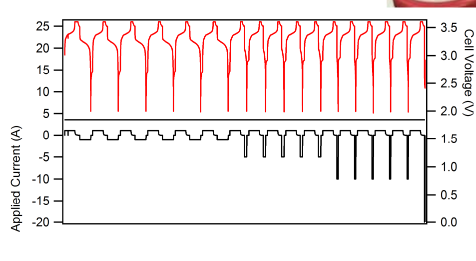
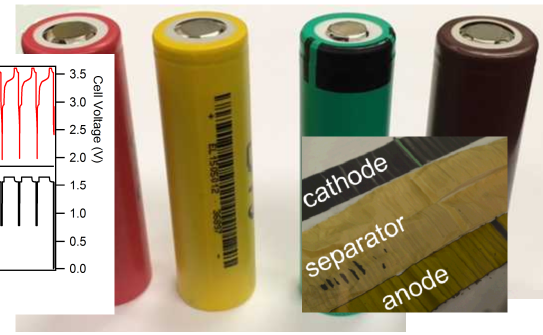
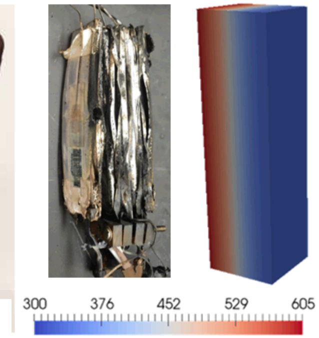
SAND2018-1846C





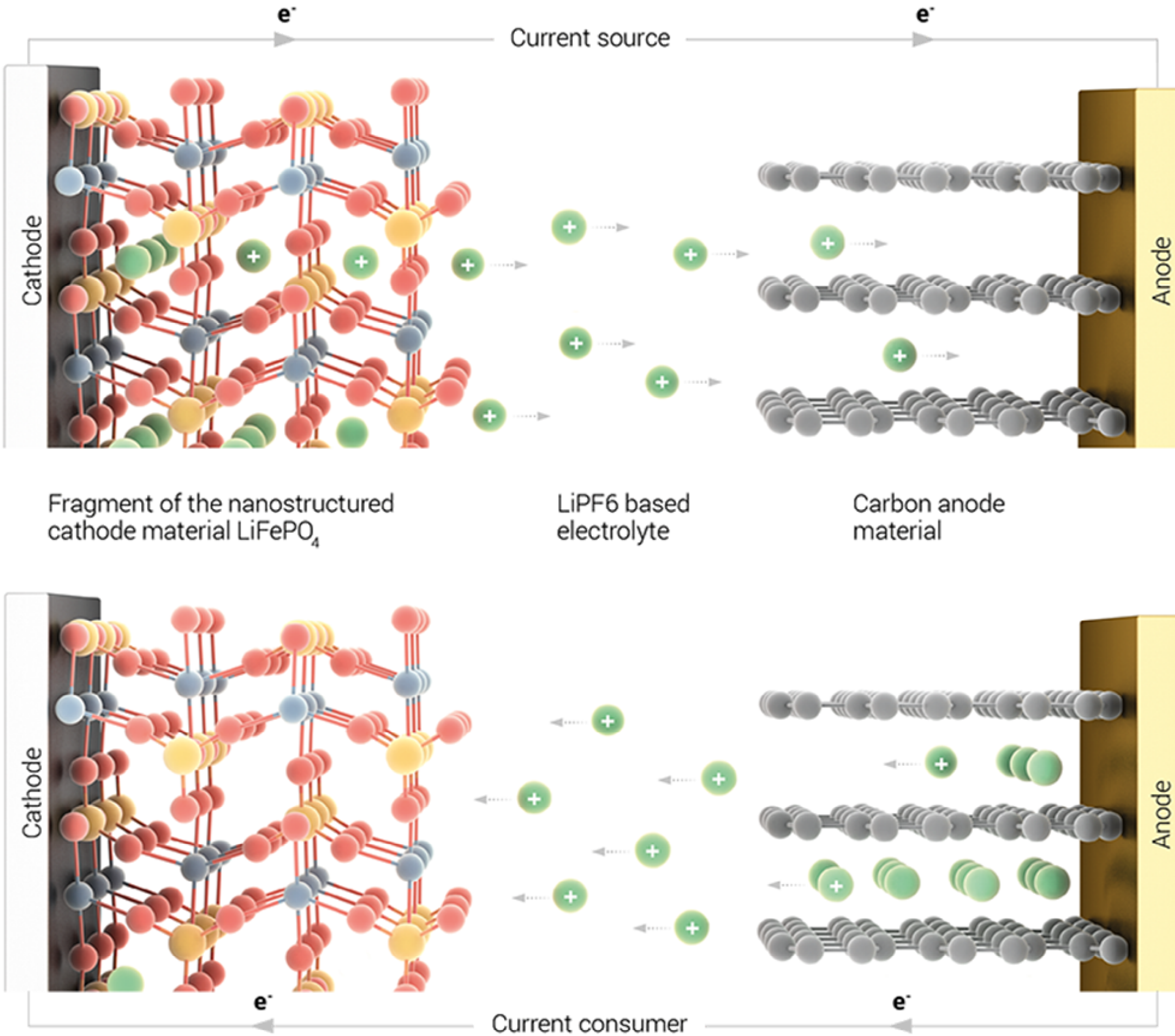


Battery Failure from a Materials, Electrochemical and Thermal Modeling Perspective

Summer Ferreira

Gordon Research Conference - Batteries
February 27, 2018

Lithium ion batteries store energy



Charging

Discharging

http://visual-science.com/projects/lithium-ion-accumulators/infographics

There are many types of lithium-ion batteries

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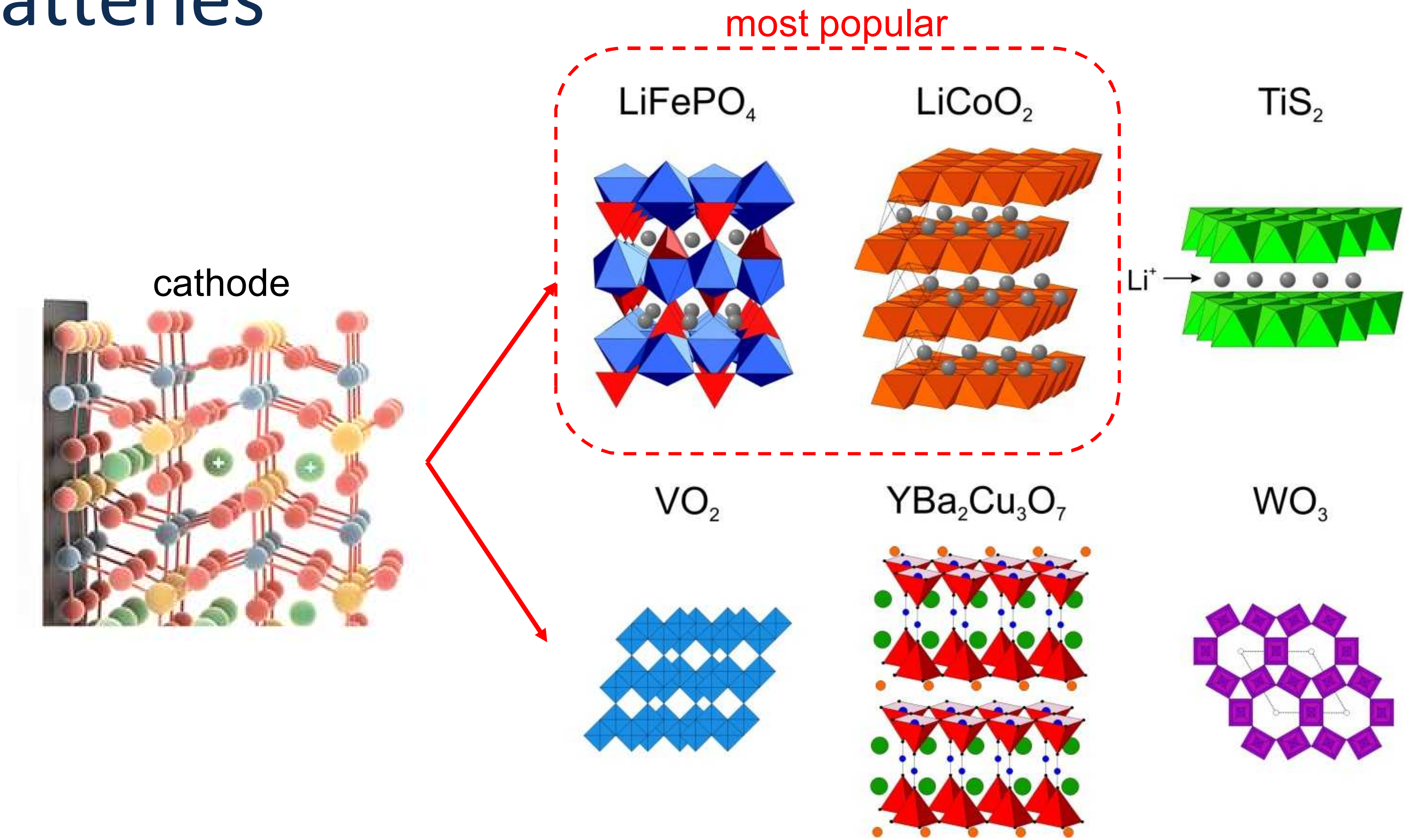
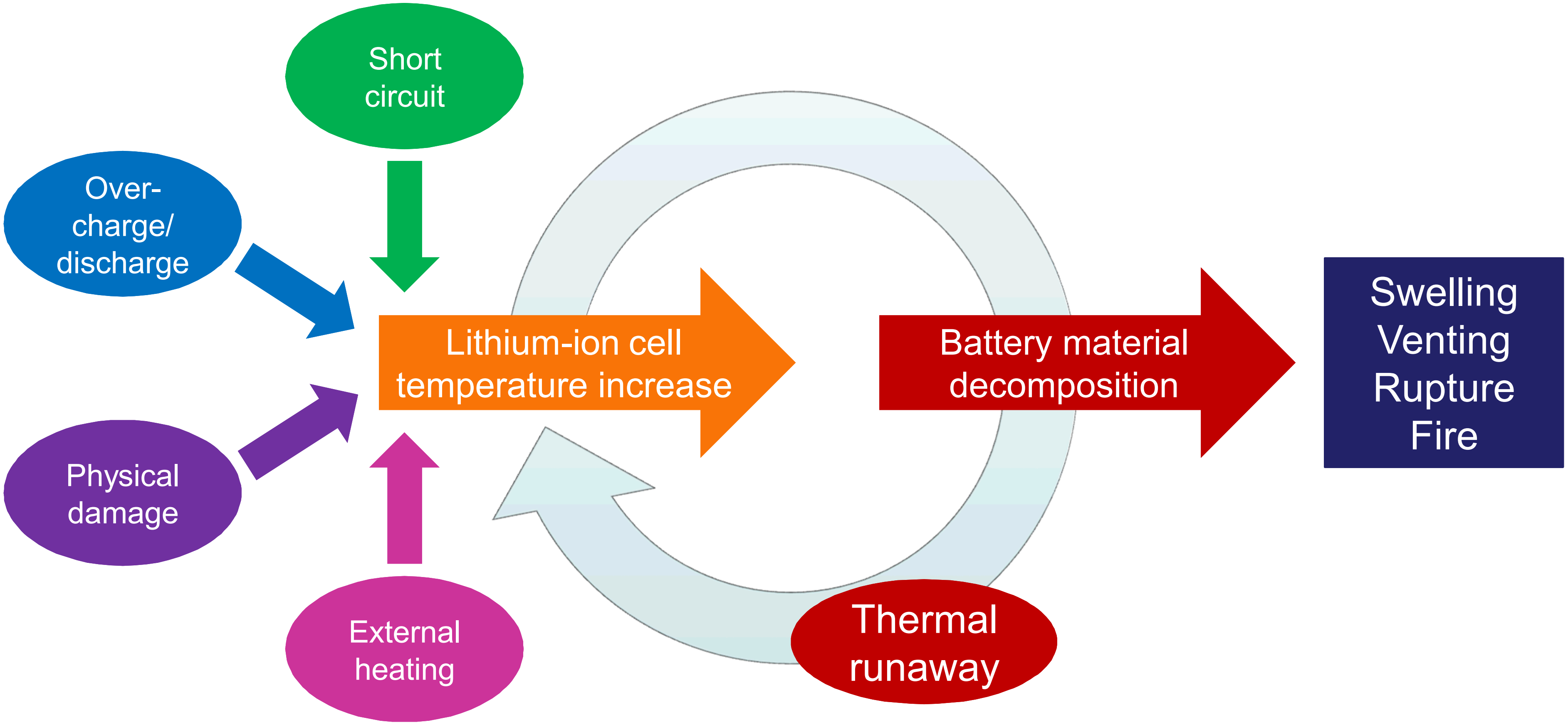


Cathode: http://visual-science.com/projects/lithium-ion-accumulators/infographics; different cathode structures: J. Molenda, M. Molenda "Composite Cathode Materials for Li-ion batteries based on LiFePO4 system" *Meetal, Ceramic and Polymeric Composites for Various Uses* 2011 DOI: 10.5772/21635

Thermal runaway is cascading failure



Impact and consequence of scale on safety

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

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

Safety issues and complexity increase with battery size

Currently urban penetration is stalled


SAFT 10 MWh storage system


US Marine Corps FOB, Afghanistan


Subway regen system, SEPTA


Urban adoption

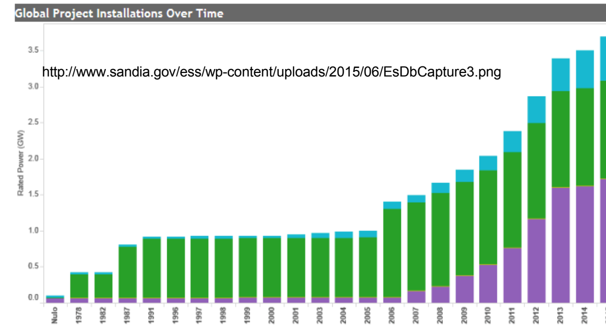
Key Challenges:

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

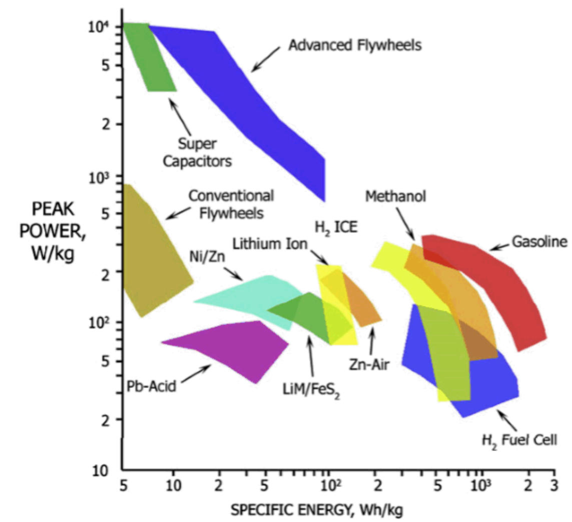
The Grid Energy Storage Safety Challenge

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


Subway regen system, SEPTA




SAFT 10 MWh storage system



Key Challenges:

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

Safety is about reducing risk:

Where risk encompasses consequence and likelihood

https://commons.wikimedia.org/w/index.php?title=User:EvanS

Field failure vs. abuse failure

Field failure

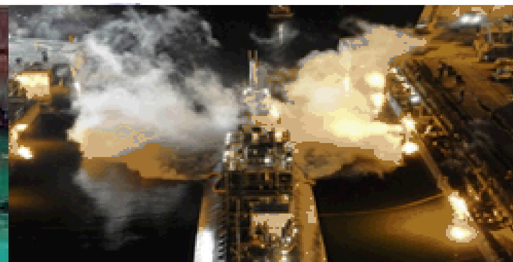
- Random
- Often the result of manufacturing defects that are difficult to predict or recreate
- Historically the greater concern to battery manufacturers

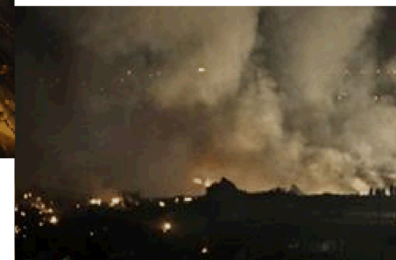
Abuse failure

- 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

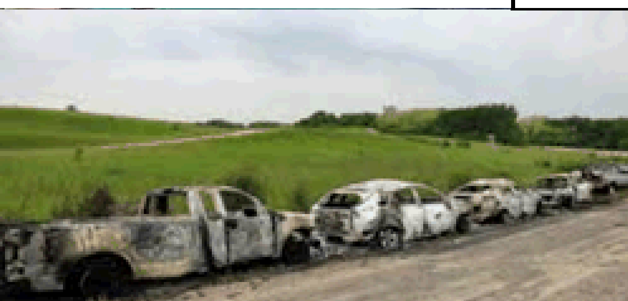
Energy Storage Safety/Reliability Issues Have Impact Across Multiple Application Sectors

2006 Sony/Dell battery recall
4.1 million batteries





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

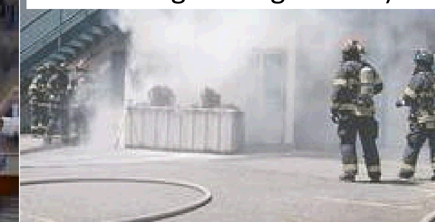


2011 Chevy Volt Latent Battery Fire at DOT/NHTSA Test Facility

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

Improving battery safety

Safety devices and systems

Cell based safety devises, ex: current interrupt devices (CID) to prevent overcharging, positive temperature coefficient to prevent large currents
Circuit control through the battery management system (BMS)
Charging systems designed to prevent overcharge conditions

Development of inherently safe cells

Safer cell chemistries
Non-flammable electrolytes
Higher temperature and shutdown separators
Non-toxic battery materials
Inherent overcharge protection

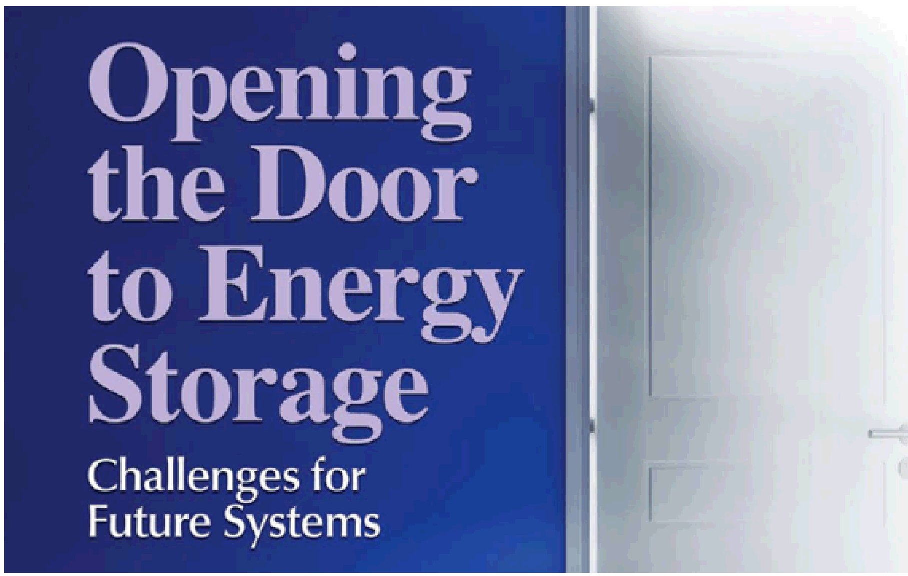
Current Technical Challenges

- 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
- Impact of age on cell failure
  - The effects of cell age on energetic failure events are largely unknown
- Internal short circuits
  - These account for the majority of spontaneous field failures, but are difficult to predict and mitigate. Further, no consensus method exists to replicate these failures in a laboratory.
- 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.

Battery Safety is timely

- Calls for attention to energy storage safety, particularly from a materials science perspective

Latest Issue
September/October 2017



EQ

Energy Quarterly

News and analysis on materials solutions to energy challenges
www.mrs.org/energy-quarterly

Images incorporated to create the energy puzzle concept used under license from Shutterstock.com.

"Manufacturing Li-ion batteries for safety and performance" title image: AllCell Technologies' Phase Change Composite

The role of the materials scientist in battery safety

There has been much negative news in the last few years about the safety of lithium batteries, from the Boeing 787 Dreamliner to hoverboards to the Samsung Note 7 phone. In each of these cases, there were multiple design and/or manufacturing problems in the batteries and control systems, which should have been identified by the manufacturer or upon importation. However, these failures occurred in less than one in a million batteries. Many manufacturers have built-in safety mechanisms. An example is the 17-in. Apple MacBook laptop, which saw many battery failures in the first 12 months. After failure, however, battery control circuits prevented any further use. There were no reported fires or human damage from these.

These problems, including notices in every airport about the Samsung Galaxy Note 7 ban, have made the public skeptical about the safety of lithium batteries. Beyond the general public, firefighters and emergency personnel worry about how to deal with high voltages in crashed electric vehicles: There have been instances of fires in electric vehicles. An upcoming concern is where to place large backup batteries in tall buildings to increase resiliency in the event of storms. The roof is out of the question, as firefighter ladders cannot reach them, and the basement is ruled out because of flooding concerns. The batteries are thus typically placed around the fourth floor, and the surrounding building has to be made fireproof.

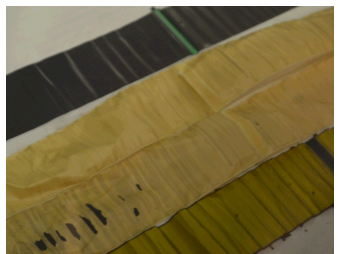
As larger batteries become more popular, in vehicles or for energy storage in buildings, it is important for materials scientists to develop built-in sensors that can identify failures before they become critical and shut down the battery. A temperature sensor may have averted the fast charging of the batteries in the Boeing 787 and perhaps a Tesla car, when the battery was below freezing temperature. It could have stopped the charging from taking place or at least limited the initial current until the cell was warm.

Improving battery failure mitigation

Collaboration: codes, standards, and regulations

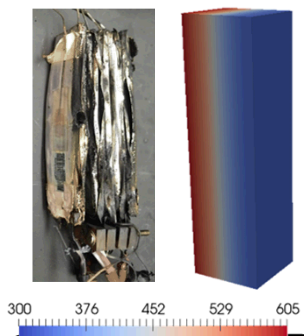
Collaboration: incident response

Baseline electrochemical performance analysis



Materials characterization and thermal stability testing

Electrochemical and whole-cell and string abuse response analysis



Modeling of thermal propagation

Collaboration: vent plume composition (NM Tech)

System selection fraught with uncertainty

Sandia National Laboratories

Problem:

- Cells have application-specific operation and performance
- Chemistry Selection for an ESS installation must consider
  - Cost
  - Size
  - Safety
  - Application
  - Reliability
  - Performance
  - Manufacturer reputation
  - Battery management
- Comparable information on cells from different manufacturers is difficult to ascertain

"Energy Storage Safety Strategic Plan" https://energy.gov/oe/downloads/energy-storage-safety-strategic-plan-december-2014

System selection fraught with uncertainty

Sandia National Laboratories

LG Chem

PRODUCT SPECIFICATION

Description	Document No.	Date	Rev
Lithium Ion LG 18650 HG2 3000mAh	PS-HG2-Rev0	2015-01-28	0

Contents

3/11

11 page document with testing details

Lithium Ion

Panasonic **NCR18650A**

Features & Benefits

- High energy density
- Long stable power and long run time
- Ideal for notebook PCs, boosters, portable devices, etc.

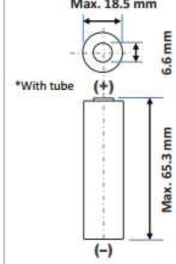
* At temperatures below 10°C, charge at a 0.25C rate.

Specifications

Rated capacity[1]	Min. 2900mAh
Capacity[2]	Min. 2950mAh Typ. 3070mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1475mA, 4.20V, 4.0 hrs
Weight (max.)	47.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density[3]	Volumetric: 620 Wh/l Gravimetric: 225 Wh/kg

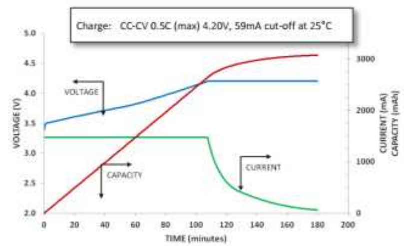
[1] At 20°C [2] At 25°C [3] Energy density based on bare cell dimensions

Dimensions

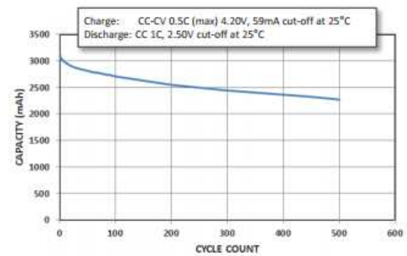


For Reference Only

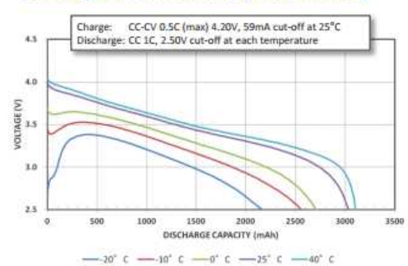
Charge Characteristics



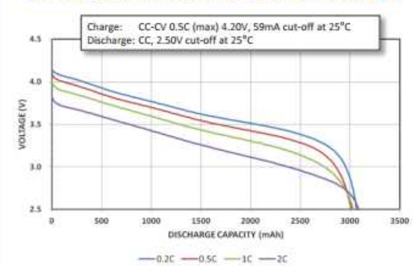
Cycle Life Characteristics



Discharge Characteristics (by temperature)



Discharge Characteristics (by rate of discharge)



The data in this document is for descriptive purposes only and is not intended to make or imply any guarantee or warranty.

Operating ranges and some data

(1) http://www.batteryspace.com/prod-specs/8427_specification.pdf (2) http://www.batteryspace.com/prod-specs/9989.specs.pdf

System selection fraught with uncertainty

Sandia National Laboratories

Problem:

- Cells have application-specific operation and performance
- Chemistry Selection for an ESS installation must consider
  - Cost
  - Size
  - Safety
  - Application
  - Reliability
  - Oversizing
  - Manufacturer reputation
  - Performance
  - Pack management
- Comparable information on cells from different manufacturers is difficult to ascertain

Approach:

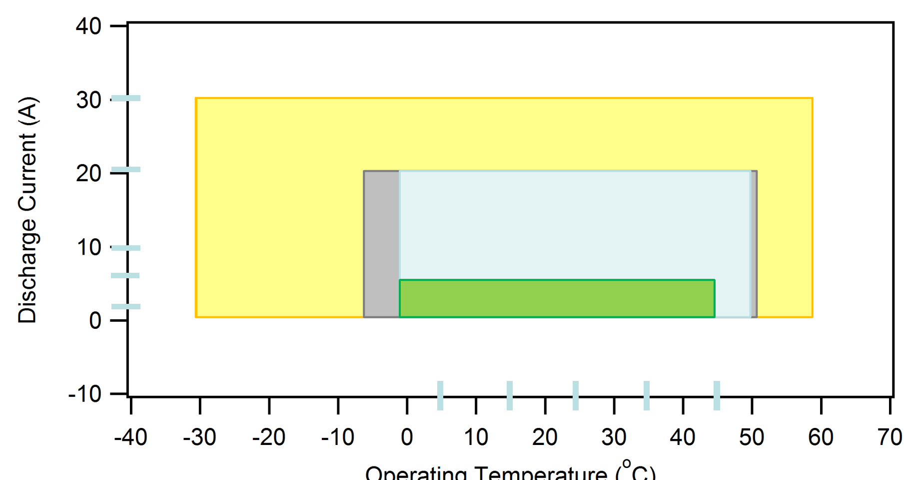
- Quantify performance with uniform methodology
- Find effects of compounding operation conditions
- Identify unintended abuse or aging conditions
- Extrapolate results to long-term cell safety and reliability

“Energy Storage Safety Strategic Plan” https://energy.gov/oe/downloads/energy-storage-safety-strategic-plan-december-2014

Cell operation constraints

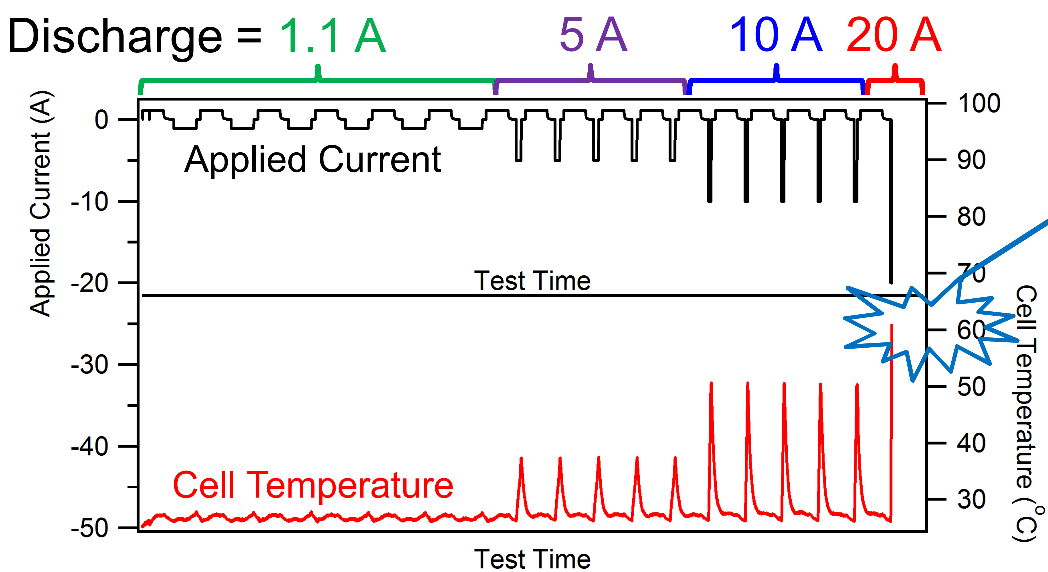
Cathode Chemistry	AKA	Specific Capacity (Ah)	Average Potential (V vs Li°/Li+)	Max Discharge Current	Acceptable Temperature (°C)
[redacted]					
$LiFePO_4$	LFP	1.1	3.3	30	-30 to 60
[redacted]					
$LiNi_{0.80}Mn_{0.15}Co_{0.05}O_2$	NMC	3.0	3.6	20	-5 to 50

LCO LFP NCA NMC



Avoiding accelerated aging or abuse

LFP, 25 °C environment



Current = 20 A (max = 30 A)
Environment = 25 °C
Cell skin Temp = 60 °C!!!

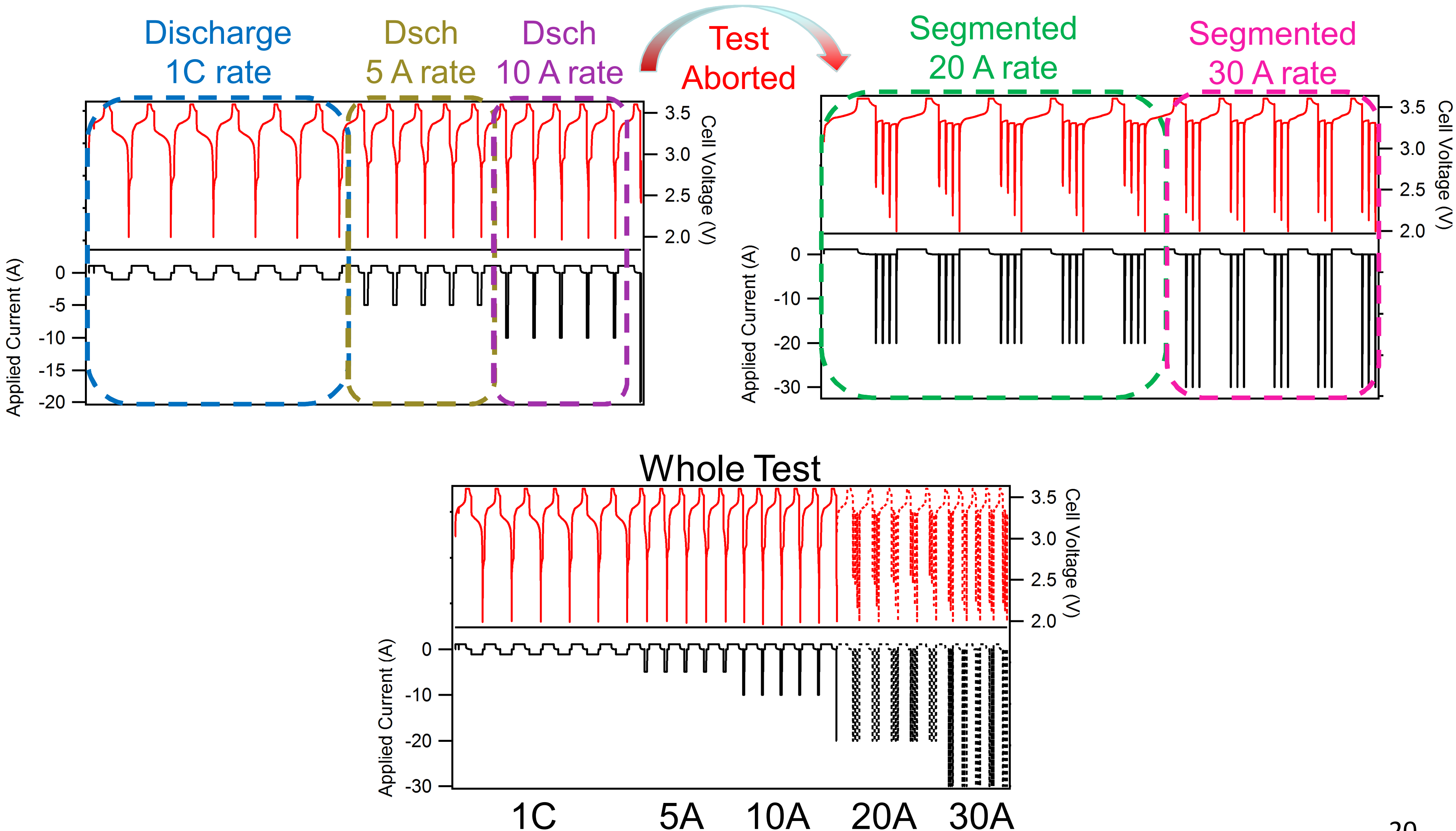
Most packs don't monitor individual cell skin temperatures.

Unintended abuse condition under 'normal' operation.

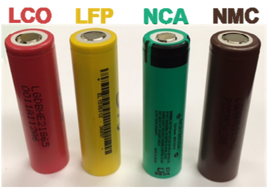
Pristine Cell

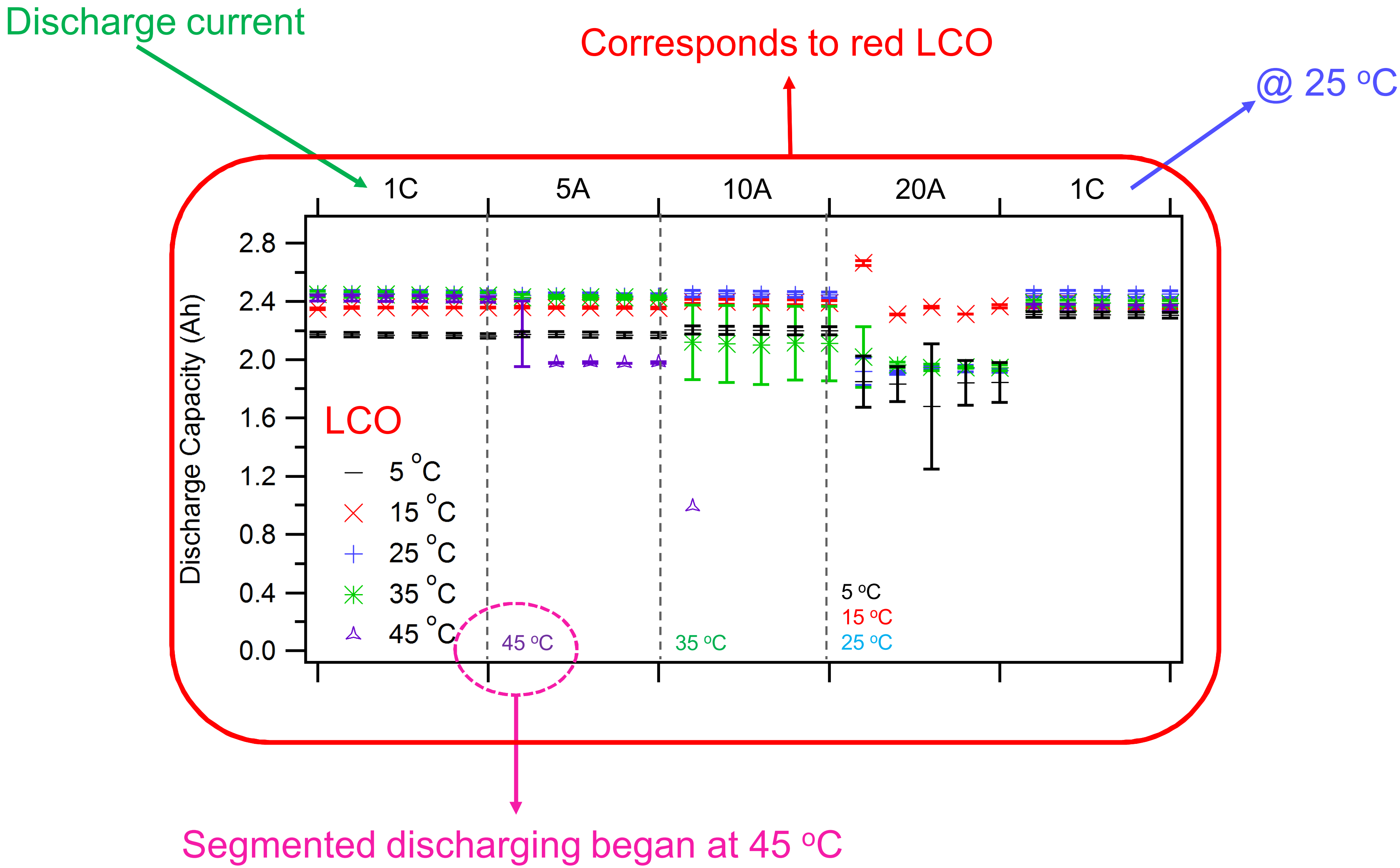
Abused Cell

Evaluating cell chemistries uniformly



Cycling data for each chemistry is coalesced on one plot

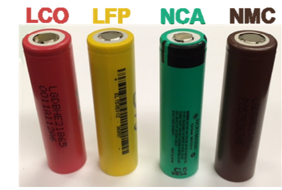


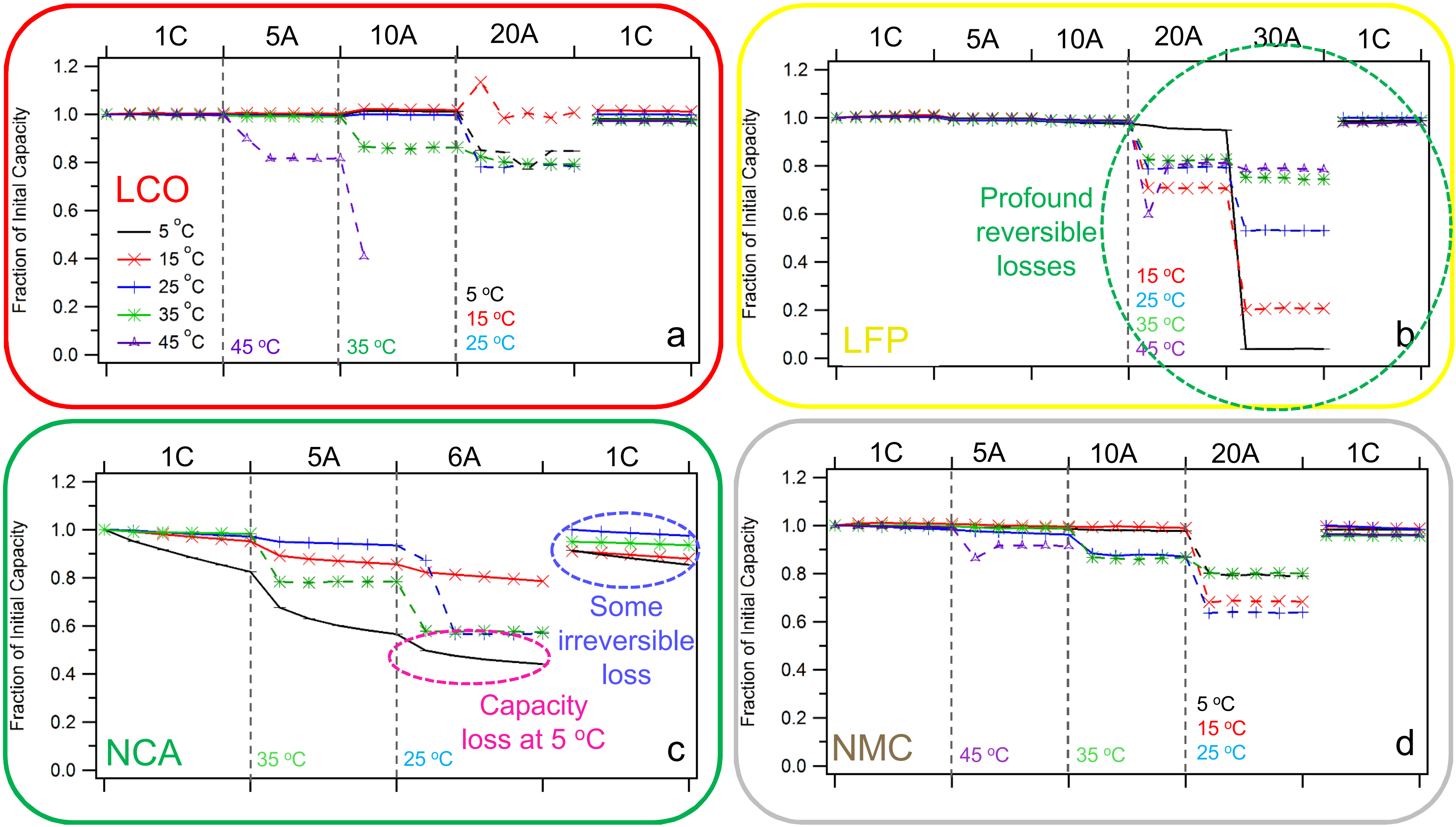


http://www.sandia.gov/energystoragesafety/research-development/research-data-repository/

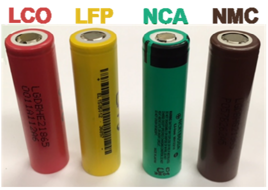
doi: 10.1149/2.1701712jes *J. Electrochem. Soc. 2017 volume 164, issue 12, A2697-A2706*

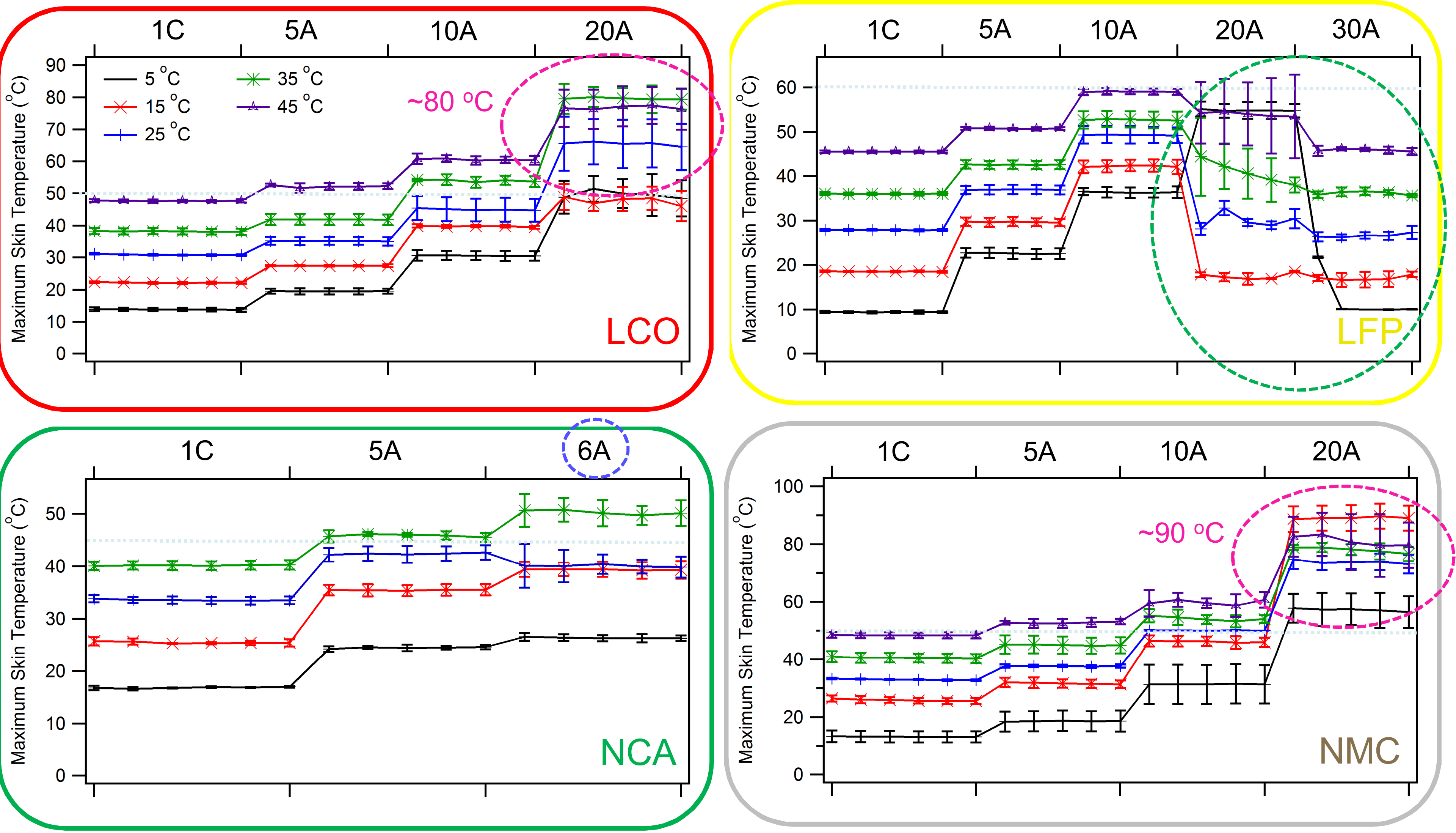
NCA experiences lasting capacity losses after cycling





Significant self-heating can occur if cells are unmonitored



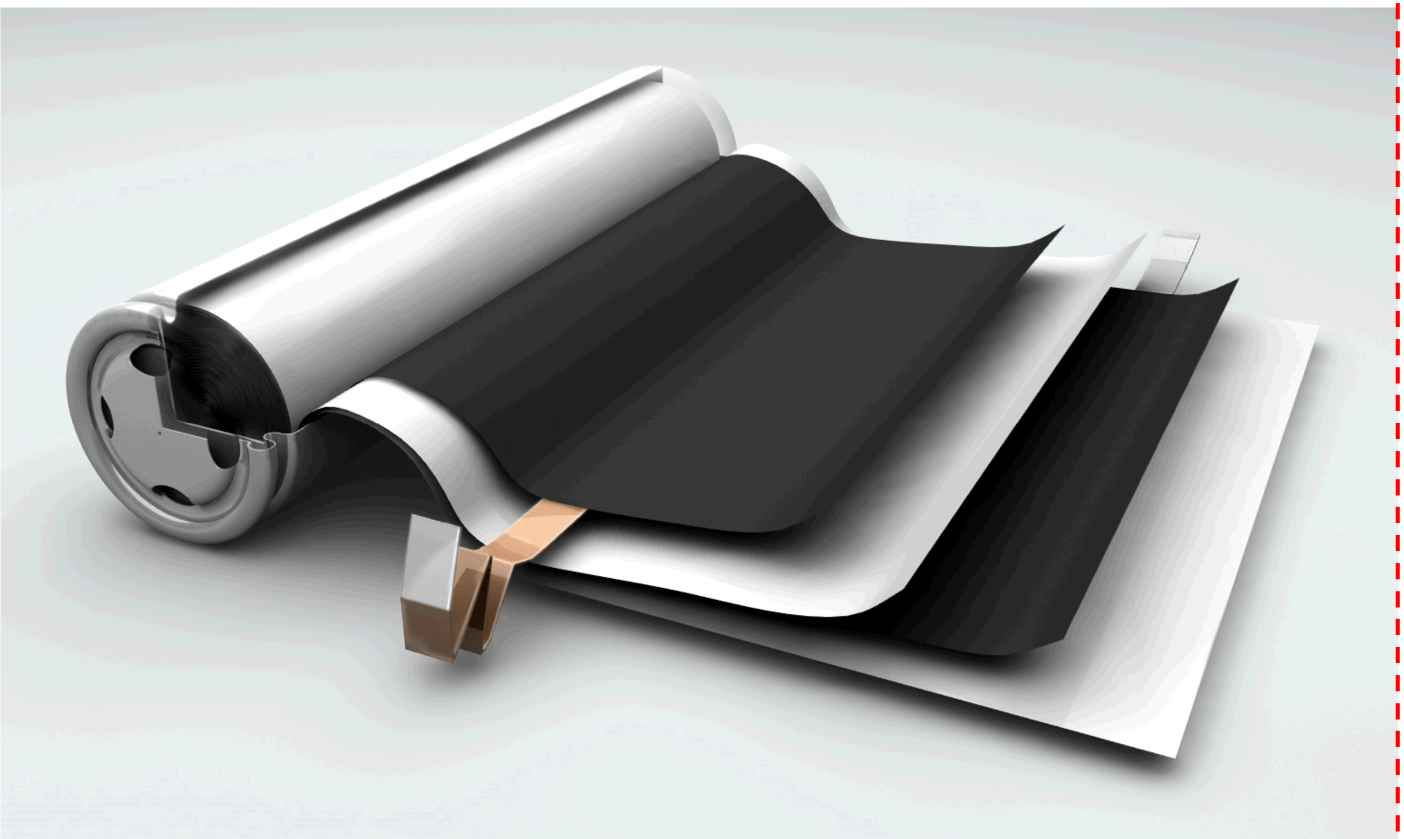


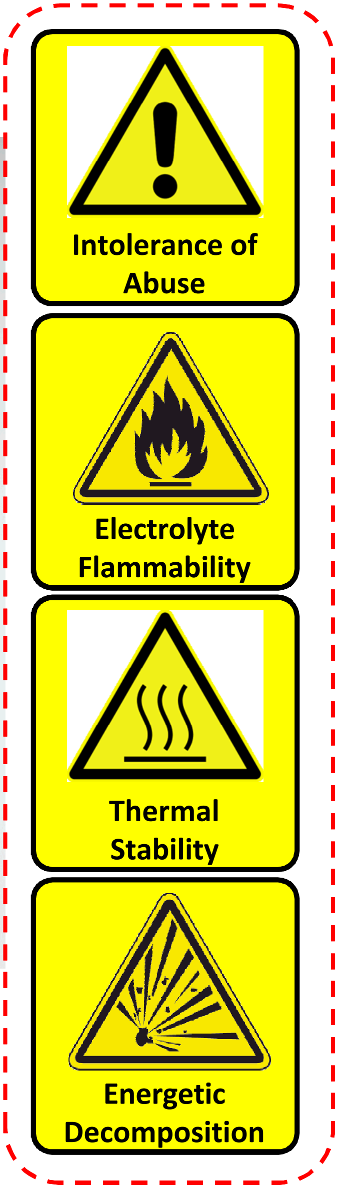
Cells are highly application-specific

- Parameters such as energy density and cost per capacity can not solely be used to choose a cell
- Operating conditions combine to produce unintended abuse and accelerated aging
- NCA experiences aging, likely from Li plating at low temperatures
- Small losses quantified here can be extrapolated to rapid cell death
- This work should be continued to include other relevant chemistries and cell formats

LCO LFP NCA NMC

Challenges with lithium-ion battery safety



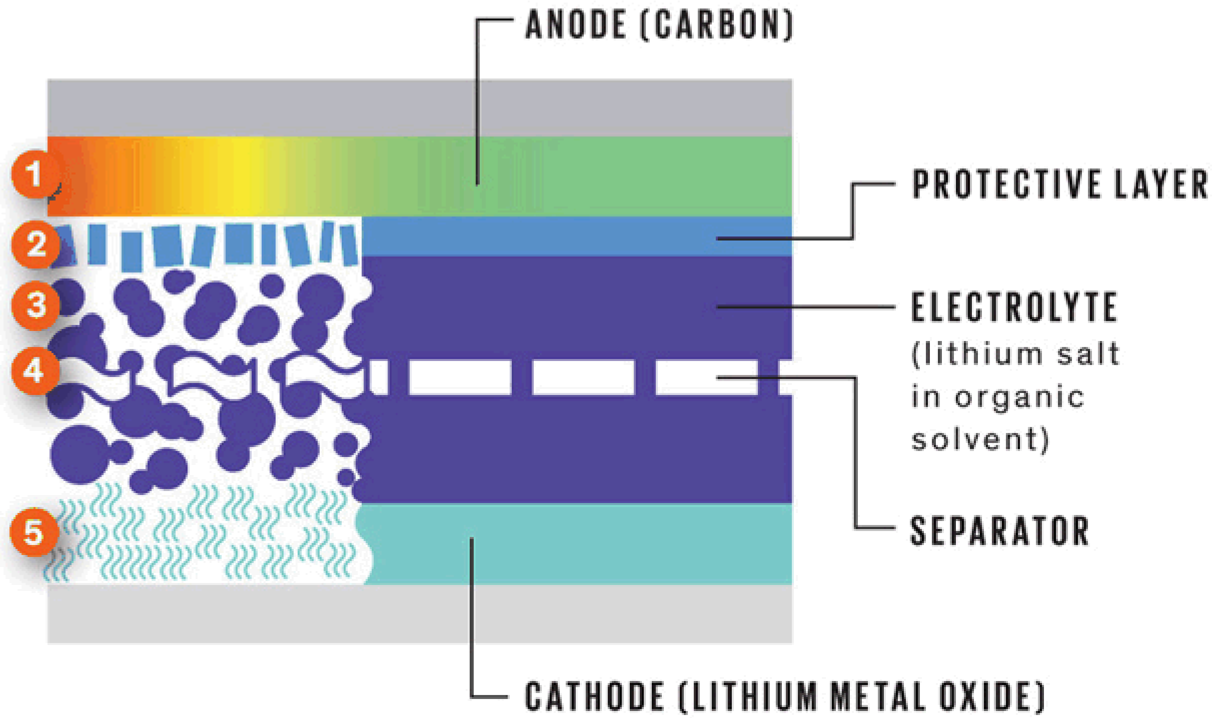


If we can figure out where issues are coming from, we can design better batteries

Cell materials are responsible for thermal runaway behaviors

Thermal Runaway in a Lithium-Ion Battery

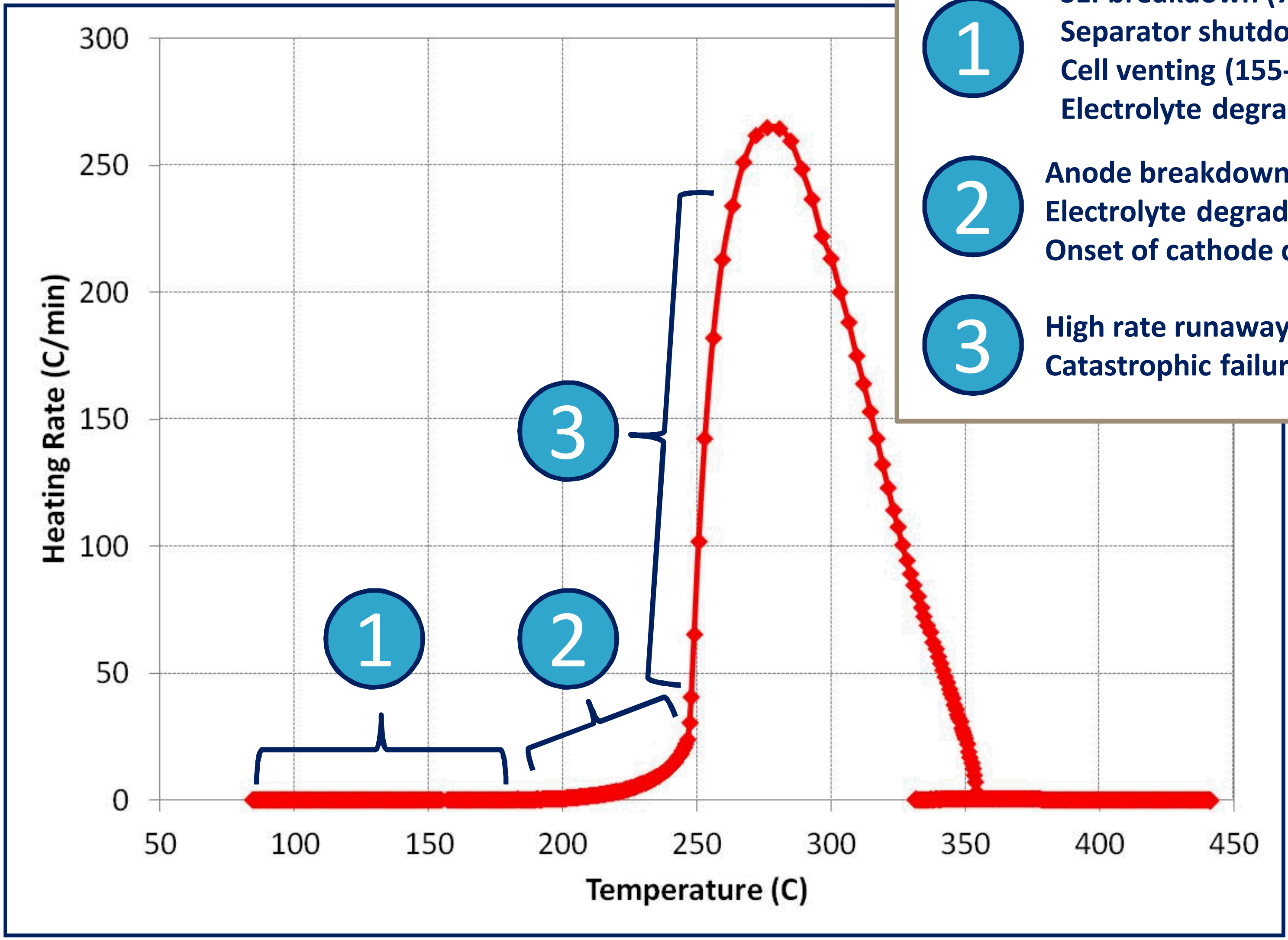
1. Heating starts.
2. Protective layer breaks down.
3. Electrolyte breaks down into flammable gases.
4. Separator melts, possibly causing a short circuit.
5. Cathode breaks down, generating oxygen.



https://www.extremetech.com/extreme/208888-doping-lithium-ion-batteries-could-prevent-overheating-and-explosion

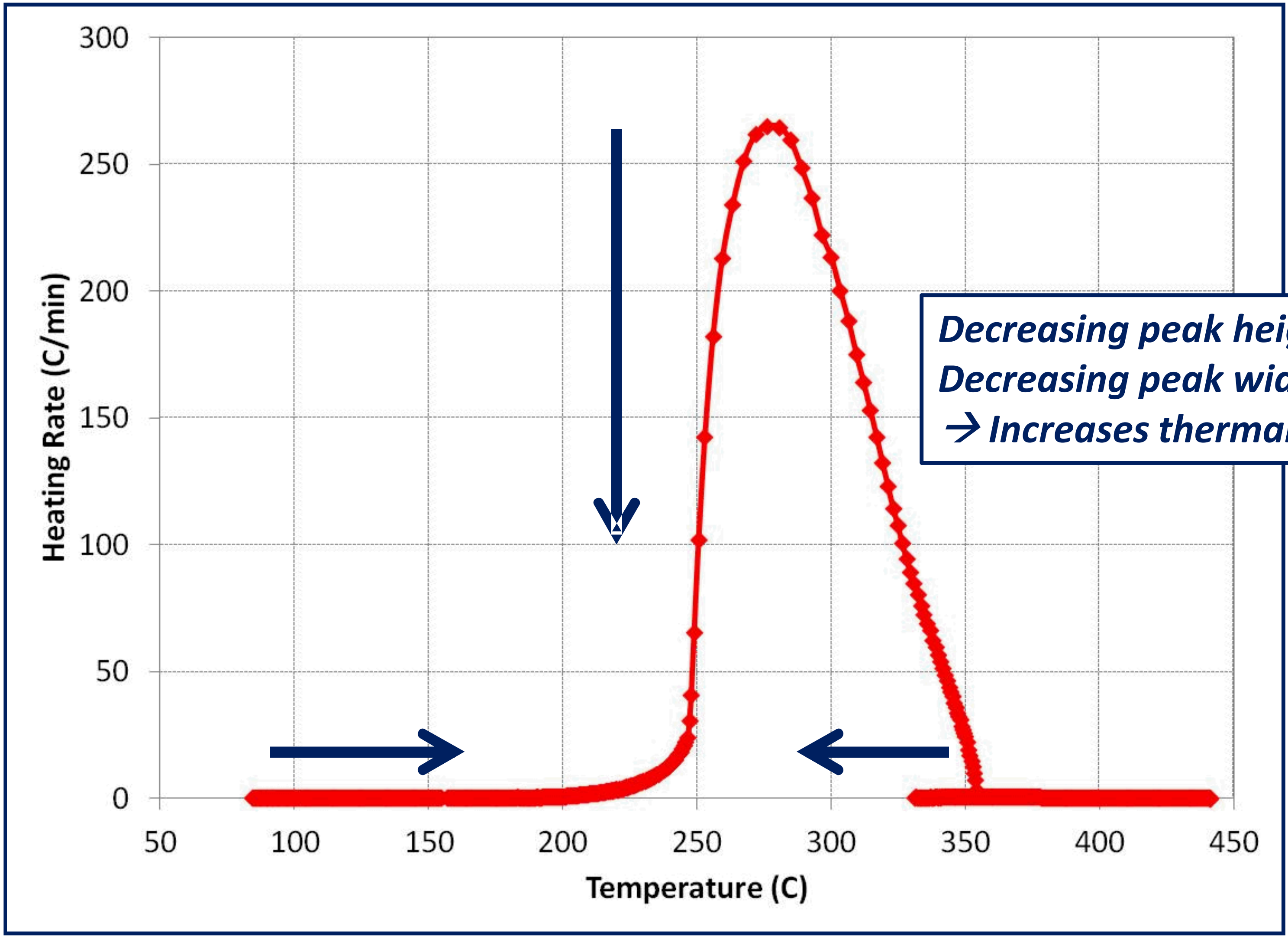
Stages of Lithium-ion Cell Runaway

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

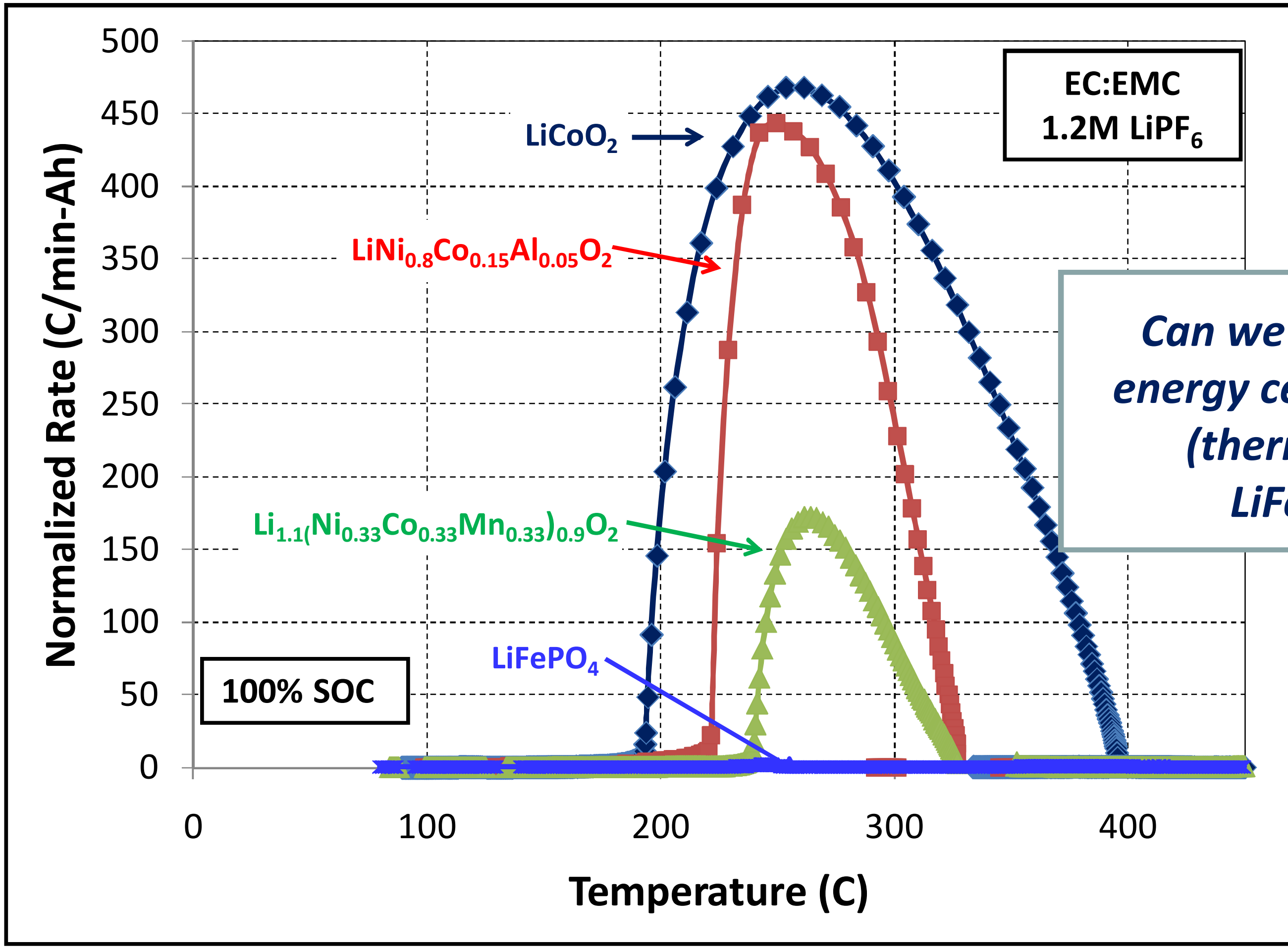
Stages of Lithium-ion Cell Runaway



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?

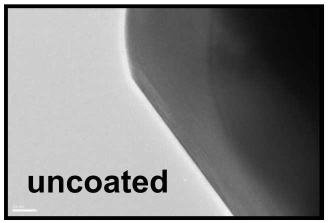
Differences in runaway enthalpy and reaction kinetics are related to oxygen release from the cathode and the electrolyte combustion

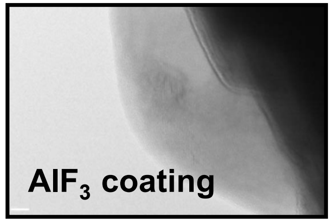
Coating Active Materials

Sandia National Laboratories

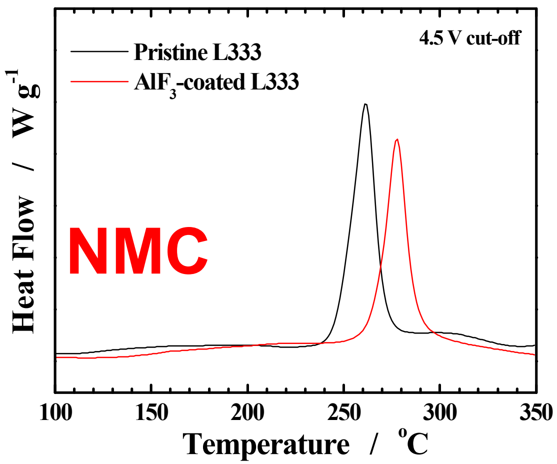
Collaboration with Khalil Amine and Zonghai Chen (ANL)

Inert coatings are used to stabilize the surface of active materials

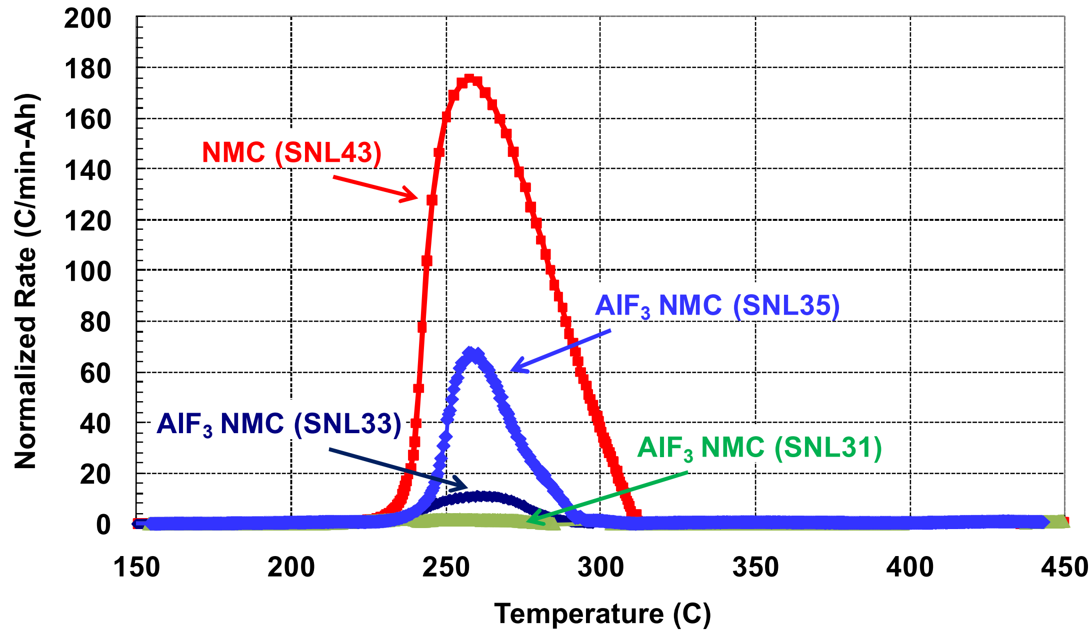




Cathode DSC

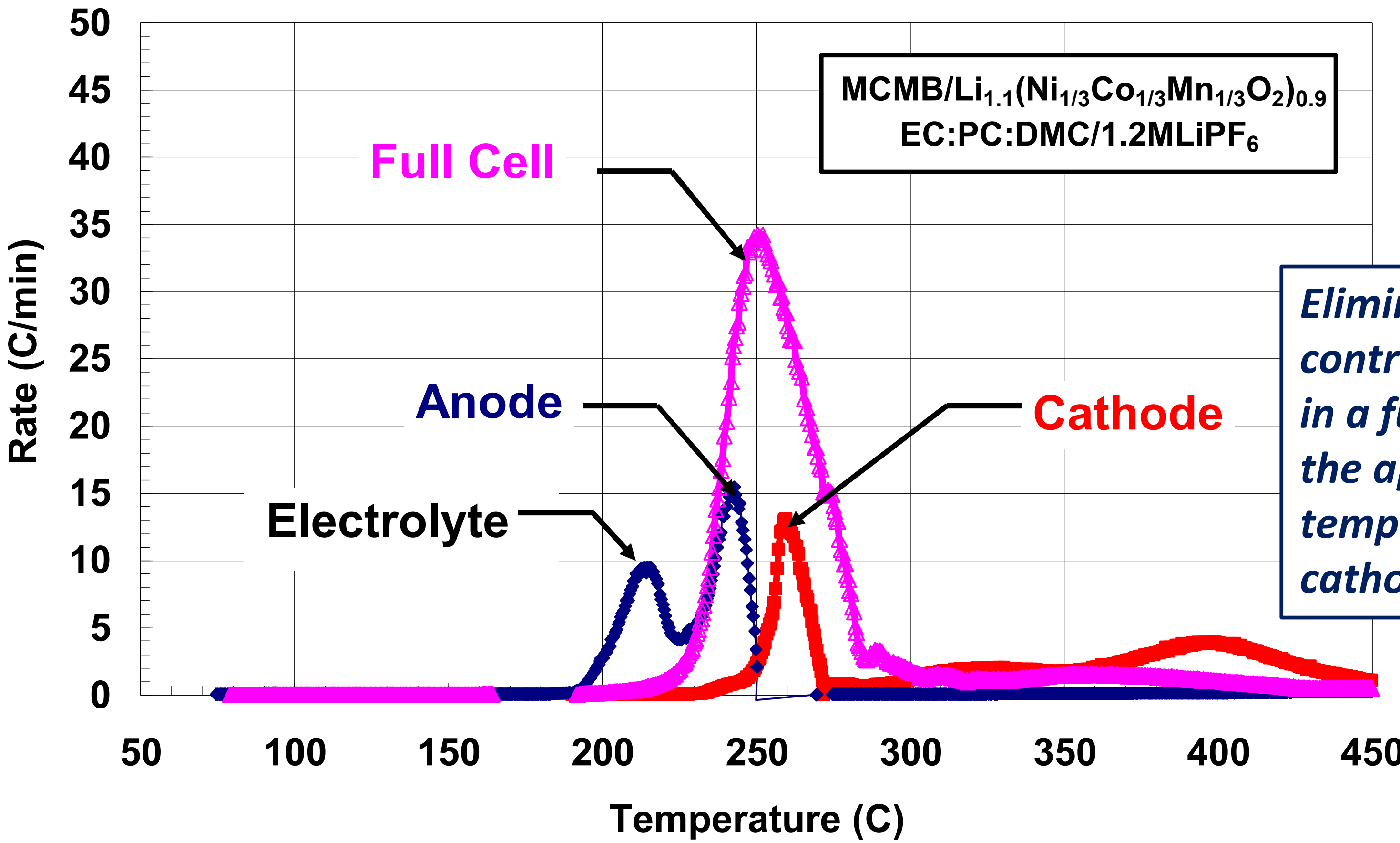


Cell ARC



Reduction in NMC cell runaway kinetics with 2% (wt) AlF_3 coatings

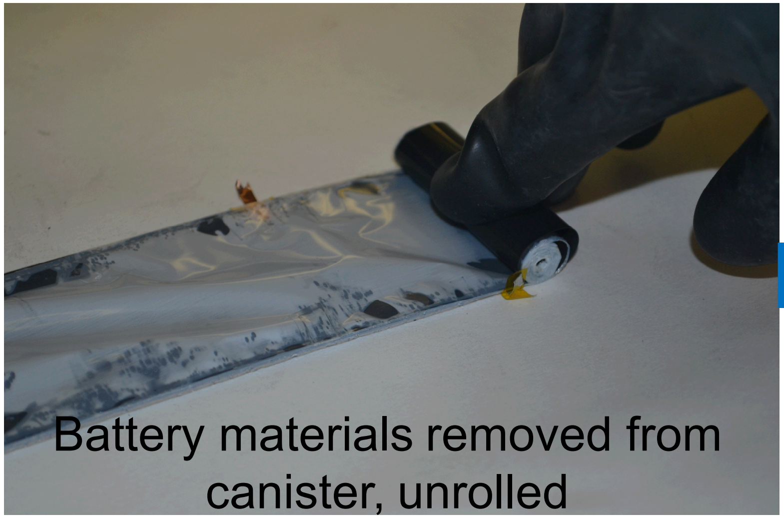
Anode and Cathode Runaway



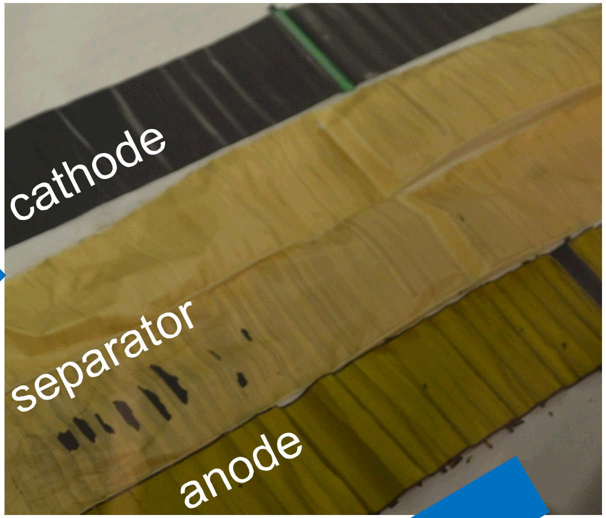
Eliminating the anode contribution to runaway in a full cell increases the apparent onset temperature for cathode runaway

Results are consistent with stabilized anode response to thermal runaway when alumina coated by ALD

Batteries are disassembled to reveal steps of failure

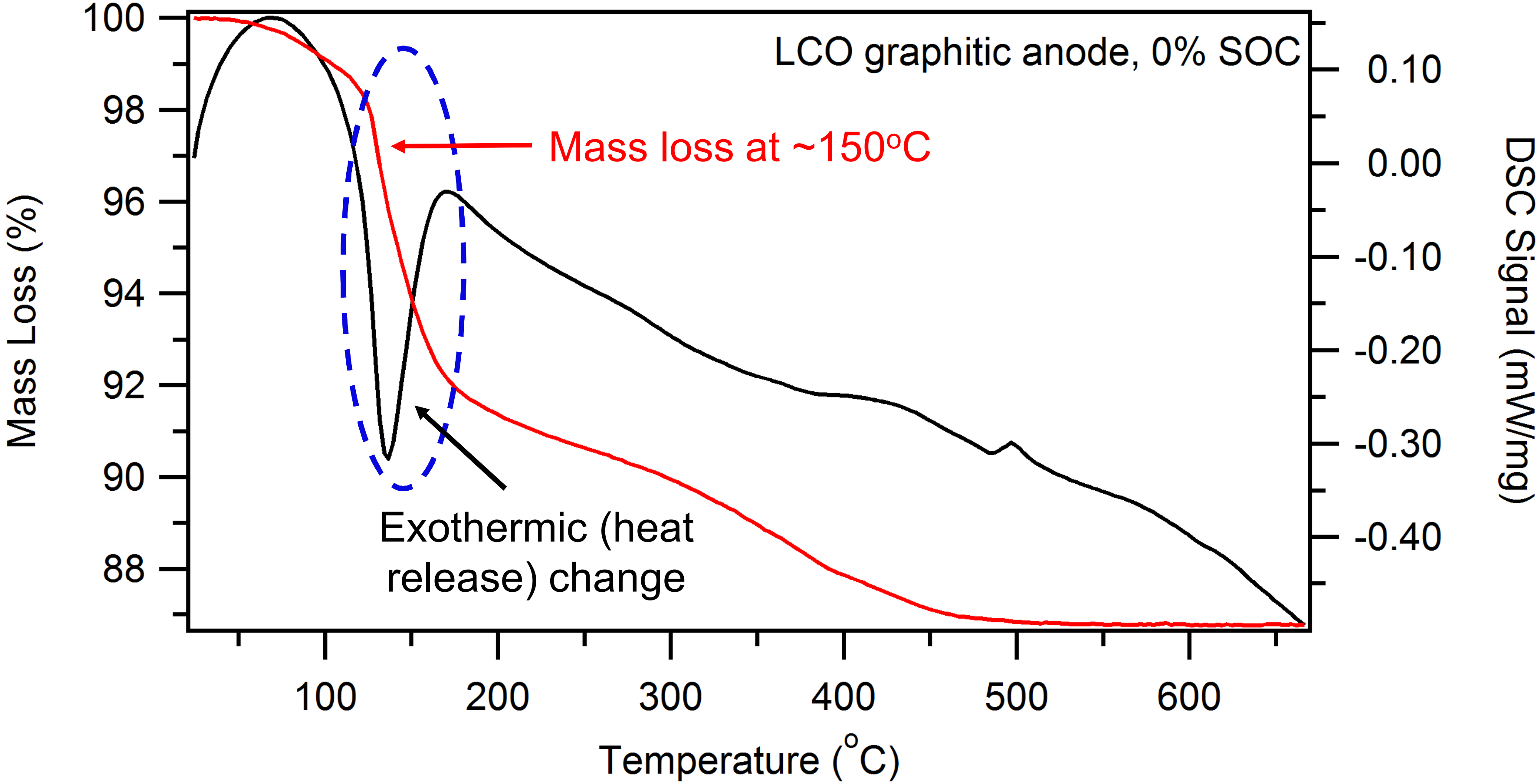

Battery materials removed from canister, unrolled

Disassembly



Temperature-resolved XRD shows how the material changes with temperature

TGA/DSC reveals thermal stability

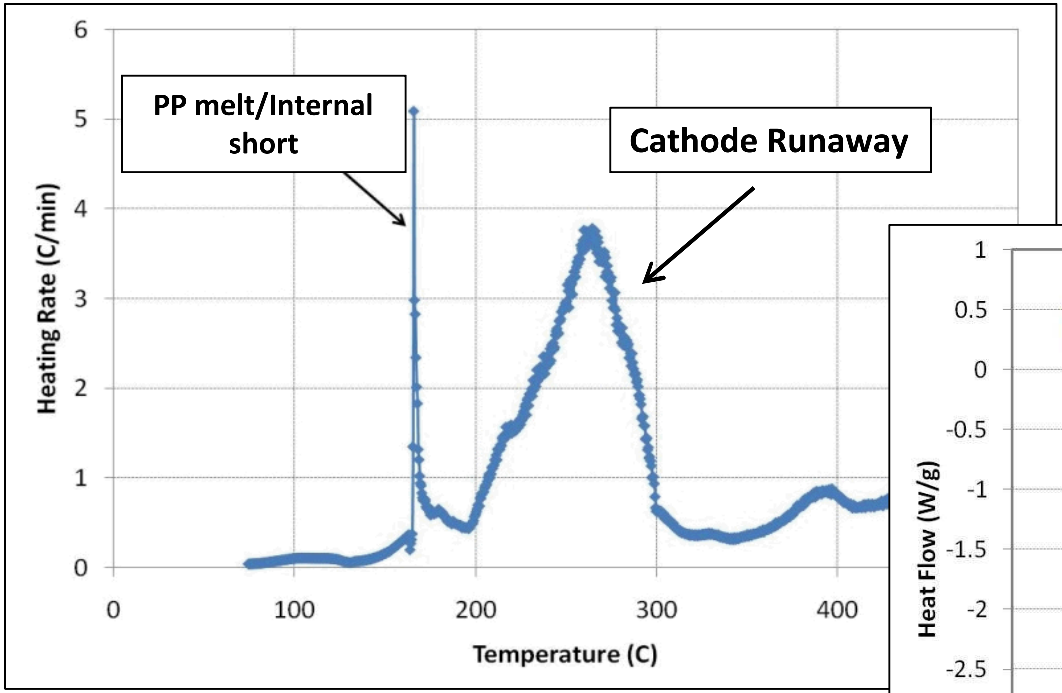


We have learned that the anode loses mass at 150°C and this also releases heat

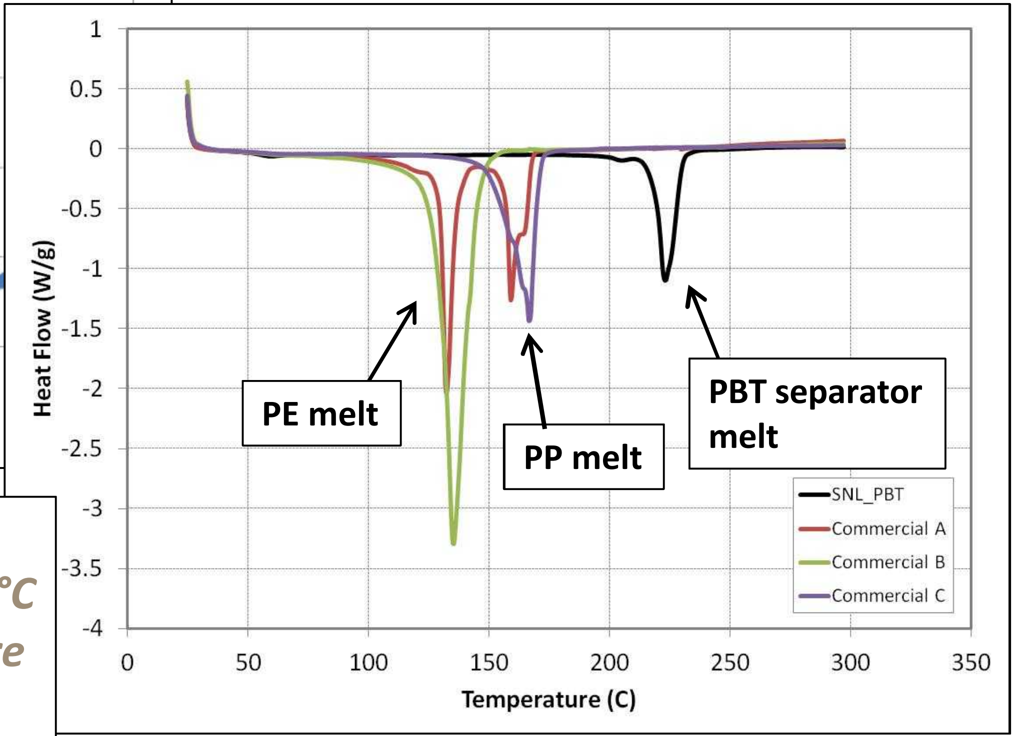
Advanced Separator Materials

Closing the gap between separator phase transition and cathode runaway temperature

Cell ARC



Separator DSC



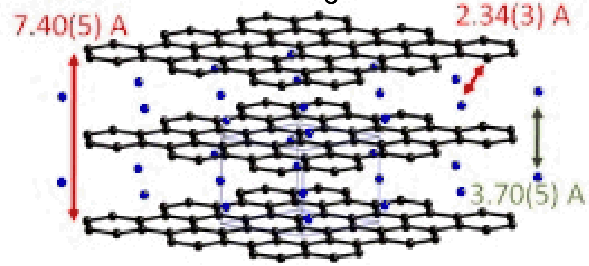
- *PE and PP melt between 135 and 160 °C*
- *Cathode runaway between 190 and 240 °C*
- *Should target higher melting temperature separators to improve cell stability*

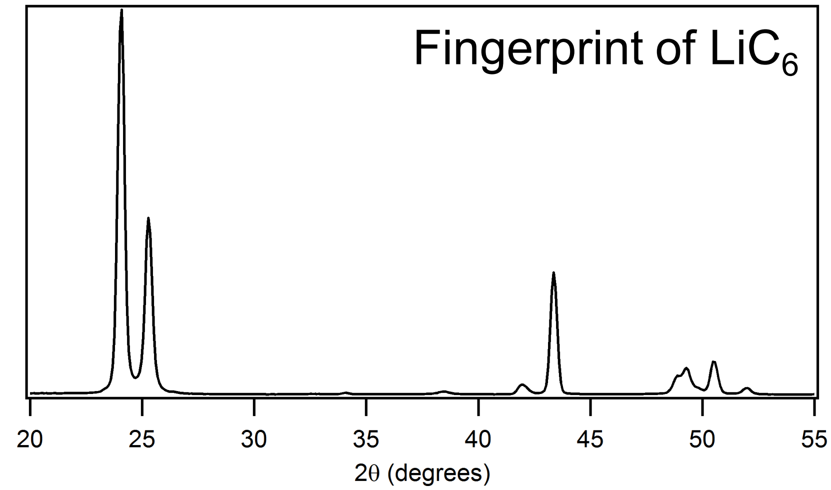
C. J. Orendorff et al. Adv. Energy Mater (2013) DOI: 10.1002/aenm.201200292

Temperature-resolved XRD exposes decomposing structure

X-ray

LiC_6

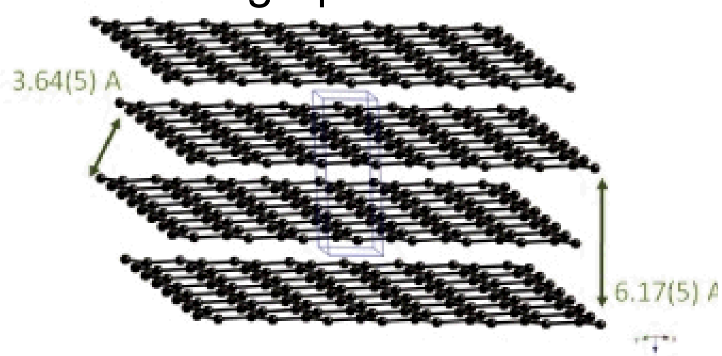


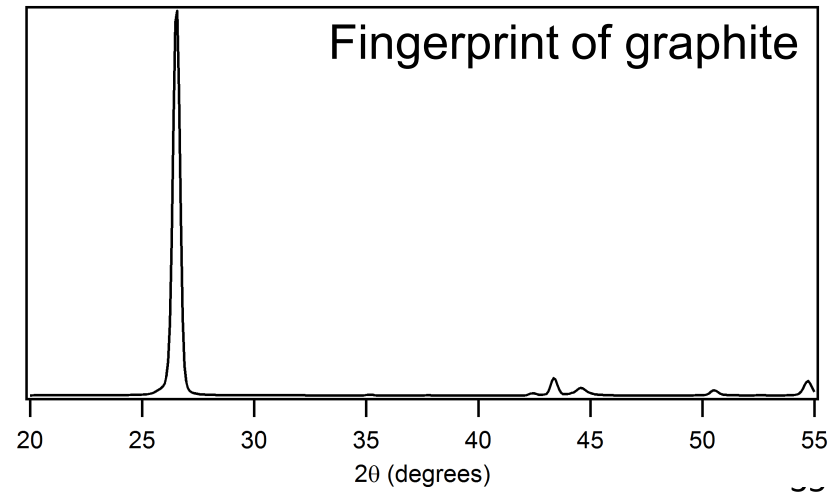


heat the battery

graphite

X-ray

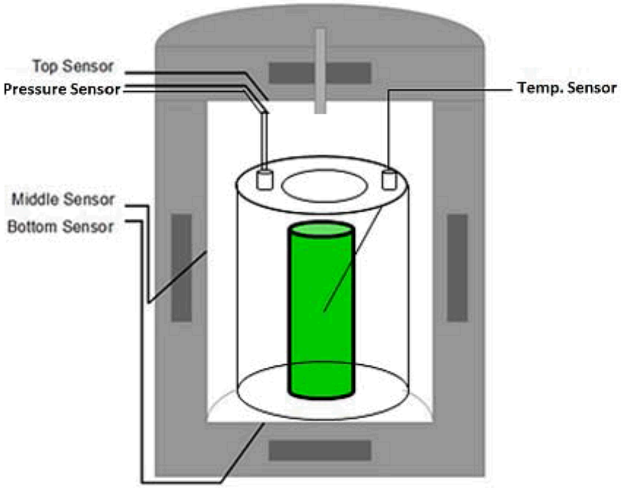


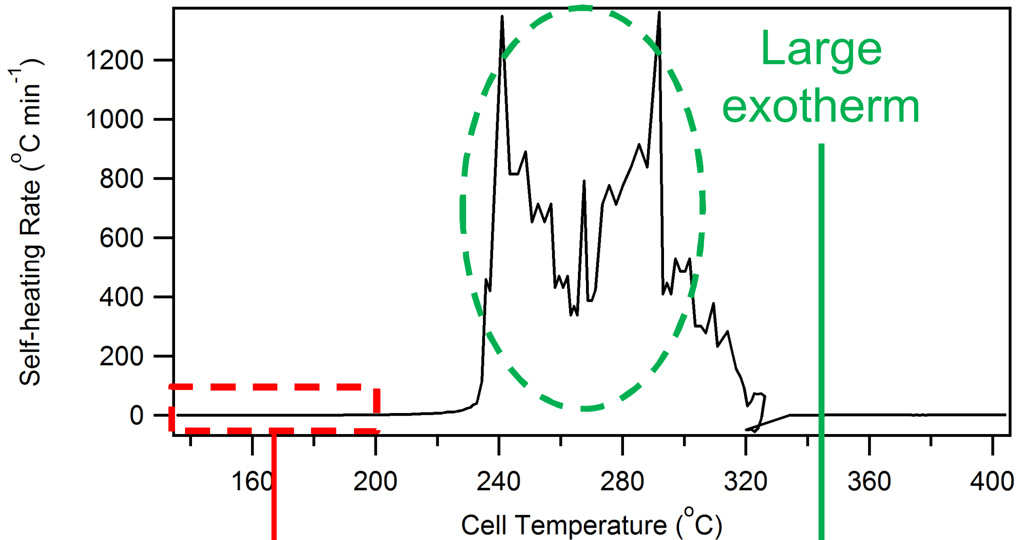


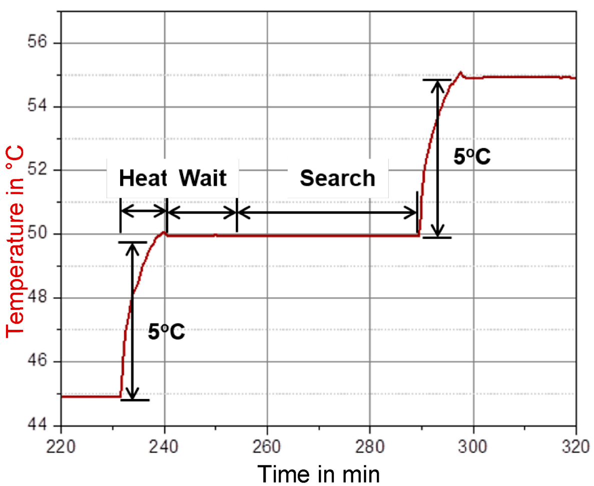
Schematic of LiC_6 and graphite: V. Petkov, A. Timmons, J. Camardese “Li insertion in ball-milled graphitic carbon studied by total x-ray diffraction” *Journal of Physics: Condensed Matter* **2011**, 23, 435003.

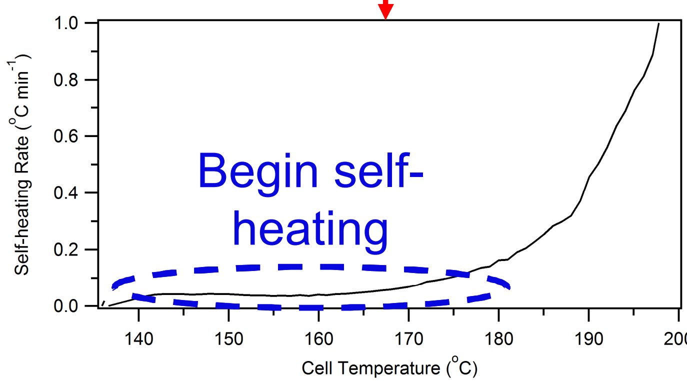
Accelerating Rate Calorimetry (ARC) demonstrates thermal runaway

Sandia National Laboratories





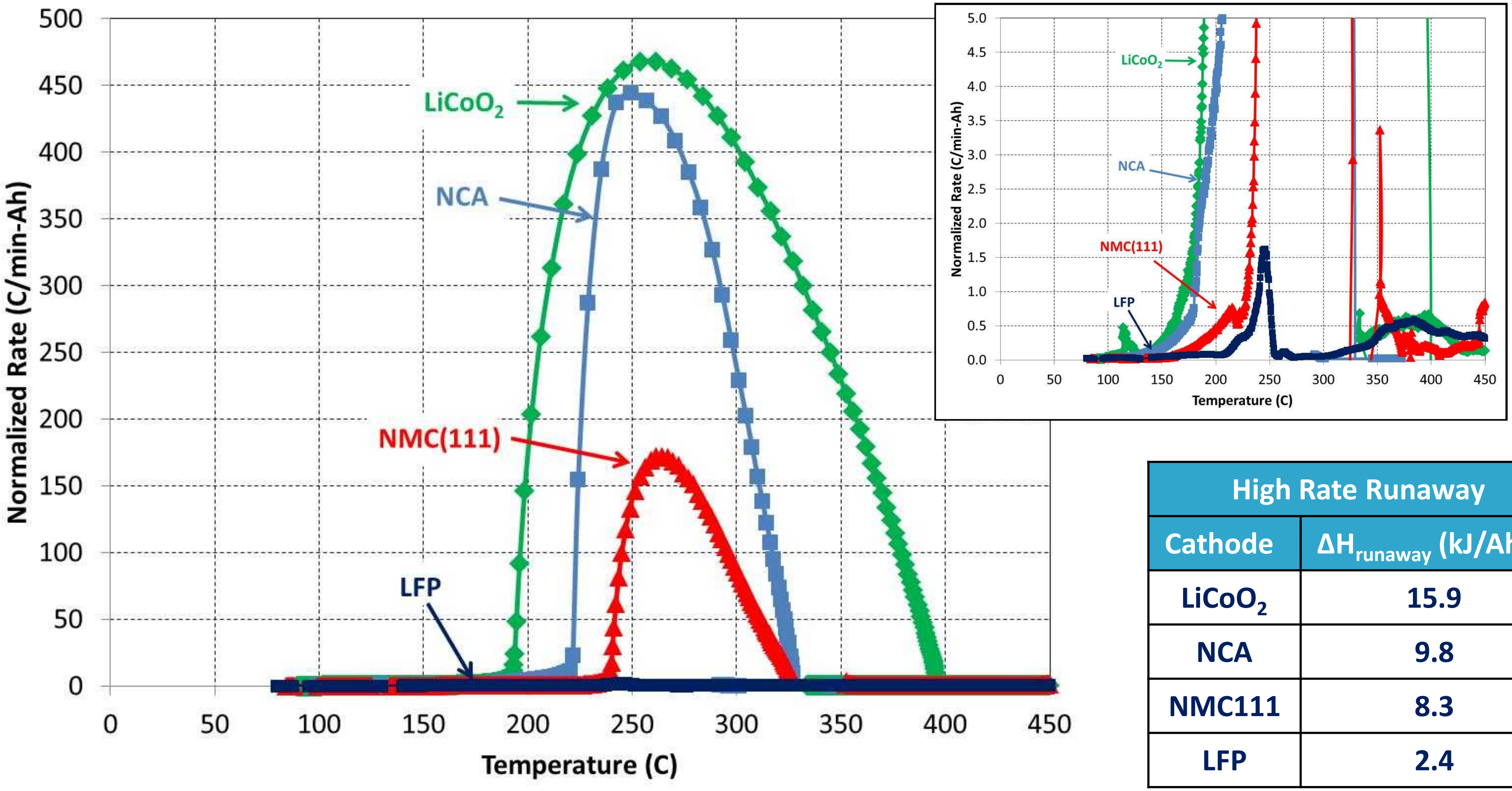




Schematic of ARC and heat-wait-seek: B. Lei, W. Zhao, C. Siebert, N. Uhlmann, M Rohde, H. J. Seifert "Experimental analysis of thermal runaway in 18650 cylindrical Li-ion cells using an accelerating rate calorimeter" *Batteries* **2017**, 3, 14.

Cell chemistry matters

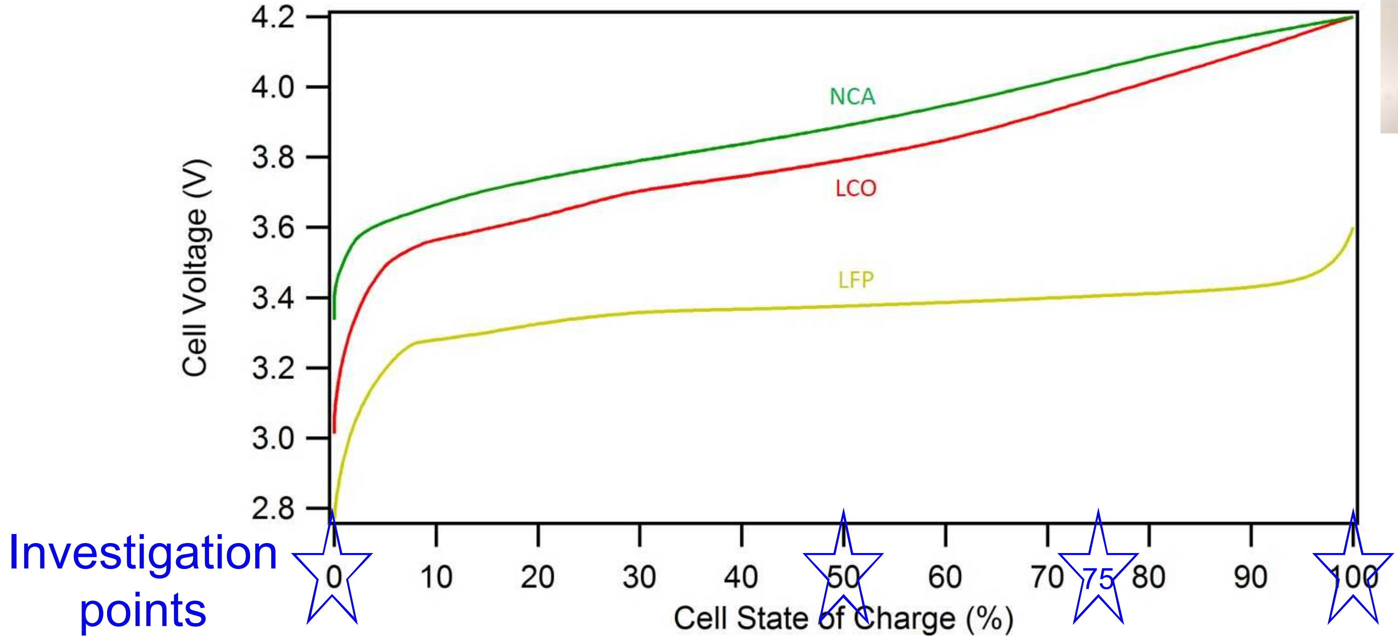
Accelerating rate calorimetry (ARC) of 18650 cells with different cathode materials



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

- **Develop an understanding of how the runaway response scales with cell size.**
- **Traditionally testing performed at 100% SOC; how does this change at lower SOC?**

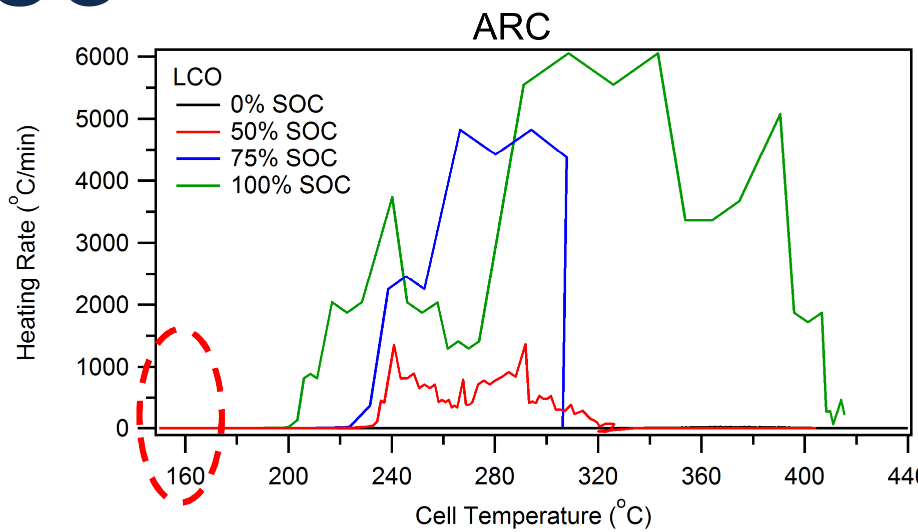
State of charge (SOC) matters

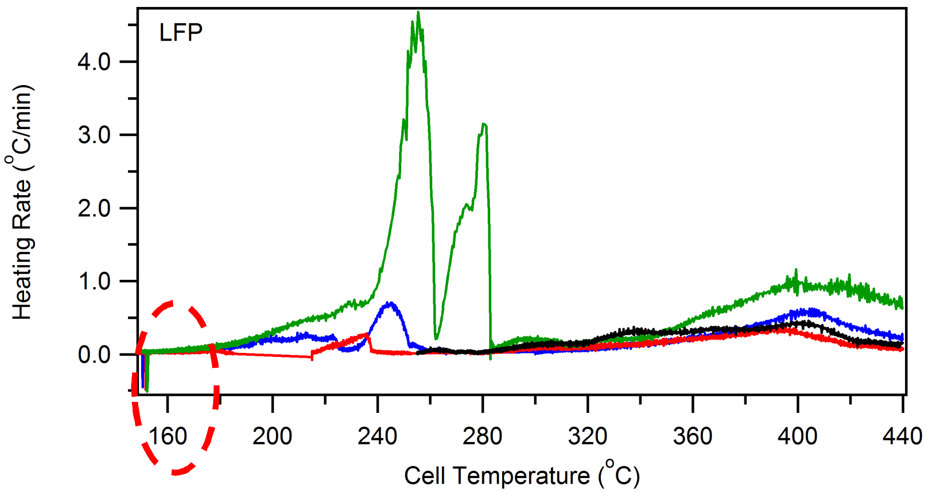


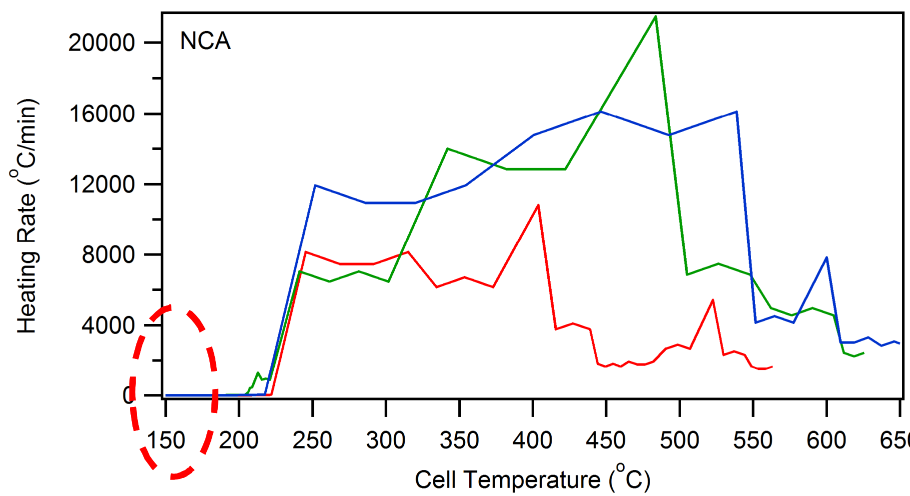
Think of state of charge (SOC) as the battery's "fuel gauge"
100%=full, 0%=empty

A full tank is more dangerous than an empty tank

Thermal runaway behavior changes with chemistry and SOC

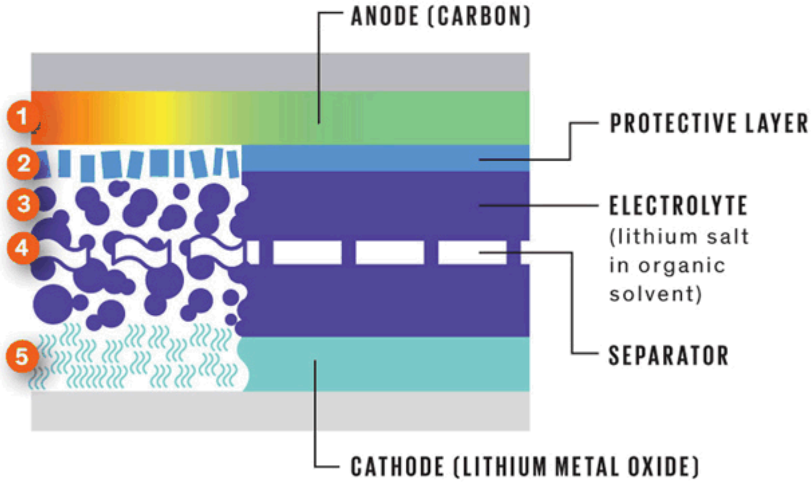






Onset temperature is ~150°C for all chemistries

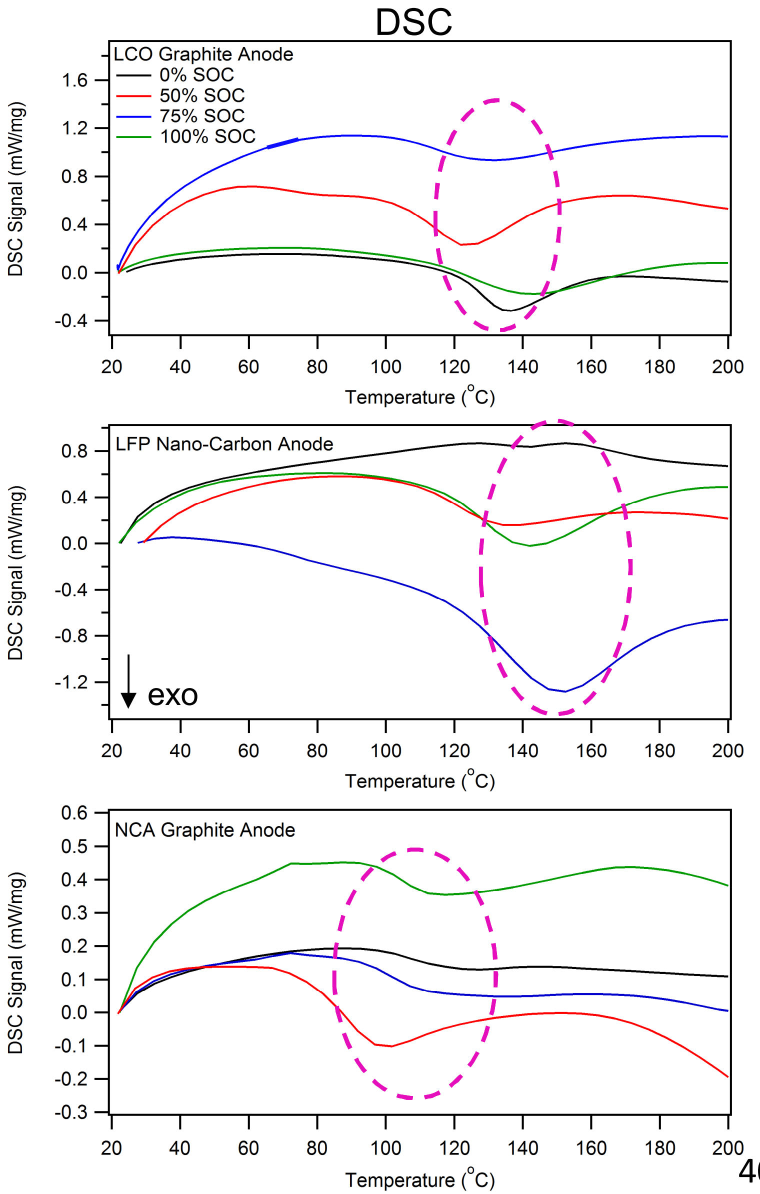
Thermal runaway begins with anode decomposition



Protective layer (2) breaks down, releasing heat (exotherm).

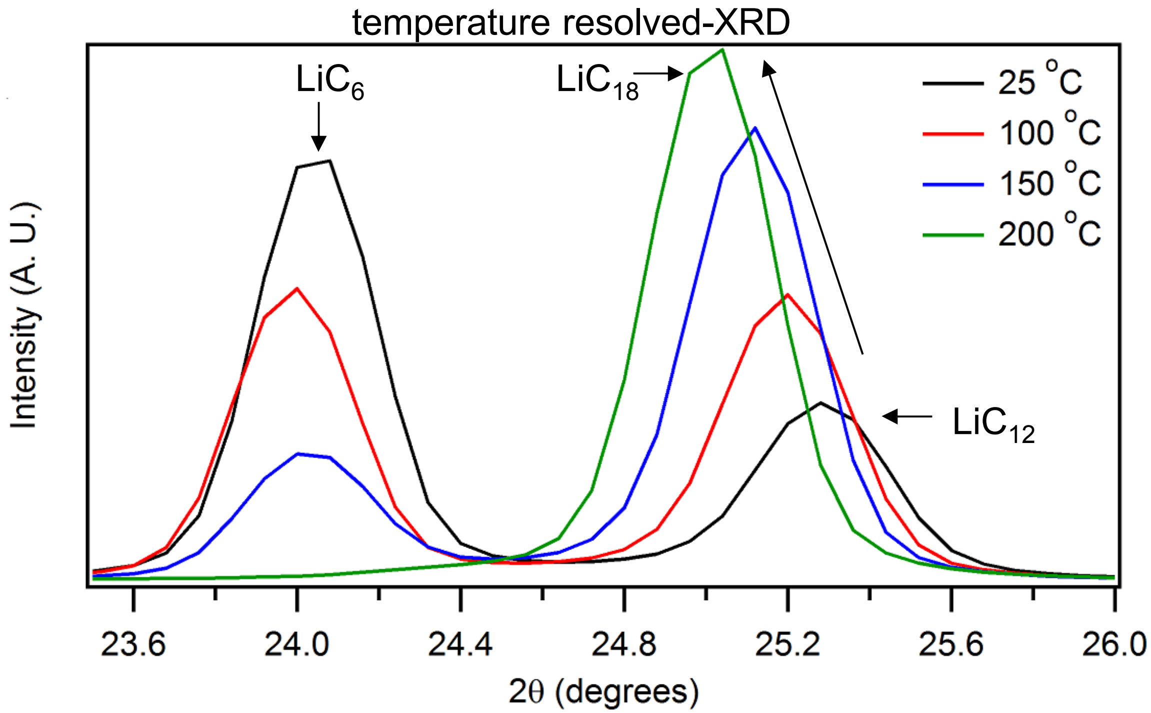
Underlying anode (1) is no longer protected, and reacts with the electrolyte (3) also releasing heat (exotherm).

This is the onset of thermal runaway detected in the ARC



Schematic of electrodes: https://www.extremetech.com/extreme/208888-doping-lithium-ion-batteries-could-prevent-overheating-and-explosion

Charged anodes decompose with temperature



As temperature increases, lithium reacts and is pulled out of the anode (recall lithium in the anode is like gas in a tank).

This de-lithiation process is exothermic (generates heat) and corresponds to the peak in DSC and onset of thermal runaway observed in ARC.

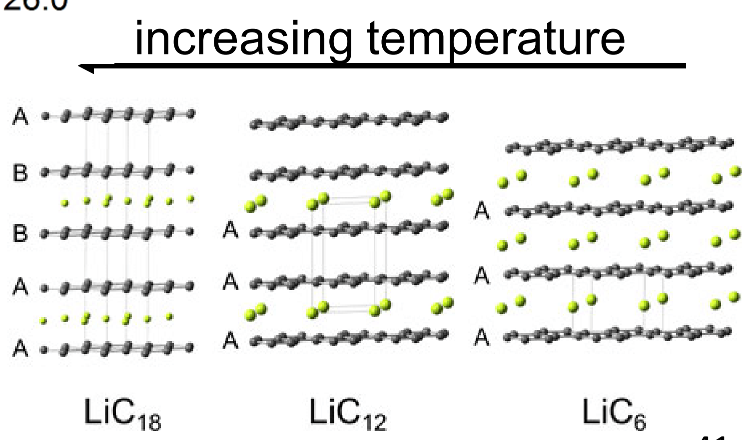
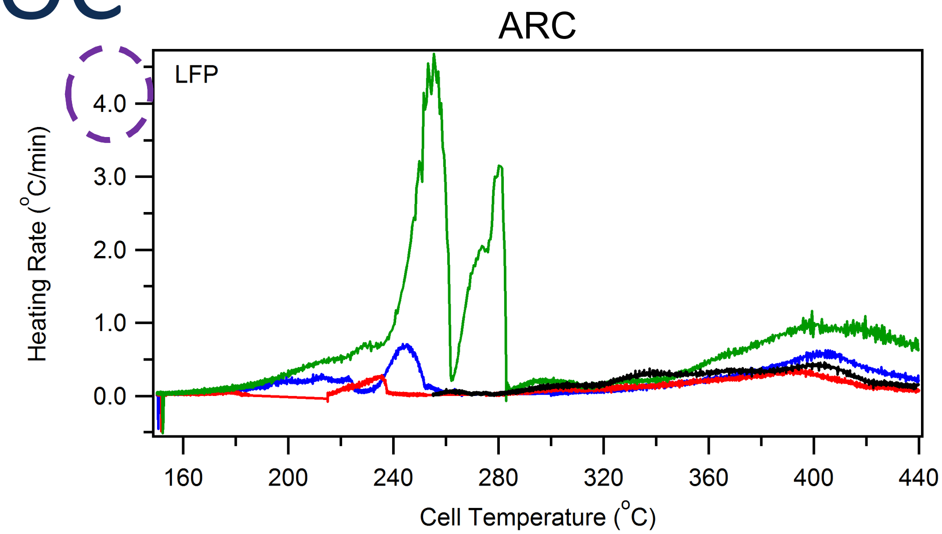
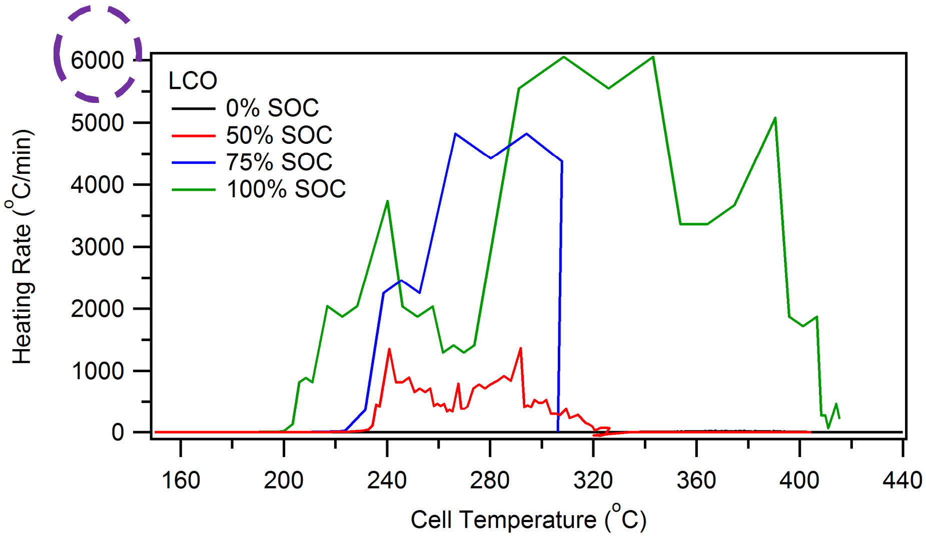


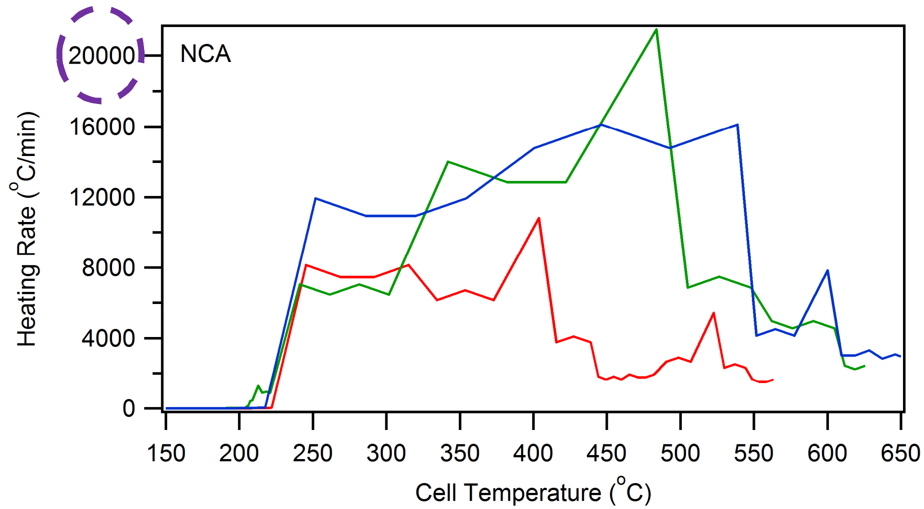
Image of LiC_6, LiC_{12}, and LiC_{18}: A. Missyul, I. Bolshakov, R. Shpanchenko "XRD study of phase transformations in lithiated graphite anodes by Rietveld method" *Powder Diffraction* **2017**, 1-7.

Thermal runaway behavior changes with chemistry and SOC

Sandia National Laboratories

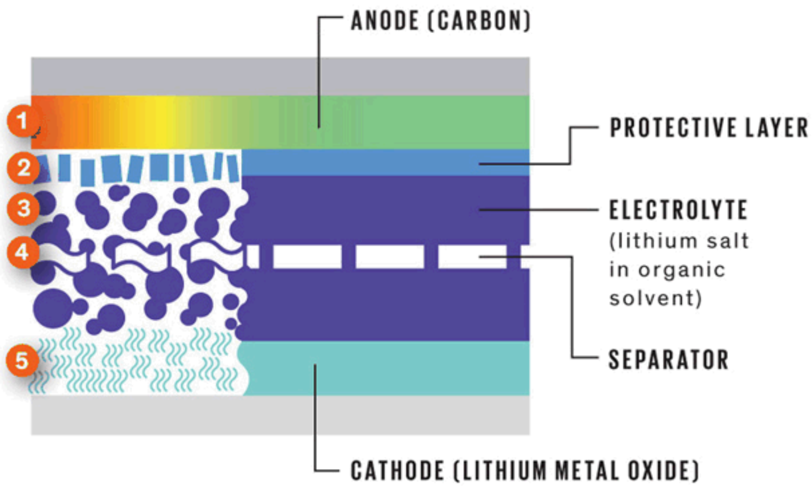


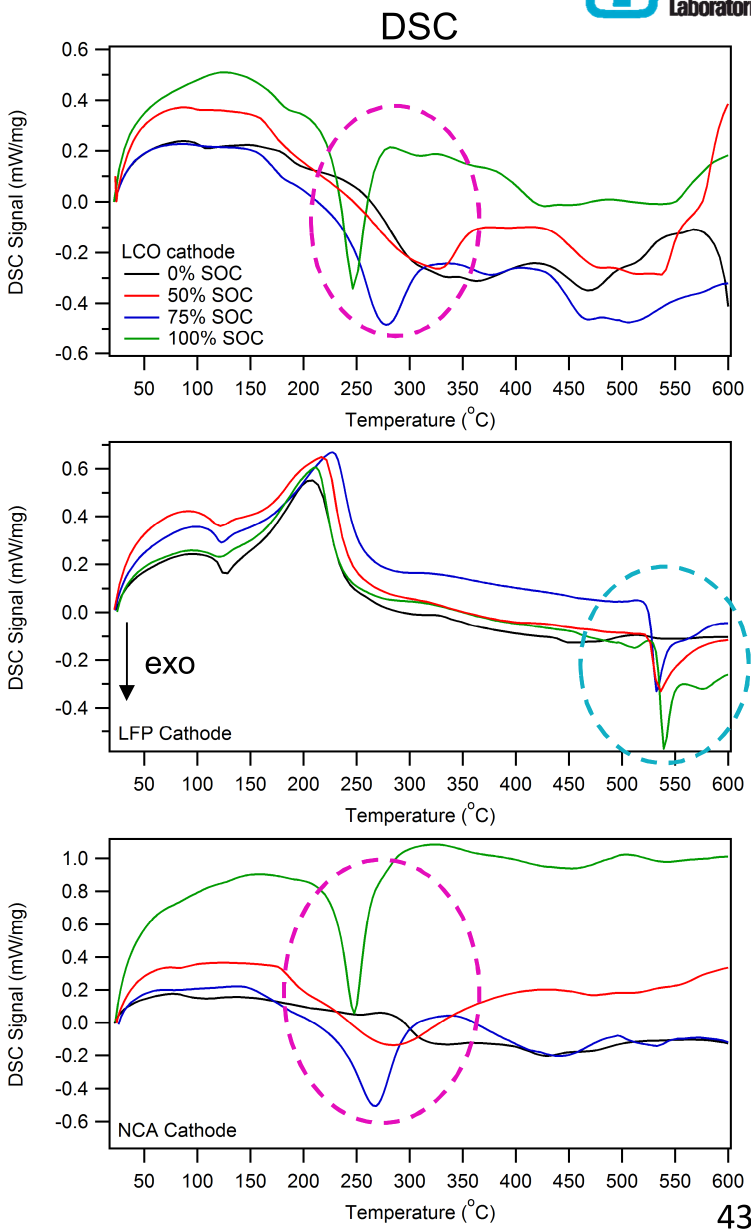




Maximum heating rate is chemistry dependent

Cathode decomposition releases a lot of heat



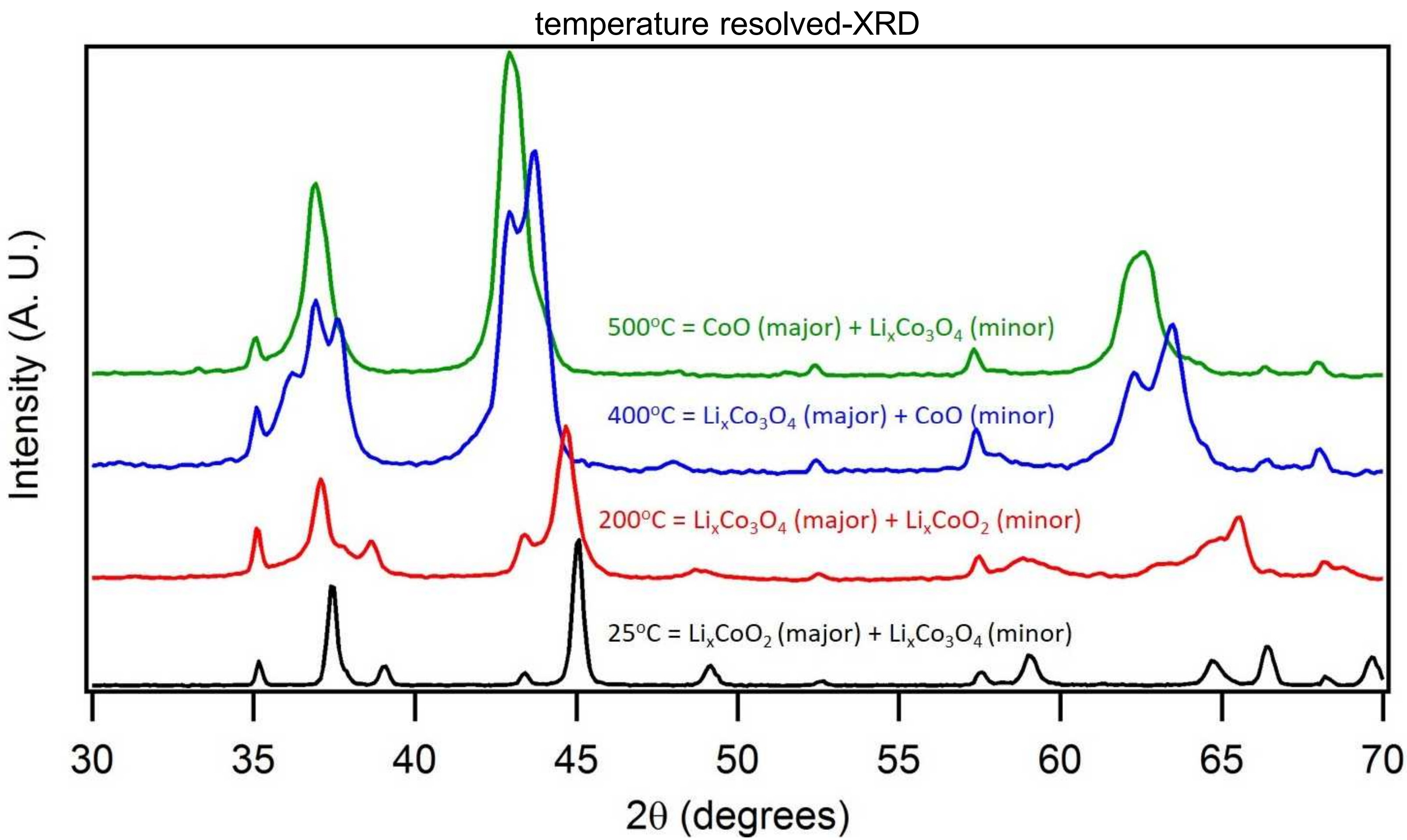


At higher temperatures, the LCO and NCA cathodes (5) break down, releasing a lot of heat (exotherm).

The LFP cathode is stable to very high temperatures

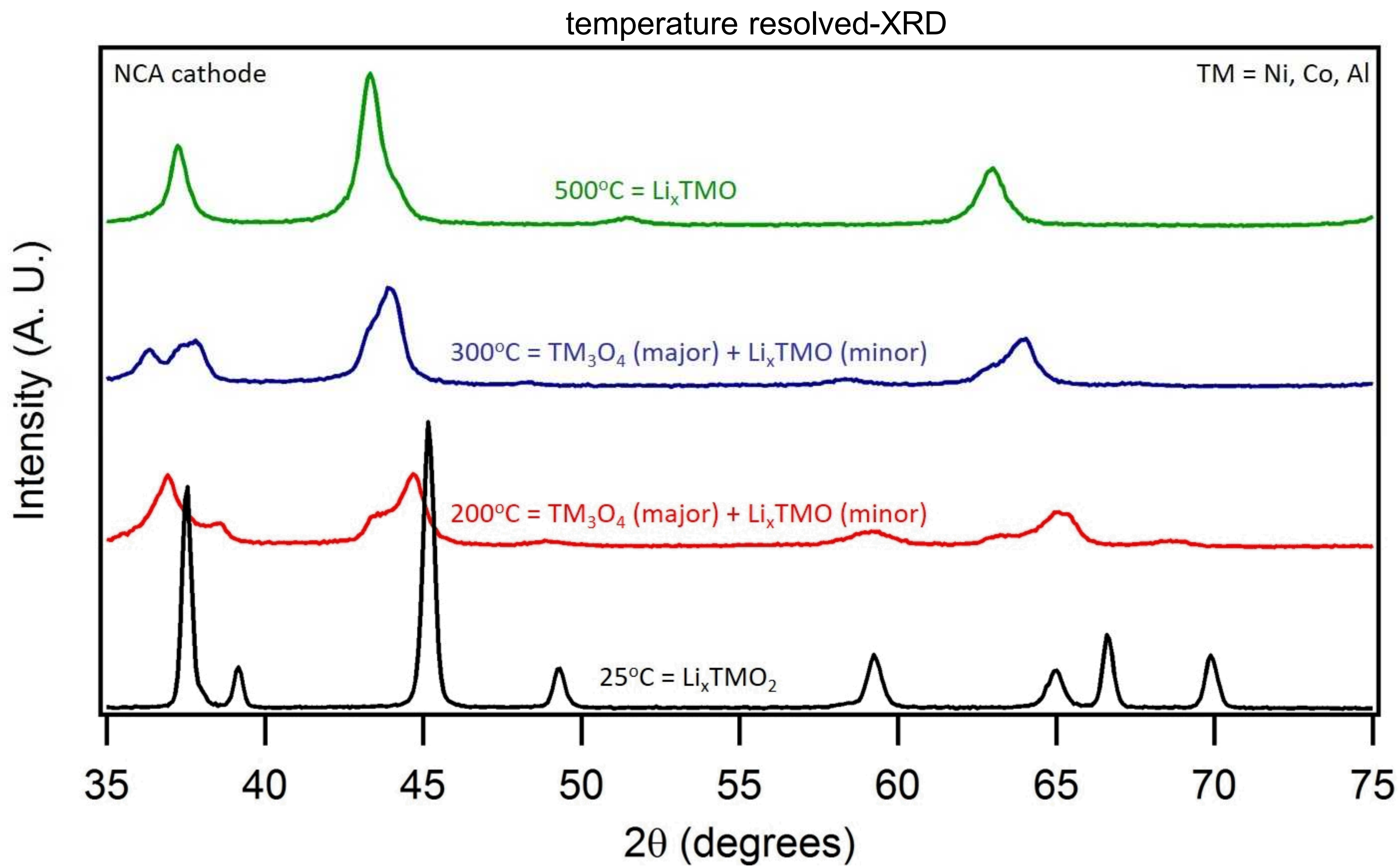
This is the peak of thermal runaway detected in the ARC (or how much heat is released).

LCO cathode decomposes slowly



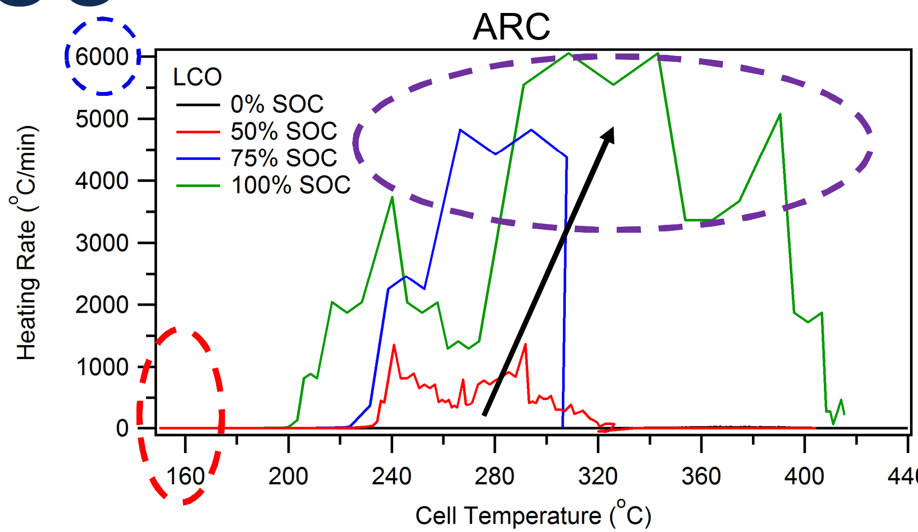
Cathode decomposition releases oxygen and heat.
Slower LCO decomposition results in lower heating rates in ARC.

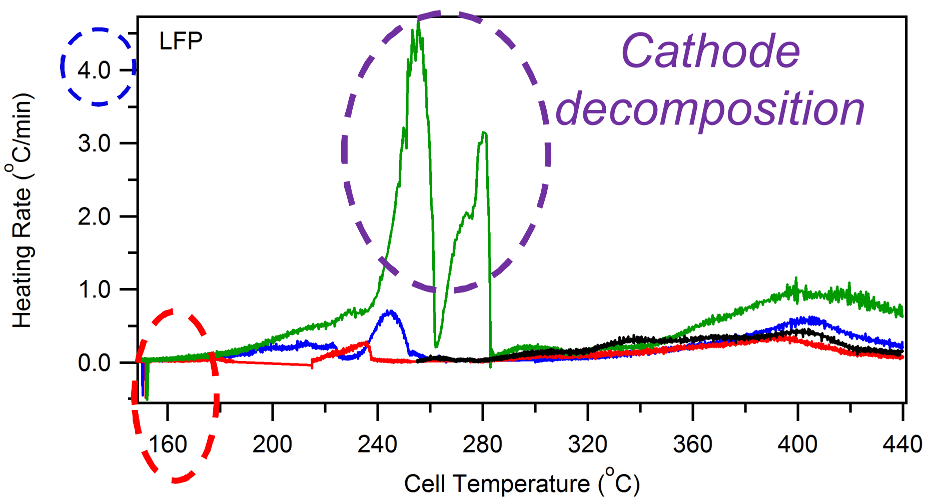
NCA cathode decomposes rapidly

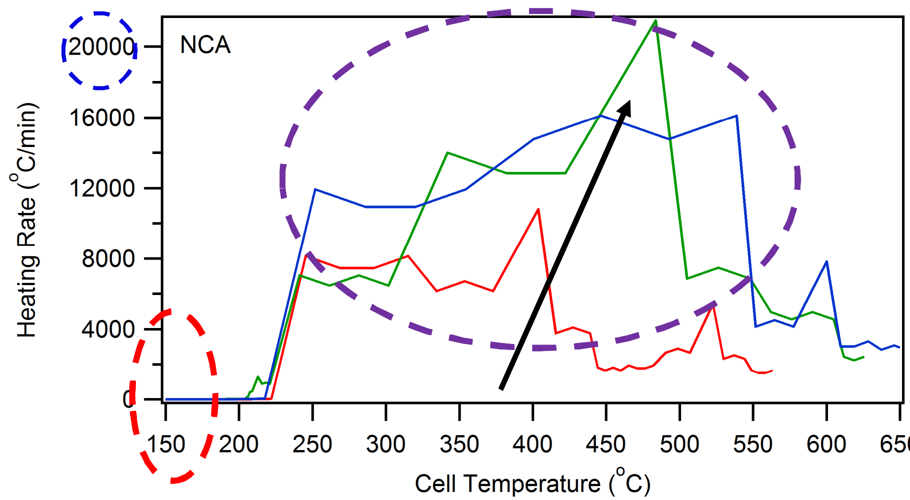


Cathode decomposition releases oxygen and heat.
Faster NCA decomposition results in higher heating rates in ARC.

Thermal runaway behavior changes with chemistry and SOC





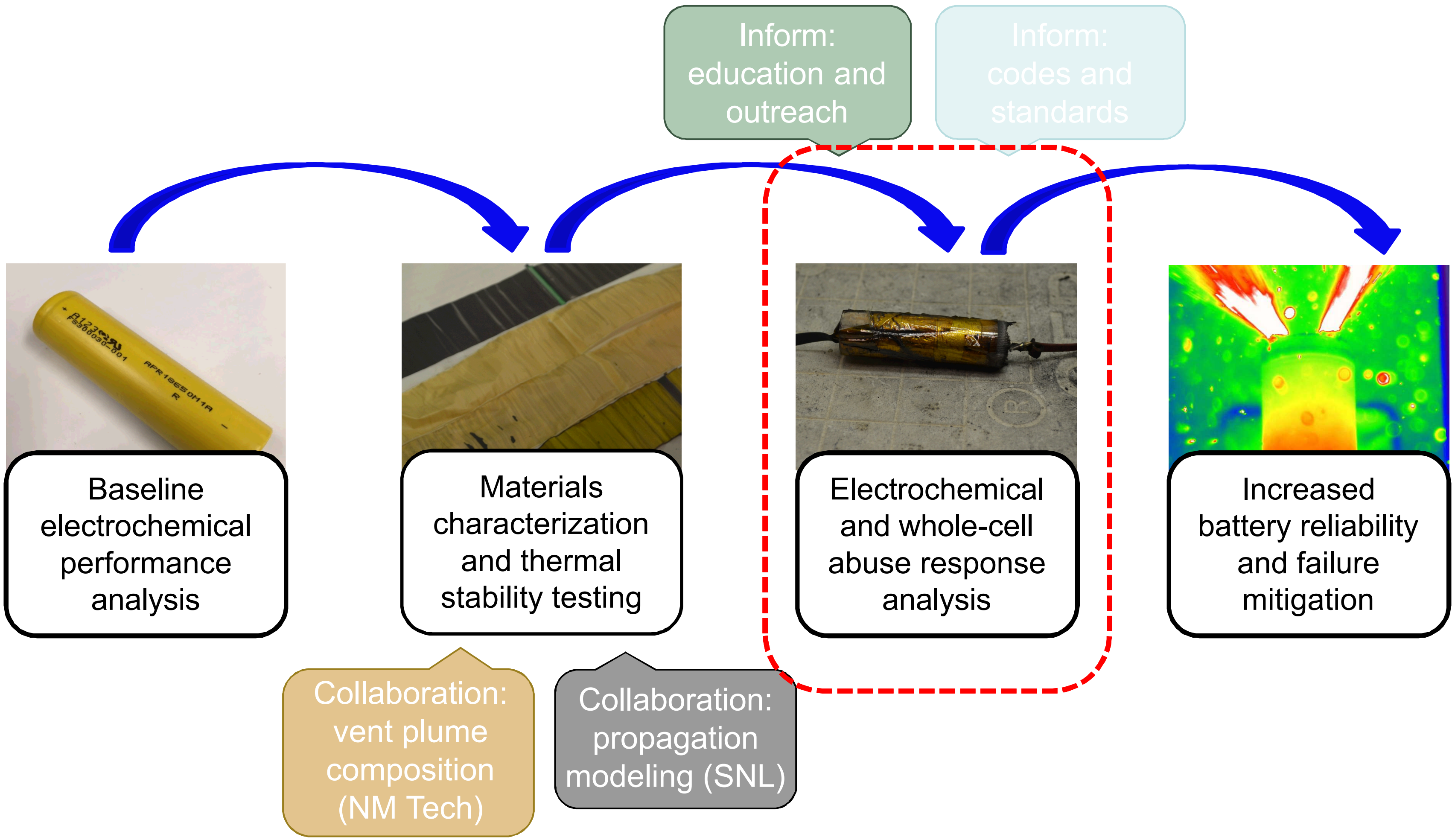


Anode decomposition

Cathode chemistry effects heat release rates

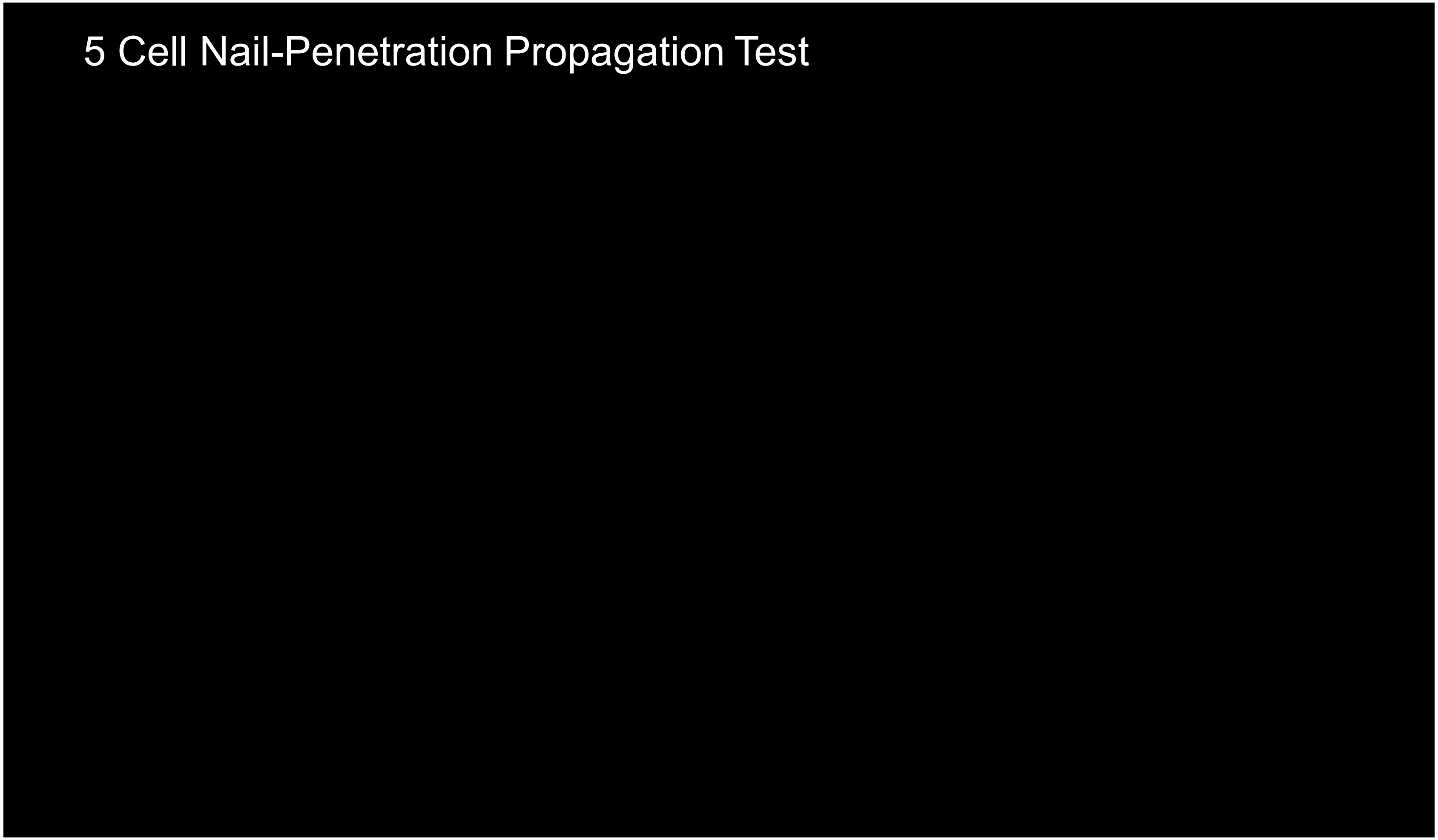
SOC effects heat release rates

Project Goal is Battery Failure Mitigation



Battery venting image: Finegan, D. P.; Scheel, M.; Robinson, J. B.; Tjaden, B.; Hunt, I.; Mason, T. J.; Millichamp, J.; Michiel, M. D.; Offer, G. J.; Hinds, G.; Brett, D. J. L.; Shearing, B.; Shearing, P. R. *Nat. Commun.* **2015**, *6*, 6924-6934.

Failure in one battery can take out a whole pack/system



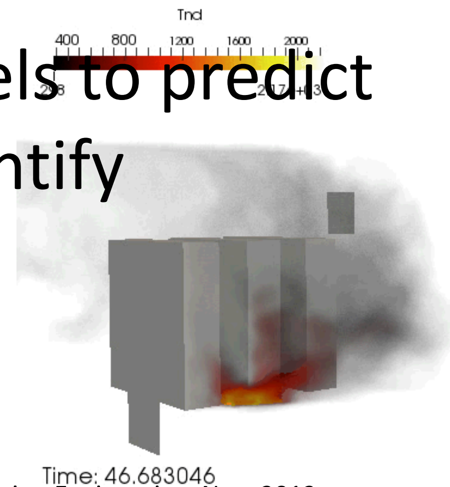
Approaches to designing in safety

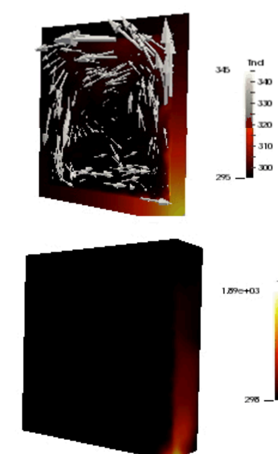
The current approach is to test our way into safety[1]

- Large system (>1MWh) testing is difficult and costly.

Consider supplementing testing with predictions of challenging scenarios and optimization of mitigation.

- Develop multi-physics models to predict failure mechanisms and identify mitigation.
- Build capabilities with small/medium scale measurements.
- Still requires some testing and validation.





[1] 'Power Grid Energy Storage Testing Part 1.' Blume, P.; Lindenmuth, K.; Murray, J. EE – Evaluation Engineering. Nov. 2012.

Models Need Parameters

- Preliminary chemistry model from literature
  - Based on Dahn group from 2000, 2001
  - Derived from calorimetry data (ARC and DSC)
  - Needs to be recalibrated

- Empirical chemical reactions
  - SEI decomposition $2\ ROCO_2Li \rightarrow Li_2CO_3 + prod$
  - Cathode-electrolyte $CoO_2 + C_3H_4O_3 \rightarrow \frac{1}{3}Co_3O_4 + prod$
  - Electrolyte-salt $C_3H_4O_3 + LiPF_6 \rightarrow prod$
  - Anode-electrolyte $C_6Li + C_3H_4O_3 \rightarrow Li_2CO_3 + prod$

- This model form has been utilized repeatedly, but requires calibration for each system because it is not expressed in terms of fundamental cell characteristics.

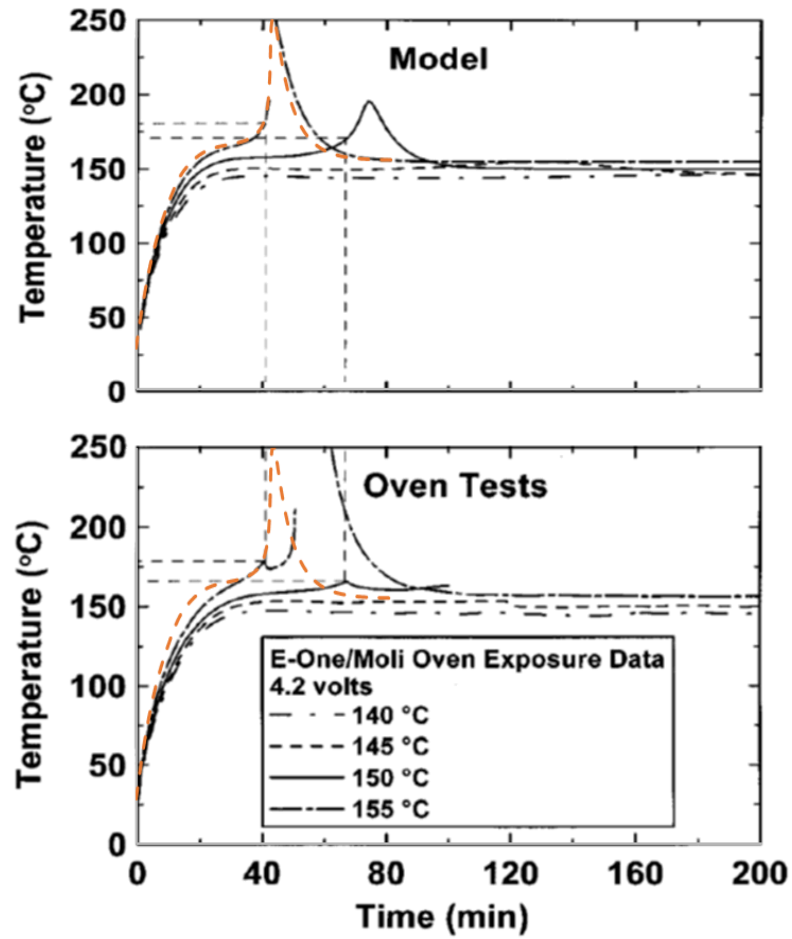
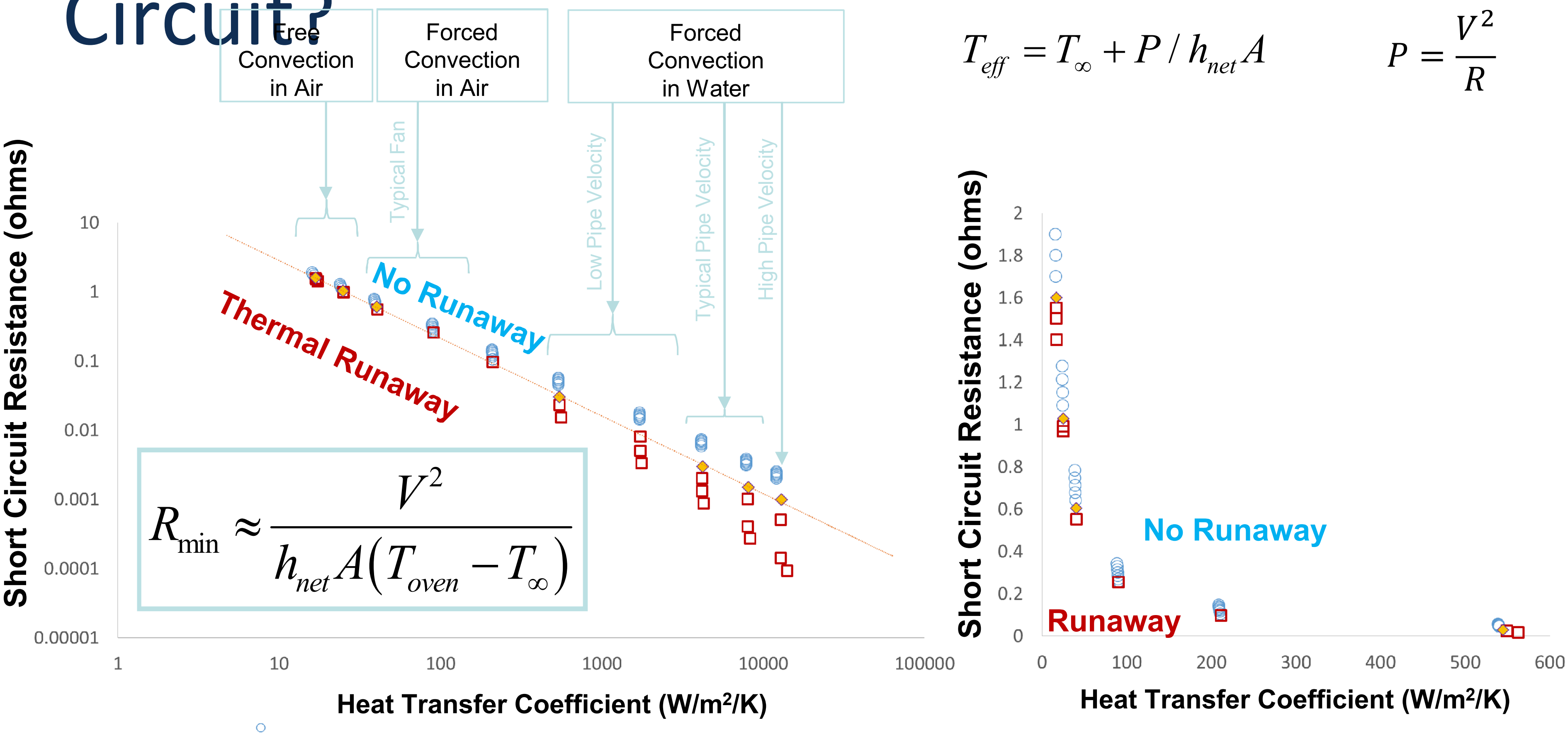


Figure 2. A comparison of oven exposure test results to model predictions: (top) model predictions and (bottom) oven test results for 18650 E-One/Moli Energy cells charged to 4.2 V.

Hatchard, T. D., D. D. MacNeil, A. Basu and J. R. Dahn (2001). Journal of the Electrochemical Society **148**(7): A755-A761.

How Much Cooling to Suppress Runaway with Internal Short Circuit?

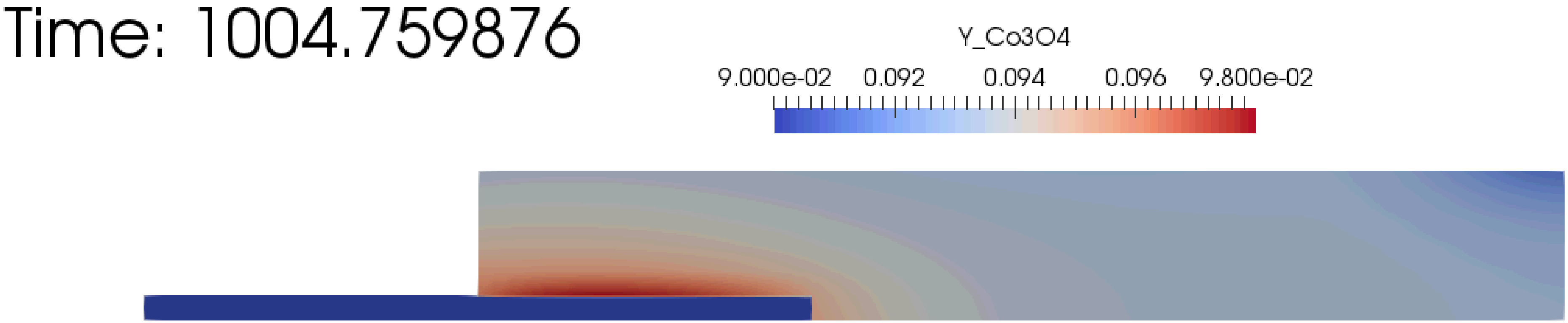


- Models can be used to estimate cooling requirements
  - Simulation shows homogeneous heating of 18650 cells (varying short resistance and cooling)
  - Internal temperature variation will be worse for large format systems and localized shorts

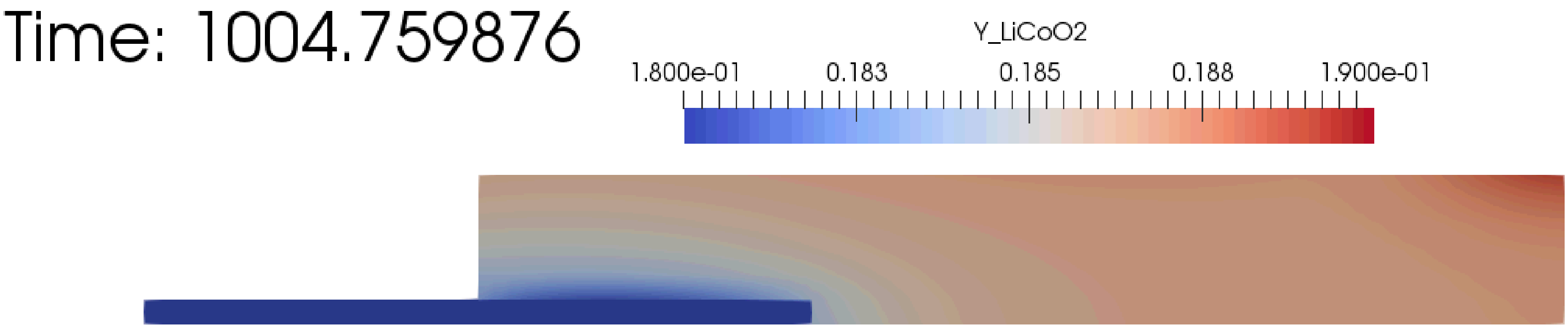
Relative importance of short-circuit versus thermal reactions

R = 1.4 ohm, h = 7 $W/m^2/K$, Meshed 18650 with 50% heat release in nail

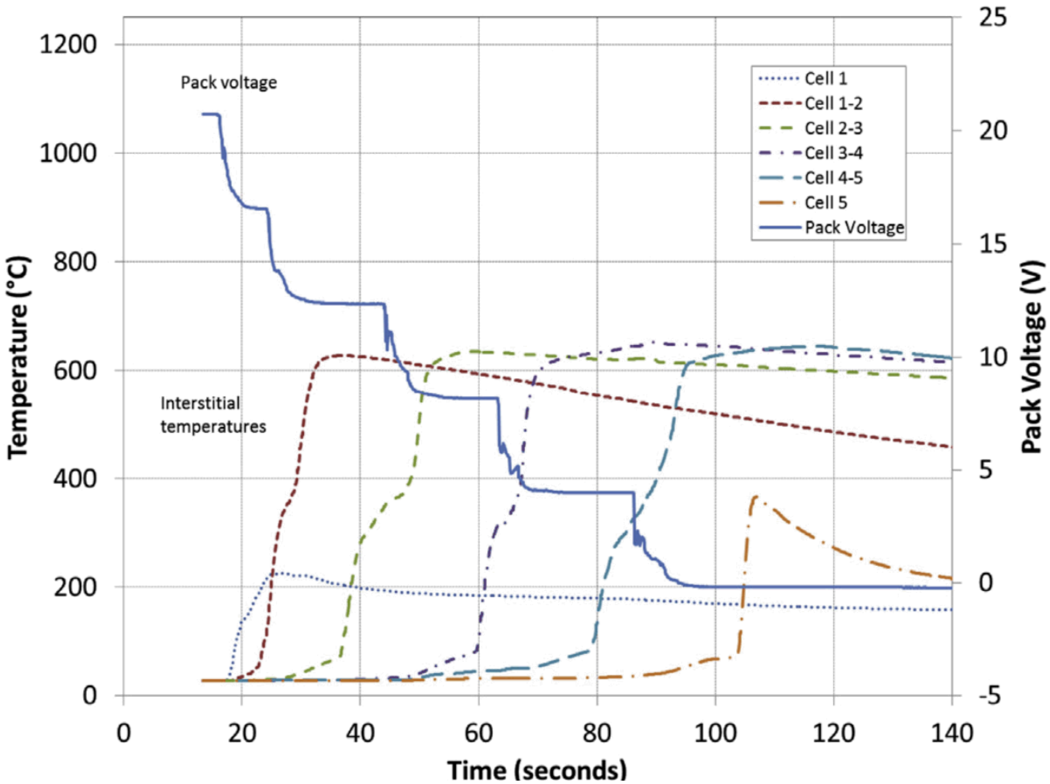
Thermal Reaction Cathode Product

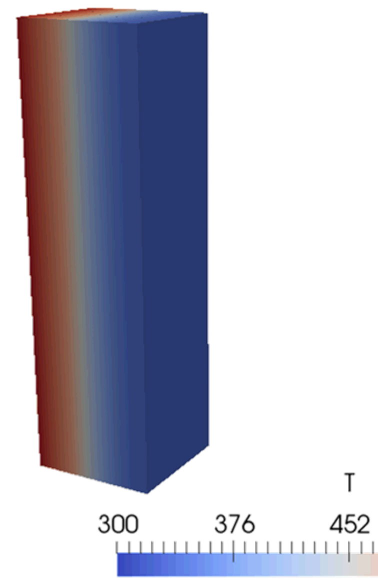


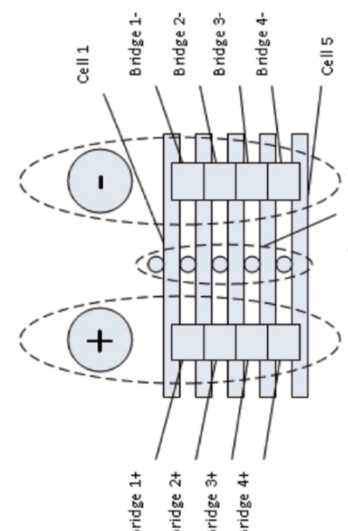
Short Circuit Cathode Product



Cascading Propagation Observed in Li-Ion Packs



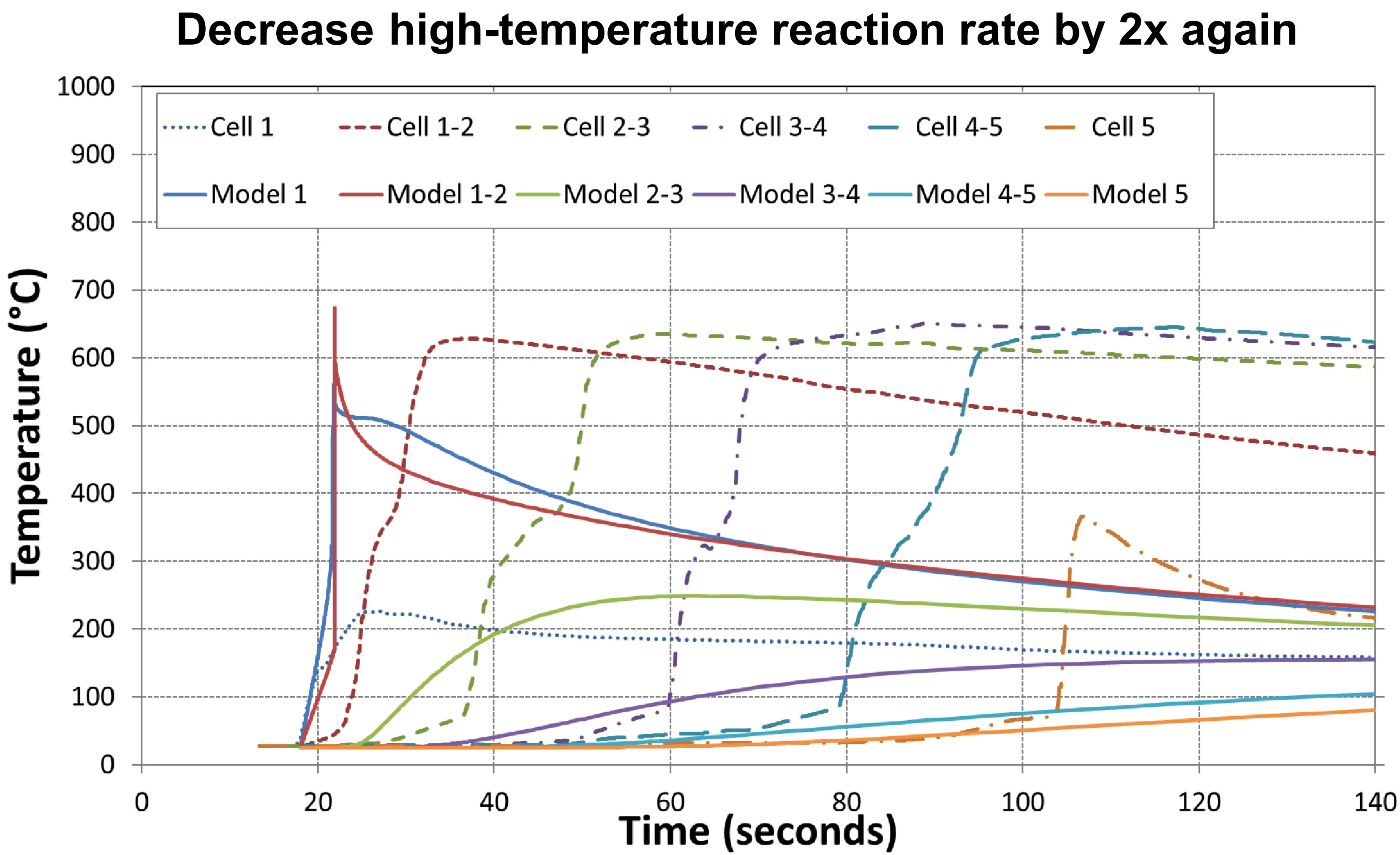




- Experimental propagation in 5 stacked pouch cells at Sandia
- Investigating effects of
  - State of charge
  - Intermediate layers
  - Cell geometry
- Good pack-scale model validation cases

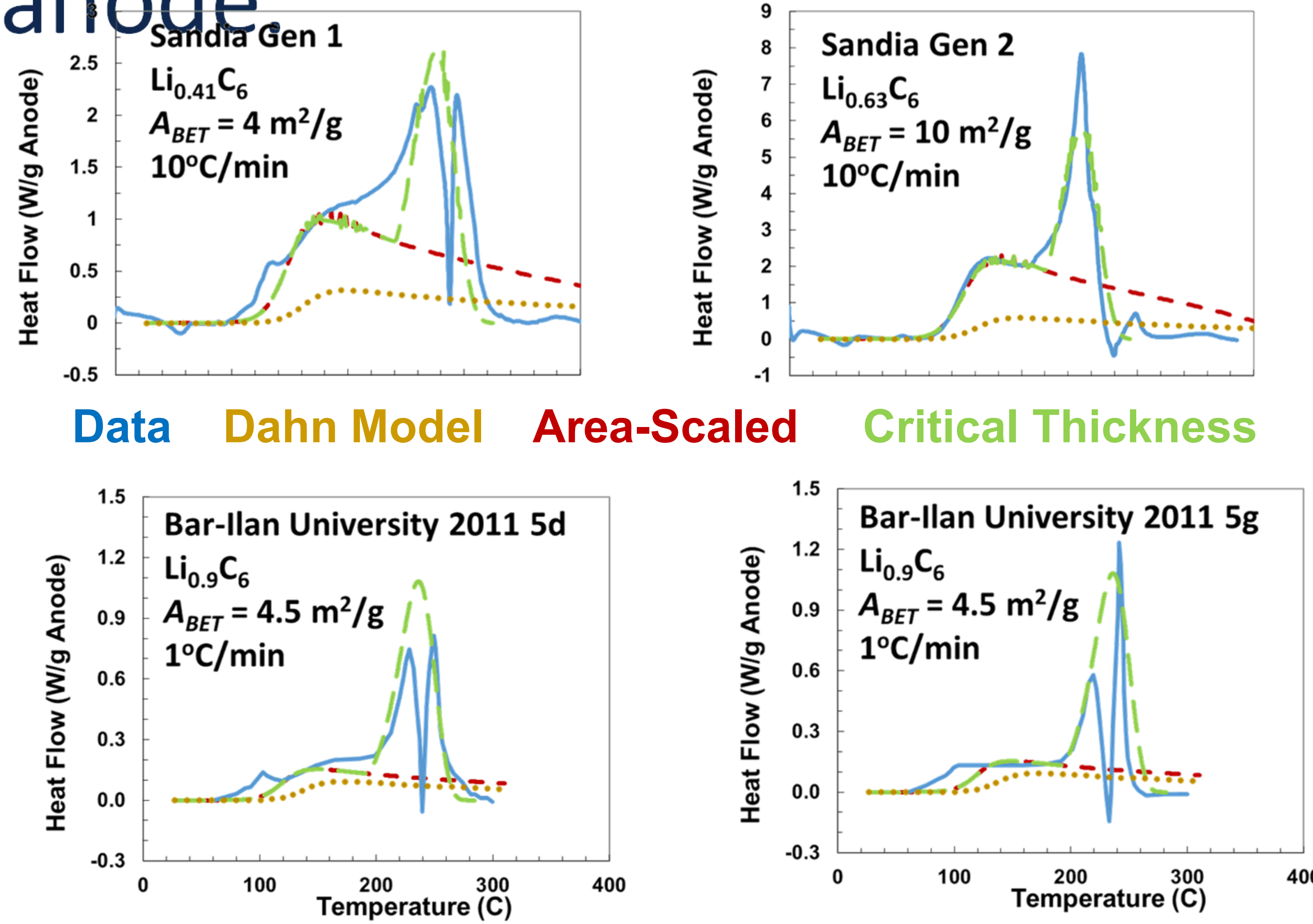
Lamb, J., et al. (2015). Journal of Power Sources **283**: 517-523.

High-Fidelity Models Required for Cascading Failure



- Propagation predictions will improve with fidelity of high-temperature chemistry

Prior models provided incomplete accounting of heat release – example for anode



Data from Lamb, J., et al. (2015). Journal of Power Sources **283**: 517-523.

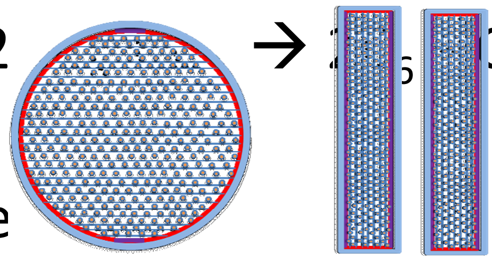
Key anode model improvements

Area-Scaled Model

- SEI Passivation layer inhibits lithium reduction of electrolyte, exp(-z).
- H_{rxn} thermodynamically consistent with 2 … → 2 … 6 … C_2H_4 + Li_2CO_3

$$\frac{dz}{dt} \propto \frac{A_{rxn,ref}}{A_{rxn}} \approx \left(\frac{A_{BET,ref}}{A_{BET}}\right)^{n_1}, n_1 < 1$$

- Reaction scales with effective surface are



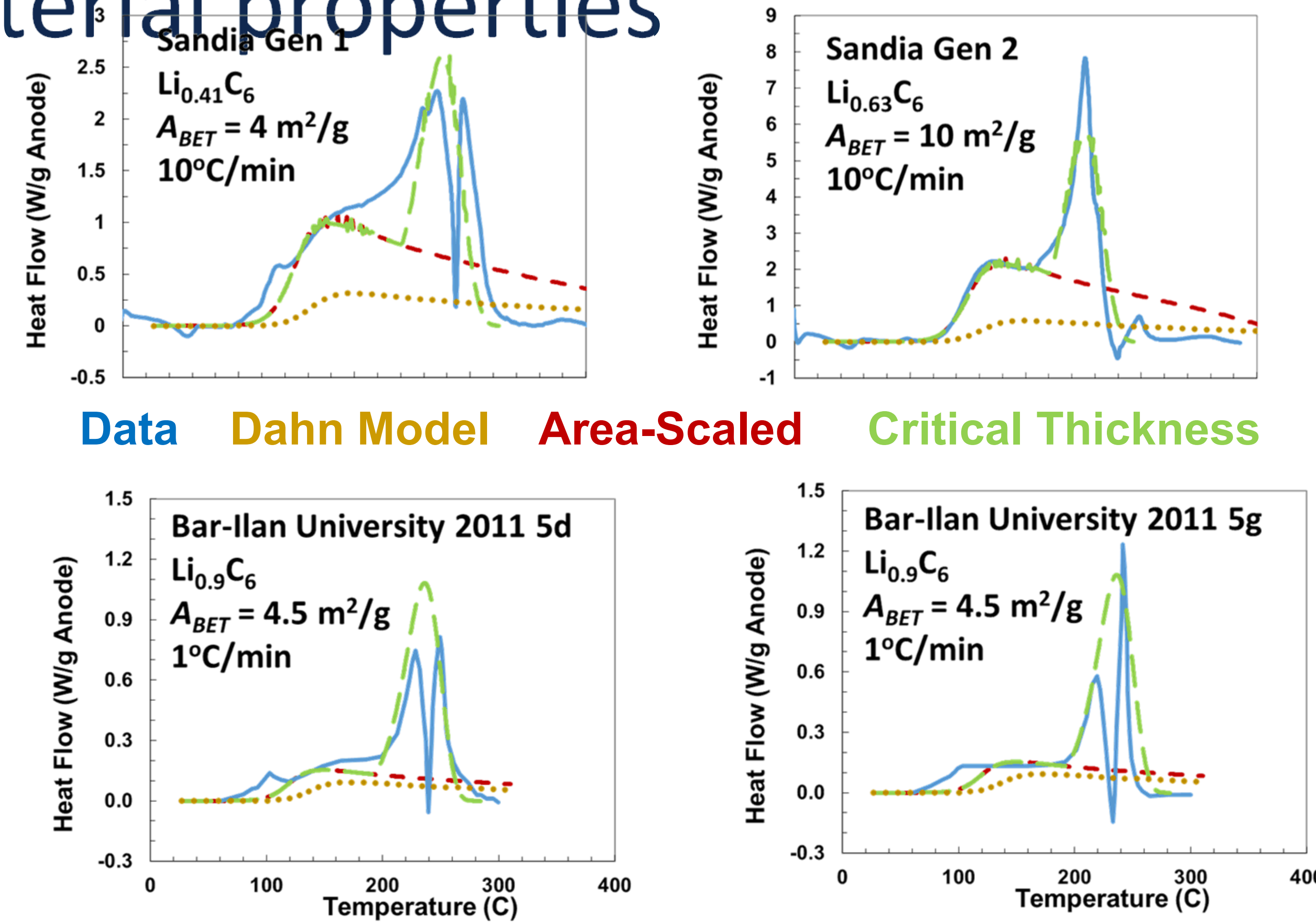
= Graphite Basal Planes (smooth)
= Graphite Edges (rough)
= SEI Layer

$$z = min(z, z_{crit}) \quad \textbf{where} \quad z_{crit} \propto x_{sei,crit}\left[\frac{A_{BET}}{A_{BET,ref}}\right]^{n_2}$$

Critical Effective Layer Thickness

- Limit to passivation layer growth with heating

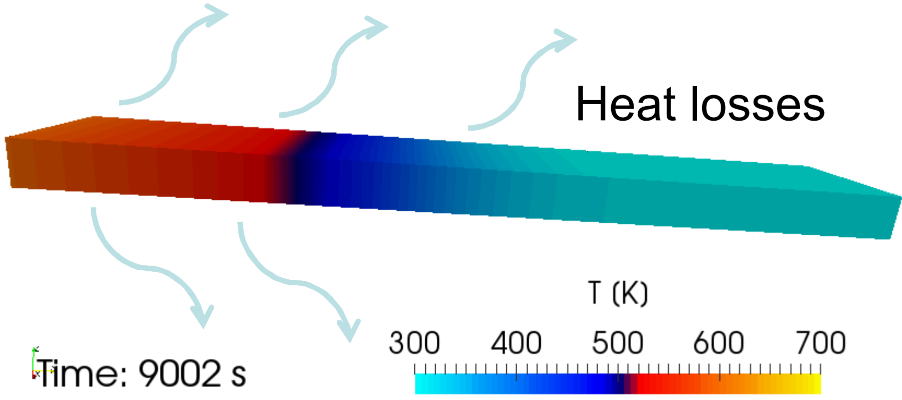
New model based on measureable quantities and thermodynamic material properties



Data from Lamb, J., et al. (2015). Journal of Power Sources **283**: 517-523.

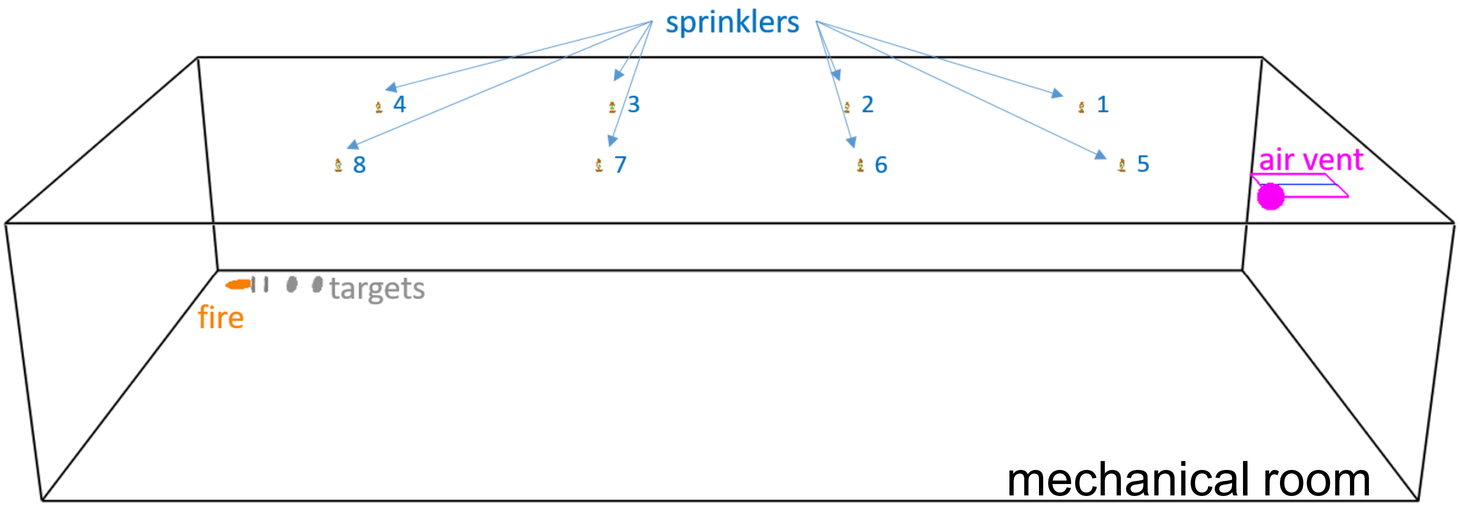
Future work

- Fit calorimetry data from a variety of battery chemistries (Sandia team and literature) to kinetic models.
- Identify configurations that inhibit initial ignition.
- Continue modeling thermal interaction of battery pack configurations.
  - Cascading versus isolated failure.
  - Inhomogeneous packs with losses.



  - Focus on heat losses required to mitigate propagation.
- Intermediate term
  - Demonstrate simulation as tool for risk-cost trade space studies through distributed sensing versus mitigation response.
  - Predict contributions of battery thermal runaway to overall fire load and as source of hazardous products.
  - Integrate reacting thermal model of battery packs with fire models in Sierra to evaluate safety of representative geometries and scenarios.
- **Ultimate goal: *Employ modeling as design tool for optimal mitigation strategies.***

Batteries in buildings need to be controlled by sprinkler systems

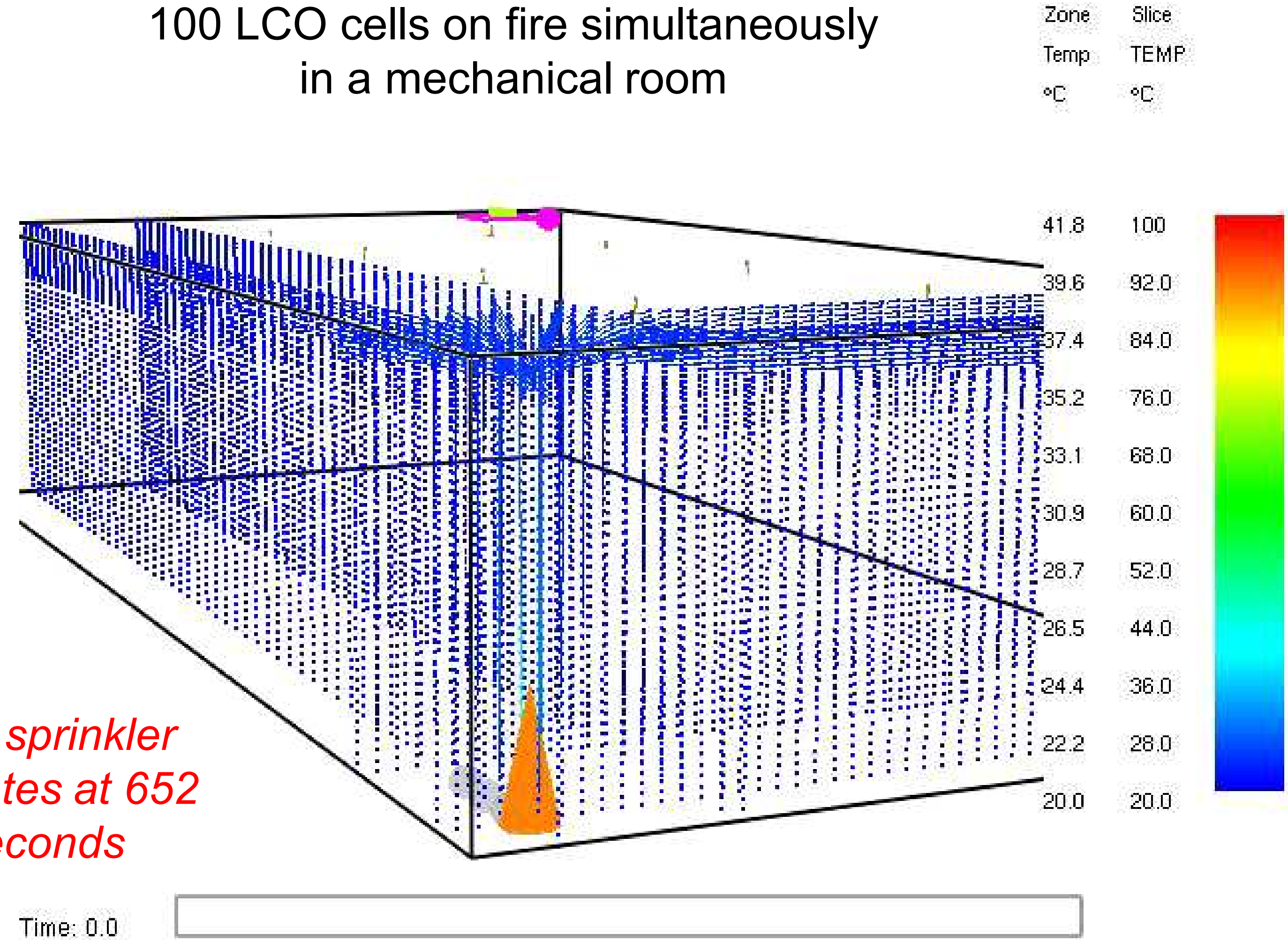


Sprinkler systems are designed to control the fire until firefighters can arrive.

More than one sprinkler activation is considered a "failed" test.

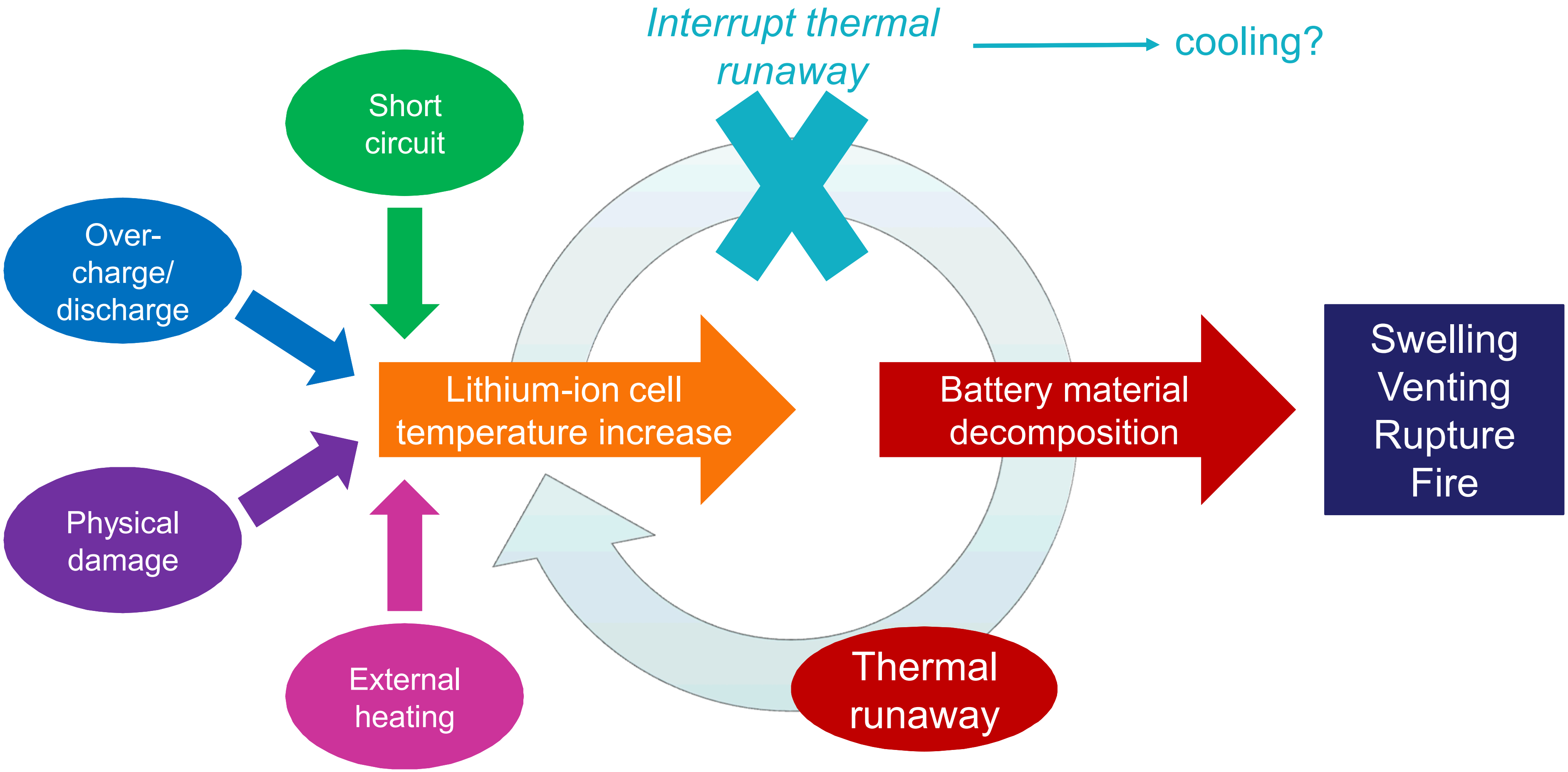
Rapid sprinkler response can control small battery fires

100 LCO cells on fire simultaneously
in a mechanical room

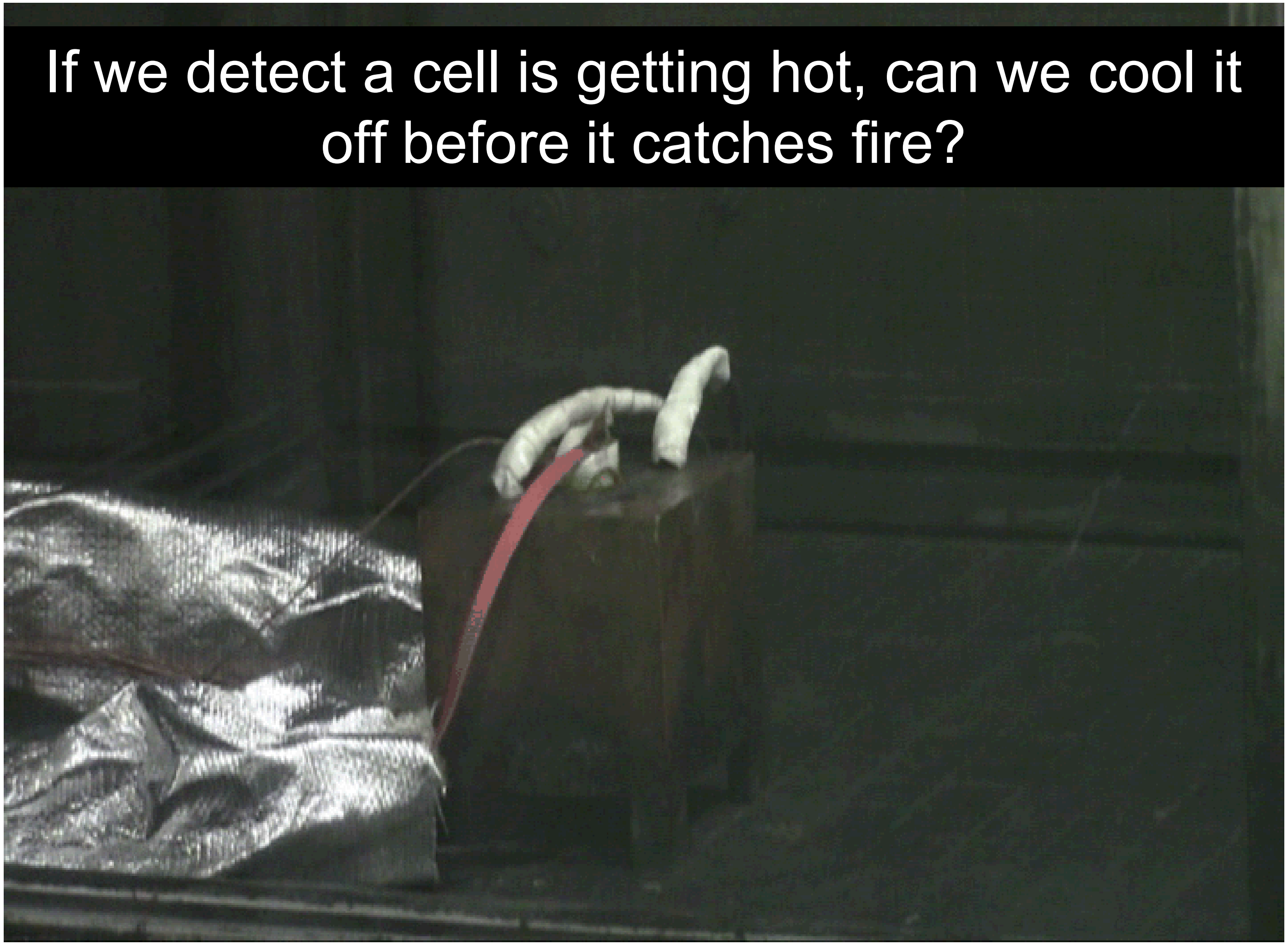


One sprinkler activates at 652 seconds

Can we prevent a battery fire?



LCO thermal runaway critical point



Battery System Safety

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

Summary

- Fielding the most inherently safe chemistries and designs can help address the challenges in scaling up lithium-ion
- Material choices can be made to improve the inherent safety of lithium-ion cells
- Testing single cell failure propagation throughout a battery system is critical for understanding the potential vulnerabilities and safety margin for a battery
- A comprehensive evaluation of all lithium-ion cell components is essential to ensure safety and reliability for these cell in large battery systems – great impact on public adoption
- No single inherently safe chemistry or mitigation strategy exists, solution in the form of numerous strategies – impact on electrochemical performance

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.

ESS Safety Team

- Heather Barkholtz
- Josh Lamb
- John Hewson
- Loraine Torres-Castro
- Randy Shurtz
- Armando Fresquez
- Sergei Ivanov
- Jill Langendorf

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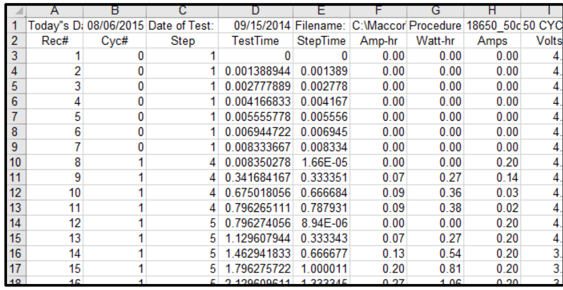
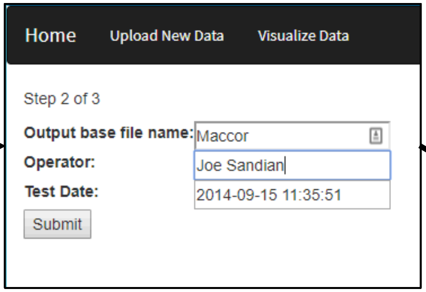
Battery tester data storage and archival

Concept: Create a tool for archival of tester data in a common data format to enable consistent analysis

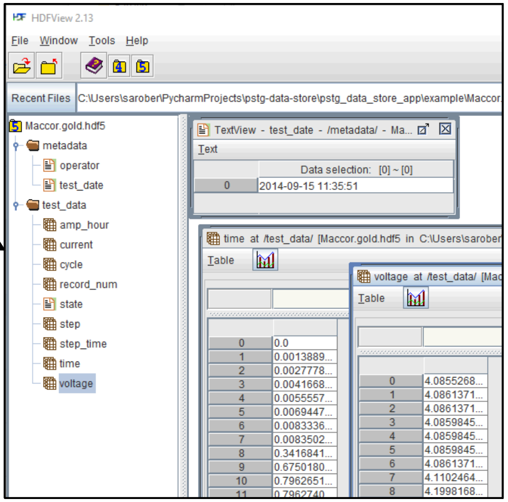


	A	B	C	D	E	F	G	H	I
1	Today"s D:	08/06/2015	Date of Test:	09/15/2014	Filename:	C:\Maccor	Procedure	18650_50c	50 CYC
2	Rec#	Cyc#	Step	TestTime	StepTime	Amp-hr	Watt-hr	Amps	Volts
3	1	0	1	0	0	0.00	0.00	0.00	4.
4	2	0	1	0.001388944	0.001389	0.00	0.00	0.00	4.
5	3	0	1	0.002777889	0.002778	0.00	0.00	0.00	4.
6	4	0	1	0.004166833	0.004167	0.00	0.00	0.00	4.
7	5	0	1	0.005555778	0.005556	0.00	0.00	0.00	4.
8	6	0	1	0.006944722	0.006945	0.00	0.00	0.00	4.
9	7	0	1	0.008333667	0.008334	0.00	0.00	0.00	4.
10	8	1	4	0.008350278	1.66E-05	0.00	0.00	0.20	4.
11	9	1	4	0.341684167	0.333351	0.07	0.27	0.14	4.
12	10	1	4	0.675018056	0.666684	0.09	0.36	0.03	4.
13	11	1	4	0.796265111	0.787931	0.09	0.38	0.02	4.
14	12	1	5	0.796274056	8.94E-06	0.00	0.00	0.20	4.
15	13	1	5	1.129607944	0.333343	0.07	0.27	0.20	4.
16	14	1	5	1.462941833	0.666677	0.13	0.54	0.20	3.
17	15	1	5	1.796275722	1.000011	0.20	0.81	0.20	3.

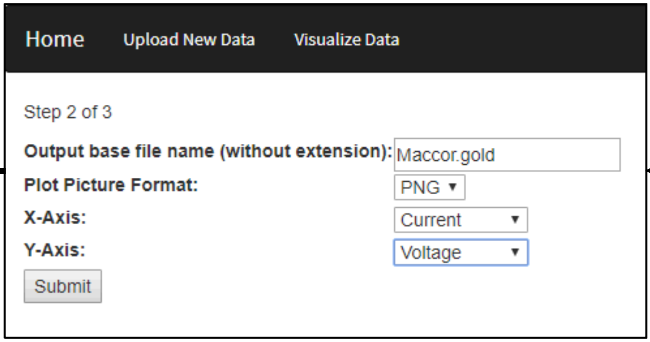
Input data (CSV, XLSX) includes tabular test data and metadata



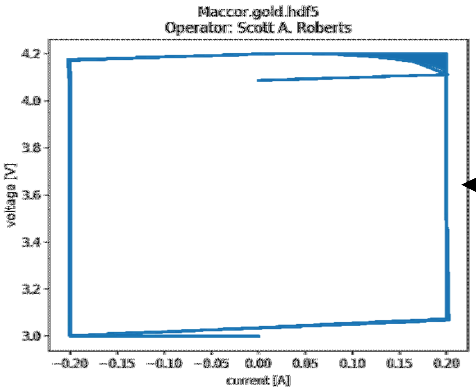
Web interface to upload data, enter metadata



Data converted to common format, stored in HDF5



Web interface to post-process



Data output to plots, excel

Completion status:

- Data format definition
- Basic conversion, post-processing routines
- Web + standalone interface

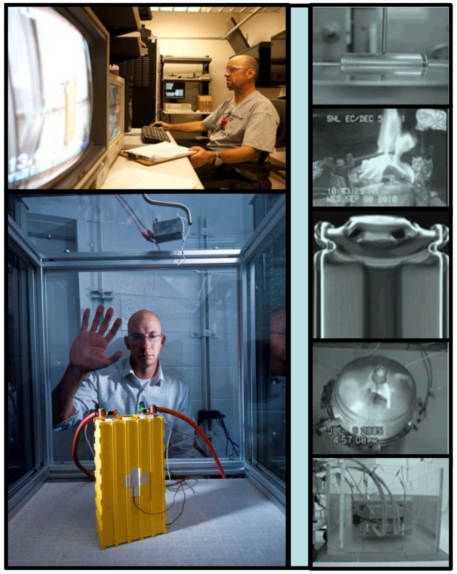
Upcoming work:

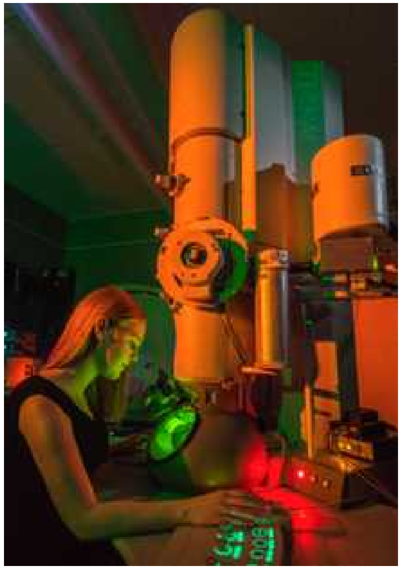
- Calculation of derived quantities (capacity loss)
- Data archival, metadata in searchable database
- Comparison/plotting of multiple data sets

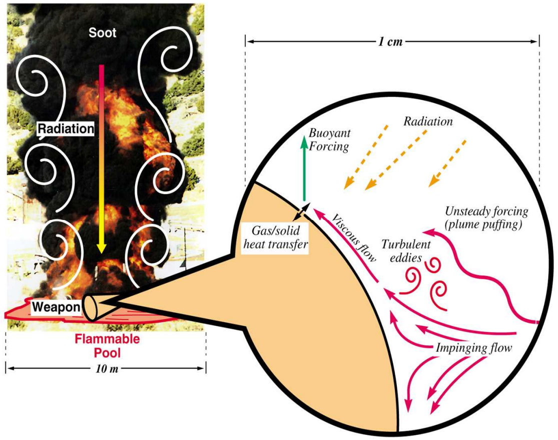
Battery safety R&D fits capabilities

Sandia National Laboratories

- Sandia houses a suite of capabilities to address ESS safety R&D
  - Battery abuse lab designed for explosive force and conflagration
  - Modeling of high energy events with Sierra
  - Center for Integrated Technology
  - Distributed energy test lab





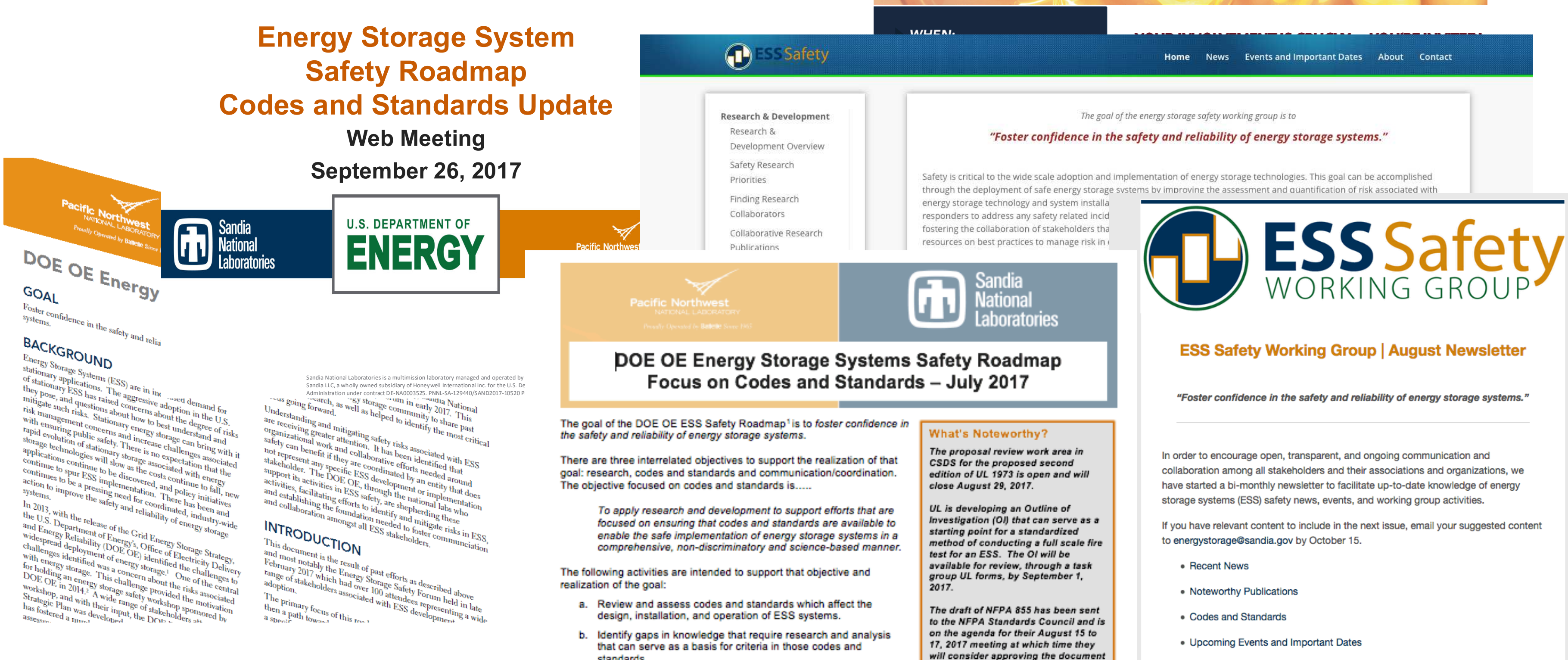


Safety Thrust Strategy and Outreach

Sandia National Laboratories

2017

- Energy Storage Safety Forum
- Energy Storage Safety Roadmap
- ESS Safety Website launch
- CS Reports, and Newsletters, Webinars



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