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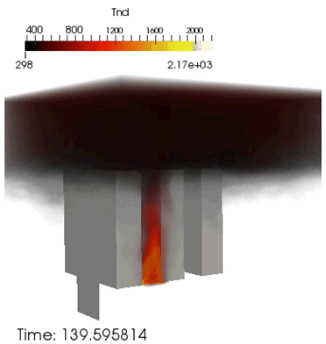

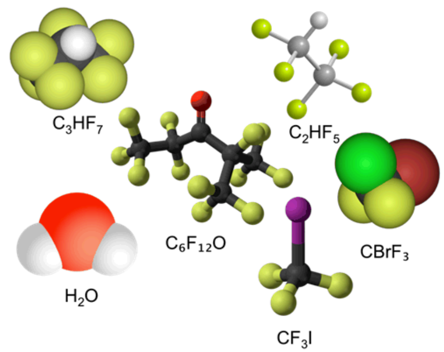

Energy Storage Technologies-Assessing Reliability and Safety

Summer Ferreira, Heather Barkholtz, Armando Fresquez

Peer Review Meeting
September 27, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

SNL Energy Storage System Analysis Laboratory

Sandia National Laboratories

Mission:

Develop and implement analytics to assess the performance and life of energy storage technologies to advance the adoption of stationary storage solutions.

Problem:

- Current testing methods differ by lab, manufacturer and customer leading to excessive and "apples to oranges" results
- Life of storage technologies uncertain yet critical to validating economics
- Potential storage customers, i.e. utilities, without experience in storage, are reluctant consumers.

Approach:

Develop advances through:
- Test protocols, using direct research and standards activities
- high precision testing spun off as an ARPA-E grant recipient in 2013

Provide ongoing:
- expertise in testing programs to customers
- verification of specific technologies

Participation in Standards Activities

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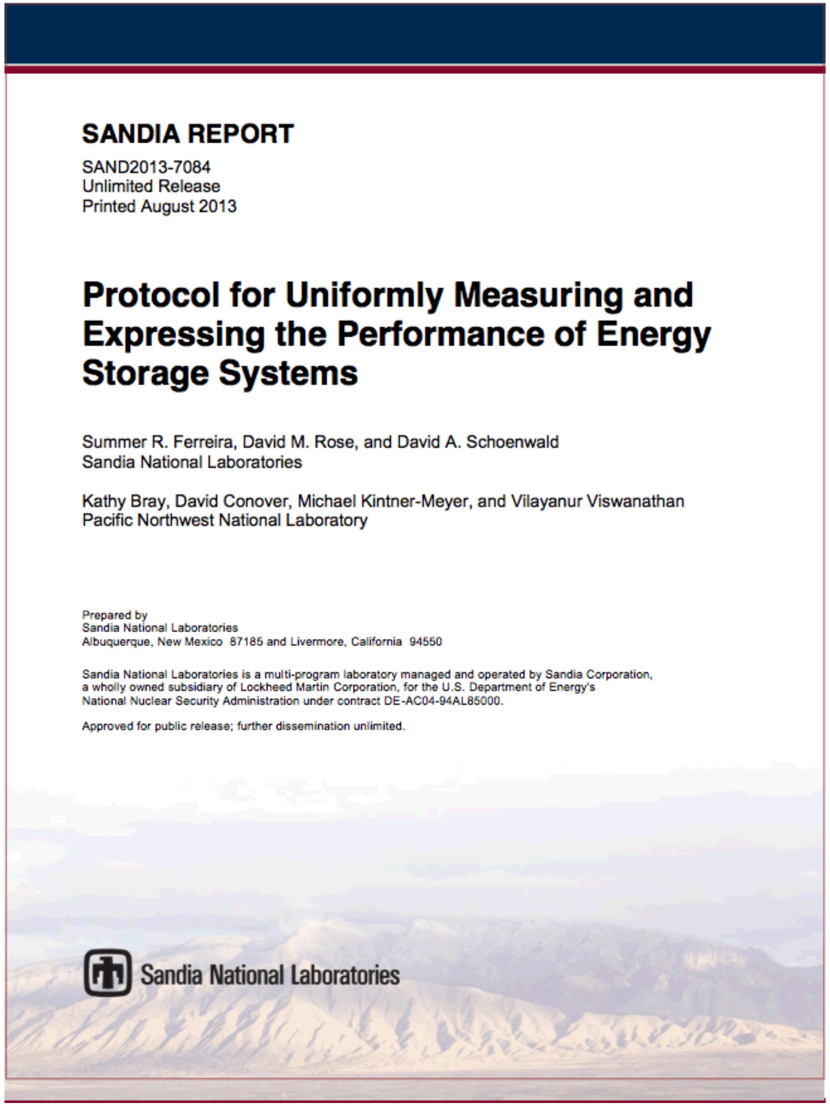
DOE Performance Protocol

- Included broad input from utility and manufacturing side.
- Initial testing and comments are welcome.

In the last two years there has been a call for standard language and testing, with definitions. In response standards development has been a large priority.



SANDIA REPORT
SAND2013-7084
Unlimited Release
Printed August 2013

Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems

Summer R. Ferreira, David M. Rose, and David A. Schoenwald
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Pacific Northwest National Laboratory

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http://www.sandia.gov/ess/pubs_tech.html

SNL Energy Storage System Analysis Laboratory

Providing reliable, independent, third party testing and verification of advanced energy technologies for cell to MW systems

Testing Capabilities Include:

- Expertise to design test plans to fit technologies and their potential applications
- OE supported testing
- CRADA opportunities
- WFO arrangements

Cell, Battery and Module Testing

- 14 channels from 36 V, 25 A to 72 V, 1000 A for battery to module-scale tests
- Over 125 channels; 0 V to 10 V, 3 A to 100+ A for cell tests

72 V 1000 A Bitrode (2 Channels)

Energy Storage Test Pad (ESTP)

System Testing

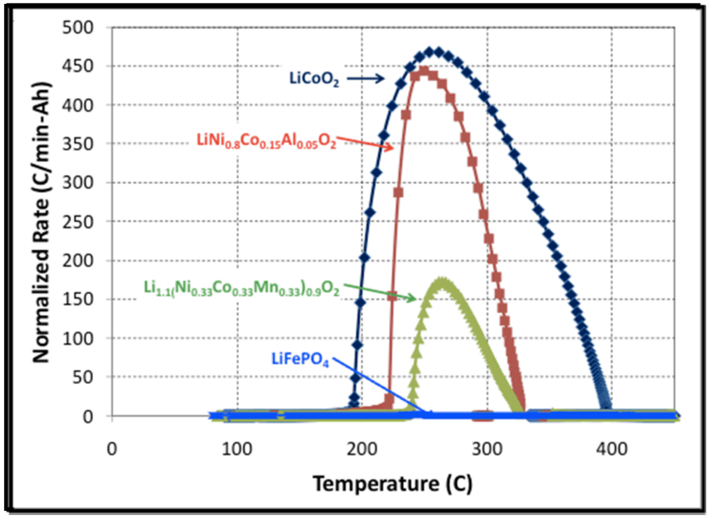
- Up to 1 MW, 480 VAC, 3 phase
- 1 MW/1 MVAR load bank

SNL Battery Abuse Testing Laboratory

Battery testing, cell measurements, and materials development to support the development of inherently safe lithium-ion chemistries

- Safety and abuse tolerance evaluation of energy storage devices from cells to kWh batteries:
  - Mechanical abuse
  - Thermal abuse
  - Electrical abuse
- Understanding degradation mechanisms that lead to cell failure
- Provide experimental data to support abuse and thermal modeling
- Cell prototyping facility for materials development

Understanding abuse tolerance



50 Wh failure event

5 Wh failure event

Impact and Consequence of Scale on Safety

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The Lack of Safety:

Endangers Life
Loss of Property
Damages Reputation
Decreases Confidence in Storage

Consumer Cells (0.5-5 Ah) → Large Format Cells (10-200 Ah) → Transportation Batteries (1-50 kWh) → Utility Batteries (MWh)

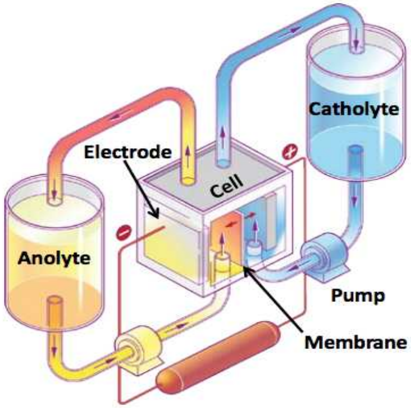
www.ford.com www.samsung.com www.saftbatteries.com

Safety issues should become paramount with increasing battery size

The Grid Energy Storage Safety Challenge

- *Variety of technologies*
- *Proximity to population*
- *Use conditions*
- *Scale and size*
- *Design considerations*
- *System complexity*

Subway regen system, SEPTA



Redox Flow Battery

SAFT 10 MWh storage system

US Marine Corps FOB, Afghanistan

Key Challenges:

Utility safety incidents have highlighted the **need for a focused effort** in safety

Examples of Recent Issues with Energy Storage Safety

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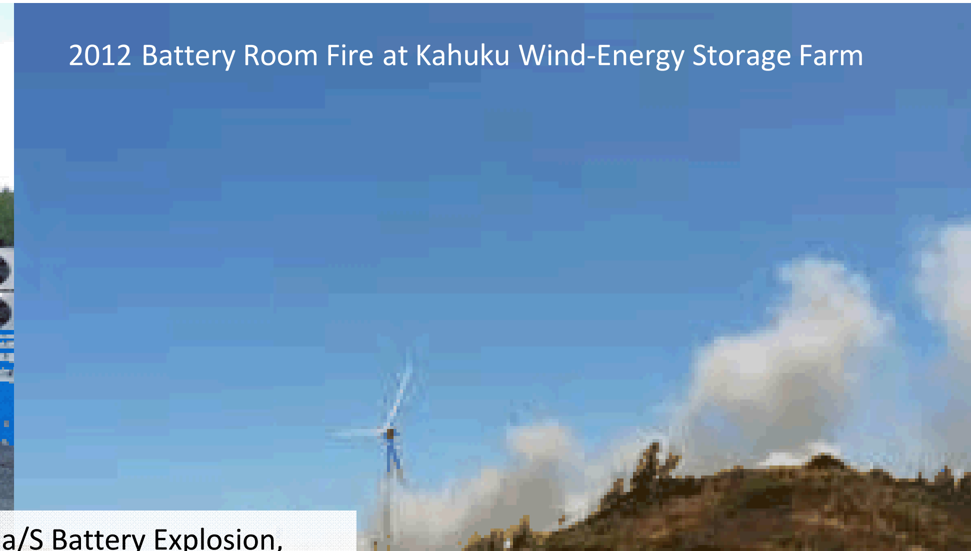
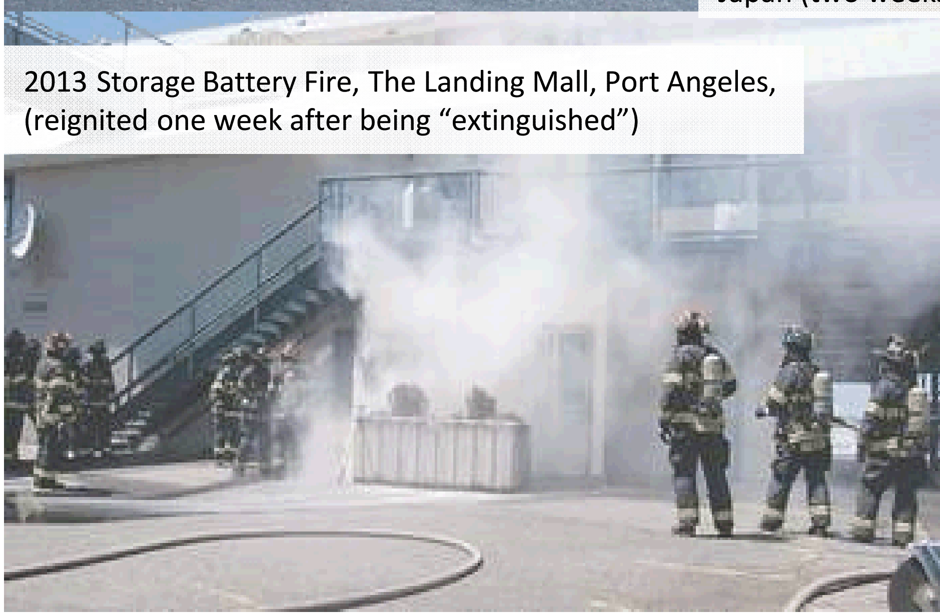
2011 Beacon Power Flywheel Failure


2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

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


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

2012 GM Test Facility Explosion, Warren, MI

Improving battery safety

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Development of Inherently Safe Cells

- Safer cell chemistries
- Non-flammable electrolytes
- Shutdown separators
- Non-toxic battery materials
- Inherent overcharge protection

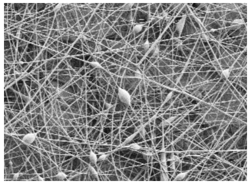
Safety Devices and Systems

- Cell-based safety devices
  - current interrupt devices
  - positive T coefficient
  - Protection circuit module
- Battery management system
- Charging systems designed

Effective Response to Off-Normal Events

- Suppressants
- Containment
- Advanced monitoring and controls

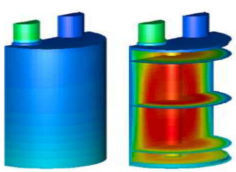
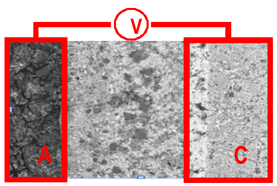
Battery Safety – Stationary Storage




Materials R&D to date:
- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

Materials R&D needs:
- Viable flow batteries
- Aqueous electrolyte batteries
- High specific heat suppressants
- Vent gas composition

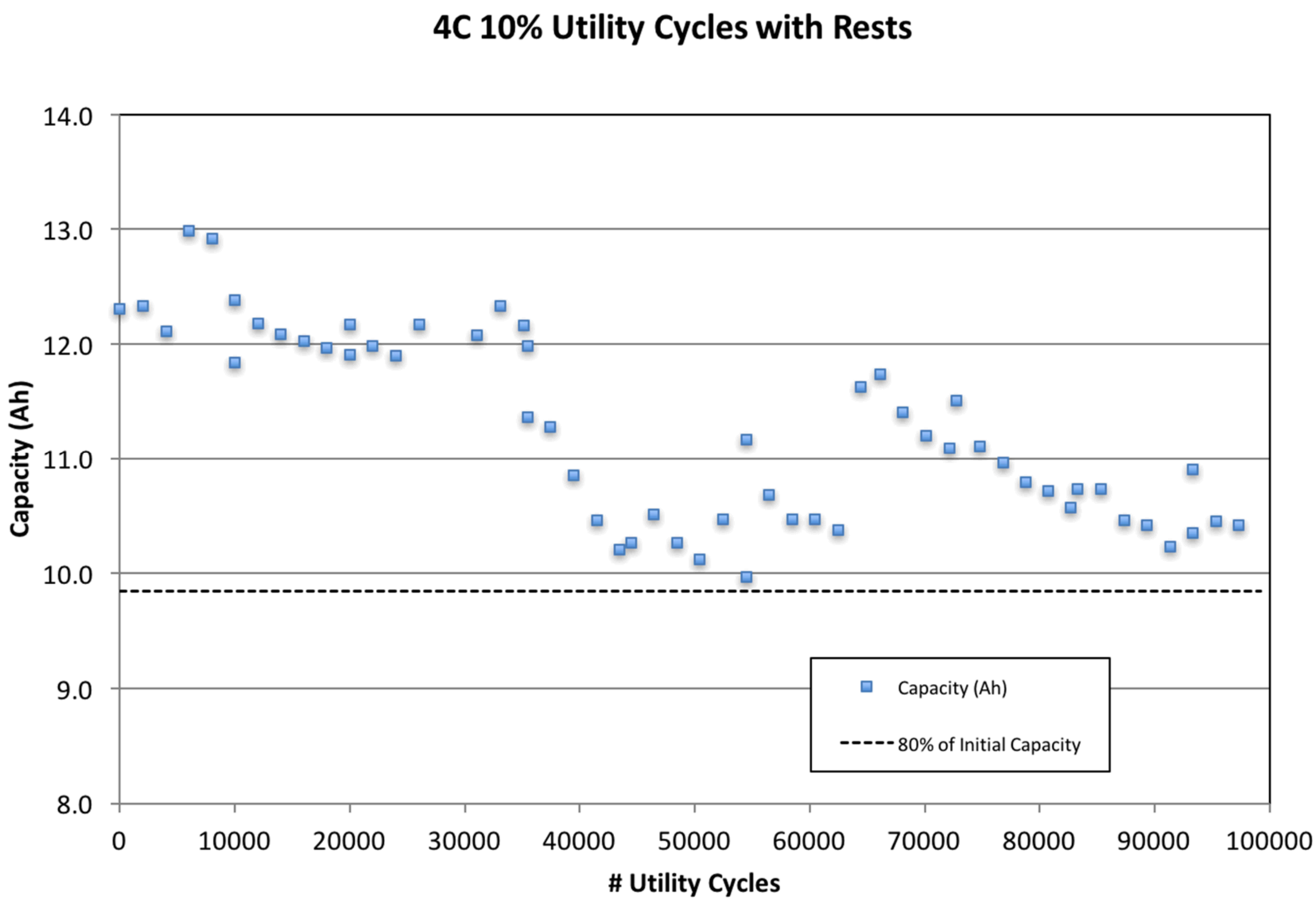

Testing
- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Suppressants and delivery with systems and environments
- Large scale thermal and fire testing (TTC)

Simulations and Modeling
- Multi-scale models for understanding thermal runaway
- Validating failure propagation models
- Fire Dynamic Simulations (FDS) to predict the size, scope, and consequences of battery fires

Procedures, Policy, and Regulation
- UL 1973-13 Batteries for Use in Stationary Applications
- ANSI/UL 9540-P (ESS Safety)
- UL 1974 (Repurposing)
- IEEE 1635-12 (Ventilation and thermal management)

LTO Lifecycle testing continuing



Equivalent throughput energy of 10,000 full discharge cycles

<20% capacity loss after ~100K+ cycles

Safety of 18650 Li-Ion Cells

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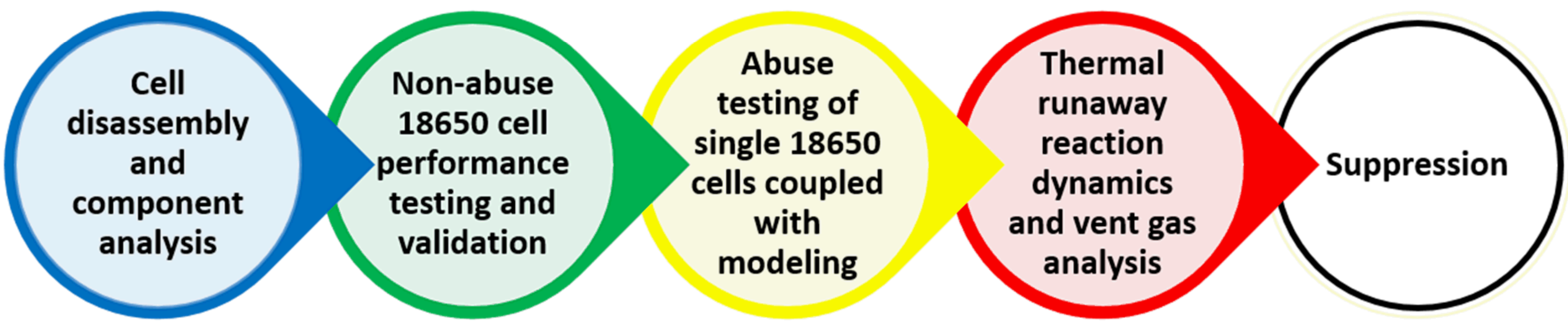
Cathode Chemistry	Nominal Capacity (mAh)	Nominal Voltage (V)	Δ T (°C)	Max Discharge Current (A)
LFP $LiFePO_4$	1100	3.3	-30 to 60	30
NMC $LiNi_{1-x-y}Mn_xCo_yO_2$	3000	3.6	-5 to 50	20
LCO $LiCoO_2$	2500	3.6	0 to 50	20
NCA $LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$	2900	3.6	0 to 45	6

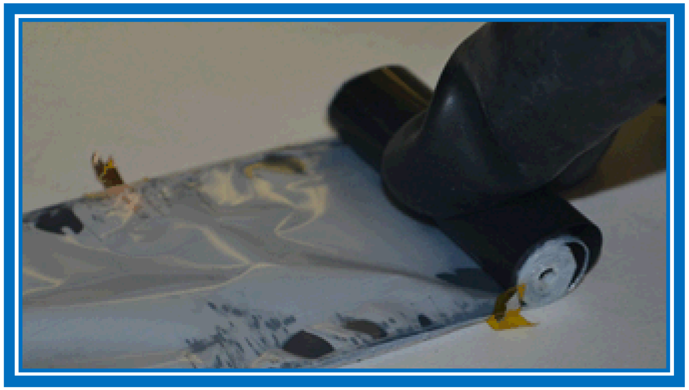
Cells of different cathode chemistries selected

Manufacturer specifications listed and are termed 'non-abuse'

Project outlined below

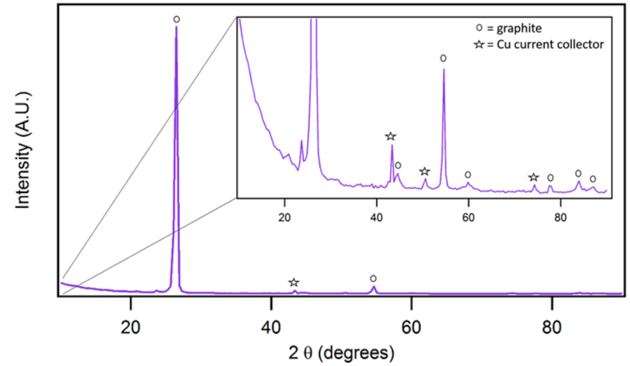


Cell Disassembly and Component Analysis

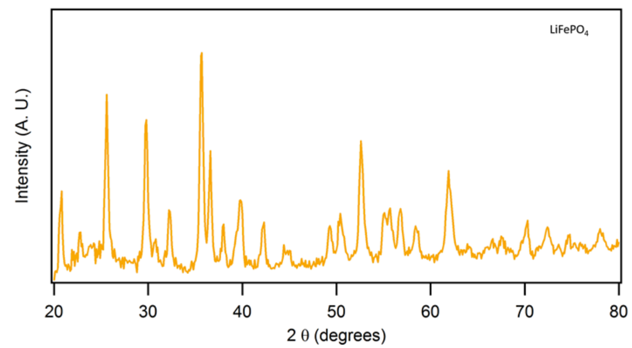


Disassembly

Progress: LFP and NCA cells were disassembled and their electrode components identified.



Graphite anode

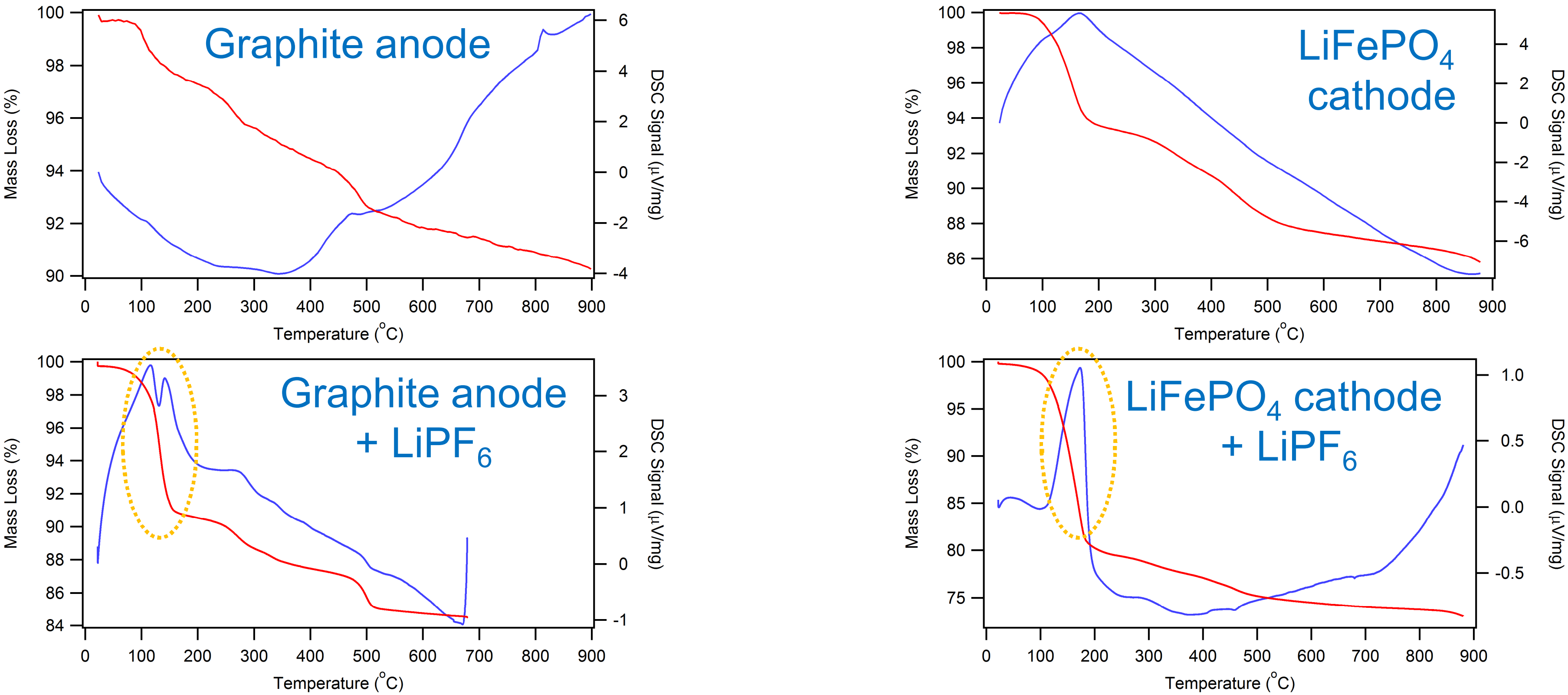


$LiFePO_4$ cathode

Plan: characterize electrolyte composition and finish other cell chemistries

Cell Disassembly and Component Analysis

Progress: Thermal stability of LFP electrodes with and without $LiPF_6$



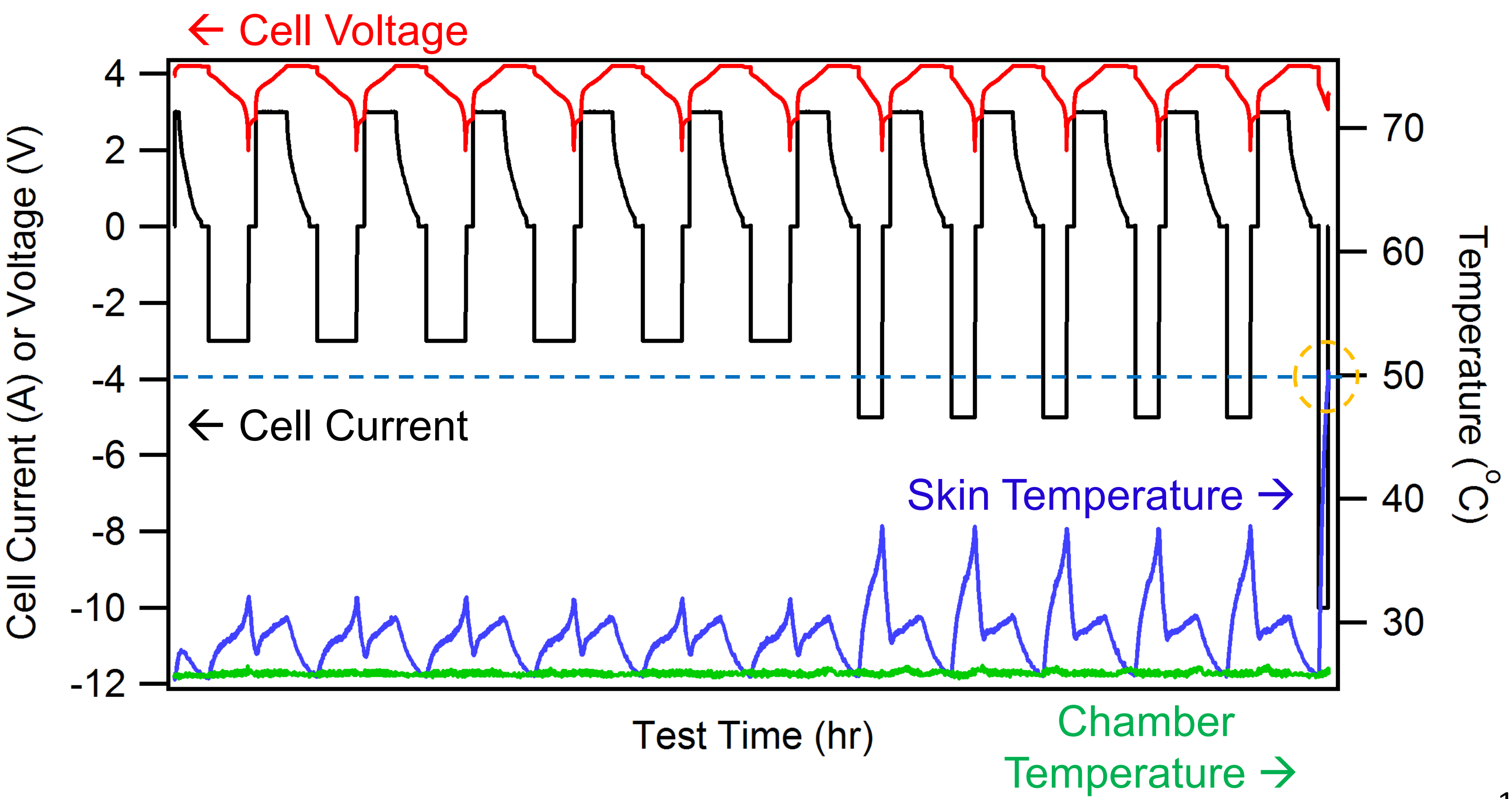
Large component of mass loss/thermal flux from $LiPF_6$ and electrode interactions

Plan: Temperature-resolved XRD to resolve phase/crystal changes

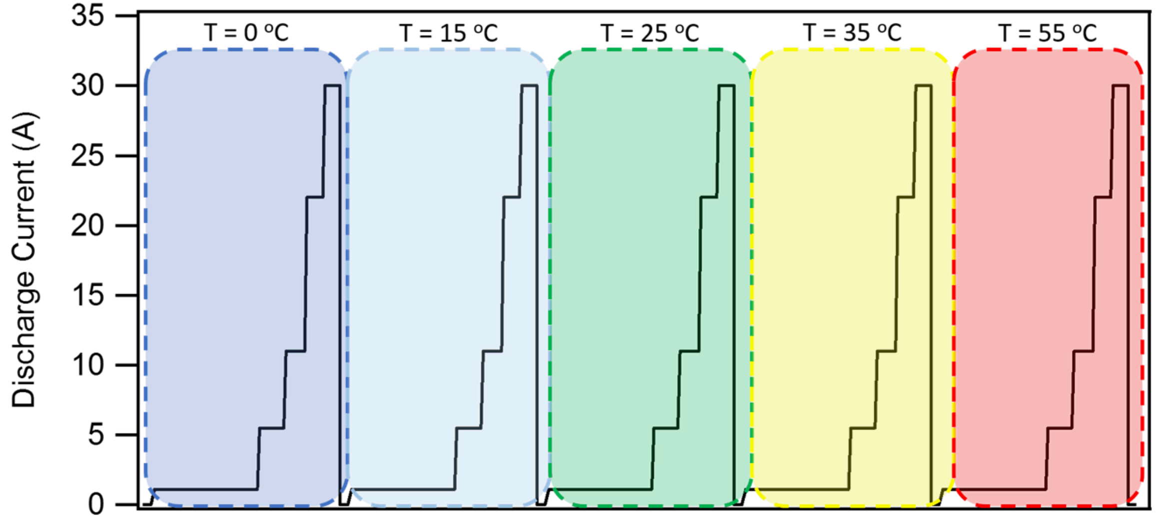
Non-Abuse 18650 Cell Performance Testing

NMC Cell, cut-off temperature = 50 °C

10 A discharge raised cell temperature to cut-off, test terminated



Non-Abuse 18650 Cell Performance Testing



Continue into 'abuse'

Plan: Complete testing as far as possible in 'non-abuse' conditions for other chemistries and chamber temperatures.

Abuse 18650 Cell Performance Testing:

Repeat test plan allowing 'abuse' temperatures – how do cells respond? Do they fail? What is the impact on performance?

Thermal Runaway and Suppression

Thermal Runaway Plan: Couple material instability data with cell failure to understand electrode decomposition mechanisms.

Estimate vent gas composition per decomposition mechanism.

Understand how cell chemistry affects cell failure.

Feed this information into models of cell failure and propagation.

Suppression Plan: Use modeling results to plan suppression testing.

Build a gas/flame model system representing thermal runaway to test suppressants more reliably.

Test available suppressants on thermal runaway of 18650 cells.

Summary

- Field the most inherently safe chemistries and designs
- Testing failure propagation to understanding vulnerabilities
- Research informed by materials understanding is critical to:
  - **Containment** of storage across scales and chemistries
  - Effective **suppressants** identification and use
  - Appropriate **hardware and software controls** to mitigate failures and propagation of failures

Through integrated R&D into failure behavior and consequences using **experimental** and **modeling** efforts across scale.

Acknowledgements

- Prof. Sehee Lee
- David Howell (DOE)
- Brian Cunningham (DOE)
- Peter Faguy (DOE)
- Prof. Steve George
- Tom Wunsch
- Trish Selcher
- Mani Nagasubramanian
- Pete Roth
- Josh Lamb
- Jill Langendorf
- Lorie Davis
- Denise Bencoe
- Travis Anderson
- Chad Staiger
- Harry Pratt
- Leigh Anna Steele
- Bill Averill
- Dave Johnson
- Scott Spangler
- June Stanley
- Kyle Fenton

Battery Safety R&D Program at Sandia: http://energy.sandia.gov/?page_id=634
DOE Office of Electricity
Office of Vehicle Technologies

Battery System Field Failures

- Single point (or multi-point) failures within the battery or outside the battery that lead to catastrophic failure
  - Internal short circuits (latent defect)
  - Use conditions
  - Abuse conditions (forseen or unforseen)
  - Control electronics failure (connectors, power electronics, boards, low voltage short)
- Internal short circuits have garnered considerable attention from consumer electronics field failures
- Other failure modes will likely gain more attention for large scale applications because the use conditions are considerably different
- Allowing single point failures to propagate through a battery is an unacceptable scenario to ensure battery safety

Motivation to Test for Failure Propagation

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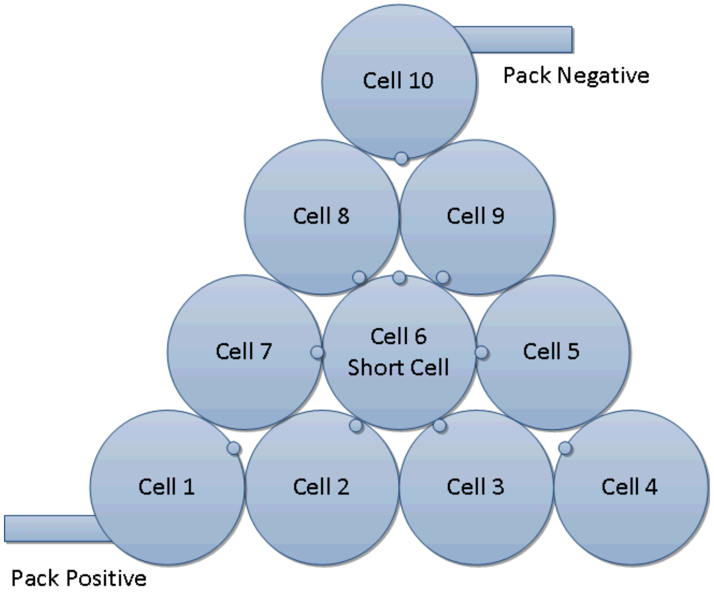
- Simply, the propensity of the energetic failure of a single cell to cause widespread thermal runaway within a battery
- Most large battery systems are designed to withstand the loss of several cells from a performance standpoint
- A point failure becomes more serious if it can send nearby cells into thermal runaway



Cells:
Panasonic
Model CGR18650CG
2250 mAh nominal capacity
Avg wt. 44g

- Diagram showing cell and thermocouple locations
- Series and parallel constructions used, series pack wired in order from Cell 1 to cell 10

Challenges with Inherent Cell Safety

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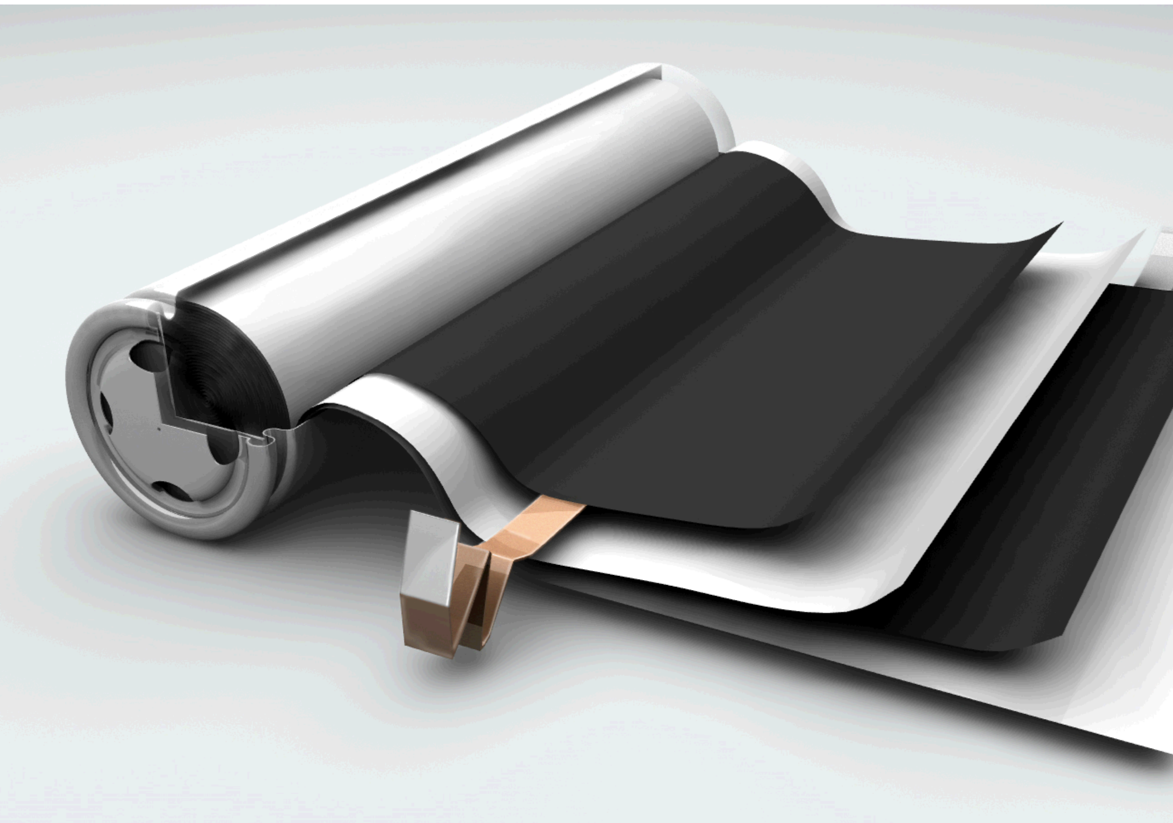

Intolerance of Abuse	Targeted solutions to mitigate in response to abuse
Electrolyte Flammability	Alternative electrolyte components
Thermal Stability	Separator stability Electrolyte combustion
Energetic Decomposition	New Materials Coatings

G. Nagasubramanian et al. J. Power Sources 196 (2011) 8604-8609
G. Nagasubramanian et al. (2013) http://dx.doi.org/10.1016/j.electacta.2012.09.065
Chen, Z. et al. Energy Environ. Sci. 4 (2011) 4023-4030
C. J. Orendorff et al. Adv. Energy Mater (2013) DOI: 10.1002/aenm.201200292

12 Ah (~50 Wh) Overcharge Abuse

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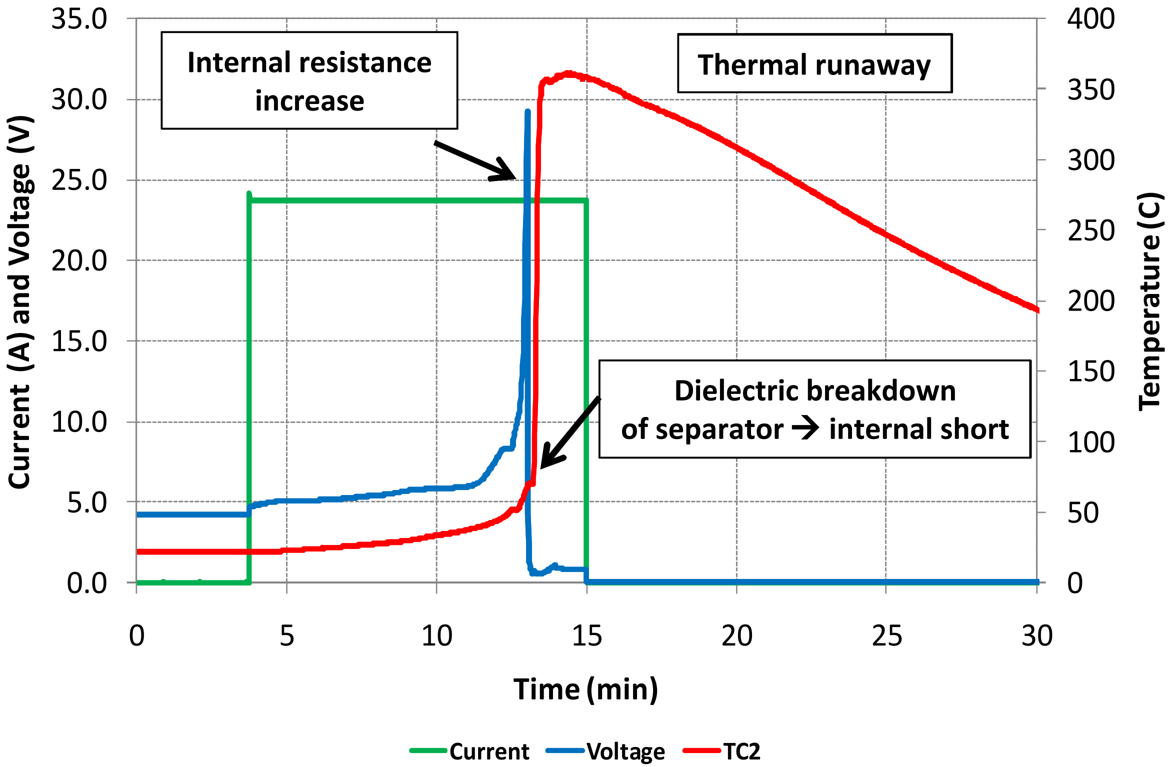


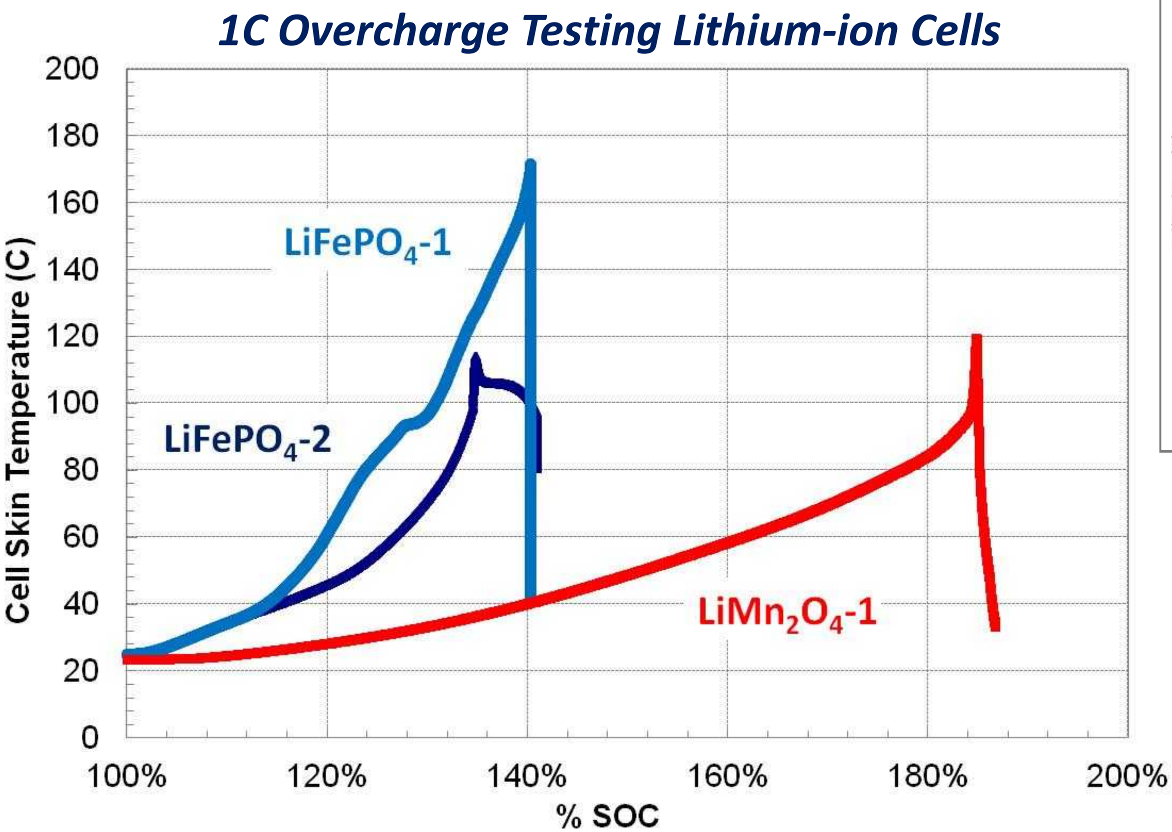
PL-8570170-2C_01 fire.mpg

Internal temperature limited due to ejection of cell contents

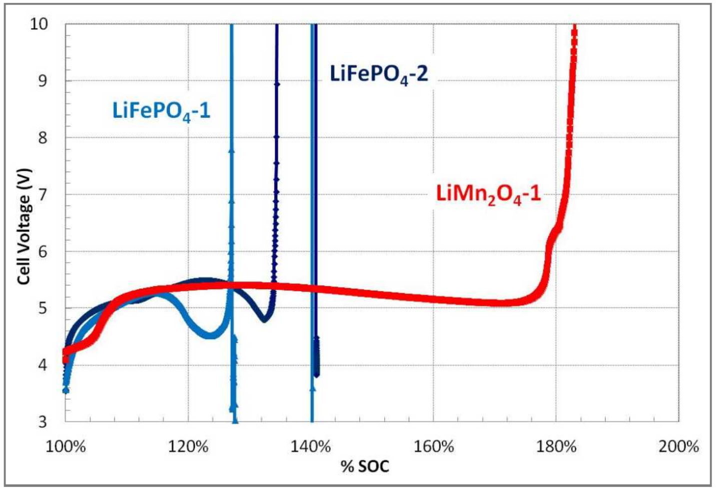
500 Wh battery failure? 5000 Wh battery failure?

Abuse Tolerance Improvements

Overcharge Abuse Tolerance



E.P. Roth, DOE Annual Merit Review 2008



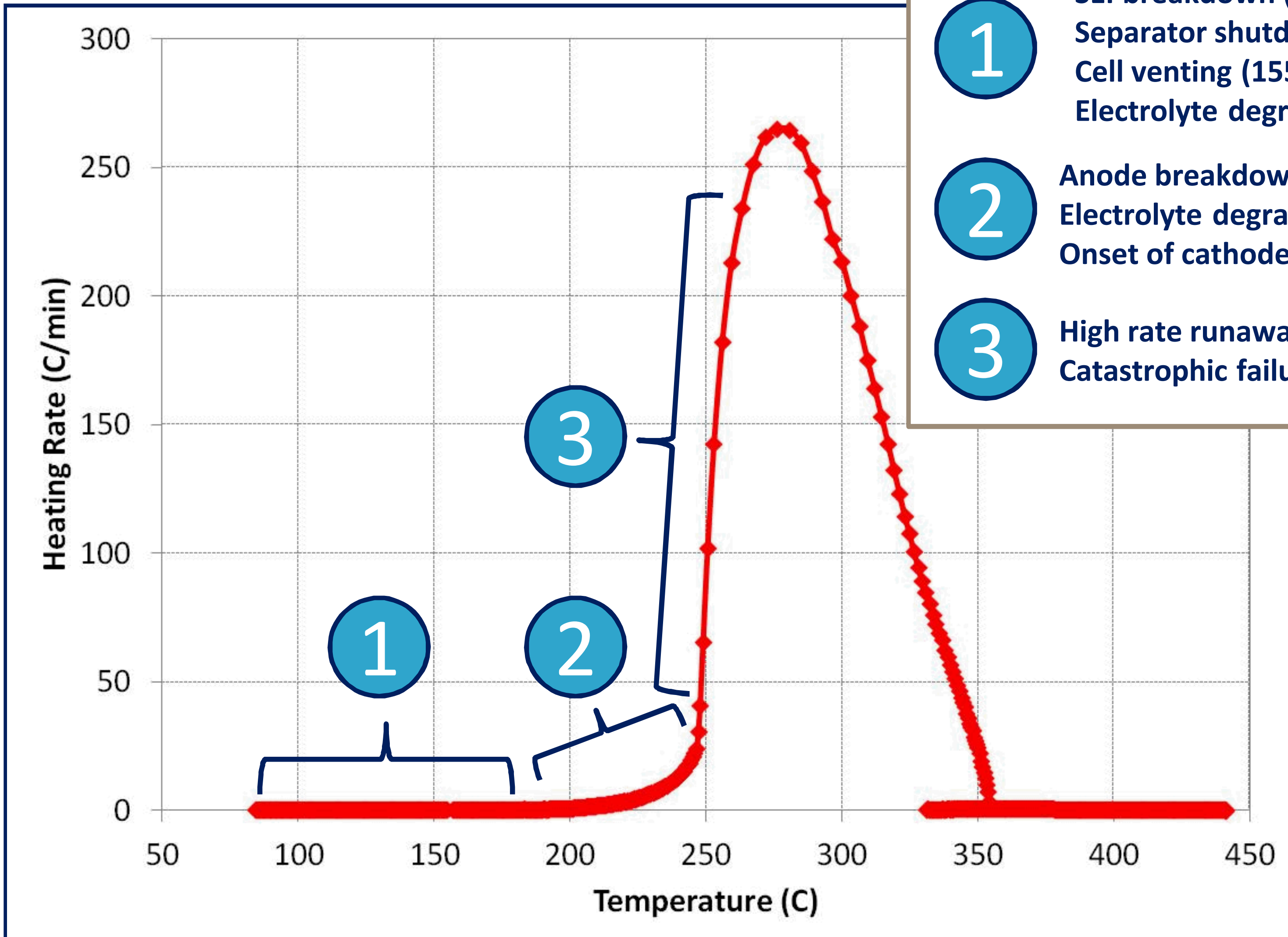
Cathode	x @ 100% SOC	Onset (SOC)
Li_xFePO_4	0	100%
$Li_xMn_2O_4$	0.1	110%
NCA	0.36	125%
NMC (111)	0.48	150%
Li_xCoO_2	0.5	160%

$LiFePO_4$ is inherently intolerant of overcharge because it is completely delithiated at 100%SOC

Energetic Decomposition

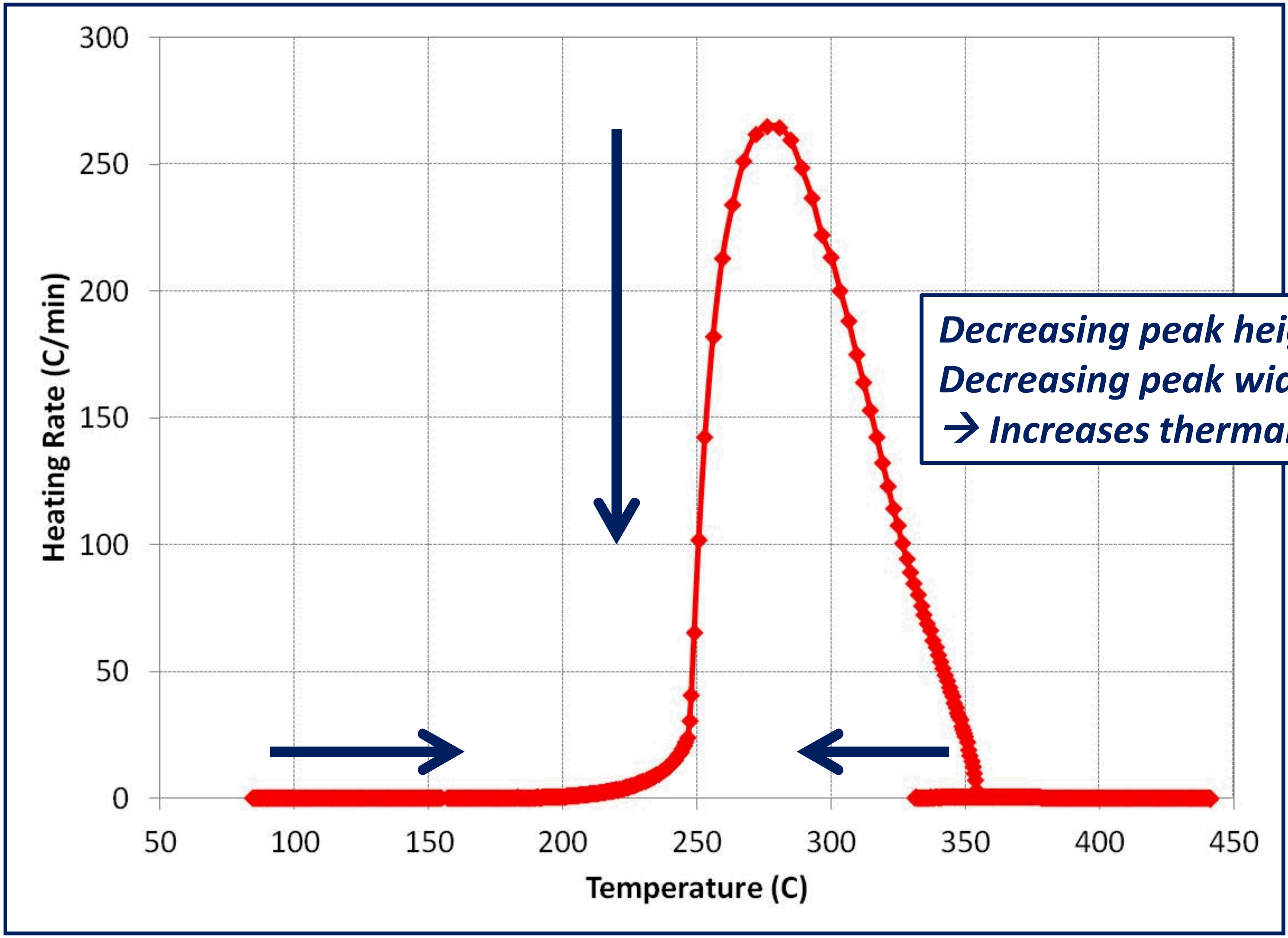
Stages of Lithium-ion Cell Runaway

Accelerating Rate Calorimetry (ARC) of a Li-ion Cell



1. SEI breakdown (70-90 C)
   Separator shutdown
   Cell venting (155-165 C)
   Electrolyte degradation
2. Anode breakdown
   Electrolyte degradation
   Onset of cathode decomposition
3. High rate runaway
   Catastrophic failure

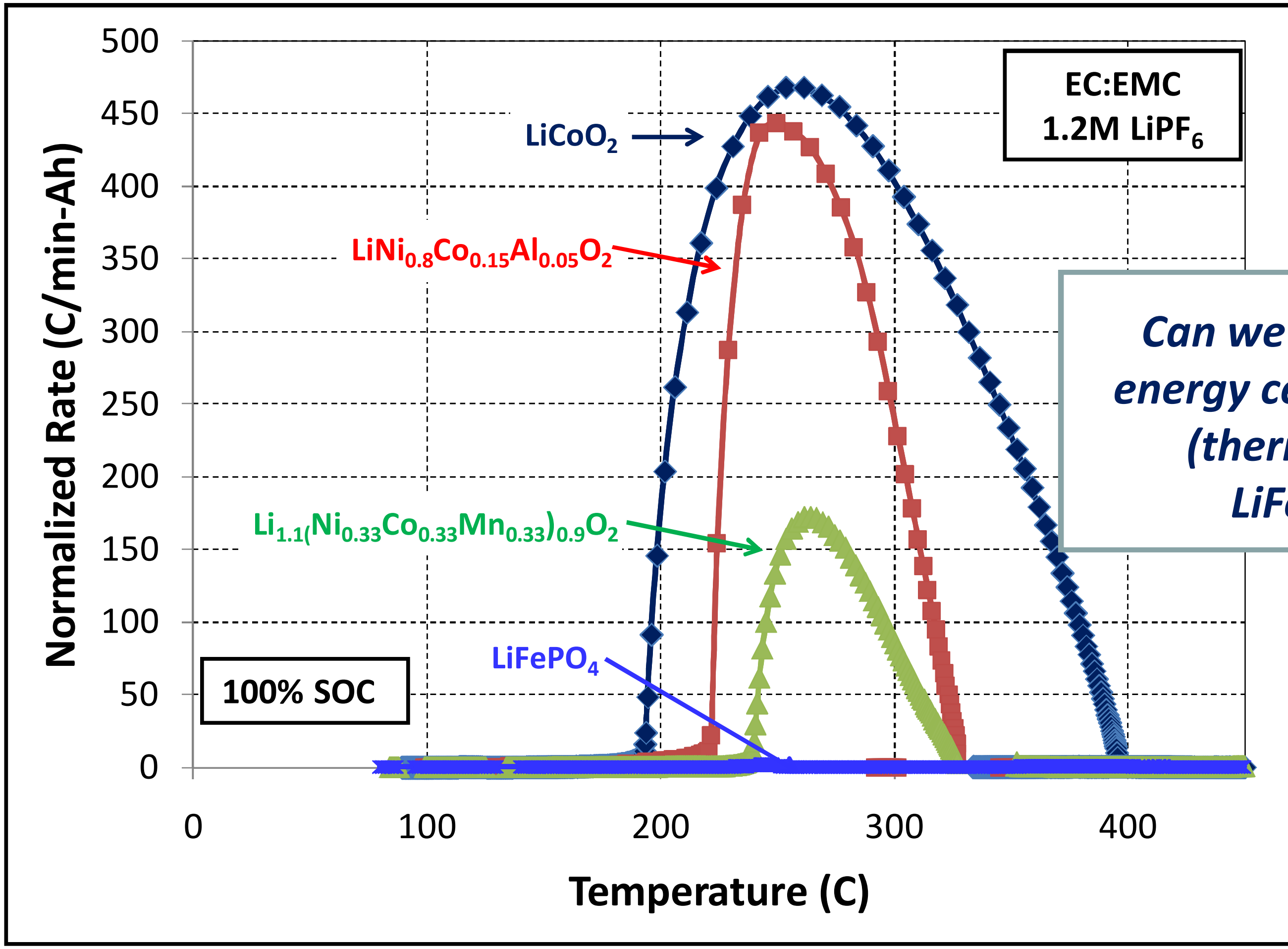
Stages of Lithium-ion Cell Runaway



Decreasing peak height
Decreasing peak width
→ Increases thermal stability

Changing Cathode Chemistry

ARC of cells with different cathode chemistries



Can we have a higher energy cell that behaves (thermally) like a $LiFePO_4$ cell?

Differences in runaway enthalpy and reaction kinetics are related to oxygen release from the cathode and the electrolyte combustion