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Hardware-in-the-Loop Electrothermal Emulator

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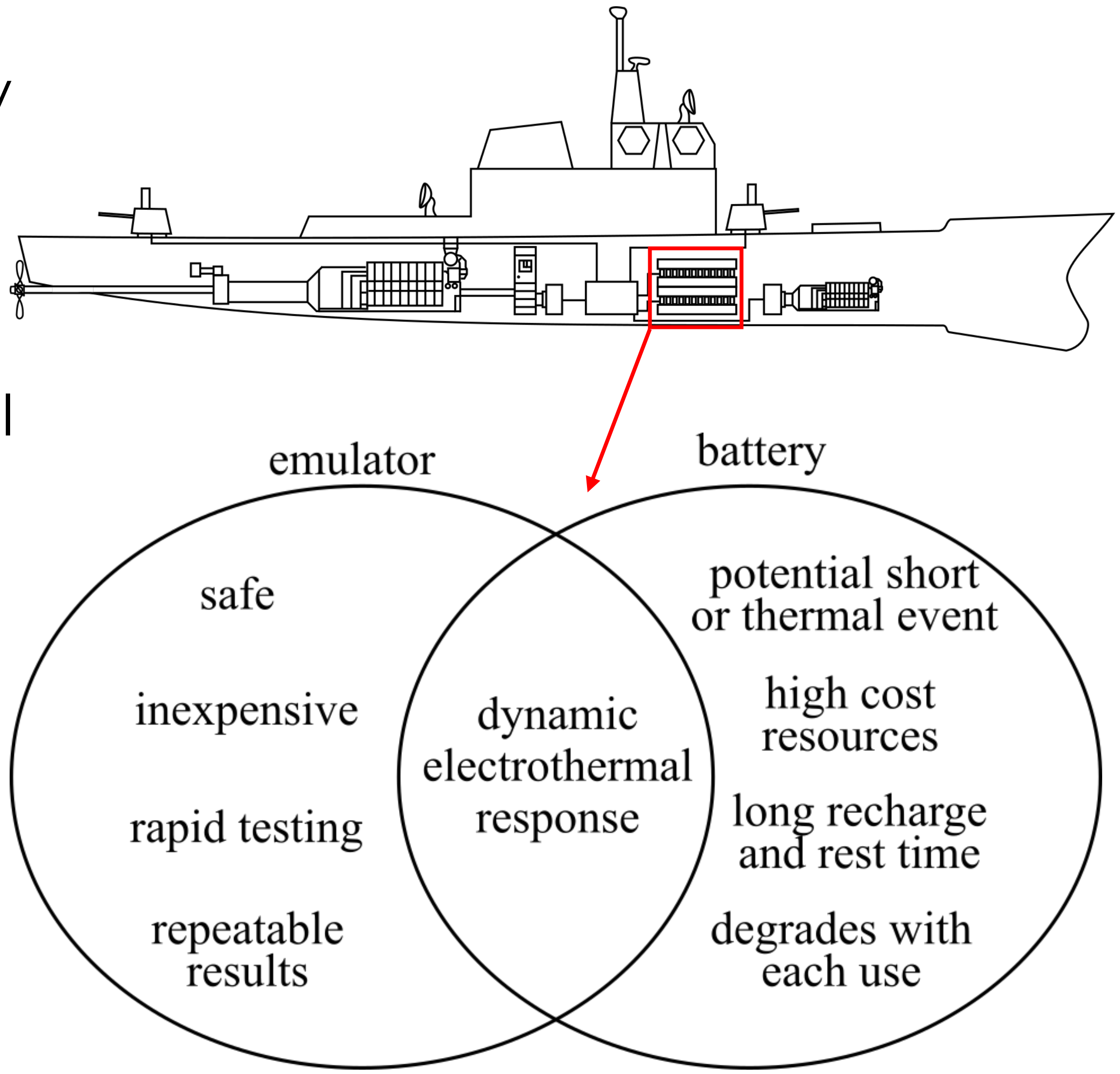
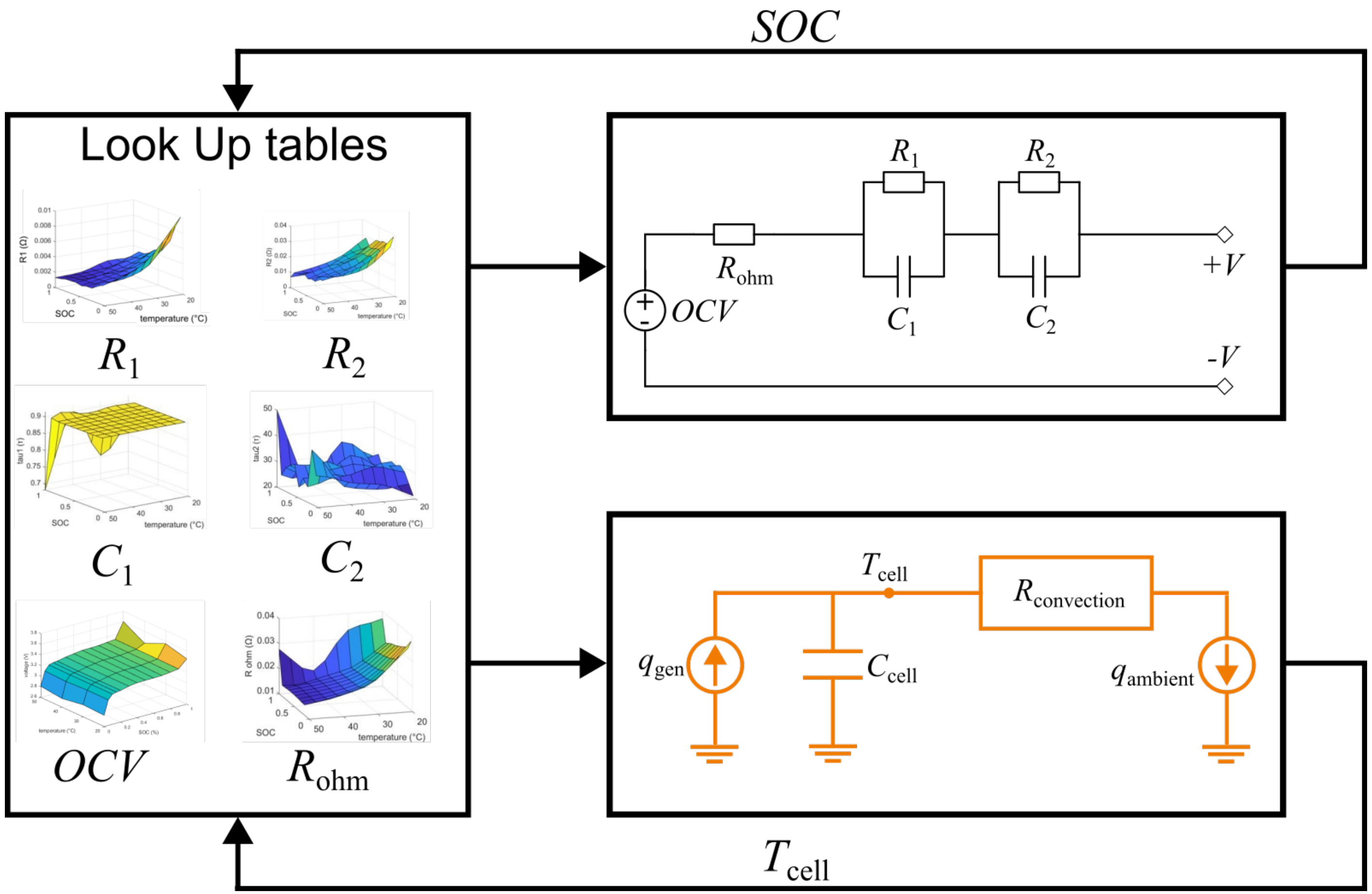
Intro

- Electrification In Naval Ships requires energy storage for buffering and supplying pulsed power
- Lithium-ion batteries provide dense and efficient energy storage but are impractical for frequent testing
- Emulation provides:
  - Repeatable conditions
  - limits cost
  - saves time
  - safety



Emulator Model

- Coupled Model
  - Electrical model
    - 2nd order equivalent circuit model
  - Thermal model
    - 1st order 1-D heat transfer
  - How they are coupled
    - Both models use look up tables dependent on the same variables
    - Electrical and thermal model input parameters are updated based on SOC and temperature

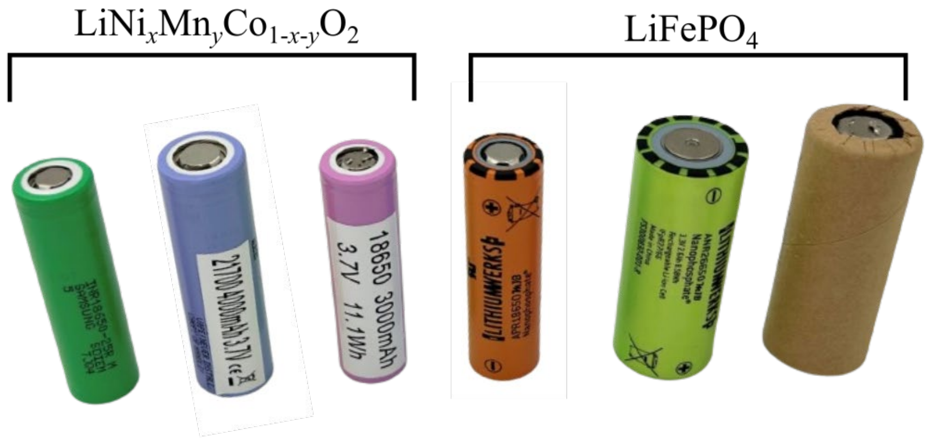


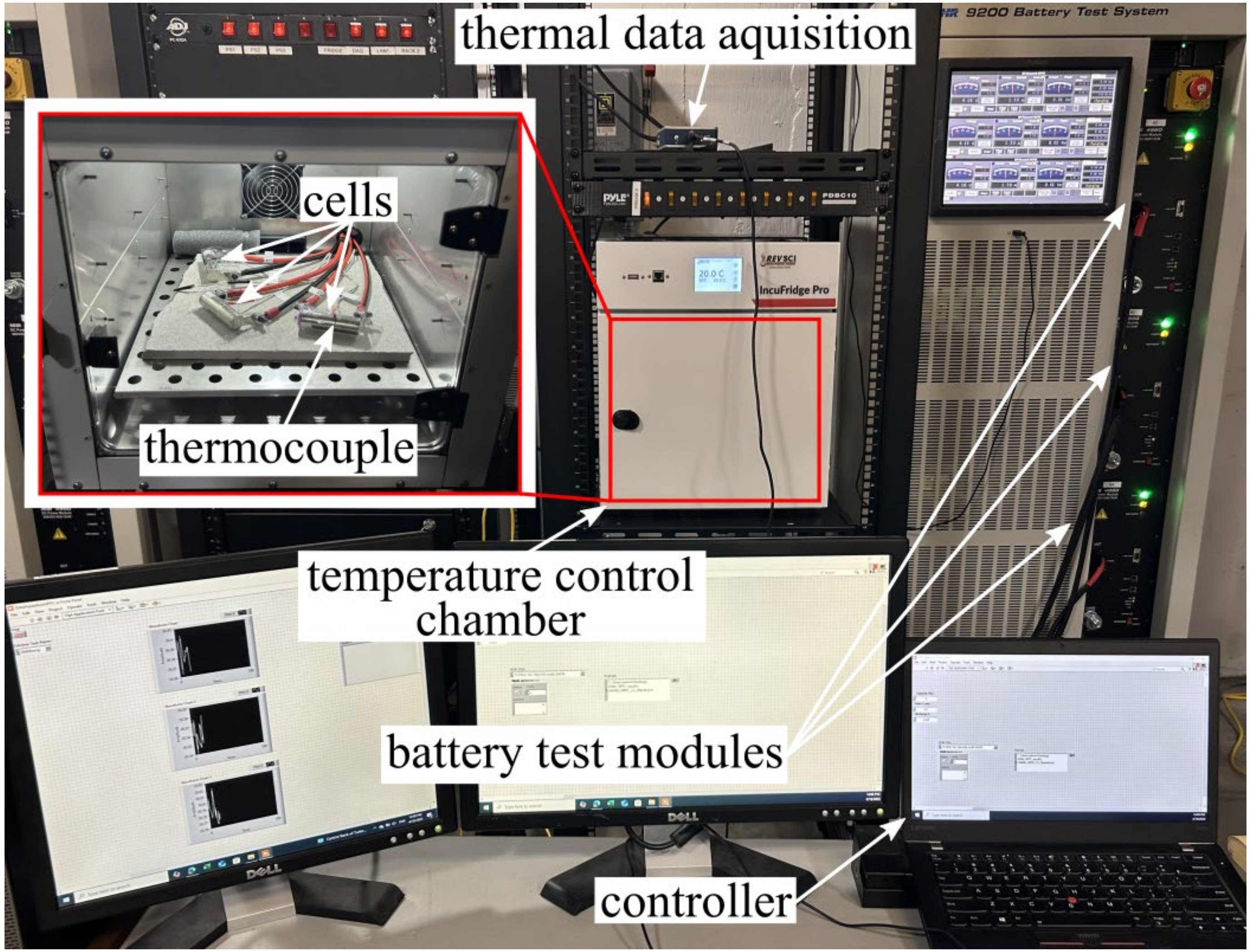
$$\frac{dV}{dt} = OCV(SOC) - IR_{\text{ohm}} - V_{R_1C_1} - V_{R_2C_2}$$

$$C_{\text{cell}}\frac{dT_{\text{cell}}}{dt} = \underbrace{\frac{T_{amb} - T_{\text{cell}}}{R_{\text{convection}}}}_{Q_{\text{ambient}}} + \underbrace{I^2R_{\text{ohm}}}_{Q_{\text{gen}}}$$

Battery Testing

- 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

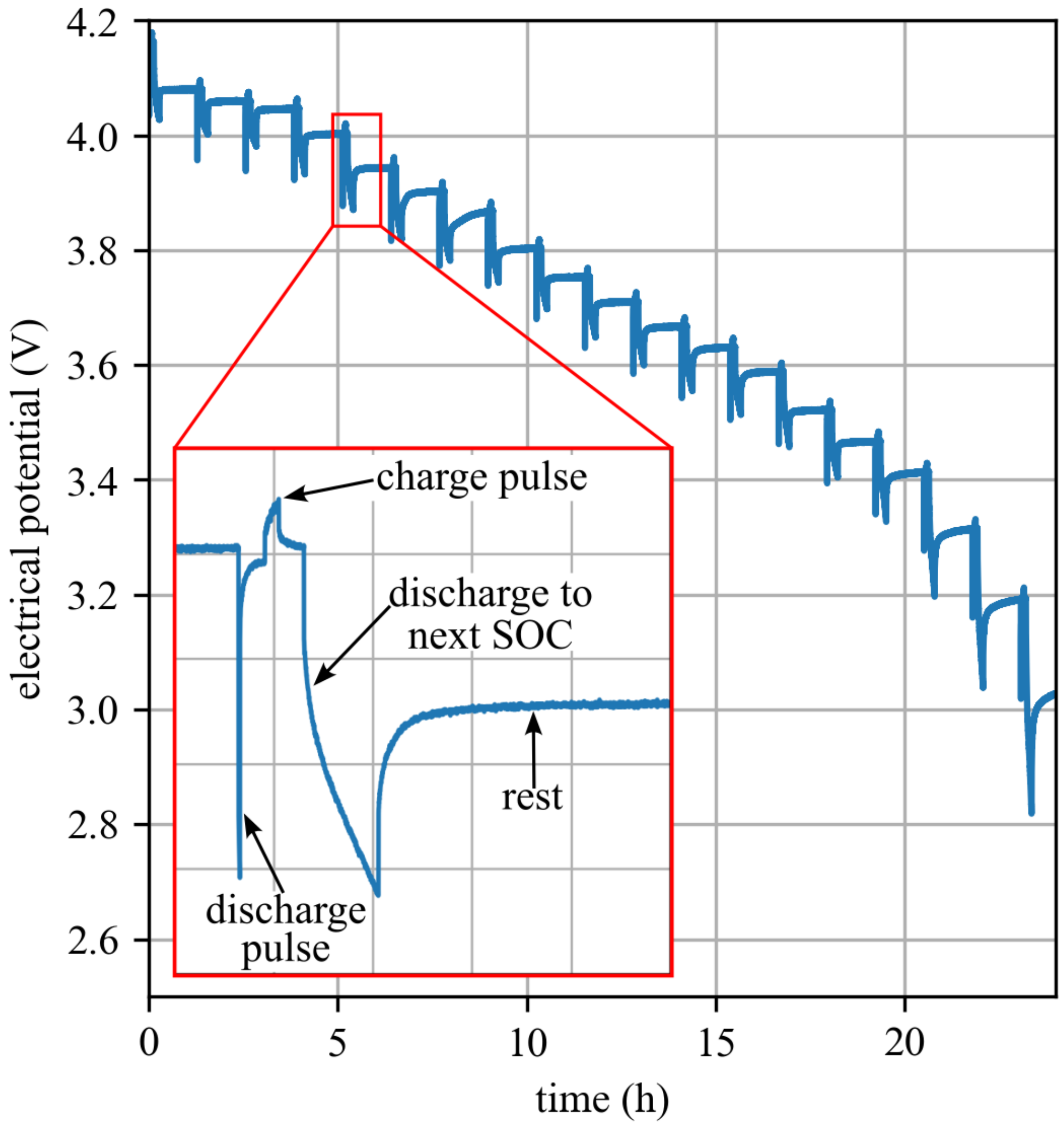




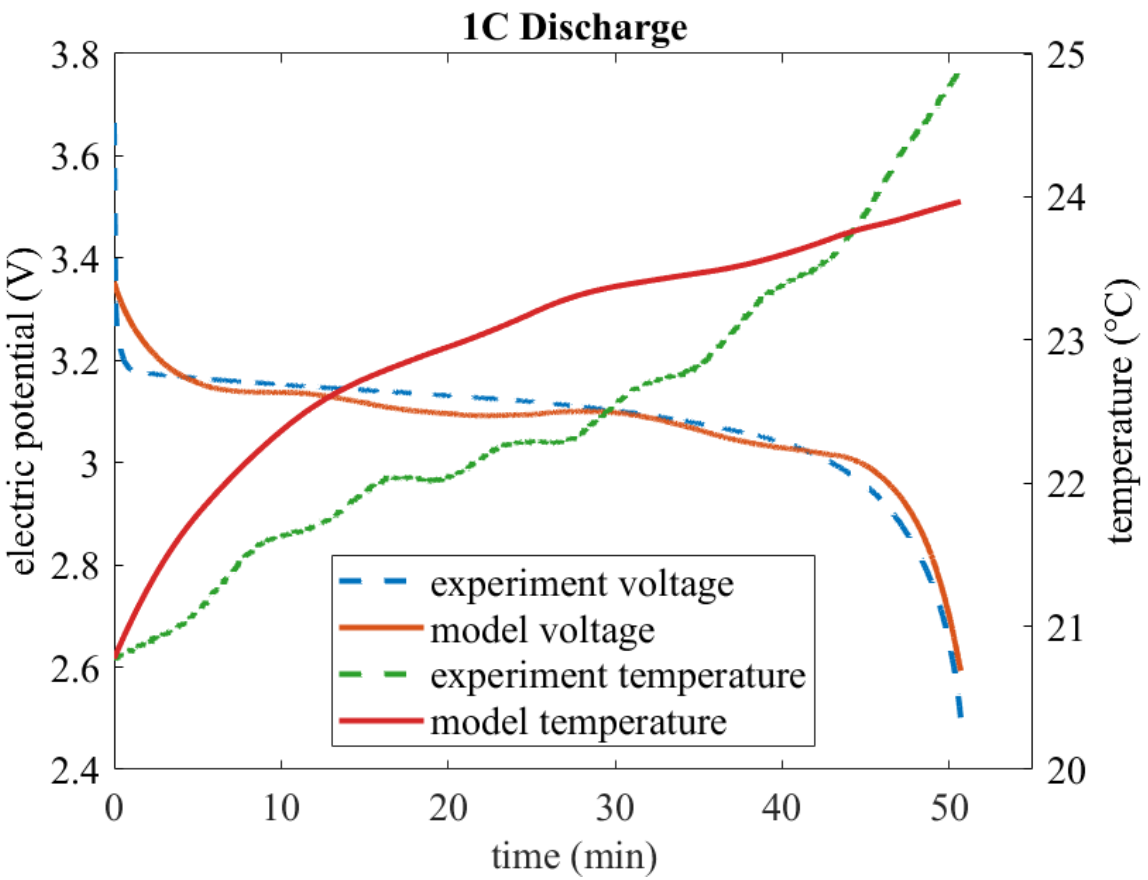
Data Collection

- Data from a K2 Energy LFP26650P
- Hybrid Pulsed Power Characterization data used to fit time constants with nonlinear regression at 20, 30, 40, & 50°C
- Heat transfer coefficient and heat capacity of battery collected from thermal steady state testing

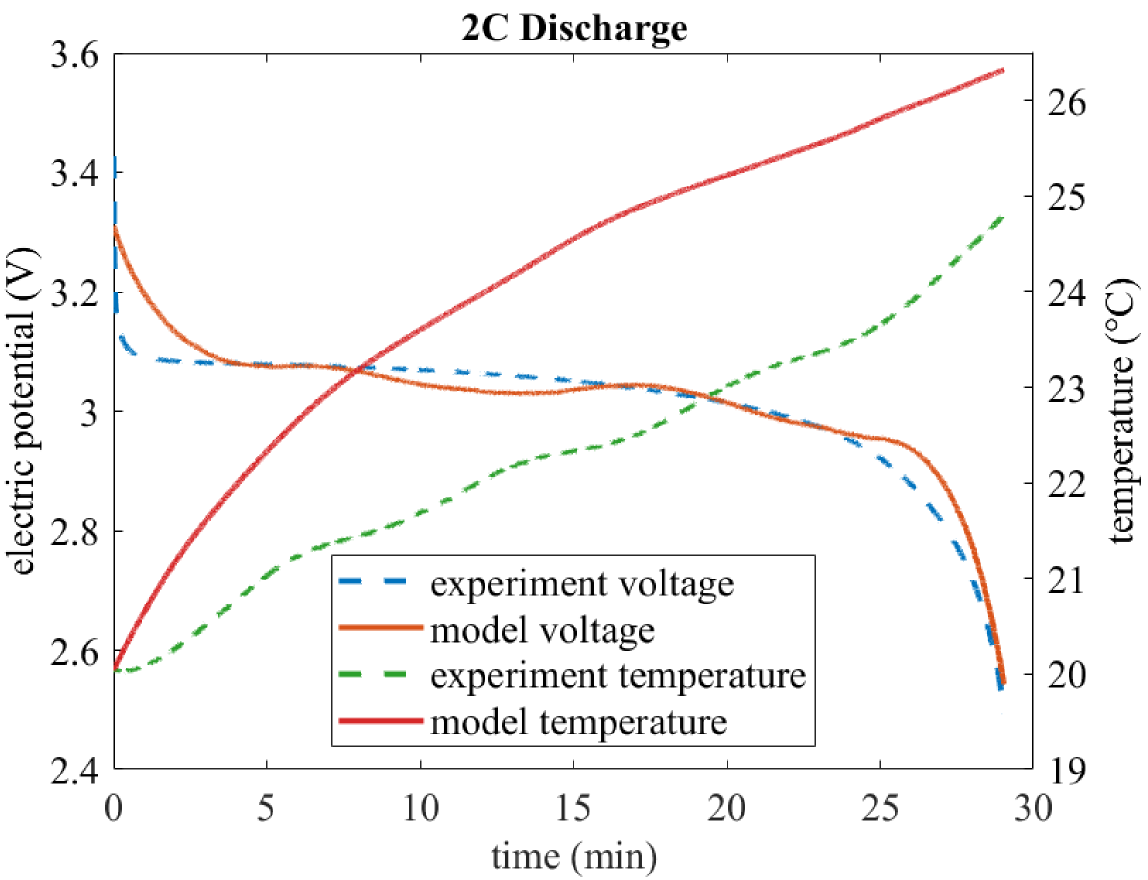
	parameters
electrical	capacity (T)
	open circuit voltage (SOC, T)
	terminal resistance (SOC, T)
	fast and slow time constants (SOC, T)
thermal	open circuit voltage (SOC, T)
	surface area
	convective heat transfer coefficient
	mass
	specific heat capacity



Model Validation

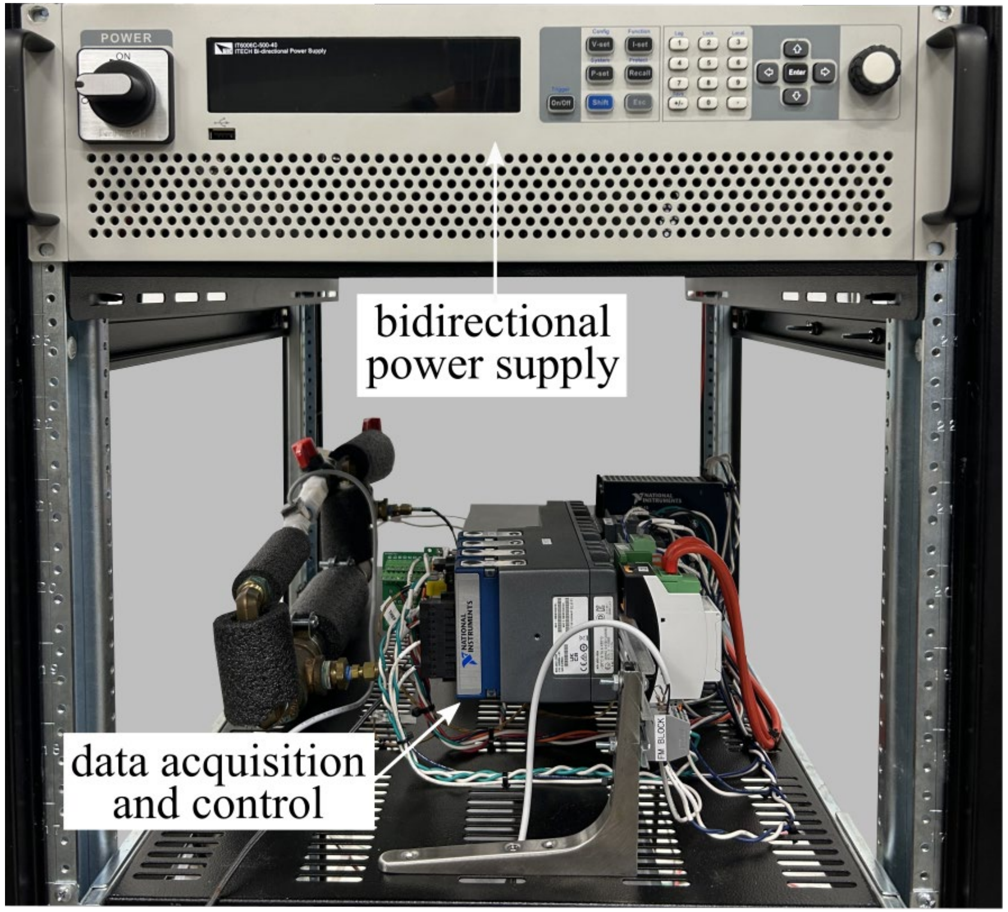


	Voltage (V)	Temperature (°C)
RMSE	0.031	0.69

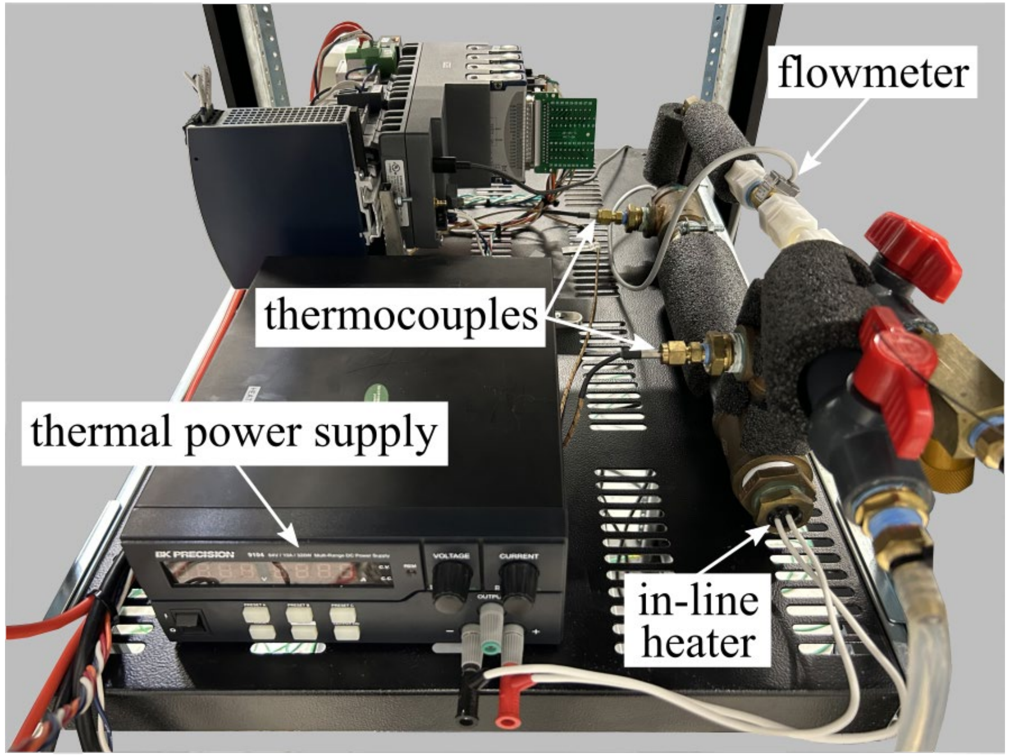


	Voltage (V)	Temperature (°C)
RMSE	0.038	1.88

Hardware Preview



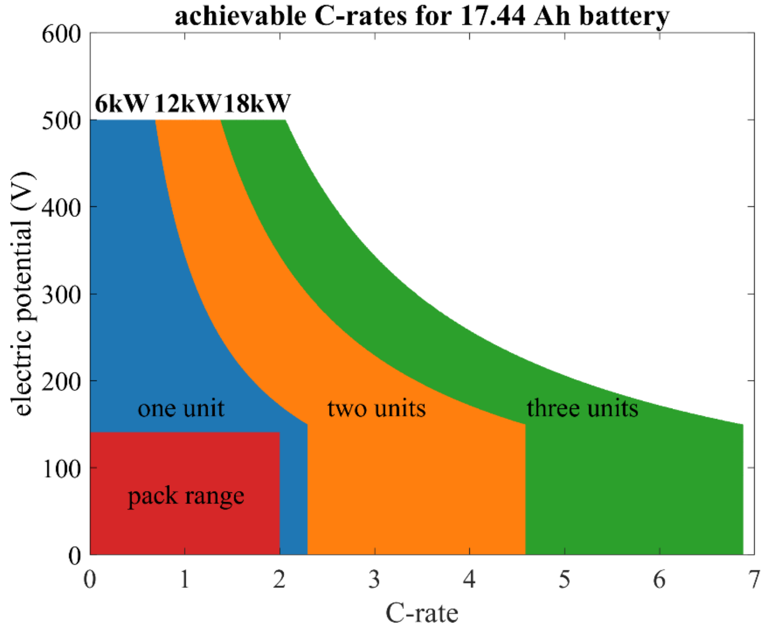
front view

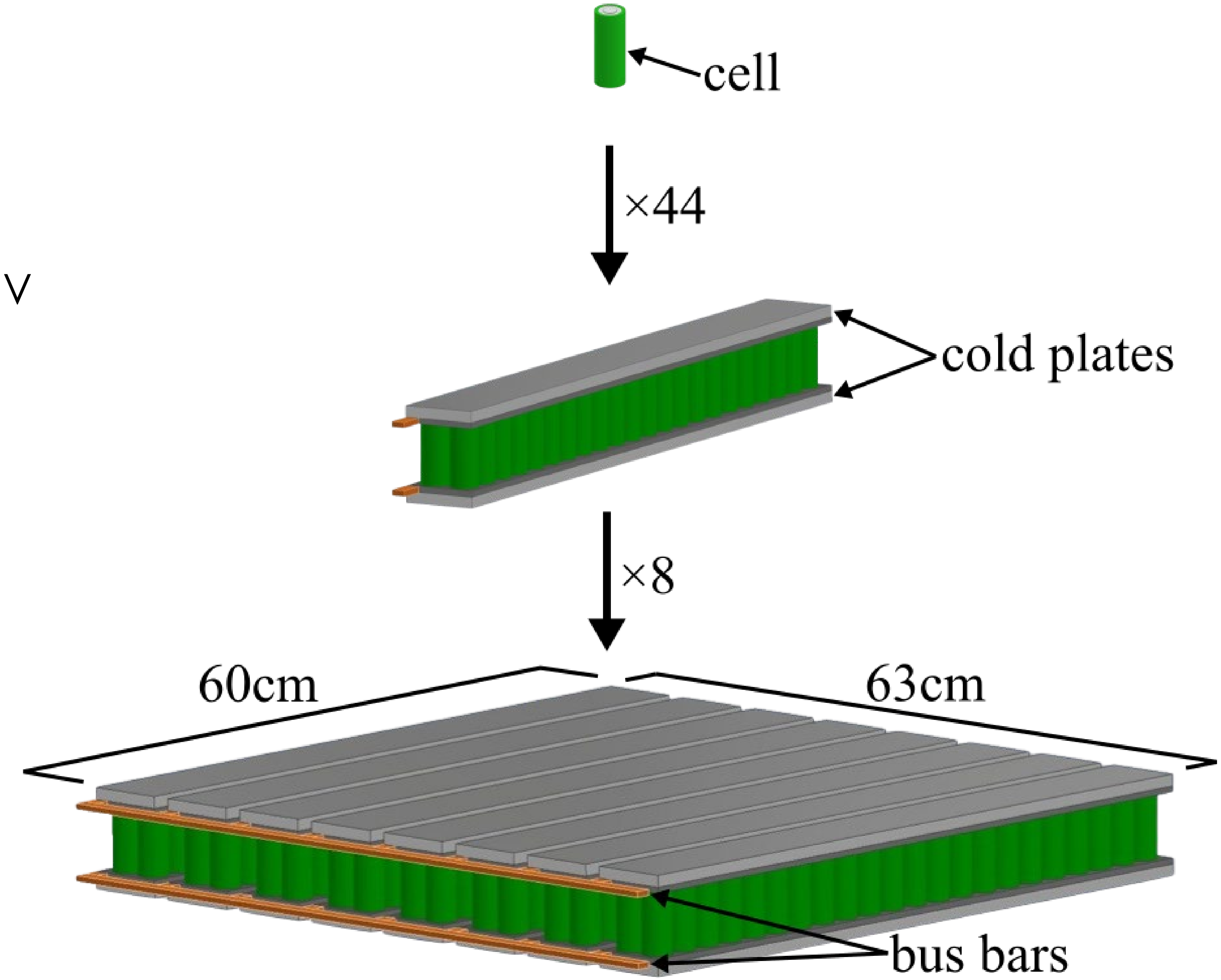


rear view

Pack Configuration

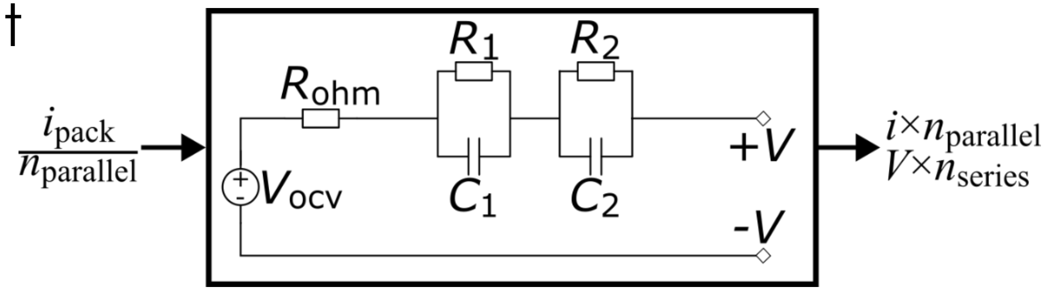
- Battery Pack
    - 44S8P
    - Nominal Voltage = 140.8 V
    - Capacity = 17.44 Ah
    - Power @ 1C = 2.456 kW
    - Power @ 2C =4.911 kW

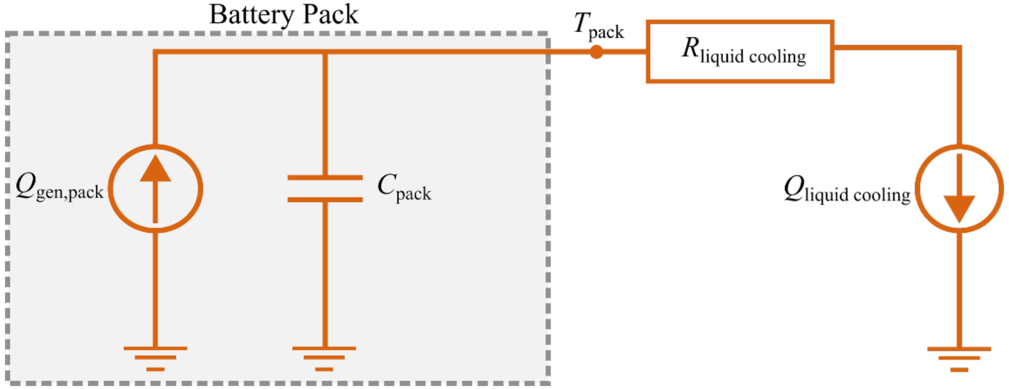




Scaling to Pack

- Making use of single cell characteristics to predict pack behavior
  - Electrical Scaling
    - Model Parameters are left the same
    - Input current is divided by number of cells in parallel
    - Voltage output is scaled by cells in series and current output is scaled by number of cells in parallel
  - Thermal Scaling
    - Q_{out} is heat from pack to liquid cooling
    - Log mean temperature difference (LMTD) is used to estimate the temperature difference driving heat transfer from pack to water
    - thermal mass, Area is scaled, current left as pack level current

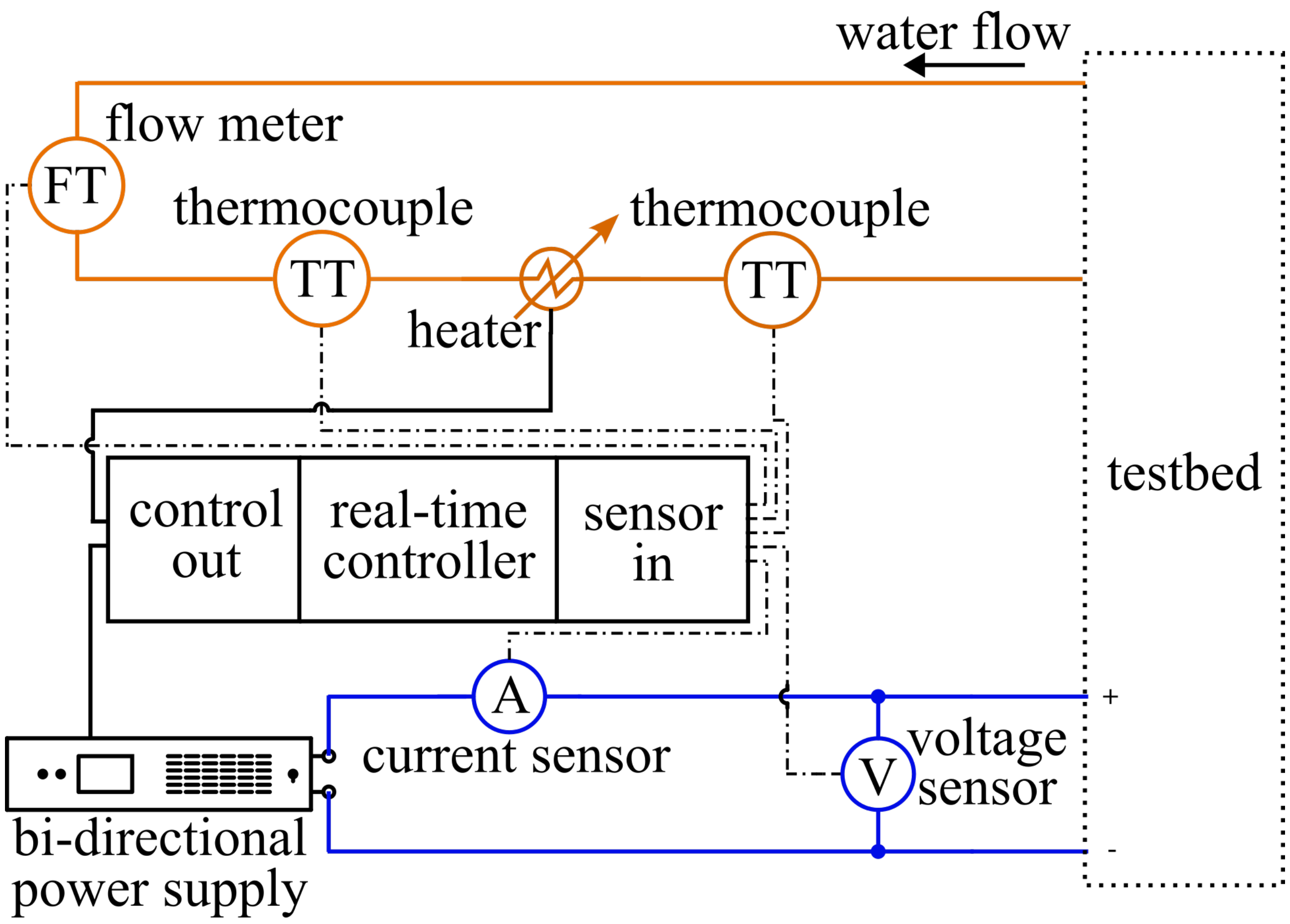


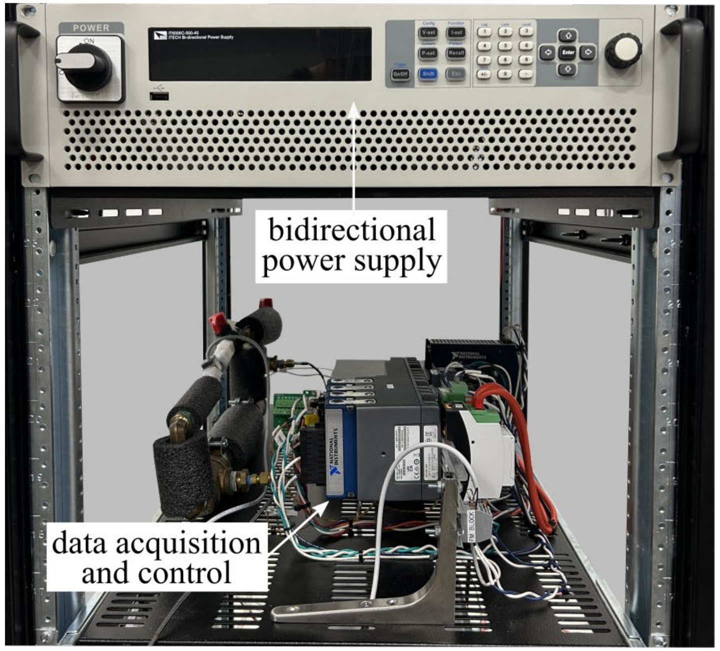


$$C_{pack}\frac{dT_{pack}}{dt} = \underbrace{-UA_{liquid\ conv}LMTD}_{Q_{out}} + \underbrace{I_{mod}{}^2 R_{ohm} n_{cell}}_{Q_{gen}}$$

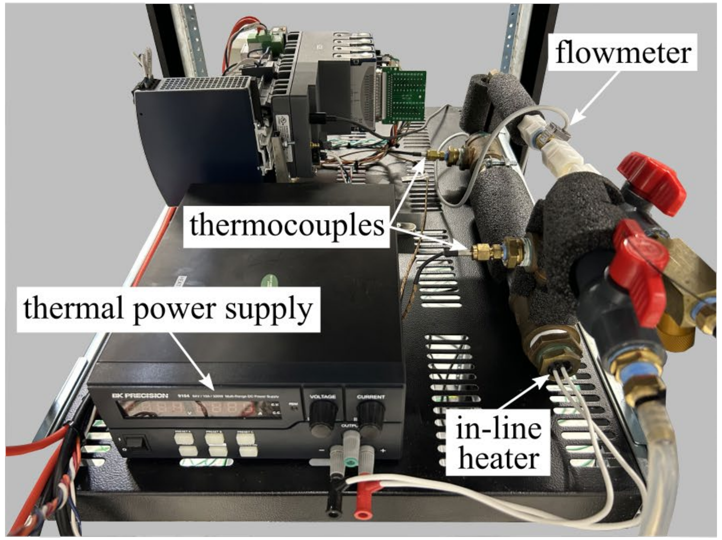
$$LMTD = \frac{\Delta T_{inlet} - \Delta T_{outlet}}{\ln\left(\frac{\Delta T_{inlet}}{\Delta T_{outlet}}\right)}$$

Hardware





front view

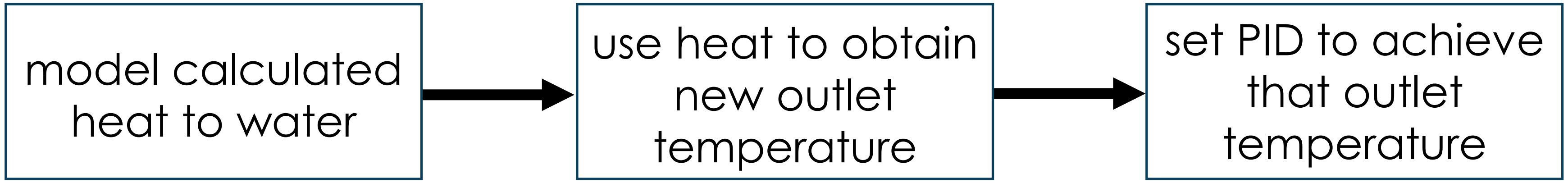


rear view

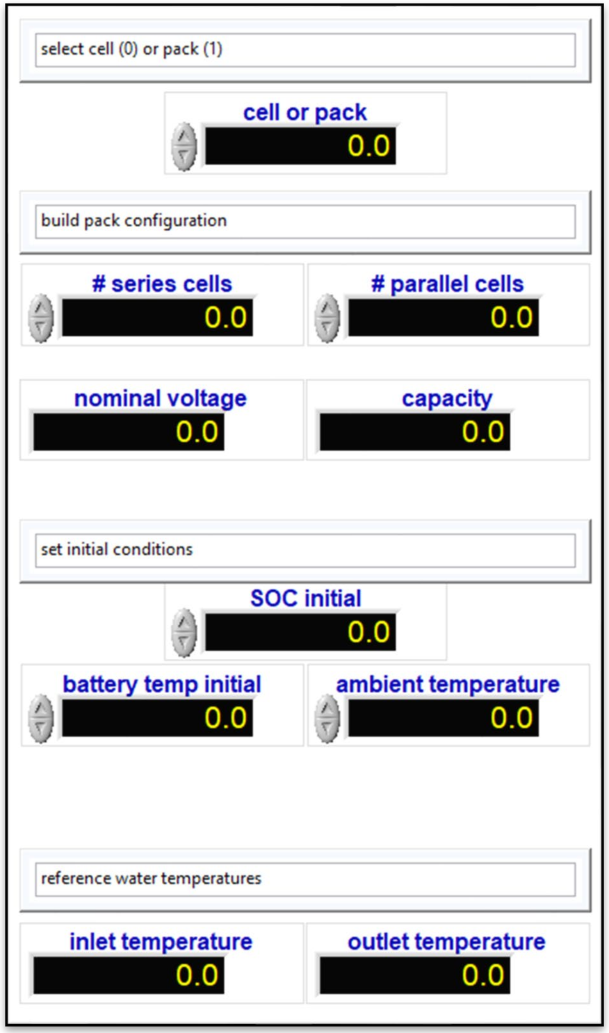
Model Interface with Hardware

- Electrical
  - Voltage setting for bidirectional is linearly scaled to the analog control input of the bidirectional power supply

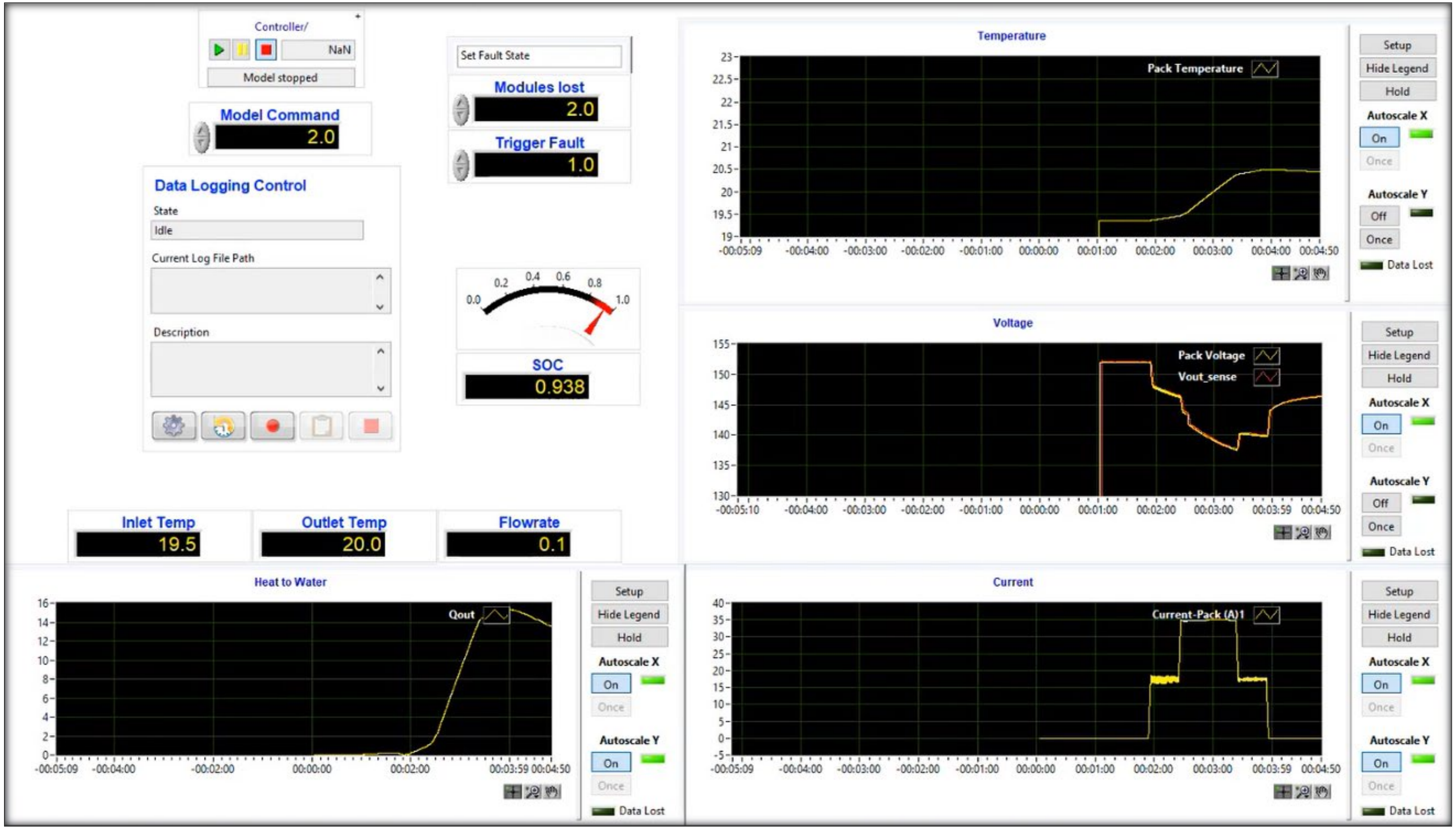
- Thermal
  - Heat loss is calculated by model (LMTD)
  - Heat loss is used to calculate outlet temperature
  - PID controller is designed to replicate calculated outlet temperature



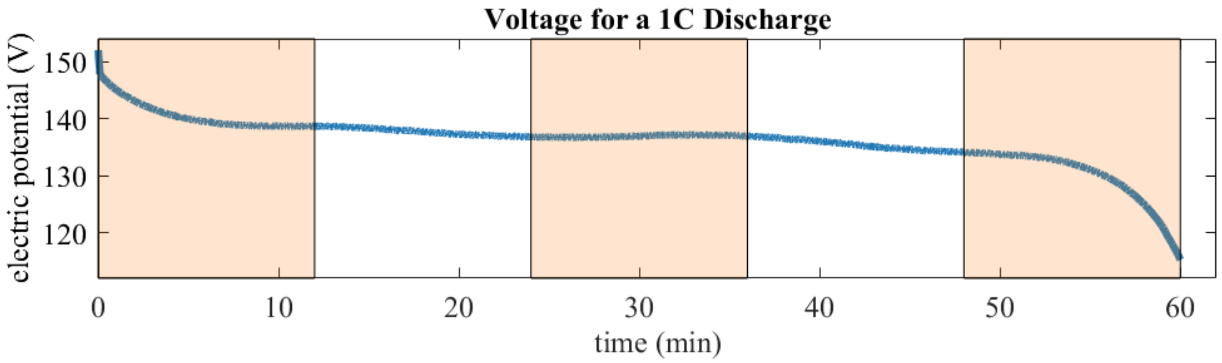
Graphical User Interface

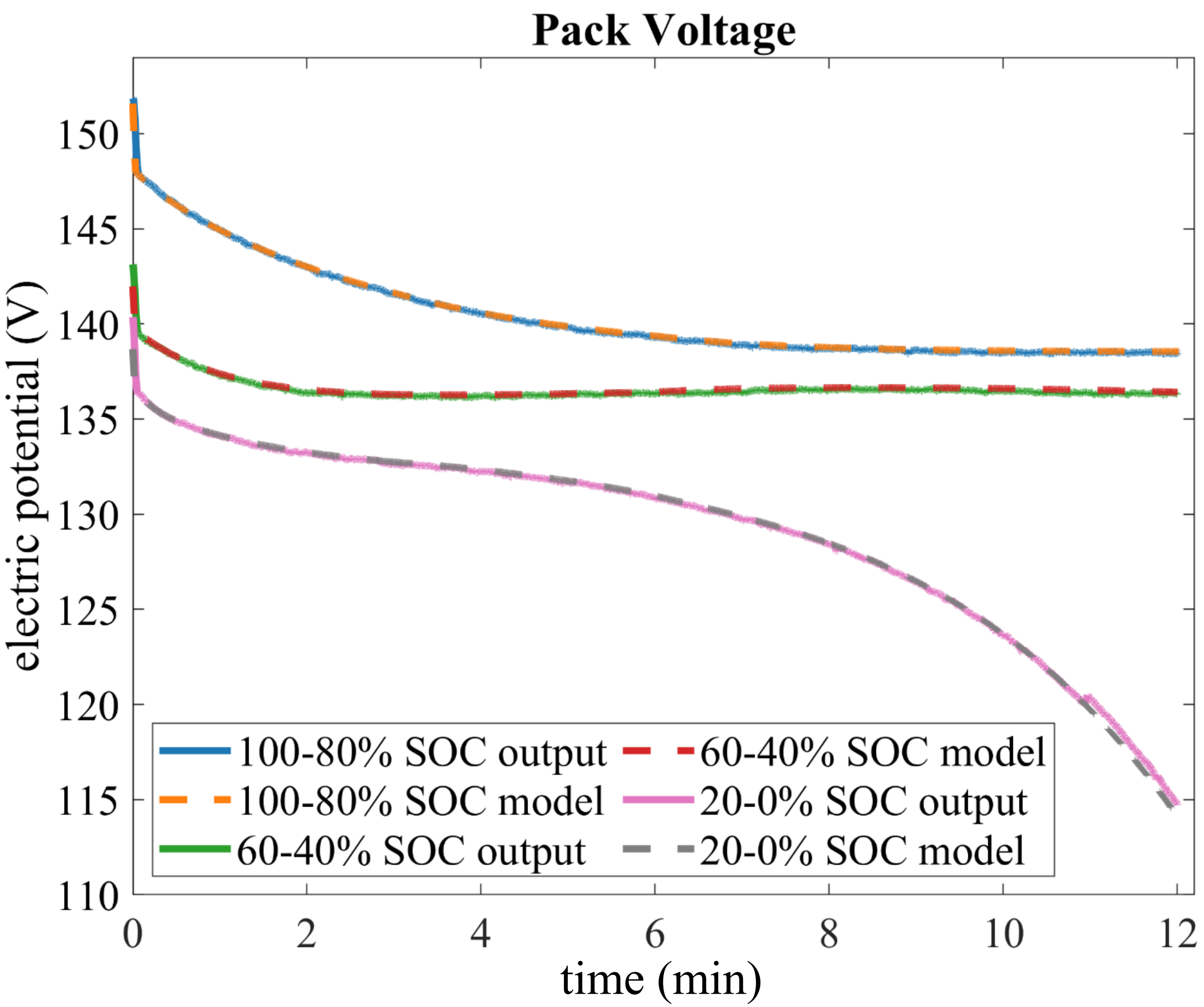


Operation screen

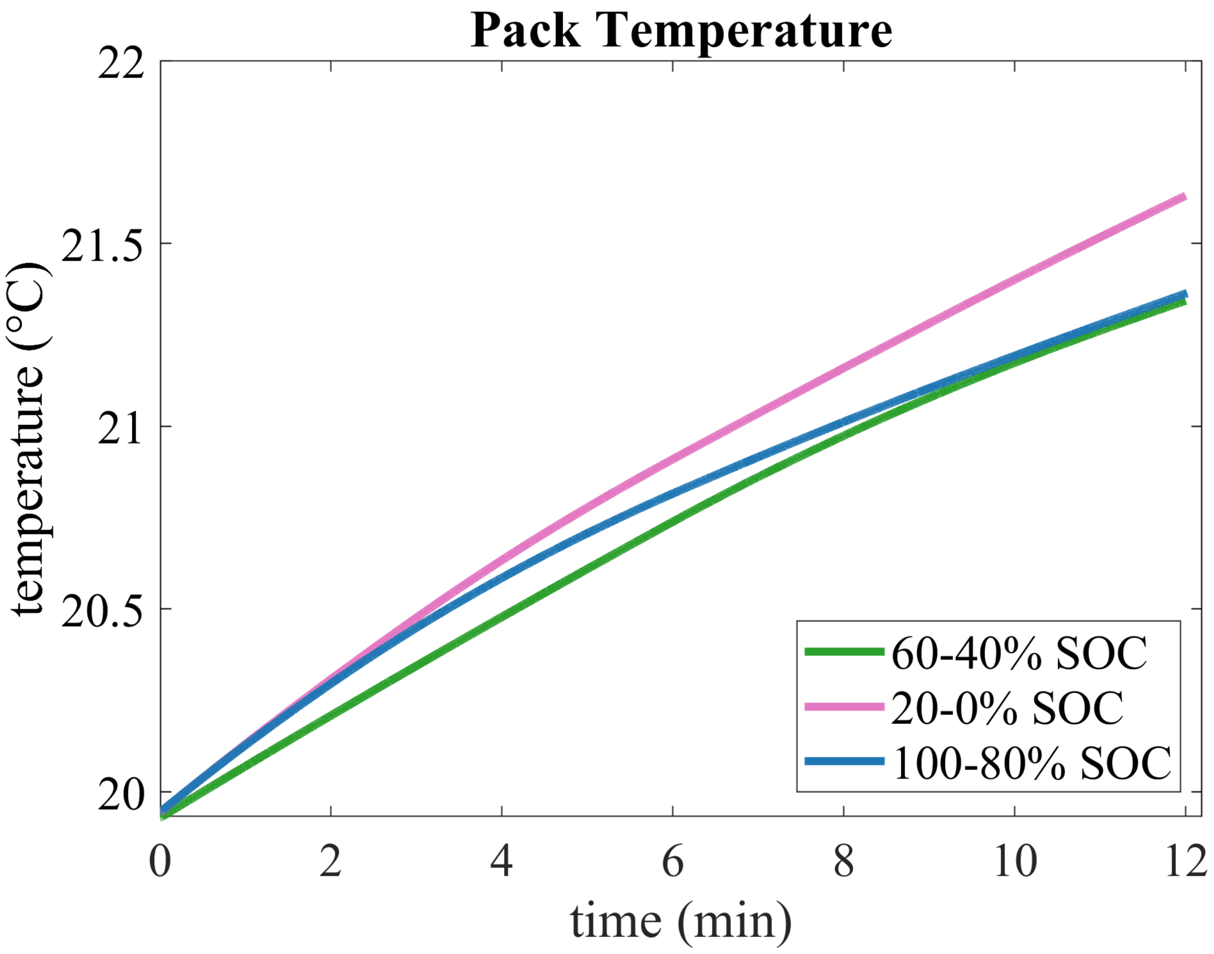


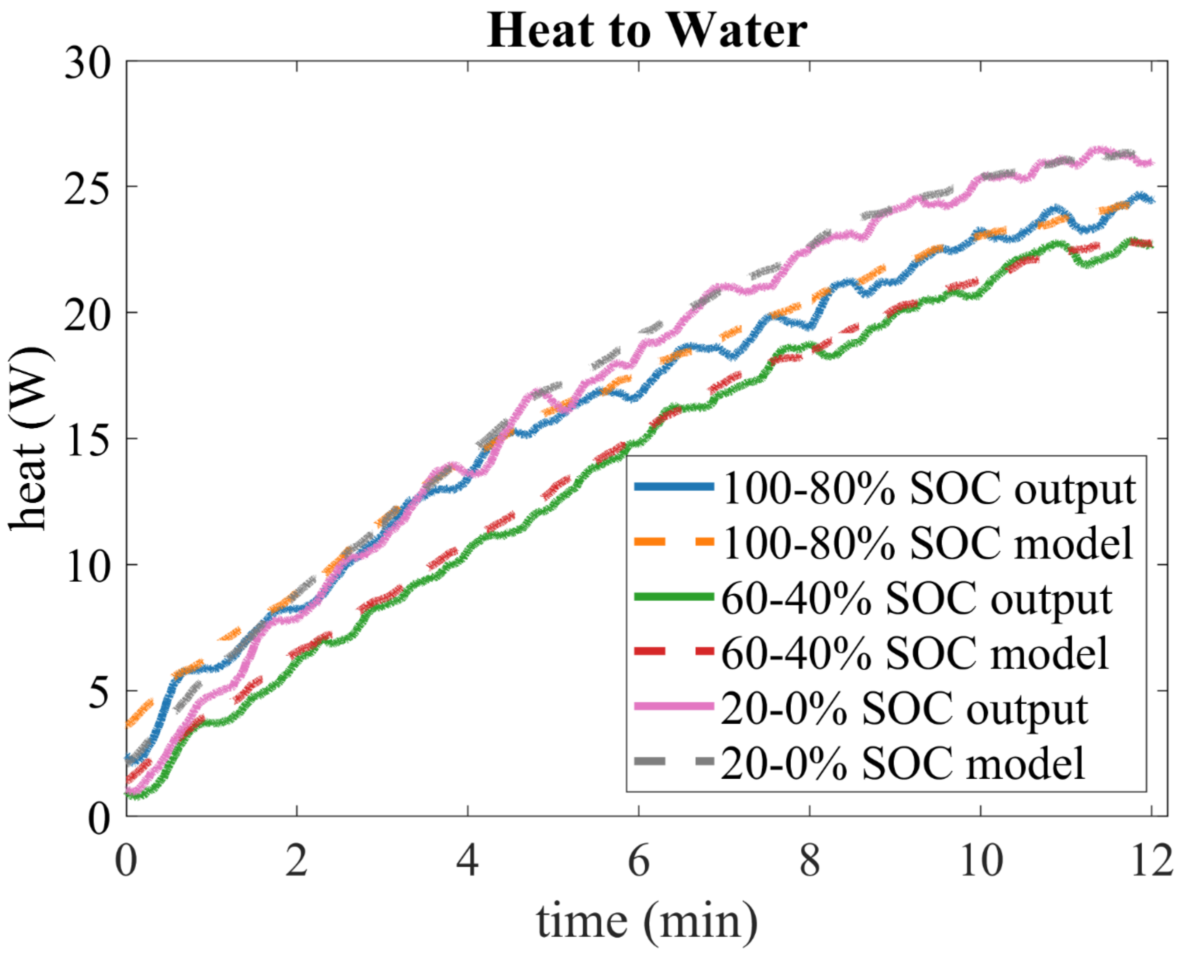
- A 1C-rate discharge was performed at 100-80%, 60-40%, and 20-0% SOC
  - Captures regions of highest and lowest DC Internal Resistance
- Displays rapid testing capability
  - No recharge, discharge to SOC, or rest necessary between tests





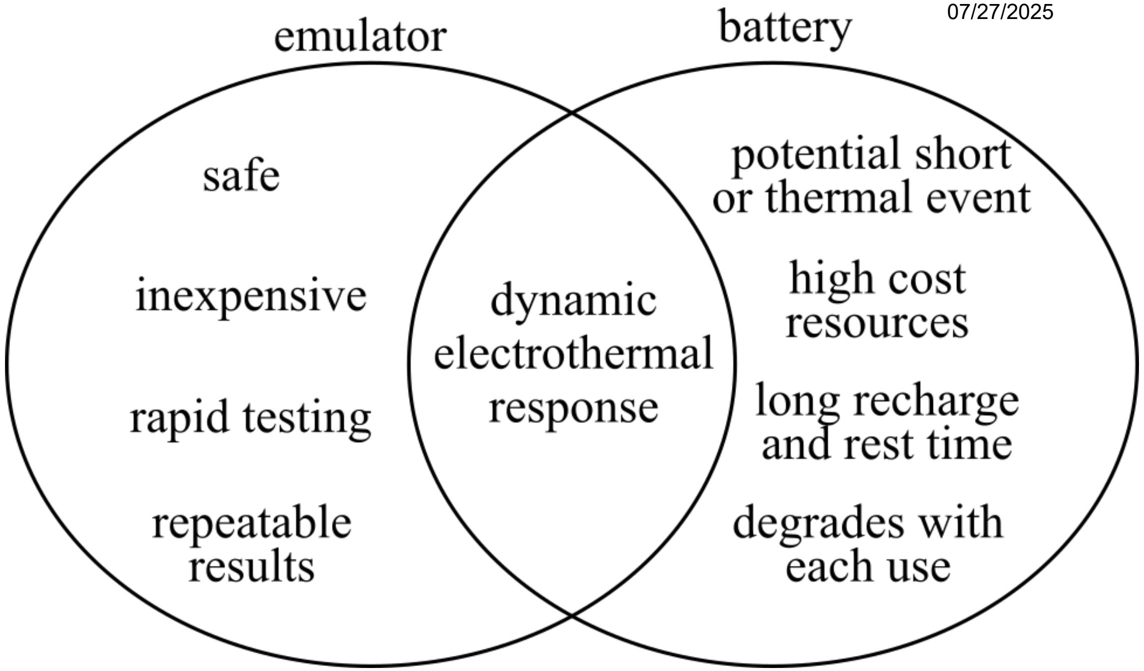
SOC discharge differences





Conclusion & Future Work

- Electrothermal battery emulator
  - Reproduces stable electrical and thermal dynamics
  - Pipeline for cell data to be used for pack level
- Future work
  - Machine learning model
  - Minor hardware tuning
  - Integrating emulator for HIL testing
  - Larger pack scaling with Egston



Publications

Previous Works

[1] Jarrett Peskar, Kerry Sado, Austin R.J. Downey, Kristen Booth, and Jamil Khan. Battery emulator for coupled electro-thermo powertrain testing. *244th Electrochemical Society (ECS) Meeting*, 2023 (awarded travel grant)

[2] Jarrett Peskar, Austin R.J. Downey, Jamil Khan, and Kristen Booth. Progress towards a coupled electro-thermo battery emulator. *2023 IEEE Electric Ship Technologies Symposium (ESTS)*. IEEE, aug 2023. doi:10.1109/ests56571.2023.10220565

[3] Jarrett Peskar, Nicholas Liger, George Anthony, Austin R.J. Downey, and Jamil Khan. Coupled electro-thermo battery emulator. *2023 Battery Safety Workshop*, June 2023

[4] Jarrett Peskar, Austin R.J. Downey, Jamil Khan and Kristen Booth. Development of a Coupled Electro-thermoBattery Emulator for Ground Test Platforms. *NASA Aerospace Battery Workshop*, November 2022

Accepted

[1] Connor Madden, Jarrett Peskar, Austin R.J. Downey, Kerry Sado, and Jamil Khan. Deep Neural Network-based Modeling of Electro-thermal Lithium-ion Batteries Responses Leveraging Hybrid Pulse Power Characterization. *2025 ASME International Mechanical Engineering Congress & Exposition (IMECE)*. American Society of Mechanical Engineers, November 2025

[2] Connor Madden, Jarrett Peskar, Kerry Sado, Austin R.J. Downey, and Jamil Khan. Electro-thermal Hardware-in-the-Loop Battery Emulator for Shipboard Systems Testing. *2025 IEEE Electric Ship Technologies Symposium (ESTS).* IEEE, August 2025

SCEPTER LAB

Acknowledgement

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Thank you!

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