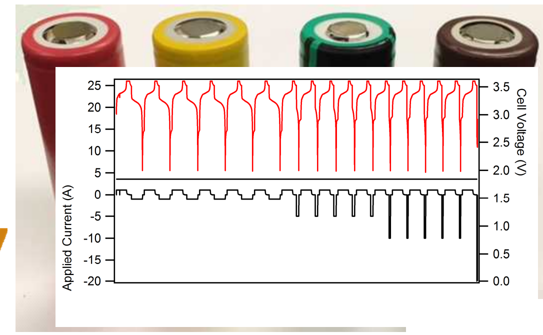
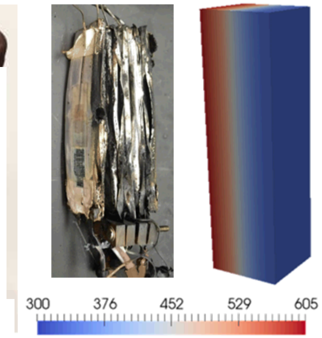
SAND2017-11767C





The DOE OE Energy Storage Systems Safety Roadmap

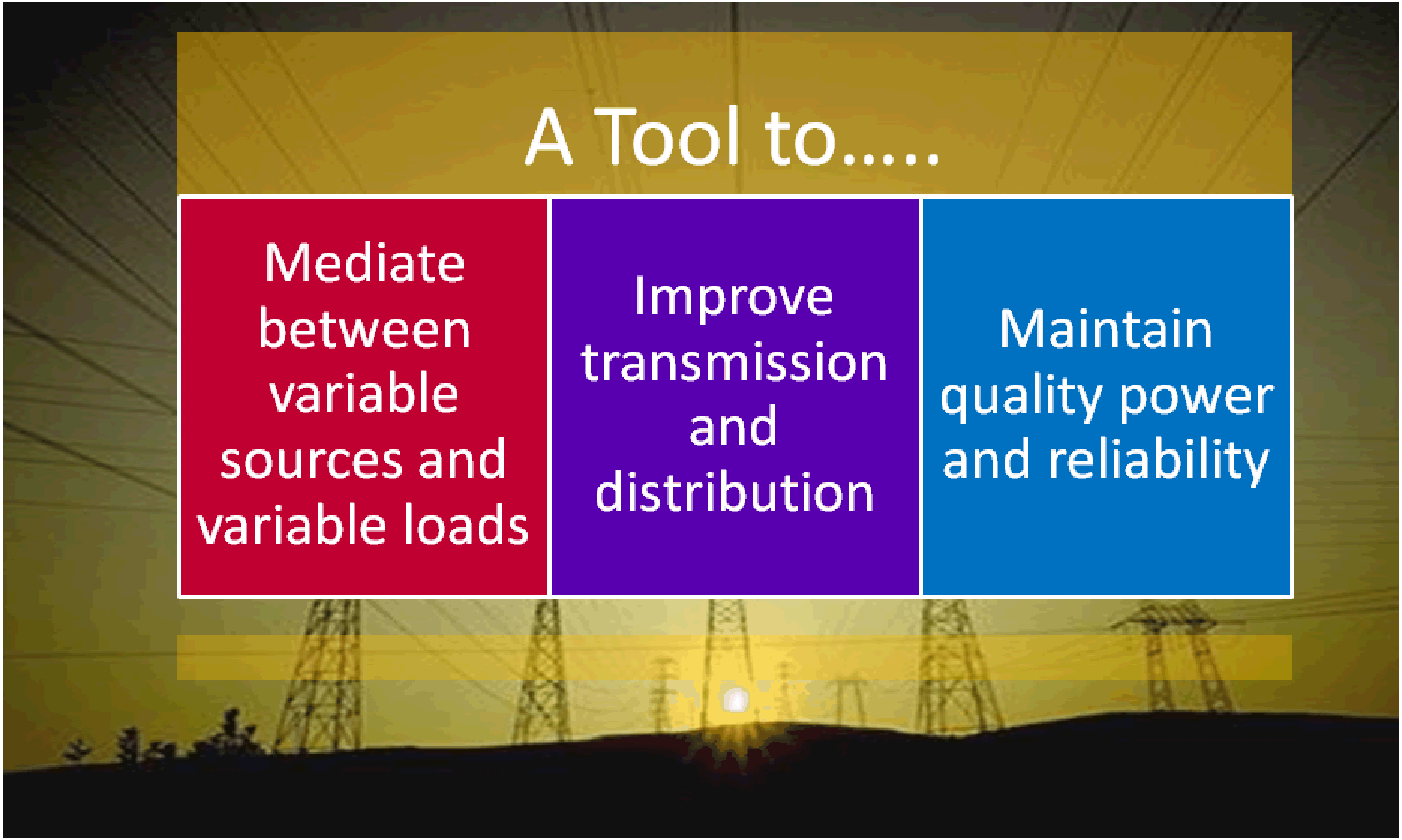
Fostering Confidence in the Safety and Reliability of ESS

Summer Ferreira

Battery Safety 2017
Thursday Nov 2, 2017

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2017-10747 C

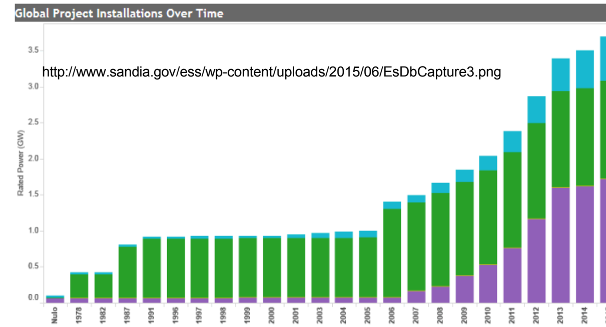
What is Energy Storage?



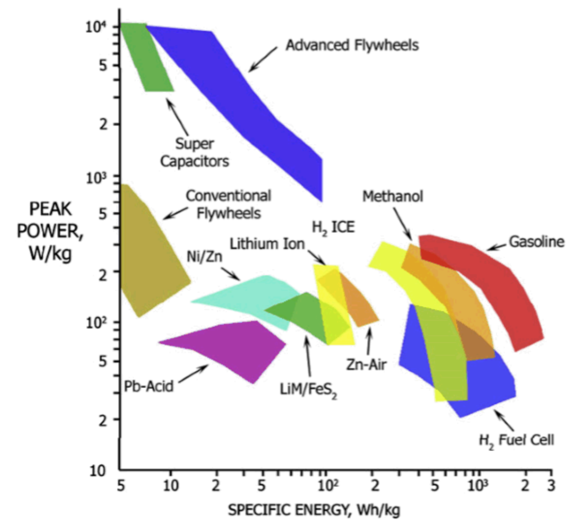
The Grid Energy Storage Safety Challenge

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


Subway regen system, SEPTA




SAFT 10 MWh storage system

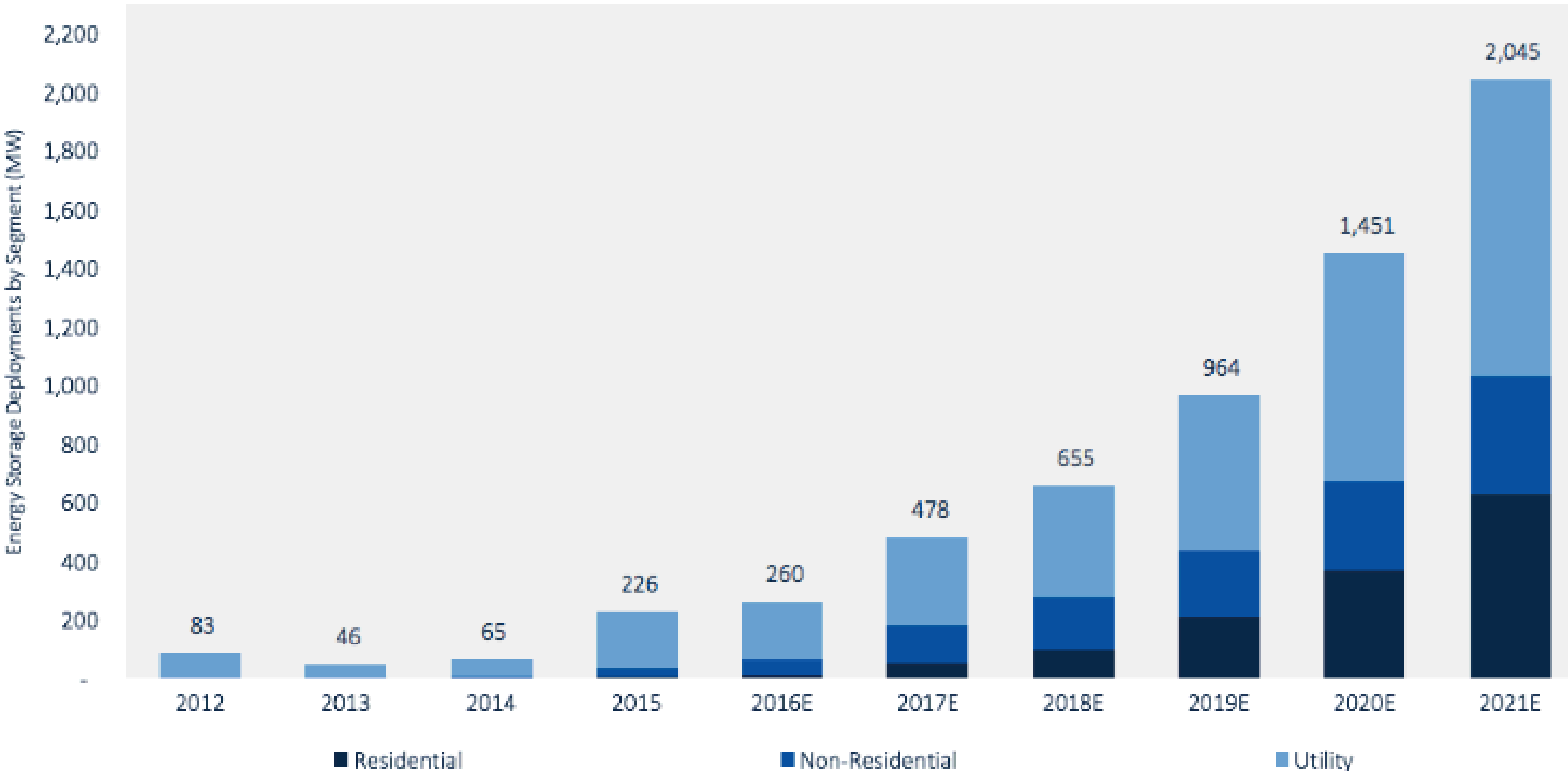


Safety is about reducing risk:

Where risk encompasses consequence and likelihood

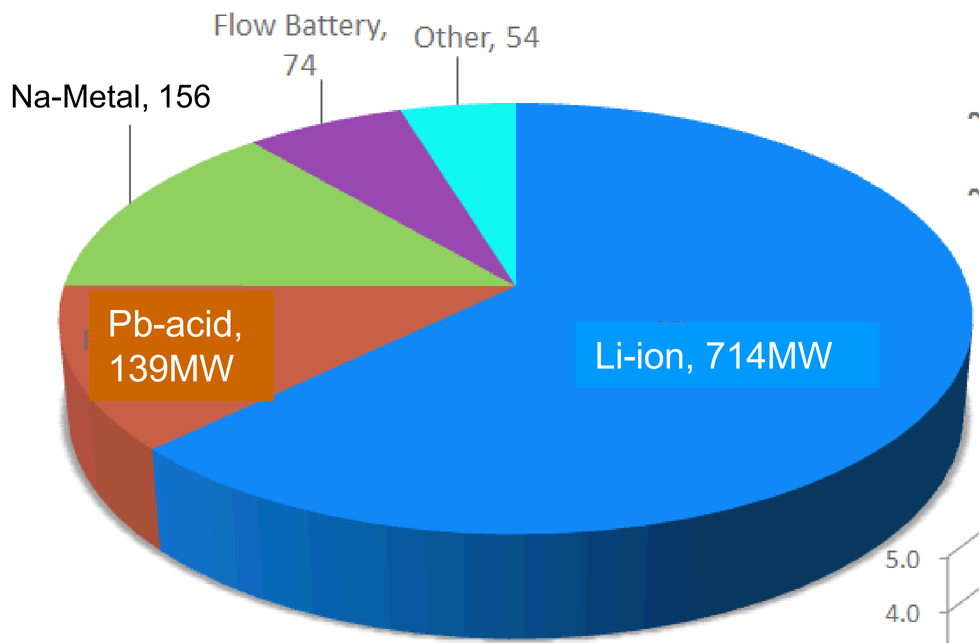
DRIVERS

Energy Storage – Projected Deployment



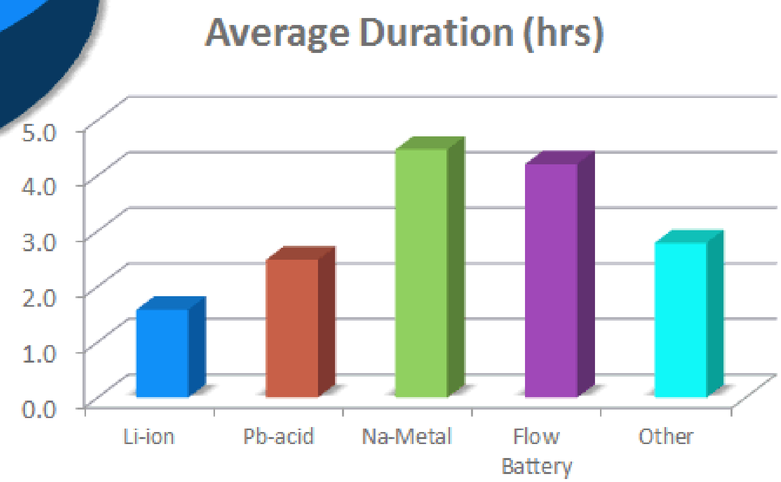
Source – Green Tech Media Inc

Global Energy Storage Deployments (Battery Only)



~ 1.1 GW of Battery Energy Storage

~110 GW of Pumped Hydro

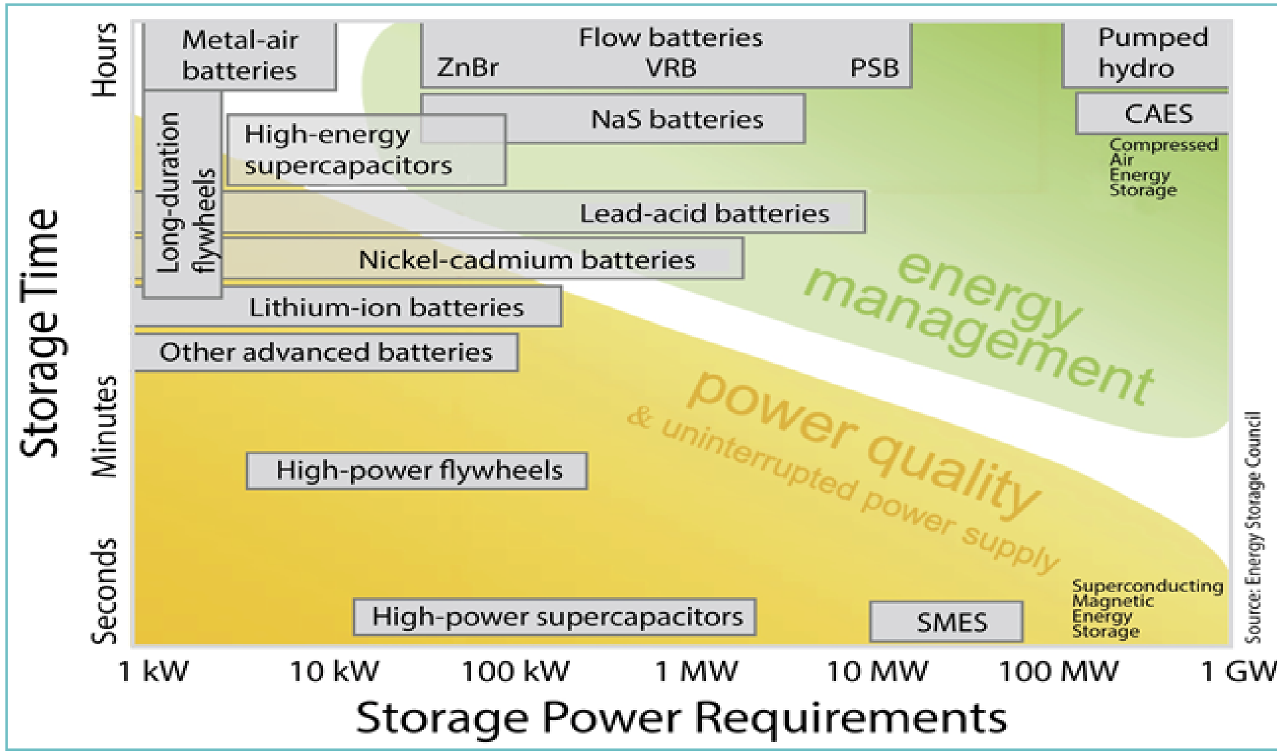


Source: *DOE Global Energy Storage Database http://www.energystorageexchange.org/*
July 2015

Energy Storage Technologies

Energy – long discharges (min to hr) ala a "10K"

- Pumped Hydro
- Compressed Air Energy Storage (CAES)
- Electrical Storage (Batteries)
- Sodium Sulfur (NaS)
  - Flow Batteries
  - Lead Acid
  - Advanced Lead Carbon
  - Lithium Ion
- Flywheels
- Electrochemical Capacitors



Power – short discharges (sec to min) ala a "100 m sprint"

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Policy Incentives and Mandates

The demand for energy storage can be accelerated through policy initiatives and incentives that provide needed support until the market matures.

- Install 1.4 gigawatts of storage capacity in New York City
- CA PUC initiative
- MA storage requirement
- OR storage requirement

CA.GOV California Public Utilities Commission

Oregon PUC Public Utility Commission

Energy and Environmental Affairs

Strategy and outreach

2013
- DOE OE Grid Energy Storage
  - Highlighted Validated Safety as needed thrust area

2014
- DOE OE Energy Storage Safety Workshop
- Energy Storage Safety Strategic Plan

2015
- Working groups formed
- R&D priorities identified

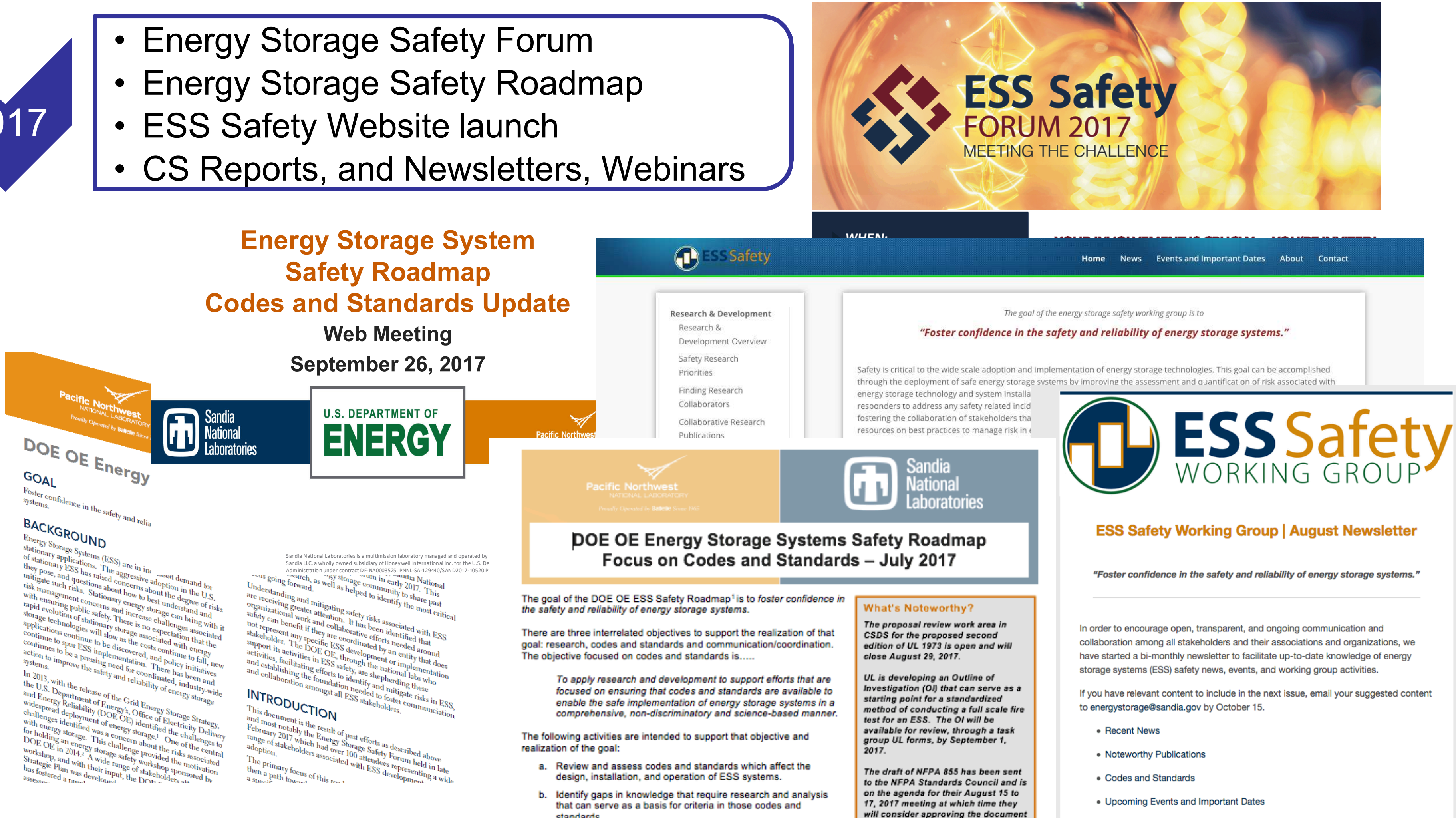
2016
- 2 articles and 7 documents
  - Regular meetings of working groups
  - Involvement in 7 standards and numerous conferences

2017
- Energy Storage Safety Forum
- Energy Storage Safety Roadmap
- Website, monthly CSR document, bimonthly newsletter

Safety Thrust Strategy and Outreach

2017

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



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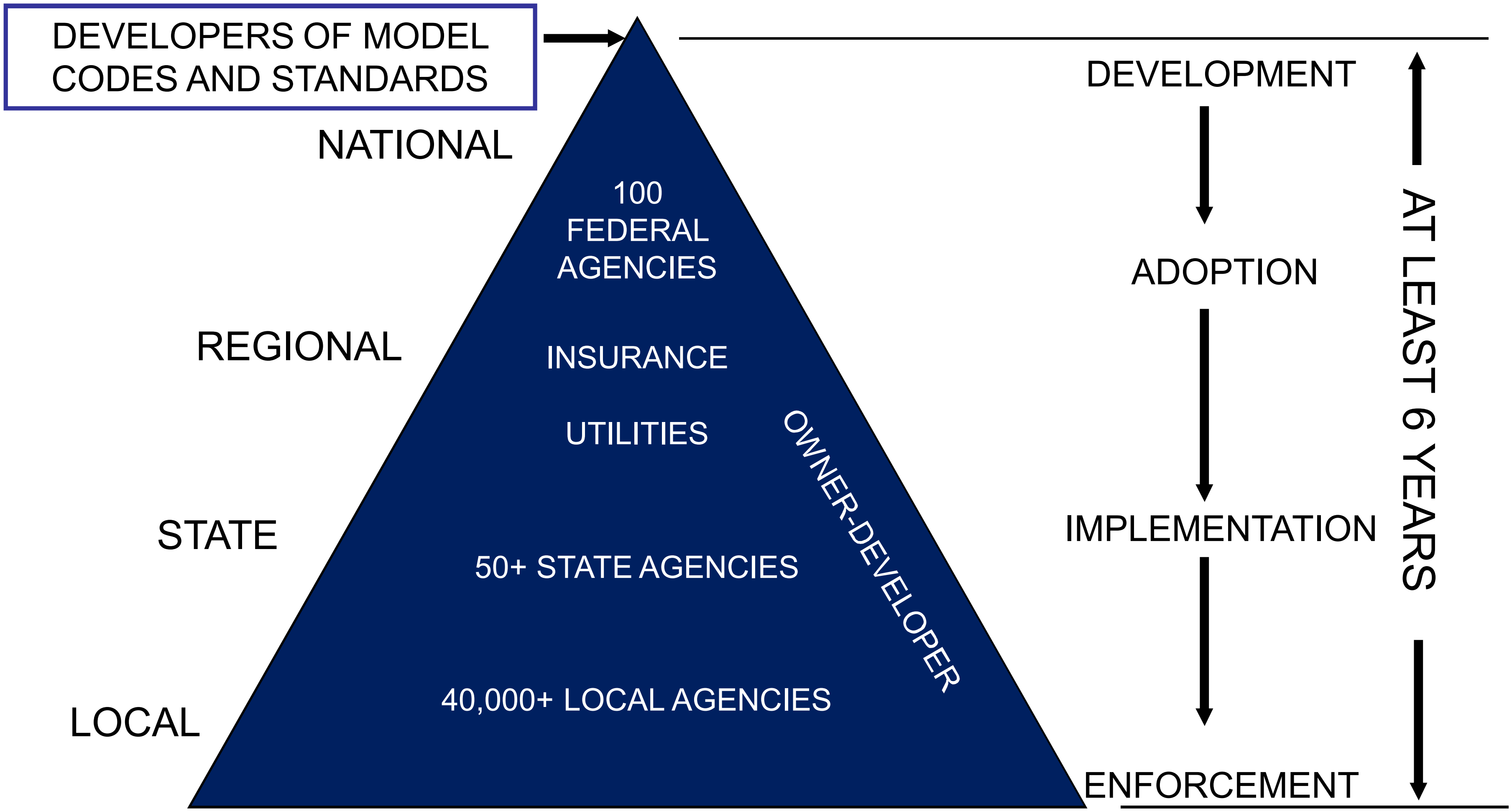
Model Codes and Standards

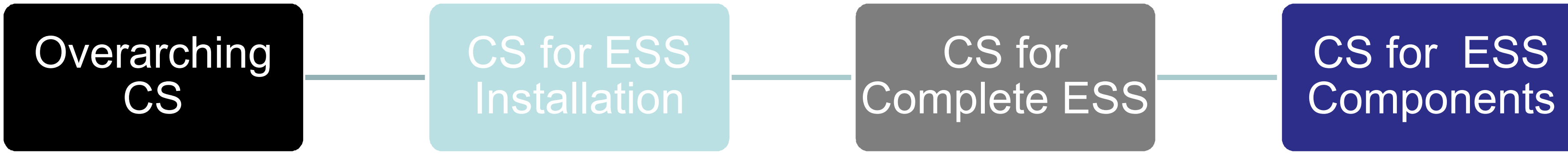
Identifying the **codes and standards that address the safety issues**

- Model codes and standards in the aggregate address the design, construction, commissioning, rehabilitation, operation, maintenance, repair, and demolition of components of the built environment, such as buildings, facilities, products, systems, and equipment therein.
- Standards each have a very specific scope and where needed will reference other standards.
- Model codes reference standards.
- Regulations, rules, laws, specifications, tariffs, contracts, and other means are the vehicles by which those model codes and standards are adopted.
- When adopted, the model codes and standards must be satisfied subject to any penalties associated with non-compliance.

Development and Deployment



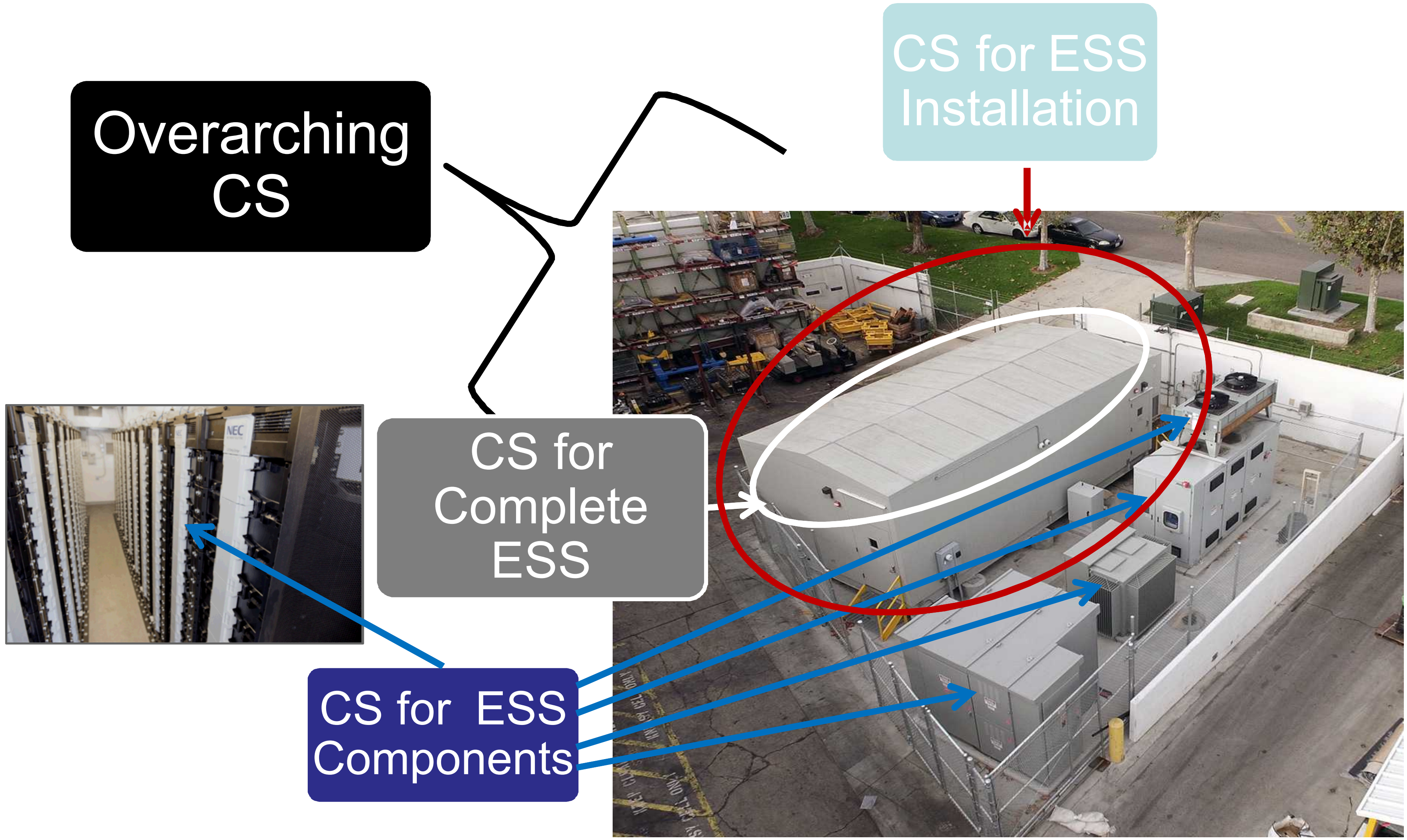
U.S. Model Codes and Standards



Model codes and standards have varying scopes relative to energy storage systems

- **Overarching – cover the built environment at large and that includes energy storage systems.**
- **Installation – address the installation of the energy storage system in relation to other systems and parts of the built environment.**
- **Complete – the entire energy storage system in the aggregate.**
- **Components – components associated with the energy storage system.**

U.S. Model Codes and Standards



U.S. Model Codes and Standards

Specific Overarching CS

- NFPA
  - 1-15 – Fire Code (next activity is to approve the 2018 edition for publication and then develop the 2021 edition)
  - 70-17 – National Electrical Code (next activity is to develop the 2020 edition)
  - 5000-15 – Building Code (next activity is to approve the 2018 edition for publication and then develop the 2021 edition)
- ICC
  - 2015 International Fire Code (next activity is to publish the 2018 edition and develop the 2021 edition)
  - 2015 International Residential Code (next activity is to develop the 2021 edition)
  - 2015 International Mechanical Code (next activity is to develop the 2021 edition)
  - 2015 International Building Code (next activity is to develop the 2021 edition)
- IEEE
  - C2-17 – National Electrical Safety Code

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U.S. Model Codes and Standards

CS for ESS Installation

- NFPA
  - 855-X – Standard for the Installation of Stationary Energy Storage Systems (first draft being finalized - anticipate the opportunity for public input from August until October 2017)
- NECA
  - 416-17 – Recommended Practice for Installing Stored Energy Systems (approved for publication and a new appendix containing a compliance checklist is under development)
- IEEE
  - 1653-2012 – Guide for Ventilation and Thermal Management of Batteries for Stationary Applications (proposed revisions were recently out for public review, comments are being resolved and release of a 2017 edition is expected in September)

U.S. Model Codes and Standards

CS for
Complete ESS

- **ASME**
  - TES-1 – Safety Standard for Thermal Energy Storage Systems (first draft being developed)
- **NFPA**
  - 791-14 – Recommended Practice and Procedures for Unlabeled Electrical Equipment (next activity is to approve the 2018 edition for publication and then develop the 2021 edition)
- **UL**
  - 9540 – Safety of ES Systems and Equipment (under continuous maintenance)

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U.S. Model Codes and Standards

CS for ESS Components

- **UL**
  - **810A – Electrochemical Capacitors (under continuous maintenance)**
  - **1741 – Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources (under continuous maintenance)**
  - **1973 – Batteries for Use in LER and Stationary Applications (under continuous maintenance)**
  - **1974 – Evaluation of Batteries for Repurposing (new standard and development of content is just getting started)**
- **CSA**
  - **283 – Battery Reuse (new standard and development of content is just getting started)**

IEC International Standards

- 62813: Lithium-Ion Capacitors for Use in Electric and Electronic Equipment – Test Methods for Electrical Characteristics
- 62932-1 (under development): Secondary Cells and Batteries of the Flow Type: Flow Batteries – Guidance on the Specification, Installation and Operation
- 62933-1 (under development): Electrical Energy Storage (EES) Systems – Part 1: Terminology
- 62933-2-1 (under development): Electrical Energy Storage (EES) systems – Part 2-1: Unit Parameters and Testing Methods – General Specification
- 62933-3-1 (under development): Electrical Energy Storage (EES) systems – Part 3-1: Planning and Installation – General Specification
- 62933-4-1 (under development): Electrical Energy Storage (EES) systems – Part 4-1: Guidance on Environmental Issues

IEC International Standards

- 62933-5-1 (under development): Electrical Energy Storage (EES) systems – Part 5-1: Safety Considerations Related to Grid Integrated Electrical Energy Storage (EES) Systems
- 62933-5-2 (under development): Electrical Energy Storage (EES) systems – Part 5-2: Safety Considerations Related to Grid Integrated Electrical Energy Storage (EES) Systems – Batteries
- 62932-1 (under development): Secondary Cells and Batteries of the Flow Type: Flow Batteries – Guidance on the Specification, Installation and Operation
- 62932-2-1 (under development): Flow Batteries – General Requirement and Test Method of Vanadium Flow Batteries
- 62932-2-2 (under development): Flow Battery Technologies – Safety

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U.S. Safety-Related Criteria

- **EPRI**
  - ESIC Energy Storage Implementation Guide 2016 (Updates 2015 Integration Guidelines)
  - ESIC Energy Technical Specification Template 2016
  - ESIC Energy Storage Commissioning Guide 2016
  - Energy Storage Safety 2016
- **DNV GL**
  - GRIDSTOR-RP-0043 Safety, Operation and Performance of Grid-connected Energy Storage Systems (2nd edition under development and out for public review 55/22 to 6/23)
- **MESA**
  - Modular Energy Storage Architecture MESA-ESS (draft specification) provides a standard framework for utility-scale ESS data exchanges

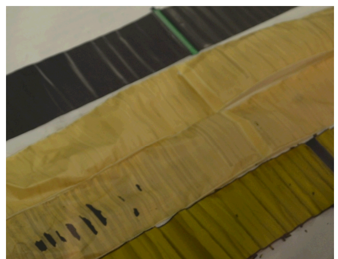
Improving battery failure mitigation

Resource: Common Data architecture, metadata and metrics software

Collaboration: codes, standards, and regulations

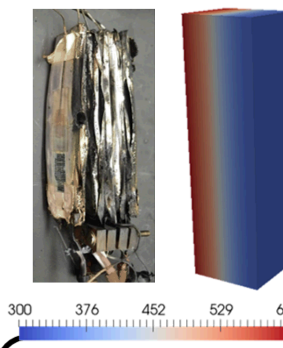
Collaboration: incident response

Baseline electrochemical performance analysis



Materials characterization and thermal stability testing

Electrochemical and whole-cell and string abuse response analysis

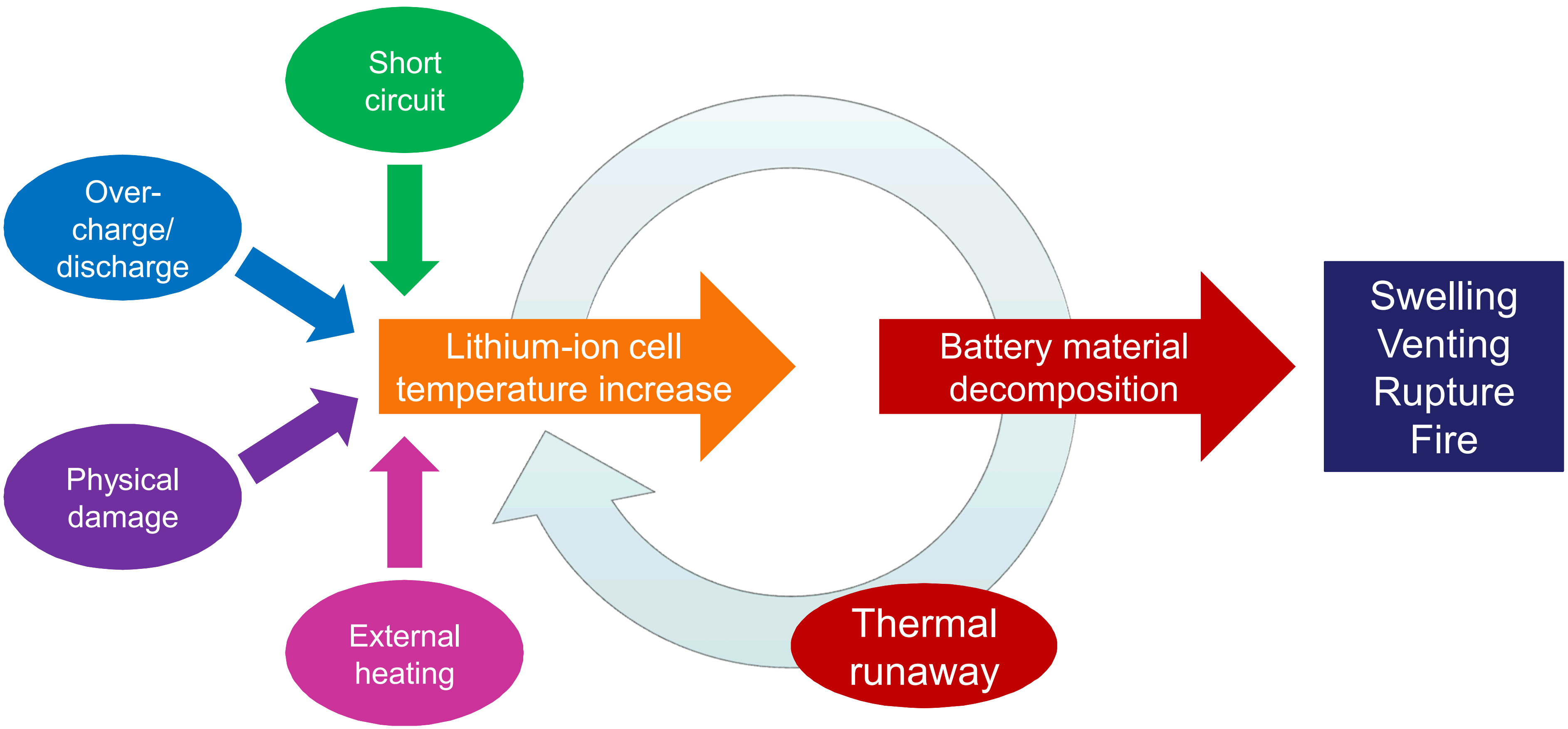


Modeling of thermal propagation

Resource: Online Data Repository

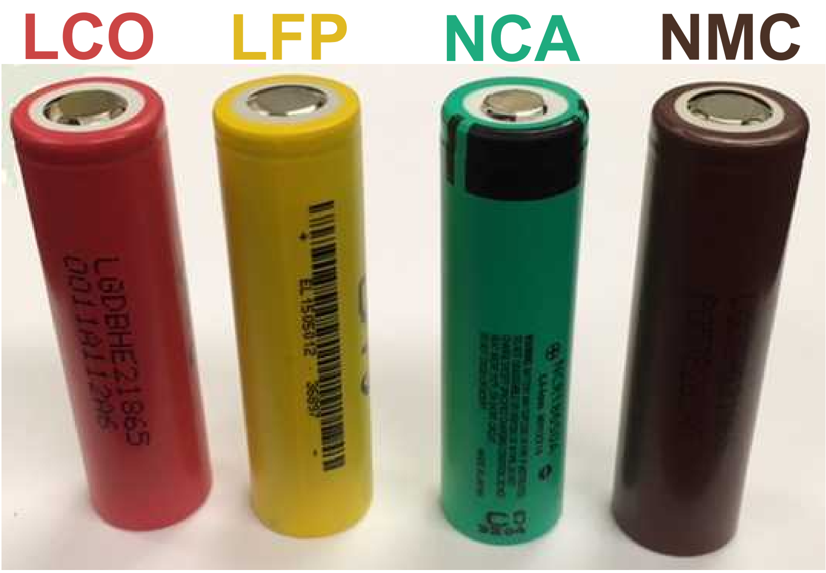
Collaboration: vent plume composition (NM Tech)

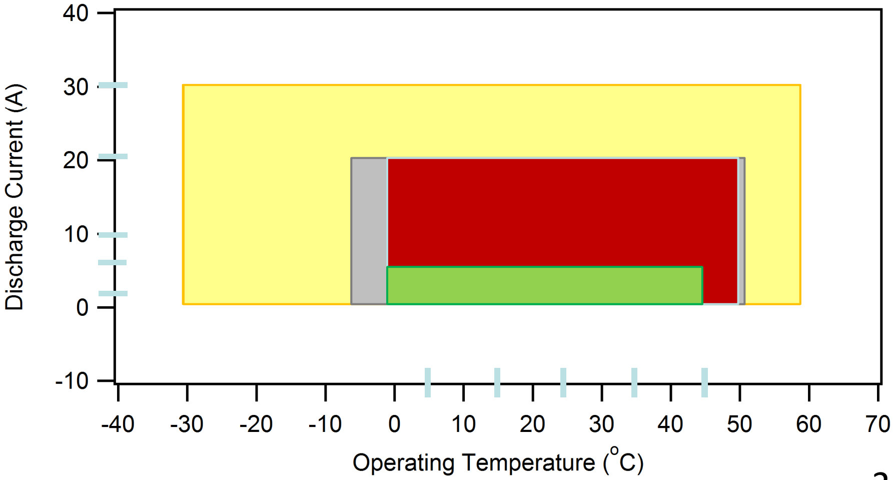
Thermal runaway is cascading failure



Cell operation constraints

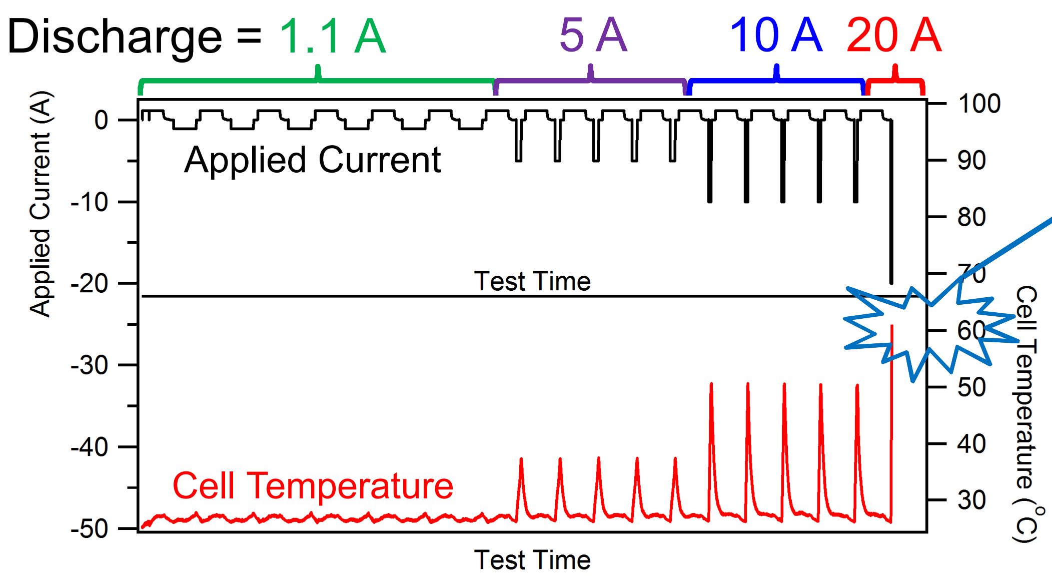
Cathode Chemistry	AKA	Specific Capacity (Ah)	Average Potential (V vs Li°/Li+)	Max Discharge Current	Acceptable Temperature (°C)
[redacted]					
$LiFePO_4$	LFP	1.1	3.3	30	-30 to 60
[redacted]					
$LiNi_{0.80}Mn_{0.15}Co_{0.05}O_2$	NMC	3.0	3.6	20	-5 to 50





Avoiding accelerated aging or abuse

LFP, 25 °C environment



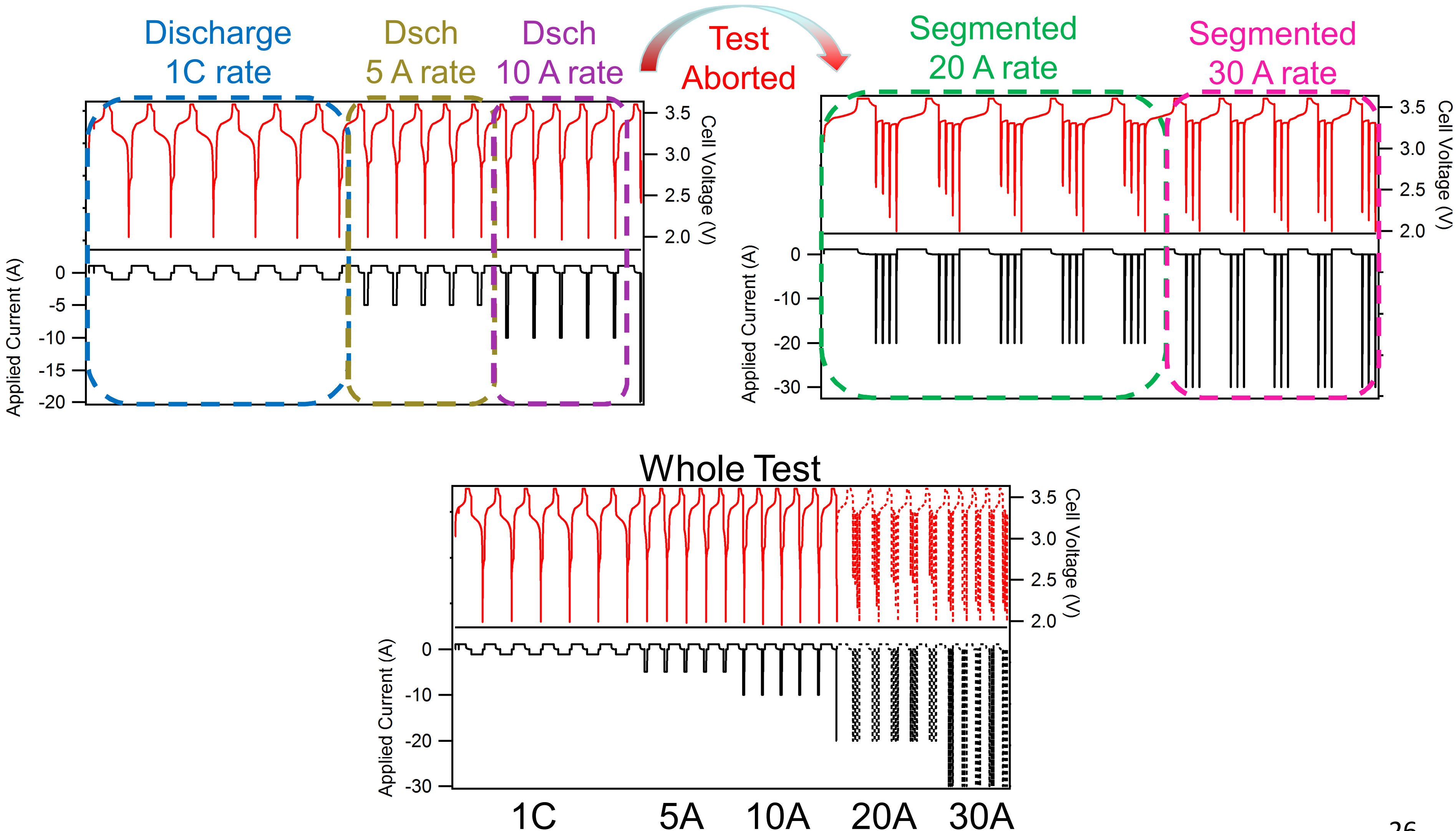
Current = 20 A (max = 30 A)
Environment = 25 °C
Cell skin Temp = 60 °C!!!

Most packs don't monitor individual cell skin temperatures.
Unintended abuse condition under 'normal' operation.

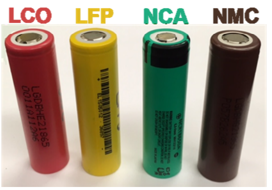
Pristine Cell

Abused Cell

Evaluating cell chemistries uniformly



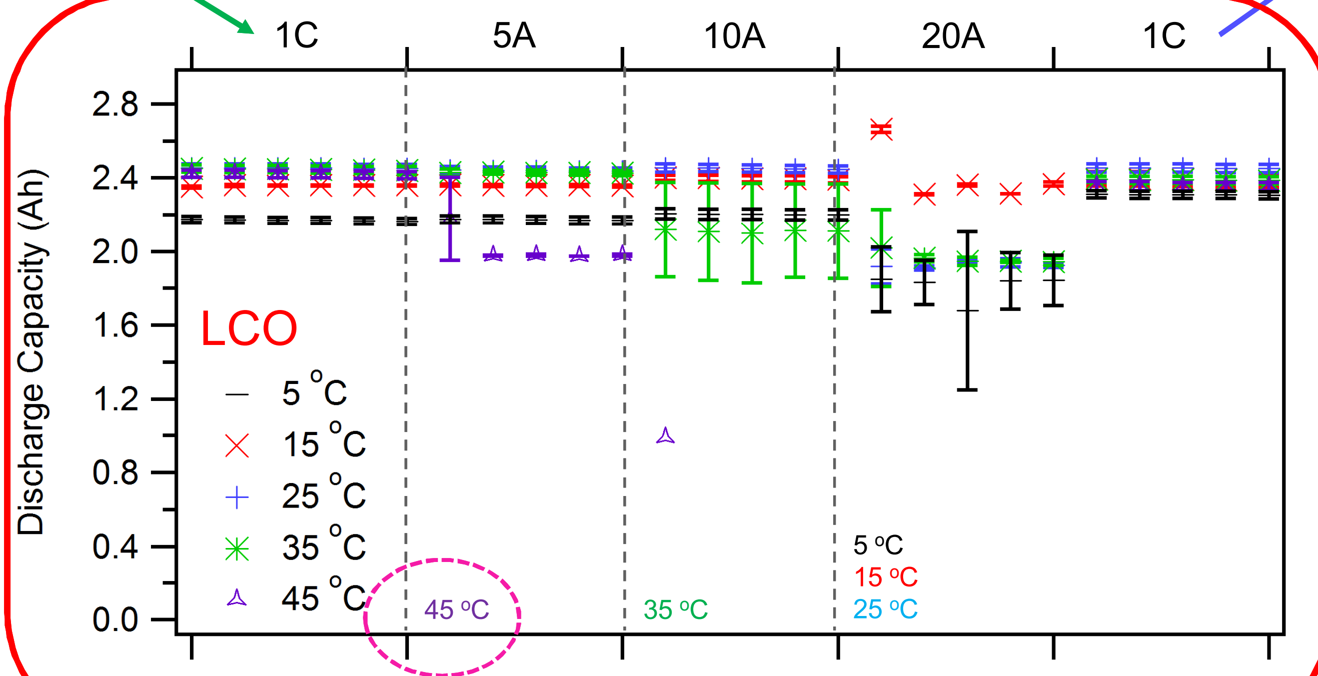
Cycling data for each chemistry is coalesced on one plot



Discharge current

Corresponds to red LCO

@ 25 °C

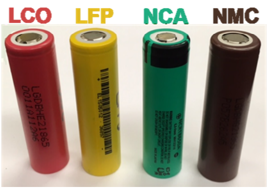


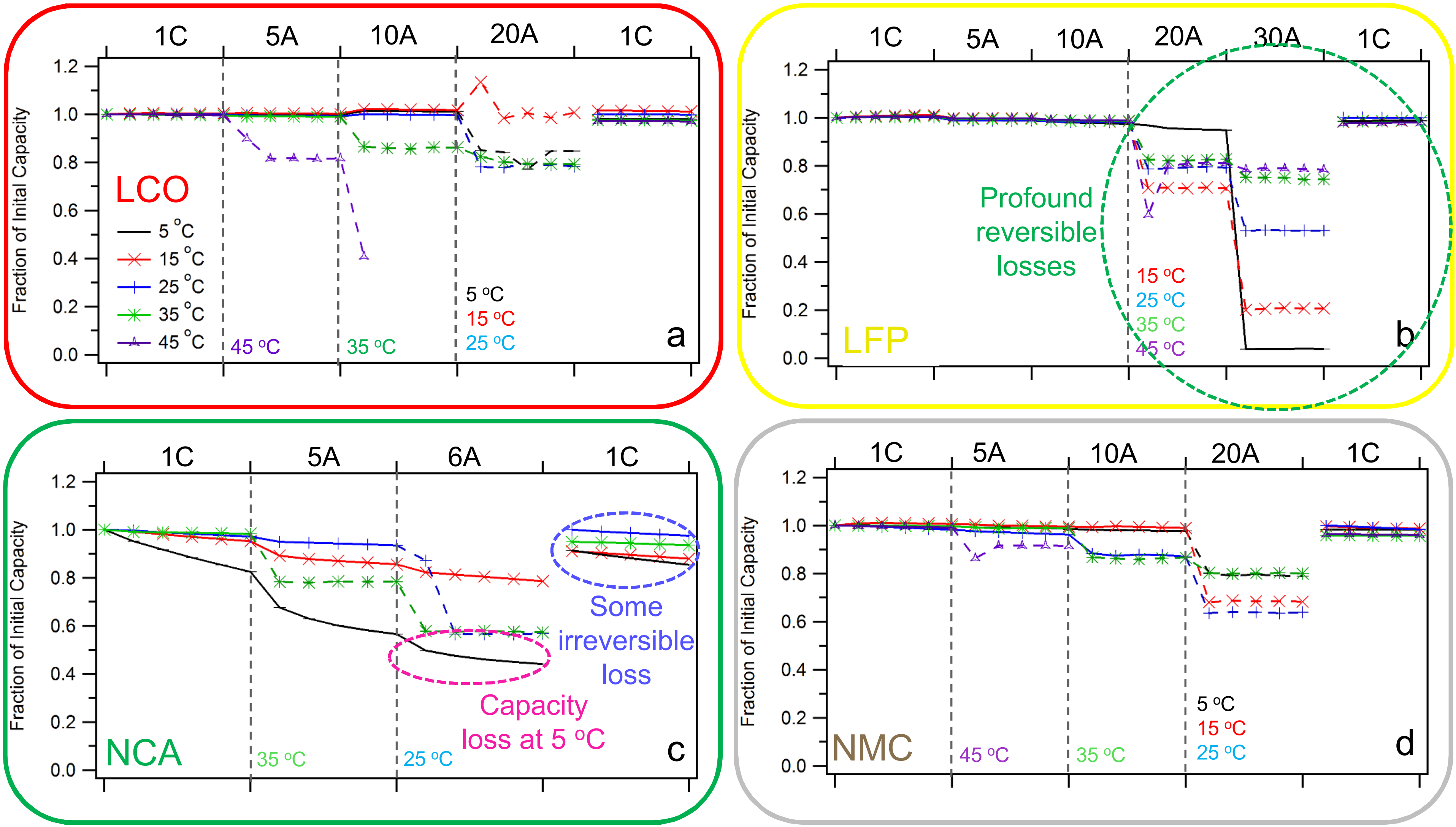
Segmented discharging began at 45 °C

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*

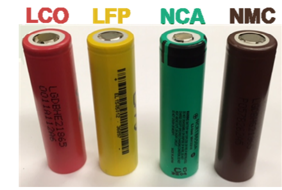
NCA experiences lasting capacity losses after cycling

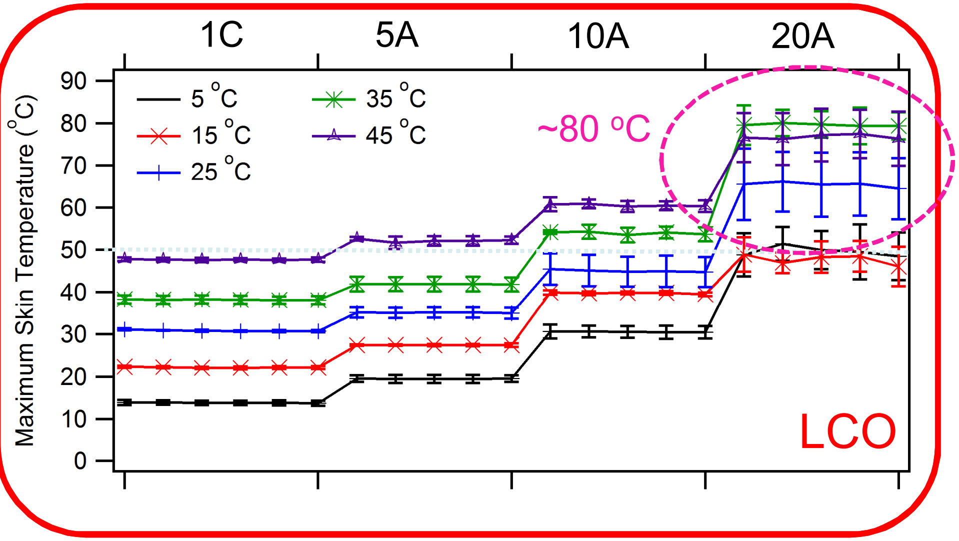


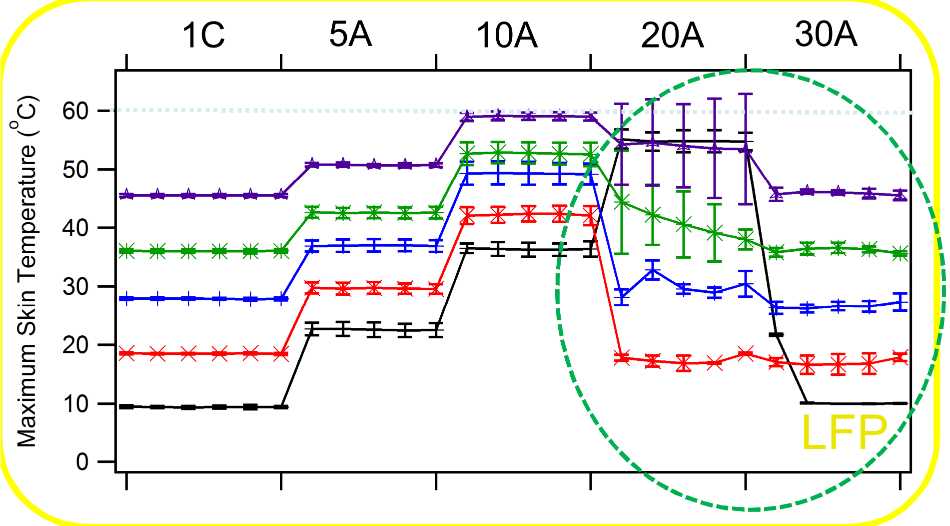


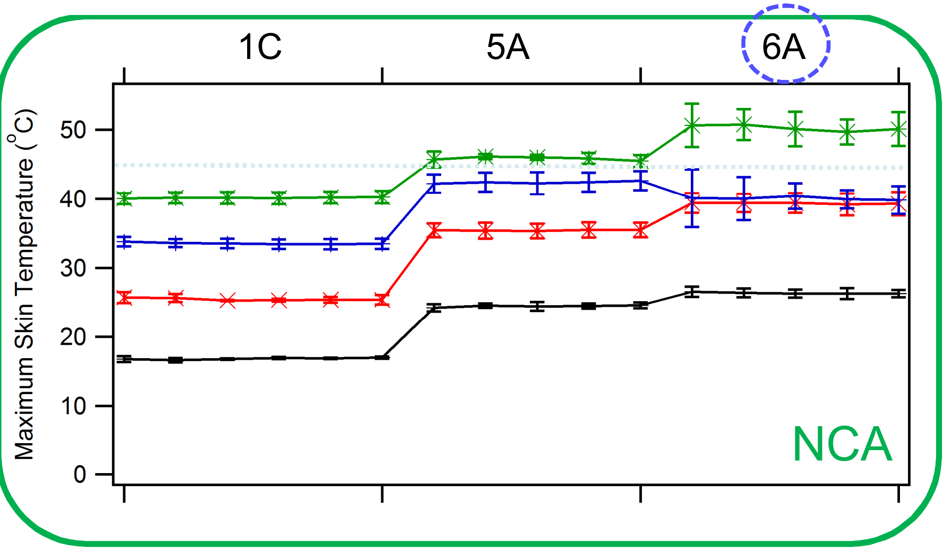
DOI: 10.1149/2.1701712jes J. Electrochem. Soc. 2017 V 164, 12 A2697

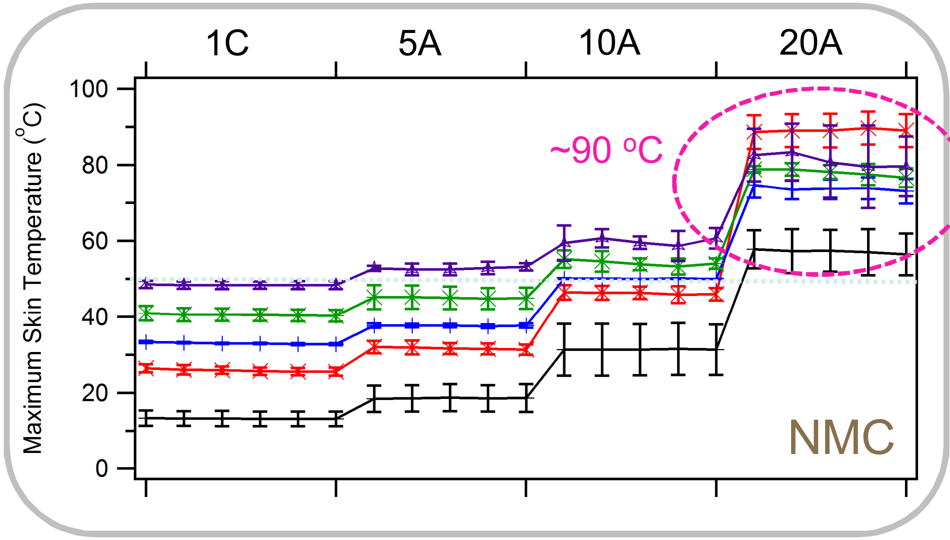
Significant self-heating can occur if cells are unmonitored



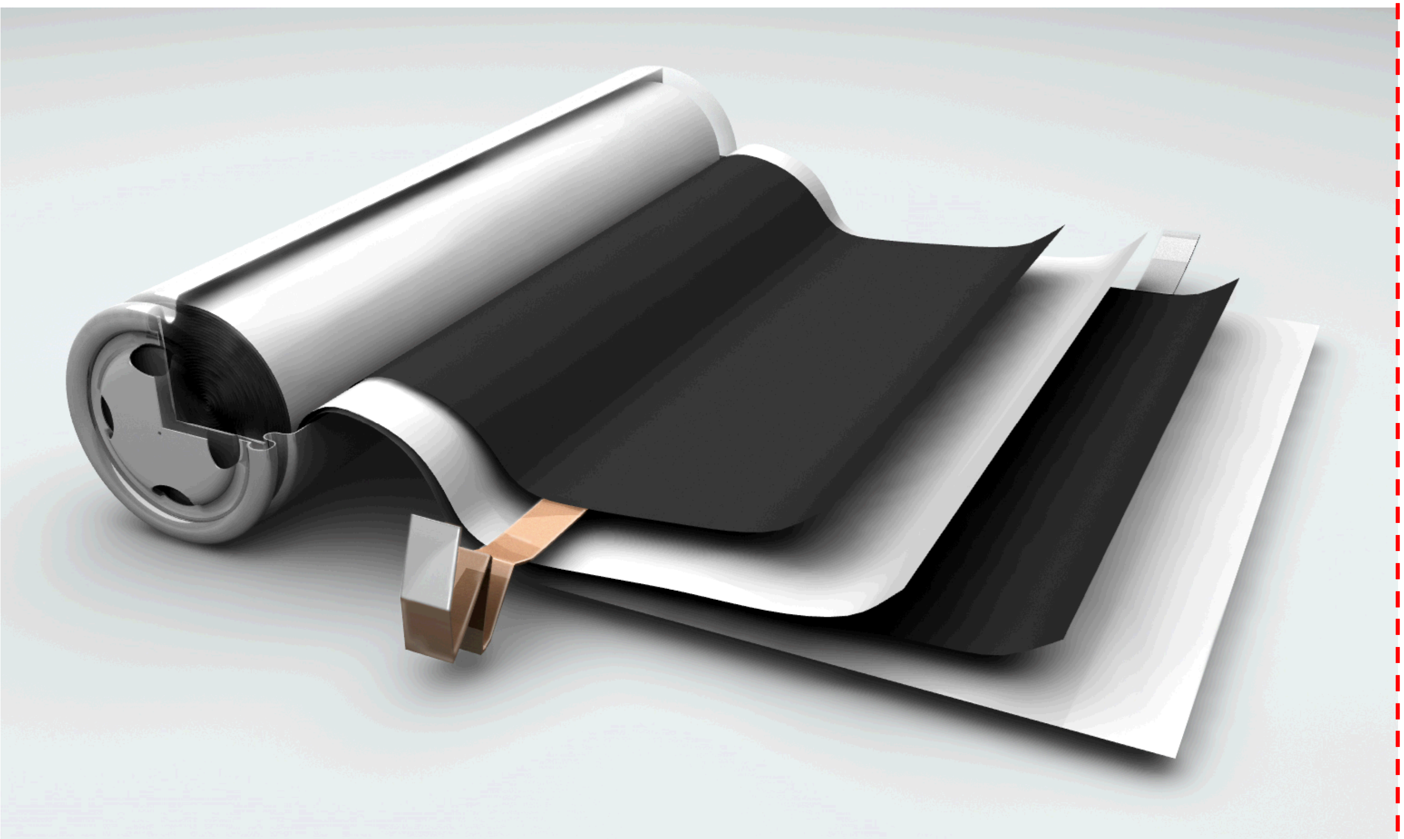


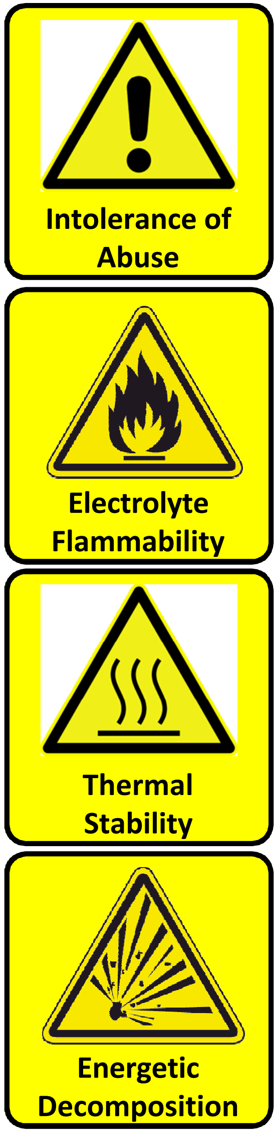






Challenges with lithium-ion battery safety



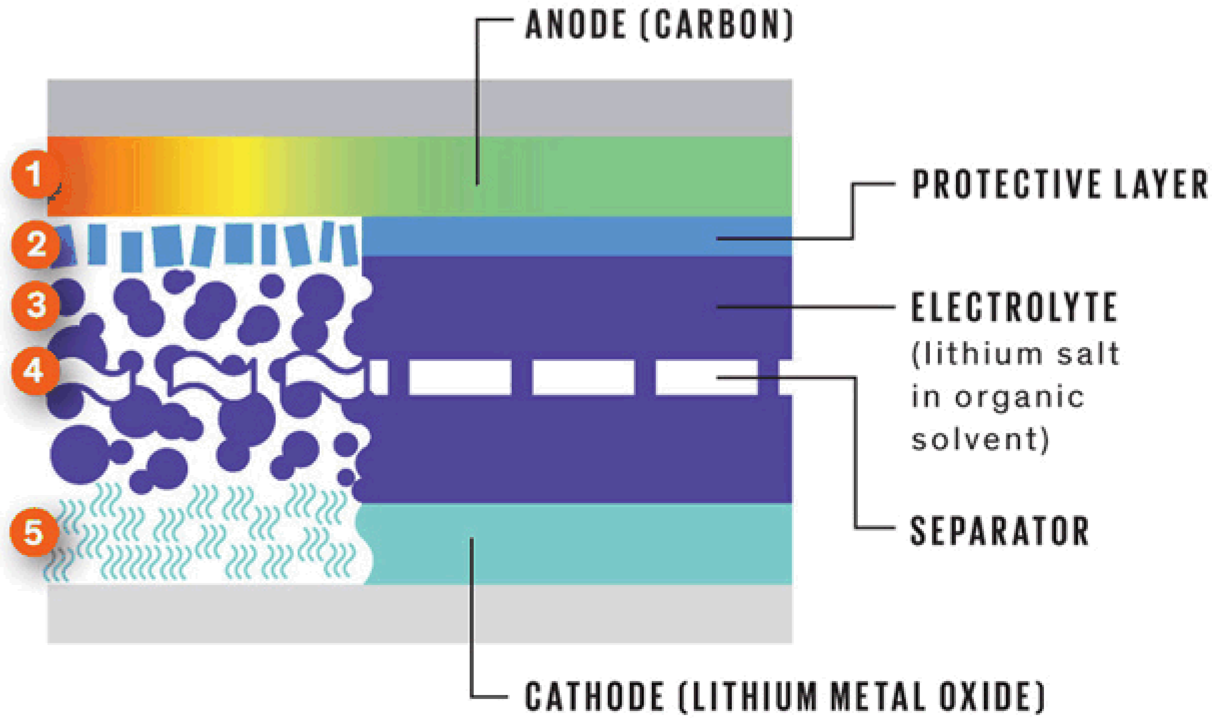


If we can figure out where issues are coming from, we can design better batteries

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

Batteries are disassembled to reveal steps of failure

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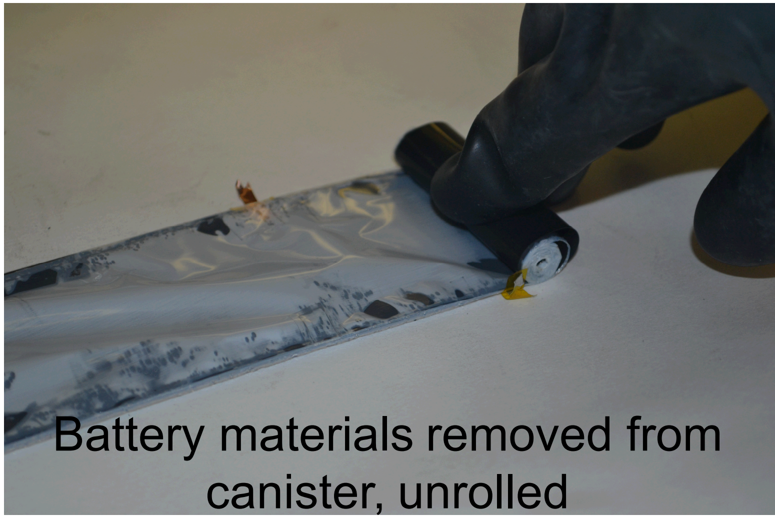
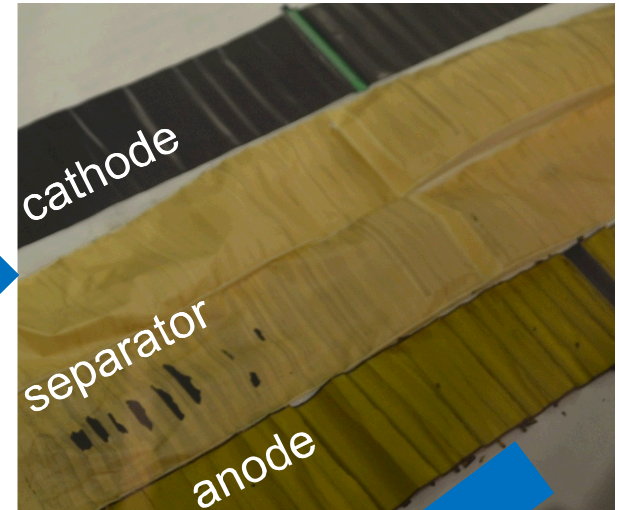
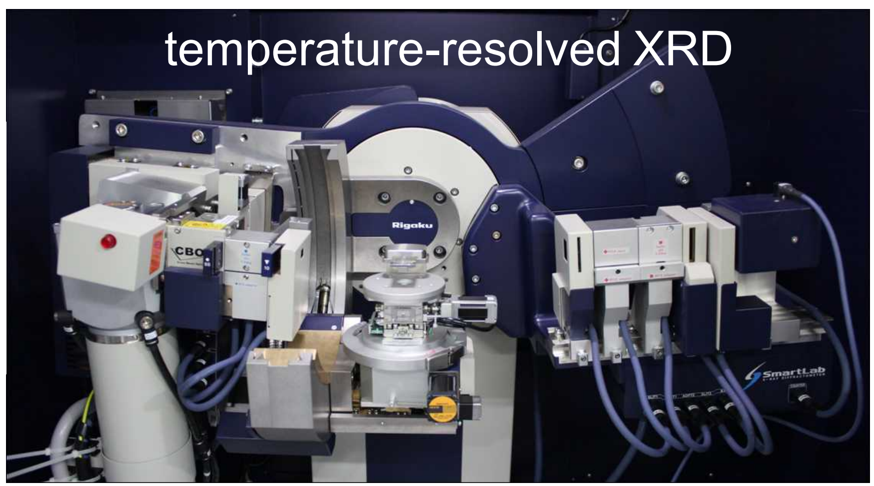


Battery materials removed from canister, unrolled

Disassembly

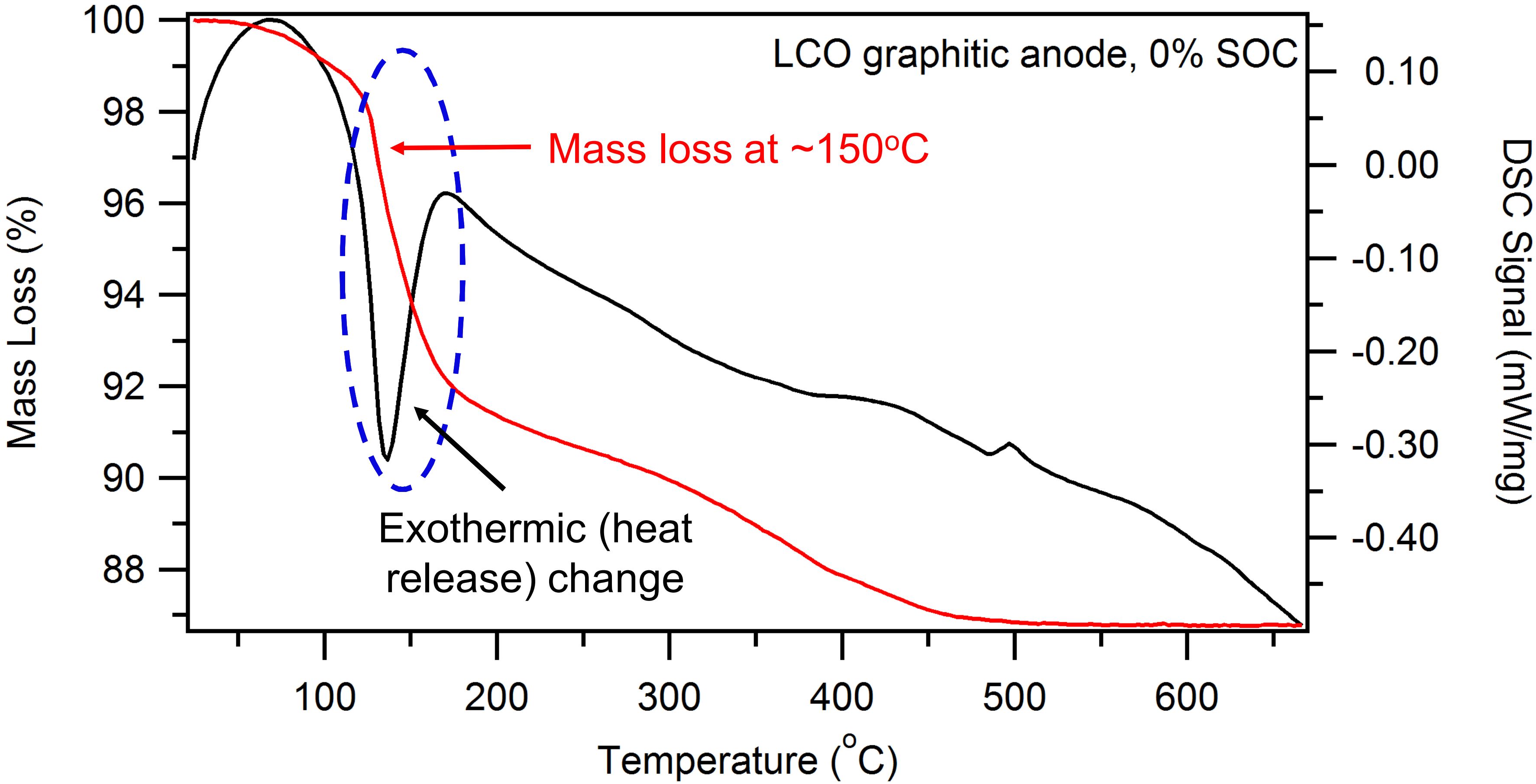




temperature-resolved XRD

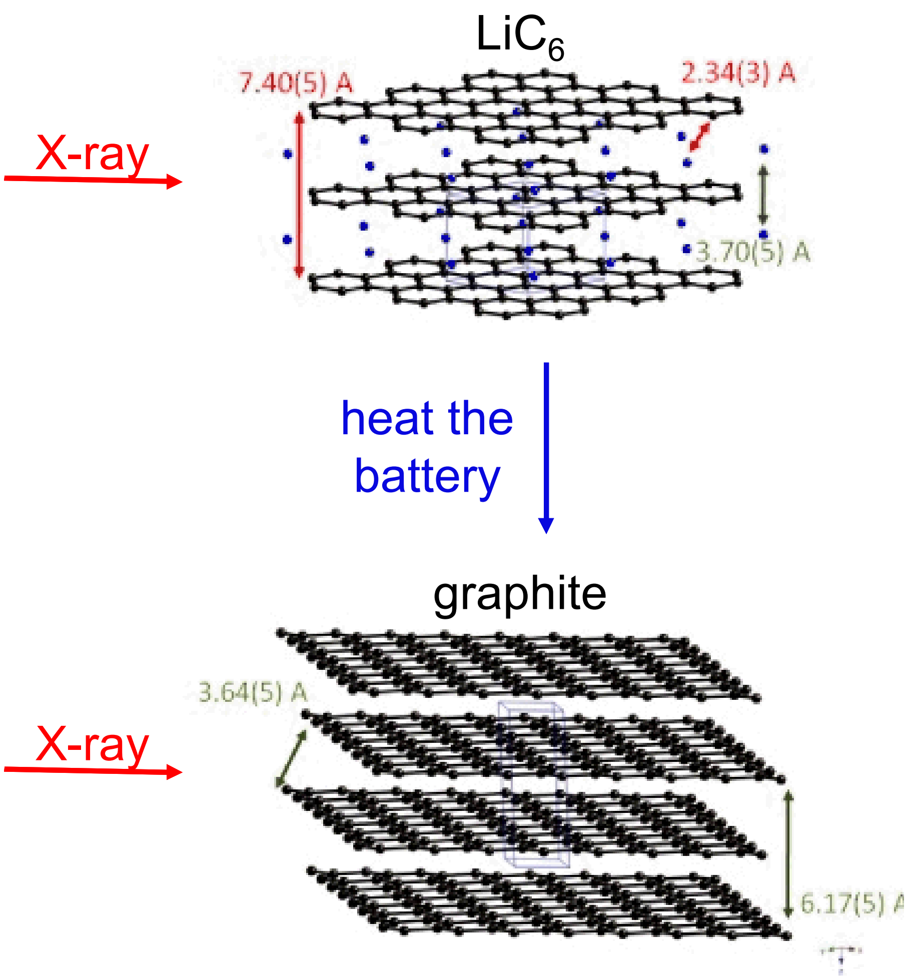
Temperature-resolved XRD shows how the material changes with temperature

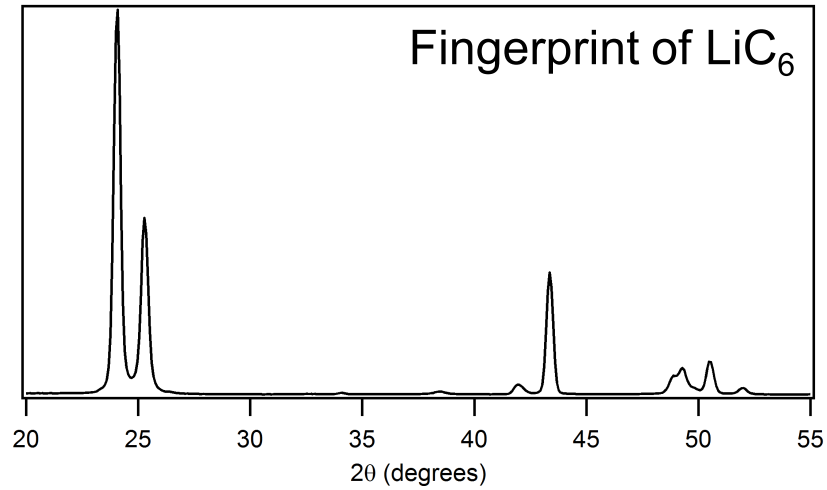
TGA/DSC reveals thermal stability

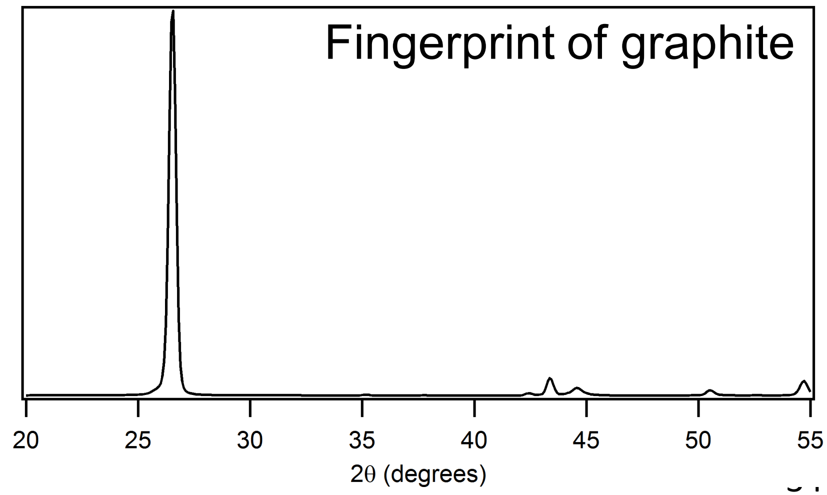


We have learned that the anode loses mass at 150°C and this also releases heat

Temperature-resolved XRD exposes decomposing structure

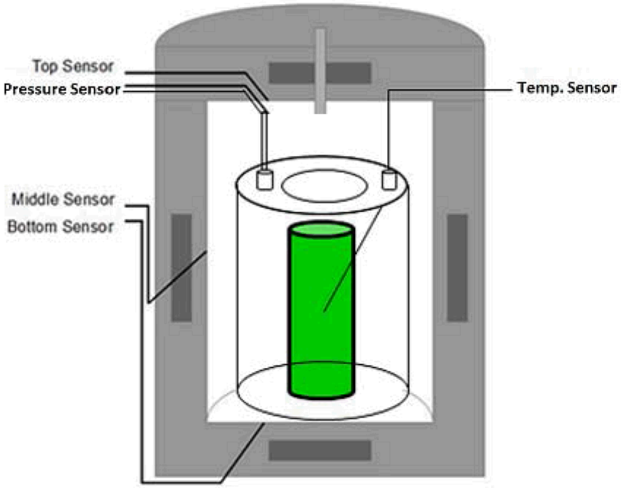


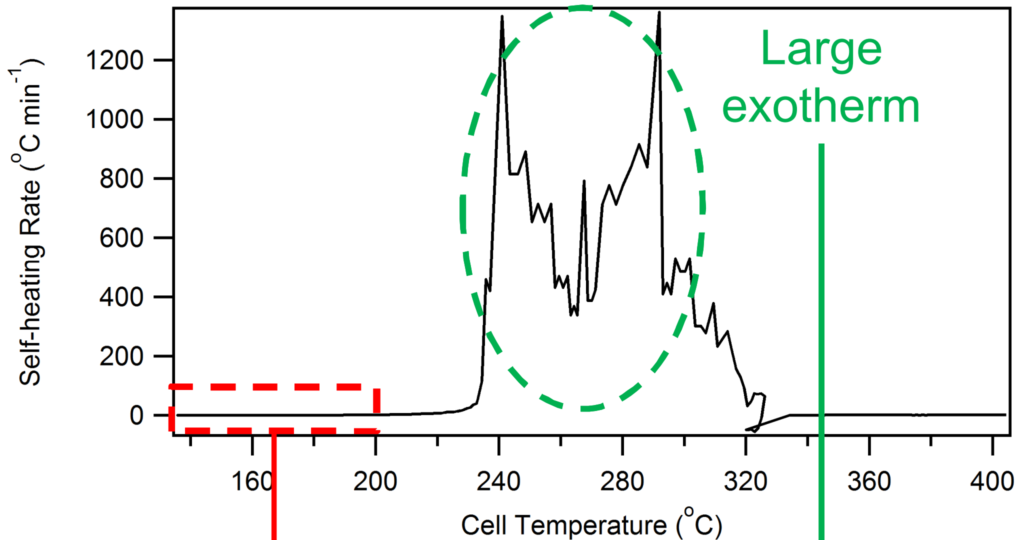


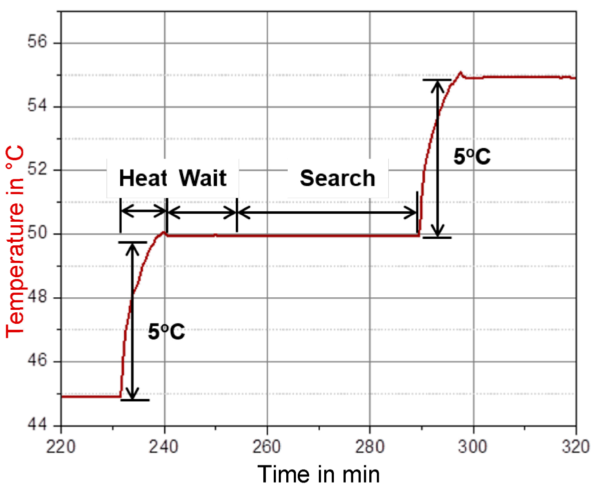


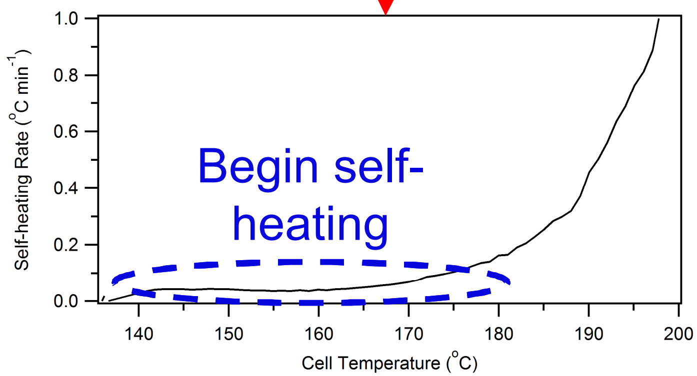
Schematic of LiC_6 and graphite: V. Petkov, A. Timmons, J. Camardese “Li insertion in ball-milled graphitic carbon studied by total x-ray diffraction” *Journal of Physics: Condensed Matter* **2011**, 23, 435003.

Accelerating Rate Calorimetry (ARC) demonstrates thermal runaway





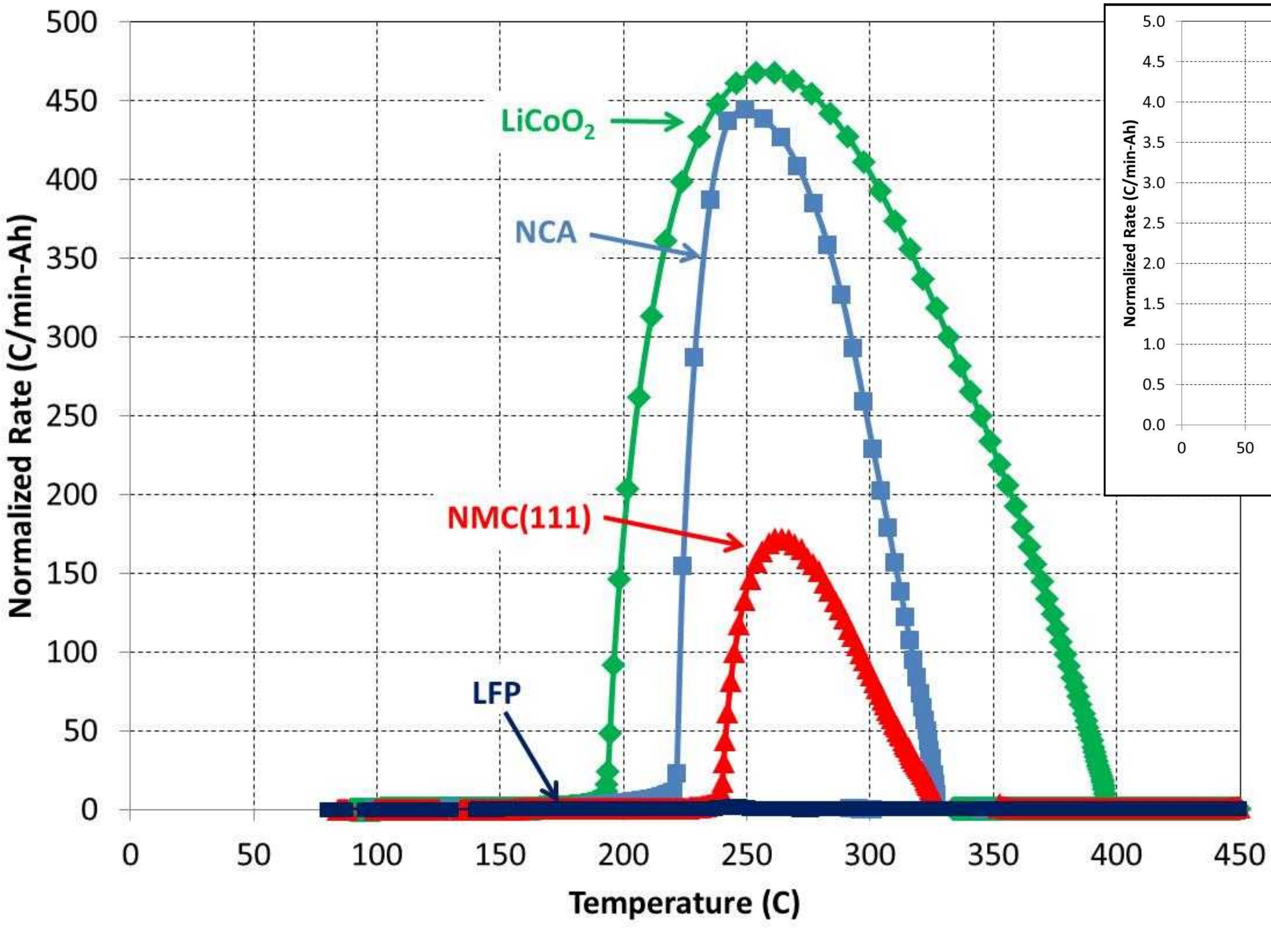


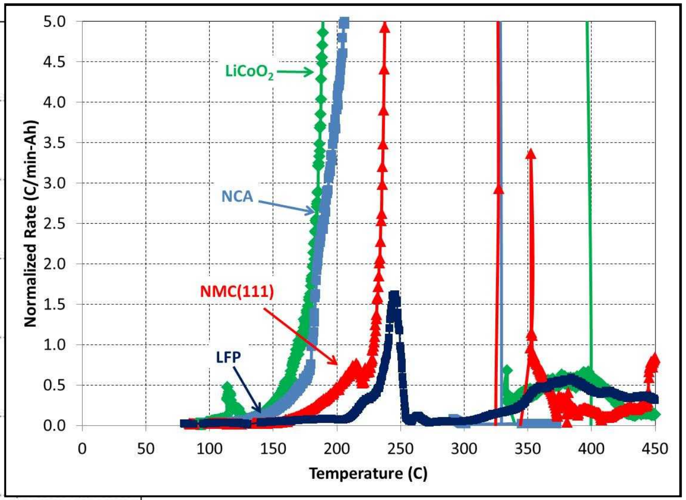


Schematic of ARC and heat-wait-seek: B. Lei, W. Zhao, C. Siebert, N. Uhlmann, M Rohde, H. J. Seifert "Experimental analysis of thermal runaway in 18650 cylindrical Li-ion cells using an accelerating rate calorimeter" *Batteries* **2017**, 3, 14.

Cell chemistry matters

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

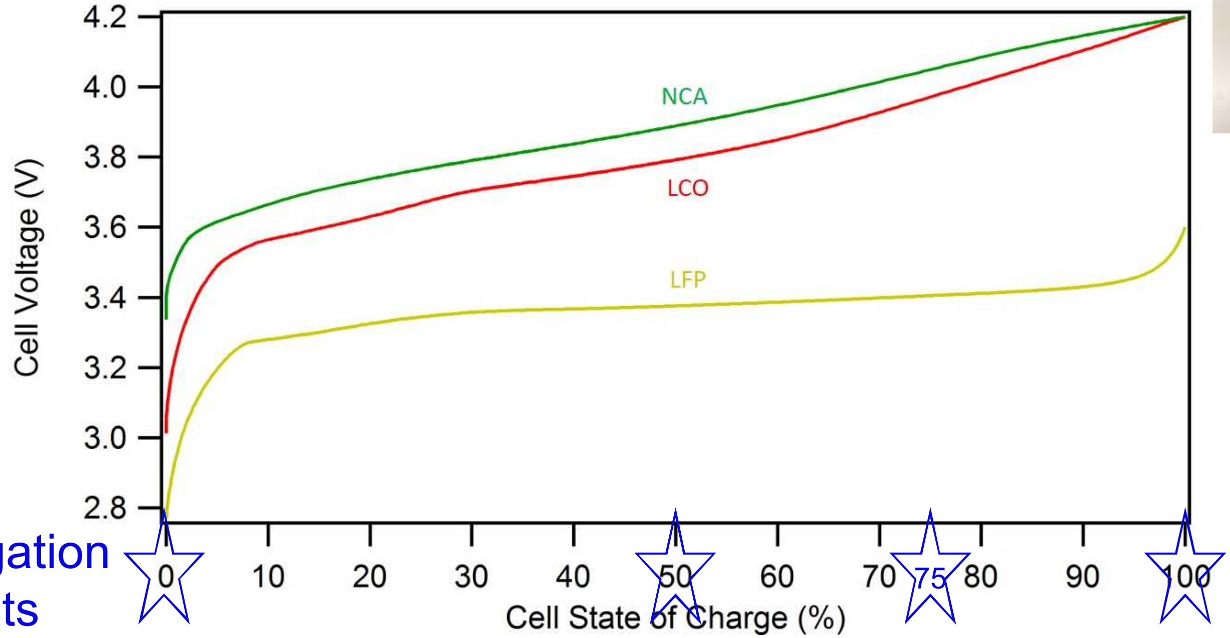




High Rate Runaway	
Cathode	$\Delta H_{runaway}$ (kJ/Ah)
$LiCoO_2$	15.9
NCA	9.8
NMC111	8.3
LFP	2.4

- **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

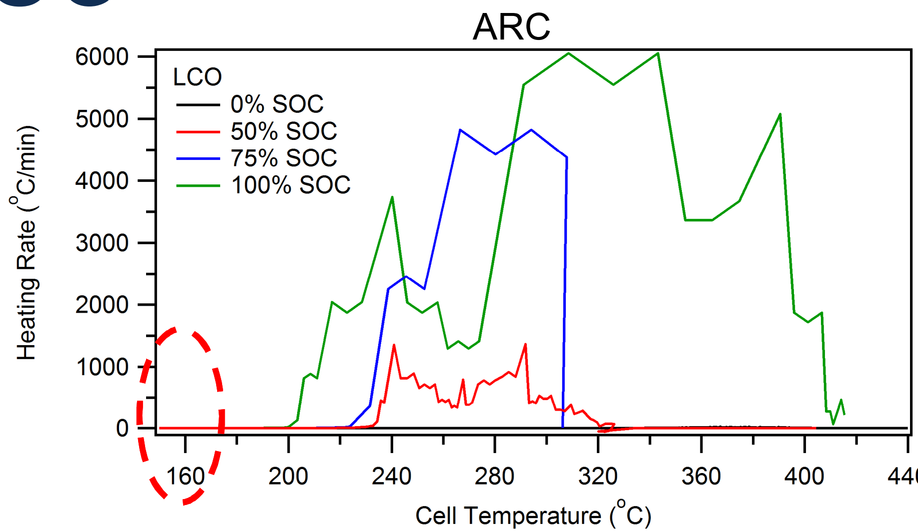


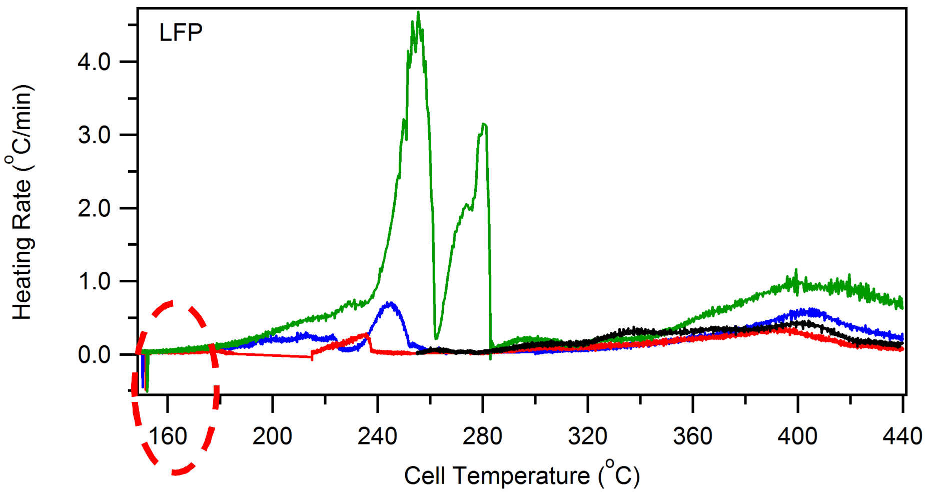
Investigation points

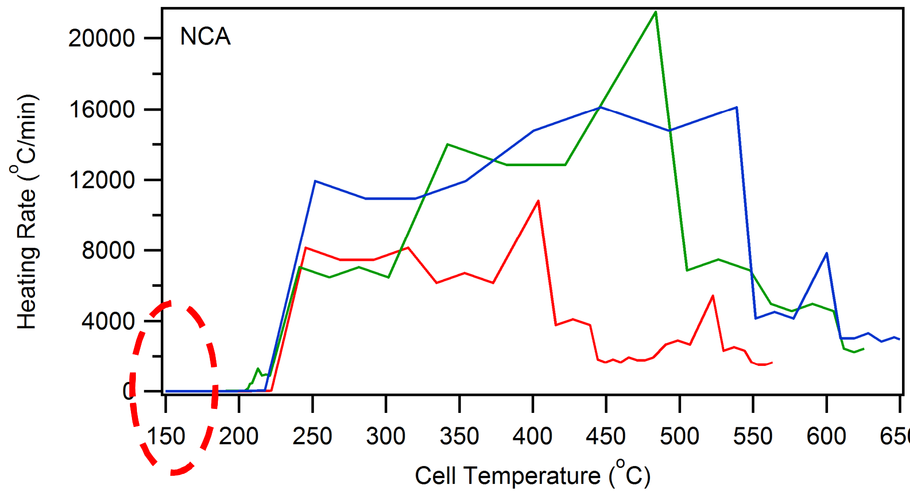
Think of state of charge (SOC) as the battery's "fuel gauge"
100%=full, 0%=empty

A full tank is more dangerous than an empty tank

Thermal runaway behavior changes with chemistry and SOC

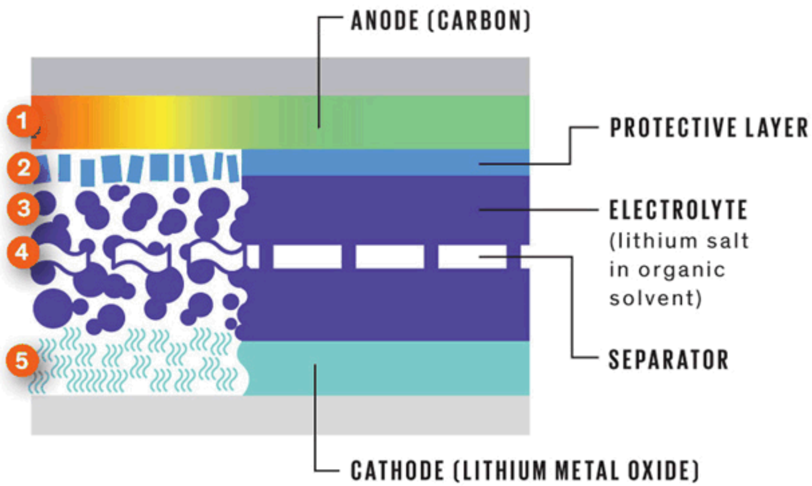


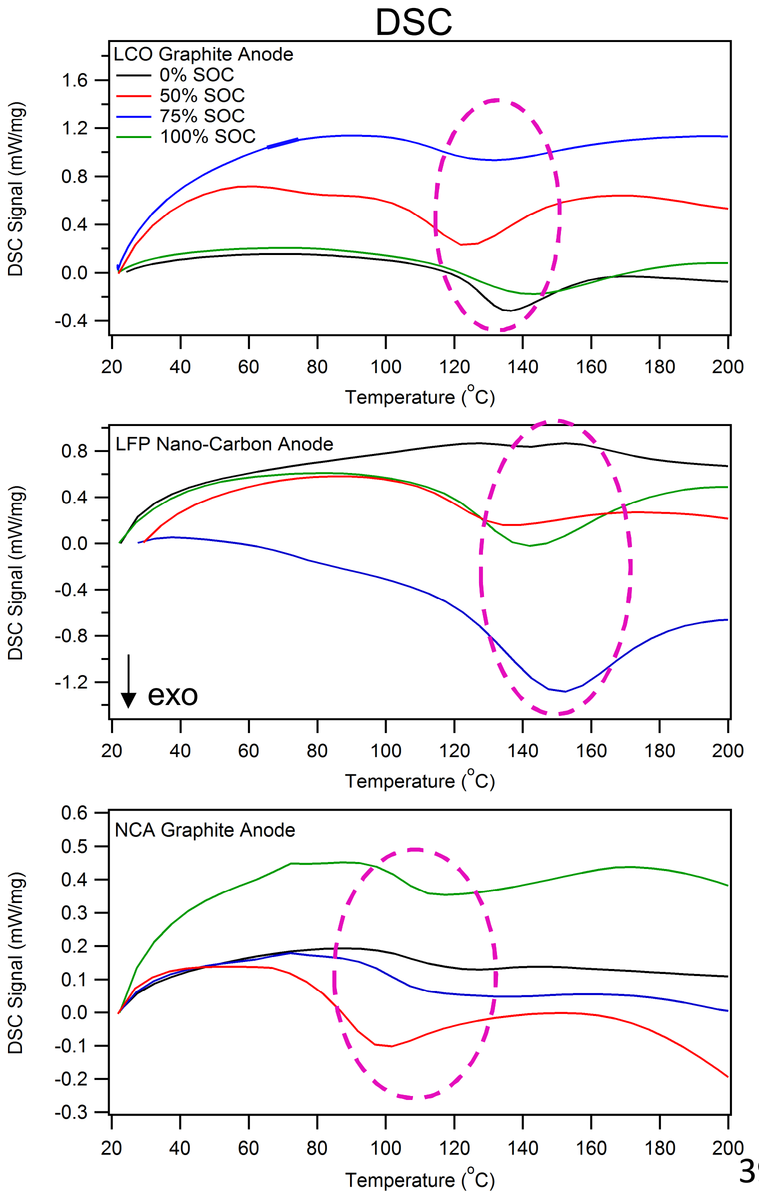




Onset temperature is ~150°C for all chemistries

Thermal runaway begins with anode decomposition





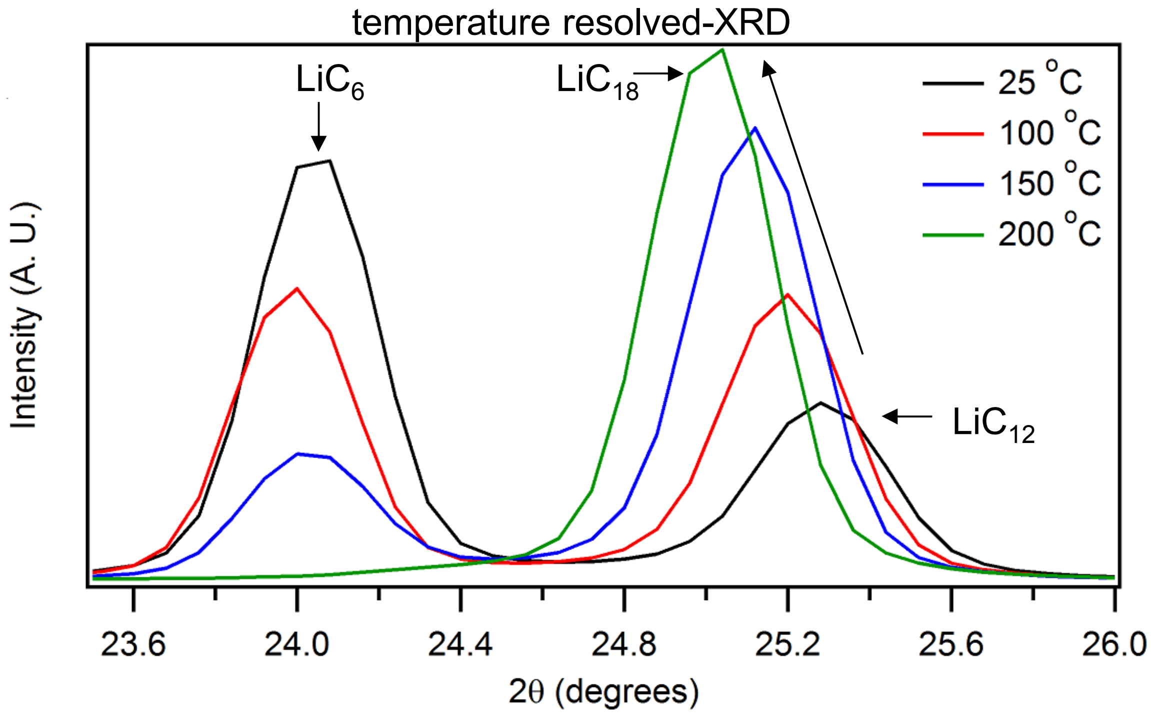
Protective layer (2) breaks down, releasing heat (exotherm).

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.

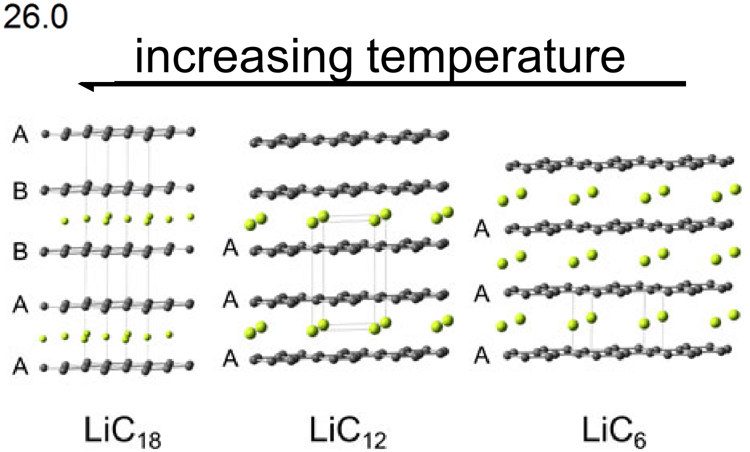
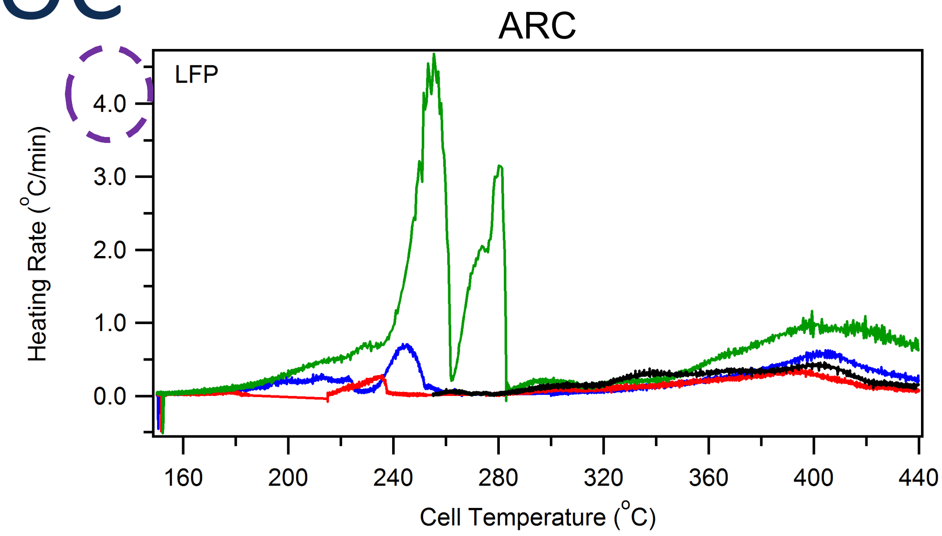
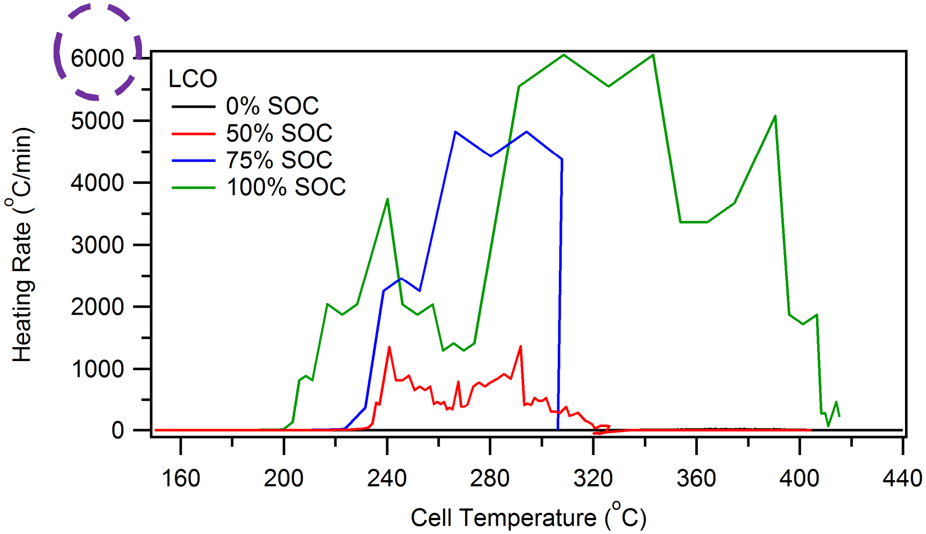
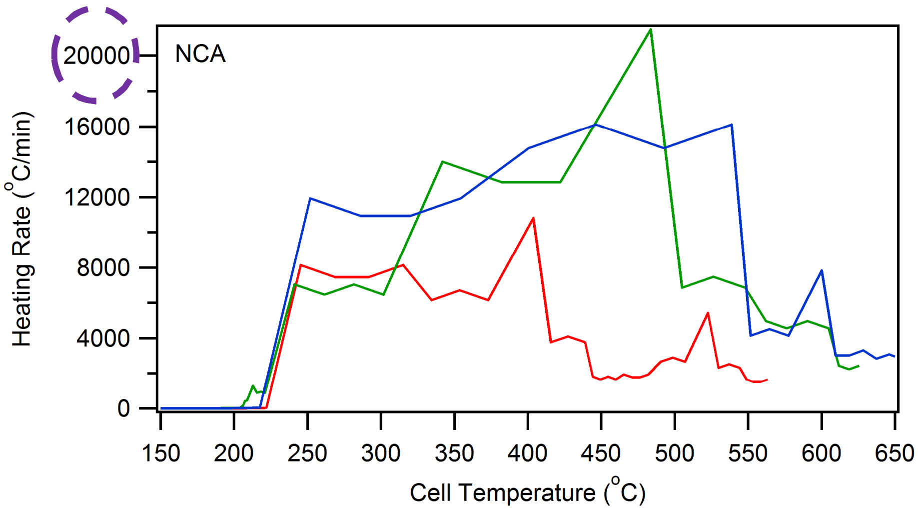


Image of LiC_6, LiC_{12}, and LiC_{18}: A. Missyul, I. Bolshakov, R. Shpanchenko "XRD study of phase transformations in lithiated graphite anodes by Rietveld method" *Powder Diffraction* **2017**, 1-7.

Thermal runaway behavior changes with chemistry and SOC

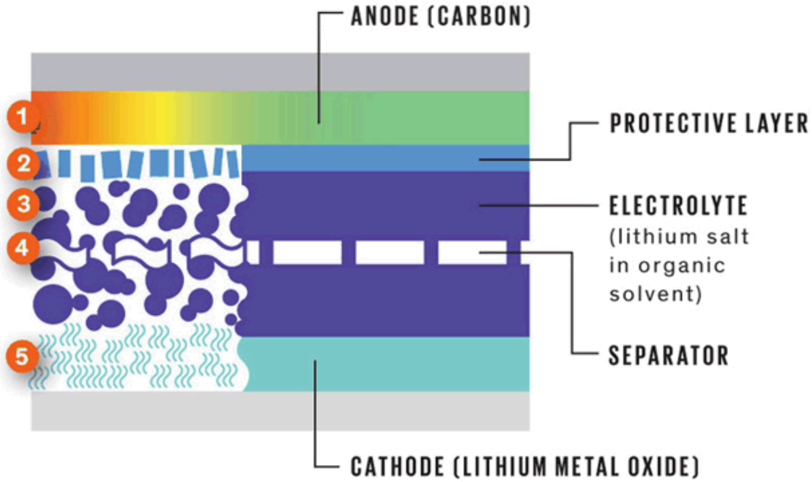






Maximum heating rate is chemistry dependent

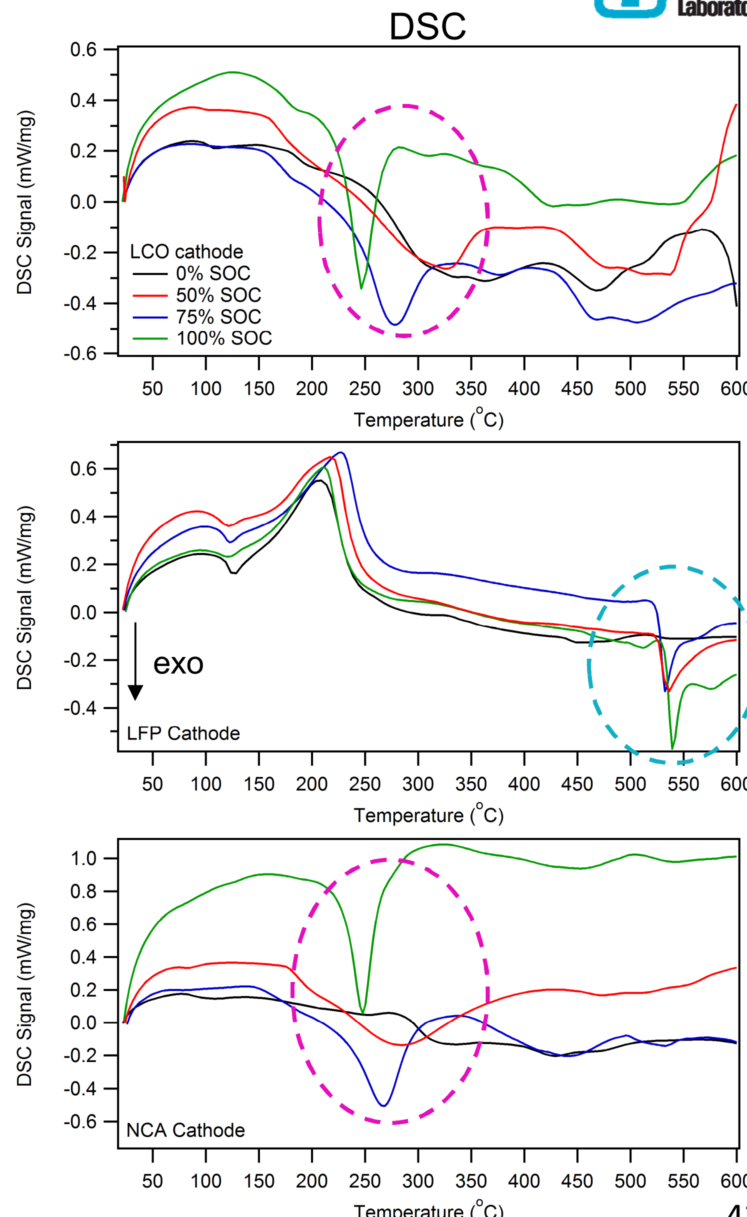
Cathode decomposition releases a lot of heat



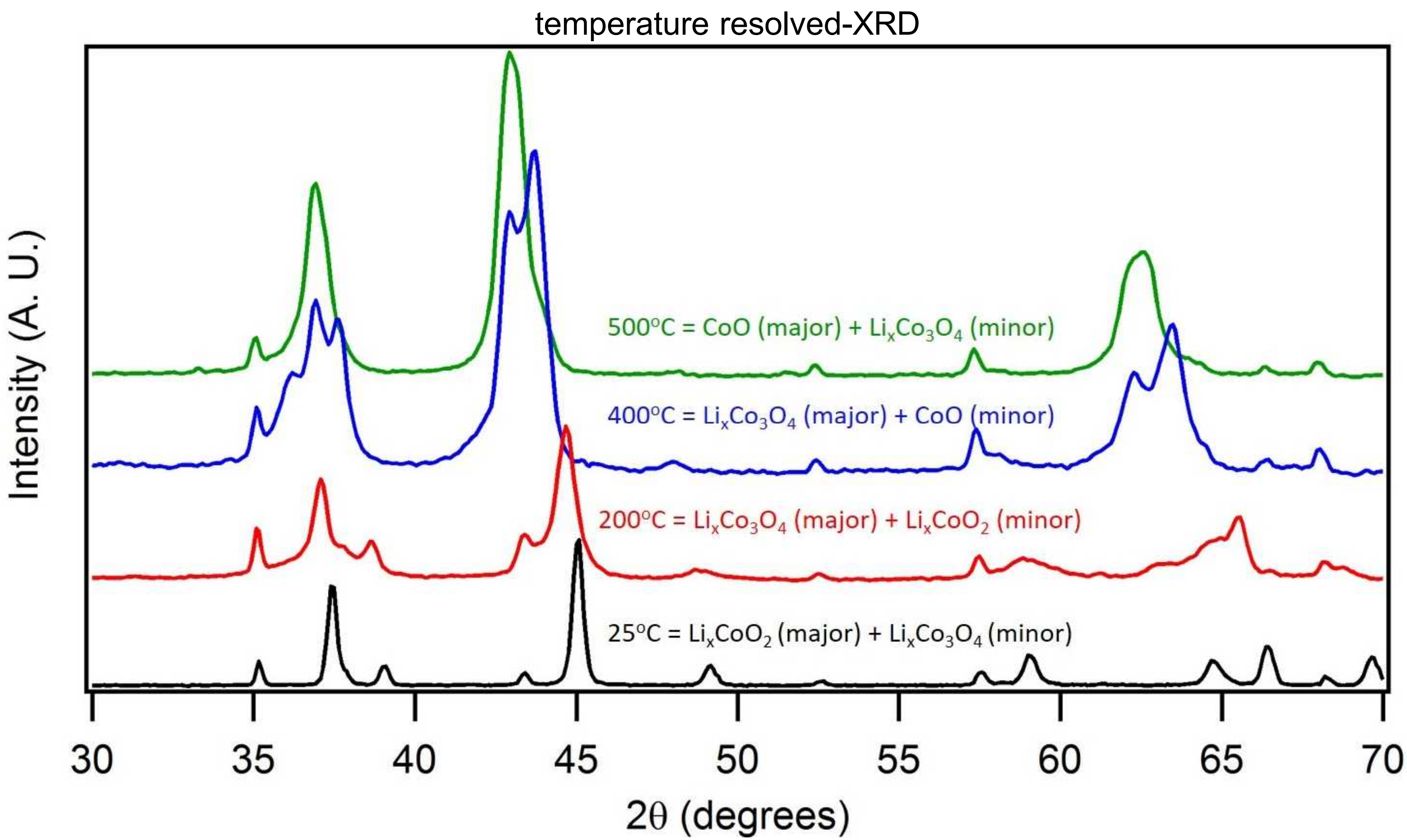
At higher temperatures, the LCO and NCA cathodes (5) break down, releasing a lot of heat (exotherm).

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).

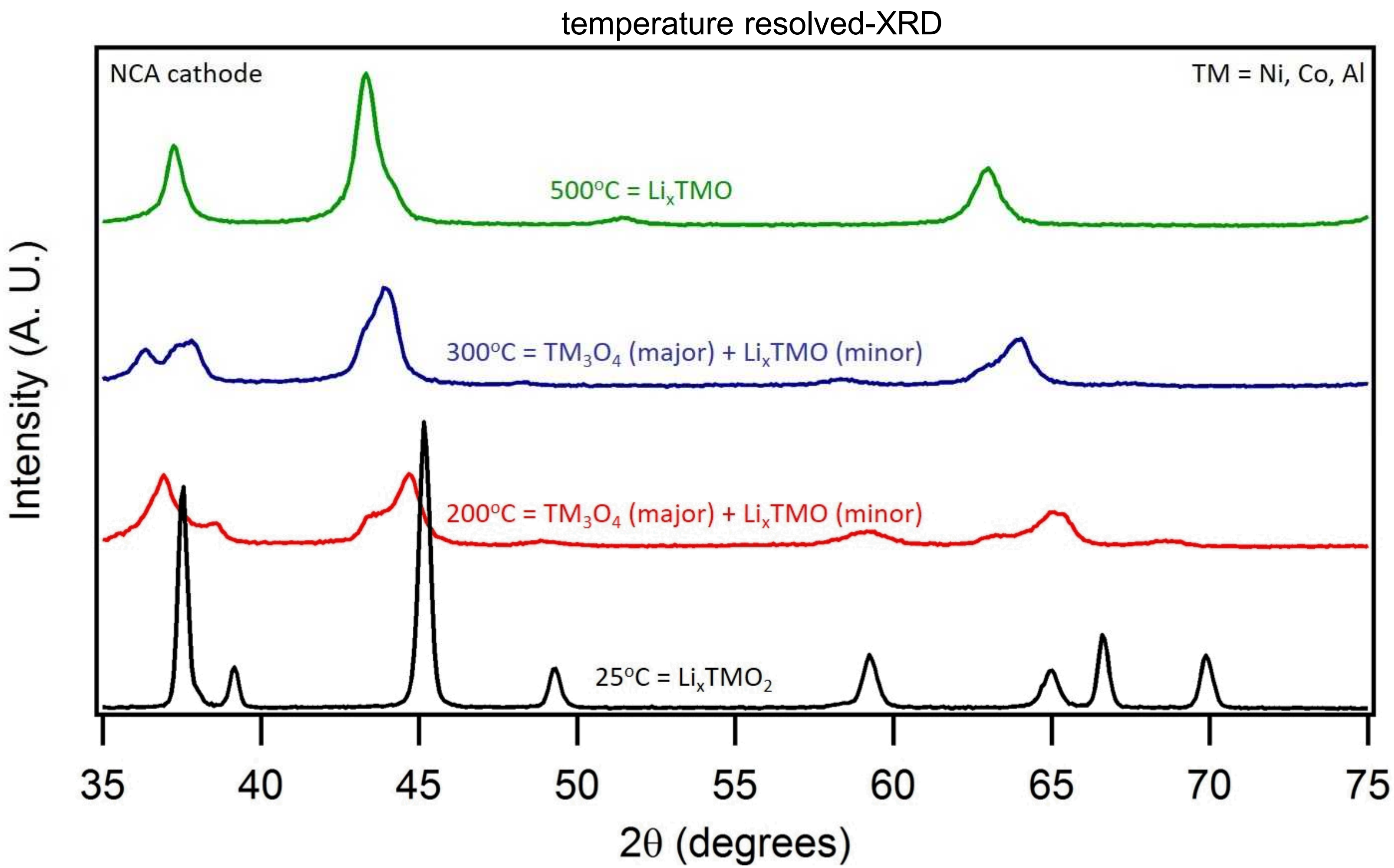


LCO cathode decomposes slowly



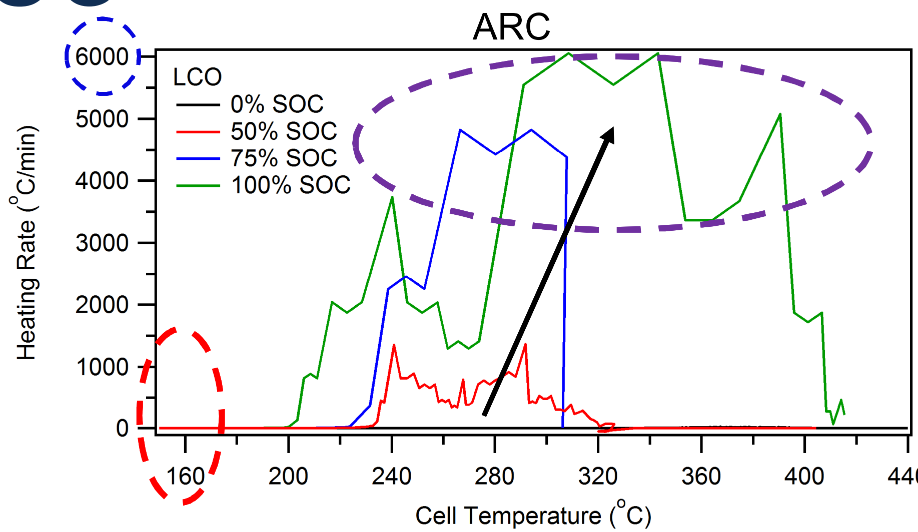
Cathode decomposition releases oxygen and heat.
Slower LCO decomposition results in lower heating rates in ARC.

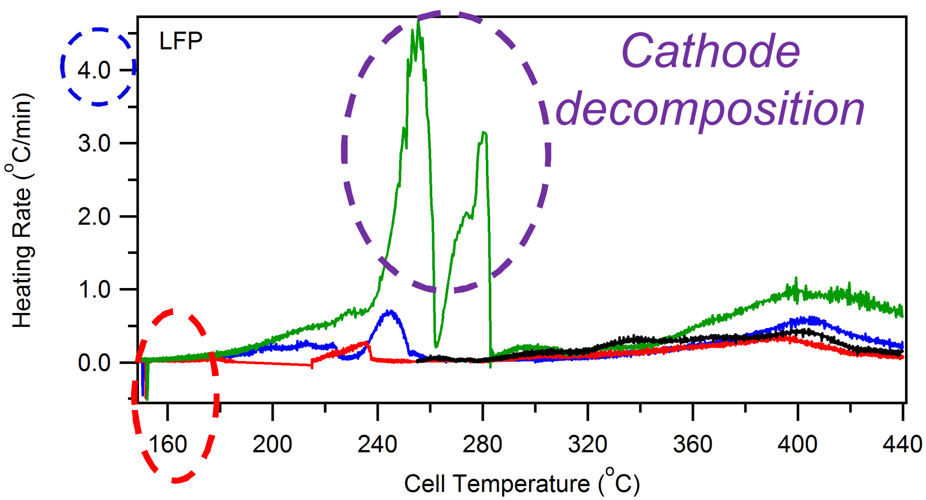
NCA cathode decomposes rapidly

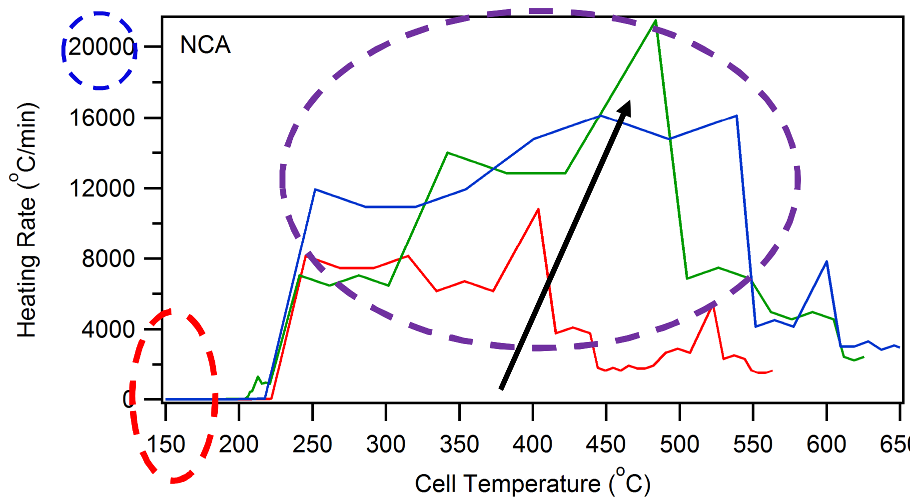


Cathode decomposition releases oxygen and heat.
Faster NCA decomposition results in higher heating rates in ARC.

Thermal runaway behavior changes with chemistry and SOC







Anode decomposition

Cathode chemistry effects heat release rates

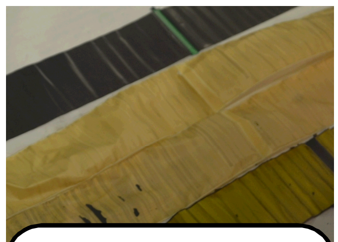
SOC effects heat release rates

Project Goal is Battery Failure Mitigation

Inform: education and outreach

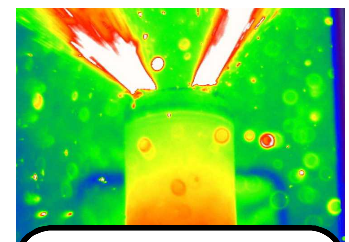
Inform: codes and standards

Baseline electrochemical performance analysis



Materials characterization and thermal stability testing

Electrochemical and whole-cell abuse response analysis



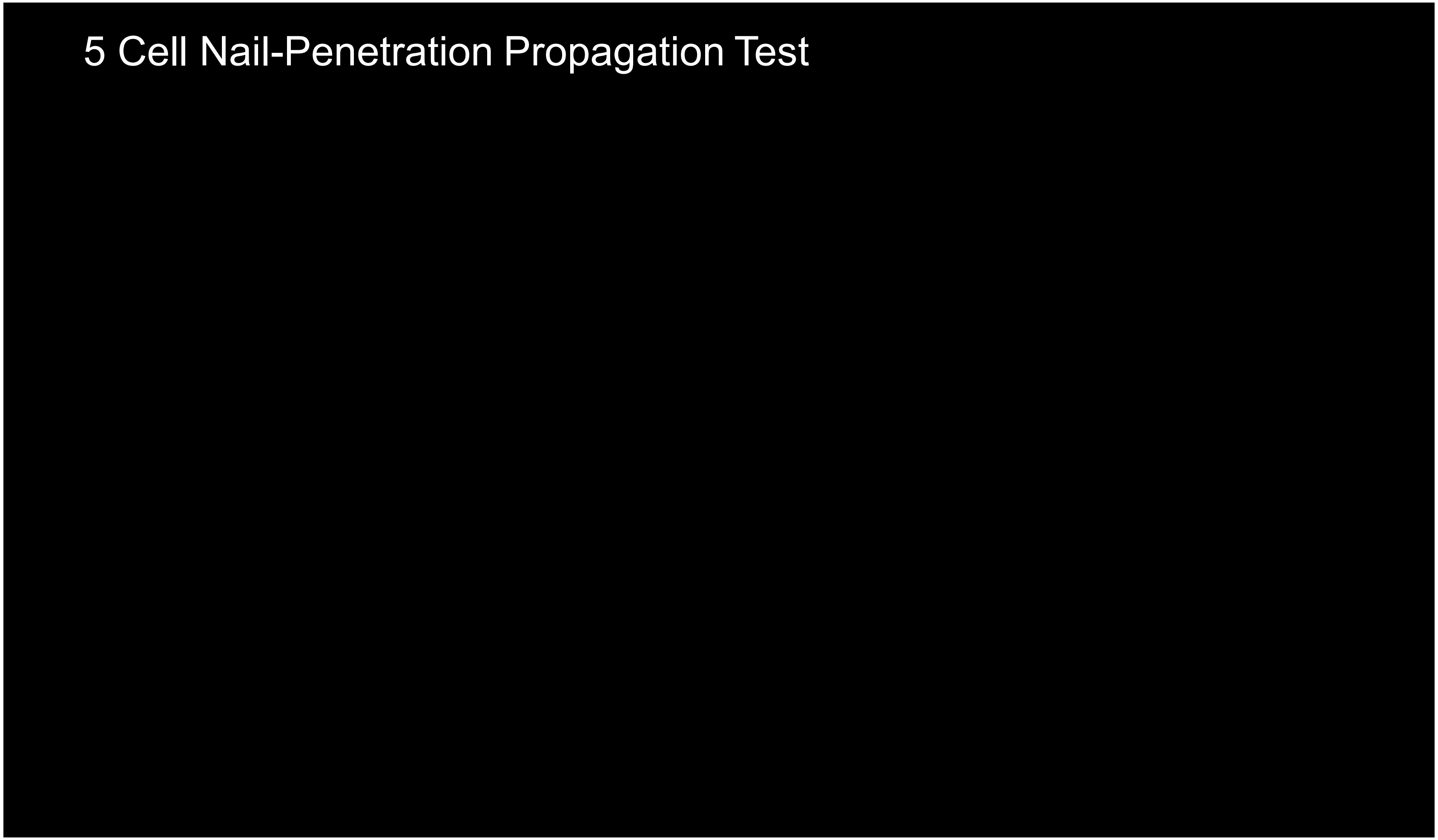
Increased battery reliability and failure mitigation

Collaboration: vent plume composition (NM Tech)

Collaboration: propagation modeling (SNL)

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.

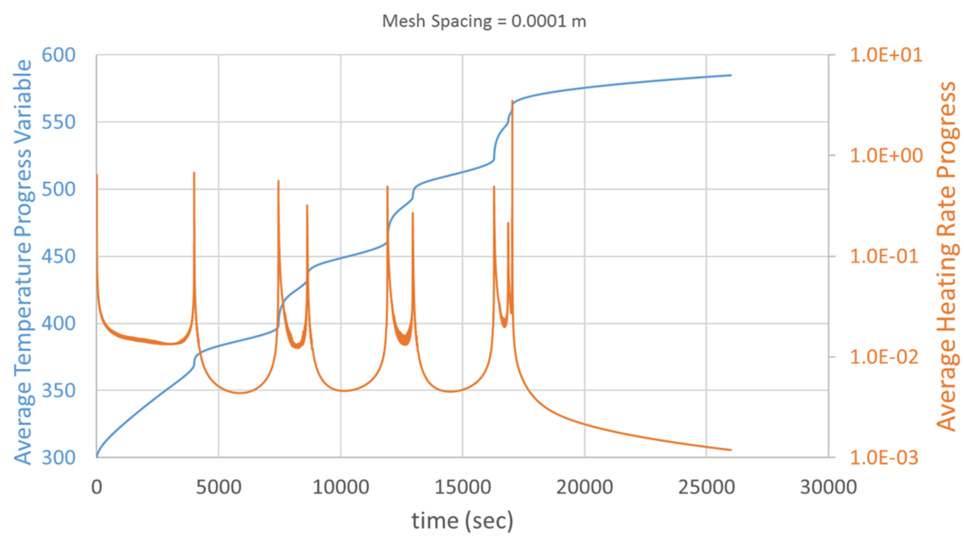
Failure in one battery can take out a whole pack/system



Fire Protection

SAFETY ISSUE

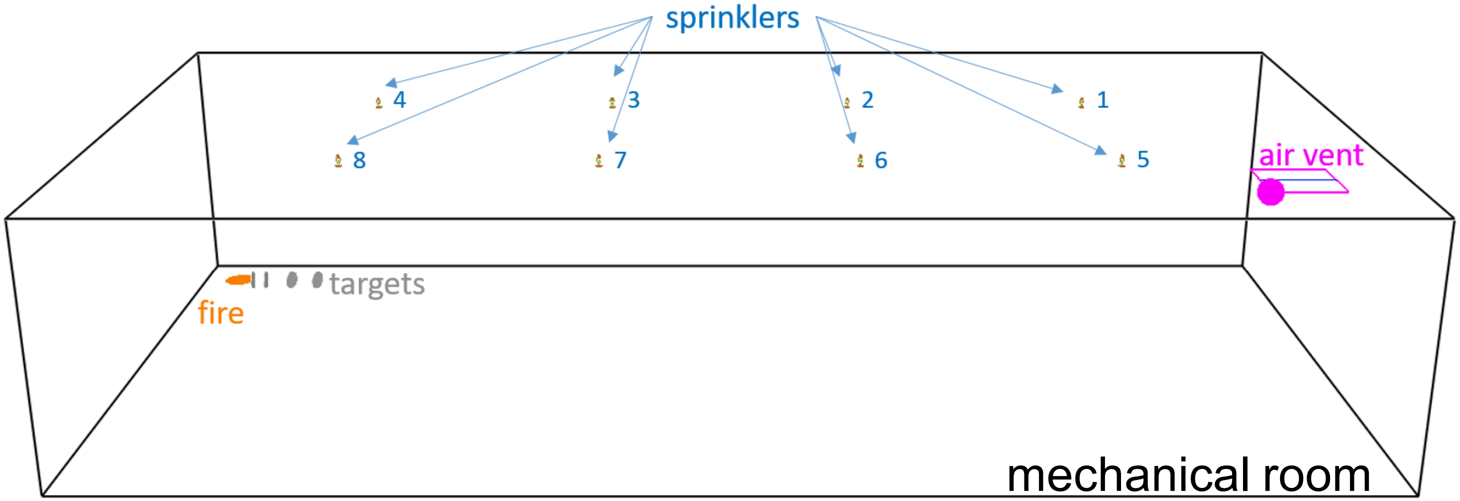
- **Water Based Systems – Battery Storage**
  - Research by Fire Protection Research Foundation, Exponent and FM Global
  - Confirmed sprinkler protection criteria for Li-ion battery storage in cartons
  - “Storage up to 4.6 m (15 ft) under ceiling heights up to 12.2 m (40 ft) **was adequately protected** by a fire protection system comprised of pendent sprinklers having a K-factor of 320 L/min/bar½ (22.4 gpm/psi½), with a nominal 74^{o}C (165^{o}F) temperature rating and a nominal RTI of 27.6 m½s½ (50 ft½s½), installed on 3.0 m by 3.0 m (10 ft by 10 ft) spacing at an operating pressure of 2.4 bar (35 psig).”



- **Gaseous Systems**
  - Reignition issues due to thermal runaway phenomenon
  - Dwell time

More information available at:
http://www.nfpa.org/news-and-research/fire-statistics-and-reports/research-reports/hazardous-materials/other-hazards/lithium-ion-batteries-hazard-and-use-assessment
“Modeling for understanding and preventing cascading thermal runaway in battery packs”, 2017 Energy Storage Systems Safety & Reliability Workshop, Feb.22-24, 2017, Santa Fe, NM.

Batteries in buildings need to be controlled by sprinkler systems

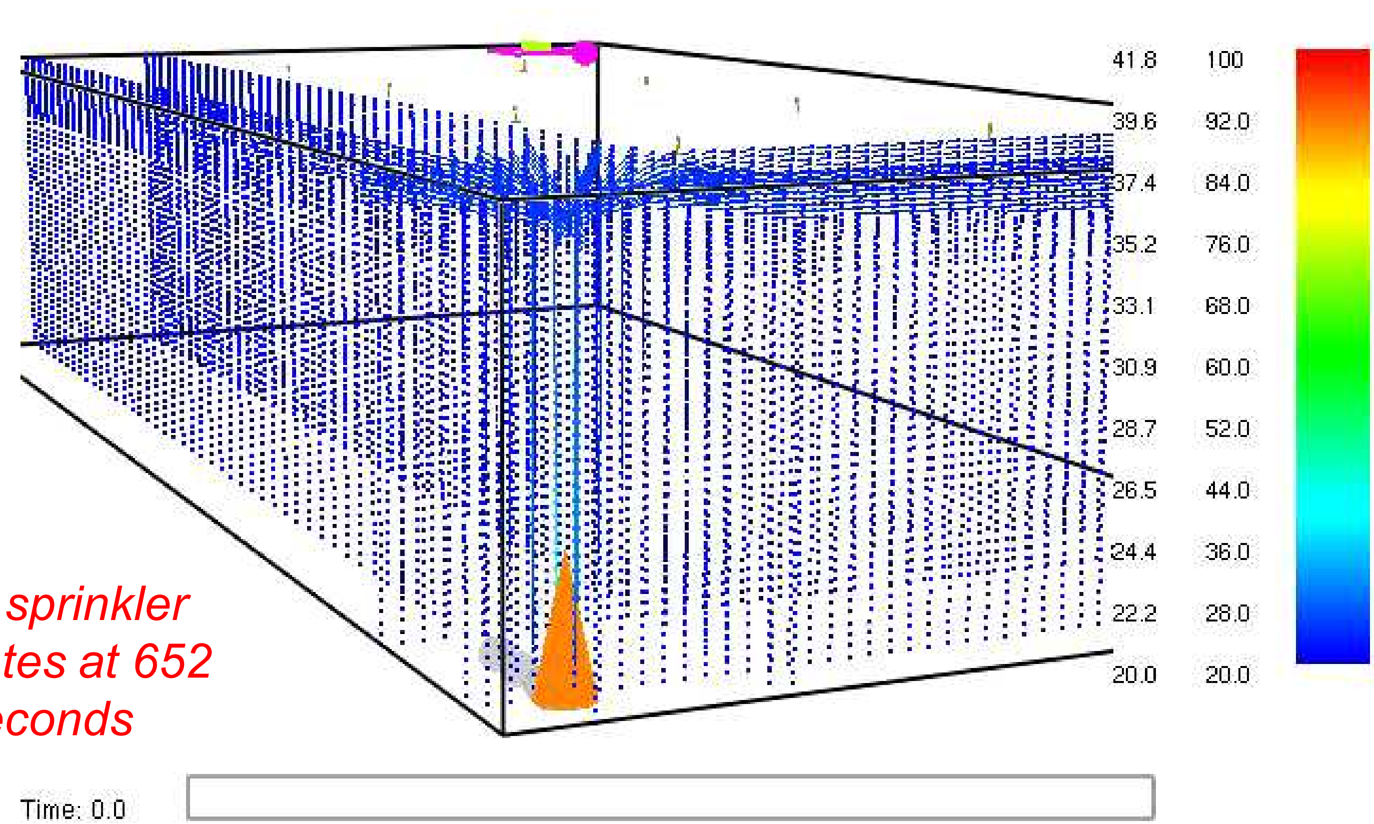


Sprinkler systems are designed to control the fire until firefighters can arrive.

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

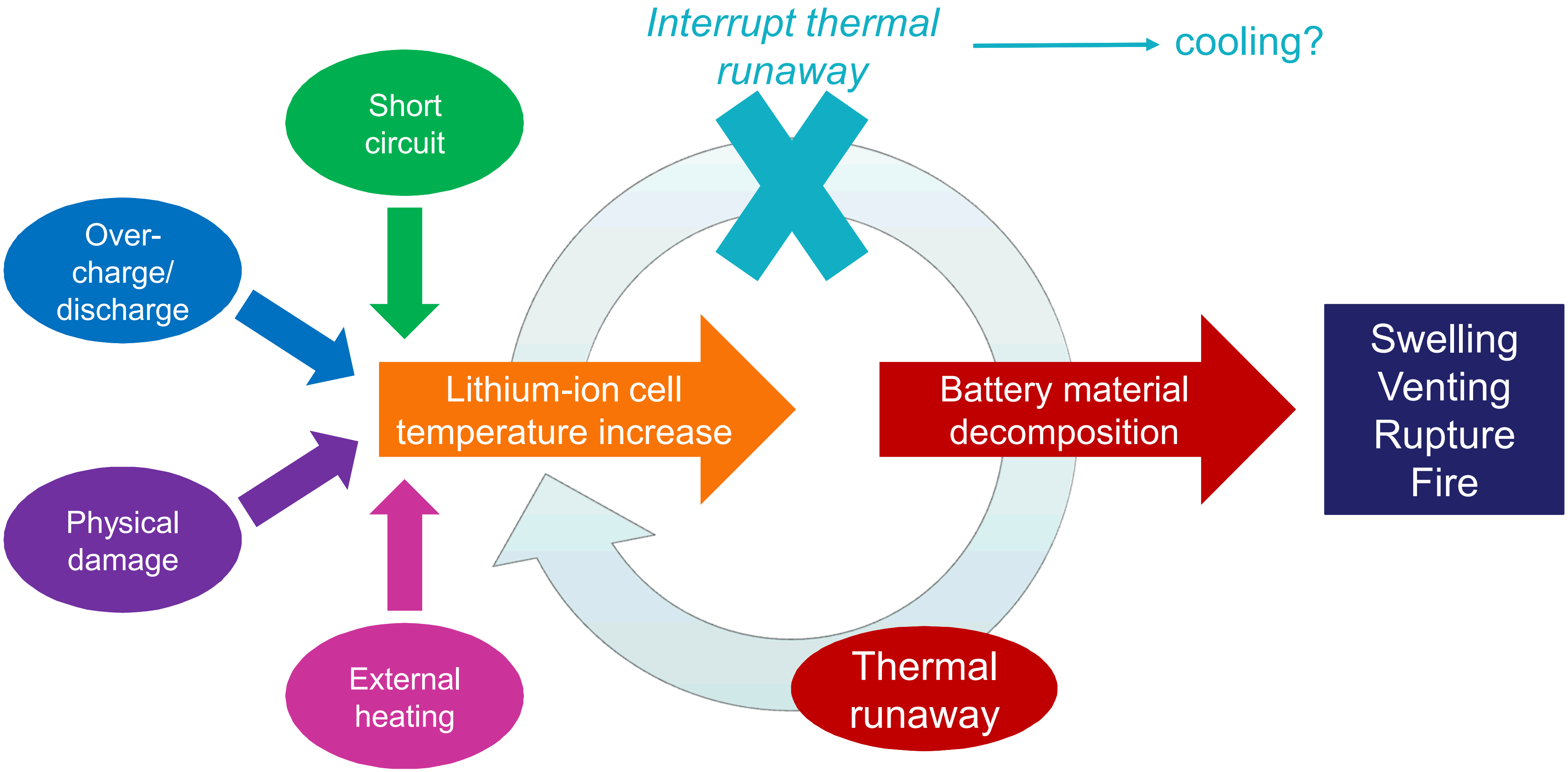
Rapid sprinkler response can control small battery fires

100 LCO cells on fire simultaneously
in a mechanical room



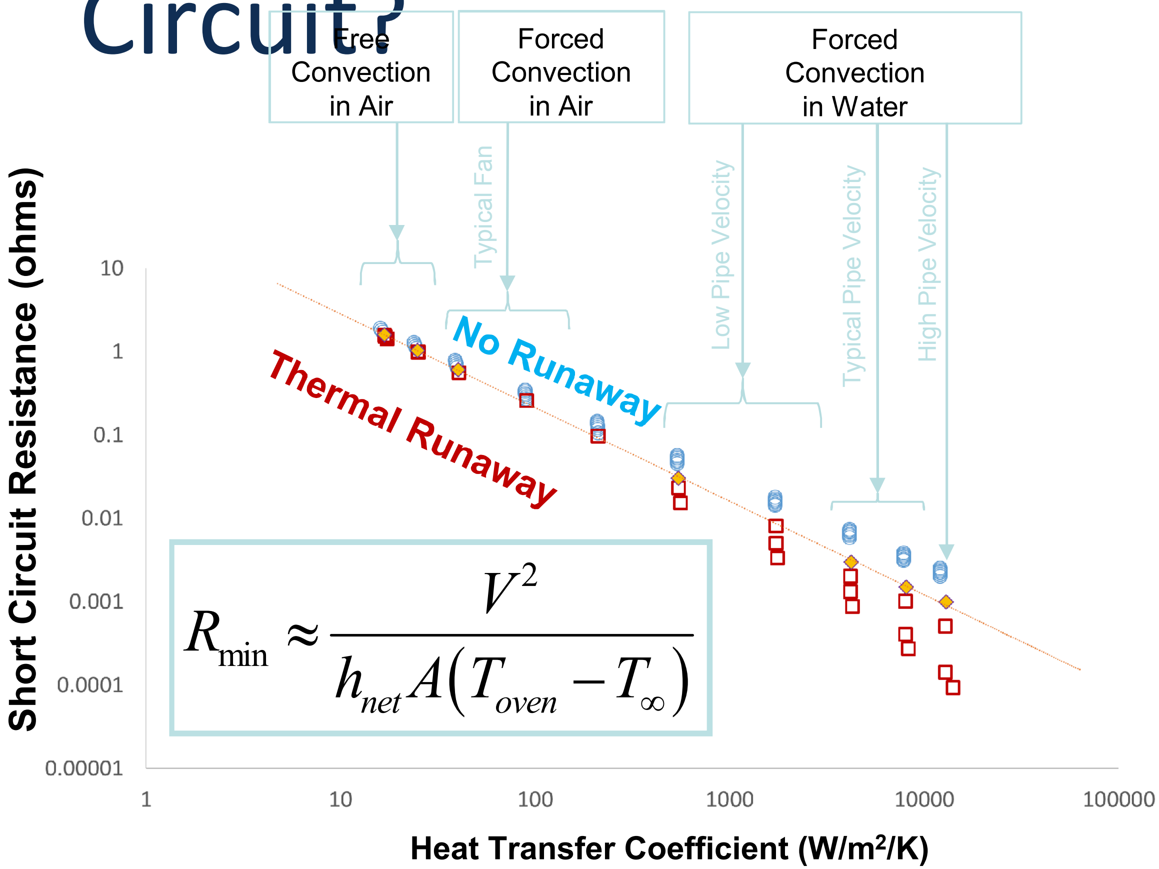
One sprinkler activates at 652 seconds

Future work: Can we prevent a battery fire?

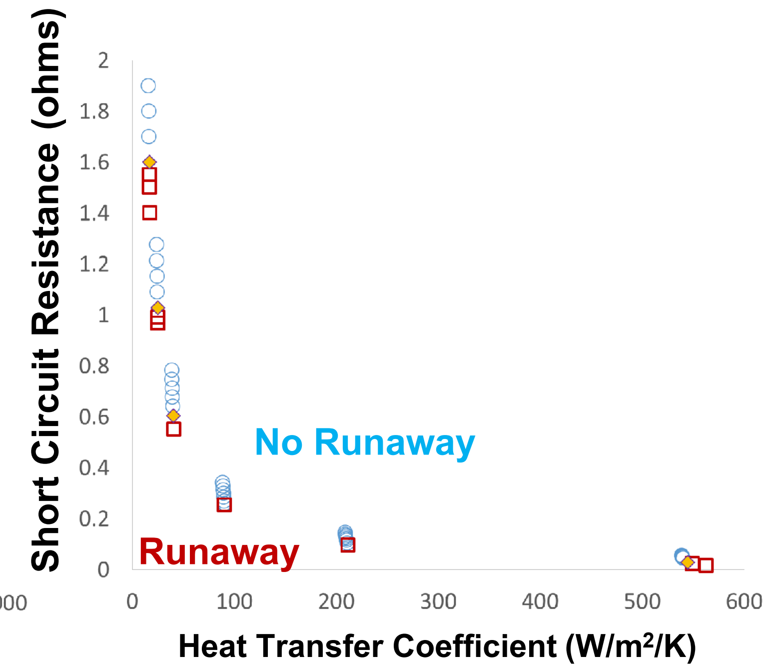


Runaway with Internal Short Circuit?

$$T_{eff} = T_{\infty} + P / h_{net} A \qquad P = \frac{V^2}{R}$$



$$R_{\min} \approx \frac{V^2}{h_{net} A \left(T_{oven} - T_{\infty} \right)}$$

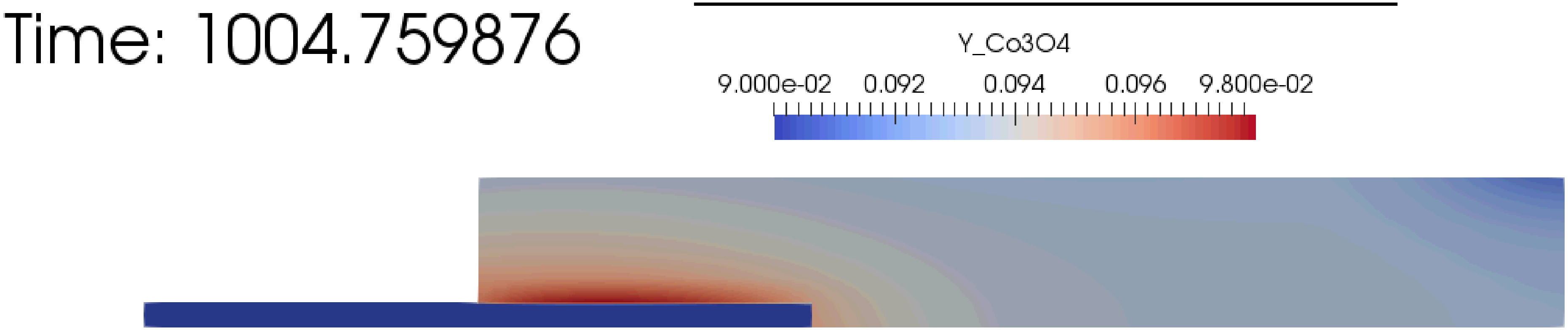


- Models can be used to estimate cooling requirements
  - Simulation shows homogeneous heating of 18650 cells (varying short resistance and cooling)
  - Internal temperature variation will be worse for large format systems and localized shorts

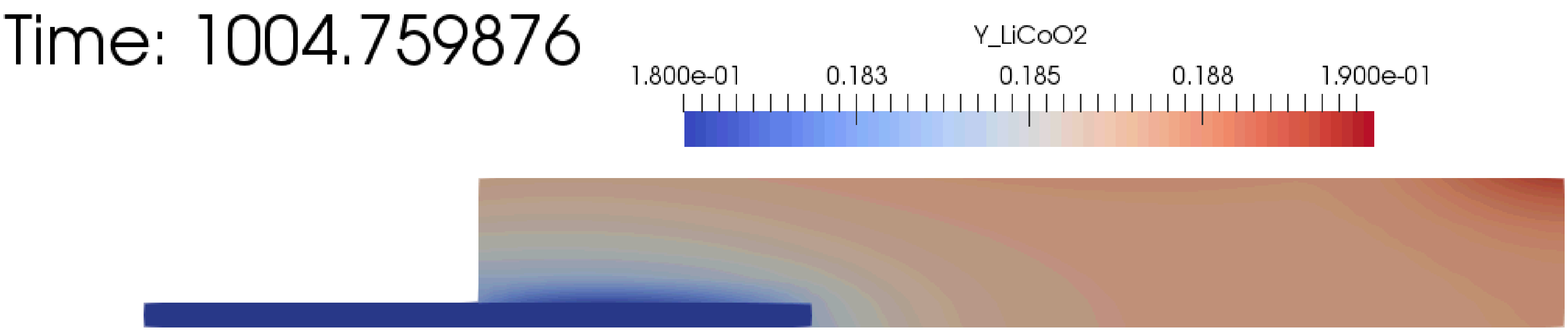
Relative importance of short-circuit versus thermal reactions

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

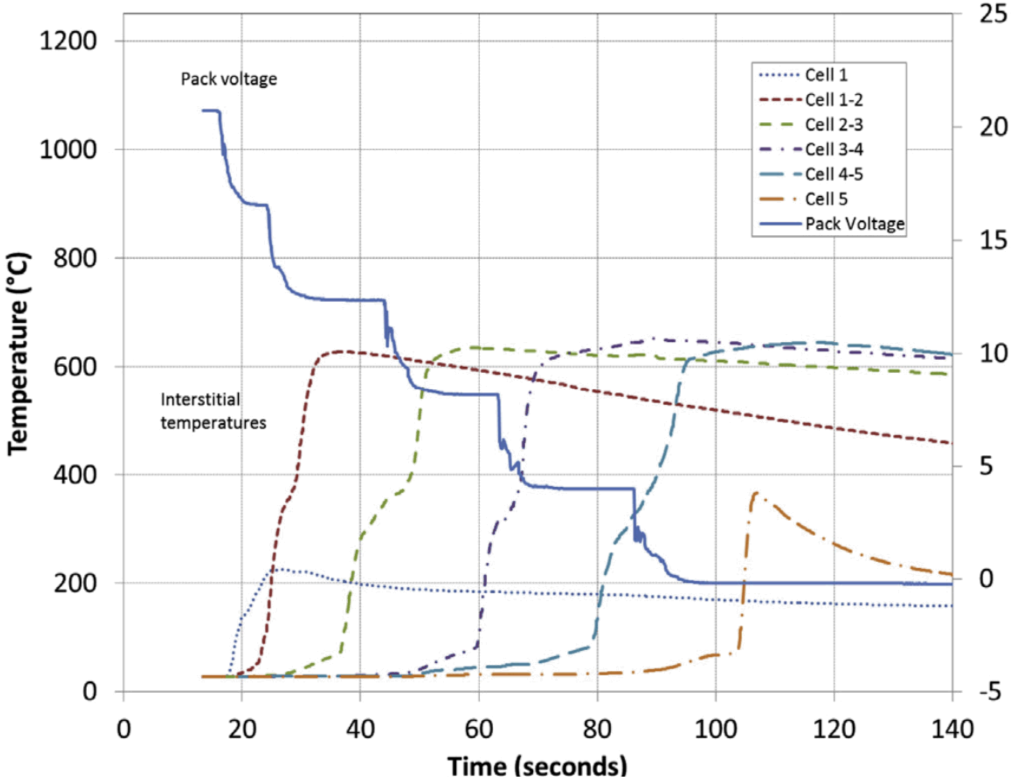
Thermal Reaction Cathode Product

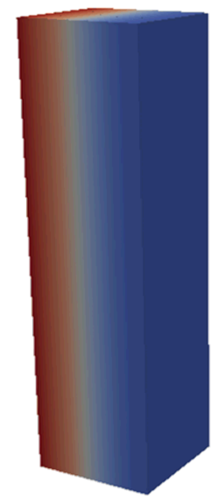


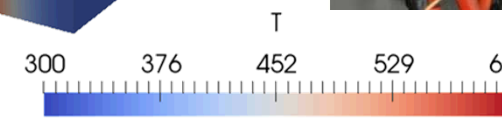
Short Circuit Cathode Product

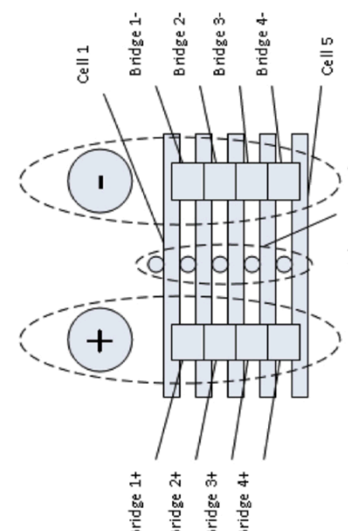


Cascading Propagation Observed in Li-Ion Packs





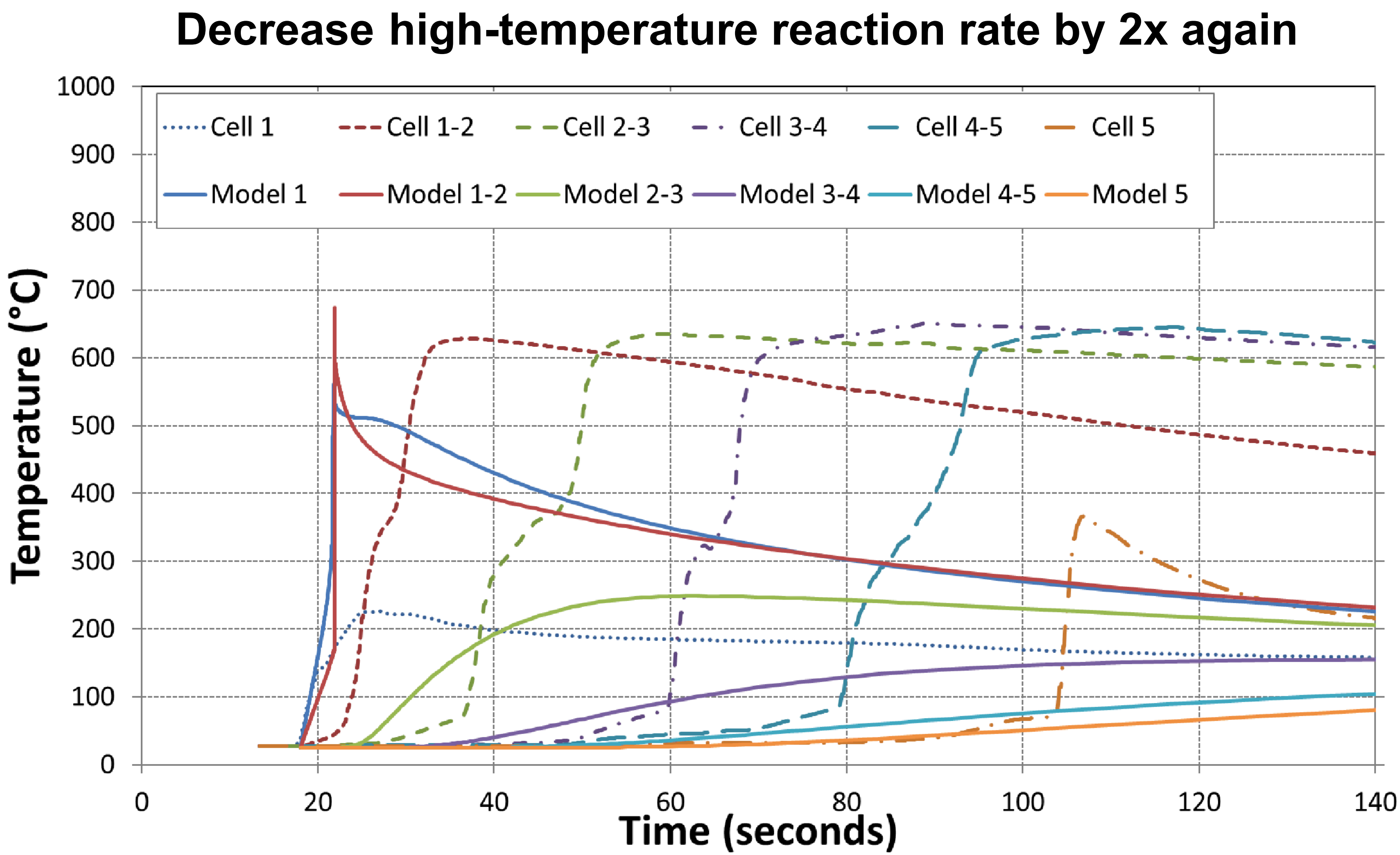




- Experimental propagation in 5 stacked pouch cells at Sandia
- Investigating effects of
  - State of charge
  - Intermediate layers
  - Cell geometry
- Good pack-scale model validation cases

High-Fidelity Models Required for Cascading Failure

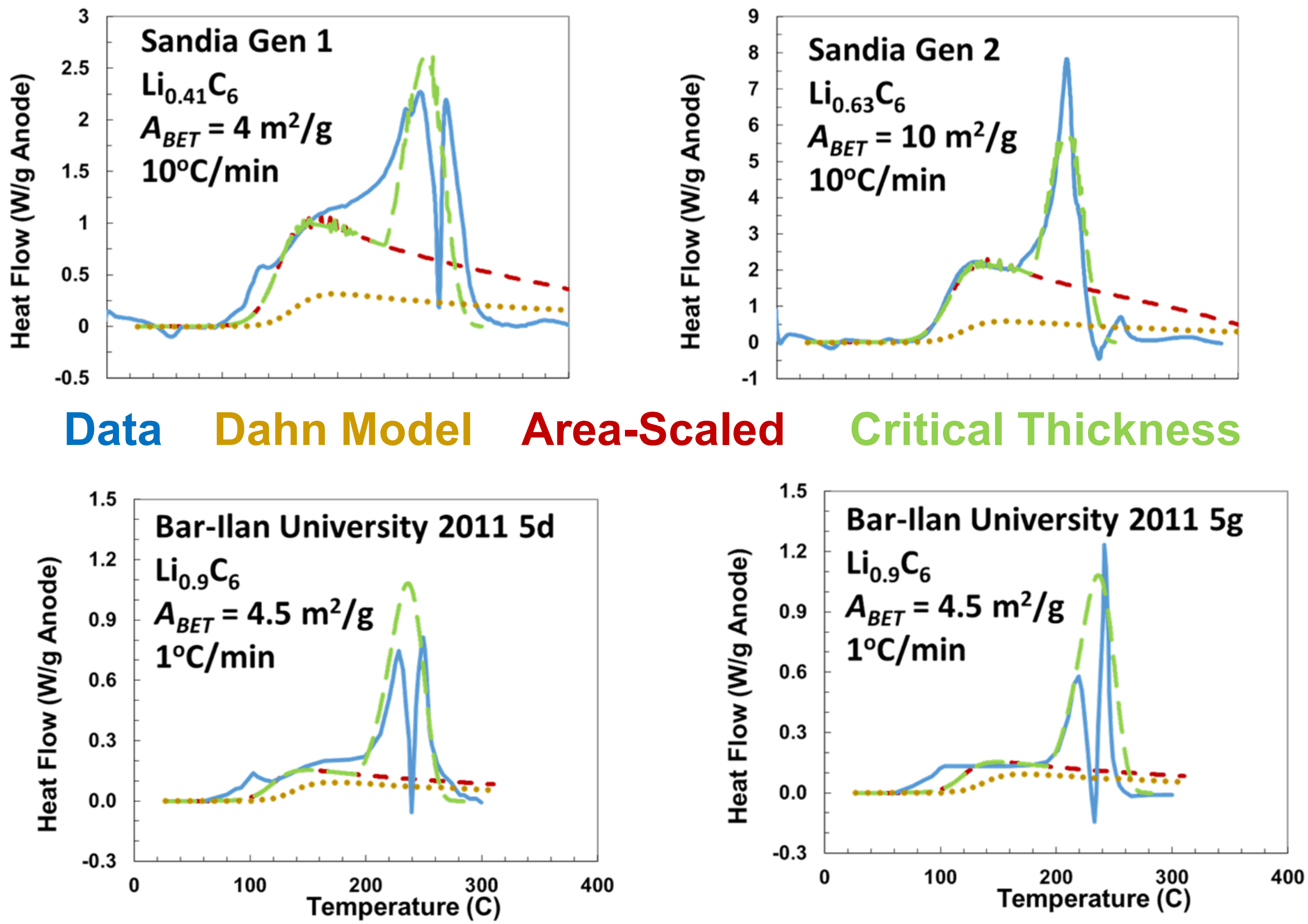
Sandia National Laboratories



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

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

Prior models had incomplete accounting of heat release



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

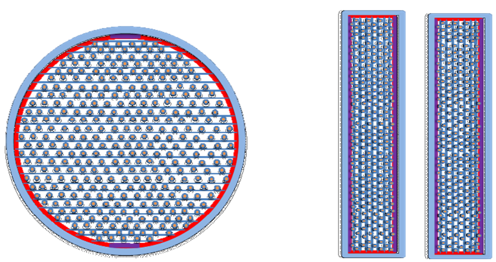
Key anode model improvements

Area-Scaled Model

- SEI Passivation layer inhibits lithium reduction of electrolyte, exp(-z).
- H_{rxn} thermodynamically consistent with $2LiC_6 + EC \rightarrow 2C_6 + C_2H_4 + Li_2CO_3$

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

- Reaction scales with effective surface area.



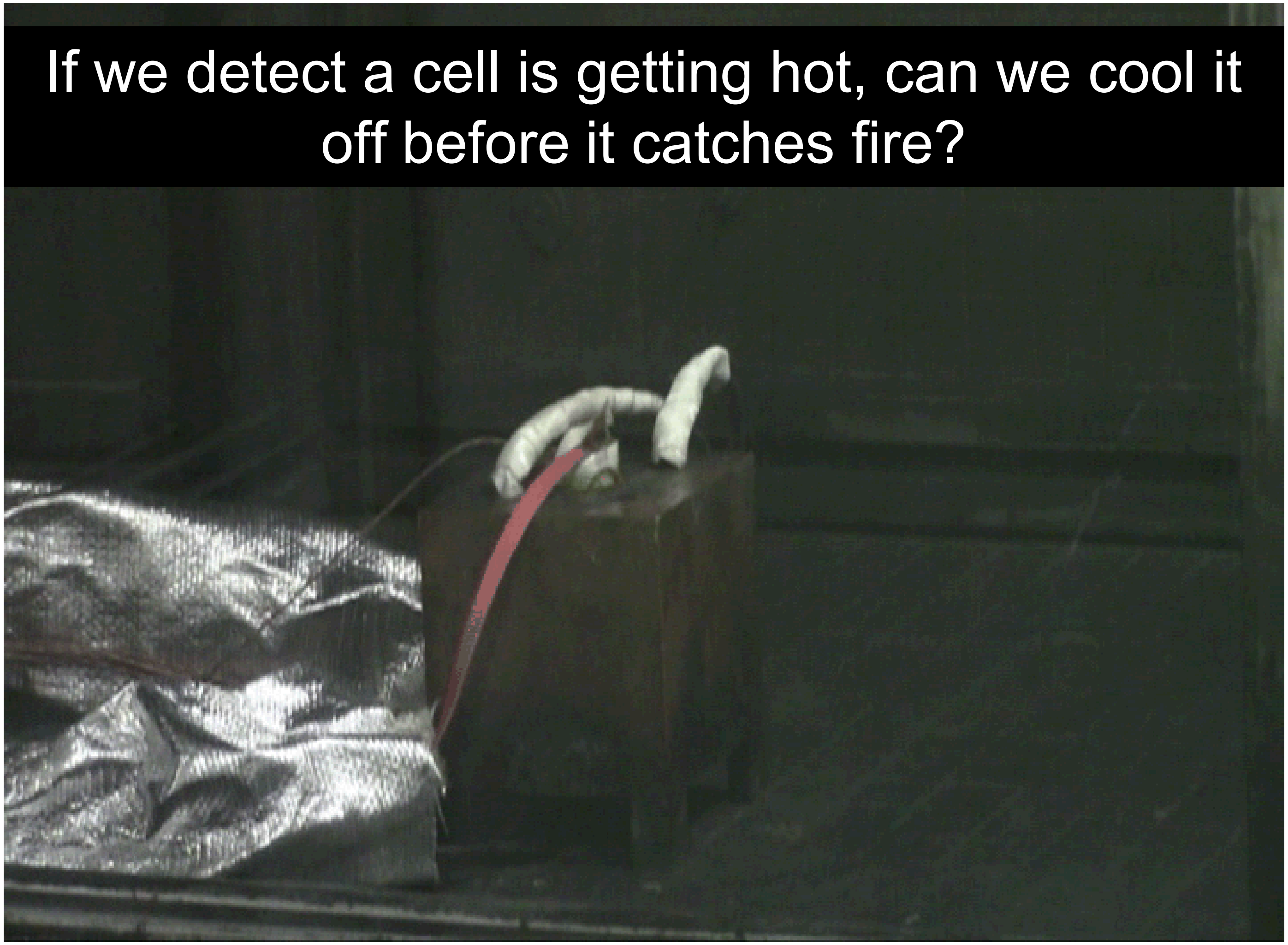
= Graphite Basal Planes (smooth)
= Graphite Edges (rough)
= SEI Layer

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

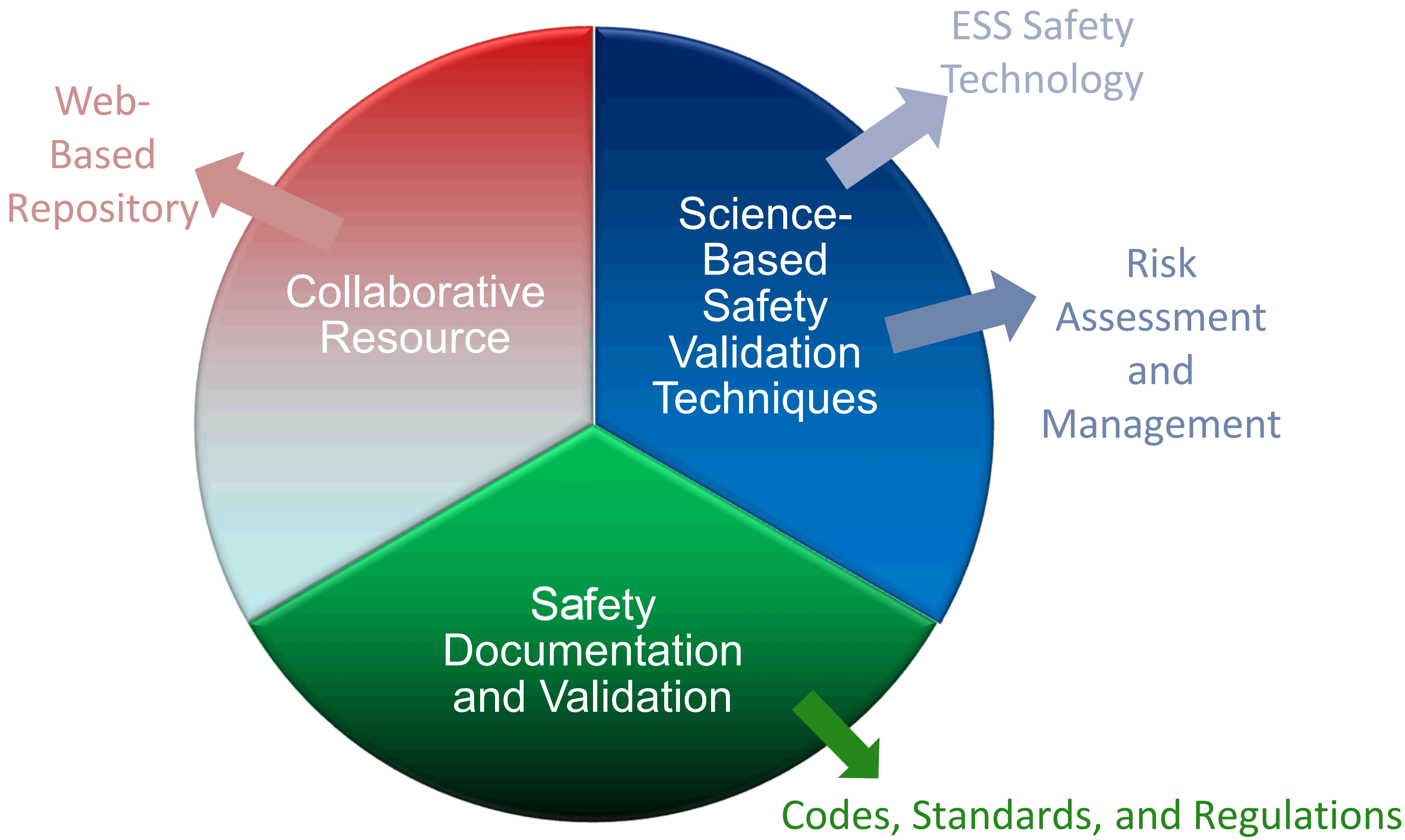
Critical Effective Layer Thickness

- Limit to passivation layer growth with heating.
  - Endothermic defoliation (or other process) observed. Fracture, cracking?
  - Defects in SEI more likely on on edges.

LCO thermal runaway critical point



Interconnected Paths to Safe Energy Storage Systems



Summary

- Coordination in ESS Safety Community
- Integrated R&D into failure behavior and consequences using **experimental** and **modeling** efforts across scale informed by materials to enable:
  - **Containment** of storage across scales and chemistries
  - Effective **suppressants** identification and use
  - Appropriate **hardware and software controls** to mitigate failures
  - Design s**afer batteries** and components

ESS Safety Team

- Heather Barkholtz
- Josh Lamb
- John Hewson
- Chris LaFleur
- Alice Muna
- David Rosewater
- Loraine Torres-Castro
- Randy Shurtz
- Armando Fresquez
- Michael Hargather (NMT)
- Frank Austin (NMT)
- Scott Roberts
- Julian Medina
- Sergei Ivanov
- Jill Langendorf
- Dave Conover (PNNL)
- Pam Cole (PNNL)

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

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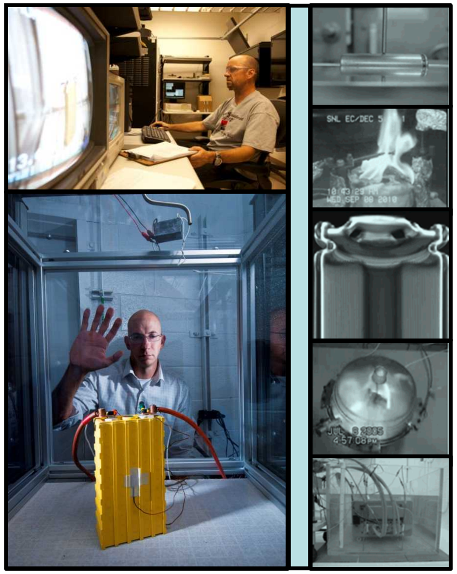
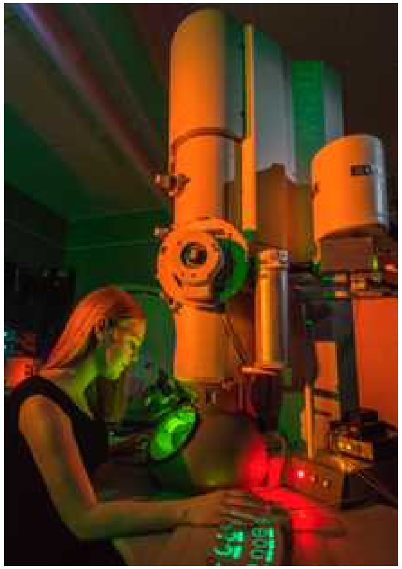
Market Drivers

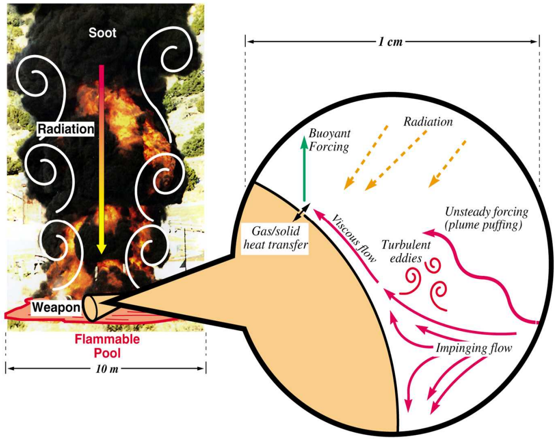
- Energy supply does not exactly track with or match demand.
- Energy produced from renewable, waste heat and other energy sources may not be acceptable for its intended use.
- Energy cost may change between peak and off-peak periods making it advantageous to “buy low and use high.”
- More traditional sources of energy may have periods when they are not readily available.
- Consumers want to move “off the grid.”
- Utilities need to more effectively operate and improve the grid.

Battery safety R&D fits capabilities

- Sandia National Laboratories uniquely equipped for ESS safety R&D
  - Renowned battery abuse lab for EV, HEV battery work
  - Distributed energy test lab for systems analysis
  - Modeling of high energy events with Sierra
  - Center for Integrated Nanotechnology







Codes and Standards

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Sandia National Laboratories

DOE OE Energy Storage Systems Safety Roadmap

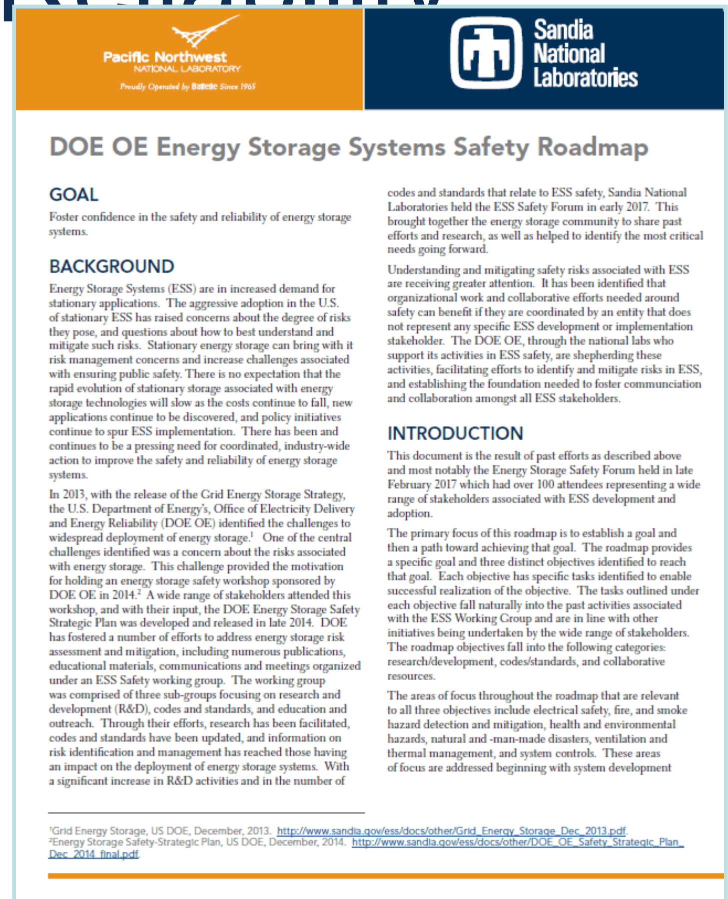
- **Accomplishments**
  - Publication of resources to facilitate compliance with C/S
    - ESS Safety Plan Review and Inspection Checklist
    - ESS Guide for Compliance with Safety Standards

Energy Storage Safety Challenge

Achieving desired growth of energy storage in the built environment that is minimally affected by safety-related incidents due to the availability of updated codes and standards that support the technology, are founded on robust research and field data, and are known to and supported by all relevant stakeholders.

OR

Roadmap to ESS Safety and Reliability



DOE OE Energy Storage Systems Safety Roadmap

GOAL

Foster confidence in the safety and reliability of energy storage systems.

BACKGROUND

Energy Storage Systems (ESS) are in increased demand for stationary applications. The aggressive adoption in the U.S. of stationary ESS has raised concerns about the degree of risks they pose, and questions about how to best understand and mitigate such risks. Stationary energy storage can bring with it risk management concerns and increase challenges associated with ensuring public safety. There is no expectation that the rapid evolution of stationary storage associated with energy storage technologies will slow as the costs continue to fall, new applications continue to be discovered, and policy initiatives continue to spur ESS implementation. There has been and continues to be a pressing need for coordinated, industry-wide action to improve the safety and reliability of energy storage systems.

In 2013, with the release of the Grid Energy Storage Strategy, the U.S. Department of Energy's, Office of Electricity Delivery and Energy Reliability (DOE OE) identified the challenges to widespread deployment of energy storage.[1] One of the central challenges identified was a concern about the risks associated with energy storage. This challenge provided the motivation for holding an energy storage safety workshop sponsored by DOE OE in 2014.[2] A wide range of stakeholders attended this workshop, and with their input, the DOE Energy Storage Safety Strategic Plan was developed and released in late 2014. DOE has fostered a number of efforts to address energy storage risk assessment and mitigation, including numerous publications, educational materials, communications and meetings organized under an ESS Safety working group. The working group was comprised of three sub-groups focusing on research and development (R&D), codes and standards, and education and outreach. Through their efforts, research has been facilitated, codes and standards have been updated, and information on risk identification and management has reached those having an impact on the deployment of energy storage systems. With a significant increase in R&D activities and in the number of codes and standards that relate to ESS safety, Sandia National Laboratories held the ESS Safety Forum in early 2017. This brought together the energy storage community to share past efforts and research, as well as helped to identify the most critical needs going forward.

Understanding and mitigating safety risks associated with ESS are receiving greater attention. It has been identified that organizational work and collaborative efforts needed around safety can benefit if they are coordinated by an entity that does not represent any specific ESS development or implementation stakeholder. The DOE OE, through the national labs who support its activities in ESS safety, are shepherding these activities, facilitating efforts to identify and mitigate risks in ESS, and establishing the foundation needed to foster communciation and collaboration amongst all ESS stakeholders.

INTRODUCTION

This document is the result of past efforts as described above and most notably the Energy Storage Safety Forum held in late February 2017 which had over 100 attendees representing a wide range of stakeholders associated with ESS development and adoption.

The primary focus of this roadmap is to establish a goal and then a path toward achieving that goal. The roadmap provides a specific goal and three distinct objectives identified to reach that goal. Each objective has specific tasks identified to enable successful realization of the objective. The tasks outlined under each objective fall naturally into the past activities associated with the ESS Working Group and are in line with other initiatives being undertaken by the wide range of stakeholders. The roadmap objectives fall into the following categories: research/development, codes/standards, and collaborative resources.

The areas of focus throughout the roadmap that are relevant to all three objectives include electrical safety, fire, and smoke hazard detection and mitigation, health and environmental hazards, natural and -man-made disasters, ventilation and thermal management, and system controls. These areas of focus are addressed beginning with system development

[1] Grid Energy Storage, US DOE, December, 2013. http://www.sandia.gov/ess/docs/other/Grid_Energy_Storage_Dec_2013.pdf.
[2] Energy Storage Safety-Strategic Plan, US DOE, December, 2014. http://www.sandia.gov/ess/docs/other/DOE_OE_Safety_Strategic_Plan_Dec_2014_final.pdf

Collaborative Resources

- **Objective –** Create a conduit for effective communication using traditional and evolving media that will serve as a forum for involvement, information sharing, and collaboration that allows stakeholders to be informed of activities being undertaken in support of energy storage safety and the roadmap.
- **Activities**
  - Develop and deploy an ESS collaborative repository strategy.
  - Secure a commitment from stakeholder associations and organizations to participate in the development and deployment of the activities planned in the ESS collaborative repository strategy.
  - Create a web-based information resource (Repository).
  - Collect relevant information concerning energy storage system risks for inclusion in the Repository. Create resources to inform the community based on the results of objectives one and two. Organize the Repository for easy access and efficient navigation by all stakeholder groups.
  - Foster the update and enhancement of the Repository information on an ongoing basis to facilitate communication regarding energy storage system risk assessment and mitigation.
  - Monitor efforts associated with communication and collaboration, report on successes and identify and address areas where increased communication and collaboration are needed

Key Takeaways

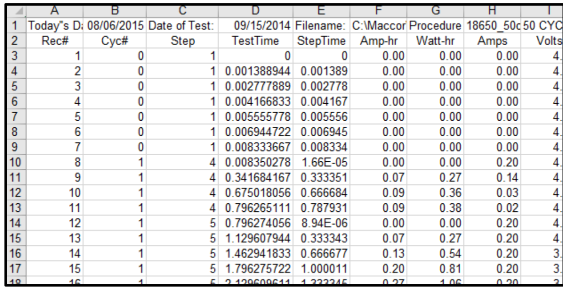
- Energy storage technologies may or may not be similar to other technologies; the system and its component parts must be validated as being safe.
- The safety of an energy storage technology is also affected by the location in which it is installed and manner in which that installation is implemented.
- While there are a set number of safety issues, the manner in which they are addressed to ensure safety is significant due to the number of variables associated with the technologies and their relationship with the built environment.
- Safety does not stop when a new system is commissioned, and the safety issues remain relevant through operation, repair, or renewal of the system and finally through decommissioning or recommissioning.

Key Takeaways

- Development and maintenance of U.S. model codes and standards is an ongoing process open to all interested parties and is facilitated by a number of standards development organizations.
- Development and maintenance of international standards is an ongoing process open to all with participation on a country by country basis with one vote per country.
- Advancements in energy storage technology and lessons learned from existing system installations will necessitate continual updating and enhancement of codes and standards.
- Once codes and standards are published there are a myriad of entities that will adopt and focus on ensuring compliance with those codes and standards.
- Participation by all relevant parties in the development, adoption, and implementation of codes and standards will help ensure energy storage technology can be deployed safety and in a timely less complicated manner.

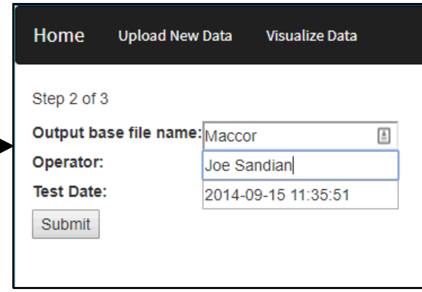
Battery tester data storage and archival

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

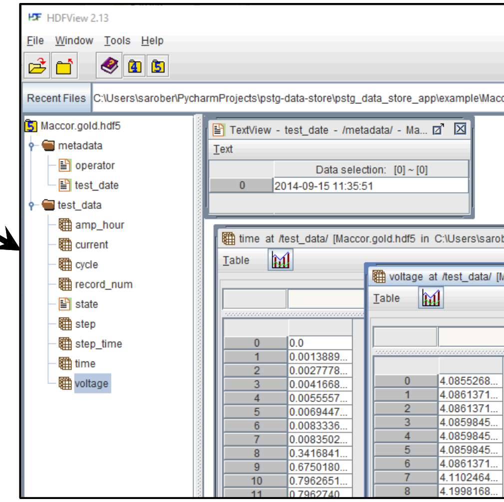


	A	B	C	D	E	F	G	H	I
1	Today"s D:	08/06/2015	Date of Test:	09/15/2014	Filename:	C:\Maccor	Procedure	18650_50c	50 CYC
2	Rec#	Cyc#	Step	TestTime	StepTime	Amp-hr	Watt-hr	Amps	Volts
3	1	0	1	0	0	0.00	0.00	0.00	4.
4	2	0	1	0.001388944	0.001389	0.00	0.00	0.00	4.
5	3	0	1	0.002777889	0.002778	0.00	0.00	0.00	4.
6	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.

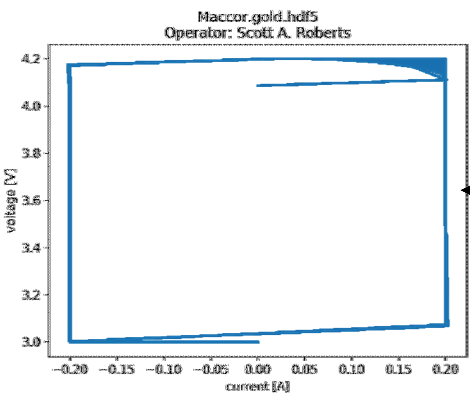
Input data (CSV, XLSX) includes tabular test data and metadata



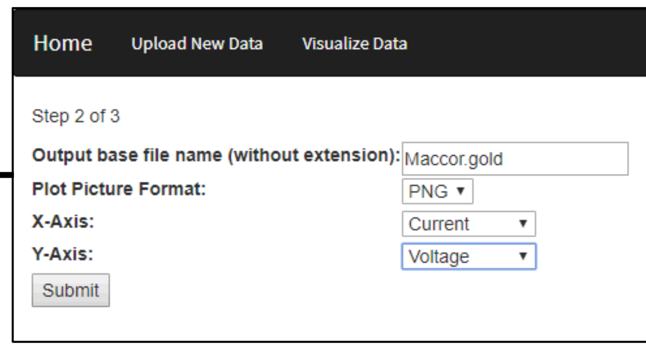
Web interface to upload data, enter metadata



Data converted to common format, stored in HDF5



Data output to plots, excel



Web interface to post-process

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