From Bench to Manufacturing

An LFP battery (product development) story

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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

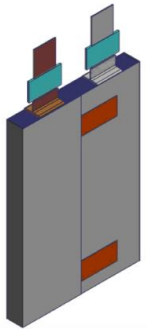
A coin cell is NOT your product

Cell to battery pack (200-300 mile BEV)

10-12 Wh

~7k 18650's → 85 kWh pack

< 50mWh



70-100 Wh

~1.2k 30Ah → 120 kWh pack

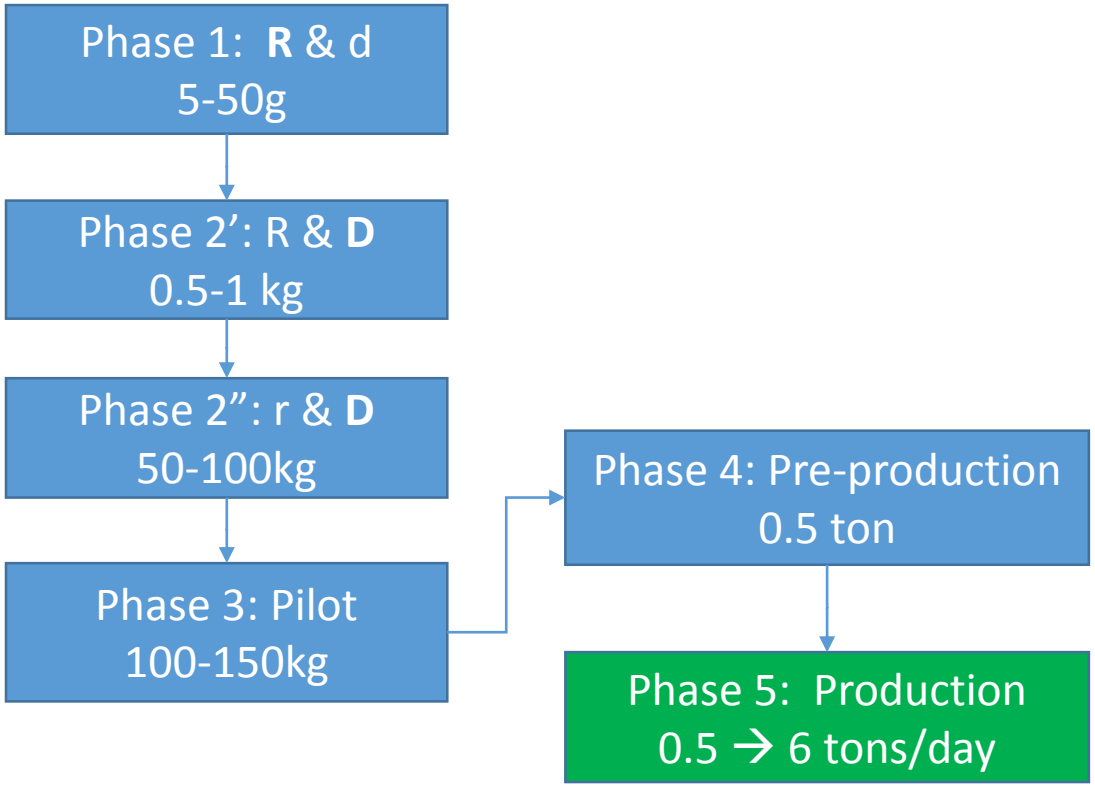
- Coin (button) cell is a first step
  - Simple test platform demonstrates: voltage window, hysteresis, specific capacity, reversible cycle life (0^{th} order)
- But many metrics don't scale from coin to a real product application
  - Can not translate: thermal management, volumetric density, total impedance, 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



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

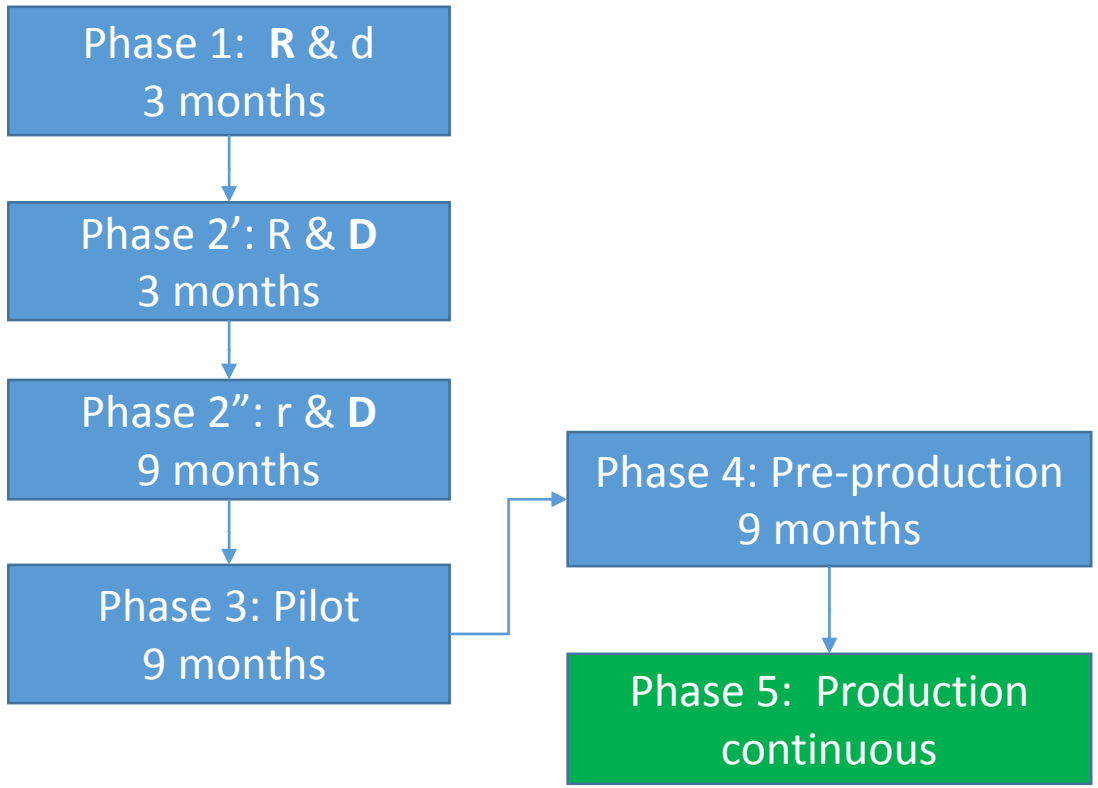
…another new product cycle

- 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 ($$$)

not one giant leap;
many tiny steps

5g samples

250kg super-sacks

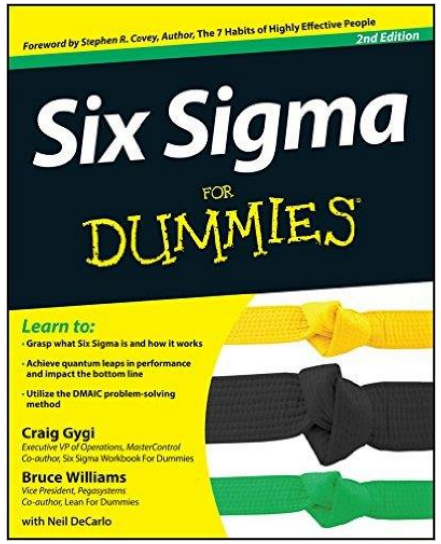
A rude awakening…

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 1year, 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.



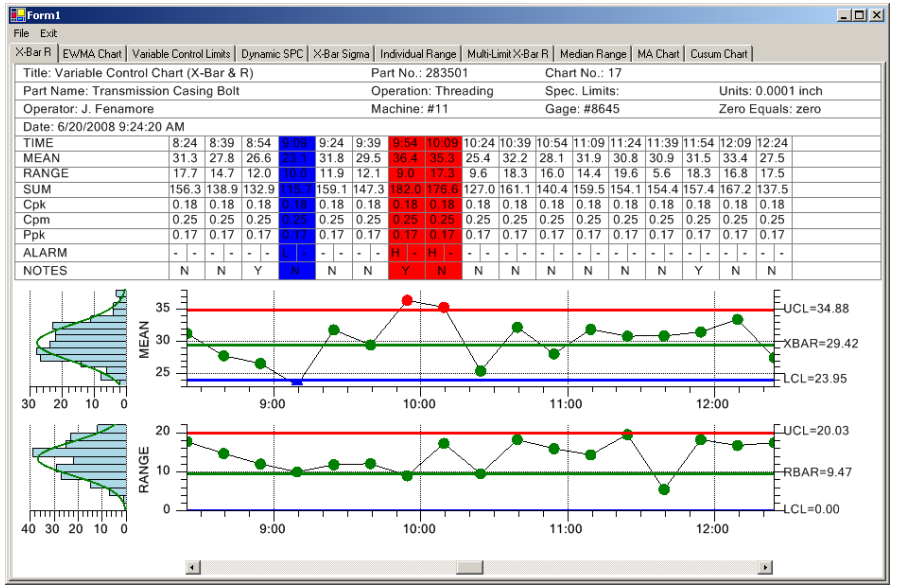
The great results didn't matter….
the message I heard was "you're a dummy."

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



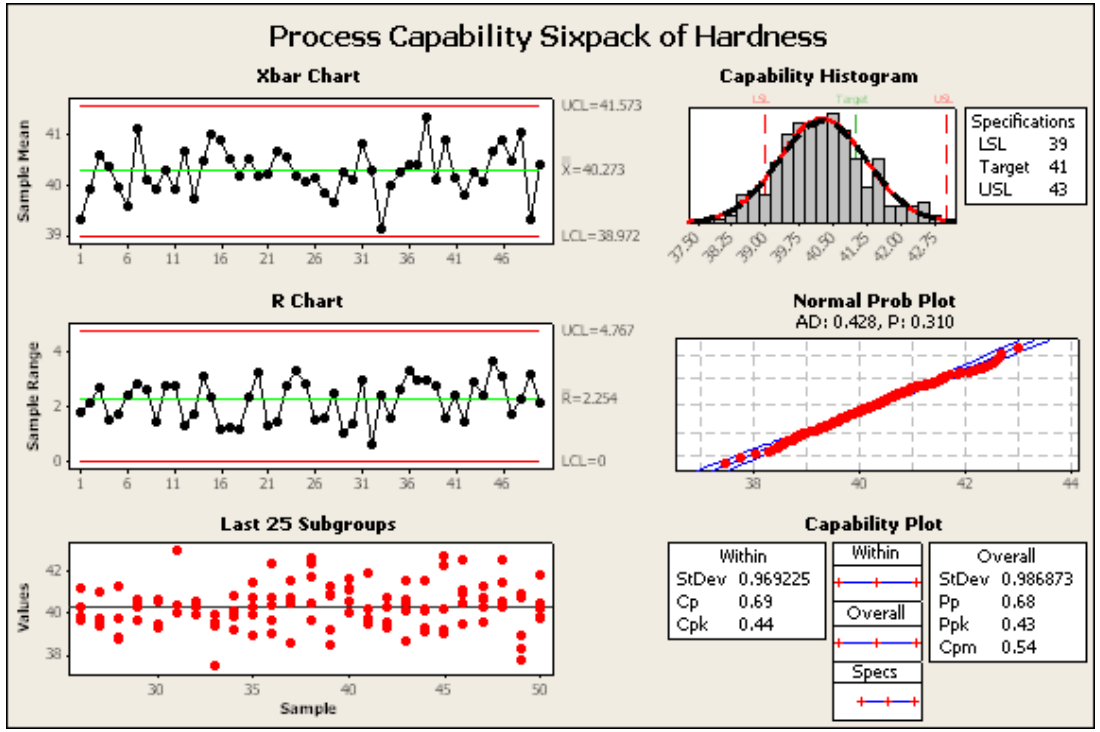
…not that kind of six-pack

Process capability index (Cpk)

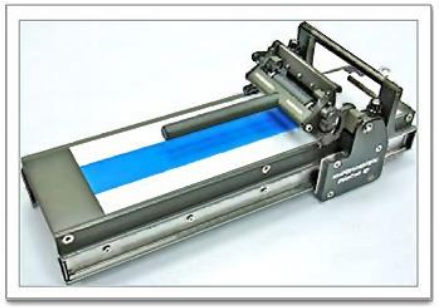
Process performance index (Ppk)

- 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



Research → Development → Pilot Scale



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.

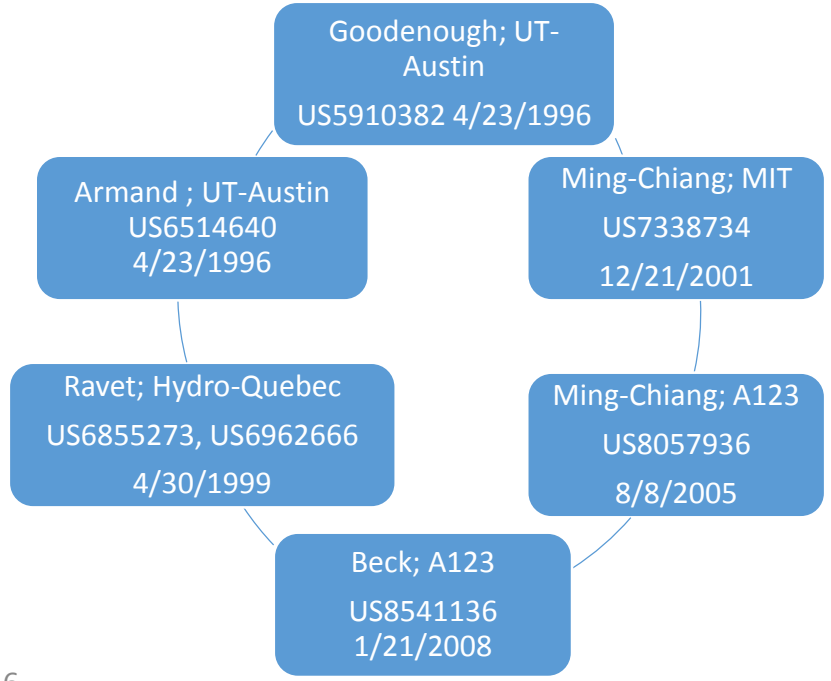
- Inevitably scaling-up will involve transferring your know-how to someone else
- People who are good at R&D aren't necessarily good at production
  - R&D change everything
  - manufacturing lock-in don't change anything
- Vital that hand-offs are planned, collaborative, transparent
- 'transfers' in-house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

Scrap iron

Phosphorite ore

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: 3σ → 0.3% defects
  6σ → 2ppm 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