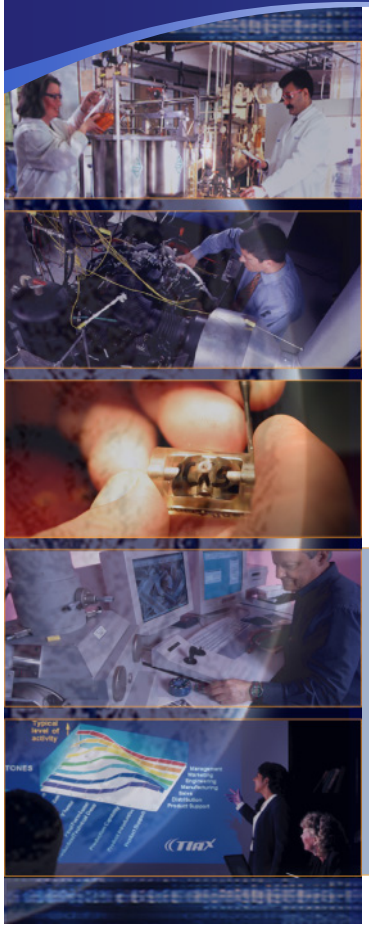
The Relationship of the Nail Penetration Test to Safety of Li-Ion Cells



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The nail penetration test has been widely used across the battery industry and battery-user community to assess lithium-ion battery safety.

- Battery companies, automotive companies and other battery users carry out nail penetration tests to assess safety of Li-ion cells, presumably to simulate internal shorts.
- The nail penetration test involves driving a metallic nail through a charged Li-ion cell at a prescribed speed.
- The cell/chemistry is deemed to have passed if there is no smoke or flame following the nail penetration (visual evaluation, sometimes as a severity level).
- Despite widespread use, the connection of the test and test parameters to actual field failures is not well understood **and** the mechanism of thermal propagation (leading to thermal runaway) is also unclear.
- Given the lack of a standard test method for the nail penetration test, the variability of test results and the tenuous connection to actual field failures, we conducted a structured evaluation of the test.

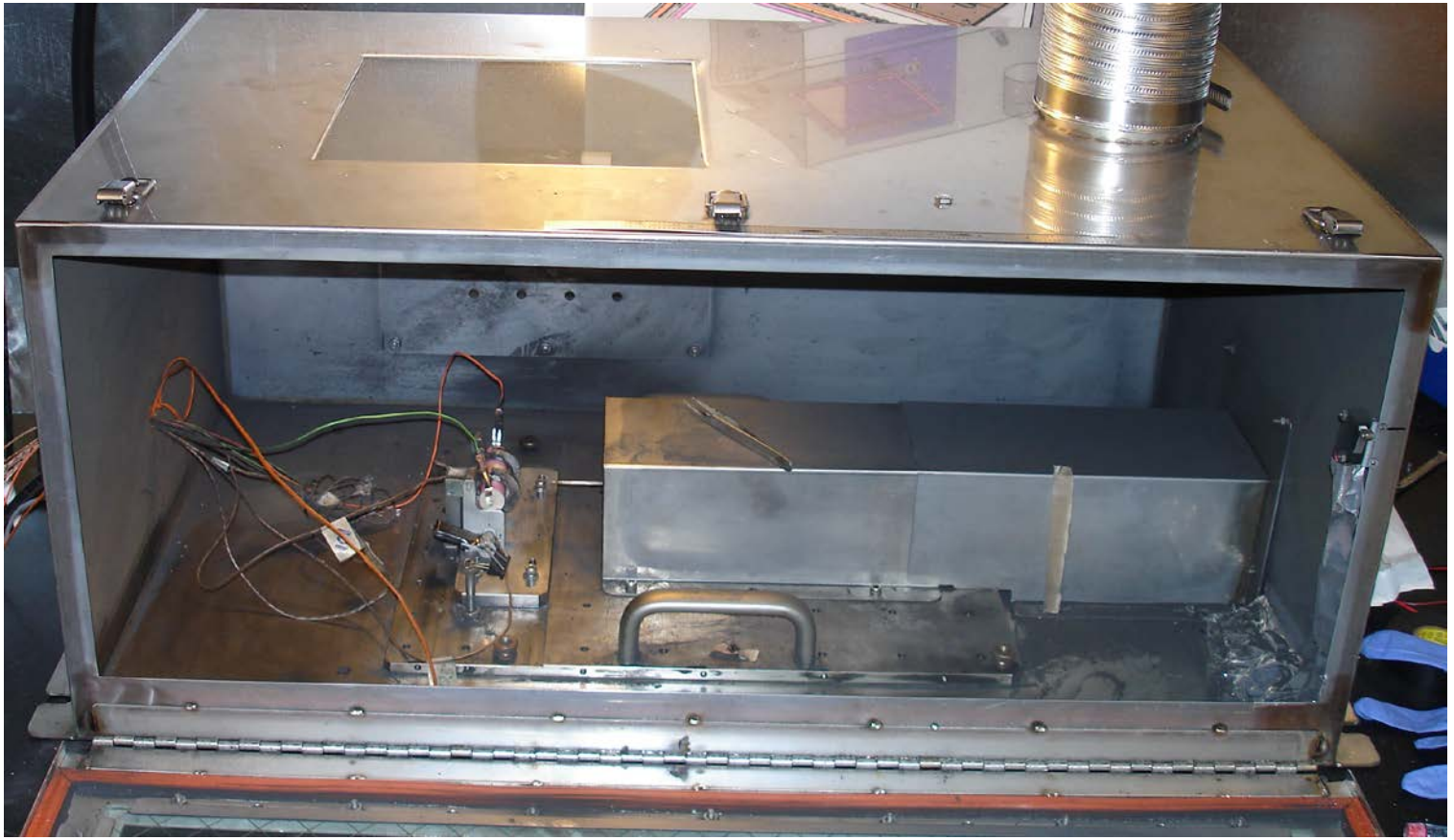
To develop an improved understanding of the nail penetration test, we designed and installed a test chamber with exquisite control over relevant parameters.

Variables in the Nail Penetration Test

- Nail speed
- Nail material
- Nail diameter
- Tip shape, taper
- Cell orientation
- Cell SOC
- Ambient conditions

The nail penetration test is not standardized - cell manufacturers have developed a variety of test conditions and/or cell modifications to "pass the test".

To develop an improved understanding of the nail penetration test, we designed and installed a test chamber with exquisite control over relevant parameters.

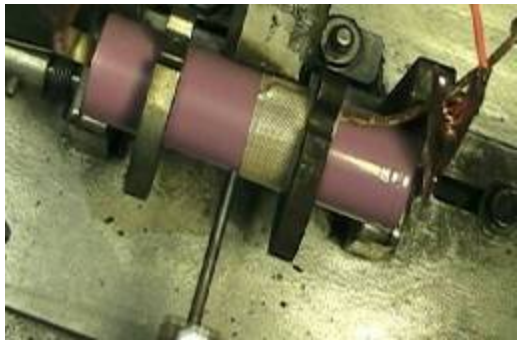


The test station is equipped for rapid acquisition of voltage, temperature and pressure data, as well as high speed photography to capture test results.

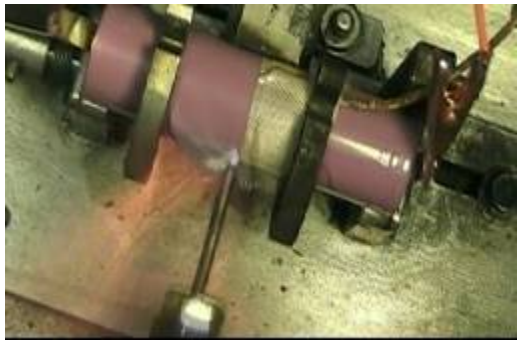

NAIL PENETRATION TEST
RESULTS

We observed a strong dependence of SOC on the outcome of the nail penetration test.

Factors That Influence Thermal Runaway During a Nail Penetration Test



t = 126 ms after nail penetrated the can wall



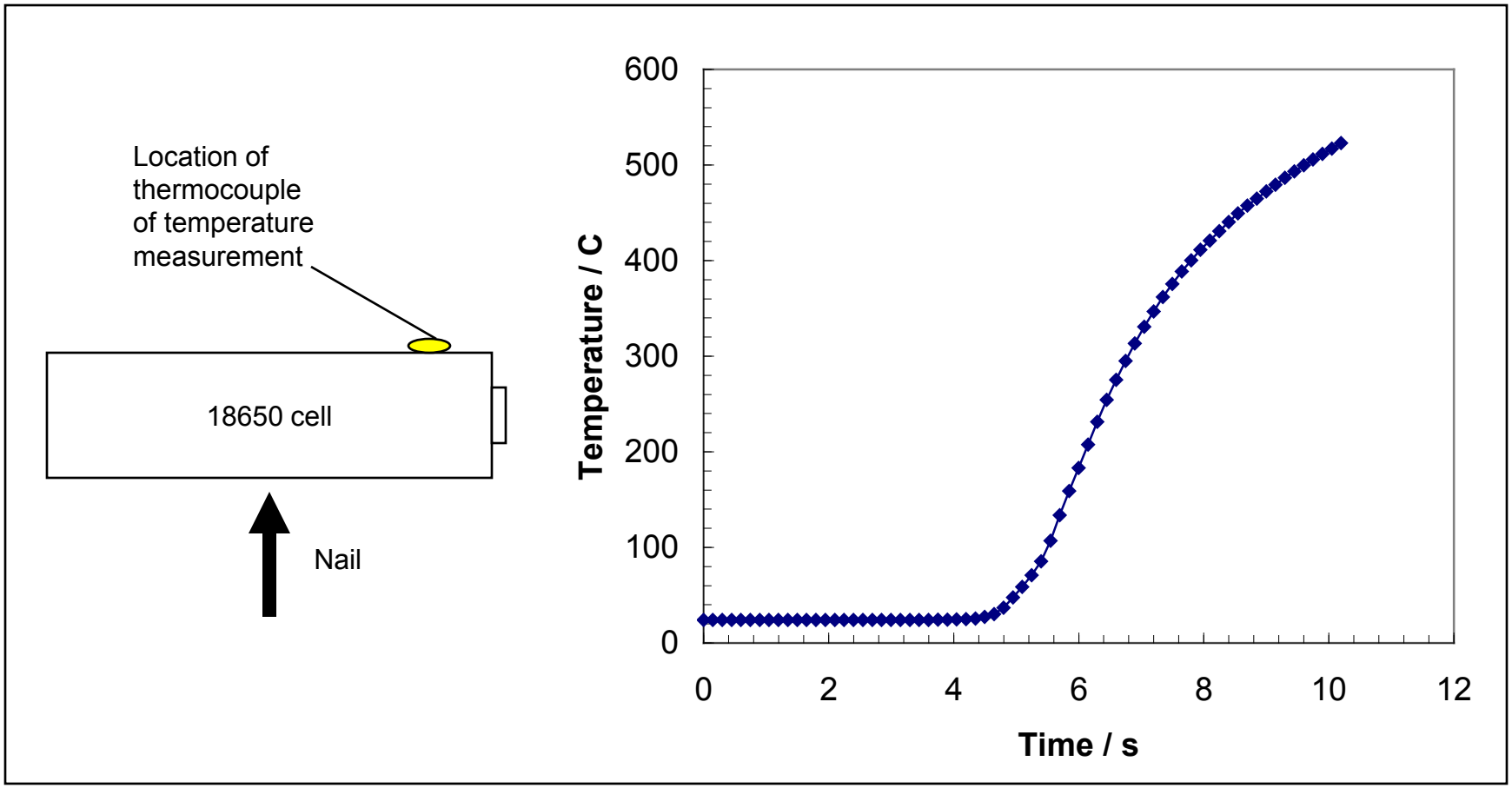
t = 158 ms after nail penetrated the can wall

t = 190 ms after nail penetrated the can wall

During the nail penetration test, it is not uncommon to observe explosions within 200 ms of nail penetration.

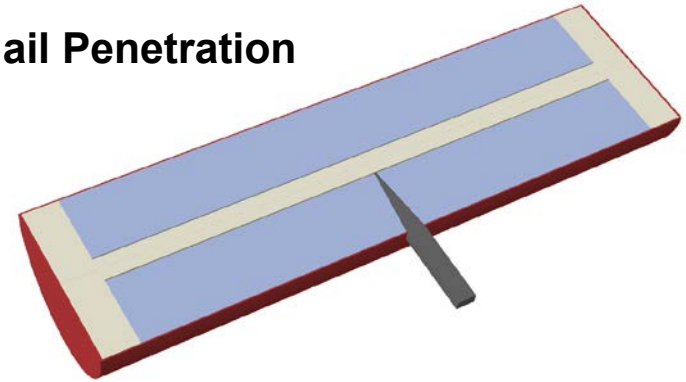
Our experimental setup allows us to characterize the nail penetration process in detail.

The macroscopic increase in temperature of a cell is significantly disconnected from the timeframe in which explosions can occur.

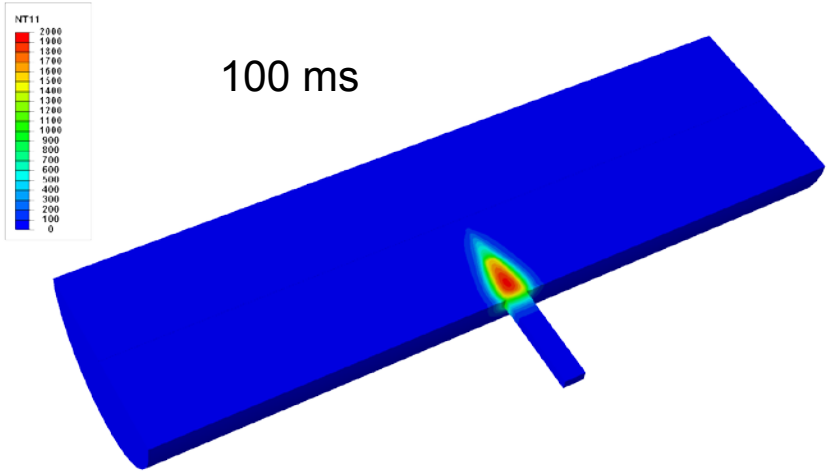


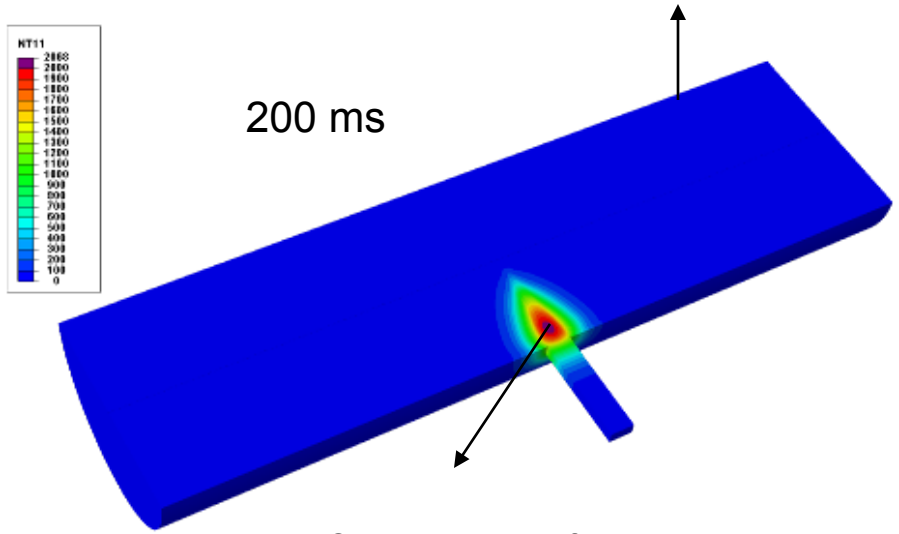
Simulations are helping understand the experimental observations.

Simulation of Nail Penetration

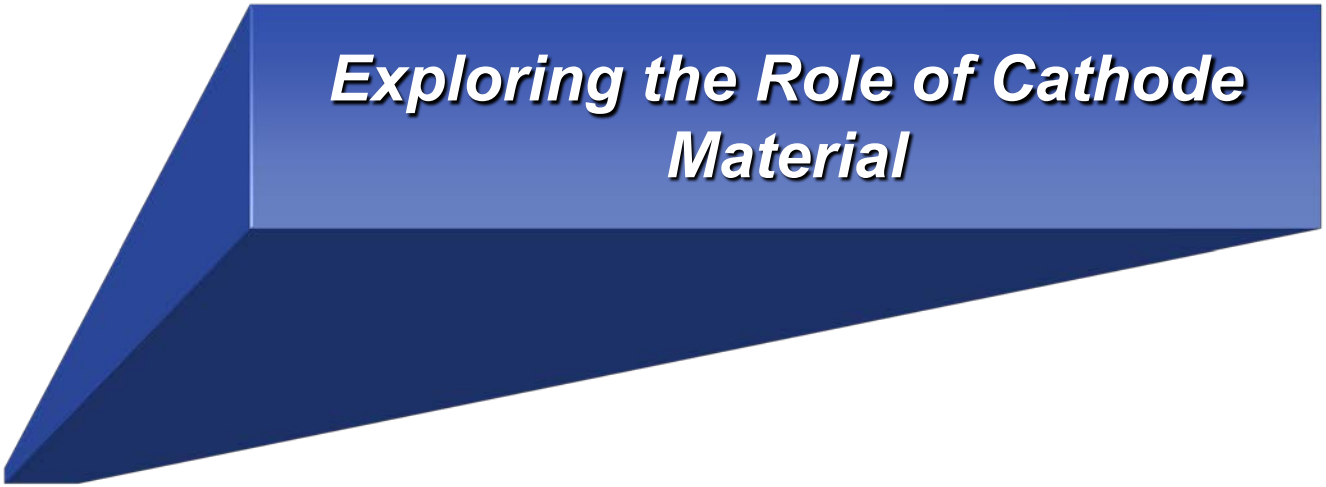


Low temperature far from the nail





Temperatures exceeding 1000°C in the vicinity of the nail


Exploring the Role of Cathode Material

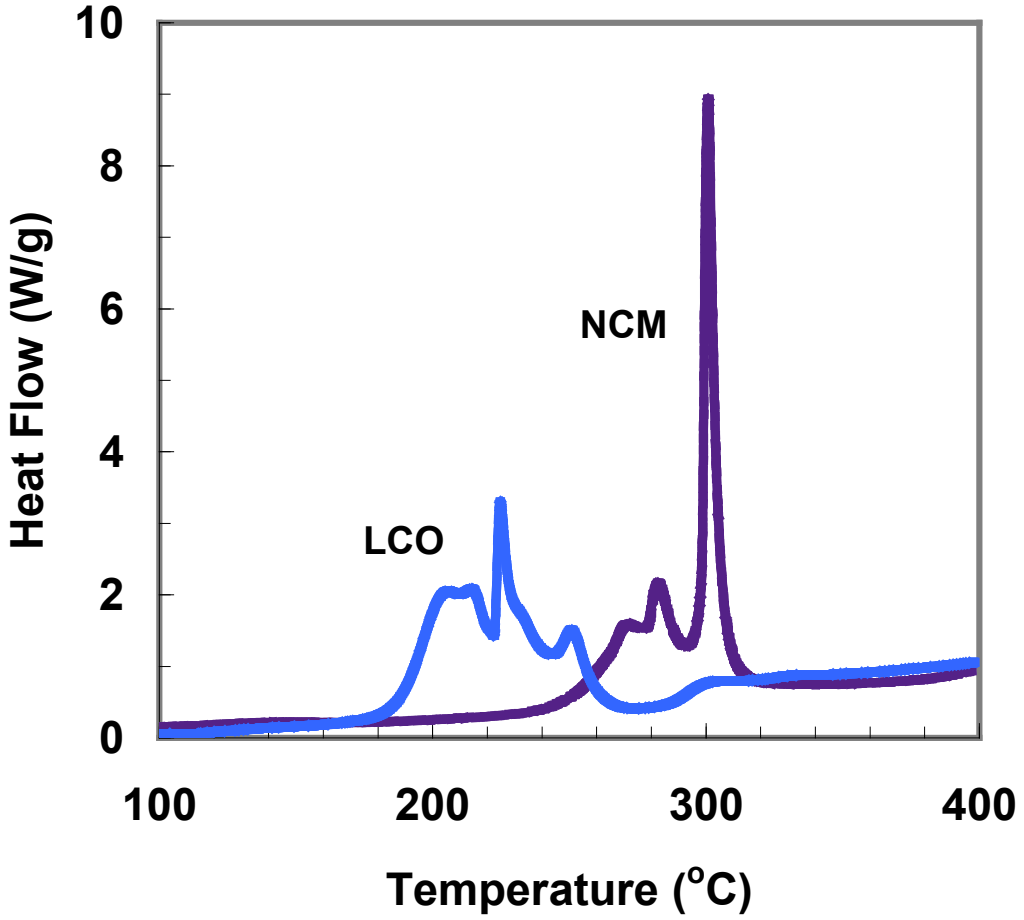
The impact of the cathode material in the outcome of a nail penetration test was also evaluated.

- We purchased commercial 2.6 Ah, 18650 cells with two different chemistries:
  - LCO
  - NCM.

- DSC measurements were used to characterize the thermal stability of these materials:
  - Cathodes were harvested from as-purchased cells
  - The cathodes were then re-built into coin cells (half cells with Li metal) and charged to 4.3 V
  - Charged cathode material was tested with 1M $LiPF_6$/carbonate electrolyte in DSC.

- Separately, 18650 NCA-power tool cells were also subjected to nail penetration test.

NCM has better thermal stability characteristics than LCO (as measured by DSC) leading many to suggest that NCM cells would be 'safer' than LCO cells.

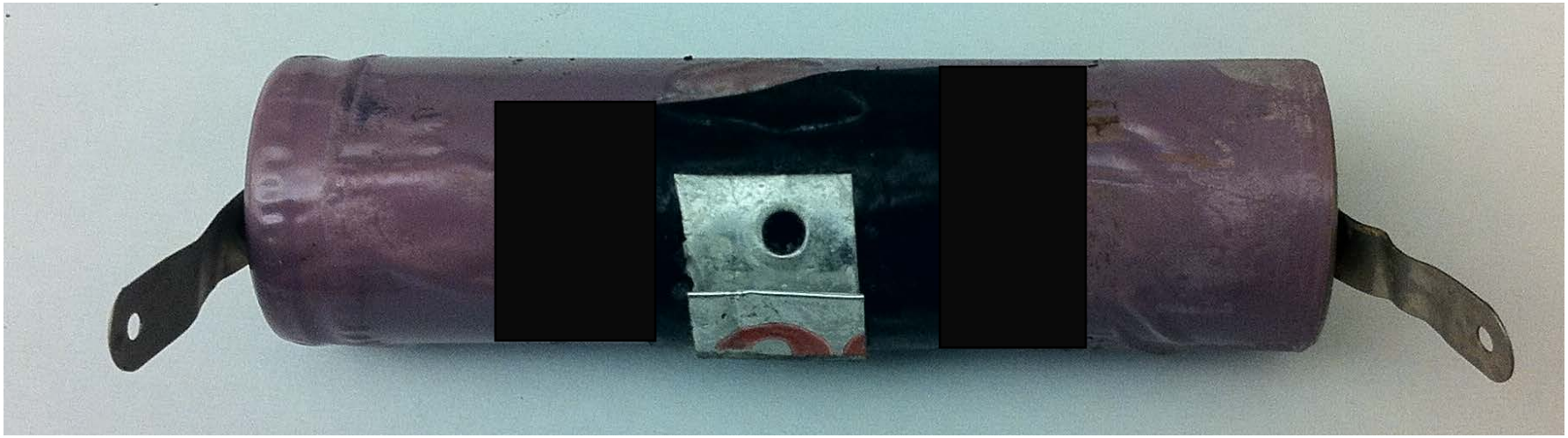


Conventional industry "rules of thumb" regarding safety often do not stand up well to more rigorous thinking.

e.g., according to conventional safety perspective, for LCO, with no heat release to 175C, we ask …

What processes take a cell to 174C, and (1) we don't do anything to intervene? and (2) won't take the cell to 250C or 275C or 300C, where NCM reacts?

In a nail penetration experiment, a commercial LCO cell experienced a mild rise in temperature, but no violent thermal runaway.



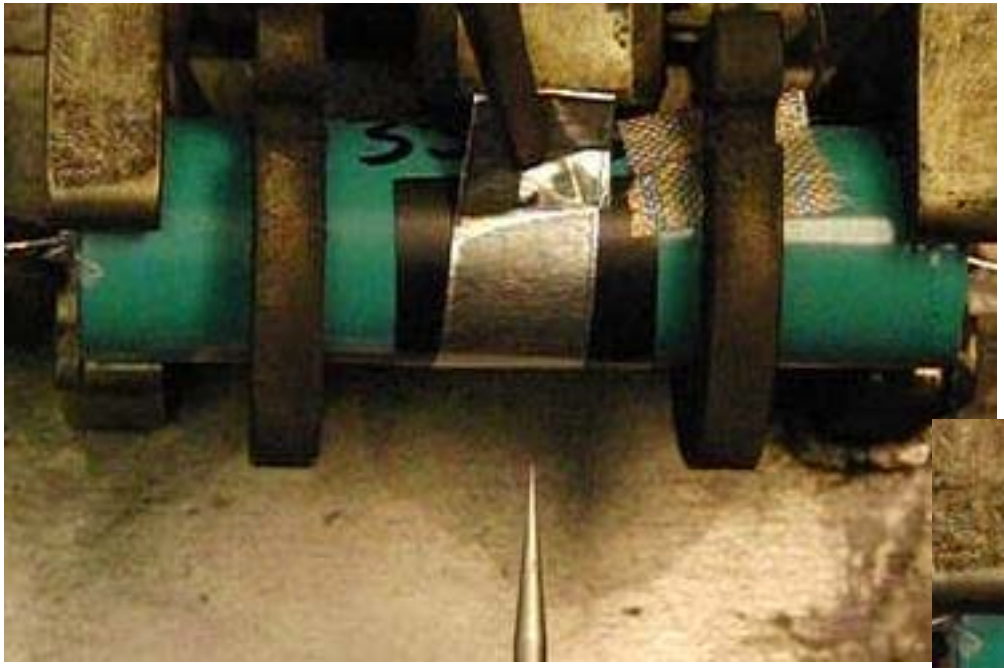
* Commercial 18650 cell, charged to 4.2 V

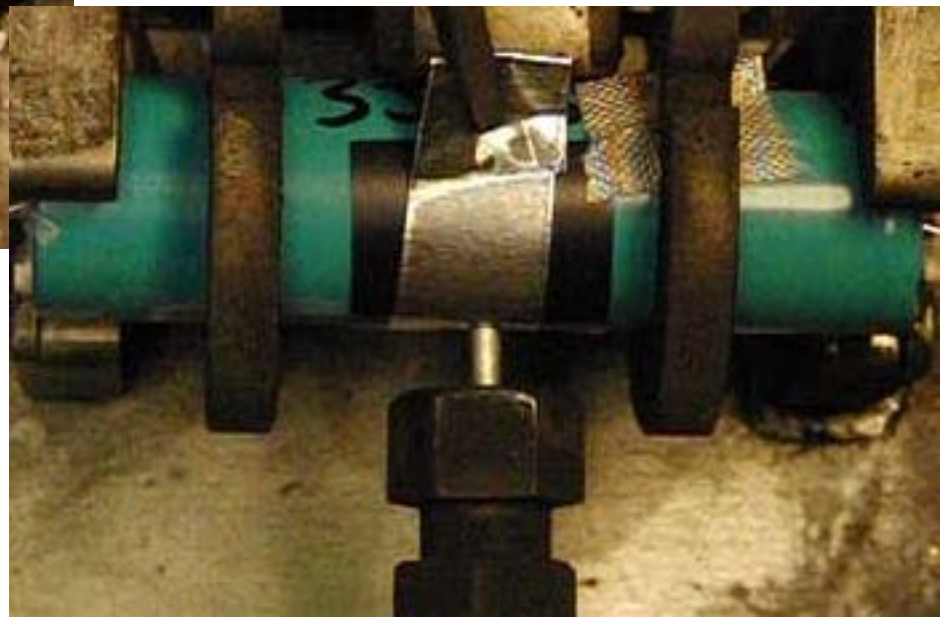
Commercial NCM cells experienced violent thermal runaway in a nail penetration test.

Taken together, these results show that there is little relationship between DSC data and whether or not thermal runaway occurs.

* Commercial 18650 cell, charged to 4.2 V

Commercial NCA cells did not experienced thermal runaway in a nail penetration test.



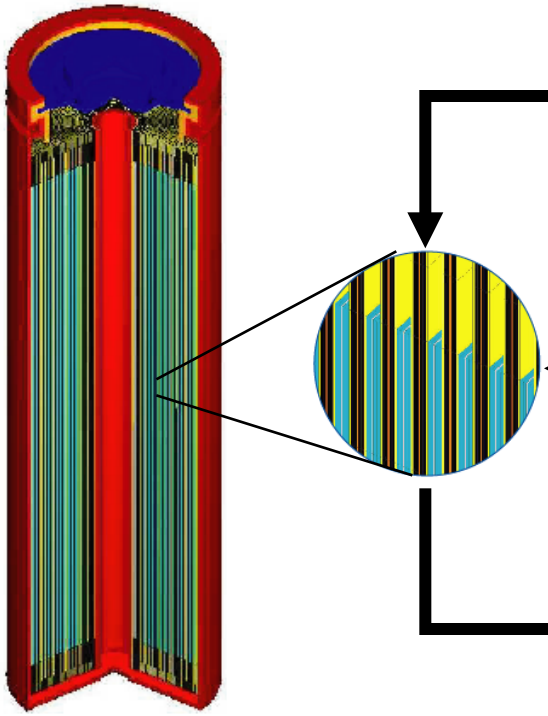


* Commercial 18650 cell, charged to 4.2 V

It is not surprising that cathode DSC measurements are incapable of predicting cell safety given the complex interactions between heat release, heat transfer, and cell design.

Condition for thermal propagation :

Rate of Heat in + rate of heat generation > rate of heat out



Heat transferred into the volume is determined by instantaneous local values of:

temperature gradient, temperature, specific heat, and thermal conductivity

Heat generation is determined by instantaneous local values of:

temperature, concentrations of reactants, kinetics and energetics of decomposition reactions

Heat transferred out of the volume is determined by instantaneous local values of:

temperature gradient, temperature, specific heat, and thermal conductivity

Safety in lithium-ion cells/batteries requires deliberate strategies to deal with the possible occurrence of internal shorts that can progress to thermal runaway.

- Thermal runaway associated with nail penetration takes place within about 200-500 ms. The process by which a cell progresses to thermal runaway due to an internal short, as occurs in the field, involves very different physical processes.
- The nail penetration test is not a useful test for the type of internal shorts that develop over time in the field.
- Nail penetration tests produce variable results, are easily gamed and do not reflect the failure method by which internal shorts result in thermal runaway.
- Nail penetration tests best represent what happens when a nail penetrates a cell under narrowly defined conditions, (but nothing about propensity for thermal runaway events in the field via grown-in internal shorts).