Review of Common Obstacles in the Development Cycle for Novel Battery Electrode Active Material Commercialization

Joint Service Power Expo 2015
Dr. James Fleetwood
Vision

A non-profit, public-private partnership joining academia, industry, and government to rapidly develop, test, and commercialize the next generation of safe, reliable, and lightweight energy storage systems.

Distinguishing Features

1. Catalyze technologies by reducing long, expensive innovation-to-commercialization development cycle
2. Does not hold patent rights, reducing concerns to jointly develop
3. IP-secure, US-based facility generating reliable data using common techniques & equipment

Core Offerings

1. Low volume cell manufacturing & prototyping
2. Full suite of test & evaluation capabilities
   - Cells, Modules, Packs, & Systems
   - Certification
3. Applied Research & Consulting
   - Design for packs, BMS, and systems
   - Competitive analysis
Advanced Energy Systems Testing and Validation Capabilities

Battery System Testing and Evaluation
- Full spectrum of T&E equipment for individual cells up to whole systems of 1MW+
- Access to environmental and abuse testing facilities at NSWC Crane that include more than $150M in hardened test labs

Microgrid Systems Testing
- Utility scale grid simulator
- Integrated solar and wind renewables on site
- Residential, community, and grid energy storage systems on site
- Facility designed with access to >6MW of available power with net metering (MISO High Voltage Node)

Cell and Pack Manufacturing
- 1% Humidity Dry Room & 10,000 Class Clean Rooms
- Commercial quality cell manufacturing equipment for multiple cell formats
- Pack design and assembly equipment
Description of Overall Development Cycle

• Theory/Model
  • Electrochemical testing
    – Active material evaluation
    – Individual electrode systems
    – Paired electrodes
    – Electrolyte selection
  • Cell format progression
    – Split cell testing
    – Half cell (coin) testing
    – Full cell (coin) testing
    – Large format pouch/prismatic/cylindrical cell testing
  • Electrode fabrication progression
    – Laboratory process
    – Slip table / doctor blade
    – Continuous coating
      • Comma bar coater dryer
      • Slot die coater dryer
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Electrochemical Testing

- Active material evaluation
  - Split cells
- Individual electrode systems
  - Half cells
- Paired electrodes
  - Full Cells
- Electrolyte selection
- Key performance metrics
  - Specific capacity (mAh/g)
  - C-Rate
  - Cycle life
  - Coulombic efficiency
  - Irreversible capacity
  - Temperature range
  - Safety
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Half Cell vs. Full Cell

• Half Cell
  – Simple system without need for balanced electrodes
  – Limited cycling due to risk of lithium dendrite formation
  – Effectively unlimited Li available

• Full Cell
  – Complete cell system with performance characteristics like that of end-use / commercial cells
  – Capable of long term and more in depth testing
Split Cell Testing

• Benefits
  – Basic empirical comparison to theoretical electrochemical properties
  – Cell system independent evaluation of charge capacity at given cycle rates
  – Indication of potential cycle life
  – Most conservative of available materials

• Drawbacks
  – Time intensive
  – Large free volume for expansion, gassing, and excess electrolyte
  – Can miss mechanical property related failure mechanisms
Coin Cell Testing

• Benefits
  – Easily & quickly constructed
  – Conservative of materials (<50 mg/cell)

• Drawbacks
  – Typically a manual assembly with less control than with split cell tests
  – Large open volumes
  – Relative overlap of anode and cathode can be unrepresentative to larger cell formats
Large Format – Full Cell

• Benefits
  – Commercial formats at industry relevant performance

• Drawbacks
  – Requires more material than small format testing
  – Requires more time per cell to construct
  – Complexity of interactions can make trouble-shooting slower
    • Less free volume in cell for cyclic expansion or gassing
    • Cell heating during cycling more likely
    • Electrode mechanical properties may become a factor
Pouch / Prismatic Cells

• Benefits
  – Minimal mechanical requirements on electrodes
    • Particularly for flat/stacked/Z-fold pouch cells
  – Flexible on geometry and # of electrode layers

• Drawbacks
  – More difficult to monitor gassing
  – Less consistency with electrolyte fill & infiltration
Cylindrical Cells

• Benefits
  – Standardized product
    • Highly commercially relevant
  – Safety features
    • Pressure relief valve
    • Over-temp shut-off
  – Most rigorous test
    • 1-20 Amps may be flowing at a time
    • Contained volume
    • Electrodes wound around tight mandrels

• Drawbacks
  – Most rigorous test
  – Much more equipment required to fabricate than previous cells
  – Must fabricate from continuous coating methods
    • 500-1000 mm electrodes typical
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Slip Table Coating Trials

**Benefits**
- Low material requirements (<50 mL of slurry)
- More flexible on slurry rheology
- Reveals general ‘coat-ability’ of electrode slurry

**Drawbacks**
- Higher variation between and within coatings
- Limited production capacity
- Slower drying rate than industrial processes
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Comma Bar Coater Dryer

• Benefits
  – More consistent coating & drying over slip table trials
  – High throughput capability
    • Even a laboratory model is capable of 3 m/min coating rates
  – Industry relevant coating process
    • Slot die is the next step up in capabilities

• Drawbacks
  – Slurry rheology governs coating quality
    • Slurry solids content at this point is a dependent variable
    • Less ability to control as-cast electrode porosity
  – Drying rate generally increases over slip table rates
    • Increases residual stresses in electrodes, particularly those with small particle sizes & high specific surface areas
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<th>Intercalation Based Electrode Components</th>
<th>Cathodes (Conversion)</th>
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- **mAh/g**: Specific capacity
- **mAh/cm³**: Volumetric capacity

**Cathodes (Conversion)**

- Zn 410 1511
- Cd 238 1159
- In 1012 1980
- Sn 960 1991
- Pb 550 1906

**Anodes (Conversion)**

- Al 993 1383
- Ga 769 1911
- Ge 1384 2180
- As 1073 2057
- Sb 660 1889

**Intercalation Based Electrode Components**

- Ti 154 1039
- V 151 1033
- Cr 146 1028
- Mn 147 1030
- Fe 149 1032
- Co 152 1035
- Ni 155 1038
- Cu 158 1041

**Components**

- Li 278 1362
- Ni 3579 2190
- Co 372 756
- Mn 2190 756
Trends in Battery Active Material Development

• Intercalation based electrodes
  – Charge/discharge based on diffusion of Li\(^+\) to and from lattice sites within the electrode structure

• Conversion based electrodes
  – Tend to have the highest theoretical capacities
  – Undergoes solid-state reaction as part of charge/discharge
  – May not have an initial source of lithium
  – Typically utilizing active materials with large volume changes during cycling

• Electrolyte development
  – Solubility of active material elements
  – Stability of SEI, particularly w.r.t. maximum operating voltage and solubility of electrode elements
Trends in Battery Active Material Development

• Dimension reduction of electrode materials
  – Shortens Li\textsuperscript{+} diffusion path for faster charge/discharge rates
  – Increases resistance to mechanical failure due to volume changes for improved cycle life
  – Increases specific surface area (m\textsuperscript{2}/g)
    • Solid electrolyte interface (SEI) layer increases in relative volume within electrode
    • Electrolyte and SEI stability requirements increase
    • Increases capillary action within electrode
      – Humidity/environmental sensitivity
      – Increases residual stresses incurred during solvent evaporation
  – Increases particle dispersion requirements
    • van der Waals forces mitigate dimension reduction via aggregation
Trends in Battery Active Material Development

• Active material protection & hierarchical microstructures
  – Typically with carbon compounds
  – Encapsulation of active materials
  – Composite electrodes
  – Often limited by complex fabrication techniques
  – Tendency towards atypical surface/interface properties
  – Unknown or low compatibility with common slurry compositions

• Active material composition optimization
  – Focusing on intercalating crystal structures with high capacity and stability over time
  – Typically has very similar optimal slurries compositions to contemporary electrodes
Conclusions

• Intercalation based electrodes are still the standard, with shorter development cycles
• What’s holding conversion based electrodes back?
  – Ideal electrolytes & stable SEI layers
  – Mechanical properties & surface science
    • Slurry composition & rheology need earlier consideration during development
    • Nanoscale active materials are much less likely to use standard slurry compositions and mixing procedures
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### mAh/g and mAh/cm³

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BIC Members
Energy Storage Technology

**The Water Analogy**
- Want water when needed, not only when it rains
- We want the right amount (i.e., energy)
- We want the right speed (i.e., power)
- **Independence & Security**
  - *ISIS: $3.2mm / day from oil*

**Why So Many Ways to Store?**
- Natural resources
- Application requirements
  - stationary v. mobile?
  - backup v. peak demand v. renewable?
- Technological advancements

**Why Focus on Batteries?**
- Well known manufacturing methods (commodity)
- Flexible format
- Flexible technical performance
- Mobile and can be stable
Reports of novel electrode active materials with seemingly paradigm shifting performance improvements over current commercial technologies are relatively common, yet the minimally reported challenges of cost, scale, and reproducibility continue to hold back the development process. The key issue in creating this gap between initial low technical readiness level (TRL) positive results and reliable high TRL performance is a lack of awareness of the full development cycle and the common obstacles presented at each stage, such as those faced in designing stable electrode slurries, balancing ionic/electronic conductivity, and ensuring long term adhesion/cohesion of electrodes. While each of these examples represent well researched fields in the materials science of battery electrodes, the hurdle is in the requisite adaptation of this knowledge base to the specific properties of any given new active material, its synthesis method, and the morphology derived thereof.

The basic steps in the development cycle of new active materials on the cell level are split cell testing, half cell coin testing, full cell coin testing, and large format testing, such as planar stacked pouch cells or cylindrical wound 18650 cells. Each stage of development introduces new complexities and potential interactions, such as maintaining uniform dispersion of the increasing volumes of slurry needed, differing drying rates as electrode mass loading is increased or larger scale coater-dryer equipment is used in production, and the effects of residual drying stresses on the ductility of electrodes wound around the small radii of curvature utilized in cylindrical cells. When developing a new active material, often initial capacity results are focused on the material itself, independent of the electrode structure necessary to facilitate its operation, any electrolyte interaction, and an appropriately balanced counter electrode. Additionally, development can continue from the cell level into module and pack testing, with a focus on safety, thermal, and power management, but for the purpose of this report, this late stage development will be discussed solely in terms of the relevant constraints it places on cell development.
Commercial Offerings

Residential

- Dozens of off-the-shelf products available
- Samsung, LG, GS Yuasa, SMA, Eaton, ABB, NEC, Toshiba
- TESLA!!
  - Marketing & price point ($3500 for 2.5 days of energy)

Community / Industrial / Government

- Again, dozens of offerings
- Applications include:
  - Emergency location backup
  - Renewable integration
  - Peak Shaving
  - Power Quality

Grid / Microgrid

- Smaller number of vendors, but still 10-15
- Applications include:
  - Renewable integration
  - Frequency regulation
  - Replace generation, transmission, distribution assets
Microgrids

**Why not create my own “grid”?**
- Local generation + storage + management software = microgrid
- Why not municipal water AND a well??

**And if I have my own grid, why not make it “smart”?**
- Devices called smart inverters and special software can shift between generation sources and grid

**Microgrid Applications**
- Remote service areas, hospitals, data centers, communication centers, municipal buildings, homes
Microgrid Laboratory

• Goal: create setting to test algorithms & controls for microgrids
• Point: BIC can test the interoperability of components and provide unbiased evaluations
• Impact: Two microgrids deployed at Indiana highschools
• Next Steps:
  • Vendors and schools in final selection
  • Install hardware, begin deployment Q3/Q4
  • School deployment over next 6-8 months
Takeaways

Is your energy infrastructure resilient?

- Terrorist Attacks: Sutton’s Law
- Natural Disasters
- Too Many Renewables?

Can policy decisions impact energy security & independence?

- Is storage required for renewable projects by your state utility commission?
- Are you encouraging customers to embrace storage with your policies and incentives?

How can the BIC help?

- Competitive analysis and consulting
  - david.roberts@bicindiana.com
  - 317-225-6112
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Microgrid Capabilities

Solar Array with Integrated EV Charging

Large Grid Storage Device (approx. 1MW)

Low Velocity/High Efficiency Wind Turbines

Facility Designed with Access to >6 MW of Available Power (MISO Energy HV Node)

Integrated Power System (IPS) Supporting Solar and Wind Data Collection and Remote Management
Critical Testing, Evaluation and Consultation for Energy Storage Solutions

- MT-30: Module Testing
- ABC-170CE: Pack Testing
- AV-900: Battery/Array Testing
- Altitude Testing
- Humidity Testing
- Thermal Cycling
Strategic Partnerships

• UL agreement announced in February 2015
  – exclusive test facility for all of UL’s large-format ESS testing in U.S.
  – undergoing ISO 17025 certification
  – BIC selected because of breadth of equipment and capabilities

• NSWC Crane: CITE agreement in final negotiation will allow personnel to access Crane’s extensive hardened T&E capabilities
  – when combined with BIC facility it will create broadest T&E capability in the U.S., if not the world
  – approved in principle; finalizing logistics of access & use
Strategic Partnerships

• Duke Energy grant for microgrid simulation
  – Announced March 2015
  – To establish microgrid testbed environment with controls and communications infrastructure sufficient to evaluate microgrid components
    • Procuring 5 ESS
    • Receiving 1MW inverter
    • Leverage installed and new renewable generation
    • Communication protocol using emerging MESA standard
  – Final supplier identification and notification in process

• Multiple Federal grant applications recently submitted with Purdue University & private industry partners; developing proposals with IUPUI
For more information on how BIC can be your trusted partner and resource, please contact:

David Roberts, President
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(317) 225-6112

Ben Wrightsman, COO & Chief Engineer
ben.wrightsman@bicindiana.com
(317) 331-1197