Integrated Cryogenic Battery and Electronics Development for Lunar Surface Power Systems

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IEEE Workshop on Power Electronics for Aerospace Applications (PEASA)

July 30, 2026

ICE CHILL

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

STMD-Funded Early Career Initiative Project (FY25)

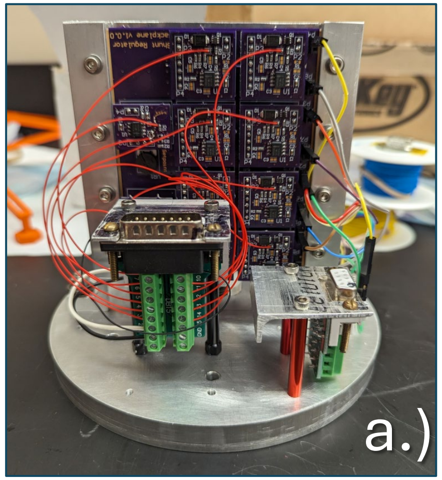
ICE CHILL Overview

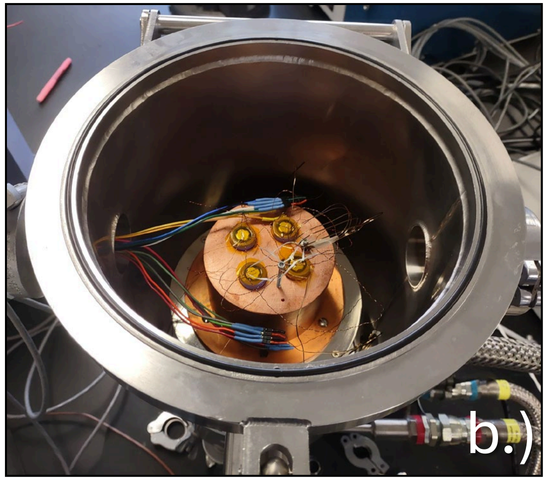
Description and Motivation:

- Commercial Li-ion batteries and battery management systems are **not intended to survive** the extreme thermal environment of the lunar night, limiting the duration of many future lunar surface missions.
- ICE CHILL is developing **cryogenic-capable battery management electronics** and **hibernation strategies** to enable **passive lunar night survival**.
- The approach seeks to **extend operational capability** beyond a single lunar day **while minimizing impacts** to system mass, volume, and power.
- **Passive survivability** has the potential to **reduce battery mass** and **overall system complexity** compared with active thermal management approaches.

Primary Project Objectives:

- **Battery** – Characterize cryogenic survivability and develop a lunar night ***hibernation protocol***
- **Electronics** – Develop cryogenic-operable battery management electronics **capable of autonomous cold-start operation** near 50 K
- **Integration** – Demonstrate an **integrated ~100 Wh** (8s1p) **battery module** in a relevant lunar thermal environment.





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.

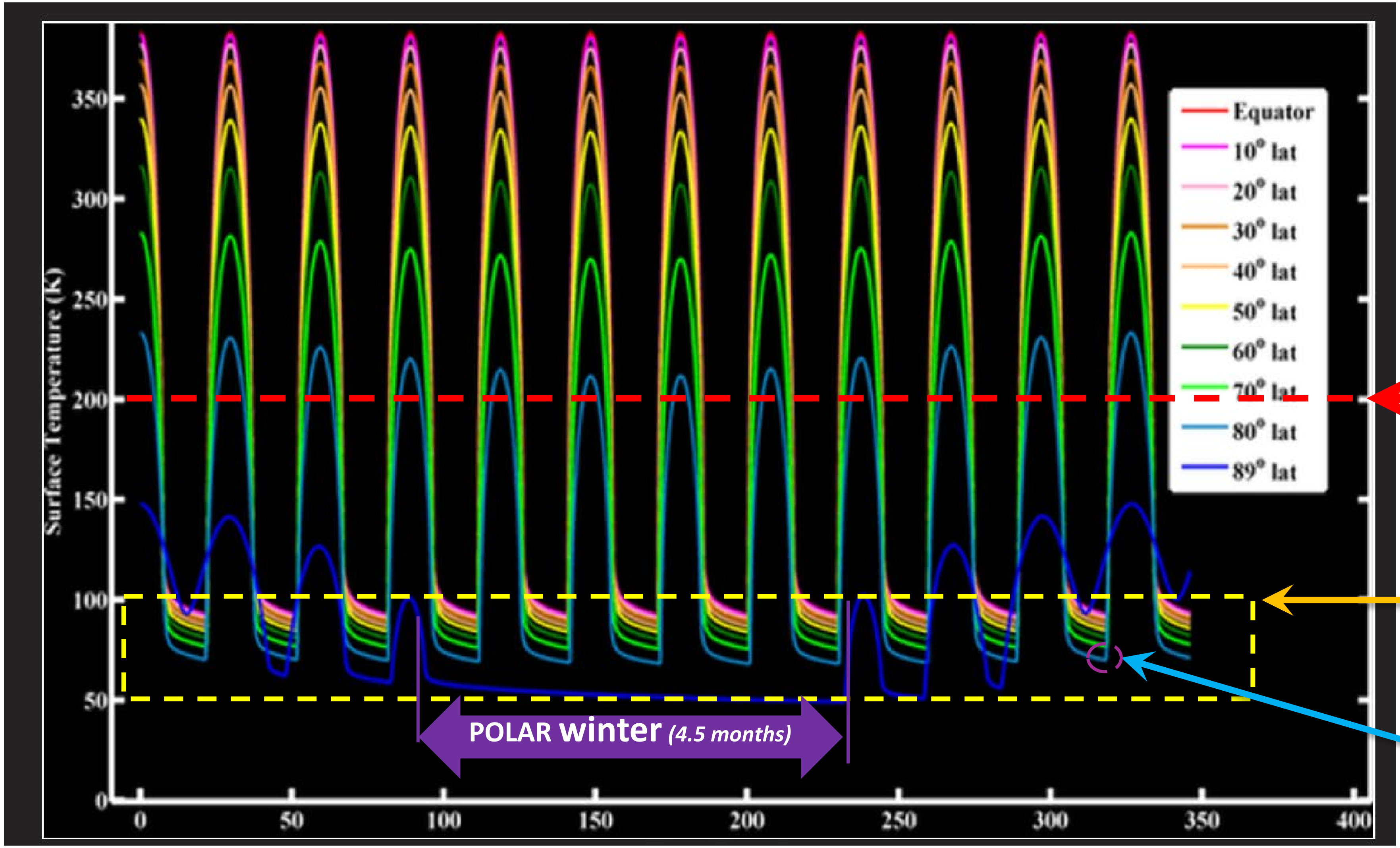
Current Status and Development

- **Technology maturation:** Progressing from TRL 3 → TRL 5
- **Cryogenic battery testing:** Characterized commercial Li-ion cells to 50K for multiple lunar nights with minimal performance degradation
- **Cryogenic electronics:** Demonstrated operation of key battery management building blocks down to 50K
- **Integrated prototype:** Battery module, electronics, and thermal management currently under development

Key Takeaway: ICE CHILL is maturing cryogenic-capable battery, electronics, and thermal management technologies from laboratory validation toward an integrated engineering prototype for future lunar surface applications.

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

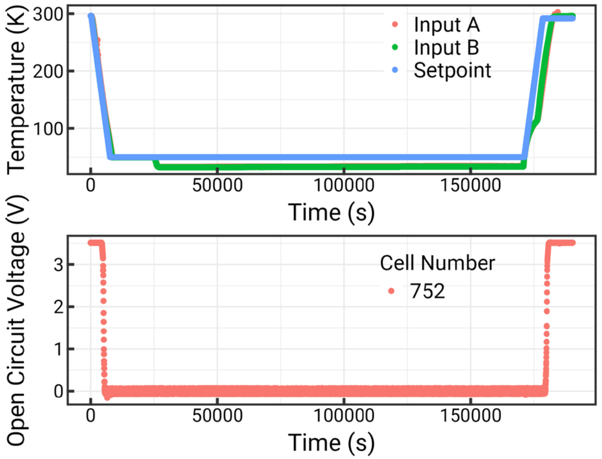
Li-ion battery approx. freeze temperature (~190K – 210K)

Lunar night is extremely cold *at all latitudes*

Lunar dawn

Integrated Approach to Cryogenic Energy Storage

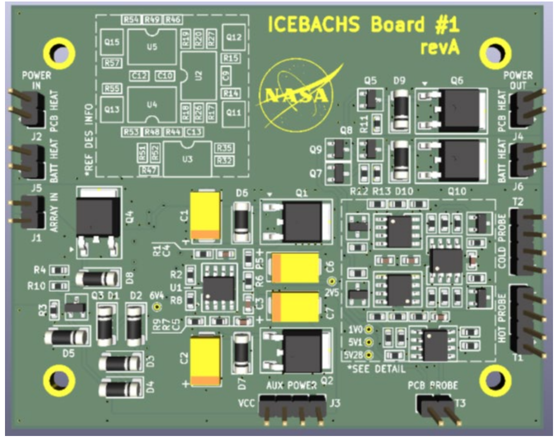
Battery Characterization



Goal: *<u>Understand cryogenic Li-ion survivability</u>*

- Characterize commercial Li-ion cells under extreme low-temperature conditions
- Determine survival limits and degradation mechanisms
- Develop hibernation protocols to minimize performance loss

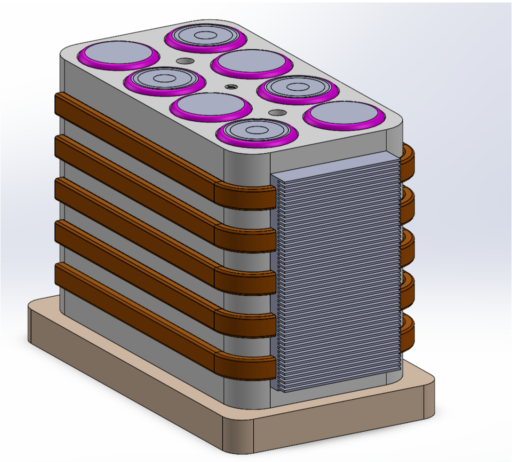
Electronics Development



Goal: *<u>Enable autonomous battery management during extreme environments</u>*

- Develop cryo-operable battery management electronics
- Characterize component operation near 50K
- Demonstrate cold-start and recovery functionality

Thermal and Case Design

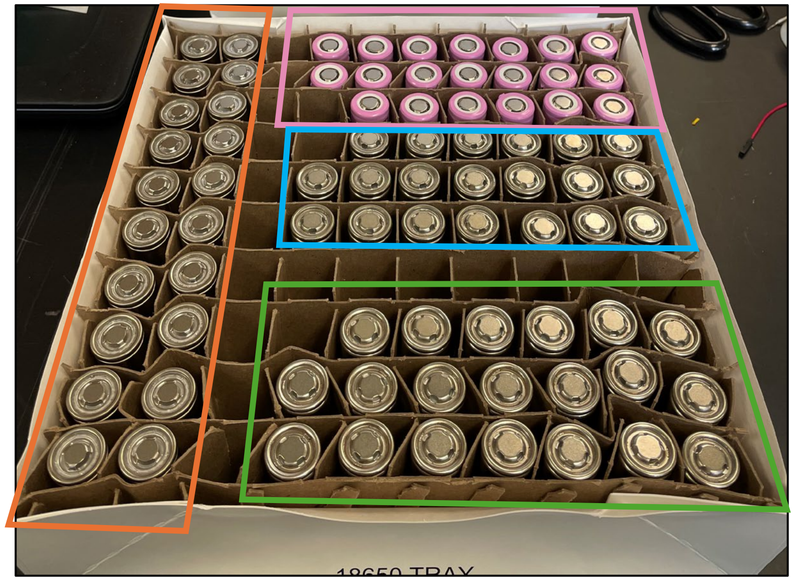


Goal: *<u>Predict system behavior and guide prototype development</u>*

- Model battery thermal response across lunar environmental scenarios
- Evaluate best- and worst-case temperature conditions
- Inform battery module design and technology maturation

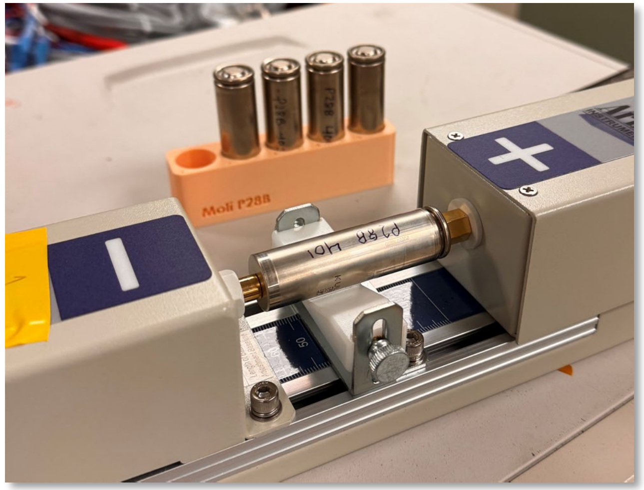
Key Takeaway: Individually maturing each technology reduces technical risk before full system integration.

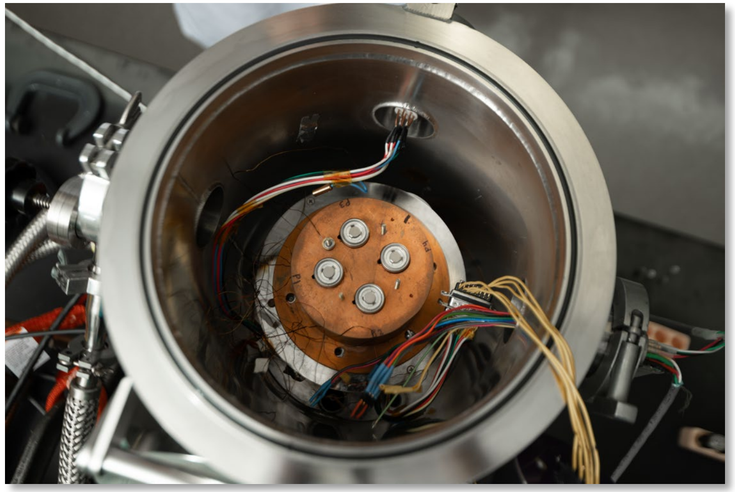
Cell Cryogenic Testing – Strategic Reserve Cells

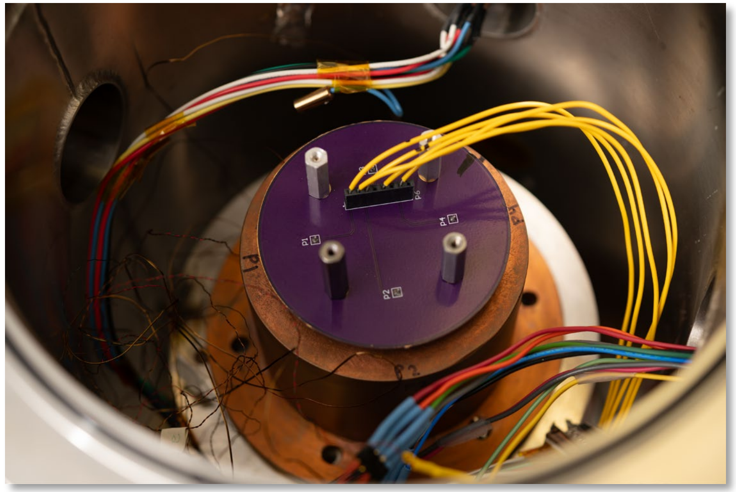


Manufacturer	Model	Capacity (Ah)
Samsung	Q30	3.0
LG	M36	3.6
Molicel	P28B	2.8
Molicel	M35A	3.6

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

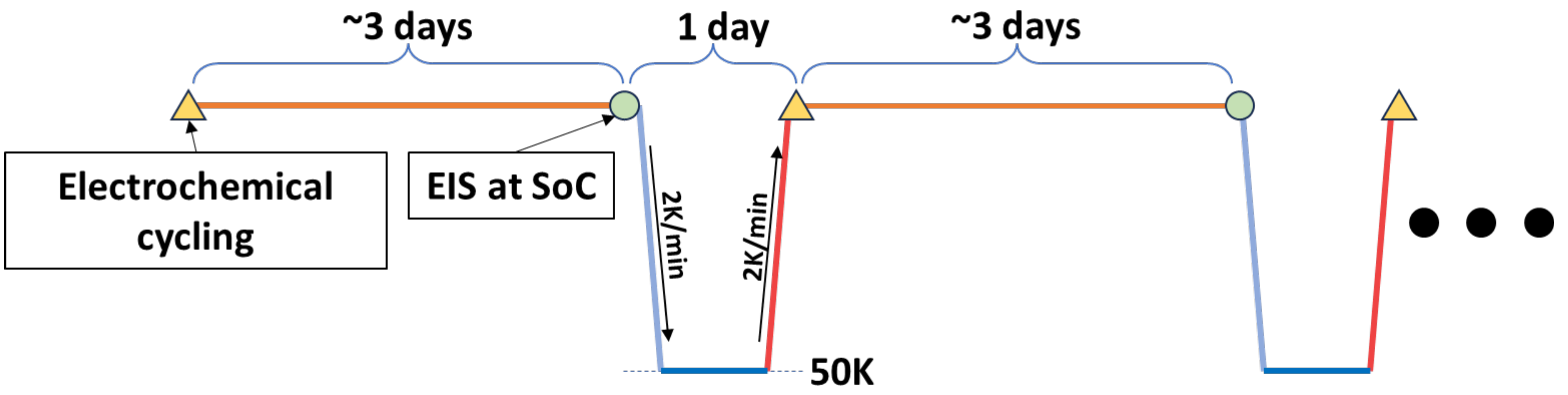


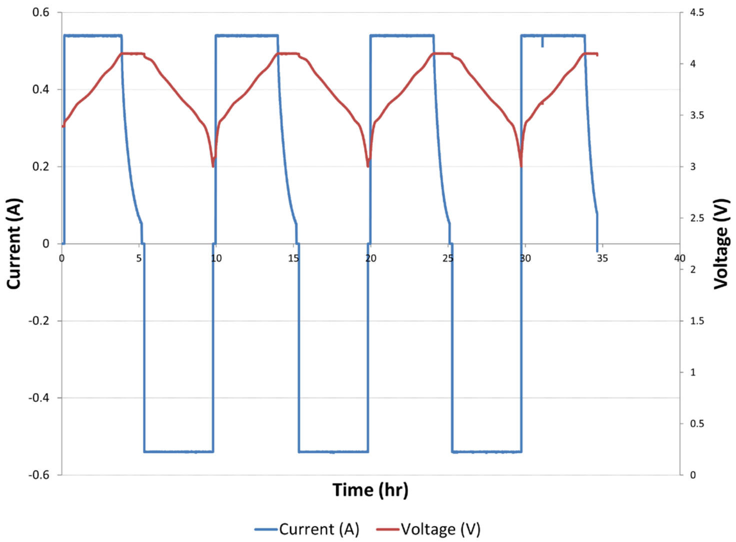




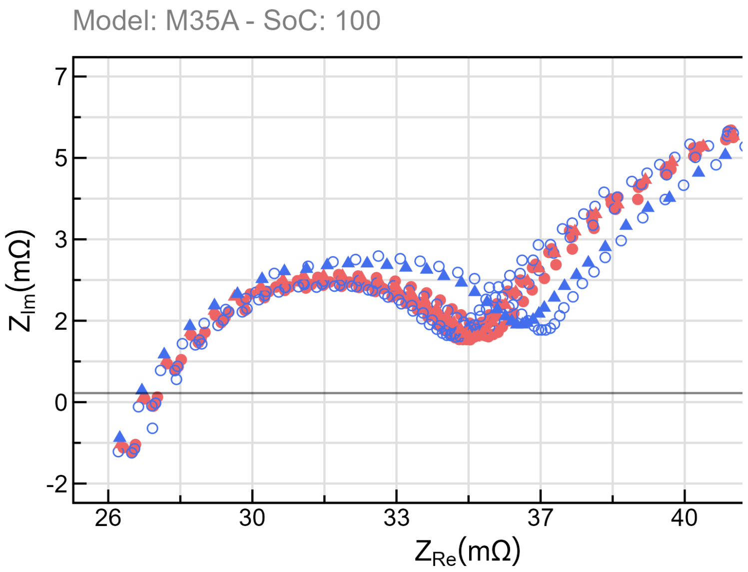
Passive Cell Hibernation Testing

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

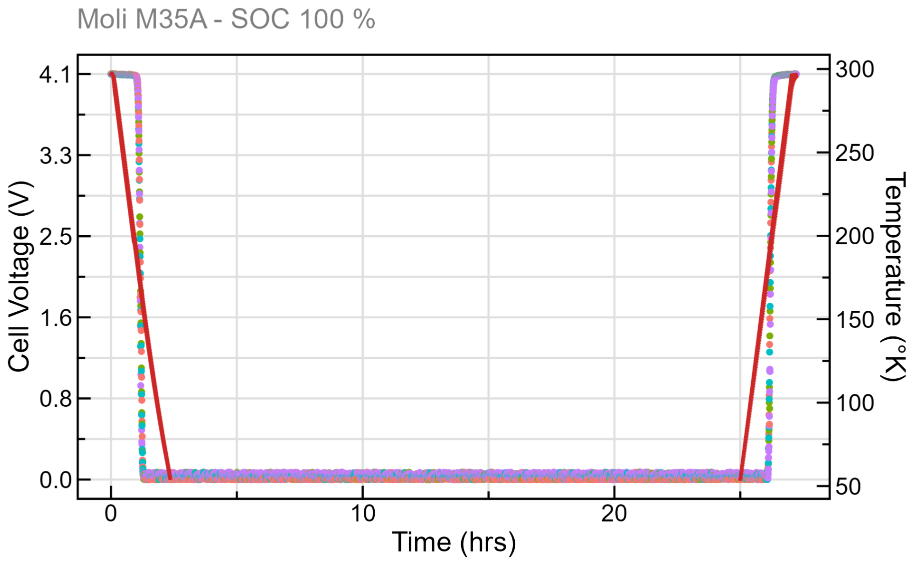




Electrochemical Cycling



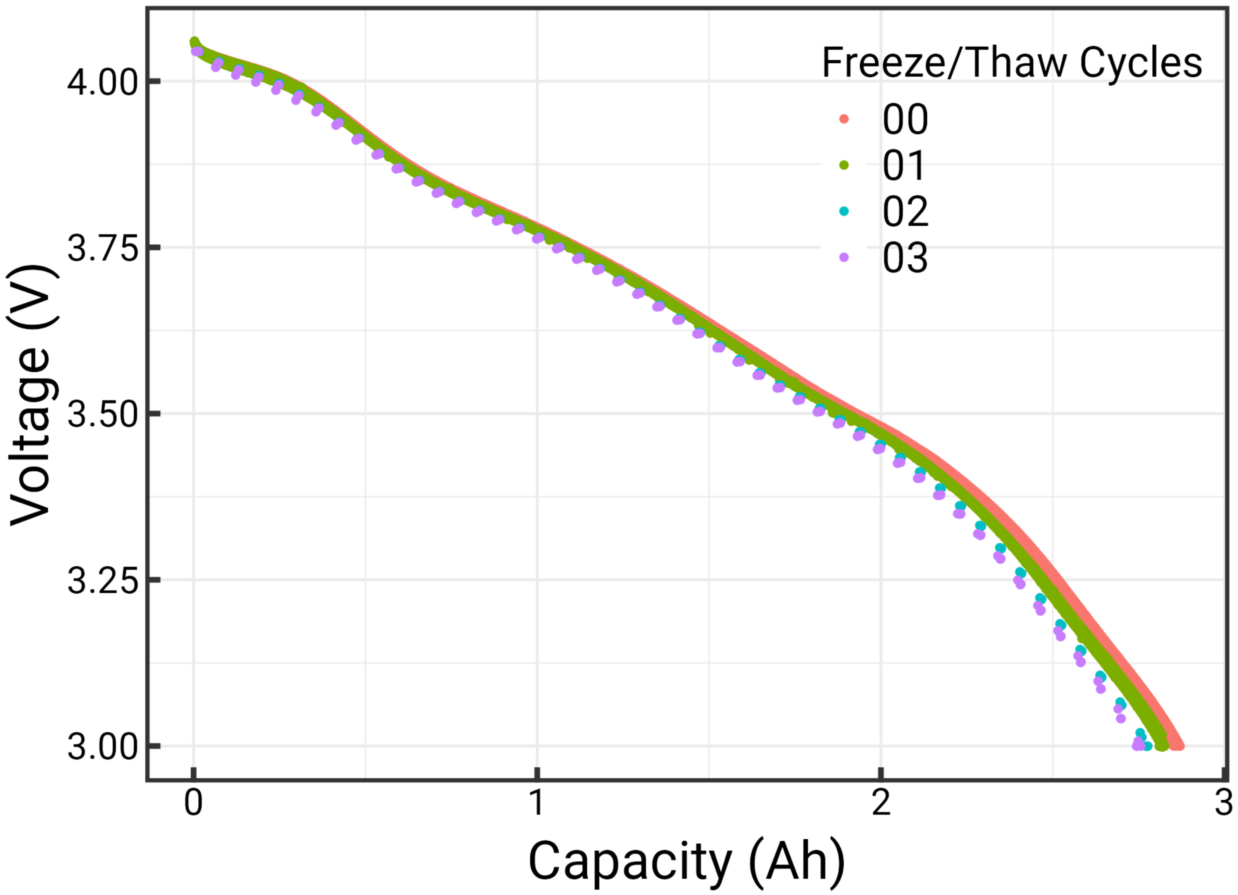
EIS



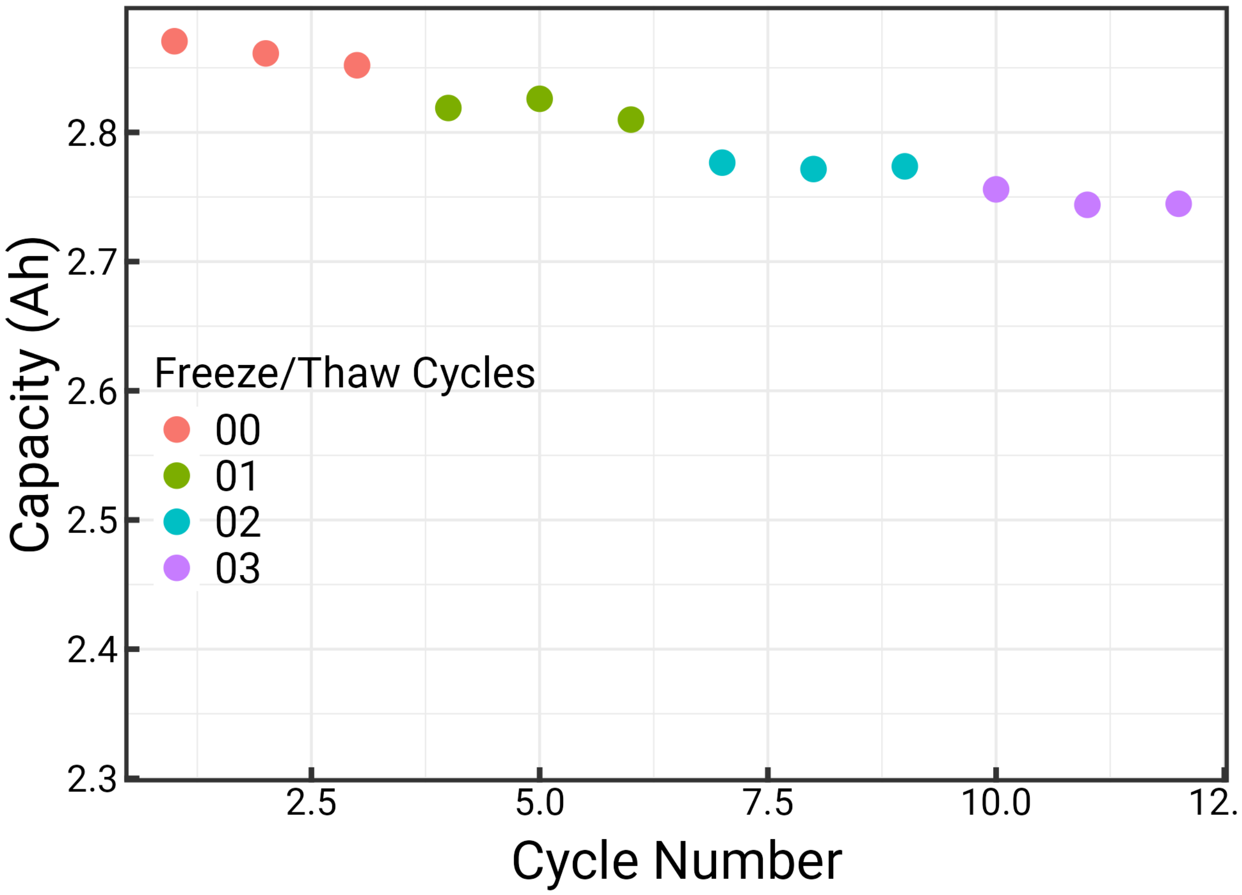
Cryo-Hibernation

Post-Hibernation Comparison of Cell Behaviors: Cycling

C/5 Discharge Cycles for Cell 507

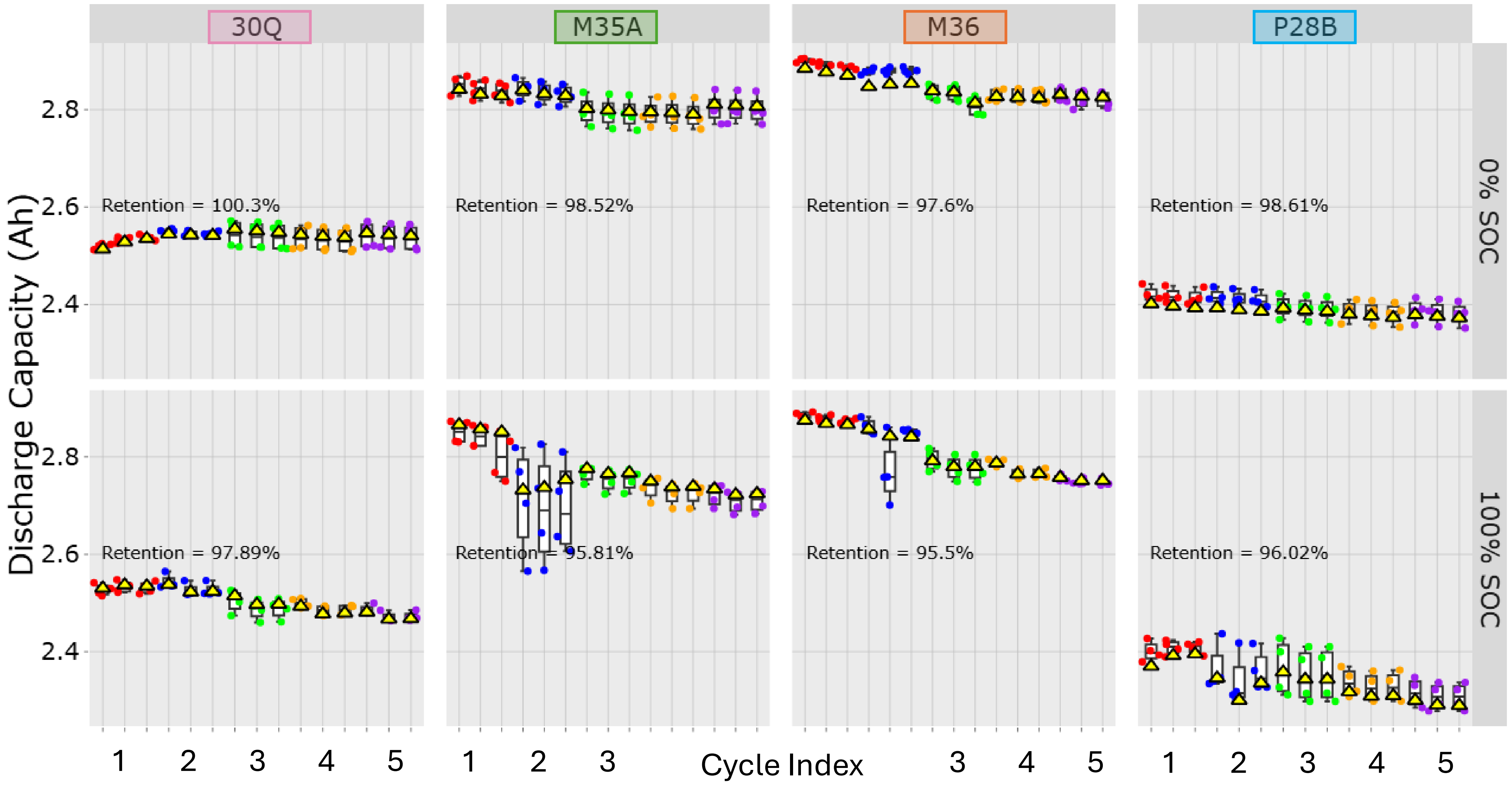


Lifetime Capacity Fade for Cell 507



This is representative data: All tested cells showed similar behavior

Post-Hibernation Comparison of Cell Behaviors: Cycling



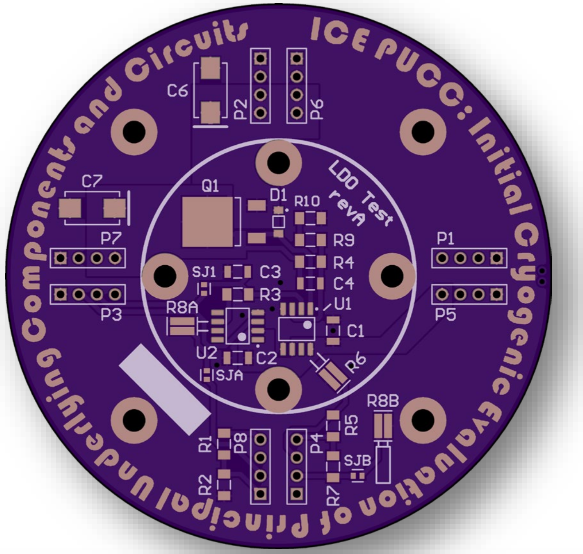
Cryogenic Cell Testing Current Findings

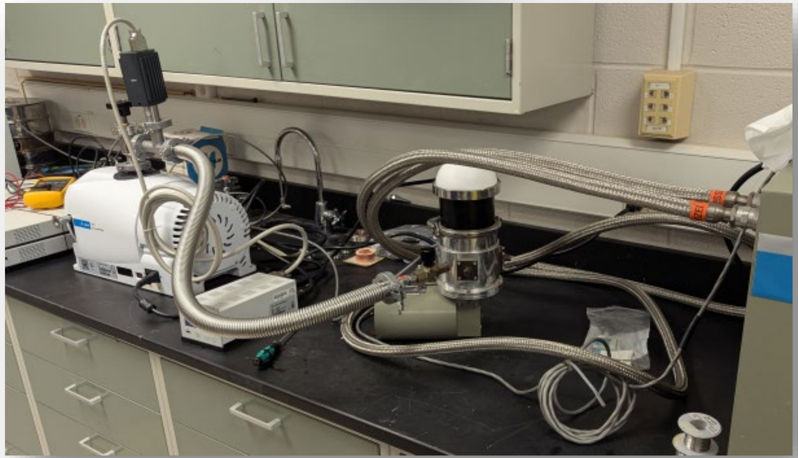
Key Technical Findings

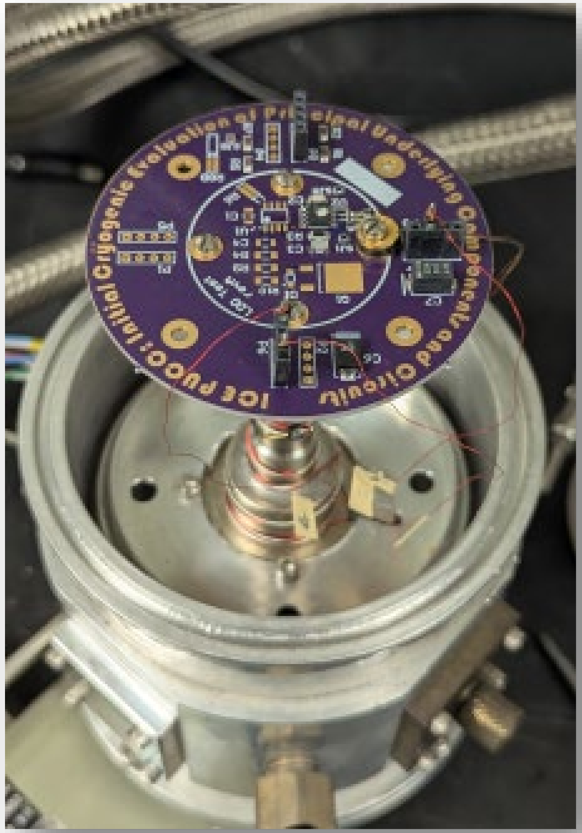
- Completed full test matrix for **multi-lunar-night assessment** across all four Strategic Reserve cell models
  - Completed 26 freeze/thaw cycles (approximately two lunar years equivalent)
- **Validated thermal ramp rates**: No degradation observed when heating ≤ 2 K/min (consistent with lunar maximum rates).
- **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 long-term lunar hibernation.
- ICE CHILL established a reusable **cryogenic battery characterization capability** that can support future technology development beyond this project.

Electronics Development – ICE PUCCs

***ICE PUCC** = Initial Cryogenic Evaluation of Principle Underlying Components and Circuits*







ICE PUCC Test Bed

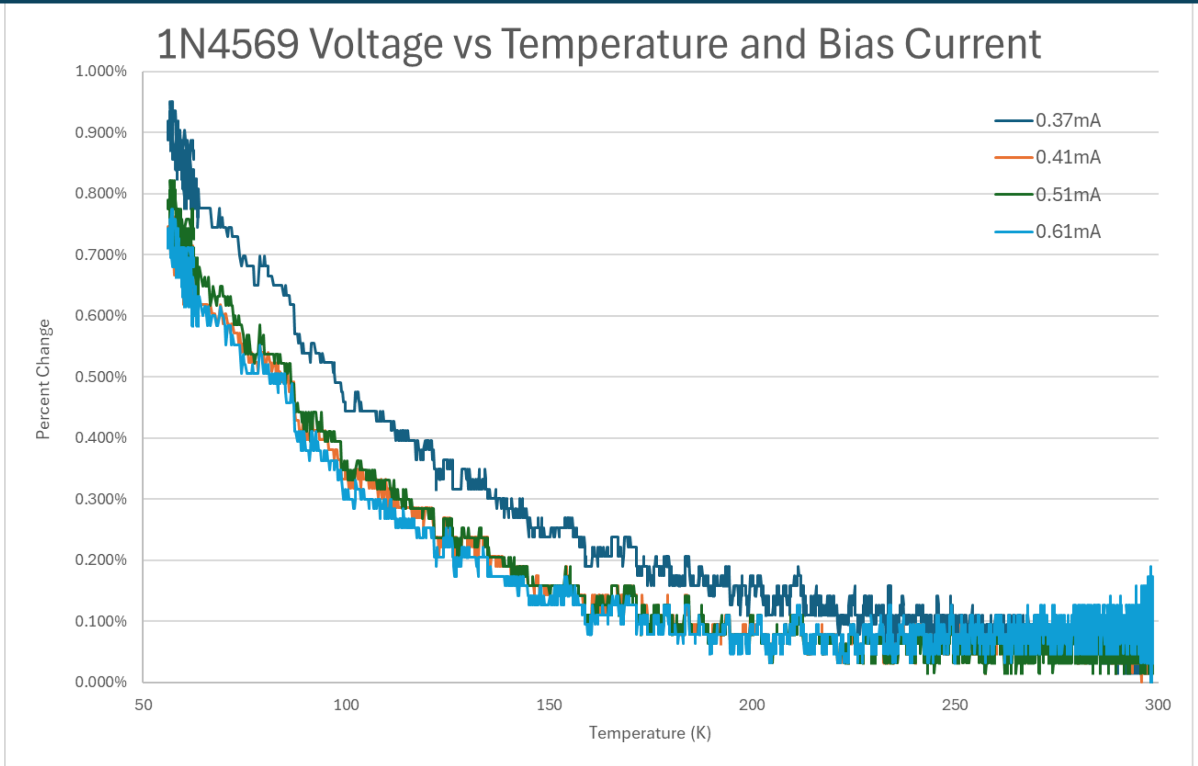
Test bed for analyzing cryogenic performance of components and circuits before integrating into larger system

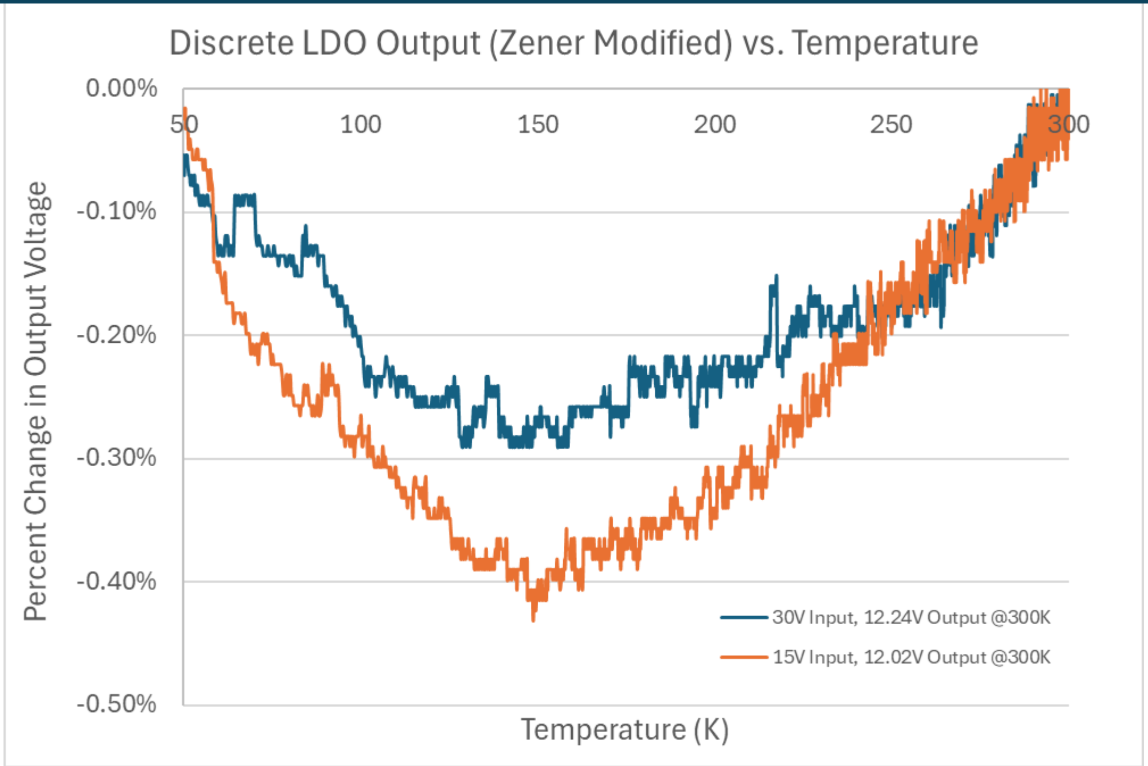
- Current sensing
- Temperature sensing
- Op-amp evaluation
- Board heater with temperature control
- LDO regulation

Electronics Parts Overview (Tested)

Good Parts (50K operation)	Problematic Parts (but workable)	Bad Parts
“Temperature Compensated” Zener Diodes	Tantalum Polymer Capacitors - Capacitance and ESR changes need to be accounted for	Regular Zener Diodes - Most exhibit more than 5% shift in Zener voltage
Multilayer Ceramic Capacitors - Class 1 are best - Class 2 are also likely good with a designed margin	ATMega328 - Some features work, others need external solutions below 100K	Voltage Reference ICs - None tested work <77K - May be able to find a fully CMOS version
Thick Film, Metal Film Resistors	Integrated LDOs - Depends on the part number - Some parts exhibit sharp runaway at temperatures lower than 100K	
Silicon MOSFETs		
Op-Amps: **OPA2990IDR, OPA2486DR**	Op-Amps (50K – 100K)	

Zener Diode Results

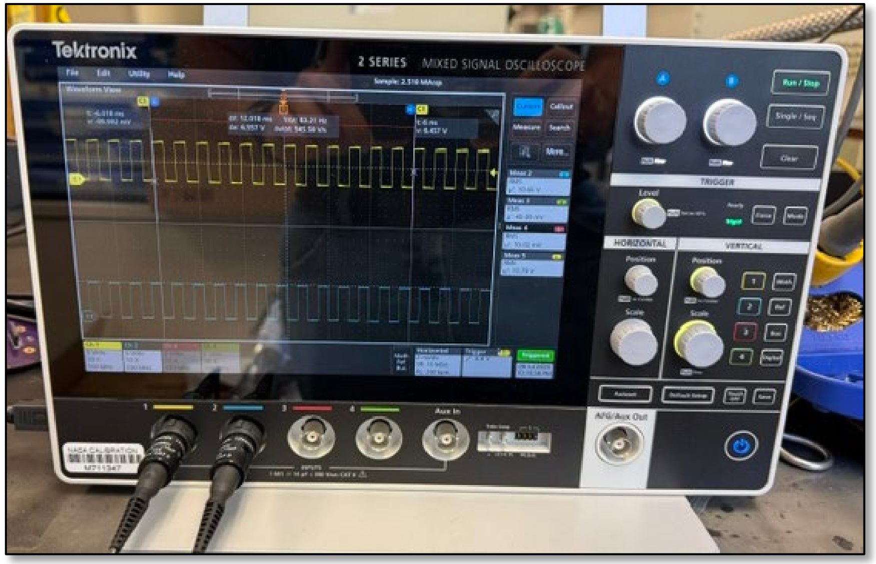




- It does not appear that the tight temperature compensation holds below -55°C, however, the drift in Zener voltage is magnitudes lower than non-compensated Zeners
- At ~50K, we saw **a less than 1%** change in Zener voltage
- Implemented Zener diode design into the LDO board and **achieved an LDO with less than 0.5% drift** in output from 300K to 50K
  - A cascaded Zener design, or controlling for bias current, can reduce the effect of varying input voltages

Cryo-Operable Op-Amp Testing

Part Number	Voltage range (V)	Max diff voltage (V)	Slew rate (V/us)	GBW (MHz)	Technology (probably)	Cold test date	Failure temp
OPA2145IDR	40	40	20	5.5	JFET	03/04/2026	>100K
TL071HIDR	42	42	20	5.25	JFET	2024 (CIF)	60K
TLV9302IDR	42	42	3	1	CMOS?	02/26/2026	49K
OPA2990IDR	40	40	4.5	1.1	CMOS?	7/13/2026	<42.5K
OPA2292QDRQ1	40	40	32	10.6	CMOS?	7/2/2026	75
OPA2486DR	48	48	15	5.6	CMOS	7/13/2026	<44.5K
OPA2596DR	85	85	100	3.75	CMOS	6/29/2026	60K



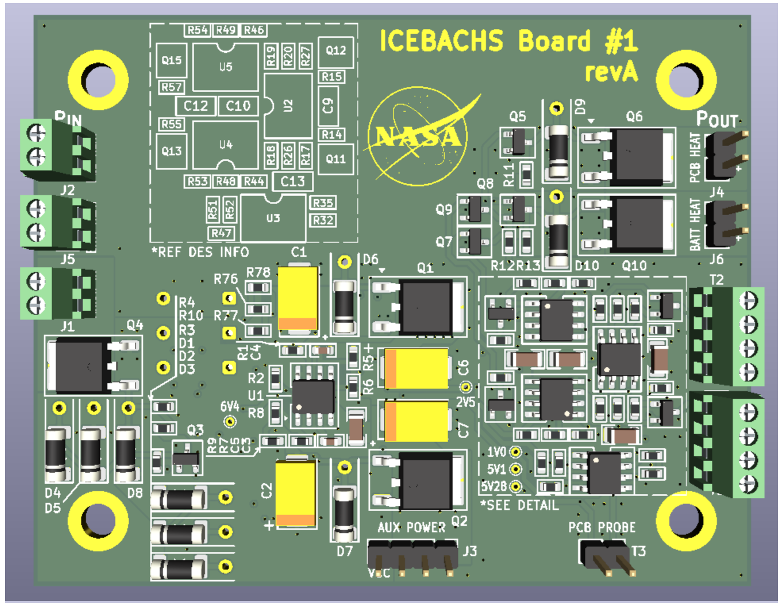
*There are reported cryo-operable op-amps at ~4K, but voltage range is only 5V

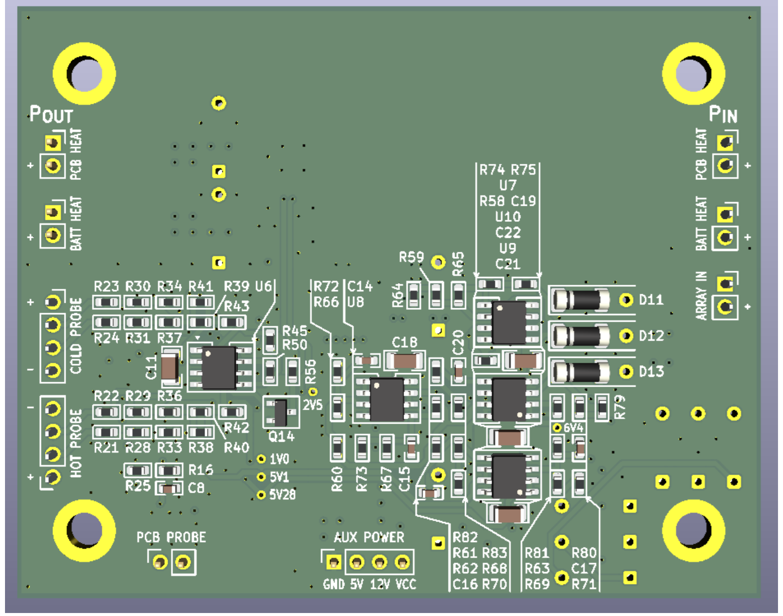
- **Operational amplifiers were evaluated using a differential amplifier test circuit** to monitor functional performance during cooldown to cryogenic temperatures
- **OPA2486 and OPA2990 maintained the expected square-wave output**, demonstrating stable operation across the tested temperature range
- **Failure was identified by loss of the output waveform as the amplifier transitioned to a high-impedance (Hi-Z) state**, preventing the device from driving downstream circuitry

Cryogenic Electronics Development

Key Technical Findings

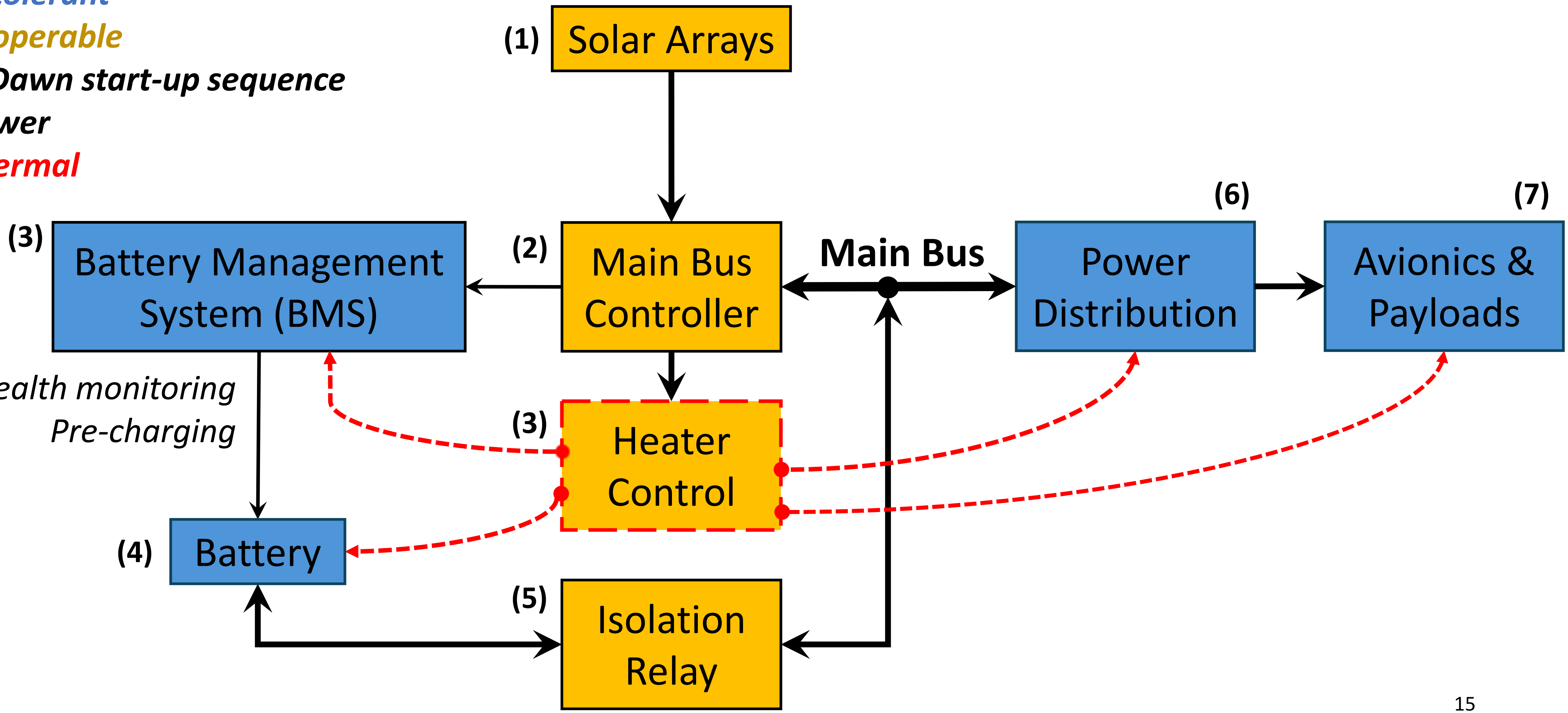
- **Cryogenic-operable solutions have been identified for all critical battery management components**, including resistors, capacitors, MOSFETs, operational amplifiers, and Schottky and Zener diodes
- **These screening results have enabled the development and validation of the ICE BACHS prototype**, providing the foundation for cryogenic battery management and heater control electronics.
- **The ICE PUCC screening platform provides a reusable capability for rapid cryogenic evaluation of commercial electronic components**, reducing future technology development risk and accelerating component selection.



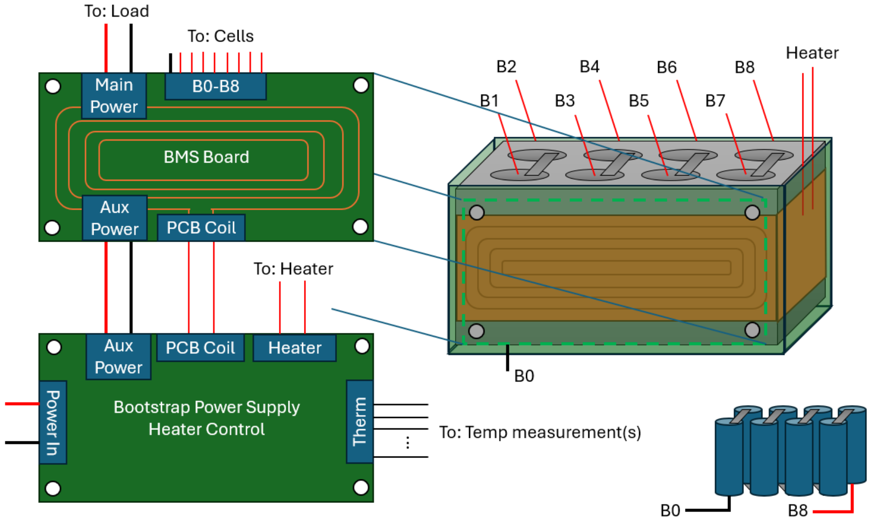


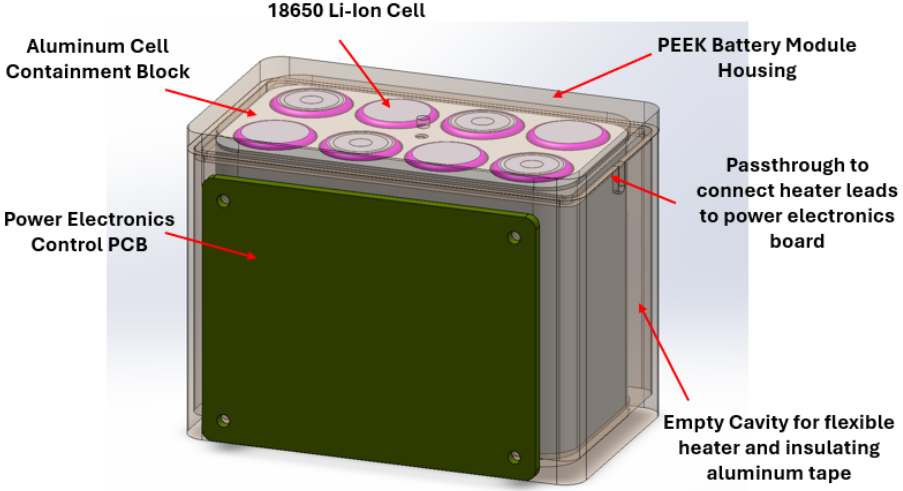
Lunar Dawn Start-Up Sequence

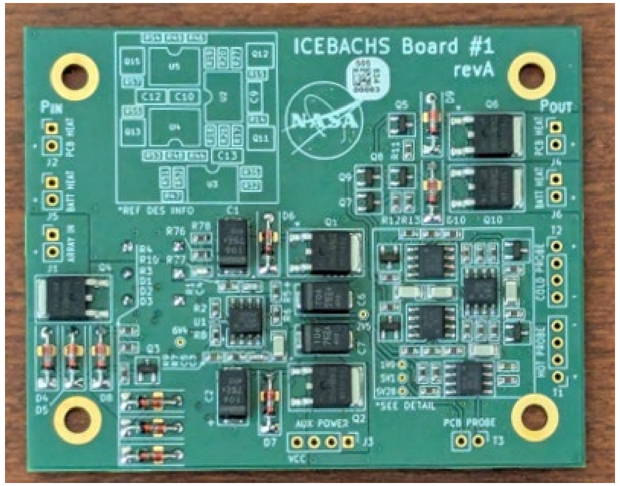
Key
Cryo-tolerant
Cryo-operable
(#) – Dawn start-up sequence
→ Power
→ Thermal

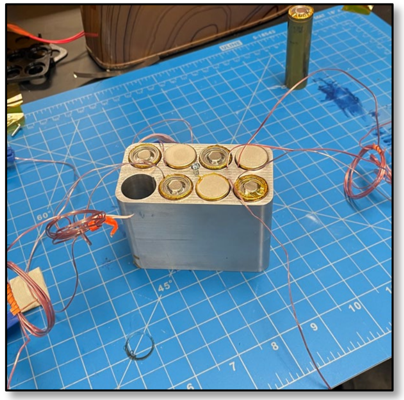


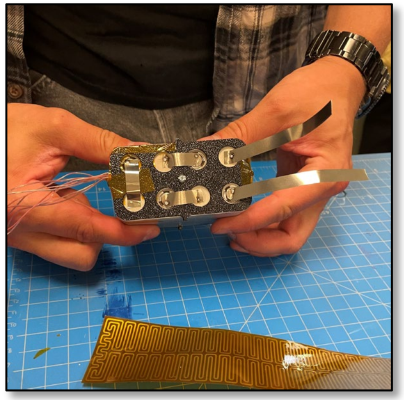
ICE CHILL Prototype and Integration

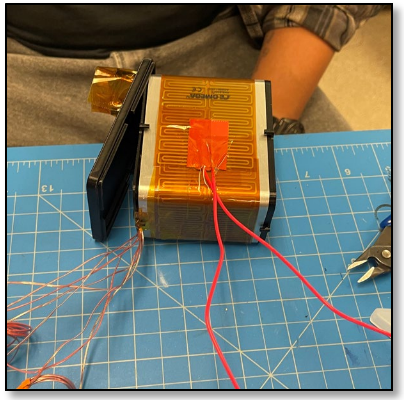


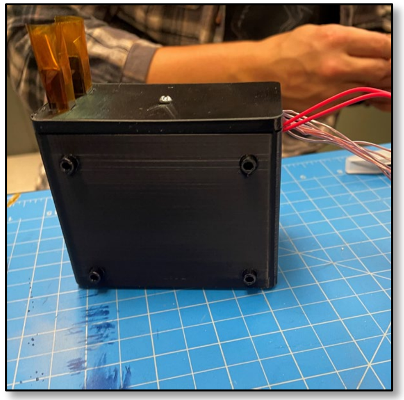












8s1p ICE CHILL Proof-of-Concept Battery Module

- **28.8V** Nominal Voltage
- **3.0Ah** Nominal Capacity

Current integration activities focus on combining validated battery, electronics, and thermal models into a representative engineering prototype.

Thank you!

Key Takeaways:

✓ Commercial Li-ion cells demonstrated survivability under repeated cryogenic exposure

✓ Cryogenic-compatible electronic building blocks have been identified and incorporated into prototype battery management hardware

✓ Automated cryogenic testing and Thermal Desktop modeling are accelerating development of integrated cryogenic energy storage systems

✓ Ongoing work is focused on integrated prototype validation and representative-environment testing

POC:
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