RECYCLING OF AUTOMOTIVE LI-ION BATTERIES

GOVERNMENT PERSPECTIVE

Linda Gaines and Jeff Spangenberger
Argonne National Laboratory
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Many different agencies are concerned about batteries

But they focus on different aspects

DOE: petroleum use, greenhouse gases; basic science and technical feasibility

EPA: emissions

DOT: transportation safety

DOC, USGS: material supply and demand

OSHA: job safety

Argonne tries to take all of these factors into account, plus ECONOMICS

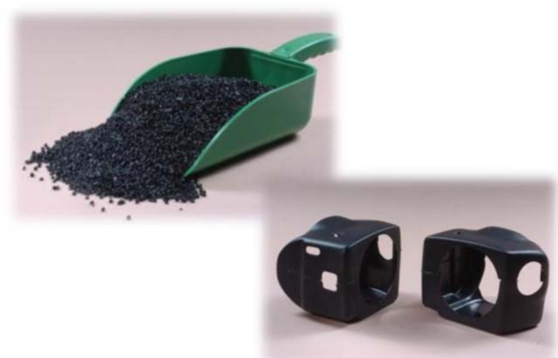
Argonne has long recycling history

Studies of production and recycling of materials date to late ‘70’s

- Included options for discarded tires
- Compared environmental aspects of aluminum and steel for auto bodies

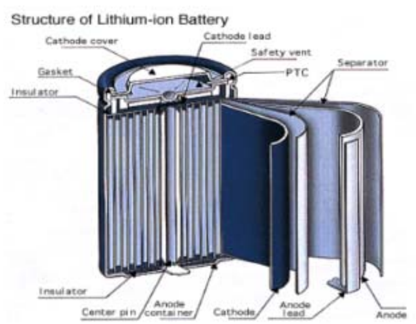
Experiments started 1987 to recover materials from shredder

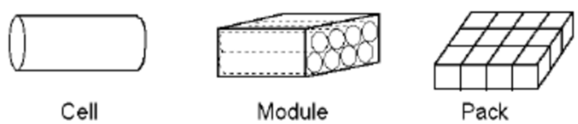
- Research first targeted foam recycling and iron oxide recovery from fines
- Then light weighting materials such as plastics, carbon fiber and light metals



Vehicle advancements for improved environmental impact must include material end-of-life research efforts to prevent an inadvertent net negative effect through the entire lifecycle. Batteries are not exempt.

An automotive li-ion battery pack is a complex system





Source: L. Gaines and R. Cuenca, *Costs of Lithium-Ion Batteries for Vehicles*, Report ANL/ESD-42 (2000)

Lithium-ion cells are more complicated than other chemistries

One recycler reports having received 16 different Li-ion cathodes!

Cell component/ battery type	Pb-acid	Ni-MH	Li-ion
Cathode	PbO_2	$Ni(OH)_2$	LCO, NCO, LFP, or LMO
Cathode plate/foil	Pb	Ni foam	Al
Anode	Pb	MH (AB_5)	graphite
Anode plate/foil	Pb	Ni-plated steel	Cu
Electrolyte	H_2SO_4	KOH	Organic solvent + $LiPF_6$
Separator	PE or PVC + silica	polyolefin	PE/PP
Cell case	PP	Stainless steel	Metal or laminate

LCO= lithium cobalt oxide; NCM= nickel, cobalt, manganese; LFP= lithium iron phosphate; LMO= lithium manganese oxide
PE = polyethylene; PVC = polyvinyl chloride; PP = polypropylene

About 35% of materials in Li-ion cells recyclable by standard methods

Cell Component	Mass %	% energy reduction by recycling
Cathode active material	22-24	
Anode active material	15-16	
Copper parts	13	64
Aluminum parts	22	74
Electrolyte solvent	12	
Plastics	4	
Steel	1	25
Carbon	2	
Binder	3	
Thermal insulation	1	
Electronic parts	0.3	

Recovery of the remaining materials is an interesting challenge

- **What active materials will be used?**
  - Cathodes: LCO, LMO, LCM, NCA,?
- Electronics mostly LCO now
- EVs moving to cheaper raw materials
  - Anodes: graphite, silicon, LTO, ?
- **New electrolytes**
- **Different coatings and configurations**
- **There will be many types of materials to recover!**

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Design for recycling
can reduce recycling costs

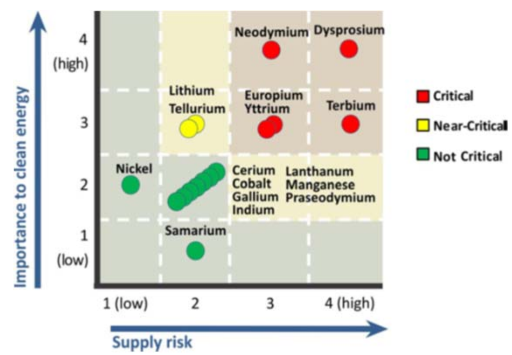
- **Include labels or other distinguishing features**
- **Use a minimum number of different materials**
- **Standardize formats and materials**
- **Avoid bad-actor materials (cadmium, arsenic, mercury, halogens)**
- **Enable easy separation of parts**
  - Design separable cooling system
  - Use reversible joining (nuts and bolts instead of welds)
  - Avoid potting compounds

Lithium supplies should be adequate but cobalt and nickel could be concerns

	Cumulative Li Demand to 2050 (MT)
Large batteries, no recycling	6.5
Smaller batteries, no recycling	2.8
Smaller batteries, recycling	2.0
	Reserve Estimates
USGS Reserves*	13
USGS World Resource*	29
Other Reserve Estimates	30+

*Revised January 2011: http://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2011-lithi.pdf

Material	Availability (MT)	Cumulative Demand	%	Basis
Co	13	1.1	9	World reserve base
Ni	150	6	4	World reserve base
Al	42.7	0.2	0.5	US capacity
Iron/ steel	1320	4	0.3	US production
P	50,000	2.3	~0	US phosphate rock production
Mn	5200	6.1	0.12	World reserve base
Ti	5000	7.4	0.15	World reserve base



Tables from: L. Gaines and P. Nelson, *Lithium-Ion Batteries: Examining Material Demand and Recycling Issues*, TMS Annual Meeting (2009); Graphic from *Critical Materials Strategy,* U.S. Department of Energy (2011)

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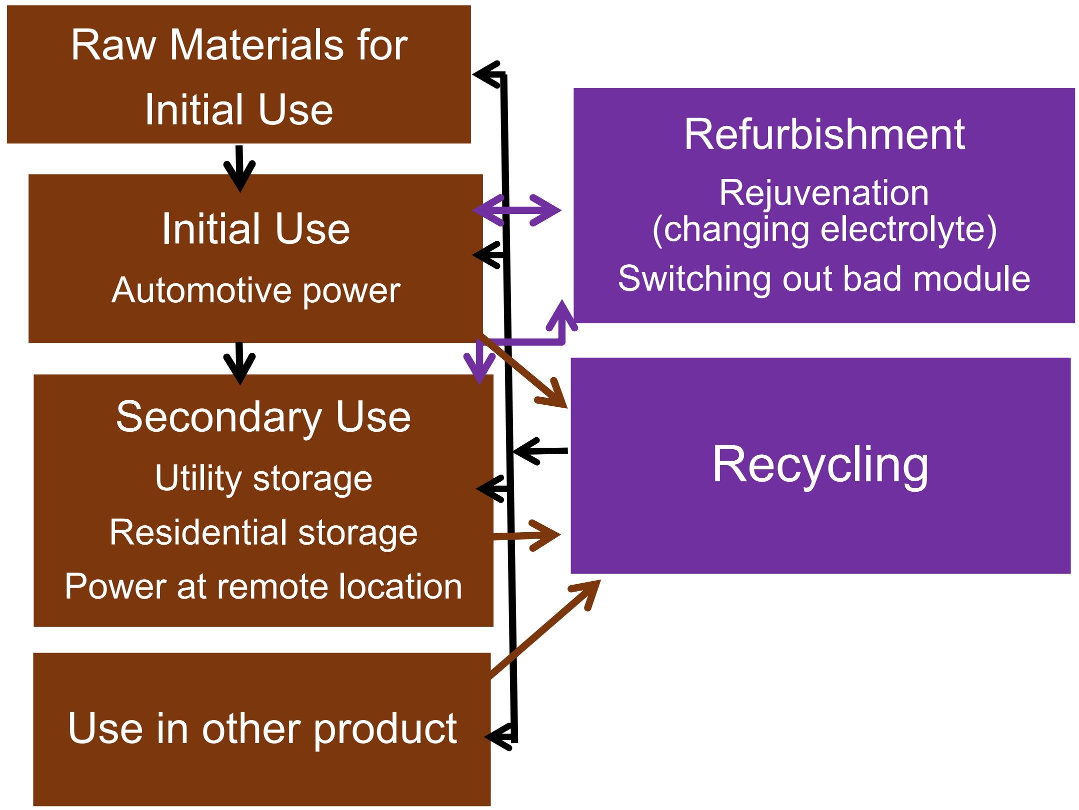
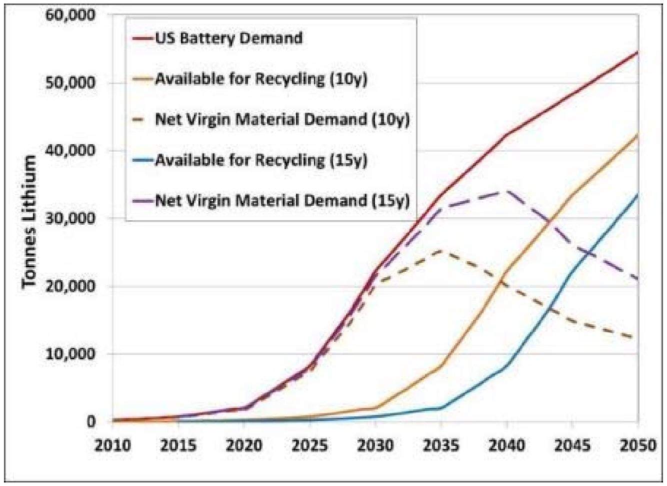
Materials could get used multiple times before recycling



Can the battery be reused?

- **Discarded automotive propulsion battery may retain 80% capacity**
- **Suitable for utility and other lower-performance uses**
- **Impacts per use are reduced**
- **Several companies refurbish and resell used EV and HEV batteries**
- **Large-scale economics under scrutiny**
  - Testing needed for high reliability
- **Battery will eventually be unsuitable for reuse and then can be recycled**
  - Reuse will delay return of material
  - Reuse could reduce material quality
  - There will be a lot of material!



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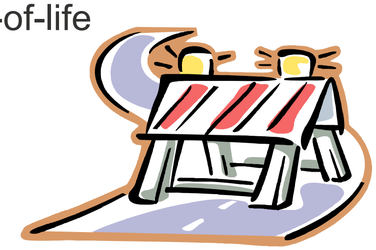
Lifecycle analysis evaluates process impacts

of a product's life cycle, from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal if any.

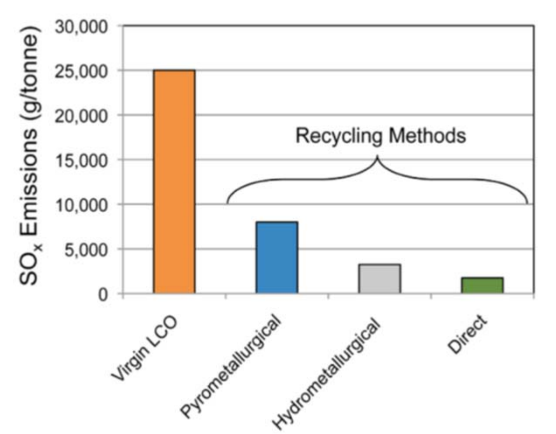
- Purpose is to clear the road for petroleum displacement via battery-powered vehicles by identifying potential roadblocks
- Availability of recycling processes can:
  - Assure against major waste problems at end-of-life
  - Reduce environmental impacts
  - Reduce raw material supply issues
  - Reduce net material costs
  - Create viable business opportunities



- Economic and institutional constraints must also be included
- Argonne is building a model to compare impacts and costs of different recycling processes
  - And developing a rating system to compare environmental performance of different batteries

Recycling minimizes battery impacts

- **Aluminum and cathode dominate battery production energy**
  - Recycled materials take less energy to make
  - More materials recycled means more energy saved
  - Recovery in form near final use maximizes value
- **Batteries are small contributors to energy use and CO_2 emissions**
- **But cathode makes significant emissions**
  - Especially if it contains Co or Ni
  - Recycling reduces burden



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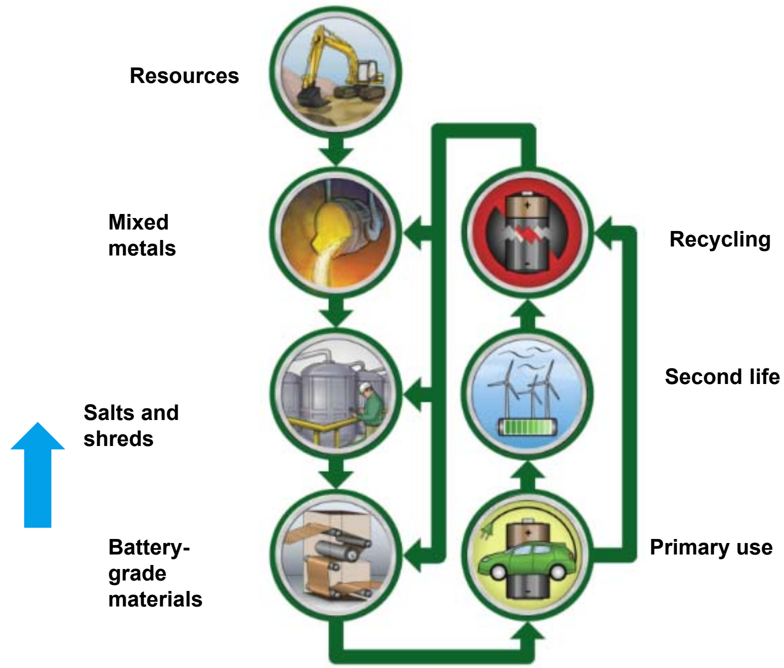
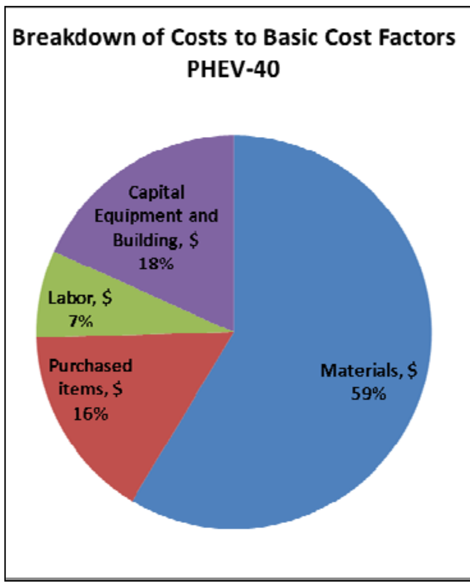
Product Value and energy saved increase to final product

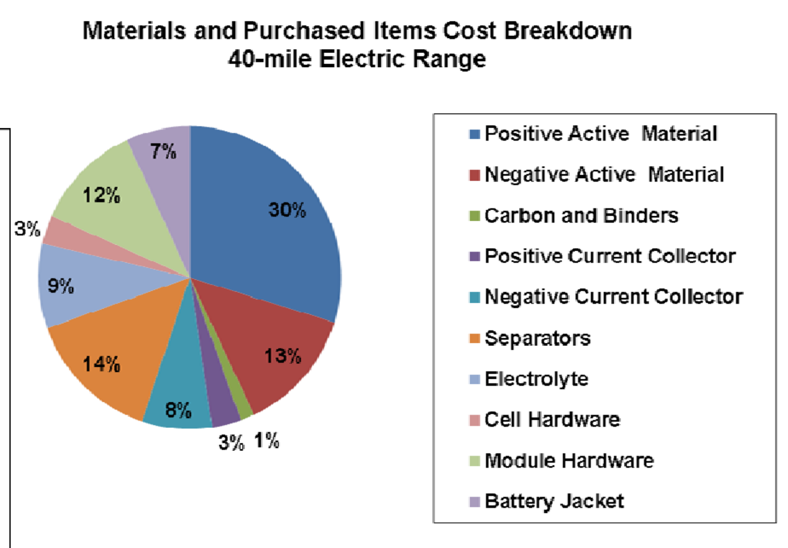
Second life gives 2 uses for 1 set of impacts



Materials dominate battery cost

Cathode is by far the largest contributor to recover



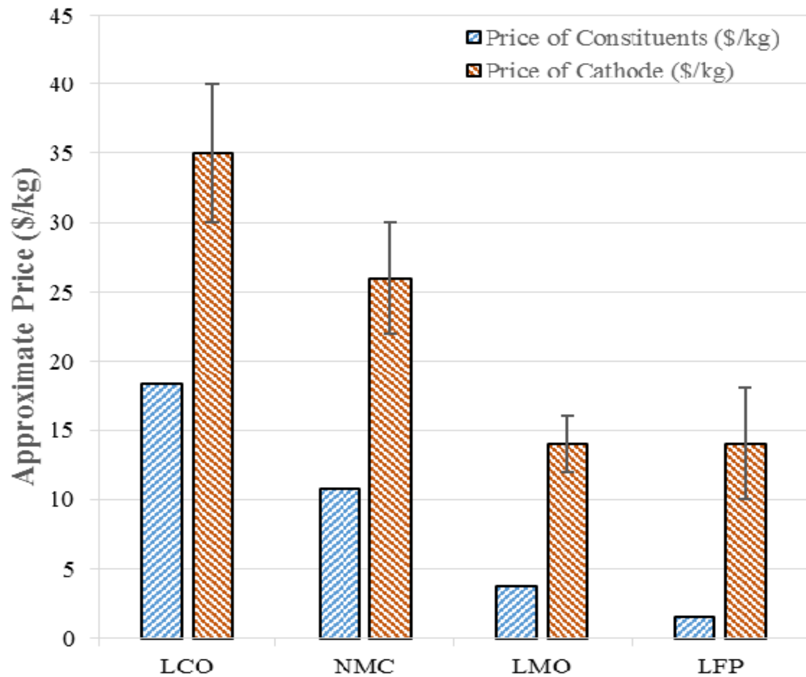


Source: K. Gallagher, Argonne, *Cost of batteries for energy storage today, in the future, and origin of cost goals: a description of cost analysis tools* (11/3/2015)

Cathode viability is key to economics

for cathodes with low elemental values

Cathode materials are valuable, even if constituent elements aren’t



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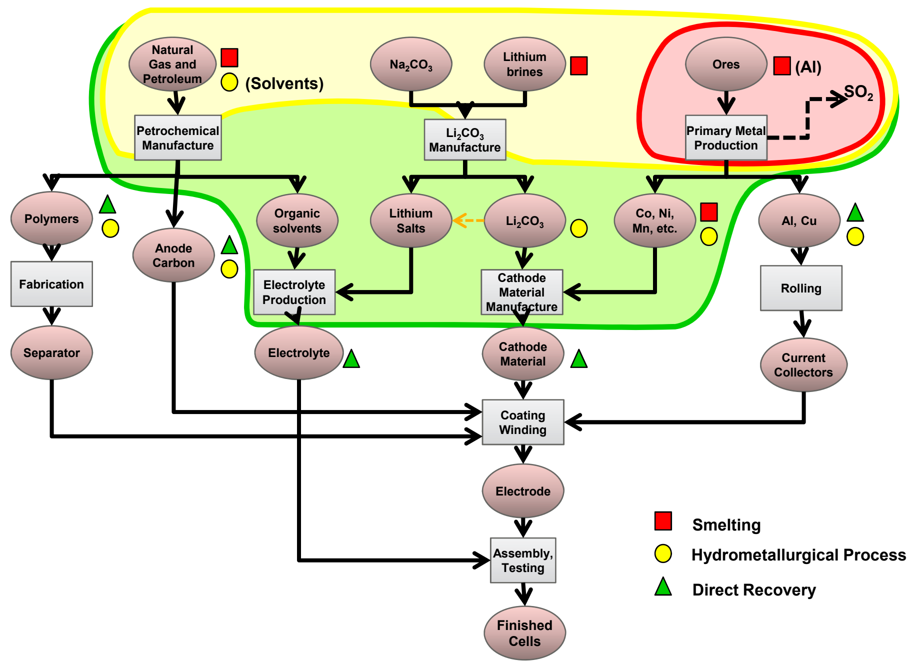
RECYCLING PROCESSES DISPLACE MATERIALS AT DIFFERENT PRODUCTION STAGES



Smelting avoids some ore processing

Pyrometallurgical process commercial in Belgium

High-temperature required

Organics are burned

Valuable metals are recovered

- Co, Ni, Cu separated by leaching
- Economics depends on them
- Not available from new chemistries

Li, Al go to slag

Flexible process input

Requires high volume

Extensive and expensive gas treatment

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DOE FUNDED A LARGE-FORMAT BATTERY RECYCLING FACILITY

Hydrometallurgical process is in operation

Several companies are active in this area

Retriev recycles Ni-MH and Li-ion batteries in Ohio

Undisclosed process was to produce battery-ready materials

From Ni-MH batteries
- Rare earths
- Nickel

From Li-ion batteries (possible)
- Anode materials
- $LiCoO_2$
- $LiFePO_4$
- Electrolyte (EC, EMC, DC)

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Initial operation recovers metals

Could recover Li_2CO_3

Insufficient feed material available, no buyer for cathode material

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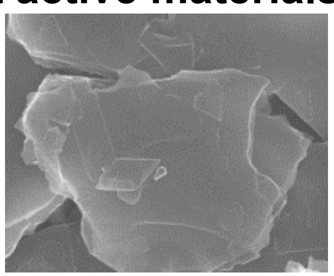
Recovery of battery-grade materials avoids impacts of virgin material production

Physical process proven on bench scale

- Direct recycling demonstrated for several chemistries
- Components separated to retain valuable material structure
- Requires uniform feed so prompt scrap is ideal
- Low-temperature process
- Does not require large volume
- But active materials might be degraded or obsolete



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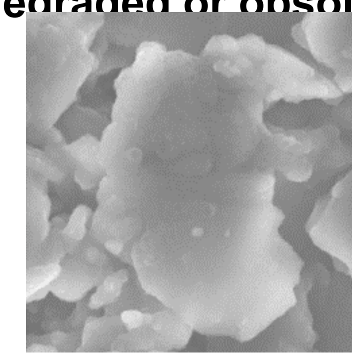

Figures from Daniel Abraham, Argonne

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Available processes recover different products

	Pyrometallurgical	Hydrometallurgical	Physical
Temperature	High	Low	Low
Materials recovered	Co, Ni, Cu (**Li and Al to slag**)	Metals and salts, Li_2CO_3	**Cathode**, anode, electrolyte, metals
Feed requirements	None	Separation desirable	Single chemistry required
Comments	New chemistries yield reduced product value	New chemistries yield reduced product value	Recovers potentially high-value materials; Could implement on home scrap

Why be Concerned about separation?

association of battery RECYCLERS

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SAE Battery Recycling Committee is addressing the issues

Completed RP on preventing cross-contamination

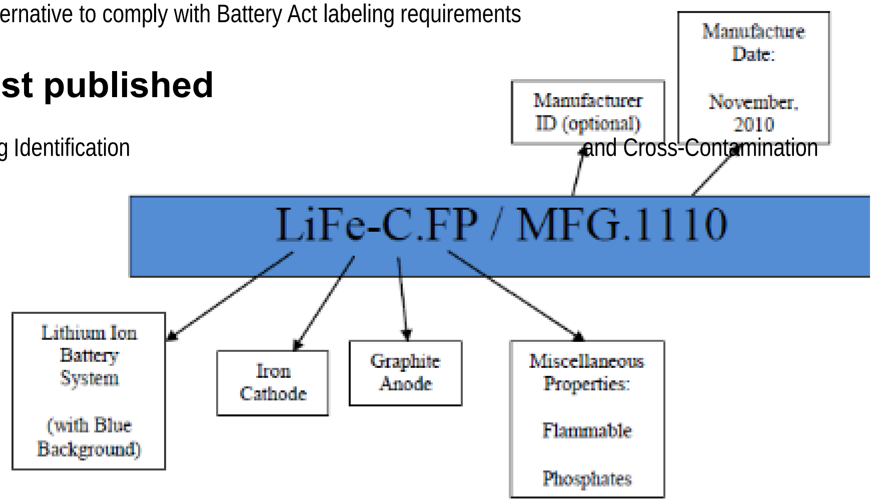
Diverse group has members from auto companies, battery makers, material suppliers, and recyclers

Addressed labeling in Document J2984

- Identification of Transportation Battery Systems for Recycling RP
- In discussion with EPA as alternative to comply with Battery Act labeling requirements

Document J3071 just published

- Automotive Battery Recycling Identification and Cross-Contamination Prevention



Source: SAE Document J2984, used with kind permission of the Society of Automotive Engineers

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Challenges to recycling can be addressed by R&D

Challenge	R&D needed to address
Long-term performance of some recycled materials is not proven	Long-term testing
There is no standard chemistry or design	Convergence of chemistries and designs Flexible processes Design for recycling Automation
There are no regulations, so restrictive ones could be imposed	Fashioning regulations that will protect health and safety without hindering recycling
Many of the constituents have low market value	Process development to recover multiple high-value materials
Low value of mixed streams, prevention of fires and explosions	Effective labeling and sorting

Thank you!

Dan Selke and Nakia Simon,
Session Organizers

Dave Howell,
DOE Vehicle Technologies Office