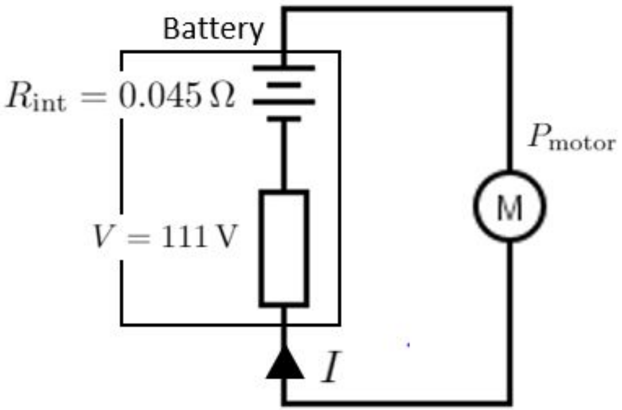
Design Constraints

- Must maintain battery temperature below 50°C for one 20 second run
- Cooling system must not draw power from propulsion system
- Design must fit within the space constraints of the battery box
- Plates must maintain sub-ambient temperature for 1 hour prior to run



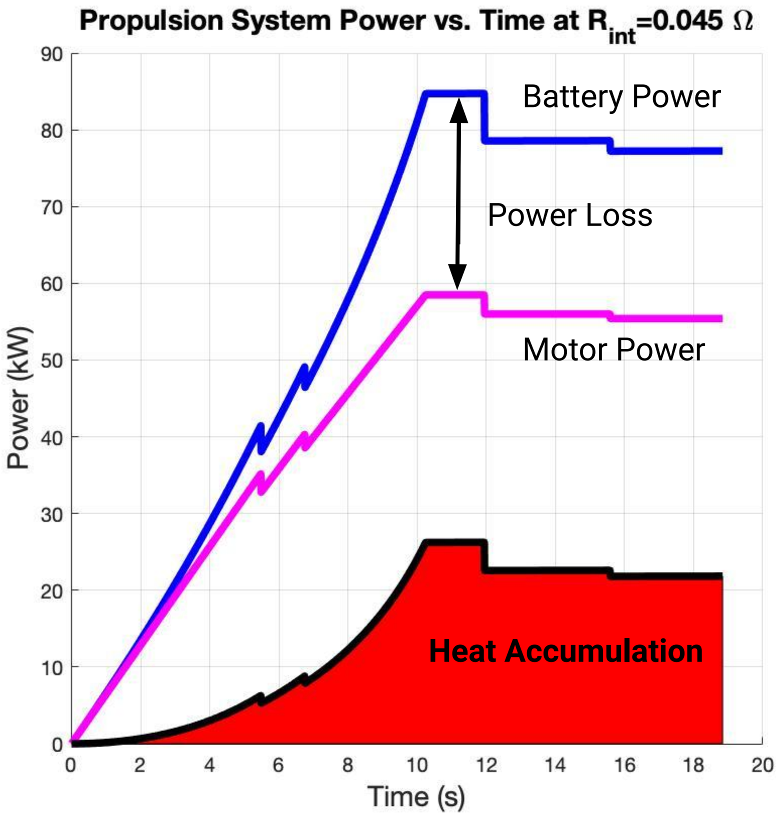


Power Modelling

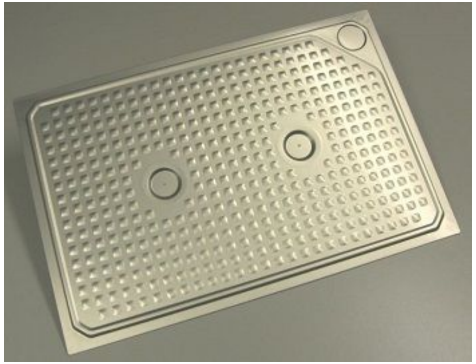


$$P_{\text{battery}} = VI = P_{\text{motor}} + I^2 R_{\text{int}}$$

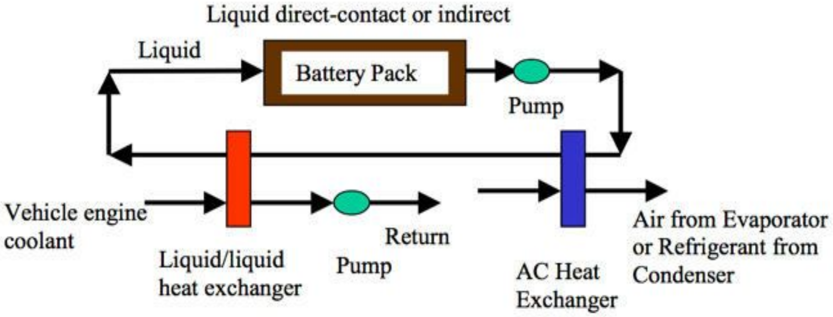
- Assumptions:
  - Battery at peak performance
  - Constant battery internal resistance $R_{INT} = 0.045\ \Omega$
- Results (upper estimates):
  - Max current 800 A
  - Heat generated in battery Q=300 kJ



Different Design Considerations



Phase Change Material



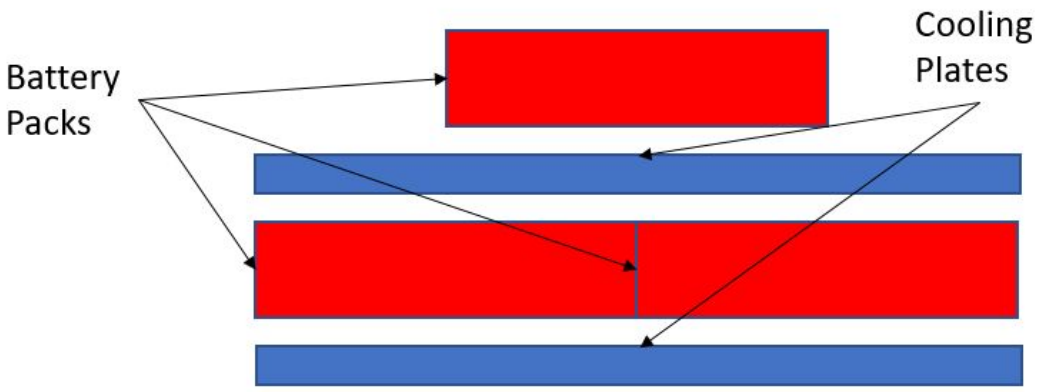
F. Active Cooling and Heating – Liquid Circulation

Active Water Cooling

Passive Water Cooling

Passive Liquid Cooling Solution

- Battery packs sandwiched between two cooling plates
- Passive system, with natural convection of water between fins
- Implementation:
    - Aluminum brazed plates on both sides of 4 battery packs
    - Thermal paste on both sides of battery to reduces contact resistance



Battery Testing

Need for testing

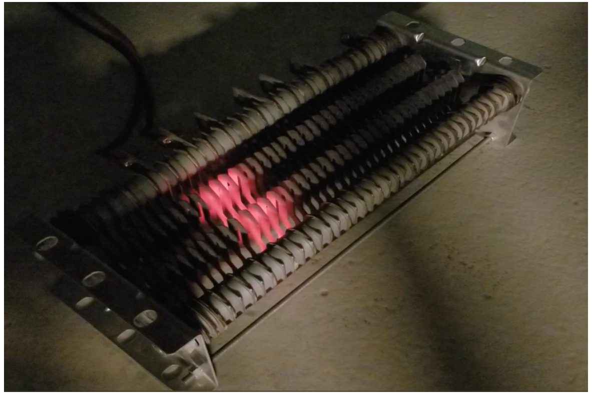
- Battery is an inhomogeneous body
  - Localized heat concentration at “hot spots”
  - Find battery surface temperature profile
- Quantify relation between temperature and R_{INT}
  - Total heat generated (Q) varies with R_{INT}
  - $R_{INT} = 0.015–0.045\ \Omega$
  - Heat Q = 60–300 kJ

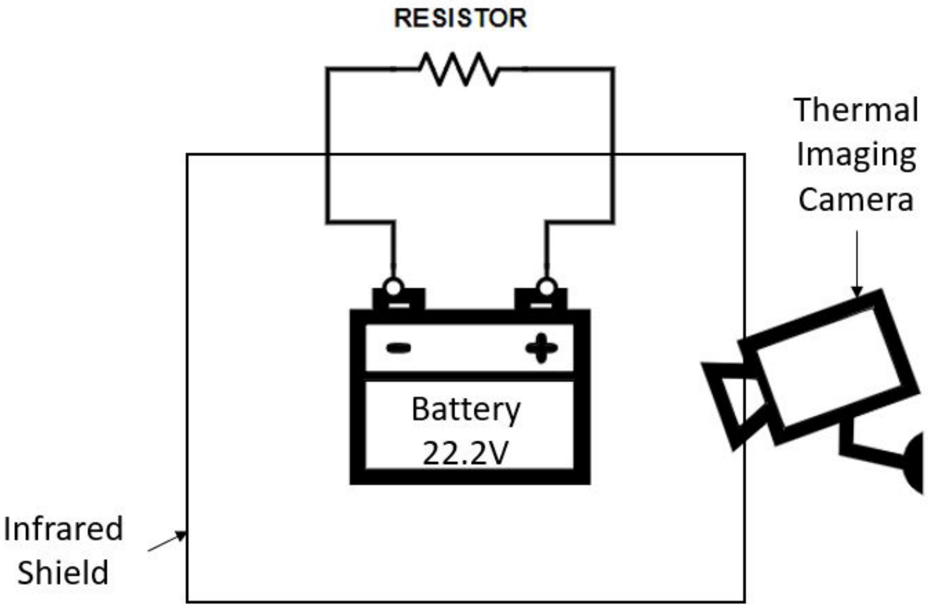
Limitations

- Li-Po batteries are covered in insulating jackets
  - Most heat generated stays inside battery
- Single battery cannot reach target current of 800 A

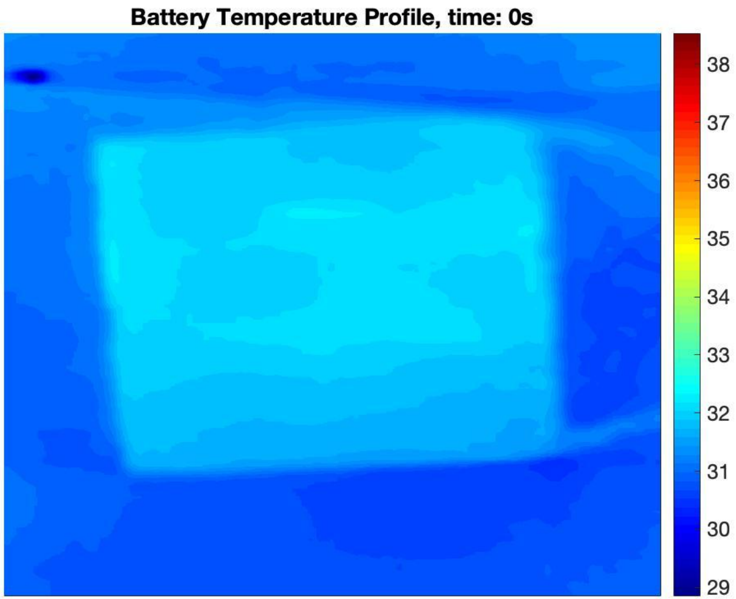
Thermal Profile - Finding Hot Spots

- Qualitatively test to find locations of "hot spots"
- Battery connected to 0.25 Ω high-power resistor
- System placed in an infrared-isolating environment
- Use thermal imaging camera to obtain surface temperature profile

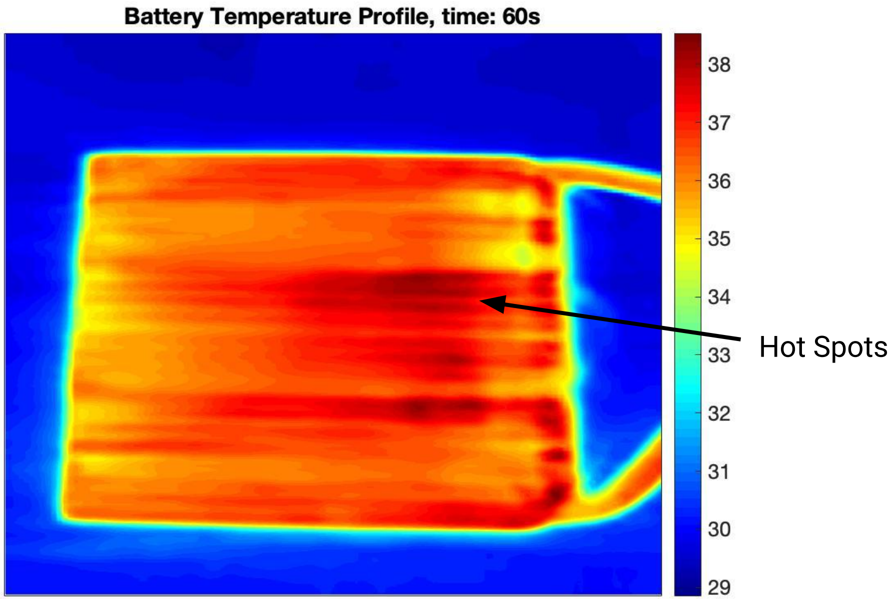




Thermal Profile - Finding Hot Spots



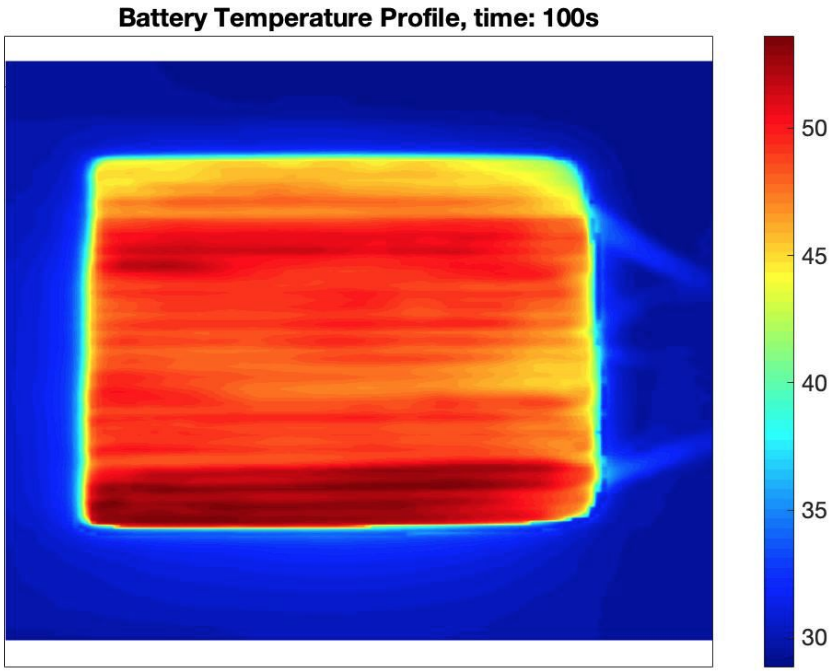
- Initial Temperature 30°C



- 100 A current applied for 60 s
- Final Temperature 37°C
- 6 kJ of heat generated in battery
- “Hot spots” in lateral bands

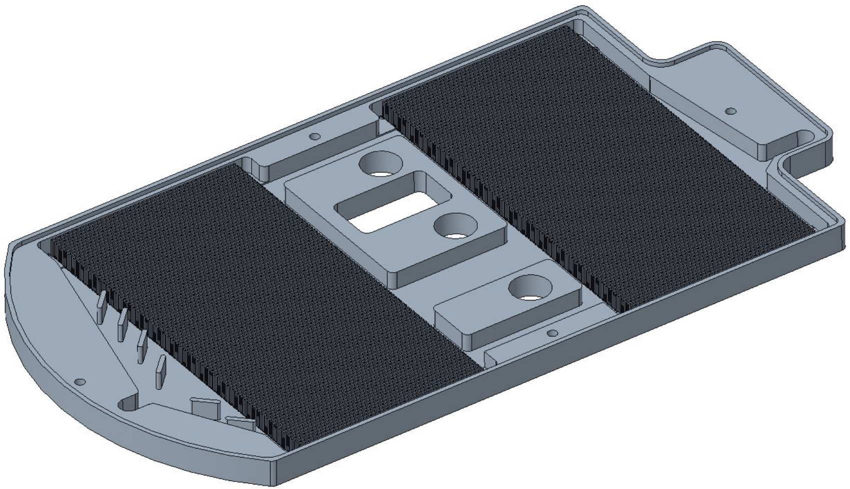
Failure During Testing

- Battery damaged during thermal profile test
  - One of the 24 cells in the battery failed
  - Balanced charger rejected battery
  - Failure caused by operating battery at too low of charge, resulting in stress on one side of the battery



Design

- Total heat generated determines volume of coolant needed
  - Coolant is water
  - Actual volume exceeds requirement
- Fins added to cooling plates in regions of contact with batteries
  - Heat generation rate determined fin density
  - Need to maintain balance between coolant volume and surface area
  - Fin location and orientation determined by manufacturing constraints
- Solution designed in consultation with Novark Technologies



Fin Design

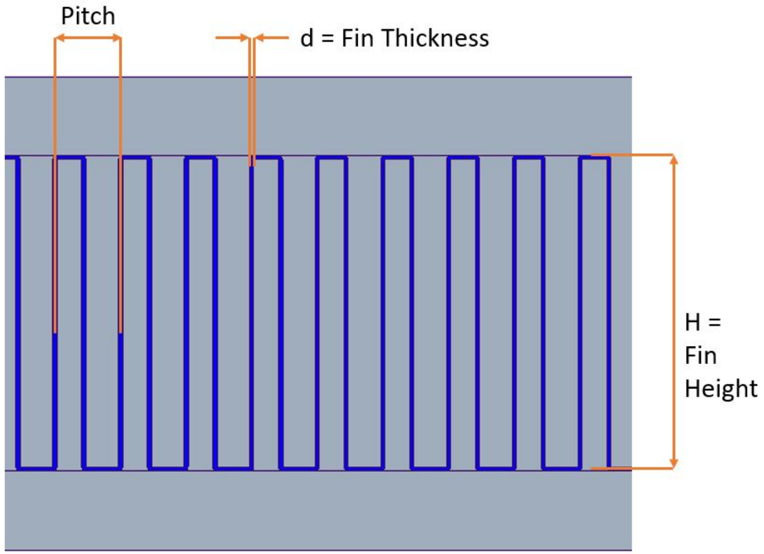
$$A_{\text{needed}} = \frac{\dot{Q}}{U \Delta T}$$

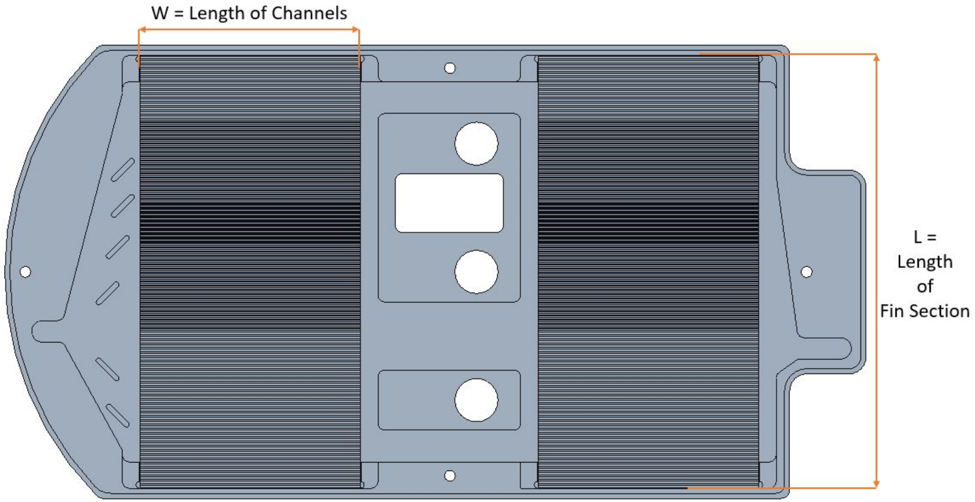
$$A_{\text{fins}} = N_{\text{fins}} \cdot \text{Perimeter} \cdot \text{Width}$$

$\dot{Q}$: Power (W)
U: Heat Transfer Coefficient (W/m^2K)

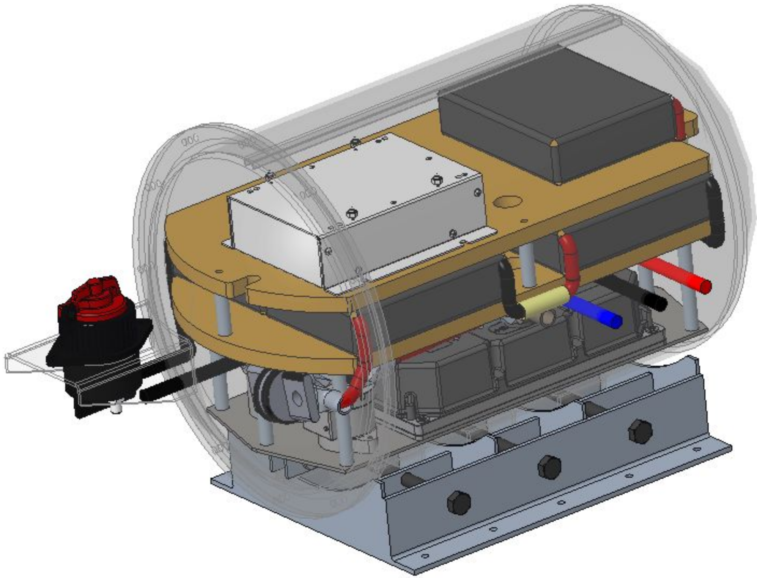
$$A_{\text{needed,region 2}} = 0.6\, m^2 \quad A_{\text{needed,region 1}} = 0.3\, m^2$$

$$A_{\text{fins,region 2}} = 0.68\, m^2 \quad A_{\text{fins,region 1}} = 0.68\, m^2$$

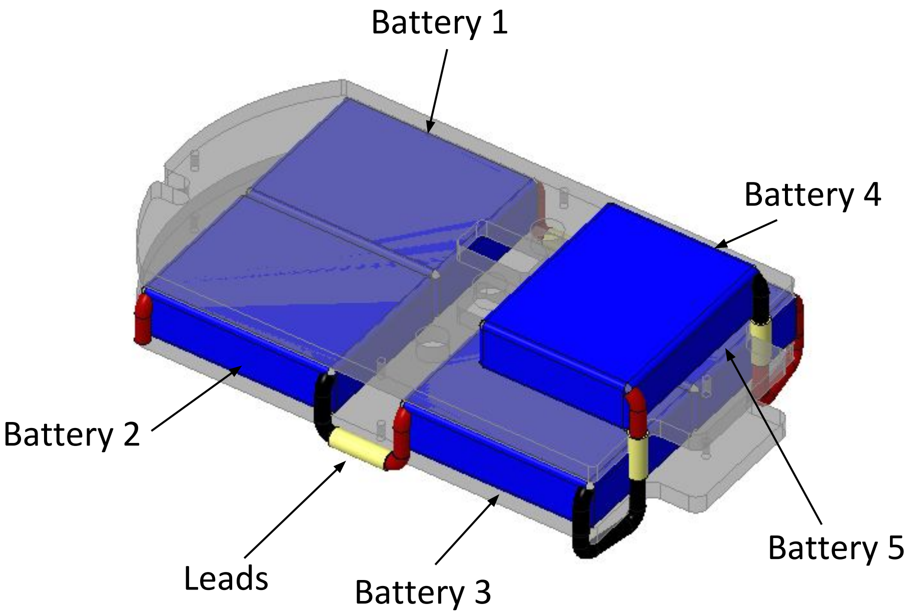


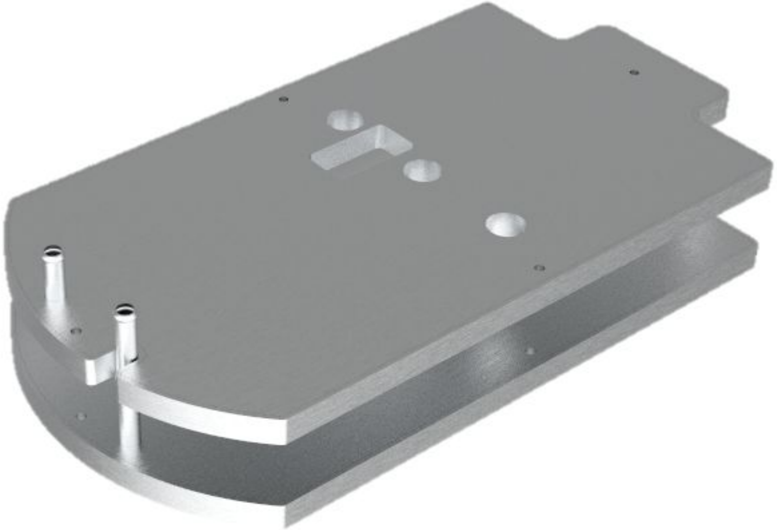


Battery Box



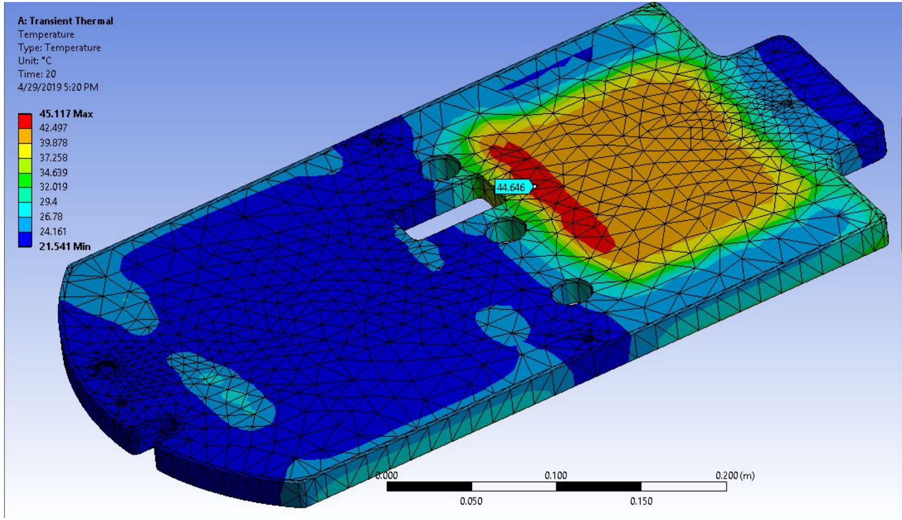
Final Plate Design

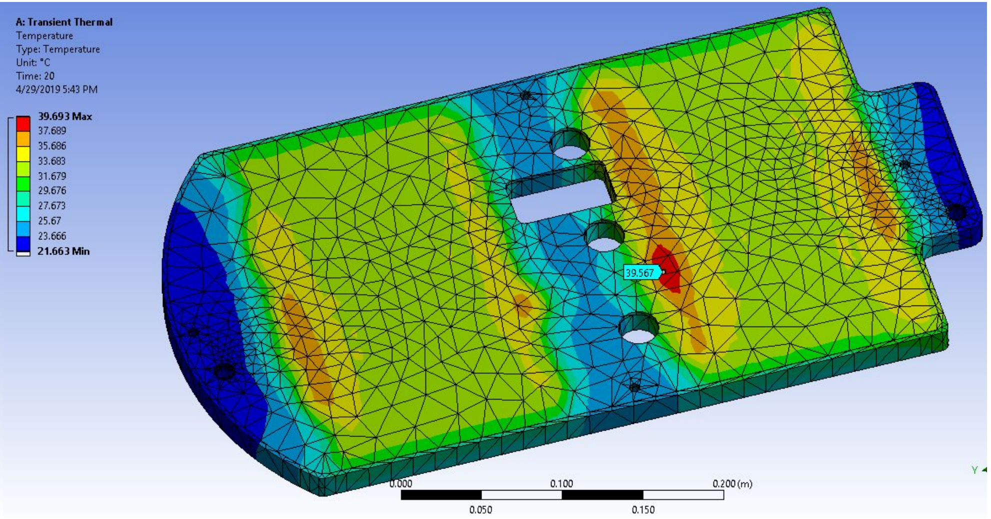




Thermal Finite Element Analysis

- Transient Analysis
- Runtime simulates competition conditions
- Highest temperatures at end of 20 second run

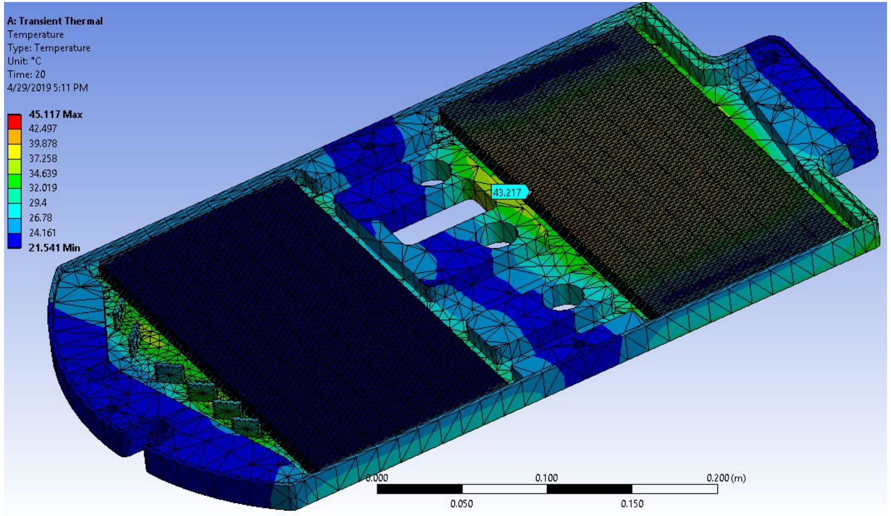




Thermal Finite Element Analysis

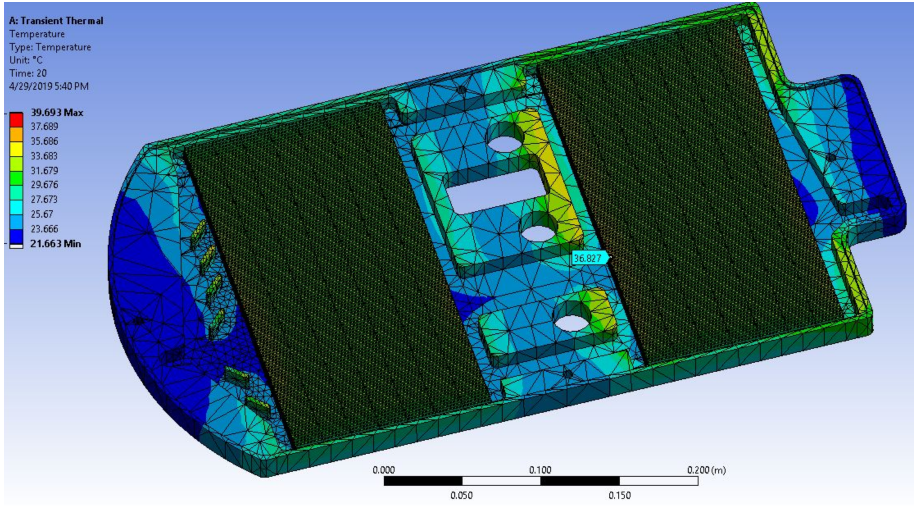
Top Plate

- 234933 linear elements
- Convective heat transfer coeff.: $750 W/m^2K$
- Constant flux condition on surfaces:
  - $72\ kW/m^2$(top)
  - $145\ kW/m^2$ (bottom)

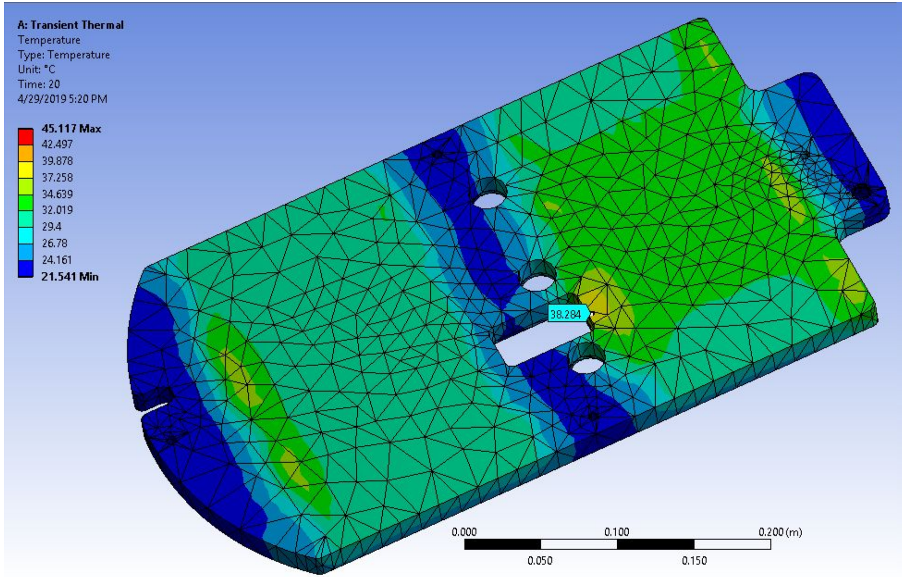


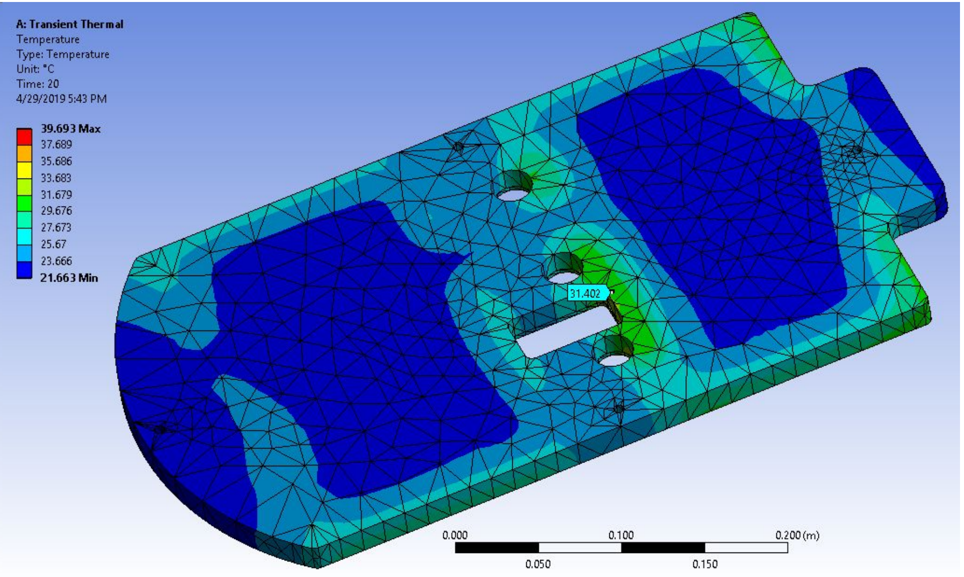
Middle Plate

- 236423 linear elements
- Convective heat transfer coeff.: $500 W/m^2K$
- Constant flux condition surfaces:
  - $72\ kW/m^2$ (top)



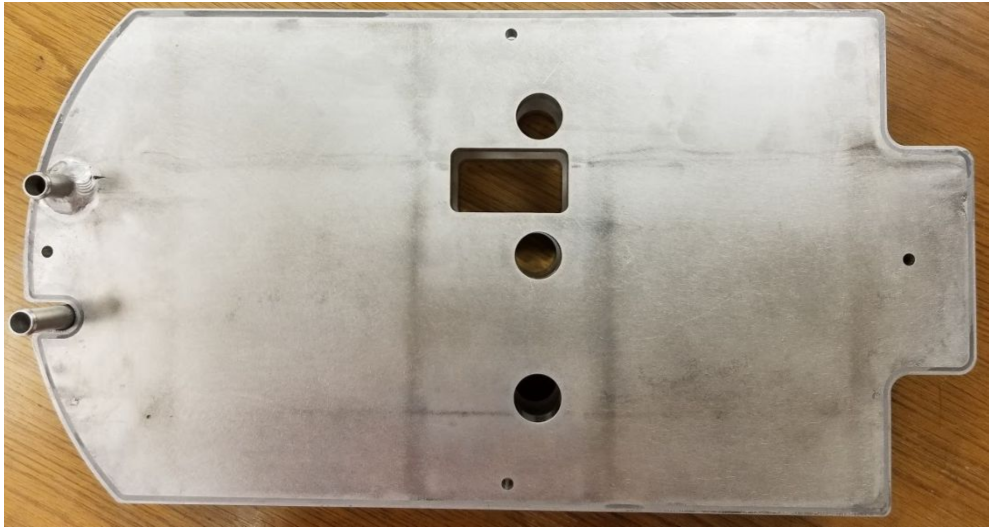
Thermal Finite Element Analysis





Fabrication and Shipping

- Manufacturing handled by Novark Technologies in Shenzhen, China
- Shipped on April 26, 2019
- Arrived on April 29, 2019



Budget

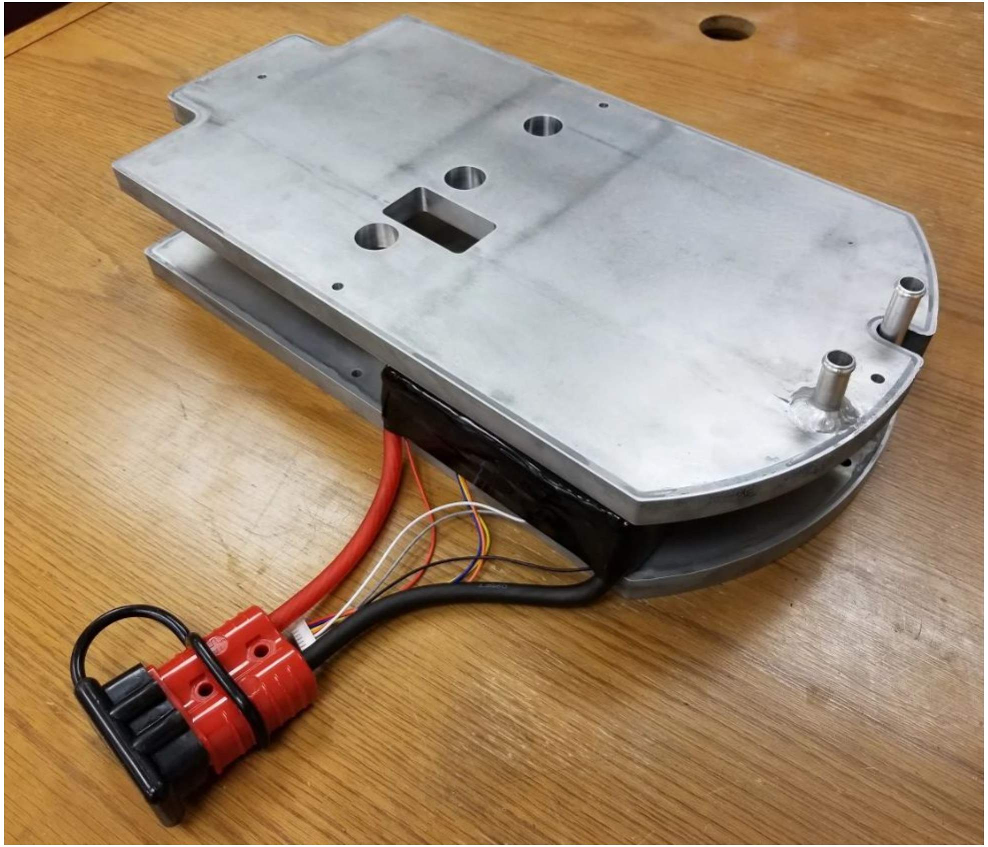
Item	Unit Price $/Unit	Quantity Unit	Total $
Cost to Team			
LiPo 22,000 6S 22.2 V Battery	540	1	540
Battery Connectors	7.5	4	30
Resistor Connectors	6	2	12
4 AWG Wire	35	1	35
Thermal Compound	10	1	10
Fuse	11	1	11
Customs Cost	175	1	175
Brazed Plate Shipment	365	1	365
Acyllic Sheets	20	2	40
Total Cost to Team			**$1,218**
Cost Covered by Novark			
Brazed Plate Production	1000	2	2000

- Major Costs
  - Battery Pack
  - Brazed plates manufactured by Novark Technologies
    - Direct cost was shipping
- Testing equipment loaned
  - Thermal imaging camera
  - Thermocouples
  - Resistor
- Battery box construction not a part of the budget
- Total cost incurred to the team is under budget

Summary & Recommendations

Summary
- Prototype design informed by battery testing and FEA
- Cooling solution delivered
- Project finished within budget and time constraints

Recommendations
- Add dry ice in battery box
- Future iterations should include a third cooling plate



Acknowledgements

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- Dr. Johnson, Mr. Chung, Prof. Smith, Mr. Mischo, Mr. Colravy, Prof. Pearlstein, Prof. Jacobi, and MechSE Business Office and staff

Appendix A - Fin Design

$$\dot{Q} = U * SA_{needed} * \Delta T$$

$$SA_{needed} = \frac{\dot{Q}}{U * \Delta T}$$

$$\dot{Q} = \frac{\dot{Q}_{batt}}{N_{batt}}$$

$$\dot{Q}_{batt} = \frac{Q}{t}$$

$$SA_{fins} = N_{fins} * Perimeter * W$$

$$N_{fins} = L/Pitch$$

$$Perimeter = 4 * (H - d) + 2 * (Pitch - 2 * d)$$

$$where:$$

$$Q = total\ heat\ generation\ (\mathrm{J})$$

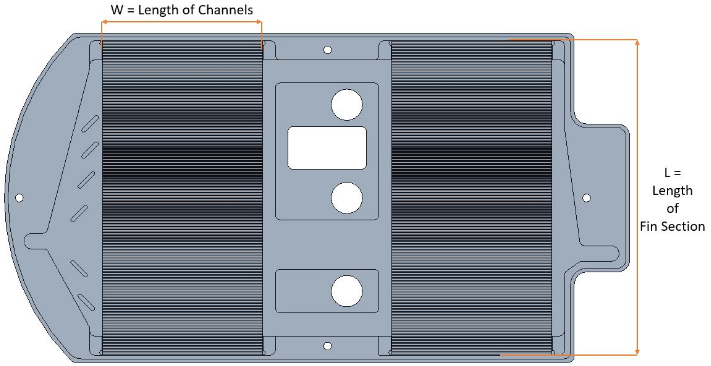
$$t = time\ of\ run\ (\mathrm{s})$$

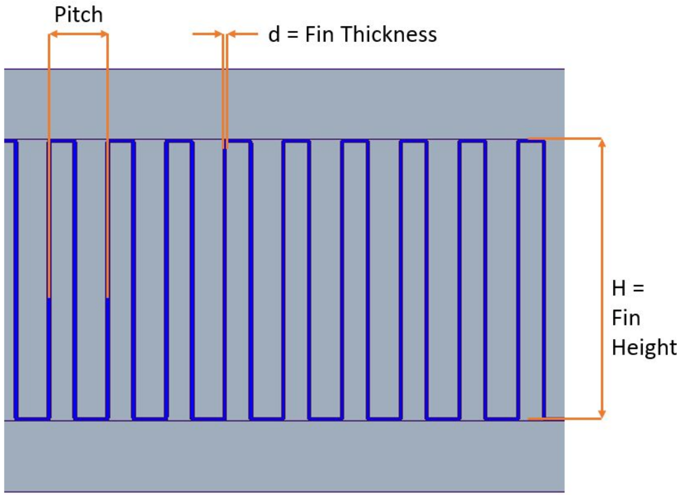
$$L = length\ of\ fin\ section\ (\mathrm{m})$$

$$H = heigth\ of\ fins\ (\mathrm{m})$$

$$W = length\ of\ channels\ (\mathrm{m})$$

$$d = thickness\ of\ fins\ (\mathrm{m})$$





Appendix B

- Heat Equation: $Q=mc\Delta T$
- Assumptions:
  - Batteries are perfectly insulated
  - Batteries can be assumed as one combined lumped capacitor
- Mass of batteries=12.65 kg, Battery Heat Generation Q=302 kJ, estimated Specific Heat of batteries c=1 kJ/kg-K
- ΔT=21.7°C increase in temperature
- Battery Heat Generation: 302 kJ, Mass of PCM = 3 kg, Latent Heat Capacity of PCM = 200 kJ/kg
- Heat Absorbed by PCM = 600 kJ, 2x heat produced can be absorbed
- Specific Heat of Water: 4.196 kJ/kg-K
- Desirable Temperature change: ΔT = 40°C
- Mass of water required: 1.64 kg

Appendix B - Continued

$$Q = mC_p\Delta T$$

$$T_{steady} = \frac{m_{batt}C_{p,batt}T_{0,batt+}m_{plate}C_{p,plate}T_{0,plate+}m_{water}C_{p,water}T_{0,water}}{m_{batt}C_{p,batt} + m_{plate}C_{p,plate} + m_{water}C_{p,water}}$$

$$T_{steady} = 20.5°C$$

$$\Delta T_{run} = \frac{Q_{gen}}{m_{batt}C_{p,batt}}$$

$$\Delta T_{run} = 26.4°C$$

$$T_{final} = T_{steady} + \Delta T_{run} = 46.9°C$$

$$m_{batt} = 2.27 \text{ kg}$$

$$m_{plate} = 6.55 \text{ kg}$$

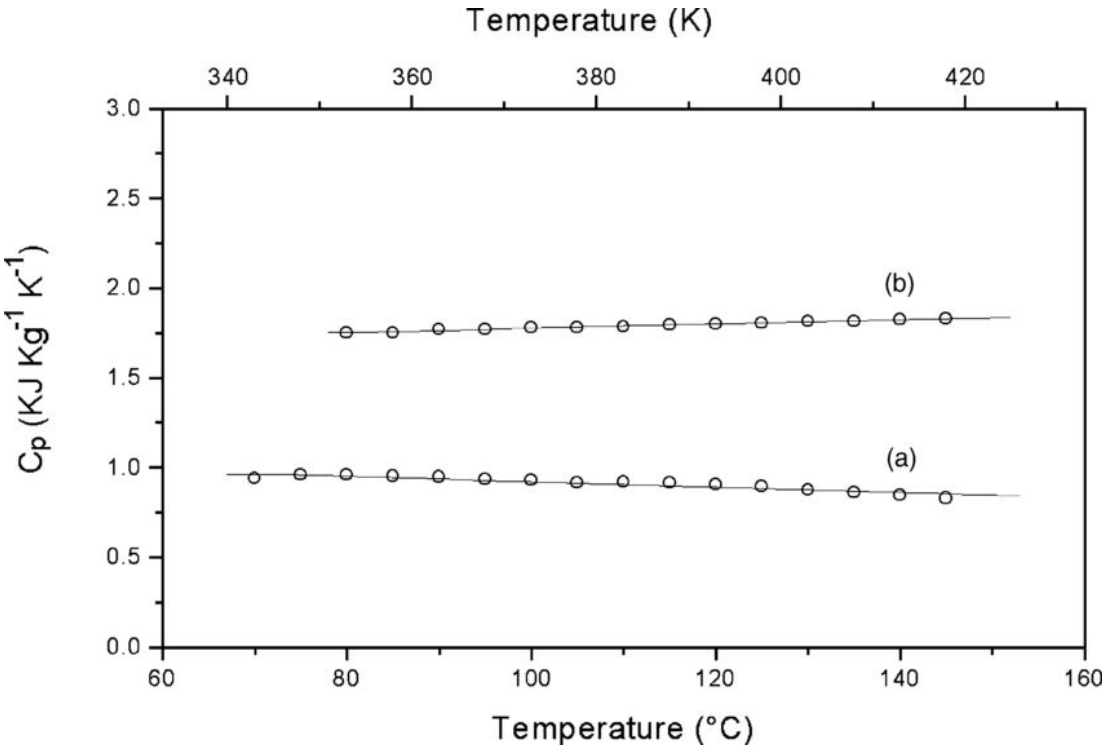
$$m_{water} = 1.90 \text{ kg}$$

$$C_{p,batt} = 1\frac{\text{kJ}}{\text{kgK}}$$

$$C_{p,plate} = 0.9\frac{\text{kJ}}{\text{kgK}}$$

$$C_{p,water} = 4.184\frac{\text{kJ}}{\text{kgK}}$$

Appendix B - Continued

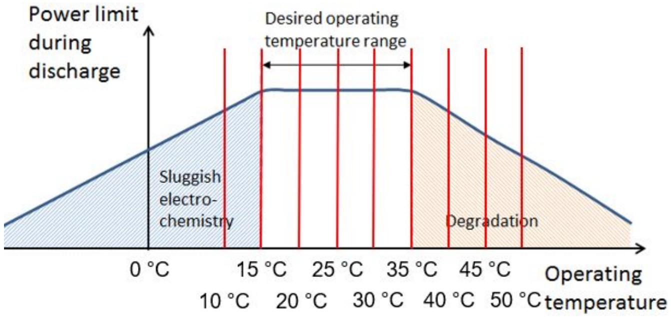


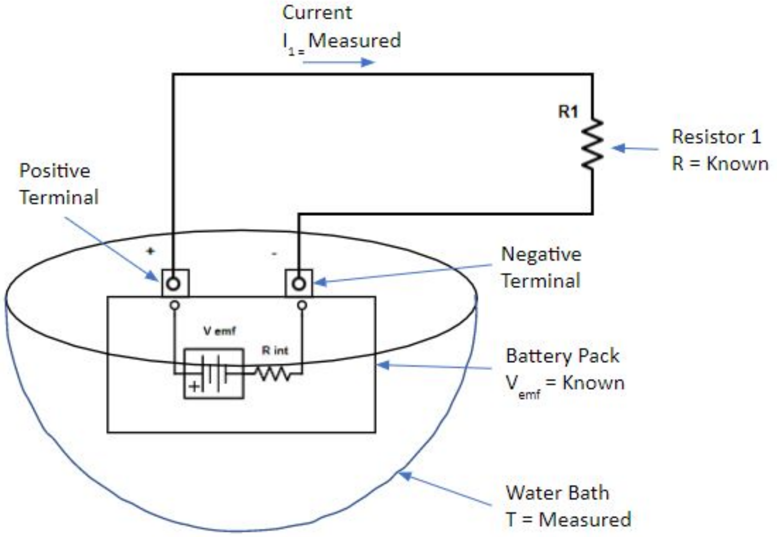
- The bottom curve in the plot shows how the heat capacity of a lithium polymer battery changes with temperature
- In our range of temperatures the specific heat is approximately 1.0 kJ/kg-K

Villano, Paola. "Specific Heat Capacity of Lithium Polymer Battery Components." Thermochimica Acta, Elsevier, 11 Jan. 2003, www.sciencedirect.com/science/article/pii/S0040603102006123.

Appendix C - Water Bath

1. Place battery in a temperature controlled water bath
2. Run bath at different temperatures at 5°C increments from 10-50 °C
3. Take voltage across battery with no load, V_{emf}
4. Complete circuit
5. Record current, I_1
6. Record voltage, $V_{Battery}$
7. Calculate internal resistance, R_{int}





Appendix C - Water Bath

- Current I_1 and $V_{Battery}$ are monitored, V_{emf} is known
- Given equation is used to calculate R_{int} at different temperatures
- Empirical curve of internal resistance vs. surface temperature of battery generated
- Function $R_{int}(T)$ allows accurate heat generation computation
- Integration of power curve gives total heat produced in system

$$V_{Battery} = V_{emf} - I_1 R_{int}$$

$$R_{int} = \frac{V_{emf} - V_{Battery}}{I_1}$$