U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

US Department of Energy

Vehicle Technologies Program

Overview of Battery R&D Activities

May 15, 2012

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VTP Battery R&D

MISSION: Advance the development of batteries to enable a large market penetration of hybrid and electric vehicles to achieve large national benefits.

Vehicle Types and Benefits

HEV

Toyota Prius → ~50 MPG
- 1 kWh battery
- Battery Power Rating: 25kW
- Battery Cost: about $1,200

PHEV

Chevy Volt → ~100 MPGe
- 16 kWh battery
- Battery Power Rating: 120kW
- Battery Cost: about $10,000

EV

Nissan Leaf → All Electric
- ≥ 24 kWh battery
- Battery Power Rating: ≥ 110kW
- Battery Cost: about $15,000

- **Battery affordability and performance are the keys. Program targets include:**
  - Increase performance (power, energy, durability)
  - Reduce weight & volume
  - Increase abuse tolerance
  - LOWER COST!
- **2015 GOAL: Reduce the production cost of a PHEV battery to $300/kWh (70% below 2008 value)**
- **EV Everywhere: Reduce the production cost of an EV battery to $125/kWh by 2022**

Commercialization Activities and Notable Accomplishments

- Nickel Metal Hydride
  - Cobasys NiMH technology: Every HEV sold uses intellectual property developed in the DOE battery program. The US Treasury received royalty fees.
- High Power Lithium-Ion (HEVs)
  - JCS nickelate technology: BMW, Mercedes and Azure Dynamics /Ford Transit Connect
- High Energy Lithium-Ion (EVs)
  - A123Systems nano iron phosphate technology: Fisker, BAE, and Hymotion's Prius, GM Spark
  - CPI/LG Chem manganese technology: GM Volt extended range PHEV & Ford Focus EV

Commercial Applications

COBASYS → Prius, Escape, Fusion

Johnson Controls / SAFT → Mercedes S400 HEV

A123 SYSTEMS → Fisker PHEV

cpi compact power, inc / LG Chem → Chevy Volt PHEV

Commercialization Activities and Notable Accomplishments

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Science with an Impact

POLYPLUS

SEEO

ActaCell

pellion TECHNOLOGIES

SAKTI3

CMC Computational Modeling Consultants, Inc.

Wasatch Molecular INCORPORATED

Licensing of Patents Generated using BATT Funding

nanoexa

envia SYSTEMS

BASF The Chemical Company

GM

TODA KOGYO CORP.

Major Technical Challenges and Barriers

Barrier/Challenge	Potential Solutions
Reduce cost Next Generation lithium ion (e.g., high capacity cathodes)	❑ Improve material and cell durability ❑ Improve energy density of active materials ❑ Improved manufacturing processes ❑ Improved design tools/design optimization
Improve abuse tolerance	❑ Non-flammable electrolytes ❑ High-temperature melt integrity separators ❑ Advanced materials and coatings ❑ Battery cell and pack level innovations such as improved sensing, monitoring, and thermal management systems
Significantly increase energy density ❑ 3rd generation lithium-ion (e.g., silicon anode) ❑ Lithium-Sulfur ❑ Lithium-air	❑ Develop ceramic, polymer, and hybrid structures with high conductivity, low impedance, and structural stability ❑ Improved electrolyte/separator combinations to reduce dendrite growth

VTP Energy Storage R&D: FY 2012

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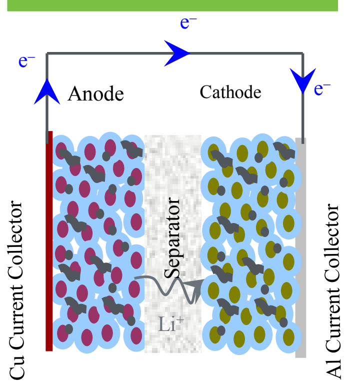
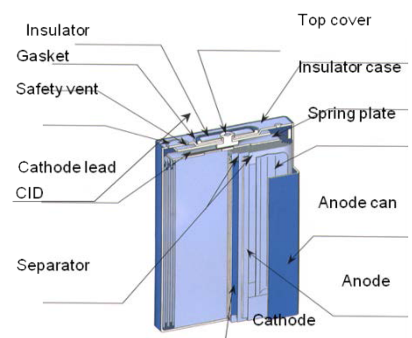
Energy Storage R&D
$93M

Exploratory Materials Research $26M	Applied Battery Research $16M	Battery Development $39M	Testing, Analysis & Design $12M





Exploratory Materials Research	Applied Battery Research	Battery Development	Testing, Analysis & Design
New Materials Research Diagnostics & Modeling	Electrochemistry Optimization Power & Capacity Life, Improvement	Next Generation Cell Development Performance & Cost Reduction	Standardized Testing Life/Cost Projections Design Tools

VTP Battery Development

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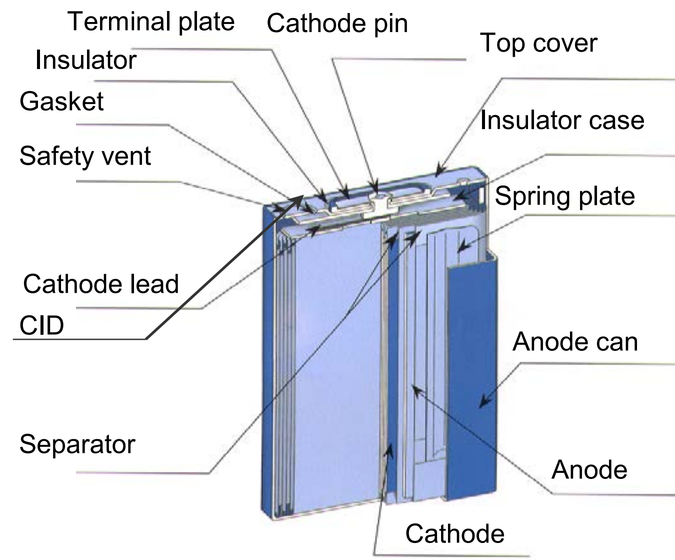
Battery Performance Targets

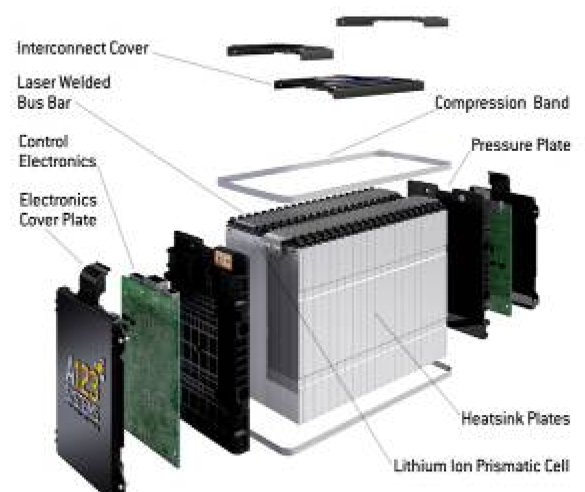
❑ EV	$125/kWh (2020)
❑ PHEV40	$300/kWh (2015)
❑ HEV	$20/KW (2010)

Battery Cell/Pack Development

- ❑ Material Specifications & Synthesis
- ❑ Electrode Design, Formulation & Coating
- ❑ Cell Design/Fabrication
- ❑ Module & Pack Design/Fabrication
- ❑ Battery Control & Safety Devices
- ❑ Detailed Cost Modeling

A123 SYSTEMS · ENVIA SYSTEMS · Maxwell TECHNOLOGIES · QUALLION · Johnson Controls · ActaCell · SK energy · CELGARD · COBASYS · K2 Energy · LG Chem · ENTEK INTERNATIONAL





(Used with permission)

PHEV Battery Performance Status

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Battery Technical Targets/Status

Data based on the results of the initial PHEV battery development contracts awarded by USABC to A123Systems, LGChem, and Johnson Controls

DOE Energy Storage Targets	PHEV (10 mile AER)		PHEV(40 mile AER)	
	Target	Status (2011)	Target	Status (2011)
Discharge Pulse Power: 10 sec (kW)	45	~70	38	~95
Regen Pulse Power: 10 sec (kW)	30	~40	25	~70
Available Energy (kWh)	3.4	3.4	11.6	11.6
Calendar Life (year)	15	8-10	10+	8-10
Cycle Life (deep cycles)	5,000	3,000-5,000	5,000	3,000-5,000
Maximum System Weight (kg)	60	~57	120	~175
Maximum System Volume (l)	40	~45	80	~100
System Production Price (@100k units/year)	$1,700	~2,600	$3,400	~6,850

EV Battery Performance Status

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Battery Performance Status

- Initial EV battery development contracts started in FY2011
- Focus on high voltage/high capacity cathodes & EV cell design optimization
- Data based on initial work from USABC Envia Systems & Cobasys/SBLimotive contracts

Energy Storage Goals	AEV (2020)	Current
Equivalent Electric Range, miles	200-300	✓
Discharge Pulse Power (10 sec), kW	80-120	✓
Regenerative Pulse Power (10 sec), kW	40	✓
Available Energy, kWh	40-60	✓
Recharge Rate, kW	120	50
Calendar Life, years	10+	TBD
Cycle Life, cycles	1,000 deep cycles	TBD
Operating Temperature Range, ^{o}C	-40 to 60	0 to 40
System Weight, kg	160-240	500-750
System Volume, liters	80-120	200-400
Production Cost (@100,000 units/year)	$125/kWh	< $600

New Awards from FY2011 FOA

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- Various companies recently awarded to develop advanced Lithium-ion cells and manufacturing processes which would reduce cost
- Each award: $2M - $5M

Awardees

Battery Cells (>300 Wh/kg and >500 Wh/l)	**Low-cost Processing and Design 2x cost reduction (<$400/kWh)**
Amprius, Inc.	Johnson Controls (Maxwell/Entek)
Dow Kokam (Dow Chemical/ORNL)	Miltec UV Int. (ANL/ORNL)
Nanosys, Inc. (LG Chem)	A123 Systems (Maxwell)
3M Company	Applied Materials (LBNL/ORNL)
Seeo, Inc.	DENSO Int'l America (NREL)
Penn. State University (ANL/JCI)	Optodot Corp (Dow Kokam, URI, Madico, ISP)

R&D Highlights: Industry

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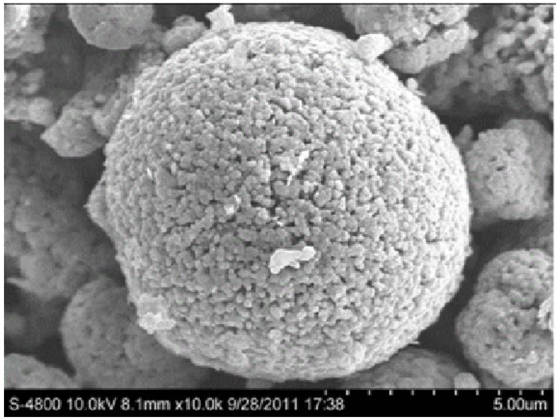
High Specific Energy Cathodes (Envia Systems)

- High Specific Energy Cell
  - Cathode – high capacity layered-layered
  - Anode – graphite
  - Successfully scaled-up cathode material and built large capacity cells (20Ah)
  - Achieved over 200 Wh/kg
- ARPA-E award to develop very high capacity silicon-carbon anode
  - Record-setting cell specific energy (>400 Wh/kg).

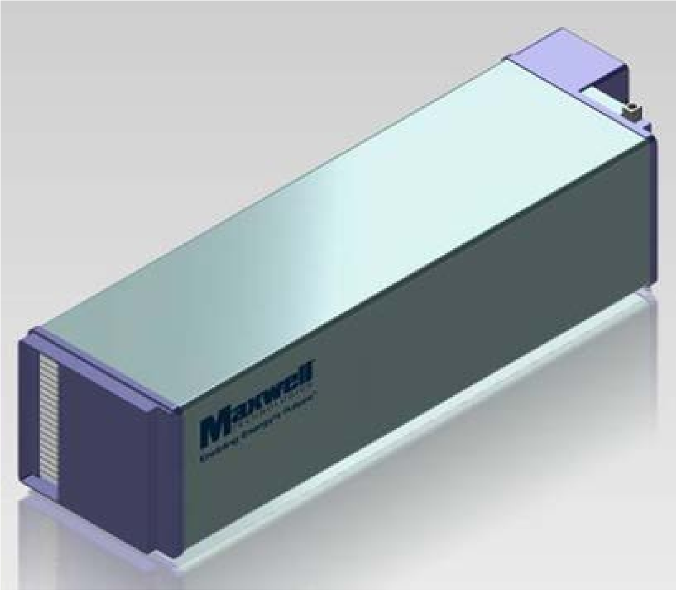


SEM image of cathode #8 used in cell build #2

Envia Systems 45Ah cells

Ultracapacitor Development (Maxwell Technologies)

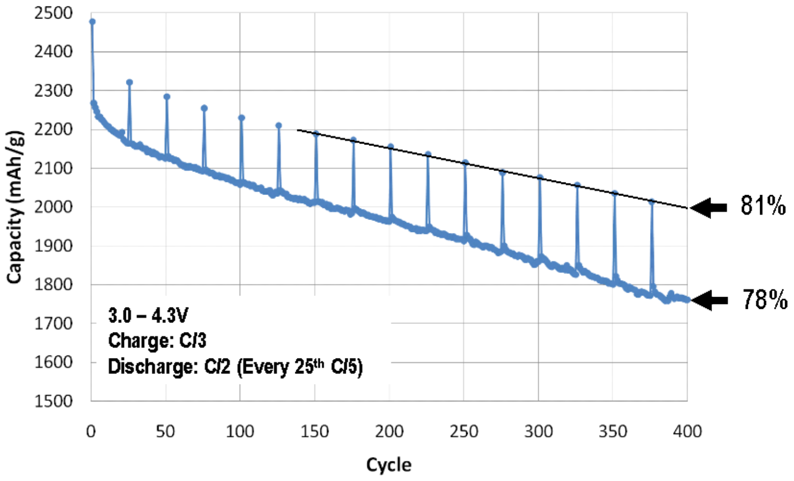
- Ultracapacitor system for power assist HEVs.
  - Developed 250 Farad prismatically-wound cells using patented dry film electrode coating process.
  - 20% reduction in volume and 17% reduction in cost (over baseline cells).
  - Good low temperature performance at -30°C.
- Developed asymmetric capacitor in small laboratory-sized cells using dry film process
  - Cycled at higher voltages than current ultracapacitors.



Proposed pack design including all cells, electronics, and thermal management

Minnesota Mining and Manufacturing Co. (3M)

- Developed very high capacity silicon alloy composite anode materials with high cycle-life
- Si-based alloy design
- Specific capacity of 2,300 mAh/g and Volumetric Capacity of 1500 mAh/cc after full lithiation and expansion
- 3M plans to commercialize this material.



Capacity retention for 18650 cell using 3M alloy, L-20772, in 2:1 blend with graphite.

Battery Materials and Cell R&D

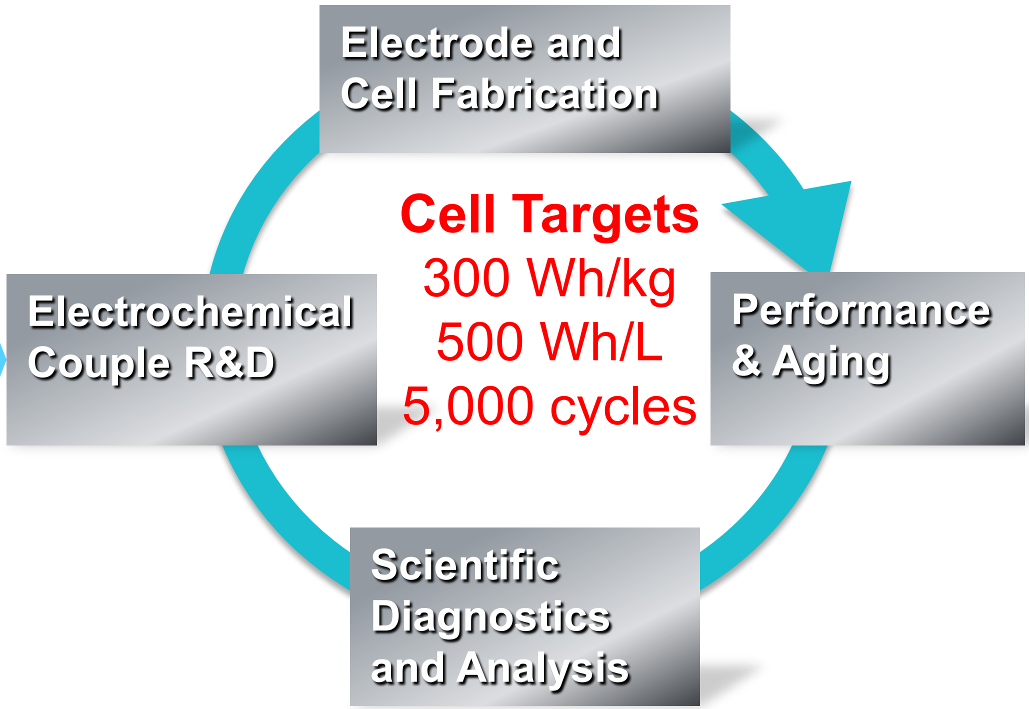
Goal: develop and expedite commercialization of advanced materials for electric drive vehicle batteries

Materials Research

Advanced Anodes (600 mAh/g)

Advanced cathodes (300+ mAh/g)

Next Generation Electrolytes (5 volt)

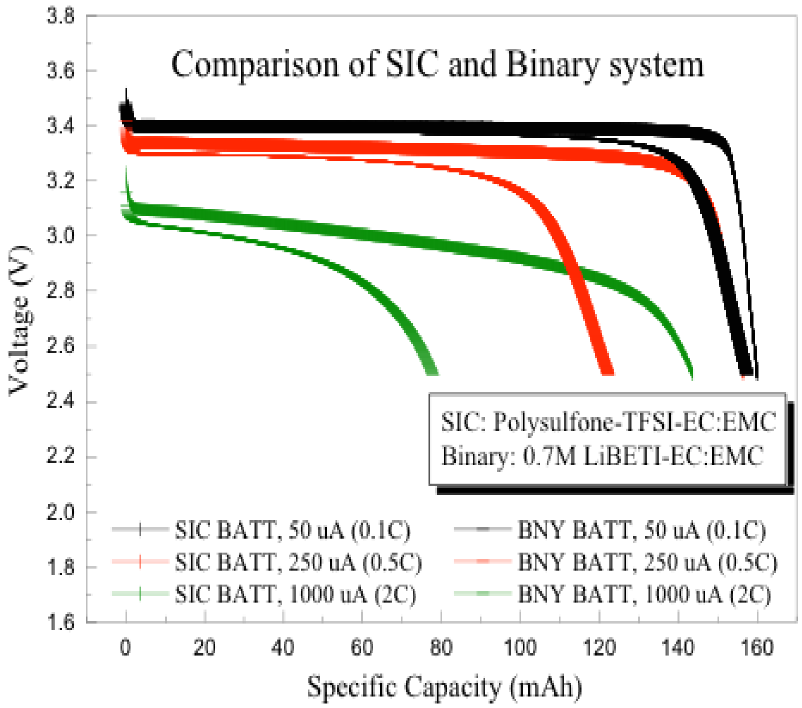


Argonne National Laboratory · Brookhaven National Laboratory · INL Idaho National Laboratory · Berkeley Lab · NREL · Oak Ridge National Laboratory · Sandia National Laboratories · Pacific Northwest National Laboratory

Supports R&D at 19 different Universities and 16 different Industry partners

High Voltage Single-ion Conducting Electrolytes (LBNL)

- High voltage single-ion conductor (SIC) gel electrolytes based on a polysulfone/carbonate blend:
  - Reduces impedance against lithium metal by an order of magnitude.
  - Potential to use as binder to enable thicker electrodes
- Stable at high voltages up to at least 4.5V
  - Stable with several high energy cathodes, including the spinel–type and composite cathodes.



Discharge capacity as a function of rate comparison for single ion conductors versus binary salt electrolytes

R&D Highlights: National Laboratories

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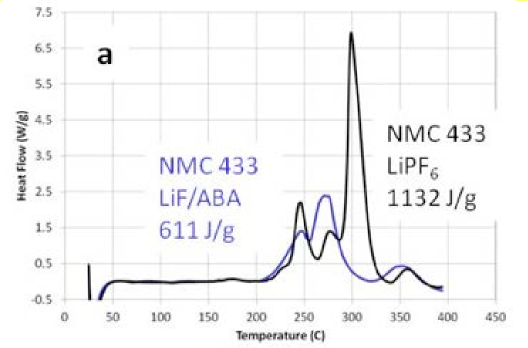
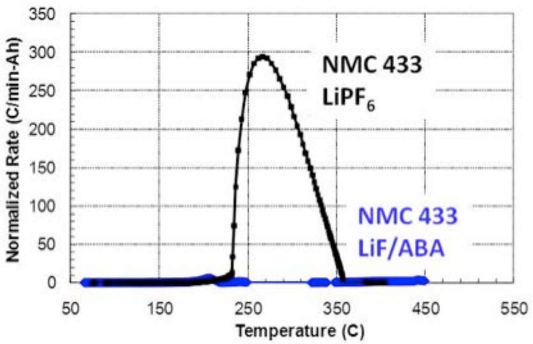
Lithium Fluoride-Anion Binding Agent Electrolytes (SNL)

- For enhanced abuse tolerance
- Significant improvements in the thermal stability of cathodes in Lithium Flouride/anion binding agent electrolytes
- Improvements in cell runaway response with the same electrolytes
  - The specific heat measured for a NMC433 cathode was reduced almost 50% : from 1132 J/g with $LiPF_6$ to 611 J/g using LiF/ABA
- Collaboration with Binrad Industries.



DSC profiles of NMC433 at 4.3 V in 1.2 M $LiPF_6$ in EC:EMC (3:7) and 1.0 M LiF/ABA in EC:EMC (3:7)



ARC profiles for NMC433 18650 cells in 1.2 M $LiPF_6$ in EC:EMC (3:7) and 1.0 M LiF/ABA in EC:EMC (3:7) at 4.3 V

R&D Highlights: National Laboratories

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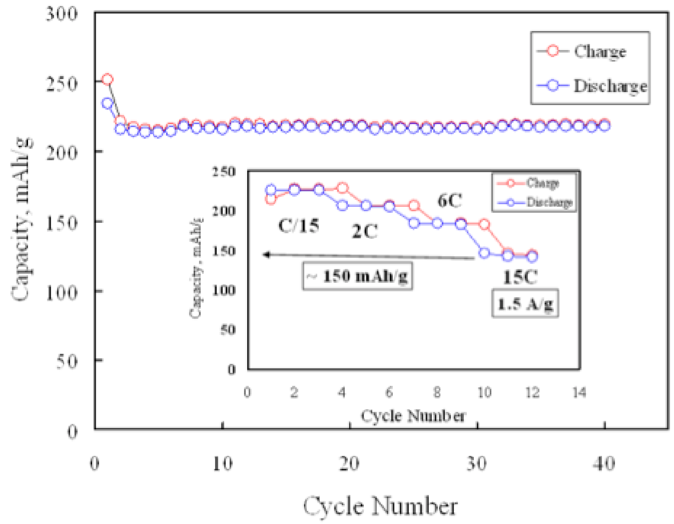
High-Energy Composite Cathode Materials (ANL)

- Li-ion exchange of the layered Na phases ($Na[M]O_2$) used to minimize site disorder in cathodes of layered oxides ($LiMO_2$) found to cost effectively produce high energy, and high rate cathode materials.
- This new material shows excellent energy density
  - Increase from ~150 mAh/g at 3.7 V to >220 mAh/g at 4.8V
  - The material retains 150 mAh.g capacity at 15C rate (inset chart)



Capacity versus cycle number (15 mA/g), and inset is the capacity versus current rate, of Li/IE-LNMO cell between 4.8V and 2.0V.

R&D Highlights: National Laboratories

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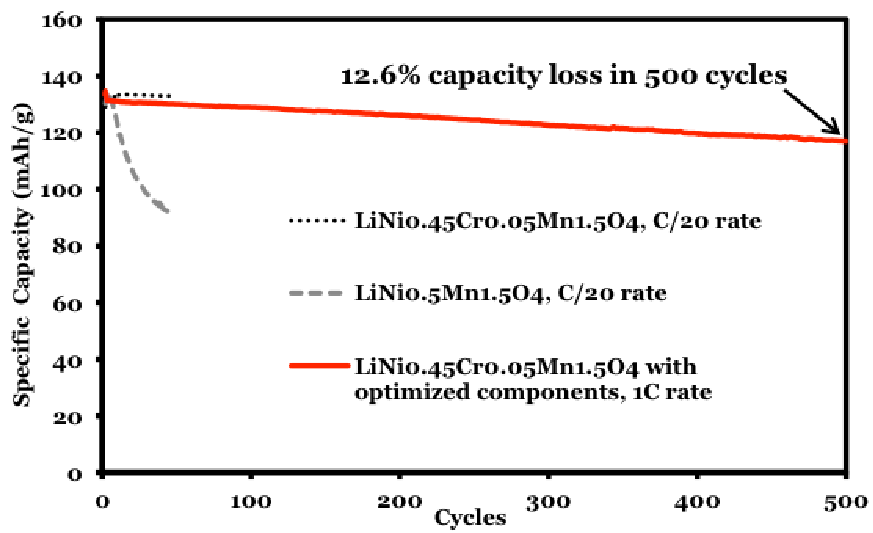
Improved Doped High-Voltage Spinel Cathodes (PNNL)

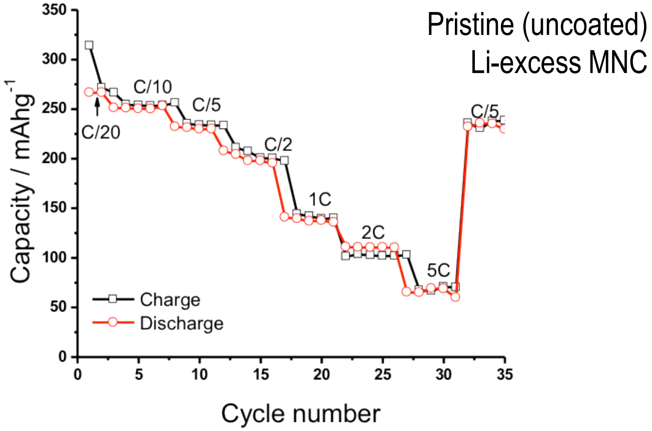
- Chromium-doped high-voltage spinel, $LiNi_{0.45}Cr_{0.05}Mn_{1.5}O_4$, which exhibits stable cycling and greatly improved efficiency.
  - Low concentrations of LiBOB improve its first-cycle efficiency , from 76% to 85%, and the rate capability increases.
  - Improvement in the Coulombic efficiency and cycling stability occur as well.

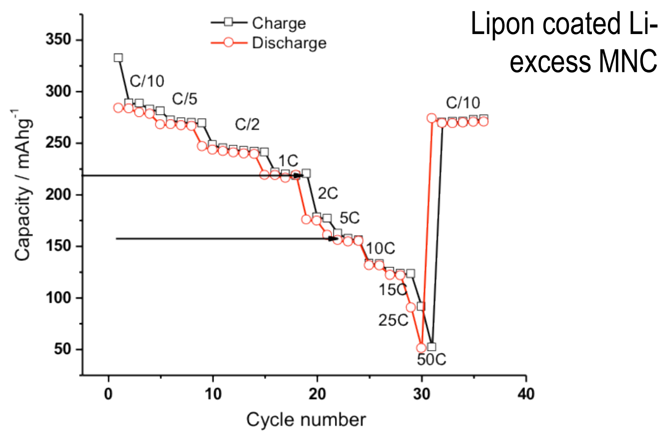


Comparison of cycling stability for $LiNi_{0.5}Mn_{1.5}O_4$ (dashed line) and $LiNi_{0.45}Cr_{0.05}Mn_{1.5}O_4$ (dotted line). $LiNi_{0.45}CrMnO$ tested with optimized electrolyte and other components exhibits excellent stability (solid line)

High-Energy Lithium-rich Cathodes (ORNL)

- Surface coating of the high voltage lithium rich material shows improvement rate performance
  - $0.6Li_2MnO_3 \bullet 0.4Li [Mn_{0.3}Ni_{0.45} Co_{0.25}]O_2$ (~200 mAh/g at C/2)
  - a few nanometer thick layer of Lithium phosphorus oxynitride (Lipon)
  - Uncoated materials capacity retained 50% of its capacity from C/5 to 2C while the Lipon coated cathodes retained 80% of its capacity.
  - Lipon coated sample demonstrated repeatable cycling 120 mAh/g at 15C





Rate Performance Comparisons at 25°C with similar electrode composition (85% active materials, 7.5 % PVDF and 7.5 % carbon (Timcal Super C65))

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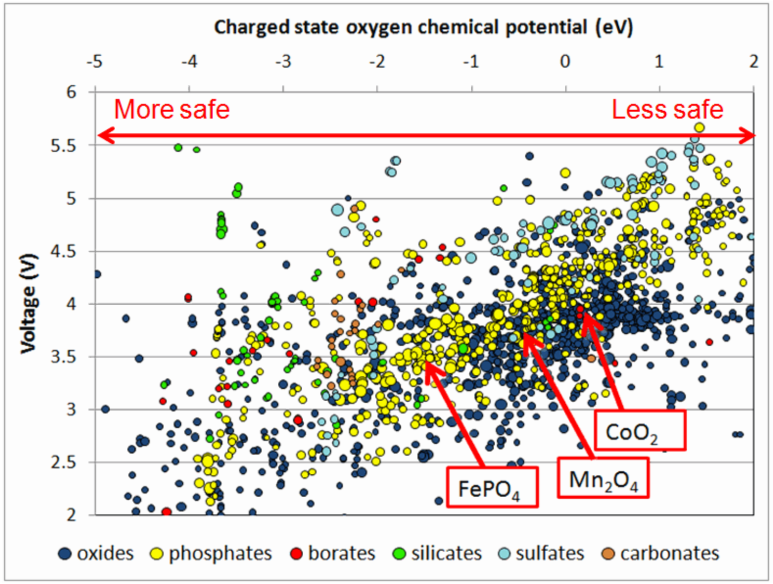
Materials Search Engine (LBNL/MIT)

- A Google-like materials search engine
  - Over 15,000 computed compounds.
  - Searchable access to general materials properties.
  - 'Apps' designed to aid in materials design for specific application areas such as Li-ion battery technology.
  - Available at LBNL website



Sample graph of a portion of the 15,000 compounds contained in the materials project database

Major R&D Achievements (2009–2011)

- Lithium-ion battery cost reduction on track (USABC)
  - Production cost reduced to ~$650/kWh for 100,000 packs/year
- Lifetime of lithium-ion batteries extended (USABC/Labs)
  - up to 10-15 years for some technologies
  - 3,000-5,000 deep discharge cycles
- Cathode technology for Chevrolet Volt battery (ANL)
  - Licensed to GM, LG Chem, BASF, Toda America, Envia
  - Focused R&D effort to solve remaining issues
- Significantly expanded R&D to develop Silicon Composite & Metal alloy materials and cells
- Research activity focused on beyond-Lithium-ion technology initiated

Recovery Act:
Battery Manufacturing

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Establish U.S. EDV battery manufacturing capacity

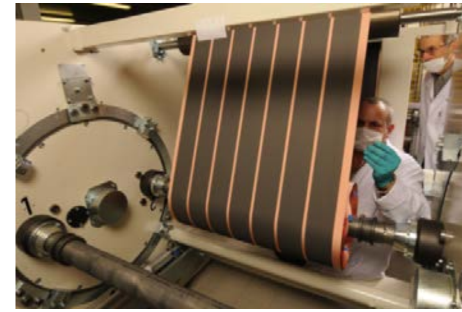
ARRA: $1.5B
INDUSTRY: $1.5B

Cell & Pack Production Capacity (10 kWh packs)

2008	0
2012	140,000
2015	500,000

~5M kWh / year

- **Johnson Controls:** cell production and pack assembly at in Holland, MI
- **A123Systems**: cathode, cell, & pack assembly in Livonia & Romulus, MI
- **EnerDel**: Cell production & pack assembly at Fishers & Mt Comfort, IN
- **General Motors**: battery pack assembly at Brownstown, MI
- **SAFT:** cell production at Jacksonville, FL
- **Exide:** advanced lead acid battery production established in Columbus, GA
- **East Penn:** Advanced Lead Acid battery production established in, PA
- **Dow Kokam:** cell & pack capability in Midland, MI in 2012
- **LG Chem:** cell & pack capability in Holland, MI in 2012



Toda America, Inc. Battle Creek Facility

A123Systems, Livonia Facility

Recovery Act:
Battery Manufacturing

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Progress

Materials Production

Cathode
- ❑ TODA: production established
- ❑ BASF: *Target: Commission in 4Q*

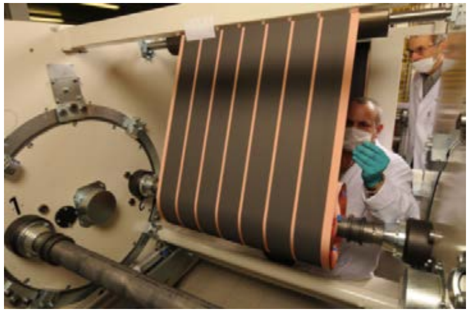
Anode
- ❑ EnerG2: production established
- ❑ FutureFuel: production established
- ❑ Pyrotek: production established

Separator
- ❑ Celgard: production established
- ❑ Entek: *Engineering scoping completed*

Electrolyte
- ❑ Honeywell: Li-salt pilot plant operational
- ❑ Novolyte: *Equipment installation*

Lithium
- ❑ Chemetall Foote: lithium hydroxide

Cell Hardware
- ❑ H&T Waterbury: production established



Toda America, Inc. Battle Creek Facility

A123Systems, Livonia Facility

Intra Government Collaborations

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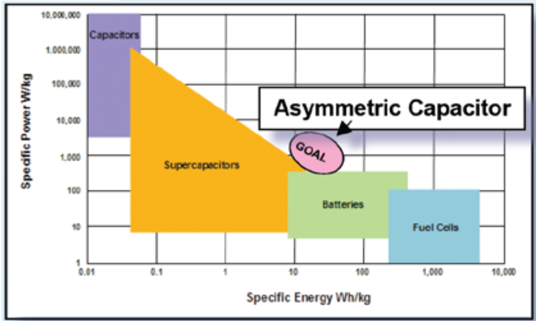
- Department of Transportation/NHTSA
  - Joint studies, working groups
  - Regulations for battery transportation
- Department of Defense
  - Tank Automotive Research, Development and Engineering Center (TARDEC)
  - U.S. Army Research Laboratory
  - Naval Surface Warfare Center/Carderock
- Environmental Protection Agency
  - Validated “BatPaC” a Lithium-Ion Battery Performance and Cost Model to support 2017-2025 CAFE and GHG regulations

Volt battery pack being prepared for test

Ultracapacitor Development

TARDEC

NHTSA



For Additional Information…

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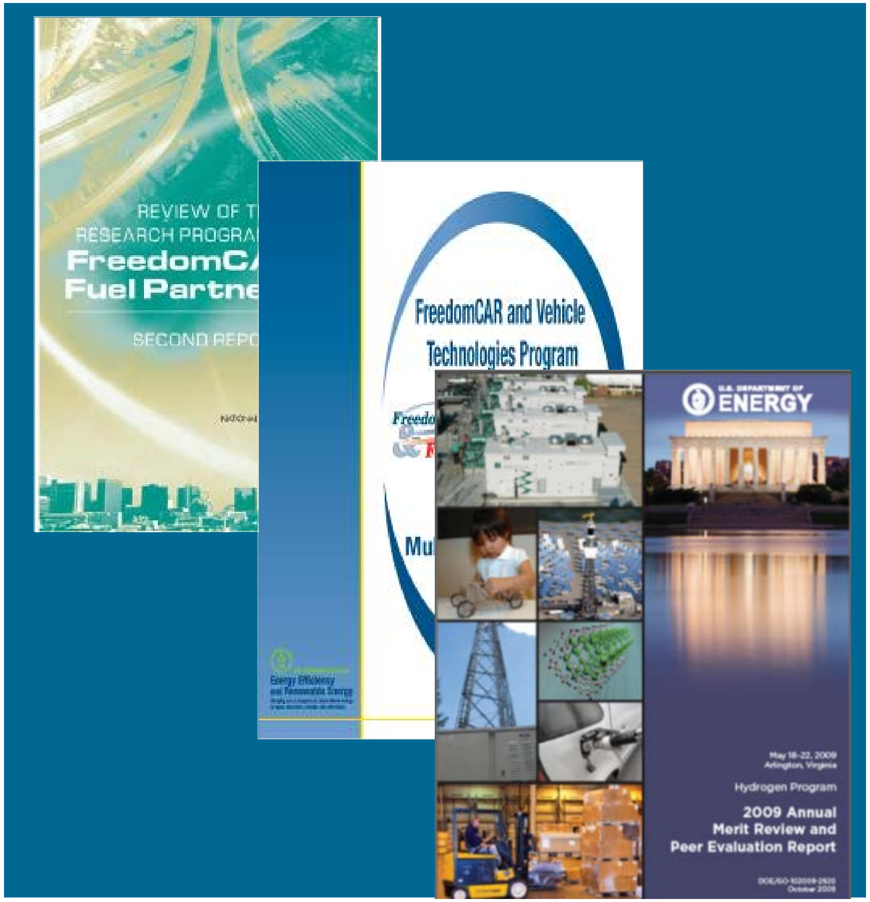

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