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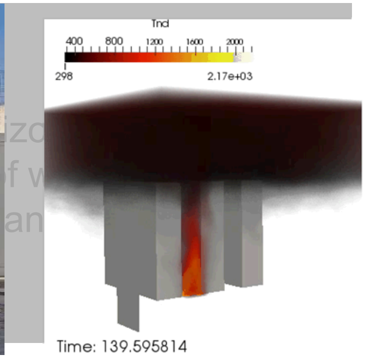

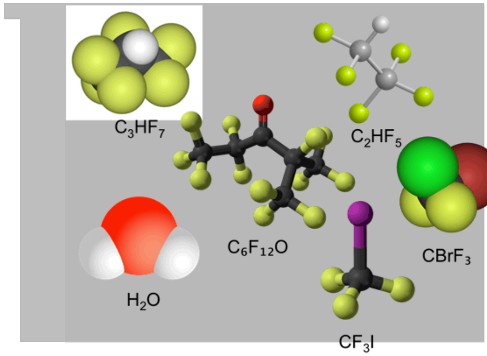

Fundamental Aspects of Large-Scale Energy Storage System Safety

John Hewson, Summer Ferreira, Joshua Lamb, Christopher Orendorff, Babu Chalamala

Power Sources Conference
June 13, 2016

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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

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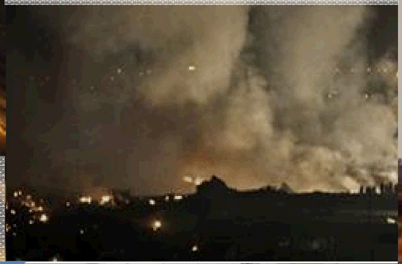
2006 Sony/Dell battery recall 4.1 million batteries


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

2010 FedEx Cargo Plane Fire, Dubai



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


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

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm


2012 GM Test Facility Incident, Warren, MI


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



2013 Boeing Dreamliner Battery Fires, FAA Grounds Fleet

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


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


By nature, stored energy can be hazardous

- Potential hazards associated with stored energy couple with inexperience regarding safety and mitigation practices.
  - What are ignition characteristics?
  - What are hazards, both thermal and chemical?
  - What mitigation is appropriate?
- Other stored energy:
  - Chemical energy in fuels.
  - Pumped hydroelectric storage.

JP-8 pool fire

- Safety characteristics need to be evaluated; standards and best-practices need to be developed.

The Problem of Scale

- Field failures of single cells are relatively rare
  - Failure rates as low as 1 in several million
- The number of cells used in the transportation and energy storage industries is potentially huge (billions)
- EV and PHEV batteries: 10-50 kWh
- Batteries for stationary storage applications: *O*(MWh)
- A single cell failure that propagates through the pack could lead to an impact even with very low individual failure rates

Single Cell
~0.5-5 Ah

Strings and large format cells
~10-200 Ah

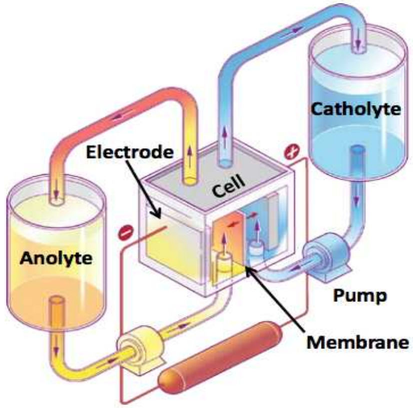
EV Battery Pack 100s-1000s cells
10-50 kWh

Stationary storage system 1000s or more individual cells
MWh+

www.nissan.com
www.internationalbattery.com
www.samsung.com
www.saft.com

The Grid Energy Storage Safety Challenge

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



Redox Flow Battery

Key Challenges:

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

Much has been done to address potential failure modes

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

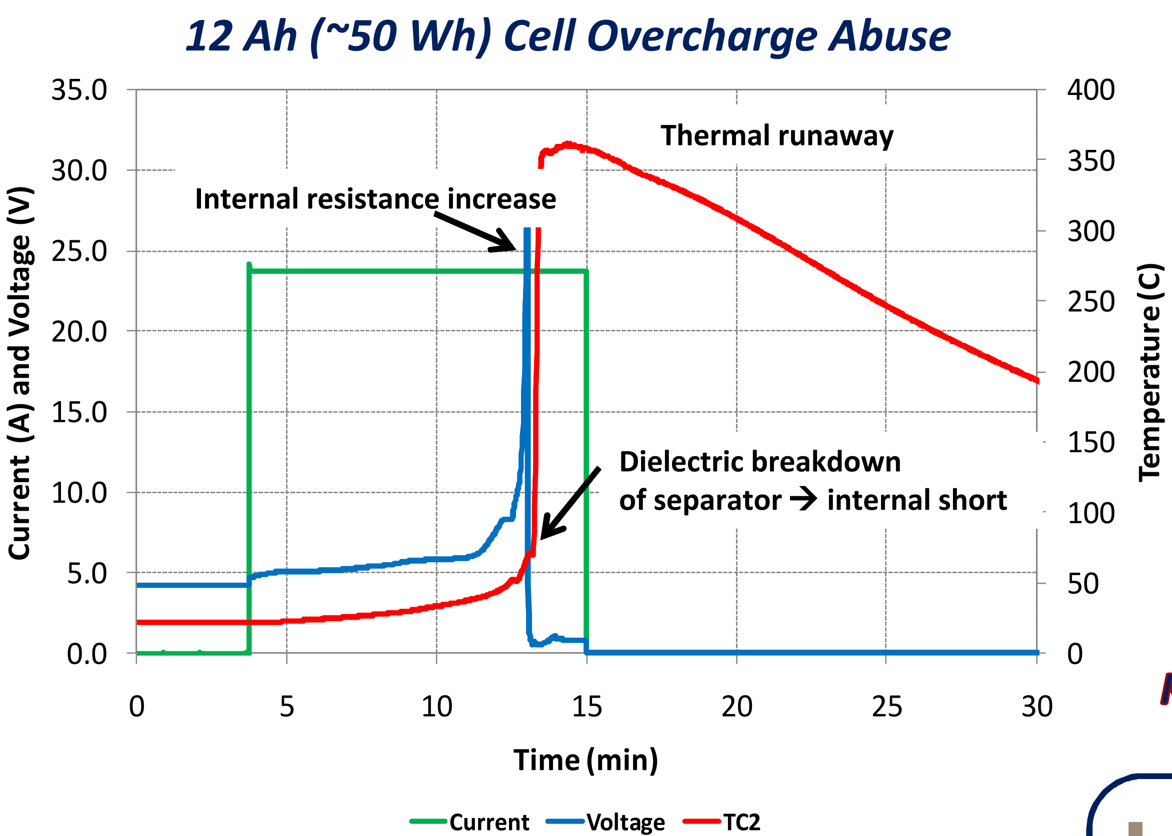
Effective Response to off-normal Events →

- Suppressants
- Containment
- Advanced monitoring and controls

Battery Abuse Testing Laboratory (BATLab)

- Comprehensive abuse testing platforms for safety and reliability of cells, batteries and systems from mWh to kWh
- Mechanical abuse
  - Penetration
  - Crush
  - Impact
  - Immersion
- Thermal abuse
  - Over temperature
  - Flammability measurements
  - Thermal propagation
  - Calorimetry
- Electrical abuse
  - Overvoltage/overcharge
  - Short circuit
  - Overdischarge/voltage reversal
- Characterization/Analytical Tools
  - X-ray computed tomography
  - Gas analysis
  - Surface characterization
  - Optical/electron microscopy

Abuse Testing



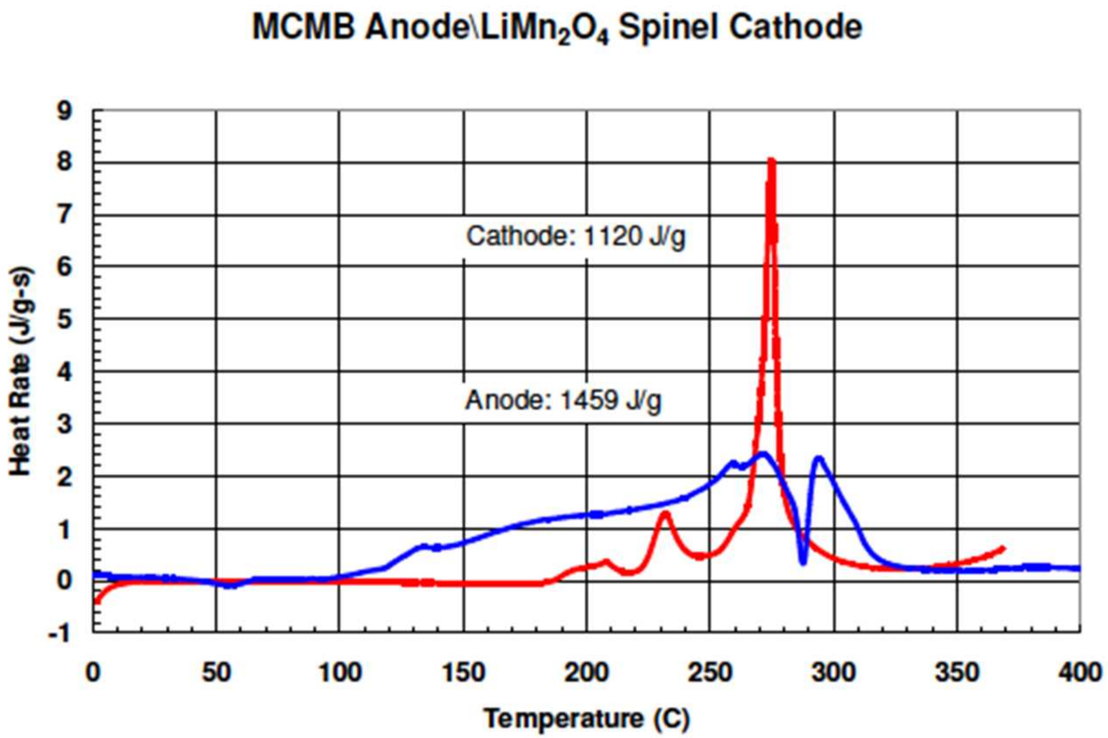
(Internal temperature limited due to ejection of cell contents)

Key Challenges:

- ***Potential heat release can exceed stored energy.***
- ***Potential cascading failure to other cells***

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

Thermal runaway is associated with anode reactions followed by cathode reactions



DSC measurements from Pete Roth

- DSC and ARC results suggest that the first step involved in thermal abuse is the breakdown of the SEI layer, exposing Li/C to the solvent.
- Further heating leads to oxygen release from cathode and reaction with electrolyte.

Changing Cathode Chemistry

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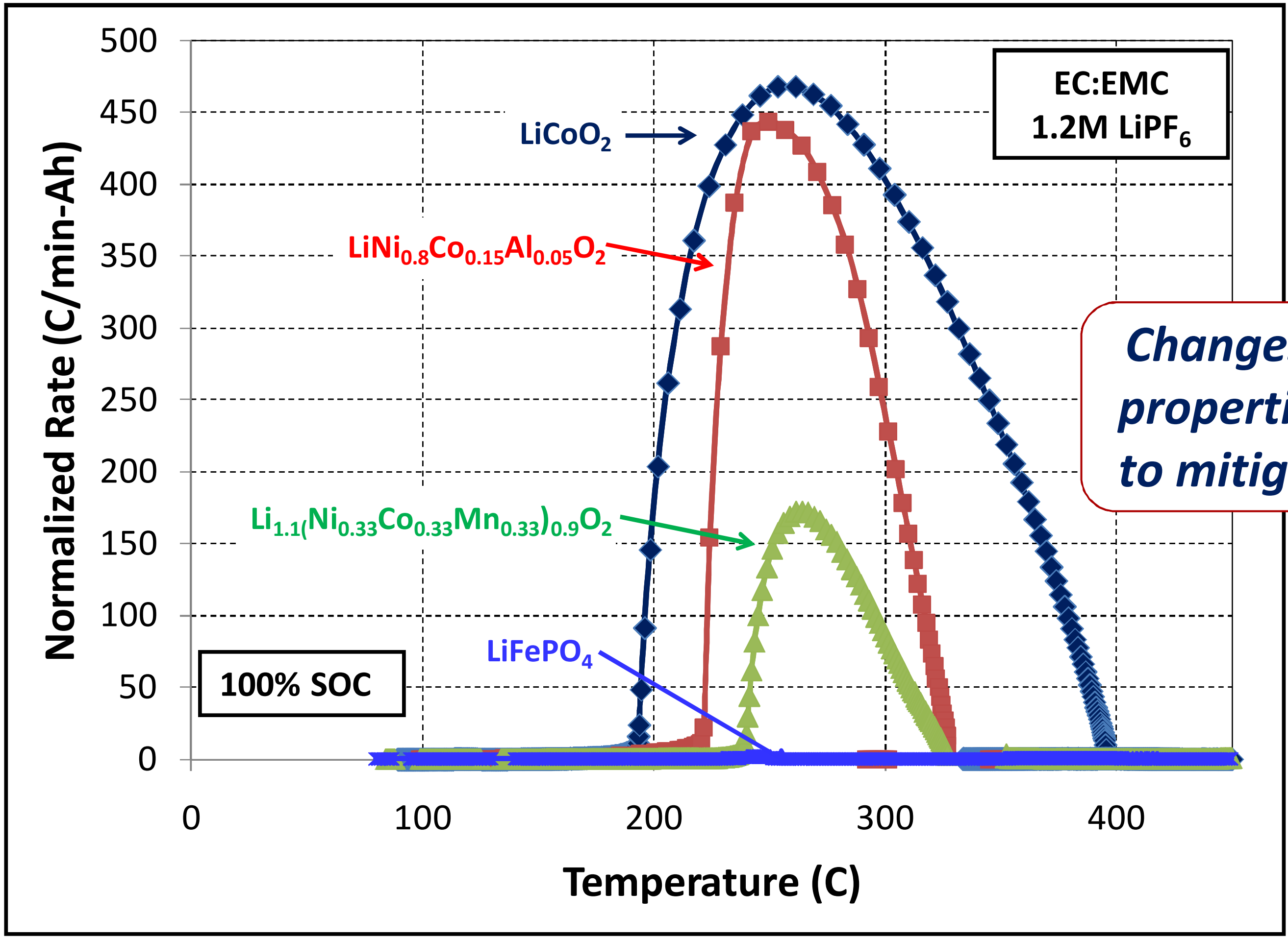
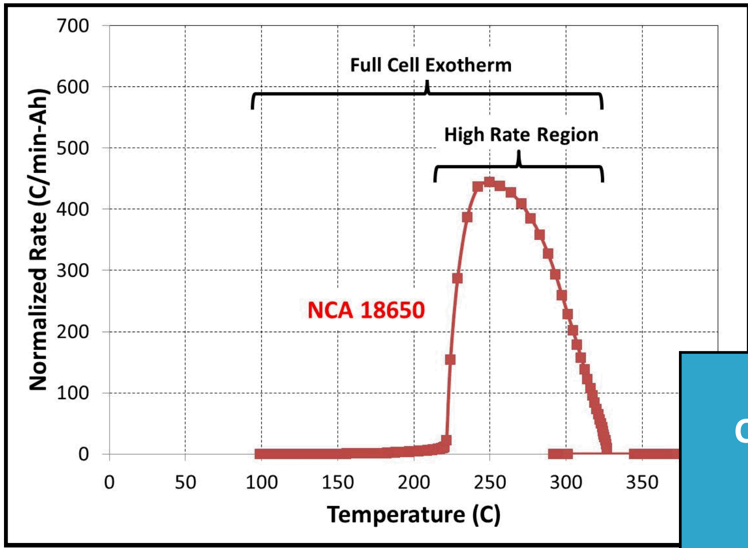
ARC of cells with different cathode chemistries



Changes in material properties: potential to mitigate runaway

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

Characterizing Thermal Runaway



Cell Type	Capacity (Ah)	Runaway Enthalpy (kJ/Ah)		Peak Heating Rate (W/Ah)
		Full Cell	High Rate Region	
LCO 18650*	1.2	28.4	15.9	281
NCA 18650*	1.0	21.6	9.8	266
NMC 18650*	0.95	22.0	8.3	105
LFP 18650*	0.9	18.0	2.4	1
LFP 26650*	2.6	8.2	4.6	65
LFP 26650‡	2.6	8.0	4.5	65

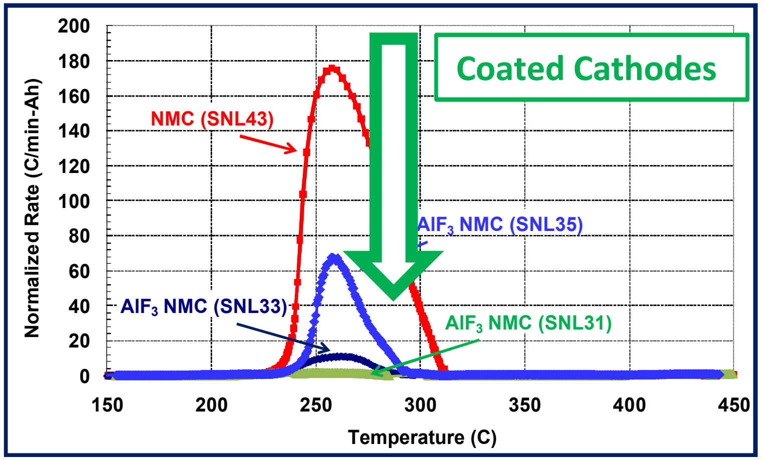
*ΔH based on dT (exotherm)
‡ΔH based on dT/dt (exotherm)

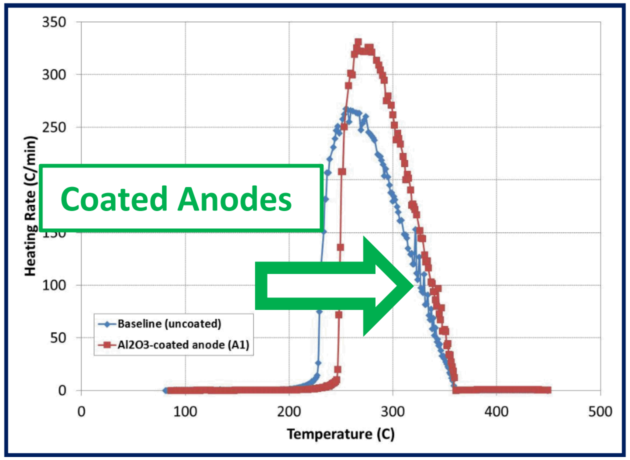
- ***Full cell runaway enthalpy shows a significant amount of heat generation from even an LFP 18650 cell***
- ***But that heat is generated at much different rates for the different cell types***

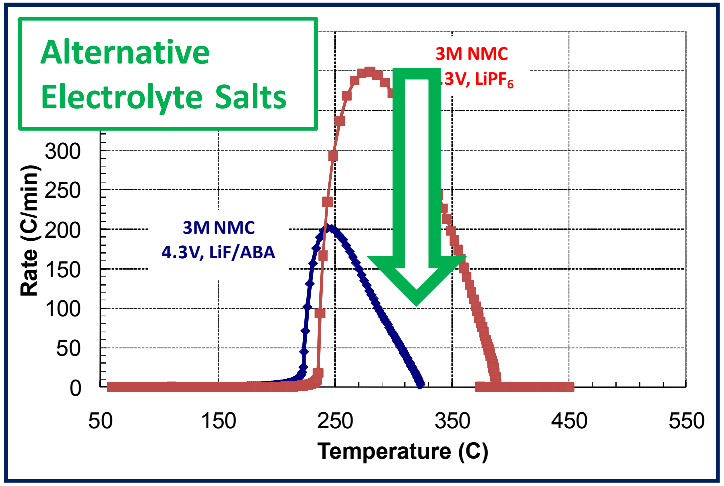
Data provide a quantitative measurement of the runaway enthalpy

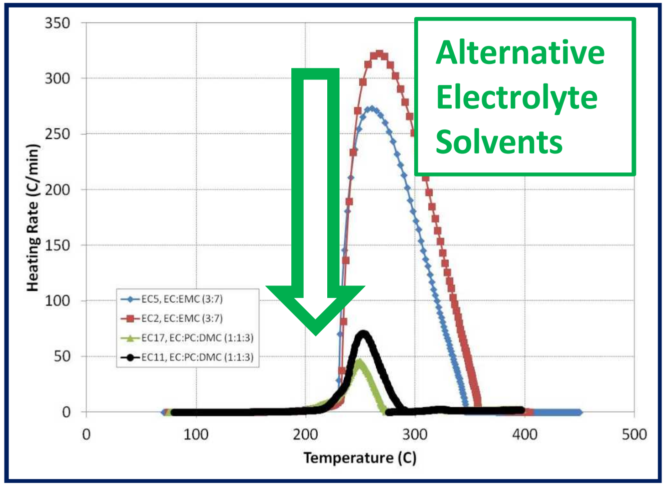
Improving Runaway Response

NMC/Graphite cells



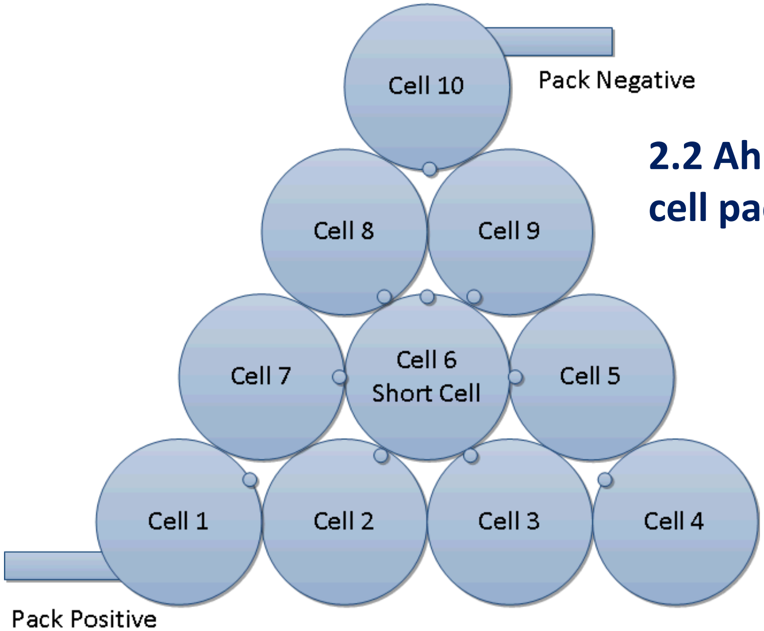




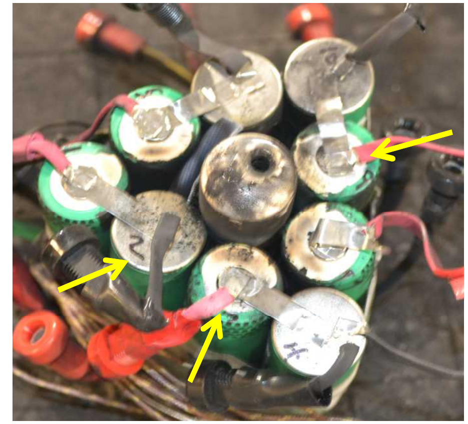


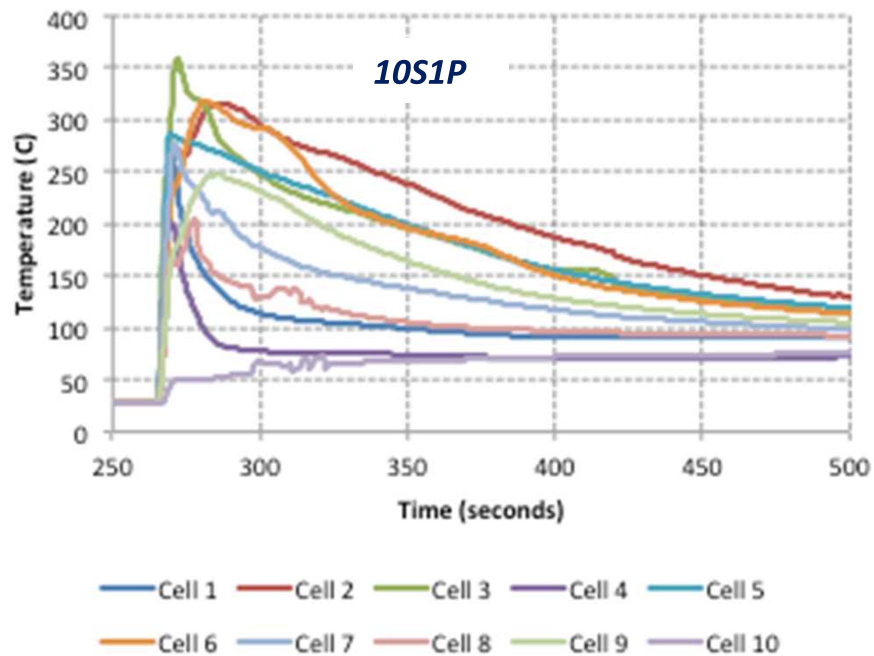
Materials choices can be made to improve the runaway response in cells
Reducing runaway enthalpy and kinetics has direct implications in battery system safety

Failure Propagation Testing



2.2 Ah CoO 18650 cell packs



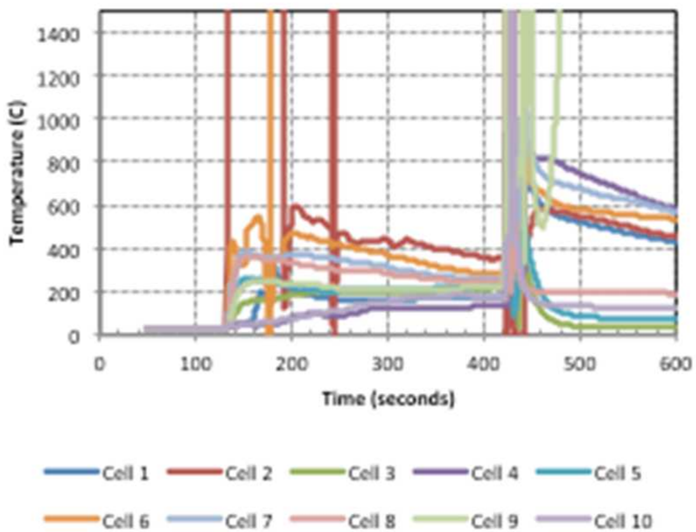


Limited propagation of the single point failure in the 10S1P pack

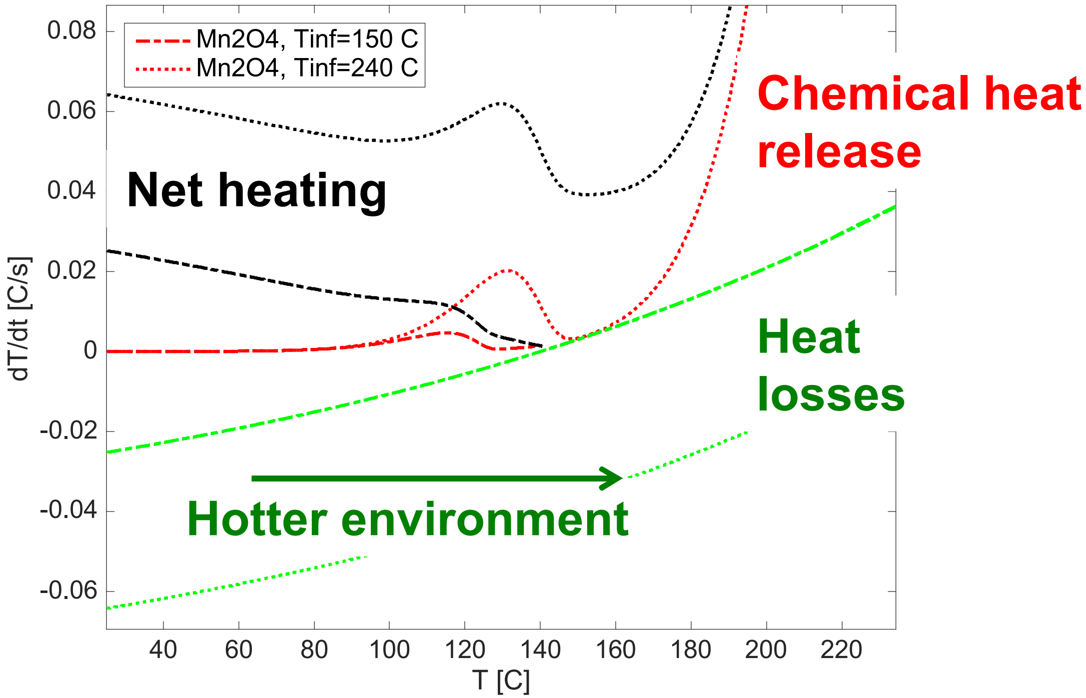
Propagation Testing – Series vs Parallel

- Comparing cells in parallel with cells in series (previous slide):
- Opportunity to discharge cell energy through failed cell leads to cascading failure through entire pack.

- Successful initiation at Cell #6
- Propagation to adjacent cells first, followed by outlying cells
- Cascading failure to entire battery over 450s
- Some thermocouples (K-type) saturated during test

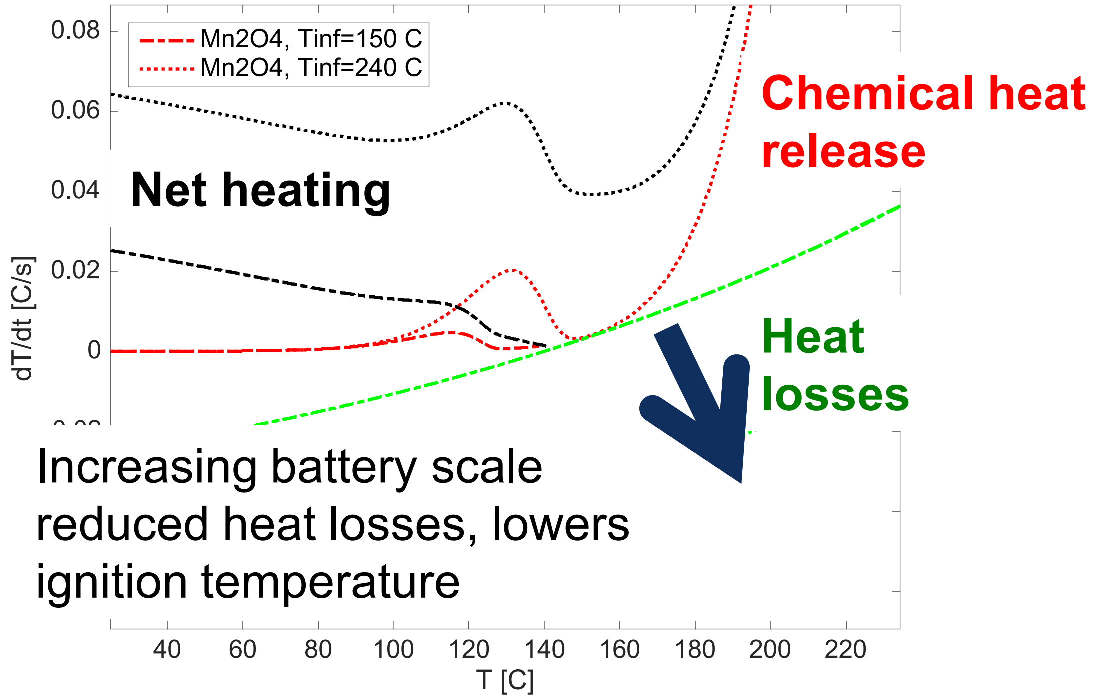


Thermal runaway occurs if heat release exceeds heat losses



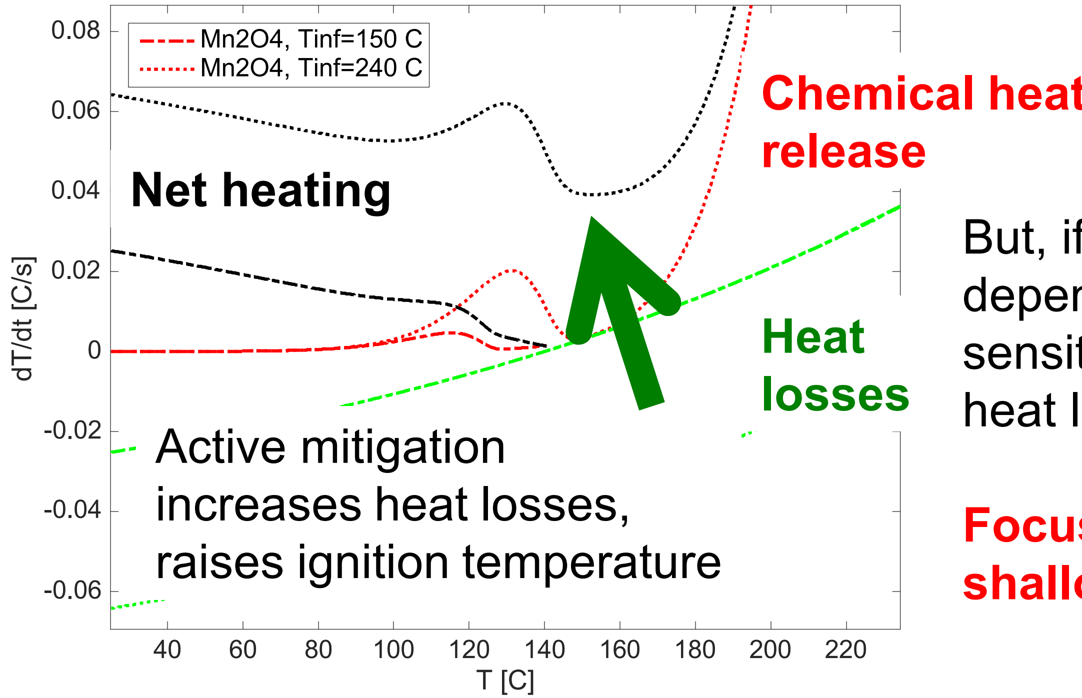
- Predicted heating rates based on ARC measurements.
- Higher environment temperature leads to thermal runaway.
- Low temperature degradation occurs in both cases.

Thermal runaway occurs if heat release exceeds heat losses



- Predicted heating rates based on ARC measurements.

Thermal runaway occurs if heat release exceeds heat losses

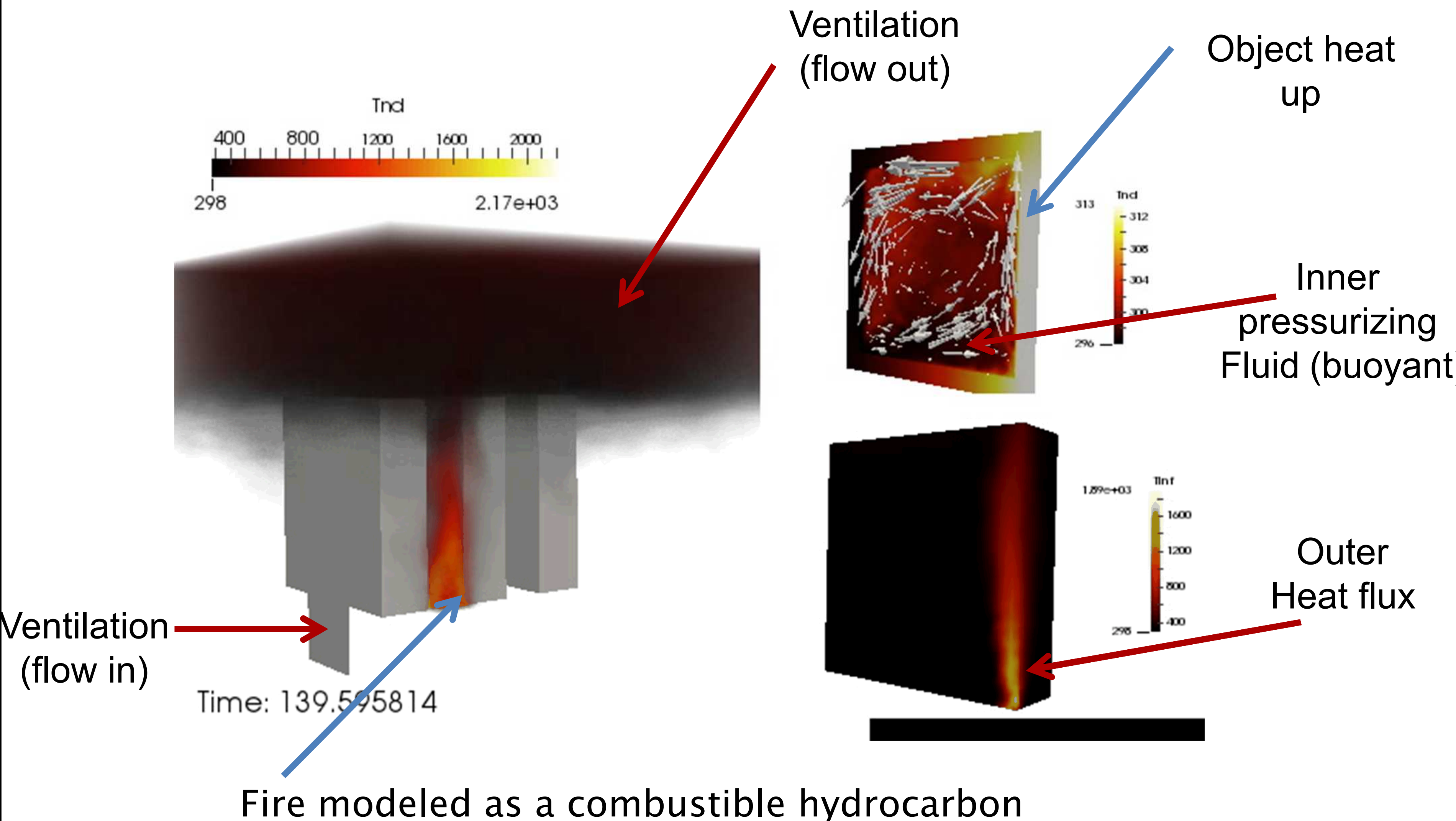


But, if the temperature dependence is strong, sensitivity to scale and heat losses is small.

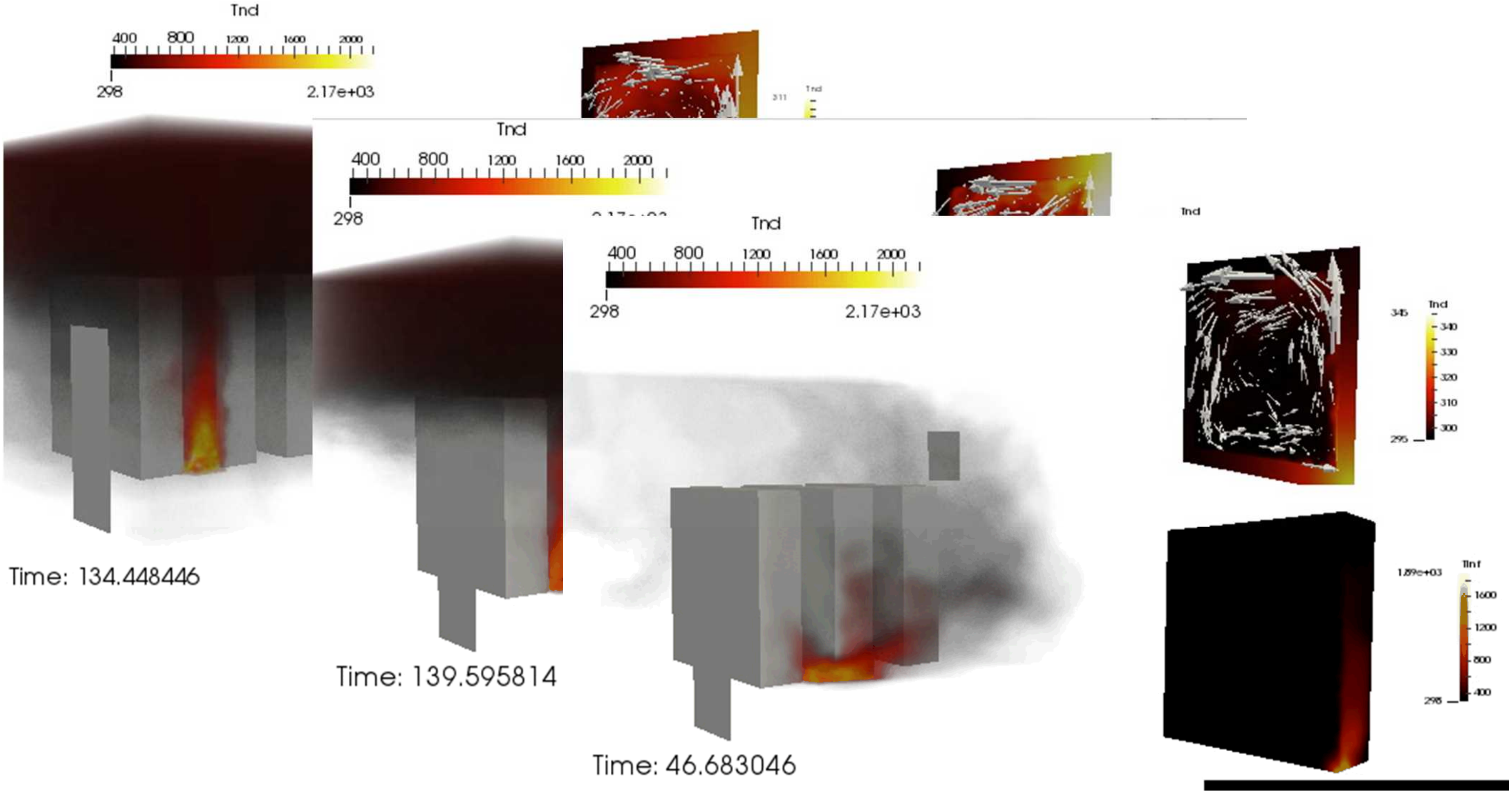
Focus mitigation on shallow-sloped regions!

- Predicted heating rates based on ARC measurements.

Predicting thermal environments in fire scenario



Models allow parameter study for large-scale scenarios Help determine pack thermal environment.



Three ventilation comparison still shot

Other hazards of energy storage: Taum Sauk reservoir

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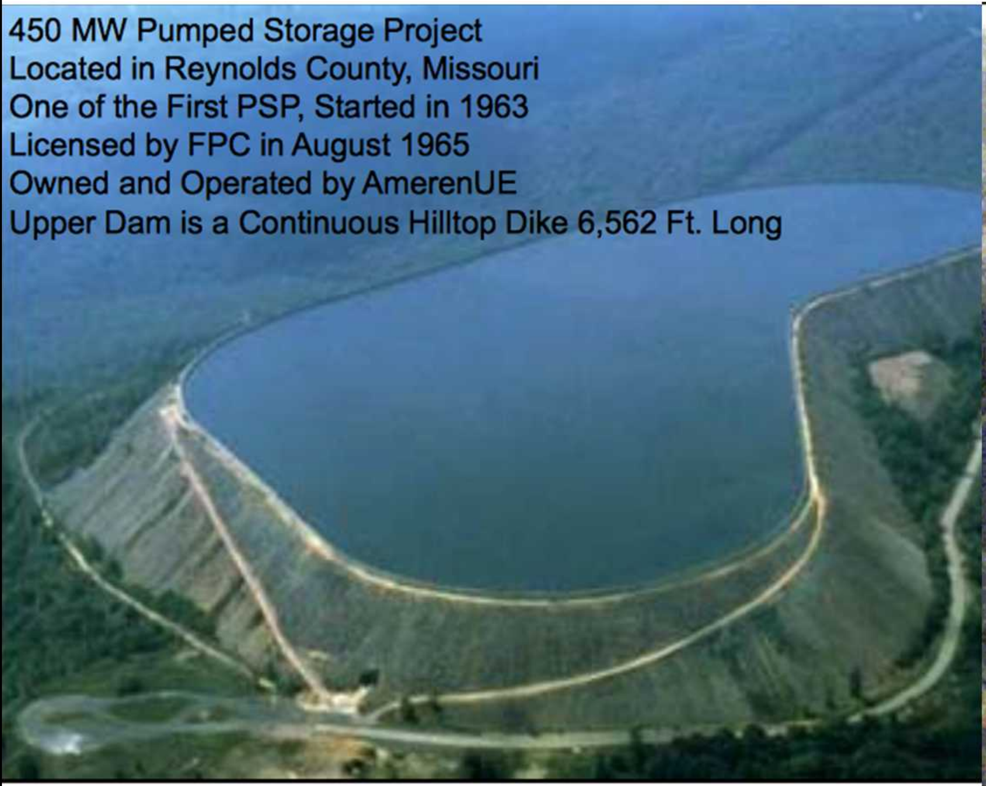
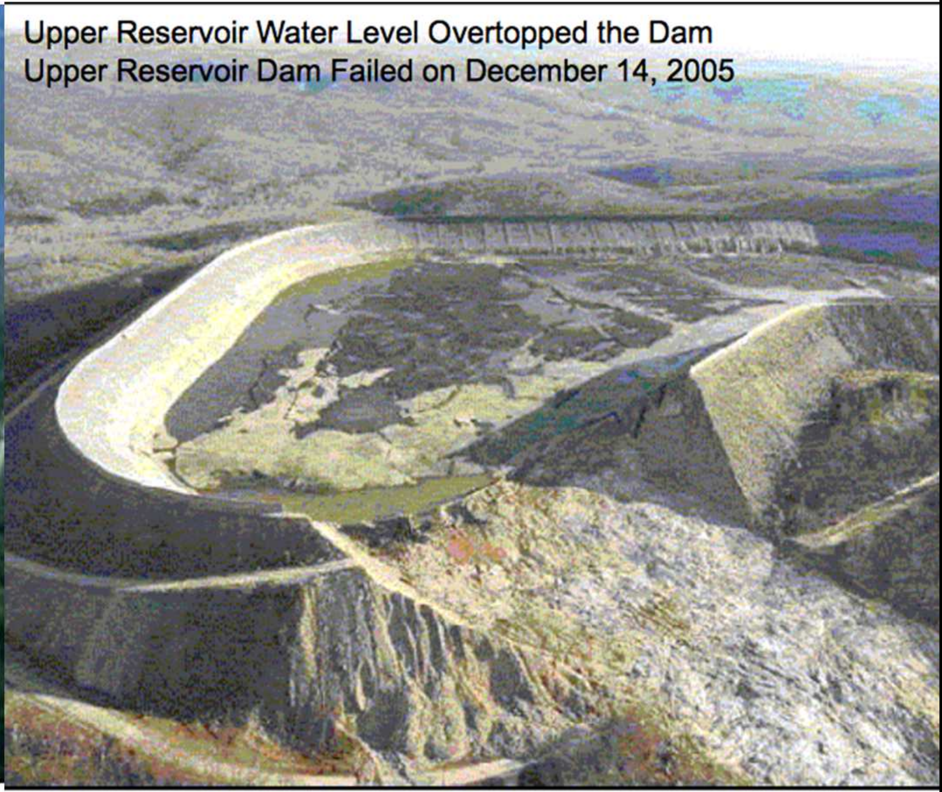
- A lesson in our reliance on sensors and apparently simple systems.
- A depth sensor became unmoored from reservoir bottom, giving false depth readings, leading to overfilling reservoir.



Taum Sauk – Upper Reservoir Full



Taum Sauk Upper Reservoir Breached

Battery Safety – Moving toward large-scale storage

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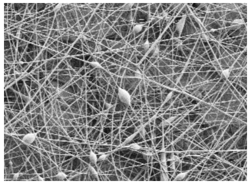
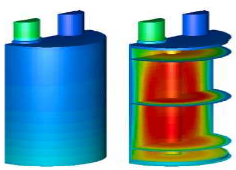
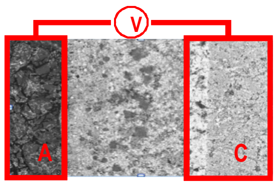



Materials R&D to date:
- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

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 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)