Silicon Nanowire Anodes for Next Generation Energy Storage

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ES126

Overview

amprius

Timeline

- Start date: October 2011
- End date: September 2014
- Percent complete: 85%

Barriers

- Performance
  - Energy Density
  - Specific Energy
  - Power
- Life
  - Cycle life
  - Shelf life

Budget

- Total project funding:
  $8,215,077
  - DOE share: $4,998,336
  - Contractor share: $3,216,741
- FY13 received: $1,112,864.43
- FY14 projected: $1,882,372.55

Partners

- Amprius – project lead
- BASF – cathode development
- Nissan – cell design

Objectives

Project Objectives

- **Develop, optimize and validate silicon nanowire anodes as a viable platform for use in conjunction with commercial cathode materials in next generation high-energy lithium-ion batteries for vehicle applications.**
- **Final performance targets:**
  - >680 Wh/L energy density, >330 Wh/kg, 300-1,000 cycles
  - Calendar life degradation indicative of 5-10 year life
  - Safe, durable cell construction

FY2013 Objectives

- **Increase cell energy while extending cell cycle life**
- **Interim performance targets:**
  - >580 Wh/L energy density, >250 Wh/kg, >300 cycles

Addresses Targets

- Energy density and specific energy, >25% higher than current state-of-the-art
- Cycle life compatible with electric vehicle applications (1,000 cycles)

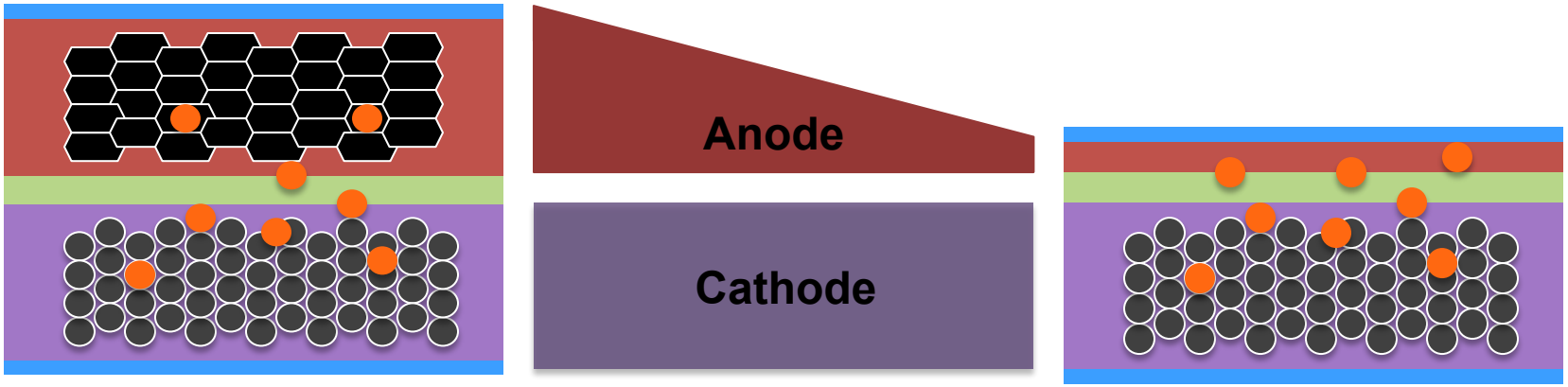
Milestones

Month/Year	Milestone or Go/No-Go Decision
Mar-13	• Designed 2.3Ah Si/LCO interim cells (Completed)
May-13	• Identified and documented process conditions and metrology necessary to optimize anode structure (Completed)
Oct-13	• Selected and documented anode fabrication process for high volumetric charge density (950 mAh/cc) (Completed) • Demonstrated interim cell performance targets with Si/LCO; >580Wh/l, >250Wh/kg, >300 cycles (Completed)
Oct-13	• Delivered interim Si/LCO cells. **Amprius' cells exceeded target energy density and specific energy by 12% and 8%, respectively, and cycled over 500 cycles at 80% depth of discharge.** Amprius' cells also passed HPPC and temperature tests. (Completed)
Mar-14	• Identify process conditions necessary to build anodes on thin (10 μm) foil. (Ongoing) • Update cell design for Si/NCM chemistry (Ongoing)
July-14	• Demonstrate final performance targets with Si/NCM-523; 2.2-2.4Ah cells with >680 Wh/l, >330 Wh/kg, and >750 Cycles (Ongoing)
Aug-14	• Model high volume anode manufacturing processes, tools and costs (Ongoing)
Sep-14	• Deliver 18 final cells and test report

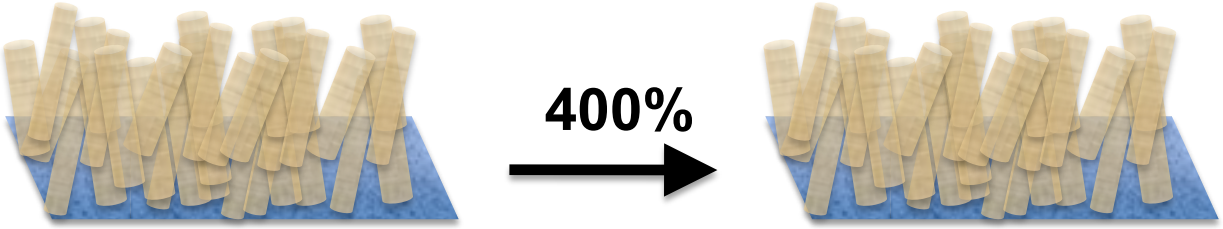
Approach:

Unique Nanowire Structure

Amprius' pure silicon nanowires significantly improves battery performance by reducing the size and weight of the anode

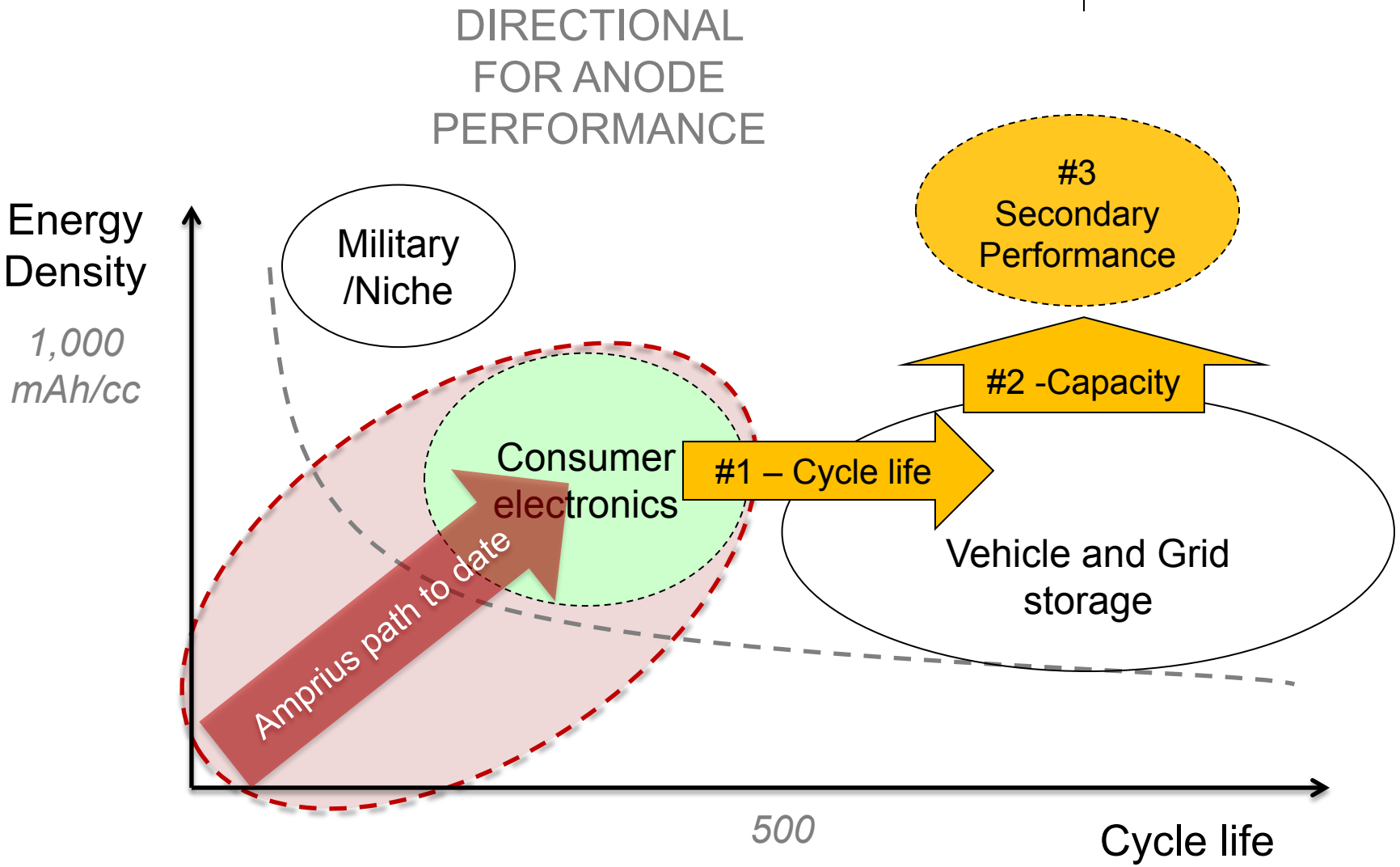


Amprius' growth-rooted silicon nanowires enable sillicon to swell and contract successfully, without compromising the battery's mechanical stability



Si $+Li^+ + e^-$ Si_xLi_y

Anode Path for the Project

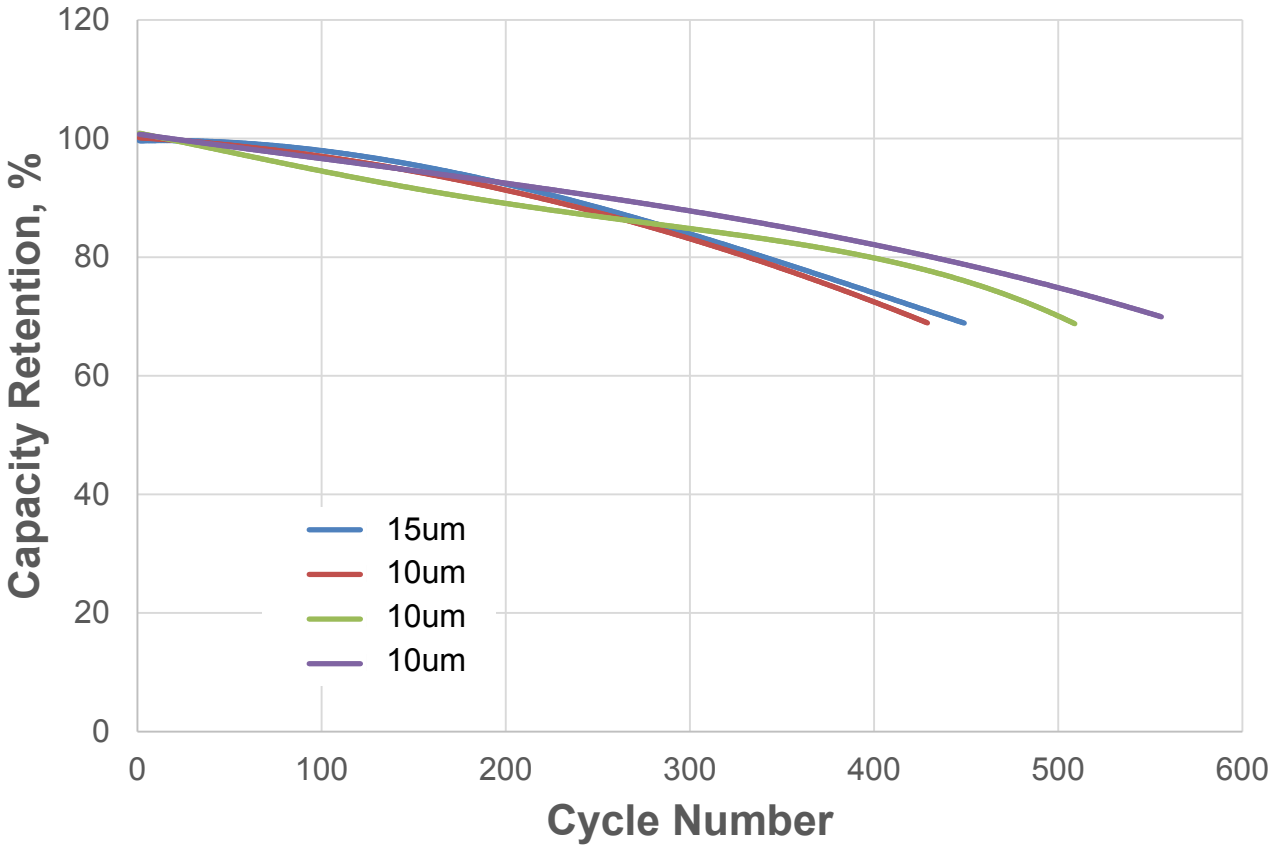


Q6-Q9 Accomplishments

amprius

- Delivered 18 Si/LCO cells to Idaho National Laboratory. Amrpius' cells exceeded the project's annual goals for specific energy, energy density and cycle life by 8-20% and passed HPPC and temperature performance tests
- Achieved over 400 cycles, 700Wh/L and 285Wh/kg at a rate of C/2 and full depth of discharge
- Developed a new nanowire growth process that reduced cell swelling to less than 5% and increased cycle life to more than 700 cycles in single-layer cells
- Developed tooling and metrology methods for silicon nanowire anode materials
- Optimized the silicon nanowire structure to increase cycle life and reduce swelling (through a design of experiment)
- Designed and developed a new 2.3Ah pouch cell

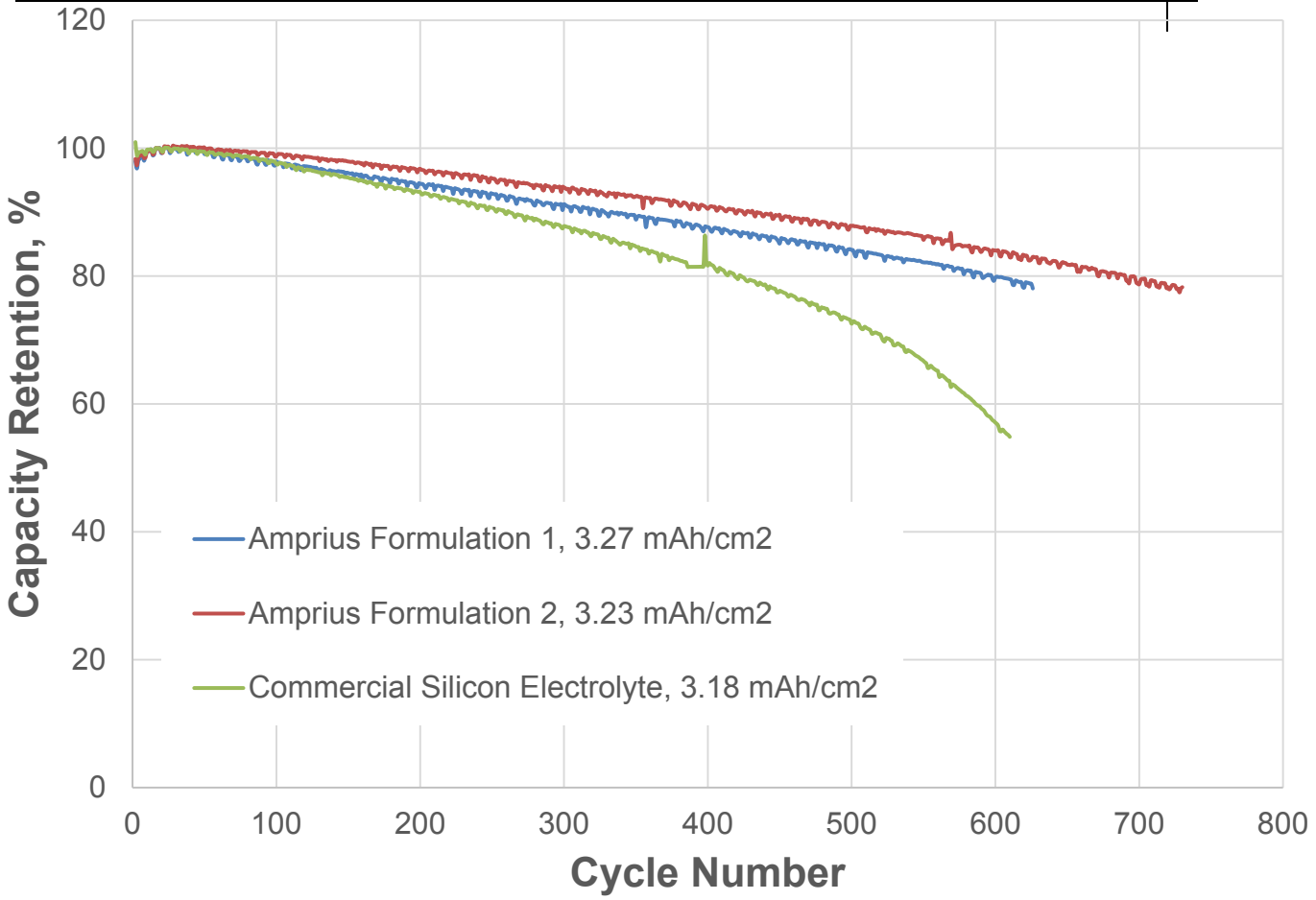
Anodes on Thin Foil



Cycle life in full cell data is not affected by foil thickness

Similar nanowire structure is achieved on 15 μm foils and 10 μm foils

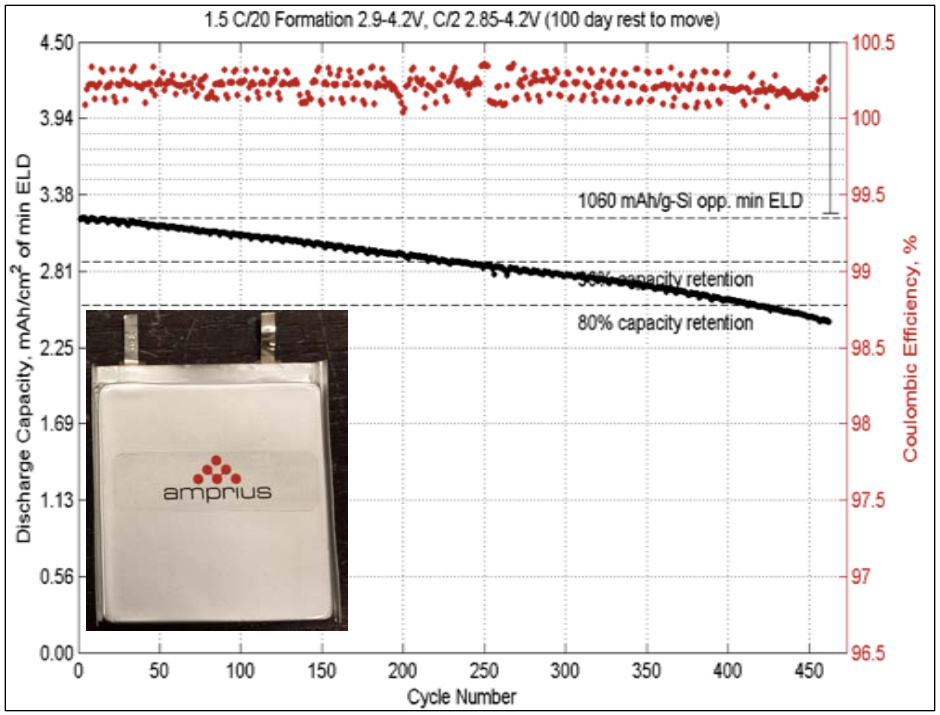
New Electrolyte Formulations

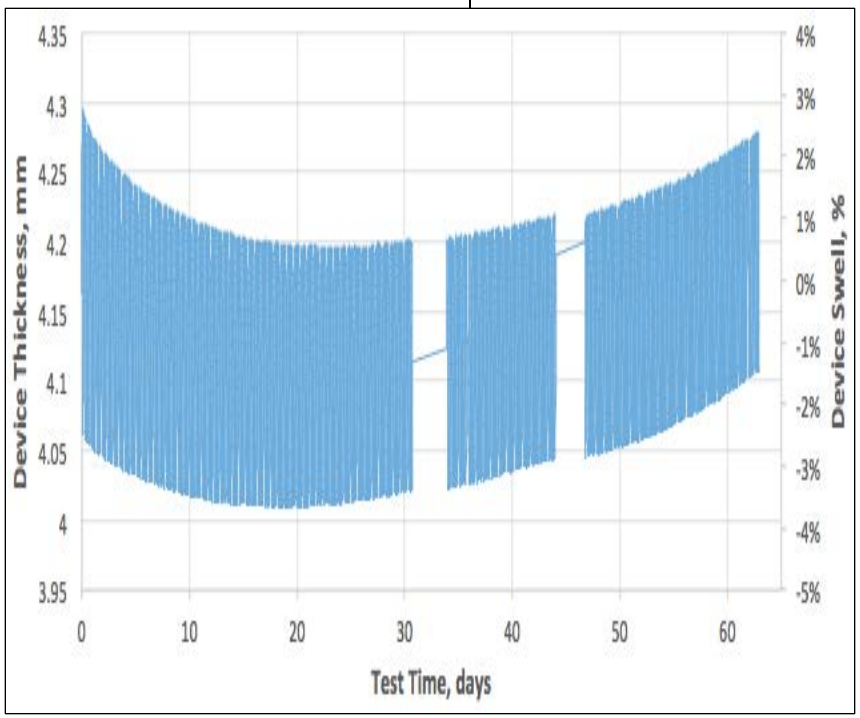


Cycle life in Si/LCO cells was increased to 700 cycles

Coulombic efficiency is stable to the end of the cycle life

New ~2.3 Ah Cells





- Pouch cell, 4.5x50x55mm including terrace, LCO cathode
- C/2 rate: Energy density >700Wh/l, Specific energy >285 Wh/kg
- Cycle life at C/2 and full depth of discharge >400 cycles
- 0-100% SOC swell <5%, cycle life swell <5%

Technical Accomplishments:

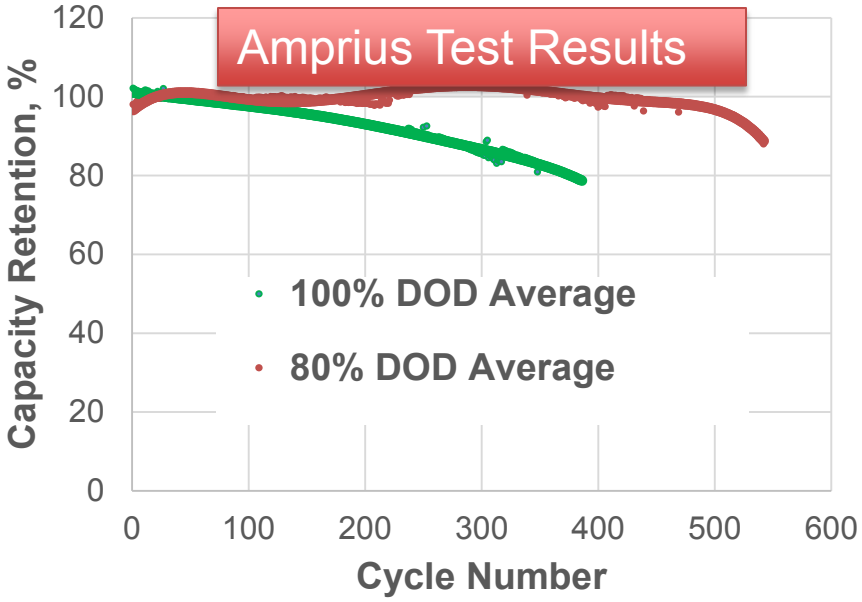
Delivered 18 Cells

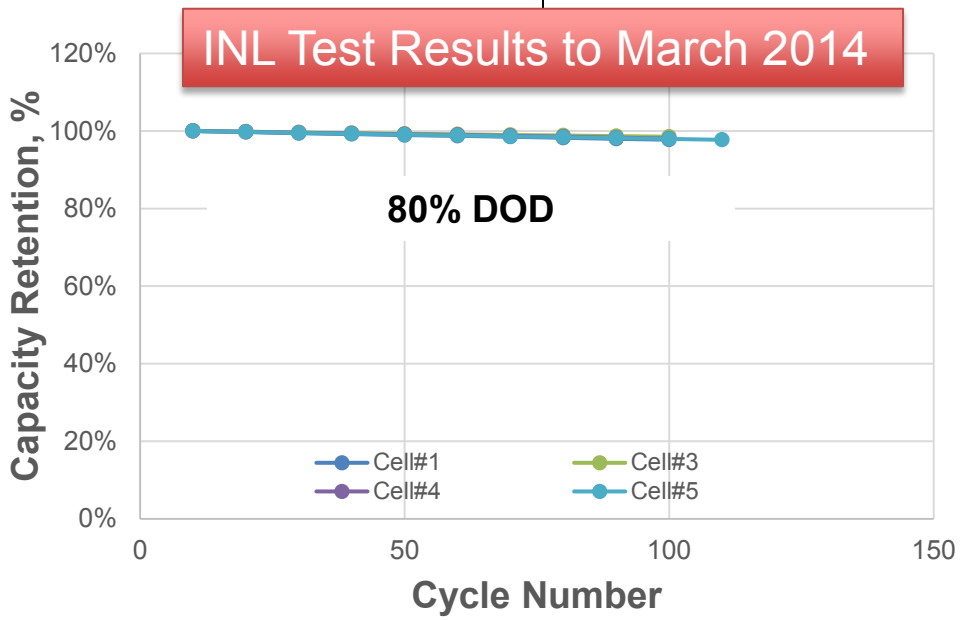
Device-ID	Nominal Device Capacity (mAh)	Nominal Device Energy (Wh)	Nominal Discharge Voltage at C/2 (V)	GED (Wh/kg)	VED (Wh/L)	Shipping OCV (V)	Shipping Z(1kHz) / mΩ	Shipping Thickness / mm	Weight/ g
D-15326	2471.51	8.74	3.54	286	680	3.53	14.6	4.48	30.59
D-15444	2368.64	8.31	3.51	272	638	3.56	18.7	4.54	30.55
D-15453	2374.74	8.32	3.50	274	641	3.56	20.2	4.52	30.36
D-15479	2402.49							4.53	30.90
D-15489	2345.52							4.56	30.84
D-15532	2337.12							4.63	30.95
D-15809	2348.51							4.37	30.70
D-15810	2398.39							4.35	30.57
D-15811	2291.63							4.42	30.90
D-15812	2335.52							4.49	30.81
D-15856	2340.72							4.49	30.98
D-15857	2394.41							4.45	31.13
D-15858	2381.25							4.48	30.25
D-15859	2393.10							4.52	30.71
D-15860	2394.57							4.47	31.21
D-15861	2258.15							4.28	30.35
D-15864	2359.38							4.38	30.85
D-15865	2335.14	8.25	3.53	267	653	3.55	15.4	4.37	30.83
Average	**2362.82**	**8.33**	**3.53**	**271.06**	**646.39**	**3.55**	**16.41**	**4.46**	**30.75**
St. Dev	**46.84**	**0.17**	**0.01**	**6.15**	**16.24**	**0.01**	**1.64**	**0.09**	**0.26**
St. Dev, %	1.98%	2.10%	0.42%	2.27%	2.51%	0.35%	9.99%	1.94%	0.86%

<2% standard deviation of the delivered lot

12% higher energy density and 8% higher specific energy than the project's Year 2 targets

Deliverable – Cycle Life



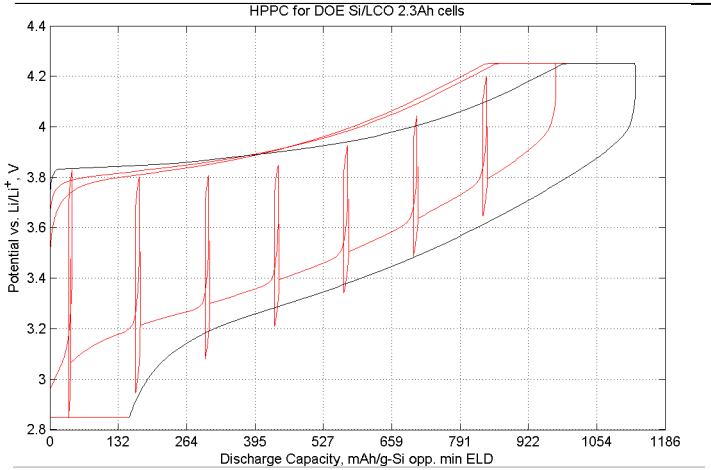


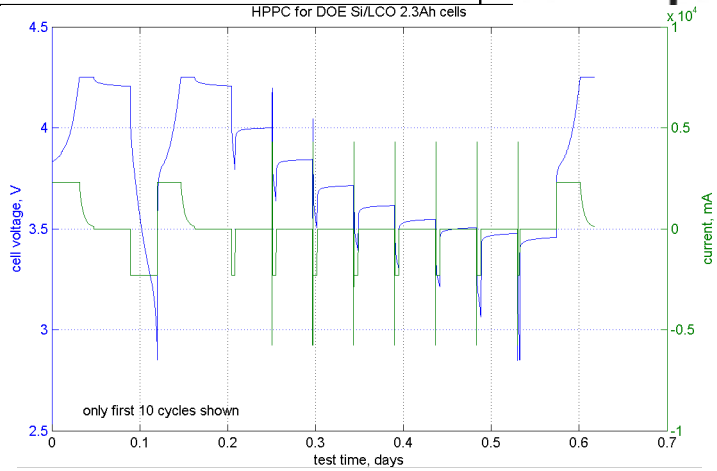
18 2.3Ah pouch cells were tested at Amprius and
18 cells were delivered Idaho National Laboratory (INL), which began testing the cells

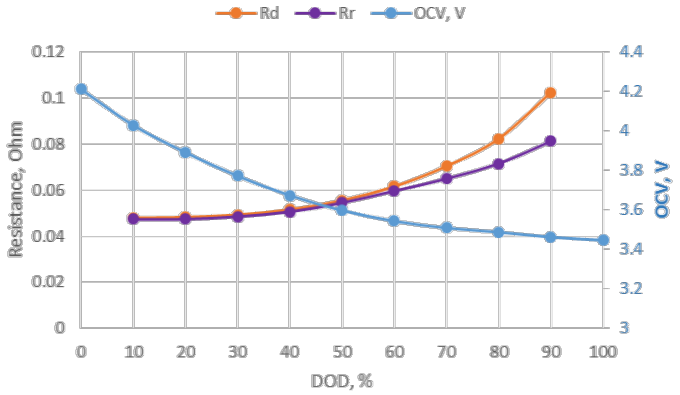
At full depth-of-discharge (DOD), Amprius' cells passed 300 cycles (C/2 rate)
At 80% DOD, Amprius' cells passed 500 cycles (C/2 rate)

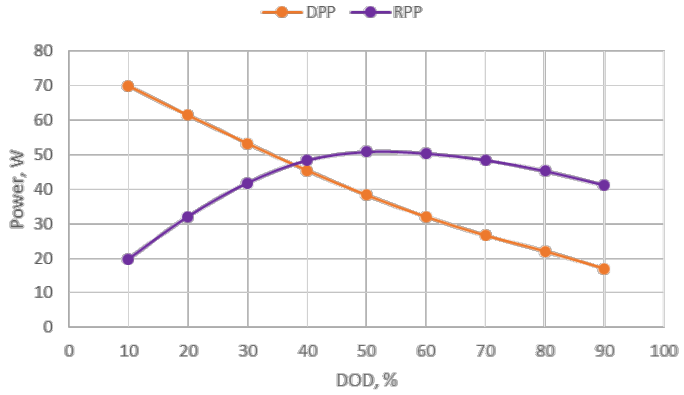
At 80% DOD, preliminary results from Idaho National Laboratory project similar cycle life performance (C/3 rate)

Deliverable – HPPC





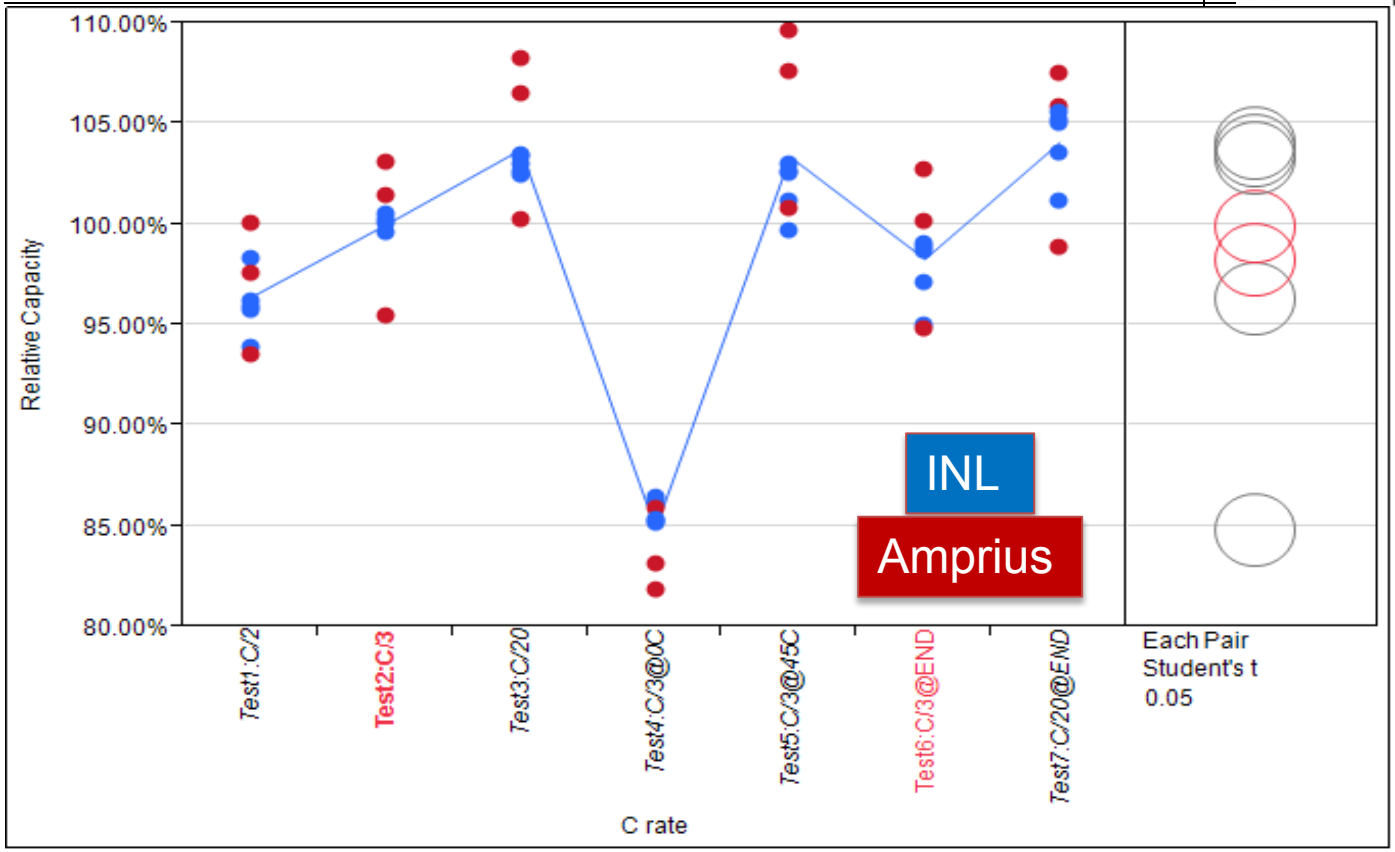




Amprius cells passed the HPPC test on all 9 discharge segments without hitting the voltage limits

INL confirms the results (but INL data is not available at this time)

Deliverable – Temperature



Capacity about 85% at 0°C relative to room temperature, 103% at 45°C

C/3 rate capacity about 3% lower than C/20 capacity

No statistical difference between before and after test measurement

Response to Reviewer Comments

Approach:

- **Comment: "performance targets in the project objective have relaxed a little since 2012"**
- **Response:** In 2011, Amprius proposed to deliver in 2014 cells that matched silicon nanowire anodes with layered-layered cathodes to achieve very high energy. Amprius' *anode* targets – the focus of the project – have remained the same. However, the performance of the layered-layered *cathode* has not improved as projected. As a result, Amprius replaced the cathode with an NCM 523 cathode, which reduced the energy targets for the cells to be delivered in 2014.

Technical accomplishments:

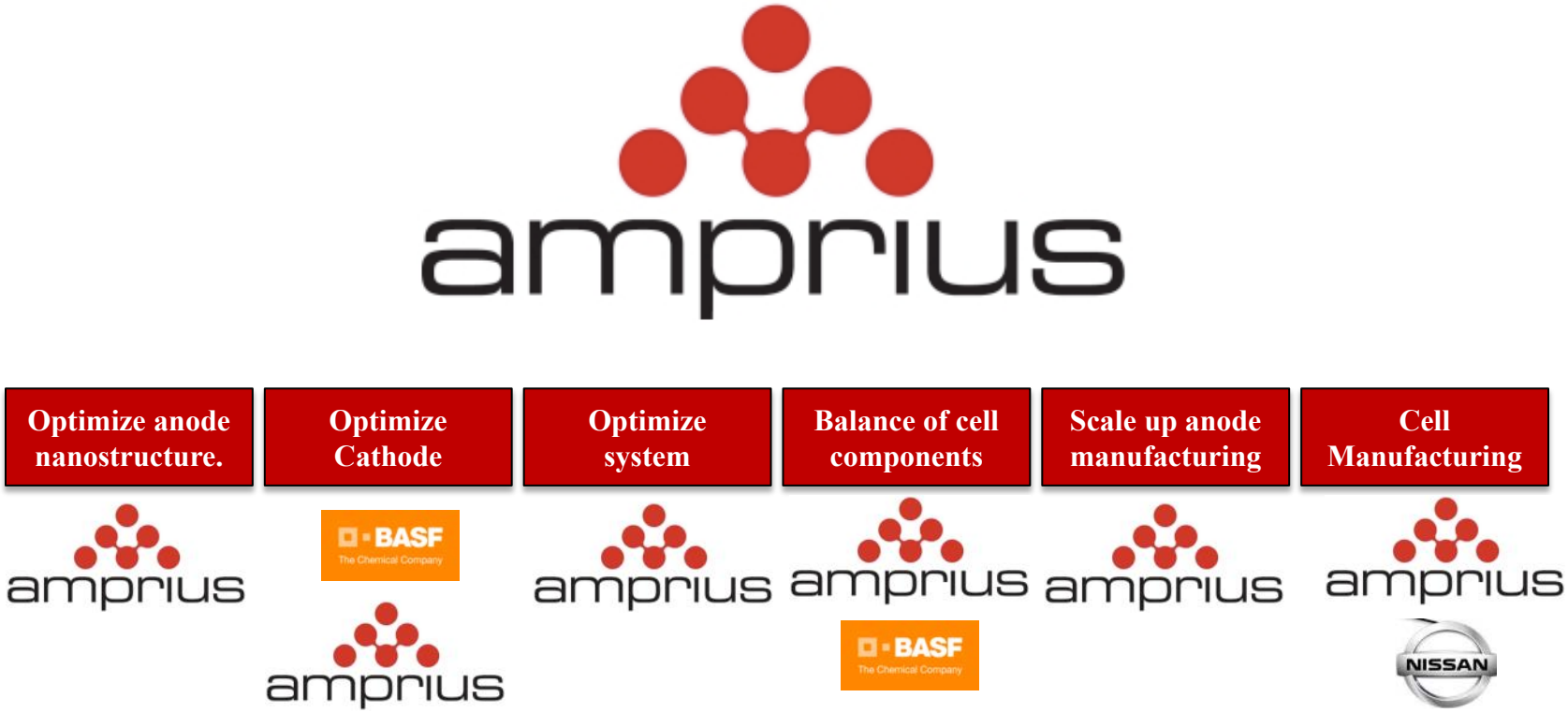
- **Comments: "temperature performance and mechanical stability are not mentioned," "many of the issues pertained to cell build quality"**
- **Response:** During the project's first year, Amprius focused on improving anode structure to enable higher energy and longer cycle life. During the second year, Amprius focused on developing a new anode production process; redesigning the cell and improving cell assembly procedures; and evaluating cell performance over a wider temperature range

Collaboration:

- **Comment: "actual specific contributions and necessity of involvement given the stated roles of all partners is unclear"**
- **Response**: Amprius is performing the overwhelming majority of project work. BASF is providing cathode and electrolyte materials. Nissan is advising on cell design.

Collaborations:

Team Overview



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Activities – Through September

Anode material efforts

- **Optimize size, structure, surface and composition of the silicon nanowires to increase cycle life and volumetric charge capacity**
- **Improve anode uniformity and production yield on 10um foils**

Electrochemistry

- **New electrolyte formulations for silicon SEI and NCM cathode**
- **Improve formation and cycling protocol**
- **Anode/Cathode matching**

Cell design and testing

- **Iterate cell design for best energy density and safety performance**
  - High temperature storage and cycle life
  - Low temperature capacity and power
  - Cell level swelling during cycling and storage

Summary

Amprius delivered 18 interim cells to Idaho National Laboratory. Amprius' cells exceeded the project's interim targets for specific energy, energy density and cycle life. The cells also passed the HPPC and temperature tests

The silicon nanowire structure enables high-energy performance; Amprius demonstrated >700 Wh/l and > 285 Wh/kg at a C/2 rate, with a cycle life of > 500 cycles (at 80% DOD) and <5% cell swelling

Meeting the project's energy density and cycle life targets for silicon anode-based cells will double the driving range of electric vehicles – accelerating vehicle electrification and reducing US dependence on foreign oil