OPTODOT *Energy Storage Solutions Through Nanotechnology*

Innovative Manufacturing and Materials for Low-Cost Lithium-Ion Batteries

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Optodot Corporation

Project ID# ES136
Tuesday, June 17, 2014

Overview

Timeline

- Start date – October 2011
- End date – September 2014
- Percent complete - 50%

Barriers/Targets

- Cost reduced by 75% to $125/kWh by 2022
- Energy density increased from 100 Wh/kg to 250 Wh/kg and 200 Wh/l to 400 Wh/l by 2022

Budget

- Total Funding: $2,999,127
  - DOE Share $2,249,127
  - Contractor Share $750,000
- Funding Received:
  - FY13: $536,499 (10/1-9/30)
  - FY14: $206,331 (10/1-2/28)
  - Total: $1,125,704 (thru 2/28)

Partners

- **Interactions/Collaborations**
  - *Madico, Inc.* – Electrode Stack Mfg.
  - *XALT Energy* – Battery Mfg. and Testing
  - *University of Rhode Island* – Electrolyte
  - *Ashland* –Solvents & Polymers
- **Project Lead – *Optodot Corporation***

Thank you to the DOE Vehicle Technologies Program for their support and funding of this project!

Project Objectives/Relevance

Project Long-term Objective

- Reduce the cost, weight, and volume of the cell's inactive components (separator, electrolyte, current collectors) by at least 20%, and preferably by at least 40%, while maintaining cell performance

Project Immediate Objectives (Oct-13 to Sep-14)

- Complete 2 Ah prototype cells utilizing separator/electrode stacks with much thinner ceramic separator (8 um thick)
  - Anticipated cost benefit from the ANL Cost Model 2.0 (16 KWh packs and 100 um thick electrodes) of about $17/kWh for thinner separator and $2/kWh for less usage of electrolyte along with a 5% increase in volumetric energy density

Relevance/Approach for a New Cost Reduction Platform for Lithium Ion Batteries

- The use of an 8 micron thick ceramic separator by itself meets the project's >20% cost improvement objectives for the inactive components, while providing 5% smaller batteries and the greater safety and longer cycle life and high temperature operation of a ceramic separator with very high dimensional stability at 220°C
- Because of its all-nanoporous structure and high compression strength, this ceramic separator provides a new cost reduction platform by enabling new processes by which lithium ion batteries can be made, including coating electrodes onto the separator and using much thinner metal current collector layers
- One approach to thinner, lower cost current collector layers is a proprietary process developed in FY13 and FY14 for depositing 3 to 6 micron thick copper and nickel current collector layers onto electrode layers

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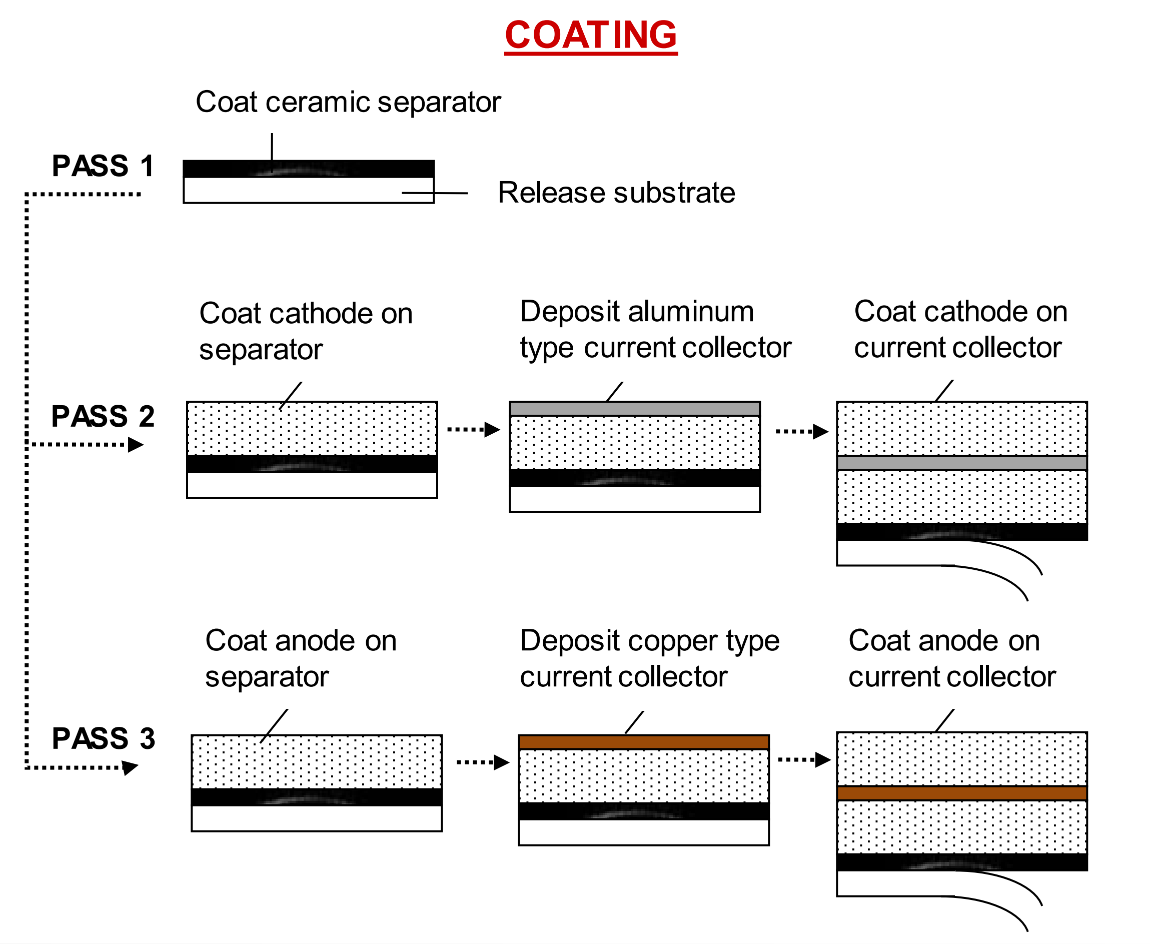
Project Milestones for FY14

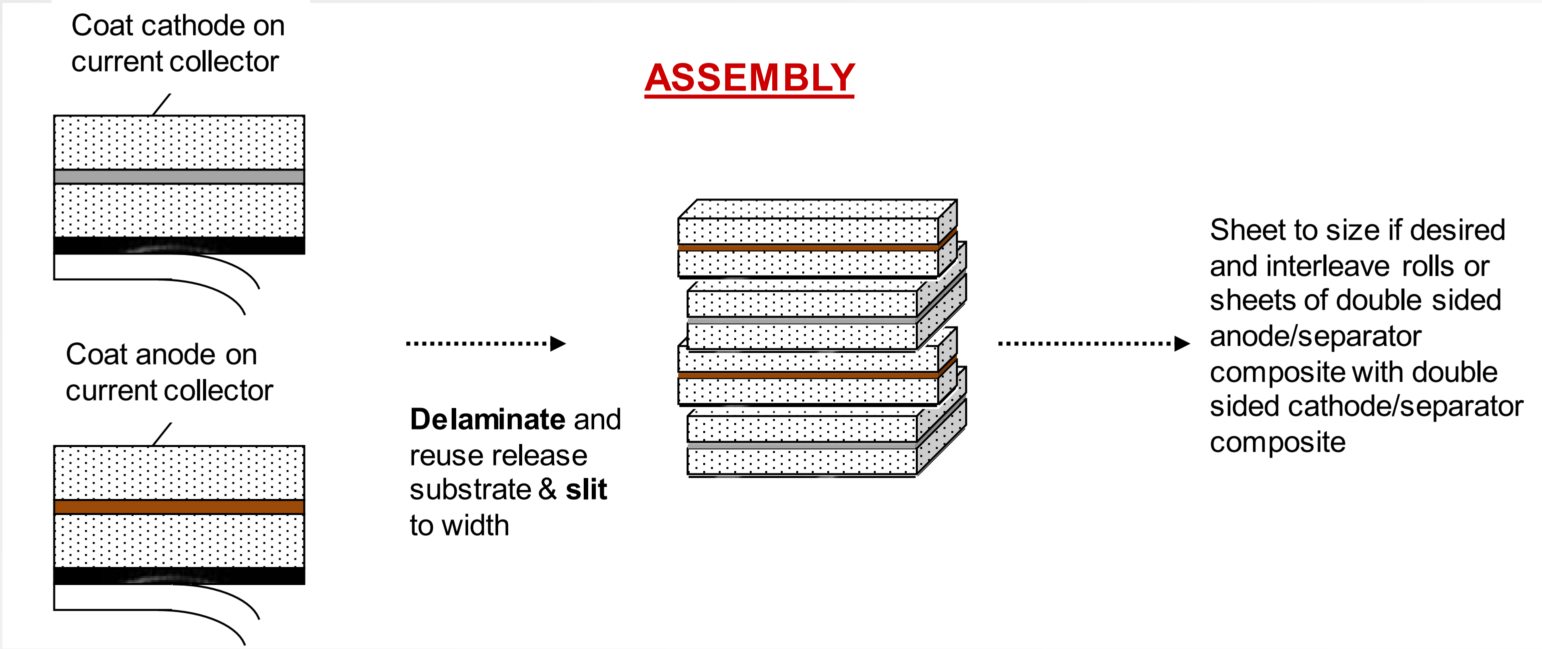
Month/Year	Milestone	Status
Jul-14	Anode coated stack cell development and testing in cells	Initial versions completed
Aug-14	Cathode coated stack development and testing in cells	Initial versions completed
Sep-14	Combined anode coated stack and cathode coated stack for 2 Ah energy cells	To be completed Sep-14
Jul-14	Investigation of mechanism of longer cycle life with ceramic separator	On schedule
Sep-14	Evaluation of new lithium salts and non-flammable electrolytes	To be completed Sep-14
Sep-14	Electrode coated stack design for 2 Ah power cells with thinner electrodes	To be completed Sep-14
Sep-14	New current collection layers and termination design options for coated electrode/separator stacks	To be completed Sep-14

Approach: Battery Stack Manufacturing Process



- **Utilizes a roll-to-roll process**
  - Lower cost
  - Higher efficiencies
  - Wider Widths
- **Electrode coatings can be in lanes to provide electrode-free current collector zones for termination**
- **Release substrate is removable, enabling interleaving of anode and cathode coated stacks**

Approach: Battery Stack Manufacturing Process



- Lower cost and lighter inactive components
  - Nanopore nature and compressive strength of ceramic separator enables overcoating with anode and cathode layers followed by calendering
  - Thinner separator reduces inactive components and cell level cost significantly
  - Thinner & lighter current collector layers
  - New inactive components are expected to be compatible with various anodes, cathode, and electrolyte materials

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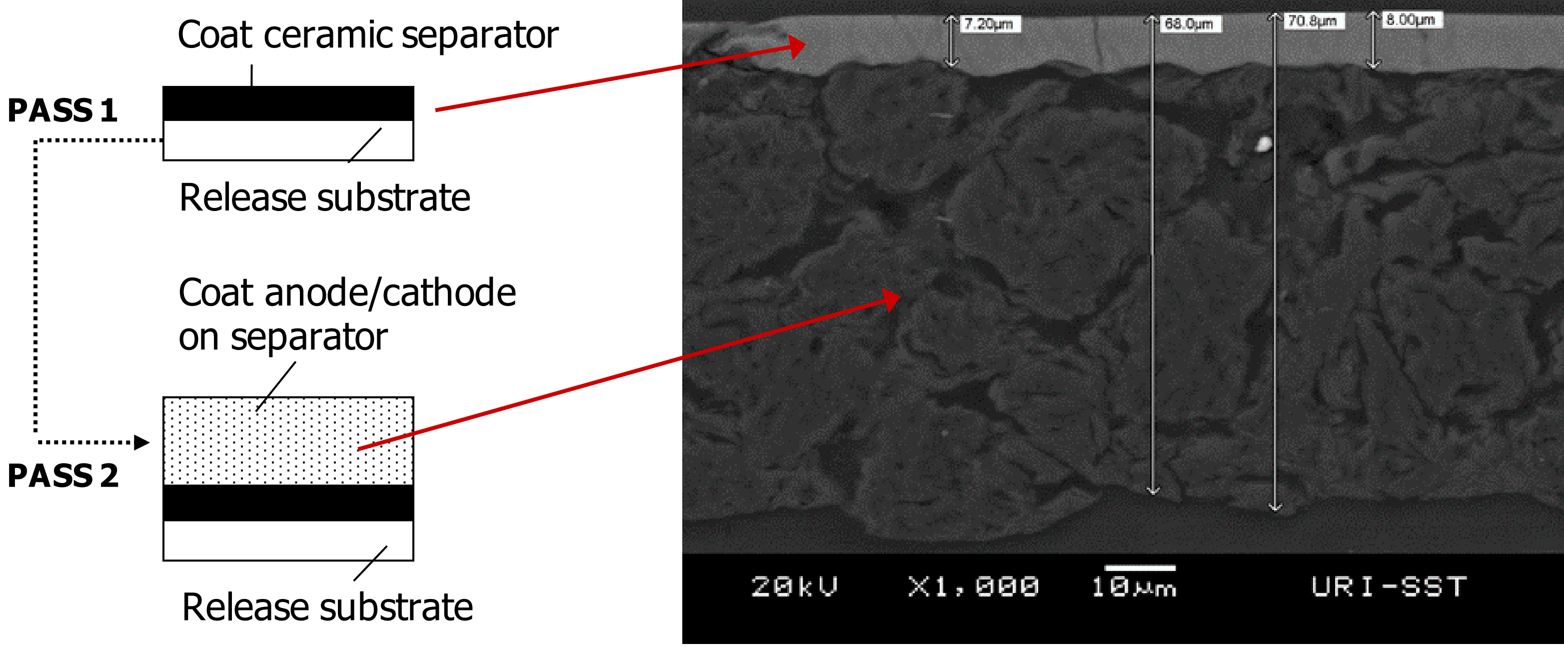
FY13/14 Accomplishments
(Mar-13 – Apr-14)

- Ceramic separator and release substrate improvements led to better quality electrode/separator stack coatings (eliminated coating defect issue), and further reduced the ceramic separator cost by ~10%

Separator/Electrode Composite
(not to scale)

Cross-Sectional SEM



NOTE: Release substrate was removed prior to cross-sectional SEM

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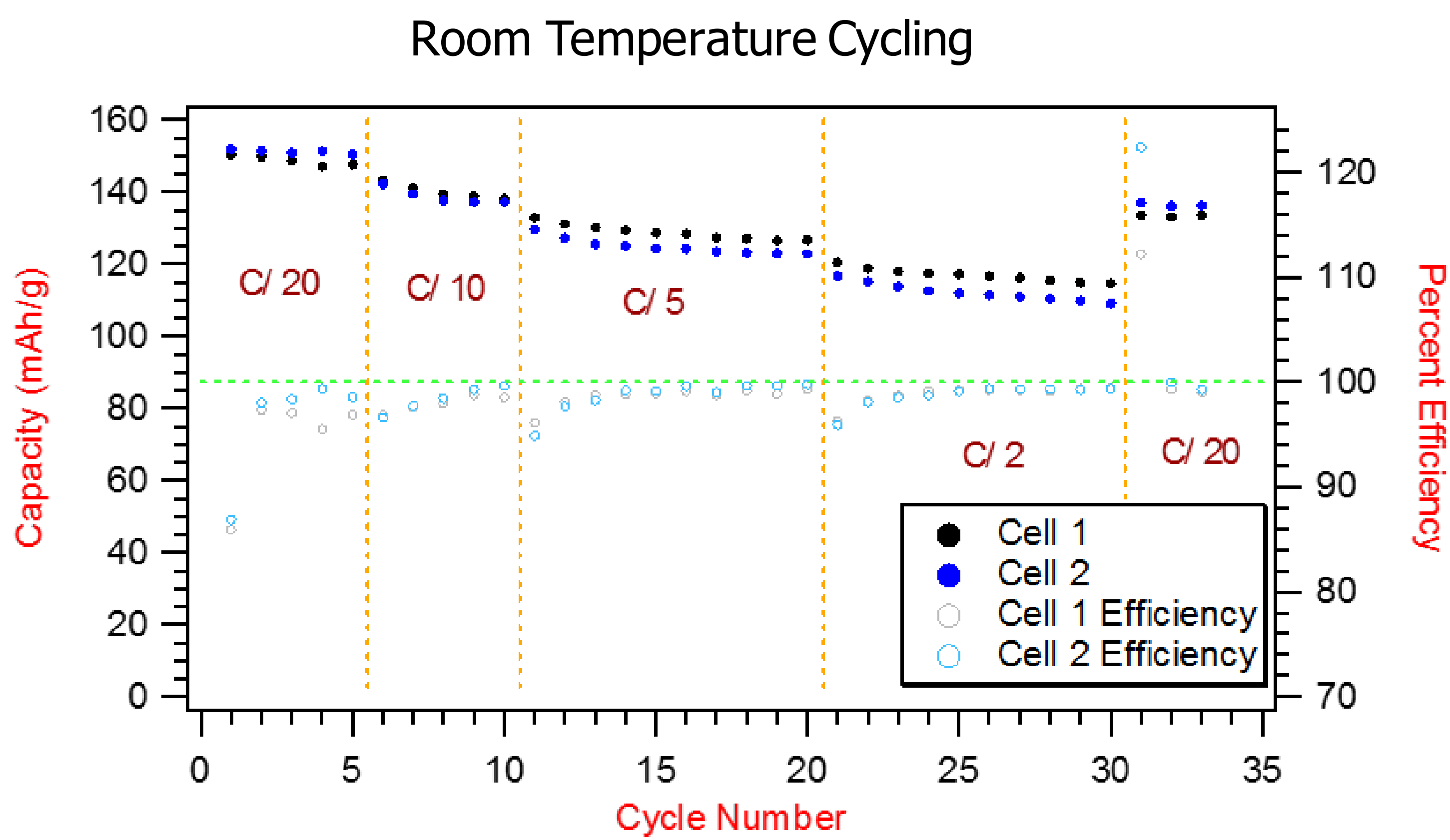
FY13/14 Accomplishments

(Mar-13 – Apr-14)



Cycling of initial prototype separator/electrode stack full coin cells with 2 um Cu and 3 um Al depositions on the anode and cathode respectively

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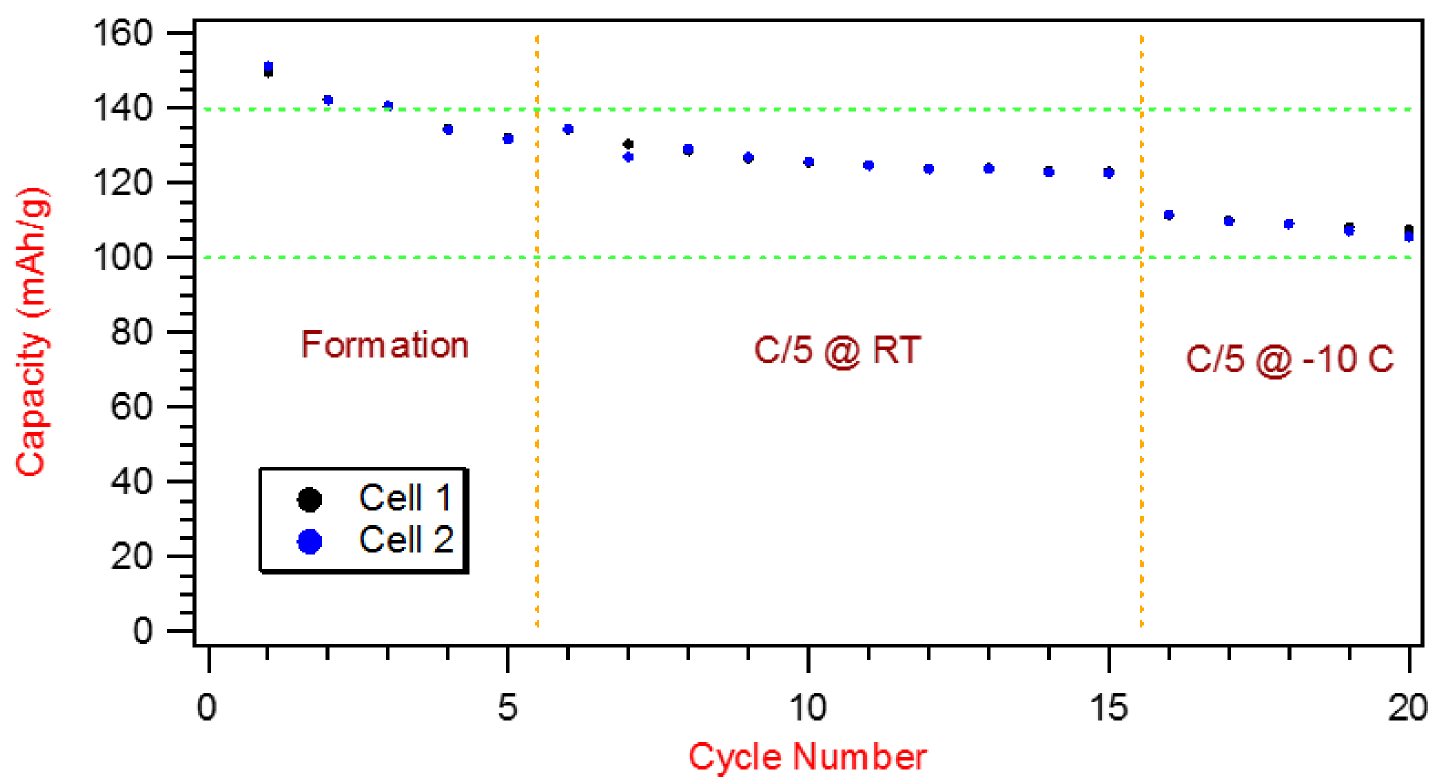
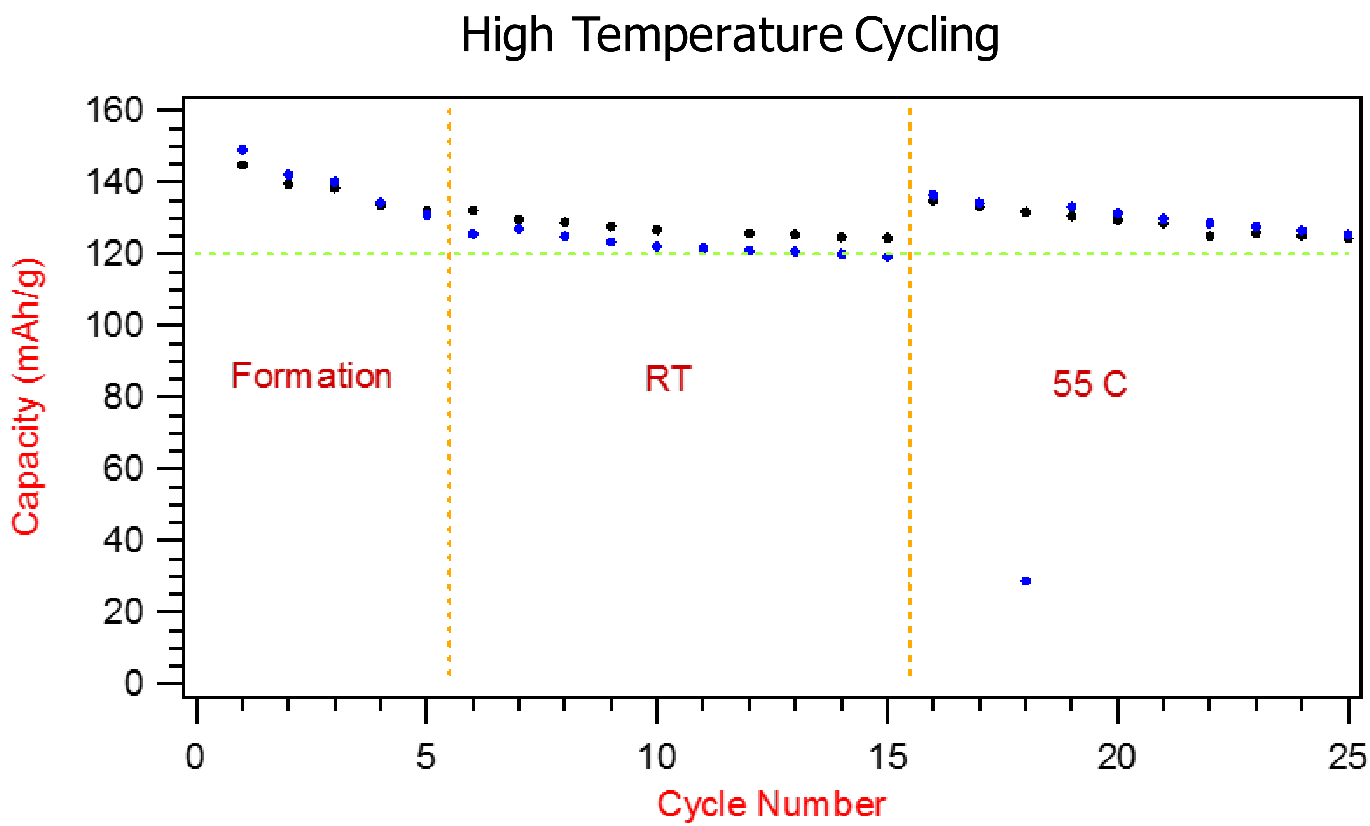
FY13/14 Accomplishments
(Mar-13 – Apr-14)

Low Temperature Cycling



Cycling Conditions: C/5 rate, Charge at RT, Discharge at -10C
Cells showed excellent cycling efficiency

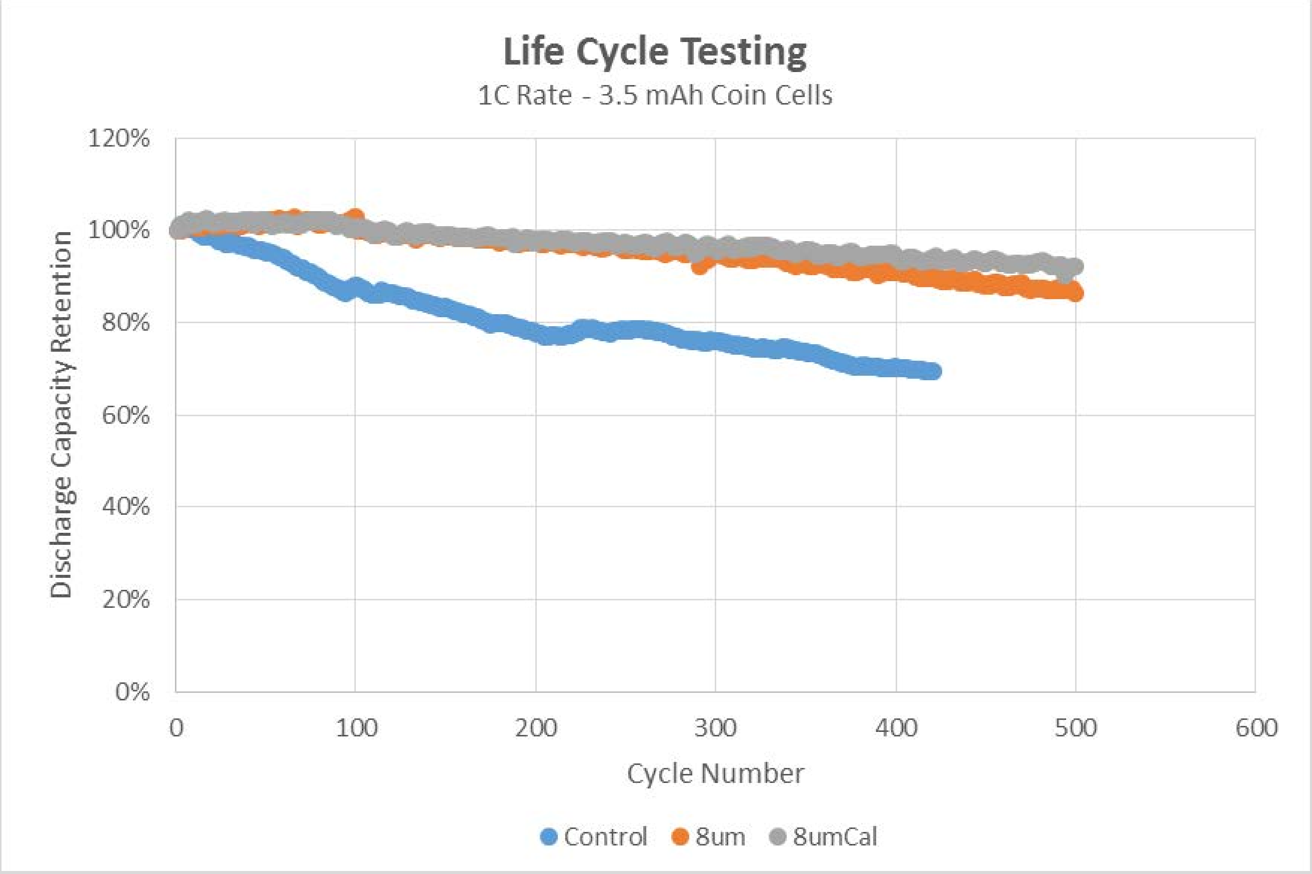
FY13/14 Accomplishments
(Mar-13 – Apr-14)



Cycling Conditions: C/5 rate
Cells appeared to regain lost capacity during rest
Cells showed excellent cycling efficiency

FY13/14 Accomplishments
(Mar-13 – Apr-14)

- Improved version of 8 micron thick ceramic separator demonstrated excellent cycle life and rate capability
  - All-nanoporous design and very narrow pore size distributions ranging from 25-75 nm average pore diameter.



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Responses to Previous Year Reviewers' Comments

FY2013 AMR Review (2 Reviewers)

- **Reviewer comment:** "It would be of great interest to the reviewer to know how this separator reacts with different cathode chemistries."
- **Response:** Our data so far is on NMC cathodes, but we expect that our ceramic separator is generic and are evaluating it with different cathodes.
- **Reviewer comment:** "… the scale-up of some of the improvements that the authors describe is going to be critical."
- **Response:** Yes, these are many new materials and processes. This year, we successfully scaled up the ceramic pigment, the improved separator, and the calendering process.
- **Reviewer comment:** "If the authors managed to prove an overall cost reduction, the authors should ask for additional support."
- **Response:** This is a good suggestion. If we achieve our cost reduction goals, we should review the options, including the DOE and our target battery customers, for additional support.

Collaborations/Subcontractors

- **Madico** (industry) on manufacturing processes of mixing & coating of the ceramic separator and of coating and/or lamination of the current collector/electrode/separator stacks
- **XALT Energy** (industry) on electrode coatings and 2 Ah cell builds
- **URI** (academic) on cell cycling testing on various ceramic separator and coated stack designs & on new electrolytes
- **Ashland** (industry) on polymer selection for battery stack coatings
- **Argonne National Laboratory** (government) on testing of 2 Ah baseline and prototype cells

Future Work

Remainder of FY14

- Optimization and scale-up of anode stack, cathode stack, and current collector/termination
- Develop coated stack designs with one-third thinner electrodes for high rate/power cells
- Continue to evaluate new lithium salts and flame retardant electrolytes
- Determine mechanism of enhanced cycle life with 8 micron ceramic separator

Final Deliverables

- Cost assessments of Li-ion cells manufactured using the current vs. improved designs
- Deliver 18 cells of baseline design and of new coated stack design with cell test plan and report on performance and abuse tolerance of these cells

Summary

- Meeting the at least 20% improved cost, volume and weight, as well as the performance requirements, for the key inactive components of Li-ion cells and developing a low cost next generation manufacturing process will help meet the DOE goals of cost reduction to $125/kWh by 2022 for EVs with double the energy density of current cells.
- Demonstrated the first examples of current collector/electrode/separator coated stacks by leveraging off of the all-nanoporous and very high compressive strength ceramic separator, the key enabling technology of this project
- The use of the 8 micron thick ceramic separator alone meets the project's $\geq$ 20% cost improvement objective for the inactive components and also improves safety and cycle life
- Our 4 partners and subcontractors, Madico, XALT Energy, URI, and Ashland, are providing coating and converting expertise and equipment, battery assembly and testing capability, electrolyte expertise, and polymer and solvent expertise.

Technical Back-Up Slides

Improved Ceramic Separator Provides Longer Cycle Life

- This significantly improved cycle life has implications for the electrolyte part of this project. The ceramic separator appears to improve the cycling and thermal stability properties of standard $LiPF_6$ electrolytes so that there is less reason to switch to a higher performance electrolyte.
- It is believed that the ceramic material in the improved separator is scavenging the HF and other acidic degradation products of the electrolyte and contributing to the formation of thin, stable SEI layers
- Accordingly, the electrolyte work is now focused on investigating the mechanism of the stabilization of $LiPF_6$ electrolyte with a view to making further improvements in cycle life, safety, and low and high temperature performance.

Release Substrate Improvements

- To optimize the coating quality and provide defect-free ceramic separator layers and electrode/separator coated stacks, FY13 work showed that a tighter release force by a factor of about 3 to 6 over previous release substrates was required between the release substrate and the ceramic separator layer.
- This was necessary to prevent premature delamination in very small spots at the interface between the separator layer and the release substrate when overcoating with the electrodes.
- Still, after the overcoating of the nanoporous ceramic separator with the electrode layer, the delamination of the coated electrode/separator stack from the release substrate was easy and efficient.