ARPA-E Electrical Energy Storage for Vehicles Post Workshop Summary

ARPA-E Background &

Workshop Introduction

Tuesday, November 3, 2009

L'Enfant Plaza Hotel, Washington, DC

What are we trying to achieve in today's workshop:

- **Deep dives** on high potential **technologies** to enable low cost, high performance EV batteries
- Identification of **key challenges and emerging opportunities** for these technologies
- Identification of high impact areas where ARPA-E programs can have a large **ADDITIONAL impact**

- Discussion of ARPA-E Battery Targets/Focus
  - Are the USABC Long Term EV Battery Goals appropriate?
  - Should ARPA-E be shooting for goals even beyond these?
  - Open new horizons in under-developed battery chemistries?
- Focus of ARPA-E vs DOE Office of Vehicle Technologies roles
- Best way to structure a $30-$45M, 3 year ARPA-E program
  - Fund multiple technology approaches?
  - Focus on one major technology challenge?

Starting Point: USABC Long Term Goals for EV Batteries

Parameters (units) of fully burdened System	USABC "Long Term Goal"
Power Density (W/L)	**600**
Specific Power- Discharge 80% DOD/30 sec. (W/kg)	**400**
Specific Power- Regen, 20% DOD/10 sec (W/kg)	**200**
Energy Density - C/3 Discharge Rate (Wh/L)	**300 (~600 cell)**
Specific Energy – C/3 Discharge Rate (Wh/kg)	**200 (~400 cell)**
Specific Power/Specific Energy Ratio	2:1
Total Pack Size (kWh)	40
Life (Years)	10
Cycle Life – 80% DOD (Cycles)	**1000**
Power and Capacity Degradation (% of rated spec)	20
Selling Price – 25k units @ 40kWh ($/kWh)	**$100/kWh ($230/kWh inflation adjusted)**
Operating Environment (^{o}C)	-40 to +85
Normal Recharge Time	3 to 6 Hours
High Rate Charge	40-80% SOC in 15 Minutes
Continuous discharge in 1 hour – No Failure (% of rated energy capacity)	75

Primary Questions Posed in Each Breakout Session

Technical approaches with promise to hit/exceed USABC Long Term EV Goals?

- What are the approaches with potential to hit/exceed USABC Long Term EV Goals? What is their potential performance?
- What is their current level of development/demonstration?
- What are the key technical challenges/barriers holding these approaches back? What needs to be improved/explored/solved? Promising approaches/areas?
- What are realistic paths to low cost with these approaches (toward $250/kWh packs)?

Secondary Questions for Each Breakout Session

- DOE Vehicle Technologies program focus on PHEV batteries vs ARPA-E focus on EV batteries appropriate?
- Major gaps in current U.S. battery funding?
- Are the USABC long term EV battery goals the right targets for ARPA-E? Should they be more aggressive?
- Levels of funding required over ~3 years for:
  - 1.) Proof of concept
  - 2.) Meaningful lab scale prototype
  - 3.) Meaningful demo of pilot manufacturing

Breakout Session #1: Beyond Lithium-Ion?

- Advanced Lithium-Ion Intercalation
  - Chair: Yet-Ming Chiang, MIT
- Non-Lithium Intercalation
  - Chair: Luis Ortiz, MIT
- Lithium-Metal (with intercalation cathodes)
  - Chair: Ilan Gur, Seeo
- Lithium-Sulfur
  - Chair: Tien Duong, DOE
- Lithium-Air
  - Chair: Steve Visco, PolyPlus

Breakout Session #2:
Non-Lithium Approaches, Manufacturing, Non-Active Components

- Zn-Air/Metal-Air

  Chair: Trygve Burchardt, Revolt

- Liquid Metal Approaches

  Chair: Reza Sarrafi-Nour, GE

- Novel Architectures/Manufacturing Processes
  - Chair: Harrold Rust, Microazure

- Advanced Supporting Components/Packaging (electrolytes, separators, packaging, etc)
  - Chair: Mark Jones, Dow

Breakout 1: Beyond Lithium-Ion?

- Advanced Lithium-Ion Intercalation
- Non-Lithium Intercalation
- Lithium-Metal (with intercalation cathodes)
- Lithium-Sulfur
- Lithium-Air

Breakout 1, Session 1: Advanced Lithium-Ion Intercalation

Key Question:

Can advanced lithium-ion battery approaches meet/exceed USABC long term EV battery goals in energy density?

Evaluation Approach:

- Take (intrinsic energy density) x (cell volume utilization, factor of 0.4) x (pack level utilization, factor of 0.6).
- Broaden definition of "intercalation compound" to include all high energy density electrode compounds that can be used in a conventional wound cell design.

Considered Intrinsic Energy of 3 Classes:

a) $LiCoO_2$ – graphite "like" baseline material: intrinsic energy is 380 Wh/kg, 1600 Wh/L

b) Current "championship" intercalation cathodes of 220 to 250 mAh/g reversible capacity used with silicon anode with 2000 mAh/g reversible capacity: intrinsic is 670 Wh/kg, 2000 Wh/L

c) Conversion reaction cathodes used with high capacity metal anodes: intrinsic is 900 Wh/kg, 4000 Wh/L

Breakout 1, Session 1: Advanced Lithium-Ion Intercalation

Achievable Cell and Pack Level Energy Density for Each Class:

a) 640 Wh/L cell, 385 Wh/L pack – misses USABC
b) 800 Wh/L cell, 480 Wh/L pack (just meets PHEV target of 500-800 Wh/L) – exceeds USABC
c) 1600 Wh/L cell, 960 Wh/L pack (comfortably meets PHEV target) – exceeds USABC

- The view is worth the climb…… Li-ion intercalation batteries hold the potential to exceed USABC long term EV battery energy density targets

Other Advantages:

- Low barrier to adoption.
- Well-understood cost curve.

Breakout 1, Session 1: Advanced Lithium-Ion Intercalation

Enablers and Challenges:

- Electrolytes to enable wider voltage and temperature window
  - Current approach is to form stable SEI – can one develop SEI-free systems
  - Coating of particles, now widely studied, is a way to pre-form the SEI
- Solid electrolyte that is also the separator and has 10^{-3} S/cm.
- Can conversion reaction compounds ever reach 6000 cycles at 80% DOD?
- Cost: With materials being 80% of cell cost, can intercalation compounds reach $0.10/Wh? The metric for active materials today is $/kg but it should be something else, at least $/Ah.

Breakout 1: Beyond Lithium-Ion?

Advanced Lithium-Ion Intercalation

Non-Lithium Intercalation

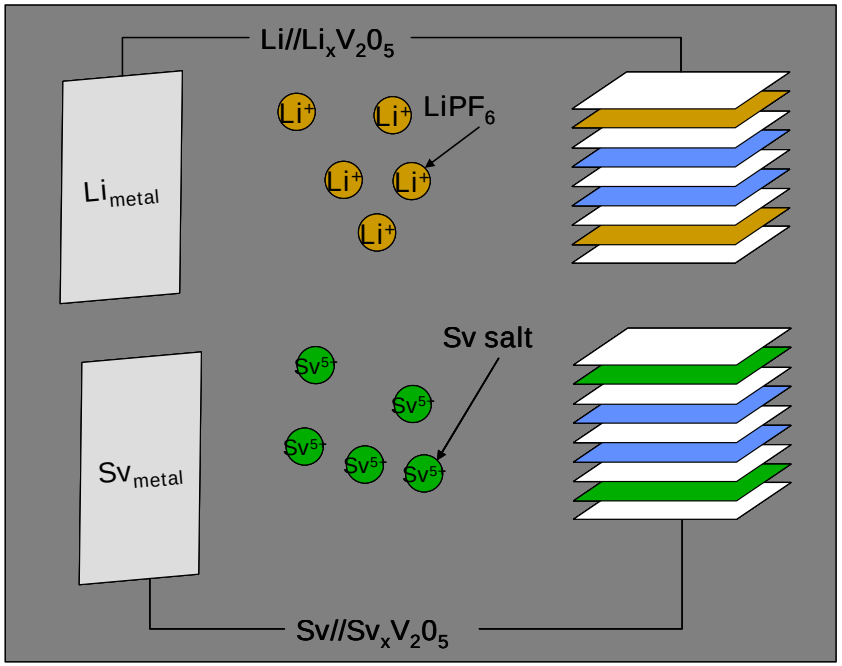
Lithium-Metal (with intercalation cathodes)

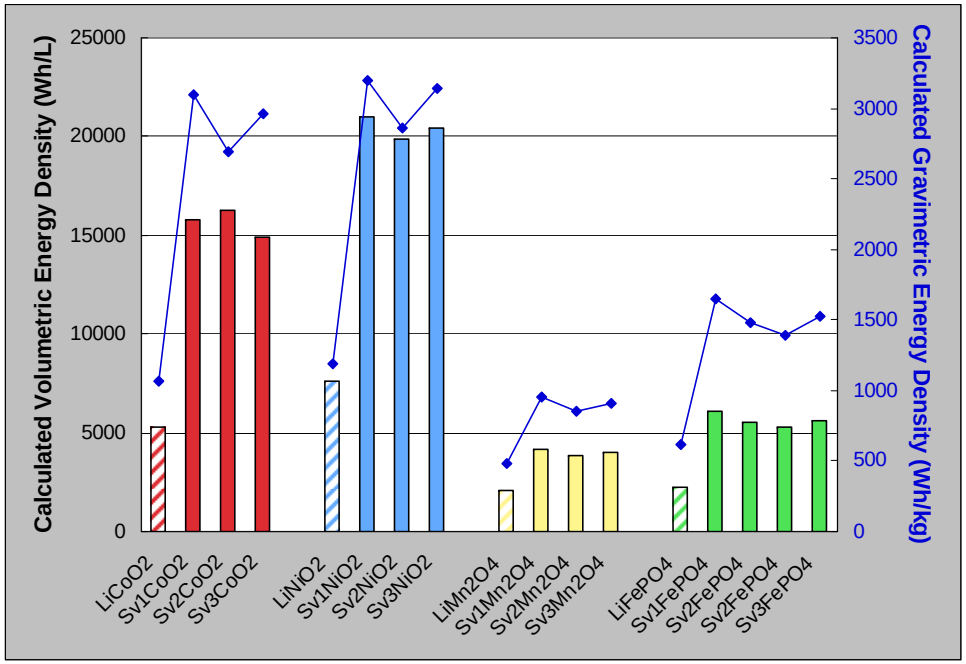
Lithium-Sulfur

Lithium-Air

Breakout 1, Session 2: Non-Lithium Intercalation

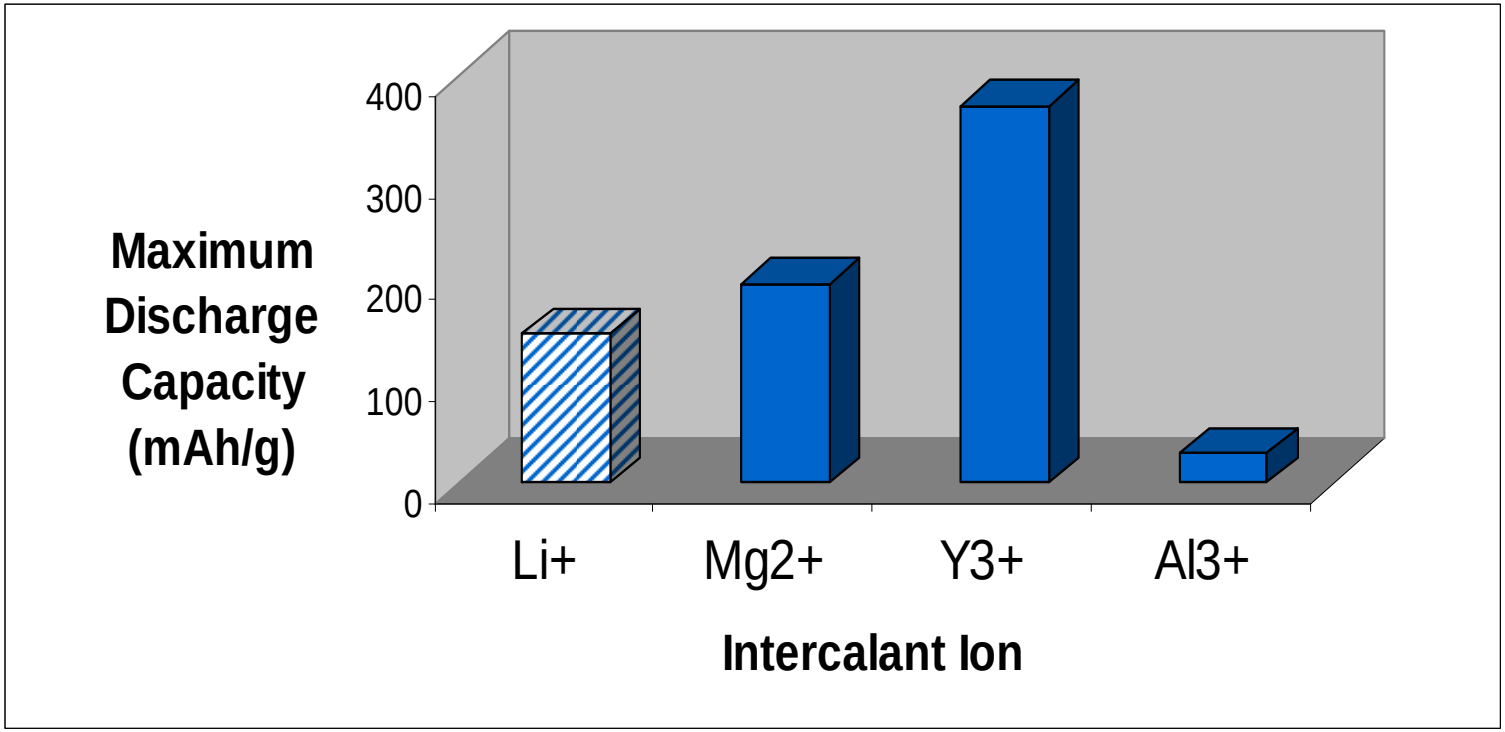
Can non-lithium based intercalation compounds to meet/exceed the long term USABC EV battery targets?





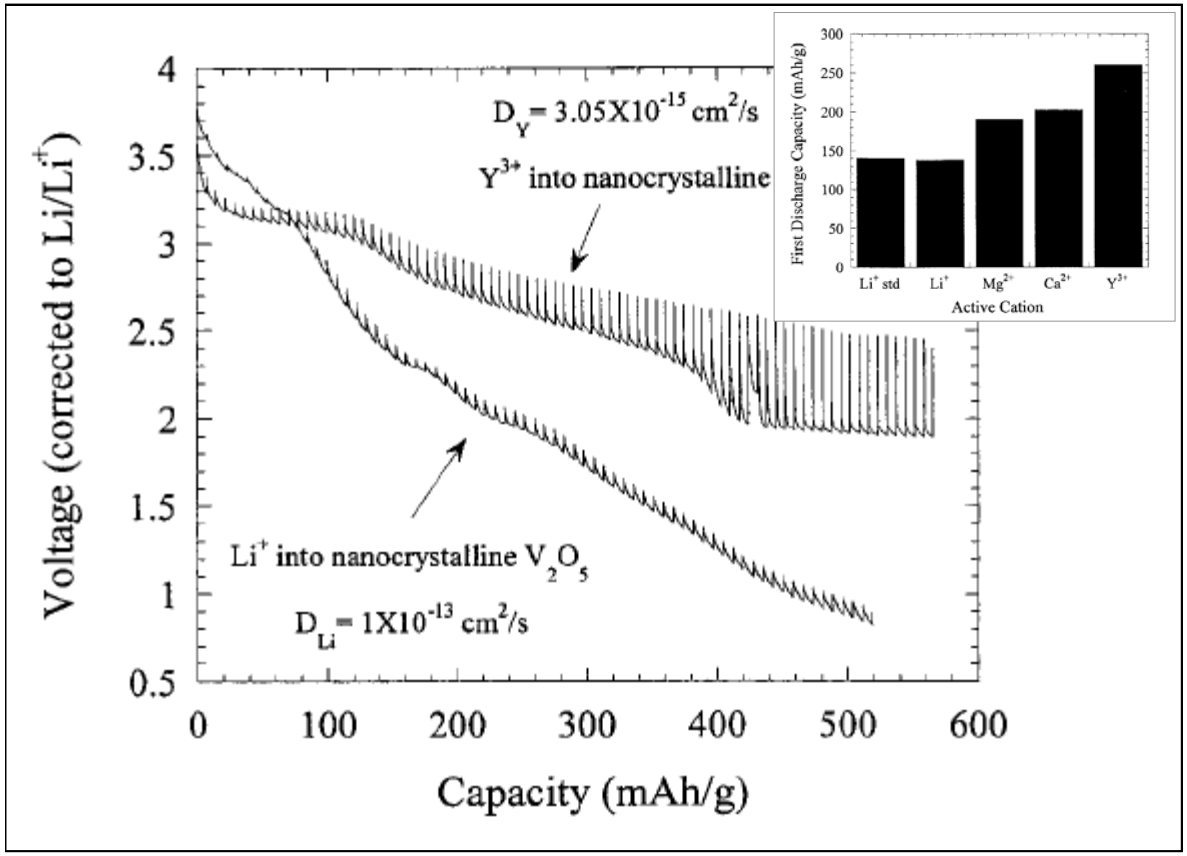
Some early modeling/experimental work indicates there may be promise, though the workshop revealed that there is some controversy amongst experts over the ultimate theoretical potential in these systems

Breakout 1, Session 2: Non-Lithium Intercalation



Early experimental work at MIT indicates increased cathode capacities are possible with multivalent non-lithium intercalants

alternate intercalants have been used successfully



Breakout 1, Session 2: Non-Lithium Intercalation

History of Non-Lithium Intercalants

- 1990 – early magnesium and Grignard electrolytes
- 2000 –
  - magnesium (Aurbach)
  - alternatives (Amatucci)
  - sodium
- 2008 – transition metals and aluminum (MIT)

Breakout 1, Session 2: Non-Lithium Intercalation

Automotive Opportunity for Batteries

- $/kWh is key
- operate on both parts of ratio
- cost reduction – forgiving chemistry/materials
- boost energy density

There is opportunity to meet Winters' breakthrough technology goal that is mentioned during Ted Miller's presentation at this workshop.

Breakout 1, Session 2: Non-Lithium Intercalation

ARPA-E Role

- swing for fences
- inspire new work
- encourage new thinking amongst battery researchers
- not to the exclusion of incremental work

Breakout 1, Session 2: Non-Lithium Intercalation

Conclusions:

- Non-lithium intercalation based batteries are an emerging class of battery materials
- There are some early indications that these materials can significantly improve energy densities over lithium-based intercalation batteries
- The theory predicting the theoretical energy density of these compounds is not yet fully worked out
- This is an area worthy of further exploration, both theoretically and experimentally, to determine how much potential these systems have
- More basic research needed in this area

Breakout 1: Beyond Lithium-Ion?

Advanced Lithium-Ion Intercalation

Non-Lithium Intercalation

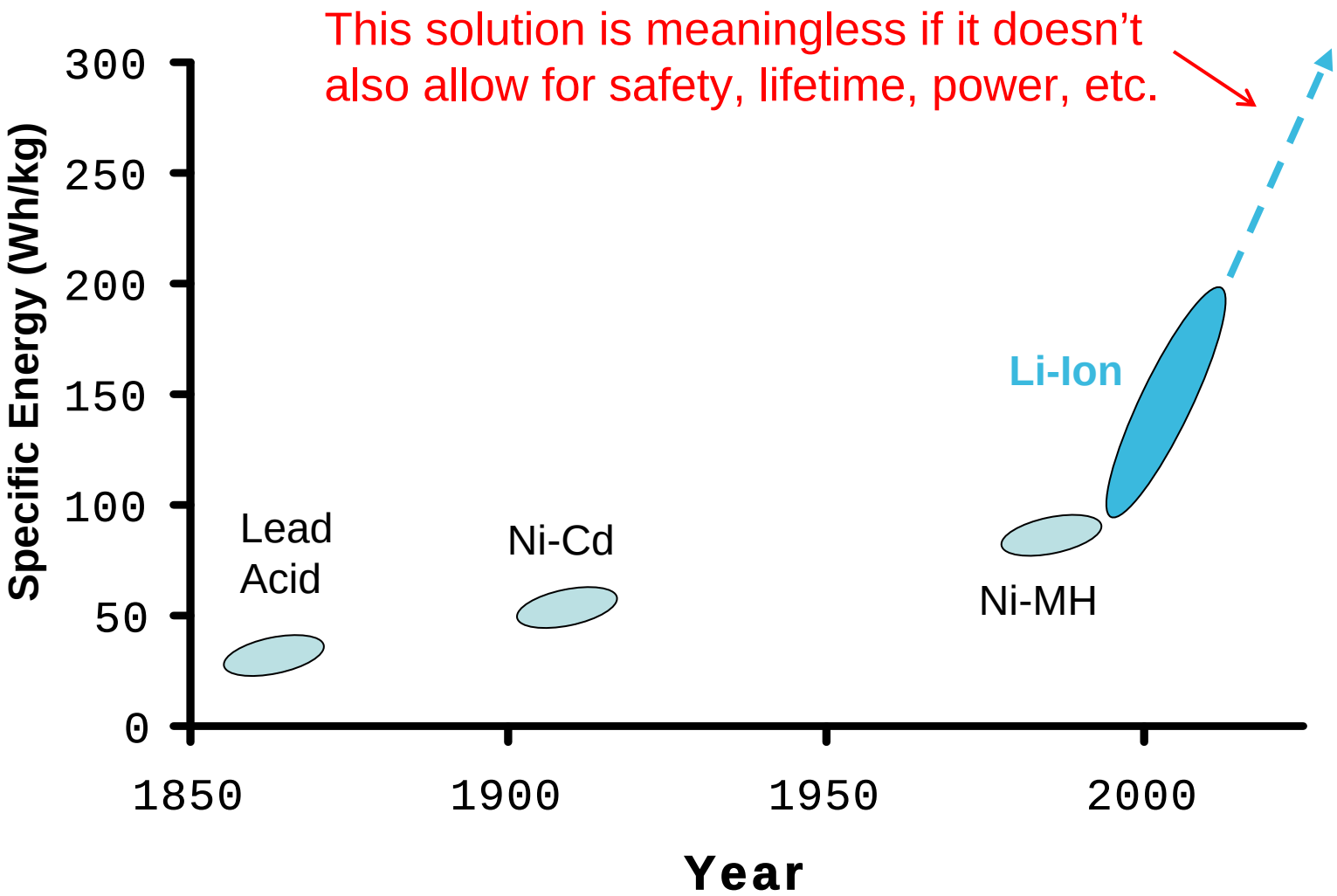
Lithium-Metal (with intercalation cathodes)

Lithium-Sulfur

Lithium-Air

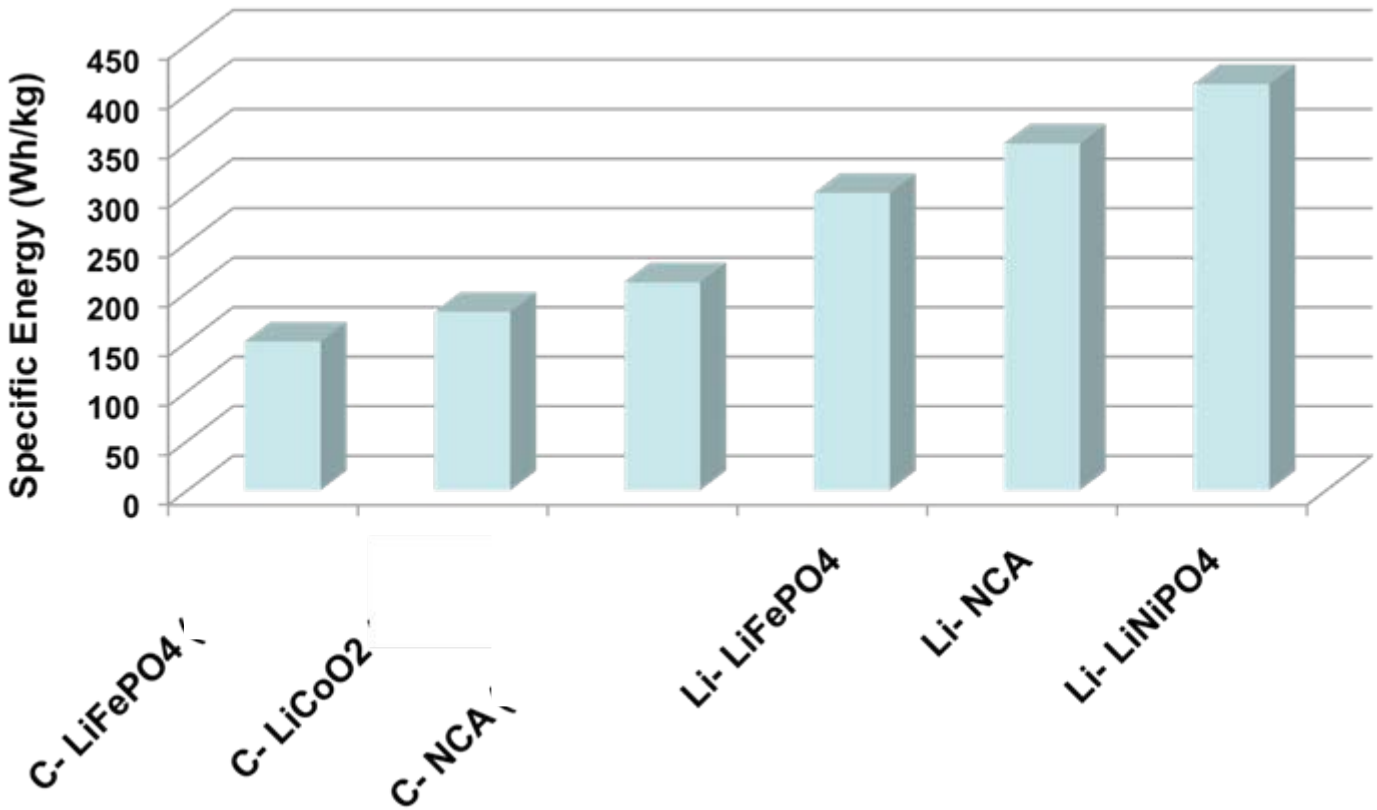
Breakout 1, Session 3: Li-Metal (w/ Intercalation Cathodes)

Li-Metal Motivation



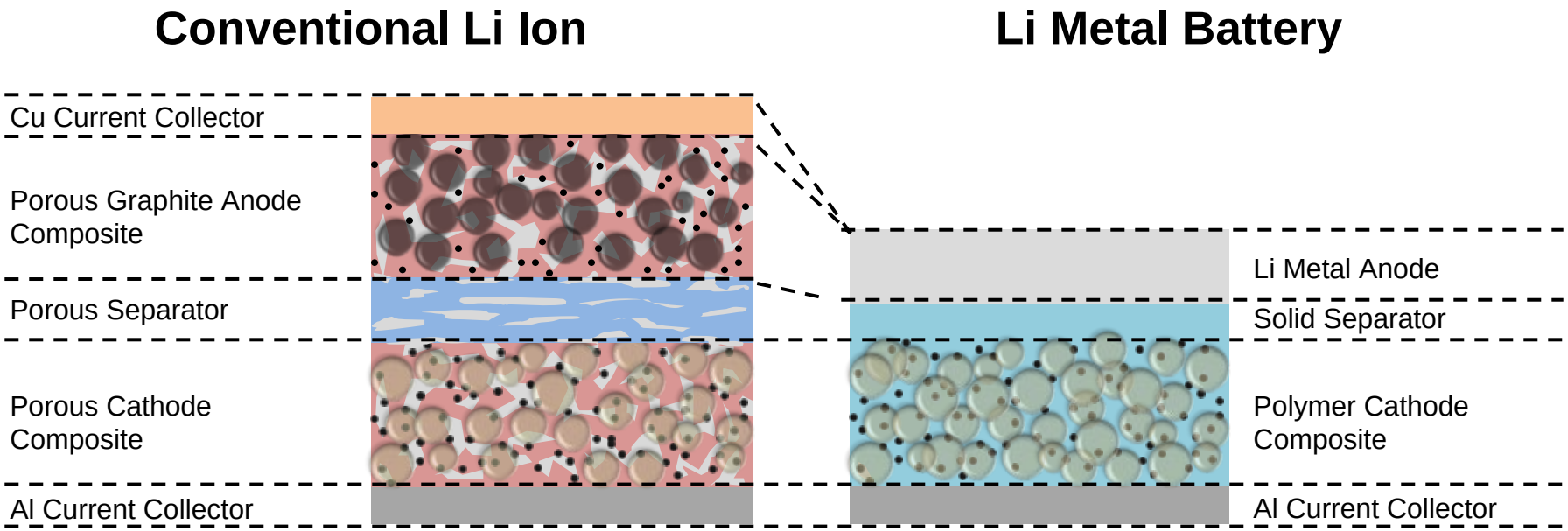
Breakout 1, Session 3: Li-Metal (w/ Intercalation Cathodes)

Li-Metal Opportunity - Energy



We can achieve practical cell spec E of 250-350 Wh/kg and 550-750 Wh/L with Li metal anode and current off-the-shelf cathodes like LFP and NCA (i.e. no additional cathode innovations needed)

Breakout 1, Session 3: Li-Metal (w/ Intercalation Cathodes)



Li-Metal Battery

Breakout 1, Session 3: Li-Metal (w/ Intercalation Cathodes)

KEY TAKE AWAYS

Potential:

- Li metal offers 10x capacity, eliminates anode binder and conductive additive, and can eliminate anode current collector

- 350 Wh/kg / 750 Wh/L cell level achievable with today's off-the-shelf cathodes (can meet USABC long term energy goals)

- Higher energy achievable with high voltage cathodes in the pipeline (450 Wh/kg / 850 Wh/L or more)

- Ability to have excess lithium in the cell offers opportunity to eliminate capacity fade as we know it today

- Lithium metal as an anode can increase energy/life above and beyond and in tandem with other developments in lithium ion.

Breakout 1, Session 3: Li-Metal (w/ Intercalation Cathodes)

Insights:

- Li metal solution providing energy is meaningless if it can't also provide lifetime, stability, safety, etc.

- Li metal issue is one of electrolyte or lithium/electrolyte interface

- Two avenues identified to provide stable lithium metal:

    - Solid electrolytes: stable (nonflammable, long cycle, long calendar) polymers exist today, but have limited low temp performance

    - Li metal coatings: could imagine creating li metal interface stable with liquid electrolytes, many issues remain including safety/cost

- Li metal's advantages are achieved if also used as current collector; otherwise, energy and cost advantages are more limited

- In general, electrolytes are a game changer for Li metal and Li ion, and is a gap in current funding

Breakout 1, Session 3: Li-Metal (w/ Intercalation Cathodes)

Potential Game Changers:

- Stable and high-performing polymer electrolytes exist today; getting them to ambient power performance is a game changer

- Using lithium metal with high conductivity liquid electrolyte would allow for thick cathodes and highest energy gains
  - Coatings to lithium metal could enable this in game changing way
  - But…this solution will also require innovation on electrolyte thermal/chemical stability / flammability

- Cheap / high throughput supply/processing/manufacturing of thin film lithium

- Enabling higher capacity/voltage cathodes
  - Bilayer or Multiplayer electrolytes is game changing path
  - single material higher stability window electrolytes

Breakout 1: Beyond Lithium-Ion?

Advanced Lithium-Ion Intercalation

Non-Lithium Intercalation

Lithium-Metal (with intercalation cathodes)

Lithium-Sulfur

Lithium-Air

Breakout 1, Session 4: Lithium-Sulfur

- What are the Li-S battery approaches with potential to hit/exceed USABC Long Term EV Goals? What is their potential performance?
  - Capacity of S=1675 mAh/g
  - Theoretical Specific Energy = 2450 Wh/kg

  Fully developed Li-S has potential to meet EV goals

  550 Wh/kg for 500 cycles by 2012 (Sion)

  600 Wh/kg for 1000 cycles by 2016 (Sion)

- What is their current level of development/demonstration?
  - Use of nitrate has interrupted polysulfides shuffle that was the main cause of poor lithium and sulfur utilization (300 cycles).
  - Demonstrated 350 Wh/kg (C/3, C/5)
  - 100 cycles 100%DOD
  - > 400 W/kg
  - Good performance at low temperature (demonstrated 100 Wh/kg @-65 C)

Breakout 1, Session 4: Lithium-Sulfur

- What are the key technical challenges/barriers holding these approaches back? What needs to be improved/explored/solved? Promising approaches/areas?
  - To achieve higher cycle life (>300 cycles)
  - Protecting the lithium anode
  - Need novel solvent to dissolve polysulfides but not attacking lithium
  - Need a mechanically strong physical barrier

- What are realistic paths to low cost with these approaches (toward $250/kWh packs)?
  - Likelihood to meet EV cost goal is high.
  - Material Cost: 46.5%, Electrolyte 20%, Lithium 10.3%, S 1.41%

Breakout 1: Beyond Lithium-Ion?

Advanced Lithium-Ion Intercalation

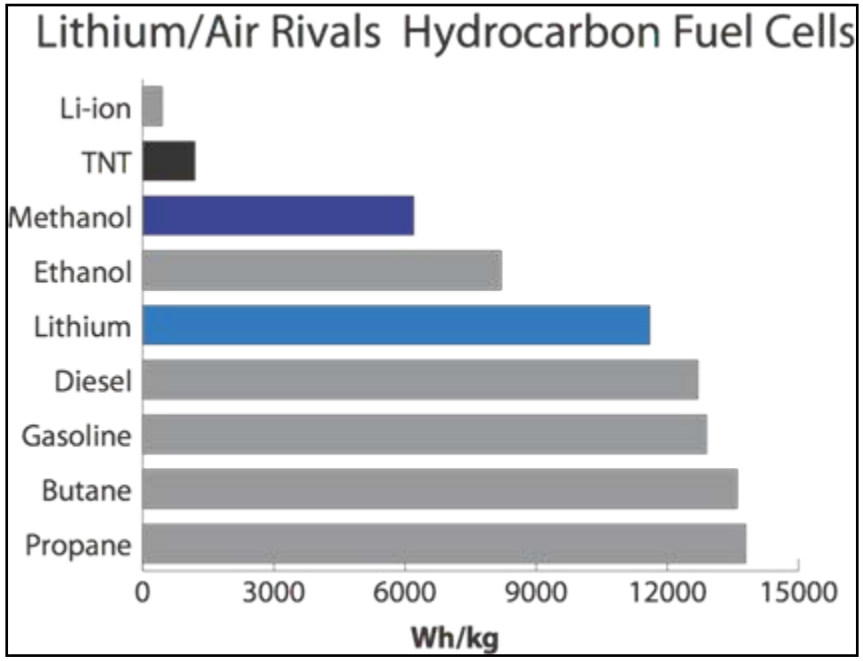
Non-Lithium Intercalation

Lithium-Metal (with intercalation cathodes)

Lithium-Sulfur

Lithium-Air

Breakout 1, Session 5: Lithium-Air



- Li-Air has very high theoretical specific energy density due to the use of O_2 from the air
- Significantly lower, although still high, upon full discharge due to mass of oxygen in battery – this is not always considered
- Volumetric energy density relatively not as favorable due to need for porous cathode volume
- Cycle life issues due to clogging of porous cathode support
- Power issues due to slow O_2 kinetics at cathode
- Round trip efficiency issues due to high overpotential at oxygen cathode

Breakout 1, Session 5: Lithium-Air

Li/Air Chemistry:

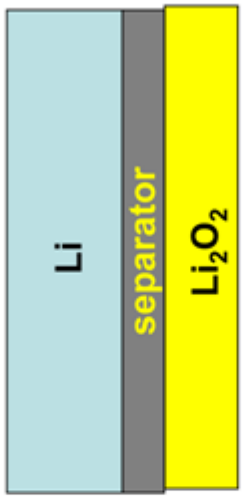
- <u>Li/O2 in aqueous electrolytes:</u>
  - Basic electrolyte: $4Li + O_2 + 2H_2O = 4LiOH$ E = 3.45 V
  - Acidic electrolyte: $4Li + O_2 + 4H^+ = 2H_2O + 4Li$ E = 4.27 V
- <u>Li/O2 in non-aqueous electrolytes:</u>
  - $Li + O_2 = Li_2O_2$ (peroxide) E = 2.96 V
- <u>Li/Water:</u>
  - Basic electrolyte: $2Li + 2H_2O = 2LiOH + H_2$ E = 2.22 V
  - Seawater (pH=8.2): $2Li + 2H_2O = 2LiOH + H_2$ E = 2.60 V

Breakout 1, Session 5: Lithium-Air

Theoretical Energy Densities: Jeff Dahn

Scalable Energy Storage: Beyond Li-Ion, Almaden Institute, August 26, 27, 2009

Bulk Li-Air



Assume no porosity required

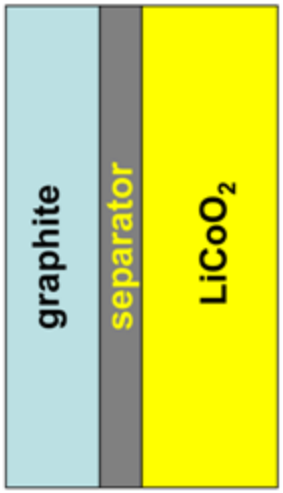
Assume perfect, zero thickness separator

Assume 3.0 V

Assume Li thickness = x

Li_2O_2 needs to be = .74x

Bulk Li-ion



Assume no porosity required

Assume perfect, zero thickness separator

Assume 3.8 V

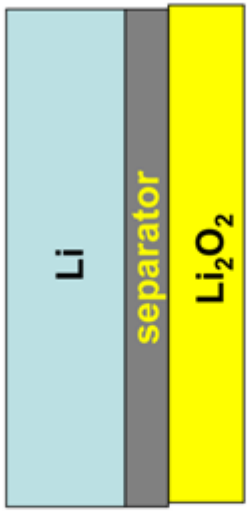
Assume graphite thickness = x

$LiCoO_2$ needs to be 1.15x

Breakout 1, Session 5: Lithium-Air

Realistic theoretical energy density advantage is large,
but not as much as sometimes stated

Bulk Li-Air



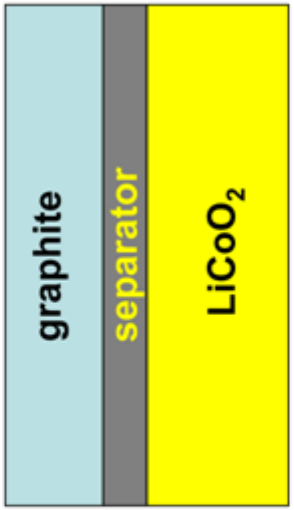
Assume no porosity required

Assume perfect, zero thickness separator

Assume 3.0 V

Get 3400 Wh/L

Bulk Li-ion



Assume no porosity required

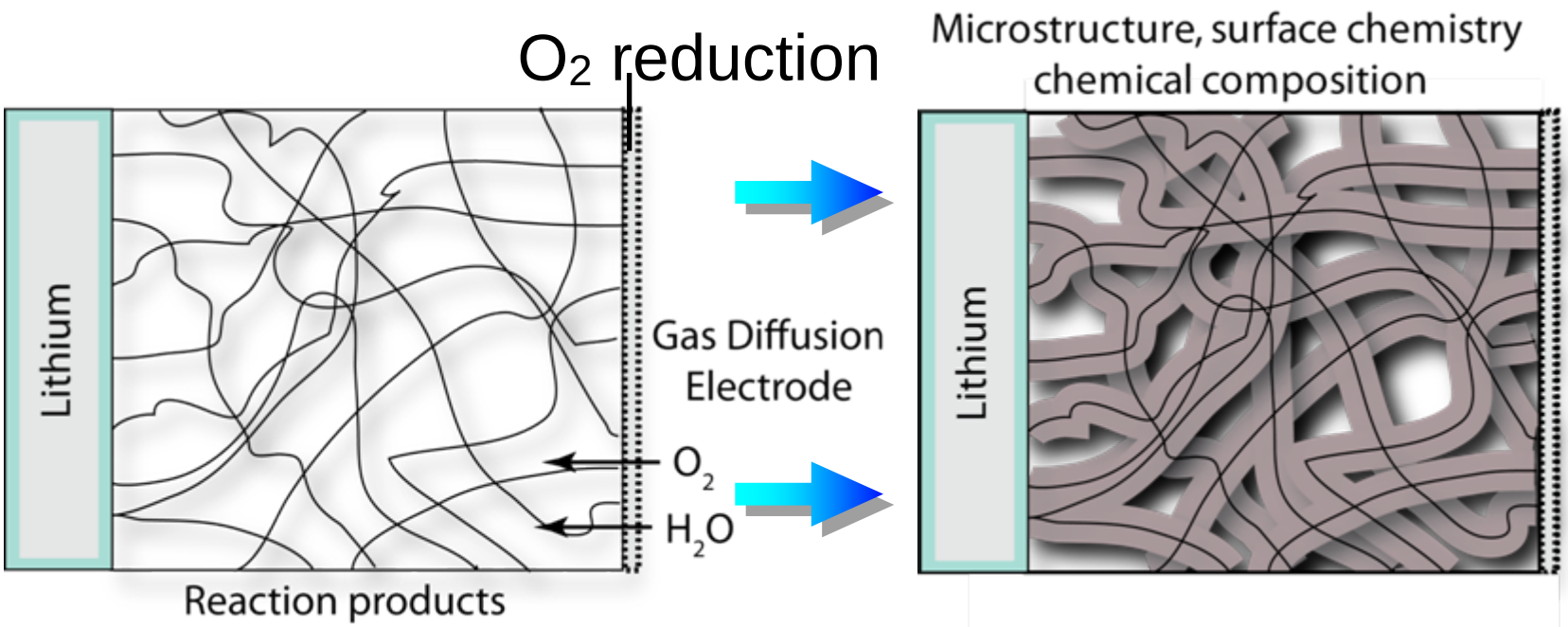
Assume perfect, zero thickness separator

Assume 3.8 V

Get 1450 Wh/L

18650 cells get 600 Wh/L now

Breakout 1, Session 5: Lithium-Air

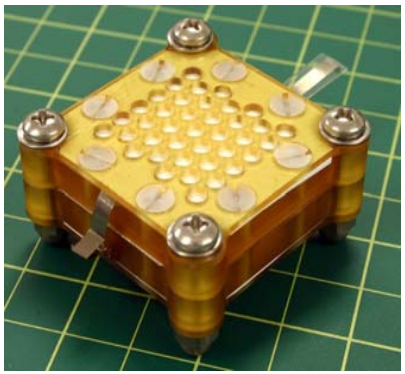


As deep discharge proceeds, volume of reaction products must be accommodated in air cathode structure allowing 100% utilization of lithium metal electrode

Breakout 1, Session 5: Lithium-Air

Advantages

- Extremely high specific energy (rivaling that possible for hydrocarbon fuel cells); commercial cells could reach 1000 Wh/kg
  - Energy for reaction is not contained in cell; large battery packs may have a safety advantage for that reason
  - Environmentally benign system
- Performance of rechargeable Li-Air:
  - Currently cycled at 0.4 mA/cm2 for 70 cycles (C/5 rate)
- Cost: Li is most expensive material in the cell
- Safety: Small cells (2 Ah) have been crushed - 2C temperature rise & 7 hour decay of OCV



Li/Air Cell (800 Wh/kg)
(Courtesy: Polyplus)

Breakout 1, Session 5: Lithium-Air

Challenges/Opportunities

- Positive Electrode
  - Develop electrocatalysts for the non-aqueous oxygen electrode to reduce electrode overvoltage
  - Explore non-aqueous electrolytes and complexing agents to increase solubility of Li_2O_2
  - Develop suitable electrode microstructures (nano-engineering) for deep reversible cycling of oxygen electrode
  - Materials exploration for porous air electrode structure
- Solid Electrolyte Separator
  - Develop thin or wind-able solid electrolyte membranes to increase cell surface area
- Negative Electrode:
  - Demonstrate suitable cycling of lithium electrodes suitable for Li/Air batteries (EV applications)
  - Negative electrode protective barrier layers
  - Examine alternative negative electrodes such as LiSi
- System Level:
  - Modeling of Li/Air (current distribution, etc.), pressurization, air management, specific gravity of battery

Breakout Session #2:
Non-Lithium Approaches, Manufacturing, Non-Active Components

- Zn-Air/Metal-Air
  - Chair: Trygve Burchardt, Revolt
- Liquid Metal Batteries
  - Chair: Reza Sarrafi-Nour, GE
- Novel Architectures/Manufacturing Processes
  - Chair: Harrold Rust, Microazure
- Advanced Supporting Components/Packaging (electrolytes, separators, packaging, etc)
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Breakout 2:

Non-Lithium Approaches, Manufacturing, Non-Active Components

- Zn-Air/Metal-Air
- Liquid Metal Approaches
- Novel Architectures/Manufacturing Processes
- Advanced Supporting Components/Packaging

Breakout 2, Session 1: Zn-Air / Metal-Air

The consensus of the group was that Zinc-Air is the only currently practical rechargeable metal-air technology beyond lithium

System	Pro	Con
Zinc Air	• Low cost (<$100/kWh potential), high energy density, Prismatic Cell: Up to 1400 Wh/kg theoretical, 400 Wh/kg tested • Flow Cell: Up to 800 Wh/kg theoretical, 300 Wh/kg tested	• Low number of cycles, low power • Low round trip efficiency (~65%) – O_2 overpotential • Best lab systems are 500 cycles • Untested abuse tolerance
Iron Air	• Relatively unknown chemistry, 1200 Wh/kg potential, but practical?	• Relatively unknown chemistry
Magnesium Air	▪ Great energy density	• Non-Rechargeable. More fundamental research required
Aluminum Air	• Great energy density	• Non-Rechargeable, Unstable
Metal Hydride Air	▪ Great energy density	• Cost – Could be more expensive (use of rare earth metals)

High energy metal-air systems suffer from rechargability issues/ large overpotentials and lifetime limiting corrosion/blocking at oxygen cathode

Effective plating of a metal must first be demonstrated in usable solvent for battery development to be considered

Zn- Air: Current State of the Art

- Practical (lab scale prismatic cell) energy density of around 1400Wh/l and 400Wh/kg.
- Practical (POC flow cell) energy density of around 800Wh/l and 300Wh/kg – depends on size of storage tank.
- Power – 200 to 300mA/cm2
- Cycles – best (lab cell) system performance around 500 cycles
- Dendrite formation – overcome, promising performance in both sealed and flow systems.

Breakout 2, Session 1: Zn-Air / Metal-Air

Challenges

- Efficiency
  - Currently around 65 – 70%
  - Target is around 80%
    - New catalysts/optimization of Air cathode
- Cycle Performance
  - Currently in the range of 100's but need to increase to 1000's
- Power Performance
  - Air Electrode performance - catalysts / surface area

Opportunities

- Joint Industry Development program for air electrode technology
  - Catalyst materials
  - Alternative support materials
  - CO2 formation (internal/external)
  - Aqueous / non-aqueous
    - Non-aqueous – Solvent loss, Power Density
    - Aqueous – Water loss
- Scale up / cell engineering

Breakout 2:

Non-Lithium Approaches, Manufacturing, Non-Active Components

Zn-Air/Metal-Air

Liquid Metal Approaches

Novel Architectures/Manufacturing Processes

Advanced Supporting Components/Packaging

Breakout 2, Session 2: Liquid Metal Approaches

Liquid Metal Battery Chemistries:

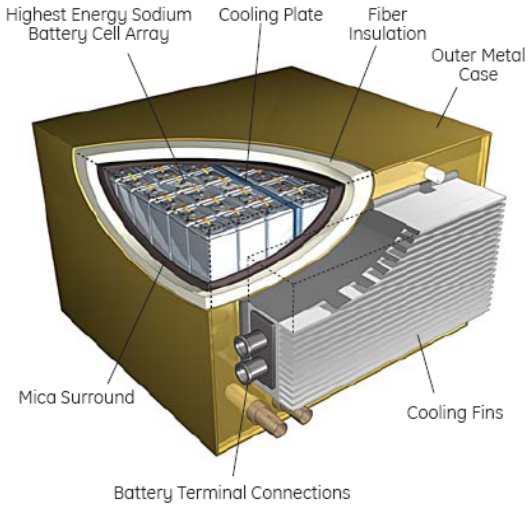
- **Sodium Metal Halide, Na-MX (e.g. M=Fe, Ni, …; X=Cl, F, …)**
- Sodium Sulfur, NaS (not suitable for vehicle applications)
- Molten Metal Cell (Don Sadoway, MIT: the system won't fit the transportation application requirements)
- Li-S/Lithium liquid alloy with ceramic membrane (Abbas Nazri, GM: limited investigations conducted in the past but not an active field)

Sodium Metal Halide the only currently known molten-metal cell system with potentials for EV applications

Breakout 2, Session 2: Liquid Metal Approaches

History of Sodium Batteries

- **1980** … First prototype of Sodium battery
- **1991** … Fleet test of EV by **Daimler Benz**
- Demonstrated **15 years** life



Application Potential of Sodium Batteries

Transportation

Stationary

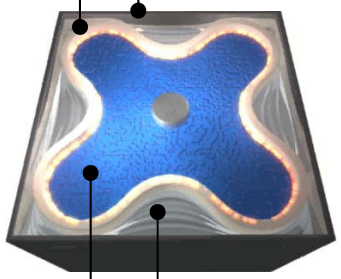
DOE/AEP

Breakout 2, Session 2: Liquid Metal Approaches

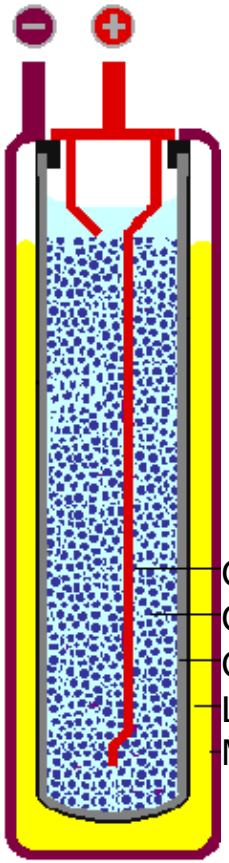
Sodium Metal Halide (Na-MX) Batteries

$$M + 2NaCl \leftrightarrow MCl_2 + 2Na \quad (M=Fe, Ni, \ldots.; X=Cl)$$

Discharged 300°C Charged



Na+ ions transfer through ceramic electrolyte between salt + nickel and sodium metal



Capabilities

- ✓Wide window of operating temperature
- ✓Faults to short
- ✓Safety: Impact, Immersion, Crash
- ✓Recycle, EHS, Life-Cycle
- ✓Low-cost (materials and components)

Breakout 2, Session 2: Liquid Metal Approaches

Batteries in Transportation Applications

Economy | Performance | PHEV-20 | PHEV-40 | Performance | Economy

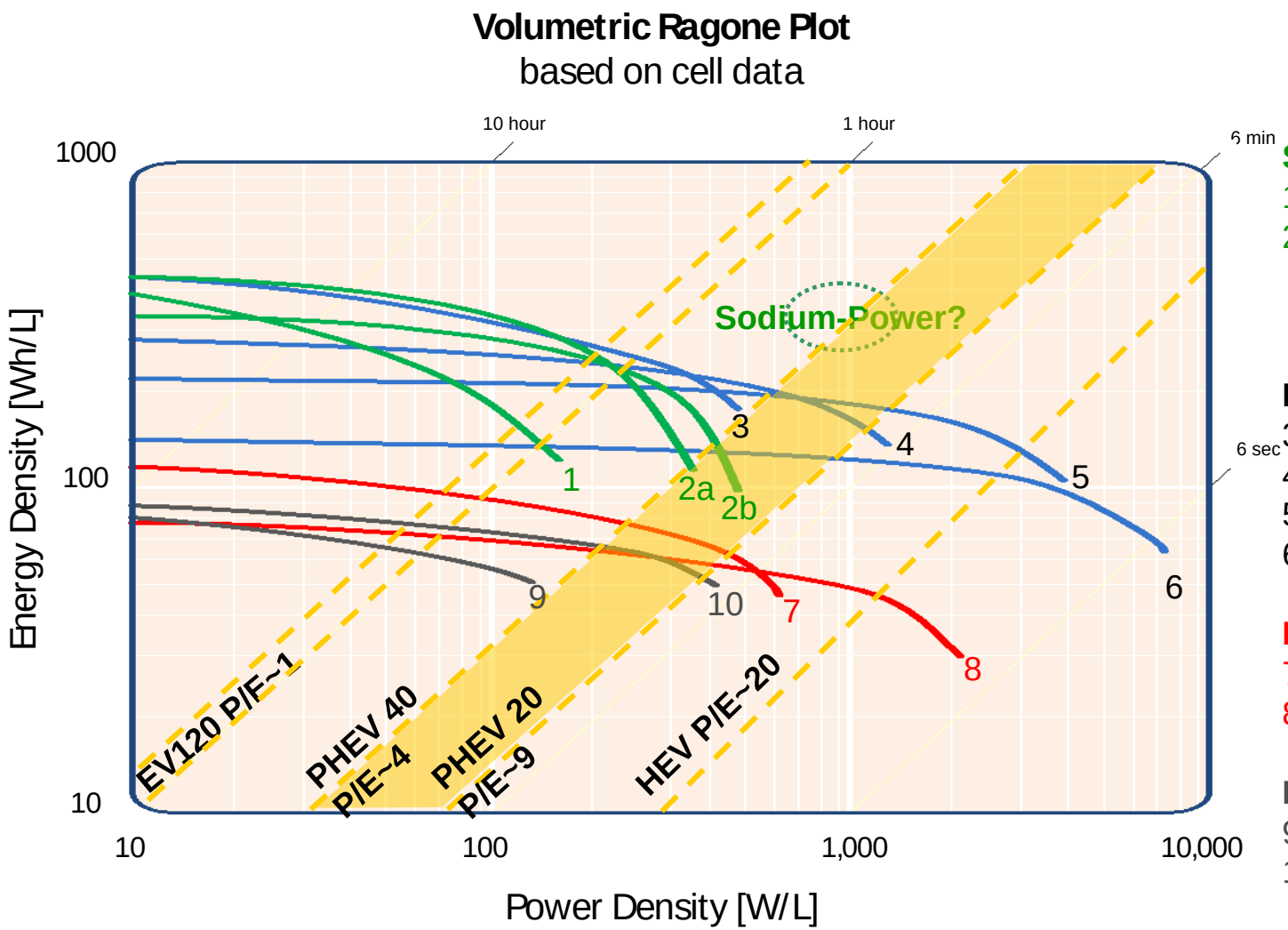
HEV's | Plug-in HEV's | EV's | Hybrid Loco

Increase in size of battery (kWh), reducing Power to Energy (P/E) ratio

Peak Power [kW]	30	50	60	100	90	30	1000
Energy Storage [kWh]	1.3	2.1	5	14	35	19	750
Pow/Eng [1/hours]	**23**	**23**	**12**	**7**	**2.6**	**1.6**	**1.5**
Applicable Battery Technology	**Power**			**Dual**		**Energy**	

Breakout 2, Session 2: Liquid Metal Approaches

Batteries in Transportation Applications



Sodium Technology
1- NaS cylindrical tube
2- Na-MX cloverleaf tube
a- Na-(Fe/Ni)Cl_2
b- Na-$NiCl_2$

Li-Ion Technology
3- 18650
4- Energy Prismatic
5- 26650
6- Power Prismatic

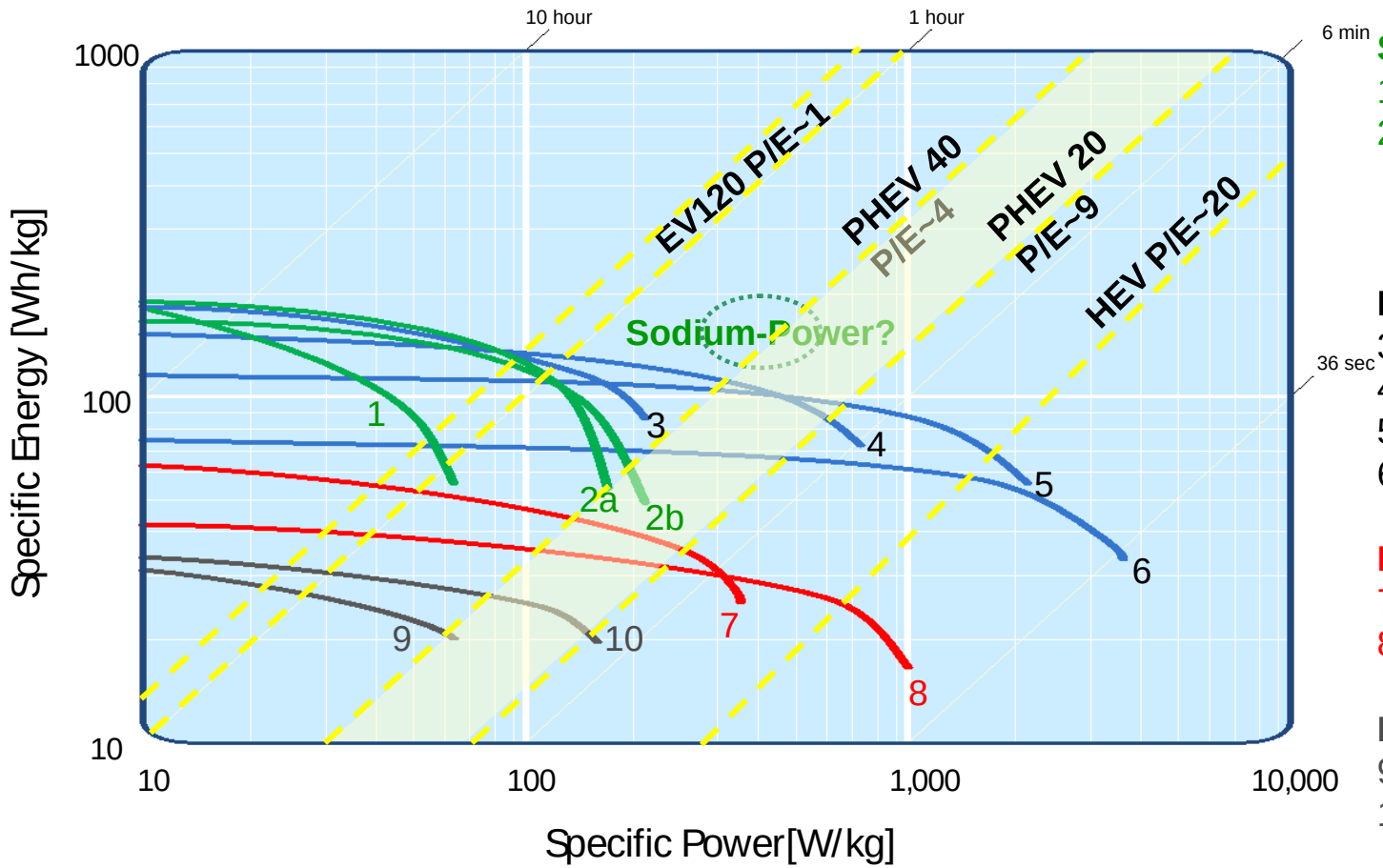
Ni-MH Technology
7- Cylindrical
8- Power Prismatic

Pb-Acid Technology
9- Graphite foam anode
10- Absorbent Glass Matt

Breakout 2, Session 2: Liquid Metal Approaches

Batteries in Transportation Applications

Gravimetric Ragone Plot
based on cell data



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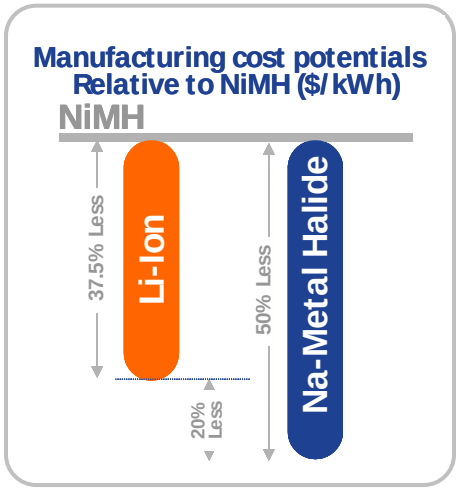
Breakout 2, Session 2: Liquid Metal Approaches

Sodium Metal Halide Battery Features

Battery Technology Performance

	PbA	Power Battery			Energy Battery		
		NiCd	NiMH	Li Ion (Power)	Li Ion (Energy)	NaS	Na-MX
Energy Density (Wh/L)	40–90	40-70	60–100	90 - 120	120- 150	170	150-200
Specific Energy (Wh/kg)	35–50	30–50	40-80	60-93	95-110	129	100-135
Specific Power (W/kg)	10-200	100-800	170-1000	1100-2000	120- 380	16	90-200
Life (years)	5	≥ 10	10	≥ 10	≥ 10	≥ 10	≥15
Maintenance	Yes	Yes	No	No	No	No	No
Toxic Material	Yes	Yes	No	No	No	No	No
Memory Effect	No	Yes	No	No	No	No	No
High Temp. Performance	Degradation					No impact	
Tech. Maturity	Mature	Mature	Mature	Developing	Developing	Mature	Partial

Cost

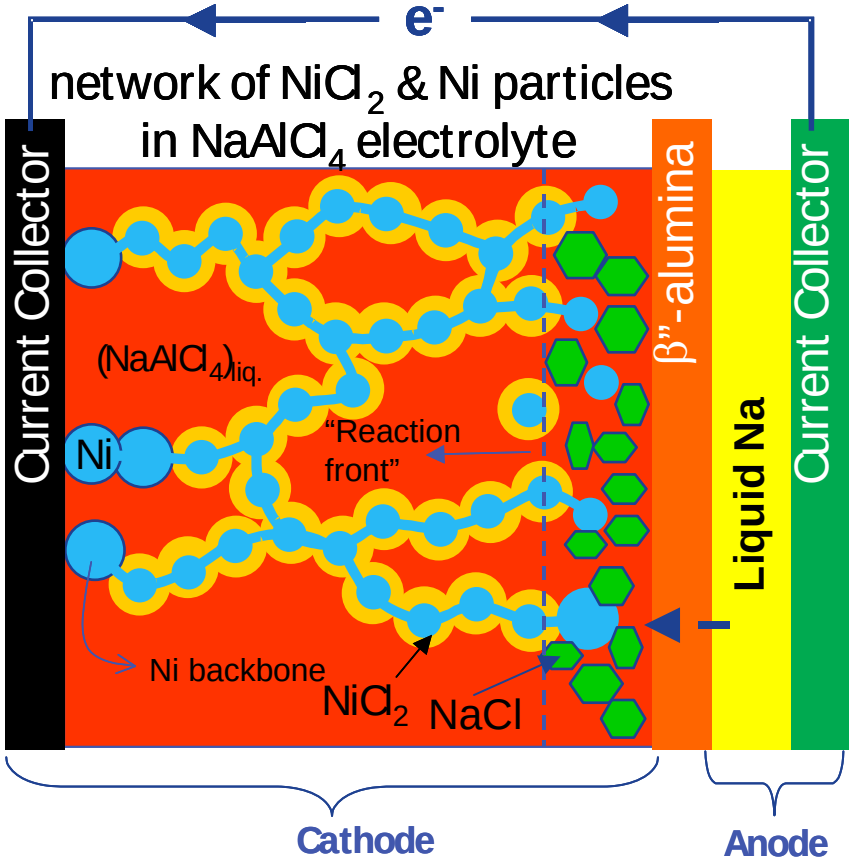


Breakout 2, Session 2: Liquid Metal Approaches

Sodium Metal Halide cell structure and electrochemistry

Charged state Discharged state

$$2Na + NiCl_2 \Leftrightarrow 2NaCl + Ni$$



Power (charge/discharge rate) enablers	Parameter Direction
▪**Internal resistance**	Decrease
•Cathode/membrane area	Increase
•Cathode thickness	Decrease
•Cathode polarization	Decrease
•Ceramic membrane thickness	Decrease
–**Cell chemistry**	
•OCV	
•Active/reaction surface area	Increase
•Liquid electrolyte conductivity	Increase
	Increase
–**Ceramic membrane**	
•Ionic conductivity	
•Maximum current density	Increase
	Increase

Breakout 2, Session 2: Liquid Metal Approaches

Parameters (units) of fully burdened System	USABC "Long Term Goal"	Na-MX batteries
Power Density (W/L)	600	⊗
Specific Power- Discharge 80% DOD/30 sec. (W/kg)	400	⊗
Specific Power- Regen, 20% DOD/10 sec (W/kg)	200	★
Energy Density - C/3 Discharge Rate (Wh/L)	300	
Specific Energy – C/3 Discharge Rate (Wh/kg)	200	
Specific Power/Specific Energy Ratio	2:1	⊗
Total Pack Size (kWh)	40	★
Life (Years)	10	★
Cycle Life – 80% DOD (Cycles)	1000	★
Power and Capacity Degradation (% of rated spec)	20	
Selling Price – 25k units @ 40kWh ($/kWh)	$100/kWh ($230/kWh inflation adj)	
Operating Environment (ºC)	-40 to +85	★
Normal Recharge Time	3 to 6 Hours	★
High Rate Charge	40-80% SOC in 15 Minutes	⊗
Continuous discharge in 1 hour – No Failure (% of rated energy capacity)	75	★

High temp batteries need a plug/auxiliary heating system when left idle for long-term!

★ Satisfy ⊗ Deficient

Breakout 2, Session 2: Liquid Metal Approaches

Key Questions:

- Are there liquid metal/Sodium metal halide battery approaches with potential to hit/exceed USABC Long Term EV Goals?
  - Yes, they can meet many energy, cost and cycle metrics
  - But, need to address P/E ratio, and heating the system
  - Room for improvement on costs, addressing temp of operation.

- What are their potential performance?
  - Upper limit on energy is ~600 Wh/Lit , 300 Wh/kg
  - Upper limit on power is ~3000 W/Lit , 1500 W/kg
  - Upper limit on cycle life is ~6000 full DoD cycles

- What are the practical limits to these approaches?
  - Resistance function vs. DoD, need to change geometry and/or chemistry
  - Typical cathode chemistry = 2.3 ~2.6 OCV; other electrochemical couples?
  - Current density limits on Beta Alumina, look at materials/treatments
  - (Micro/Nano)-structured cathode electrodes

Breakout 2, Session 2: Liquid Metal Approaches

Key Questions (cont):

- What are the key technical barriers holding these approaches back? What needs to be improved/solved? Promising approaches/areas?
  - Beta alumina failure and degradation
  - Cathode chemistry and morphology changes over cycles (degradation)
  - 3-D cathode microstructure optimization to help achieve full potential
  - Heat up time from frozen state, acceptance in market? *Fleet only use (near term)*?
    - Fuel based heating, or super thermal insulation systems
  - Cold conducting Beta alumina and cathode chemistries??
  - Reduce operating temperature by using eutectic liquid electrolytes ??

- What are realistic paths to low cost with these approaches (toward $250/kWh packs)?
  - Sodium chemistry is made from low cost, sustainable materials
  - Sodium cells have seals, bonds, nickel electrodes …, performance improvements can reduce the cost
  - Manufacturing yield (ceramic membrane, seals, …) can help reduce costs further
  - Simplified assembly and manufacturability… to help achieve high production.

Breakout 2, Session 2: Liquid Metal Approaches

Paths Forward:

- Resurrect good technologies and apply continuous improvement
  - Explore new technologies, but also keep consistency in funding.
  - Consistency of purpose and continuation of promising efforts.
  - Loss of knowledge over time
- Improve P/E ratio to help broaden applicability to PHEV
  - To achieve power metrics and fast(er) charge rates
- System engineering
  - Waste heat recovery with PHEV engines coupled to high temp battery

Breakout 2, Session 2: Liquid Metal Approaches

ARPA-E Programmatic Questions:

- DOE Vehicle Technologies program focus on PHEV batteries vs ARPA-E focus on EV batteries appropriate?
  - Have a $/kWh/cycle life/Efficiency
    - to get a "levelized" energy cost over life comparison

- Major gaps in current U.S. battery funding for liquid metal?
  - Yes, gap exists. Previous work in Sodium fell in late 1980's.

- Are the USABC long term EV battery goals the right targets for ARPA-E? Should they be more aggressive?
  - Not more aggressive. Long term targets were developed. Keep them.

- Levels of funding required over ~3 years for:
  - 1) Proof of concept - $500k ~ $1M/year
  - 2) Meaningful lab scale prototype - $2M ~ $3M/year
  - 3) Meaningful demo of pilot manufacturing- $2M ~ $4M/year
  - (Depends upon previous work and maturity of supporting tech.)

Breakout 2:

Non-Lithium Approaches, Manufacturing, Non-Active Components

Zn-Air/Metal-Air

Liquid Metal Approaches

Novel Architectures/Manufacturing Processes

Advanced Supporting Components/Packaging

Breakout 2, Session 3:
Novel Architectures/Manufacturing Technologies

- What novel cell/battery architectures and manufacturing processes can be brought to bear to drive improvement in battery performance and costs towards EV mass market goals?
  - 2X energy density improvement needed
    - 200 Wh/kg at pack level (~400 Wh/kg at cell level)
  - 2X cost reduction

- Synergy of ideas towards goals likely needed

Breakout 2, Session 3:
Novel Architectures/Manufacturing Technologies

Architecture

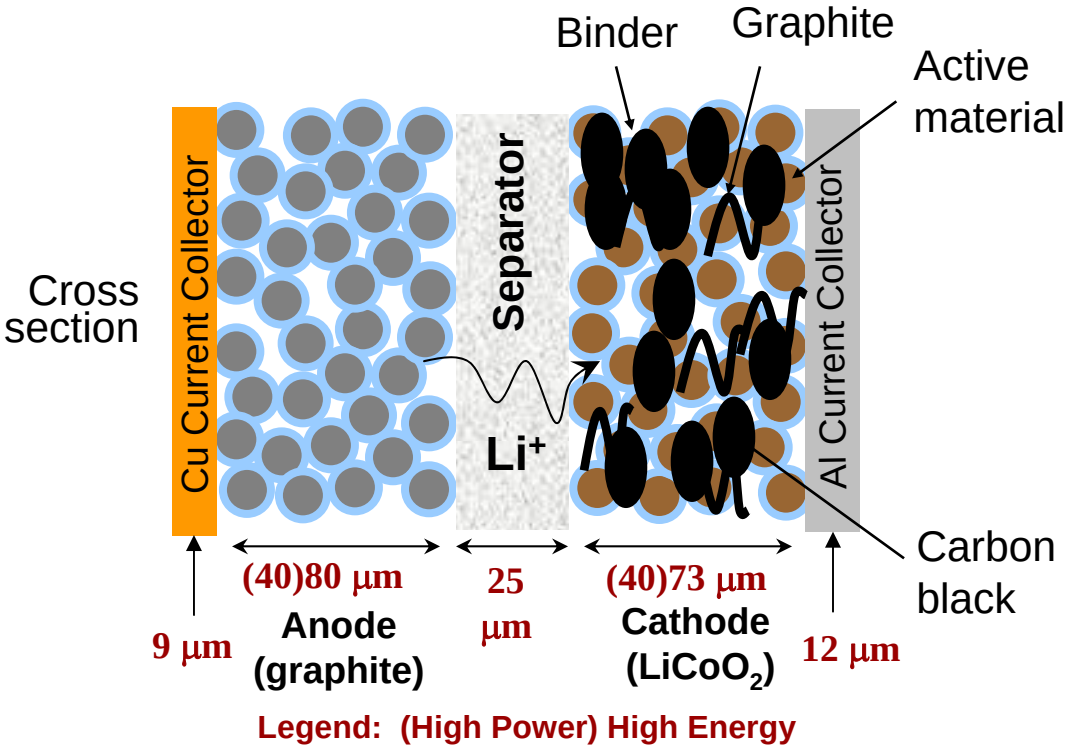
- Improvements in energy density for Li-Ion cells historically driven by improvements in materials and chemistry
- Resulting rate of improvement has been slow at ~6% per year
- Basic architecture of cells has been largely unchanged
- Manufacturing processes mature and optimized around current architectures for best case cost
- Cost reductions going forward largely driven by increased energy density and materials cost reduction
- Significant improvements in energy density possible by implementing new architectures that minimize inactive material
- Synergistic with material and chemistry advancements
- Higher energy density can be key enabler of cost reduction given

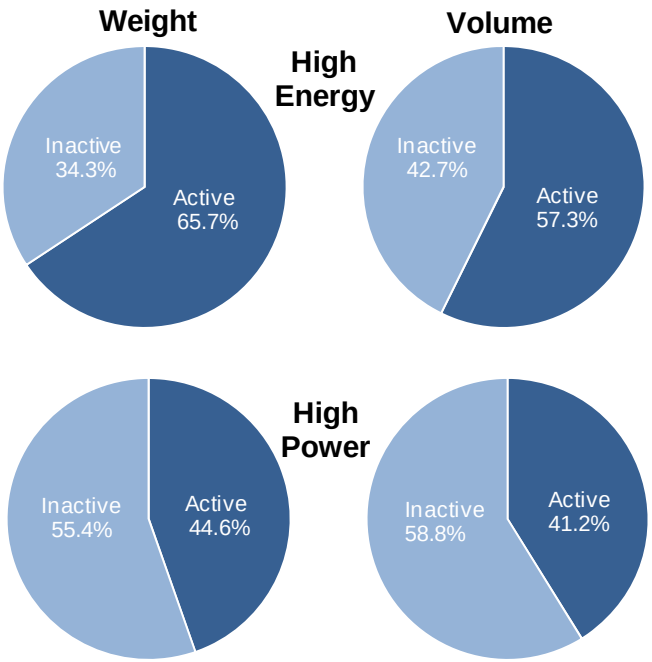
Breakout 2, Session 3:
Novel Architectures/Manufacturing Technologies

Manufacturing Techniques

- Opportunities to improve existing manufacturing process costs exist, but overall cost may be still dominated by material costs
- Packaging and formation costs are areas of opportunity
- New architectures will also require well thought high volume manufacturing processes
- What new manufacturing technologies can be brought to bear to make major improvements in costs?
- Can we leverage learning in other industries?

Breakout 2, Session 3:
Novel Architectures/Manufacturing Technologies





Conventional Cell Architecture

- Significant waste in both weight and volume
- Designs optimized for high energy OR high power (fast charge)
- Huge impact in energy density for fast charge
- Industry focused on improving chemistry and materials

Breakout 2, Session 3:
Novel Architectures/Manufacturing Technologies

Output:

- Alternate cell architectures (e.g. 3D) has potential to increase energy density and reduce cost
  - 50% energy density; 25-50% cost reduction
  - Funding is needed to drive technology into larger format cells
  - Need to create partnerships with equipment manufactures
- Group felt definition lacking for cell format in vehicles
  - Requires industry and governmental focus to drive one solution
- Transition to pouches needs to happen for cost and performance reasons
  - 5-10% lower cost, 30% energy density improvement
  - Requires advancements in safer chemistries to be practical
- Further work should go on in super caps and combined super cap/battery systems
  - 2X energy density opportunity
  - Requires new efforts on defect reduction (pin holes)
- Advancements in better state of charge measurement needed
  - 5-10% energy density and cost reduction opportunity

Breakout 2, Session 3:
Novel Architectures/Manufacturing Technologies

Output (cont):

- New metrology technology needed to increase in line yield and ultimately binning yield
  - 25-30% cost reduction
- Direct printing technologies should be looked at more deeply to reduce manufacturing costs
  - Requires improvements in materials capacity to make feasible
- Need governmental sponsorship of organization to define new processes for existing and new architectures & domestic equipment development
  - U.S. needs to be a leader in manufacturing technology for batteries
  - Won't happen for existing process techniques and architectures

Breakout 2:

Non-Lithium Approaches, Manufacturing, Non-Active Components

Zn-Air/Metal-Air

Liquid Metal Approaches

Novel Architectures/Manufacturing Processes

Advanced Supporting Components/Packaging

Breakout 2, Session 4:
Advanced Supporting Components/Packaging

- **Separators**
  - important characteristics
    - reservoir for electrolyte
    - electrically non-conducting
    - ion conducting
- **Electrolyte**
  - better liquid electrolytes
    - low temperature (!)
    - higher voltage stability
    - intrinsic safety / self-extinguishing
    - no penalty additives
  - solid polymer and ceramic electrolytes
    - combine separator and electrolyte
- **All-ceramic batteries**
  - no flammable electrolytes
  - good thermal stability
- **Packaging**
  - seems mundane but is actually an important choke point
  - long term stability
  - thermal management
    - flexible cooling
    - shape conducive to cooling
    - *autos won't be accommodating longterm*
  - many failures are actually packaging failures
  - packaging dramatically impacts safety
  - current collection is frequently an issue

Breakout 2, Session 4:
Advanced Supporting Components/Packaging

Metrics:

- Difficult to form isolated goals for integrated system
  - recommend comprehensive set of goals
  - specify performance of a cell (minimum scale? 1 Ah)
  - must stress valid comparisons
- USABC is the right track
  - add safety goal
  - careful incorporation of balance of system (to include other chemistries)
  - $/cycle varies with application
- P/E ratio as a metric for development
  - maintain versus improve
  - ambiguity for PHEV / EV
- Cost
- Safety
  - no organic
  - self-extinguishing

Breakout 2, Session 4:
Advanced Supporting Components/Packaging

Possible Breakthroughs:

- electrolytes today limit low temp performance for Li ion
  - power retention at low temperature -30C / 20% power ability
  - other chemistries may solve battery issues
- more cost effective separators
  - low cost free-standing
  - applied / cast separator
  - improved manufacturing
- high voltage electrolytes
  - enable use of current generation at higher voltage
  - new high voltage cathodes
- electrolytes that don't require SEI layer
  - reduce capacity fade
  - decrease impedance
- all ceramic Li & Li ion batteries
  - solid state batteries and/or 3D batteries

ARPA-E - Some Key Workshop Take-Aways

ARPA-E – Some Key Workshop Take-Aways

- There is a strong wave of innovation rising in the U.S. battery community.
- Lithium-ion batteries have significant room for continued improvement to meet USABC Long Term EV Battery Targets; they should not be ignored.
- Advanced electrolytes and anode protection layers, such as solid polymer and ceramic electrolytes, are critical to enable Li-metal anode based batteries.
- Li-S battery technology is continually maturing in energy density and cycle life; key issues are in the solvent, anode protection, and S cathode conductivity.
- Li-Air technology is still in its early stages. Significant basic science work will be required, especially on air-cathode. Large prize in terms of energy density at the end of the tunnel.
- Zn-Air/Metal-Air: strong promise and good progress to date, air breathing cathode is still a major area where work needs to focus for power and efficiency; opportunities in metals other than Zn needs more exploration.
- Na-$NiCl_2$ batteries – strong recent progress and many positive attributes; thermal management is an issue and makes fleet applications most appealing.
- For the U.S. to regain battery manufacturing leadership, novel high performance battery architectures and new manufacturing processes need to be developed and deployed domestically; little opportunity in traditional materials and slurry coating based processes.