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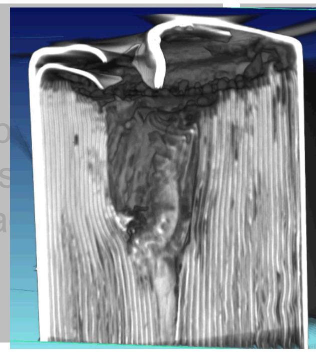

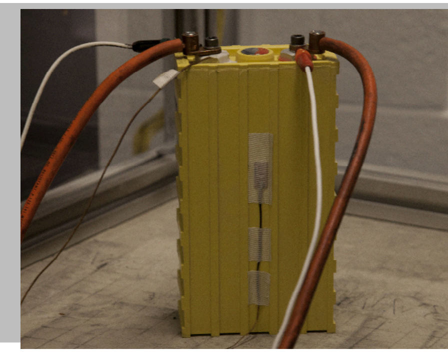

Safety testing of electrochemical cells and systems

Joshua Lamb

Next Generation Batteries 2015, La Jolla, CA

April 22, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

I. Safety concerns of large batteries
II. Low level battery system testing
III. Large scale modeling.
IV. Testing difficulties of large battery systems

Energy Storage Safety/Reliability Issues Have Impact Across Multiple Application Sectors

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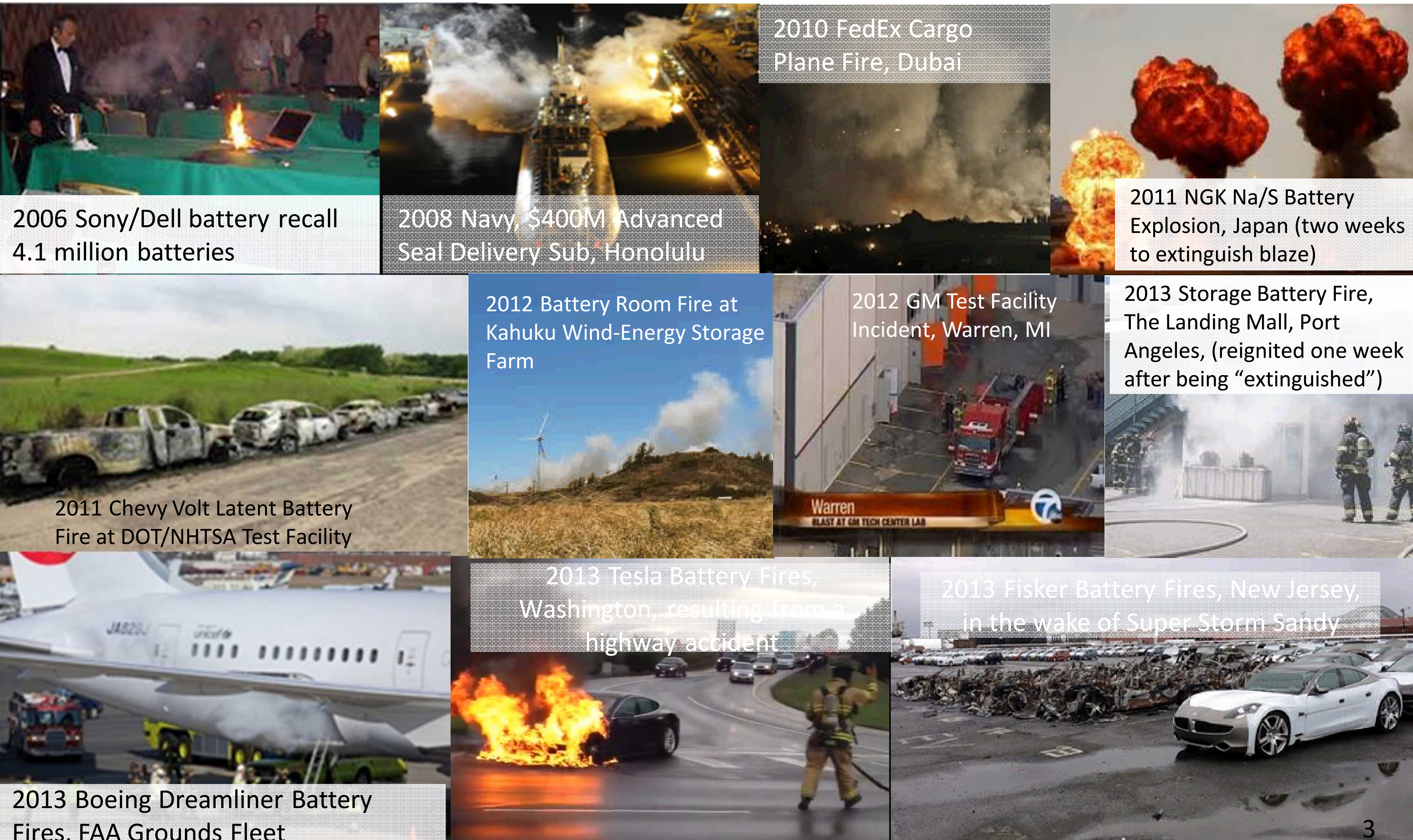

2006 Sony/Dell battery recall 4.1 million batteries

2008 Navy, $400M Advanced Seal Delivery Sub, Honolulu

2010 FedEx Cargo Plane Fire, Dubai

2011 NGK Na/S Battery Explosion, Japan (two weeks to extinguish blaze)

2011 Chevy Volt Latent Battery Fire at DOT/NHTSA Test Facility

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

2012 GM Test Facility Incident, Warren, MI

2013 Storage Battery Fire, The Landing Mall, Port Angeles, (reignited one week after being "extinguished")

2013 Boeing Dreamliner Battery Fires, FAA Grounds Fleet

2013 Tesla Battery Fires, Washington, resulting from a highway accident

2013 Fisker Battery Fires, New Jersey, in the wake of Super Storm Sandy

System-Level Battery Safety

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Field failures could include:

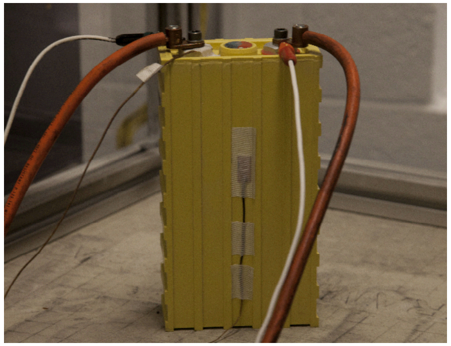
- Latent manufacturing defects
- Internal short circuits
- Misuse or **abuse conditions**
- Ancillary component issues

Any **single point failure** that **propagates** through a entire battery system is an **unacceptable** scenario to ensure battery safety

Fisker incident in the wake of Super Storm Sandy , New Jersey, 2012

Increasing hazards with scale

Single cells ~ 0.5-5 Ah
Impact typically limited to immediate device
Field failures are most typical mode of failure, abusive failures often the result of misuse



Strings and large format cells ~10-200 Ah
Potential for more serious impact
Potential for a single cell failure to impact the entire string
Typically not as closely monitored as larger packs

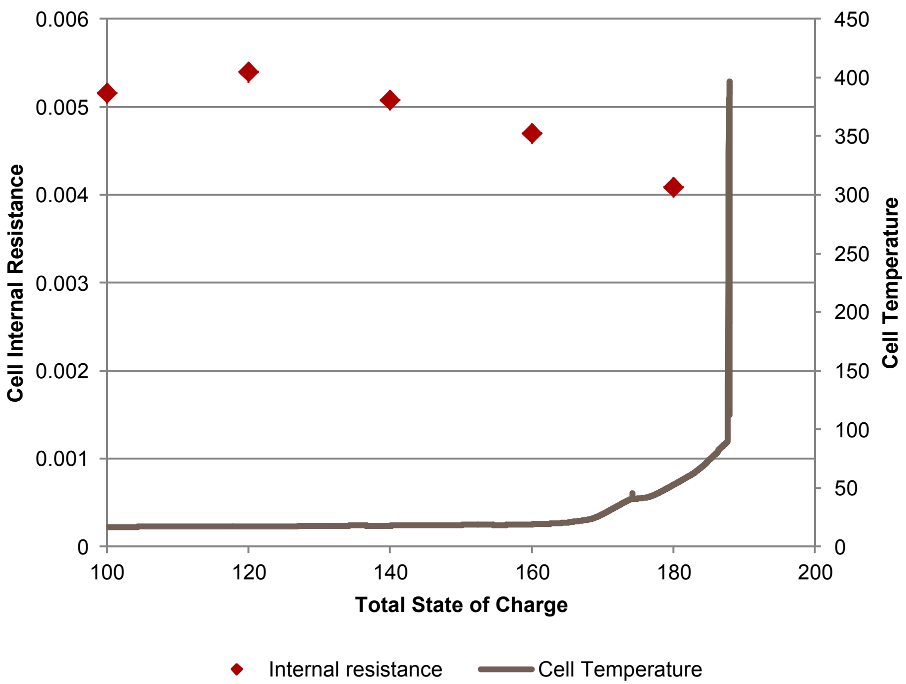
EV batteries ~10-50+ kWh
Failure can potentially consume entire vehicle
Monitoring capabilities typically reliant on BMS
High voltage and loss of isolation can lead to failure as well
Potential for stranded energy complicates response

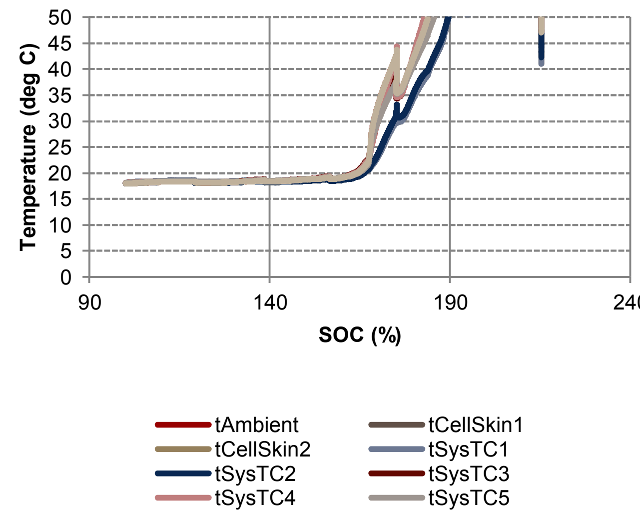
Stationary/Industrial batteries MWh +
Large, complex systems
Inability to remove high voltage during an incident

Current Technical Challenges

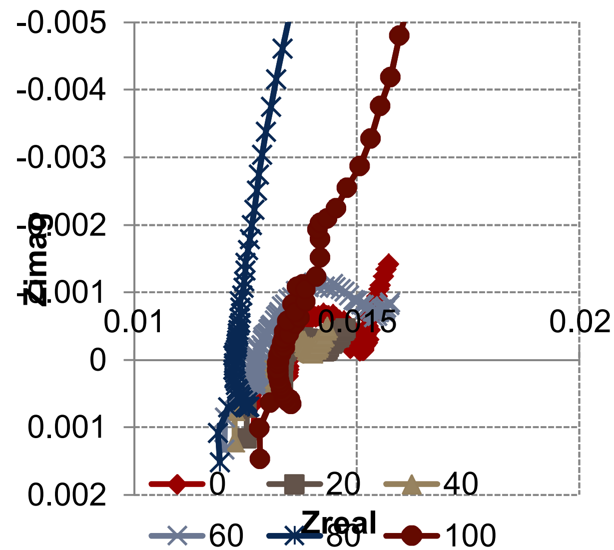
- Energetic active materials
  - Exothermic decomposition of active materials, significant gas generation, combustibility of electrolyte and electrolyte vapors
- Electrolyte products during runaway
  - Cell venting releases both gaseous electrolyte products as well as aerosolized electrolyte. This mixture is often highly flammable.
- Intolerance to abuse conditions, particularly high temperature and overcharge
  - Potential solutions to overcharge include electro-active separators and overcharge shuttles
- **Failure propagation**
  - A single cell failure can carry enough energy to propagate throughout a battery system, engaging otherwise healthy cells.
- **State of potentially damage battery systems**
  - A damaged battery system may conceal significant stored energy remaining (stranded energy).
  - Determination of battery stability after a potentially abusive event.
- **How are large, stationary batteries impacted by external events?**
  - Modelling is attractive in this case as testing is both difficult and costly

Single cell overcharge





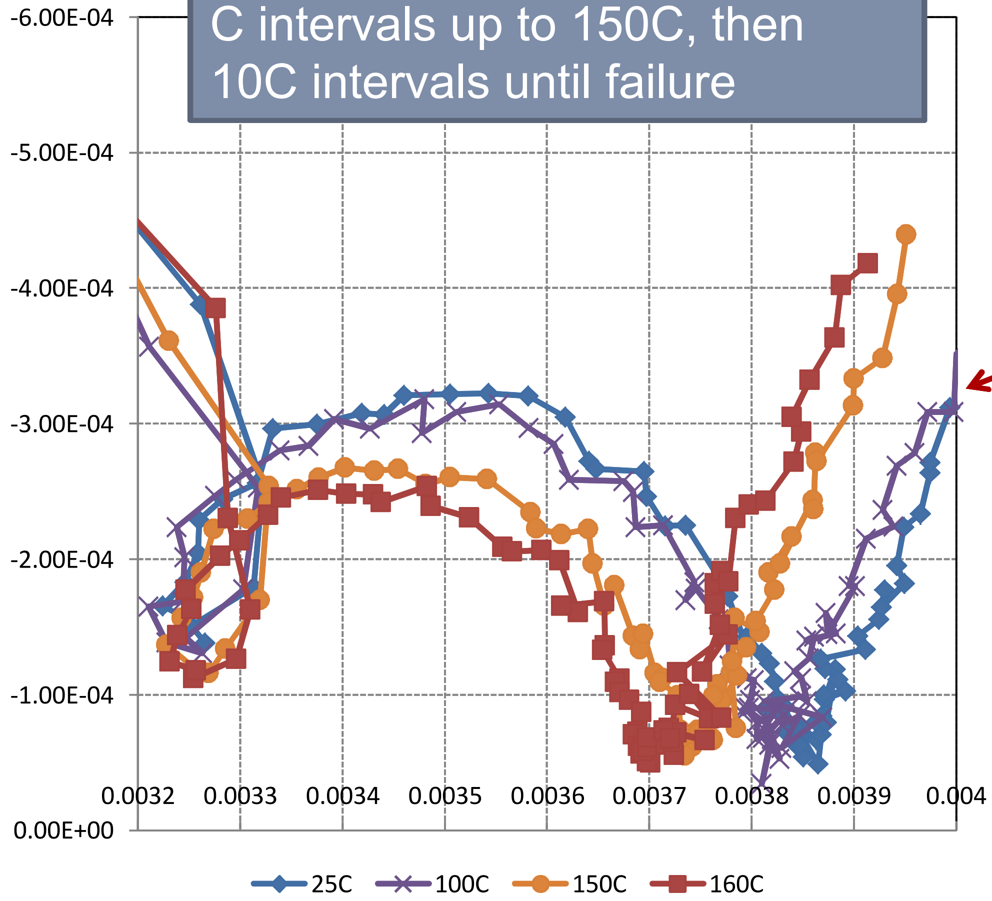
Temperature during testing- Temperature remains close to ambient up to 60% Overcharge, beginning to increase rapidly above 70% overcharge

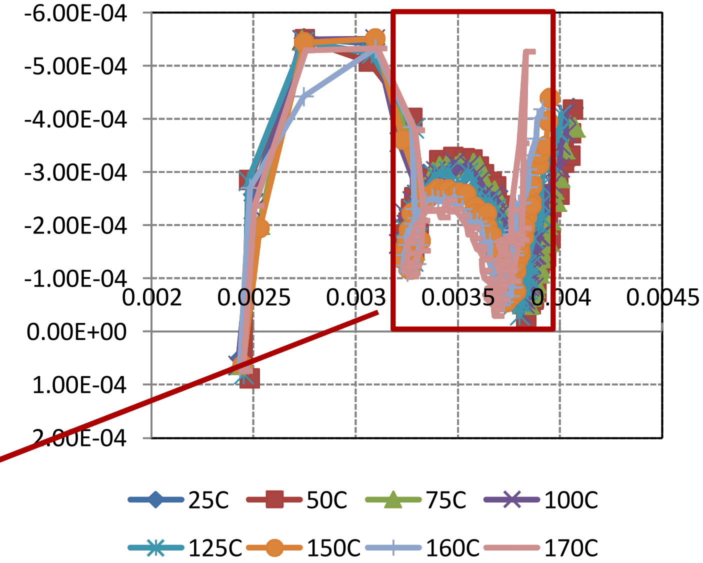


Impedance spectra at increasing states of overcharge Reduction in charge transfer resistance (radii of semicircles) from 0-40% overcharge, similar to impedance changes seen in normal charging, increasing over 60% overcharge.

Safety testing - Advanced diagnostics of abused cells

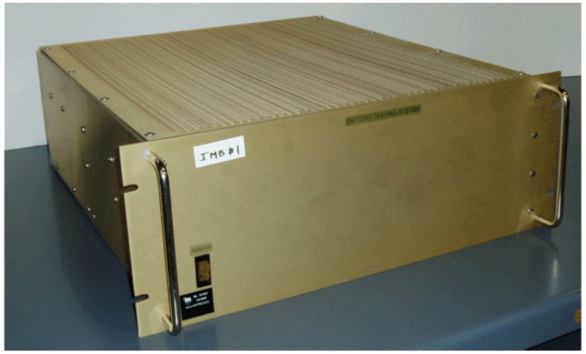
Impedance data collected at 25 C intervals up to 150C, then 10C intervals until failure



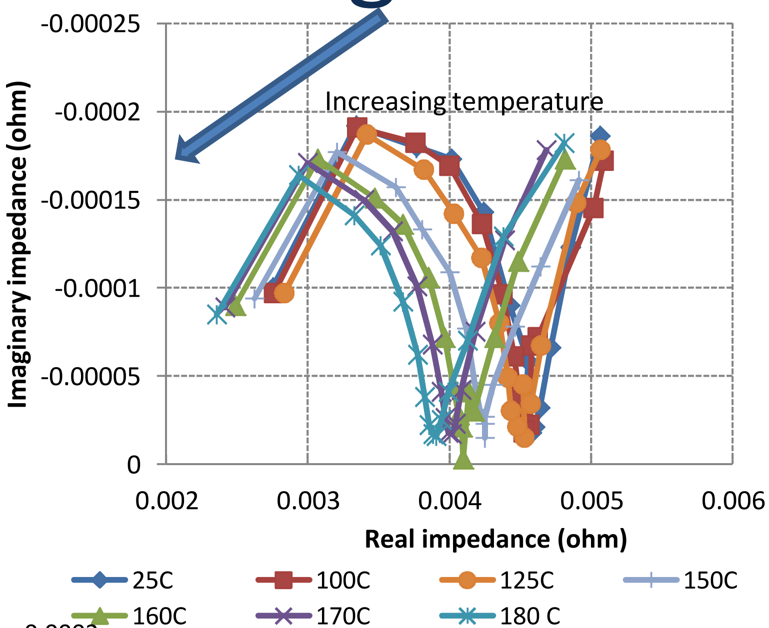


Little change observed up to 100C.
Shifts in R_{CT} observed as temperature increases above 100C.
Thermal runway observed during data collection at 170C

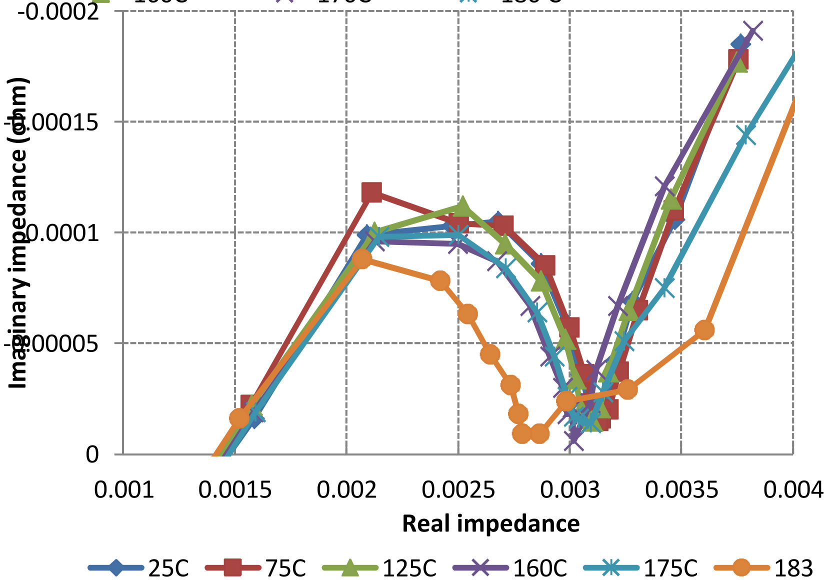
Fast impedance monitoring



Impedance measurement box developed by INL



Impedance data collected after temperature is allowed to equilibriate vs. scans taken every 20 seconds during a 3 °C/min thermal ramp test



Failure Propagation Testing

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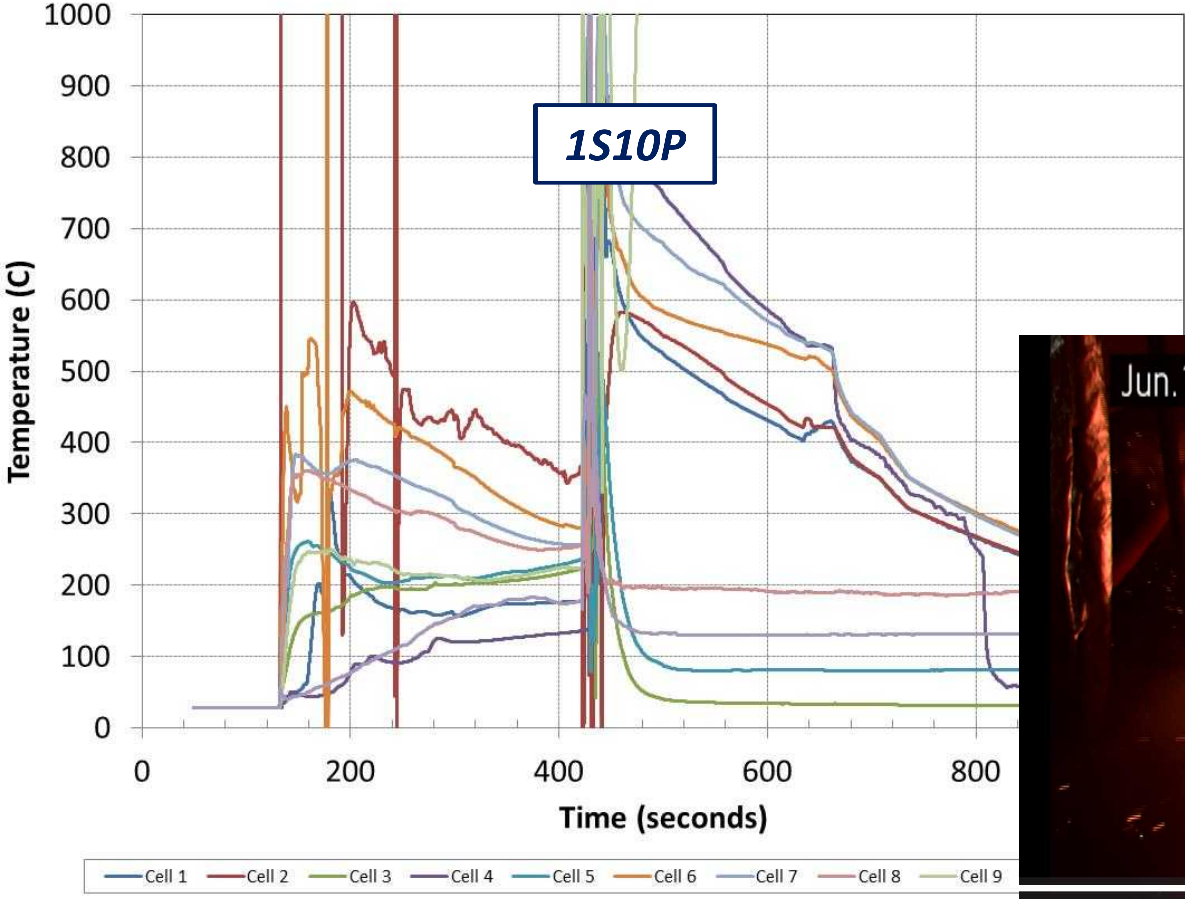
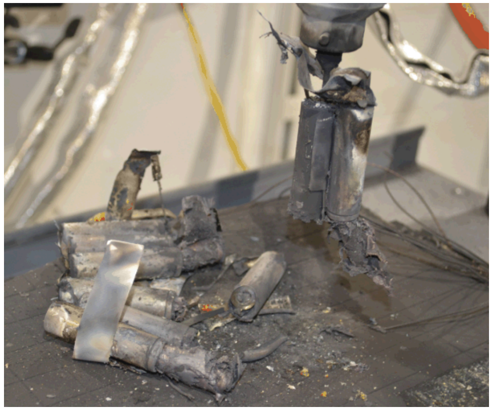
10S1P and 1S10P configurations
2.2 Ah 18650 cell packs (92 Wh at 100% SOC)
Failures initiated by mechanical insult to the center cell (#6)

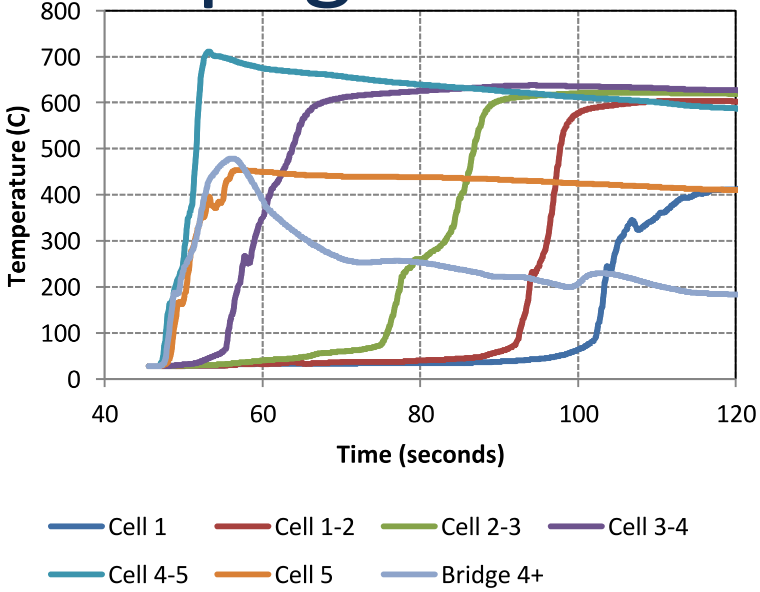


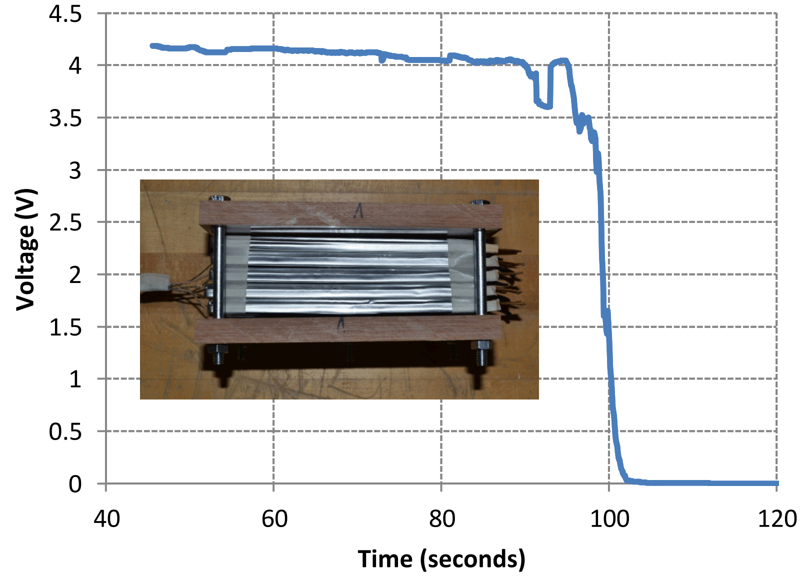


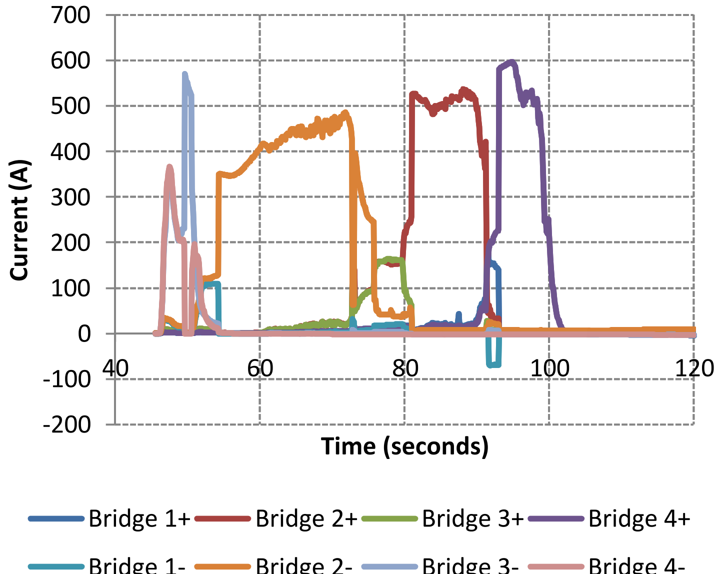
Complete propagation of a single point failure in the 1S10P pack

Orendorff, C. J. "Propagation Testing of Multi-Cell Batteries", SAND2014-17053, August 2014

Propagation Testing (1S5P)

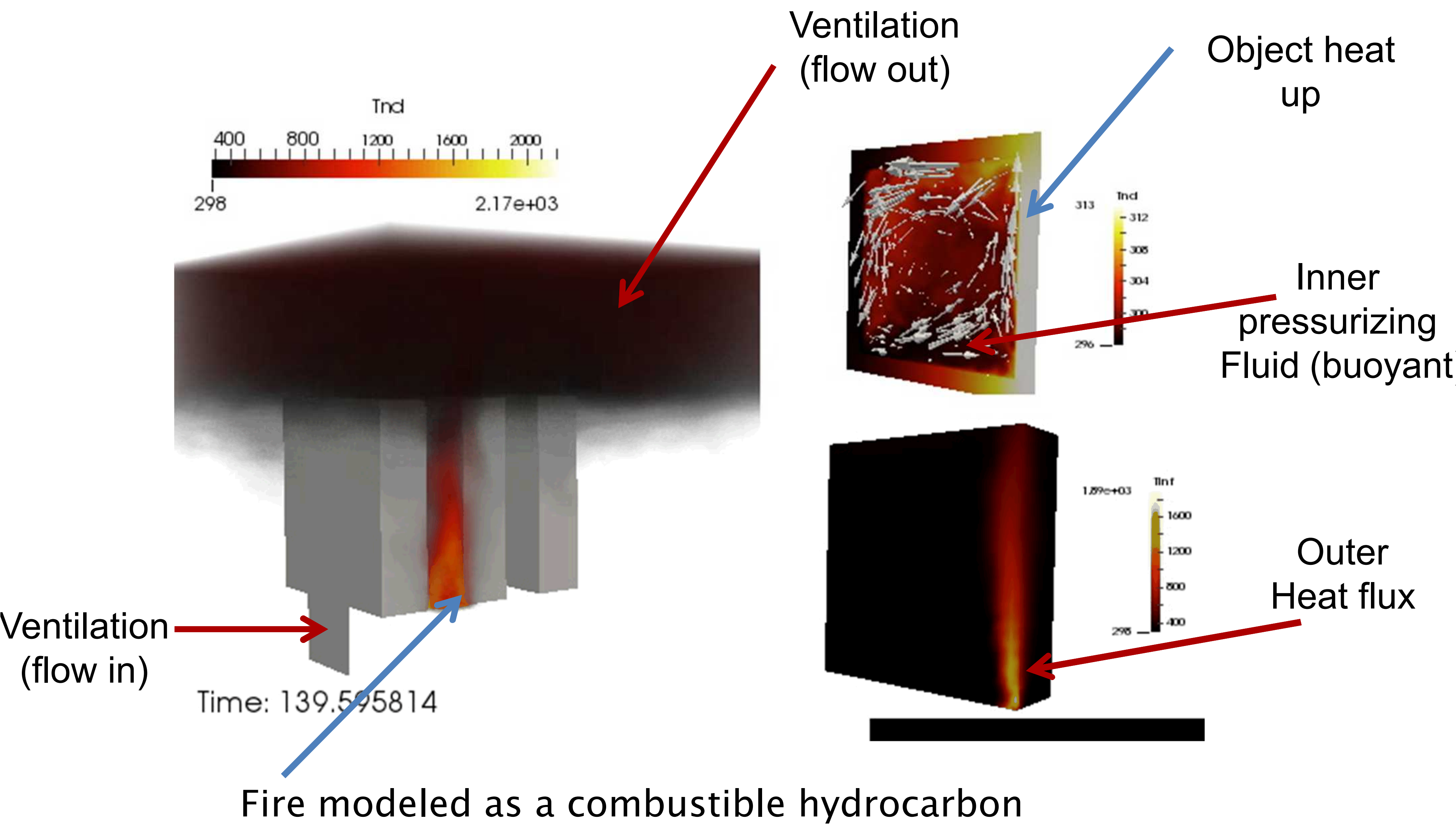




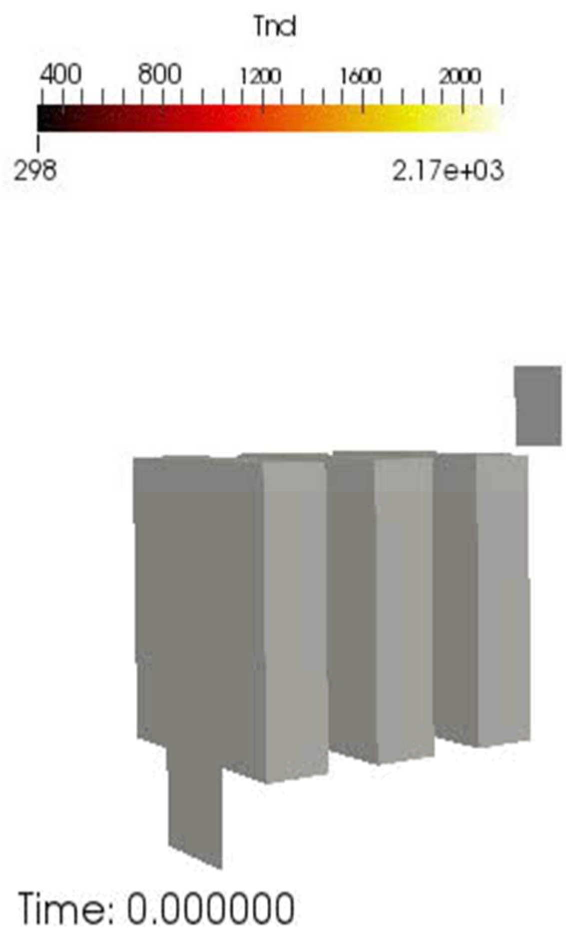


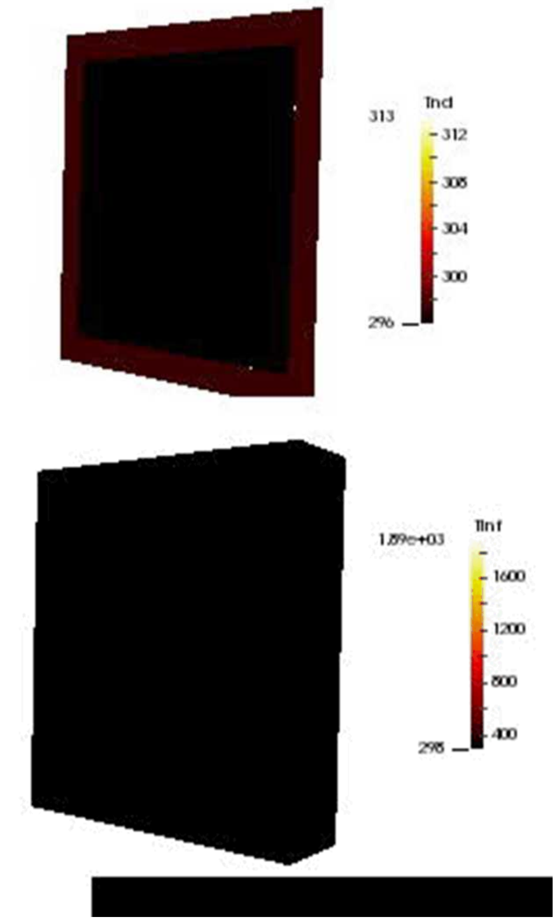
- Failure and runaway initiated at Cell #1
- Heat flux gauge data collected 32” from pack
- Temperature corrected current flowing through bridges

Modeling - Applying Sierra simulation tool to battery fire scenarios



Modeling - Ventilation effect on fire plume dynamics (2/3)





Ventilation is 1 m/s

Challenges of large pack testing – some lessons learned

- Cost and time of planning goes up exponentially
- Beware the fuel-air explosion
  - Gasses released from thermal runaway are often flammable and may result in an explosive mixture in an enclosed space
- High voltage becomes a significant hazard
- How to handle batteries/system after test
  - What if the system is damaged but many individual cells are still healthy?
- Destructive testing may mean intentionally bypassing BMS safety systems

Summary

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- Impedance analysis of abused cells show strong trends in internal resistance for single cells, but changes become more subtle as the cell increases in complexity
- Fast impedance measurements have been demonstrated, including continuous monitoring of a cell under a continuous rate thermal abuse test
- Parallel configurations of cells show significant discharge through the electrical connections during a single cell failures
  - Contributes significantly to runaway in 18650 packs
- On going work will focus on increasing complexity of pack design
  - More complex electrical configurations, including taking isolation faults into account
  - Cell separation using cooling plates and/or insulation; presence of active cooling
- Early work shows how fire modeling may be used to improve understanding of large battery fires
  - More work is needed, in particular to show how the batteries themselves may contribute to the fire

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