# Advanced Battery Recycling

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Project ID:  ES205

# Overview

## Timeline

- Project start: October 2012
- Project end: September 2014
- Percent complete:66%

## Budget

- Total project funding
  - DOE share $1M
  - Contractor share: N/A
- Funding received in FY13 $500K
- Funding for FY14 $500K

## Barriers

- Noted VT Barriers that are addressed with Advanced Battery Recycling
  - Cost: The project shows feasibility to reduce or eliminate the end-of-life cost for recycling advanced lithium-ion chemistries.
  - Rare Earth Minerals: The project successfully recycles lithium and dilute cobalt cathode materials for advanced battery manufacturing.
  - Abuse Tolerance, Reliability and Ruggedness: The project demonstrates successful recycling of 10-20% and 50% capacity faded materials, which proves ongoing reliability and ruggedness of advanced materials after use and abuse.

## Partners

- Oregon State University, Corvallis
  Elemental, surface and structural analyses
- XALT Energy
  Material source and manufacturing partner
- Project lead – OnTo Technology

# Relevance / Objectives

***Project Objectives:***

1. *Working with a lithium battery manufacturer, demonstrate the number of times that large format lithium-ion, cobalt de minimis batteries may be recycled.*
2. *Perform the rejuvenation process on the kilogram scale.*
3. *Assemble recycling prototype process-line.*
4. *Build full cells through manufacturing partner, with capacity > 2Ah.*
5. *Perform the recycling process on another material.*

***Relevance to Vehicle Technology Program:***

*The Advanced Battery Recycling project develops manufacturing qualified material from recycling:*

A. *Increases the durability of materials from generation to generation of battery manufacturing, and*
B. *Improves the affordability of advanced batteries by increasing the potential value at end-of-life.*
C. *Helps to protect the Public Health and Environment with efficient recycling*

***Impact on Barriers:***

*The Advanced Battery Recycling project impacts barriers:*

I. *Cost: The projects shows feasibility for a processor to buy end-of-life cobalt de minimis batteries, and profitably sell recycled material at projected future costs: shows feasibility to end fees at end-of-life.*
II. *Rare Earth Minerals: Cobalt and lithium are recovered from the active material and reused in recycled material, and remain in the battery material niche.*
III. *Abuse Tolerance, Reliability and Ruggedness: Recycling of 50% faded batteries is demonstrated in the project, further demonstrating abuse tolerance of cobalt diminimis chemistries, such as NMC, and their durability to be successfully recycled through this technology.*

# Milestones

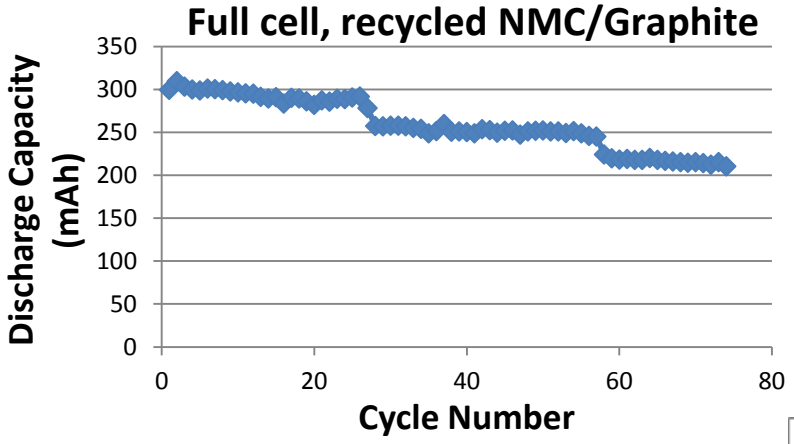
1. *Working with a lithium battery manufacturer, demonstrate the number of times that large format lithium-ion, cobalt de minimis batteries may be recycled.*
   - *First iteration is underway.*
   - *Severely faded material is processed and recovers to match standard performance.*
   - *Full cells were manufactured from recycled material and compared to standards.*
2. *Perform the rejuvenation process on the kilogram scale.*
   - *Accomplished in 2012, refined in 2013 and 2014.*
   - *1 L reactor volume can host active material mass of 500g.*
   - *Mass yield of active cathode material is 87%, limited to transfer losses.*
3. *Assemble recycling prototype process-line.*
   - *Accomplished in 2012, refined in 2013 and 2014.*
4. *Build full cells through manufacturing partner, with capacity > 2Ah as requested in the RFP.*
   - *First 2Ah cells built from recycled material are being tested in parallel with standard material.*
   - *High yield allows for a total of six 2.2Ah cells to be made from scrap feedstock of 16Ah.*
5. *Perform the recycling process on another material.*
   - *Accomplished with NMC-lithium metal oxide battery formulation in 2013*
   - *Another cobalt diminimis lithium-ion formulation is under evaluation.*

# Approach/Strategy

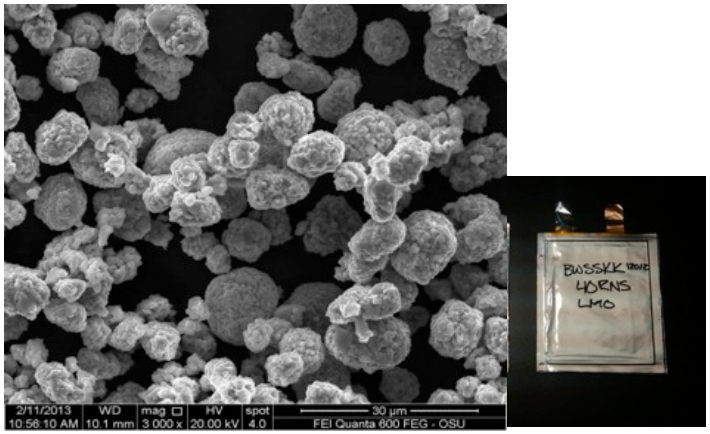
- Unique aspects of the developmental work:
  - Harvest and rejuvenate active material from 10-20% & 50% faded cells.
  - Match the performance characteristics of standard and recycled materials.
- Developments to address the project's technical barriers:
  - Develop process scale.
  - Reproduce recycled material performance with process scale.
- Project integration with other deployment projects within the VT Program:
  - Demonstrate successful recycling (harvest and rejuvenation) of cobalt diminimis lithium-ion EV grade batteries supplied from XALT Energy.
  - Develop rejuvenation process to produce material with performance matching the standards supplied by our partner.
    - Half-cell performance check as a function of process parameter.
  - Demonstrate manufacturing using recycled material with partner.
- Planned milestones for FY14 and current status toward them.
  - First recycled material 2.2 Ah full cells manufactured in OEM setting.
    - Prequalification with half-cells matches standard performance.
    - Full cell comparison between recycled and standard is underway.
    - Capacity and initial cycling match between standard and recycled.
  - Accelerate fade these cells in-house, and then repeat the recycle process (underway).
  - Perform materials analysis on half-cell prequalified materials (underway).

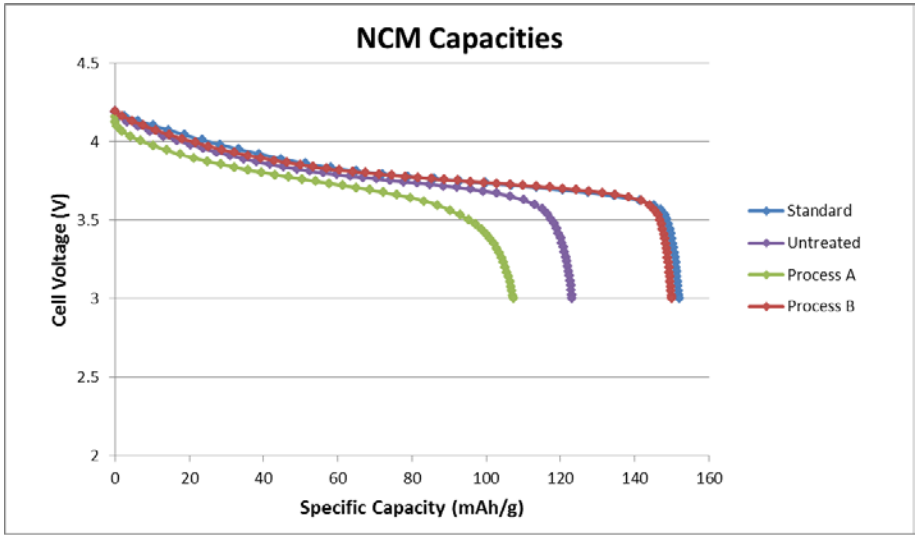
# Technical Accomplishment:

## proof of concept for recycling NMC from 13% faded cells



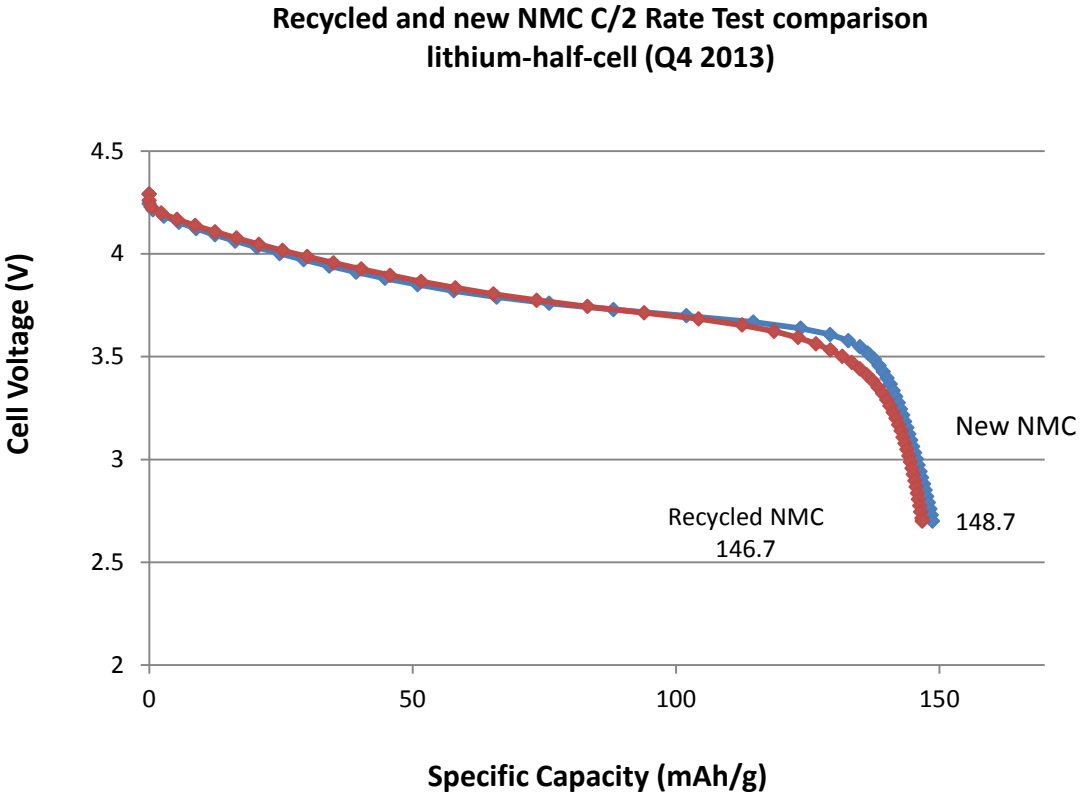

- Recycled NMC (R-NMC) matches specific capacity of standard NMC. (graph below from Q4 '12)
- R-NMC maintains rosette appearance. (SEM Q1 '13)
- First full cell with graphite, made in-house, has good cycle characteristics. (graph to left, representative pouch-cell in photo, Q1 '13)
- Challenges Identified: rate capability of R-NMC was low compared with NMC. Resolution of that challenge is demonstrated in the next technical accomplishment slides.



# Technical Accomplishment:

## Development of R-NMC rate capability performance Starting from lightly faded cells

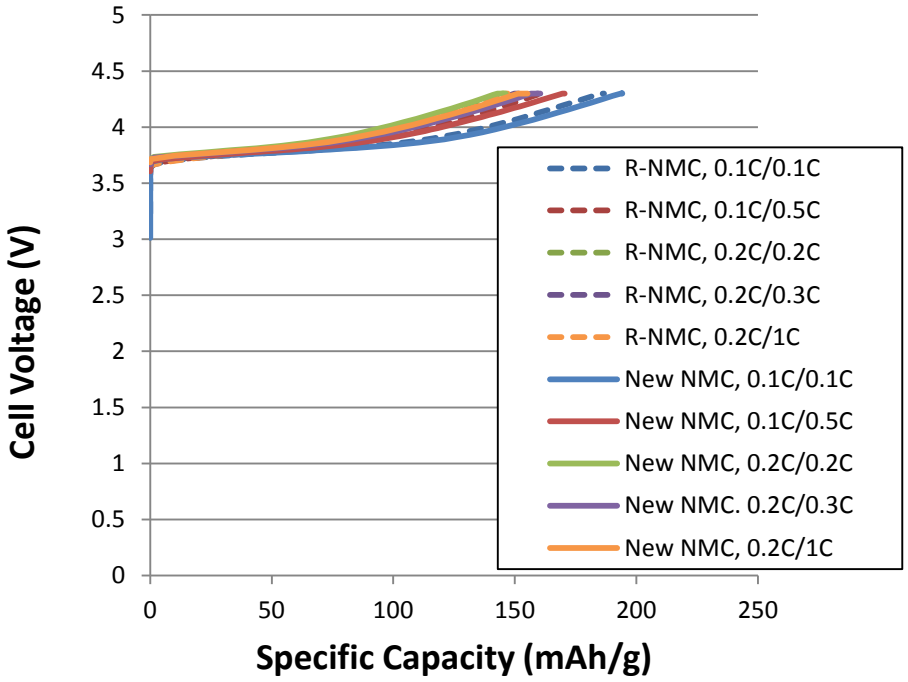



- Recycled NMC (R-NMC) matches specific capacity of standard NMC at C/2. (Q4 '13)
- Resolves challenges identified for rate capability.
- Move onto processing of heavily faded cells, details in the next technical accomplishment slide.

Addresses program goal to match performance criteria between recycled and standard material, and to work with a lithium-ion battery manufacturer.

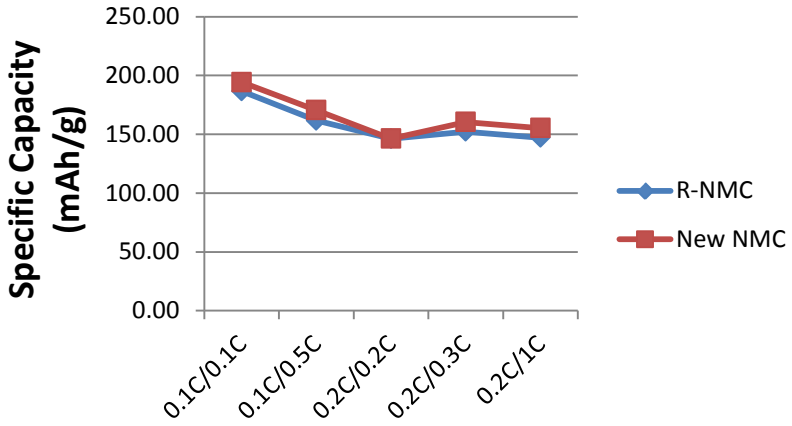
# Technical Accomplishment:

Develop recycling process that produces high rate & capacity R-NMC
Comparative charge data, ***source material is 50% capacity faded***




| Specific Charge Capacities (mAh/g) | | |
|---|---|---|
| Cycle (Rate) | R-NMC | New |
| 1: 0.1C | 187 | 194 |
| 2: 0.1C | 162 | 171 |
| 3: 0.2C | 146 | 146 |
| 4: 0.2C | 152 | 160 |
| 5: 0.2C | 147 | 155 |

Matches rate capability to within 4% of new material.

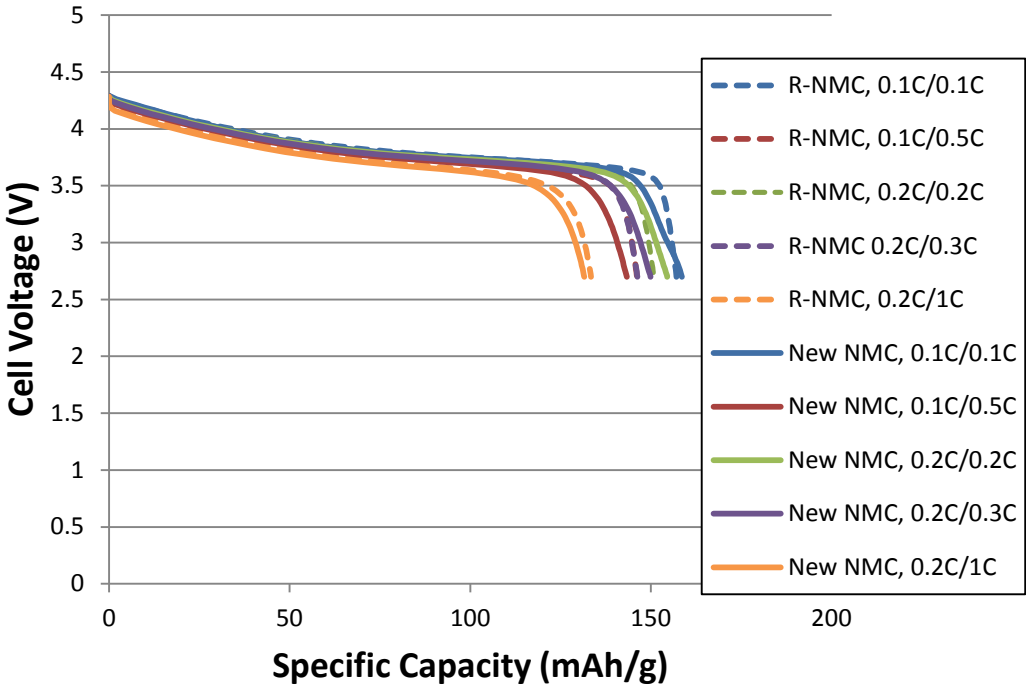



Addresses program goal to match performance criteria between recycled and standard material, develop a kilogram scale reactor for recycling, and to work with a lithium-ion battery manufacturer. (successful prequalification for manufacture).

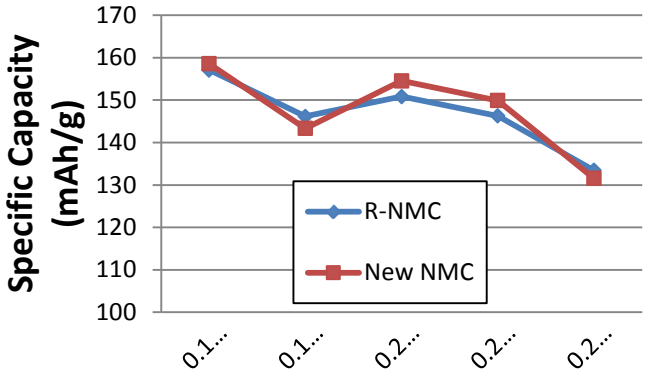
# Technical Accomplishment:

Match the high rate & capacity of R-NMC with standard material

Discharge Data, ***source material is 50% capacity faded***




| Specific Discharge Capacities (mAh/g) | | |
|---|---|---|
| Cycle (Rate) | R-NMC | New NMC |
| 1: 0.1C | 157 | 159 |
| 2: 0.5C | 146 | 143 |
| 3: 0.2C | 151 | 155 |
| 4: 0.3C | 146 | 150 |
| 5: 1C | 133 | 132 |




Matches rate capability between recycled and new material, within 2%.

Addresses program goal to match performance criteria between recycled and standard material, develop a kilogram scale reactor for recycling, and to work with a lithium-ion battery manufacturer. (successful prequalification for manufacture).

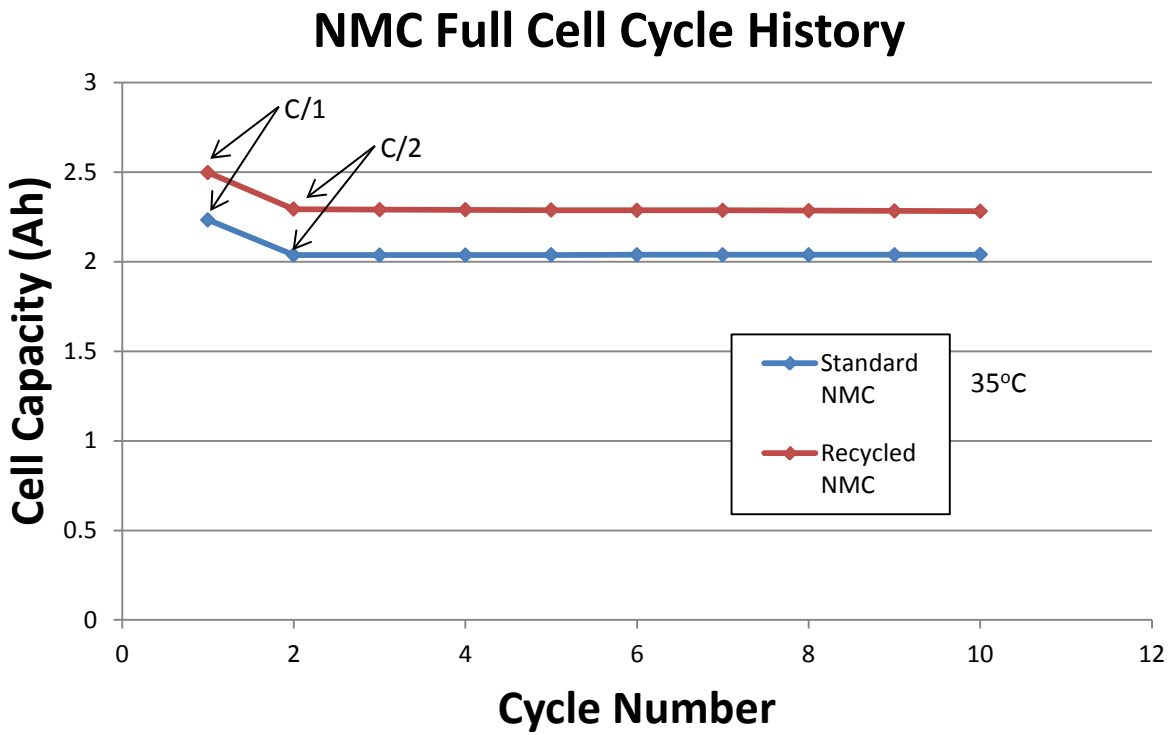
# Technical Accomplishment:
# Cells built from recycled material

Standard graphite/R-NMC, 2.2 Ah capacity, meets cell criteria from RFP


- ***source material is 50% capacity faded***
- Six recycled material cells with 2.2Ah capacity @ 0.5C @ 30°C
- Five standard cells with 2Ah capacity @ 0.5C @ 30°C.
- Same coating specifications, one extra cathode/anode sheet in the recycled cell to provide an offset in capacity vs. cycle # comparison.
- Cycling is underway: C/2 / C/2 (CC charge/CC discharge), 4.2-2.7V, 30°C

Addresses program goal to have an OEM build full cells from recycled and standard material. Two, faded 8Ah cells were recycled, the material was used to produce six 2.2Ah cells; demonstrates high yield, losses due to material transfer. Addresses VT cost barrier for end-of-life disposal/destruction fees. Demonstrates feasibility to recycle material for battery manufacturing; addresses rare earth material, and abuse tolerance.

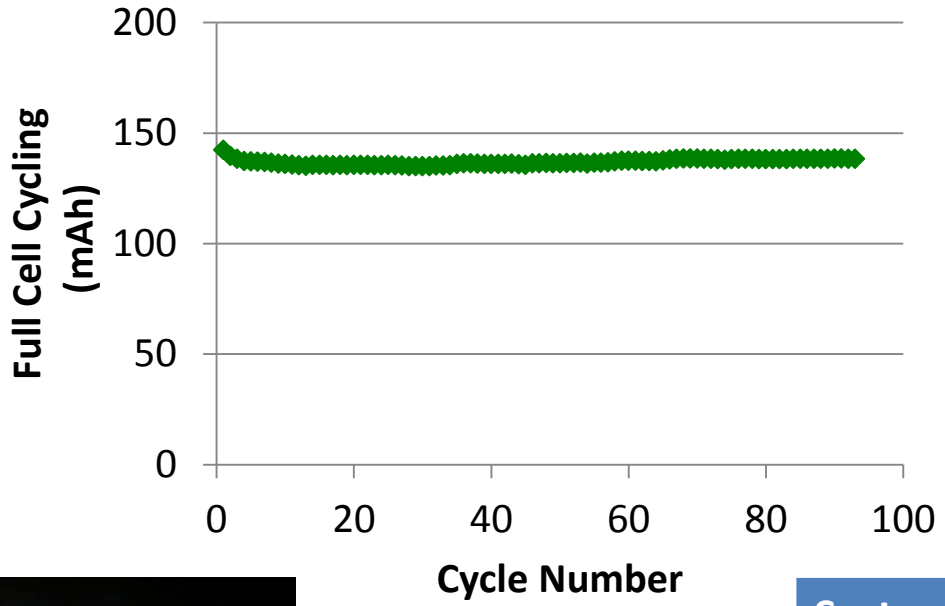
# Technical Accomplishment:
## Comparison of recycled and standard material in full cells




Addresses program goal to have an OEM build full cells from recycled and standard material. Demonstrates feasibility to recycle material for battery manufacturing; addresses conservation/reuse of lithium; recycling of faded cells demonstrates the ruggedness and abuse tolerance for advanced materials.

# Technical Accomplishment:

Proof of concept for recycling a Mixed Oxide and LMO
Source material is an EV prototype cell from Nissan and subsequently faded by 20%




Addresses program goal for recycling an additional cobalt diminimis chemistry. This is a mixed oxide sourced from Nissan-Sumitomo.


| System | mAh/g | Rate |
|---|---|---|
| Standard/ Li | 130 | C/20 |
| Recycled/ Li | 130 | C/20 |

# Collaborations

- XALT Energy
  - Contributor.
  - Industry within the VT Program.
  - Critical collaborator supplying new and faded cells, standards and recycled. material manufacturing test runs.
- Nissan-Sumitomo
  - Contributor.
  - Industry outside of the VT Program.
  - Provided relevant battery packs for recycle testing.
- Chrysler
  - Contributor.
  - Industry within the VT Program.
  - Provided relevant battery packs for recycle testing.
- Oregon State University
  - Subcontractor.
  - University, outside of the VT program.
  - Performed material characterization and analyses.
- Willamette University
  - Subcontractor.
  - University outside of the VT program.
  - Performed material characterization and provided undergraduate internships.

# Remaining Challenges and Barriers

- Full cell cycling and accelerated fading is underway for standard and recycled material cells.
- Will a second recycling iteration be as successful as the first?
- Material characterization is underway for recycled material used in the for manufacturing new cells.
- Proof of concept recycling of other cobalt diminimis lithium-ion chemistries & mixtures is underway.

# Proposed Future Work

- Evaluate R-NMC 2Ah cells side-by-side with standard material.
  - Compare capacity, rate capability, self discharge and fade characteristics. The FOA asks for 2Ah cells to be made in the project.
- Accelerate fade the R-NMC cells.
  - Use previous method: C/2 rate charge/discharge @ 45$^{o}$C.
- Harvest and rejuvenation of R-NMC cells to address the possibility of 3$^{rd}$ round manufacturing.
  - After side-by-side capacity fade comparison.
- Practice recycling technology developments on the mixed oxide work accomplished early in the project (slide 12).
- For the second round of recycling, if prequalification is successful, we will make cells with our OEM partner.
  - If this milestone cannot be achieved due to performance, we will address alternate possibilities such as mixing recycled and new material in order to meet performance, alternatively, we will examine alternate markets for material use considering the performance that is attained. (i.e. perhaps a market that would require energy rather than power).
- Material characterization (upcoming milestone)
  - Techniques will be evaluated to remove potential contaminants that may be found in the recycled materials.

# Summary

- Relevance:  Innovative recycling of high performance cobalt diminimis lithium-ion chemistries can help achieve VT goals to reduce cost, demonstrate advanced materials durability, address critical material concerns, and helps to protect the public health and environment.
- Approach:  Teams with a manufacturing partner to qualify recycled material.
- Technical Accomplishments:
  - Heavily faded NMC cells were harvested and rejuvenatd to produce R-NMC with charge/discharge characteristics equivalent to new NMC in prequalification half-cells.
  - Performed the process on liter scale reactor, representing a 10x scale of the proof of concept system.
  - Produced the first ever recycled vehicle grade lithium-ion batteries with 2.2Ah capacity.  Initial side by side comparison shows equal performance between recycled and standard materials.
- Collaborations: First ever manufacturing efforts with recycled material in an OEM setting with XALT Energy.  Recycling development of EV grade, faded cells from manufacturers including XALT, Chrysler and Nissan. Undergraduate research efforts supported with internships with Willamette University; Graduate research efforts support the project with Oregon State University.
- Future Work: Side by side life and fade comparison for recycled and standard NMC. The initial cycling behavior is identical between R-NMC and standard; after 20% fade, the R-NMC cells will be recycled again.
  - Examination of recycling another lithium-ion battery chemistry.