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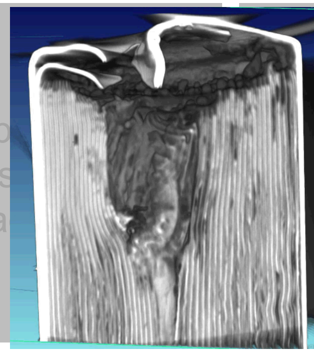

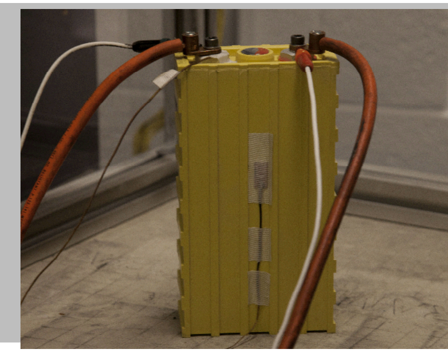

Battery Safety and Abuse Testing at Sandia National Laboratories

Joshua Lamb

January 19, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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INTRODUCTION TO THE BATERY ABUSE TESTING LABORATORY (BATLAB)

Capabilities and Infrastructure

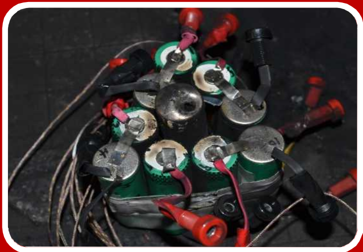
- ***Battery Abuse Testing Laboratory (BATLab)***
- ***Cell Prototype Facility***
- ***Battery Calorimetry***
- ***Modeling and Simulations***
- ***Materials Development R&D***
- ***Thermal Test Complex (TTC)***
- ***Burn Site, Laurence Canyon***

Thermal Test Complex (TTC)

Understanding Battery Safety

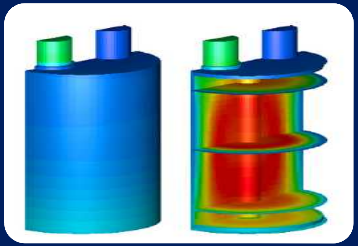
Materials R&D

- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials



Testing

- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Large scale thermal and fire testing (TTC)
- Development for DOE Vehicle Technologies and USABC



Simulations and Modeling

- Multi-scale models for understanding thermal runaway
- Validating vehicle crash and failure propagation models
- Fire Simulations to predict the size, scope, and consequences of battery fires

Procedures, Policy, and Regulation

- USABC Abuse Testing Manual (SAND 2005-3123)
- SAE/UL procedures and standards
- R&D programs with NHTSA/DOT to inform best practices, policies, and requirements

Program Support & Collaborations

Sandia National Laboratories

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM LLC

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

USCAR

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INL
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A Teledyne Technologies Company

SOLIDPOWER Battery

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

MICHIGAN

Challenges with Lithium-Ion Materials

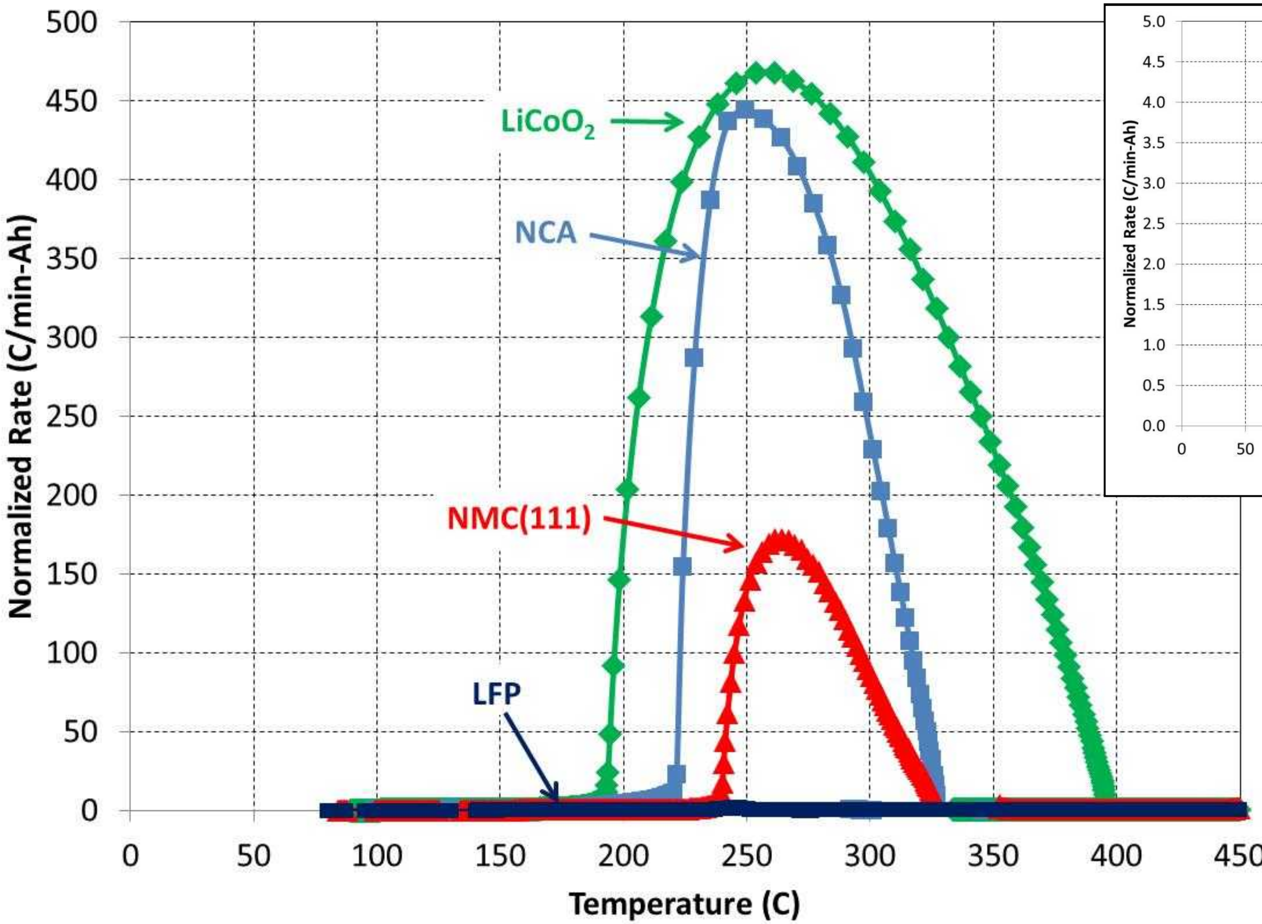
Lithium-ion Materials Issues:

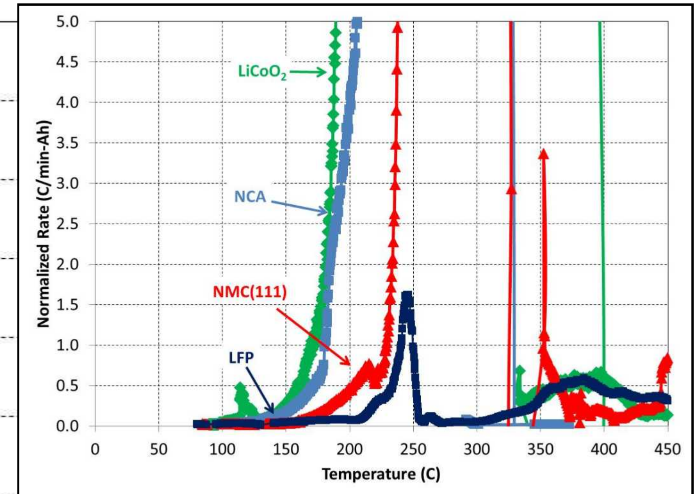
- Energetic **thermal runaway**
- Electrolyte **flammability**
- **Thermal stability** of electrolytes and separators
- Inherent **intolerance** of abuse conditions

Materials choices and interfacial chemistry can impact these safety challenges

Calorimetry of Lithium-ion Cells

Understanding the Thermal Runaway Response of Materials in Cells





High Rate Runaway	
Cathode	$\Delta H_{runaway}$ (kJ/Ah)
$LiCoO_2$	15.9
NCA	9.8
NMC111	8.3
LFP	2.4

Can high energy cathodes behave like LFP during thermal runaway?
Where do high capacity Si/C anodes fit on this plot?

MECHANICAL TESTING OF ELECTROCHEMICAL CELLS AND BATTERIES

Lamb, J. and C. J. Orendorff (2014). "Evaluation of mechanical abuse techniques in lithium ion batteries." Journal of Power Sources **247**(0): 189-196.

Field failure vs. abuse failure

Field failure

- Random
- Often the result of manufacturing defects that are difficult to predict or recreate
- Historically the greater concern to battery manufacturers

Abuse failure

- Caused by an external stimulus that pushes a cell outside its safe operating conditions
- Can generally be grouped as: Thermal, Electrical and Mechanical abuse
- Traditionally a laboratory curiosity – performed due to convenience rather than accurate recreation of conditions

Internal Shorts and Mechanical Testing

- Internal short circuit is still the primary cause of field failure in cells
- Nail penetration is the traditional test used due to the lack of an accepted method to create internal short circuits
  - Often approached simply as a test that must be passed
- Few systemic evaluations of mechanical testing exist

Mechanical ISC techniques

Blunt rod- first used by UL and NASA

Nail penetration

Crush

Motorola/ORNL – spherical pinch

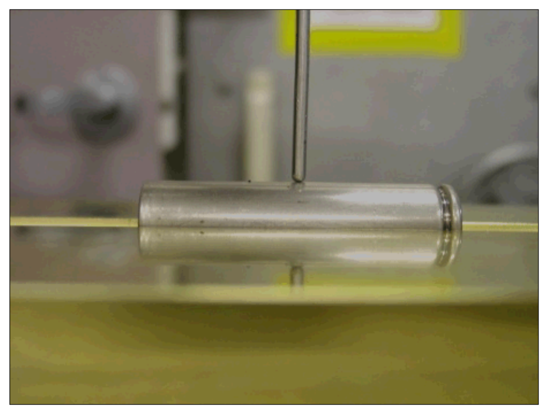
SAE J2464 (ISC test omitted)

Internal short triggers

TIAX – internal defect w/cycling

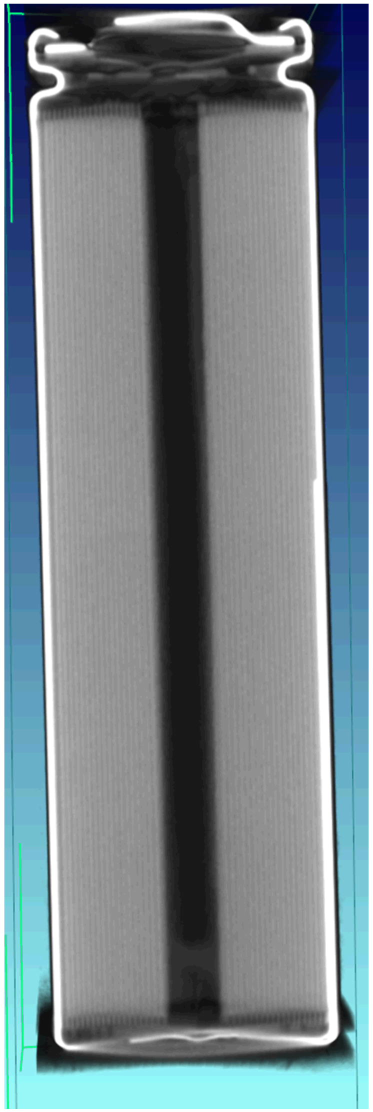
SNL – low melting point metal

Saft – internal heater



DOE testing programs have a vested interest in evaluation of various ISC testing methods. Historically, the SNL viewpoint is that mechanical techniques are not representative of ISC, but may be useful as a runaway trigger

Testing methods



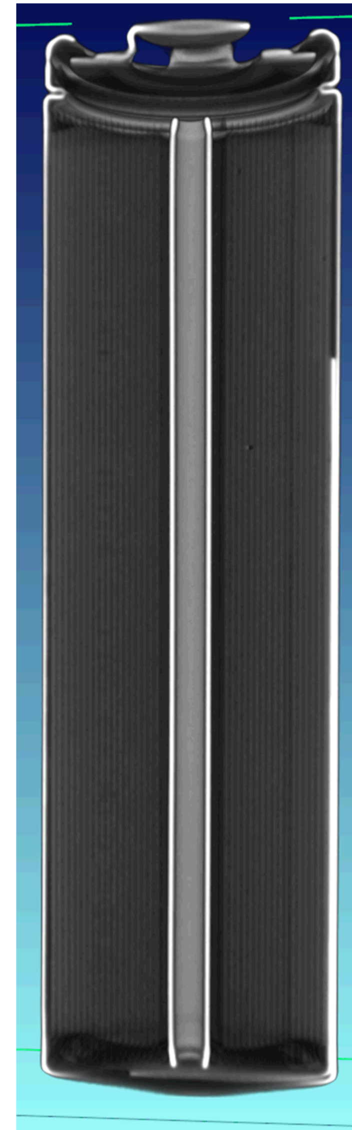
Differences in basic cell construction may lead to differing responses to abuse conditions

- Presence/absence of center rod
- Dead space in can
- Differing size/position of negative tab

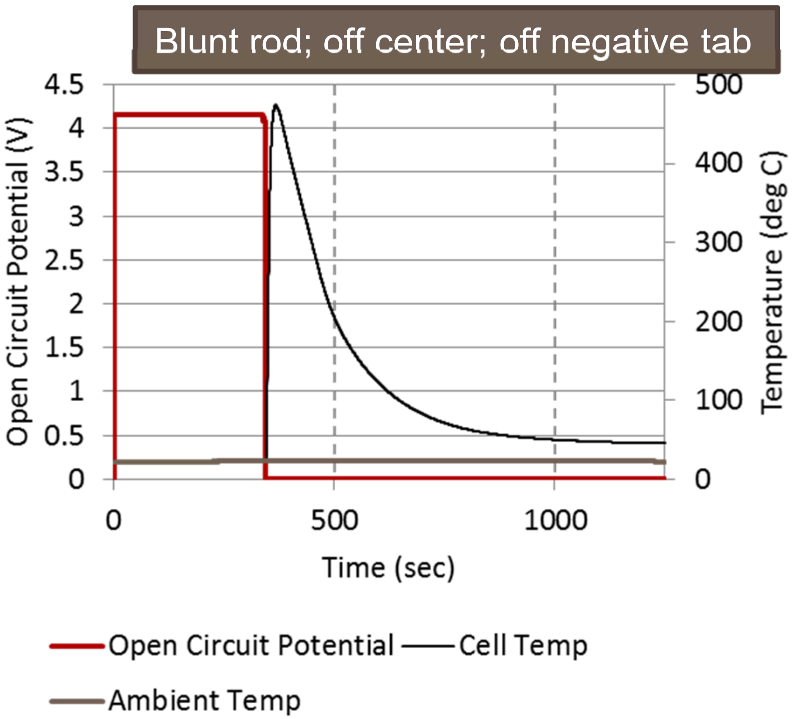
Test conditions		
Speed	2 mm/min	
Construction	316 SS	
Nail Tip	5 mm	
Temperature	RT	60C
End Conditions	100 mV drop	20 mm penetration

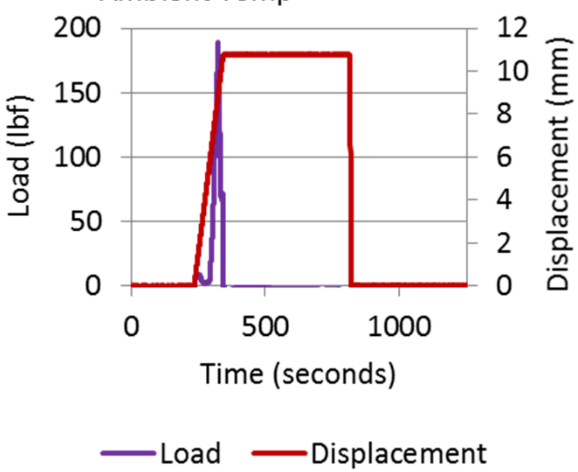
Cell type A

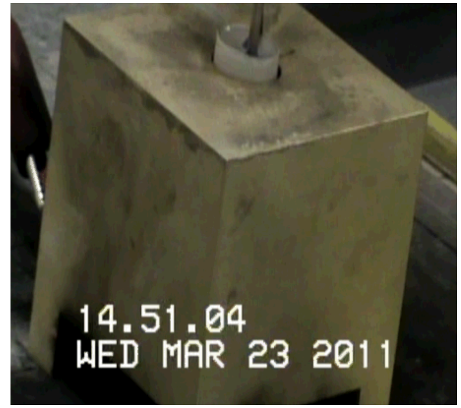
Cell type B



Results: Axial Loading



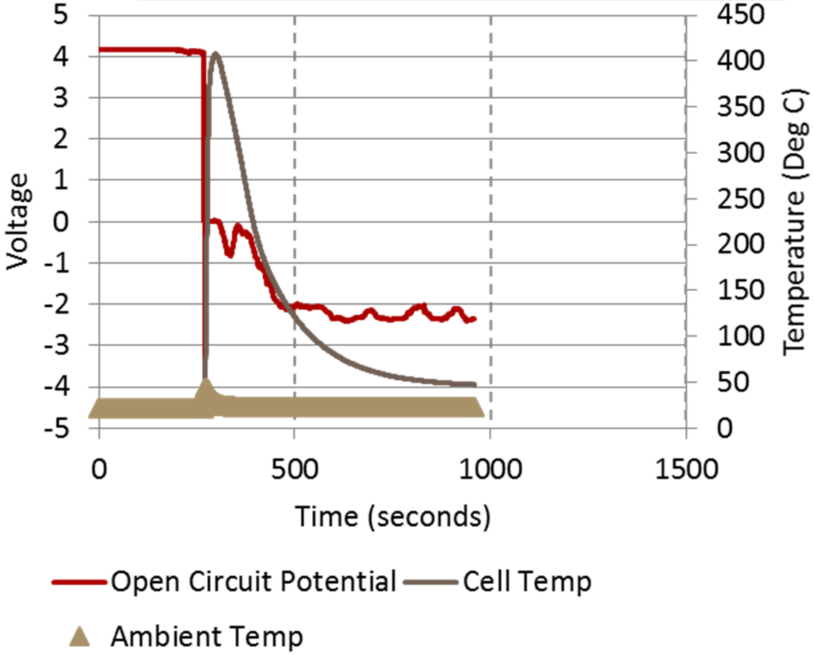


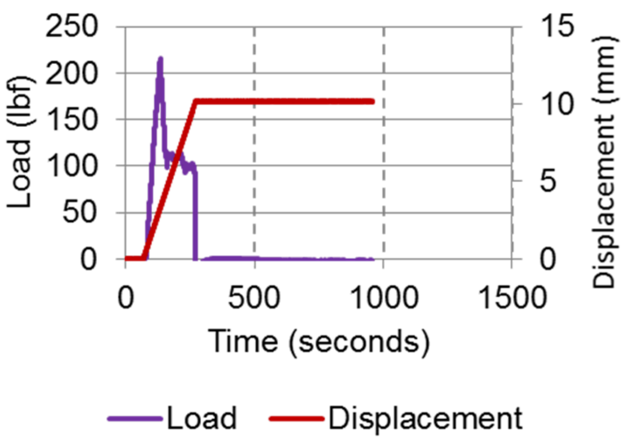


- Resulted in hard short with high temperature and sharp drop in voltage
- Not shown: crush directly on center difficult to fully short as rod passed through empty center

Results: Axial Loading

Blunt rod; off center; on negative tab





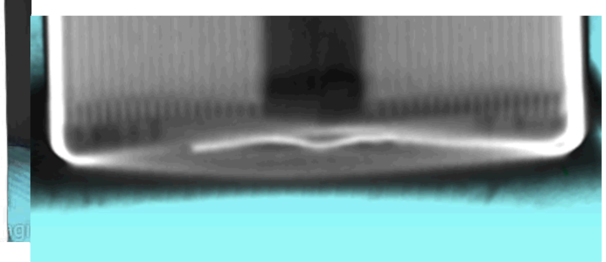
- Noisier voltage curve after short
- Hard short occurs shortly after penetration

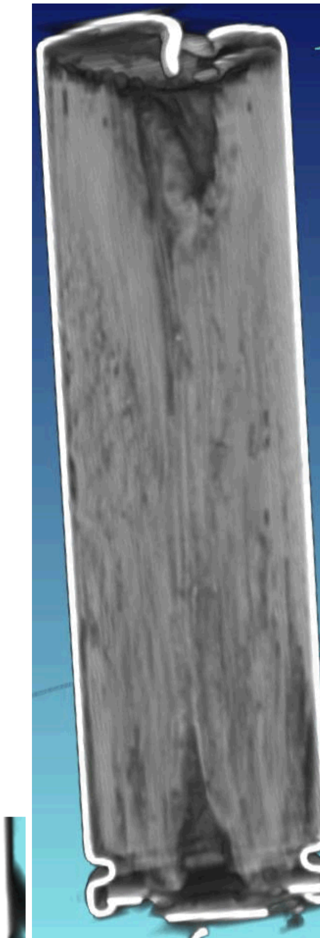
Internal damage – Axial load

Blunt rod; off center; off negative tab

Short location

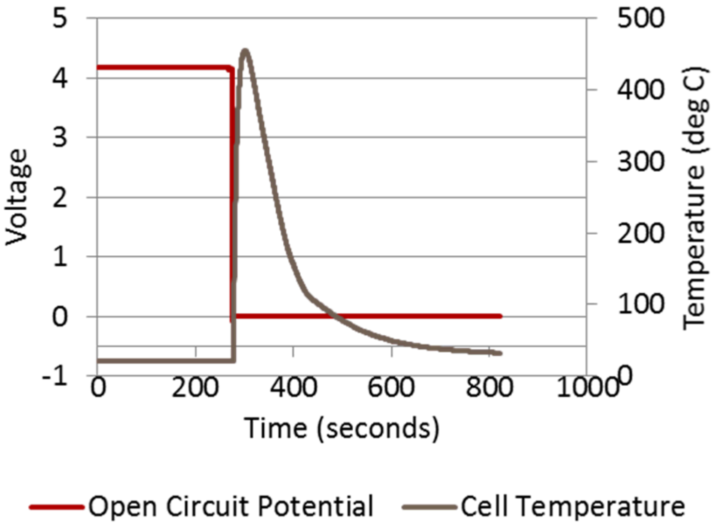
- Propagation of short through cell towards vent. Damage becomes more extensive near vent from flow of escaping gas
- Large gap between can and electrodes prevent contact without cell puncture
- Limited use for internal short circuit due to large degree of cell damage before short, but reliable runaway initiation

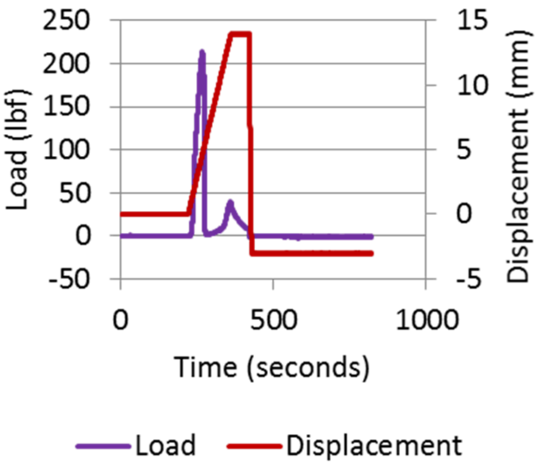




Results: Transverse load

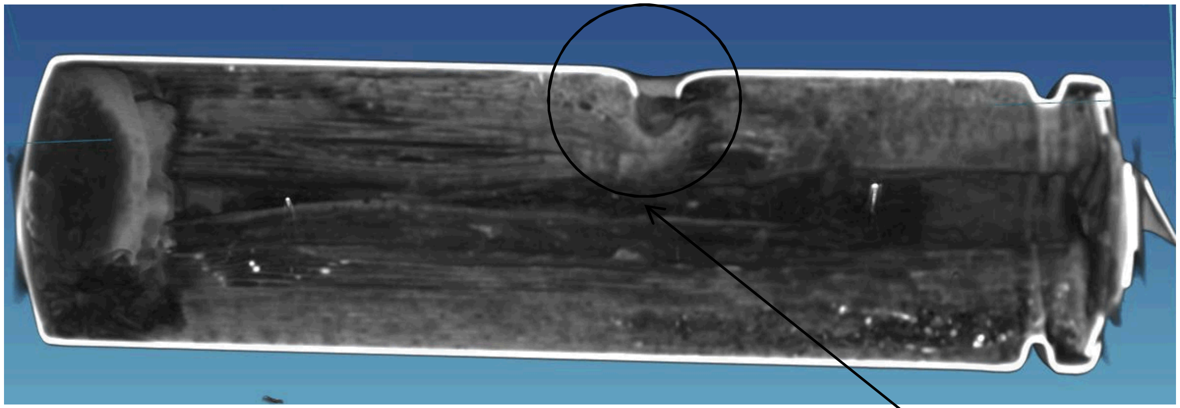
Blunt rod transverse indentation



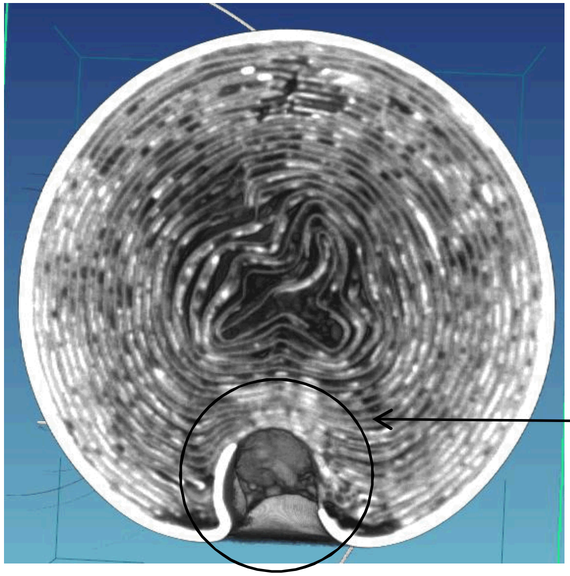


- Cell type A: no internal core
- Catastrophic cell failure; all escaping gas comes through puncture or vent

Catastrophic short failure



Propagation of failure through cell



Short location – electrode collapses into core and escaping gas through vent forces jelly roll up towards vent

Failure: Soft short with partial recovery

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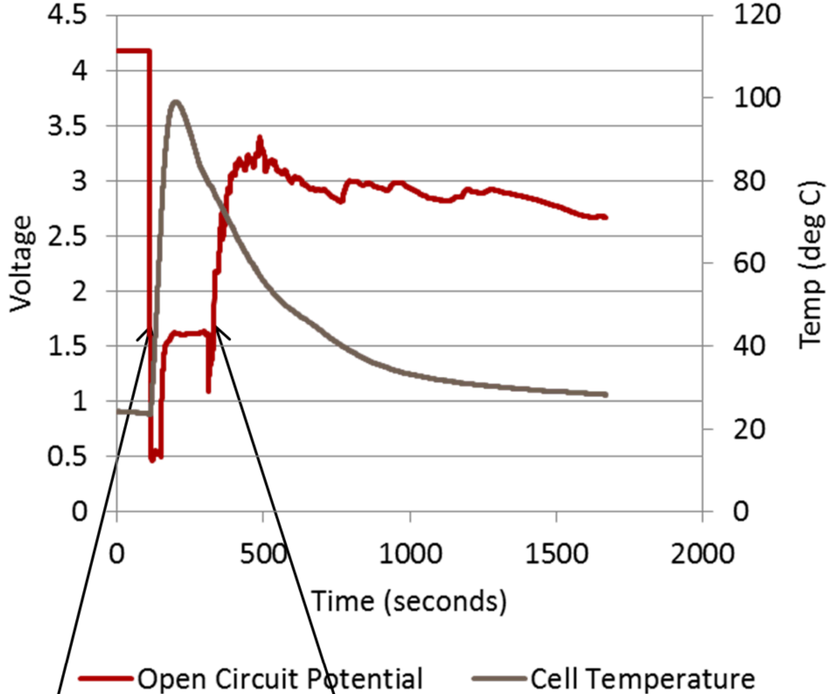
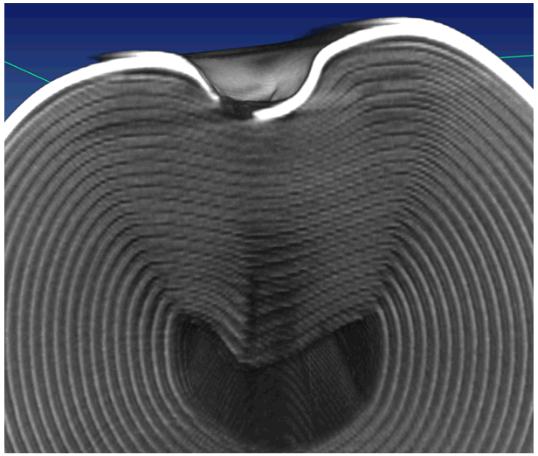
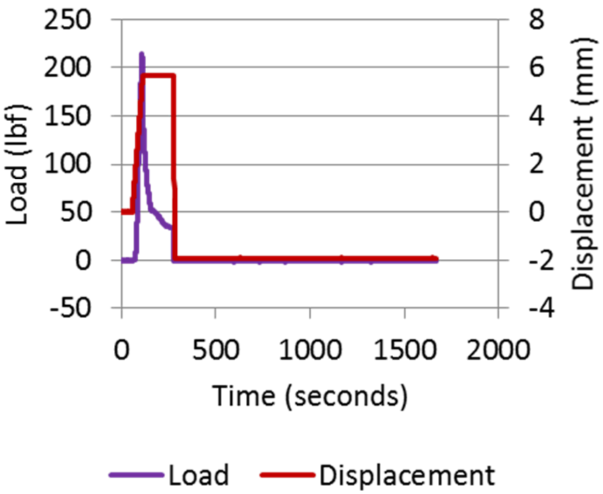
Blunt rod transverse indentation



Initial short

Partial recovery after removing load





Cell shorting between layers. Electrode is able to deform and collapse into open space in core of cell.

Effect of Cell construction: Cell type B

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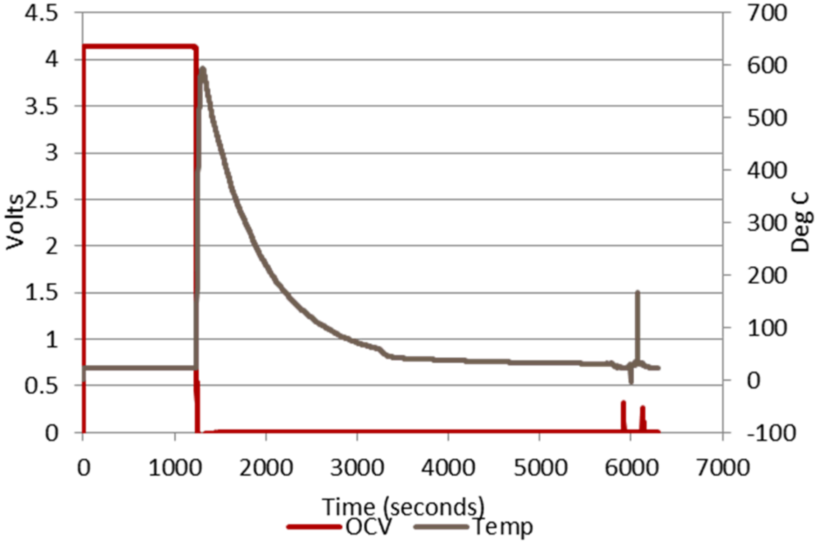
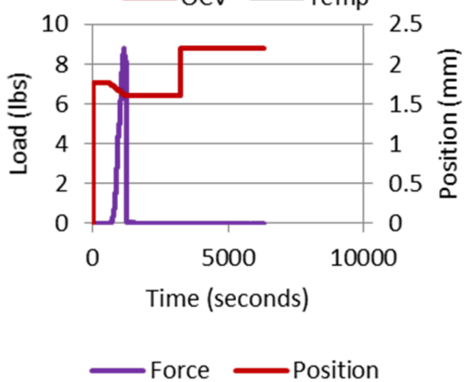
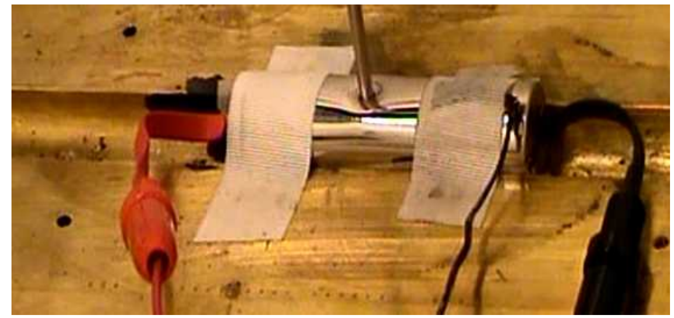
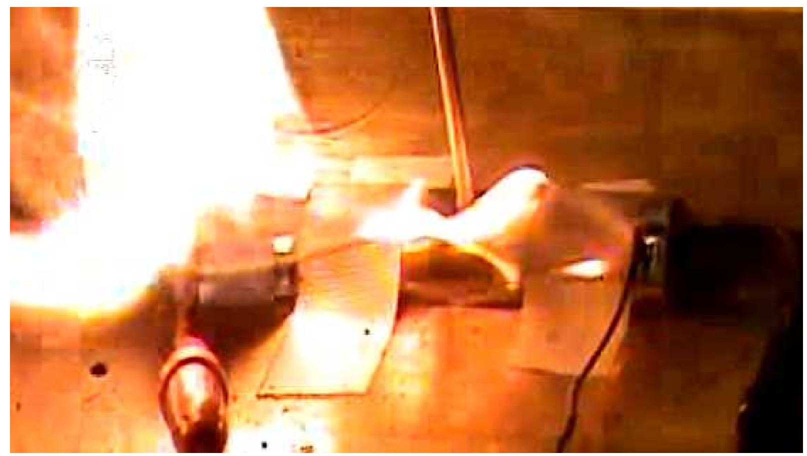
Blunt rod transverse indentation



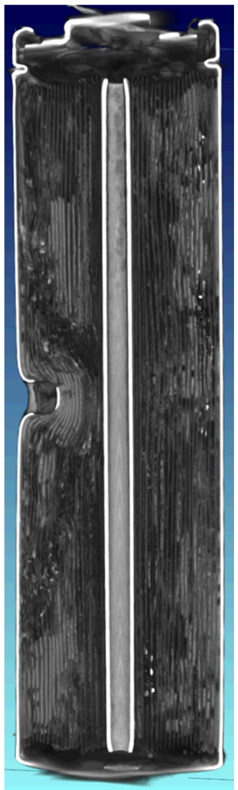


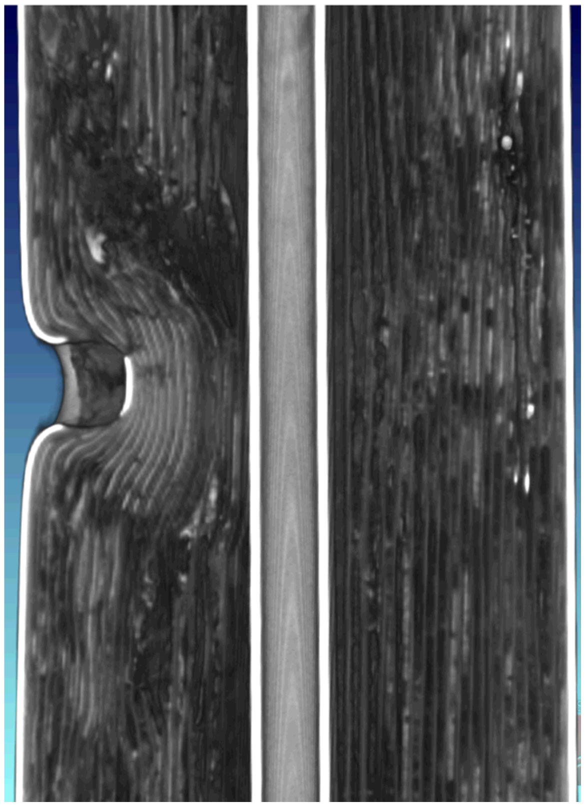




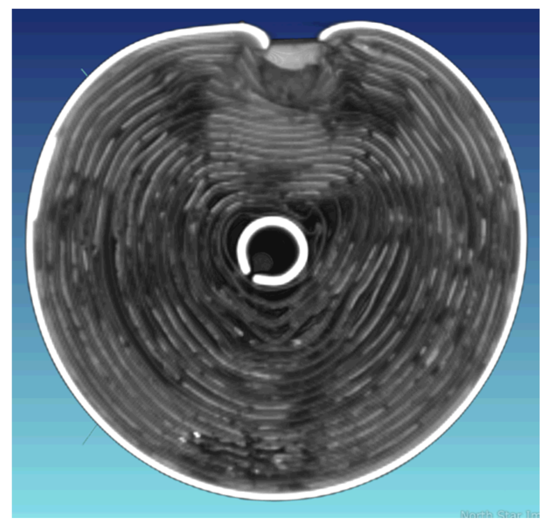
- Catastrophic failure readily seen
- Very high temperatures and self ignition

Cell type B continued





- Center core restricts contents during catastrophic failure
- Creates an effective “backing plate” allowing the electrode to be sandwiched between blunt rod and core



Elevated temperature - Cell type A

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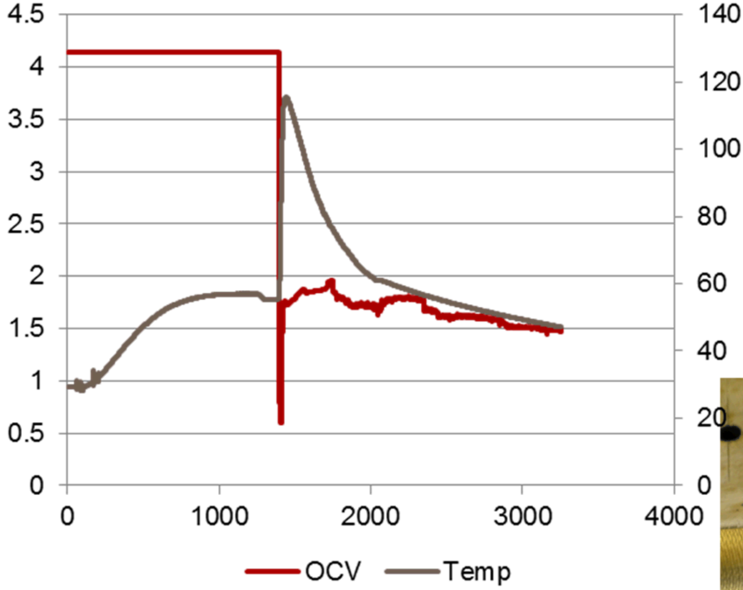
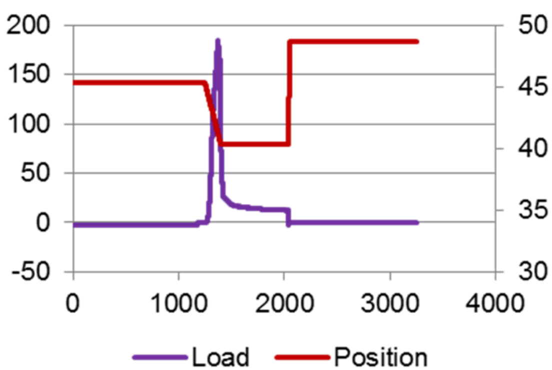
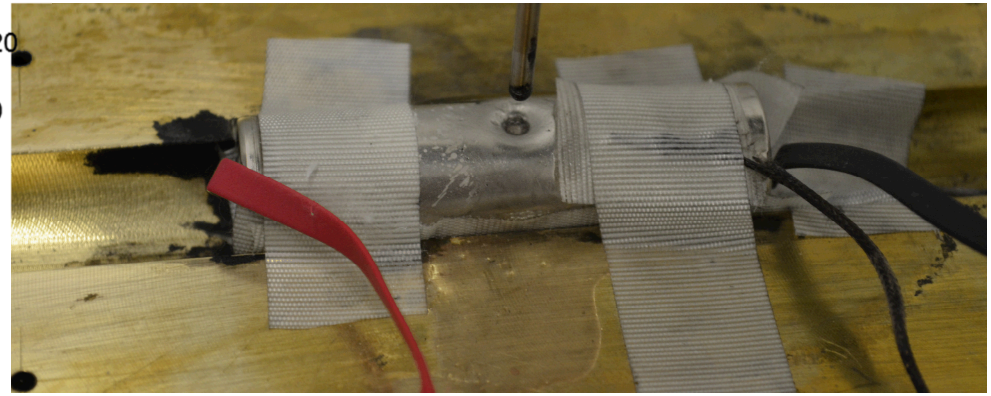
Blunt rod transverse indentation, 50 °C



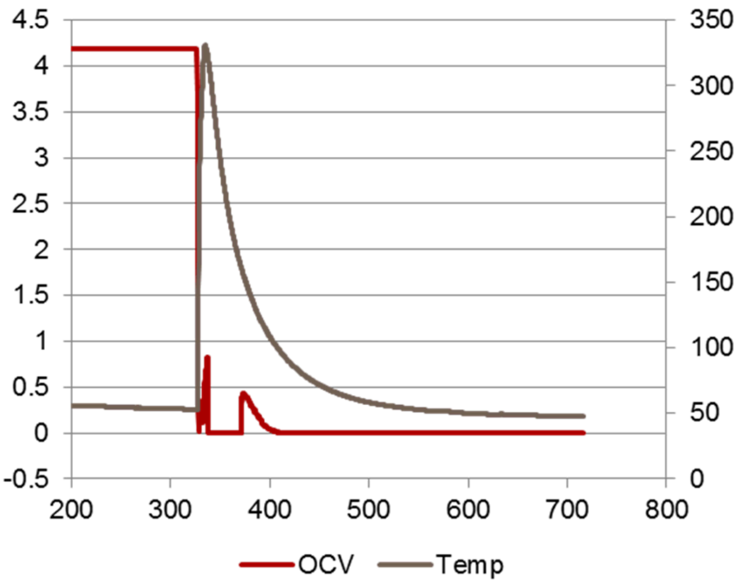


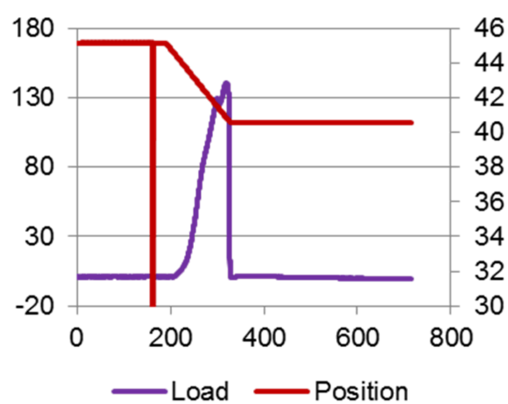


- Full short observed, but no catastrophic failure
- Repeatably observe 100 mV drop before catastrophic failure occurs

Elevated temperature – Cell type B

Blunt rod transverse indentation, 50 °C



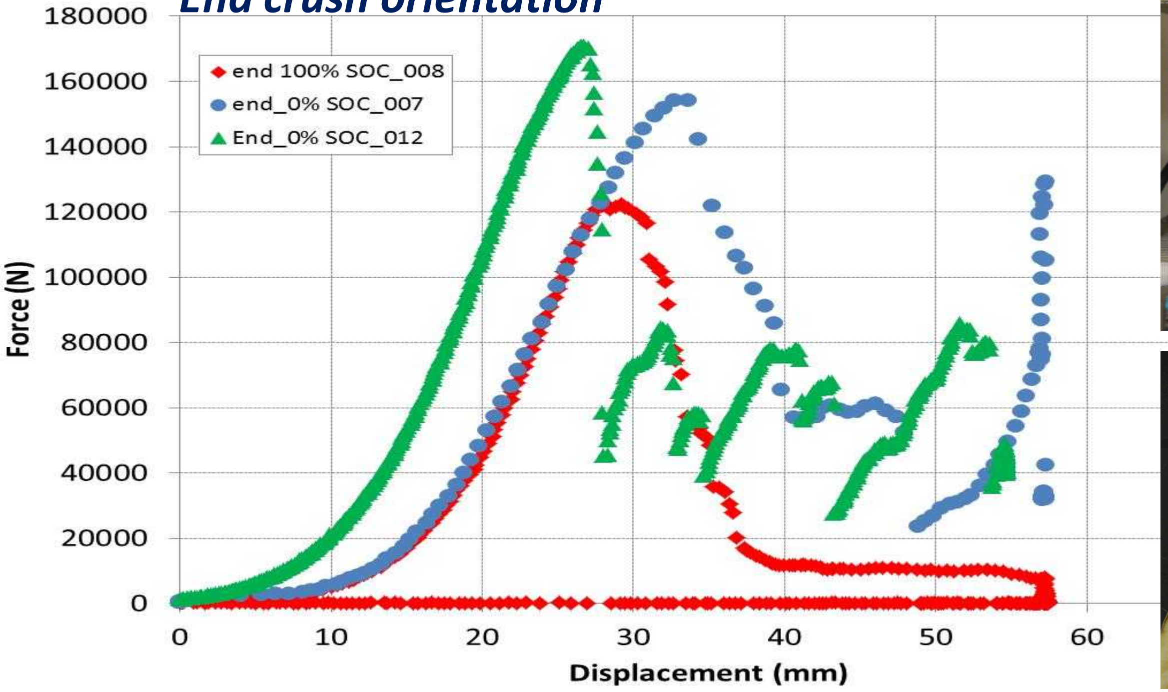


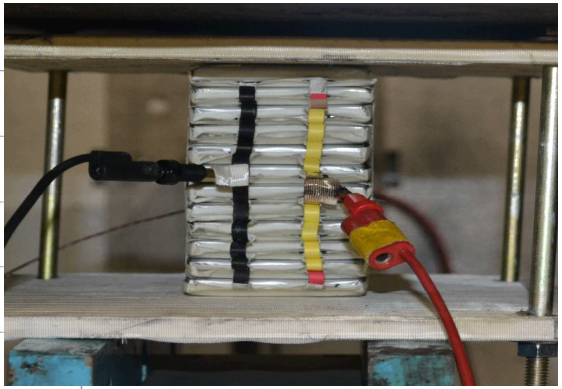
- Very catastrophic failure
- Rupture of can
- Ejection of cell contents

Battery Crash Worthiness

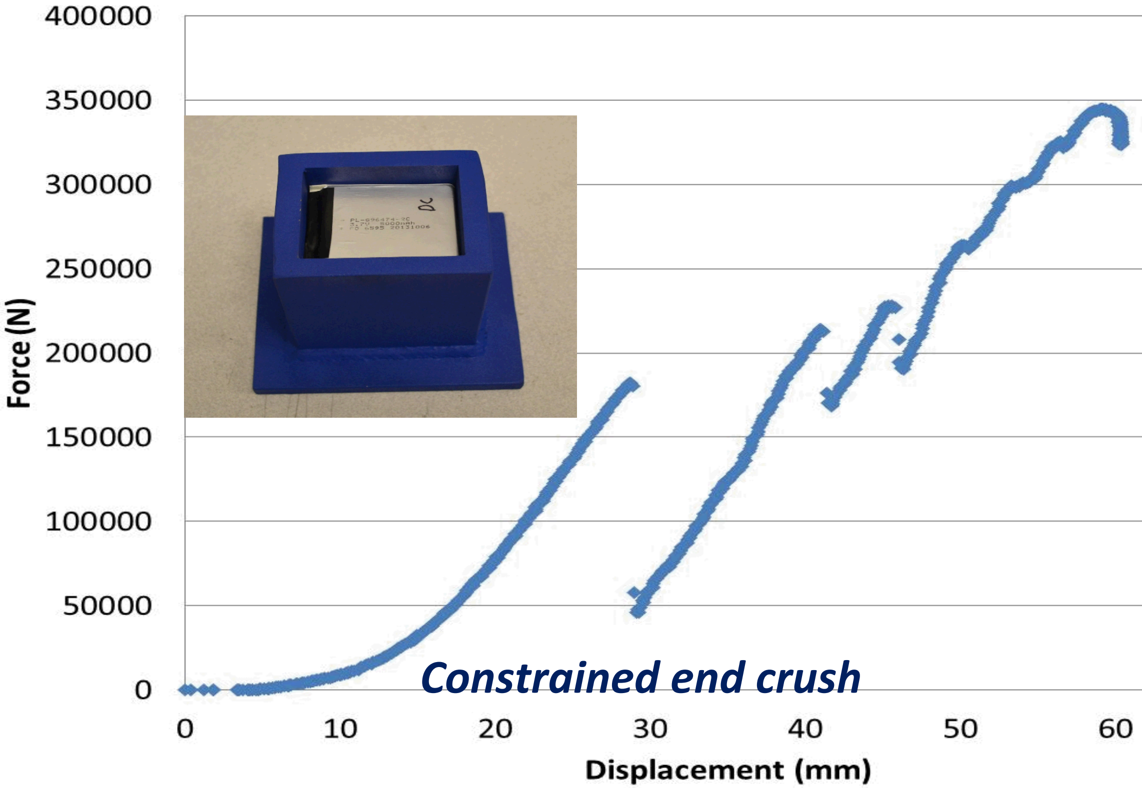
Mechanical testing support of battery mechanical model development

End crush orientation





Crash Safety



Fully constrained 12 cell pack (0% SOC) crushed along the longest dimension.

Crash Safety

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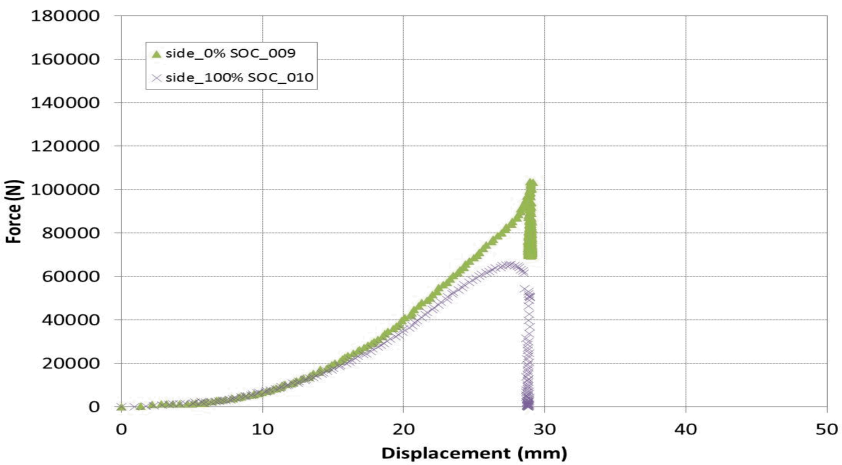
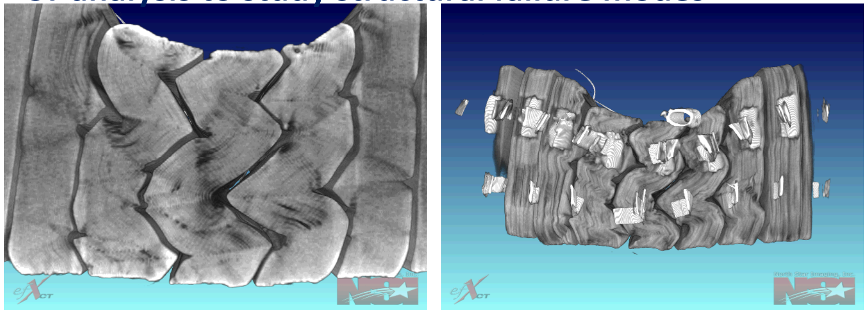
Mechanical behavior under compression



Analog "pole test" of a battery

CT analysis to study structural failure modes



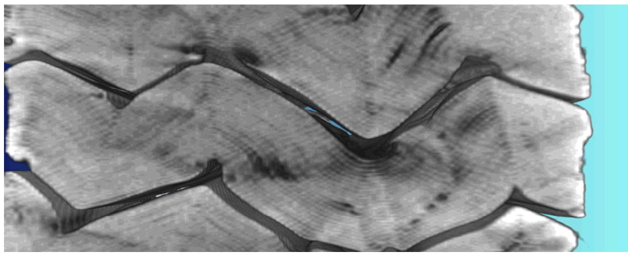
Determining baseline mechanical behavior of batteries during crush/impact testing
Testing support to validate mechanical models for batteries during a crash scenario

Crush of 1S12P battery

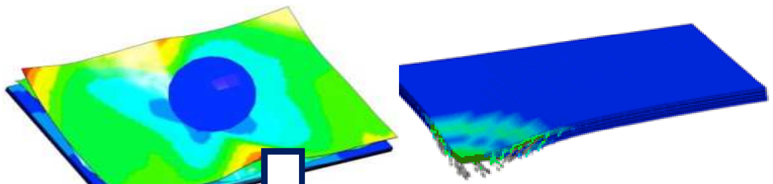
Crash Safety Modeling

Computer Aided Engineering for Batteries (CAEBAT) DOE VTO and NREL

Battery Crush Experiment (SNL, USCAR)

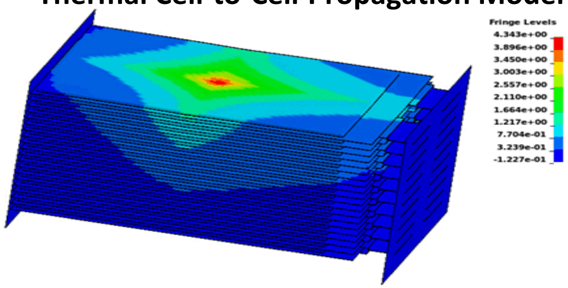


Cell-level Mechanical Model (MIT)

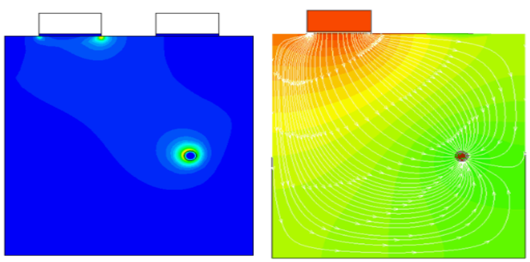


Integrated Thermoelectrochemical & Mechanical Model (NREL)

Thermal Cell-to-Cell Propagation Model



Thermoelectrochemical Model



- ***Use battery crush data to validate the integrated model***
- ***Develop a predictive capability for battery thermal runaway response to mechanical insult***

Summary and Conclusions

- Repeatability of mechanical testing dependent heavily on cell construction
  - Differences in manufacture designs can have an effect on results
  - Level of uniformity of manufactured cells may contribute to results
  - Central core restricts expansion of cell contents during catastrophic failure
- Reproducible runaway with axial penetration
  - Candidate technique for propagation through multi cell packs
- Prismatic pouch cells show similar rates of failure
  - More detail on pouch cells in JPS article
- Crush testing of 1S12P shows shearing failure in long direction, buckling failures in shorter directions
- CT scans show how buckling may lead to internal shorting

Acknowledgements

- Technical team
  - Christopher Orendorff
  - Leigh Anna Steele
  - Ganesan Nagasubramanian
  - Kyle Fenton
  - Summer Ferreira
  - Babu Chalamala
  - Bill Averill
  - Pete Roth
  - Scott Spangler
  - Jill Langendorf
- DOE – Office of Vehicle Technologies
  - Dave Howell
  - Brian Cunningham
  - Peter Faguy
- DOT- NHTSA
  - Phil Gorney

THANK YOU

Timeline of notable safety events

- 2006- Dell recalls 4.1 million laptops due to fire risk
  - Manufacturing defect in LIB cited as cause
- 2007- Apple laptop fire originating from battery
  - Ultimately leads to 1.8 million unit recall
- 2011 Zotye Electric taxi catches fire
  - Investigation links fire to defective battery
- 2011 – Chevrolet Volt spontaneously ignites 3 weeks after crash testing
  - Cause thought to be leaking coolant from the battery system that ultimately shorted the battery
  - Illustrates the stranded energy problem
- 2011 Fisker Automotive recalls 239 vehicles due to fire risk
  - Risk tied to potential coolant leak
- 2012 BYD e6 electric taxi ignites after being struck at high speed
  - Investigators link fire to high voltage line damage
- 2012 Fisker Karma cited as cause of a garage fire that spread to the attached home
  - A good deal of controversy surrounds this event. The fire inspector cited the vehicle as the origin, however the car was not plugged in and the battery pack remained intact
- 2012 1 Toyota Prius and 16 Fisker Karmas caught fire after being submerged in seawater for an extended period as a result of Hurricane Sandy
  - In both cases damage to the electrical system was cited as the cause of the fires
- 2013 Boeing 787 Dreamliner grounded ~4 months following multiple LIB incidents
  - Cause of battery failures still undetermined