Extreme fast charging: Identification of failure modes and routes to improve performance

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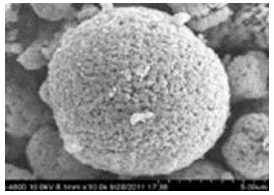
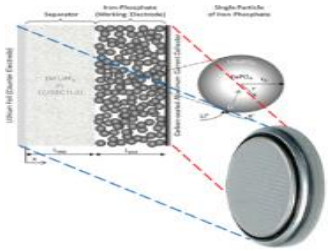
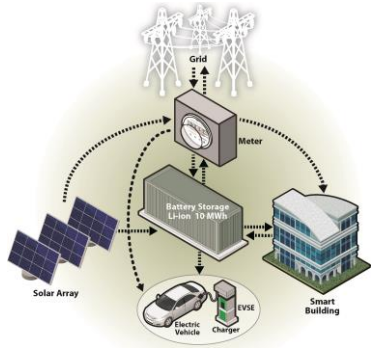
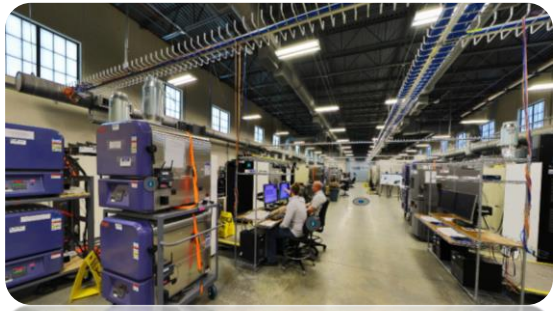
Energy Storage and Electric Transportation at INL







Molecular Material Studies ***Advanced Battery Systems*** ***Future Electrified Mobility Systems***



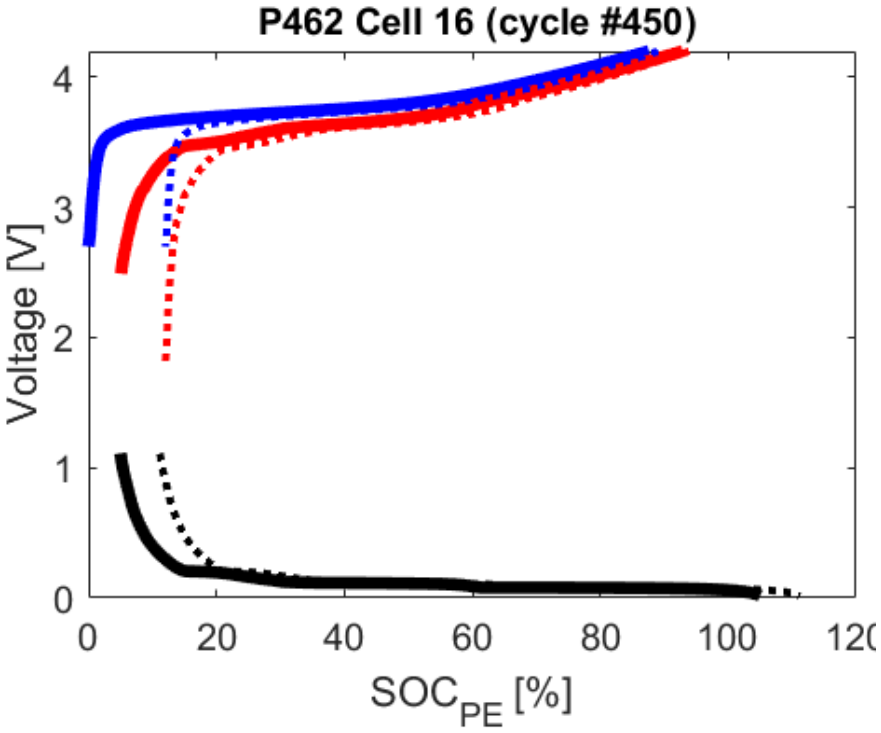
Battery Test Center (BTC)

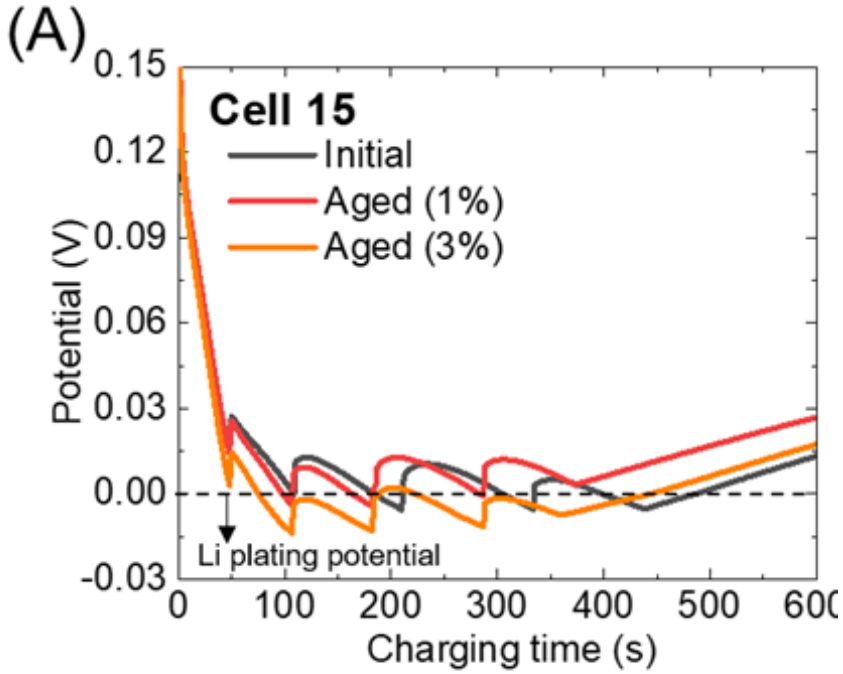
Non-destructive Battery Evaluation Lab (NOBEL)

Electric Vehicle Infrastructure Laboratory (EVIL)

Kim et al., *Energy Storage Materials* (2022)
Chinnam et. al *ACS Applied Energy Materials* (2021)

Battery Aging Due to Fast Charge



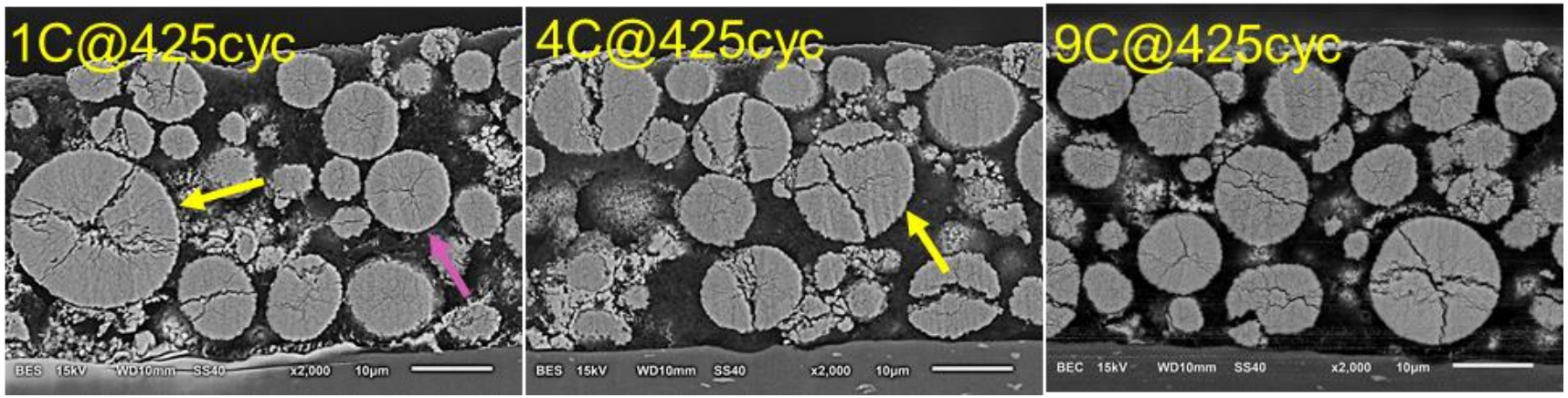


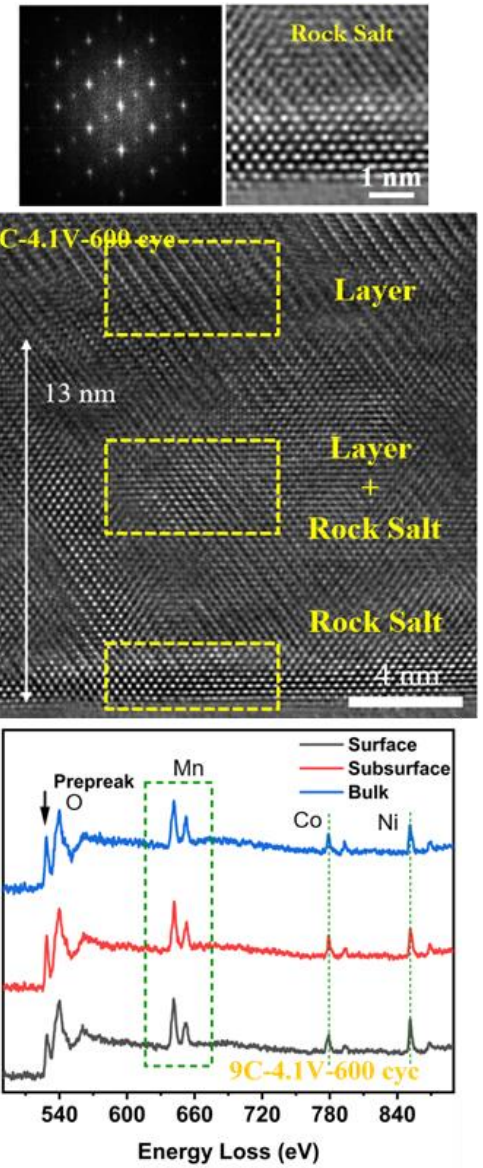
- Li plating is typically only partially reversible
- Results in electrically isolated Li – Eventual loss of capacity and performance

AGING AT THE POSITIVE ELECTRODE

NMC532 and 811 post-test: Aging mechanisms

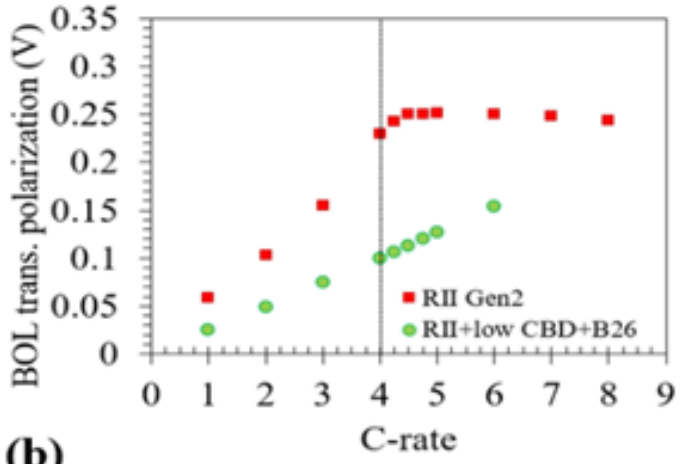
- Interprimary particle separation (IPPS or cracking) with distinct evolution.
- NMC811 better at retaining performance enhanced electronic conductivity
- Bulk structure remained layered. More surface reconstruction at higher C-rates.





Tanim et. al. *Energy Storage Materials (2021)*
Tanim et al. *Adv. Energy Materials (2022)*

Post-tests were performed at Argonne



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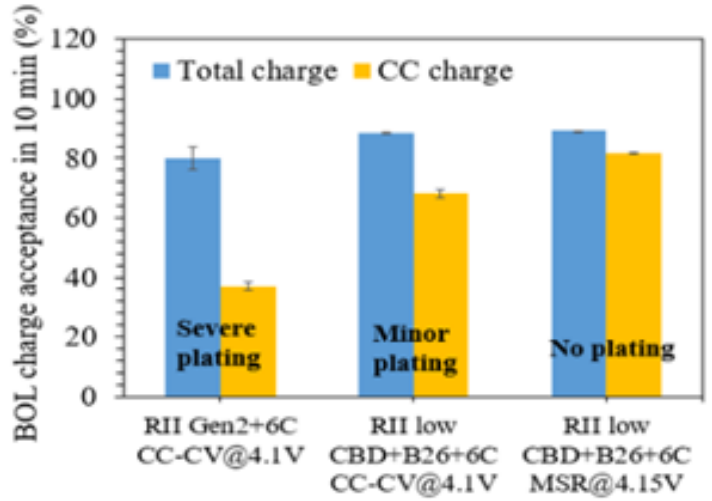
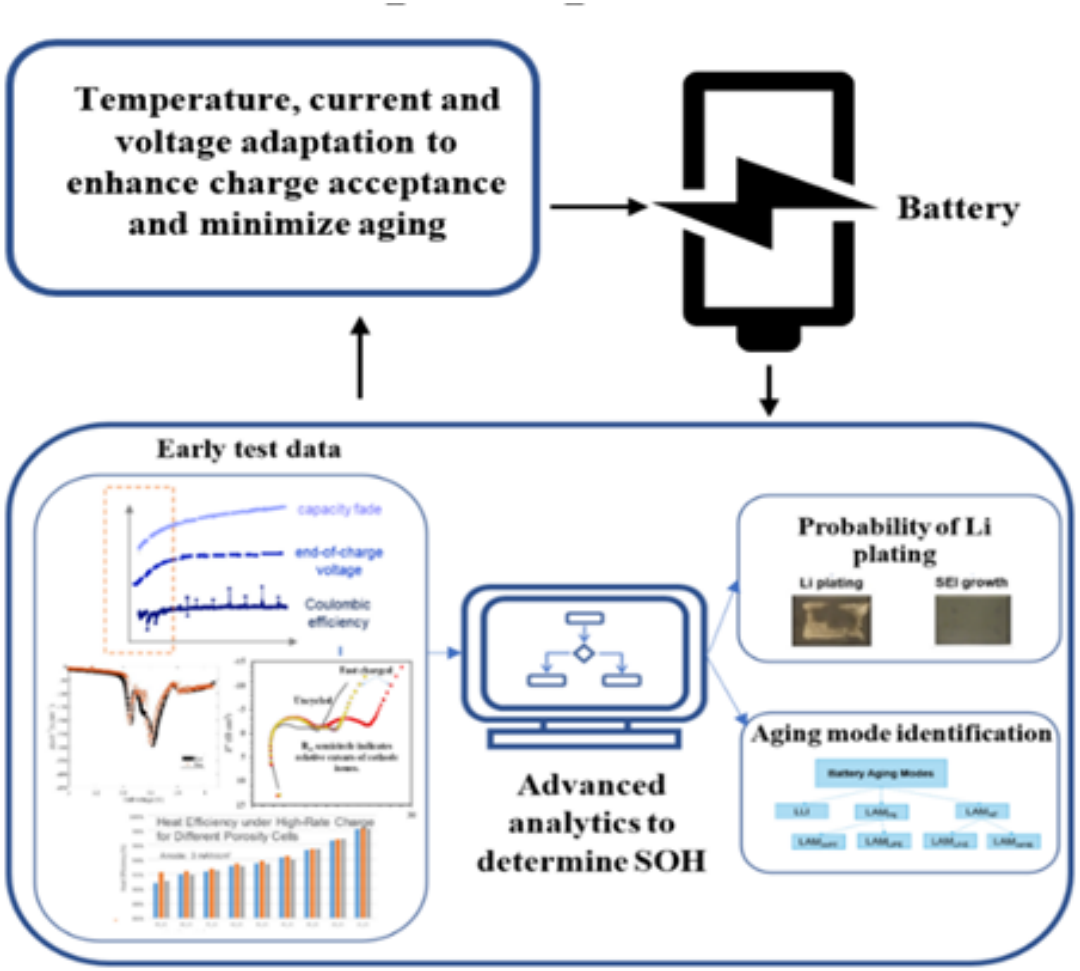
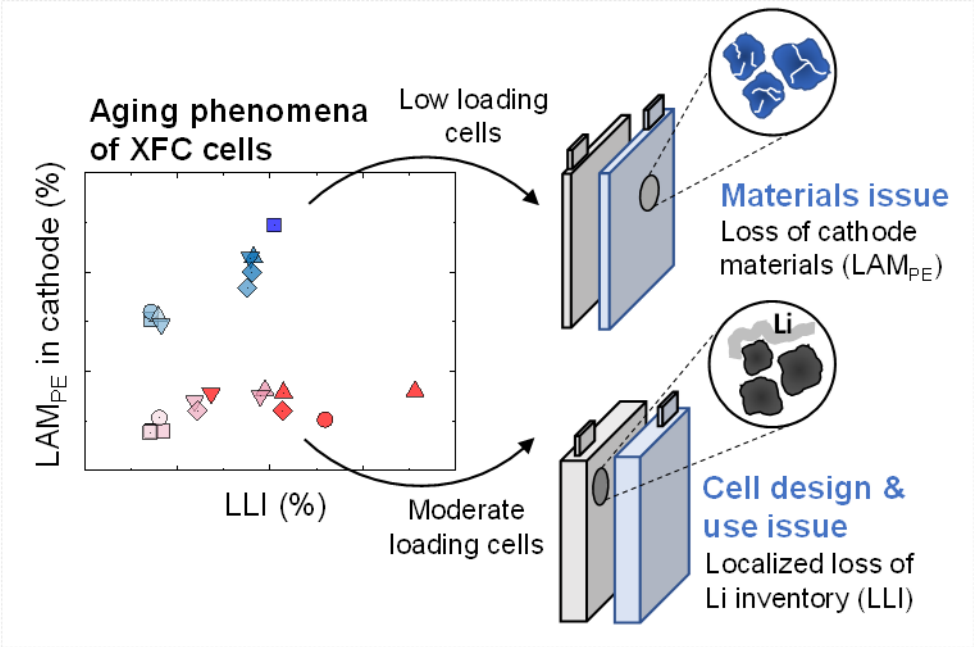


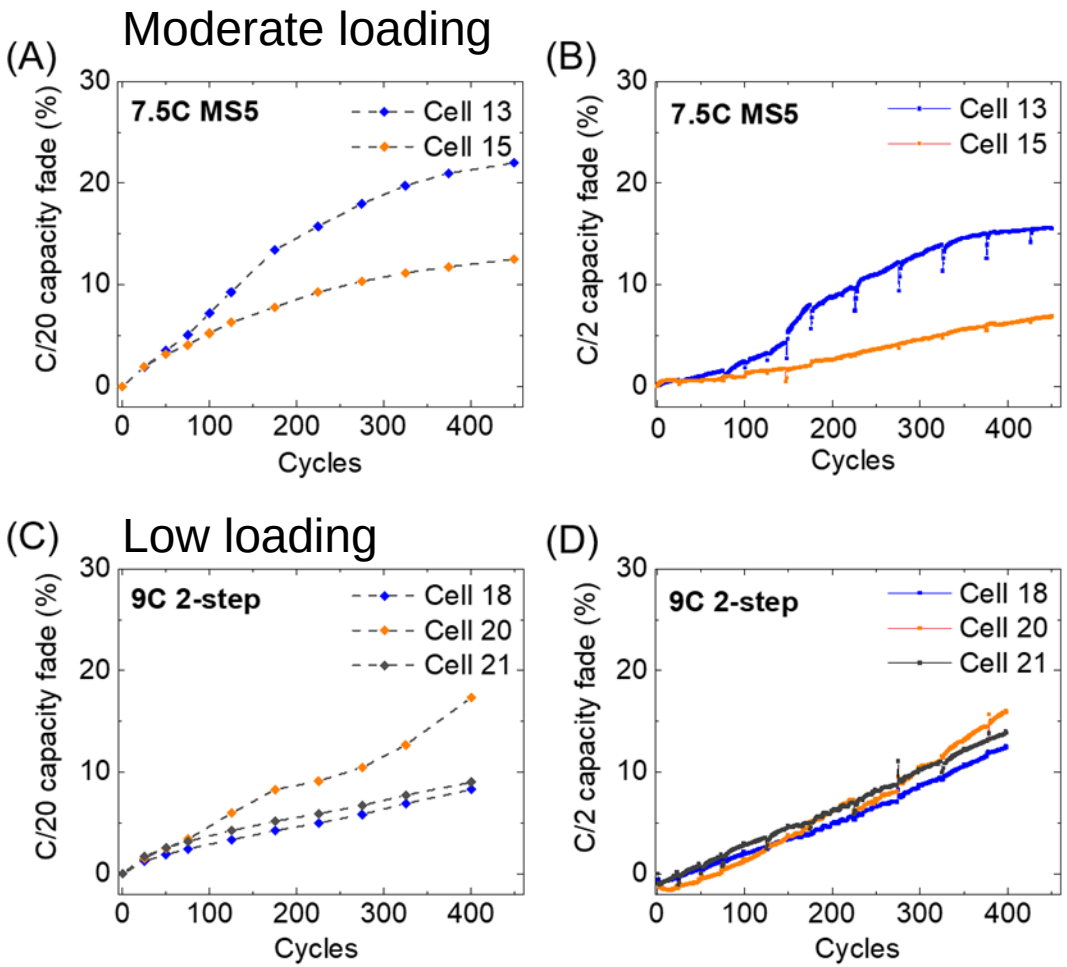


Use understanding of cell design to develop protocols and rapid understanding of failure modes

Increasing Cell Energy

- Electrode loading increased by 50% (from 2 to 3 mAh/cm^2)
- Max current decreased but overall protocol structure maintained



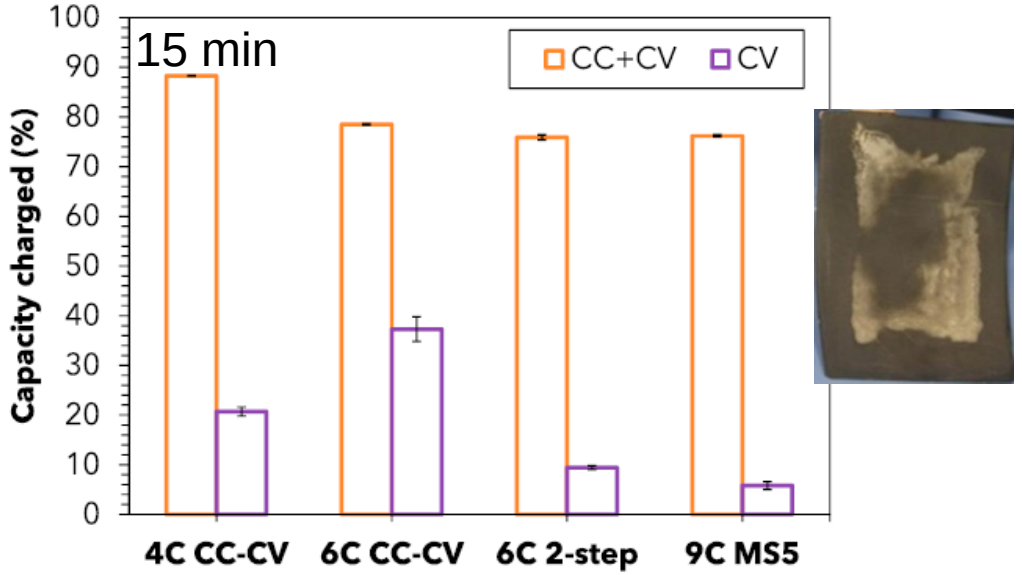


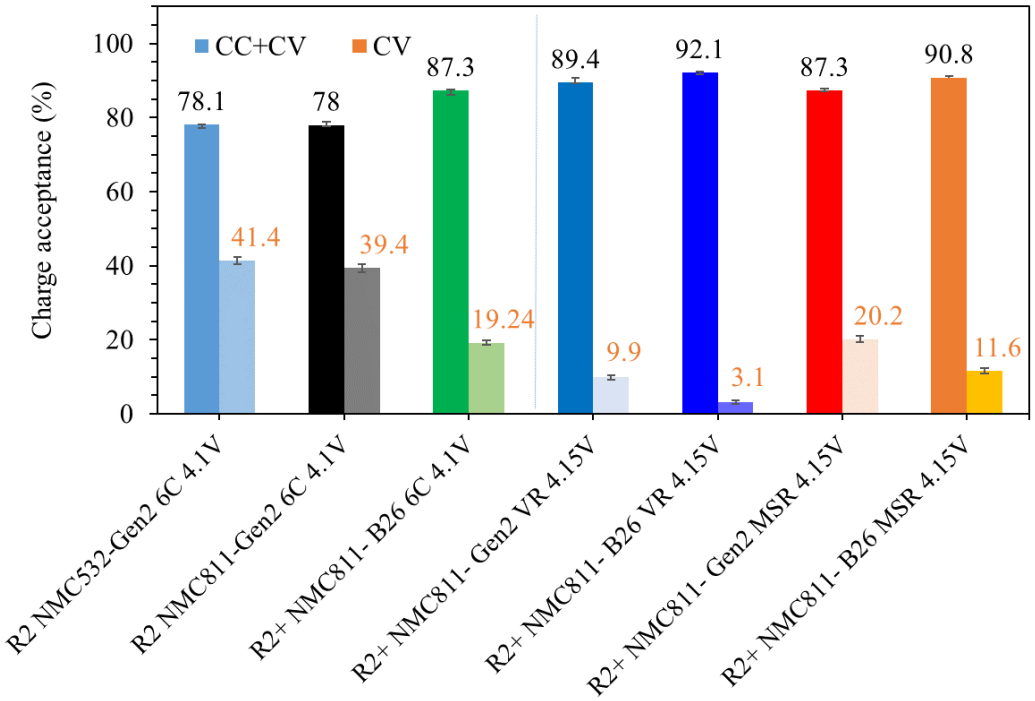
Chinnam et al, *ACS Appl. Energy Mat.,* (2021)

Advancing charge acceptance during short duration charging

- Reduced time during CV portion of the charge
- Same negative electrode loading
- Able to increase charge acceptance 10+%

- ***Key changes – Charge protocol, electrolyte, cathode material (NMC811 vs NMC532)***





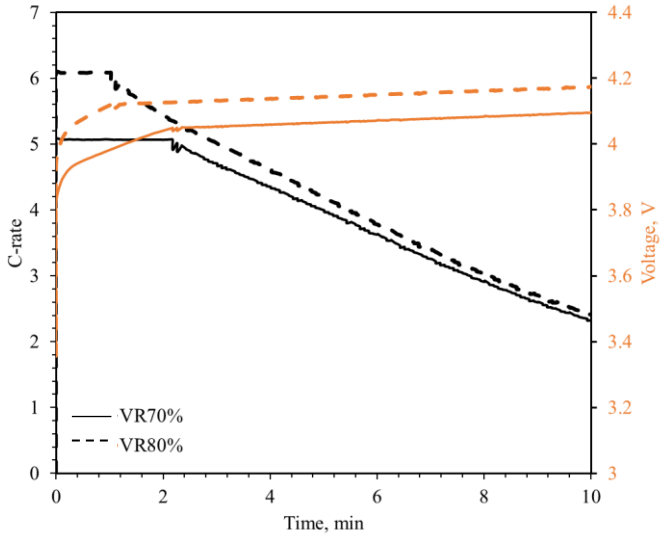
Tanim et al, Cell Reports Phys. Sci, 2020, 100114
Chinnam et al, ACS Appl. Energy Mat., 2021, 9133

Advanced Charge profiles

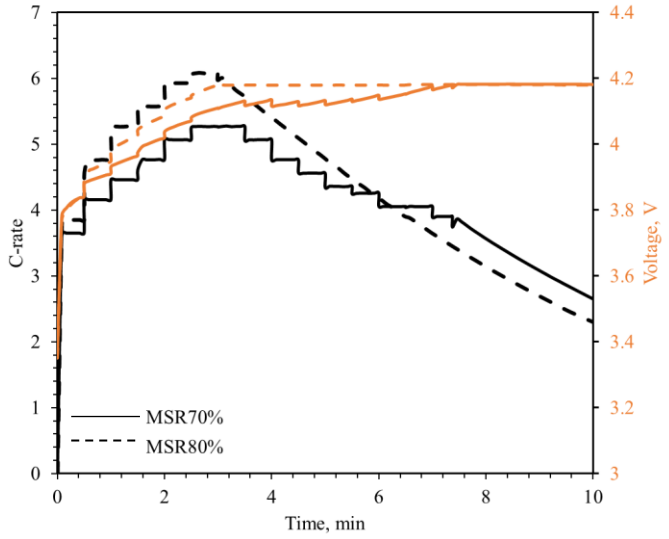
Charge protocols – Can be readily tailored to specific builds with early characterization

- **Voltage Ramp** – Goal to minimize Li plating by maintaining negative electrode potential above 0V vs Li
- **Material Stress Reduction (MSR)** – Reduced stress on materials by ramp to higher current. Current determined based on cell overvoltage and impedance characteristics
- Protocols developed to minimize plating and align with infrastructure design

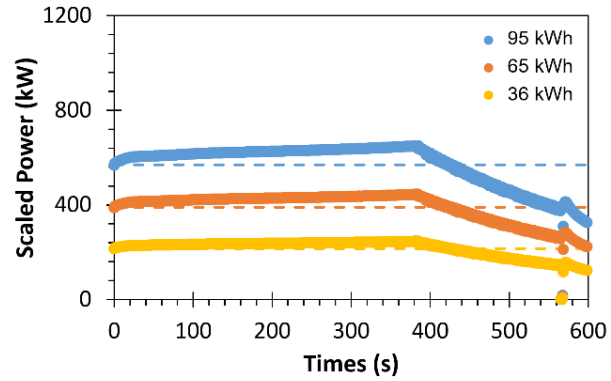
Voltage Ramp



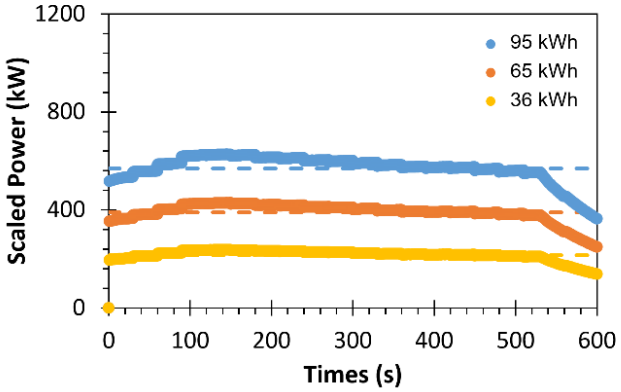
Material Stress Reduction



(b) Voltage Ramp (VR)



(c) Material Stress Reduction (MSR)

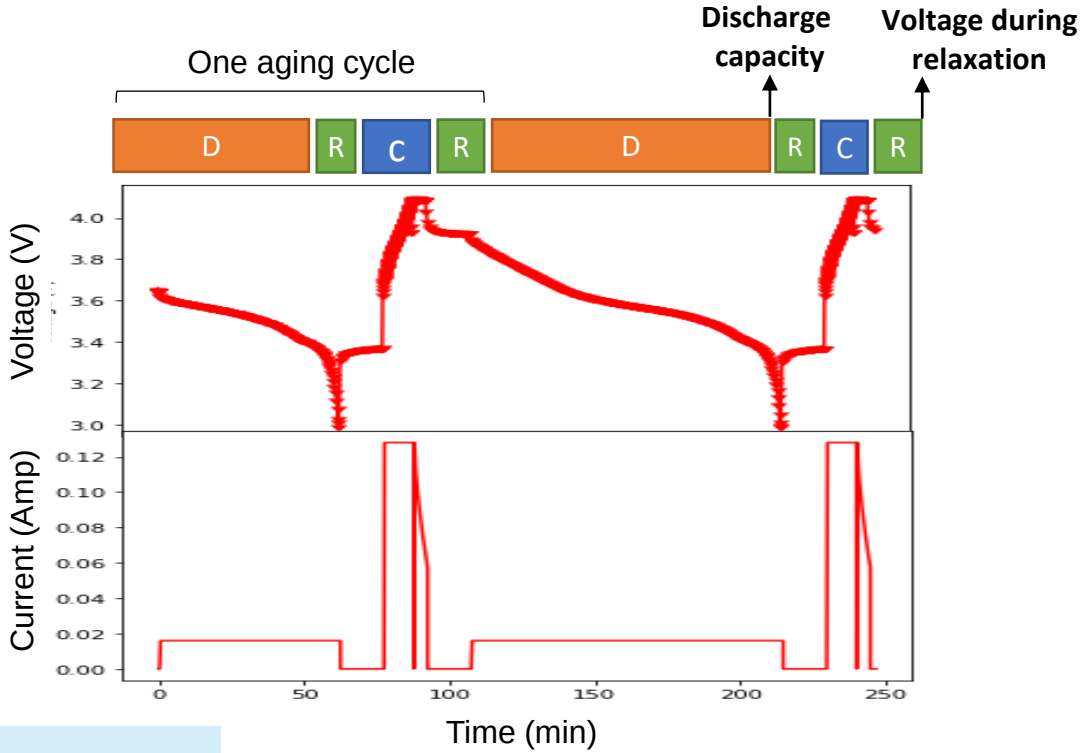


Kim et al, Energy Technology, 2022, 2200303

INL's approach: aging features + data-driven

Electro-chemical (EC) signatures are battery properties or performances collected along cell cycling throughout lifetime - Use of both experimental and synthetic data

Aging phenomena → EC signature responses → "rules" for determining what aging happening



EC signatures

- Capacity
- Voltage
- Current
- Power
- Resistance
- Coulombic Efficiency
- Incremental capacity (IC) curves
- …and many more collected at cycle-by- cycle or RPT

Chen et al, Cell Reports Phys Sci, 2021, 100352

Test procedures and electrochemical signatures

600+ life cycles

Beginning of life test

RPT 0 (@ C/20)

Reference performance test (RPT): check points of cell performance

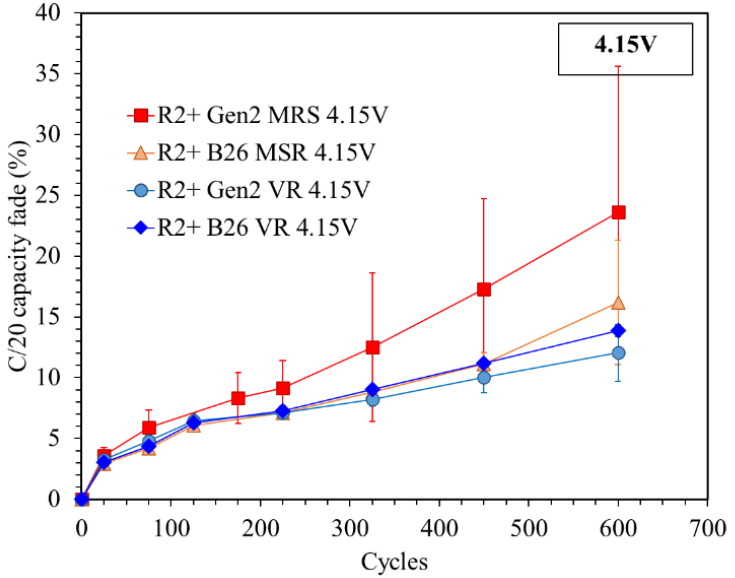
Cycle life (450 Cycles)

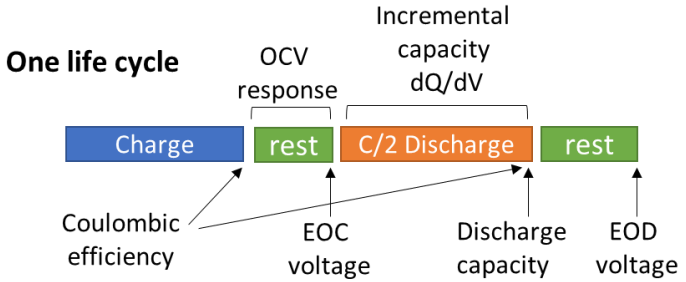
Run specific charging protocols

RPT N (@ C/20)

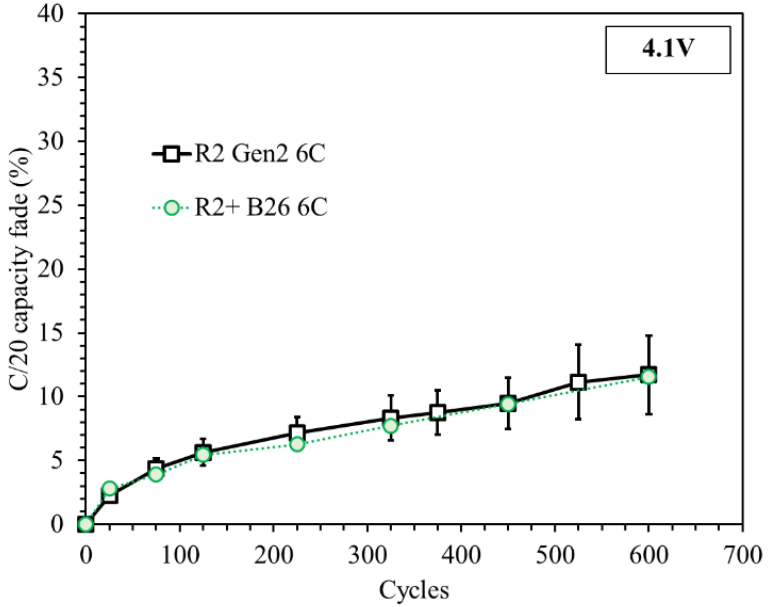
RPT: every 25 – 100 cycles
N = 1 - 11

End of test





Electrochemical signatures (voltage, capacity, CE…) evolving *along with aging cycles* can be used as signatures reflecting the aging of battery

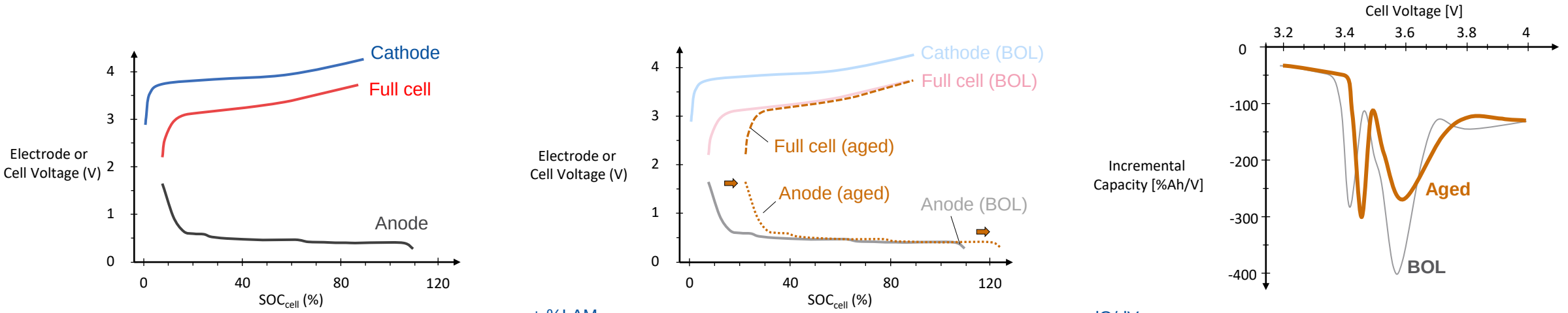


Lots of battery data are needed to cover aging cases

To identify other aging modes and complex pathways:

- Extensive amounts of different aging cases are needed
- Difficult to *experimentally* cover *all* cases
- **"Simulated battery"** → user control what type and how much aging present and generate "synthetic data"

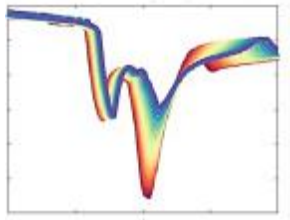
Electrode potential curves shifts due to aging, then IC curves are obtained

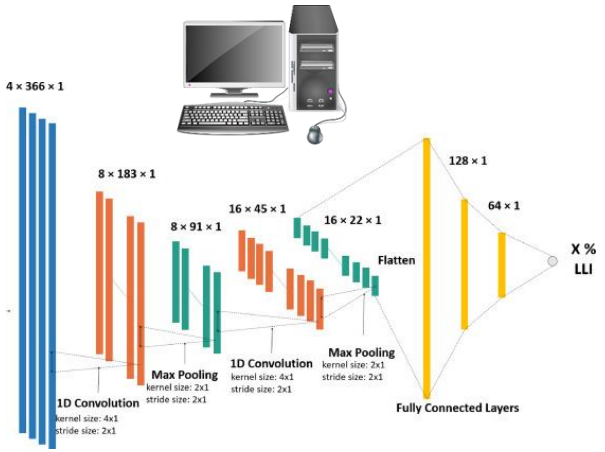


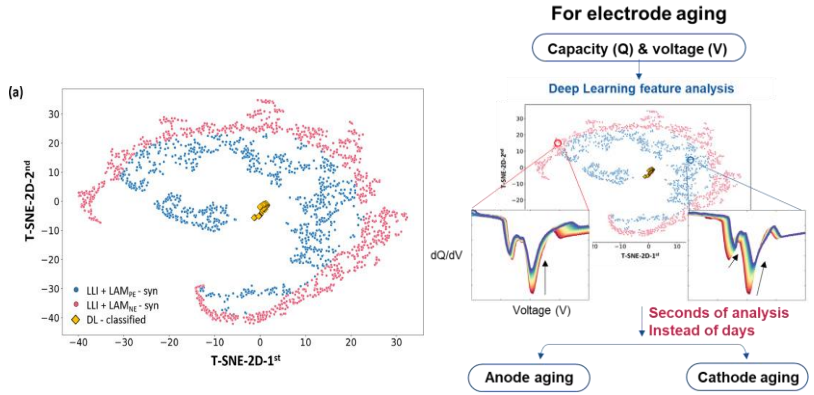
Dubarry, Liaw et al., *Journal of Power Sources* (2012)

Deep learning advances the aging detection framework

Aging detection framework construction:



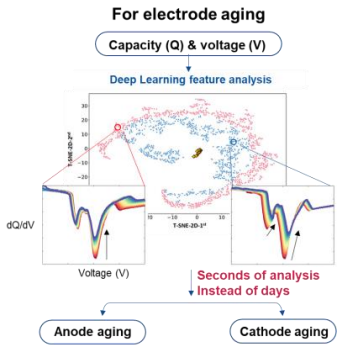




Simulated IC curves Given %LLI & %LAM → **Deep learning pattern analysis** → Computer-recognizable features For aging classification

Application:

Experimental Data →



Aging detection framework

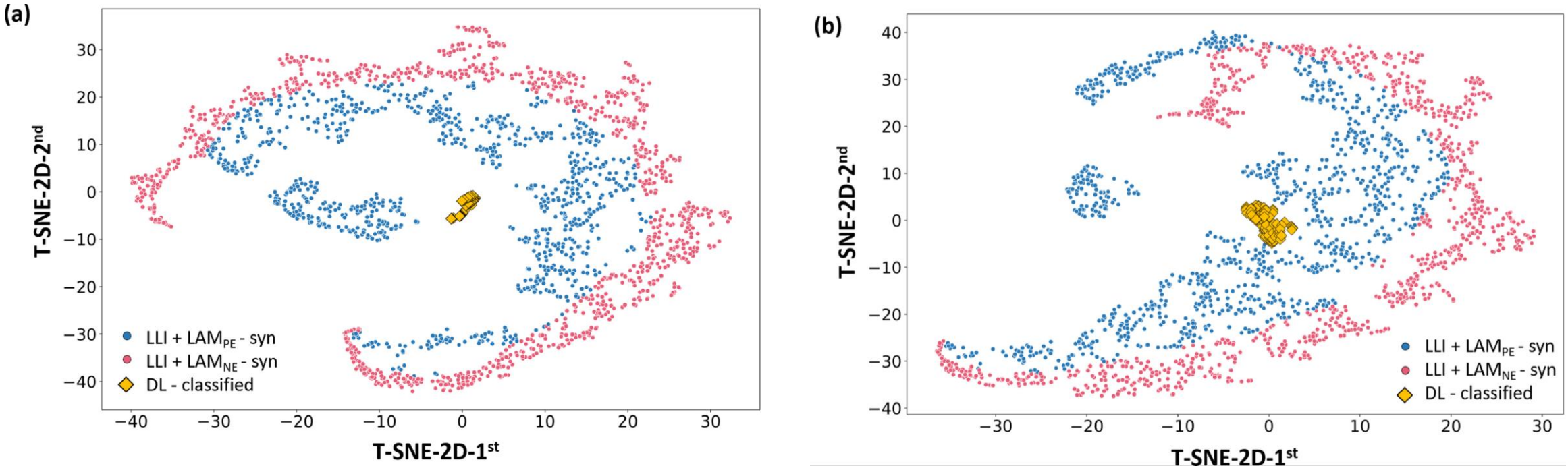
→ % LLI
% LAM_{PE}
% LAM_{NE} → Aging pathway along lifetime →

- Strategies coping with aging
- Insights designing better batteries

Kim et al, *Energy Storage Materials* (2022)

Testing on Experimental Data - Classification

Experimental IC Data at early RPT cycles → Preprocessing → Dominant Aging Mode Classification

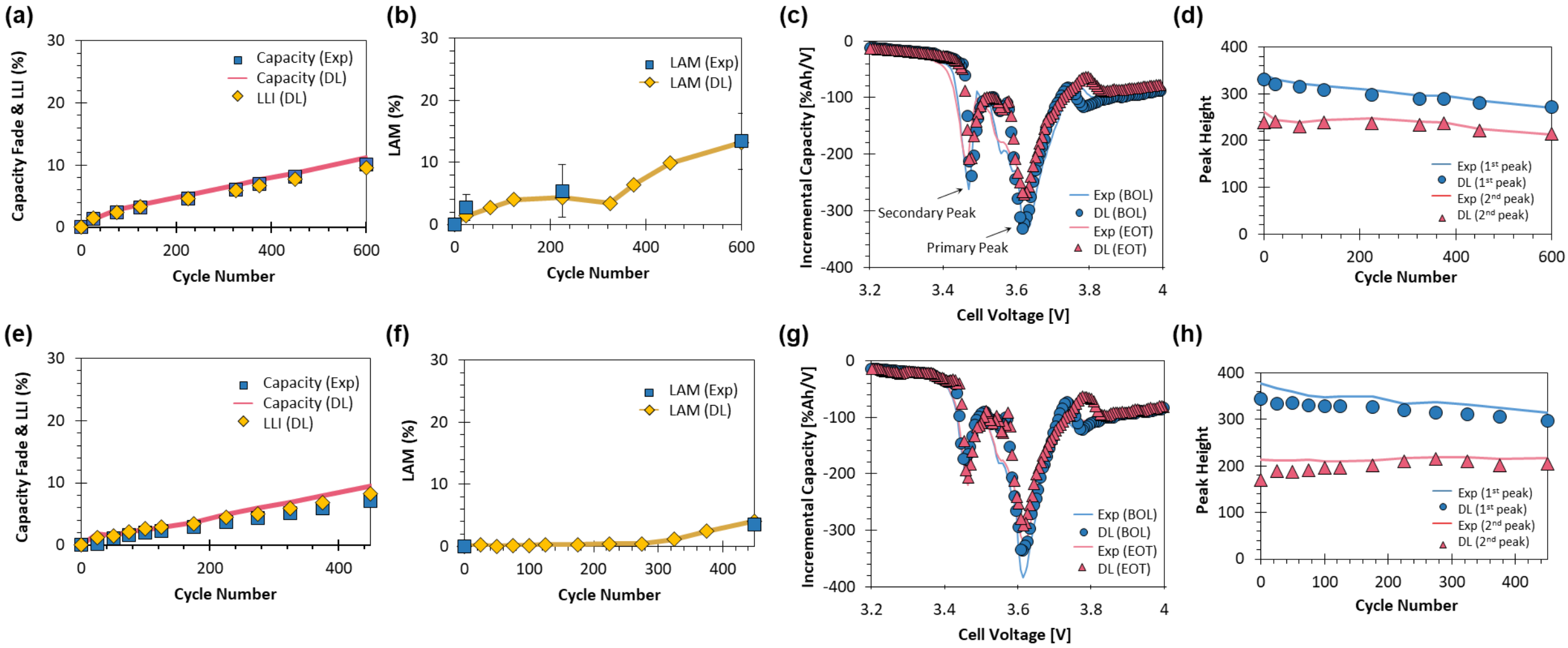


A 2D visualization map using *t*- SNE for both synthetic data sets and DL-classified experimental data, with two loading cases: (a) low-loading and (b) moderate-loading under two dominant aging modes—i.e., LLI + LAM_{PE} and LLI + LAM_{NE}.

Kim et al, *Energy Storage Materials (*2022)

Kim et al *Energy Storage Materials* (2021)
https://doi.org/10.1016/j.ensm.2021.07.016

Validation of Aging Constituents

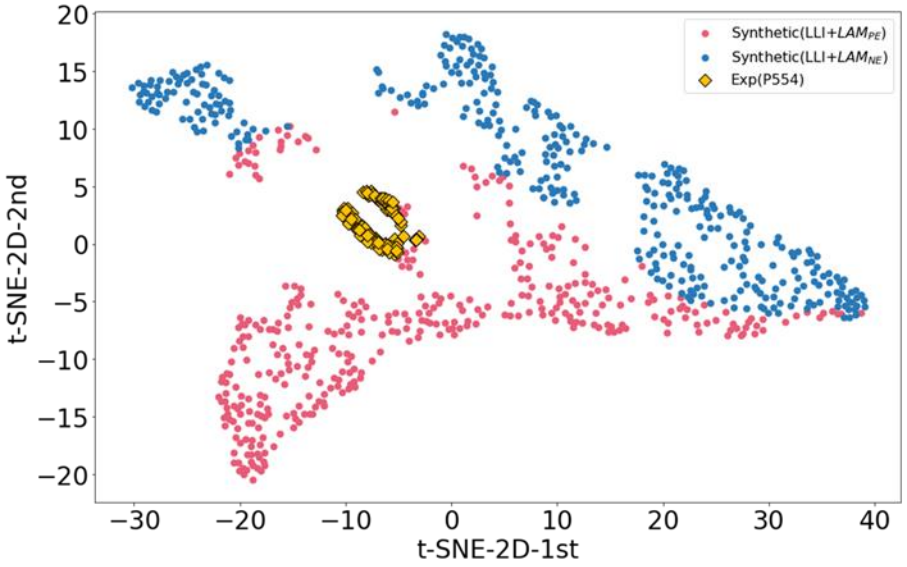


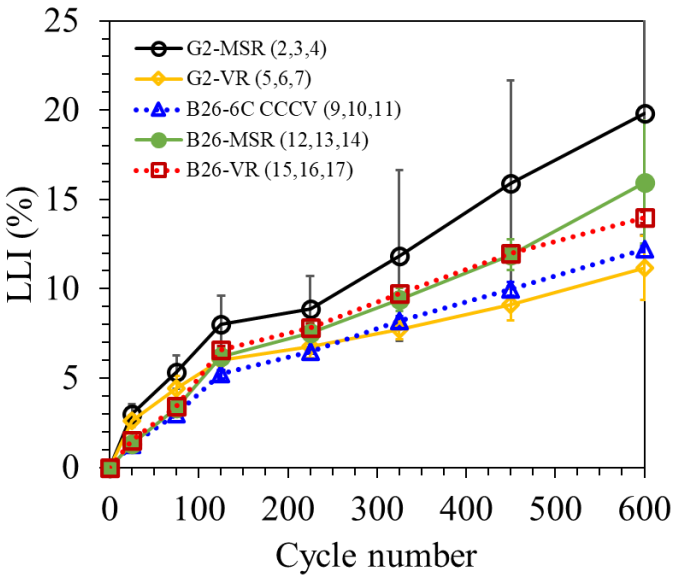
DL framework successfully validated with experimental data

Applied to most recent results

Rapid Ability to Transfer Learning from NMC532 to 811

- Like earlier work can readily classify and quantify extent of degradation modes
- Looked at LLI and LAM (not shown)
- Close alignment in use of synthetic data which can be readily transitioned across chemistries and cell design types
- Still working to understand ability to classify variations in cell design
- Only a few instances of Li plating detected using decision tree analysis





Summary

- Ability to achieve 90+% charge acceptance possible due to use of advanced protocols and electrolytes
- Use of ML methods developed to identify Li plating and classify and quantify degradation modes
  - Use of synthetic data enables direct flexibility in expanding methods beyond use of experimental data
- Failure modes can be used for future development of protocols

Contributors, Collaborators and Acknowledgements

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