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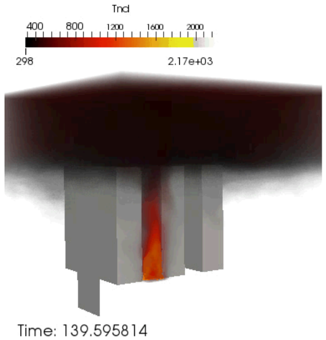

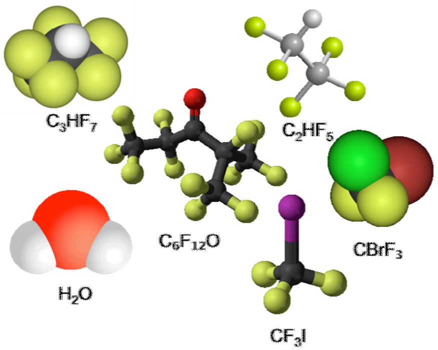

Safety R&D Challenges in Stationary Storage Systems

EE8—Grid-Scale Energy Storage

Josh Lamb, John Hewson, Summer Ferreira

Materials Research Society Spring Meeting
March 29, 2016

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Impact and Consequence of Scale on Safety

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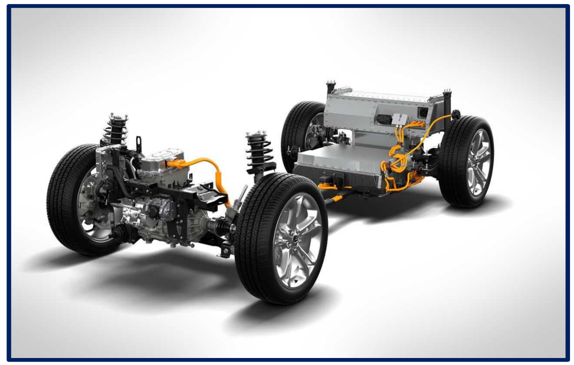
The Lack of Safety:

Endangers Life

Loss of Property

Damages Reputation

Decreases Confidence in Storage



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

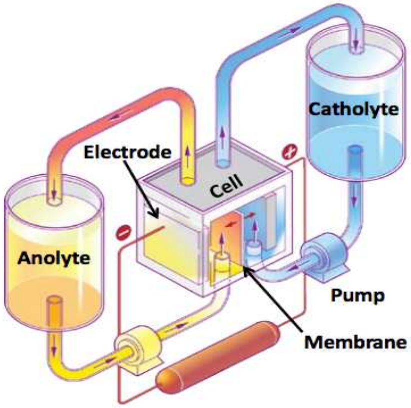
www.ford.com www.samsung.com www.saftbatteries.com

Safety issues should become paramount with increasing battery size

The Grid Energy Storage Safety Challenge

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


Subway regen system, SEPTA



Redox Flow Battery

SAFT 10 MWh storage system


US Marine Corps FOB, Afghanistan

Key Challenges:

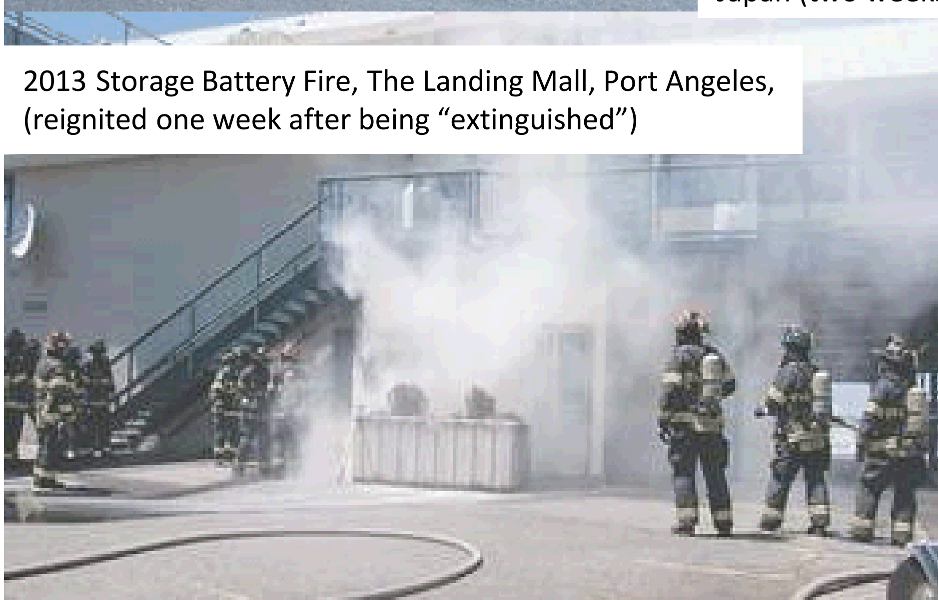
Utility safety incidents have highlighted the **need for a focused effort** in safety

Examples of Recent Issues with Energy Storage Safety

2011 Beacon Power Flywheel Failure

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

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



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

2012 GM Test Facility Explosion, Warren, MI

Improving battery safety

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Development of Inherently Safe Cells

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

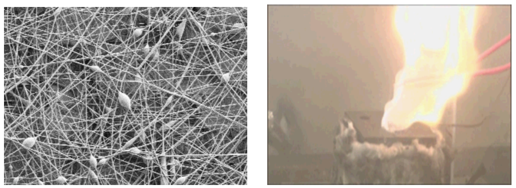
Safety Devices and Systems

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

Effective Response to off-normal Events

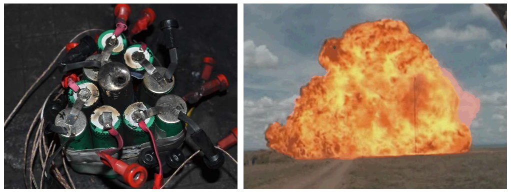
- Suppressants
- Containment
- Advanced monitoring and controls

Battery Safety – Stationary Storage

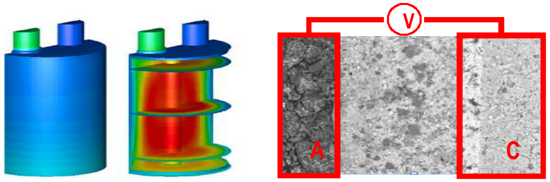


Materials R&D to date:
- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

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



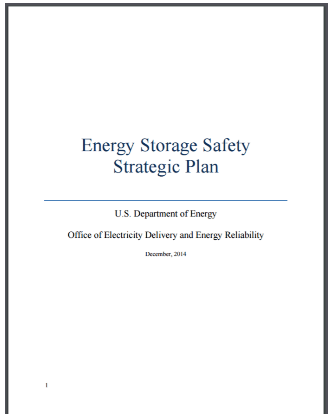
Testing
- Electrical, thermal, mechanical abuse testing
- Failure propagation testing on batteries/systems
- Suppressants and delivery with systems and environments
- Large scale thermal and fire testing (TTC)



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

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

Grid Energy Storage Safety Initiative


Energy Storage Safety Strategic Plan

U.S. Department of Energy

Office of Electricity Delivery and Energy Reliability

December, 2014

SNL building capabilities, postdocs hired at SNL

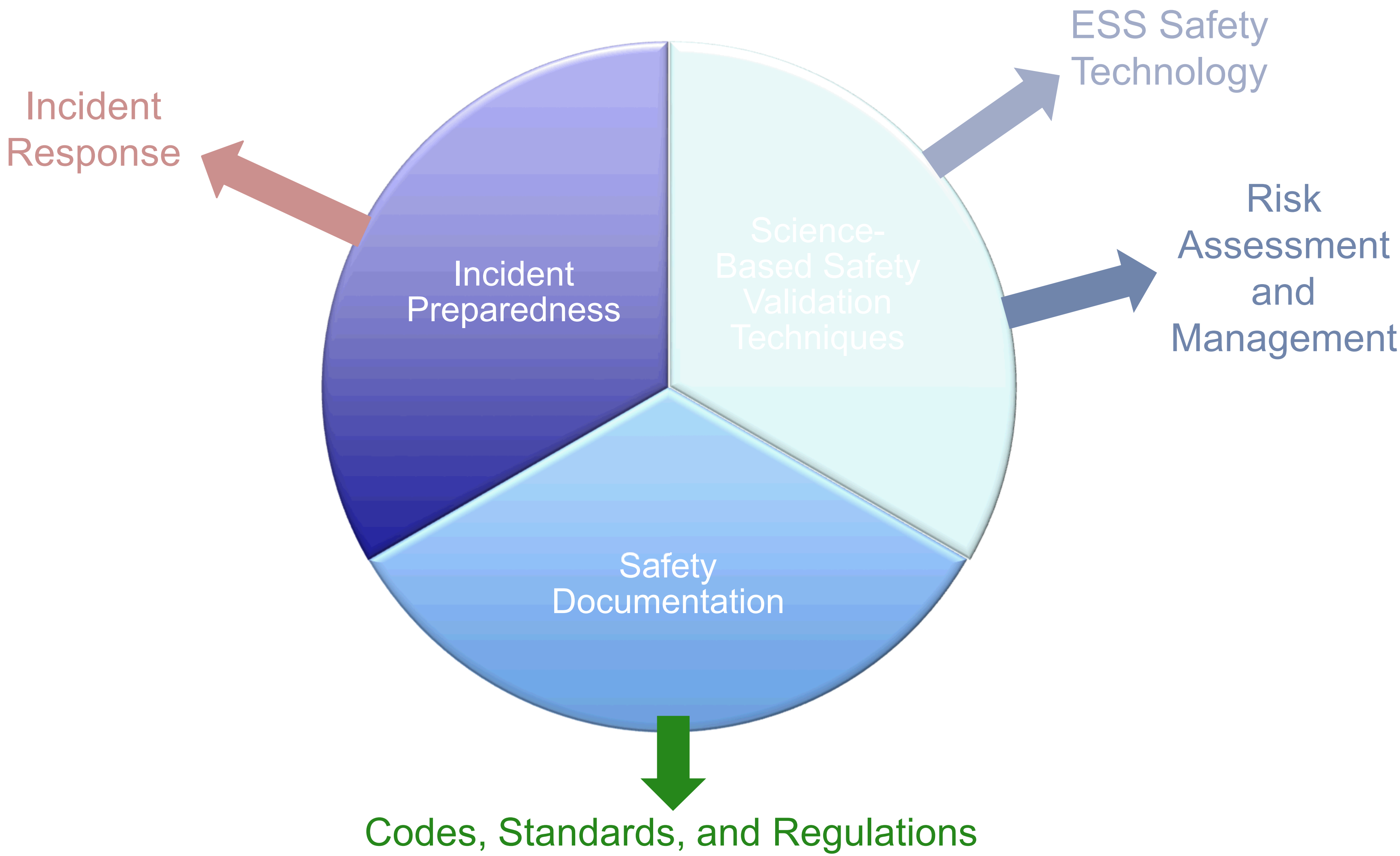
2013 → 2014 → 2015 → 2016 → 2017 →

DOE OE Workshop for Grid Energy Storage Safety

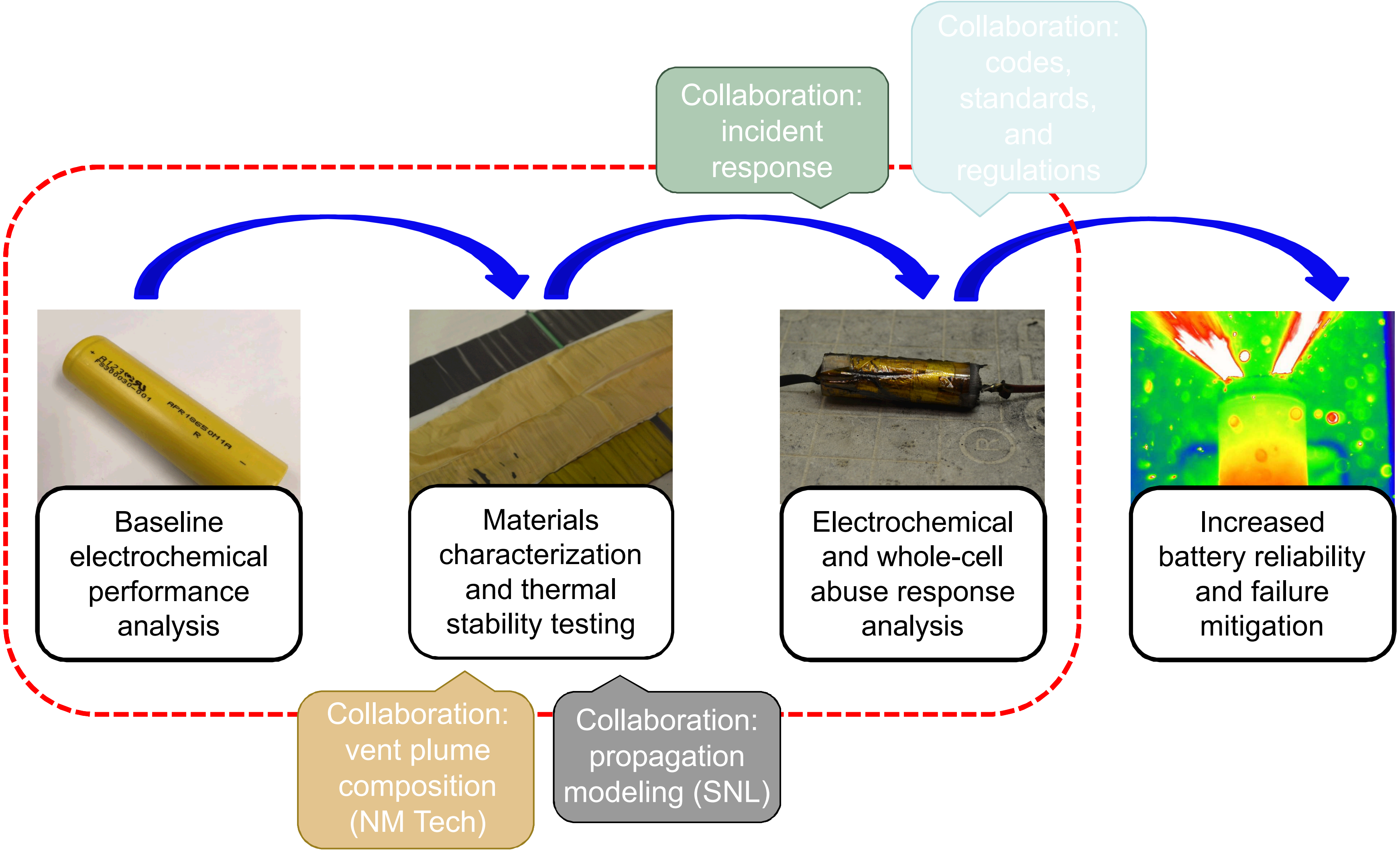
Working groups formed

Meeting the Challenge: 2017 ESS Safety Forum, Santa Fe NM

Interconnected Paths to Safe Energy Storage Deployment and Operation



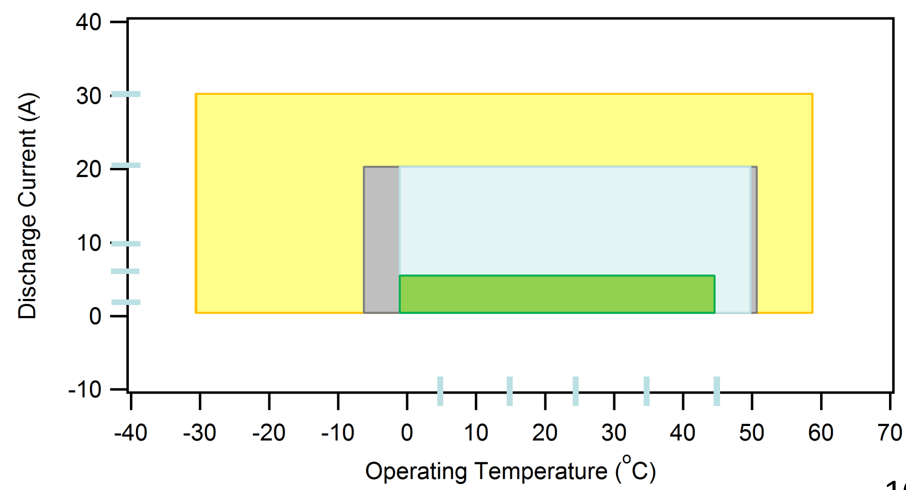
Project Goal is Battery Failure Mitigation



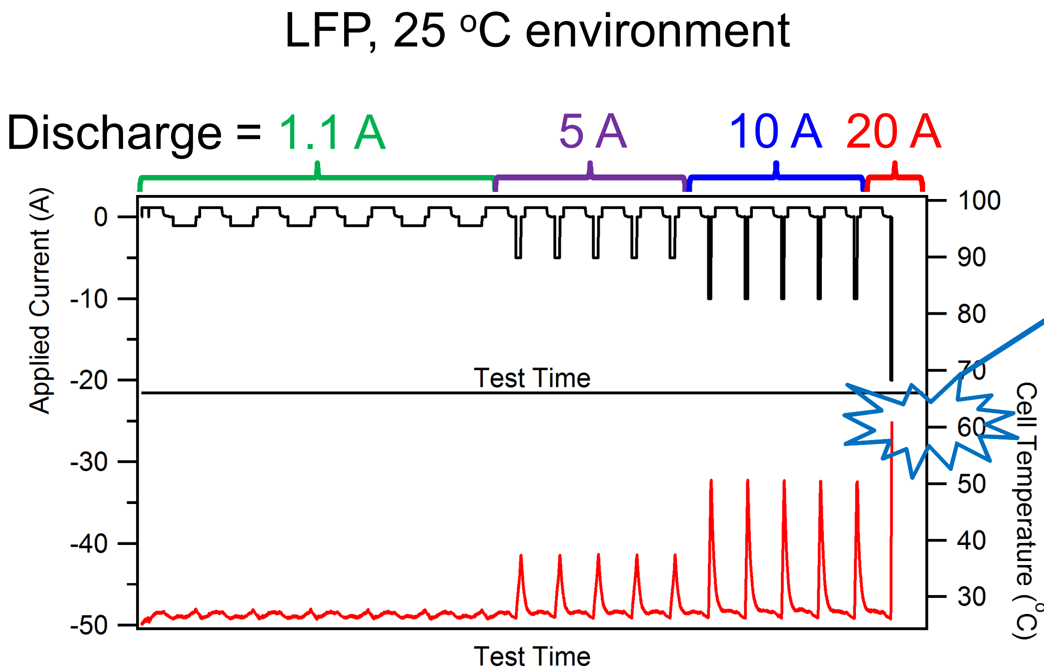
Battery venting image: Finegan, D. P.; Scheel, M.; Robinson, J. B.; Tjaden, B.; Hunt, I.; Mason, T. J.; Millichamp, J.; Michiel, M. D.; Offer, G. J.; Hinds, G.; Brett, D. J. L.; Shearing, B.; Shearing, P. R. *Nat. Commun.* **2015**, *6*, 6924-6934.

Cells and Manufacturer Specs.

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



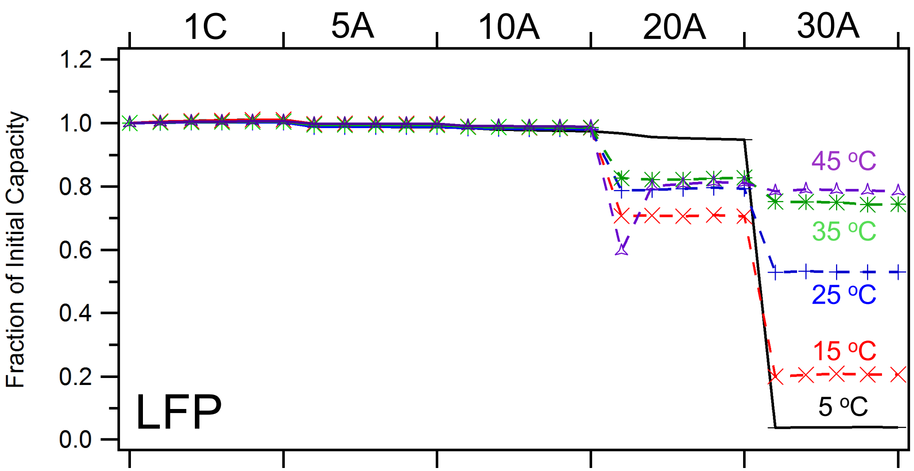
Avoid accelerated aging or abuse

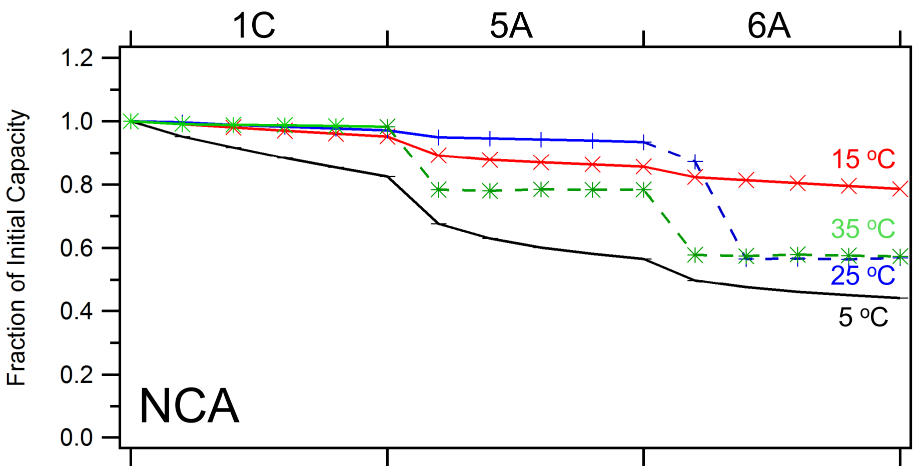


Current = 20 A (max = 30 A)
Environment = 25 °C
Cell skin Temp = 60 °C!!!

Most packs don't monitor individual cell temperatures and manufacturer specifications don't mention self-heating. This allows for an unintended abuse condition under 'normal' operation.

Degree of capacity loss varies with temperature, current, and chemistry



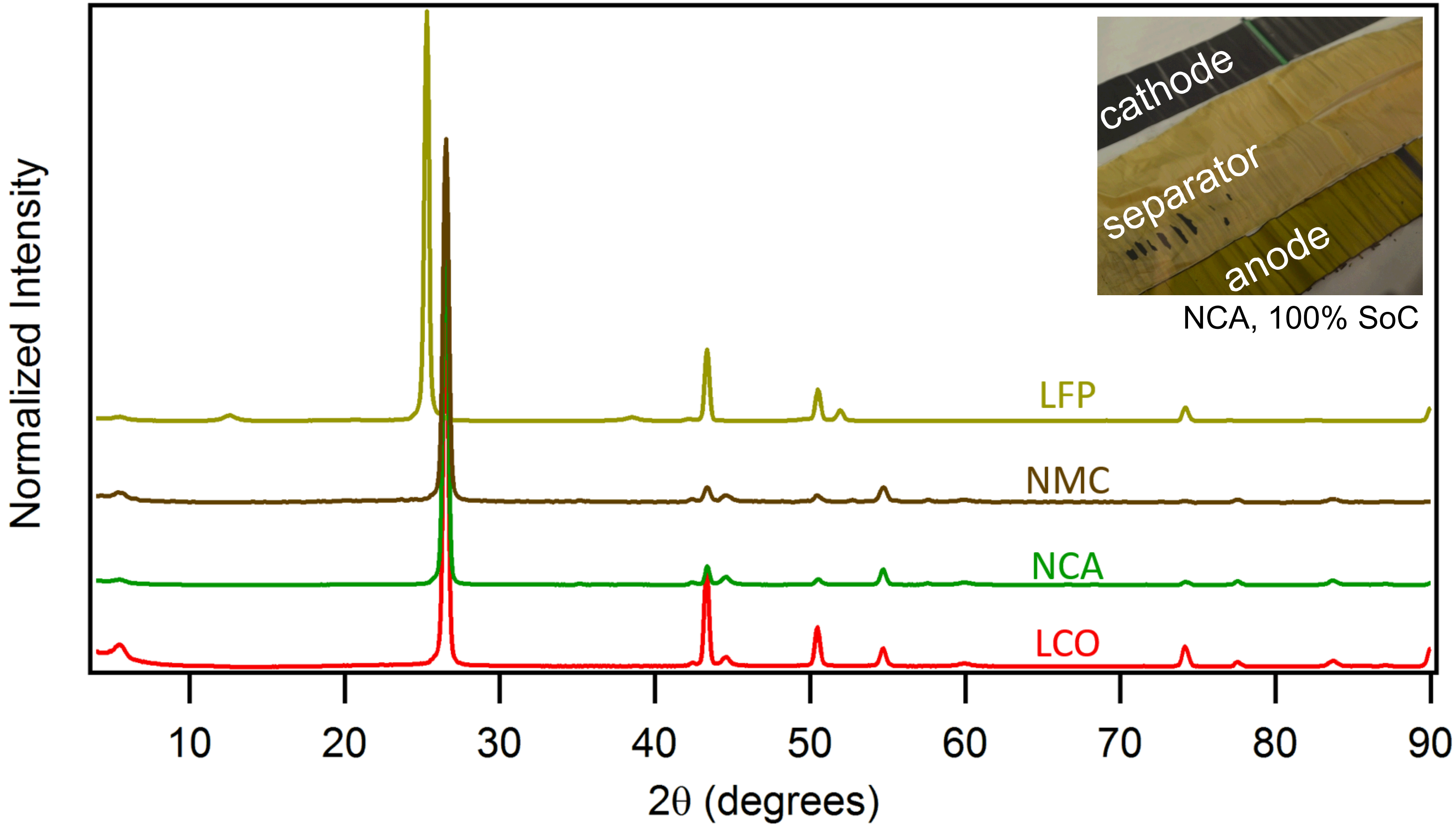


- No temperature effects at currents ≤ 10 A
- higher temperature = less capacity loss

- Capacity loss with higher currents, higher/lower temperatures
- 15 °C immune to most losses

Although manufacturer specifications allow battery operation at certain conditions, the battery may not perform well.

Reverse-engineering reveals a unique LFP anode



LFP has the highest thermal runaway onset temperature and smallest maximum heating rate, it also has the only unique bulk anode material.

NCA anode unstable at higher SoC

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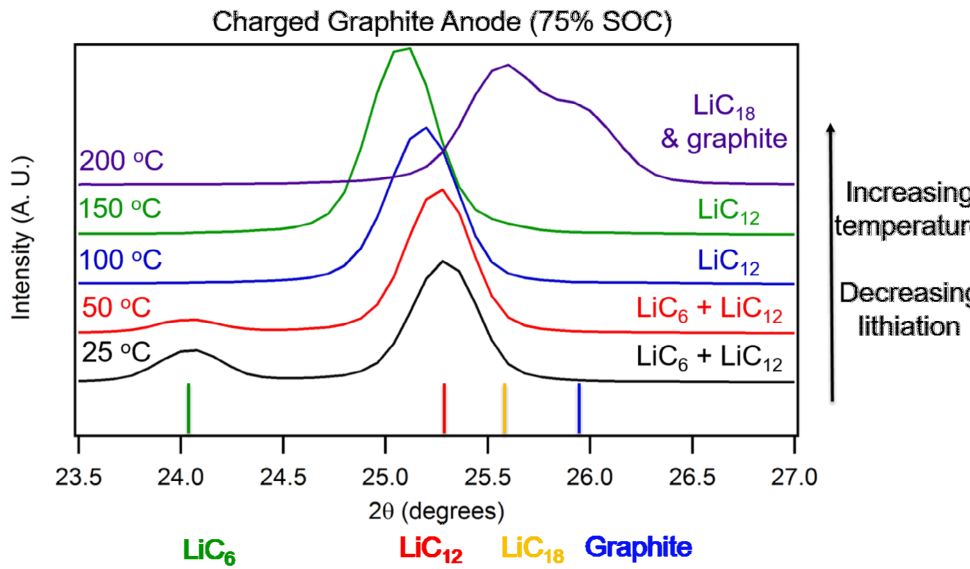

NCA anode begins to decompose at temperatures as low as 50 °C. This results in poor temperature tolerance in both electrochemistry and abuse-response.

NCA anode unstable at higher SoC

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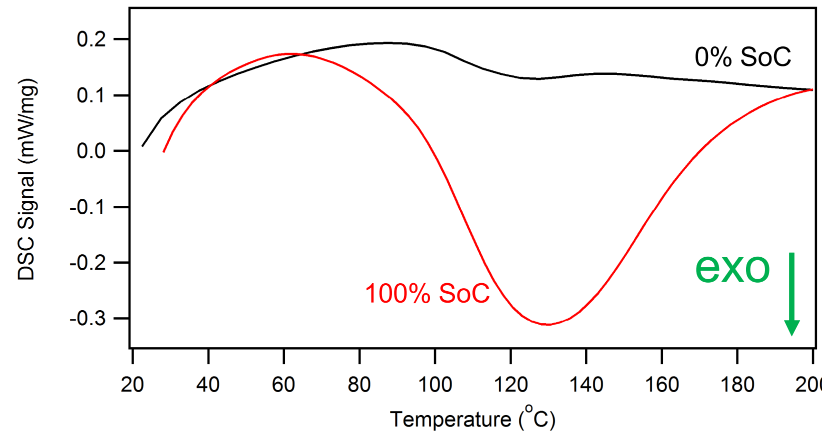
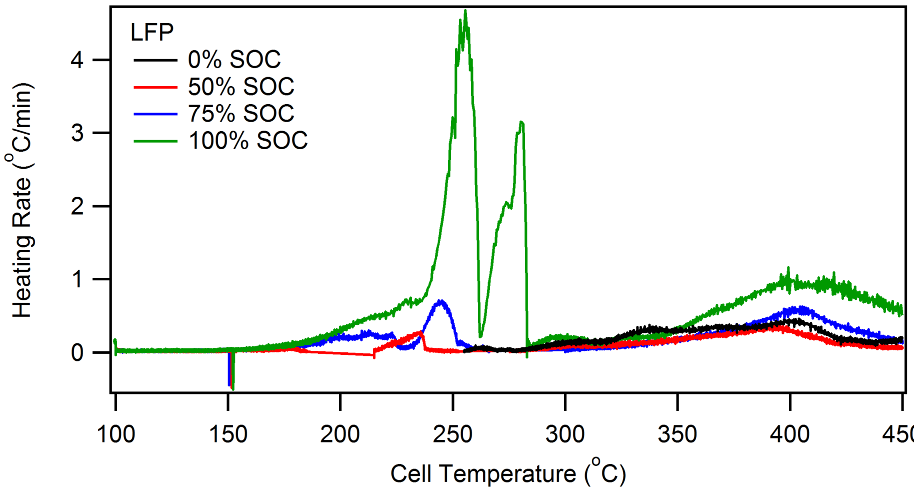
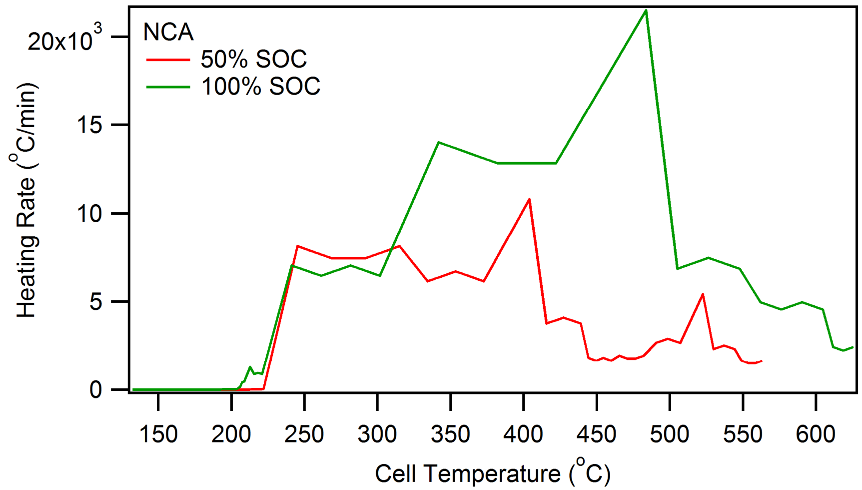


The NCA anode undergoes exothermic reactions of increasing intensity at higher SoC. This is the source of NCA's low thermal runaway onset temperature.

NCA much more reactive than LFP in ARC

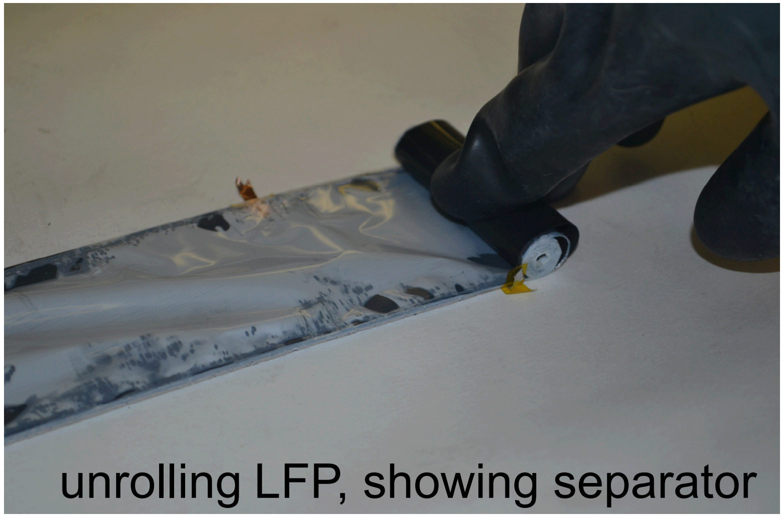


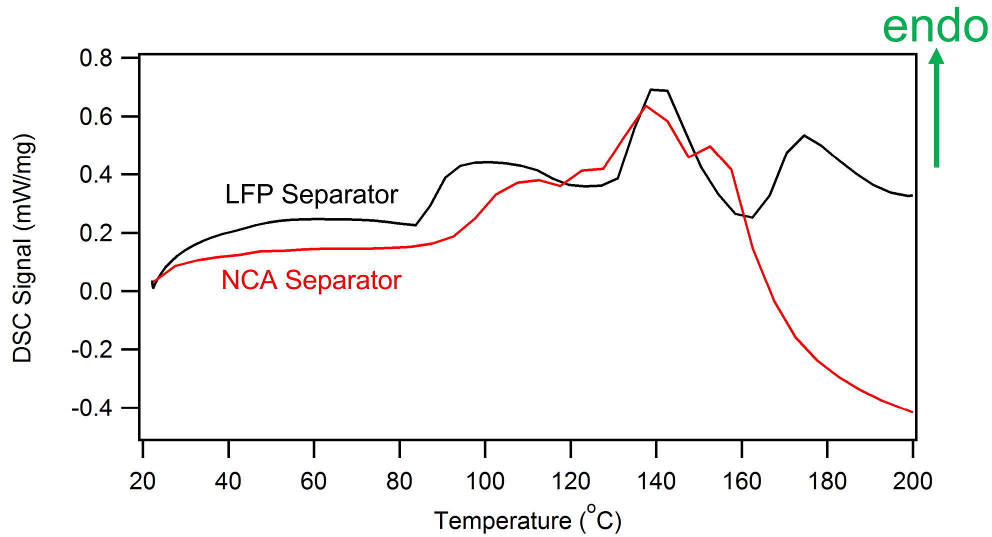


- No runaway at lower SoC
- Maximum recorded heating rate = ~5 °C min^{-1}
- Maximum recorded heating rate = ~20,000 °C min^{-1}
- Energetic failure four orders of magnitude larger than LFP

Identifying cell components and quantifying material stability coupled with well-known ARC data yields pathways for materials- or cell-level safety engineering.

LFP separator melts at a lower temperature than NCA





- Shutdown separator standard in commercial cells
- Designed to melt and become insulating, preventing runaway

- LFP melting onset =
- NCA melting onset =

Although NCA is less stable overall, the LFP cell has a safer separator. This illustrates the need for safety-driven battery engineering.

Abuse Testing

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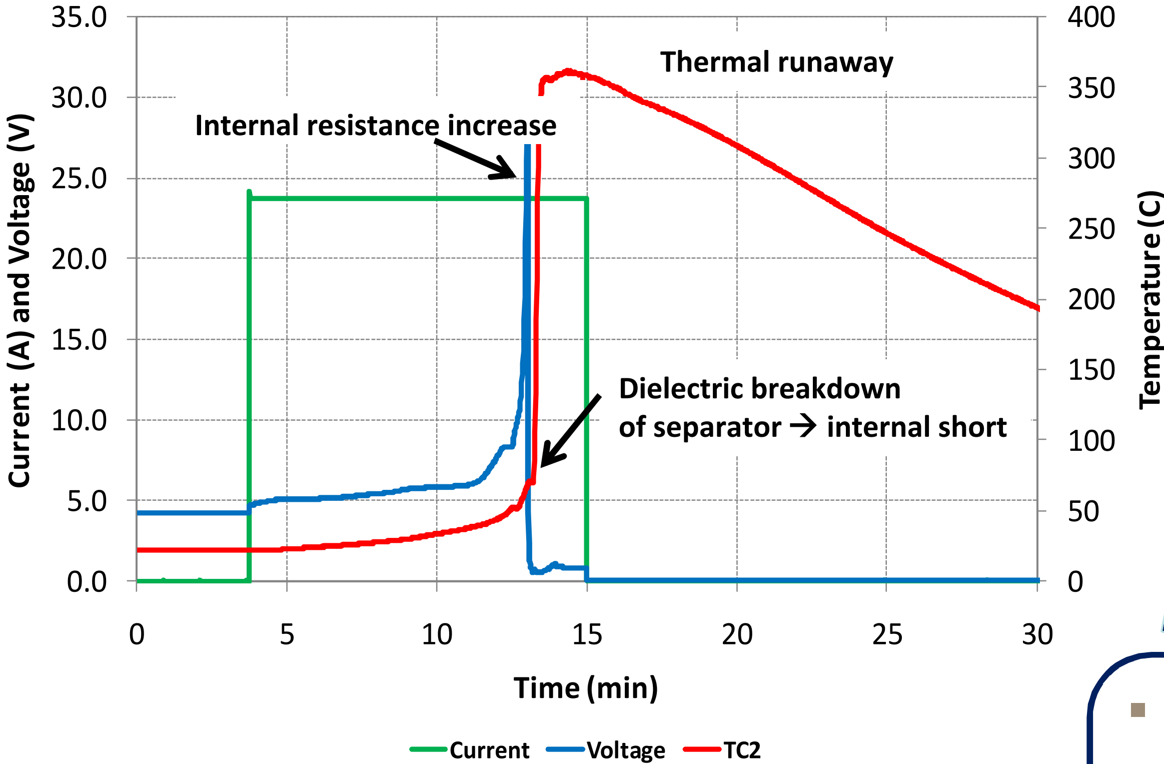
12 Ah (~50 Wh) Cell Overcharge Abuse



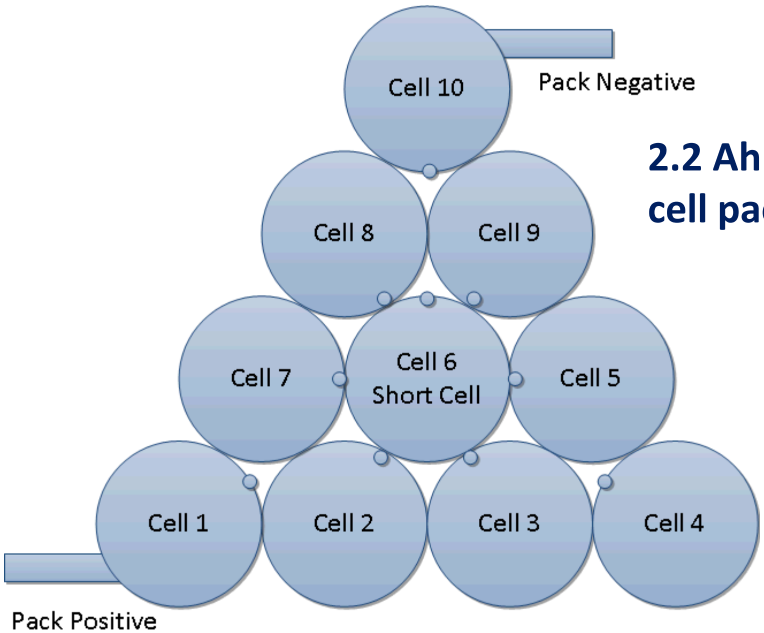
(Internal temperature limited due to ejection of cell contents)

50 Wh cell in 8' containment
50 kWh battery failure -- 50 MWh battery failure?

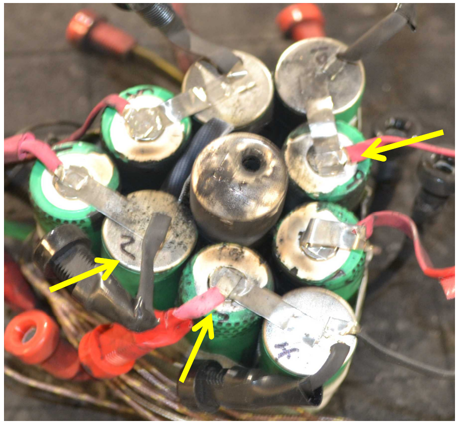
Key Challenges:

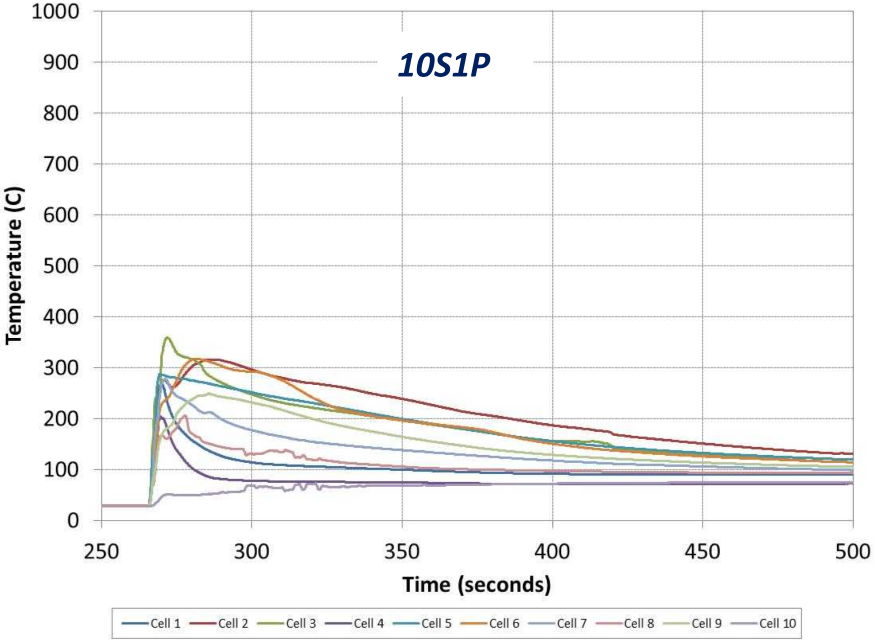
- *Abuse tolerance*
- *Heat generation*
- *Flammability*
- *Neighboring cells thermal runaway or propagation*

Failure Propagation Testing



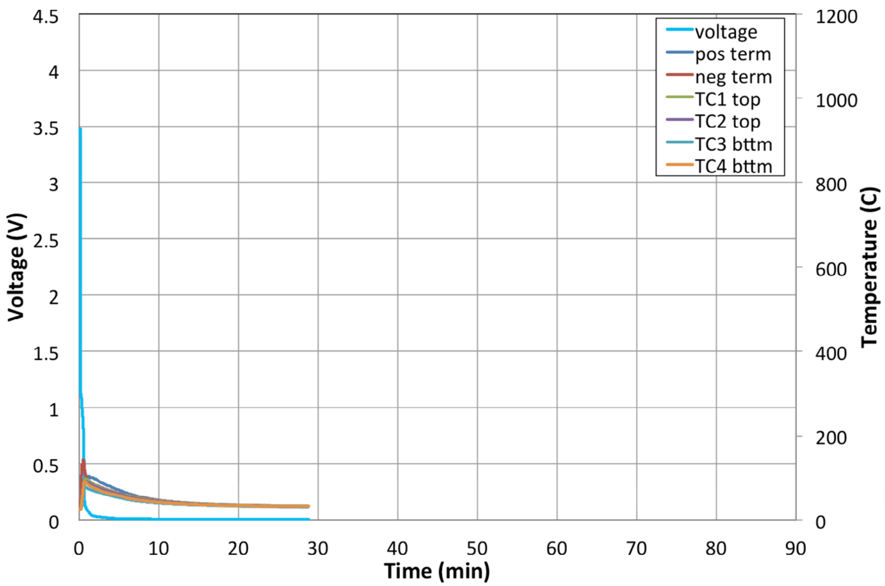
2.2 Ah CoO 18650 cell packs

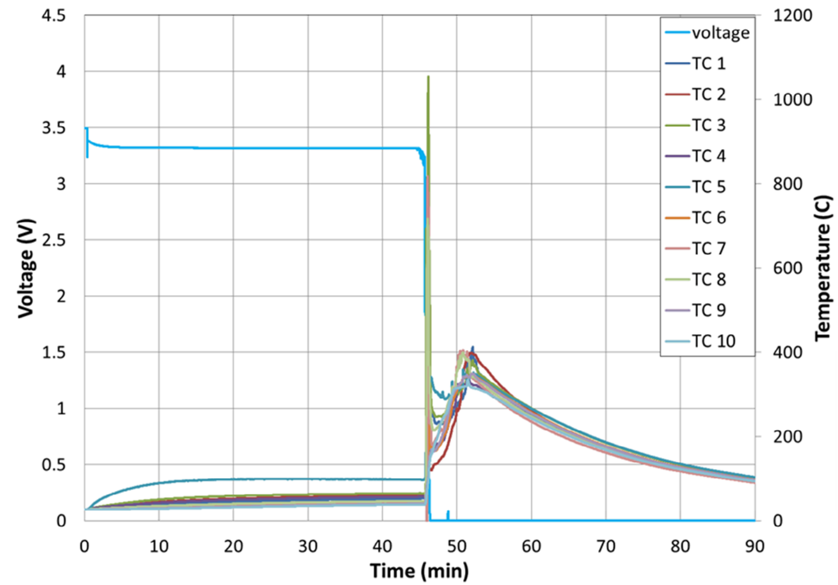




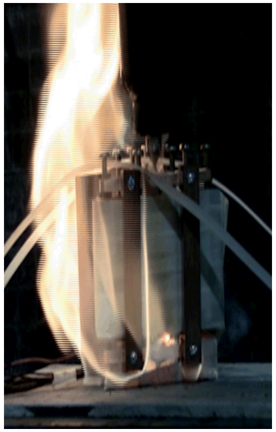
Limited propagation of the single point failure in the 10S1P pack

Cell behavior doesn't translate at scale





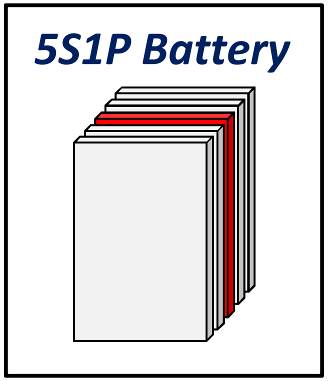
- Stand-alone 26650 $LiFePO_4$ cell abuse causes thermal release and rapid cooling.
- Cell failure in a pack leads to thermal runaway under load

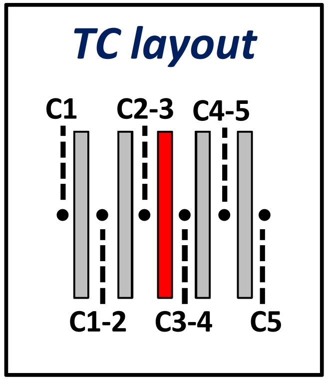


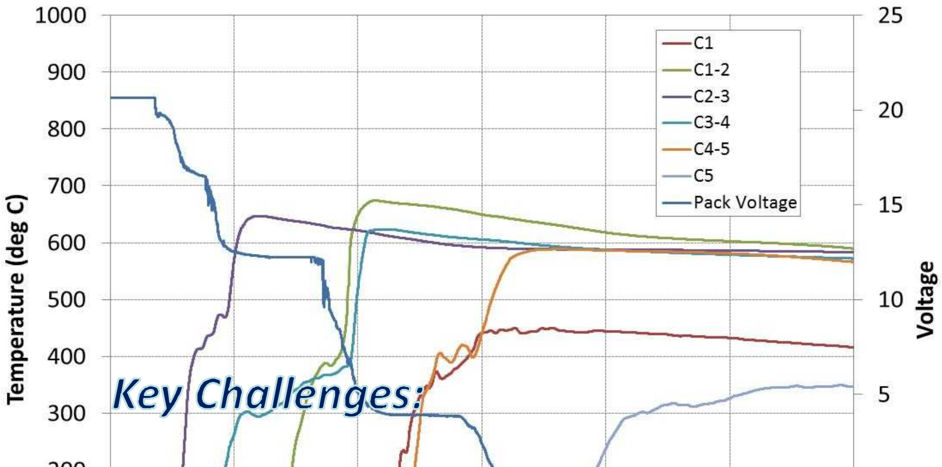
Key Challenges:

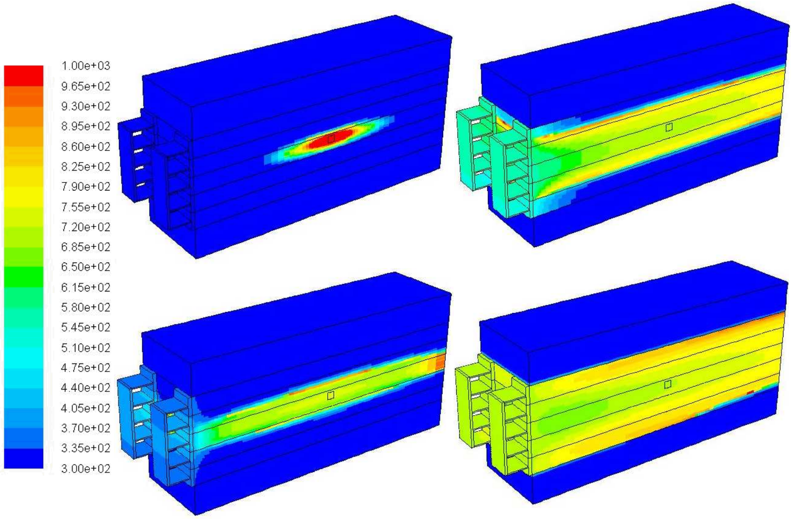
- ***Containment design***
- ***Suppression system details***

Propagation Testing (5S1P)









Modelling performed showing temperature profiles after initiation (Chuanbo Yang and Gi-Heon Kim at NREL)

Key Challenges:

- *Scale – What test setup size becomes representative of real conditions*
- *Statistical significance – Abuse consequences can be highly stocastic*
- *Modeling at high confidence – Robust models need complementary data*

Li-Ion Battery Electrolyte Gas Evolution Studied

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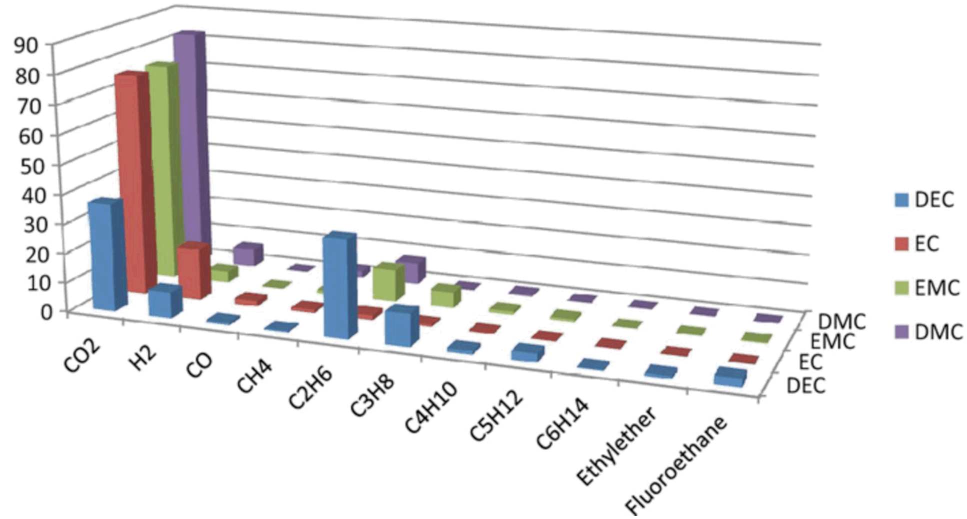
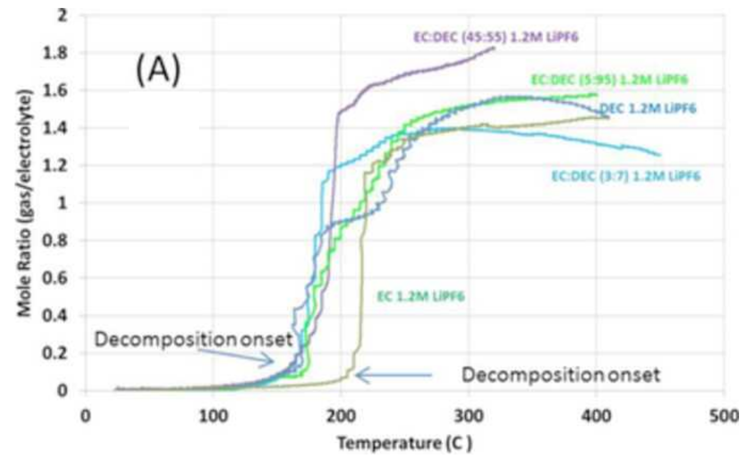




- Composition ratios among CO_2, Hydrocarbons and hydrogen as a function of Electrolyte
- DEC and EC had more gas volume as well as a higher ratio of combustible components

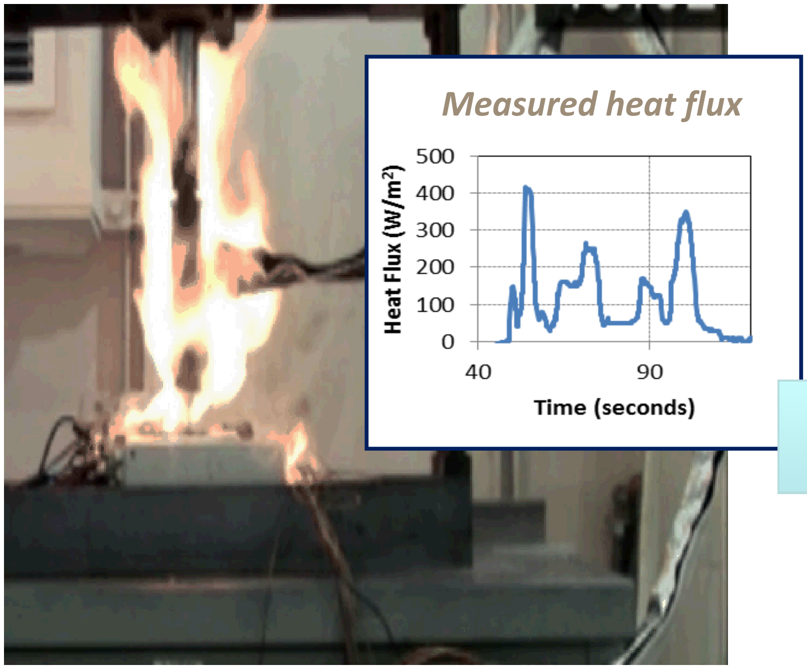
Key Challenges:

- ***Conflagration scenarios need to be understood***
- ***Suppression system designed***
- ***Human health concerns mitigated***

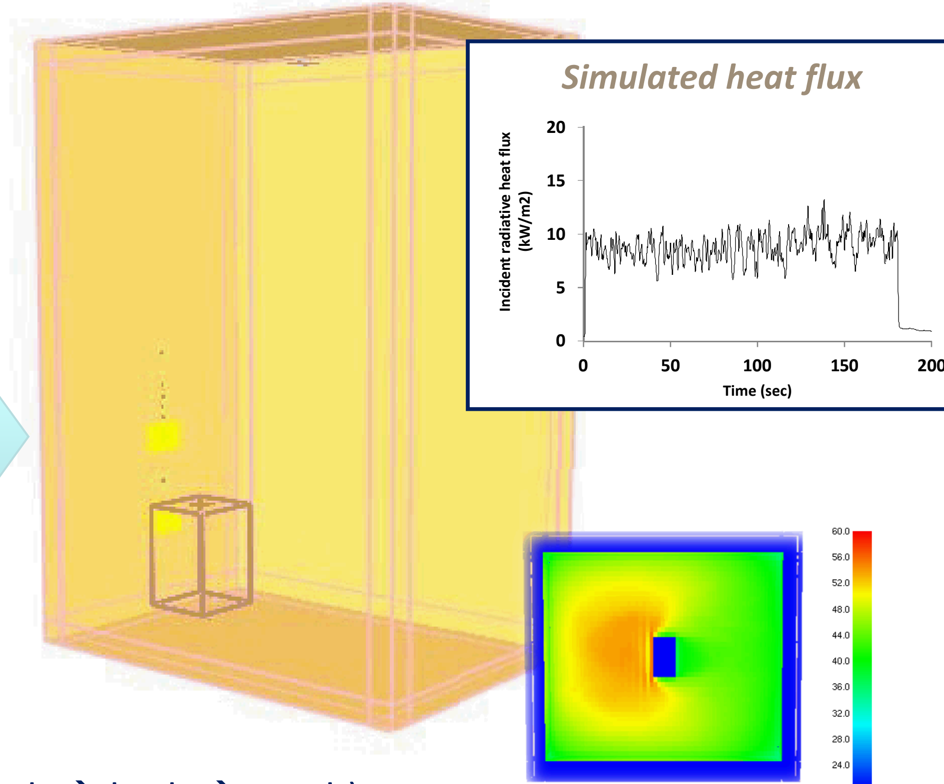
Joshua Lamb et al. J. Electrochem. Soc. 2015;162:A2131-A2135

Quantifying Battery Fires

Experimental Data from Battery Fires



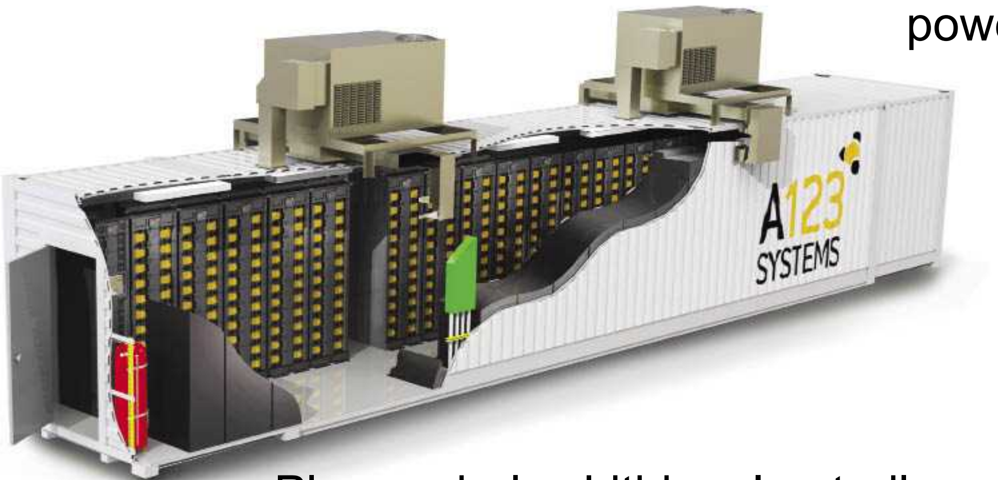
Fire Dynamic Simulations (FDS) of Battery Fires



Test bay ceiling temperature

- Scale up experiments to **validate FDS models** (Wh → kWh → MWh)
- Feedback to **design** storage systems
- Inform **fire suppression** system design
- Provide to regulatory agencies (NFPA, IEEE, UL etc.), utility companies, etc.

Failures at scale necessitate modelling



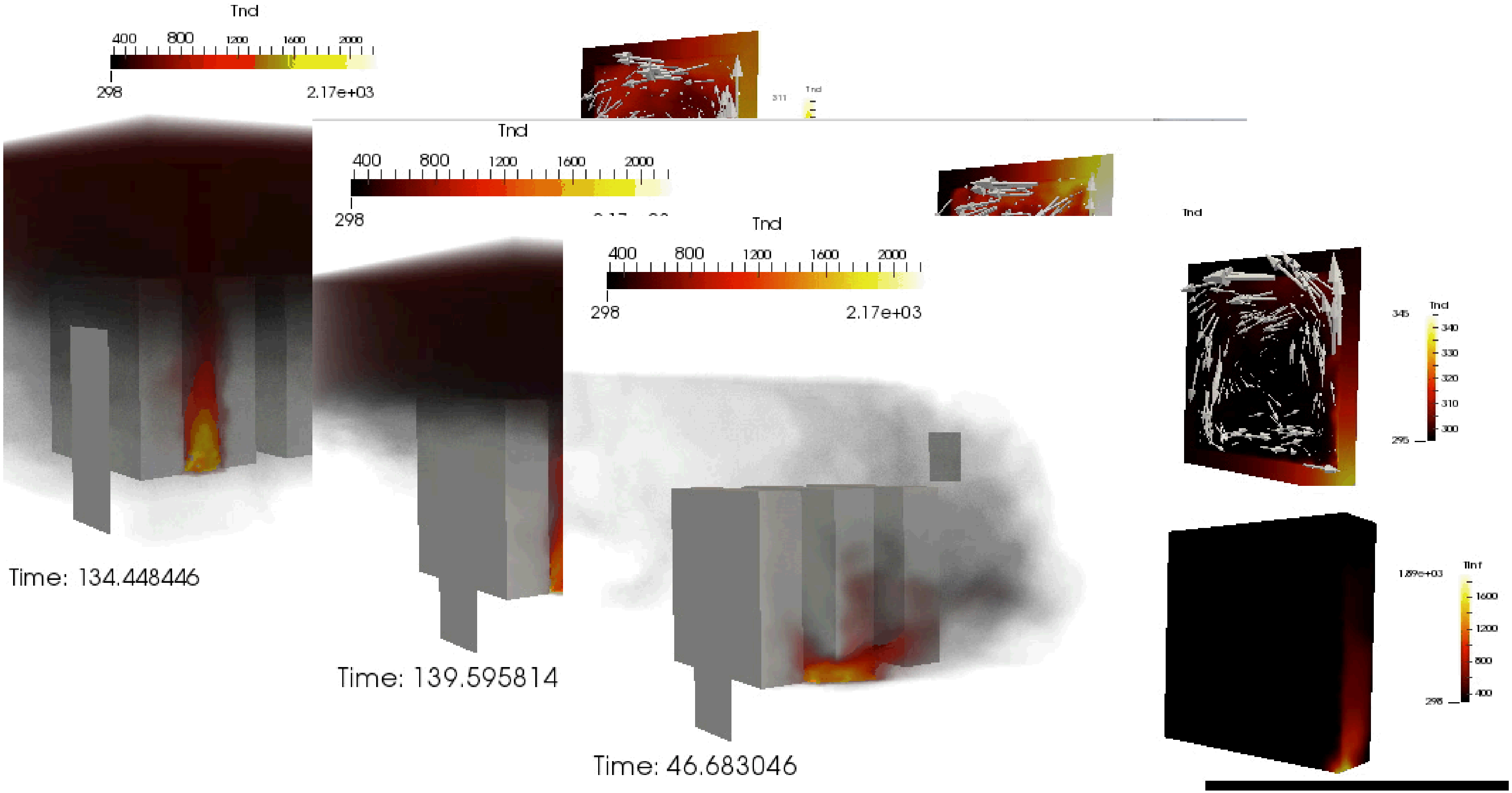
Plug-and-play Lithium Ion trailer

racks of batteries

power conditioning system

Lead acid Alaska facility designed to replace back-up diesel

Plume dynamics



Three ventilation comparison still shot

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.

References

- 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.
- Krieger, E. M.; Cannarella, J.; Arnold, C. B. *Energy* **2013**, *60*, 492-500.

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