HIGH ENERGY ANODE MATERIAL DEVELOPMENT FOR LI-ION BATTERIES

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SiNode Systems, Inc.

DOE Annual Merit Review

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ES240

Overview

Timeline

- Project start date: August 2014
- Project end date: July 2016
- Percent complete: 33%

Barriers

- Barriers addressed
  - Performance (energy, power)
  - Life (cycle and calendar)
  - Cost ($/kWh)

Budget

- Total project funding: $1M
- Funding received in FY14: $500k
- Funding for FY15: $500k

Partners

- Interactions/collaborations
  - Navitas Systems: prototyping, safety
  - Northwestern University: characterization
- Project lead
  - SiNode Systems

Relevance – Project objectives

- **Goal/Objective:**
  - Develop a high capacity Si-C based anode that can exceed DOE performance targets when paired with commercial cathode materials
  - Further optimize its manufacturability to meet commercially viable production protocols.

- **End performance targets:**
  - 200 Wh/kg cell energy, 1000 cycles
  - 750~1500 mAh/g anode, 1000 cycles

- **Year 1 Deliverables**
  - Cycling performance of prototype cells with comprehensive report on failure modes
  - Preliminary cost estimate for materials ($/kWh) and roadmap for cost reduction to DOE target
  - Initial report on safety testing and plan for safety qualification

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Milestones (Phase II Year 1)

Date	Milestone or Go/No-Go Decision	Status
November 2014	▪ High energy and volume materials processing improvements	Ongoing
	▪ Complete scale-up processing to larger format	Complete
	▪ Electrode densification approaches identified	Complete
	▪ Initiated *in-situ* characterization plan	Complete
February 2015	▪ Process environment improvements for improved cycling	Complete
	▪ Electrode modification investigation for improved cycling	Complete
	▪ Investigate suitable materials for electrode densification	Ongoing
	▪ ***Design and build initial prototype cells for DOE***	Complete
May 2015	▪ High capacity electrode formulation improvements	On Schedule
	▪ Validation of low-cost, high-volume raw material	On Schedule
	▪ Validate improved processing approach	On Schedule
	▪ ***Design and build updated prototype cells***	On Schedule
August 2015	▪ Complete electrode densification study	
	▪ Complete mechanical properties characterization	
	▪ ***Complete YR1 design and final cell build deliverable***	
	▪ ***Finalize initial safety testing report***	

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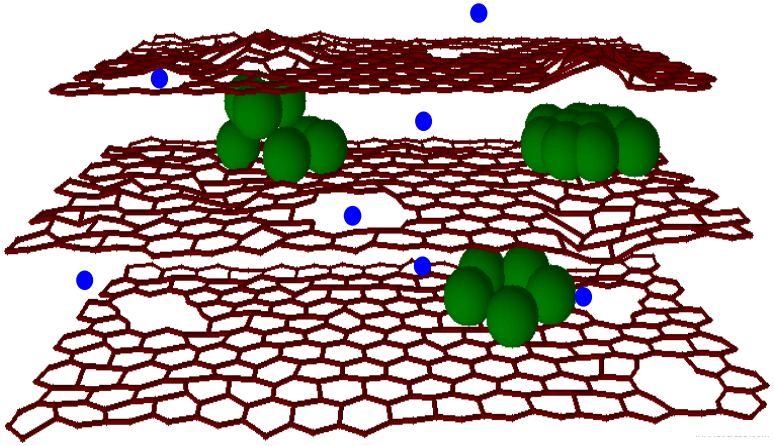
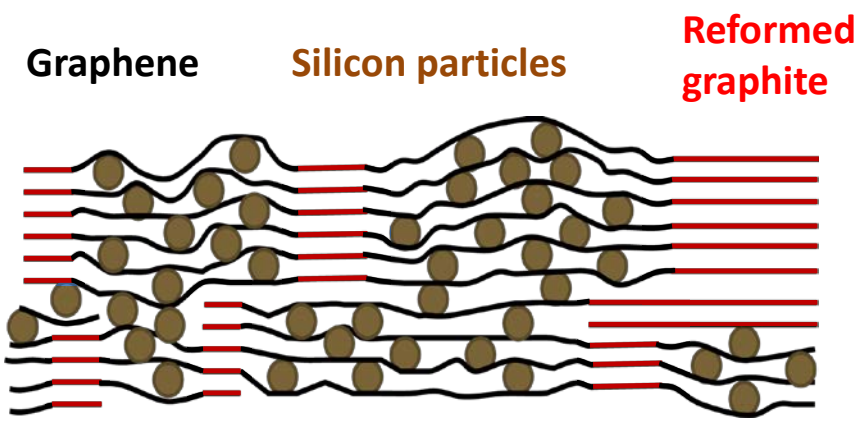
Approach: 3-D graphenic architecture





Developed 3D structure that provides stable environment for Si cycling to improve performance (energy, power) as well as extended cycle life

- Tailorable Si% and anode specific capacity, typically ~750 – 2000 mAh/g
- Accommodate volumetric strain without compromising mechanical stability
- Processing method compatible with commercially-available silicon and graphene materials
- Low-cost graphite-derived precursor enables technology that can achieve DOE cost targets
- “Holey graphene” material enables rapid Li-ion diffusion through enhanced diffusion channels
- Processing techniques allow for self-supporting anodes with minimal inactive material component

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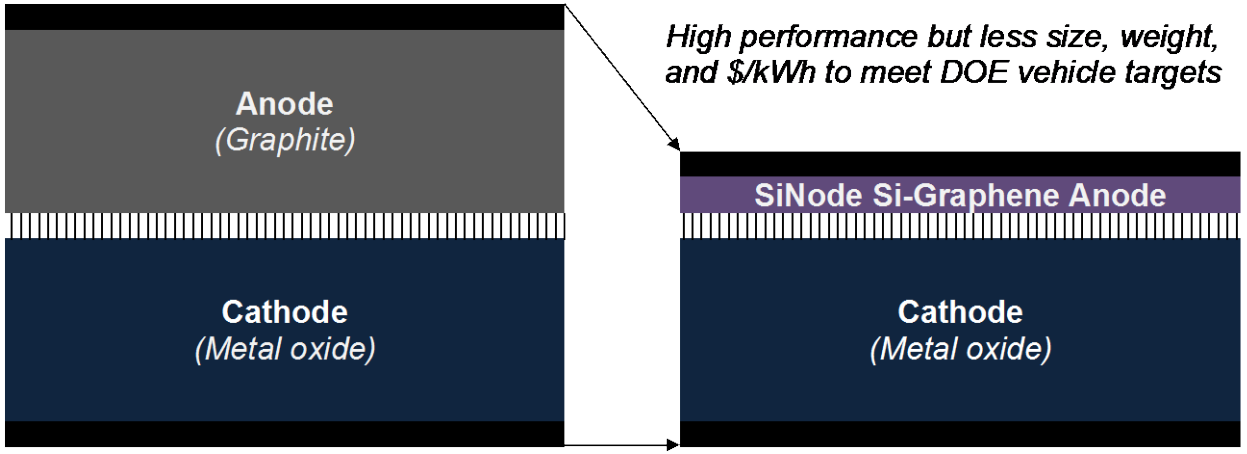
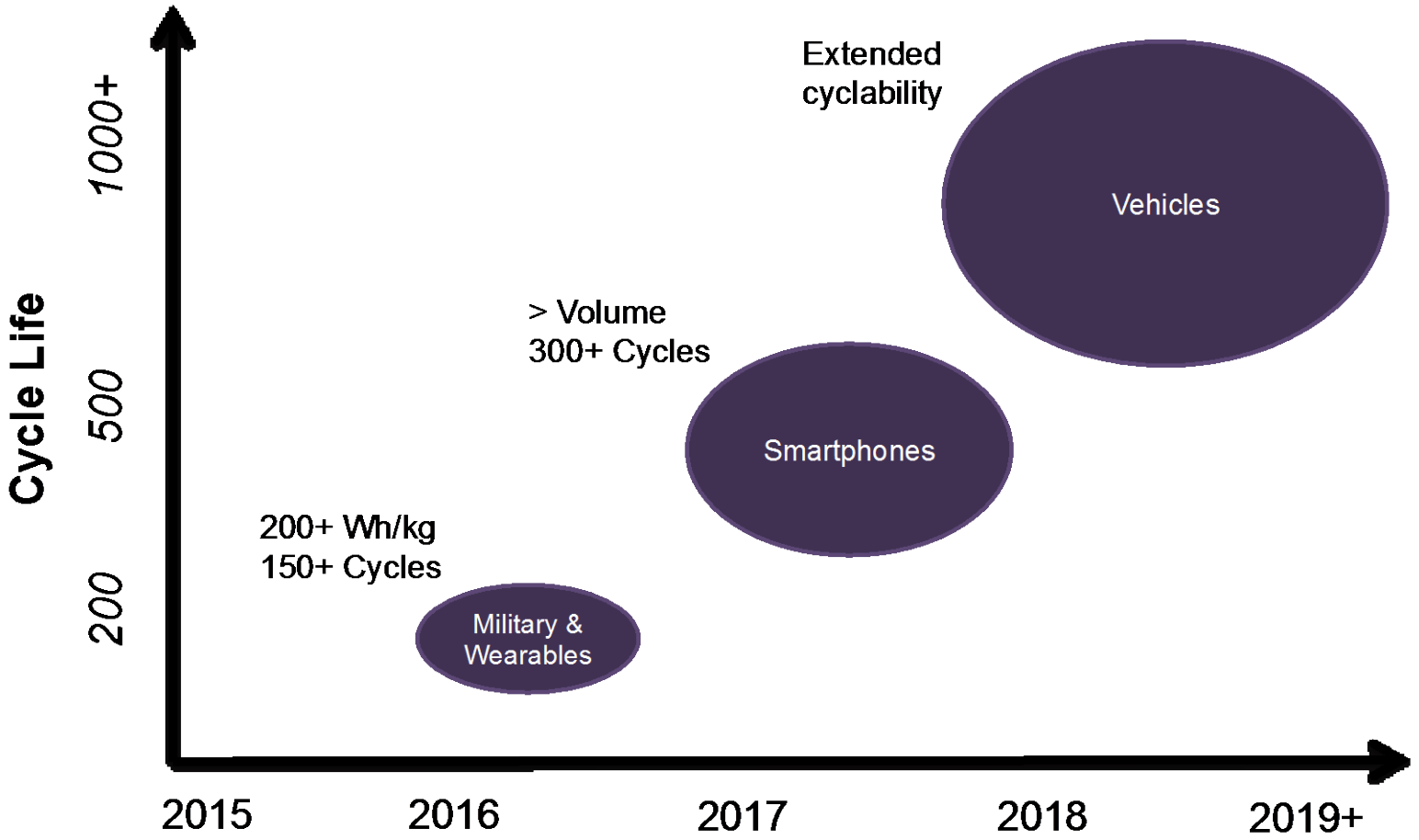
Approach: Value proposition



	Current Li-Ion Battery	SiNode Powered Battery
Cell Capacity	2 Ah	2 Ah
Anode Capacity	350 mAh/g	>2000 mAh/g
Anode Mass	6 g	1 g
Anode & Cathode Mass	17 g	12 g
Cost	$400-$500 / kWh	<$150 / kWh (Projected)

Approach: Staged market penetration



Production: Lab Prototypes → Pilot Scale → Large Scale

Funding: SBIR, Angels → SBIR, VC → Corporate Partner, PE

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Technical Accomplishments: Overview (Q1-Q2 Progress)

- ✓ Constructed prototype cells containing baseline initial Si-graphene anodes paired with NCA cathode electrodes
- ✓ Examined for rate performance, cycle life, and failure mode analysis
- ✓ Prototype failure analysis has driven development of improved anode processing
- ✓ Improved electrode processing and electrolytes to enable enhanced cycle life
- ✓ Developed additive, processing, and treatment steps to extend electrode cycle life and minimize ICL
- ✓ Commercial materials sources have been validated and integrated into system, driving significant cost reductions

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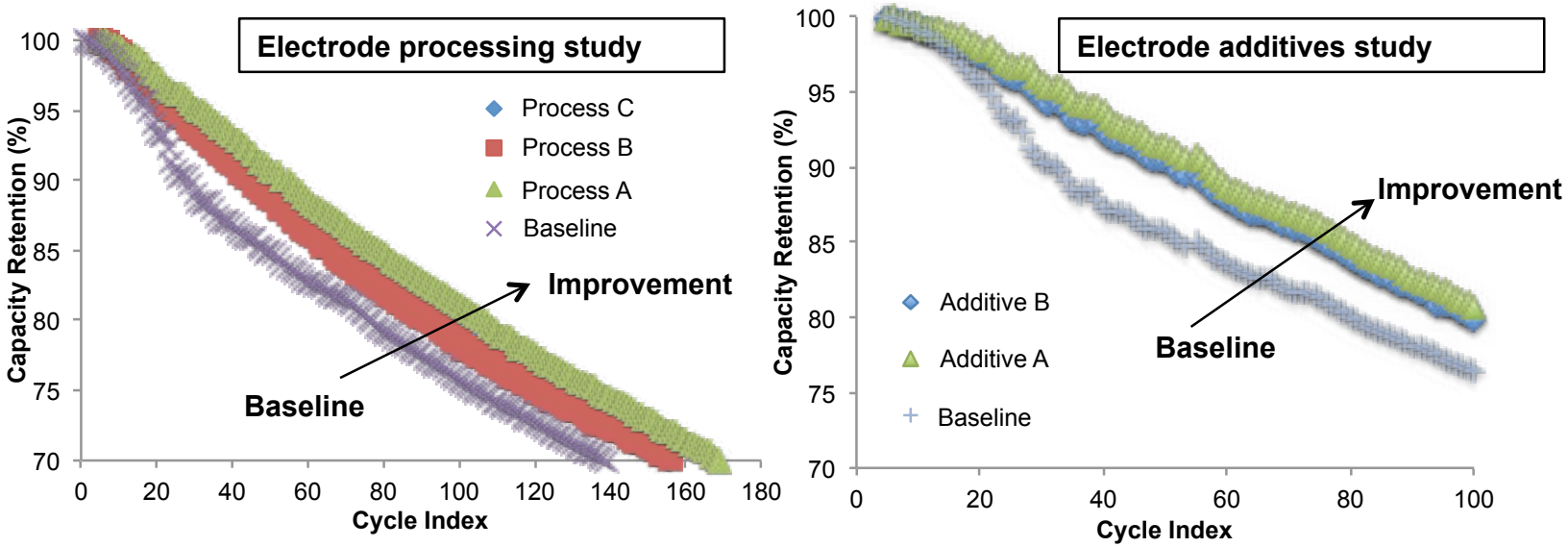
Technical Progress: Process improvements to improve stability

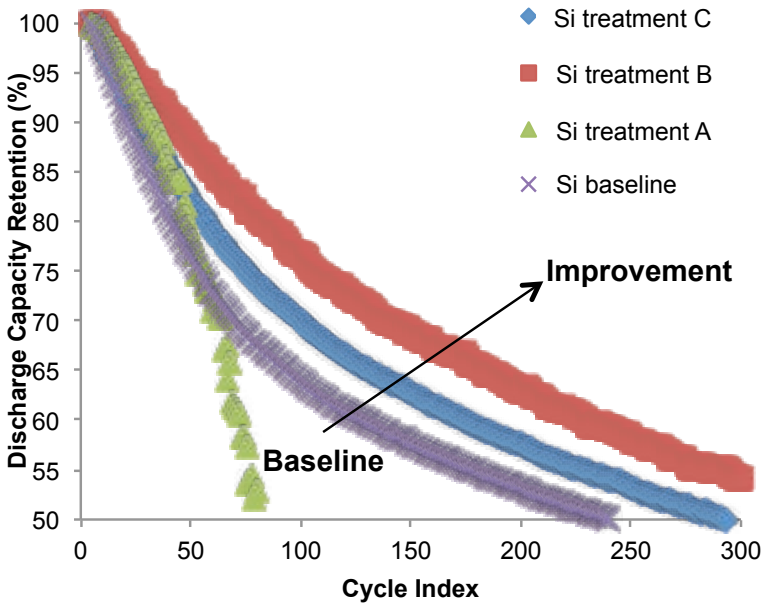
Si-graphene system is responsive to process improvements and additives to improve capacity and retention

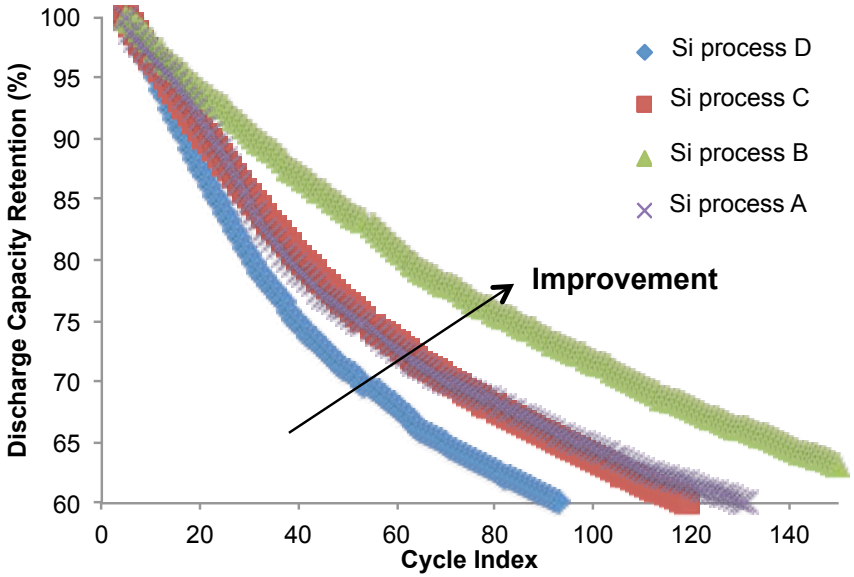
- Electrode processing conditions and additives were identified that improved upon the baseline formulation (up to 45% improvement in stability)
- Improved procedures corresponded with better CE and voltage profiles



Ongoing studies include formulation and processing improvement, formation protocol optimization, failure mode analysis, and accelerated testing

Technical Progress: Silicon processing development

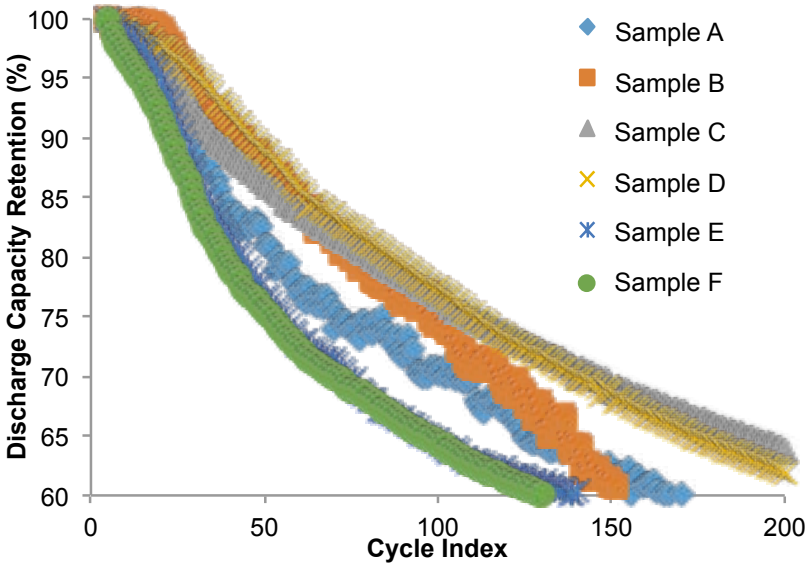


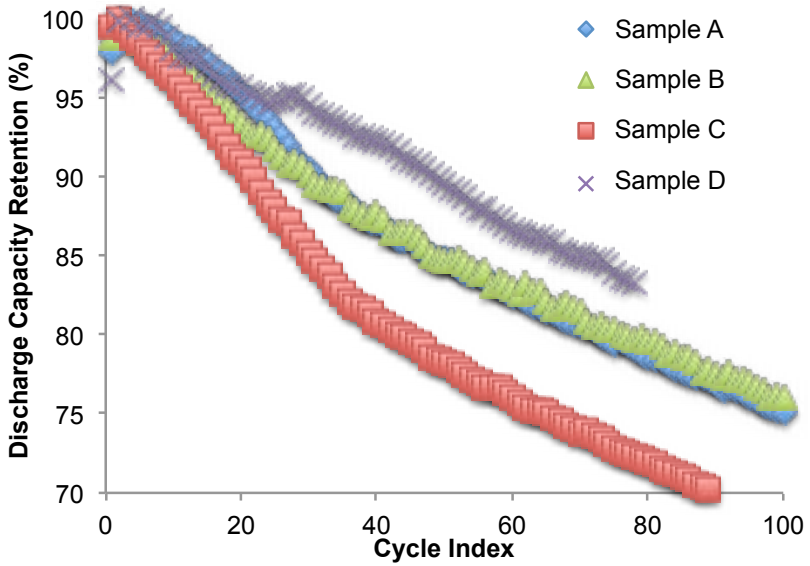


- Si surface treatments were identified that could influence cycle life and electrode stability; Surface treatments also influenced irreversible capacity loss (ICL) values
- In-house processing of commercial Si particles can significantly alter electrochemical performance
- Process changes can extend cycle life by >100%

Internal silicon surface treatment and processing steps enables cycle life extension and rate performance

Technical Progress: Materials sourcing for cost reduction

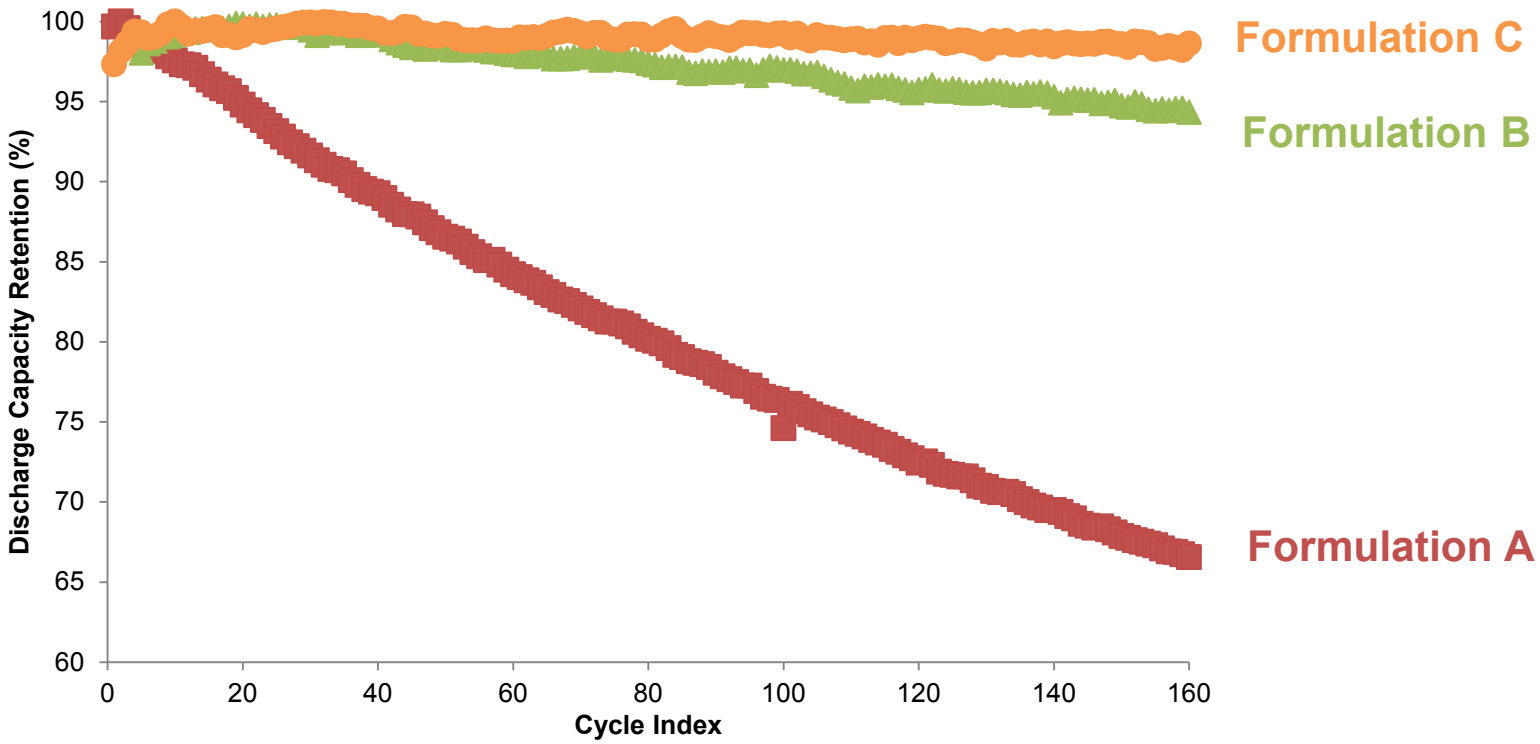




- >20 samples from materials suppliers tested
- >3 alternative sources performed better than initial Si materials
- Improved graphene formulation has been identified and integrated
- Materials sourcing also improves Coulombic efficiency and conductivity

Integrating commercial suppliers/partners and sourcing from multiple vendors has significantly decreased costs and increased scale

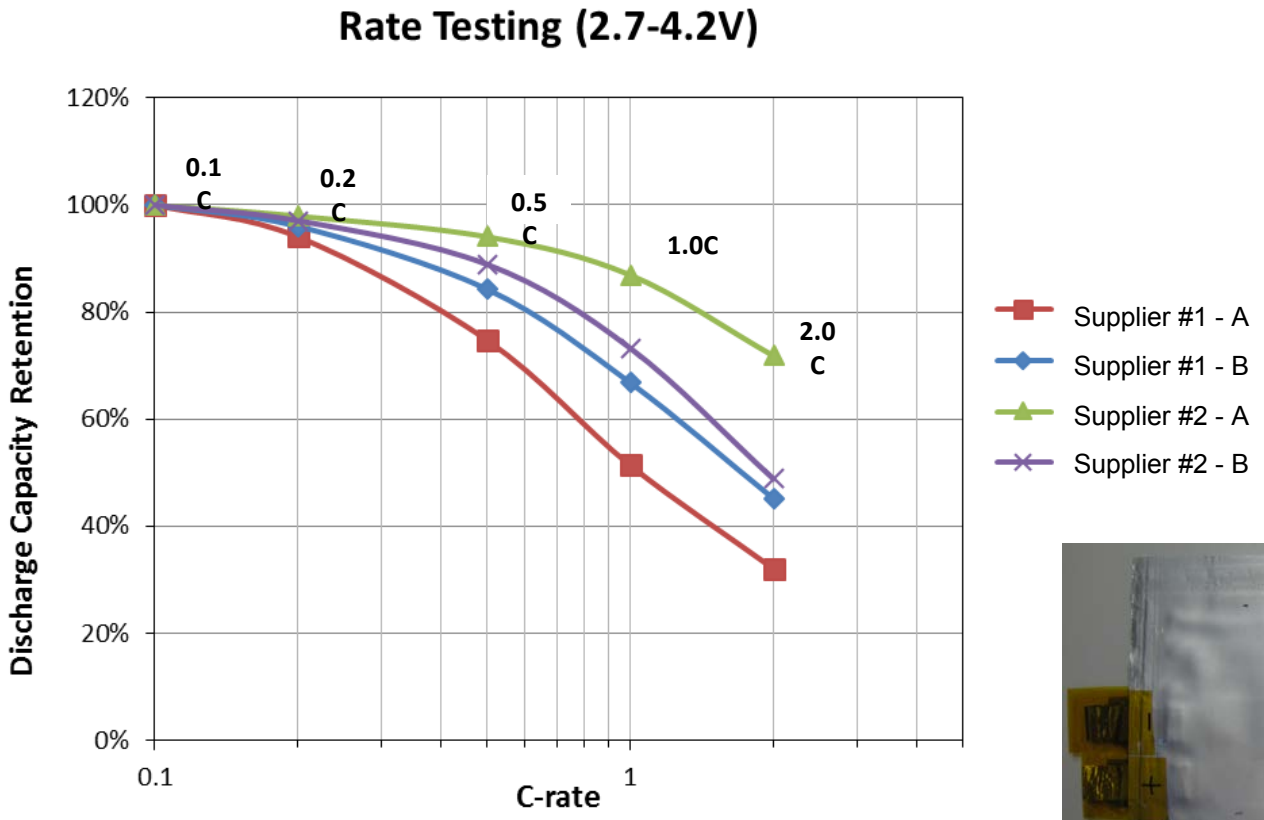
Technical Progress: Formulation development

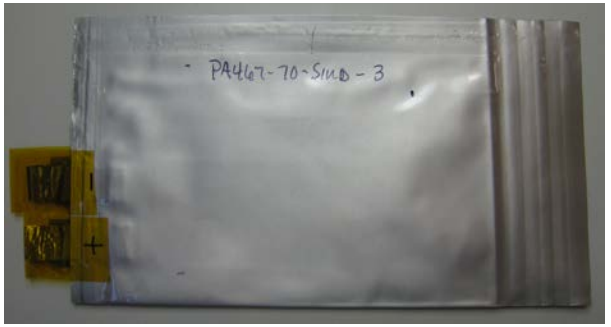


- Formulations B & C offers significantly improved cyclability compared to Formulation A
- All formulations offer >1000 mAh/g discharge capacity

Materials sourcing, composition, and in-house processing can significantly influence cyclability

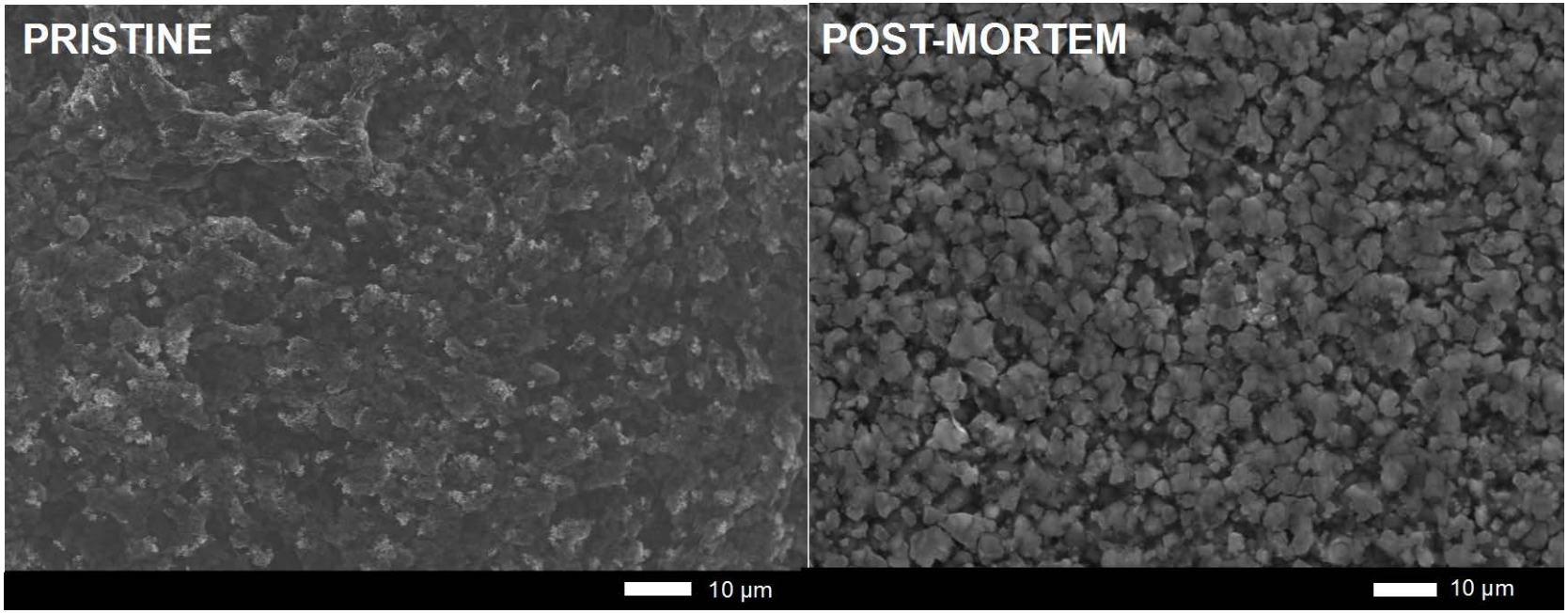
Technical Progress: Prototype rate performance





- Commercial materials suppliers offer different rate performance
- Ideal supplier has been identified and further development is underway
- Lower than expected rate performance is attributed to anode delamination issues

Technical Progress: Post-mortem analysis



- Post-mortem analysis shows electrode structure is still intact
- Prototype failure mode is attributed to poor adhesion to current collector
- Electrodes with improved adhesion and decreased resistance have been developed
- SEI layer consists of C, F, O, P, and other trace elements

Collaborators

Partner	Purpose
NAVITAS SYSTEMS	▪ Prototype development ▪ Cell construction ▪ Materials supply ▪ Safety testing
NORTHWESTERN UNIVERSITY	▪ Sample characterization ▪ Analytical work ▪ Materials treatments
MERCK	▪ Materials supply ▪ Assess manufacturing costs ▪ Sample characterization

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Remaining challenges & barriers

Performance characteristics & cycle/calendar life

- Current materials do not yet exceed DOE/USABC 2020 goals for commercialization
- Prototypes with longer cycle life and high energy required for commercialization
- Iterative cell design, materials formulation, optimized formation protocols, improved SEI formation, reduced impedance etc. will improve performance characteristics to achieve long-term targets

Cost

- Electrode processing, formulation, and scale-up manufacturing required to achieve long-term cost targets
- Further improve manufacturability to meet conventional production protocols

Safety testing

- Initial testing on prototype cells required to determine characteristics

Proposed future work

FY14

- **Anode development**
  - Further improve in-house anode processing procedure
  - Validate low-cost, high-volume raw material integration
  - Preliminary cost estimate for materials and roadmap for cost reduction
  - Determine optimal manufacturing route for electrode formation
  - Down-select formulations and demonstrate improved performance characteristics
- **Prototype cells**
  - Improve cell design and complete YR1 cell deliverables
  - Examine failure modes associated with current cell design and integrate into development plan
  - Perform initial safety and abuse testing investigation

FY15

- **Anode development**
  - Finalize anode formulation, sourcing, and processing
  - Scale-up materials processing
- **Prototype cells**
  - Develop optimized cell design and electrode loading
  - Evaluate formation/testing protocol and electrolyte to extend cycle life
  - Assemble/deliver final YR2 cell deliverables
  - Conduct safety validation and environmental testing

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Summary

- SiNode is developing a Si-C anode that can exceed DOE performance targets when paired with conventional cathode materials
- Unique structure provides improved Si environment for extended cycling
- Materials sourcing, treatment, and processing steps have been examined in order to improve electrode cyclability
- Surface coatings and processing provides greatest opportunity for improvements
- Inexpensive raw materials can be easily integrated into existing processing
- Preliminary prototypes demonstrate high energy and opportunity for long cycle life
- Future work focuses on extending prototype cyclability, materials formulation & scale-up, and safety testing

THANK YOU