Battery Emulator for Coupled Electro-Thermo Powertrain Testing

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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.

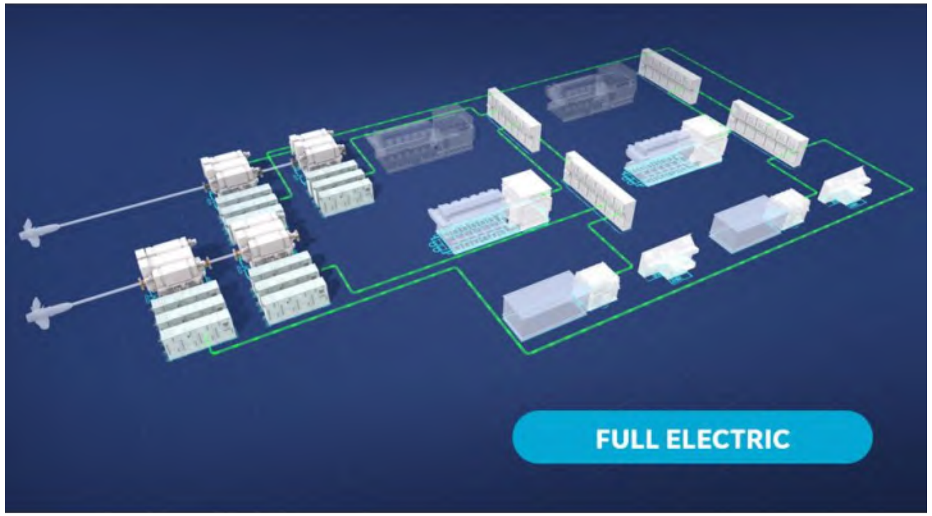
Tesla car in Oslo 2016 [1]

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 ships.



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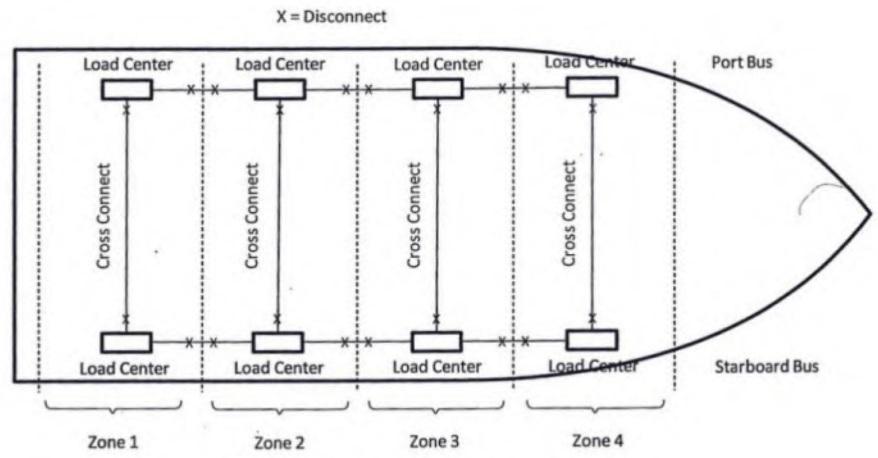
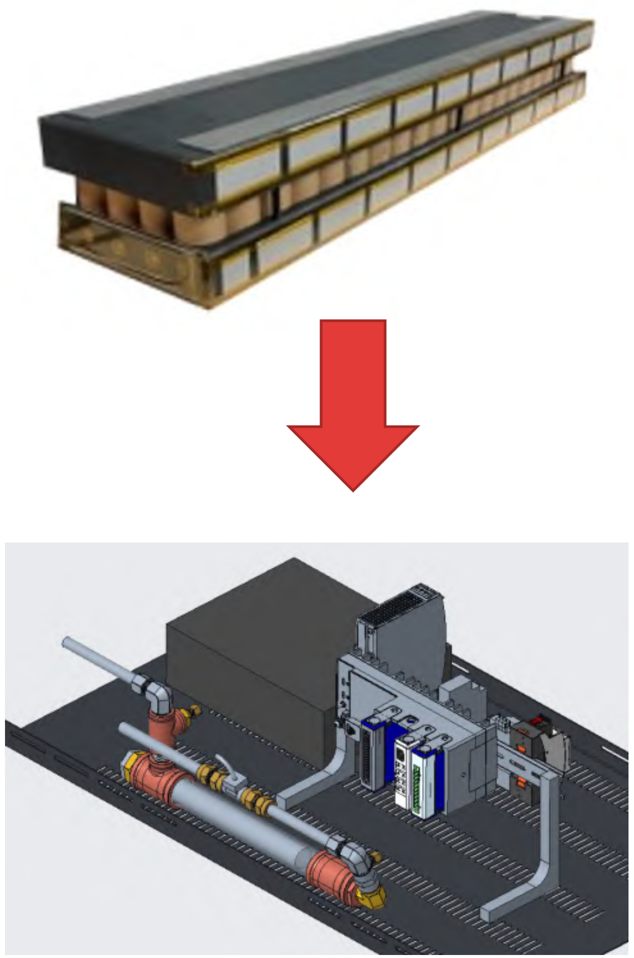


[4]

[3]"Solutions - Naval Electric Power & Propulsion." *GE Power Conversion*, https://www.gepowerconversion.com/product-solutions/Naval-Electric-Power-Propulsion.
[4] Van Hemmen, Rik. "Better Ship Electric Arrangements - Martin, Ottaway, Van Hemmen &Amp; Dolan, Inc." Martin, Ottaway, Van Hemmen & Dolan, Inc., 24 July 2020, martinottaway.com/rhemmen/better-ship-electric-arrangements.

Battery Emulator

- Goal:
  - Enable safe exploration of energy storage under extreme 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
- Real-time Operations:
  - The emulated battery 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



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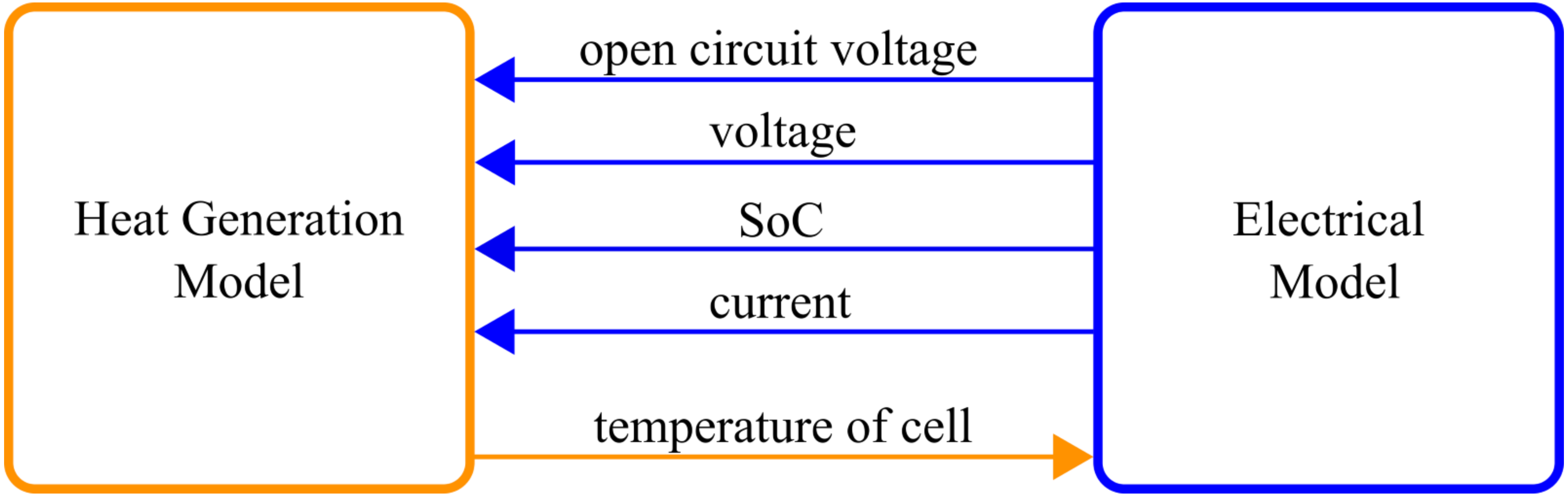
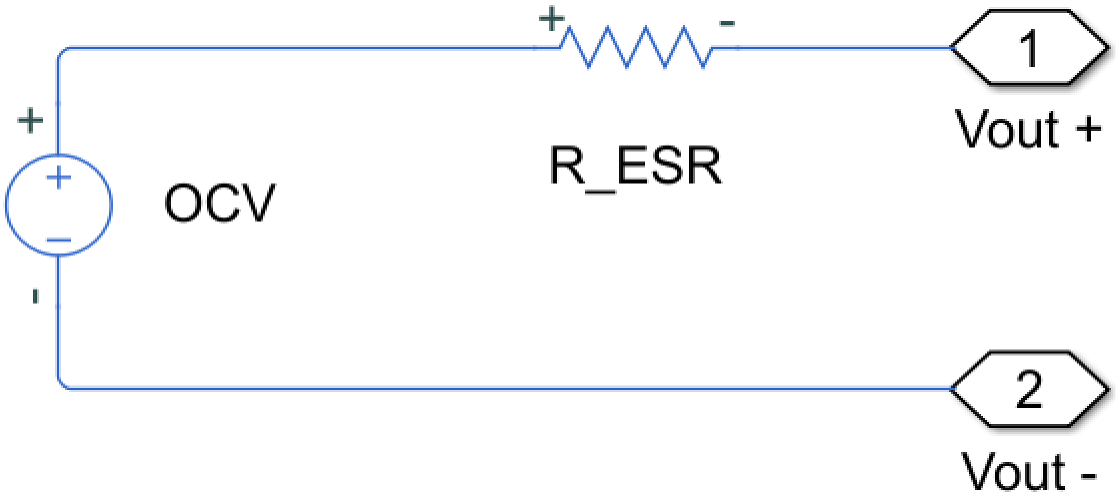
Battery Model

- A coupled electro-thermal model
- Parameters are dependent on each other
- Model uses ode14x solver to extrapolate values



Coupled Electrical Model

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



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

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Coupled Thermal Model

- An isothermal reduced order heat generation model.

Original Eq [1]:

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

Implemented Eq (added natural convection and liquid cooling):

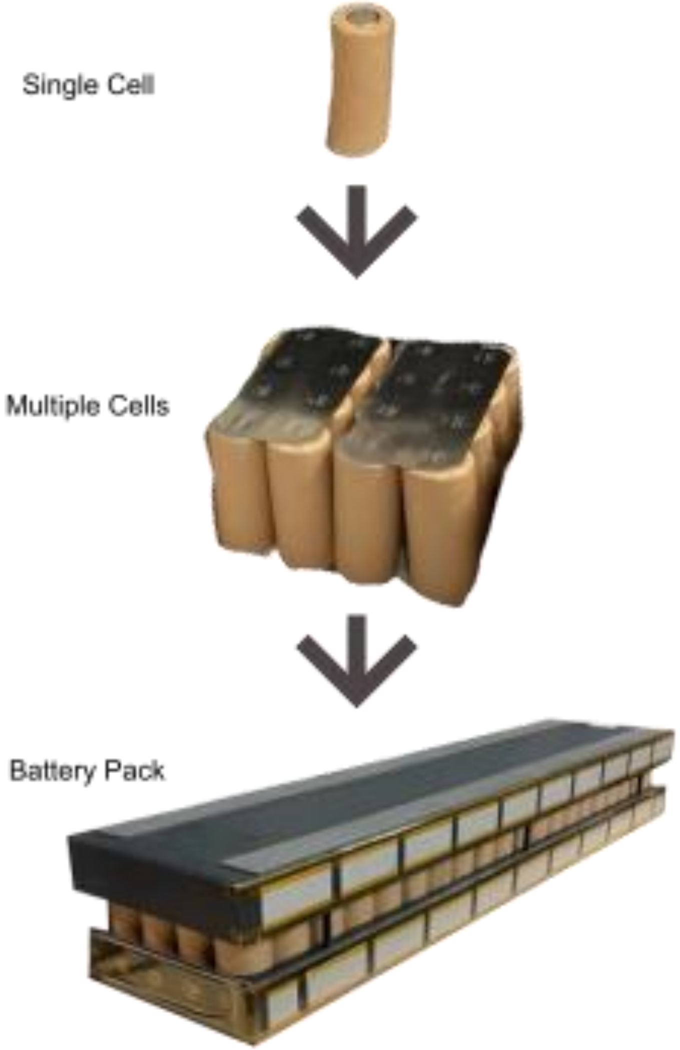
$$\dot{Q} = I\left(U_{\text{avg}} - V\right) - IT\frac{\partial U_{\text{avg}}}{\partial T} - Ah(T_{\text{cell}} - T_{\text{amb}}) + \dot{m}_{\text{liquid}} c_{\text{liquid}}(T_{\text{in, liquid}} - T_{\text{out, liquid}})$$

- 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

[1] 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

Model Scalability

- Can scale up single cell to represent larger battery packs
- 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



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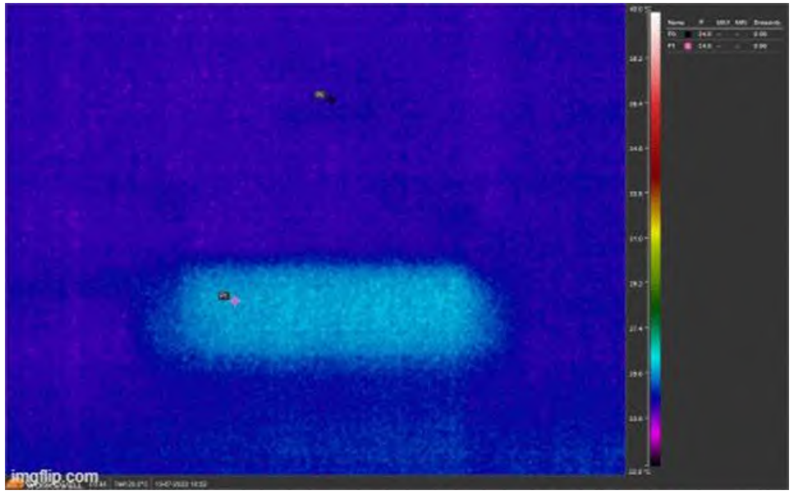
Data Gathered

- Data from a K2 Energy LFP26650P
- 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 2nd order polynomial to the OCVs with respect to the temperature range at each SOC step.

	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 [5]
	mass
	specific heat capacity [6]

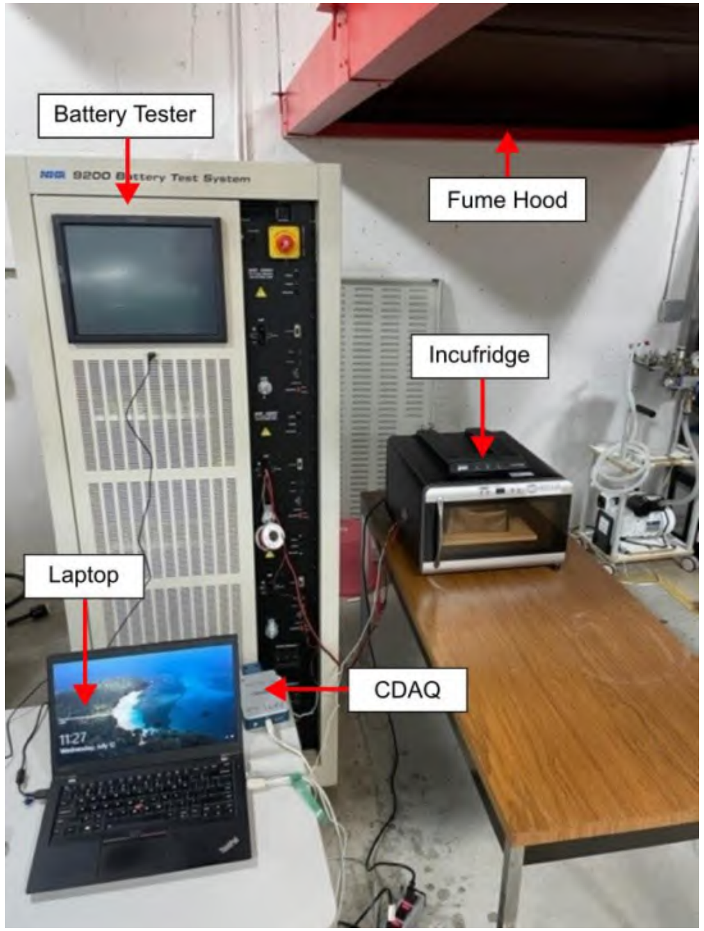


[5] X. Zhang *et al.*, "Evaluation of convective heat transfer coefficient and specific heat capacity of a lithium-ion battery using infrared camera and lumped capacitance method," *Journal of Power Sources*, vol. 412, pp. 552–558, Feb. 2019, doi: 10.1016/j.jpowsour.2018.11.064.

[6] 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.

Battery Tester

- NHR 9200 Battery Tester
  - Machine is controlled using labview on a laptop
- Incufridge
  - Regulates the temperature of the battery.
  - Temperature is tracked by two thermocouples



Pulse Power Characterization

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

Equations:

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

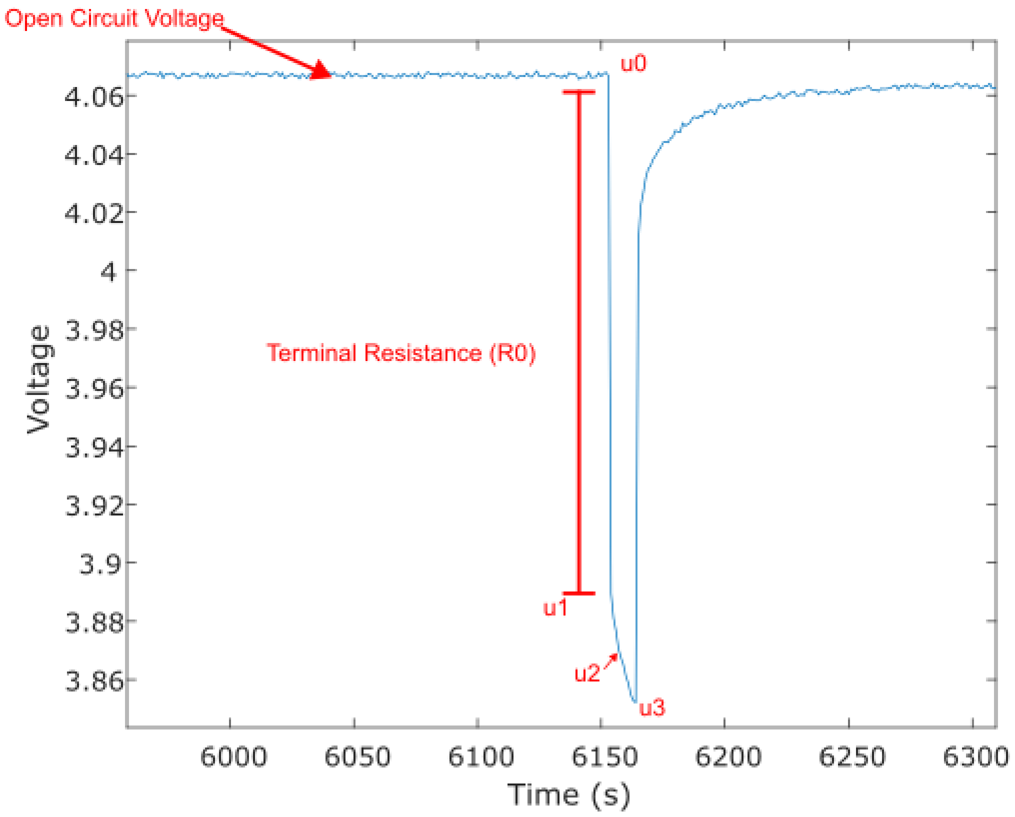
For 2-time constant dynamics:

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

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

$$t_1 = R_1 C_1$$

$$t_2 = R_2 C_2$$



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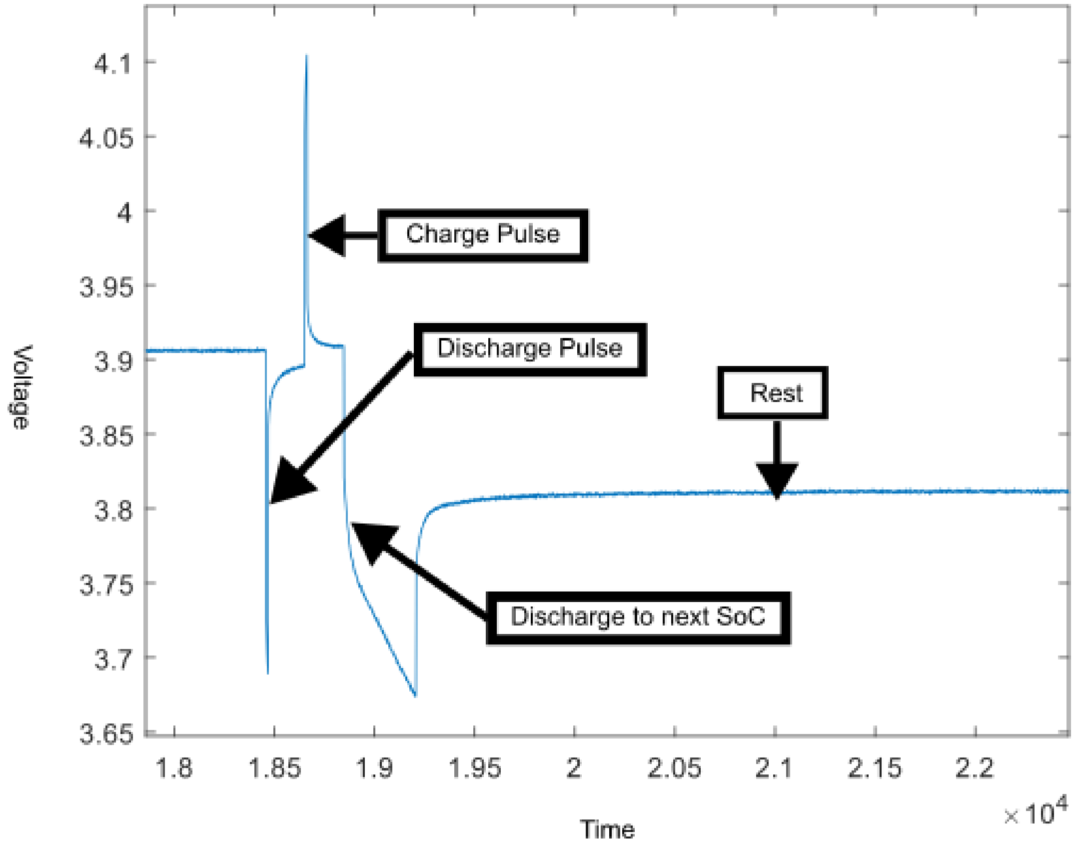
[7] S. Thanagasundram, R. Arunachala, K. Löffler, T. Teutsch and A. Jossen, "A cell level model for battery simulation," in *European Electric Vehicle Confrence*, 2012.

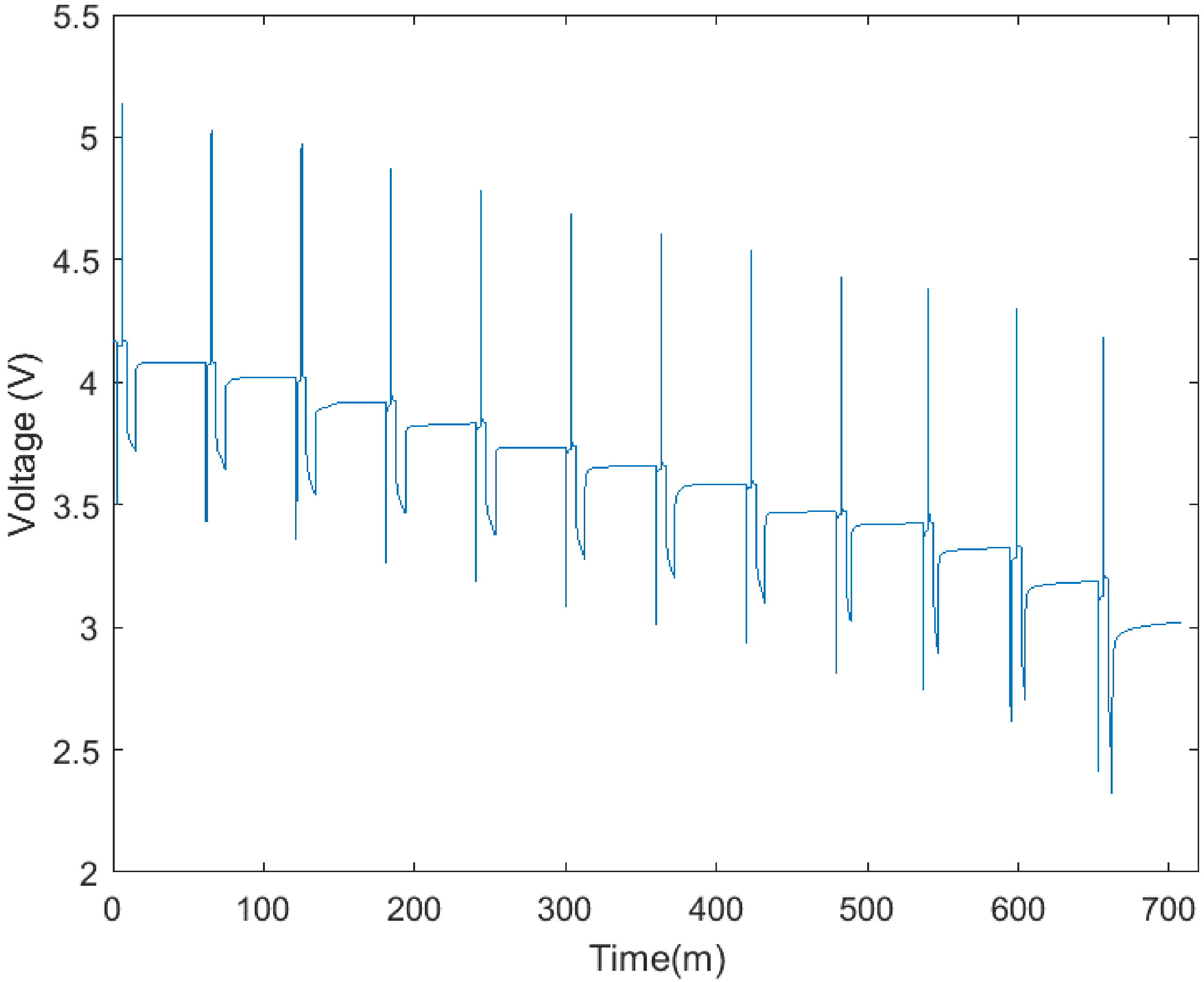
Pulse Power Characterization

- 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.



Pulse Power Characterization

- 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



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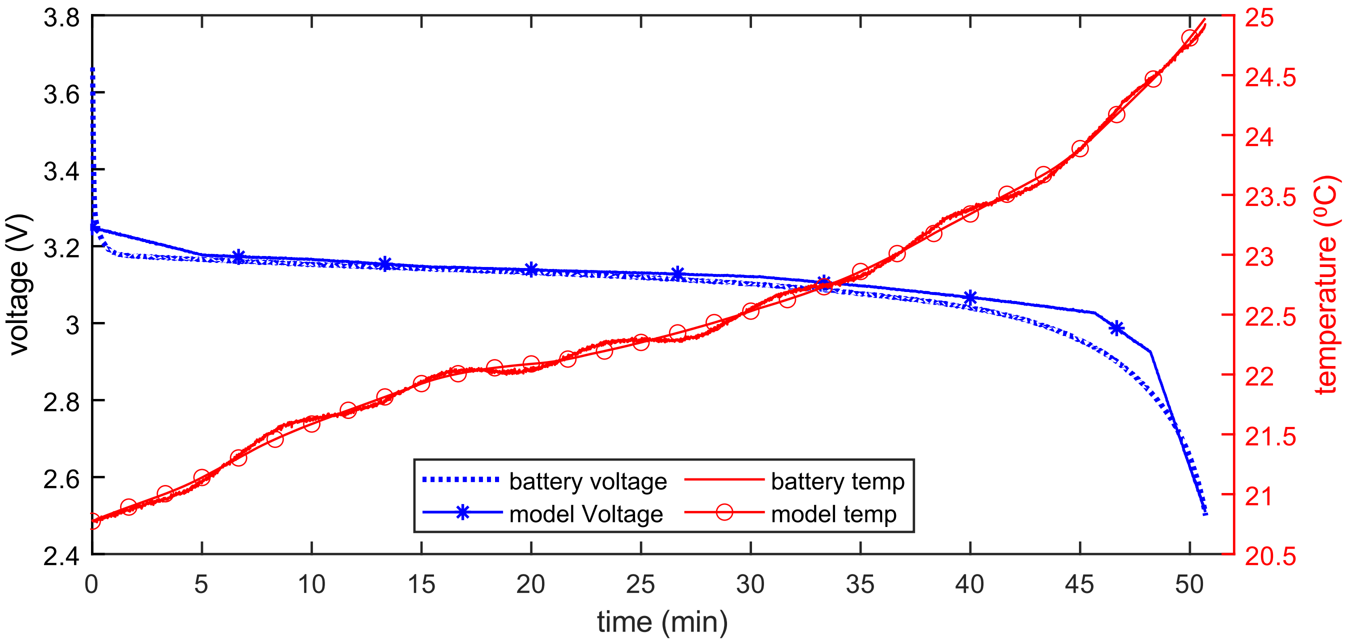
Model Result

- 1C discharge to 2.5V cutoff
- Modeled voltage with 0.82% average absolute error.
- Modeled temperature with 0.15% average absolute error.



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

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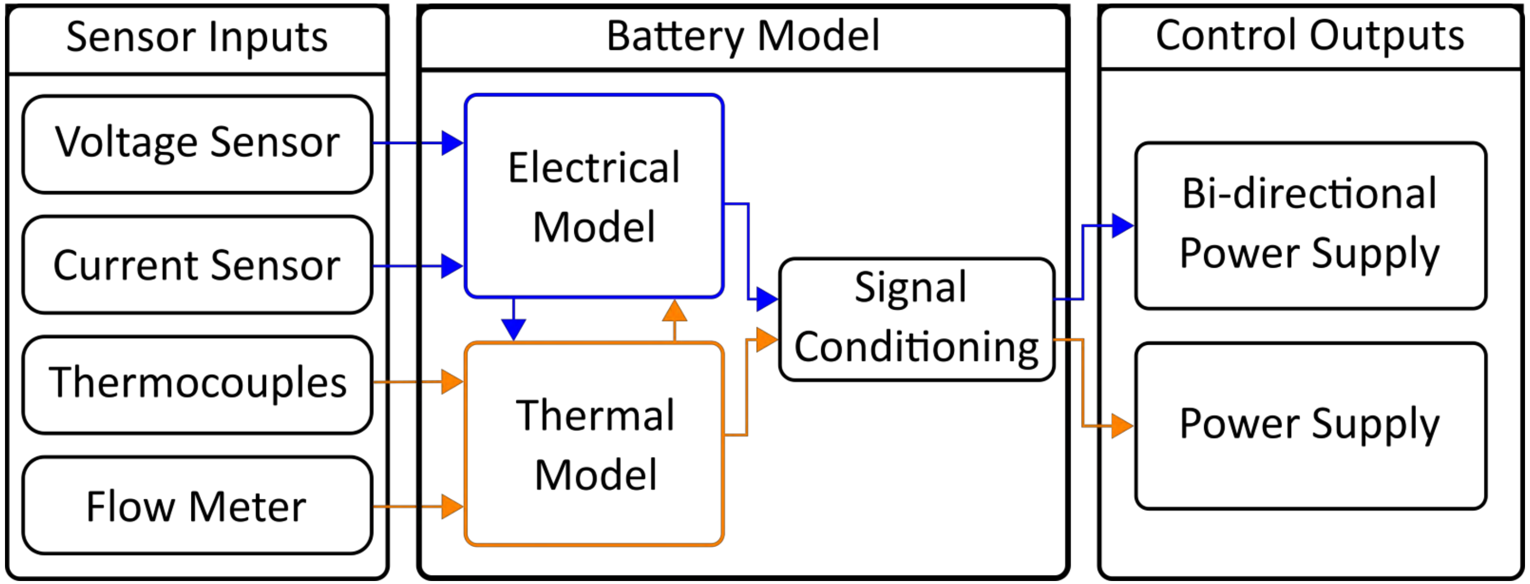
Model Implemented on Hardware

- 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:



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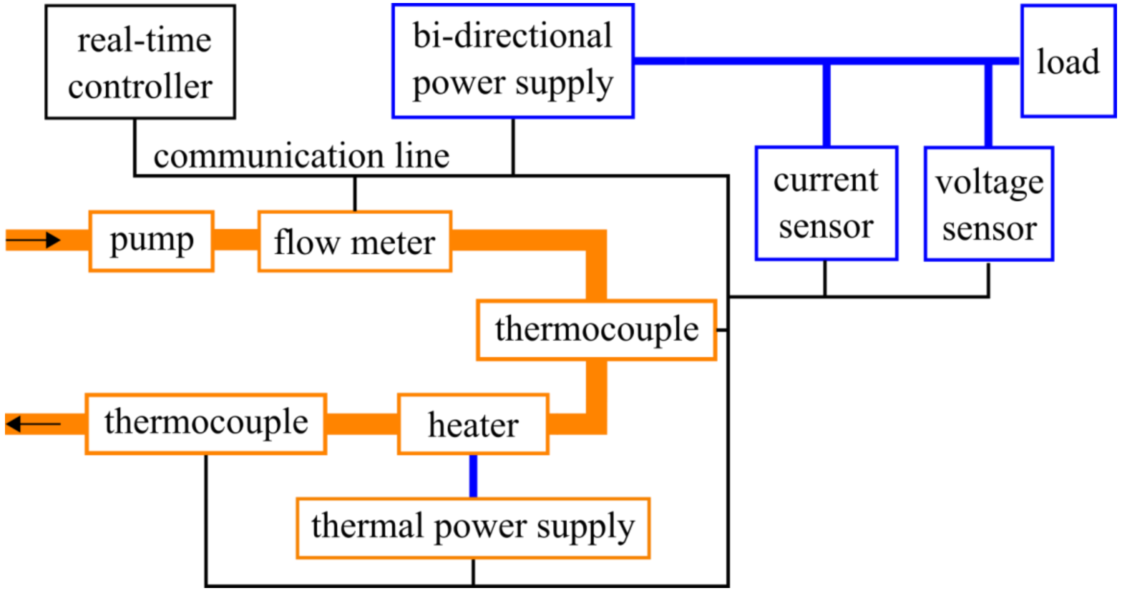
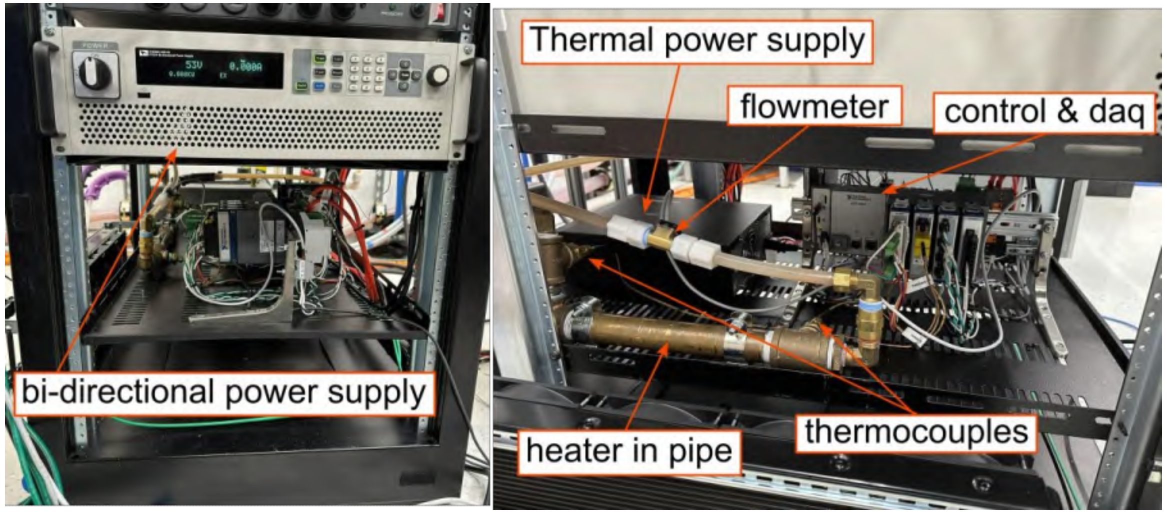
Hardware Setup

Diagram of complete setup:

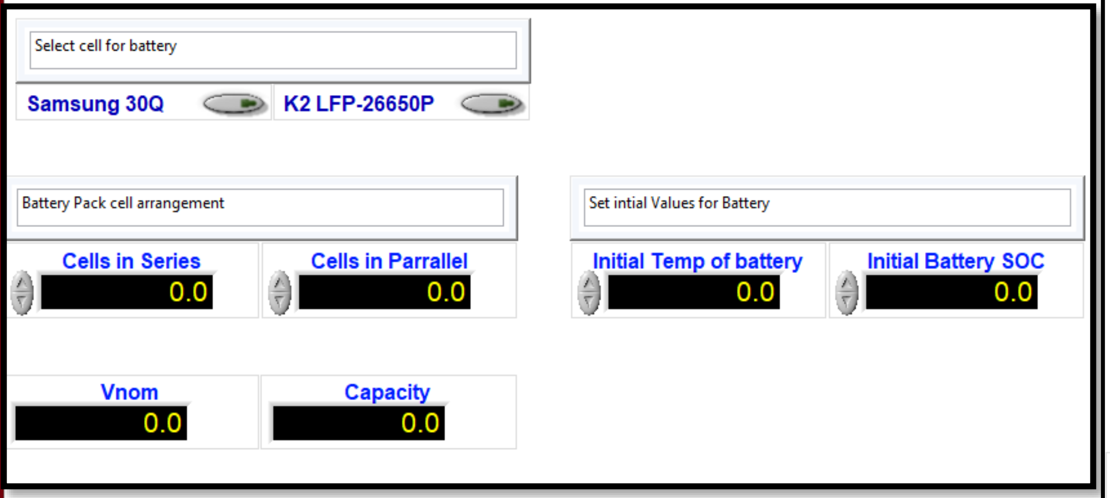


Physical Setup:

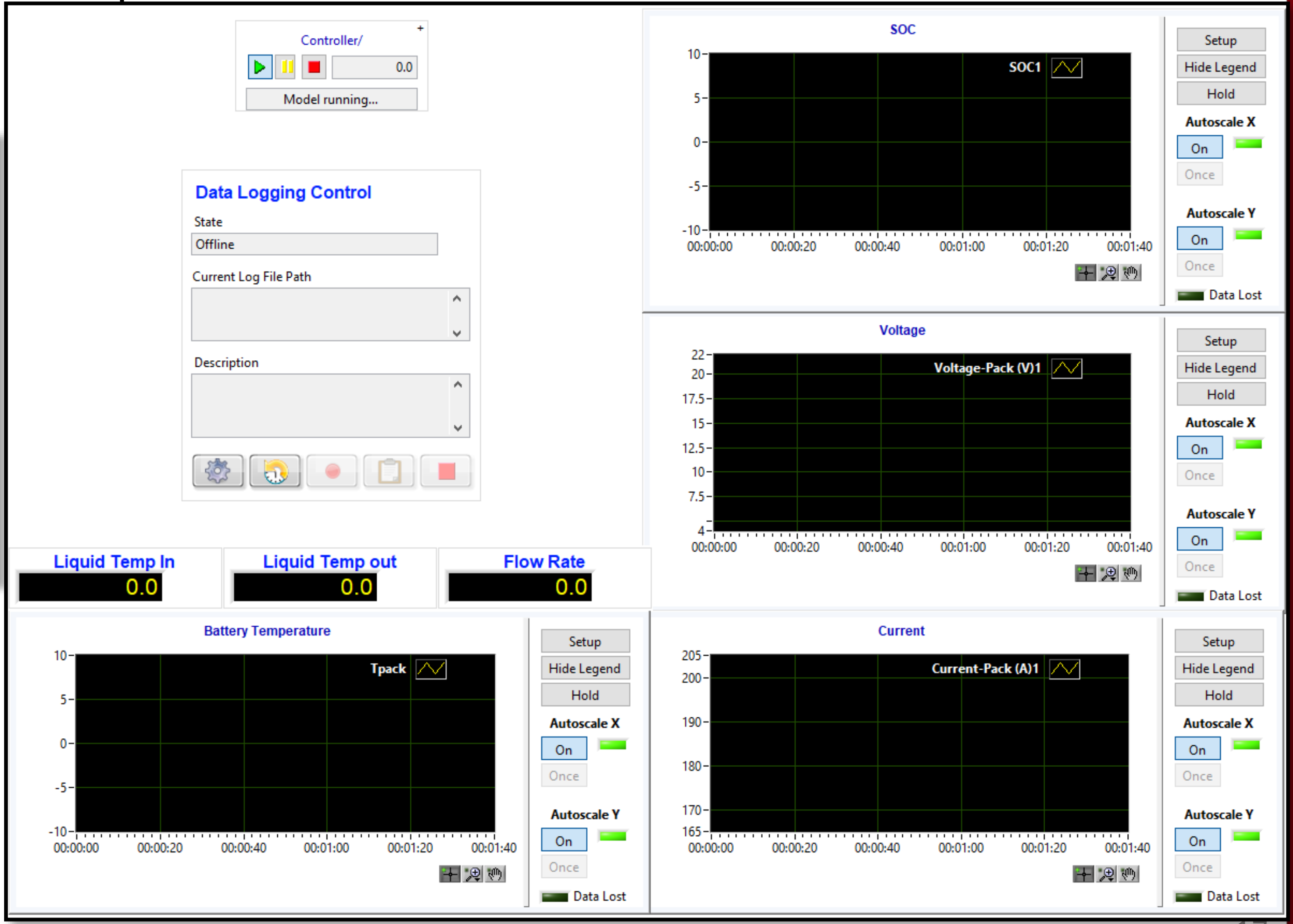


Emulator Interface

- Initialization Screen:

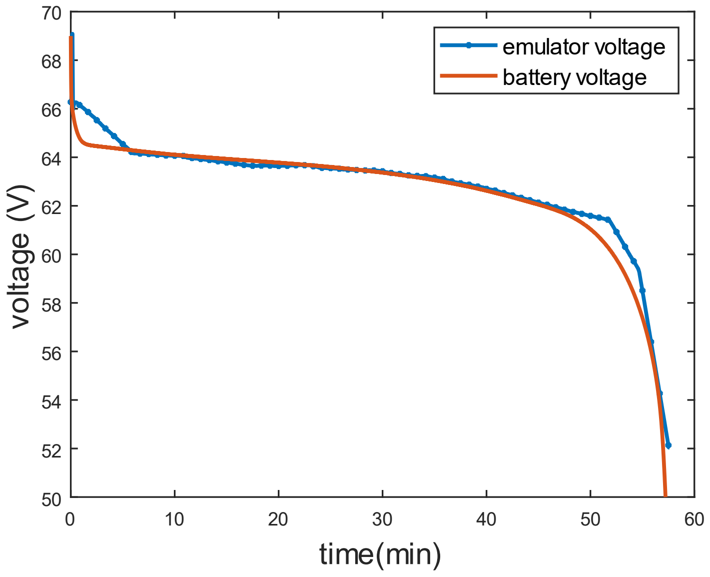


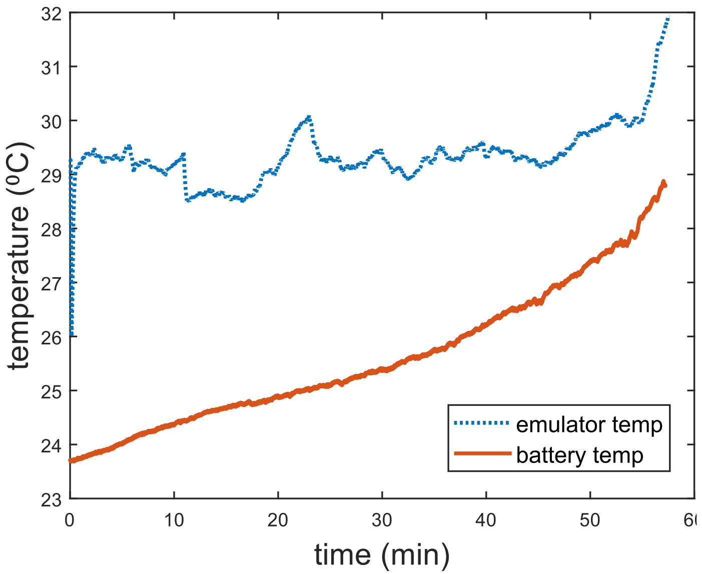
- Operation Screen:

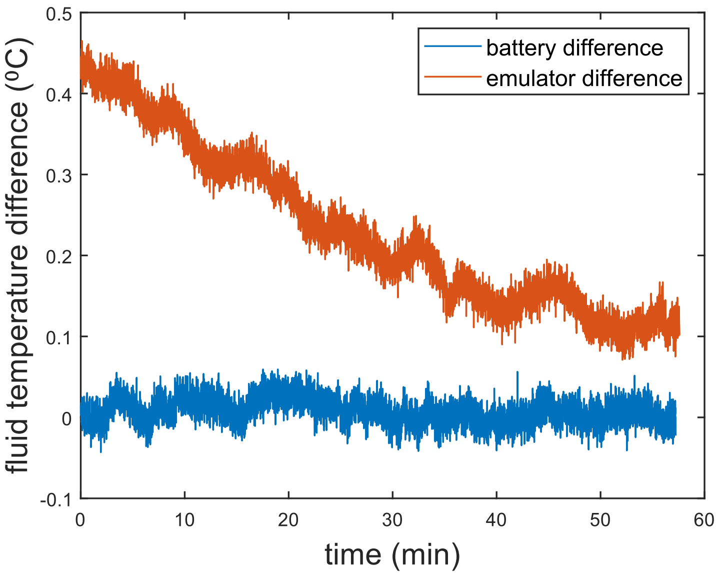


Emulator Results

- Emulator 1C(10.2 amps)
- discharge test
- Emulated voltage with 5.8% absolute average error
- Emulated temperature with 12.85% average absolute error







Discussion

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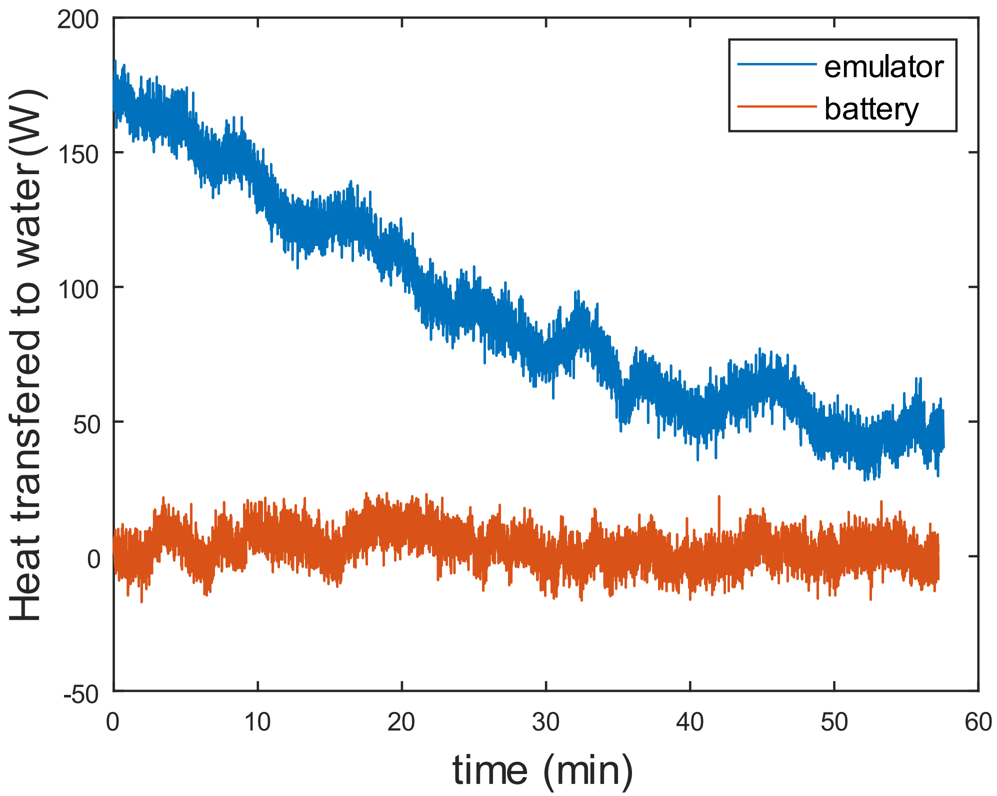
Emulator Results (back up)

- Emulator setup transferred a large amount of heat to the water
- Reasons for error:
  - Noise in thermocouples
  - Pump is adding an overwhelming amount of heat
  - Need a better radiator and or better placement



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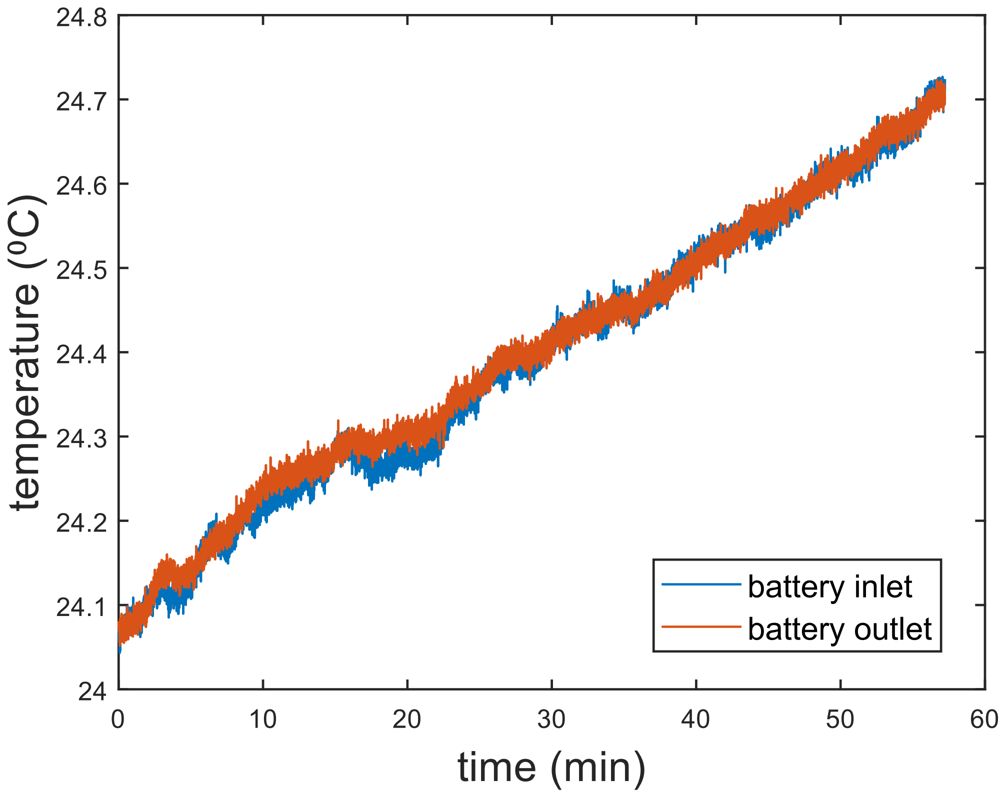
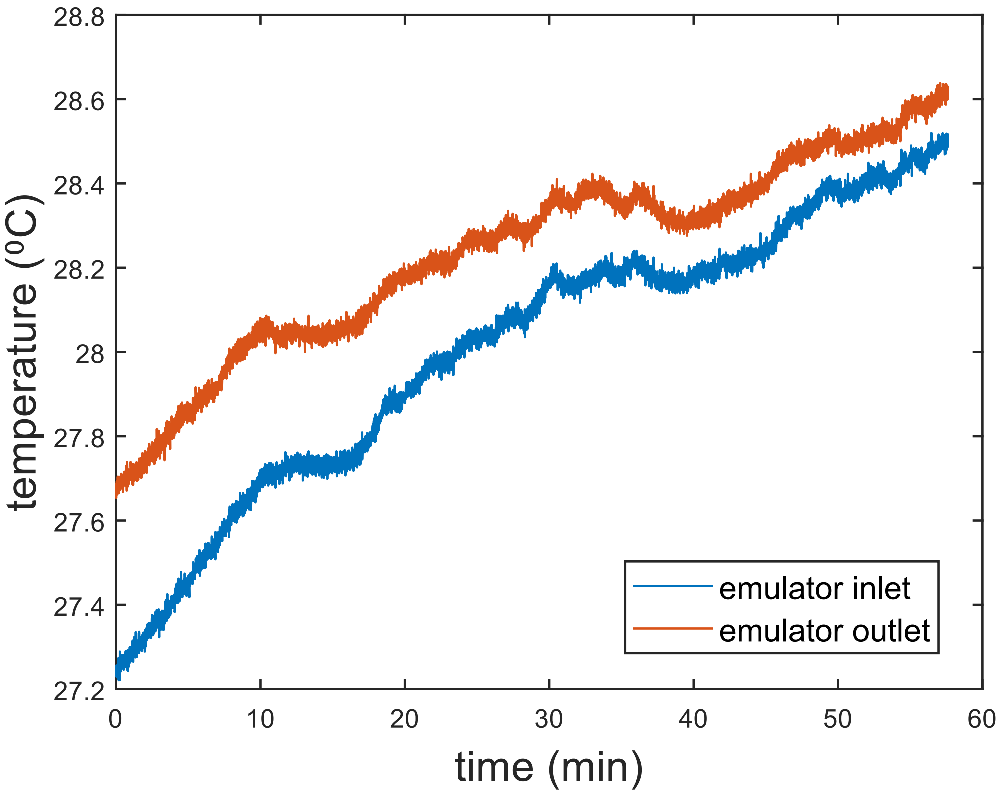
Temperature graphs

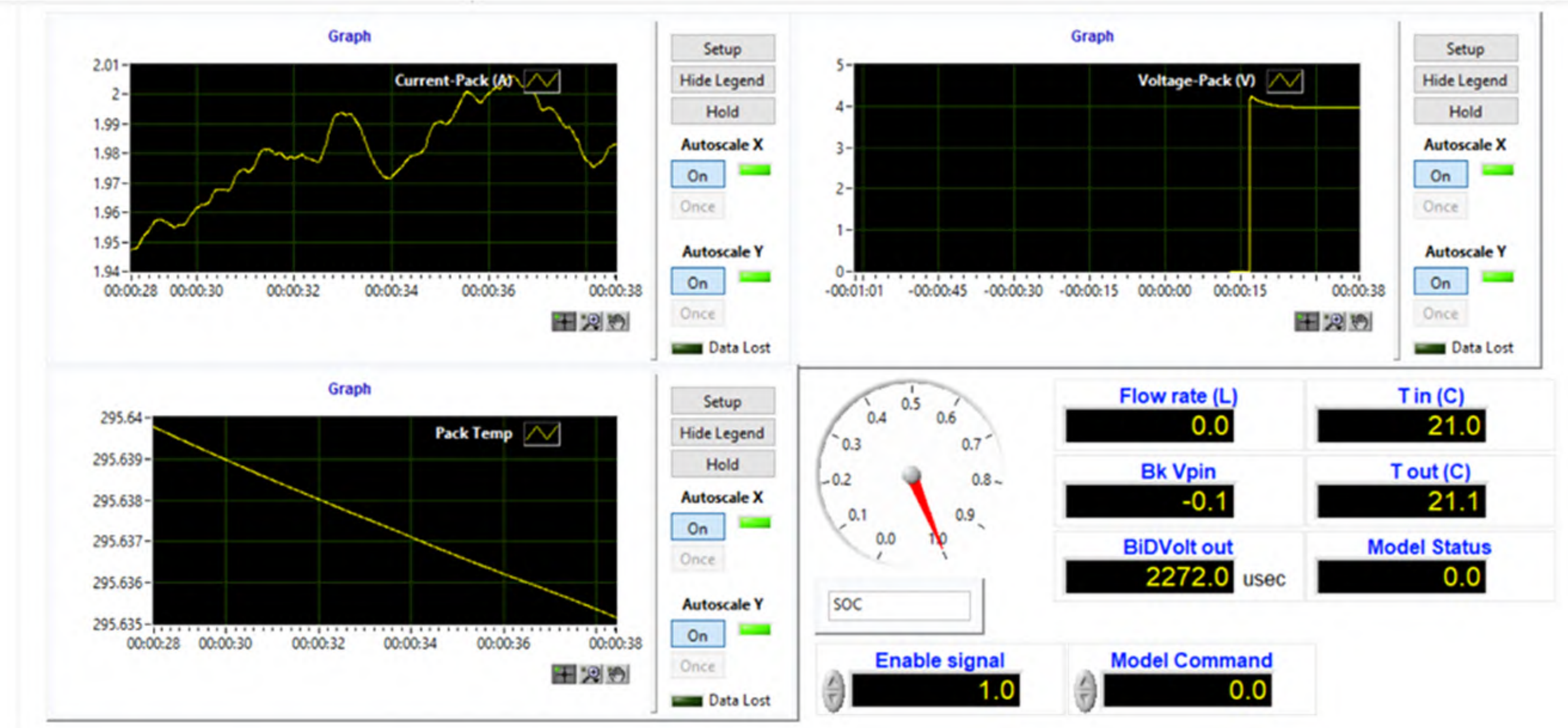
- Battery and emulator inlet-outlet temperatures





Emulator interface (backup slide17)

- Graphic interface shows State of charge, and electrical and thermal properties.



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Associated Conference Paper

Paper title: Battery Emulator for Coupled Electro-Thermo Powertrain Testing

Battery emulation systems are useful for testing and evaluating powertrain systems; but typically,only consider the electrical characteristics of a battery. Powertrains with shared cooling components/systems between batteries and power electronics would benefit from hardware-in-the-loop testing facilities that consider both the electrical and thermal aspects of energy storage. In this work a battery emulator that physically emulates both the electrical and thermal characteristics with a coupled electro-thermal powertrain testbed is demonstrated. The coupled electro-thermo model links the electrical and thermal outputs together and calculates them in real-time. The electrical model is an equivalent circuit representation of a battery making use of experimental data from tested cells. The electrical model is coupled to the thermal model through temperature-dependent parameters of the cell resistance and open circuit voltages. The thermal model is a lumped isothermal reduced order heat generation model. This model will calculate the net heat generated from the ohmic losses, entropic losses, and losses to cooling (liquid and ambient). The thermal model is coupled to the electrical model by being dependent on the cell's state of charge and using the cell's current and voltage outputs for its governing equations. Models are parameterized on experimental data acquired through pulsed hybrid testing. In this work, a 3.5 kWh battery pack with a discharge of 40 amps at 48 volts generating 38.4 Watts of heat is emulated in an electro-thermo powertrain testbed configured to represent an electric naval platform such as a small autonomous boat subjected to both baseline and pulsed loading. The electrical emulation is performed through a bidirectional power supply and thermal emulation through a resistive heater. The electro-thermo powertrain testbed then dissipates the emulated electrical energy through power convertors and electronic loads while the thermal energy is dissipated through a heat exchanger that also cools the power convertors. Numerical and experimental validation demonstrate that the coupled electro-thermo battery emulator is capable of accurately representing the electrical and thermal aspects of a 3.5 kWh battery. Limitations in terms of
emulating batteries at higher temperatures and current draws are discussed. Effects of scaling the coupled electro-thermo battery emulator are also presented.

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