National Aeronautics and Space Administration

NASA's Advanced Energy Storage Systems Battery Development

"Silicon Anode Based Cells for High Specific Energy Systems" Amprius, Inc

NASA Aerospace Battery Workshop
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Outline

- **Overview of NASA's Game Changing Development Program & Advanced Energy Storage Systems (AESS) Project**
- **AESS Goals for Battery Development**
  - Category 1 vs Category 2
  - Phased development
- **Amprius Phase I Efforts**
- **Amprius Phase II Progress & Upcoming Work**

Game Changing Development Program (GCD)

- **Space Technology Mission Directorate**
- **Supports Agency strategic goal to “create the innovative new space technologies for our exploration, science, and economic future”**
- **Responsible for advancing space technologies, with an emphasis on groundbreaking, transformational approaches**
- **Mid-range TRL 3-5/6**
- **Combination of NASA in-house directed efforts and competed efforts**

Advanced Energy Storage Systems (AESS) Project Overview

- **Goal: Develop and demonstrate technologies for safe, abundant, reliable, and lightweight energy storage**
  - Category 1: Develop & demonstrate energy storage devices with high specific energy and integrate into an optimized battery pack design to preserve weight and volume benefits
  - Category 2: Develop ultra-high specific energy storage devices that increase the specific energy beyond the limits of lithium-ion chemistry capability

Technology Development Phase	TRL at end of Phase (Cat. One)	TRL at end of Phase (Cat. Two)	Anticipated Number of Awards*	Value of Each Award	Period of Performance (POP)
Phase I	4	3	4	Up to $250K per	Up to 8 Months
Phase II	5	4	2	Up to $1M per	Up to 12 Months
Phase III	6	5	1	Up to $2M	Up to 15 months

AESS Battery Development Goals

- **Technology Advancements**
  - Lightweight lithium ion batteries with >300 Wh/kg capability
- **Technology advances mean-**
  - Lighter, more powerful batteries for EVA suits, rovers, transportation elements, etc.
- **Pull technology**
  - ISS & exploration EVA suit power, uncrewed and crewed rover power, exploration transportation element power, etc.

Key Performance Parameters		
Performance Parameter	Category 1 Goal Cell/Battery	Category 2 Goal Cell/Battery
Specific Energy (Wh/kg)	300/250	400/350
Cycle Life (cycles)	200	200
Operational Temp. (ºC)	0 to 30	-10 to 30

Phased Project Execution

- **Phase I contracts – 4 awards**
  - 1 Category 1 effort, 3 Category 2 efforts
  - Competitive process
- **Phase II contracts underway for first 9 (of 12) months**
  - Competitive process
  - Amprius, Inc partnered with Enersys (Quallion) “Silicon Anode Based Cells for High Specific Energy Systems”
  - University of Maryland “Garnet Electrolyte Based Safe, Lithium-Sulfur Energy Storage

Amprius, Inc. Overview

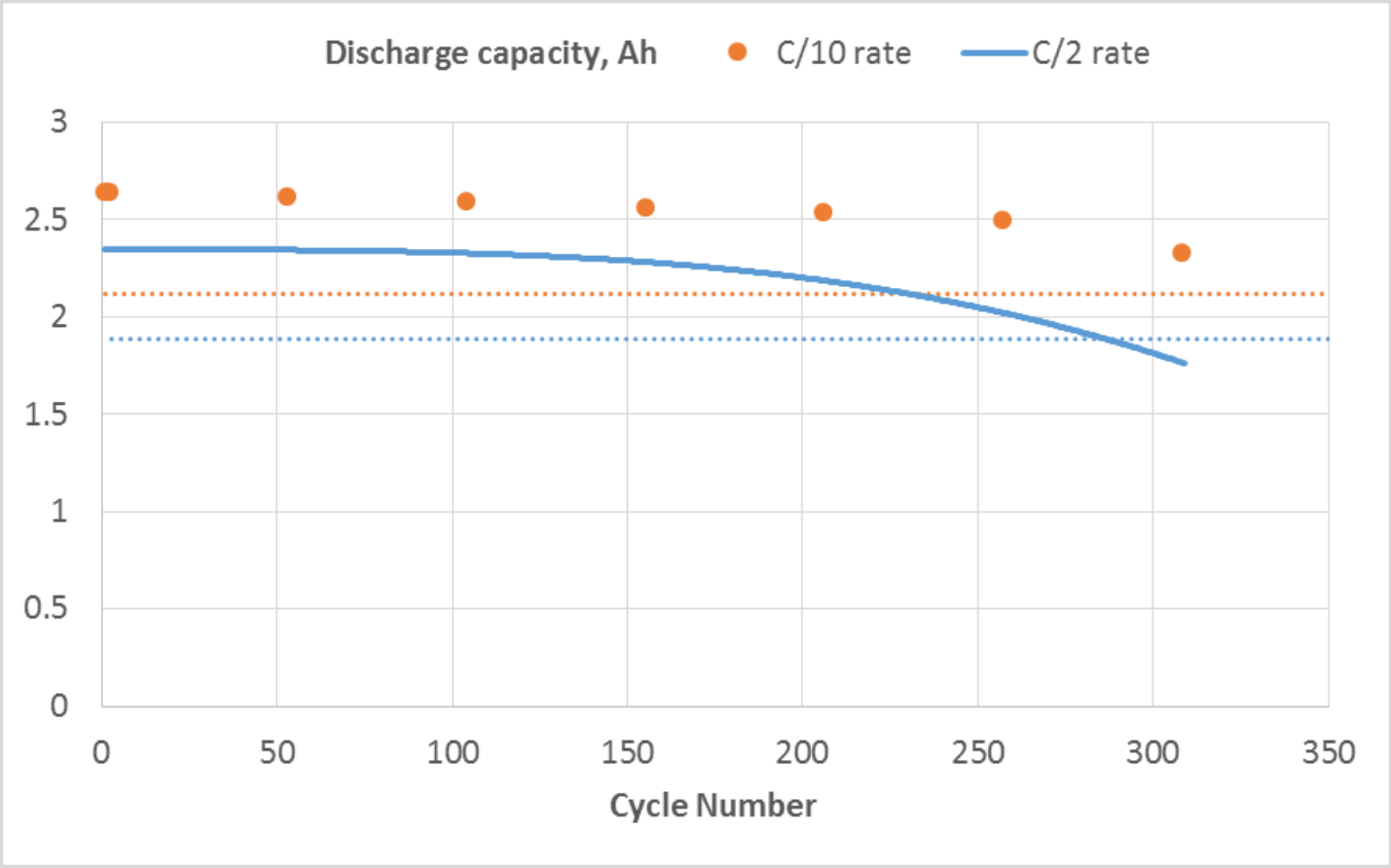
- **Amprius, Inc headquartered in Sunnyvale, CA**
- **Develops, manufactures and sells lightweight, high energy lithium-ion cells**
  - Pure silicon nanowire technology from Stanford University
  - Silicon-enabling electrolytes and cell components
- **Other government efforts: DARPA, Dept. of Commerce, DOE, Army, USABC**
- **Commercial Projects (Sample): Top 3 Defense Contractor and Top 3 Smartphone Manufacturer**

Phase I Effort Overview

- Design a cell with specific energy of ≥300 Wh/kg at end of life when discharged at a rate of C/10
- Cycle life of ≥200 cycles at 90% depth of discharge and a rate of C/2
- Maintain specific energy and cycle life at the temperature NASA specified, 20° C
- Pass hotbox test (exposure to 110° C for 30 minutes)
- Pass over-discharge test (150% discharge at 1C rate)
- Pass short circuit test
- Pass overcharge test (C/5 rate for 5 hours)
- Preliminary design of a battery pack to achieve NASA's end-of-project requirements

Cell Test Results

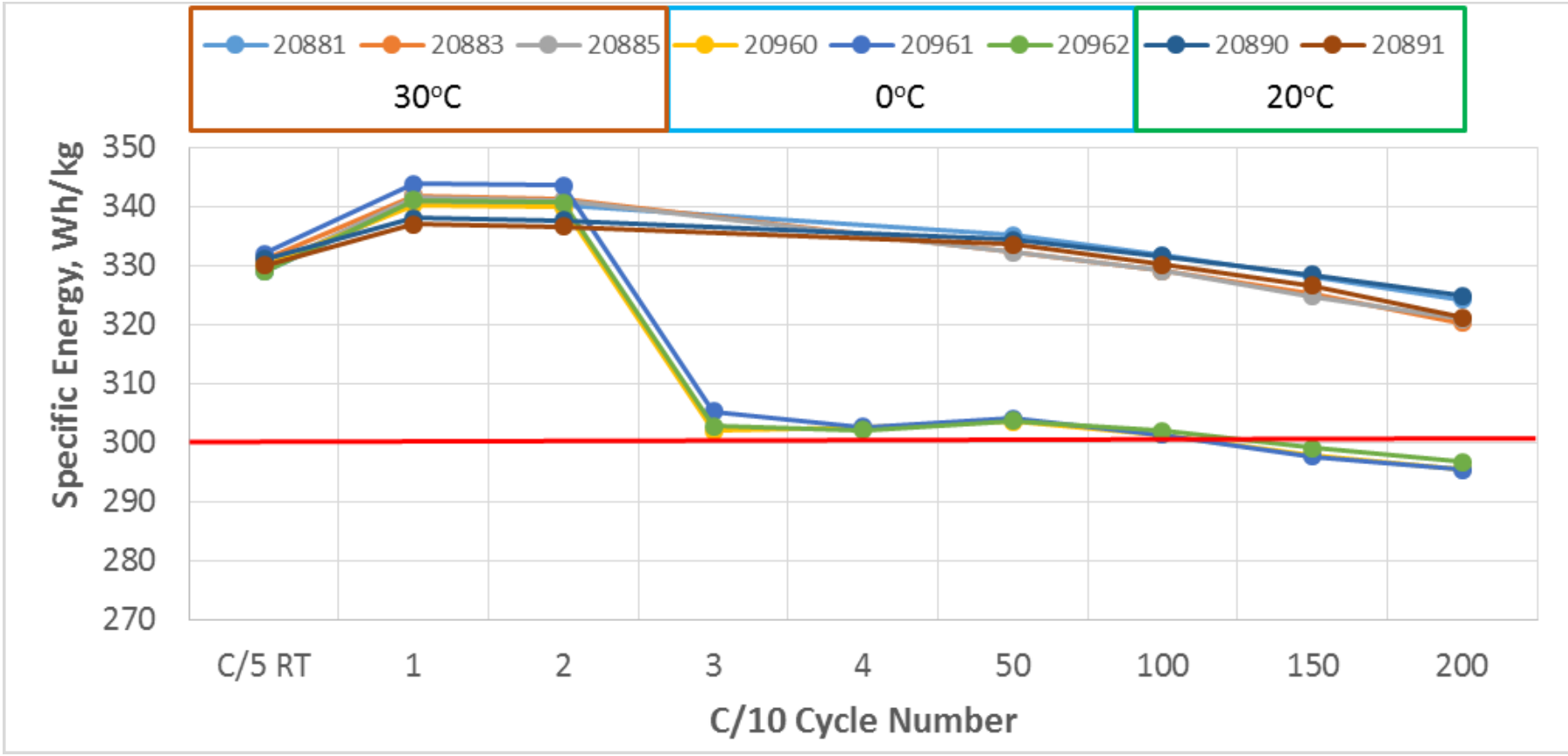
- Amprius' cells met NASA's energy (≥ 300 Wh/kg) and cycle life (≥ 200 cycles) goals at 20° C



Note: Dotted lines represent 80% of capacity for each cycling rate (C/10, C/2)

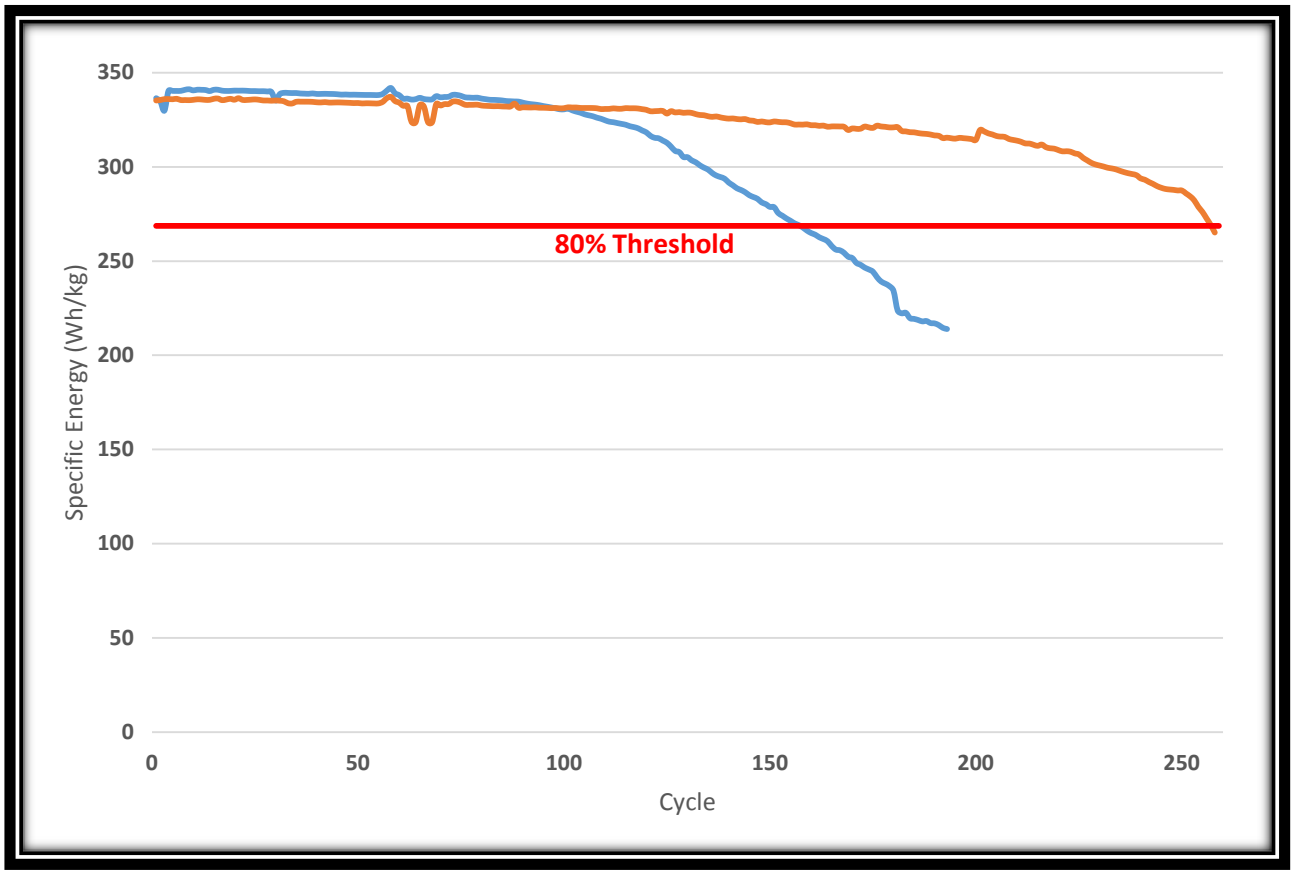
Temperature Test Results

- Excellent performance down to 0° C



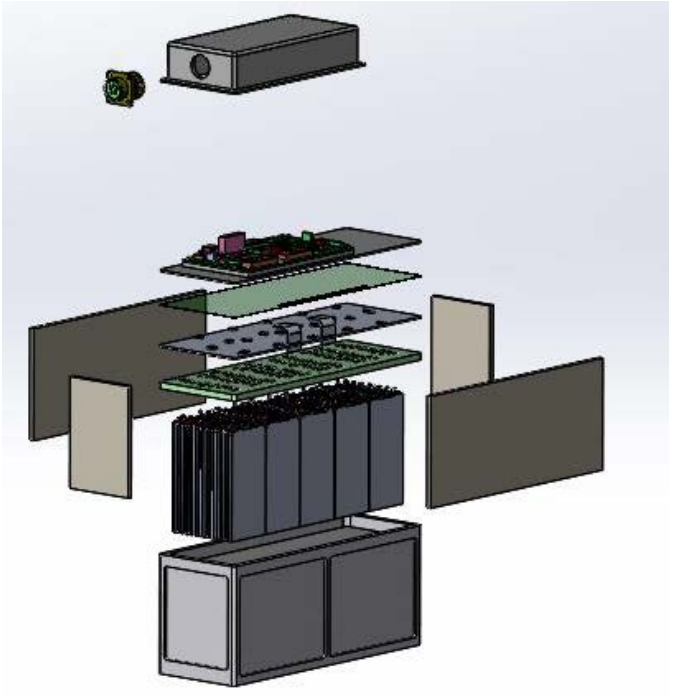
Independent NASA Assessment

- Received 2 cells to test at NASA GRC
- 1 cell had more rapid capacity loss, ~150 cycles
- 250 cycles to 80% capacity of remaining cell



Phase I Major Accomplishments

- ✓ **Cells met >300 Wh/kg specific energy goal and 200 cycle goal**
  - Good low temperature performance
- ✓ **Preliminary battery pack design**
- ✓ **Proposed optimized cell design based on battery pack**
- ✓ **Verified cell performance at NASA GRC**



Phase II Requirements

- **Optimize cell design**
- **Design, build & test brass board battery**

Performance Parameter	Cell Level	Battery Pack
Total Energy		1625 Wh
Specific Energy[1]	>300 watt-hour (Wh)/kg	250Wh/kg
Cycle Life[2, 3]	200	200
Operational Temperature[4]	0^0 to 30^0 C	0^0 to 30^0 C
Volume		4 Liters
Mass		6.5 Kg
Voltage		28V
Discharge Rate	C/10	C/10
Safety	Tolerant to Electrical and Thermal Abuse[5]	Tolerant to Electrical and Thermal Abuse[6]

1. Cell energy parameters are for the beginning of cell life, and measured at a temperature of 20 °C, C/10 discharge rate.
2. A cycle shall be considered a full 100% charge followed by discharge to 90% depth-of-discharge.
3. Target cycle life> 200 cycles, with 80% specific energy retention at cycle #200.
4. Performance over the entire range of temperatures per Section 1.4.1
5. Safety tests will be conducted on battery cells per Section 1.4.1.
6. Tolerance to battery-level safety/abuse tests will be determined per Section 1.4.1.

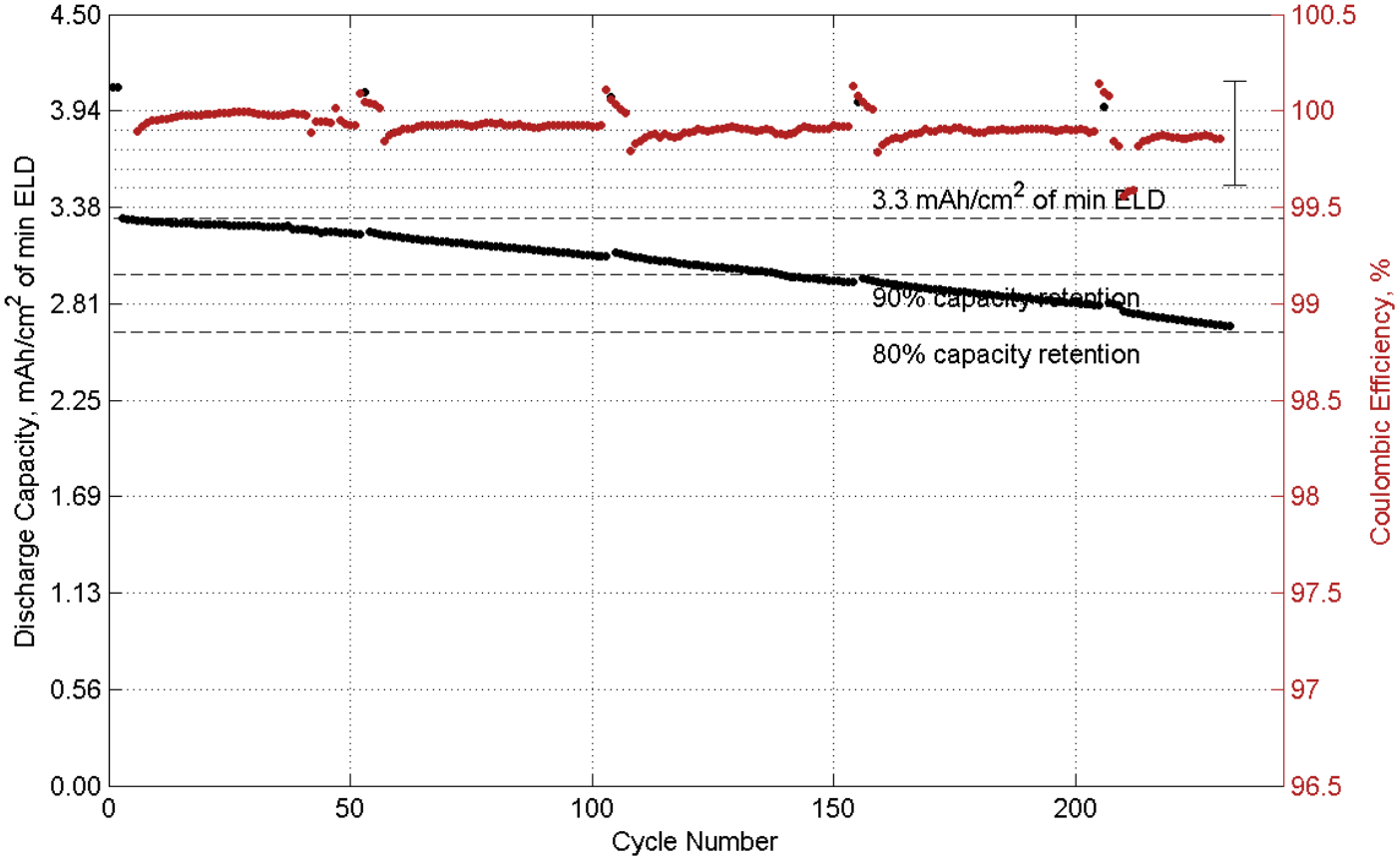
Optimized Cell Design

- NASA's Battery Specs: 1,625Wh, 28V, 58Ah
  - 5.8Ah capacity would be a good target for Amprius' cells
- **Cell capacity: 5.8Ah**
- Cell energy: 21Wh
- Energy density: 860 Wh/L
- **Specific energy: 340 Wh/kg**

- Cells 2x length of Phase I cells

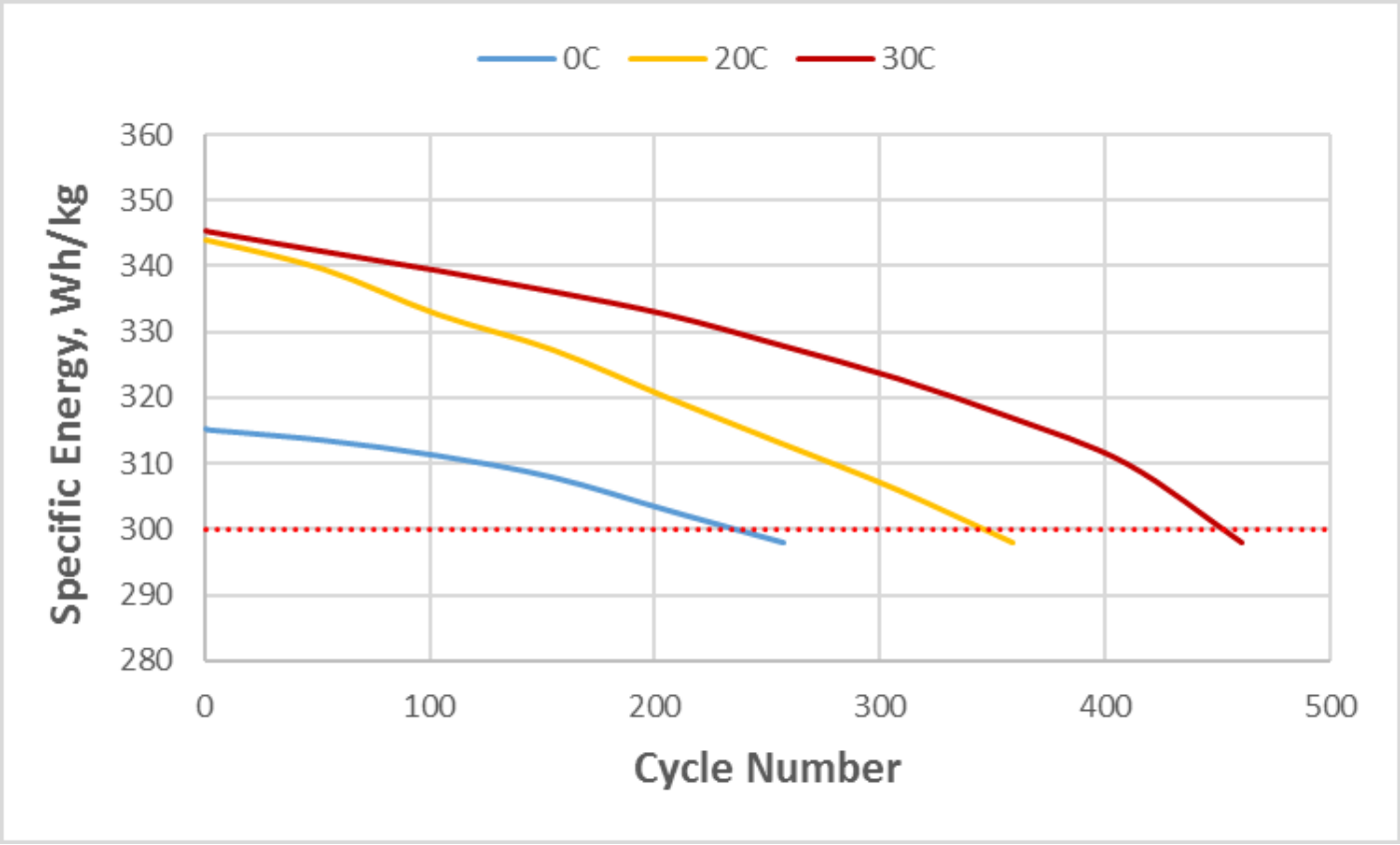
Cell Test Results

- Amprius cycled cells at a C/2 rate and 90% DOD with full DOD C/10 capacity checks after each set of 50 cycles



Temperature Test Results

- Amprius' cells met NASA's energy (≥ 300 Wh/kg) and cycle life (≥ 200 cycles) goals over the entire temperature range
- Amprius tested 3 cells at each temperature (0° C, 20° C & 30° C)

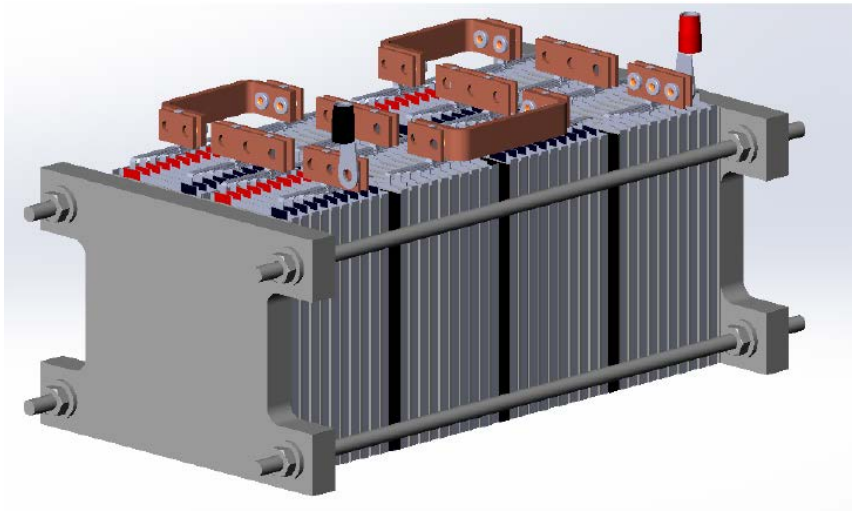


Cell-level Safety Testing

- Over-temperature up to 110° C (for a minimum of 1 hour)
  - No fire, no explosion, small voltage drop after 1h exposure
- Reversal with 150% excess discharge from 0 V at 1C rate
  - Voltage went into reversal after ~10min, stabilized after spike to -12V, vent without fire or explosion
- External hard short tests (load less than internal resistance of the cell held for a minimum of 3 hours)
  - Cell tabs could not withstand currents during short circuit and melted before full cell discharge
- Overcharge fully charged cell at C/5 rates for 6 hours
  - Cells reached max of ~5.3V and ~85° C with no fire or explosion
- Overcharge fully charged cell at 1C rate for 6 hours
  - Cells exploded soon after reaching 5V, ~30min into test

Battery Build Progress

- **Partnered with Enersys (Quallion) for battery design & build**
- **~40 cells available for battery assembly and testing as of October**
- Brass board design will be an 8S – 10P configuration
- Virtual cells will connect via copper bus bars
- Battery Management System (BMS) previously designed on other program will be modified to account for the cell pack output level, parameters, and quantities
- BMS is mounted on top of battery pack
- Enersys completed a module cell pack for safety level testing



Upcoming Work

- Amprius will provide additional (80) cells for pack assembly
- Battery performance testing is tentatively scheduled to start 10/17
  - Testing at the Cell Pack Level
  - Testing at the BMS Level
    - Two-fault tolerance to overcharge
    - Overdischarge
    - External short
- Conduct safety analysis from current design
- Prior to conducting the thermal runaway test, EnerSys plans to assemble a single cell pack and initiate a thermal event
- Amprius shall work with EnerSys to make a *best effort* to assemble hard prismatic cells with silicon nanowire anodes
  - Amprius will compare the specific energy of pouch and prismatic cells
- Cell delivery (5) to NASA GRC for independent assessment

THANK YOU FOR YOUR ATTENTION

Questions & Comments

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