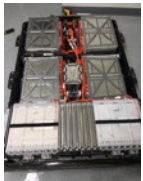


# Thermal Runaway Thresholds at Cell Level Affected by Chemistry, Capacity and State-of-charge

- Hsin Wang, Lianshan Lin and Mali Balasubramanian
- *Oak Ridge National Laboratory*

ORNL is managed by UT-Battelle, LLC for the US Department of Energy



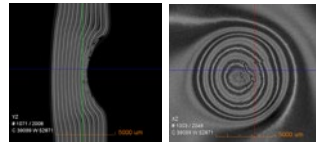
Battery Pack



Battery Modules



Battery Cells



XCT: Indented Battery

June 3, 2026



U.S. DEPARTMENT  
of ENERGY

# Progression of Li-ion Safety

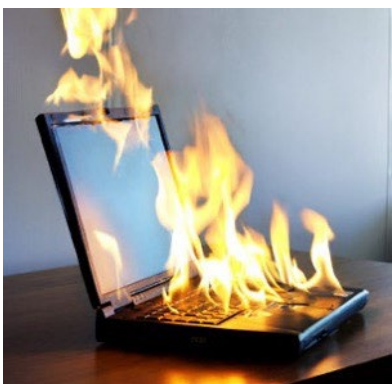
1998-2000



Cell Phones  
Laptops  
Single-cell Failure

## Appliances

- 1/1,000,000 failure chance
- Manufacturing defects, abuse
- Simulate internal short circuit: mechanical, thermal, electrical



2010-2013

EV Cells  
Large format  
Large numbers  
Single-vehicle  
Accidents

## Electric Vehicles

- Accident due to collision
- Mechanical abuse is real



2016-2020

DOE OE Energy Storage

Large format  
Large numbers  
Large capacity

## Energy Storage

- Stationary system deployment
- Propagation
- Accidents in EV and ESS increased

2026 ->

New Challenges for Energy Storage

New Chemistries  
Higher Capacities  
More Sensors

## New Solutions

- Managing Hazards and Safety data using ML/AI
- Early Warning detection and pattern recognition

# Li-ion Battery Safety Testing: Thermal Runaway

- **Mechanical Abuse**

- Deformation: bending, dropping, impact, intrusion of external objects
- Testing: Nail penetration, indentation, pinch, pinch-torsion
- Mechanism: Induce internal short circuit -> thermal runaway

- Thermal Abuse

- Overcharging/discharging

**Limitations of Safety Studies:**

- Number of cells are limited
- Hard to compare results of different tests
- Safety Tests vs Relative Risk

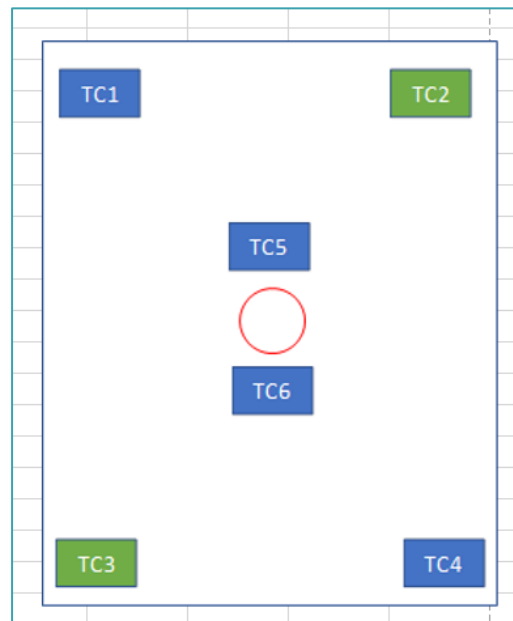
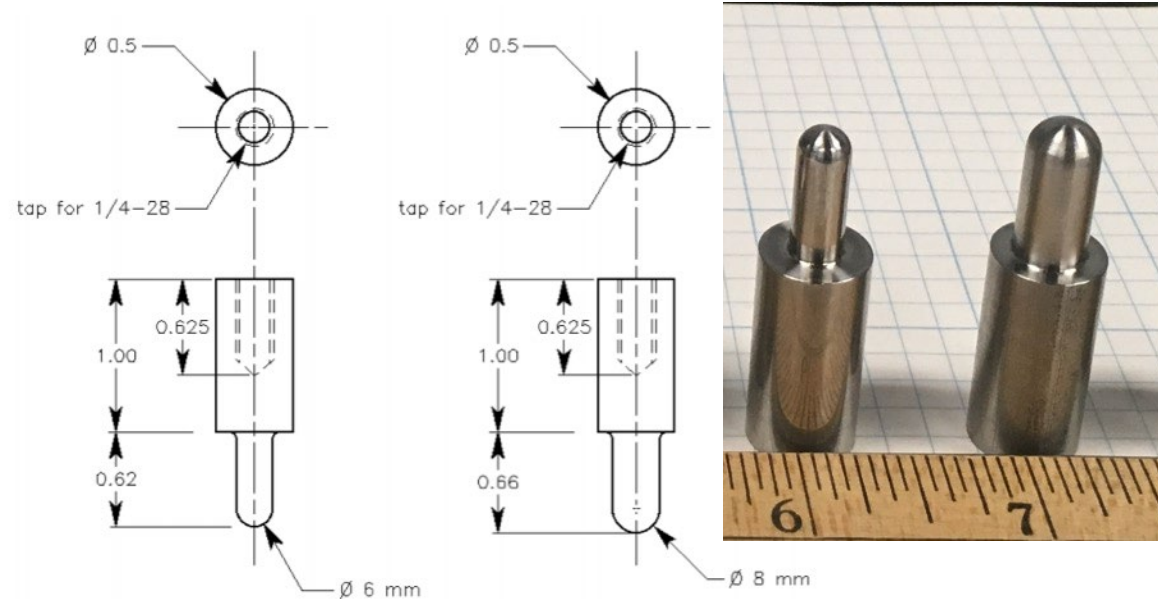
# Updated ORNL-Sandia Test Procedures and Standards

## Internal Short-circuit Induced Thermal Runaway

- Mechanical abuse (indentation)

### Updated Test Protocols:

- Cycle cell 3-5 times at C/2 between 3.0-4.2V to determine SOC and discharge to test SOC
- Hydraulic or servo-motor driven load frame
- 6 mm punch (most sensitive, small contact)
- 0.05 inch per minute compressive loading
- 25 mV  $V_{oc}$  drop
- Hold the punch after short circuit
- Temperature measurement:
  - 5 mm from the indenter
  - At cell corners when possible



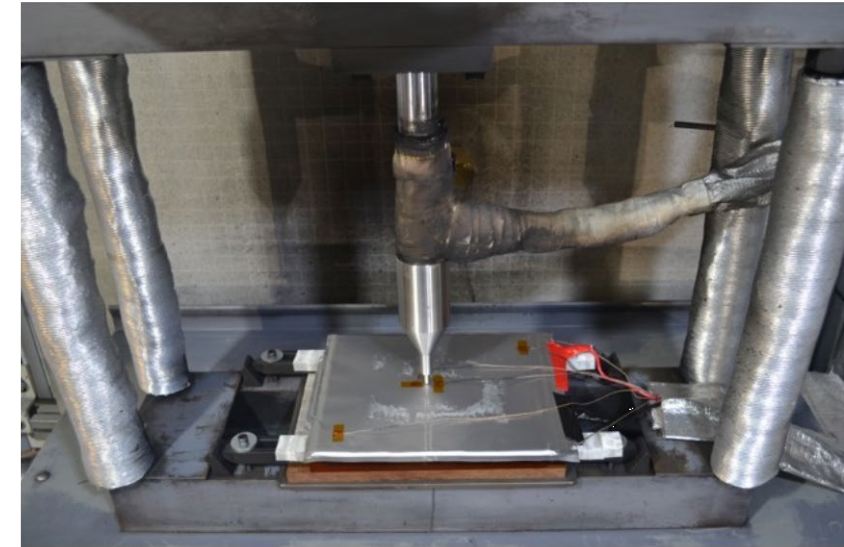
Punches for Battery Testing		
ELC-2019.03.001	Scale: 1.5:1	
Dimensions: inches (unless otherwise specified)	Material: stainless steel	
Make four (4) pieces of each		
Edgar Lara-Curzio	ORNL	March 2019

Select the most sensitive test to allow safety risk Ranking (similar to USABC and UL small indentation test)

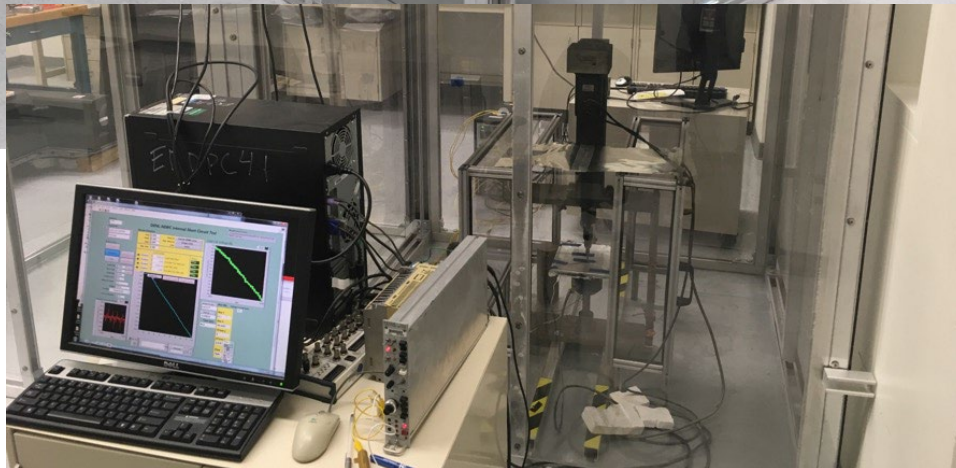
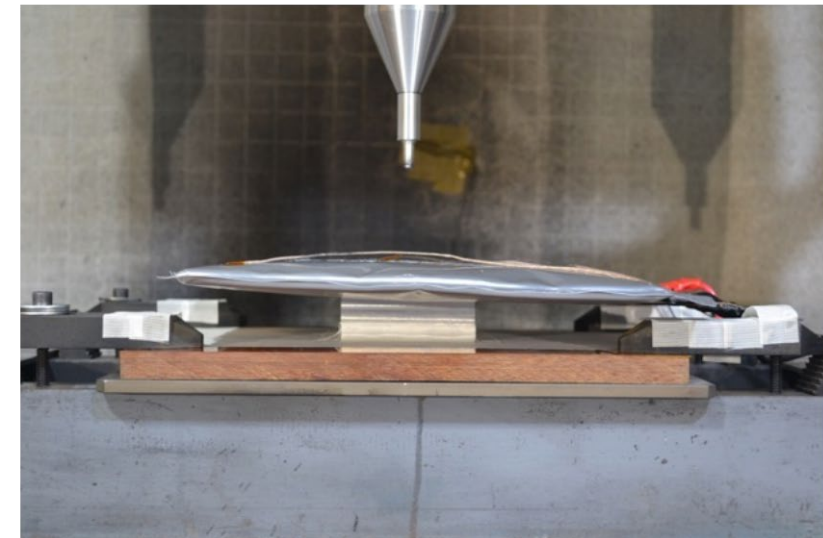
Thermocouple Locations on Large-format Cells

# ORNL and Sandia Testing Facility: Large Format Cells

**Nissan Leaf Cell in Sandia Test Chamber**

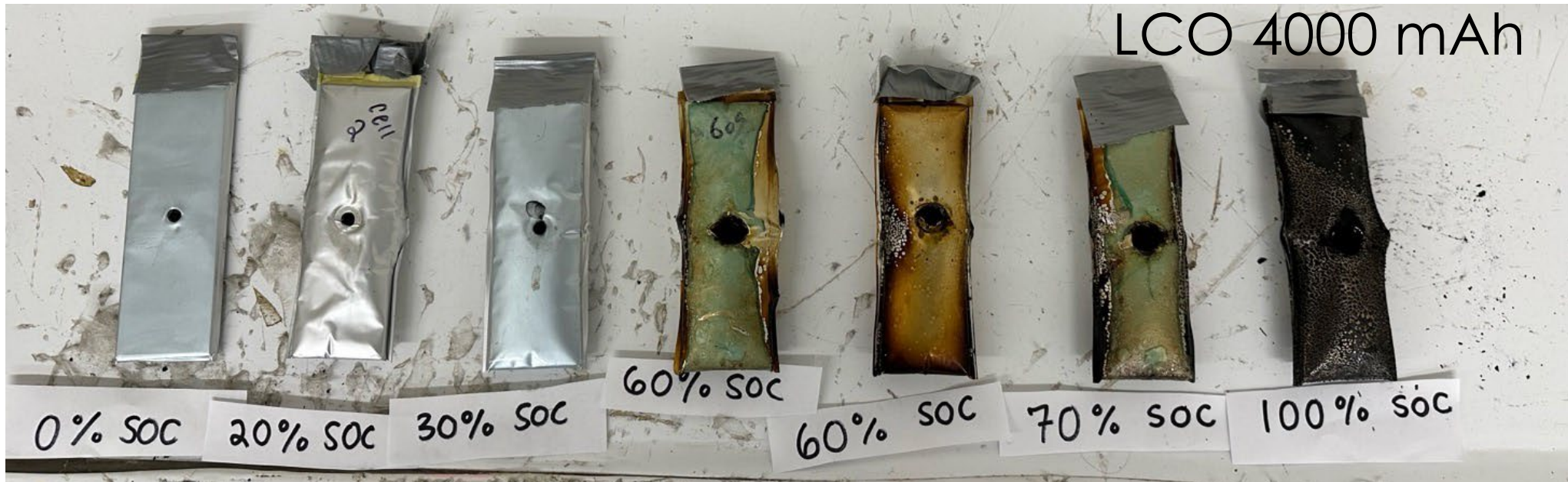


**Nissan Leaf Cell After Indentation**



# Mechanical Abuse Thermal Runaway Tests: Visual Inspections

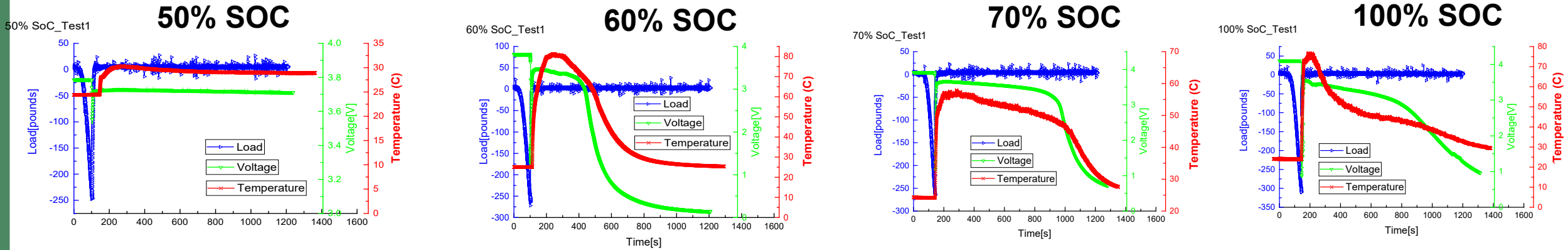
Post Indentation Test



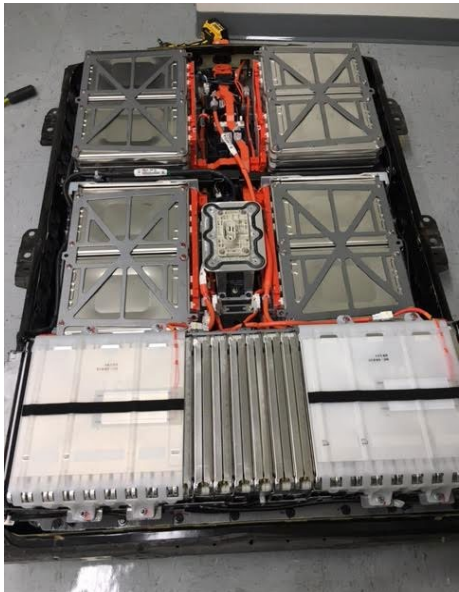
Thermal runaway threshold is related to chemistry, capacity, and SOC

# Development of Thermal Runaway Risk Database

## Characteristic Responses from 500 mAh Li-ion Cells as Function of SOC



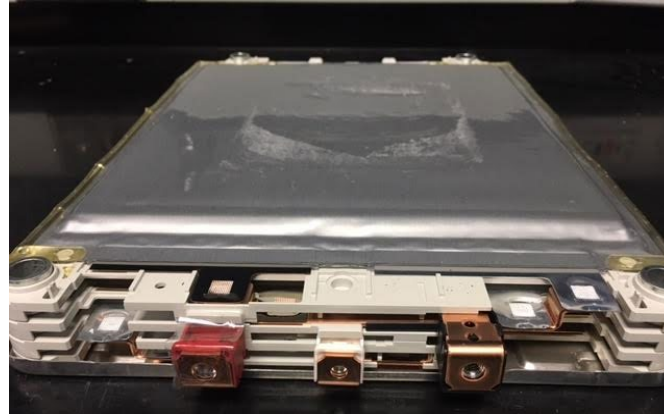
## Large Format Nissan Leaf Cells Tested at ORNL and Sandia



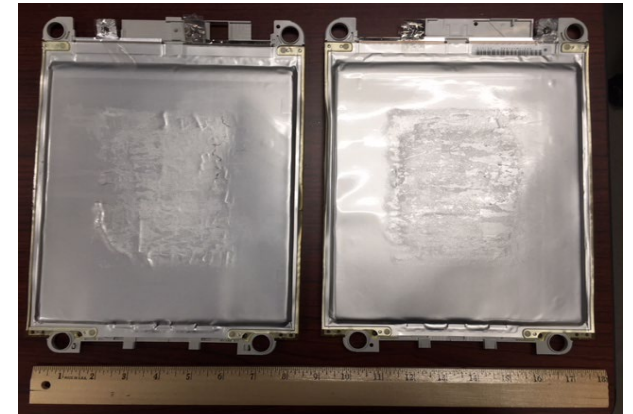
Nissan Leaf Battery Pack



Nissan Leaf Battery Modules

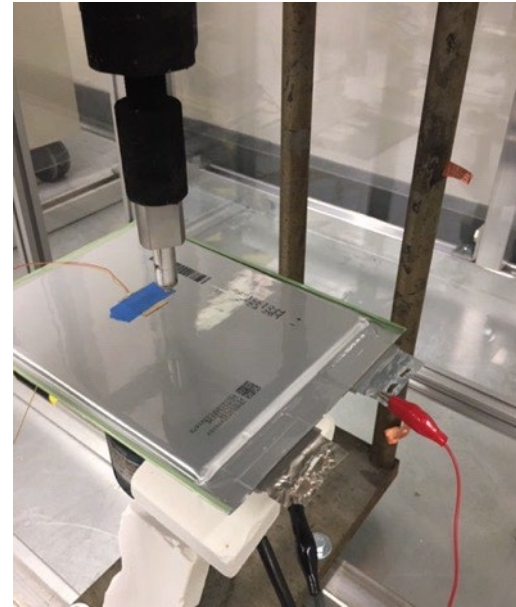
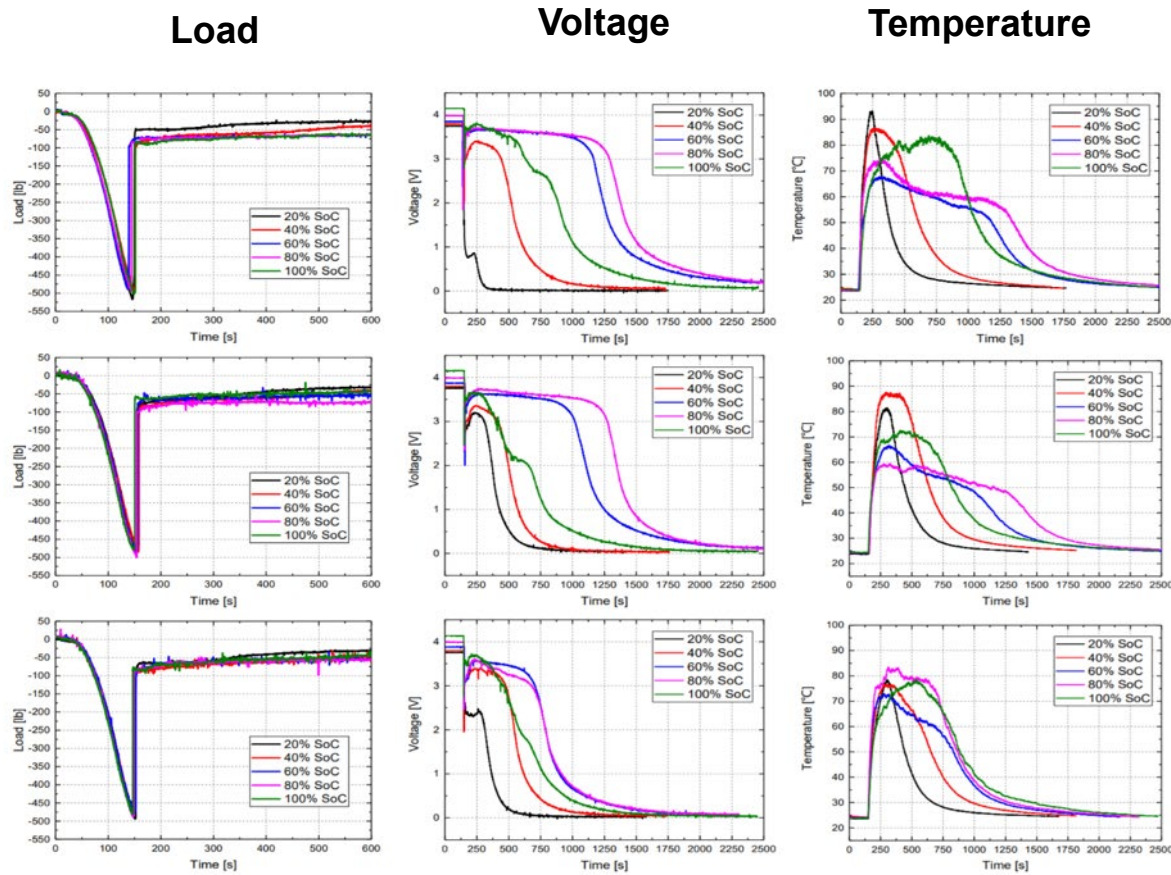


Disassembled Module



Individual Cells (32 Ah)

# Thermal Runaway Risks for Li-ion Batteries (ORNL-Sandia)



## Test Data and Cell Information:

- Cell Capacity
- Loading curve: before & after short
- Cell Voltage: drop and response
- Cell Temperature vs. Time
- Open cell voltage
- Anode thickness
- Cathode thickness
- Separator thickness
- C/2 Charge curve
- 1C discharge curve

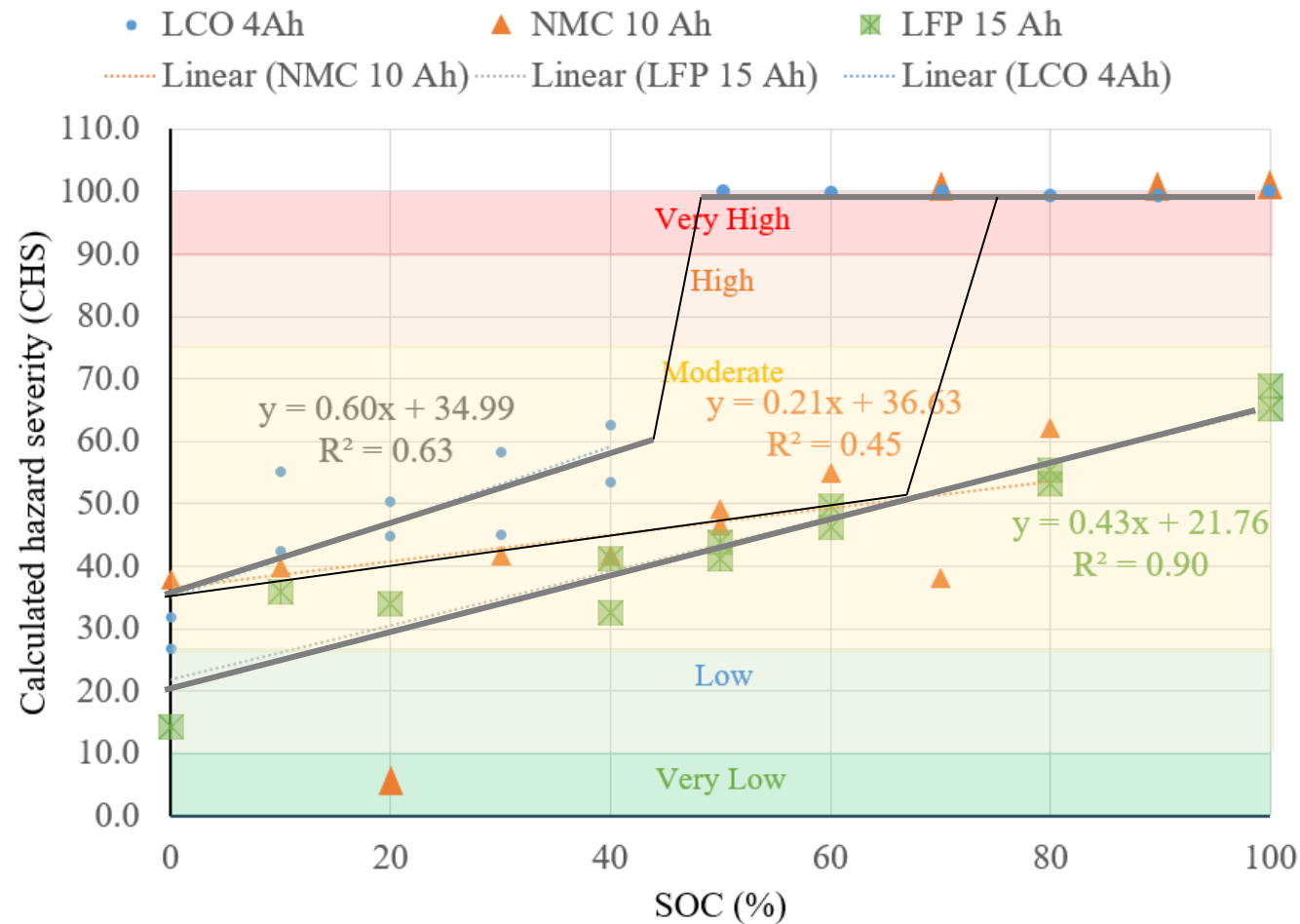
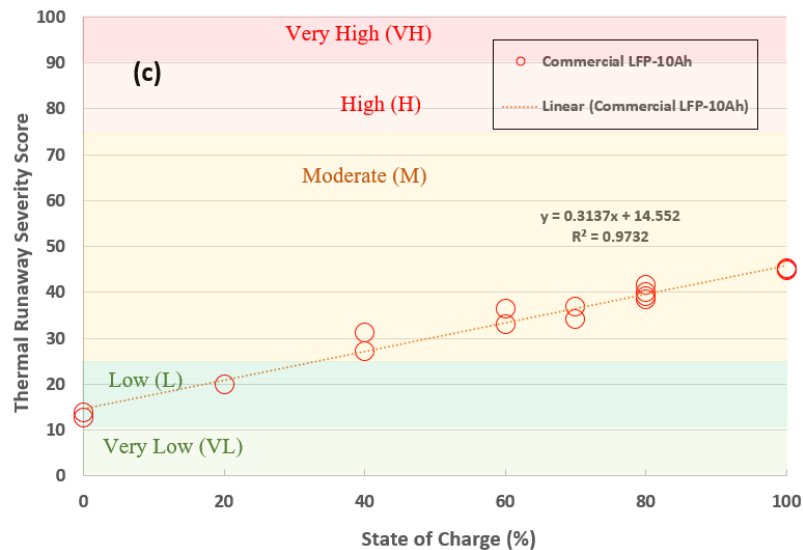
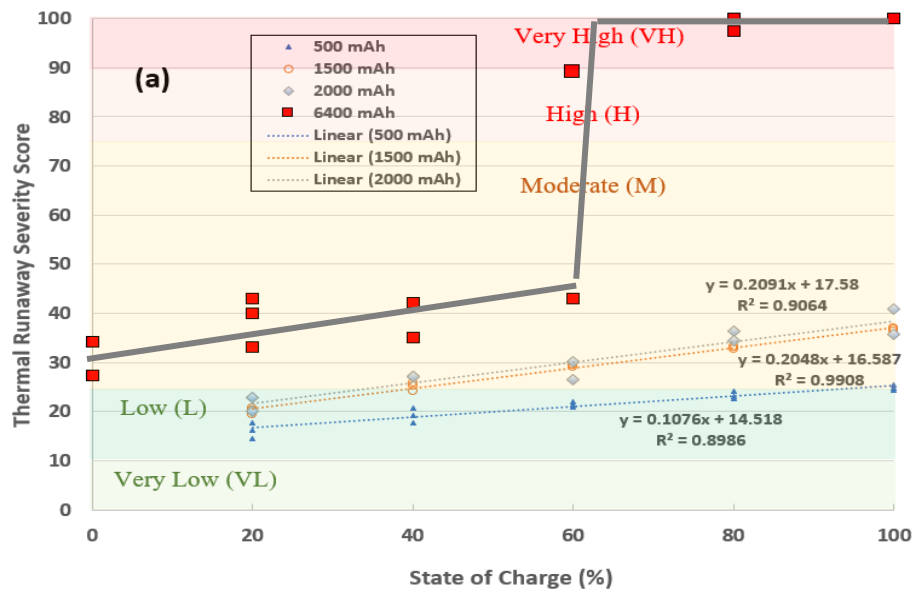
## Example of Traditional Data Analysis

Cell Capacity (mAh)	500	500	500	500	500
SOC %	20%	40%	60%	80%	100%
Test Cell Capacity (mAh)	100	200	300	400	500
Voc (V)	3.75	3.784	3.861	3.991	4.147
V drop Initial (V)	0.25	2.284	0.351	3.581	3.955
V at 300 sec (V)	0.0183	0.095	0.407	0.15595	0.033569
Sum of V*Δt (V-Sec)	120.63	110.47	220.09	77.176	29.462
Load at failure (lb)	-338	-337.52	-345.7	-355.16	-353.82
Load during hold (lb)	-81.79	-88	-131.6	-170.04	-147.09
Temp Max	79.83	78.055	82.93	81.913	86.655
Sum of ΔT*Δt (K-Sec)	6685.3	8093.482	10168.27	14668.71	17089.57
Time to reach Tmax (sec)	62.57	33.6	61.2	60.8	57.8

Small Cells Testing at ORNL:  
 SOC: 20%, 40%, 60%, 80%, 100%  
 Capacity at 500, 1500, 200 mAh  
 Number of Cells: 4 cells/condition

ESS Batteries at Various SOC:  
 Sandia: 30%, 50%, 75%, 100%  
 ORNL: 20%, 40%, 60%, 80%, 100%

# Results: Severity Score Plots and Hazards Ranking/Prediction

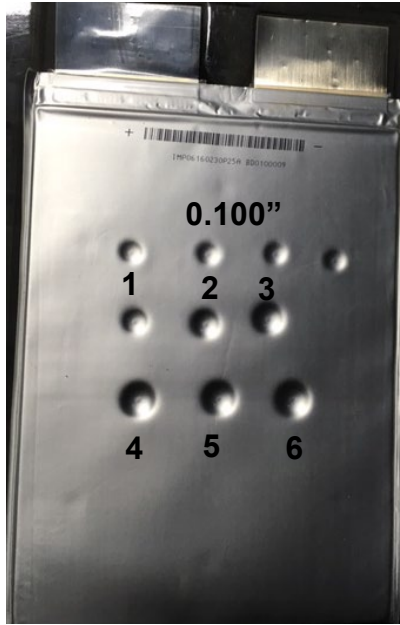


**Thermal runaway originates from a localized short circuit**

# **Threshold of Thermal Runaway**

## **Mechanical Damages Inside a Cell**

# Incremental Indentation Tests



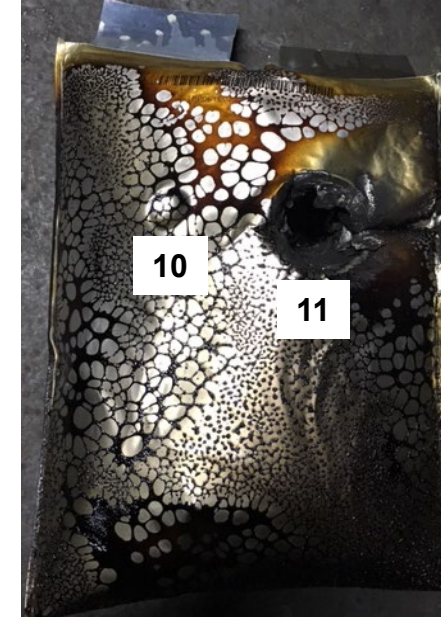
Cell#1: IMP0160230P25A BD100009  
Step 1: 0.100 inch was repeated 4 times!

Test Steps	Displacement(in)	mm	Short
1	0.1	2.54	No
2	0.125	3.175	No
3	0.15	3.81	No
4	0.175	4.445	No
5	0.2	5.08	No
6	0.21	5.334	No



Cell#2: IMP0160230P25A BD100008

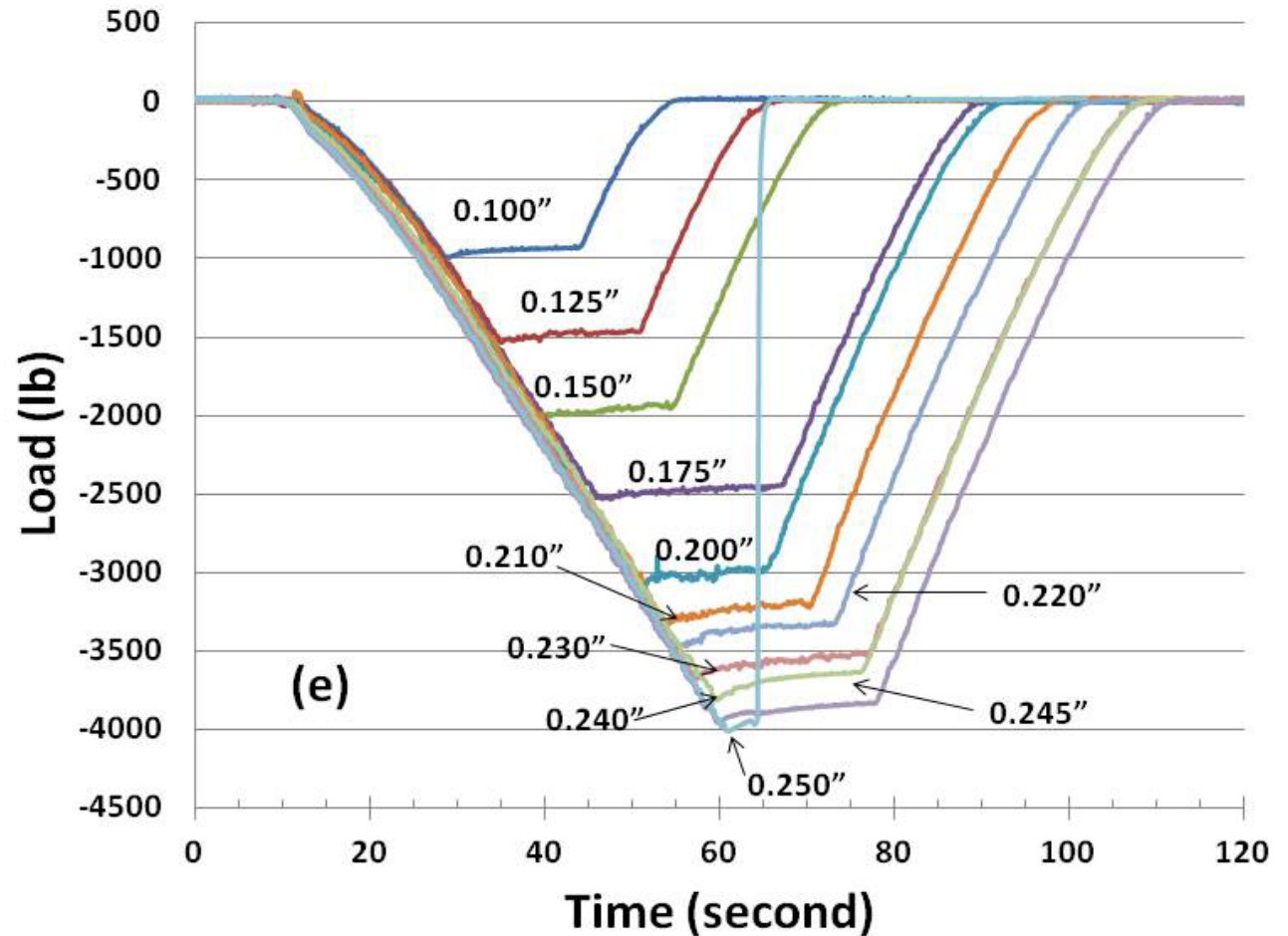
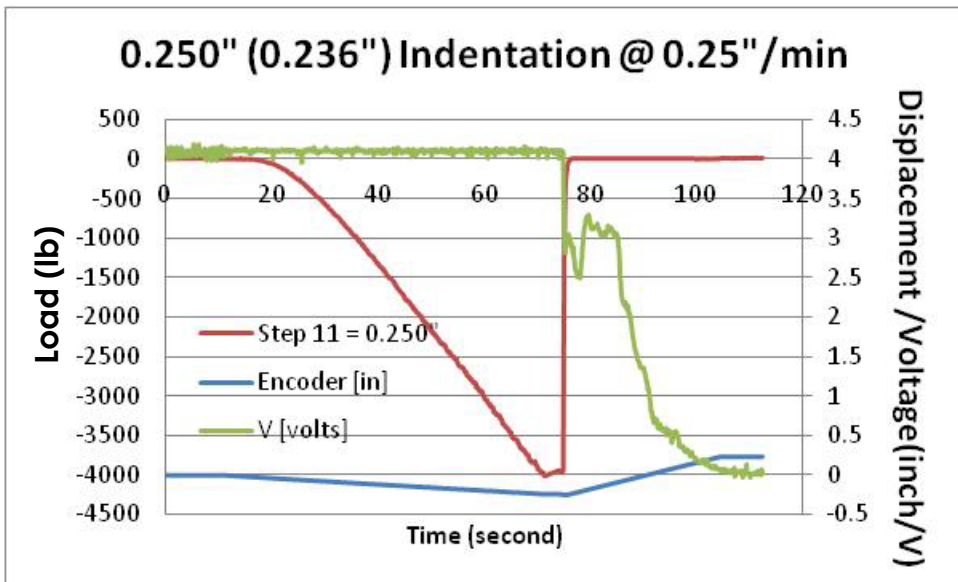
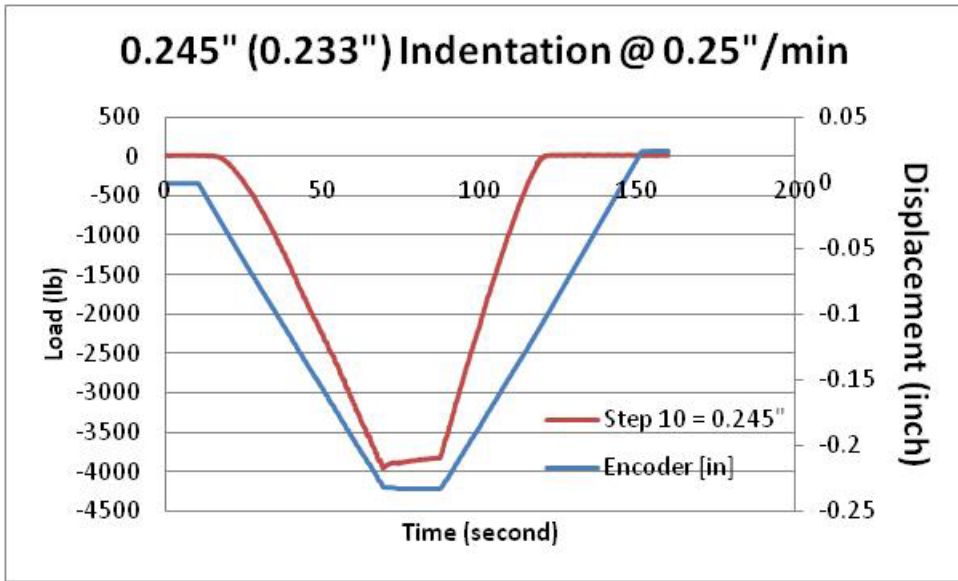
Test Steps	Displacement(in)	mm	Short
6	0.21	5.334	No
7	0.22	5.588	No
8	0.23	5.842	No
9	0.24	6.096	No
10	0.245	6.223	No



Cell#3: IMP0160230P25A BD100006

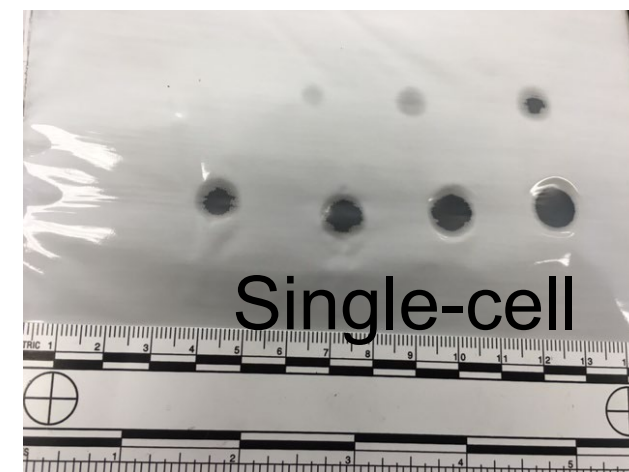
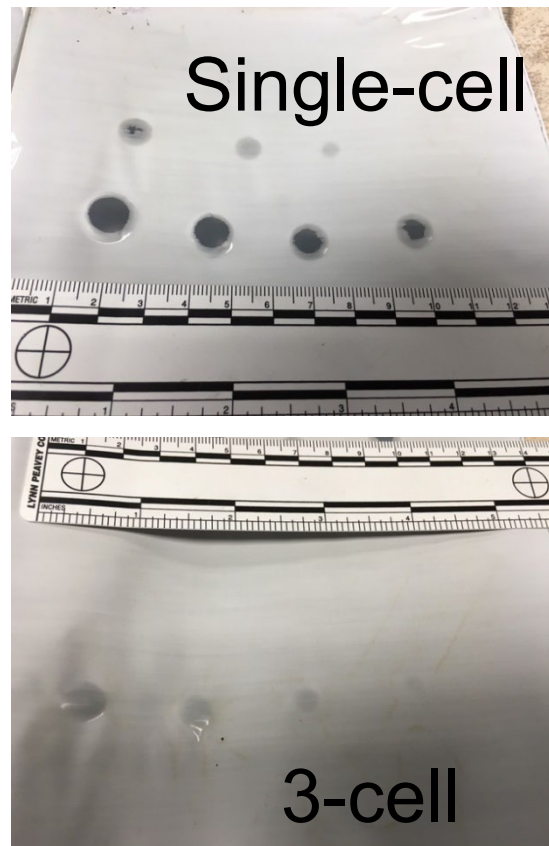
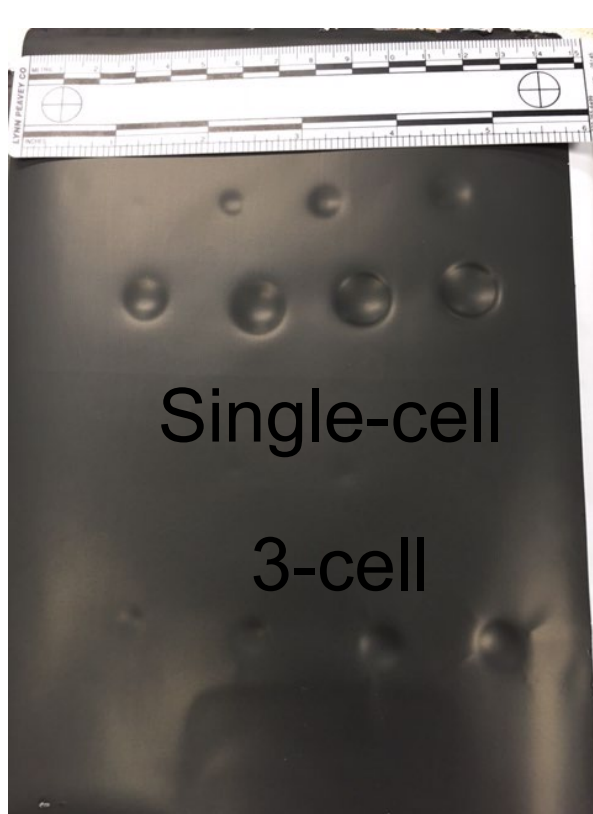
Test Steps	Displacement(in)	mm	Short
10	0.245	6.223	No
11	0.250	6.350	Yes

# Incremental Indentation: Deformation Threshold



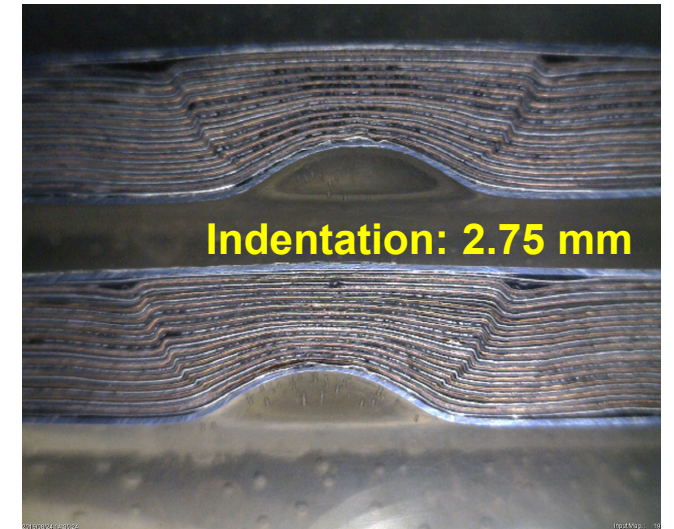
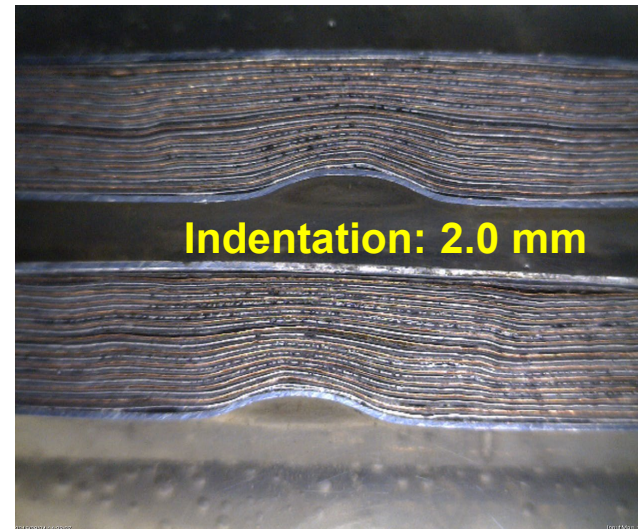
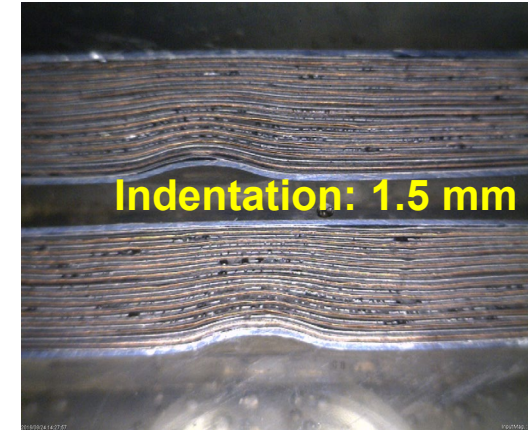
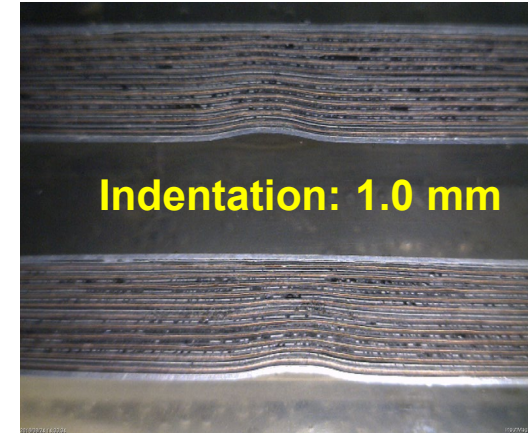
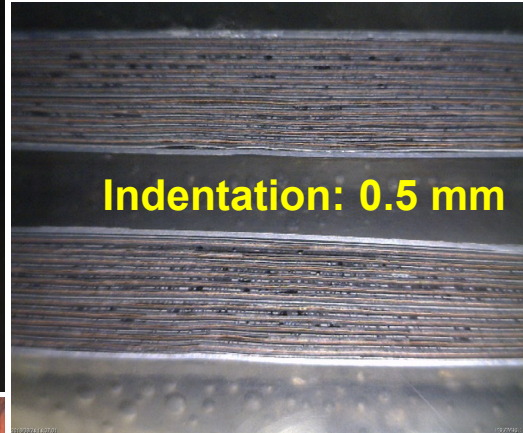
# Post-mortem Pictures of Separators: 0.025" - 0.200"

Eight single cell indentations and eight 3-cell indentations

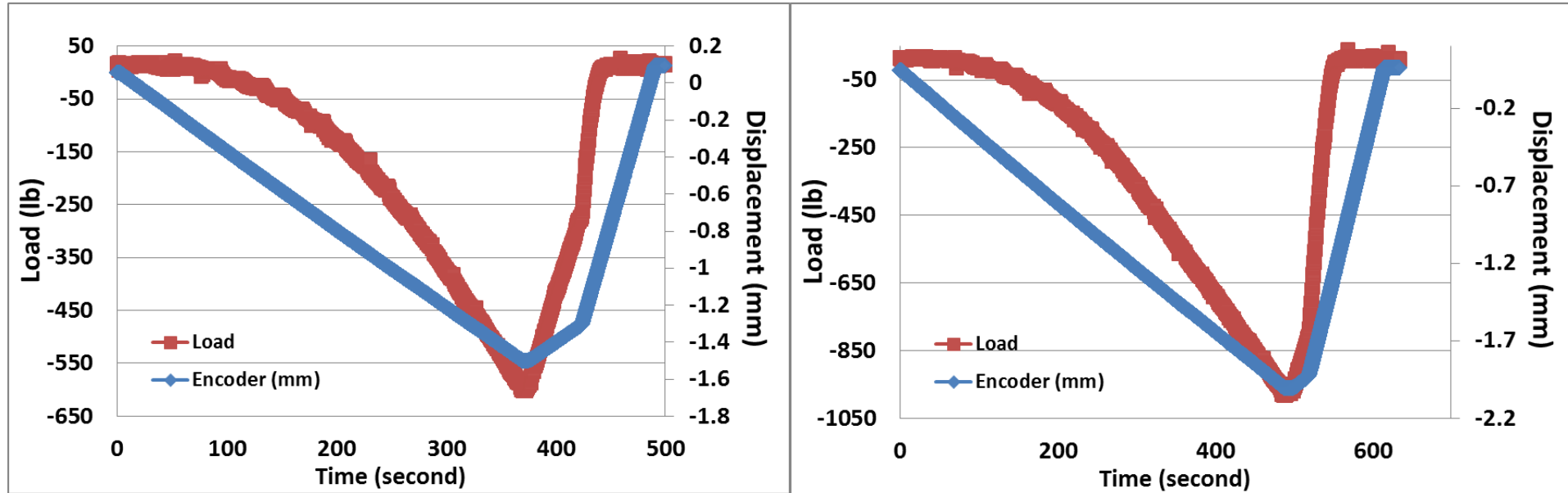


- >80% deformation under compression with no short circuit (1" diameter ball)
- 1/3 of deformation in 3-cell stack (large impact absorption capacity in pouch cell)

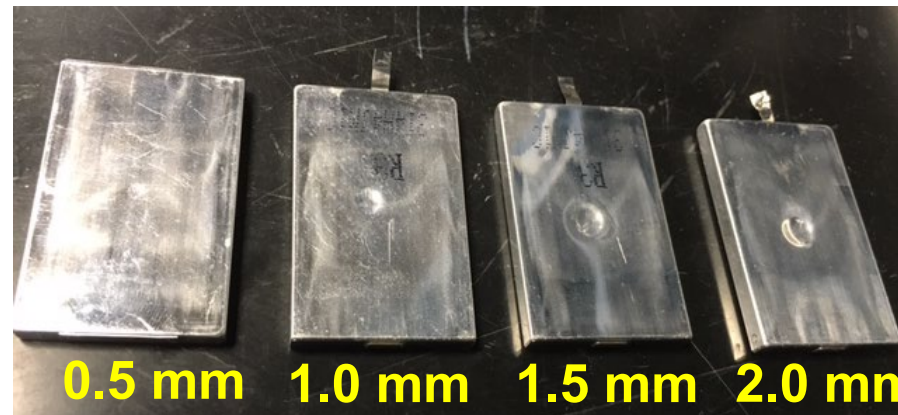
# Batteries in Aluminum Cans: Deformation is Preserved



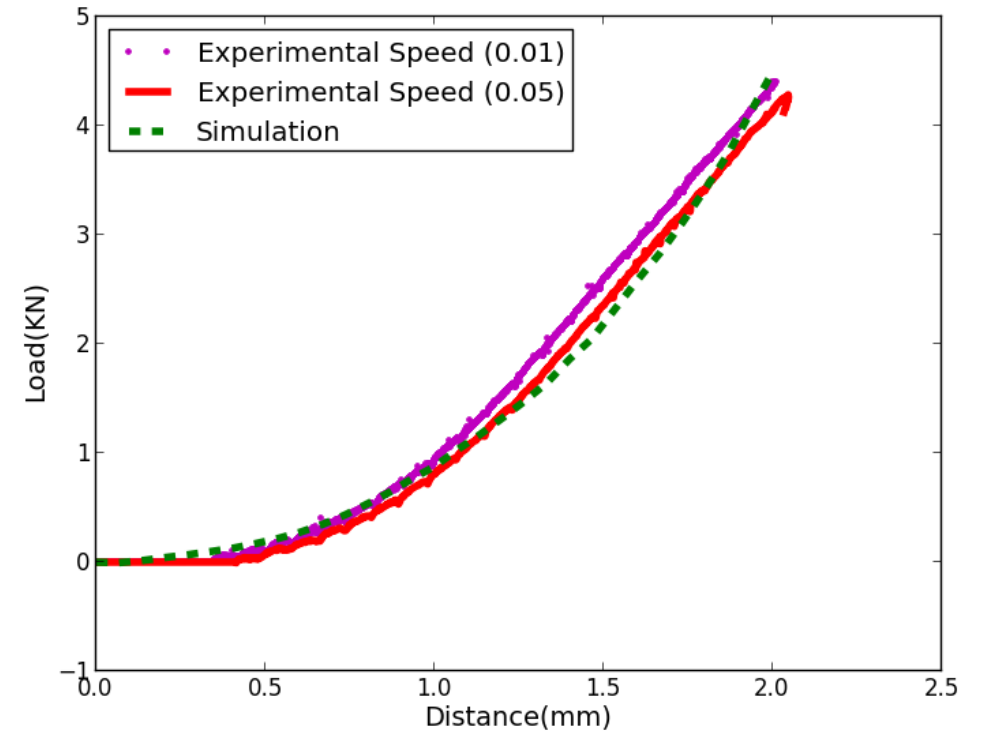
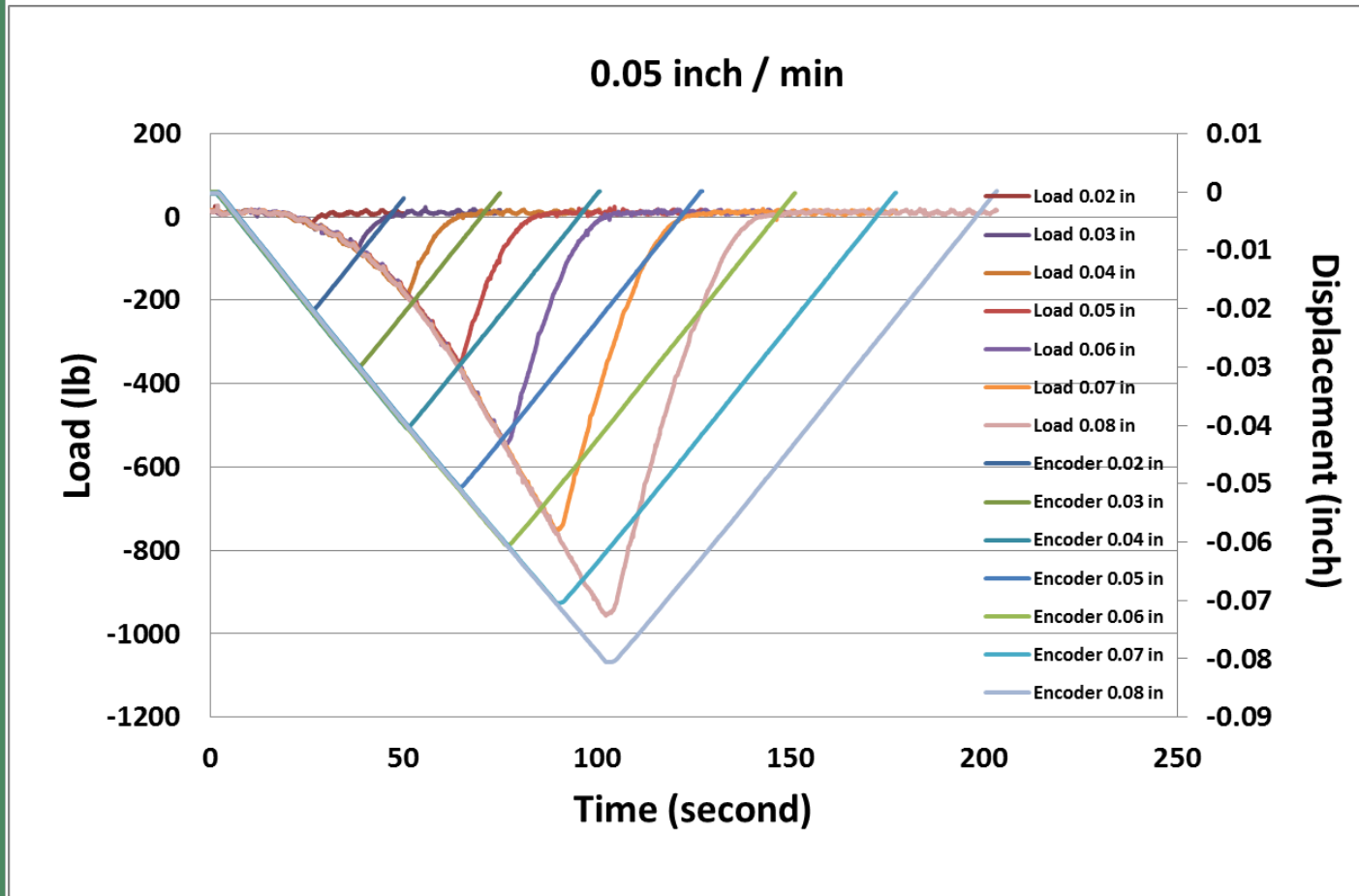
# Speed = 0.01 in/min Single-Side Indentations



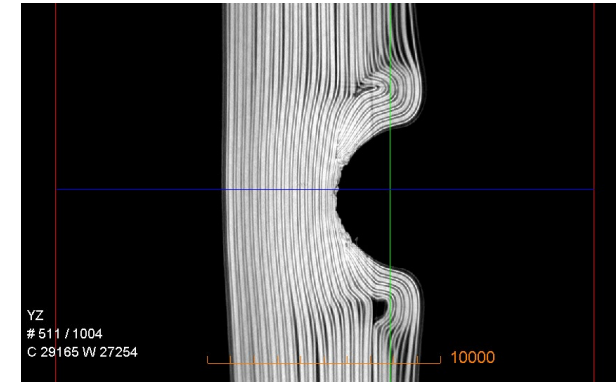
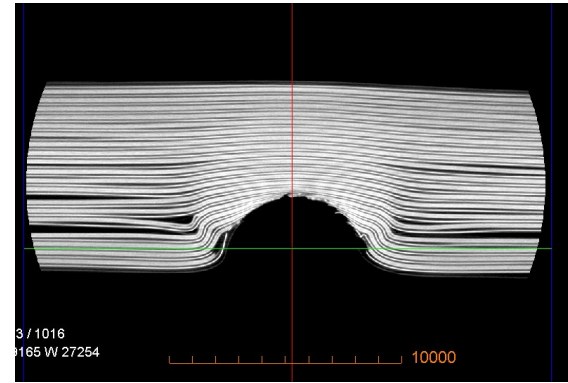
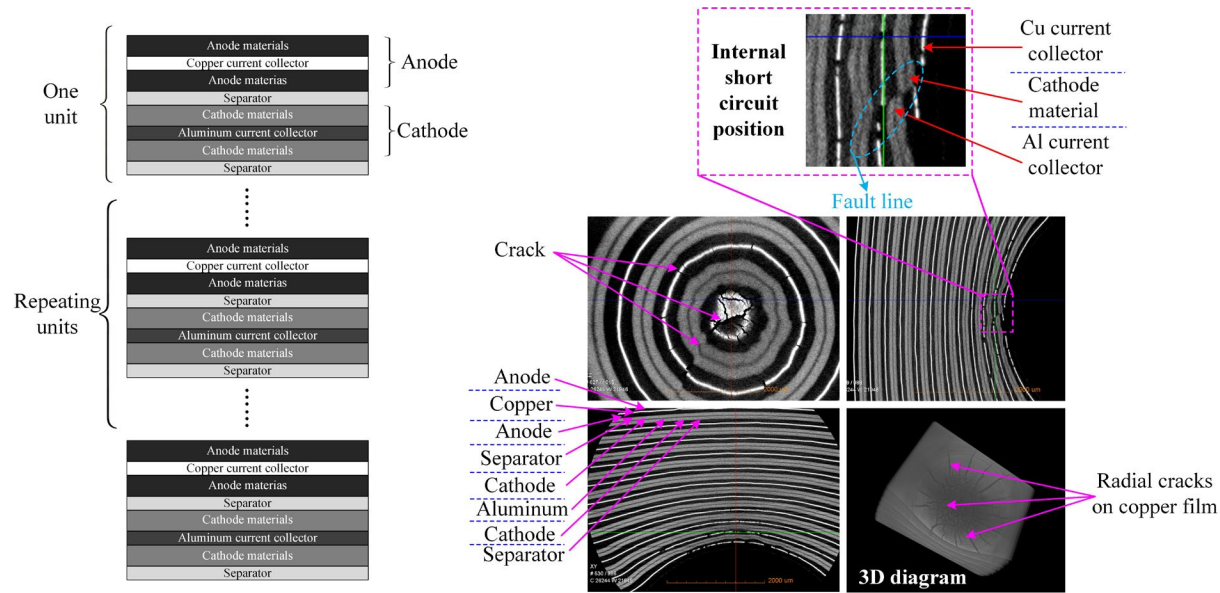
Cell Thickness 4.147 mm



# 0.05"/min Indentation: Highly Reproducible

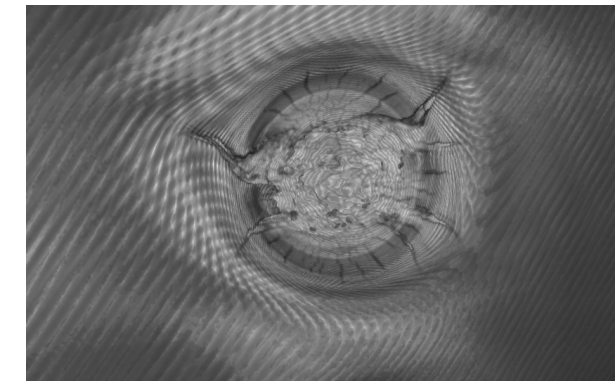
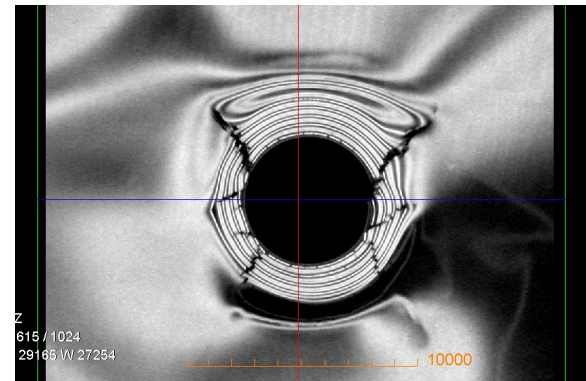
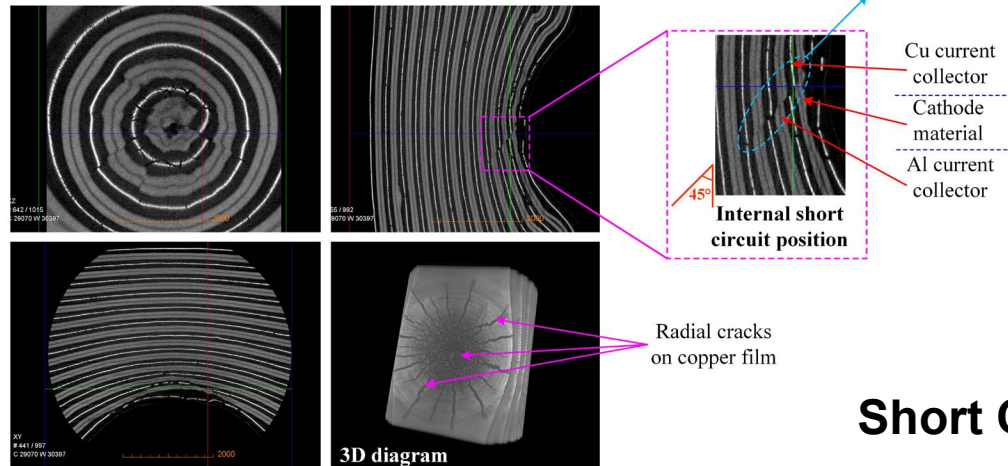


# X-ray Computed Tomography (XCT) Scans of Indented Chevy Volt Cell



(a)

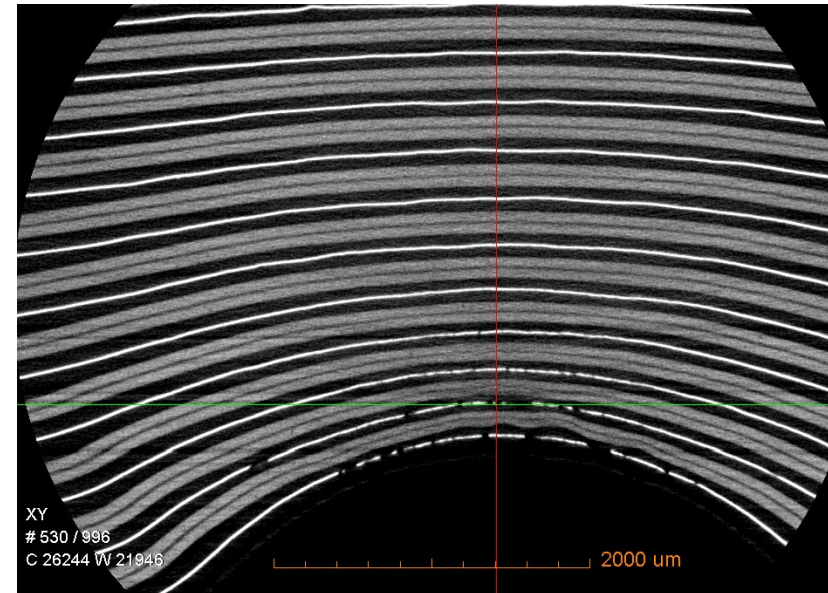
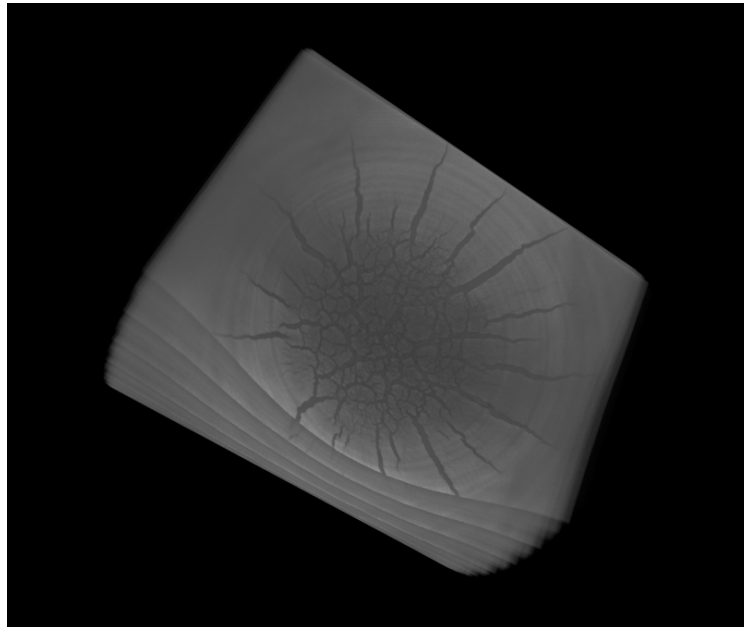
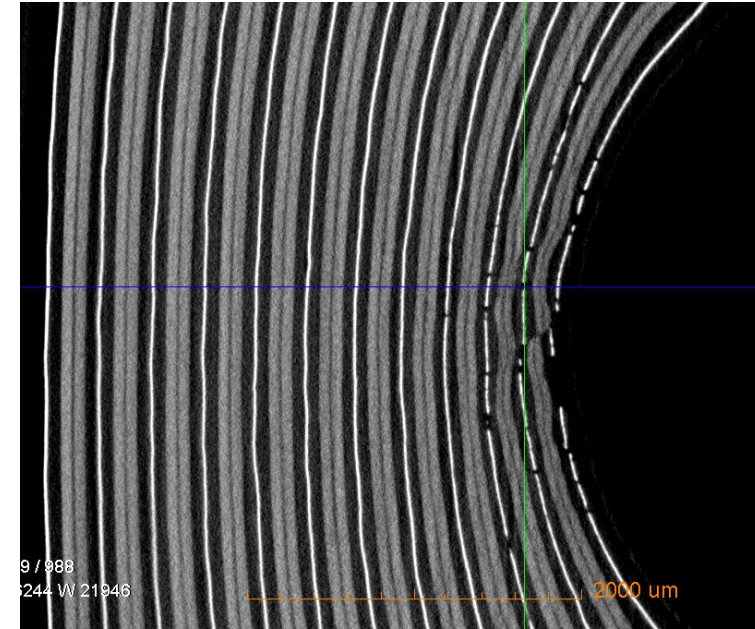
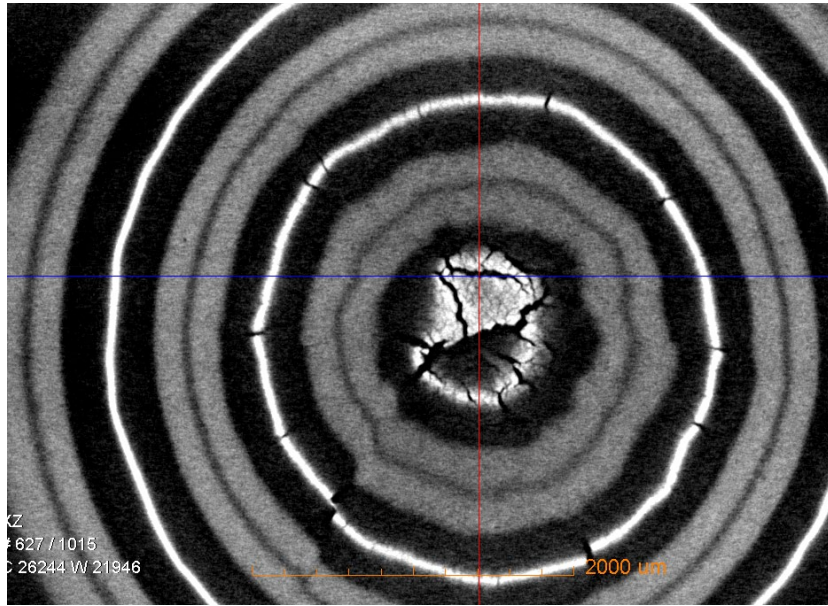
(b)



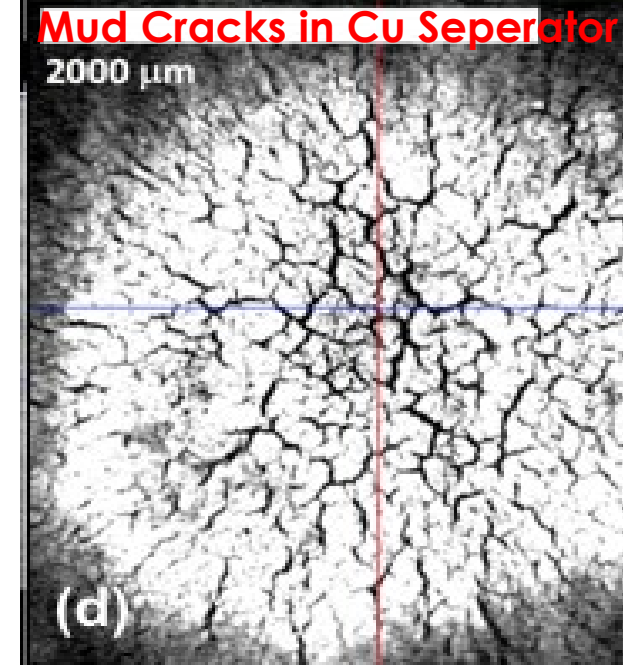
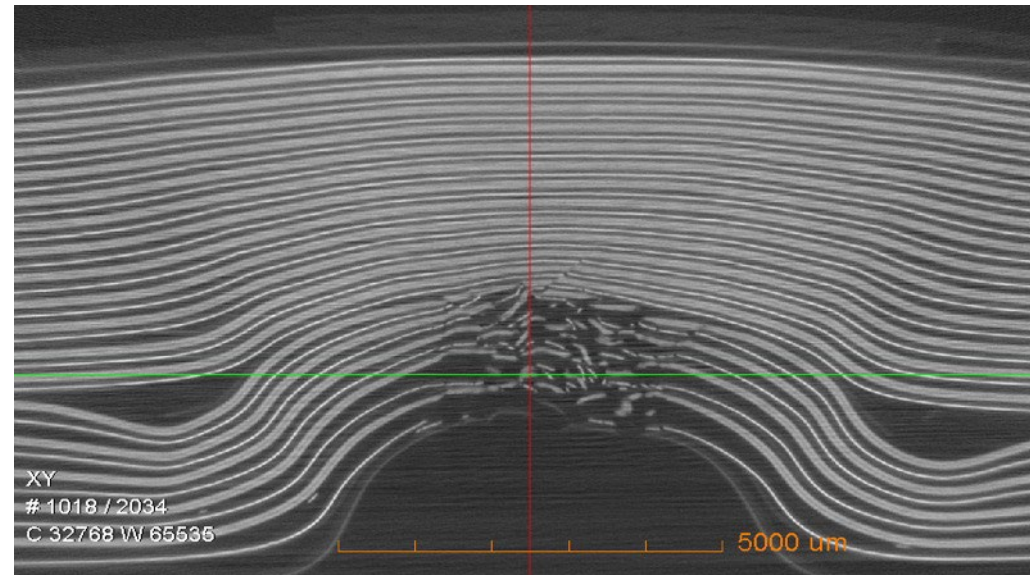
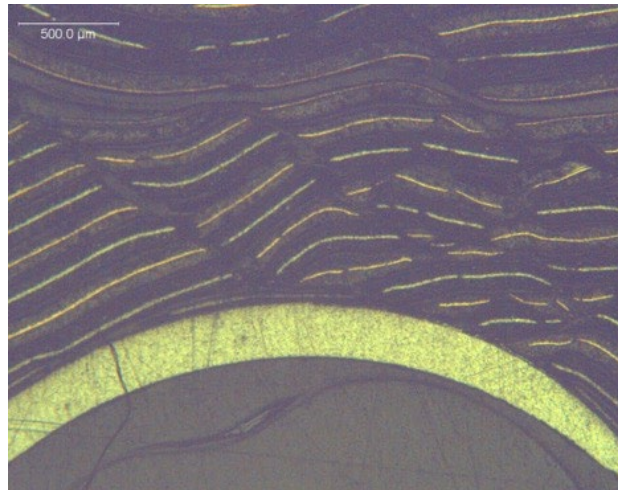
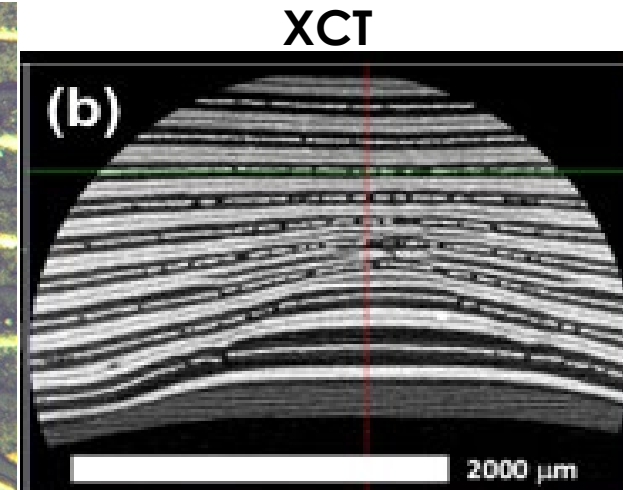
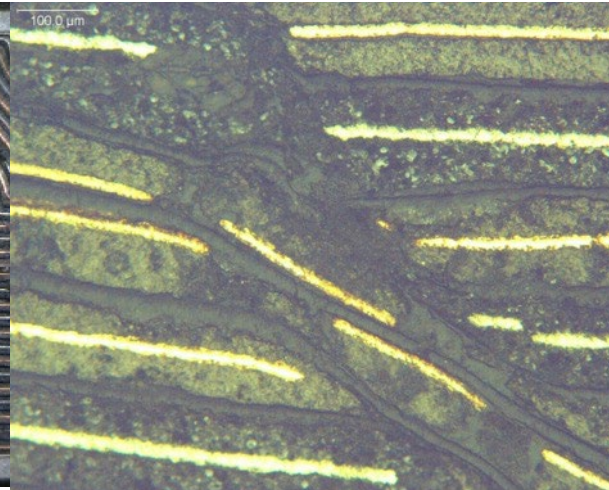
(c)

Short Circuit Induced on a Chevy Volt Cell Discharged to 2.80 V

# High Resolution XCT Scans

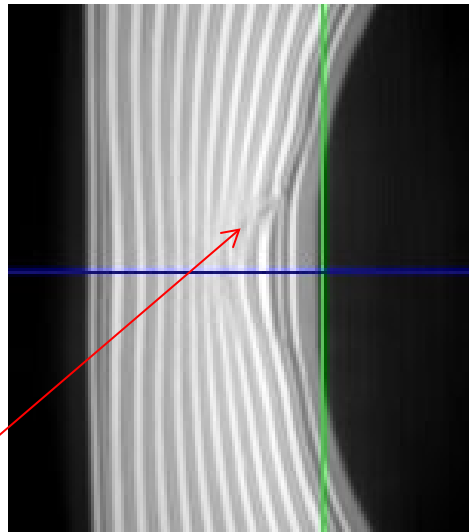


# Mechanical Abuse: Deformation and Failure of Layers



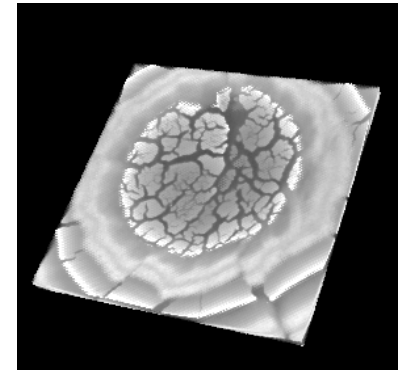
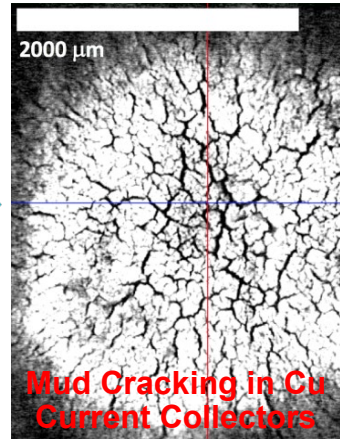
# The Origin of Mechanically Induced Short Circuit

1/2 inch Indenter



Through Layer Failure

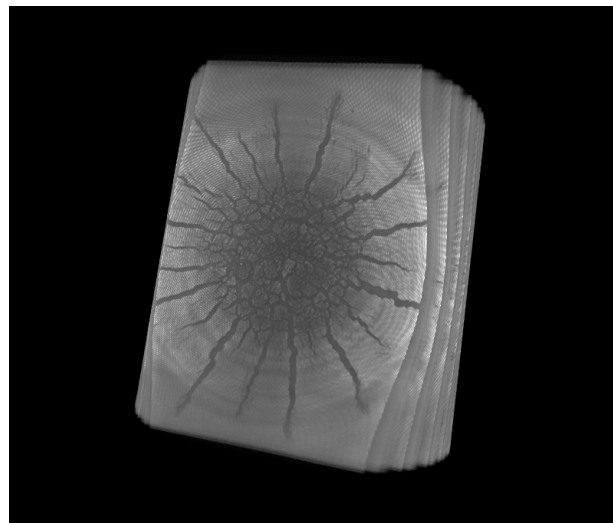
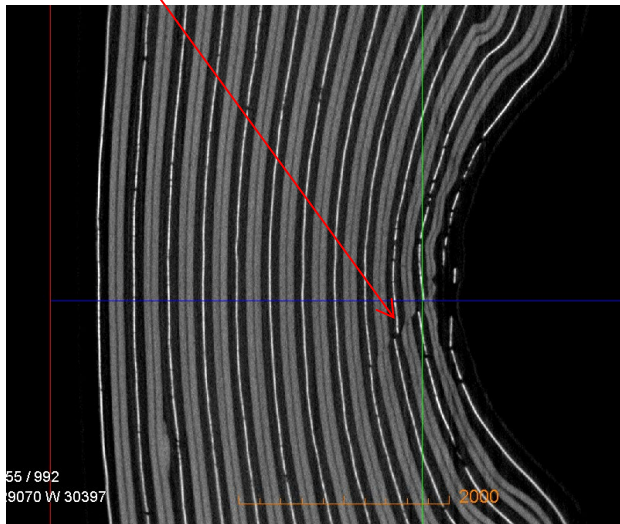
Copper fragmentation



Failure Origin:

- Separator Failure
- Anode Failure
- Cathode Failure

1/4 inch Indenter



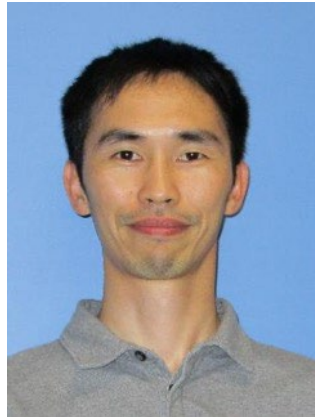
# Summary

- Thermal runaway threshold is observed under selective testing conditions
- It is useful in comparing relative risks of various cell chemistries, capacities, and SOC's
- Mechanical deformation is complicated with extensive internal damages
- Battery safety is achievable by understanding and properly managing the risks

# Thank You!



**Hsin Wang**  
Material Science & Technology Division  
Material Scientist, Testing



**Lianshan Lin**  
Material Science & Technology Division  
Mechanical, Database



**Mali Balasubramanian**  
Emerging & Solid-State Batteries  
Program Manager

## **Collaborators:**

DOE Sandia Labs: Loraine Torres-Castro and Team

This work was supported by the Department of Energy (DOE), Office of Electricity (OE) at Oak Ridge National Laboratory managed by UT-Battelle LLC under contract DE-AC05-00OR22725