Approved, DCN# 43-10373-22

Development of a Coupled Electro-thermo Battery Emulator for Ground Test Platforms

Jarrett Peskar[1], Austin R.J. Downey[1], Jamil Khan[1], Kristen Booth[2]

[1]Department of Mechanical Engineering
[2]Department of Electrical Engineering

UNIVERSITY OF
South Carolina

Distribution A: Approved for public release, distribution unlimited.

Thermal Runaway

- Thermal runaway is a self feeding process that can lead to combustion of the batteries.
- Better cooling methods and testing at the extremes will help mitigate this risk.
- A battery emulator is proposed to be a helpful tool for developing better cooling methods at the extremes of battery use.

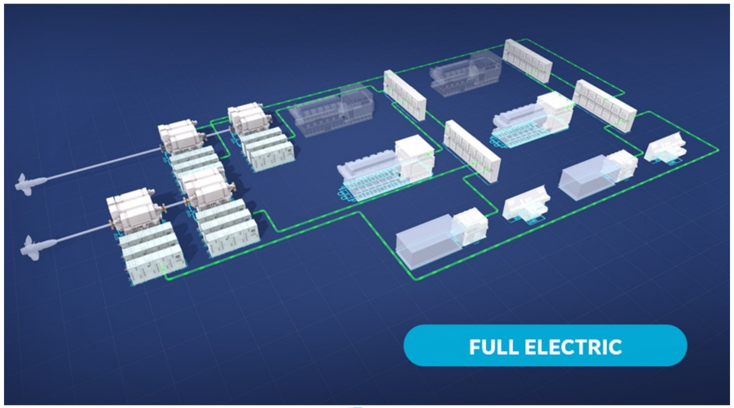
Tesla car in Oslo 2016 [1]

Tesla Megapack in Australia 2021 [2]

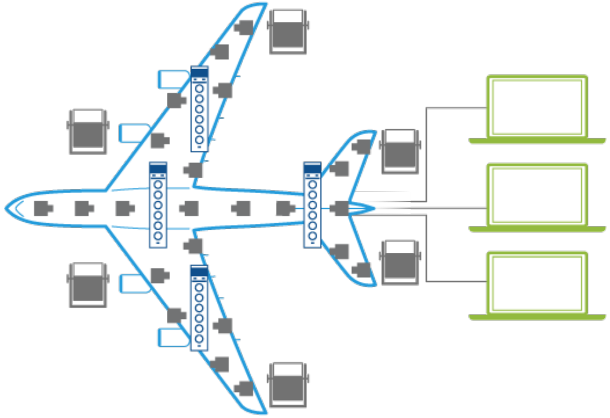
[1] Mauger, Alain & Julien, Christian. (2017). Critical review on lithium-ion batteries: are they safe? Sustainable?. Ionics. 23. 10.1007/s11581-017-2177-8.
[2] Ben. “Why Thermal Runaway Is the Real Killer in Battery Fires.” *Zenaji*, 31 Jan. 2022, https://zenaji.com/why-thermal-runaway-is-the-real-killer-in-battery-fires/.

Emulator Applications

- Will be able to work on any system that a physical battery can attach too.
- Being developed to work with digital twin test bed for naval propulsion at University of South Carolina.
- Looking to be used in ground testing/ digital twins of electric aircrafts.



[3]



[4]

[3]"Solutions - Naval Electric Power & Propulsion." *GE Power Conversion*, https://www.gepowerconversion.com/product-solutions/Naval-Electric-Power-Propulsion.

[4] "Knowledge." *Ground Vibration Testing - Vibration Simulation | Brüel & Kjær*, https://www.bksv.com/en/knowledge/applications/structural-dynamics/ground-vibration-test.

Distribution A: Approved for public release, distribution unlimited.

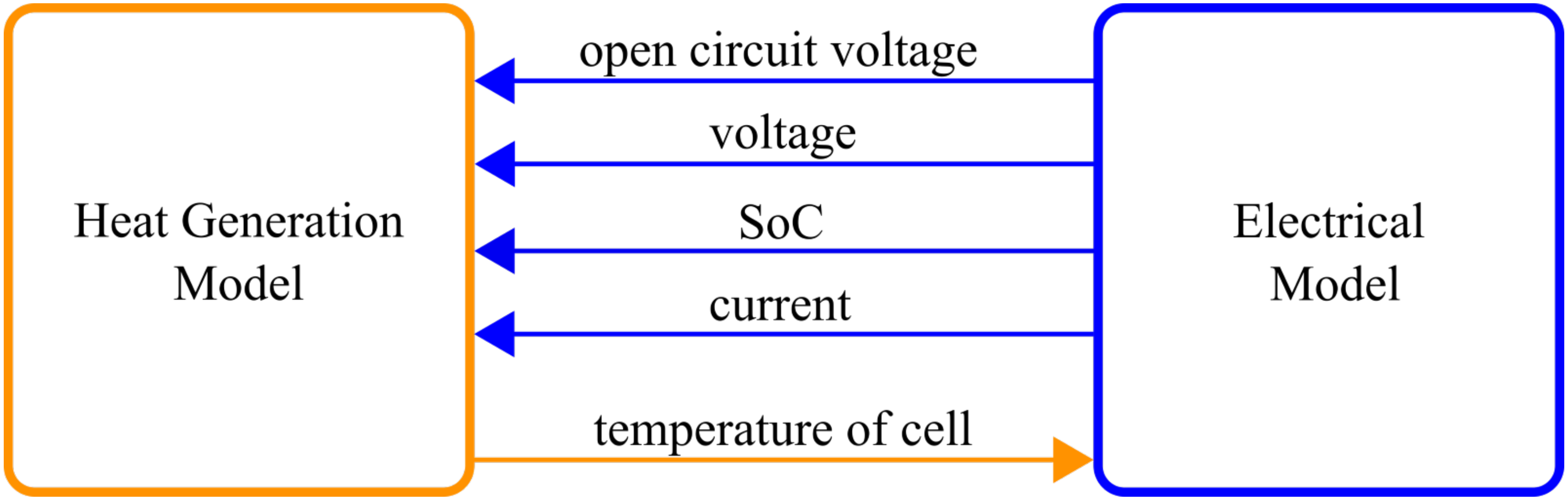
Battery Emulator

- Goal:
  - Enable safe exploration of distributed energy resources under extreme (equipment threatening) conditions
  - Emulate characteristics of large battery at all system connections -- electrical terminals and fluid ports -- based on actual behavior of a single cell of the type used in the battery
  - Investigate thermal and electrical coupling effects at system level
- Real-time Operations:
  - The single cell experiences V, I, and thermal stresses scaled-down from the system interface. The system experiences V, I and thermal stresses scaled up from the single cell response.
  - Real-time interface between cell and system includes a fully-sensorized and actuated digital twin of the battery, based on Simulink models, that runs on NI edge computing device.

UofSC South Carolina

Battery Model

- A coupled electro-thermal model
- Parameters are dependent on each other



Coupled Electrical Model

- Equivalent electrical circuit:
    - Simple equivalent circuit used initially
    - Later can add more dynamics by replacing ESR with RC circuit

- Governing equation:
    - $V_{\text{out}}(t) = OCV(SoC, T) - i(t_0)R_{\text{ESR}}(SoC, T)$
    - Open Circuit Voltage (OCV) and Equivalent Series Resistance (ESR) values are organized into lookup tables

South Carolina

Coupled Thermal Model

- An isothermal reduced order heat generation model.

Original Eq [5]:

$$\dot{Q} = I\left(U_{\text{avg}} - V\right) - IT\frac{\partial U_{\text{avg}}}{\partial T} + \sum_{l} \Delta H_{l}^{\text{avg}} r_{l} + \int \sum_{j} \sum_{i} \left(\overline{H_{ji}} - \overline{H_{ij}^{\text{avg}}}\right)\left(\frac{\partial c_{ij}}{\partial t}\right) dv$$

Implemented Eq (added natural convection and liquid cooling):

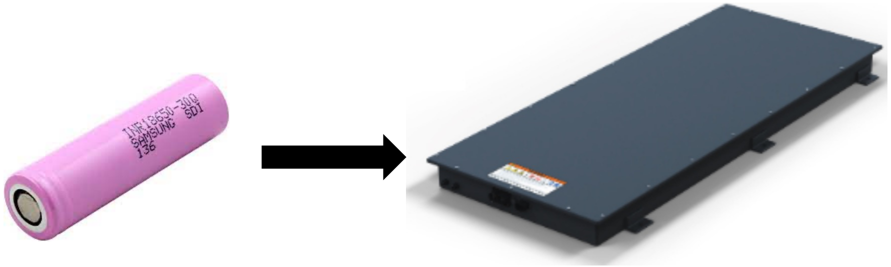
$$\dot{Q} = I\left(U_{\text{avg}} - V\right) - IT\frac{\partial U_{\text{avg}}}{\partial T} - Ah\left(T_{\text{cell}} - T_{\text{amb}}\right) + \dot{m}_{\text{liquid}} c_{\text{liquid}}\left(T_{\text{in, liquid}} - T_{\text{out, liquid}}\right)$$

- Equation Assumes uniform current density, uniform heat generation and no mass transport limitations
- Works well with low charge/discharge rates
  - At low rates side reactions and mixing is negligible

[5] Y. Zeng, D. Chalise, S. D. Lubner, S. Kaur and R. S. Prasher, "A review of thermal physics and management inside lithium-ion batteries for high energy density and fast charging," *Energy Storage Materials,* vol. 41, pp. 264-288, 2021

UofSC South Carolina

Scalability



- Can scale up single cell to represent the larger battery packs such as a Lithos battery pack:
  - 350V 36Ah, up to 10C discharge (360 Amps)

- Battery model is electrically and thermally scalable
  - Electrically:
    - OCV obtained by multiplied by number of cells in series
    - Capacity/current obtained by multiplying by number of cells in parallel
    - Terminal resistance by equivalent resistance of the parallel and series arrangement
  - Thermally:
    - Thermal mass of all cells and case sum together
    - Convective surface area scaled to surface area of the fluid interface

- Assumptions:
  - Uniform heat, SOC, and current in all cells of the battery

Distribution A: Approved for public release, distribution unlimited.

Data Gathered

- Data from a Samsung 30Q 18650
- Experiments used to find electrical parameters.
- Heat transfer coefficient and heat capacity of battery values taken from literature.
- dU/dT parameter found by fitting a 2^{nd} order polynomial to the OCVs with respect to the temperature range at each SOC step.
- Currently do not have a liquid cooled battery to take parameters from.

	Parameters need
Electrical	nominal voltage
	capacity (T)
	open circuit voltage (SoC, T)
	terminal resistance (SoC, T)
Thermal	open circuit voltage (SoC, T)
	dU/dT (SoC, T)
	surface area
	convective heat transfer coefficient [6]
	mass
	specific heat capacity [7]
Liquid cooling (Not found yet)	pipe wall thickness
	pipe length
	pipe thermal conductivity
	pipe cooling contact area
	pipe hydraulic diameter
	pipe cross-sectional area
	mass flow rate of liquid
	density of liquid

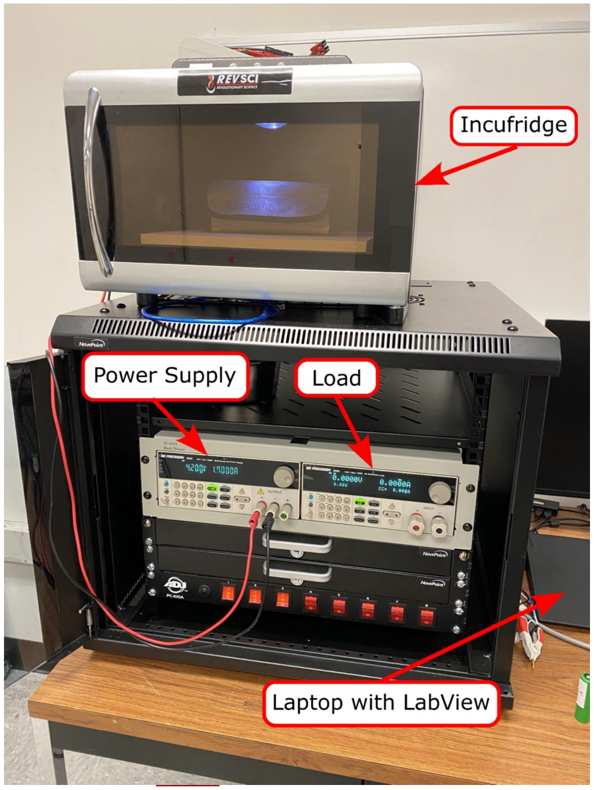
[6] X. Zhang *et al.*, "Evaluation of convective heat transfer coefficient and specific heat capacity of a lithium-ion battery using infrared camera and lumped capacitance method," *Journal of Power Sources*, vol. 412, pp. 552–558, Feb. 2019, doi: 10.1016/j.jpowsour.2018.11.064.

[7] J. C. Chin, S. L. Schnulo, T. B. Miller, K. Prokopius and J. Gray, "Battery performance modeling on maxwell x-57," *AIAA Scitech 2019 Forum,* 2019.

Distribution A: Approved for public release, distribution unlimited.

Battery Tester

- Built in house to perform Pulsed Power Characterization (PPC) testing
  - Composed of a load, power supply, incufridge, thermocouples, and a laptop with LabVIEW.



Pulse Power Characterization

- Get parameters from pulse response of battery. Equations and profile from [7]

Equations:

$$R_0 = \left(\frac{u_0 - u_1}{i}\right)$$

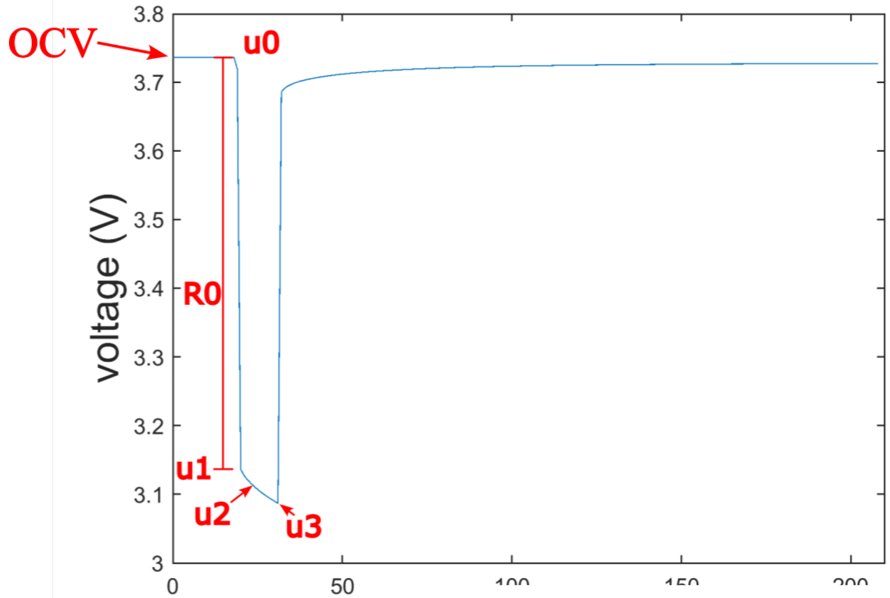
For 2-time constant dynamics:

$$R_1 = \left(\frac{u_1 - u_2}{i}\right)$$

$$R_2 = \left(\frac{u_3 - u_2}{i}\right)$$

$$t_1 = R_1 C_1$$

$$t_2 = R_2 C_2$$



[7] S. Thanagasundram, R. Arunachala, K. Löffler, T. Teutsch and A. Jossen, "A cell level model for battery simulation," in *European Electric Vehicle Confrence*, 2012.

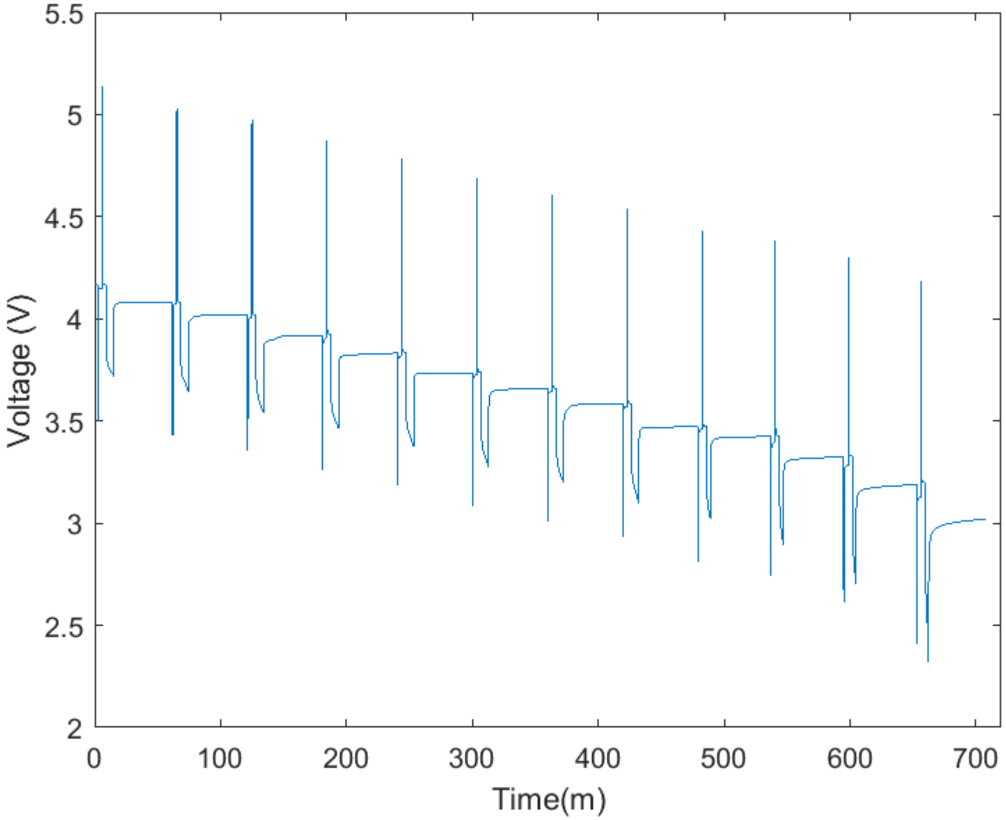
Distribution A: Approved for public release, distribution unlimited.

Approved, DCN# 43-10373-22

Pulse Power Characterization

- Profile: 2C discharge pulse (10 sec), 3 min wait, 2C charge pulse (10 sec), 3 min wait, discharge to next SoC step, rest 1 hr.
- Repeat pulse discharge/ charge events at every 10% decrement of SoC from 100% to 20% and at every 5% decrement from 20%-0%
- Temperature range: 13,20,30,40, and 48 °C

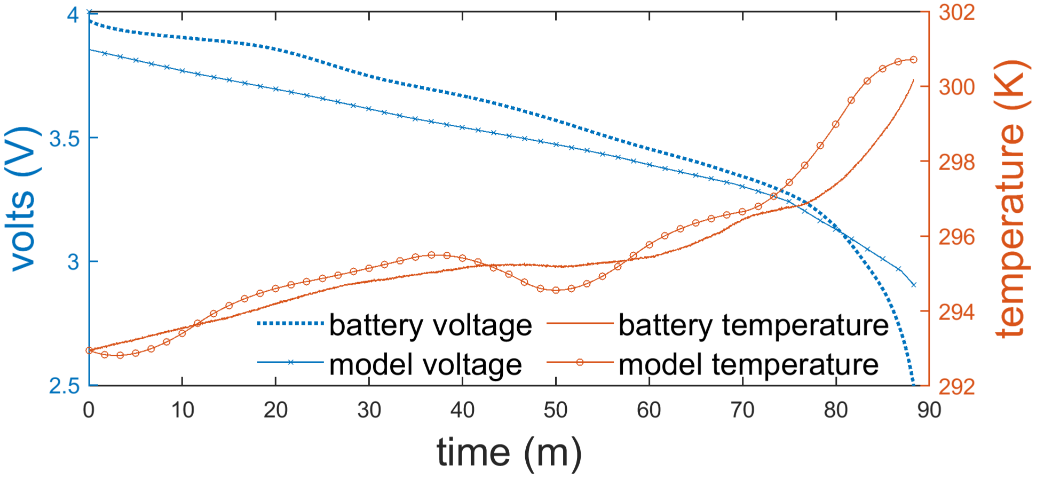
A PPC test run at 20ºC



Distribution A: Approved for public release, distribution unlimited.

Model Result (Air convection only)

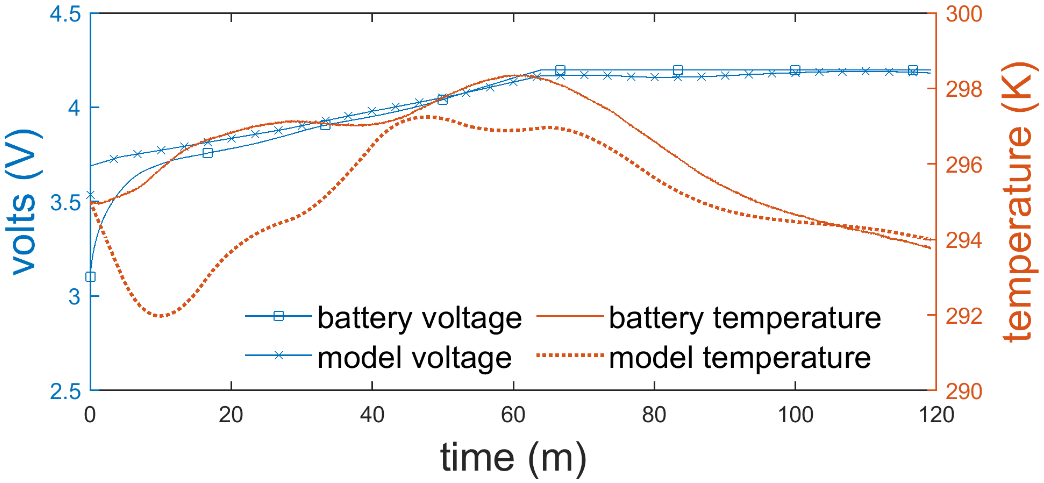
- 0.5C discharge to 2.5V cutoff
- Modeled voltage with 2.93% average absolute error.
- Modeled temperature with 0.10% average absolute error.



*Note, these tests recorded only the battery surface temperature. Core temperature can be up to 10ºC hotter than the surface.

Model Result (Air convection only)

- 4.2V 0.5C CC-CV charge to 150mA cutoff
- Modeled voltage with 1.10% average absolute error.
- Modeled temperature with 0.43% average absolute error.



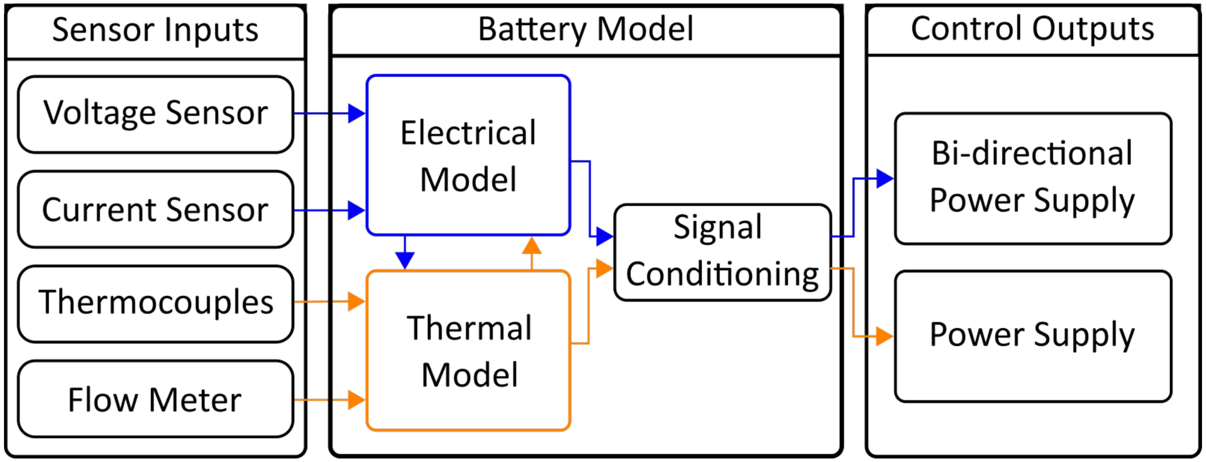
*Note, these tests recorded only the battery surface temperature.
Core temperature can be up to 10ºC hotter than the surface.

UofSC South Carolina

Distribution A: Approved for public release, distribution unlimited.

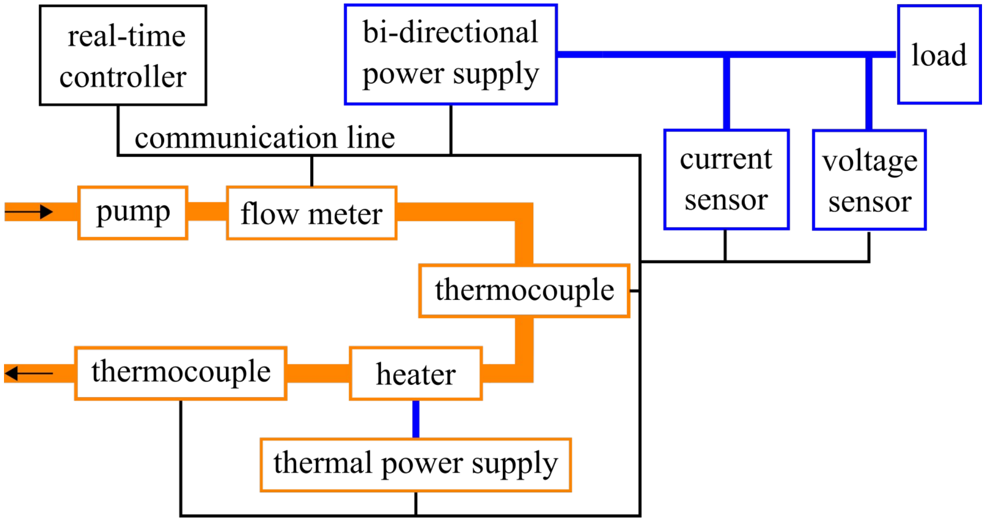
Model Implemented on Hardware

- Real-time controller (cRIO-9054)
  - Receives real-time data from sensors.
  - Outputs real-time control signals to power supplies
- Control Scheme will be uploaded to real-time controller:



Hardware Setup

Diagram of complete setup:



real-time controller

bi-directional power supply

load

communication line

current sensor

voltage sensor

pump

flow meter

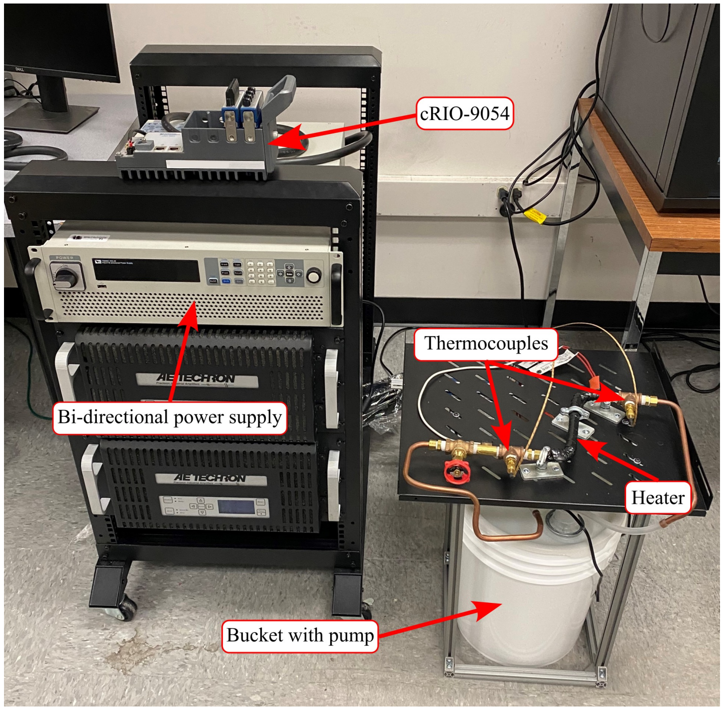
thermocouple

thermocouple

heater

thermal power supply

Physical Setup:



Distribution A: Approved for public release, distribution unlimited.

Discussion

This work was supported by the Office of Naval Research under contract no. N00014-22-C-1003 and no. N00014-20-C-1106. The support of the ONR is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Navy

Jarrett Peskar

jpeskar@email.sc.edu

Department of Mechanical Engineering, UofSC