# Mechanical Abuse and Safety Risks of Large-format Li-ion Cells

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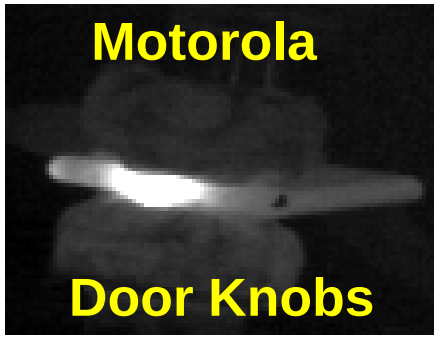
# Internal Short Circuit in Consumer Electronics to Mechanical Abuse in Electrical Vehicles

- **Internal Short Circuit (ISCr):**
  - **Without external trigger**
  - **One in several millions chance**
  - **Incidents reported in consumer electronics cells**
- **Mechanical Abuse in EV**
  - **Triggered by crash involving EV and deformation**
  - **High probability**
  - **Incidents reported**
- **UL 1642 for small Li-ion cells: Mechanical abuse tests (<5 grams of metallic Li), crush, impact, shock and vibration (Pass/Fail)**
- **Large format cells: No official mechanical abuse tests from UL, USABC, NHTSA or other organizations**

# Improved ORNL Pinch Test

*Mechanical Testing System (MTS) Load Frame*




*Schematic of cell pinch test setup*

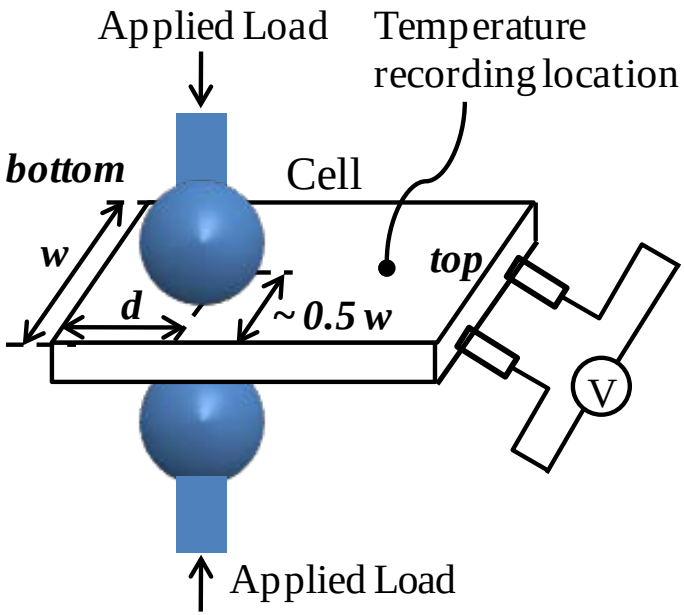
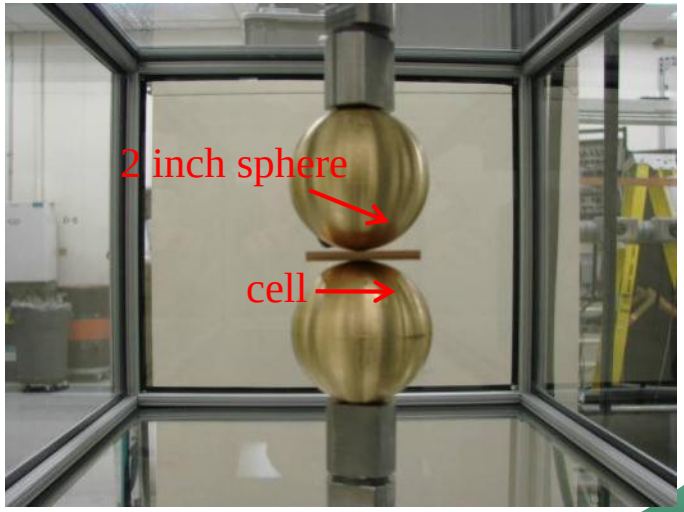
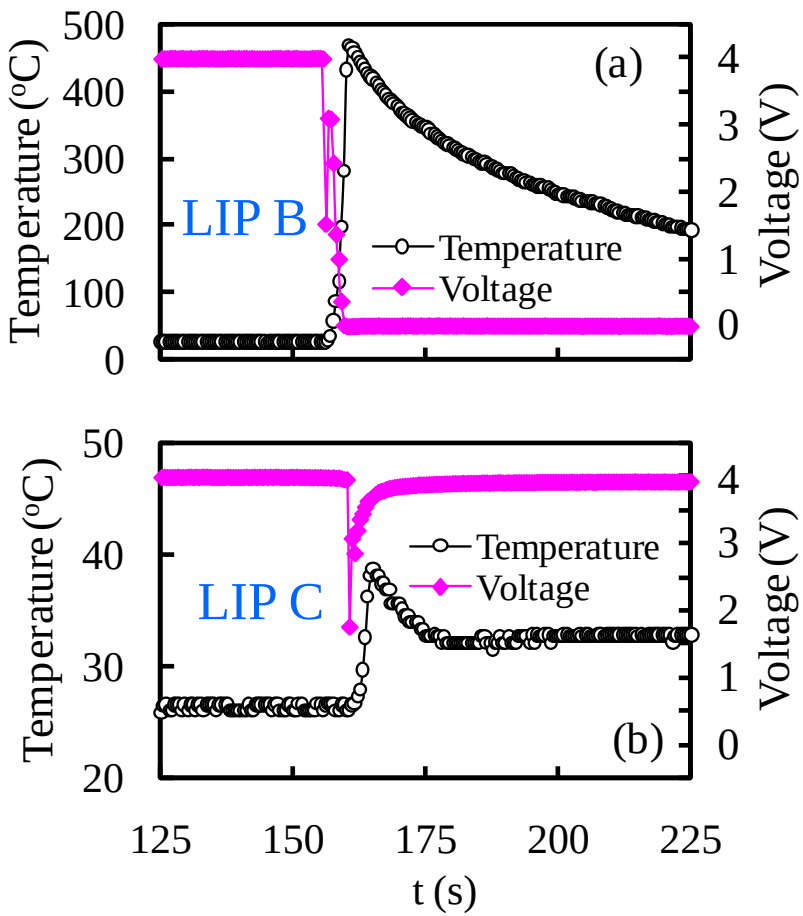



*Photo of cell pinch test setup (close-up)*



# Thermal Runaway vs. Normal Cell Response






- LIP C cell with special separator has lower risk of thermal runaway than LIP B cell!

Wei Cai, Hsin Wang, Edgar Lara-Curzio and Hossein Maleki, "Internal Short Circuit Testing of Prismatic Li-ion Cells: An Improved Pinch Test with Multiple Parameter Controls", ***Journal of Power Sources***, Volume 196, Issue 18, pp7779-7783 (2011)

# ORNL pinch test can help distinguish cells with different thermal stability characteristics

| Cell type | $V_{ocv}$ (V) | Discharge capacity (mA•hrs) | No. of cells tested | No. of cells thermal runaway |
|---|---|---|---|---|
| Li-ion A | 3.8 | 340 | 30 | 0 |
| | 4.0 | 590 | 6 | 0 |
| | 4.1 | 680 | 6 | 2 |
| | 4.2 | 770 | 6 | 6 |
| LIP B | 3.7 | 160 | 6 | 0 |
| | 3.9 | 880 | 6 | 0 |
| | 4.0 | 1180 | 6 | 6 |
| LIP C | 3.7 | 160 | 6 | 0 |
| | 4.0 | 1160 | 6 | 0 |
| | 4.1 | 1350 | 6 | 4 |
| | 4.2 | 1490 | 6 | 6 |

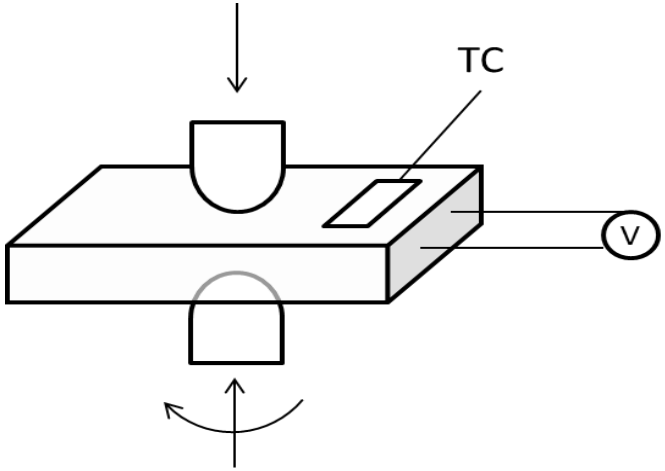
- The risk of thermal runaway during ISCr increases as the cells' state of charge and capacity increase!
- Pinch test still created larger damage areas to allow more sensitive evaluations

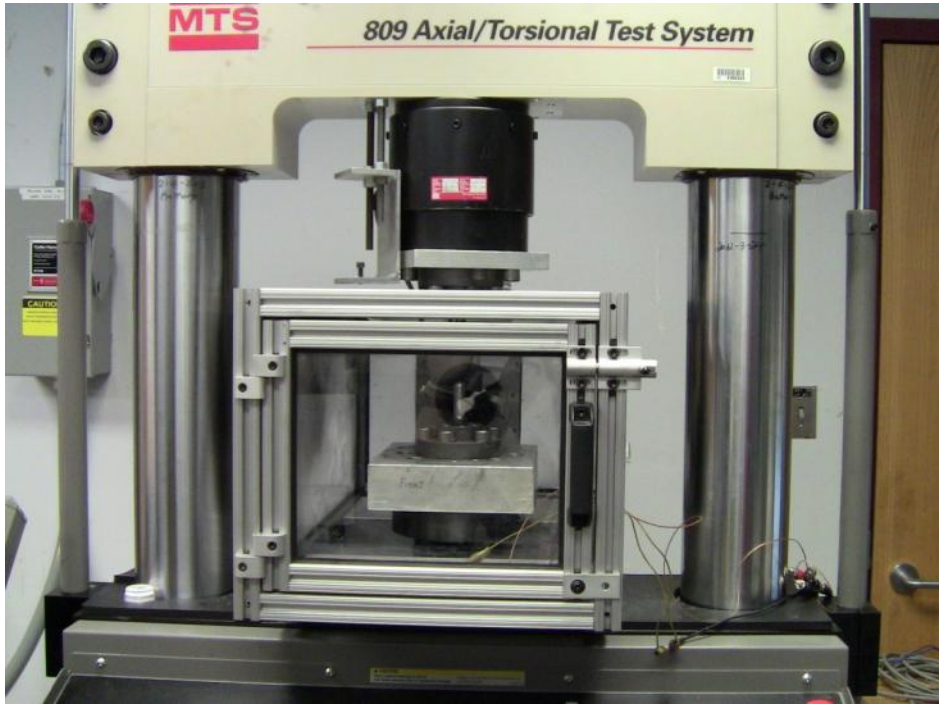
# Thermal Runaway Risks

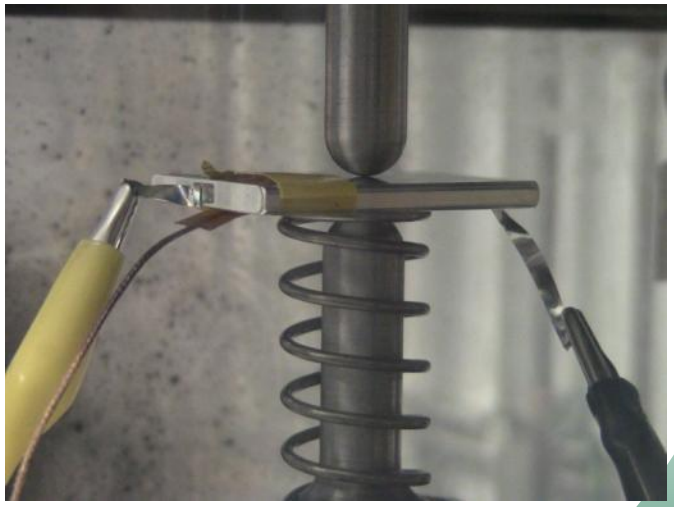
- **We recognized a change of concept on battery safety is necessary:**
  - **Thermal runaway will occur in high capacity Li-ion cells under various abuse conditions**
  - **The concept of a PASS/FAIL test to assure safety is not practical**
- **At cell level, it is possible to develop sensitive test(s) to assess the risk of thermal runaway**
- **Knowing the risk factor allows cells to be compared**
- **A pinch/torsion test was developed at ORNL and NSWC for such purpose**

# Experiment Setup: Pinch-Torsion

- **Biaxial servo-hydraulic testing machine**
- **In-house made fixture with a tip diameter of 0.5”**

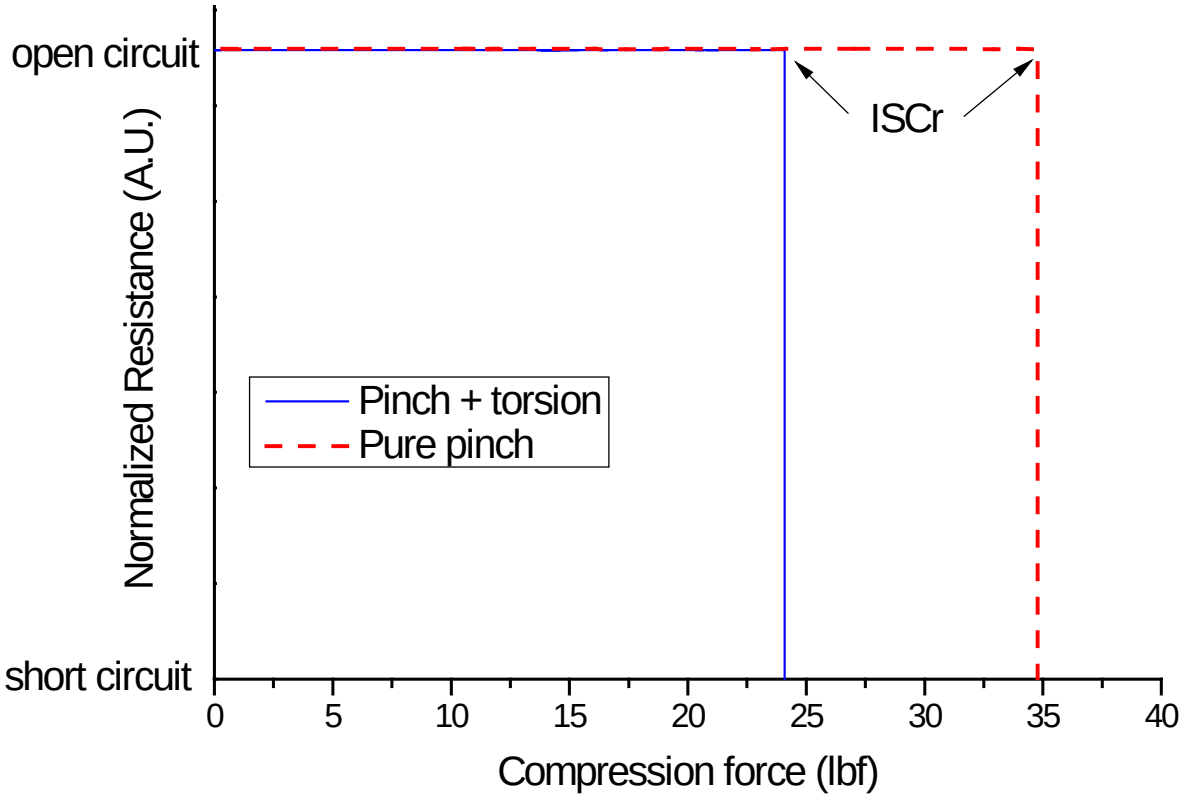


# Concept Demonstration: Testing of single-layered prototype cells

- **Internal short circuit was created at lower axial loading when torsion was added.**



# Testing of Commercial Li-Ion Batteries

- No thermal runaway occurred at 4.1 V
- At 4.2 V, Cell B had lower thermal-runaway rate (1/6) than Cell A (4/6) → Capability to distinguish cell safety performance at fully charged states

| Cell | Voltage (V) | Discharge capacity (mAh) | Number of test | Number of thermal runaway | Average $T_{peak}$ (°C) |
|---|---|---|---|---|---|
| **Li-ion A** | 3.8 (AR) | N/A | 6 | 0 | 22.5 |
| **5 x 35 x 66 ($mm^3$)** | 3.9 | 683 | 6 | 0 | 21.6 |
| **25.0 g** | 4.0 | 873 | 6 | 0 | 24.0 |
| | 4.1 | 1000 | 6 | 0 | 30.3 |
| | 4.2 | 1125 | 6 | 4 | 30.2* |
| **Li-ion B** | 3.8 (AR) | N/A | 6 | 0 | 31.0 |
| **8 x 40 x 70 ($mm^3$)** | 3.9 | 1507 | 6 | 0 | 24.3 |
| **47.5 g** | 4.0 | 1925 | 6 | 0 | 25.2 |
| | 4.1 | 2222 | 6 | 0 | 31.8 |
| | 4.2 | 2503 | 6 | 1 | 26.3* |

* Excluding cells that went thermal runaway

# Evaluate Thermal Runaway Risk

| Hazard Level | USABC description |
|---|---|
| Level 0 | No effect |
| Level 1 | Reversible loss of function |
| Level 2 | Irreversible defect/damage |
| Level 3 | Leakage, mass loss <50% |
| Level 4 | Venting, mass loss >50% |
| Level 5 | Fire or flame |
| Level 6 | Rupture |
| Level 7 | Explosion |

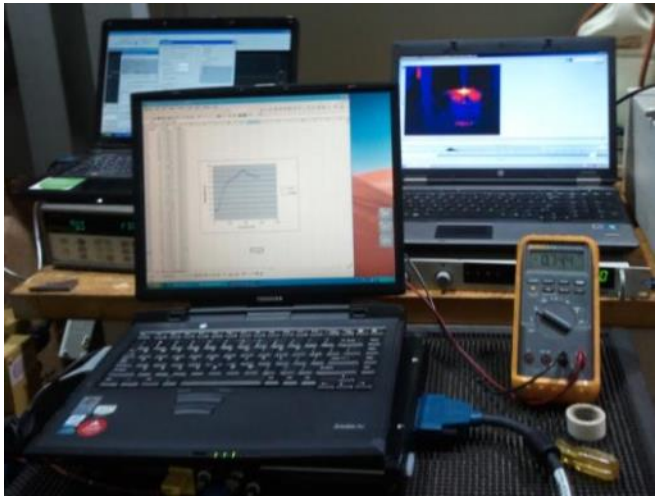
| TRR Score | Damage Description | | Equivalent USABC Hazard Level |
|---|---|---|---|
| | Voltage | Temperature | |
| 0 | Soft short, small V drop followed by recovery | No significant temperature rise (< 30ºC) | 0-1 |
| 50 | Continuous voltage drop without recovery | Significant temperature rise (30-100ºC) | 2-3 |
| 100 | Quick voltage drop | Rapid temperature rise (> 100ºC within 2-10 seconds) | 4-7 |

# Thermal Runaway Risks of 1150 mAh and 2500 mAh Cells

| Cell type | Voltage(V) | Average Discharge capacity (mAh) | Number of test | Failure load (N) | Individual TRR Score | | | | | | Average TRR Score |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | As received | Unknown* | 6 | -714 ± 19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 3.9 | 683 | 6 | -771 ± 40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4.0 | 873 | 6 | -778 ± 31 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4.1 | 1000 | 6 | -698 ± 32 | 0 | 0 | 0 | 50 | 0 | 0 | 8.3 |
| | 4.2 | 1125 | 6 | -797 ± 64 | 0 | 100 | 0 | 100 | 100 | 100 | 66.7 |
| B | As received | Unknown* | 6 | -1217 ± 44 | 0 | 0 | 50 | 0 | 0 | 0 | 8.3 |
| | 3.9 | 1507 | 6 | -1206 ± 27 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4.0 | 1925 | 6 | -1183 ± 41 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4.1 | 2222 | 6 | -1220 ± 48 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4.2 | 2503 | 6 | -1157 ± 76 | 0 | 0 | 0 | 0 | 100 | 0 | 16.7 |

Pinch + Torsion tests are more sensitive to compare cells

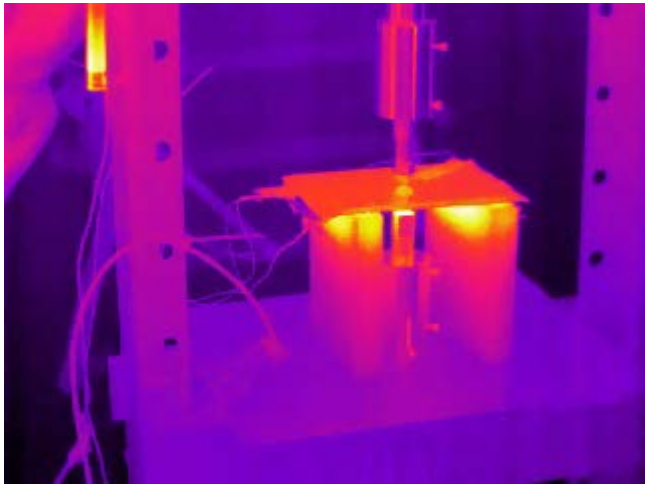
# NSWC Carderock, MD Facility

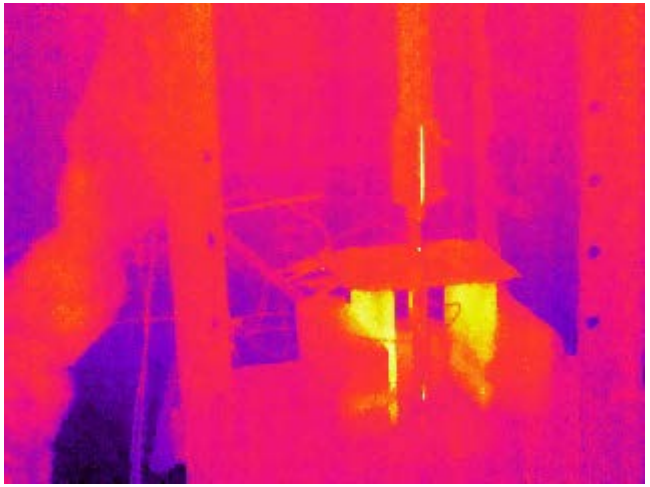
Testing of large format Li-ion cells

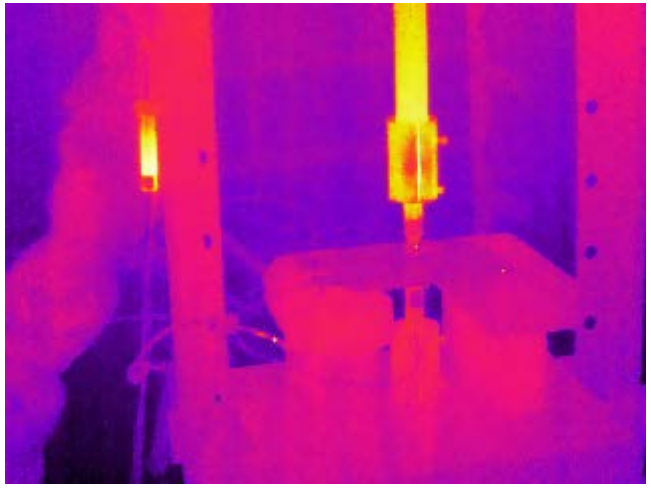
# Infrared Movies of Safety Testing

15 Ahr

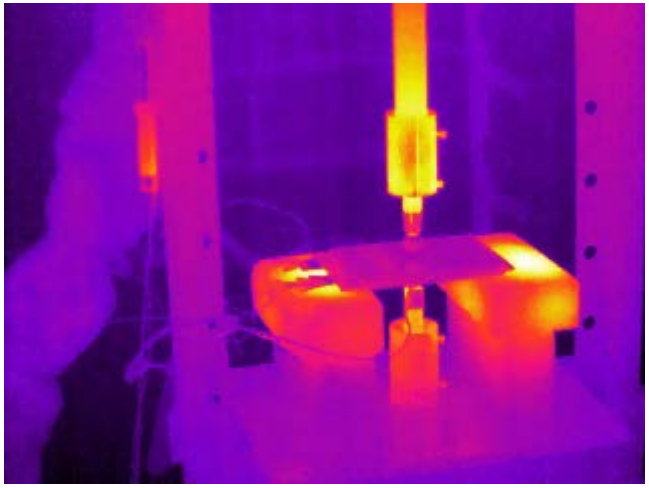


20 Ahr





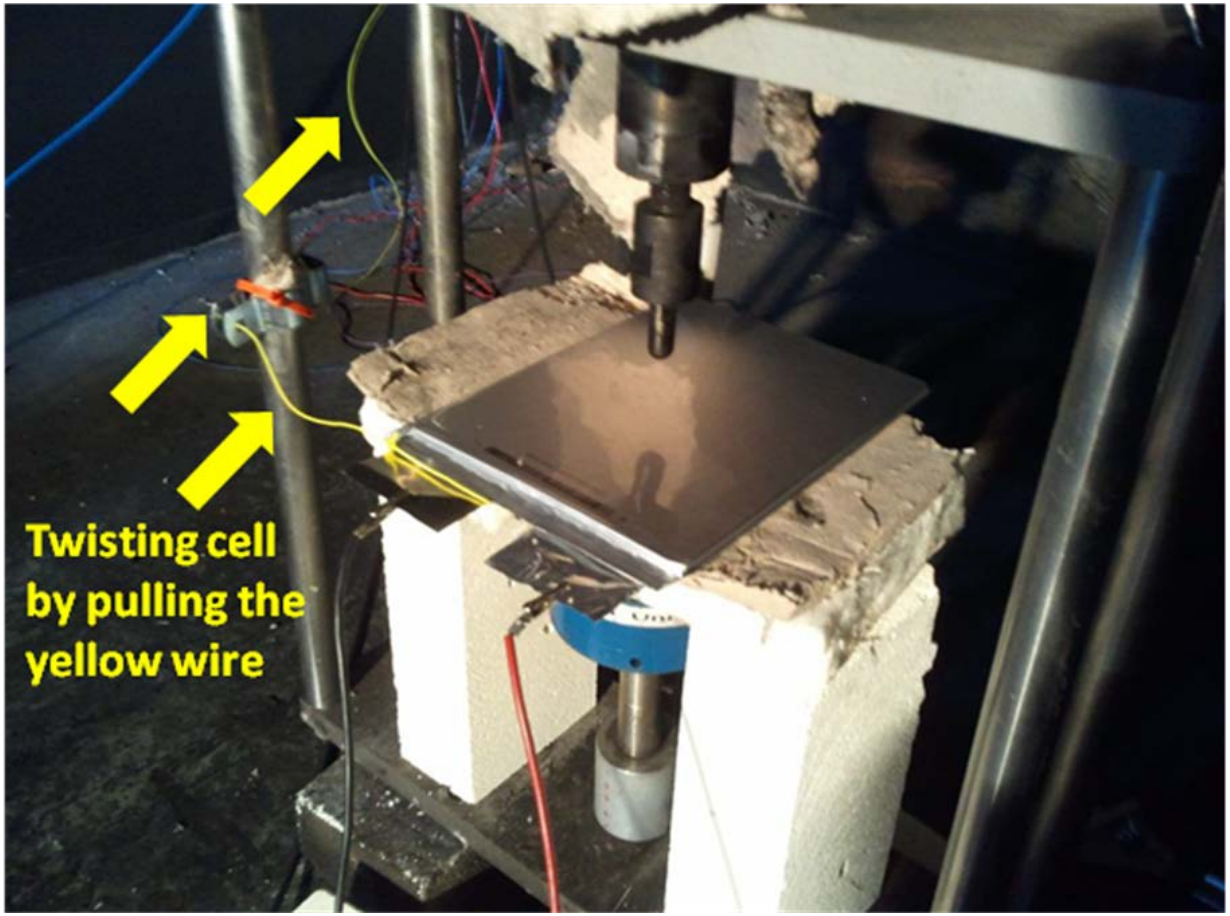
35 Ahr



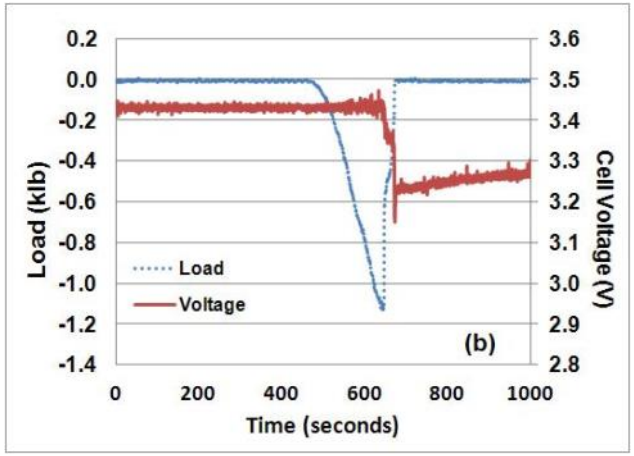
60 Ahr

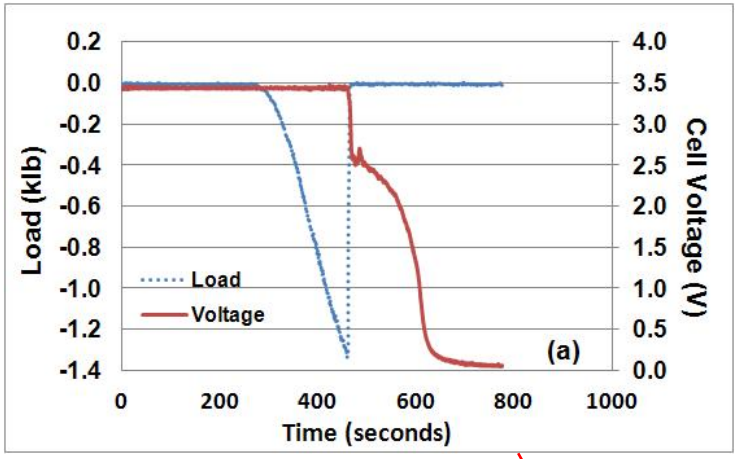
# Large Format LFP and NMC Cells

**After testing several cells with pinch test, it was found twisting during pinching is needed: improvised pinch-torsion test by pulling a wire attached to anode tab**



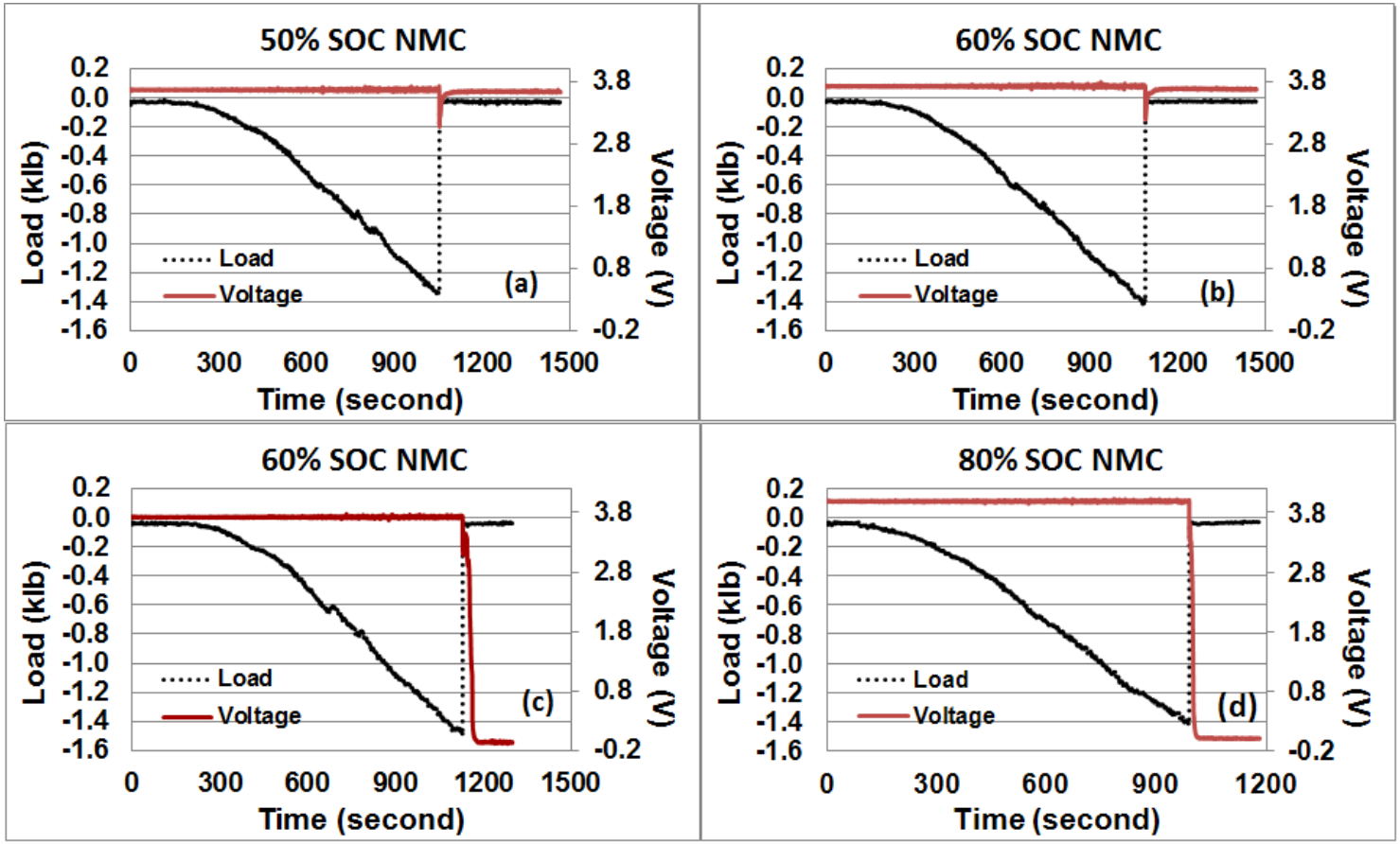
# LFP 100% SOC Pinch vs. Pinch + Twist




Pinch + Twist allowed 100% SOC cells

# Half of 25 Ahr NMC Cells Went to Thermal Runaway at 60% SOC




Under the same testing conditions 100% SOC LFP cells have less risk of thermal runaway than 60% SOC NMC cells

# Thermal Runaway Risks of Large Format Cells

**LFP cells tested at 100% and 90% SOC.**

| Cell | Voltage (V) | Capacity (Ahr) | SOC % | Number of Tests | Number of thermal runaway | Safety Score | Thermal Runaway Risk |
|---|---|---|---|---|---|---|---|
| LFP Cells | 3.33 | 16.2 | 90 | 5 | 0 | 100 | 0 |
| | 3.43 | 18.0 | 100 | 4 | 0 | 100 | 0 |

**NMC cells tested at various SOC.**

| Cell | Voltage (V) | Capacity (Ahr) | SOC (%) | Number of Tests | Number of thermal runaway | Safety Score | Thermal runaway risk |
|---|---|---|---|---|---|---|---|
| NMC Cells | 3.68 | 12.5 | 50 | 4 | 0 | 100 | 0 |
| | 3.71 | 15.0 | 60 | 6 | 3 | 50 | 50 |
| | 4.00 | 20 | 80 | 1 | 1 | 0 | 100 |
| | 4.05 | 23 | 92 | 1 | 1 | 0 | 100 |

**Hsin Wang, Edgar Lara-Curzio, Evan Rules and Clint Winchester, "Mechanical Abuse Simulation and Thermal Runaway Risks of Large-Format Li-ion Batteries", *Journal of Power Sources*, in press, January (2017)**

# Summary

- **The pinch-torsion test has been shown to be a reliable safety evaluation tool for small and large capacity cells**
- **Further improvements on large format cell testing are needed: automated system and optimize test parameters**
- **Simulation and modeling are important to optimize the test**
- **Thermal Runaway Risk scoring system is proposed to evaluate cell safety**