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

**P.I. – Dr. Steve Carlson**

Project ID# ES136

## Optodot Corporation

2015 DOE Vehicle Technologies Program
Annual Merit Review and Peer Evaluation Meeting

Tuesday, June 9, 2015

# Overview

## Timeline

- Start date – October 2011
- End date – September 2015
- Percent complete - 75%

## Barriers/Targets

- Cost reduced 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:**
  - FY14: $502,914 (10/1-9/30)
  - FY15: $159,388 (10/1-2/28)
  - Total: $1,581,676 (thru 2/28)

## Partners

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

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

# Project Objectives/Relevance

**Overall 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

**<u>Project Immediate Objectives (Oct-14 to Sep-15)</u>**

- Complete project deliverables of eighteen 2 Ah cells utilizing separator/electrode stacks with a much thinner ceramic separator (8 um thick) and with a coated current collector layer adapted for termination with nickel tabs
- Cost assessment for new materials and process -- Anticipated cost benefit from the ANL Cost Model 2.0 (16 KWh packs and 100 um thick electrodes) is about $17/kWh for thinner separator

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

- The use of an 8 micron thick all-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 and high voltage operation of a ceramic separator with very high dimensional stability at 220°C (no shrinkage).

- Because of its all-nanoporous structure and high compression strength and heat stability, 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 thinner copper and nickel metal current collector coated layers made by a xenon flash lamp sintering process.

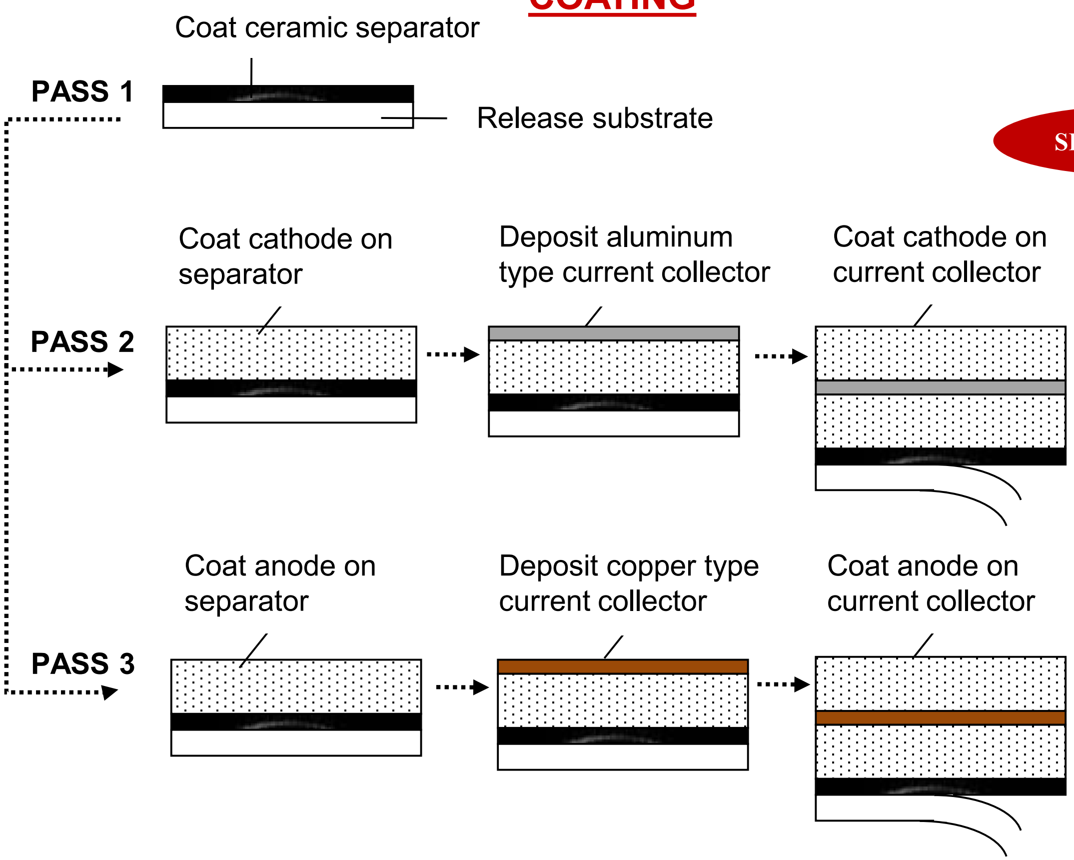
- The unique properties of the ceramic separator of preventing any penetration of pigments from overcoatings, of providing electrode-free areas on the edges of the coated stack that can be adapted for the tabbing area and for edge reinforcement for greater mechanical strength of the anode and cathode coated stacks, and of adhering to adjacent layers enable lower process costs.

# Project Milestones for FY15

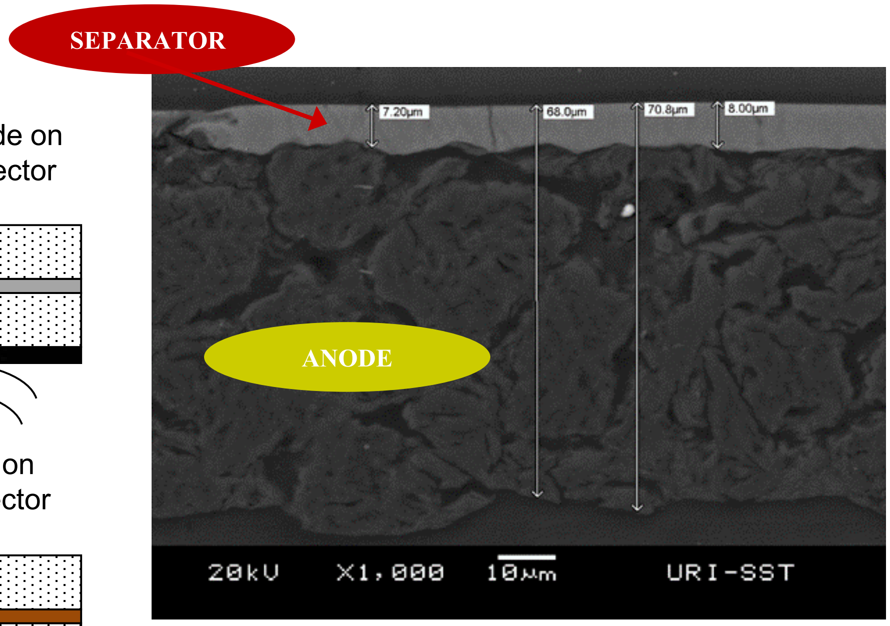
| Month/Year | Milestone | Status |
|---|---|---|
| Feb-15 | Develop the sintered metal current collector layer materials and design for cell assembly | To be completed May-15 |
| Apr-15 | Build 2 Ah power and energy cells and start cycling performance testing | To be completed Jun-15 |
| Jun-15 | Complete the manufacturing process design for anode stacks for both energy and power cells | To be completed Jun-15 |
| Jun-15 | Complete the manufacturing process design for cathode stacks for both energy and power cells | To be completed Jun-15 |
| Sep-15 | Complete performance and cost assessment of 2 Ah power cells with 5 micron ceramic separator and thinner electrodes | To be completed Sep-15 |
| Sep-15 | Complete detailed cost assessment of new and control 2 Ah energy cells for both new materials and process cost improvements | To be completed Sep-15 |
| Sep-15 | Complete project deliverables of final project report and of eighteen 2 Ah new and control energy cells with performance test data | To be completed Sep-15 |

# Approach: Battery Stack Manufacturing Process

## COATING

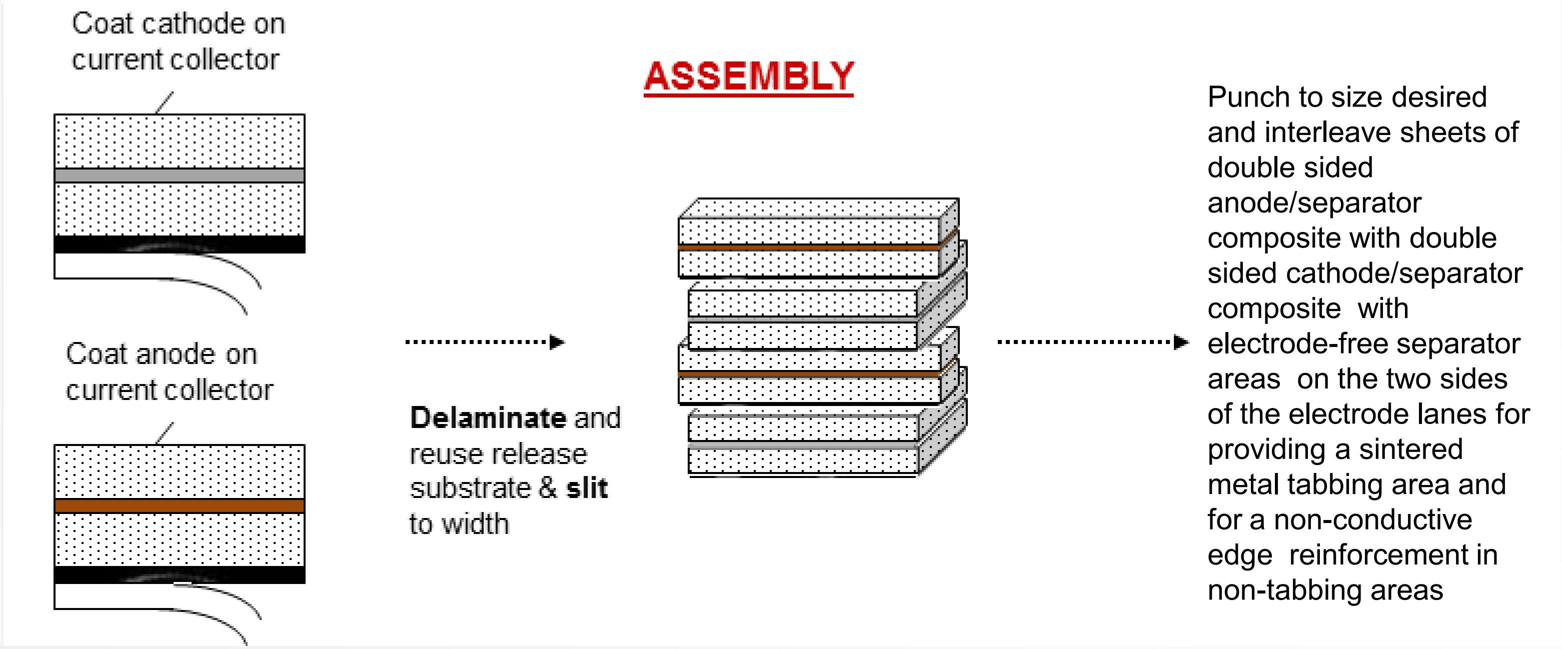



*Cross-Sectional SEM*




- 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

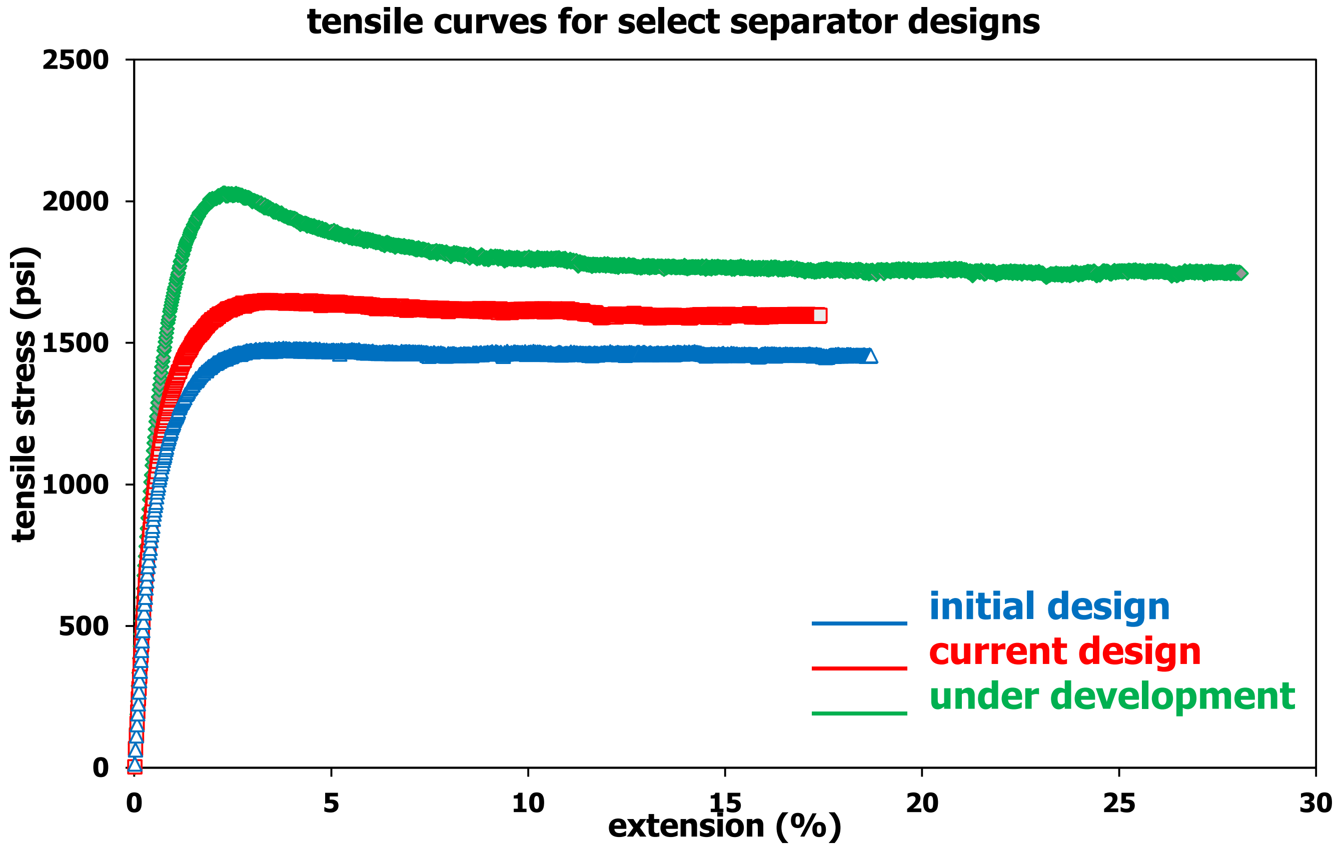
# Approach: Battery Stack Manufacturing Process




- Lower cost and lighter inactive components
  - Nanopore nature and compressive strength of ceramic separator enables overcoating with anode, cathode, and other 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, cathodes, and electrolytes

# FY14/15 Accomplishments
## (Apr-14 – Apr-15)

## Separator Mechanical Improvements




**Increased separator strength promotes improved toughness and durability of the coated stack for subsequent processing.**

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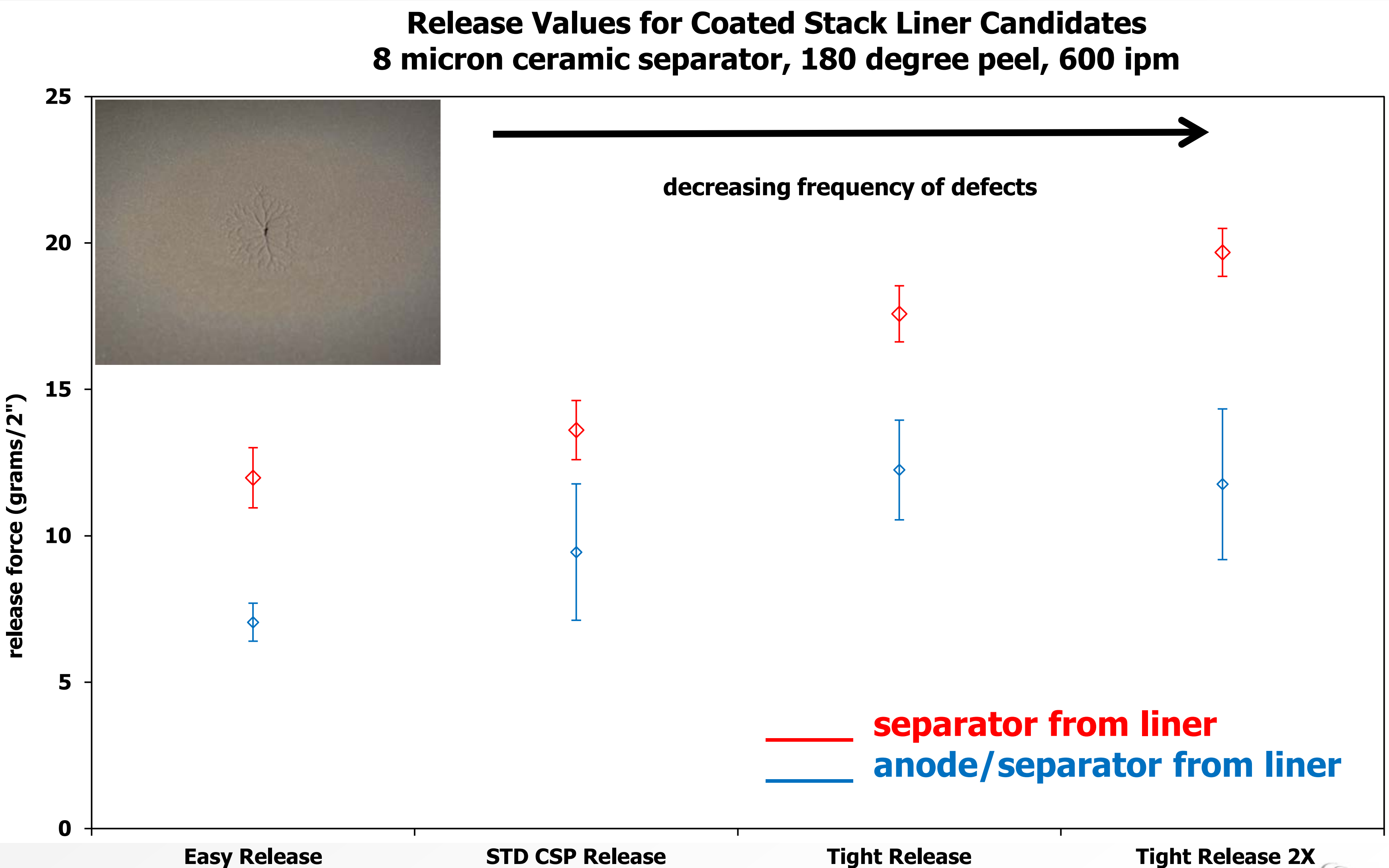
# FY14/15 Accomplishments
## (Apr-14 – Apr-15)





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# FY14/15 Accomplishments
## (Apr-14 – Apr-15)

**Developed Basic Design for Advanced Cell Manufacturing:**

- Coat 5 to 8 micron ceramic separator full width on release substrate
- Coat & calender first electrode layer in lanes onto separator layer
- Coat & xenon flash sinter current collection layer in pattern that is wider than the electrode lanes (with an extra thick patch on electrode-free separator for tabbing area after sintering and with non-conductive, non-sintered edge reinforcement from the same thickness of metal precursor ink as on the electrode area. Use 0.5 to 1 ohm per square metal, 5 to 10 micron thick sintered coatings (nickel or copper) as current collector layers
- Coat & calender second electrode layer in same lane position as first electrode layer
- Delaminate electrode stack from release substrate; do optional 1 to 2 micron thick safety shutdown coating on the separator; slit to width; and punch into desired sheet shape (continued on next slide)

# FY14/15 Accomplishments
## (Apr-14 – Apr-15)

**Developed Basic Design for Advanced Cell Manufacturing:**

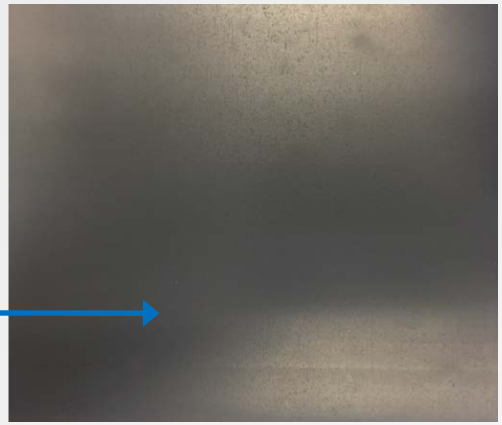
- Optionally adhere a small metal foil piece to the separator edge tabbing area to extend out beyond the edge of the sheet for better welding (metal tabs adhere well to the separator layer with the assistance of solvent and heat)
- Stack electrode sheets and, if needed, use free-standing pieces or rolls of the all-ceramic separator to provide insulation as needed to the coated stack and as an outer wrap for the coated stack (as with metal tabs, the ceramic separator adheres well to electrode layers, separator areas, and any other adjacent areas with the assistance of solvent and heat or when the cell is filled with electrolyte)
- Weld the nickel or other metal outside lead to the tabbing area
- Optionally vacuum dry, since the ceramic separator is very heat stable; if the safety shutdown layer is present, use a lower temperature that does not cause premature shutdown
- Place cell stack in pouch, fill pouch with electrolyte, and seal as done in conventional cell manufacturing

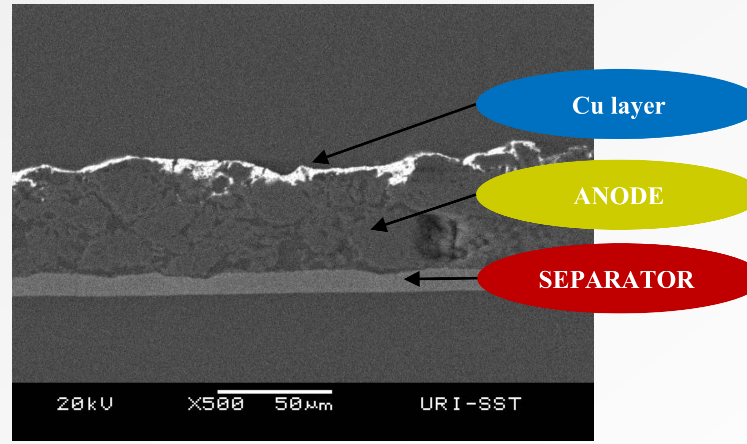
# FY14/15 Accomplishments
## (Apr-14 – Apr-15)

### Sintered Copper Current Collector

After Coating,
Before Sintering

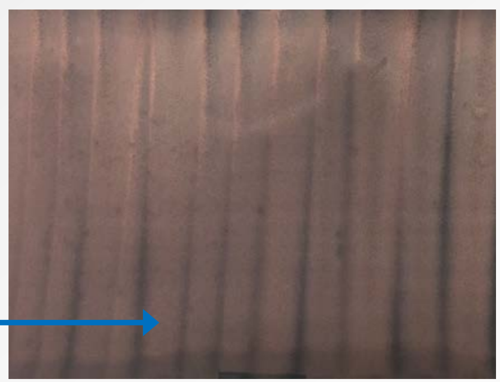
Not conductive

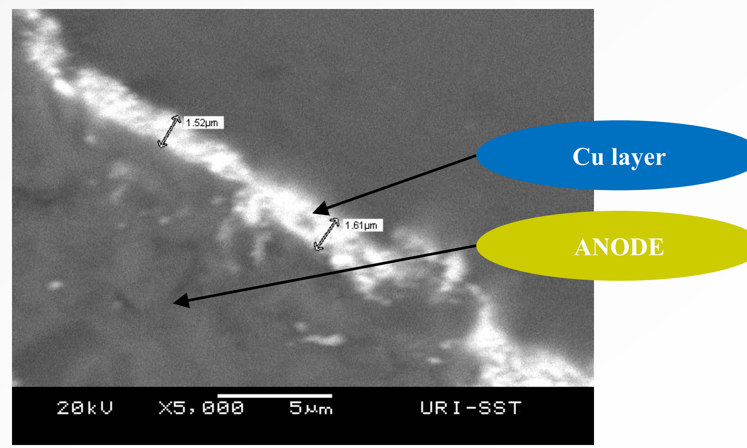





After Coating,
After Sintering

0.5-1.5 ohms

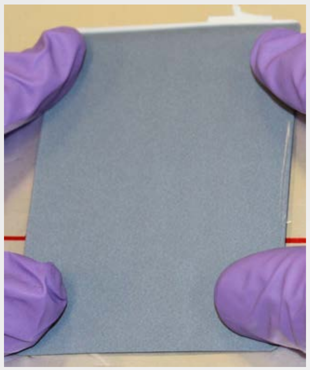




# FY14/15 Accomplishments
(Apr-14 – Apr-15)

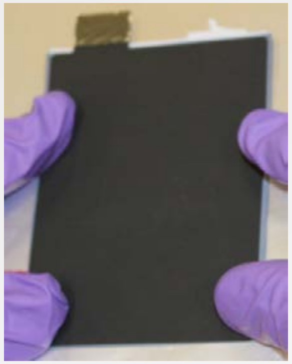
## Example of Alternative 2 Ah Cell Development Using Bare Metal Foils

**Stack 1**



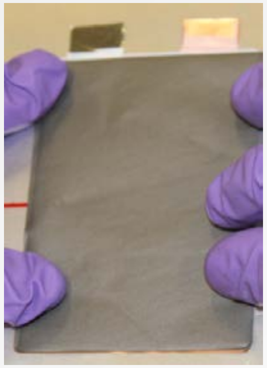
Place anode coated separator (stack 1) on a plane surface

**Stack 1 +2**



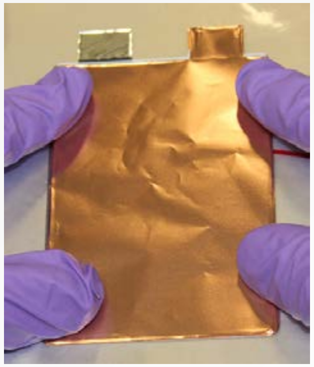
Position the double side cathode (stack 2) on the stack 1

**Cu foil+Stack 1+2+3**



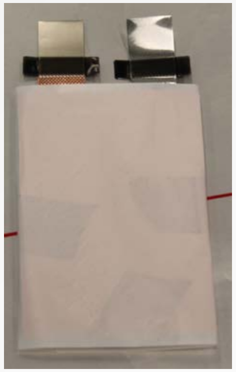
Apply the glue on the edge of stack 1. Glue the anode coated separator (stack 3) on stack 1

**Cu foil+ Stack 1 +2+3+Cu foil**



Position the copper foil on stack 3.

Wrap the assembly in a separator, weld the tabs



Package the assembly in a pouch cell butter cup

# Responses to Previous Year Reviewers' Comments

FY2014 AMR Review (3 Reviewers)

| Reviewer Comments from 2014 Annual Merit Review | | Response |
|---|---|---|
| "..concerns the degree of technical work that will be required in developing internal tabbing." | ⇨ | Two approaches of sintered metal tabbing areas with an optional attachment of a short metal tab as an intermediate and of laminating thin metal foils into the stack have been developed. |
| ".. long-term and high-temperature cycling are needed to validate the stability of the interfaces." | ⇨ | Yes, the cells with coated stacks need to have this testing. 8 micron thick free-standing ceramic separators of this project in cells adhere to the electrodes similar as in the coated stack cells and show good cycling and stability. |
| ".. wondered if the electrode stack will survive the typical pressure used to calender electrodes" | ⇨ | Further work this year has shown that the ceramic separator functions well after calendering and is only compressed by 5 to 10% and the electrode layer calender as they normally do with about a 30% compression. |

# Collaborations/Subcontractors

| | |
|---|---|
| MADICO® | **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 |
| THE UNIVERSITY OF RHODE ISLAND | **URI** (academic) on cell cycling testing on various ceramic separator and coated stack designs & on new electrolytes |
| XALT Energy | **XALT Energy** (industry) on electrode coatings and 2 Ah cell builds |
| ASHLAND. With good chemistry great things happen.™ | **Ashland** (industry) on polymer selection for battery stack coatings |
| Argonne NATIONAL LABORATORY | **Argonne National Laboratory** (government) on testing of 2 Ah baseline and prototype cells |

# Remaining Challenges and Barriers

- The release properties for delaminating the cathode stack have varied and have often been too high to enable delamination
- The anode stack has shown some tendency to curl that makes it difficult to build the cell stack with multiple anode stacks and cathode stacks
- The sintering process and design needs to be optimized for copper and nickel current collector layers with a preference to use nickel for both the anode stacks and the cathode stacks
- The tabbing process needs to be proven in 2 Ah cell builds
- Coordinating efforts between multiple subcontractors and locations in order to keep the project on schedule

# Future Work

**Planned Work**

- Put the improved release film designs with an easier release than before to test for satisfactory ease of delamination and curl in coating of energy and power electrode stacks at XALT Energy
- Develop coated stack designs with one-third thinner electrodes and 5 micron thick separator for high rate/power cells
- Optimize the metal sintering design and process, particularly for nickel current collector layers
- Prove the tabbing design and process in 2 Ah cell builds at XALT Energy

**Provide 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

## Relevance
- 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.

## Approach
- Roll-to-roll processing
- Nanopore nature and compressive strength of ceramic separator enables overcoating with anode and cathode layers followed by calendaring
- Thinner separator reduces inactive components and cell level cost significantly
- Thinner & lighter current collector layers
- Simpler and less expensive cell assembly for flat cells

## Technical Accomplishments
- 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
- Developed new process of sintering to make metal current collection layers with a new process for tabbing and termination

## Future Work
- Optimization and scale-up of anode stack, cathode stack, and current collector/termination into 2 Ah cells with extensive cycling testing
- Develop coated stack designs with one-third thinner electrodes and separators for high rate/power cells
- Complete the project final report, cost assessment, and 2 Ah cell deliverables

# *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 and lower cost electrolyte.
- The capability to vacuum dry at a high temperature right before filling with electrolyte provides even longer cycle life.
- Accordingly, the electrolyte work is now focused on investigating the mechanism of the stabilization of $LiPF_6$ electrolyte by analyzing cycled cells with and without the vacuum drying at the end of the dry cell assembly process 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.
- Further work in FY14/15 has shown that an intermediate release force and the use of a new release coating layer developed by Madico still prevents the premature delamination but provides more ease of delamination of the anode stacks and the cathode stacks.