From Bench to Manufacturing

An LFP battery (product development) story

Larry Beck
Ann Arbor, MI
Outline

• My Story
  • A product development timeline (from 5g/batch to >5 tons/day)
  • Launched a new cathode powder (3 times); cylindrical and prismatic cell formats; into HEV, BEV and low-voltage packs

• Product Development Cycle
  • R&D vs Pilot vs Production
  • Six-sigma, APQP

• Lessons Learned:
  • technology transfer
  • role of IP, etc.
  • Importance of Supply Chain
  • Cost of quality
  • Design for Manufacturing
A coin cell is NOT your product

Cell to battery pack (200-300 mile BEV)

- Coin (button) cell is a first step
  - Simple test platform demonstrates: voltage window, hysteresis, specific capacity, reversible cycle life (0th order)

- But many metrics don’t scale from coin to a real product application
  - Can not translate: thermal management, volumetric density, total impedance, volume-expansion, calendar life....
  - Big 3: economics, scale-ability, manufacturing path
An academic’s learning curve...

Making cathode active material(s)
• **1st** product: low-cost LFP
  • Using different starting materials
  • Increase the yield/output (but utilize existing process equipment)
• **2nd** round: even lower-cost LFP
  • redesign process (all new equipment)
  • improved utilization, yield/output, operational costs
• **3rd** round: ultra low-cost LFP
  • New BOM, new process, more efficient equipment, etc....

**1st LFP product steps - by scale**

- **Phase 1:** R & d
  - 5-50g
- **Phase 2':** R & D
  - 0.5-1 kg
- **Phase 2'':** r & D
  - 50-100kg
- **Phase 3:** Pilot
  - 100-150kg
- **Phase 4:** Pre-production
  - 0.5 ton
- **Phase 5:** Production
  - 0.5 → 6 tons/day

L Beck, ARPA-E Review 3/25/2016 4
My 1st product journey extended…
Electrode product development

Validation testing reveal a problem …
• Pilot scale LFP validation testing ran into some hick-ups (not a drop-in)
• That new ‘low-cost’ LFP wasn’t the same as the previous LFP
  • cathode slurry rheology was different
  • electrode drying was different
  • 18650 cell winding was different
  • Electrolyte ‘wetting’ different
  • etc.

…which led a new project
• To implement the new LFP into existing product meant we had to ‘re-engineer’ the cathode
  • New slurry formulation, new mixing procedure, new mixer, new coating procedure, new drying profile, new QC testing and specs
  • In other words it was another new product to launch

Repeat the product cycle for electrode:
R&d→r&D→Pilot→Pre-production→production launch
This cycle took less than 1yr and over-lapped the LFP launch timing.

Extended to cell product development

Another problem uncovered...
• Pilot version of the new cathode (w/new LFP) behaved differently in the cell
  • Cathode was thinner (jelly-roll was too loose in the can)
  • Cell performance differences
    • Different OCV
    • Different charge acceptance
    • Different thermal performance

...another new product cycle
• To implement the new cathode with the new LFP we decided to design and launch as a new cell
  • Longer electrode, higher loading, increased energy density
  • Lower impedance enable faster charge capability
  • Improved cycle life and improved temperature performance

Repeat the product cycle for electrode:
R&d→r&D→Pilot→Pre-production→production launch
This cycle took about 2yrs and over-lapped the LFP and cathode launch timing.
First Product Development Timeline

1st product launch experience

- 2.5+ yrs. to product launch LFP
  - 5 times longer than I expected!
- Why?
  - I didn’t understand how to “sell” the product (even inside my own company)
  - I underestimated Quantity/Quality of data required for risk mitigation
  - Inevitable technical “hick-ups” along the way
  - Customer also drives the time-line; not everything is under your control
Product Development Phase Gates

• **Phase 1: Research;** Big R & little d
  - Basic research mode; proof-of-concept and discovery; looking for big improvements
  - Probably extremely cautious about sampling/sharing; filing lots of provisional IP

• **Phase 2: Development;** little r - Big D
  - Developing repeatable processes and reproducible products; looking for stability
  - Talking to customers, sharing initial “internal” test results

• **Phase 3: Pilot Scale**
  - Production *intent* equipment, process and materials; working on a control plan
  - Developing product specs and process specs; Sampling to potential customers

• **Phase 4: Pre-production**
  - Using production equipment and process; Locking-in product specs & process
  - Definitely working closely with customers MOU; they are validating your product

• **Phase 5: Product launch (PPAP/ PSO)**
  - Shipping to customers; under contract (inventory management, shipping schedules)
  - Changes require a MCO from customer and probably new validation testing ($$$)
A rude awakening...

1 year into my 1st product development...

• We had made (and tested) almost two tons of LFP
• Predicting 50% the COG of LFP at that time
• Testing was showing better performance in 18650/26650s
  • 20% gain is energy density (same format)
  • cycle life data for 1 year, projecting >10 years

• Then CTO and COO asked me ...
  • What are the Cpk values?
  • What’s the expected first year scrap rate?
  • What’s the expected yielded A-grade cell cost after final QC cull?

... then I was handed the book.

The great results didn’t matter....
the message I heard was “you’re a dummy.”

Process Capability: use six-sigma, get a six-pack

Demonstrating product (performance) is reproducible is #1 prerequisite to de-risk any new product/technology

• Without proof of a stable product (and process) you can’t convince people your product is ready

• How many times has your product been reproduced?
  • Without changing any knobs or intentional ‘experimenting’
  • “Get these engineers out of my factory!”

Demonstrate product is stable with statistical process control
not that kind of six-pack

Process capability index (Cpk)
Process performance index (Ppk)
• How often will your process yield a product outside of the customers specification?
  • If Cpk = 1 (2-tailed) ~ 0.27% of the time (1 out of 370)
• How often is your manufacturing process out of control?
  • If Pp if > 1 then process may be running within your historical control limits (+/-3s)
  • But if Ppk is < Pp then the process is not centered around the target (too close to either the upper or lower spec)

Many data software packages have ‘quality’ plug-ins
From Research to Development

• Research: discovery, proof-of-concept, technology differentiation
  • Scale: typically small (but not necessarily)
  • should include a look at manufacturing approaches
• Development: can it scale? what will it cost? how fast can it be made? what parts do I need? how does it fit together?
  • Looking at component interaction effects
  • root-cause to find failure-modes
  • must include a manufacturing approach
  • Scale: larger but still not very large

...to Pilot Scale

• Manufacturability:
  • Demonstrating production intent process, equipment
  • Does not mean beyond a coin cell (not about cell form-factor)
• In-house vs. collaborative
  • Can work with a toll manufacturer to prove concept viability but there are risks
Pilot-Phase to Pre-Production

Should be the home stretch...

• If the phase gates were followed
  • APQP w/and FMEA’s (next slide)
• If not...could be learning what you should already know
  • about the product, basic technology or processes
  • Learning at a huge scale and at huge cost!
Advanced Product Quality Planning (APQP)

The product development guide-book

• for the entire automotive supply chain
• Developed by Big 3 OEMs, Automotive Industry Action Group
• APQP and PPAP is a set of rigid rules that your product development, product acceptance process and future production

Is not the same as....
• ISO/TS 16949
• That’ just a ‘certification’ that you have any quality system (including a document control system)

Five manuals, buy them all

1. APQP Introduction
2. Failure Mode and Effects Analysis (FMEA)
3. Statistical Process Control (SPC)
4. Measurement Systems Analysis (MSA)
5. Production Part Approval Process (PPAP)
Technology Transfer; the important human element

Progressing through 5 product development phases will involve a lot of people with diverse skill sets.

• Inevitably scaling-up will involve transferring your know-how to someone else
• People who are good at R&D aren’t necessarily good at production
  • R&D change everything
  • manufacturing lock-in don’t change anything
• Vital that hand-offs are planned, collaborative, transparent

• ‘transfers’ in-house vs. outside/collaborative (toll or JV)
  • Protecting IP is important but so is clarity; finding the balance is key
  • enough detail to be effective
• Be intentional about the human aspect
  • Train your team in the basics of project management
  • Hone conflict resolution skills
Impact of IP (FTO) on product design

Brief history of the LFP IP battle...

- Dec 2005 -- Hydro-Quebec and UT-Austin filed infringement suit against A123Systems
- April 2006 -- A123Systems filed counter-lawsuit and requested reexamination of two cases
- 2008 Goodenough invalidated in Europe
- April 2011 -- Markman ruling in TX courts resulted in narrower-scope on key claims in all reexamined patents resulting in settlement btw all parties
- LiFePO4+C Licensing AG, Switzerland -- set up in 2011 to administer the combined LFP portfolios managing all future licensing
- Includes at least six additional companies
  - Mitsui, Sumitomo, Sud-Chemie, Clariant, BASF, ALEES, Tatung (Johnson Matthey)

- Legal battle was going on through the entire low-cost LFP development and product launches
- **Impacted everything:** phase gate reviews, product specs, launch timing, CAPEX approvals
Importance of Supply Chain

Specialty suppliers are OK for R&D

• Specialty chemical suppliers
  • E.g. American Elements, Sigma-Aldrich
  • Quantities from 10g-2kg (won’t take you to pilot)
  • Lots may be traceable (CoA)
  • Quantities aren’t guaranteed, typically very limited

• Battery inventory vendors (2nd tier)
  • Like MTI (how many of us have purchased from them?)
  • Same issues plus...no traceability, you don’t know who the original manufacturer is; quality can be questionable

...but not for Pilot/Pre-production trials

• $$$, not sustainable or even practical for larger quantities

• Need guaranteed quantities, and scheduling to mitigate the risk in your own program

• Supplier change late in development is a **HUGE** risk
  • Changing a component (anode type, cathode vendor) is going to mean a change in your product performance
  • Finding a “fix” or reworking your battery will force a delay in your schedule
    • Usually one ‘phase’ cycle (repeat phase 2“)
Supplier Quality Audits

Supplier quality impacts your quality

- If your component supplier’s makes a change (intentional or not) it’s going to impact both you and your customer
  - Routine audits, inspections, on-going quality improvement initiatives
  - A ‘good’ relationship with your suppliers makes this on-going give-and-take at least bearable
Where battery materials come from...

Visiting a key supplier (maybe the 10th time?)

had just signed our first supplier contract
Cost of Quality

R&D tests turn into QC gates

• Research tools like SEM, EDS, TEM, XCT, TOF-SIMS are cool, bread-and-butter for R&D
• But imagine running TEM, XCT on pilot production scale
  • What kind of tests are important enough to ‘qualify’ and release product to your first customers
  • Cheap, fast enough to be practical
  • Just as effective at catching outliers

Product design targets turn into product specifications

• Your targets in early product development are somewhat flexible (early days)
• At each phase gate the acceptance criterion should get tighter
• Remember: $3\sigma \rightarrow 0.3\%$ defects
  $6\sigma \rightarrow 2$ppm defects
• Multiple that to a 7000 cell BEV-pack
  • 2ppm defective cells translates to
  • 14/1000 packs could contain a defect cell
  • Hence 100% inspection
Design (early) for Manufacturing

Take-home message

• For the technology to be widely adopted it has be accessible
• Adopt processes (early) that are scale-able and flexible
• Understand root-cause of issues (mechanistic) and design your product/process to eliminate
• **Poka-yoke ポカヨケ**
  • No matter how good the technology is, the product is only as good as you can make it
• Design products with reasonable tolerances
  • That means limit testing and validation by customer
• Develop good measurement systems
  • both accurate and easy to implement
Thank you

“working” trips to China