Advanced Battery Recycling

OnTo Technology LLC
Steve Sloop

August 19, 2014

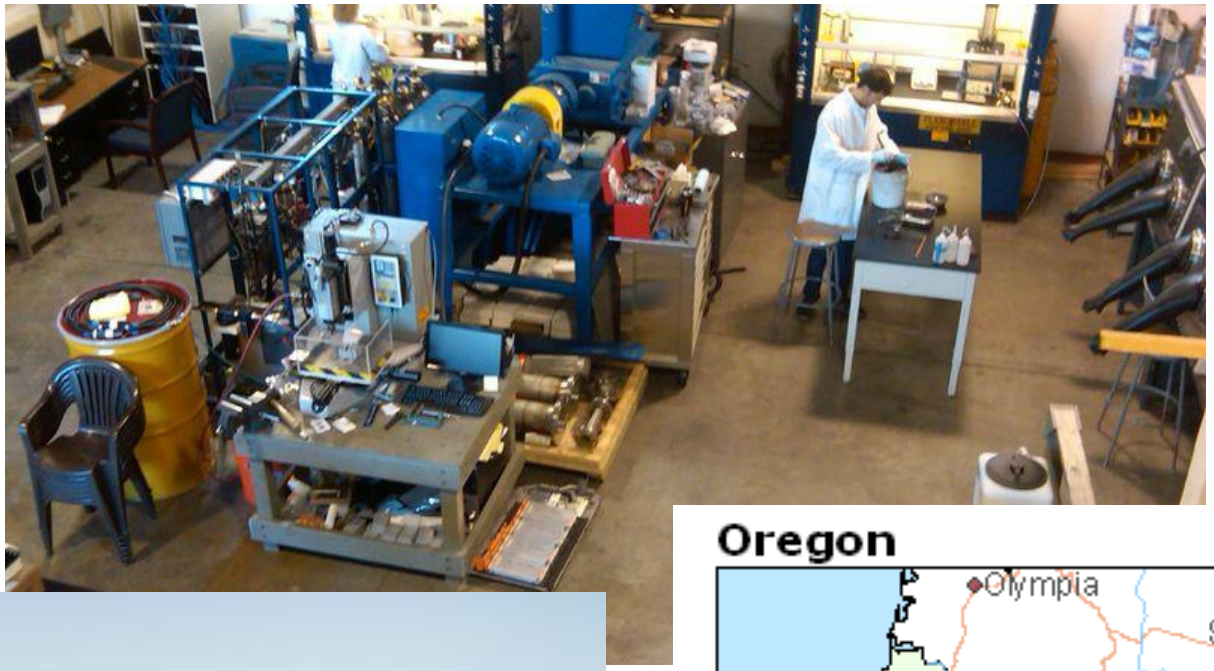
9th US – China

EV and BT Workshop

Includes research results funded from DOE SBIR award DE-SC0006336

Overview

- Existing Approaches and some market data.
- Process overview.
- Technical results for LCO and NMC.




Oregon
Olympia
Spokane
Portland
Salem
Eugene
Bend
Boise
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History of OnTo

- 2003 Founded the company to develop lithium-ion battery recycling technologies

Business model is to license the technology

- 2004 Oregon Department of Energy Loan
- 2005-2007 LGChem Apple Computer Recall
- 2006-2008 US VRP
- 2007-2011 National Science Foundation SBIR Awards
- 2008-2010 Ecobat, licenses advanced recycling technology
- 2010-2011 Environmental Protection Agency SBIR
- 2011-2012 Oregon Nanoscience and Microtechnologies GAP award
- 2011-2014 US Department of Energy SBIR Phase I and II Awards

(Small business innovation research)

SBIR/STTR Program Basic Structure

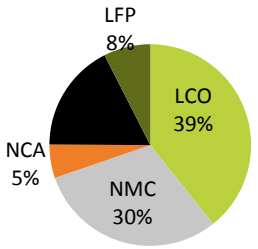
- Phase I
  - Feasibility Study, Proof of Concept
  - $150k Max, for 6 Months
- Phase II
  - Full Research and Development Effort
  - $1 Mill Max, for 12 Months
- Phase III
  - Commercialization Stage
  - Seek External Funding [No Use of SBIR funds]
    - Non-SBIR federal funding, OR
    - Private sources

Only Phase I winners may apply for a Phase II. Phase I and II awardees can move to Phase III.

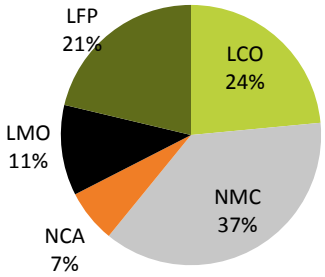
(From the SBA Website)

Battery Recycling will have to grow

Cathode active materials in 2012: 75 000 Tons



Cathode active materials in 2025: > 330 000 Tons



- Layered metal oxides are important over the next 11 years.
- Useful in large and small format applications.
- OnTo can recycle most any cathode material in the projection.
- Pilot scale capability through support of DOE SBIR grant.

Cobalt diminimis chemistries have little to no smelt value

Cathode	Price of Constituents ($/lb)	Price of Cathode ($/lb)
$LiCoO_2$	8.30	12–16
$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	4.90	10–13
$LiMnO_2$	1.70	4.50
$LiFePO_4$	0.70	9

A Look through the Crystal Ball at the Future of Automotive Battery Recycling
Linda Gaines
Argonne National Laboratory (2014)

Company	Battery Types	Process	Location
Umicore	All + E-Scrap	Pyrometallurgy + Electrowin	Hooboken Bel
Toxco	Li, Ni Based	Cyromilling (Li), Pyrometallurgy (Ni)	Trail BC Baltimore OH
Dowa	All + E-Scrap	Pyrometallurgy	Japan
CVRD (INMETCO)	Ni Based	Pyrometallurgy	Ellwood City Pa
RMC	All	??	ON
Salesco Sytems	All + Hg	Pyrometallurgy	Phoenix, AZ
Bethlehem Apparatus	Hg Based	Pryrometallurgy	Hellertown PA
XStrata	All + E-Scrap	Pryrometallurgy, Electrowin	Horne Que, Nikkelverk Nor, Sudbury Ont
Toho Zinc	Ni-Cd, Ni-MH	Pyrometallurgy	Onahama Jp
Japan Recycle Center	All	Pyrometallurgy	Osaka Jp
OnTo Technology	Li	Solvent Extraction (CO_2)	Bend OR
Accurec	All	Pyrometallurgy (V)	Mulhiem GDR
Korea Zinc	Ni-Cd	Electrowin	Onsam, Kor
SNAM	Ni-Cd, Ni-MH, Li	Pyrometallurgy (V)	Saint Quentin Fallavier Fr
AERC	All + Hg	Pyrometallurgy	Allentown PA, Hayward CA, West Melbourne FL.
NIREC	Ni Based	Pyrometallurgy	Dietzenback
Erachem (Revatech)	Mn	Pyrometallugy	Terte Bel.
DK	All	Pyrometallurgy	Duisburg GR
GMA &CO	Zn Based	Pyrometallurgy	
NQR	Hg	Pyrometallurgy (V)	Lubeck
REDUX	Zn based	Pyrometallurgy	Dietzenbach
Varta	??	??	Hanover GR
Batrec AG	Li, Hg	Pyrometallurgy	Wimmis, CH
SAFT-NIFE	Ni Based	Pyrometallurgy	Oskarhamn, SW
AEA Technology	Li	?	Sutherland Scotland
IPGNA Ent. (Recupyl)	All	Hydrometallurgy	Grenoble, FR
AFE Group (Valdi)	All	Pyrometallurgy	Feurs, FR, La Palais sur Veine, FR
Citron	All	Pyrometallurgy	Zurich CH, Rogerville, FR
Zimaval (Cite Plus, Suez SA)	Zn, Mn, Hg	Hydrometallurgy	Falaise FR
Euro Dieuze/SARP	All	Hydrometallurgy	Lorraine FR
Seche Environmental (Tredi)	Cd, Hg	Pryometallurgy	Salaise sur Sanne
EBS	Zn Based	Hydrometallurgy	Austria

Ellis, T; Mizra, A (2005)," Battery Recycling:
defining the market and identifying the technology required to keep high value materials in the economy and out of the waste dump "

Sample of recycling rates

EU sales figures, return flows and collection rates of Li-ion batteries (2002–2007) (source: ACCUREC Recycling).

	2002	2003	2004	2005	2006	2007
Sales in tonnes	3771	4977	6712	8210	9138	13,181
Return in tonnes	17	54	170	175	418	354
Collection in %	0.5	1.1	2.5	2.1	4.6	2.7

Development of a recycling process for Li-ion batteries

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Recycling can be exempt from universal waste

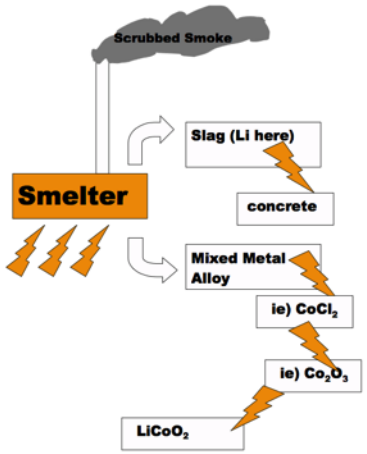
Battery disposal

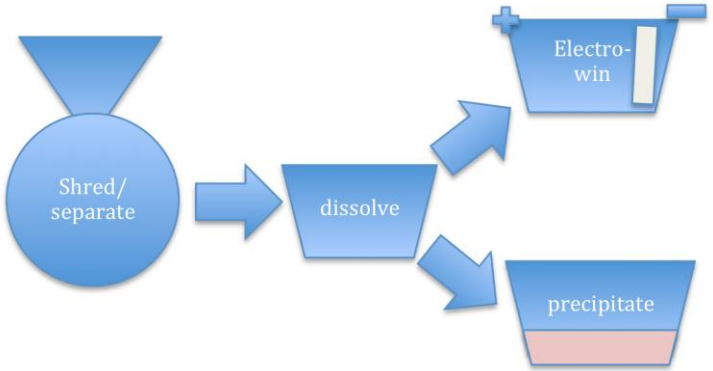
The Tesla Roadster's lithium-ion batteries do not contain heavy metals such as lead, cadmium, or mercury. Therefore, they are exempt from hazardous waste disposal standards in the U.S., as defined in the Universal Waste Regulations. However, the battery cells do contain recyclable materials and Tesla Motors encourages recycling whenever possible. For information about recycling, contact Tesla Motors. If disposing without contacting Tesla, contact local, state, or federal authorities for information about the appropriate methods for disposal and recycling. Disposal regulations vary depending on location.

From the Tesla Roadster Emergency Responder Guide

Existing Technologies

Smelting and hydrometallurgy





- One technique generally requires the other.
- Extraction for metallic value: Co, Cu, Ni.
- Alloys or leachates require intensive purification.
- Co dilute batteries have no residual value, may require fees for processing and disposal.
  - When that happens, the battery manufacturer must rely on mined material for manufacturing.
- Lithium from rechargeable systems is not recycled in these processes.
- Cannot contribute to cost reduction for the advanced battery market.

OnTo / Sloop Patents

TITLE	Assignee	Serial #	Filing Date	**Gov't Rights**	Notes
REINTRODUCTION OF LITHIUM INTO RECYCLED BATTERY MATERIALS (U.S.)	Steven E. Sloop ONTO	12/390,364	February 20, 2009	**Yes**; made under contract with U.S. Government Agency NSF (contract no. 0750552).	Approved 4/24/14
RECYCLING OF BATTERY ELECTRODE MATERIALS (U.S. Continuation-in-Part Application)	Steven E. Sloop ONTO	12/709,144	February 19, 2010	**Yes**; made under contract with U.S. Government Agency NSF(contract no. 0750552).	Pending. Awaiting examination.
REINTRODUCTION OF LITHIUM INTO RECYCLED BATTERY MATERIALS (PCT Application)	Steven E. Sloop ONTO	PCT/US2009/034779	February 20, 2009		Pending.
Recycling Batteries Having Basic Electrolytes; (U.S.)	Steven E. Sloop ONTO	US # 8,497,030	2009(?)		Approved 2013. Supercritical fluid deactivation of batteries.
TRADE SECRETS regarding deactivation of lithium-ion batteries and recycling of lithium-ion battery materials	ONTO				
U.S. Patents sold to EB and licensed back to ONTO Nos. 7,198,865, 7,858,216 and 8,067,107, along with their foreign equivalents in Australia, Brazil, China, Europe, Japan and South Korea (the "Sold Patents").	EB	US #'s 7,198,865, 7,858,216 8,067,107	2003	N/A	Supercritical fluid extraction of electrolytes. R&D allowed use, and not necessary for commercial operations

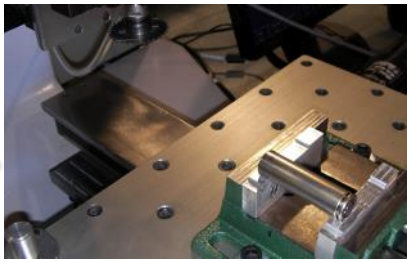
Chemistry-centric, Large Niche market opportunities

- Easily handled, application-sorted chemistries.
- EV
  - Major recycling growth is expected by 2020.
  - Chinese, EU and US market growth drivers.
- Grid, large format energy storage.
- Electronic scrap.
  - Service industries supporting portable devices.
  - Call to Recycle collects in excess of 2000 tons/year
- Battery manufacturing scrap.
- Military.
  - BA-2590 is the standard rechargeable lithium ion pack used around the world.
  - The 6-T is a large format lithium-ion pack being developed for multiple uses.

OnTo Process: chimie-douce, direct
Low Capital Cost, High Efficiency

1. Open Packs or Modules

2. Open cells / shred



3. Extract Ely

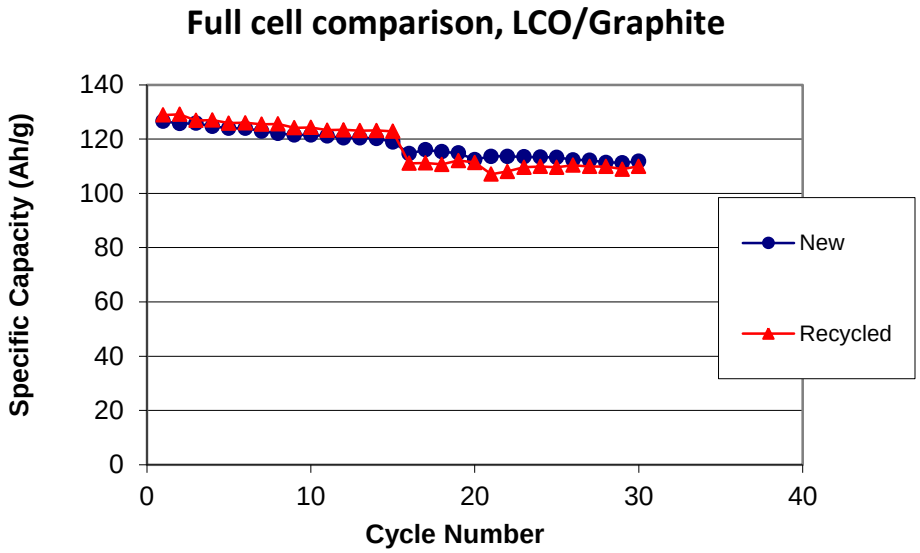
4. Separate powder

5. Refurbish Electrodes

6. Dry and Prep.

7. Finished product

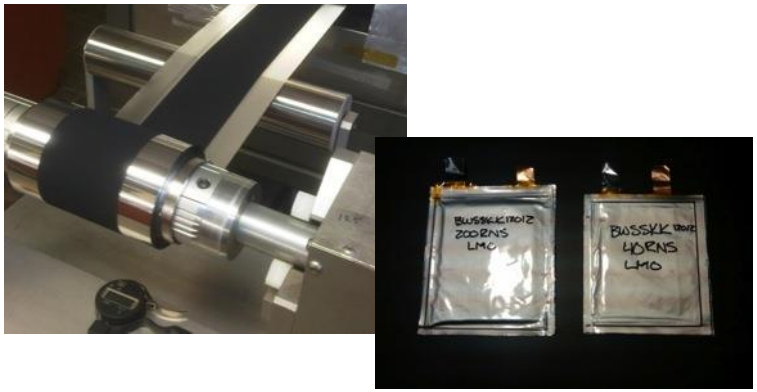
Comparison of Recycled and New LCO



High specific capacity lithium cobalt oxide.

Low fade rate in full cells.

Commercial grade pouch cells.

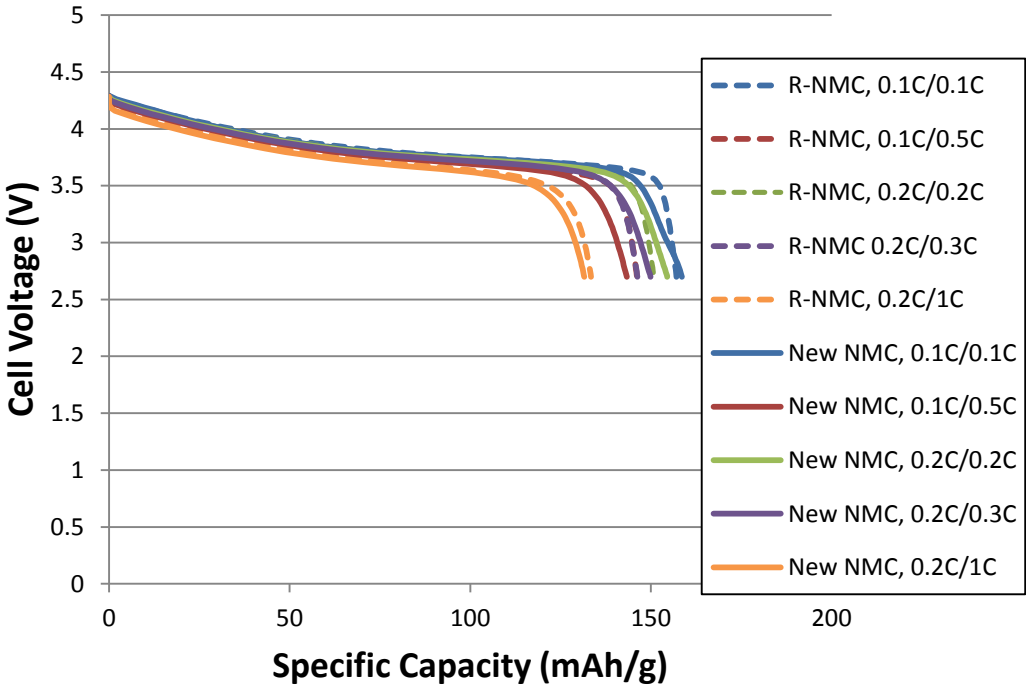


Sample	Half-cell specific capacity (mAh/g)
Recycled material	150
New material	150

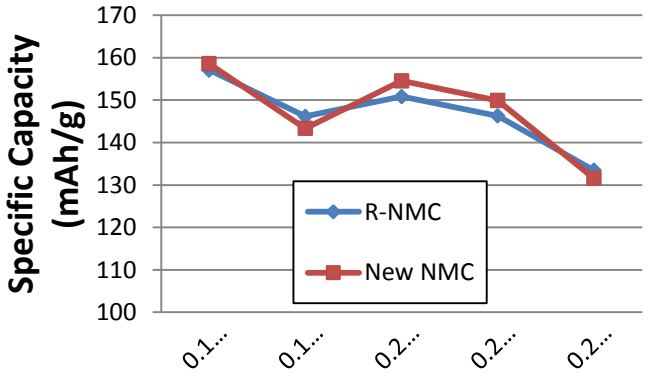
Recycled NMC pre-qualification Li/NMC:

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

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



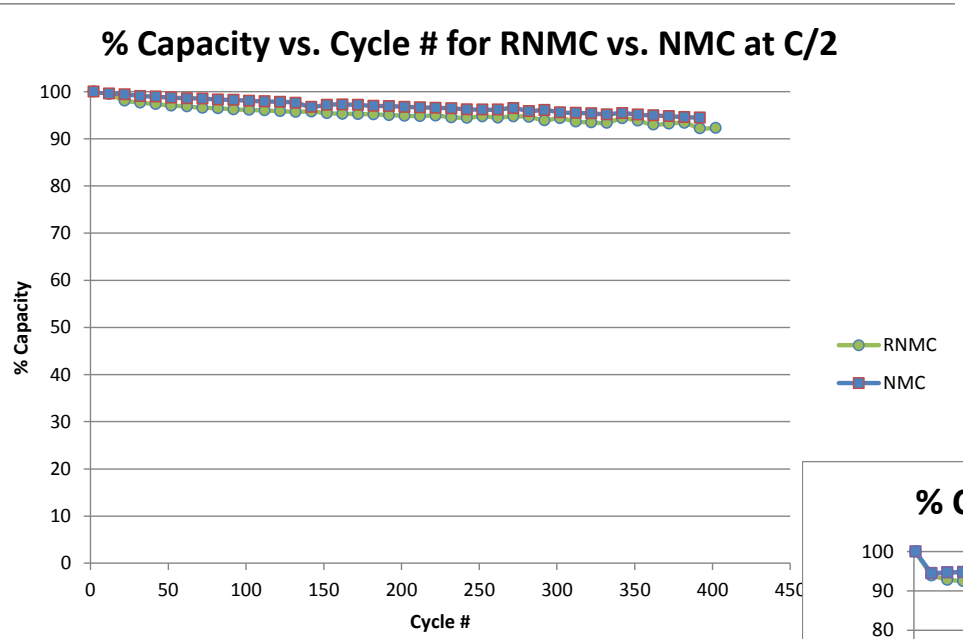
Specific Discharge Capacities (mAh/g)		
Cycle (Rate)	R-NMC	New NMC
1: 0.1C	157	159
2: 0.5C	146	143
3: 0.2C	151	155
4: 0.3C	146	150
5: 1C	133	132

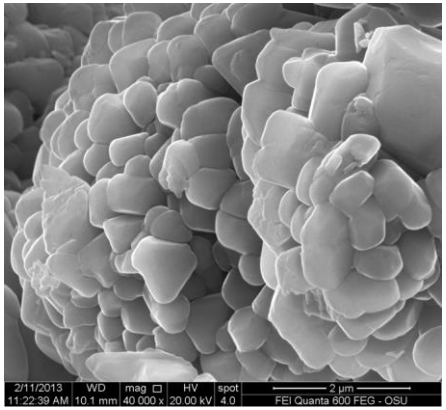


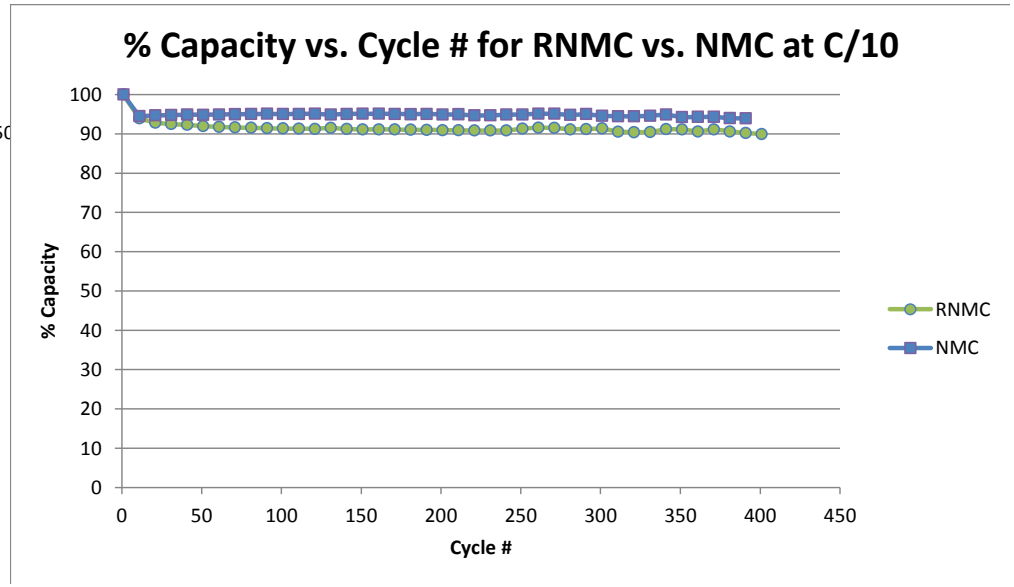
Matches rate capability between recycled and new material, within 2%.

Addresses program goals 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 (Xalt).

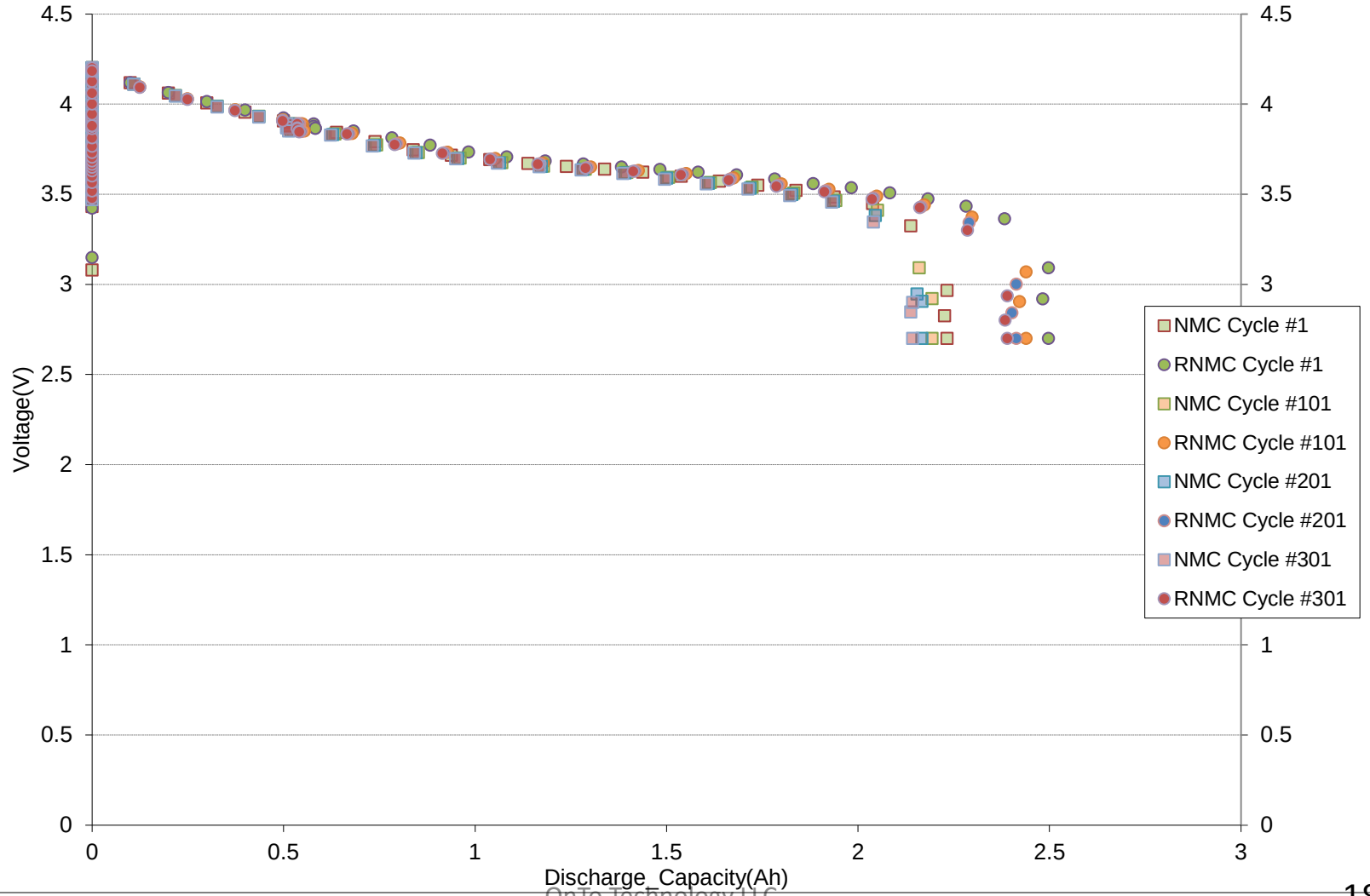
Comparison of New and Recycled NMC



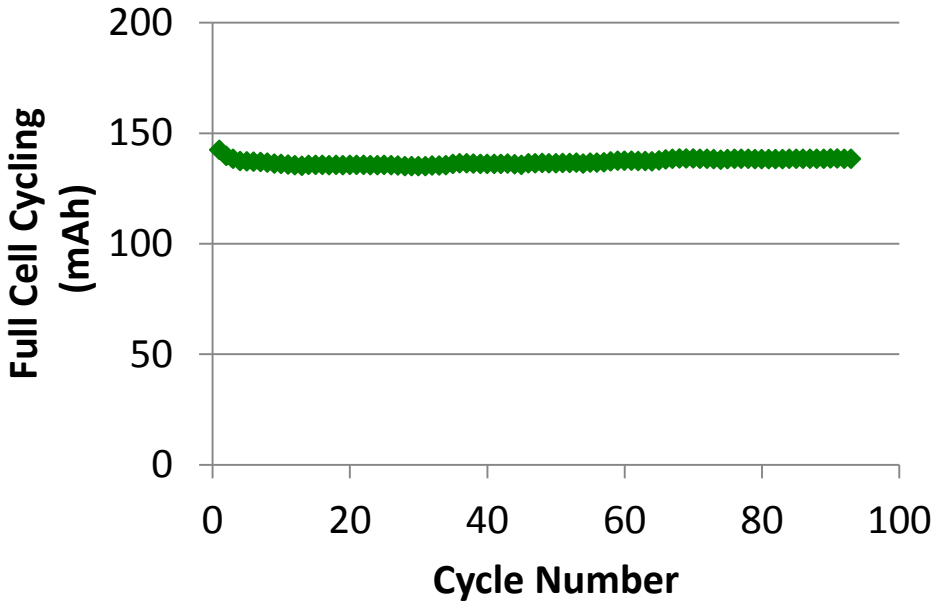




Voltage vs. Discharge Capacity for RNMC vs. NMC at C/10

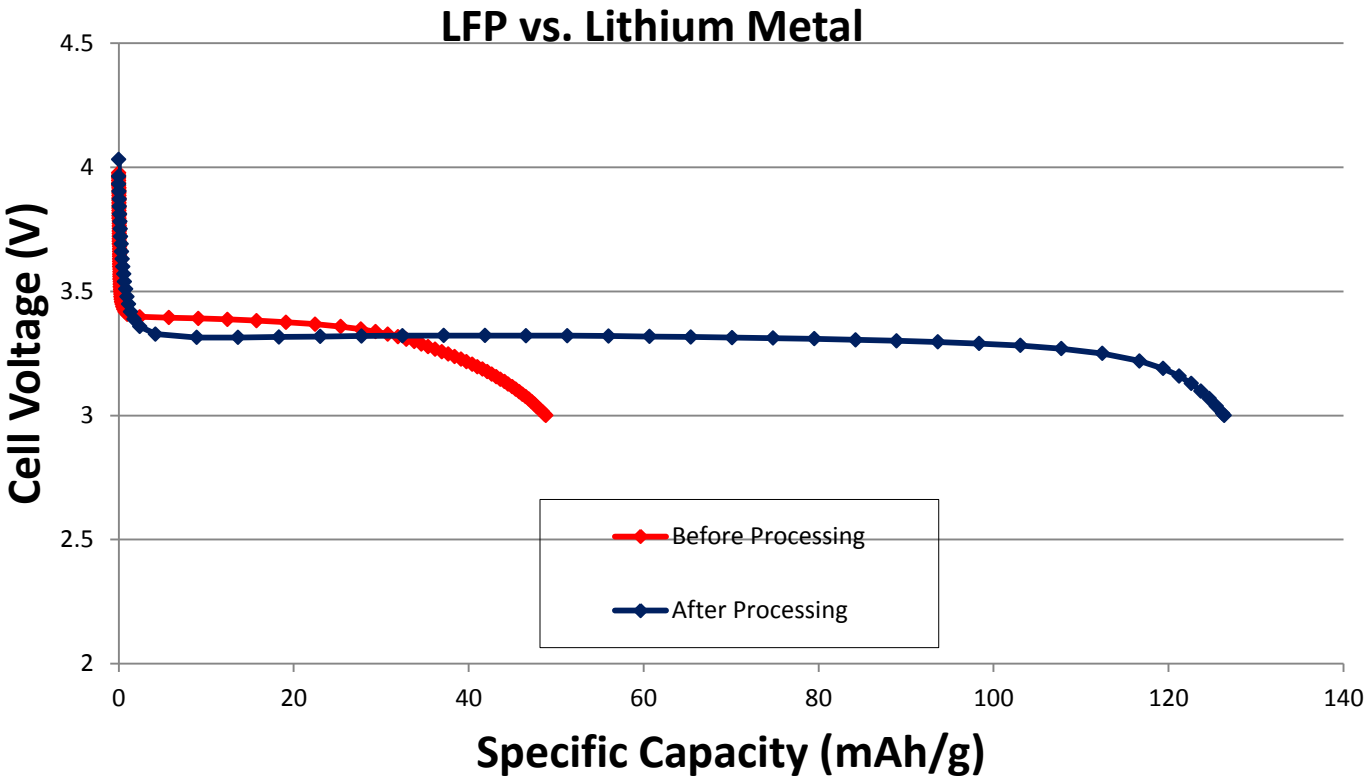


Recycling of Mixed Oxide with LMO



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

Recycling of Iron Phosphate

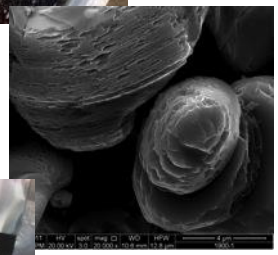


Harvested from a severely faded, abused, large format cell.
Process successfully returns the original specific capacity ~130 mAh/g

Summary for Lithium-ion advanced battery recycling

Scrap, end of use

Application: EV, phone…



- Low cost processing – can contribute to significant cost savings.
- Chemistry flexible.
- Environmentally friendly.
- Scalable.
- OnTo can help the battery industry to…
  - Develop recycling plans for large and small batteries for various uses.
  - Start processing materials for manufacturing qualification.
  - Develop use of recycled material in manufacturing new batteries.

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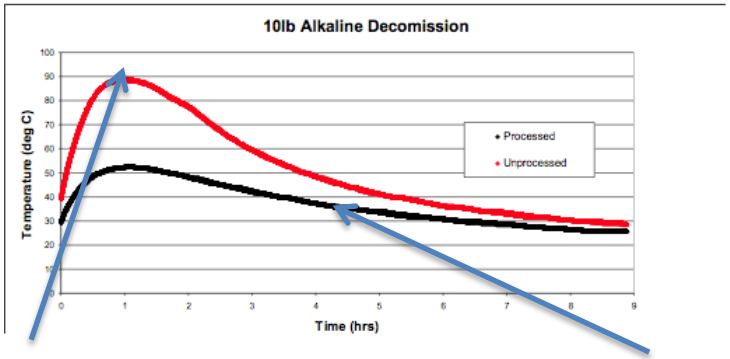
Spare slides

Battery Deactivation Processes

improve safety for alkaline, metal hydride, lithium…



Fire and heat
no treatment

No fire or heat
with treatment

- Neutralize batteries in-state, without caustic material, without waste.
  - Treated alkaline waste can be disposed ordinarily.
- Addresses risk of fire.
- Removes process hazards.
- Patented and PCT pending.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Declarations under Rule 4.17:
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*

Recycling Technologies Sample

Company/ institute	Hydro	Pyro	Direct	Notes
Umicore	X	X		
Ecobat			X	Ellis, WO2011143061
OnTo			X	Sloop Patent Application No. 12/390,364 (patent issues this week)
Recupryl	X			Farouk Tedjar WO2003021708
Toxco/KBI	X	X	X	Smith 8,616,475
Cannon			X	Kawakami 6,329,096
Valence			X	Mathew 6,150,050
Korea Institute of Geosciences	X			Lee 6,844,103

Energy savings :
Cost savings

- LCO example.
- Direct recycling is estimated to require 1/62 the energy of smelt recycling.
- Recycles lithium.
- Recycles Aluminum too.
- Avoids emission of S and As in ore processing.
- Develops new domestic sources of advanced material.
- Can be modeled after successful battery recycling economies such as lead-acid.