Quantitative Failure Mode and Effect Analysis for Battery Diagnosis

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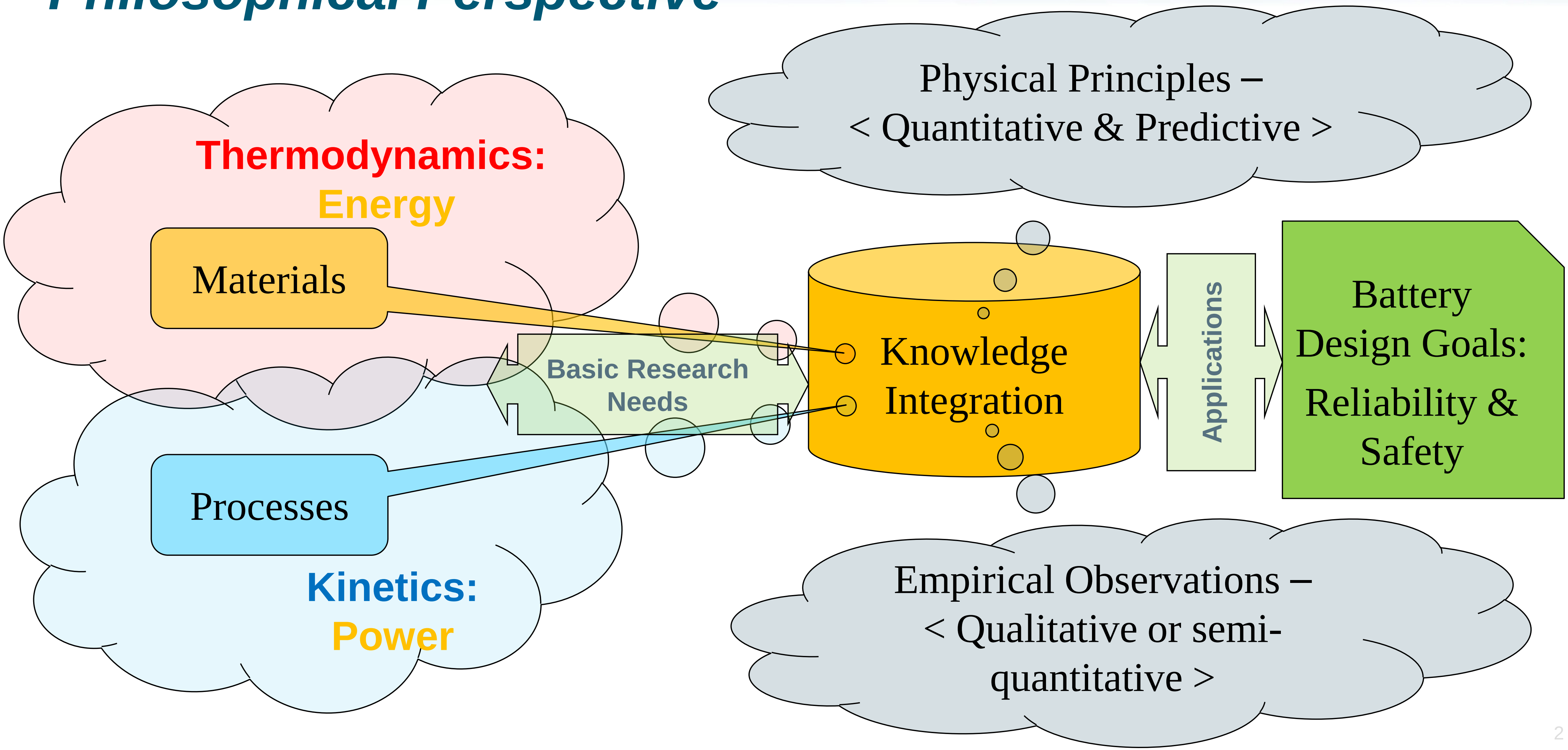
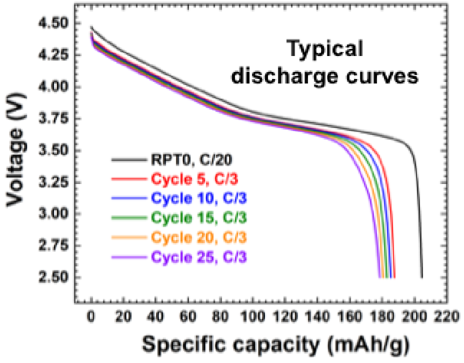
Philosophical Perspective

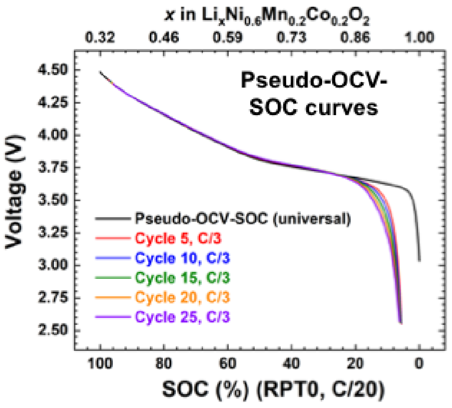


From Failure Analysis to Life Prediction

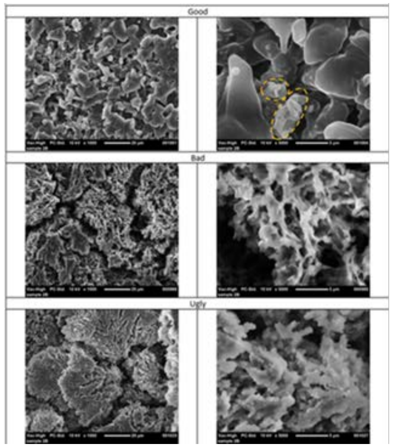
Thermodynamics:

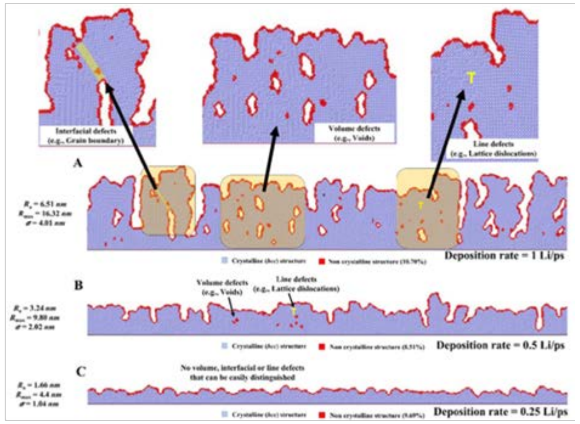


Experimental Conditions

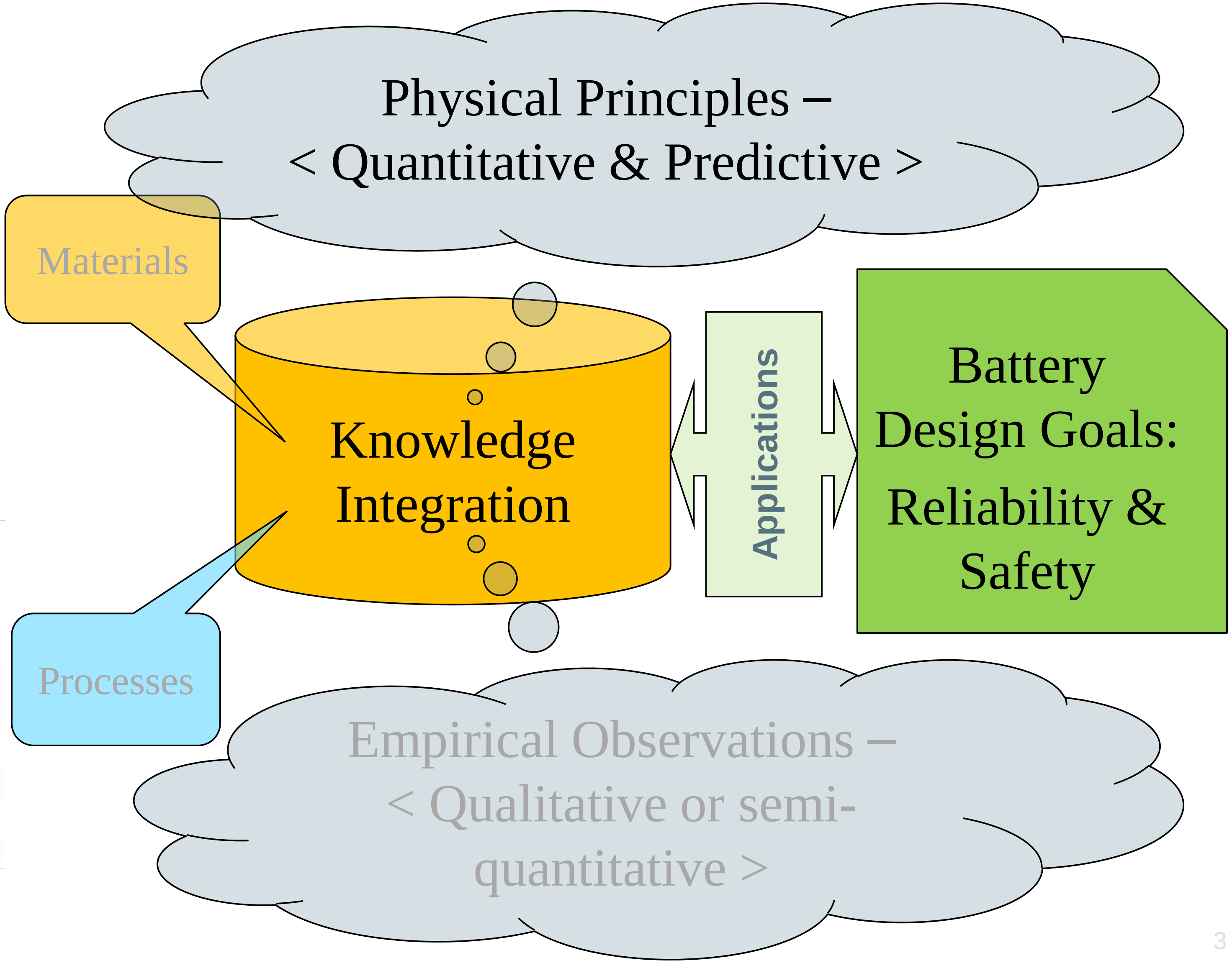


State of the System





Kinetics:



Outline

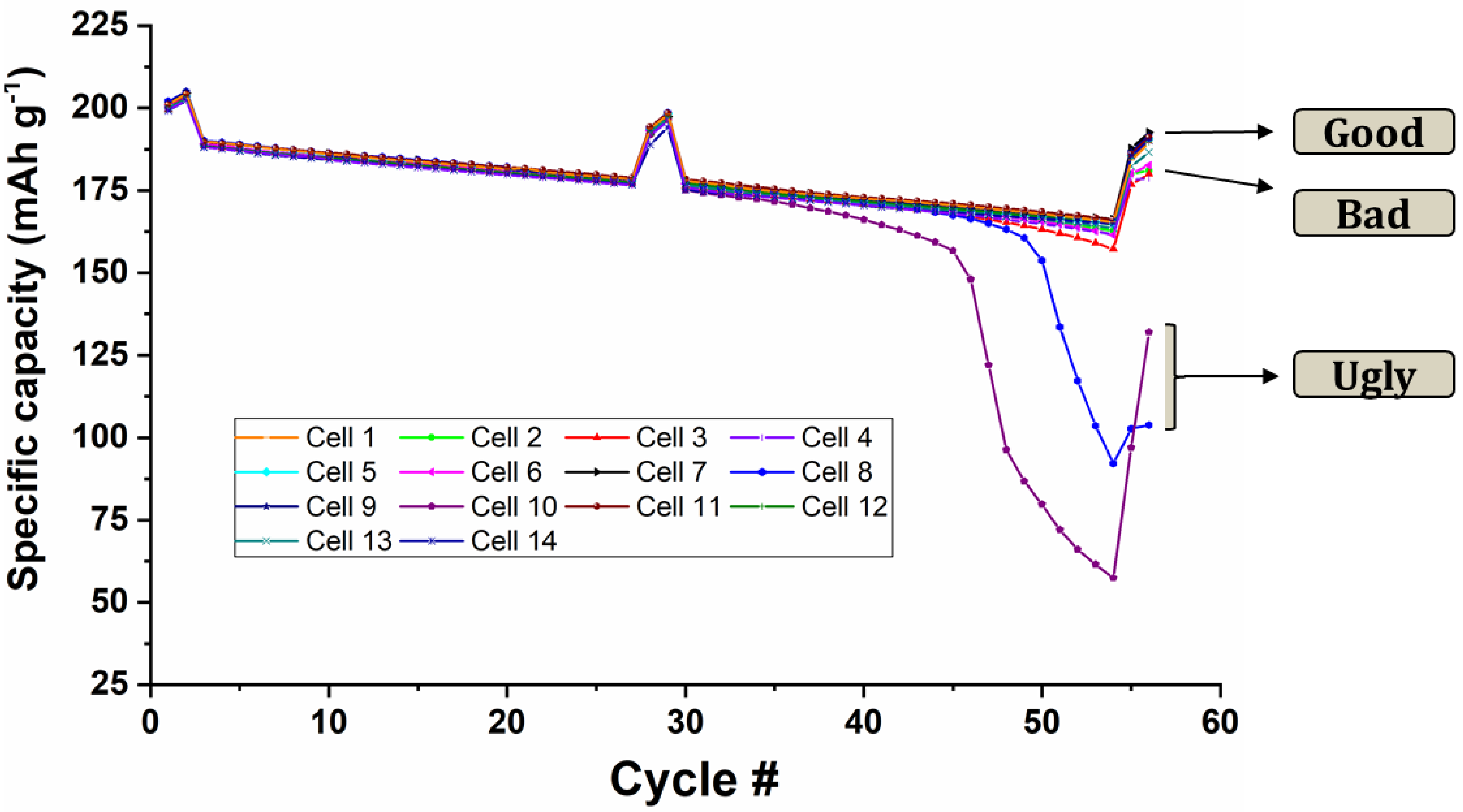
To support quantitative analyses on battery reliability and safety:

- **Needs: Failure analysis (FA) and failure mode and effect analysis (FMEA) is important to guide cell design and qualification.**

- **Approach: Quantitative electrochemical analytic diagnosis (eCAD) to address currently qualitative diagnosis and to significantly accelerate progress in cell design for better cycle life, reliability and safety**

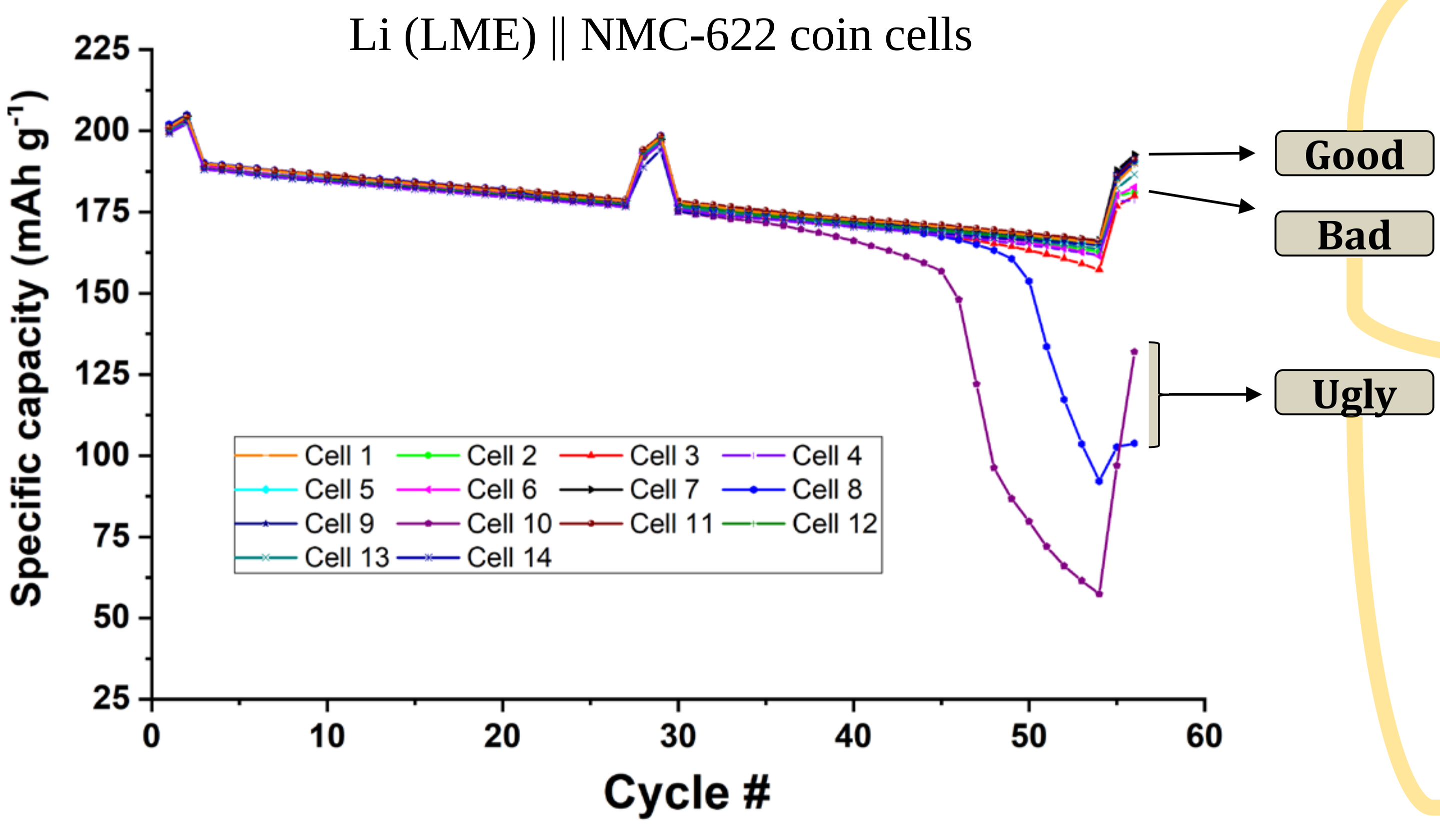
- **Accomplishment: Quantify capacity fading modes and effects during life cycle of any individual rechargeable Li battery cell**

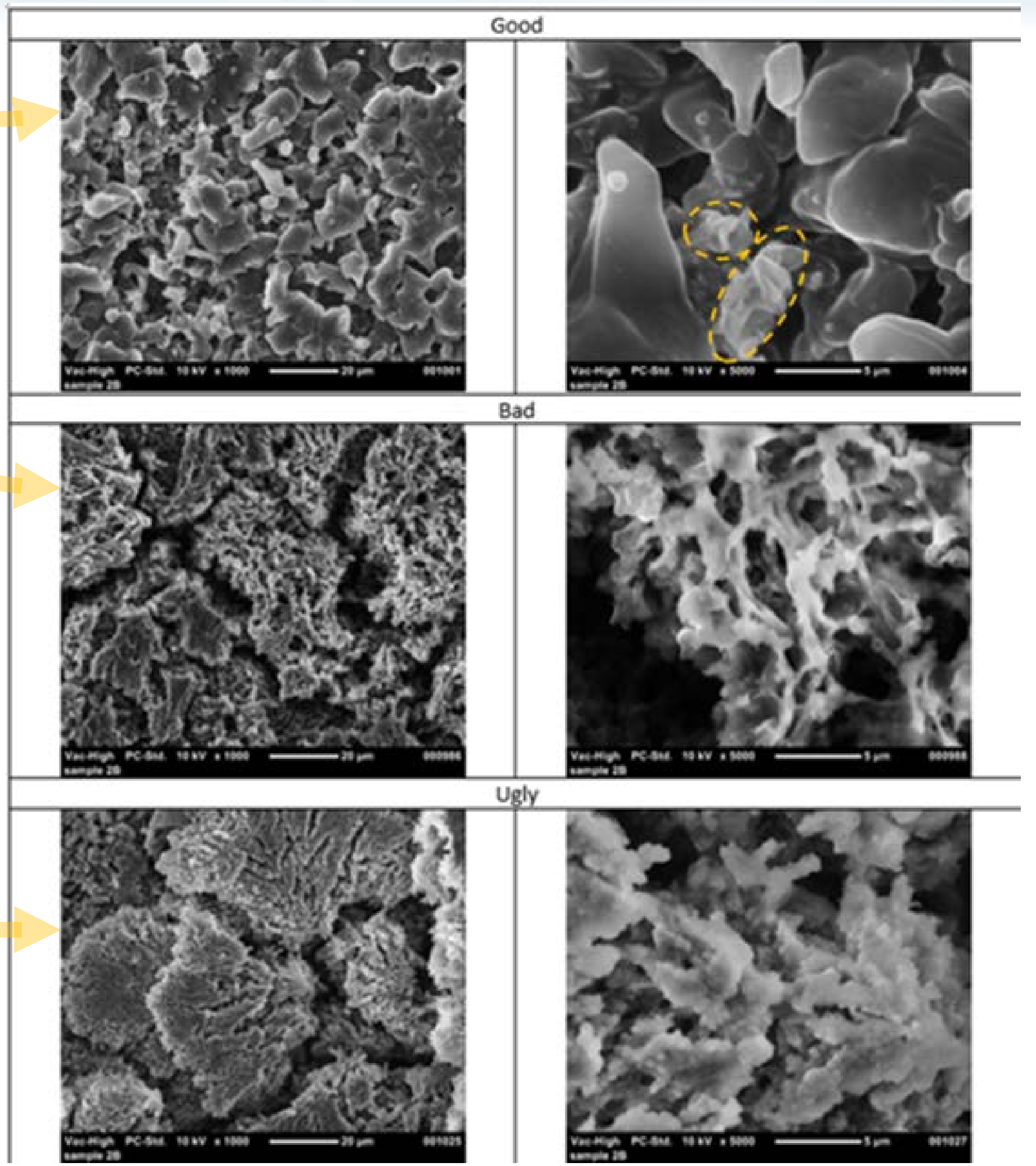
- **Goal in Future Work: Develop a better strategy to quantify durability, reliability and safety in order to enable precise control of cell design and production**



Exemplified by an eCAD Analysis on 14 Li || NMC-622 cells of the same build

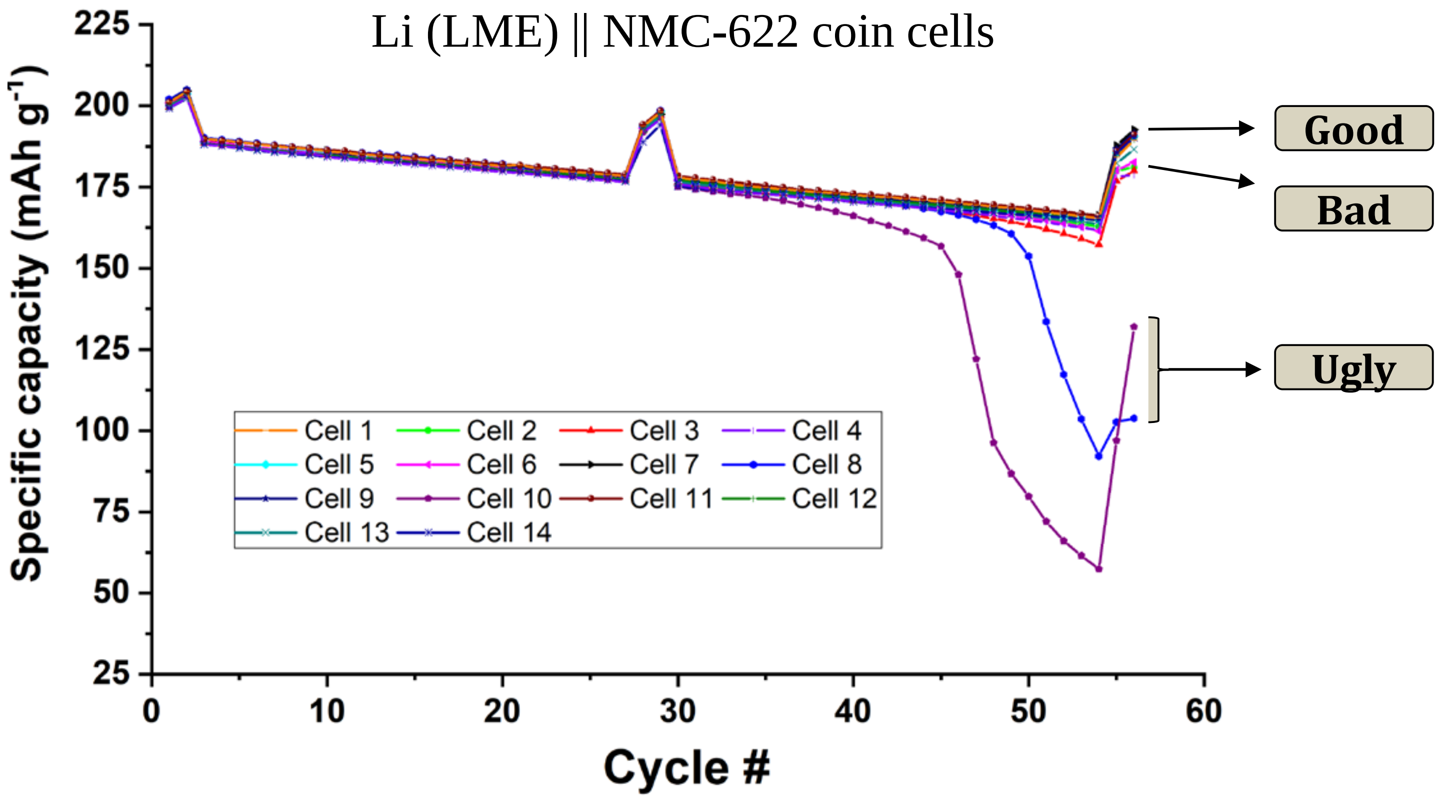
Cycle Life in Li || NMC Cells





Cycle life sensitively depends on Li inventory

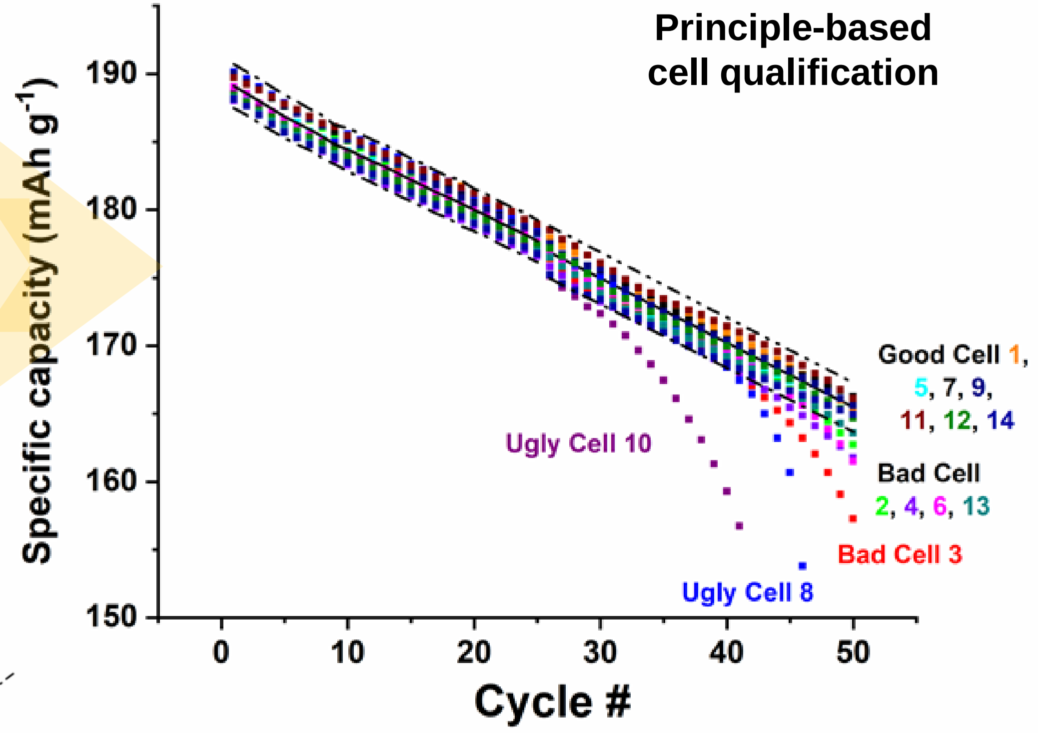
Cycle Life in Li || NMC Cells

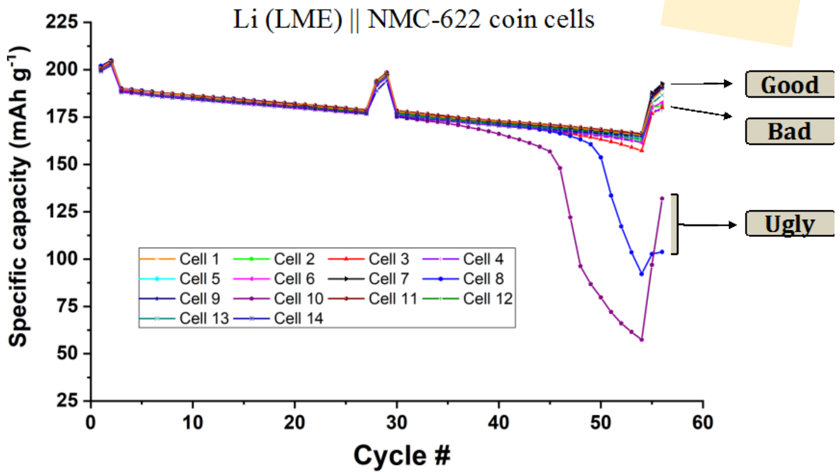


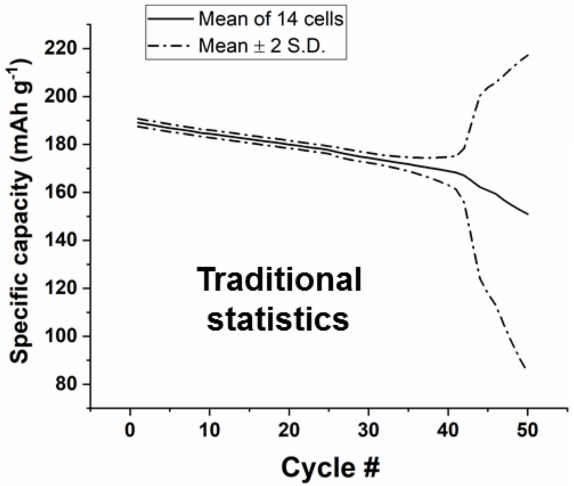
- **Consistency in 14 cells offers an excellent basis for eCAD**
- **Complete life cycle revealed from Good to Bad and Ugly**
- **Full analysis on failure mechanism to identify every single attribute to capacity fade**
- **Quantitative results for all capacity fade attributes**
- **Uncover and quantify Loss of Li Inventory (LLI) for charge and discharge regime, respectively, which does not appear in charge retention measurements**
- **Life prediction for individual cell**

Cycle Life in Li || NMC Cells

- **Principle-based cell qualification with statistics**
- **Quantitative down to individual cells, cycle-by-cycle**
- **Failure mode and effect analysis (FMEA) with quantification**
- **Solid basis for individual cell model for prediction**

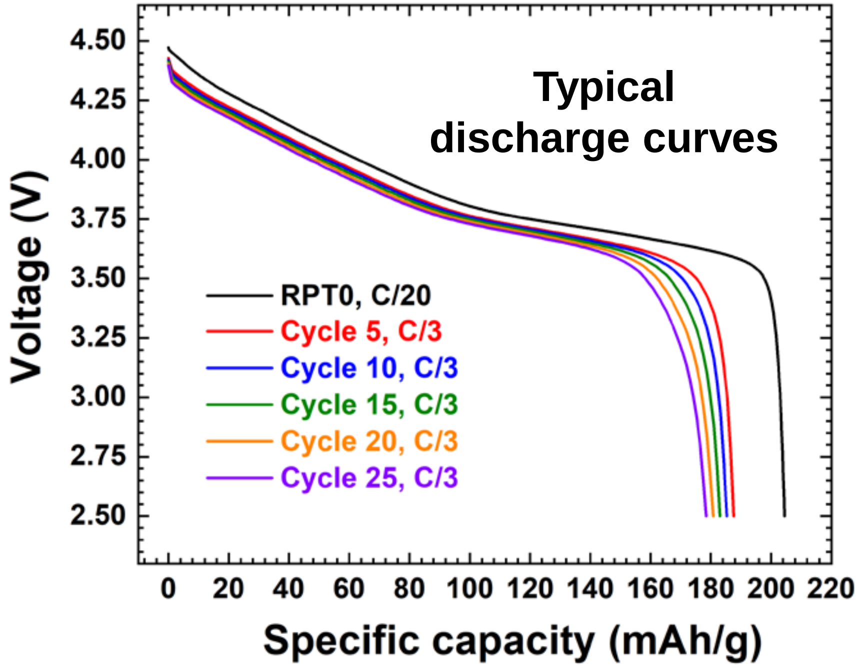




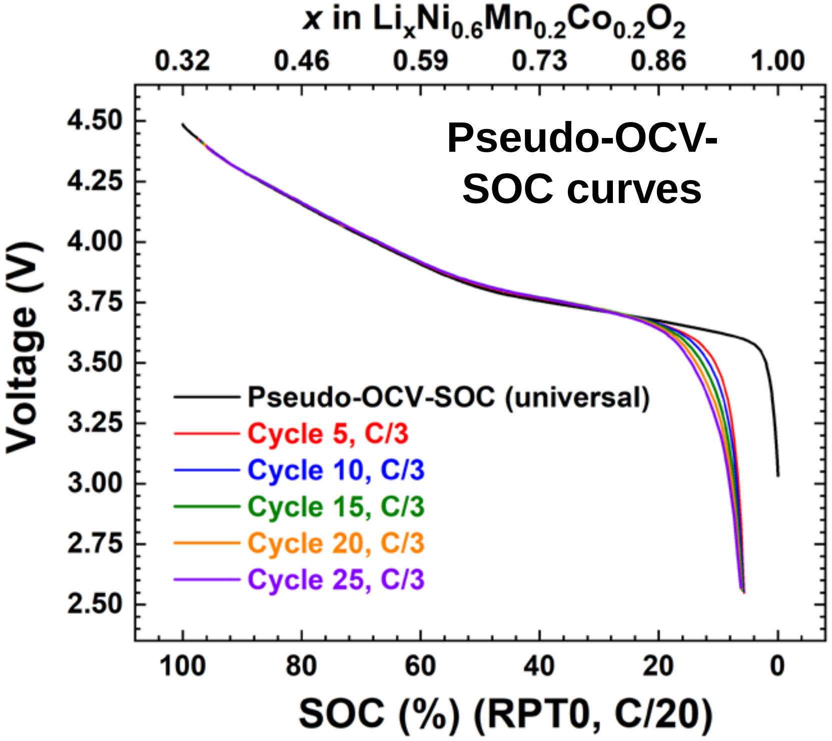


State of Charge (SOC)-based Performance Analysis

- **Remove bias from experimental conditions to reveal true SOC correspondence — Separate thermodynamic and kinetic attributes**



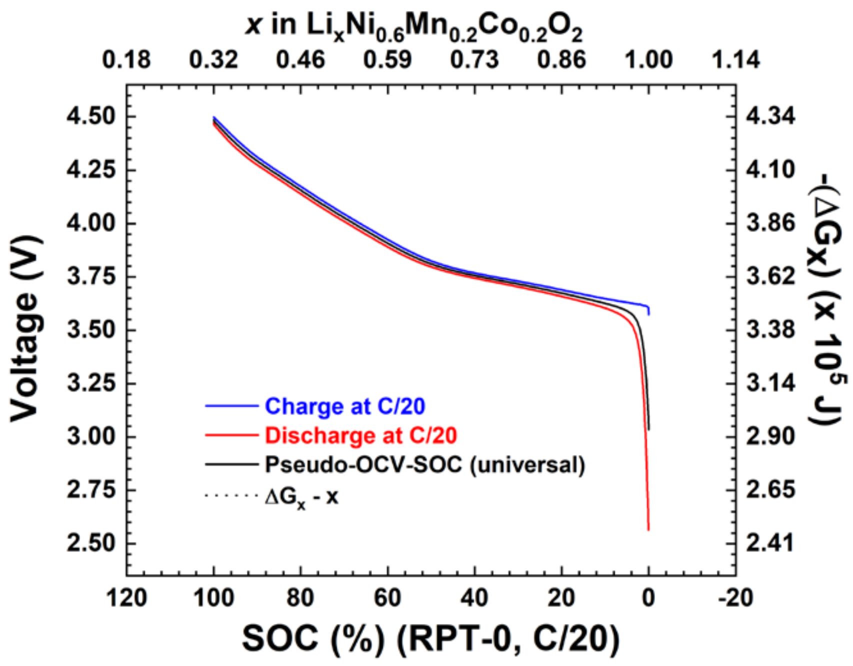
Experimental Conditions



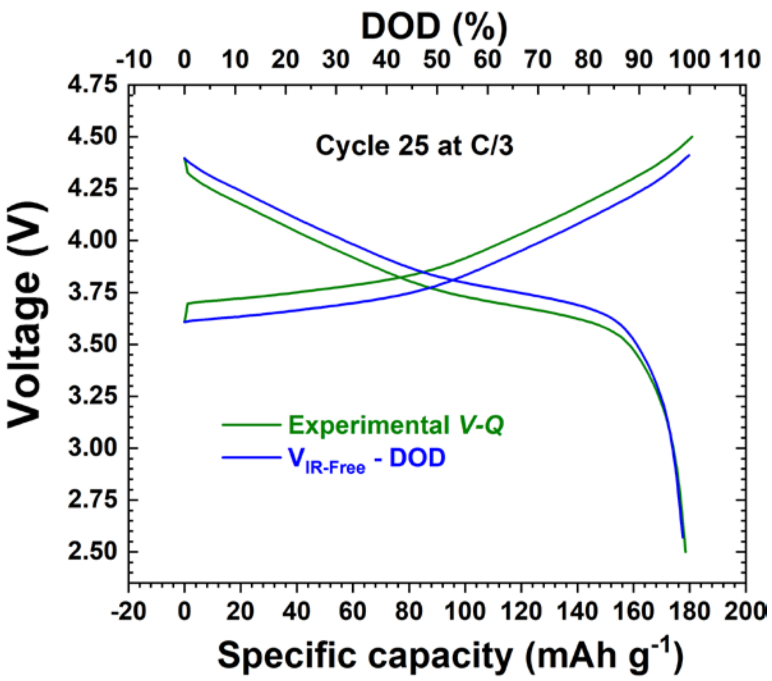
State of the System

Convert Discharge Curve to Voltage vs. SOC Relationship for Capacity Fade Analysis (CFA)

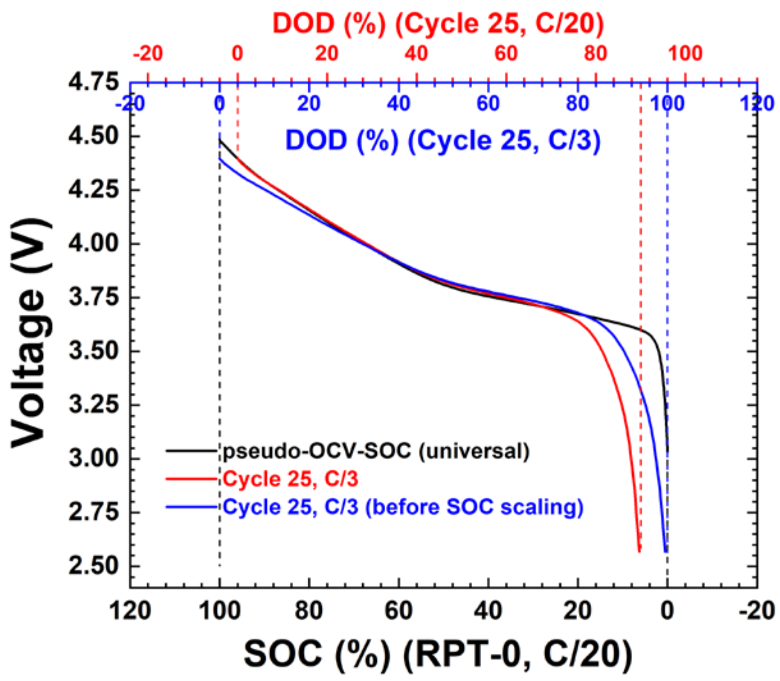
(a) Derive the universal *OCV-SOC* curve



(b) Remove polarization & scale to DOD

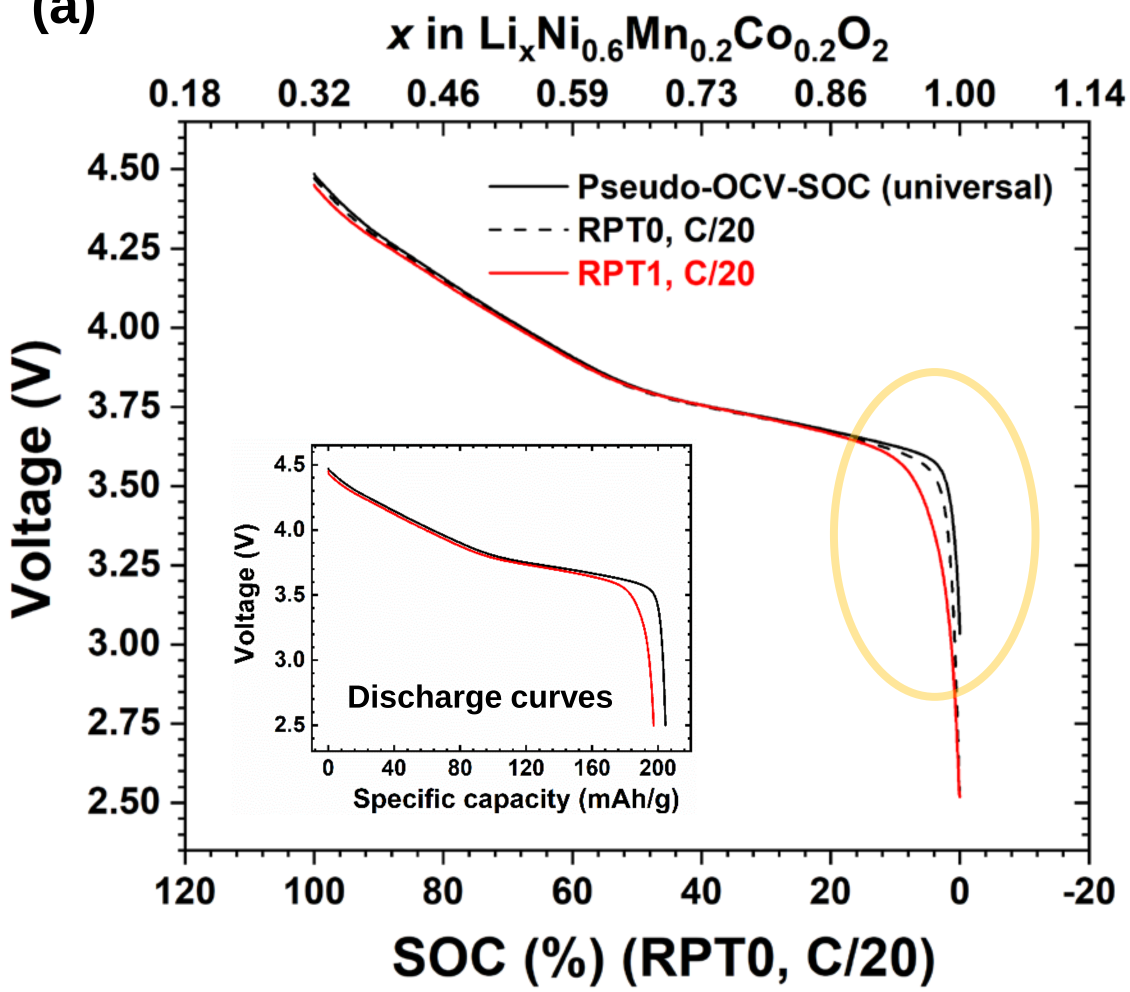


(c) Proper scaling of SOC from DOD

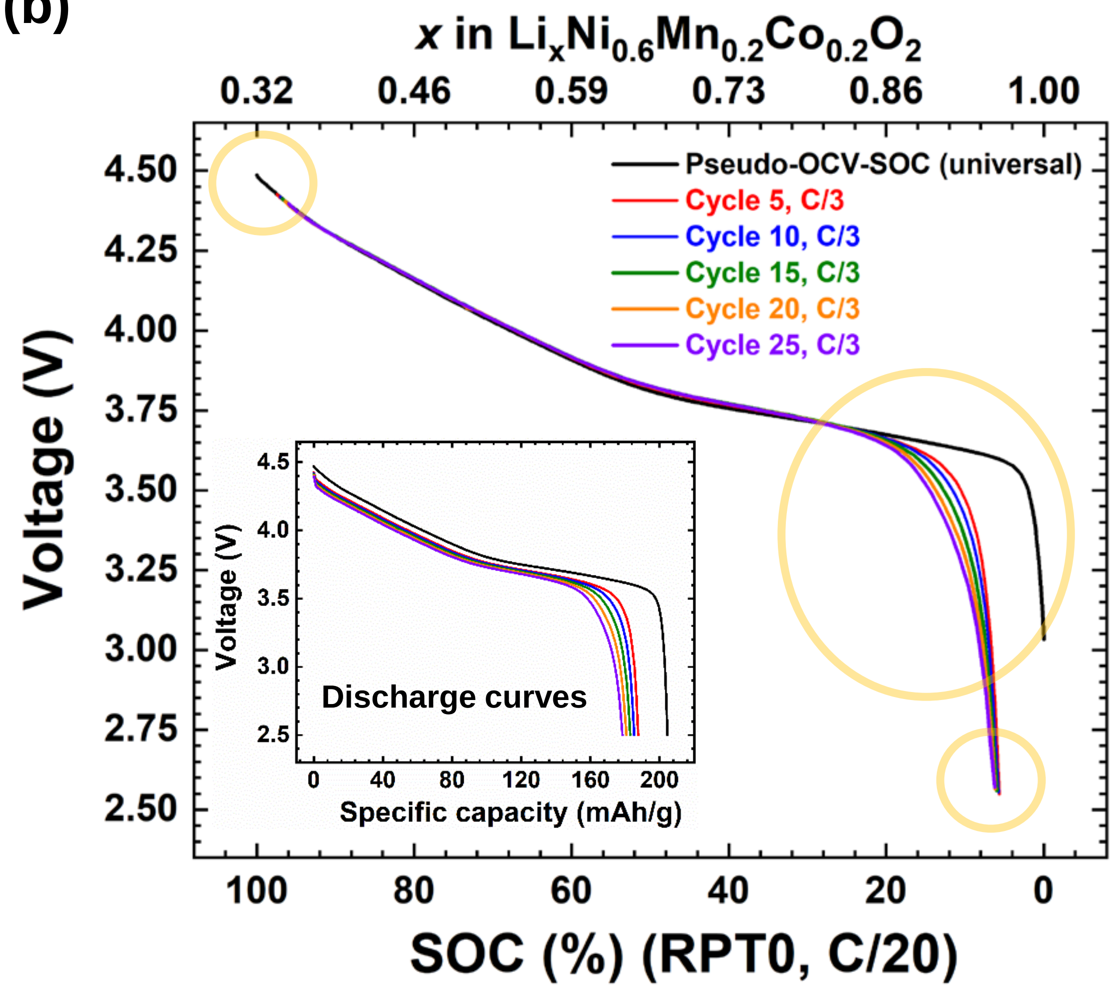


Rate Dependence of Cell Aging Reflecting Capacity Fade Attributes

(a)

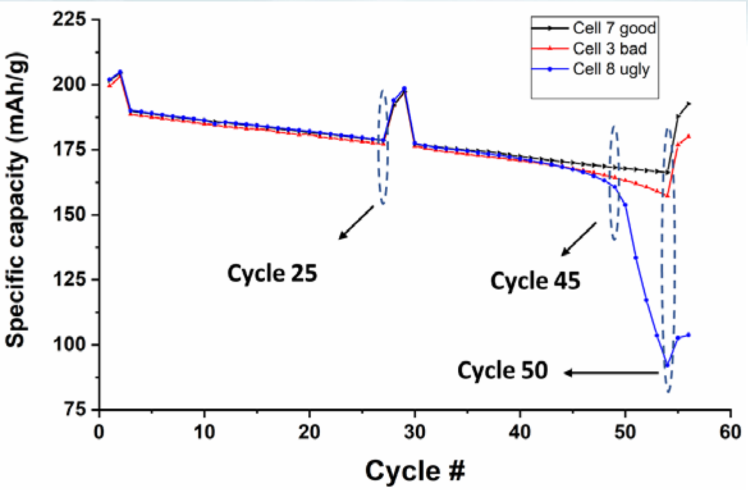


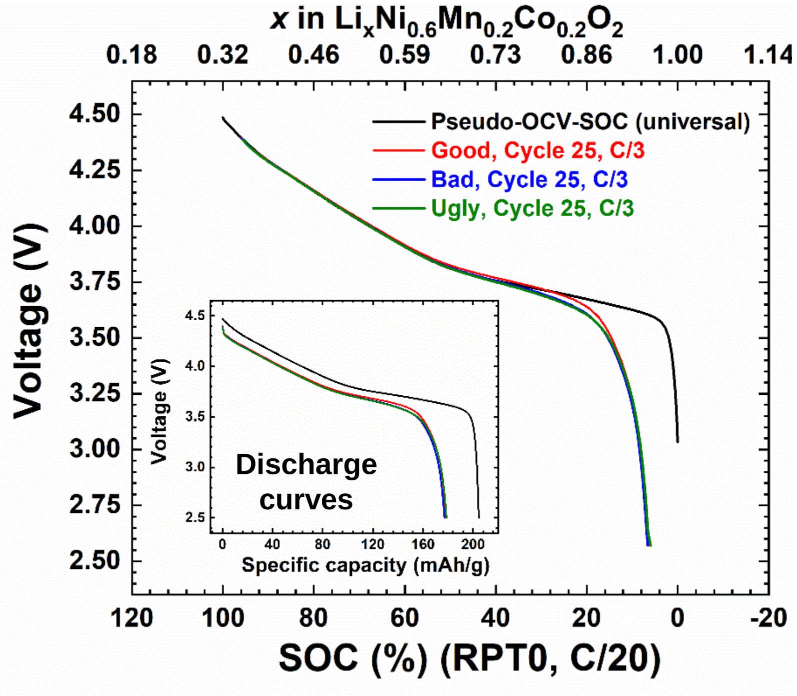
(b)

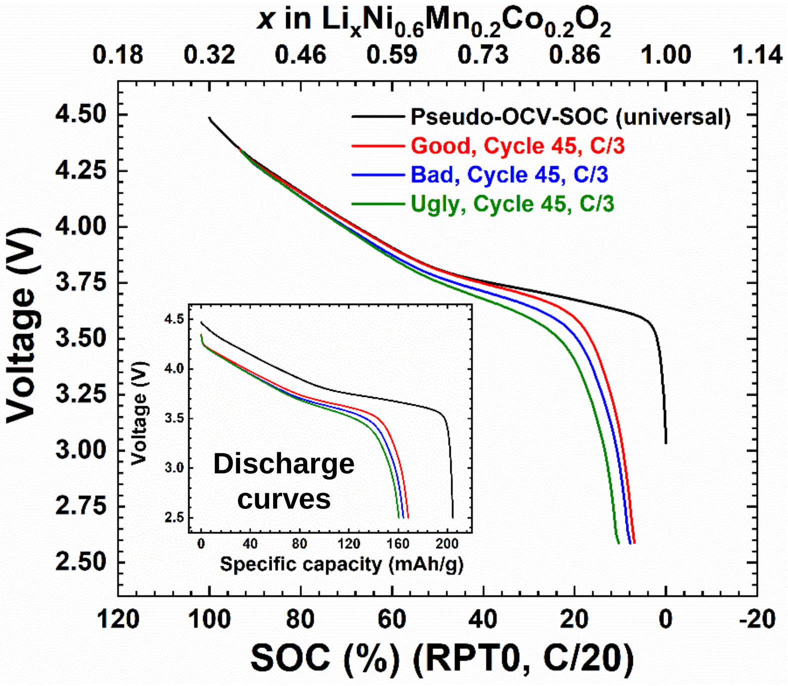


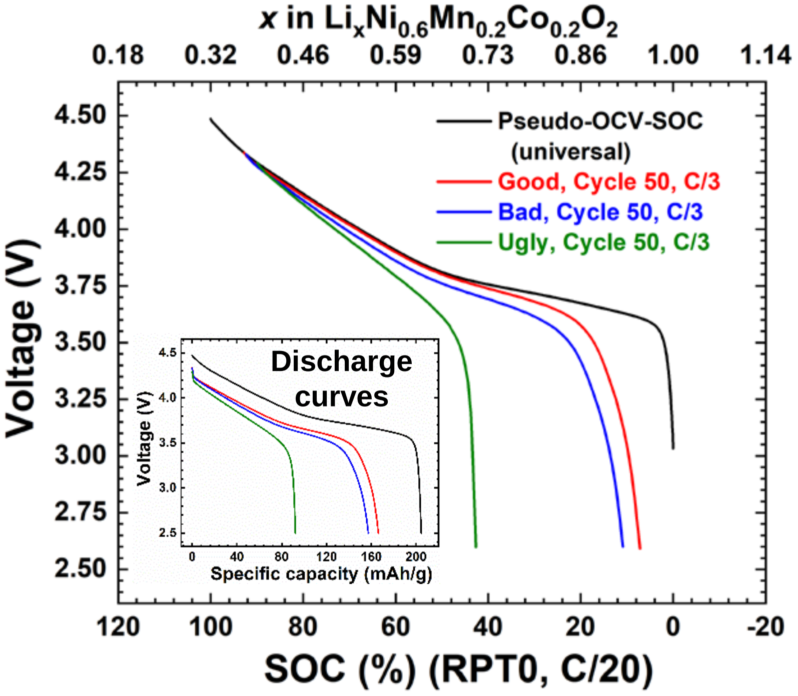
Failure Analyses on Cell Variability

- **Complete life cycle**
- **Cell-to-cell and cycle-by-cycle**
- **Remove NMC influence to reveal LME issues**



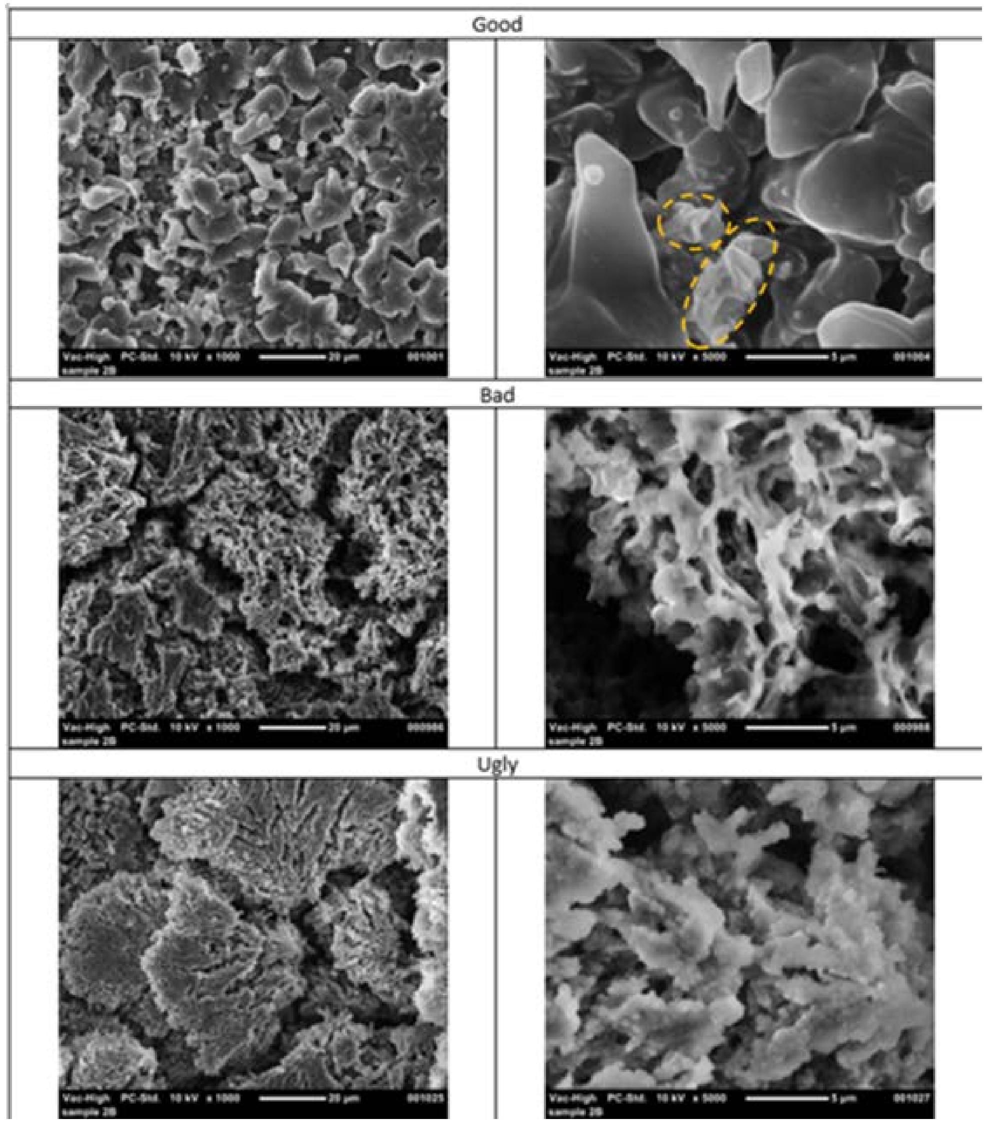






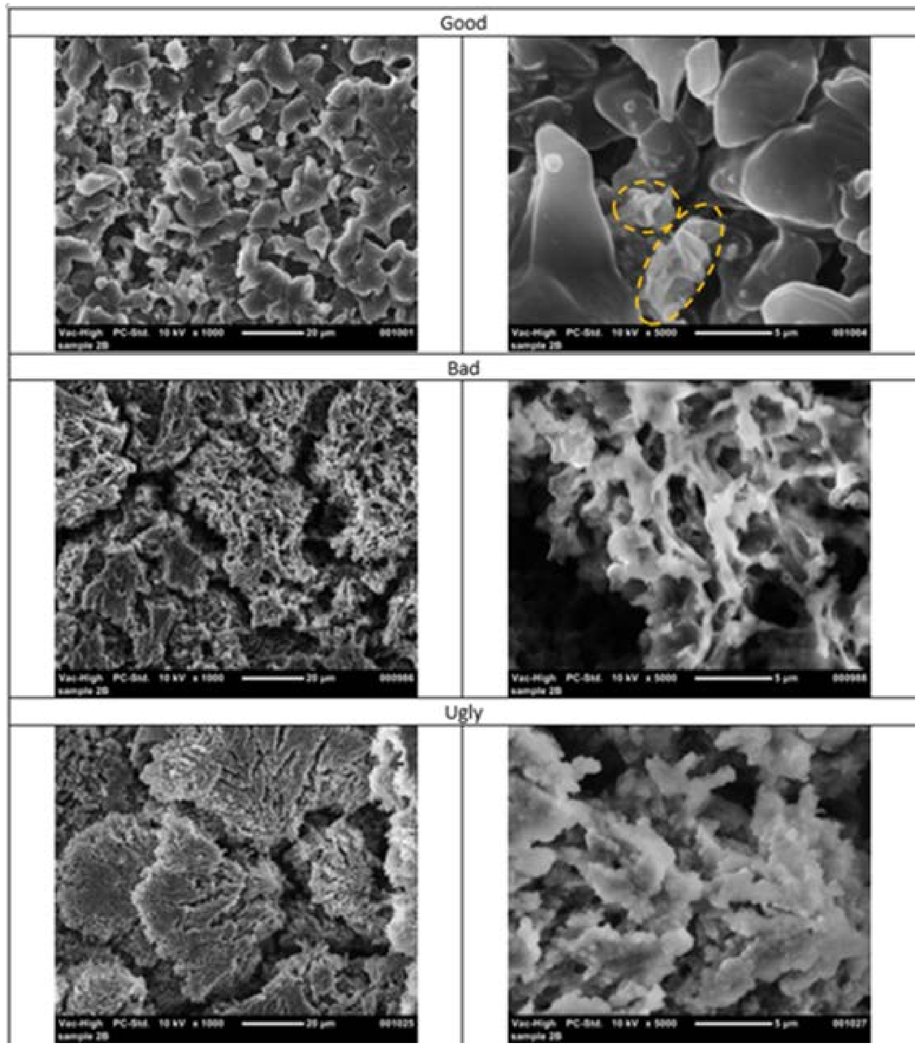
Li Anode Morphology

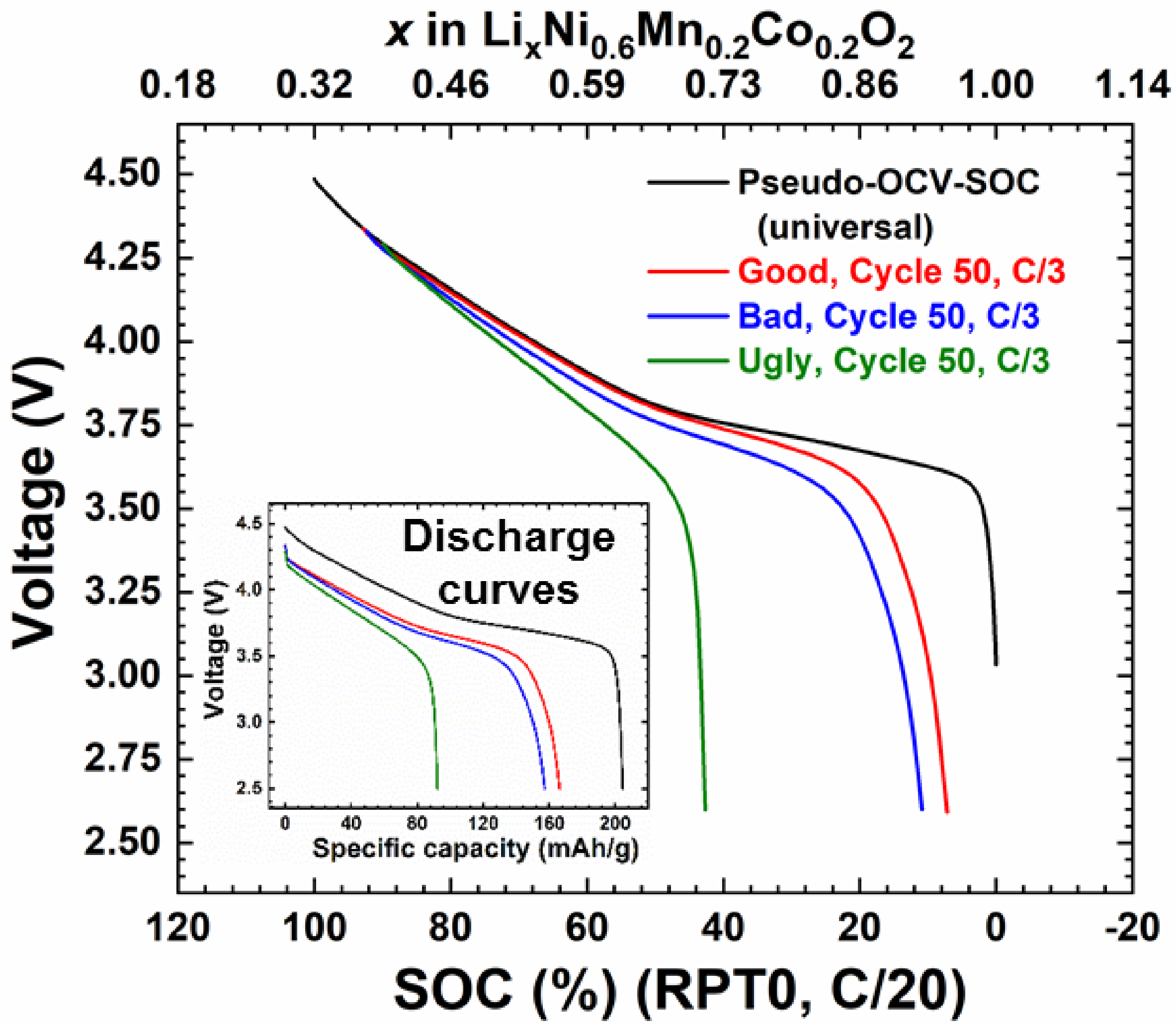
1. **Good cell —Platelet morphology, homogeneous stripping of Li — good reversibility & less inactive (dead) Li**
2. **Bad cell —Sponge morphology, high porosity with deep pits and trenches —charging effect is indicative of inactive Li (dead Li), implying much increased electrolyte consumption from that of Good cells**
3. **Ugly cell —Coral reef like morphology with high content of inactive Li and heavy SEI coating — indicating very limited Li inventory to generate useful capacity**



SEM images of Li metal electrode of the Good, Bad and Ugly cells at the end of life

Relate Failure Modes to Li Anode Morphology

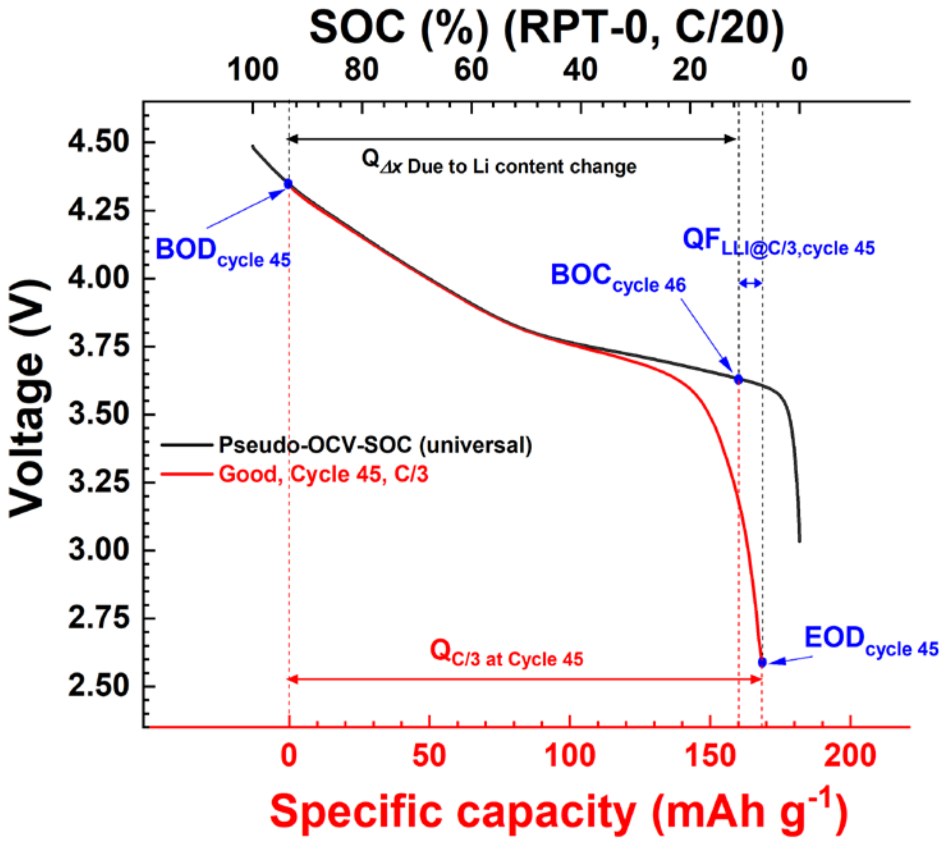


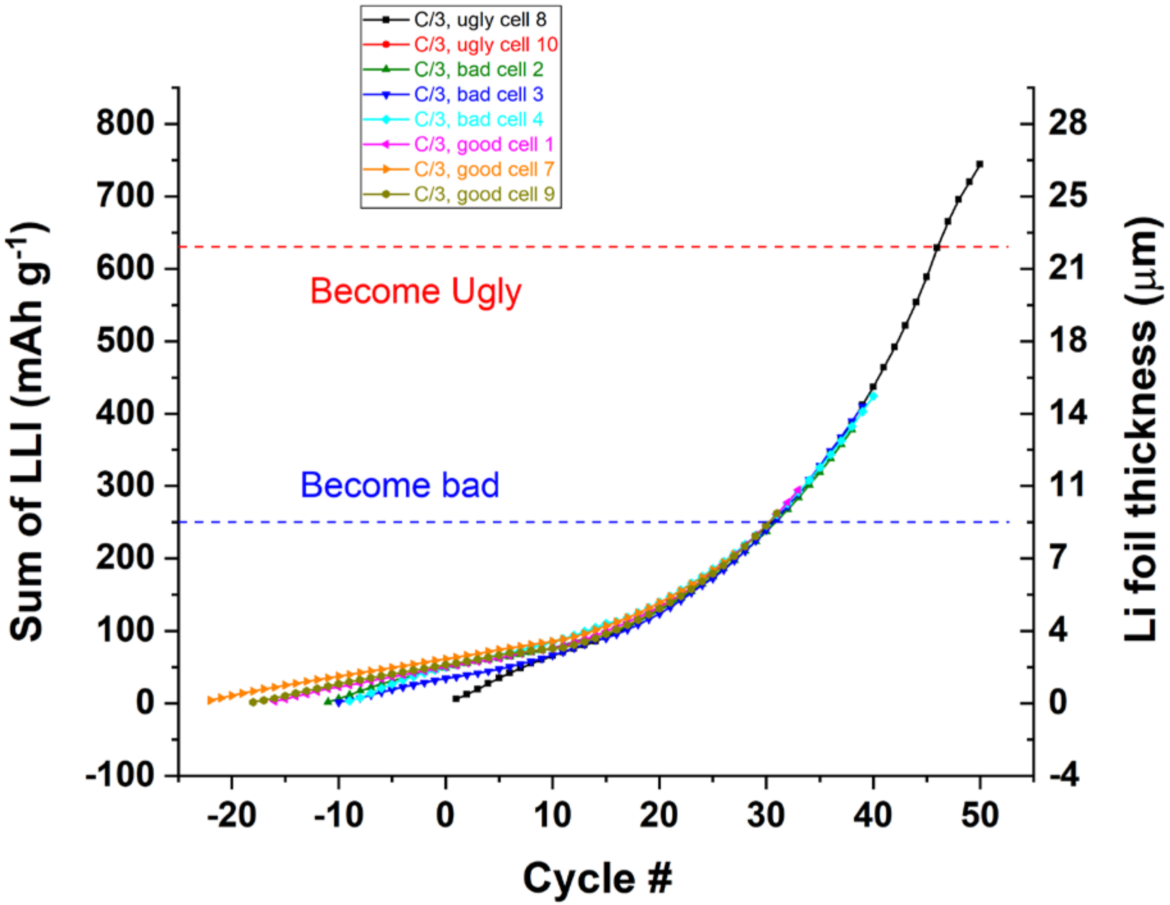


SEM images of Li metal electrode of the Good, Bad and Ugly cells at the end of life

Quantify LLI for Early Life Prediction

$$LLI = Q_{\Delta x} - Q_{tester}$$





The left-axis Y is in mAh/g base on NMC mass (0.011764g).
The right-axis Y is Li foil thickness d in μm, d = (LLI) *0.011764*10000 / (3860*1.603*0.534).
the coin cell area is 1.603 cm^2, Li density 0.534 g/cm^3, Li specific capacity 3860 mAh/g.

Goals and Future Work

- Applying electrochemical analytic diagnosis (eCAD) as a tool for material, electrode and cell performance analysis in cell designs to establish a library (database) for developing quantitative metrics for cell design, production, and BMS.
- Enable a combinatorial approach for a cradle-to-grave feedback loop to modernize cell design, development, production, operation, re-purposing, and recycling.
- End-to-end, streamlined battery control and management (BCM) based on materials properties, electrode architecture, electrolyte composition, cell balance, environmental aging, operational stress, and control strategy.
- Identify sensitive parameters for long cycle life design and operation.
- Establish a quantification tool for reliable cycle life prediction, cell performance management, and safe operation of battery systems.