Advanced High-Performance Batteries for Electric Vehicle (EV) Applications

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Amprius, Inc.

June 6-10, 2016

ES241

Overview

Timeline

- Start date: January 2015
- End date: January 2018
- Percent complete: 40%

Barriers

- Performance
  - Energy Density
  - Specific Energy
  - Cost
- Life
  - Cycle life

Budget

- Total project funding:
  $5,501,098
  - DOE share: $2,750,549
  - Contractor share: $2,750,549
- FY15 received: $393,611
- FY16 projected: $885,724

Partners

- Amprius – Project Lead

Objectives

Project Objectives

- Match silicon nanowire anodes with an advanced (high capacity and high energy density) cathodes and state-of-the-art cell components
- Develop, test and deliver 2Ah, 10Ah and 40Ah Li-ion cells with silicon nanowire anodes that meet the USABC 2020 goals
- **Main final performance targets:**
  - 350 Wh/kg and 750Wh/L at EOL
  - 2:1 Power:Energy ratio
  - 1,000 DST cycle life

Addresses Barriers

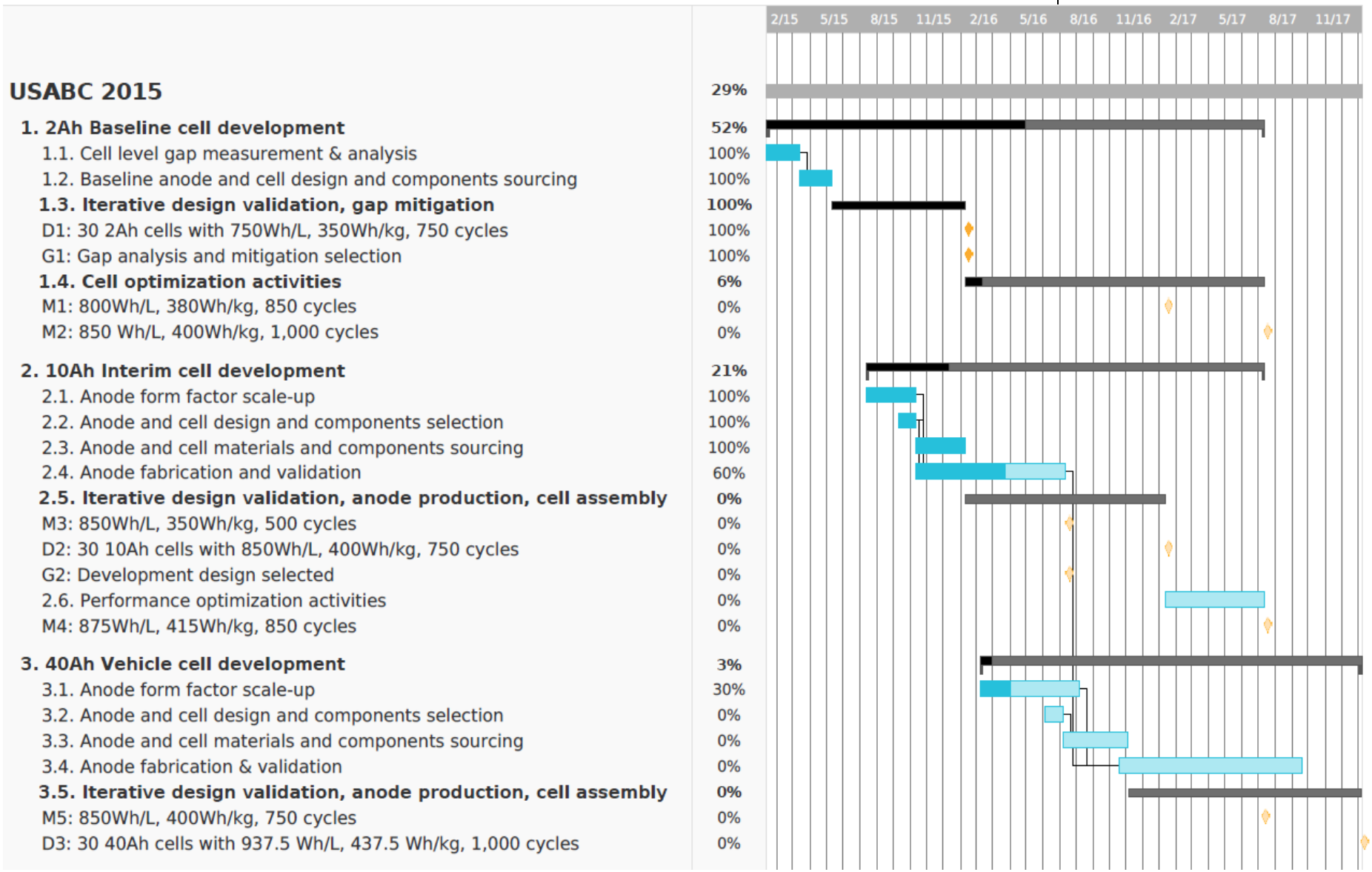
- Increases ***energy density and specific energy*** by reducing the mass and volume of the anode material
- Reduces the amount of anode material needed (high capacity per gram), reducing the ***cost*** per Ah
- Increases ***cycle life*** of cells with silicon anodes by optimizing the material in Amprius' rooted nanowire structure

Milestones and Timing

Month/Year	Milestone or Go/No-Go Decision	Status
Jan-16	Milestone/Deliverable: • Deliver 30 pouch cells with a capacity ≥ 2 Ah, energy density ≥ 750Wh/L, specific energy ≥ 350Wh/kg, DST cycle life ≥ 750	Complete
Jan-17	Milestone/Deliverable: • Achieve ≥ 800 Wh/L, ≥ 380 Wh/kg and ≥ 850 cycles in a ≥ 2 Ah cell • Deliver 30 pouch cells with a capacity ≥ 10 Ah, energy density ≥ 850Wh/L, specific energy ≥ 400 Wh/kg, and DST cycle life ≥ 750	On Track
Jul-17	Milestones: • Achieve ≥ 850 Wh/L, ≥ 400 Wh/kg and ≥ 1,000 cycles in a ≥ 2 Ah cell • Achieve ≥ 875 Wh/L, ≥ 415 Wh/kg and ≥ 850 cycles in a ≥ 10 Ah cell • Achieve ≥ 850 Wh/L, ≥ 400 Wh/kg and ≥ 750 cycles in a ≥ 40 Ah cell	On Track
Jan-18	Deliverable: • Deliver 30 pouch cells with a capacity ≥ 40 Ah, energy density ≥ 937.5 Wh/L, specific energy ≥ 437.5 Wh/kg, and DST cycle life ≥ 1,000	On Track

Relevance:

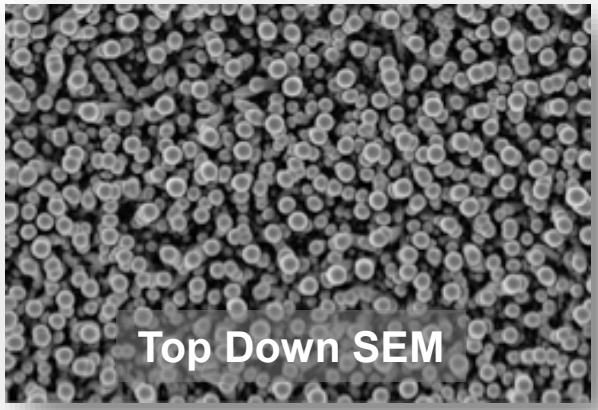
Milestones and Timing

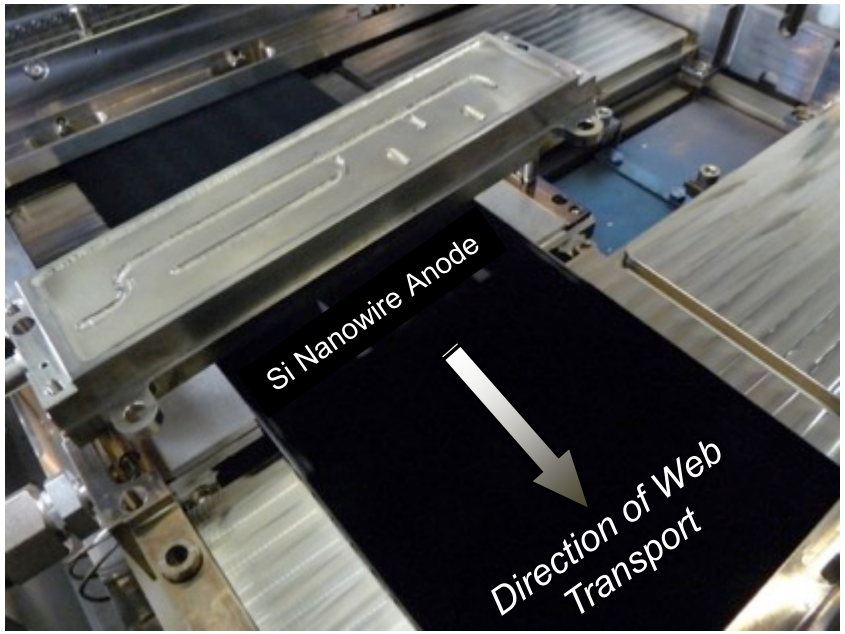


Approach:

Silicon Nanowires enables high energy

Amprius' growth-rooted silicon nanowires enable silicon to swell and contract successfully, without compromising the battery's mechanical stability





- 1/3-1/5th of graphite anode thickness
- High content active silicon materials (100%)
- Ideal and adjustable porosity distribution
- High mass loading (2-3 mg/cm^2)
- High conductivity and connectivity
- Low tortuosity – high rate capability

During Q1 2016, Amprius tested a first of its kind pilot line tool for roll-to-roll production of double-sided, rooted silicon nanowire anodes

Amprius Path to USABC Goals

Match silicon nanowire anodes with advanced (high capacity and high energy density) cathodes and state-of-the-art cell components

Develop anode and other cell components in a 2 Ah cell form factor to mitigate gaps in performance toward USABC goals

De-risk form factor scale-up in an intermediary cell form factor of 10 Ah

Develop 40 Ah cells that meet USABC goals in a VIFB—/99/300 cell size designation

FY 2015 Accomplishments

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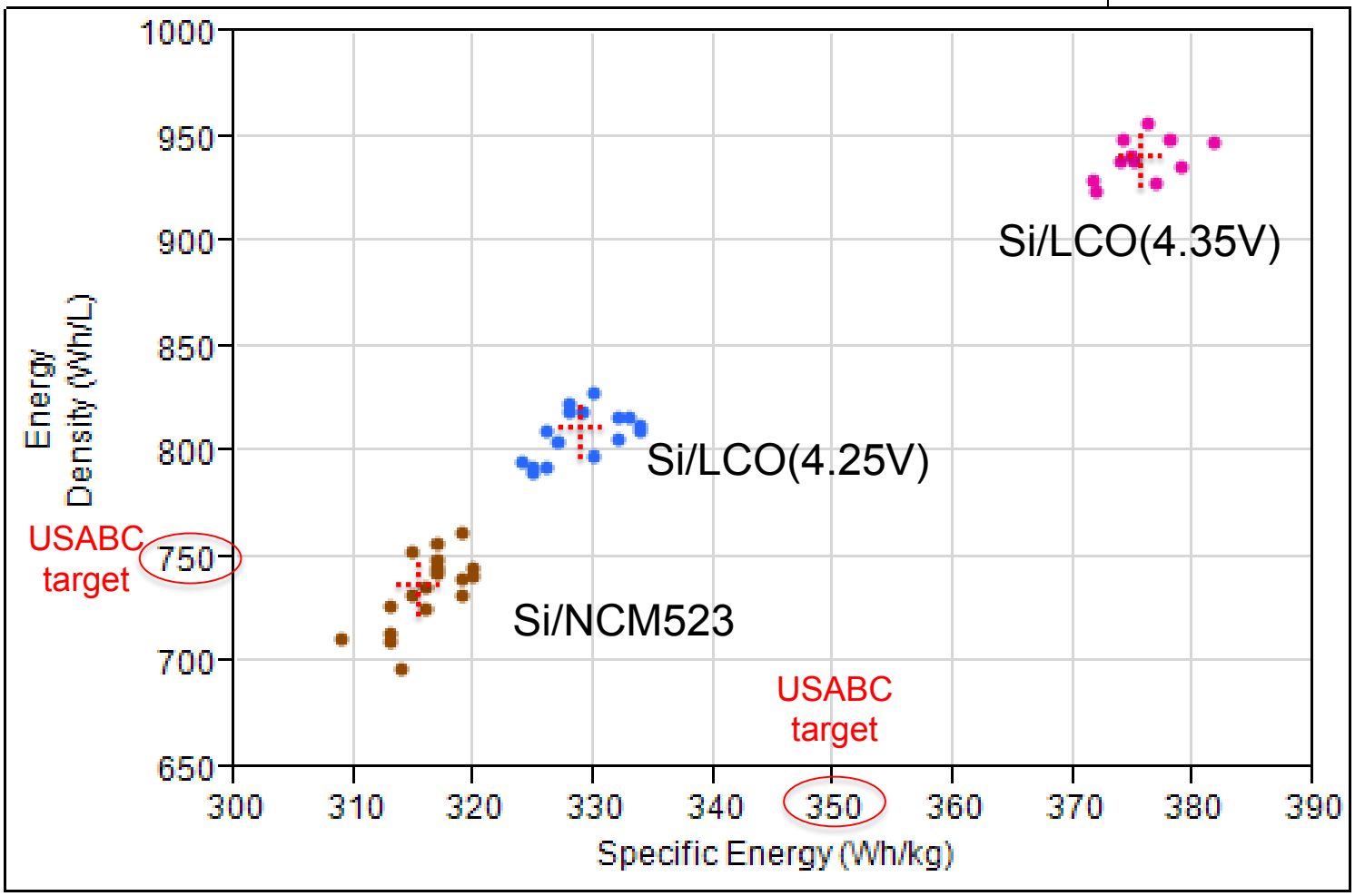
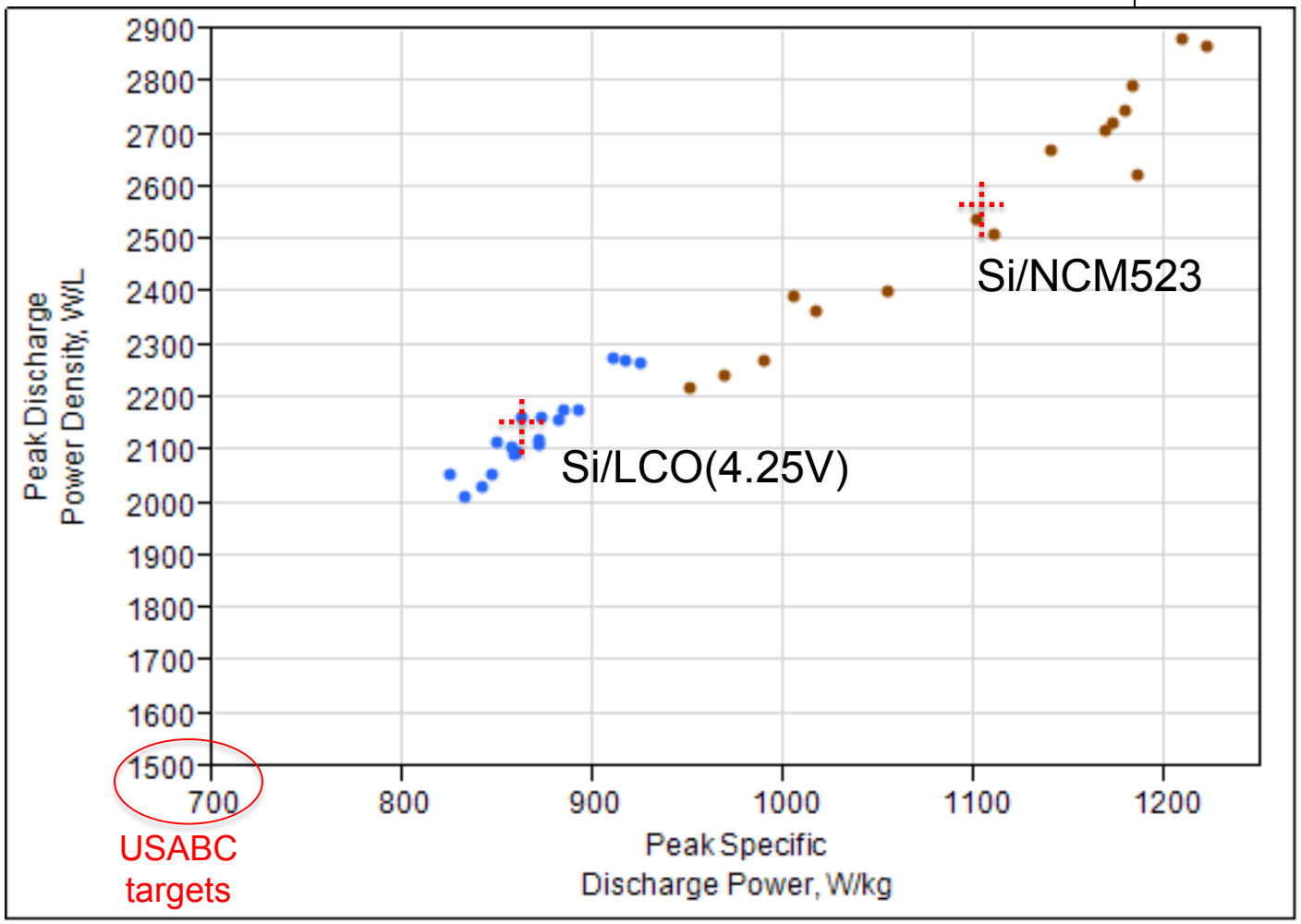
- Developed silicon nanowire cells with capacities of 2.6 - 3.1Ah (cathode dependent)
- Completed the gap chart analysis – with results exceeding performance targets for many criteria
- DST cycle life – Exceeded 500 cycles with NMC cathode and 300 cycles with LCO cathode
- Delivered 30 Silicon Nanowire-NMC cells to INL and SNL for performance and safety evaluation
- Completed 10Ah cell design and tooling. Tested first 10 Ah cell prototype

Gap Analysis - Energy



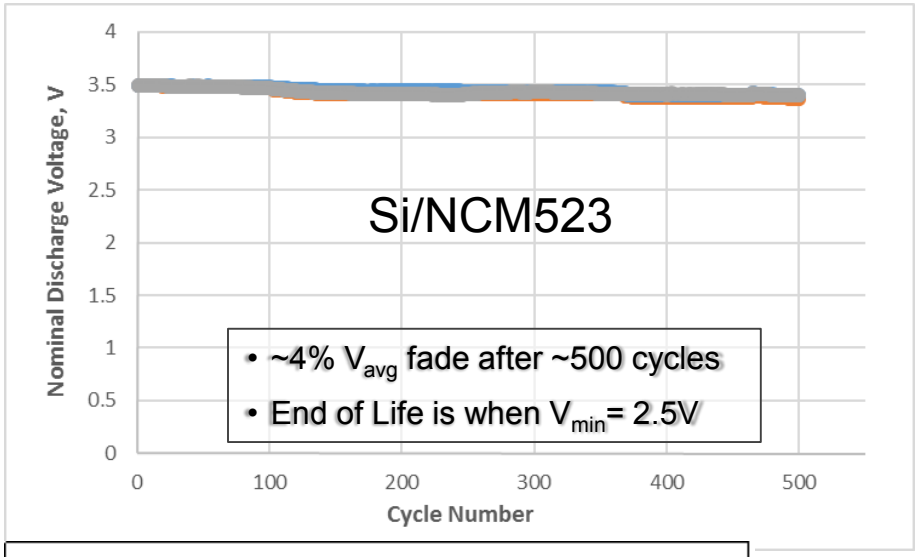
- Cathode energy density and specific energy has to be higher than that of NMC523 – minimum 180 mAh/g
- Advanced cathodes meet the requirements

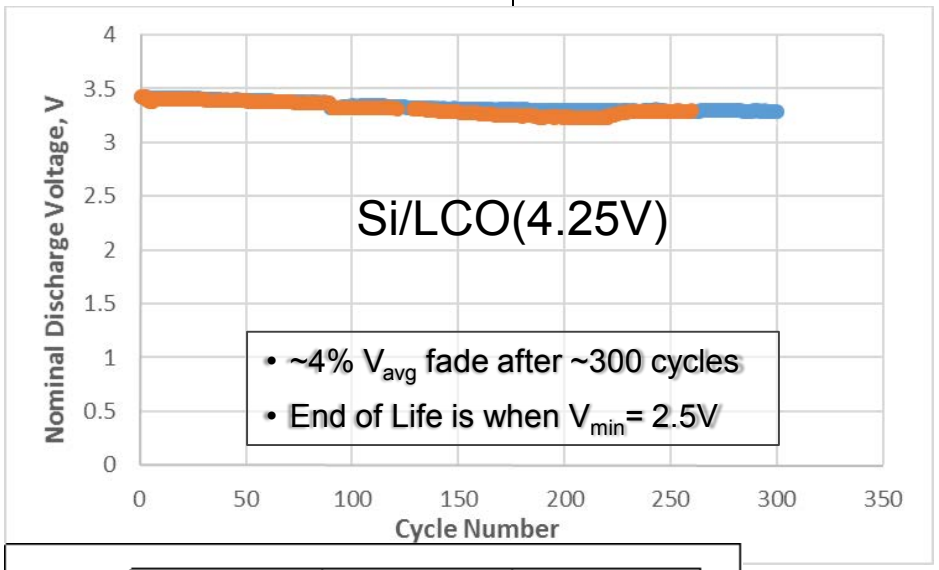
Gap Analysis - Power

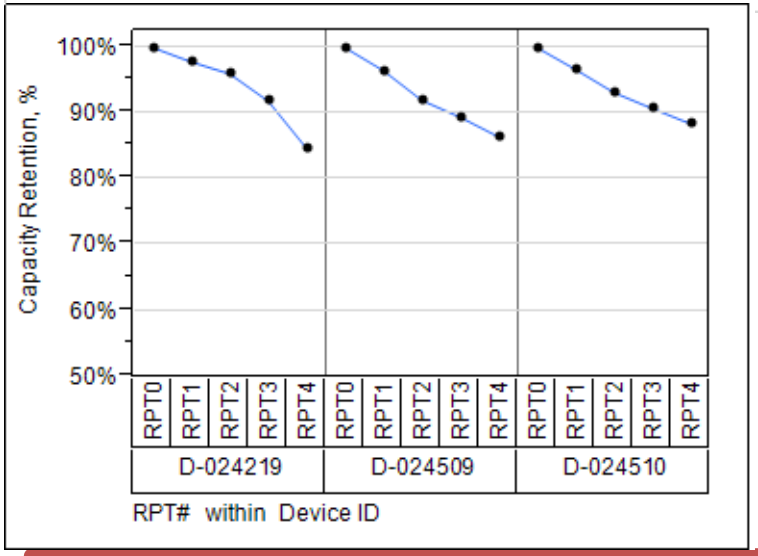


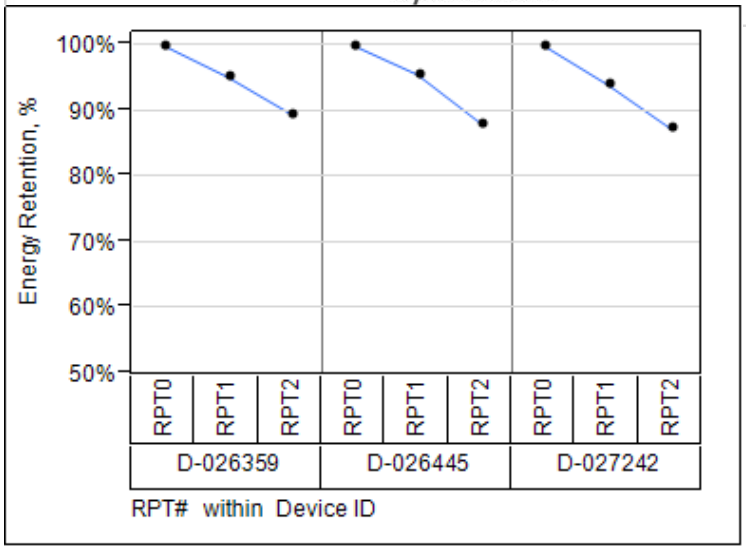
•Initial power performance exceeds EOL targets by more than 20% - good reserve for operational life

Gap Analysis – DST Cycle Life



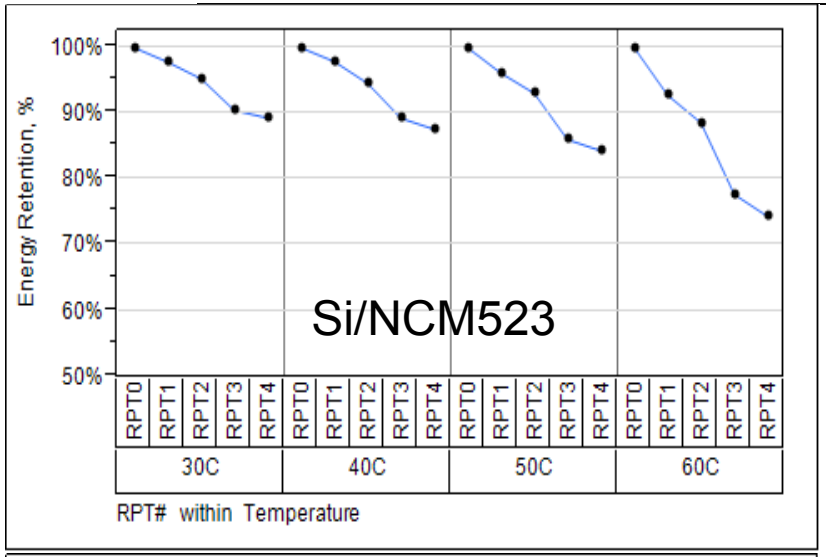


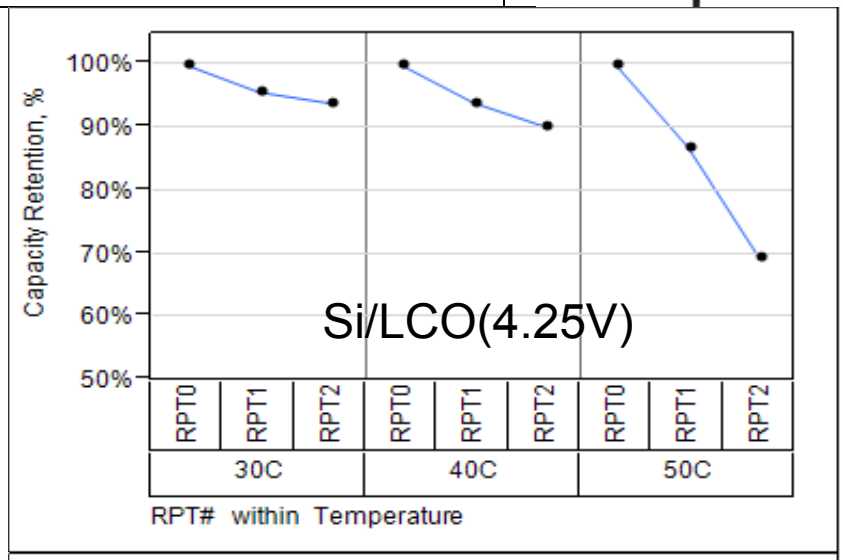


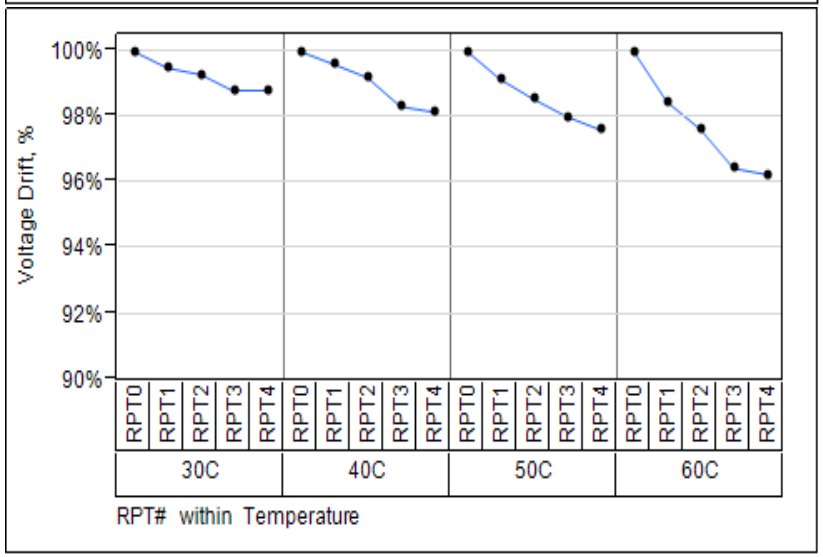


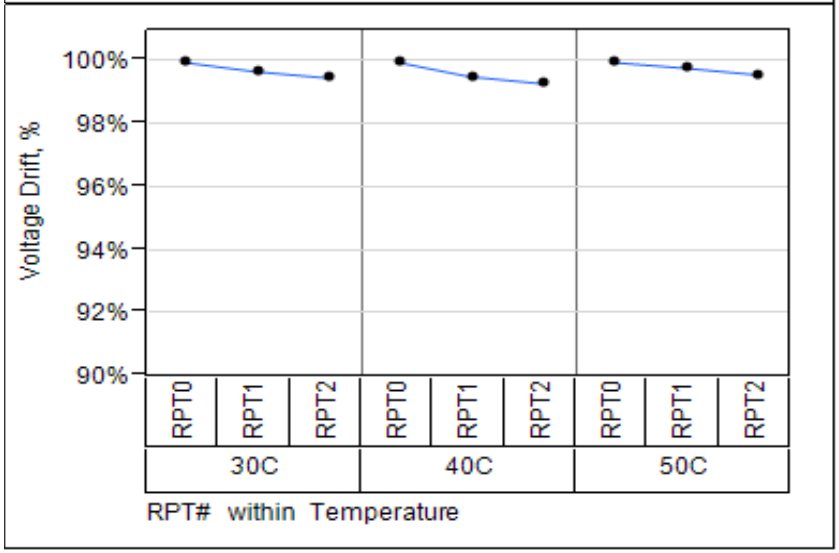
- Reference Performance Tests (RPT) were performed every 120 cycles (~32 days)
- NMC has better cycle life than LCO

Gap Analysis – Calendar Life Test



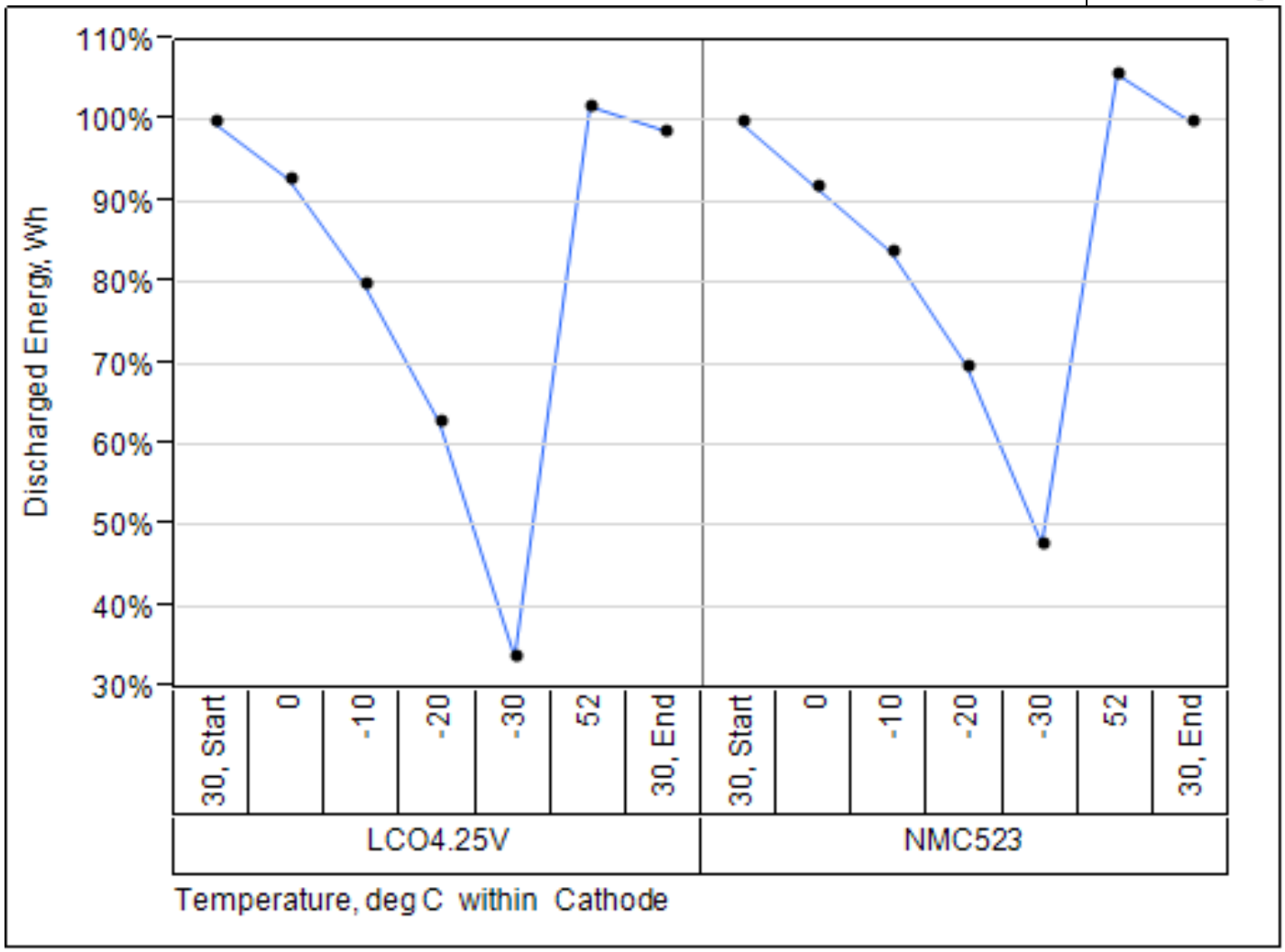






- Reference Performance Tests (RPT) were performed every ~32 days of storage
- NMC has better calendar life than LCO

Gap Analysis – Temperature Performance Test

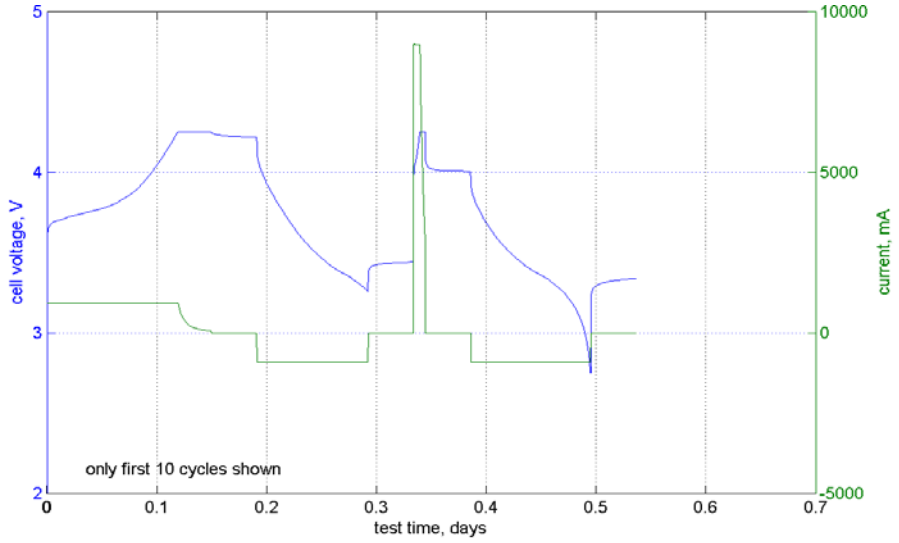


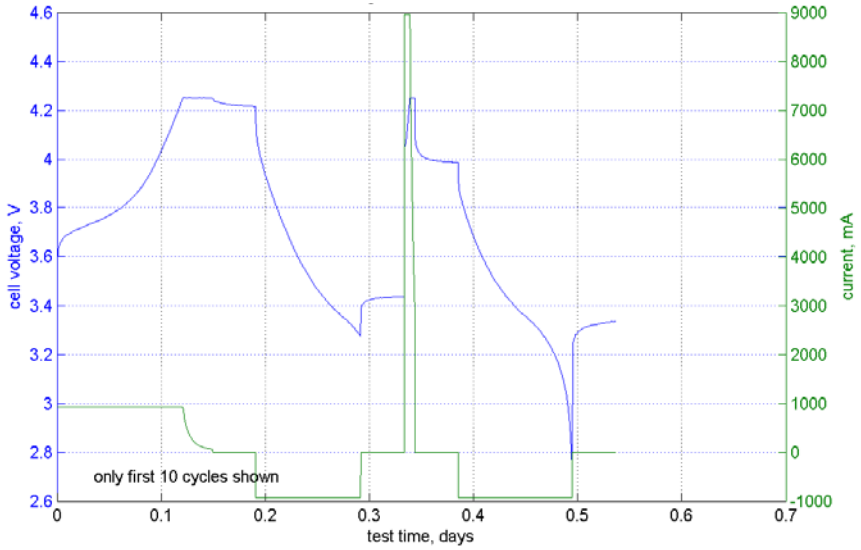
•NMC has slightly better performance at -20 ºC and meets USABC targets (70% energy available)

Gap Analysis – High Rate Charge Test

Test Protocol:

- Discharge the operational capacity (80%) from a fully charged cell at C/3 rate
- Charge for 15 minutes at 3.2C rate; taper the remaining time if Vmax100 is reached





	Capacity Removed, Ah	Capacity Restored in 15 min, Ah	Capacity Restored in 15 min, %	Energy Removed, Wh	Energy Restored in 15 min, Wh	Energy Restored, %
Cell 1	2.24	1.85	82.6%	8.00	7.60	95%
Cell 2	2.24	1.83	81.7%	8.01	7.61	95%

Amprius' cells met USABC goals (>80% capacity restored in 15 minutes)

Gap Table for SiNW cells with NCM and LCO cathode

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Characteristics at 30°C and End of Life	Units	USABC Goals – Cell Level	Amprius Q3 (LCO) Cell Level	Amprius Q3 (NCM-523) Cell Level	Comments
Peak Discharge Power Density, 30 s Pulse	W/L	1500	2147/2585	2089/2368	From HPPC/PPT
Peak Specific Discharge Power, 30 s Pulse	W/kg	700	873/1052	906/1025	From HPPC/PPT
Peak Specific Regen Power, 10 s Pulse	W/kg	300	400 at 1% DOD	157 at 1% DOD 839 at 10% DOD 1301 at 20% DOD	VmaxPulse=Vmax100 for NCM
Available Energy Density @ C/3 Discharge Rate	Wh/L	750	808	705	Beginning of Life
Available Specific Energy @ C/3 Discharge Rate	Wh/kg	350	329	306	Beginning of Life
Available Energy @ C/3 Discharge Rate	kWh	N/A	0.01	0.009	Beginning of Life
Calendar Life	Years	15	TBD	TBD	Under evaluation
DST Cycle Life (80% DOD)	Cycles	1000	300-400	500-600	Needs Improvement

Gap Table for SiNW cells with NCM and LCO cathode

amprius

Characteristics at 30°C and End of Life	Units	USABC Goals – Cell Level	Amprius Q3 (LCO) Cell Level	Amprius Q3 (NCM-523) Cell Level	Comments
Selling Price @ 100K units	$/kWh	$100	TBD	TBD	
Operating Environment	°C	-30 to +52	-30 to +52	-30 to 52	Meets Criteria
Normal Recharge Time	Hours	< 7 Hours, J1772	3 Hours	3 Hours	Meets Criteria
High Rate Charge	Minutes	80% ΔSOC in 15 min	82% ΔSOC in 15 min	Not measured	TBD
Maximum Operating Voltage	V	N/A	4.25	4.1	NCM-523 operated at 4.25V vs. Lithium
Minimum Operating Voltage	V	N/A	2.75	2.5	
Peak Current, 30 s	A	400	5.6	8.25	From Peak Power test
Unassisted Operating at Low Temperature	%	> 70% Useable Energy @ C/3 Discharge Rate at -20°C	> 60% Useable Energy @ C/3 Discharge rate at 0 °C	> 70% Useable Energy @ C/3 Discharge rate at -20 °C	Meets Criteria for NMC
Survival Temperature Range, 24 Hr	°C	-40 to+ 66	-40 to 85	-40 to +66	Meets Criteria
Maximum Self-discharge	%/ mon	< 1	TBD	TBD	Under Evaluation

Response to Reviewer Comments

New Project, Not Applicable

(No Prior Comments)

Amprius looks forward to reviewing and replying to your comments

Please don't hesitate to ask questions now – or by email to ionel@amprius.com

Collaborations:

Team Overview

Amprius is the only team member; there are no subcontractors on the project

Amprius has to date performed the overwhelming majority of project work. However, Amprius has and will continues to engage external vendors to assist with the development and coating of advanced cathodes

Remaining Challenges and Barriers

Sourcing high energy density coated cathodes and materials

- NMC materials are produced in a variety of formulations and structures. Selecting a material with high capacity and high cycle life requires a large number of trials and coating conditions of high quality – similar to those in state of the art commercial cells

Cycle life improvement

- Amprius continues to increase the cycle life by optimizations of the electrolyte formulation, anode structure, cathode materials and coating, and separator type

Energy density and specific energy

- Although specific silicon nanowire-cathode combinations exceed USABC targets at beginning of life, the margin needs to be higher in order to meet the targets at end of life
- High energy density and specific energy cells usually have lower cycle life. Optimizations and improvements in one direction have to be verified for effects on the rest of specifications

Activities – Through FY2016

Continue cell optimizations to increase cycle life and energy

- Evaluate new, higher energy cathode materials
- Iterate electrolyte formulations in DST cycle life

Finish testing 10Ah cell performance toward gap table specifications

- Iterate cell design and test 10Ah cells to select configuration for second year deliverables

Prepare equipment, fixtures and materials for year 3 cell format (40Ah)

- Scale-up anode to form factor required
- Design cell and source components

Summary

Amprius assembled and evaluated cells with silicon nanowire anodes and NMC523 cathodes that achieve 315 Wh/kg and 740Wh/L and cycle over 500 DST cycles

Amprius assembled and evaluated cells with silicon nanowire anodes and LCO cathodes that achieve over 340 Wh/kg and 800 Wh/L and cycle over 300 DST cycles

Both Silicon Nanowire-NCM and Silicon Nanowire-LCO cells exceed power specifications and meet USABC's target operating and survival temperature ranges

Amprius delivered 30 cells with a capacity higher than 2Ah for external performance and safety evaluation