Use of Nail Puncture Tests and Internal Temperature Sensors for Simulation of Abusive Damage During Operation in Li-ion Batteries

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Background and Safety Concerns

- Lithium-ion batteries are becoming predominantly used in many applications
- Many safety concerns during operation, especially in abusive environments
  - UAVs, AUVs, EVs, satellites, etc.
- Examples of accidents during operation
  - Samsung Galaxy, Tesla, Boeing 787

https://news.softpedia.com/news/samsung-galaxy-s7-edge-catches-fire-while-charging-507925.shtml#sgal_1

https://www.cnn.com/interactive/2019/03/business/tesla-history-timeline/index.html

https://www.npr.org/2013/01/25/170231466/boeings-787-problems-remain-a-mystery

Objective of Testing

- Improved analysis
  - Monitoring of internal and external temperatures provides more information
- Extension of testing standards
  - Many verifications from testing standards employ use of go/no-go determination on integrity of cells under test
  - Cycling of cells during and after abuse gives more information on effects during operation

Purdue Safety Map
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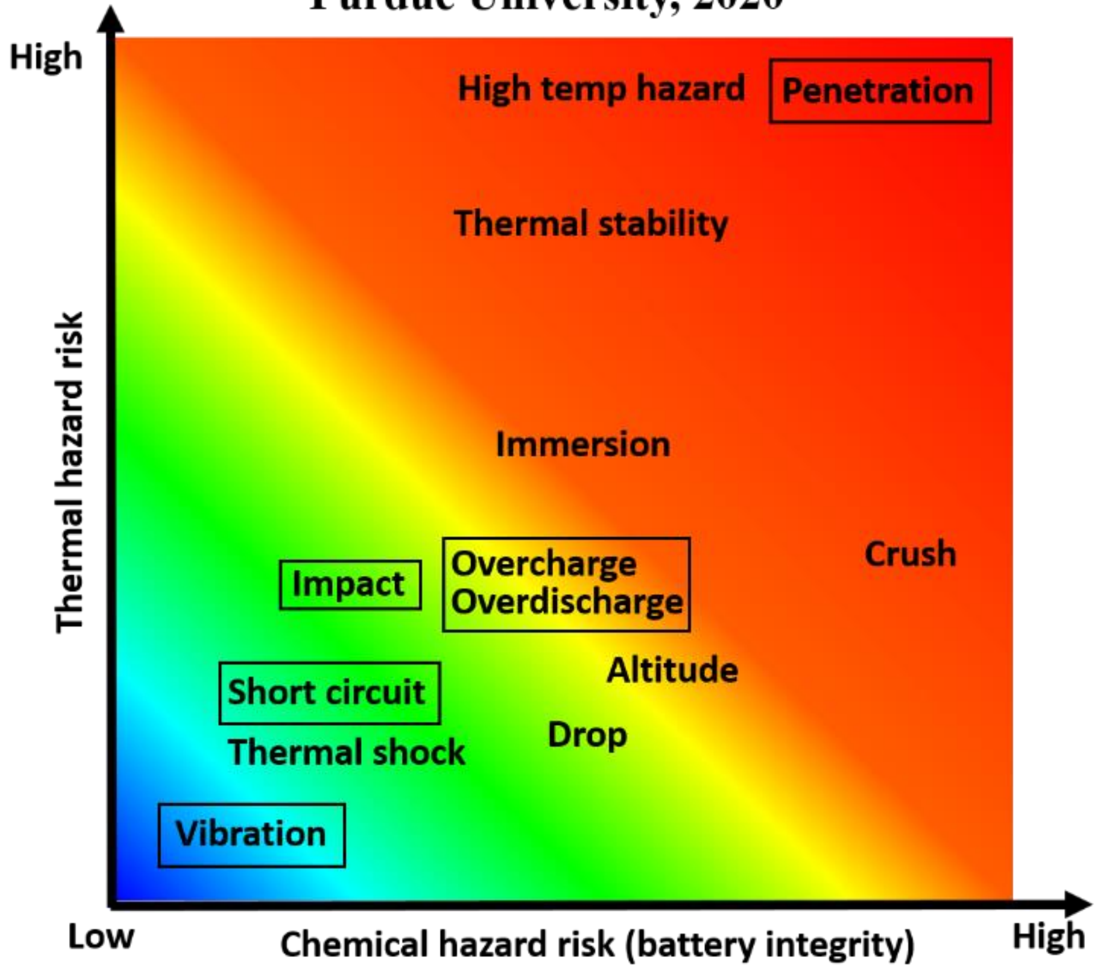
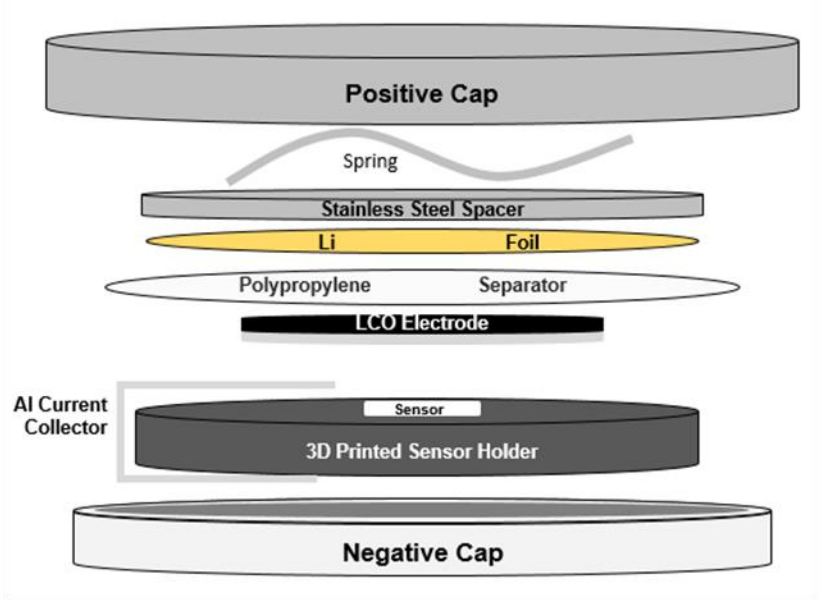
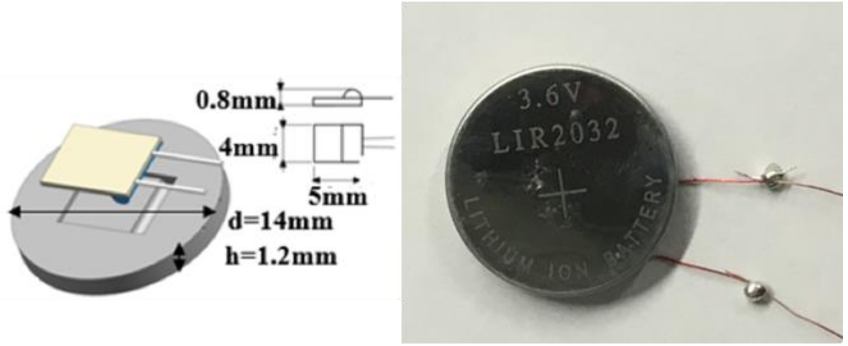


Internal Sensors in Custom Cells

- LCO coin cells constructed with RTD-embedded spacers
  - 4 cells with varying cathode diameters
    - 9.5 mm
    - 12.5 mm
    - 14.9 mm
    - 15.6 mm
  - External short circuit for 24 hours in accordance with NAVSEA 9310
  - Temperature data obtained with internal and external sensors

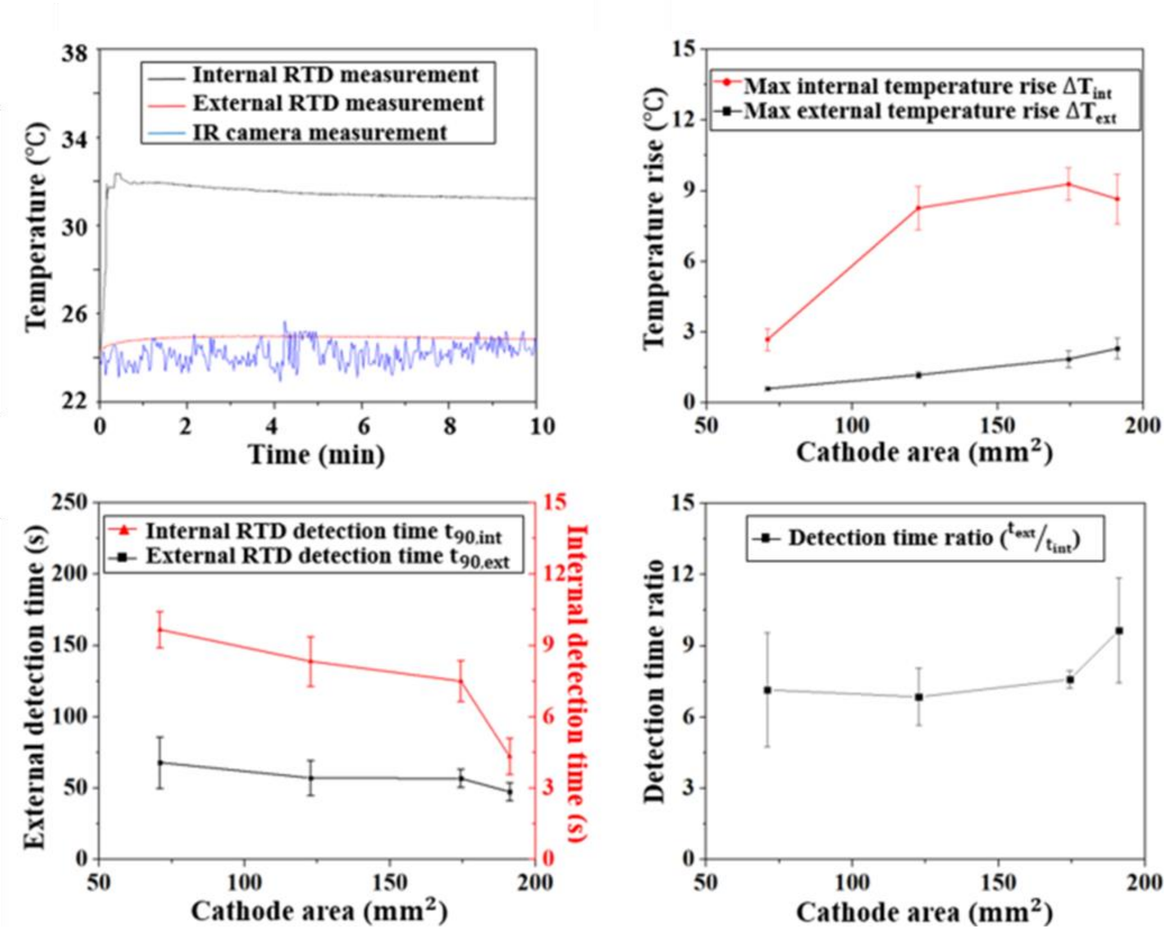




Li, B. et al., 2019, “Lithium-ion Battery Thermal Safety by Early Internal Detection, Prediction, and Prevention,” Scientific Reports.

Internal Sensors in Custom Cells

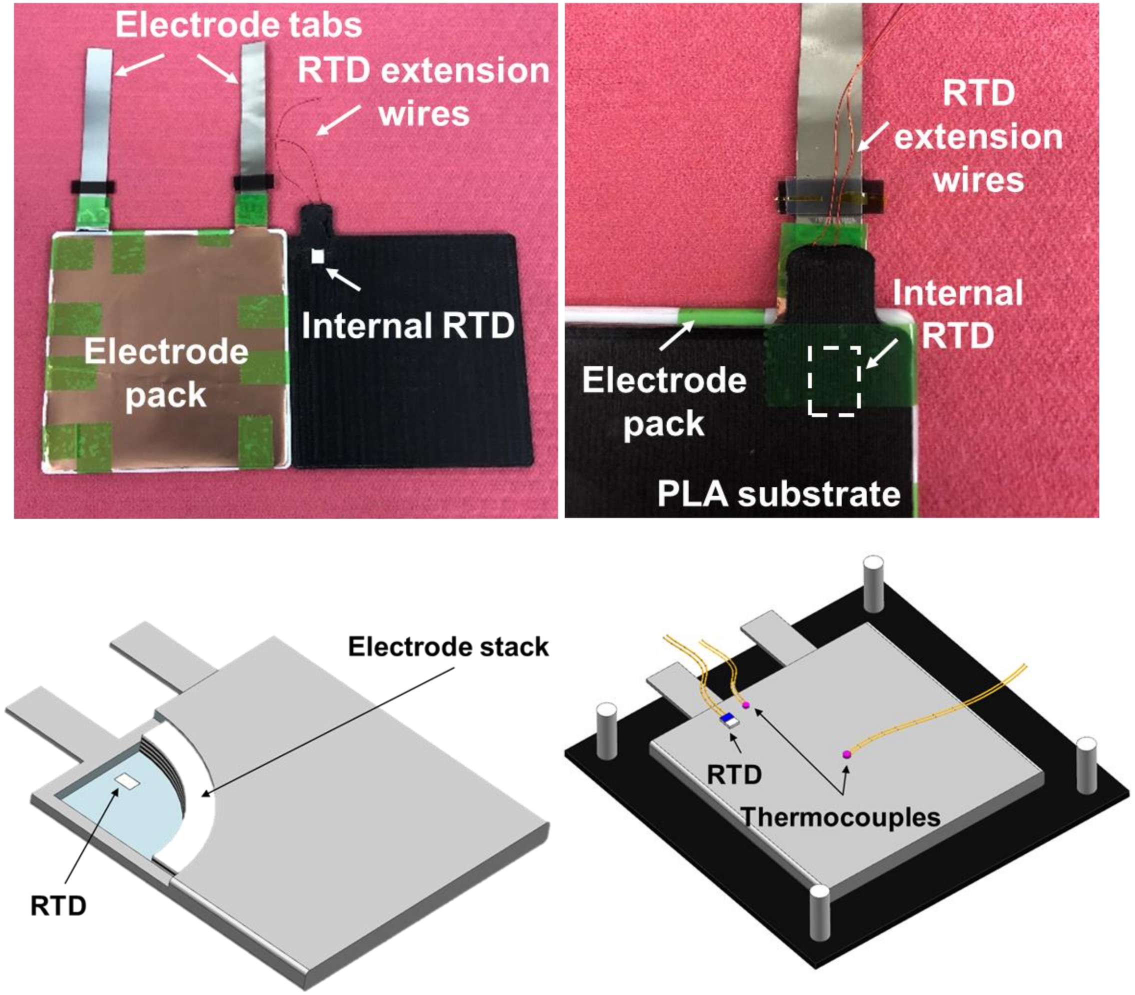
- Results
  - Larger amount of active material results in higher peak temperature
  - Increased difference between internal and external change in temperature
  - Decreased length in time to detect t90 (time to reach 90% of temperature change)
  - Improved detection time ratio with increased amount of active material



Li, B. et al., 2019, "Lithium-ion Battery Thermal Safety by Early Internal Detection, Prediction, and Prevention," Scientific Reports.

Internal Sensors in Custom Cells

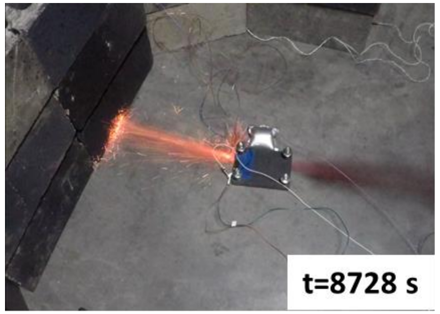
- Overcharge of pouch cells
  - 2 cells each constructed with a substrate containing an internal RTD placed near the electrode terminal where highest temperature is expected
  - Cells used NMC cathodes with RTDs underneath the electrode stacks facing the current collector of the anode
  - One cell included an internal volume for gas accumulation to test effect of increased internal pressure

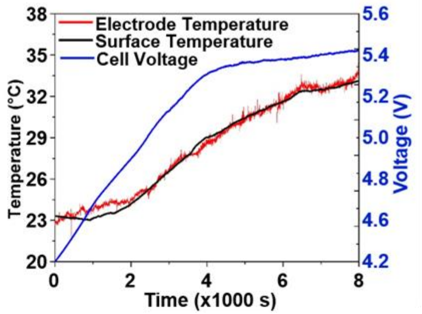


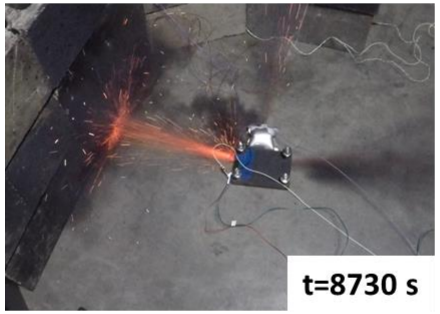
Li, B. et al., 2021, "Operando Monitoring of Electrode Temperatures During Overcharge-Caused Thermal Runaway," Energy Technology.

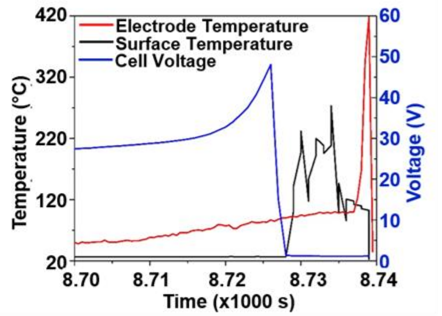
Internal Sensors in Custom Cells

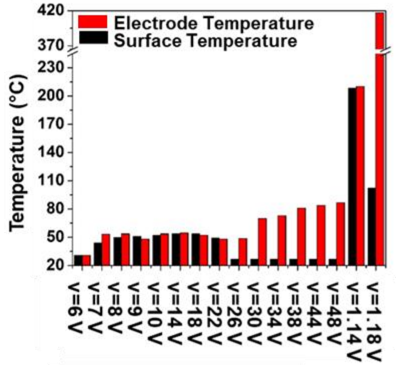
- 1 C overcharge results (with gas accumulation volume)
  - Minimal difference between internal and external cell temperatures until increase in C-rate
  - Increased pressure from gas accumulation leads to higher thermal resistance and slower response of external sensor
  - Abrupt increase in surface temperature due mostly to combustion of cell







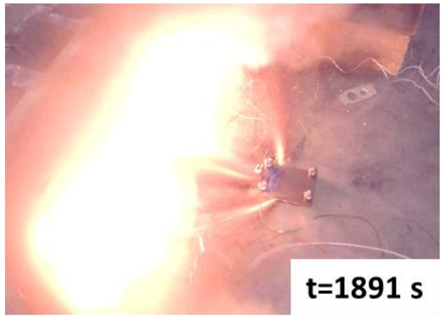


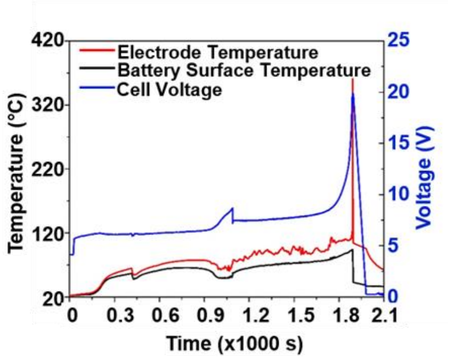


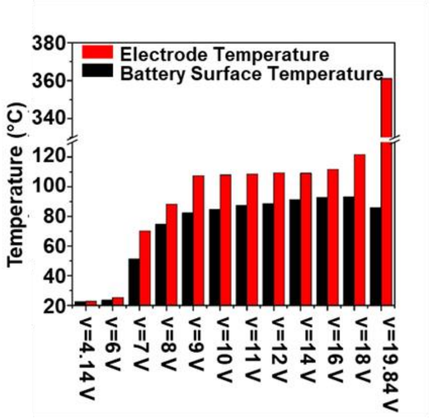
Li, B. et al., 2021, "Operando Monitoring of Electrode Temperatures During Overcharge-Caused Thermal Runaway," Energy Technology.

Internal Sensors in Custom Cells

- 5 C overcharge results (with no gas accumulation volume)
  - Higher difference between internal and external temperatures at beginning due to higher current
  - Explosion and combustion occurred much sooner due to less gas accumulation during overcharge
  - Less material was released during explosion due to low pressure at time of rupture



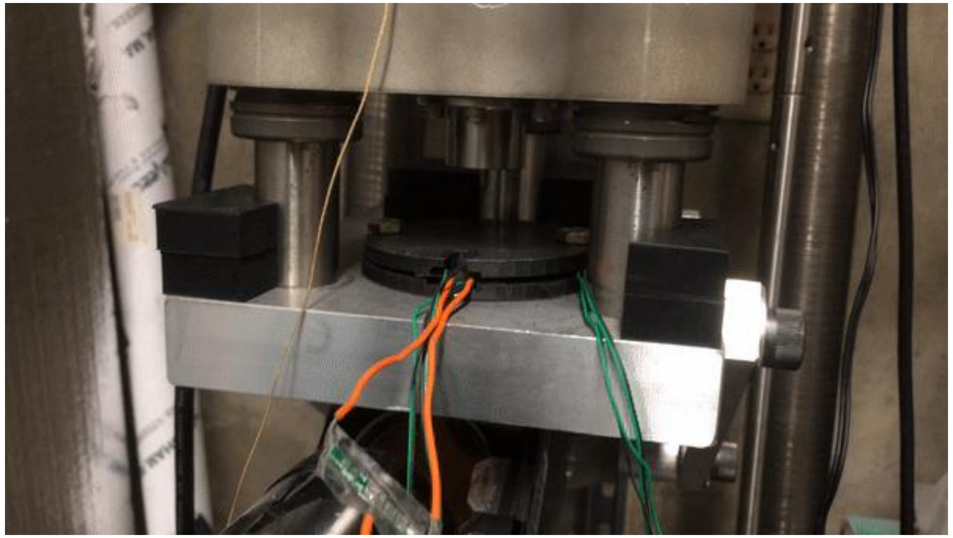


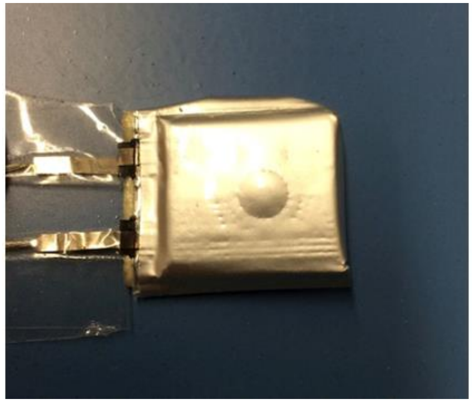


Li, B. et al., 2021, "Operando Monitoring of Electrode Temperatures During Overcharge-Caused Thermal Runaway," Energy Technology.

Nail Punctures

- LCO prismatic cells
  - Allow cells to cycle normally for approximately 24 hours to obtain initial performance data
  - Partial nail puncture on cycling cells with nail removed immediately and continued operation afterwards
  - Investigate response and decreased performance due to physically damaged electrodes and exposure to atmosphere

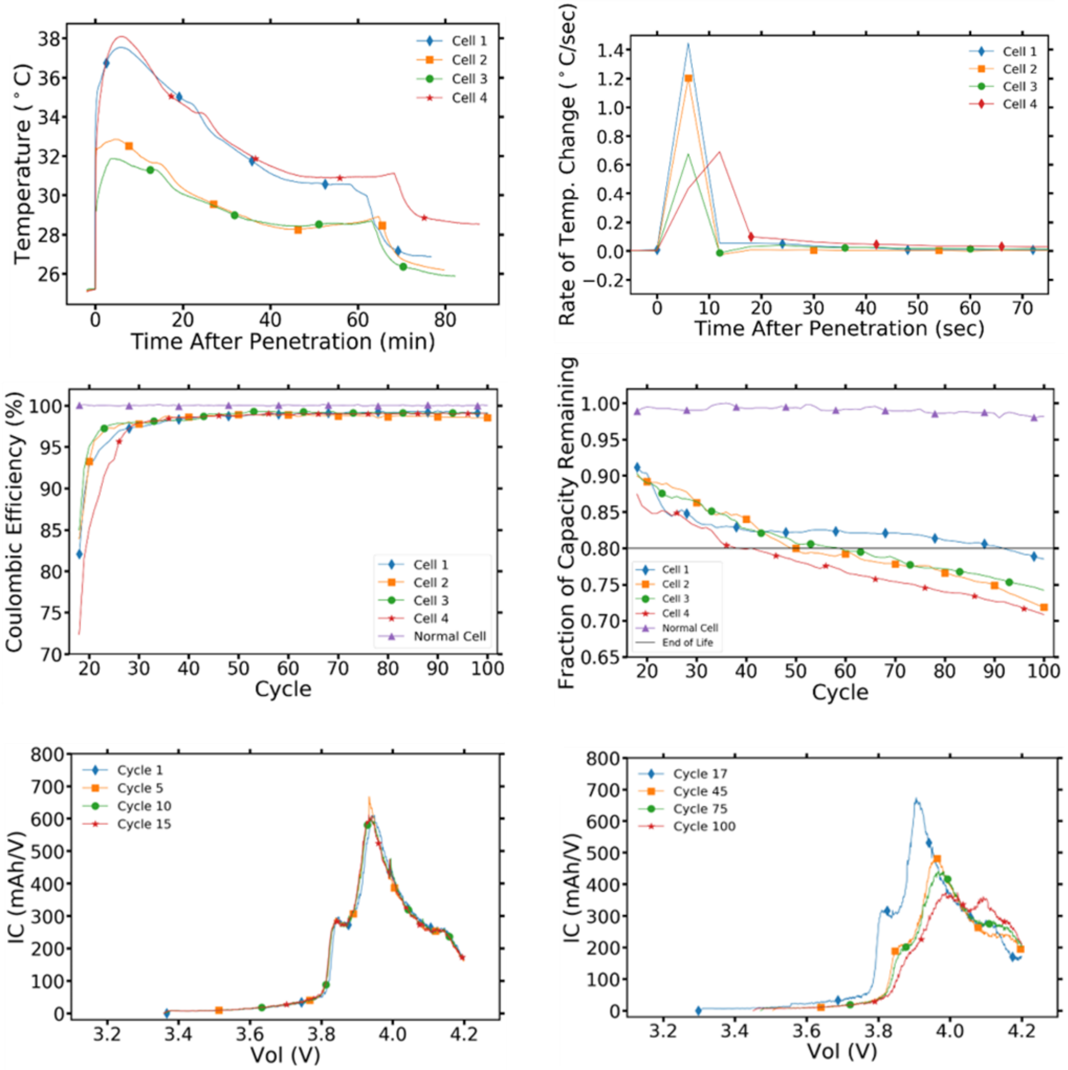




Jones, C. et al., 2021, “Determining the Effects of Non-Catastrophic Nail Puncture on the Operational Performance and Service Life of Small Soft Case Commercial Li-ion Prismatic Cells,” eTransportation.

Nail Punctures

- Results
  - Nail puncture causes an initial spike in temperature, and slightly higher operating temperatures afterwards
  - Coulombic efficiencies initially drop due to higher charge capacities from increased operating temperatures
  - Cells experience accelerated degradation due to loss of material and exposure to atmosphere after nail puncture



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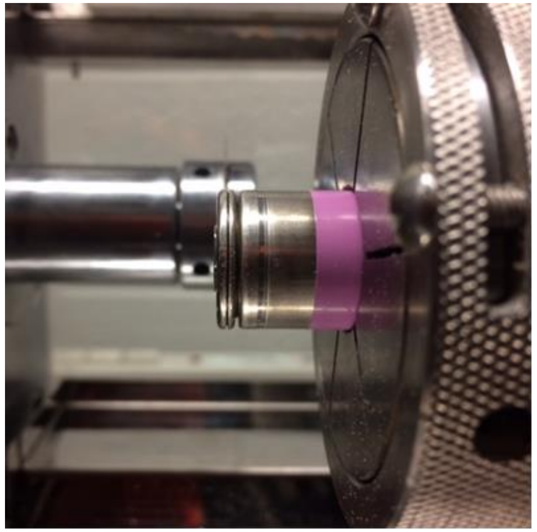
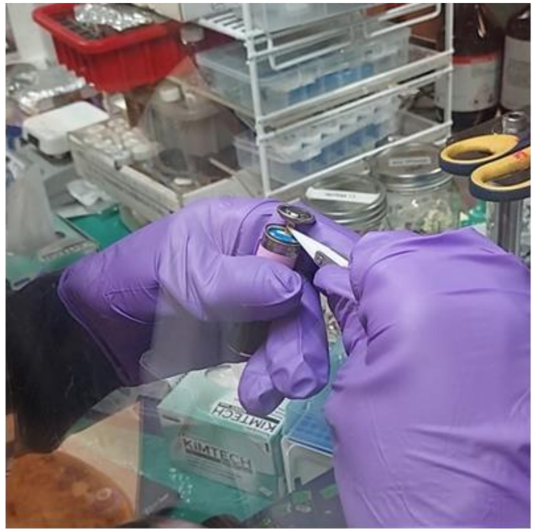
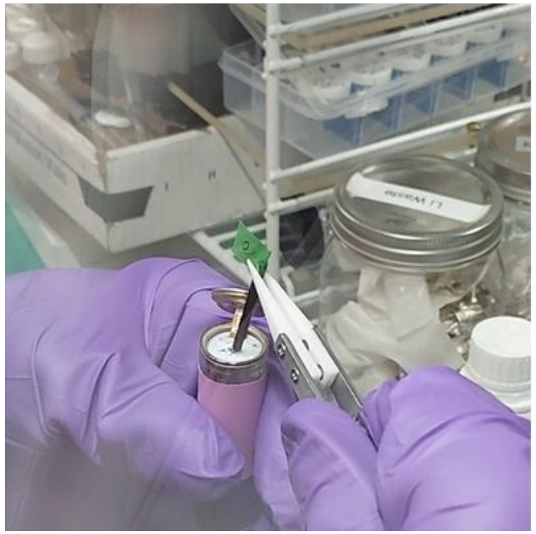
Use of Commercial Cells

- 18650 RTD insertion
  - Perform characterization tests and discharge to 3.0 V
  - Cut around top of cell until gasket is reached
  - Transfer cells into glovebox with inert atmosphere
  - Remove top of cell and widen interior opening of electrodes
  - Insert RTD into middle of cell and close top of cell
  - Seal top of cell with epoxy
  - Reperform characterization tests

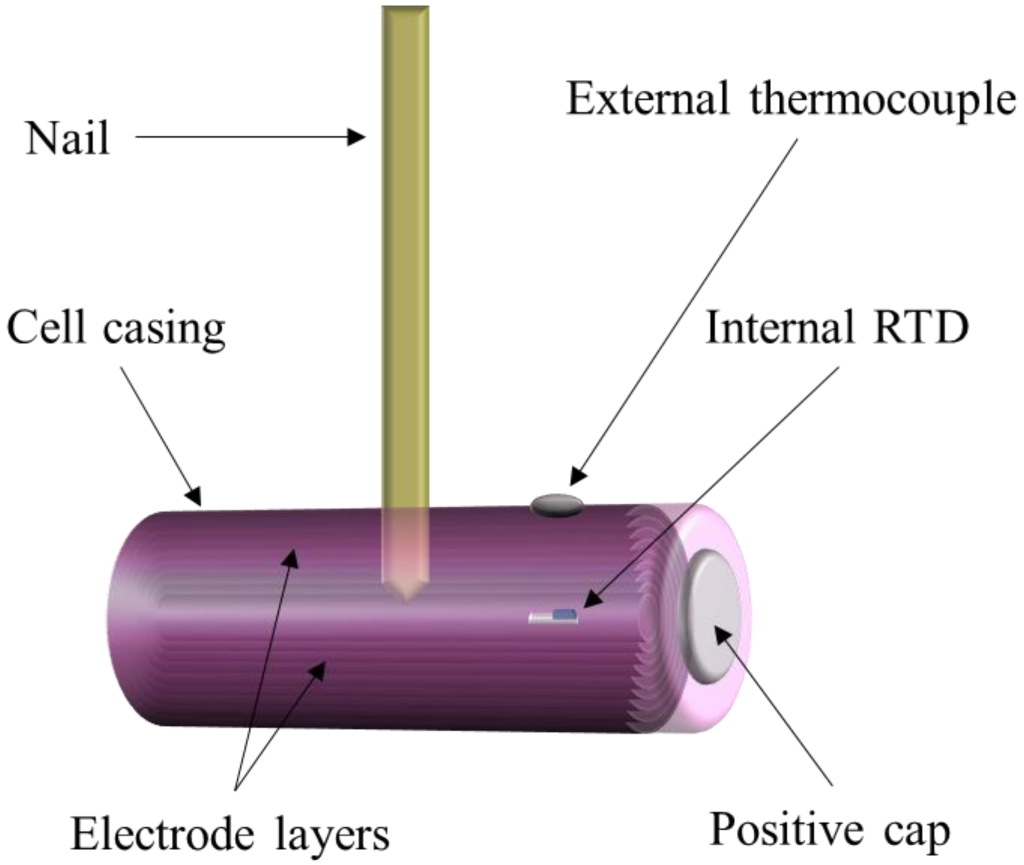




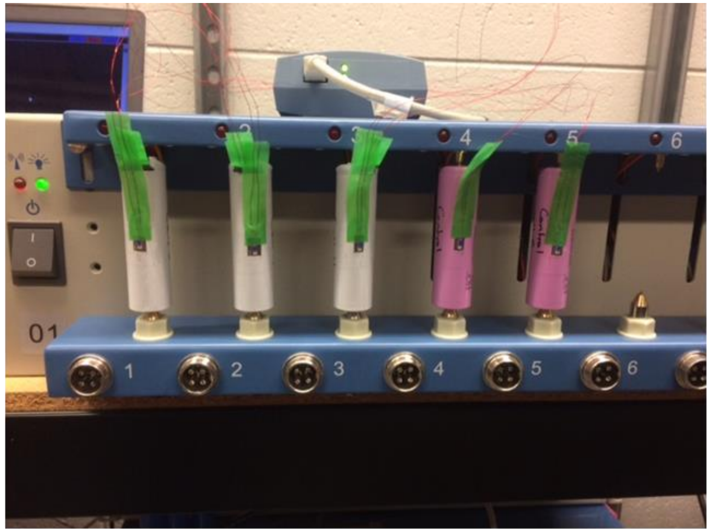


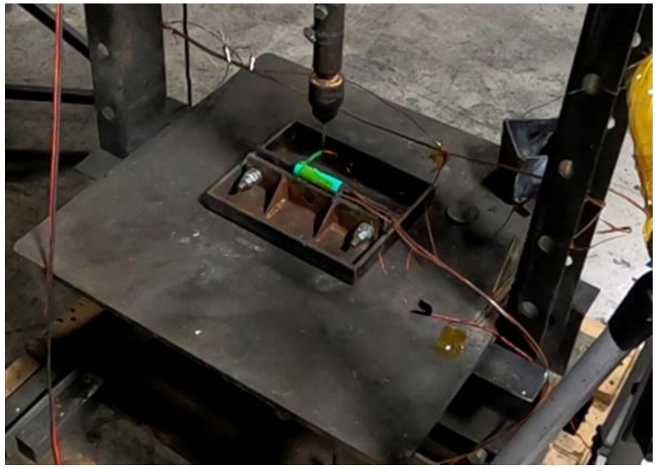
Use of Commercial Cells

- Methods of testing
  - Normal cycling
    - Individual cells
    - Battery packs
    - Comparison of internal and external temperatures during operation
    - Temperature distribution of cells operating in battery packs
  - Nail punctures
    - Cells are tested at differing SOC and have different amounts of aging at time of puncture
    - Investigation into difference in internal and external temperatures and rates of temperature change



Use of Commercial Cells





Summary

- Internal sensors provide improved indication of temperature response and can detect thermal runaway sooner than external sensors
- Abusive tests that allow cells to continue cycling afterwards provide valuable operational information that can lead to improvements in design and implementation
- Methods of inserting sensors into commercially available cells are being continuously improved for enhanced capabilities of monitoring internal temperatures

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Questions?