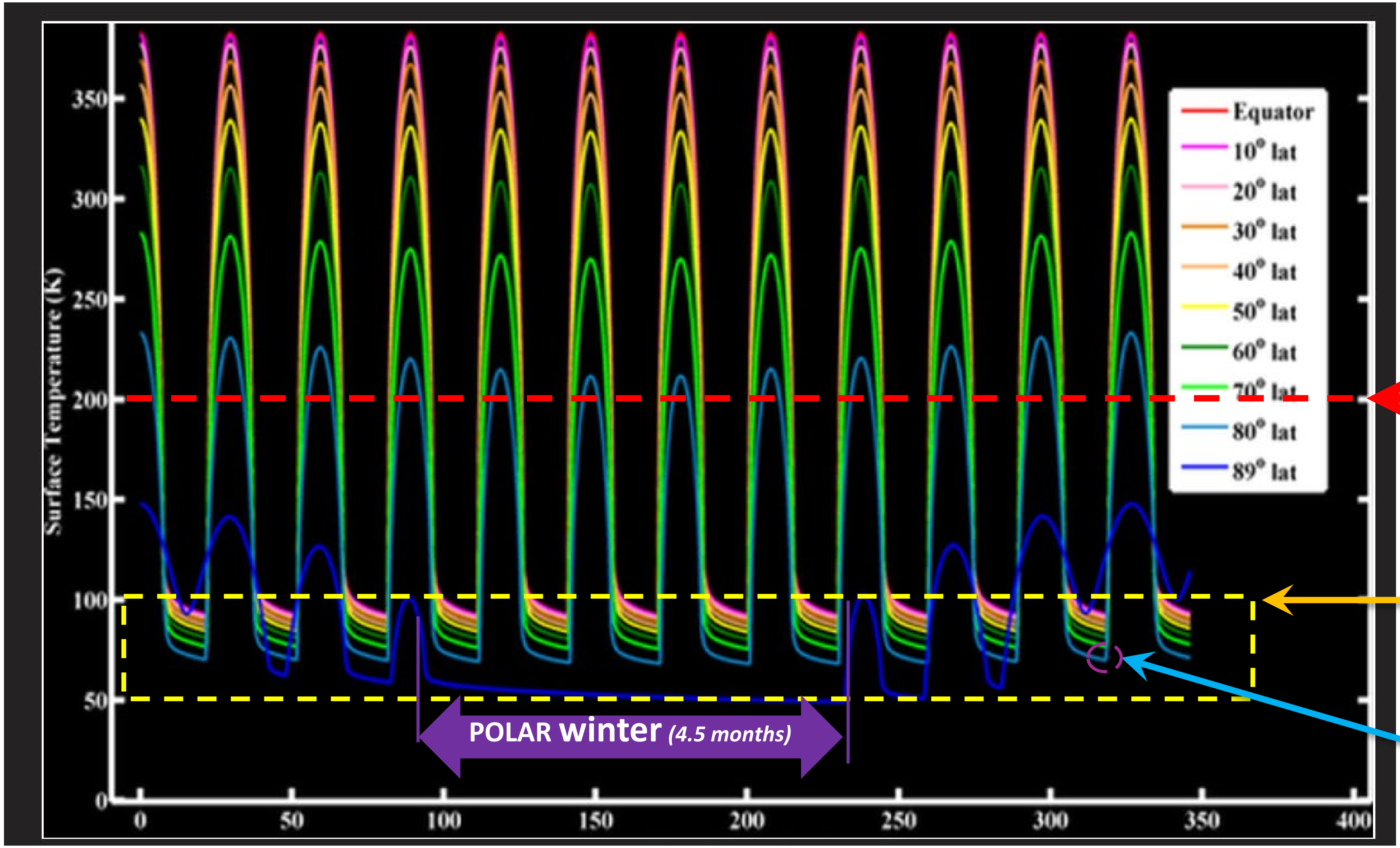
Cryogenic Hibernation Assessment of Commercial Cells for Space Flight Applications

PI & Presenter: Dr. Brian Holler, NASA GRC - LEX

IAPG CWG Spring 2026

The Extreme Lunar Environment

Thermal model calculations of monthly & annual lunar surface temperature variations at various latitudes



- **Day**: 150-400 K highs based on latitude
- **Night**: 50-100 K lows *all latitudes*

  Duration (non-polar): ~354 hrs (~14.75 Earth days)
- **Lunar Polar Winter:** Sun is below horizon for ~4.5 months

Li-ion battery approx. freeze temperature

Lunar night is extremely cold *at all latitudes*

Lunar dawn

Image permissions per Dr. N Petro/NASA GSFC, Dr. D Paige/UCLA

CLPS
COMMERCIAL LUNAR PAYLOAD SERVICES

National Aeronautics and Space Administration

January 2024
Peregrine Mission One
Astrobotic

Mission Failure before landing
<u>Did not reach lunar surface</u>

March 2, 2025
Blue Ghost 1
Firefly Aerospace

Landed successfully, operated for the lunar day
Operated ~5 hours into lunar night, then lost power

2024

2025

February 22, 2024
IM-1 (Odysseus)
Intuitive Machines

Soft-landed (but tilted)
Mission ended at Dusk
<u>Did not survive lunar night</u>

March 6, 2025
IM-2 (Athena)
Intuitive Machines

Landed sideways
Power depleted soon after landing
<u>Did not survive into night</u>

ICE CHILL

Integrated Cryo-operable Electronics to Conditional Hibernation for Li-ion Longevity

NASA Glenn Research Center, contact: brian.a.holler@nasa.gov

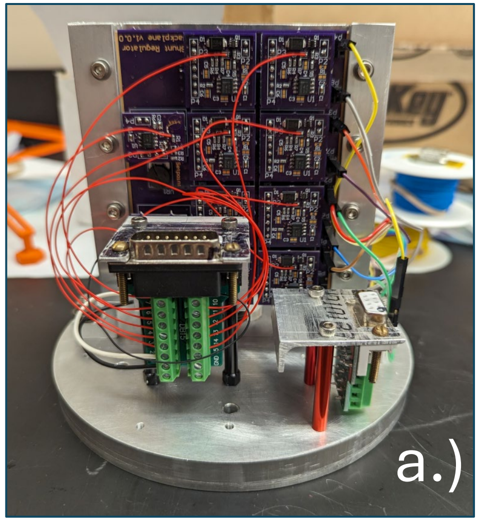
Project Overview

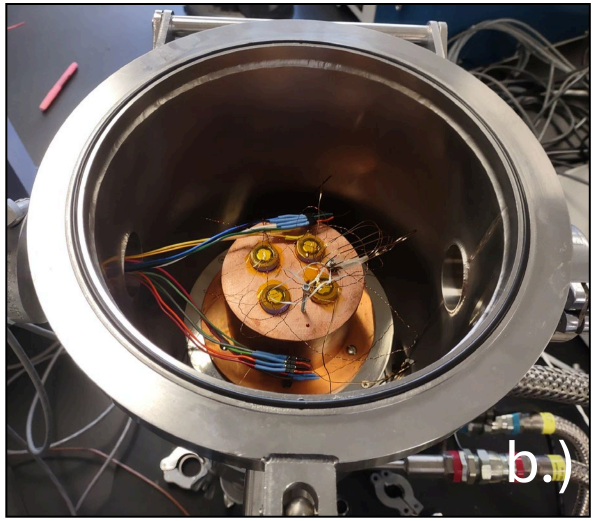
Description and Motivation:

- **Batteries and battery management systems are not designed to survive the extreme cold of the lunar night**, which restricts available missions
- Develop and demonstrate **a novel, easily integrable BMS** to enable Li-ion battery hibernation passively through the lunar night with zero excess degradation
- Enables **longer mission time** (>1 lunar day) with **minimal impact on system size** or payload capacity
- Allows for a **significant launch cost savings** due to the reduced required battery mass when compared to current solutions

Primary Project Objectives:

- **Design** and **build** an integrated battery package/electronics system demonstrating lunar dawn mode to **enable Li-ion cell hibernation** through the lunar night (*Phase 1*)
- Experimentally determine **battery cell survival conditions** with a zero-degradation criterion to inform PHM inclusion in microcontroller embedded electronics (*Phase 2*)
- Perform **appropriate environmental tests** of each design to raise technology readiness level (TRL) from 3 to 5





a.) Cryo-operable Solar Shunt Regulator to enable Lunar Dawn Recover Mode.
b.) Commercial 18650 Li-ion cells in cryochamber for low-temperature hibernation down to 50K.

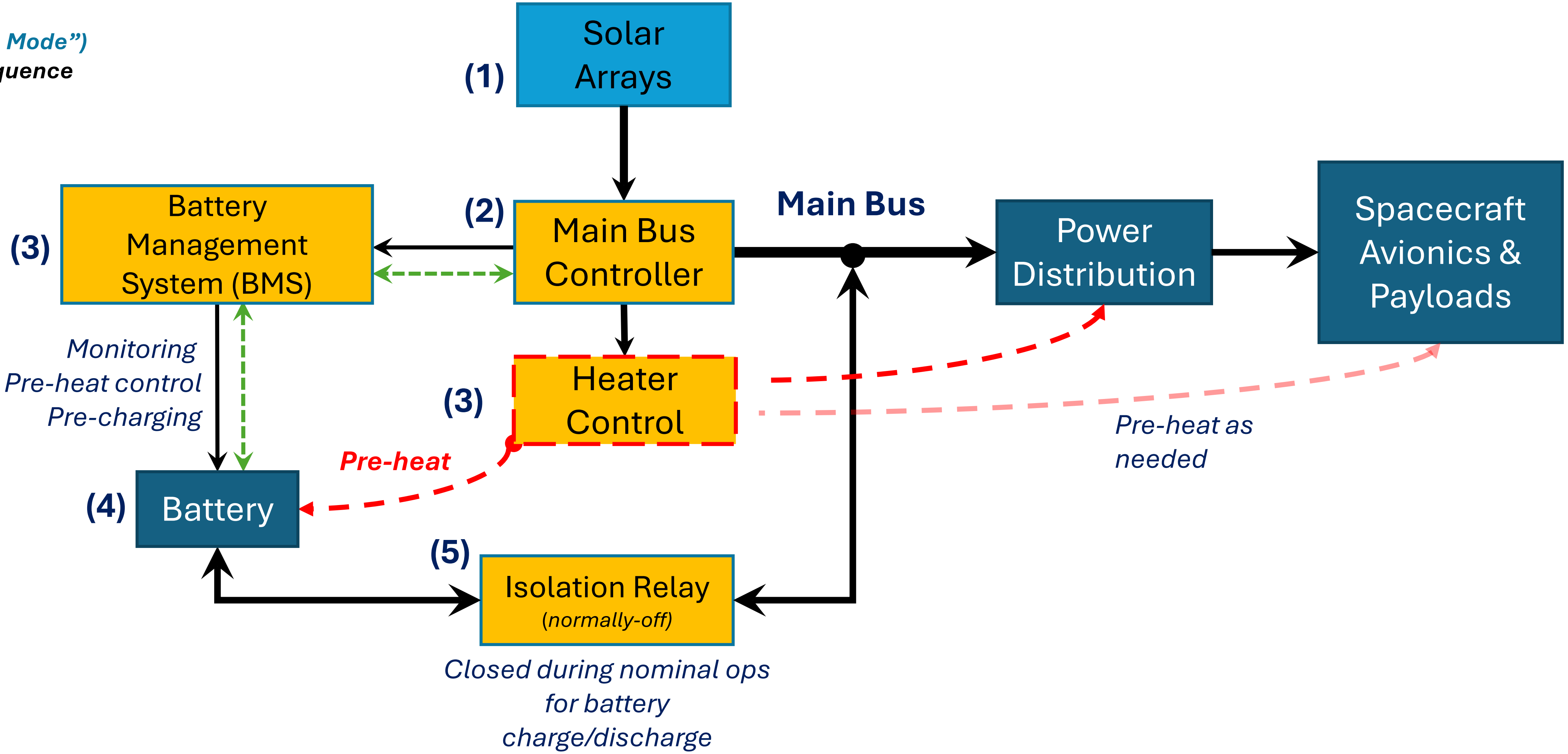
ICE CHILL **Technology**

Current Solution	Phase I	Phase II
Either **only operate for 1 lunar day** *or* requires up to **1000s of kWhs** to stay warm during lunar night • Mass • Money • Power	*Passively* survive a single lunar night → **100% mission life increase** → **Reduction in required mass and redevelopment costs**	Efficient hibernation protocol, smart BMS, state-of-health prediction → ***Many* more lunar nights!**

Concept of Operations

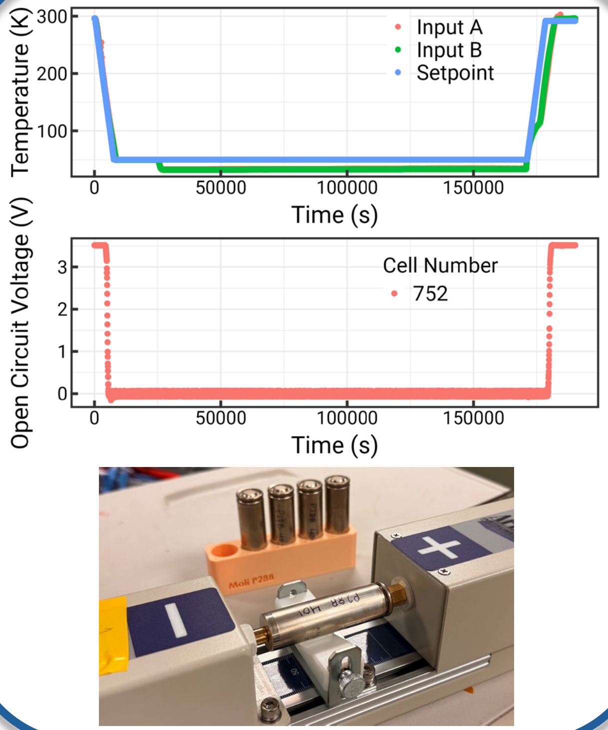
Key
Cryo-tolerant
Cryo-operable ("Dawn Mode")
(#) – Dawn start-up sequence

→ Power
→ Thermal
→ C&DH

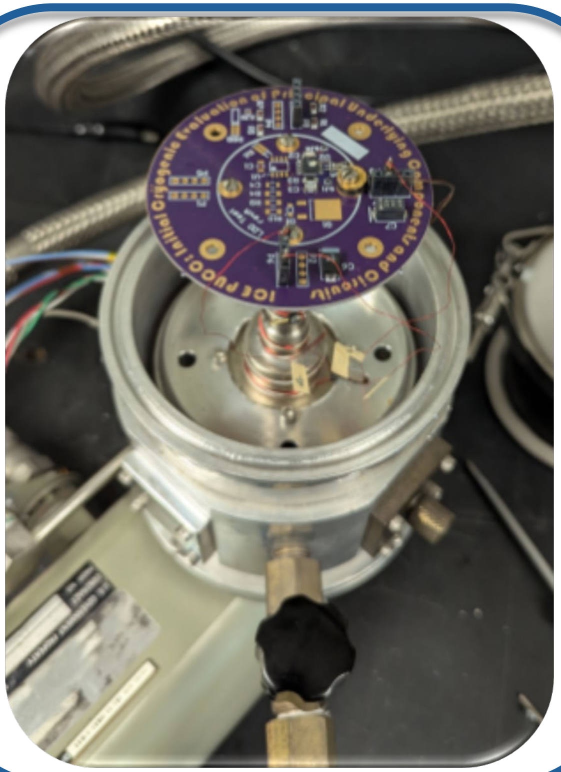


Technical Status Overview

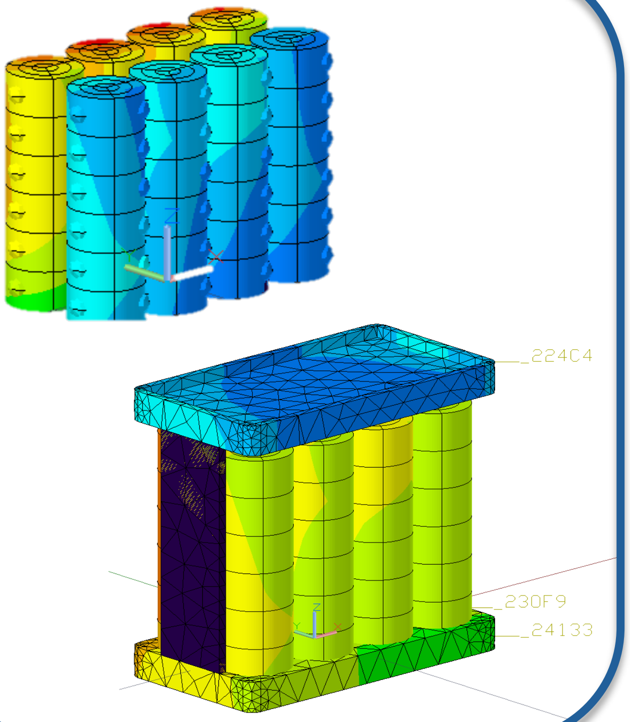
Battery Characterization



Electronics Development



Thermal and Case Design



Technical Status Overview

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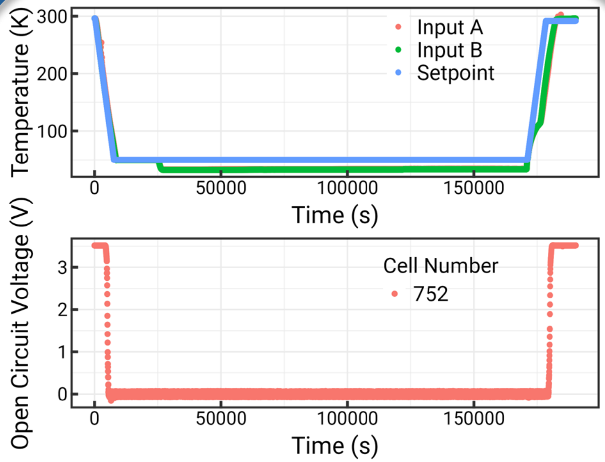

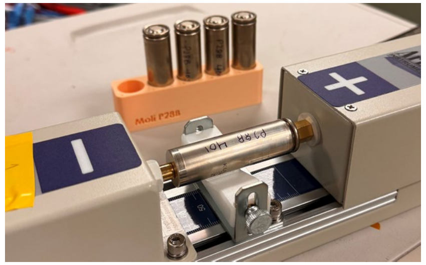

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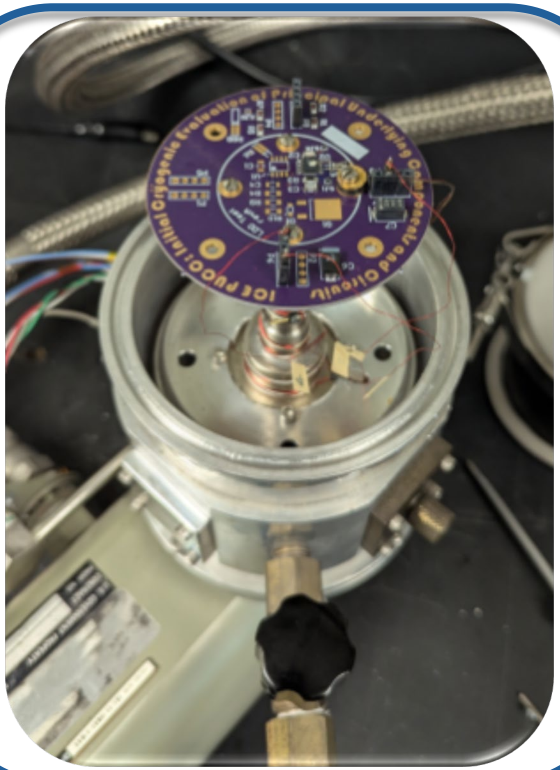

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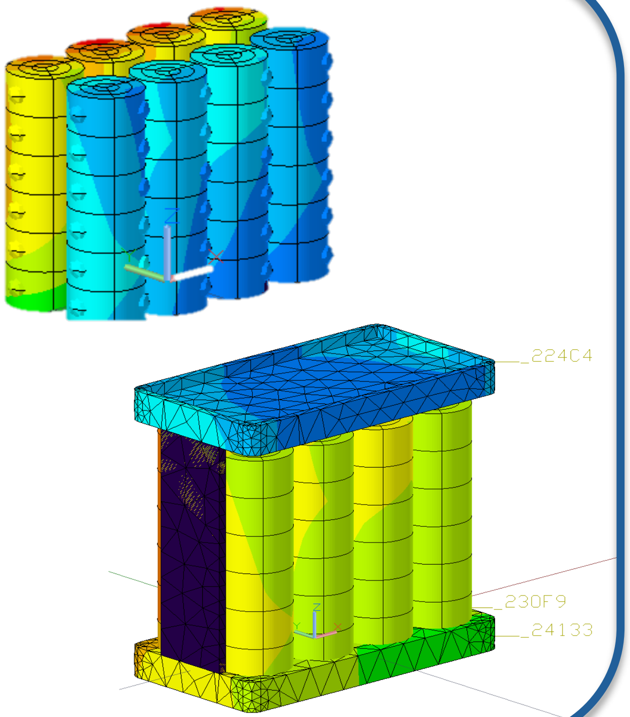
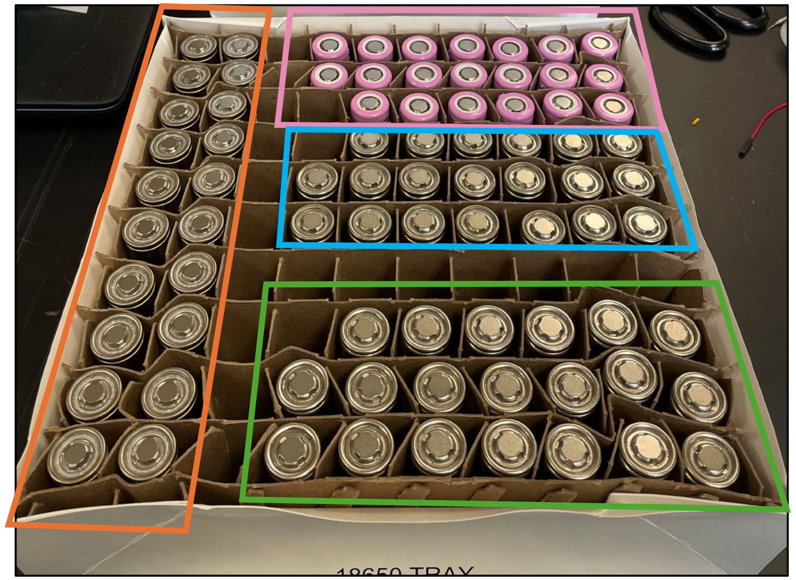
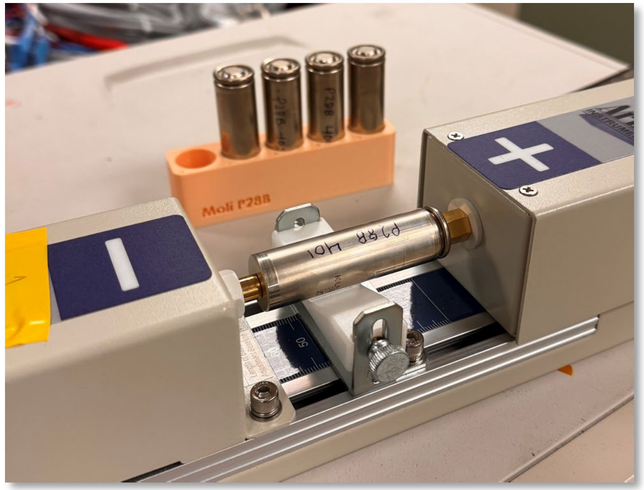


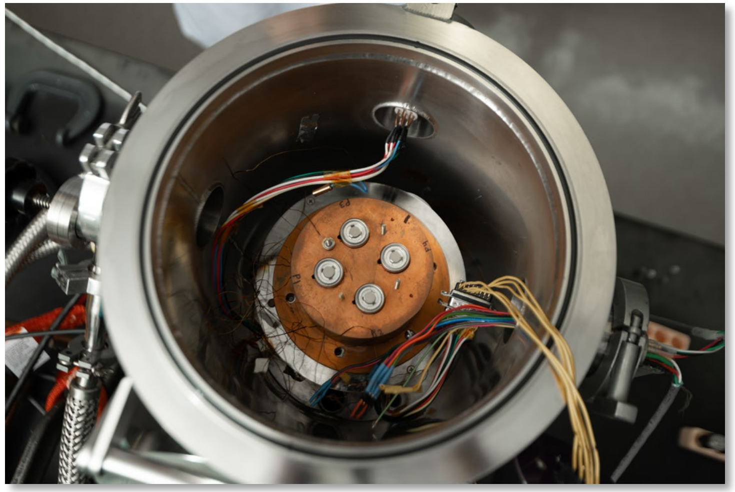
Battery Cryogenic Testing

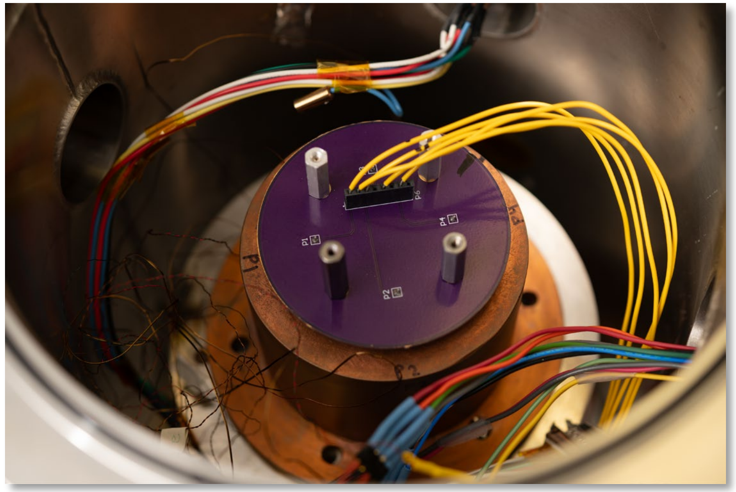


Manufacturer	Model	Capacity (Ah)
Samsung	Q30	3.0
LG	M36	3.6
Molicel	P28B	2.8
Molicel	M35A	3.6

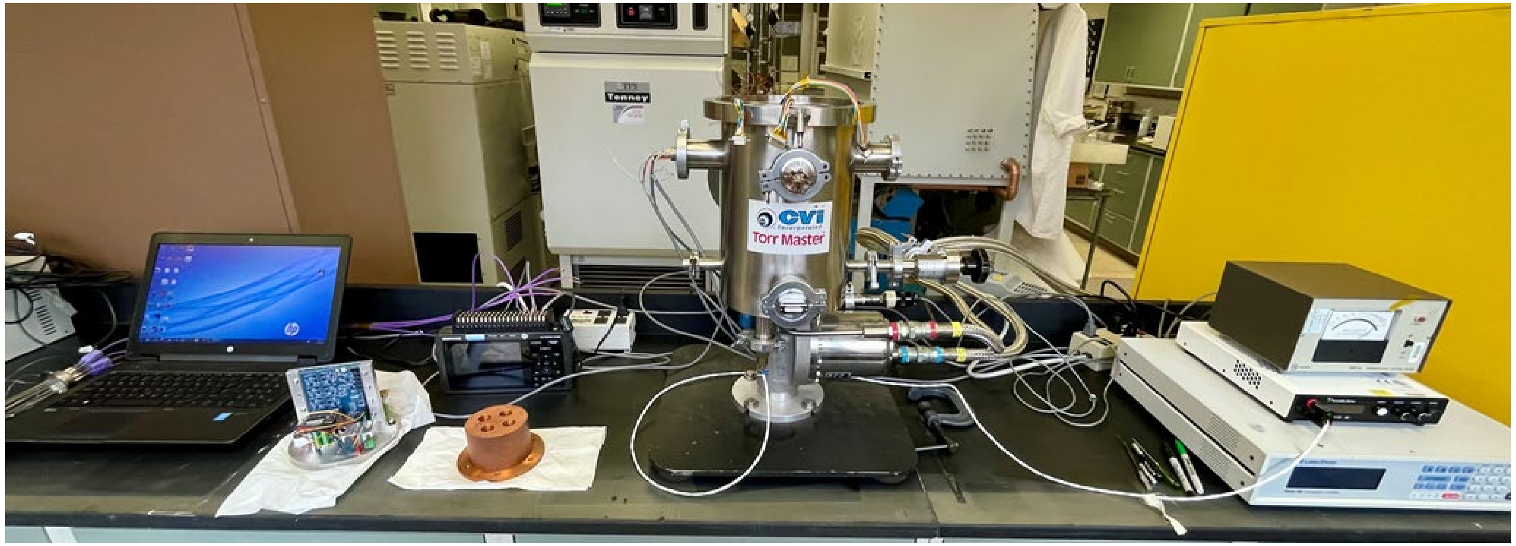
1. Preliminary Electrochemical Cycling, establishment of test charge level (0%, 100%)
2. Preliminary Electrochemical Impedance Spectroscopy (EIS)
3. Cryo-Hibernation Event
4. Post Electrochemical Cycling
5. Post EIS

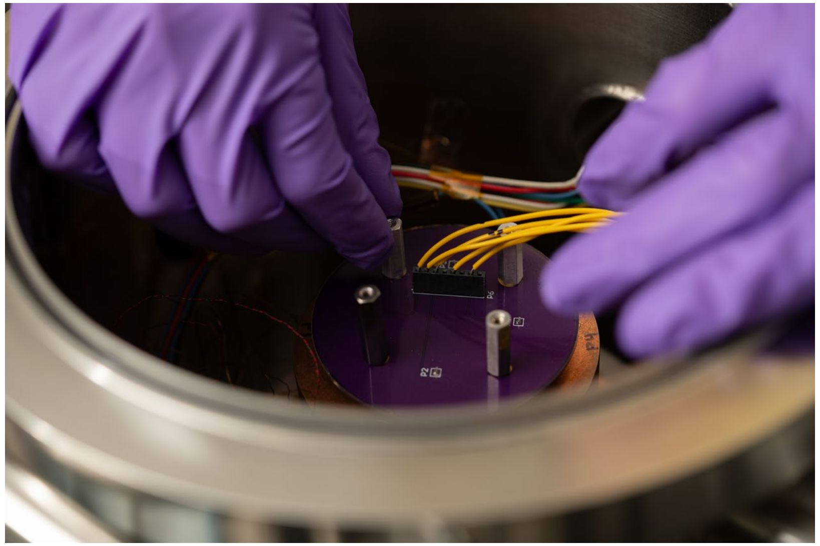


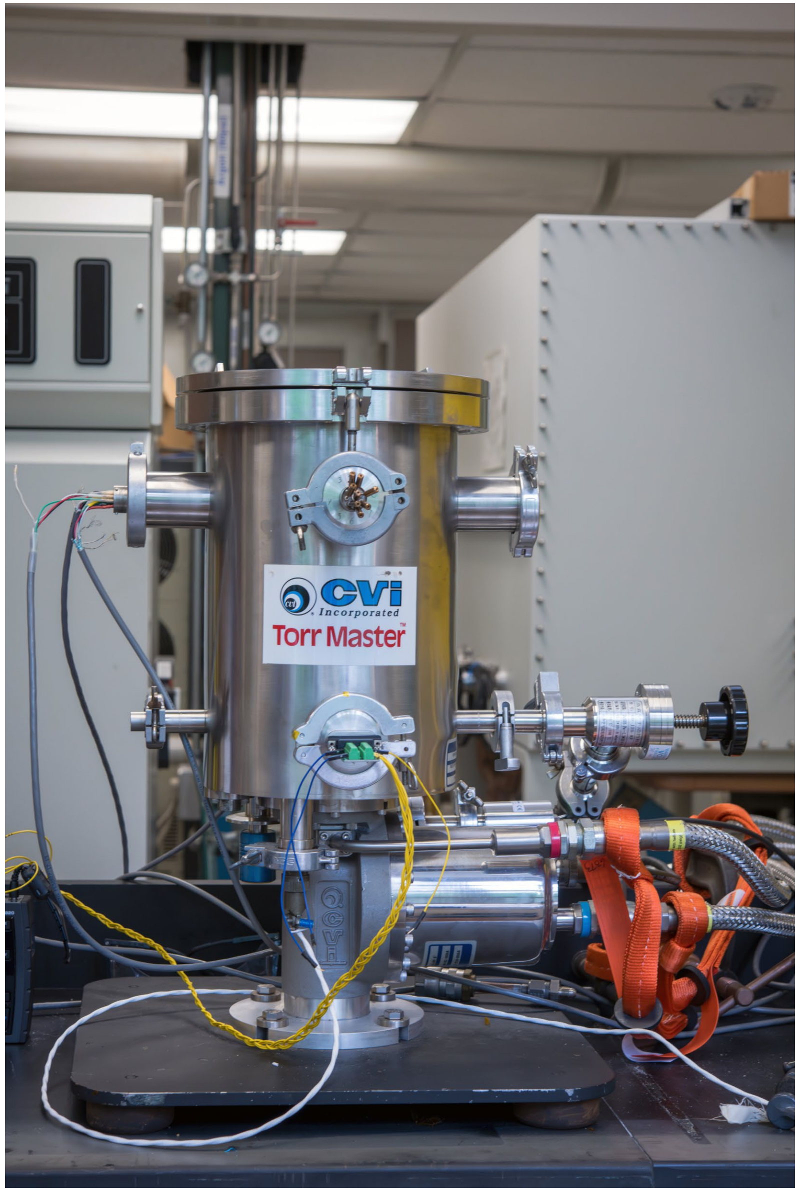




Cryochamber Test Setup







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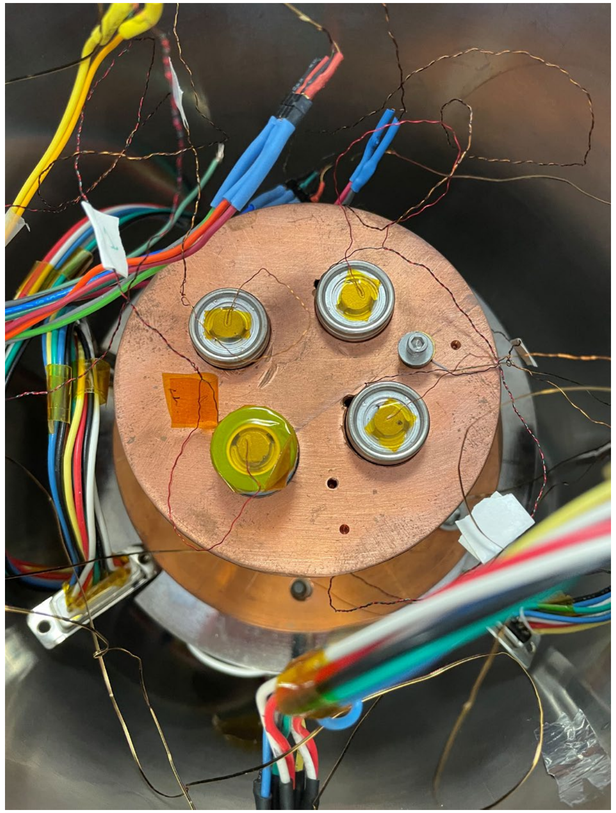
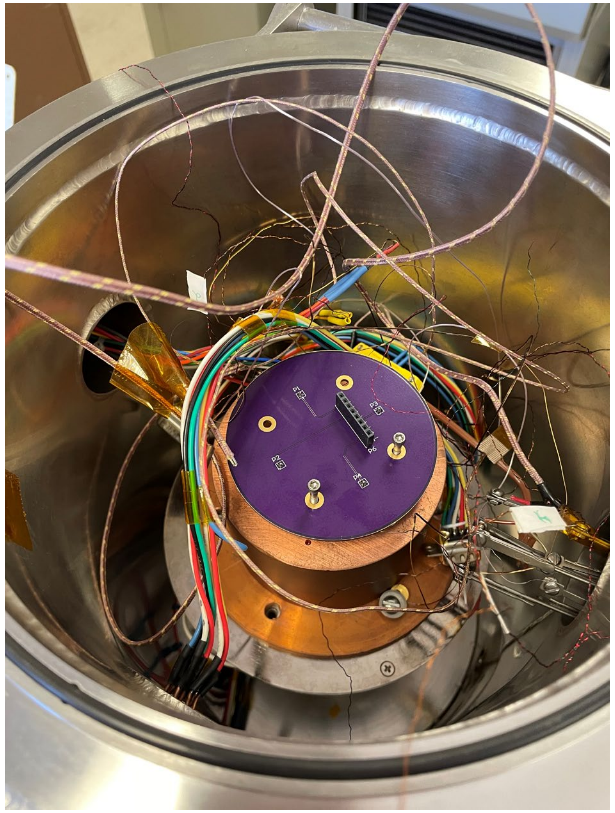
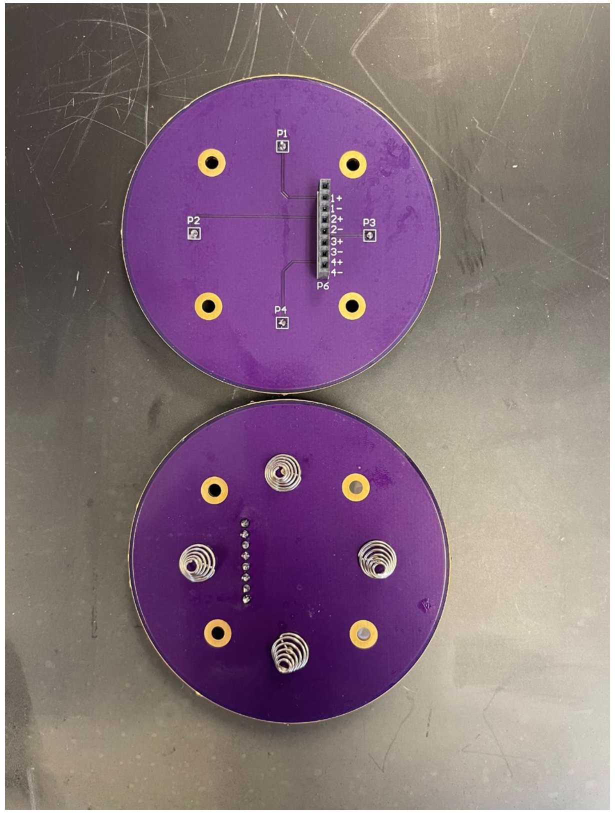
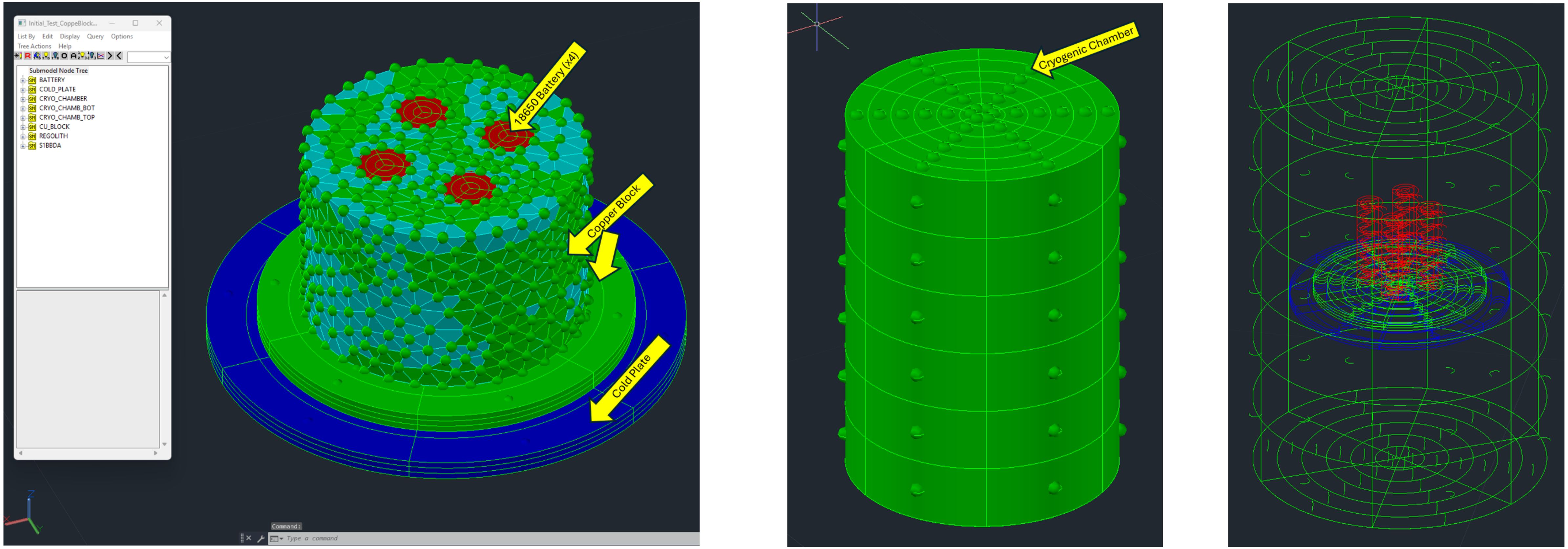






Gen 1 Thermal Model and Thermal Environment

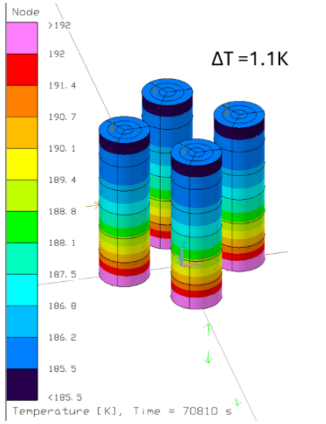


Focused on Cryogenic Chamber environment and its lunar equivalent

Starts at 293.15K, cooldown rate 2K/min till it hits 50K, dwells at 50 K for 8 hours, then warms up in temperature either naturally or at 2 K/min.

Parametric Studies

Had concerns of degradation via temp gradients across the cell:
In Situ Observation of Thermally Activated and Localized Li Leaching from Lithiated Graphite | ACS Energy Letters - Harrison Szeto, Vijay Kumar, and Yangying Zhu, *ACS Energy Letters* **2024** *9* (9), 4218-4224, DOI: 10.1021/acsenergylett.4c01571



Thermal Response of Batteries with Cp = 5000 J/kg/K

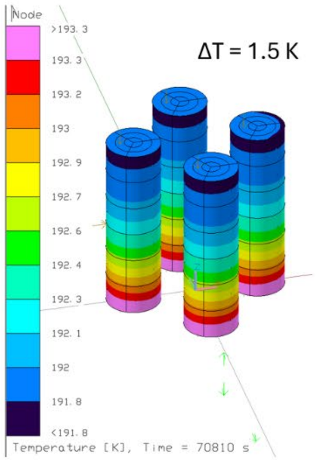
Investigated battery thermal properties and Copper Block contact

Heat Capacity (C_p)

- **Parametric sweep:** 800–5000 J/kg/K.
- **With Copper Block:** sensitivity at ~2500 J/kg/K ($\Delta T \approx$ 3K); ~6.5K at 5000 J/kg/K.
- **Without Copper Block:** larger ΔT across batteries.
- **Realization:** Copper Block acts as a thermal dampener, masking gradients → $\Delta T < 1$K at high C_p.

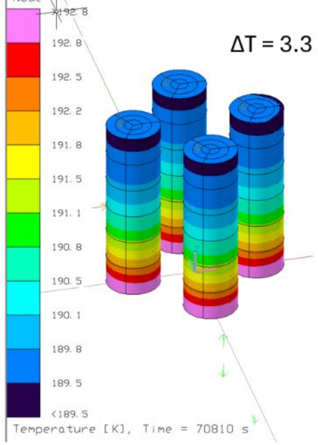
Thermal Conductivity (κ)

- **Isotropic sweep:** 1–100 W/m/K without Copper Block.
- **Literature**: ~13 W/m/K.
- Even extreme values (100 W/m/K) → negligible impact

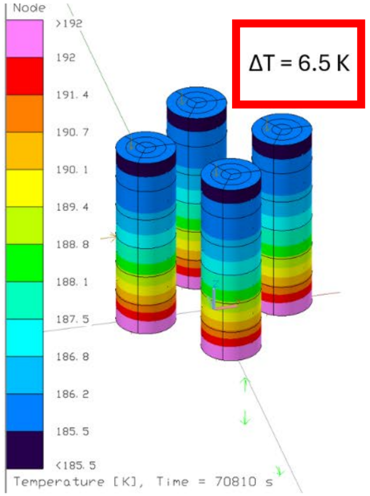


Thermal Response of Batteries with Cp = 1000 J/kg/K

With Copper Block



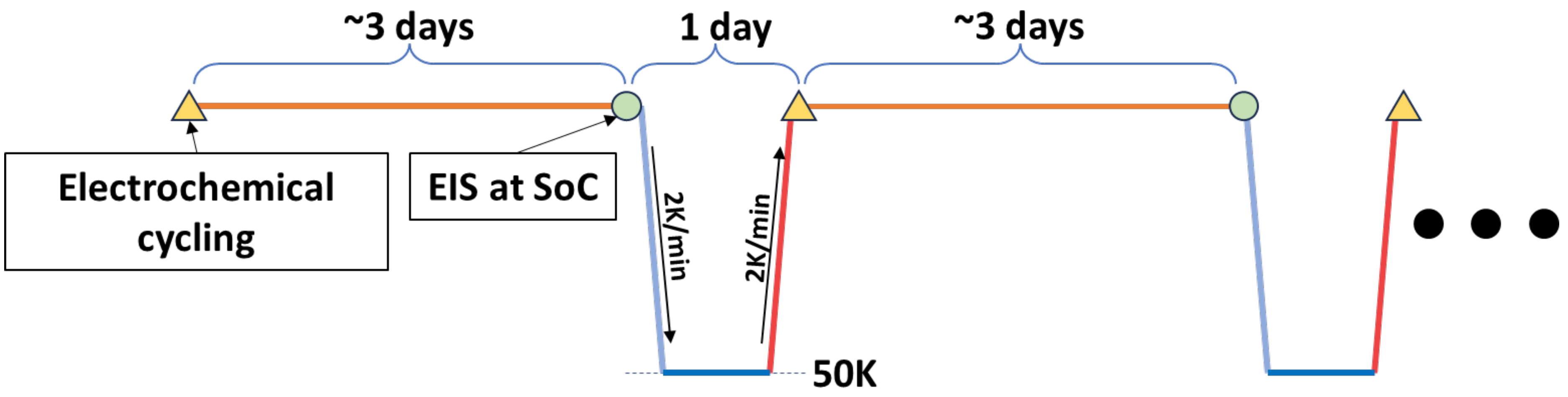
Thermal Response of Batteries with Cp = 2500 J/kg/K

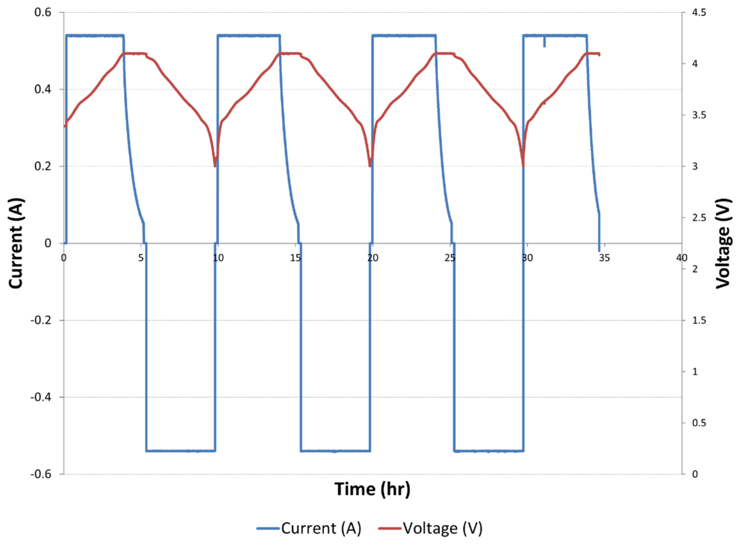


Thermal Response of Batteries with Cp = 5000 J/kg/K

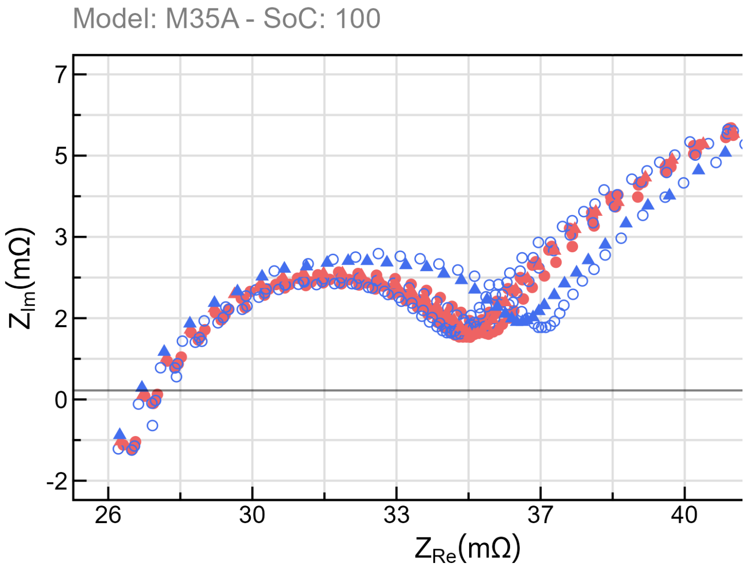
Passive Battery Hibernation Testing

Combinatorial Test Matrix
- State of Charge
- Temperature Ramp Rate
- Dwell Time

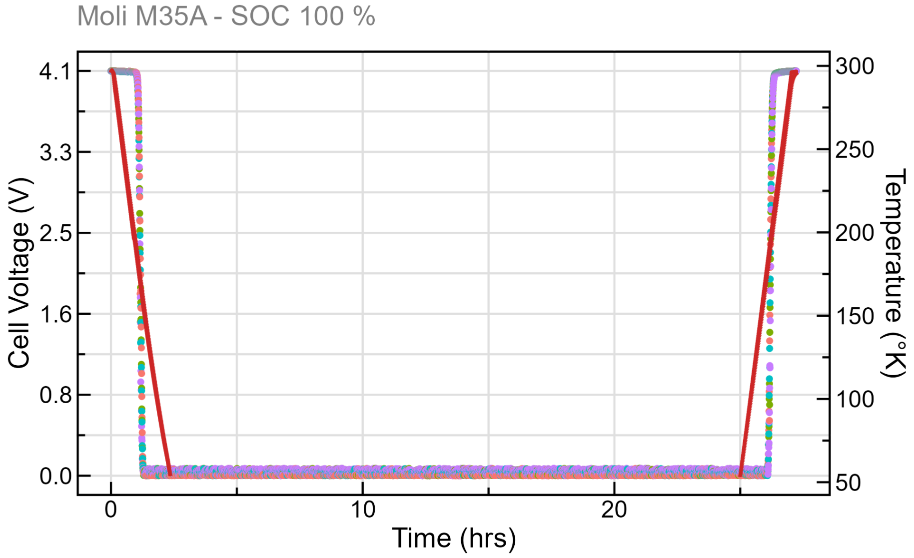




Electrochemical Cycling

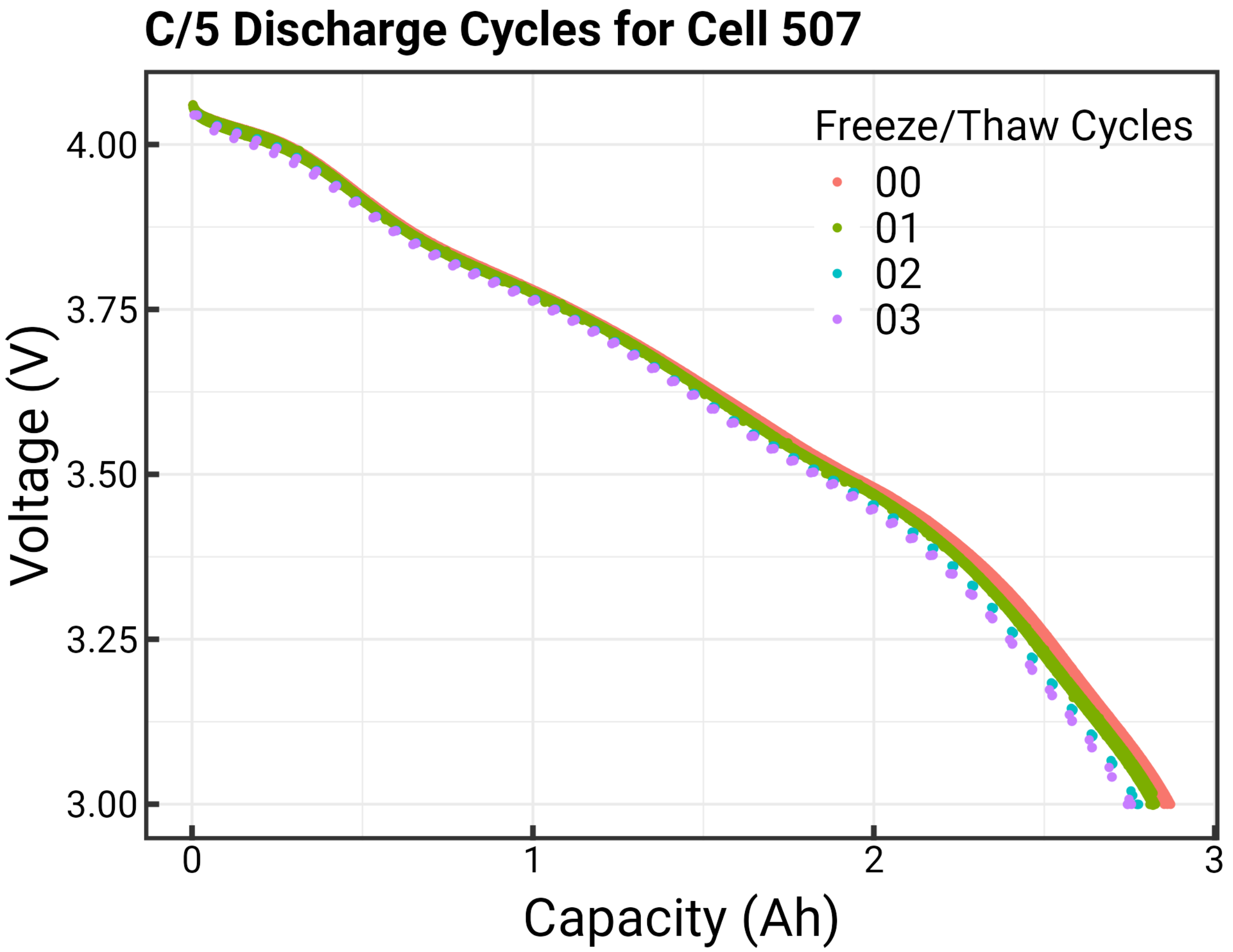


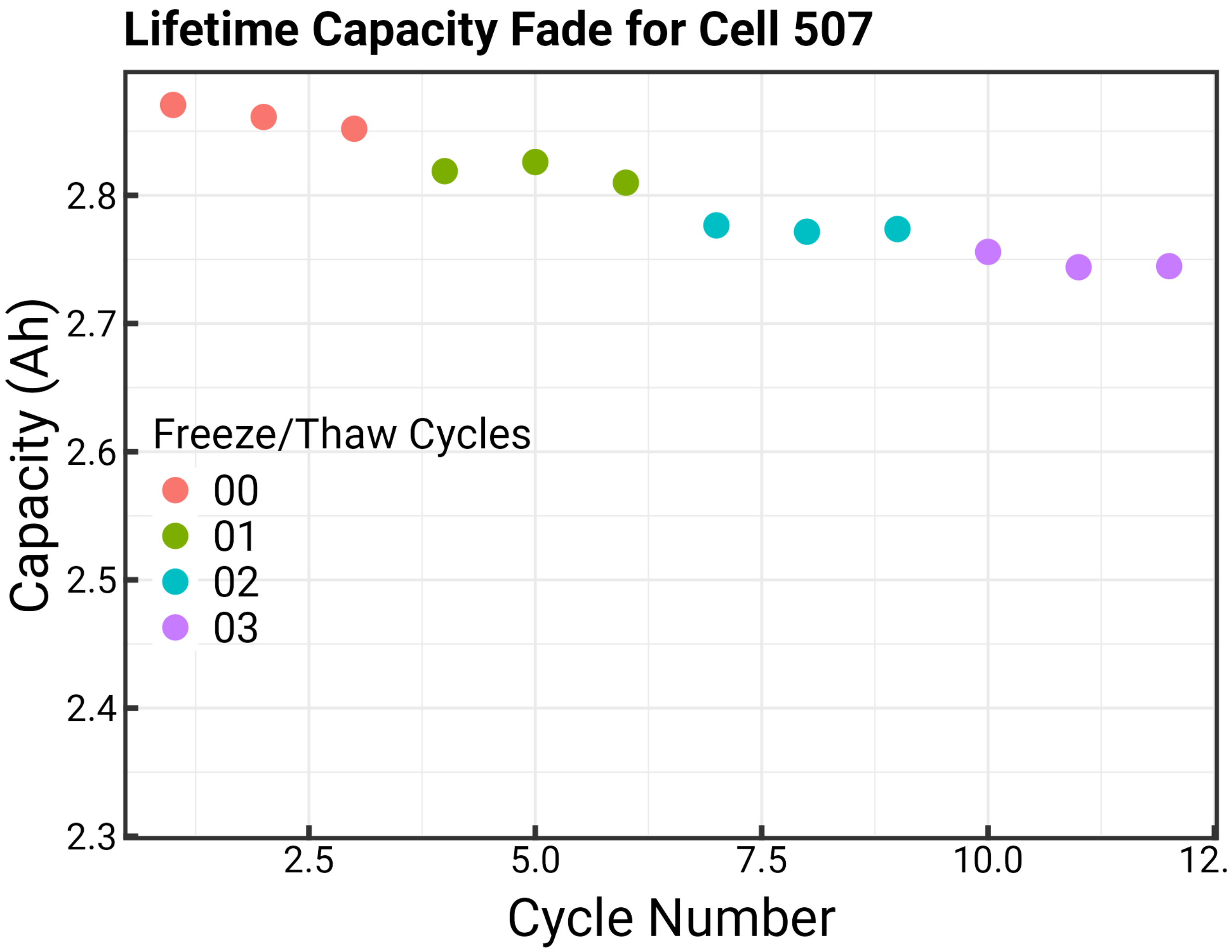
EIS



Cryo-Hibernation

Post-Hibernation Comparison of Cell Behaviors: Cycling



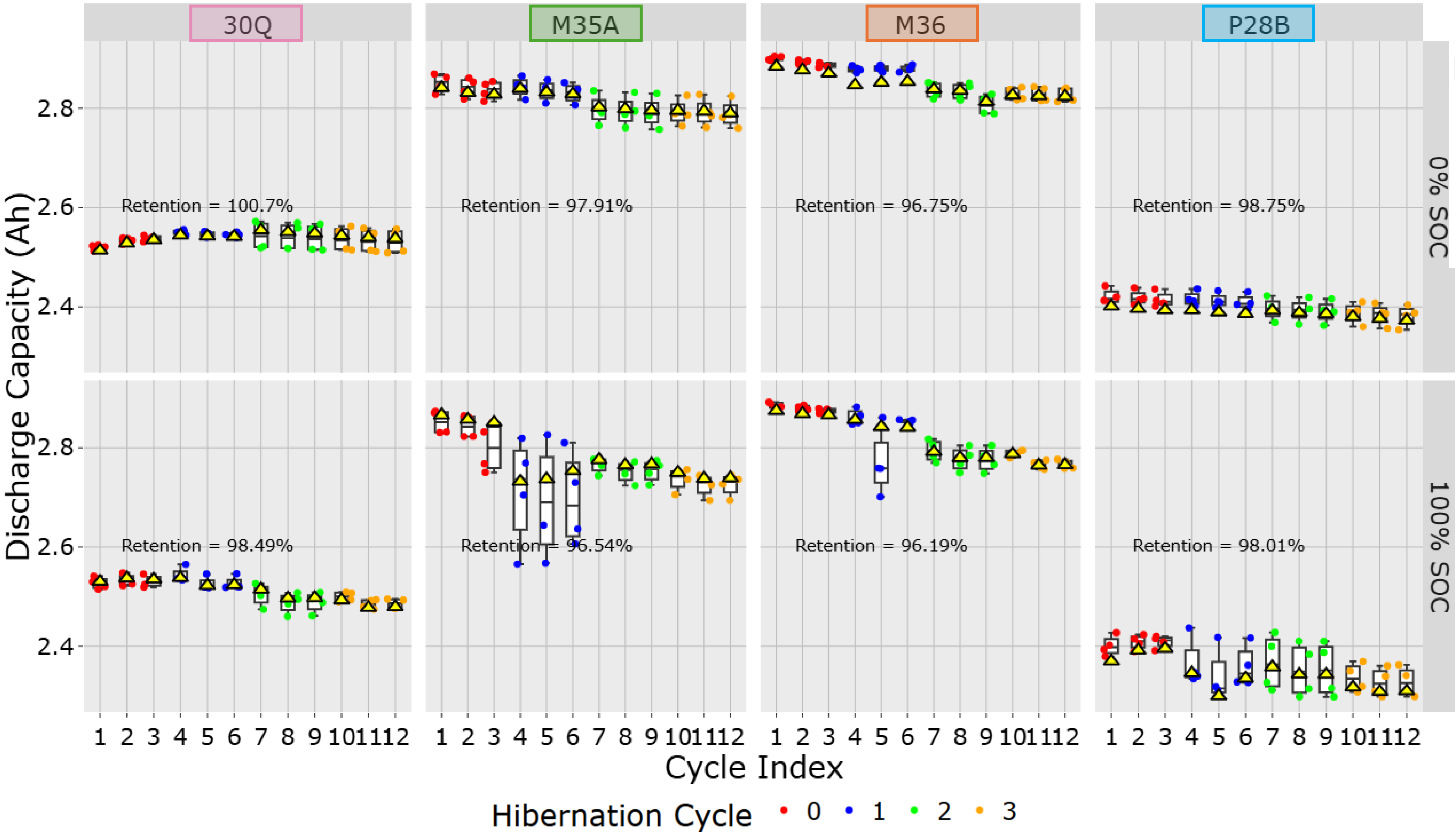


This is representative data: All tested cells showed similar behavior

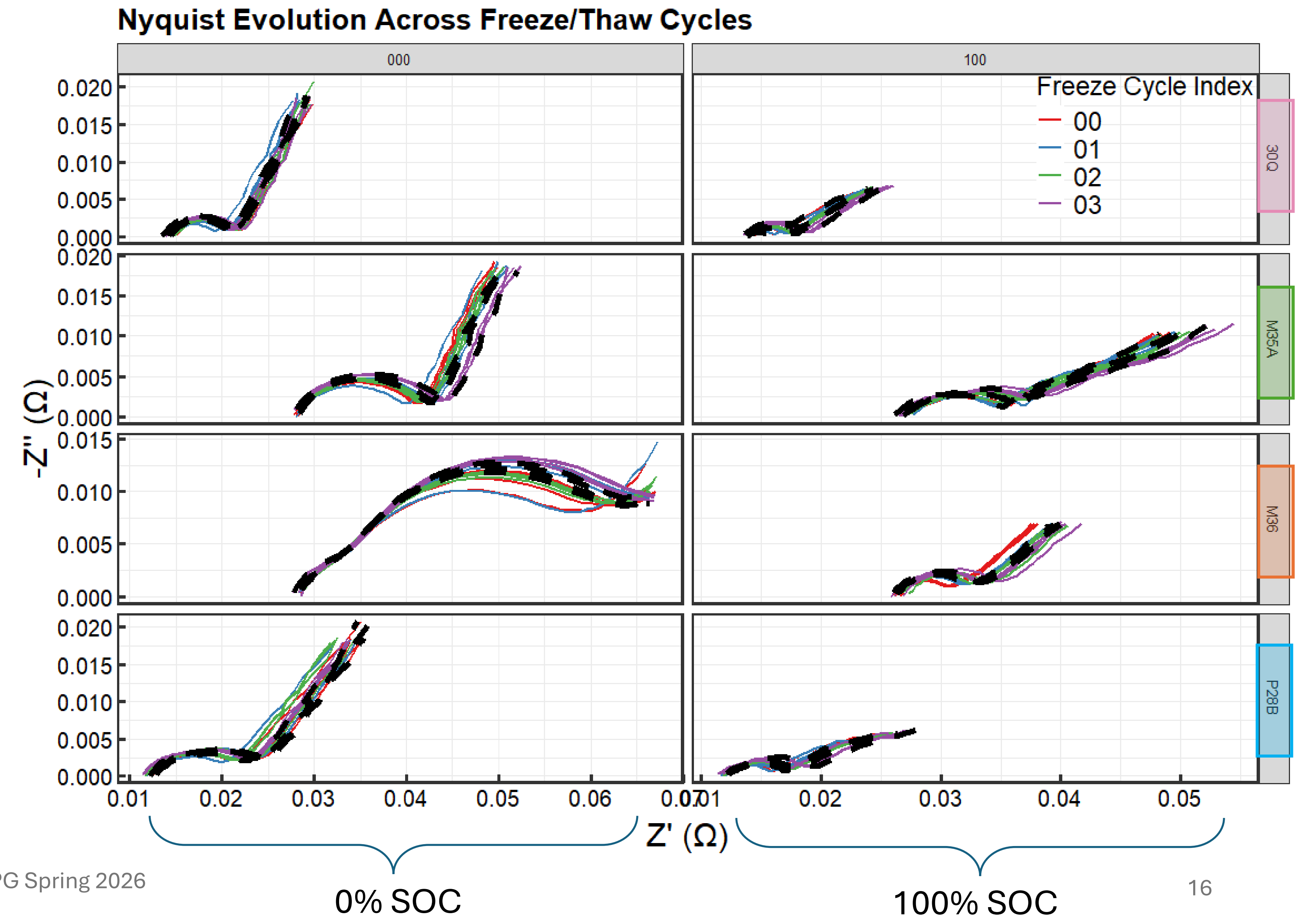
Post-Hibernation Comparison of Cell Behaviors: Cycling

Battery Cycle Testing Test:

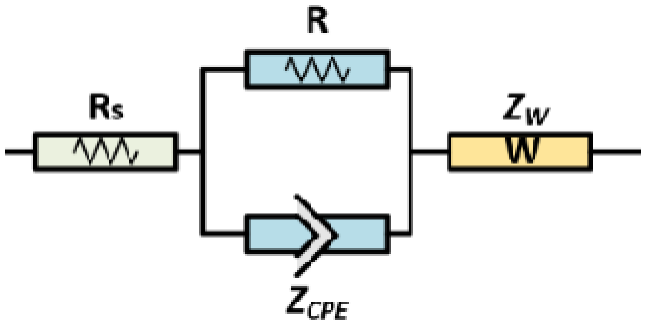
1. Rest 10 minutes
2. Variable Reset
3. C/5 Charge to 4.1V
4. Taper at 4.1V until 50mA
5. Rest 10 minutes
6. Discharge to 3.0V at C/5
7. Repeat steps 1-6 for a total of 3 cycles
8. Charge to designated SoC%

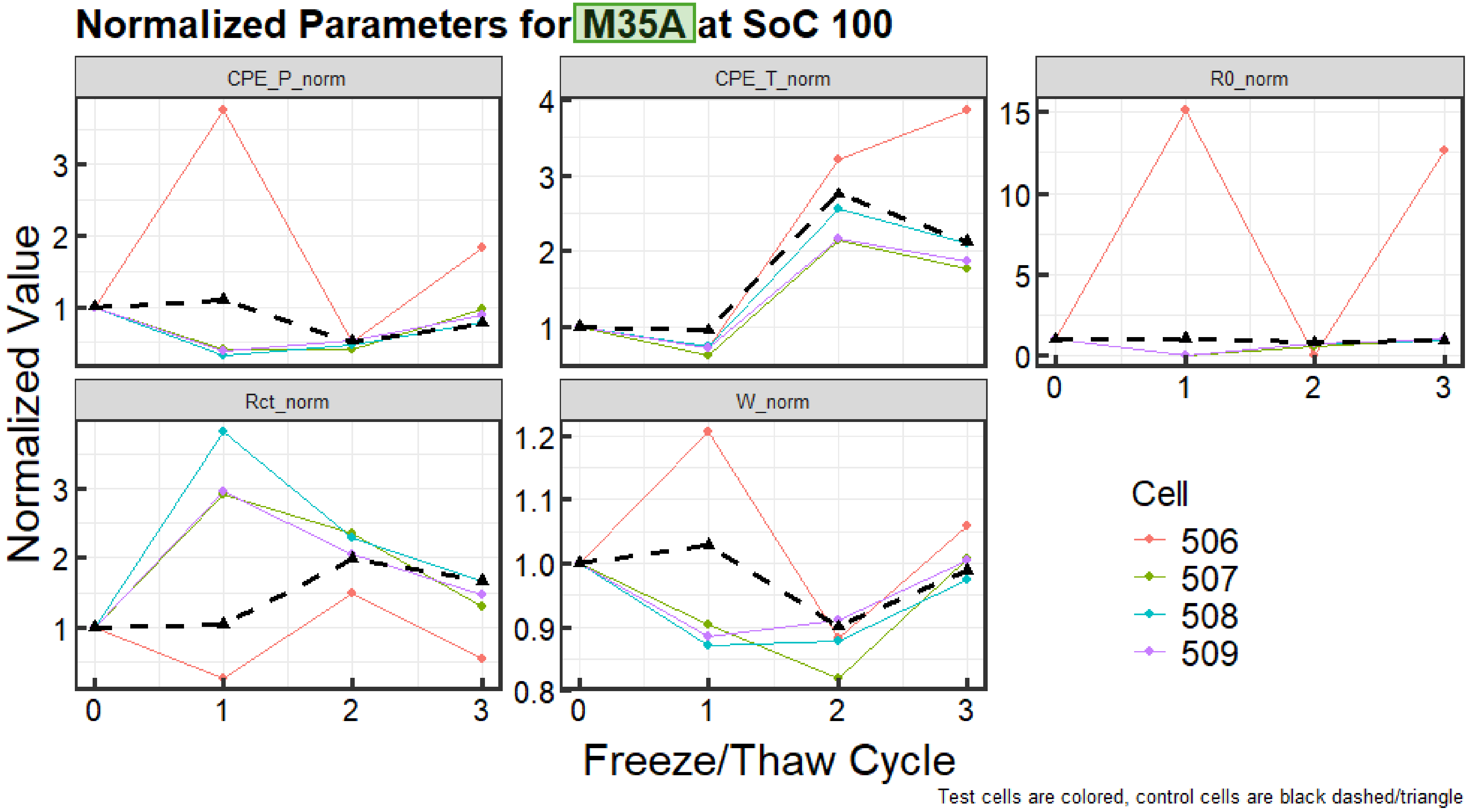


Post-Hibernation Comparison of Cell Behaviors: EIS

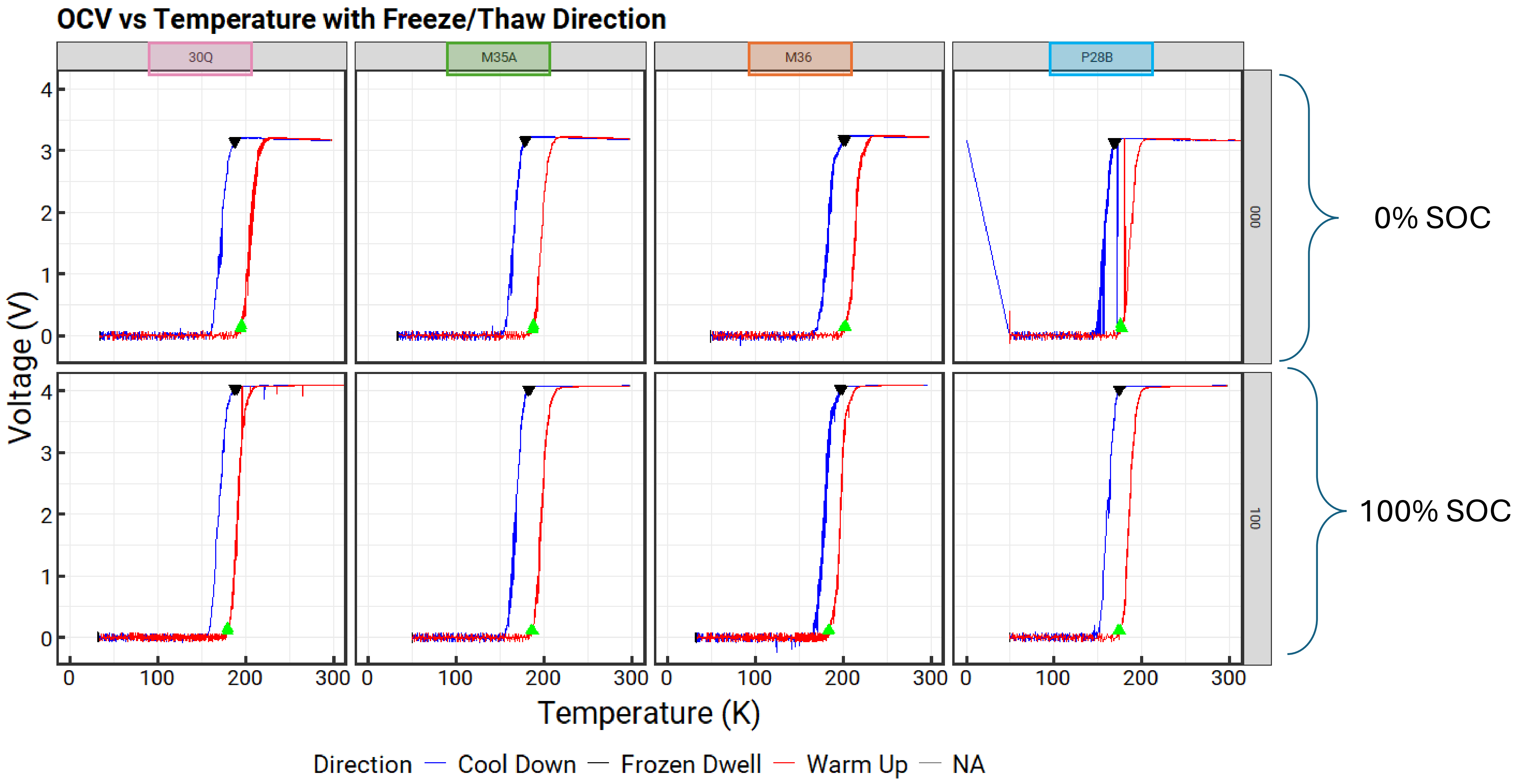


EIS Equivalent Circuit Model Parameter Fitting





OCV Recovery Hysteresis



Cryogenic Testing Current Findings

Big Take-aways (so far)

- Completed full test matrix for **single-lunar-night assessment** across all four Strategic Reserve cell models (working on multiple-night assessment)
- **Validated thermal ramp rates**: No degradation observed when heating ≤ 2 K/min (consistent with lunar maximum rates).
- **Optimized dwell testing:** Demonstrated that extended low-temperature dwell (~14 days) is unnecessary; 1-day dwell sufficient once thermal equilibrium (~8 hr) is reached.
- **Confirmed hibernation success**: All cells recovered OCV and maintained minimal capacity degradation across all tested parameters
- **Preliminary insight:** Depleted cells (0% SoC, lithium stored in cathode) may be more favorable for lunar hibernation.

Upcoming Future Work – Putting it all Together

Battery Future Work
- Continue long-term cycling (>= 100 cycles) to assess cell lifespan across multiple lunar days.
- **Down-select** to two best-performing cell models for higher testing throughput.
- Perform **non-destructive CT scans** (GLIMPSE) to study internal structures.
- Use long-term data to advance **BMS health and charge estimation models.**

Electronics Future Work
- Expand cryogenic testing of circuits, components, and evaluation boards.
- Assess **microcontroller performance** at cryo temps; add heaters as needed.
- Build and validate a **full BMS** integrated with cells in vacuum chamber.

Thermal Future Work
- Analyze **Gen 2 battery pack design**.
- Size heaters to achieve **2 K/min heat-up** (equator vs. South Pole).
- Develop thermal package to meet target heat-up rate.
- Validate **thermal runaway prevention**.

System Level Future Work
- Begin assembly of **8s1p battery pack** (28V, 3Ah, 80W system).
- Integrate BMS with battery system.
- Conduct **environmental testing** (radiation, EMI).
- Finalize and document operational protocols.

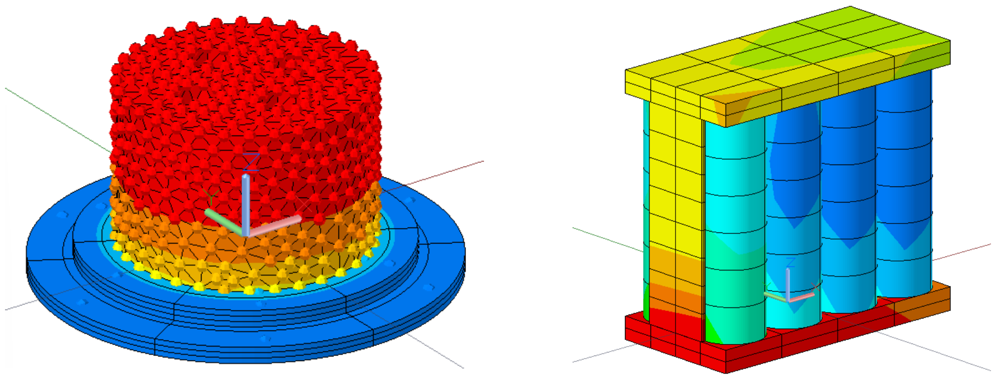
Thank you!

Single-Night Hibernation Works!
- Cells survived initial lunar night testing with minimal degradation

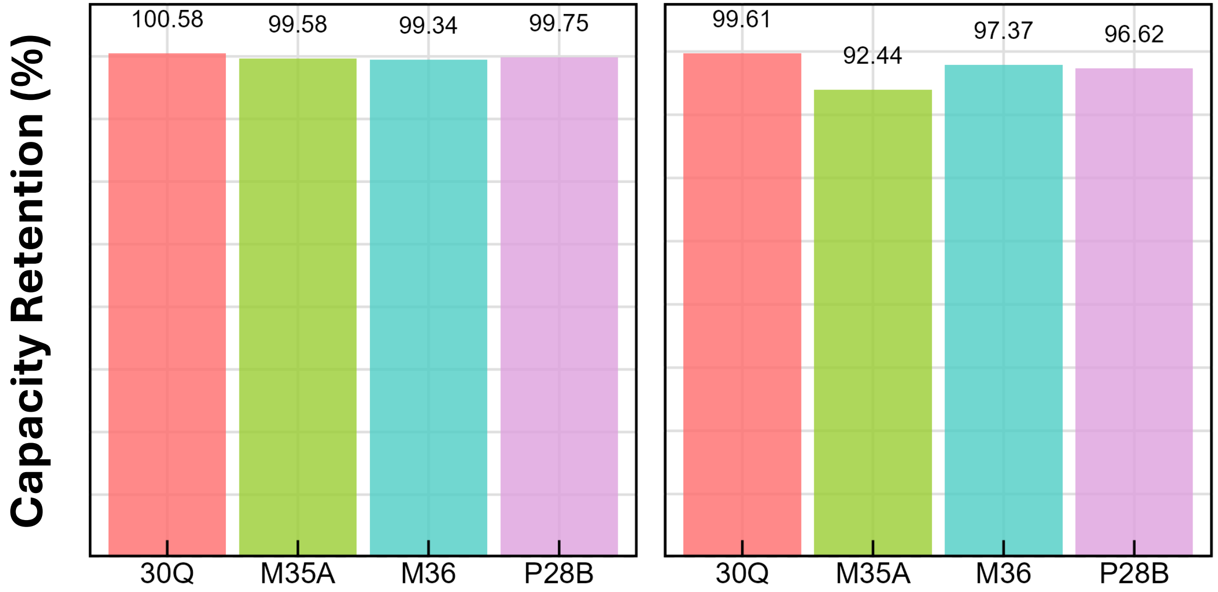
Technology Infusion Underway
- Engaging with Moon-to-Mars programs, rover teams, and lunar infrastructure groups

Next Steps: Multi-Night & Integration
- Wrapping up multi-night evaluations and moving toward full battery + BMS integration

POC:
brian.a.holler@nasa.gov



0% SOC **100% SOC**



Single Night Cryogenic Hibernation Capacity Retention