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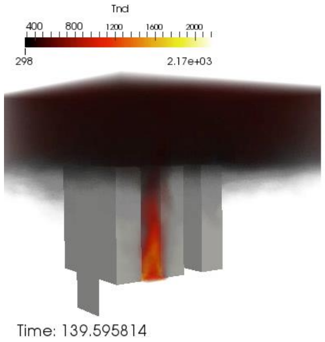

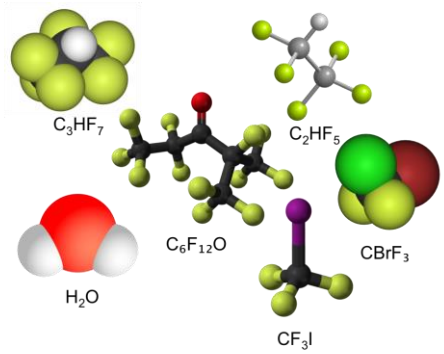

Grid-tied Energy Storage Safety

International Conference on Battery and Hydrogen/Fuel Cell

September 06, 2016

Stan Atcitty, Summer Ferreira, John Hewson, Josh Lamb, Heather Barkholtz

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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DOE Office of Electricity Energy Storage Program

- The goal of the Energy Storage Program is to develop advanced energy storage technologies and systems, in collaboration with industry, academia, and government institutions that will increase the reliability, performance, and competitiveness of electricity generation and transmission in the electric grid and in standalone systems.
- This program is part of the DOE Office of Electricity Delivery and Energy Reliability.
- The Energy Storage Program is managed by Dr. Imre Gyuk.

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

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Albuquerque, New Mexico

Livermore, California

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex Plant, Amarillo, Texas

Tonopah, Nevada

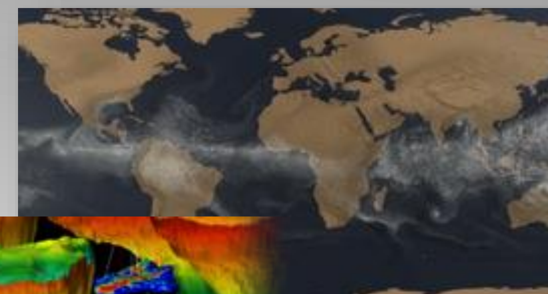
Energy & Climate

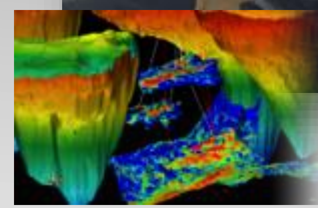
Energy Research

ARPAe, BES Chem Sciences, ASCR, CINT, Geo Bio Science, BES Material Science

Climate & Environment

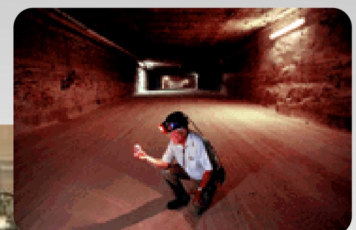
Measurement & Modeling, Carbon Management, Water & Environment, and Biofuels





Nuclear Energy & Fuel Cycle

Commercial Nuclear Power & Fuel, Nuclear Energy Safety & Security, DOE Managed Nuclear Waste Disposal



Renewable Systems & Energy Infrastructure

Renewable Energy, Energy Efficiency,

Grid and Storage Systems

Transportation Energy & Systems

Vehicle Technologies, Biomass, Fuel Cells & Hydrogen Technology

Energy Storage Is Critical to the Stability and Resilience of the Electric Grid

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Traditional Grid

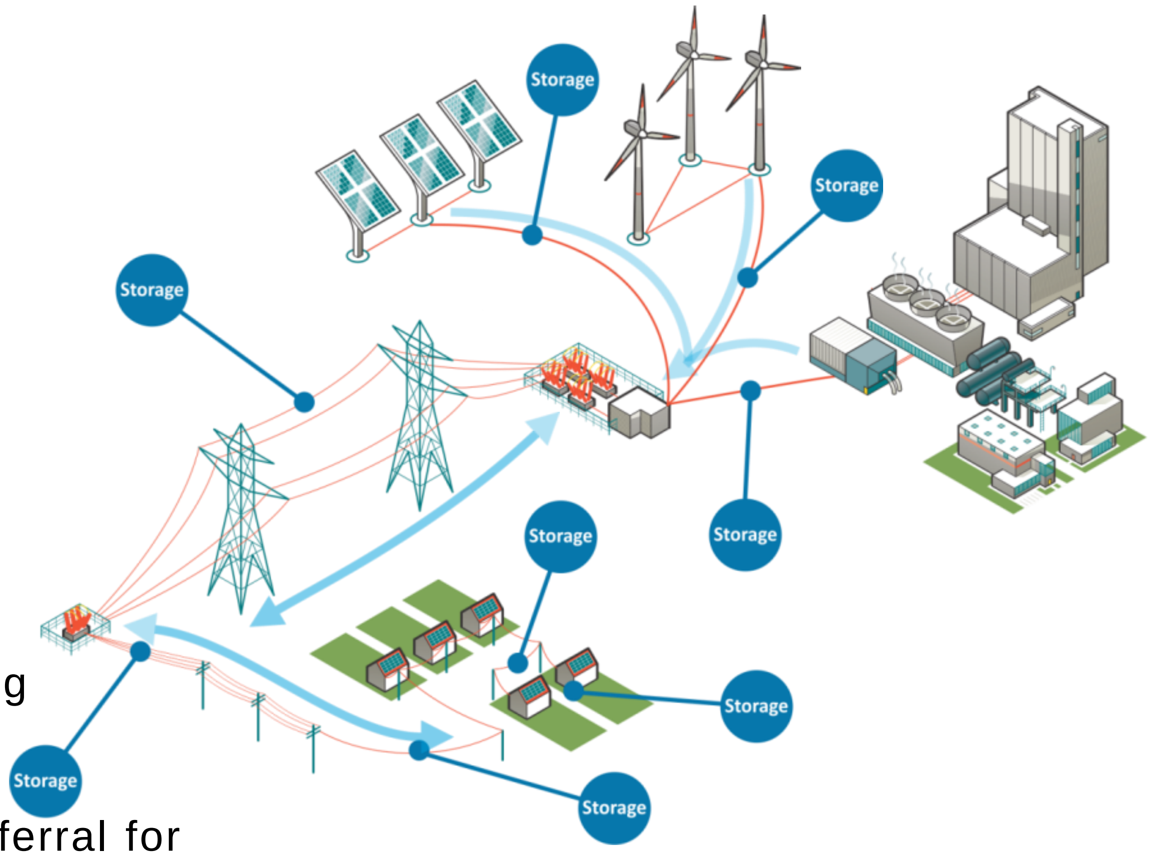
- One way flow
- Little/no renewable energy

Today's Grid

- Integration of grid-scale and distributed renewable generation beginning, but with limited penetration

Future Grid

- Storage provides buffering capability to enable high penetration of variable renewables and asset deferral for T&D systems (load management, ancillary services)
- Efficient two-way flow



Energy Storage Technologies

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Energy

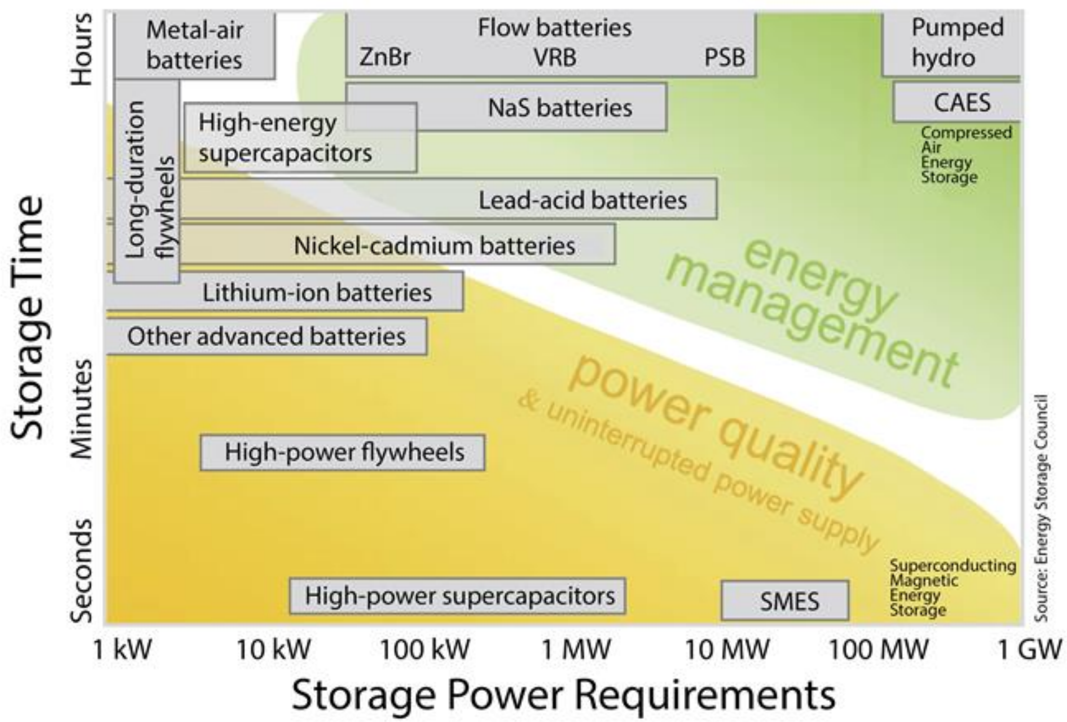
- Pumped Hydro
- Compressed Air Energy Storage (CAES)
- Batteries
  - Sodium Sulfur (NaS)
  - Flow Batteries
  - Lead Acid
  - Advanced Lead Carbon
  - Lithium Ion
- Flywheels
- Electrochemical Capacitors

Power

Two regimes, multiple technologies:

Power – short discharges (sec to min):
flywheels, capacitors, SMES, some batteries

Energy – long discharges (min to hr):
batteries, H_2 fuel cells, CAES, pumped hydro



Benefits of Electricity Storage

- Maintain quality power and reliability
- Provide customer services — cost control, flexibility, and convenience
- Improve T&D stability
- Enhance asset utilization and defer upgrades
- Increase the value of variable renewable generation

The Need for Energy Storage Safety Protocols

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As an increasing number of energy storage systems are deployed, the risk of safety incidents increases.

Damage to Facilities

2012 Battery Room Fire at Kahuku Wind-Energy Storage Farm

- There were two fires in a year at the Kahuku Wind Farm
- There was significant damage to the facility
- Capacitors in the power electronics are reported to be associated with the failure.

Impact to First Responders

2013 Storage Battery Fire, The Landing Mall, Port Angeles WA

- First responders were not aware of the best way to extinguish the fire,
- It reignited a week after it was thought to be extinguished.

Impact and Consequence of Scale on Safety

The Lack of Safety:

Endangers Life

Loss of Property

Damages Reputation

Decreases Confidence in Storage

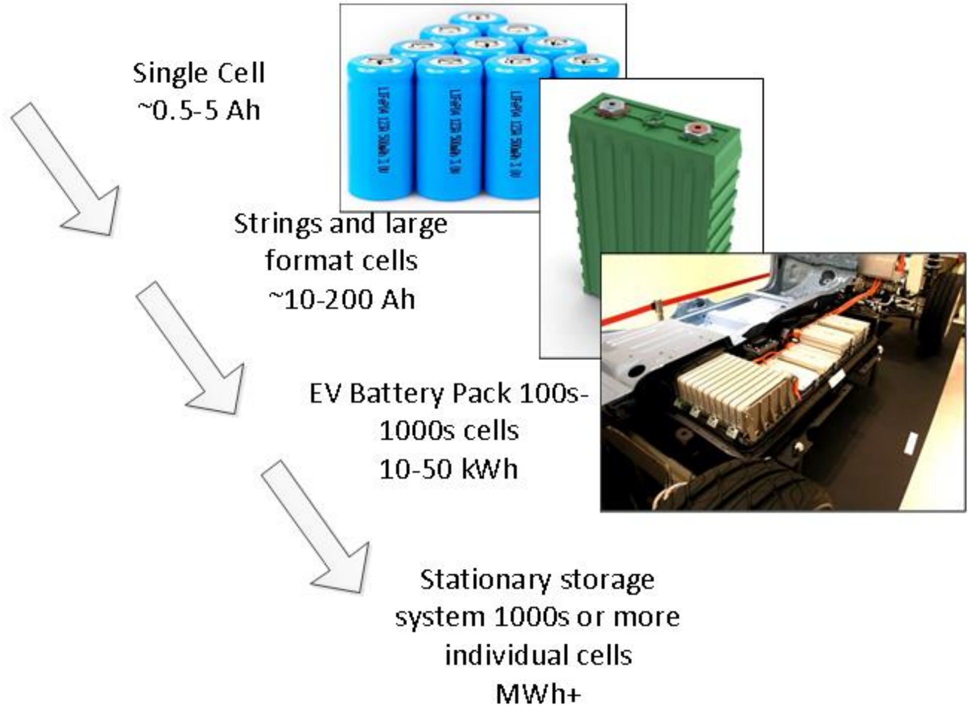
Consumer Cells (0.5-5 Ah) → Large Format Cells (10-200 Ah) → Transportation Batteries (1-50 kWh) → Utility Batteries (MWh)

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

Safety issues should become paramount with increasing battery size

The 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: (MWh)
- A single cell failure that propagates through the pack could lead to an impact even with very low individual failure rates



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

Current Approach to Safety

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

- **Extensive destructive tests for safety (crush, burn, etc.)**
- **Large system (>1MWh) testing is difficult and generically not done.**

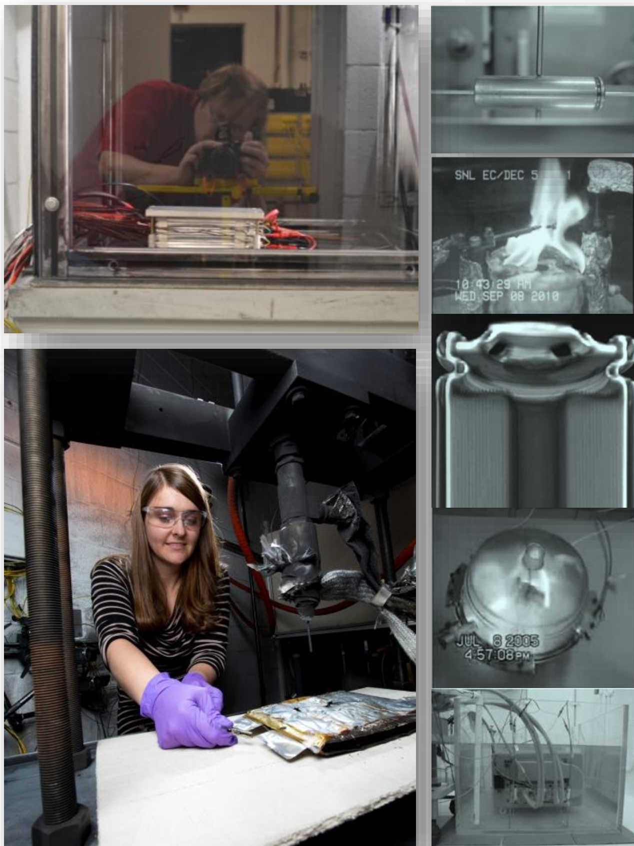
Shortcoming of the current approach:

- **Lacks capability to predict untested failure mechanisms with high reliability, i.e. can only design to prevent known failure modes.**
- **There are few published codes and standard for safety of storage systems.**

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

Sandia Energy Storage Capabilities

Cell and Module Testing
Battery Abuse Testing Laboratory (BATLab)



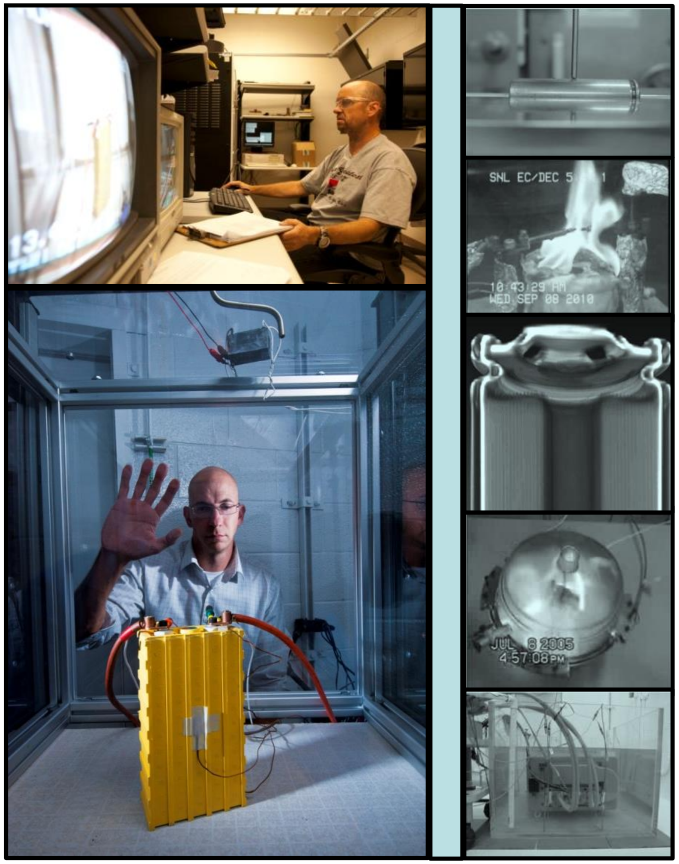
Battery Pack/System Testing
Thermal Test Complex (TTC) and Burnsite

Battery Calorimetry

Battery Abuse Testing Laboratory (BATLab)

Sandia National Laboratories

- 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



Sandia Battery Safety R&D – Stationary Storage

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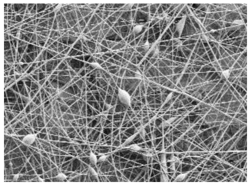
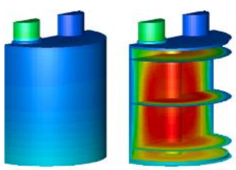
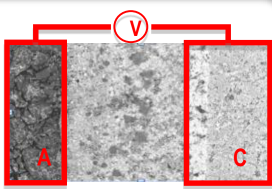


Materials R&D to date:
- Non-flammable electrolytes
- Electrolyte salts
- Coated active materials
- Thermally stable materials

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)



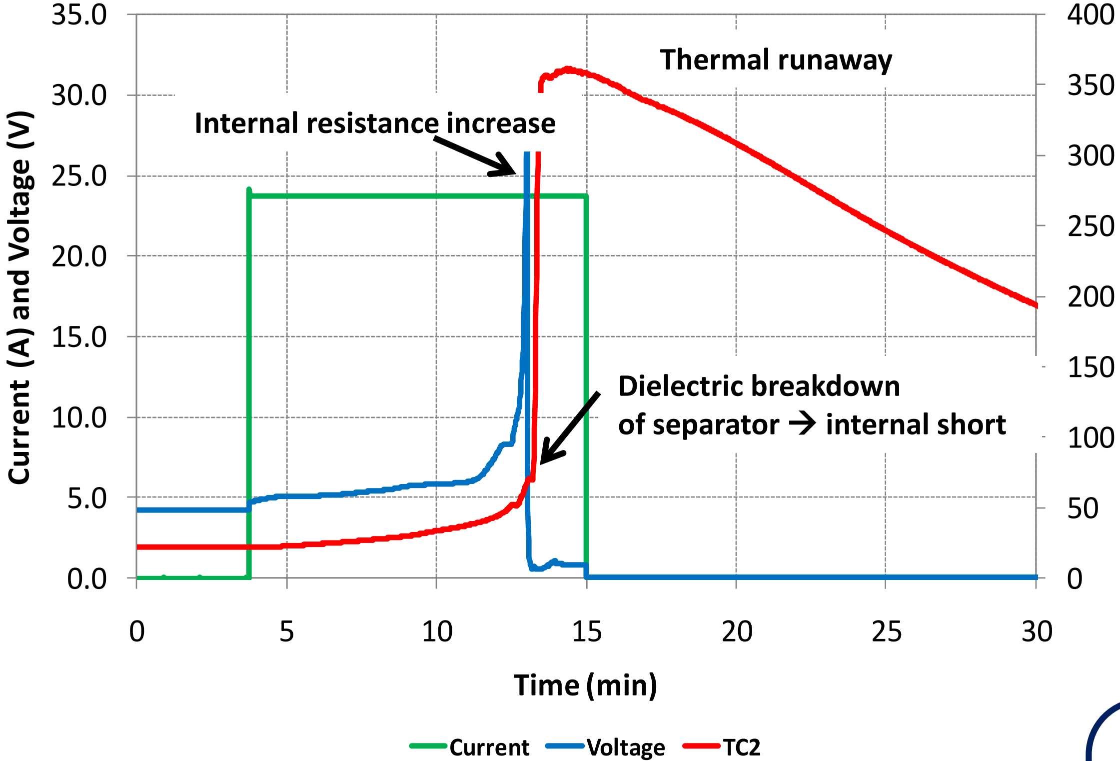


Simulations and Modeling
- Multi-scale models for understanding thermal runaway
- Validating failure propagation models
- Fire Dynamic Simulations (FDS) to predict the size, scope, and consequences of battery fires

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)

Abuse Testing

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:

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

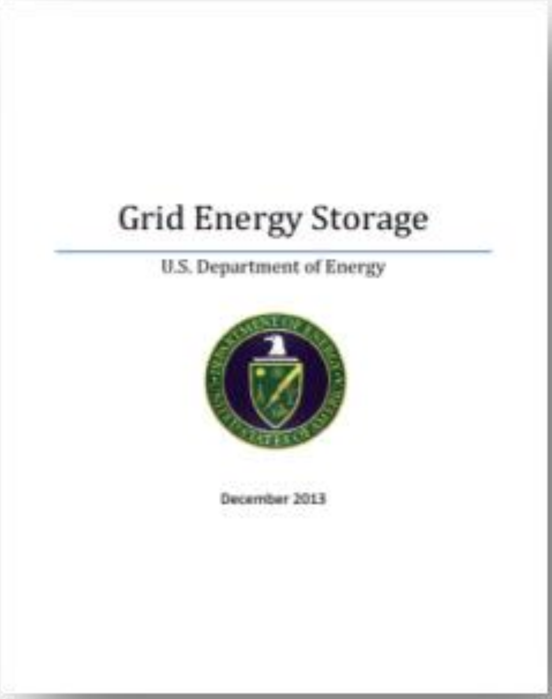
Challenges for Grid Energy Storage

During the commissioning hearings of Dr. Moniz to head US DOE, Senator Wyden requested a strategic plan for grid energy storage.

DOE Published the report in December 2013

<u>Four Critical Challenges were identified</u>

1. Cost Competitive Energy Storage Technologies
2. **Validated Reliability and Safety**
3. Equitable Regulatory Environment
4. Industry Acceptance



DOE Office of Electricity Organized

Sandia National Laboratories

Safety is an overarching concern

- National Laboratories: Sandia, PNNL
- Utility Organizations: EPRI, NRECA
- Fire Departments, Fire Fighters
- Building Commissions
- Insurance Industry
- Testing Laboratories

2014 FEB AUG SEP DEC **2015** JAN MAR APR MAY **2016**

DOE OE Workshop for Grid Energy Storage Safety
- Attended by 70 thought leaders from stakeholder groups across the energy storage industry

Overview of Development and Deployment of Codes, Standards, and Regulations Affecting ESS Safety Published

Inventory of Safety Related Codes and Standards Published

Grid Energy Storage Safety Strategic Plan Published
- Based upon outcomes of the DOE OE Workshop for Grid Energy Storage Safety
- Outlines a path forward for ESS safety initiatives

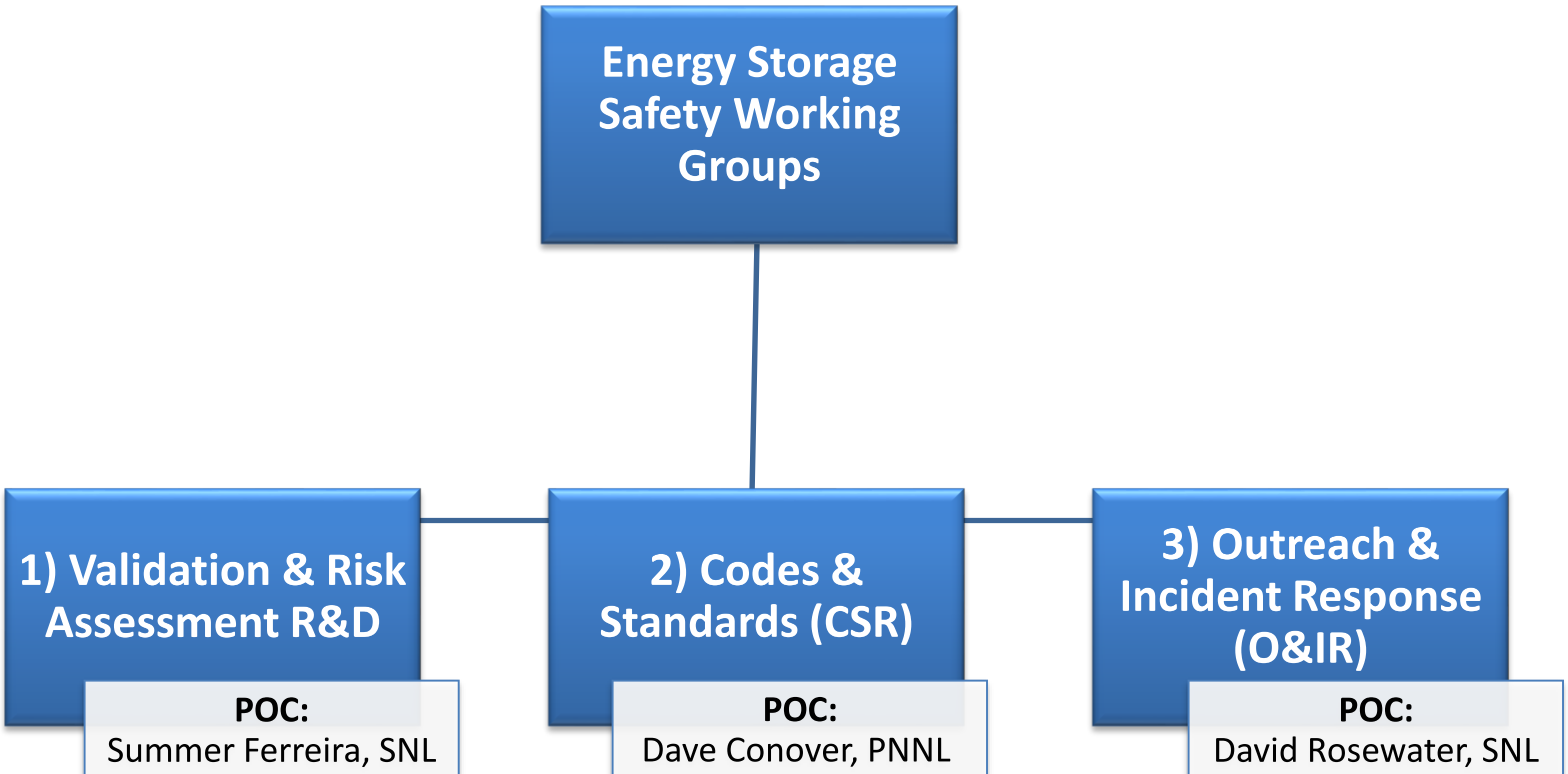
Energy Storage Safety Working Group Established

Energy Storage Safety Preliminary Team Web Meetings
- Identified and prioritized safety gaps related to energy storage:
  - safety validation and risk assessment R&D,
  - codes and standards, and
  - safety outreach and incident response

Energy Storage Safety Strategic Plan

- **Science-based Safety Validation Techniques**
- **Incident Preparedness**
- **Safety Documentation**

Energy Storage Safety Working Group (ESSWG) Organizational Structure

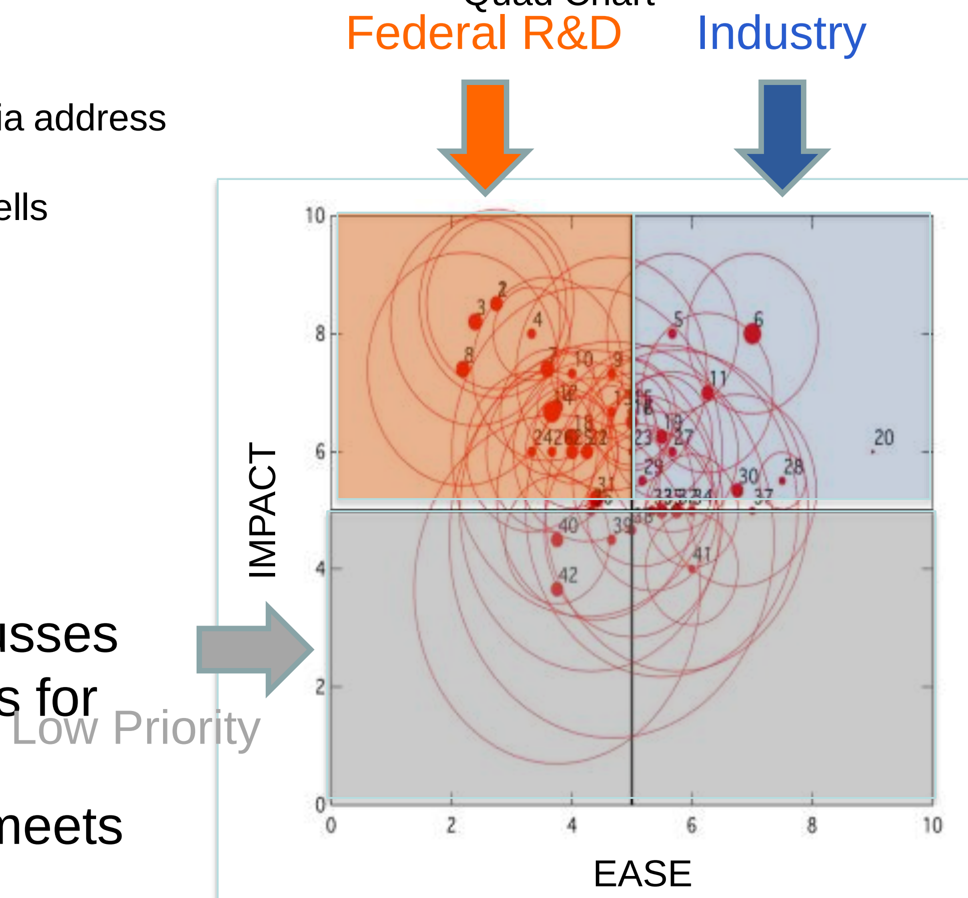


R&D Prioritization

Key need – Identify R&D efforts that will have the largest impact on the safety of the industry.

- Work to date
  - Ongoing work in labs, industry and academia address
  - safety in an ad hoc manner.
  - Focused largely on performance of single cells
- Short term priorities identified:
  - **Fire Suppression testing** and analysis
  - **Thermal runaway** research
  - **System scale burn test**
  - **Commodity classification** development
  - **Fire and vent gas modeling** and analysis
- Subcommittee formed and discusses topics individually to create basis for white paper on priorities.
- Report out to committee which meets on alternate months.

Safety Validation and Risk Assessment Quad Chart



2016 DOE OE/Sandia R&D Safety Projects

- **Electrochemical Energy Storage Abnormal Thermal Modeling**
  - PI: John Hewson, Dept. 1532, Fire Science and Technology Department
  - Short Term Priority Topic Areas: *Thermal Runaway Research, System Scale Burn Test, Fire and vent gas modeling and analysis*
- **Safety Analysis and Model Validation of Electrochemical Storage in Abnormal Thermal Environments**
  - PI: Josh Lamb, Dept. 2546, Power Sources R&D Department
  - Short Term Priority Topic Areas: *Thermal Runaway Research, System Scale Burn Test, Fire and vent gas modeling and analysis*
- **Fire Suppressant Analysis and Characterization**
  - PI: Summer Ferreira, Dept. 2546, Power Sources R&D Department
  - Short Term Priority Topic Areas: *Fire and vent gas modeling and analysis*

2016 DOE OE/Sandia R&D Safety Projects

- Model of large-scale failure
- Predicted best suppressant application method
- Suppressant characteristics in smaller scale testing

Electrochemical Energy Storage Abnormal Thermal Modeling

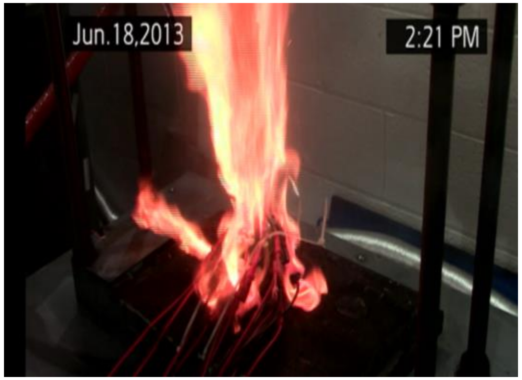
- Cell pack failure; real-world data
- Model information for validation

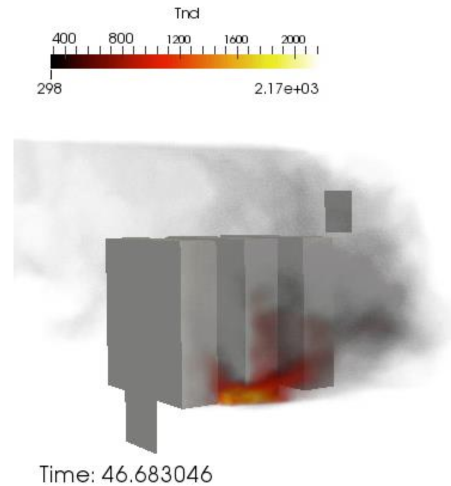
Fire Suppression Analysis and Characterization

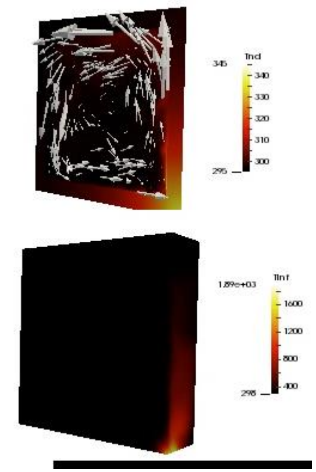
Safety Analysis and Model Validation of Electrochemical Storage in Abnormal Thermal Environments

- Method of cell failure
- Cell failure propagation
- Effect of suppressant

Electrochemical Energy Storage Abnormal Thermal Modeling





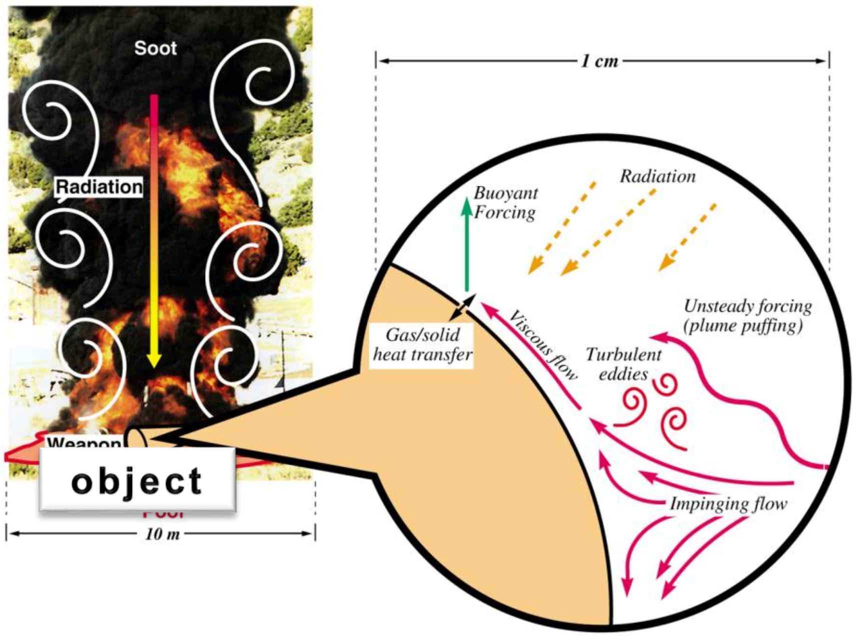


Goal

- Develop multi-physics models to improve understanding of the risks associated with energy storage devices in abnormal thermal environments (i.e. fires). An objective is to predict criteria for cascading failure to aid in developing mitigation strategies.

Electrochemical Energy Storage Abnormal Thermal Modeling

- Leverage the large DOE-NNSA Investments in Sierra-Mechanics Integrated Code simulation tools developed at Sandia National Laboratories under the Advanced Scientific Computing (ASC) program for Science-based Stockpile Stewardship by applying these tools to battery safety analysis



Heat transfer mechanisms in a fire

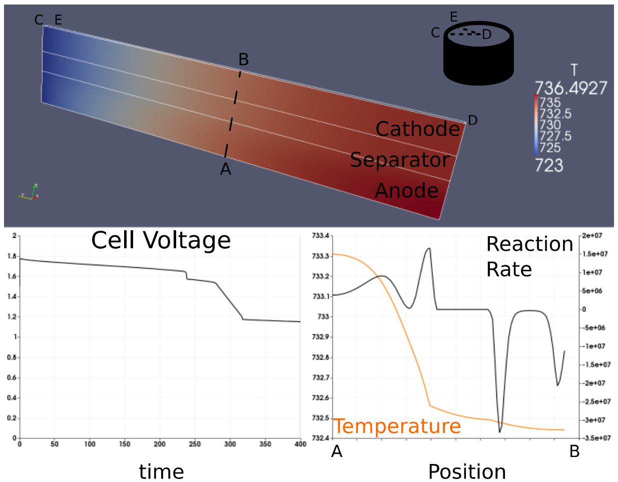
Physics:

- Turbulent fluid mechanics (buoyant plumes)
- Participating Media Radiation (PMR)
- Reacting flow (hydrocarbon, particles, solids)
- Conjugate Heat Transfer (CHT)
- The simulation tool *predicts* the thermal environment and object response

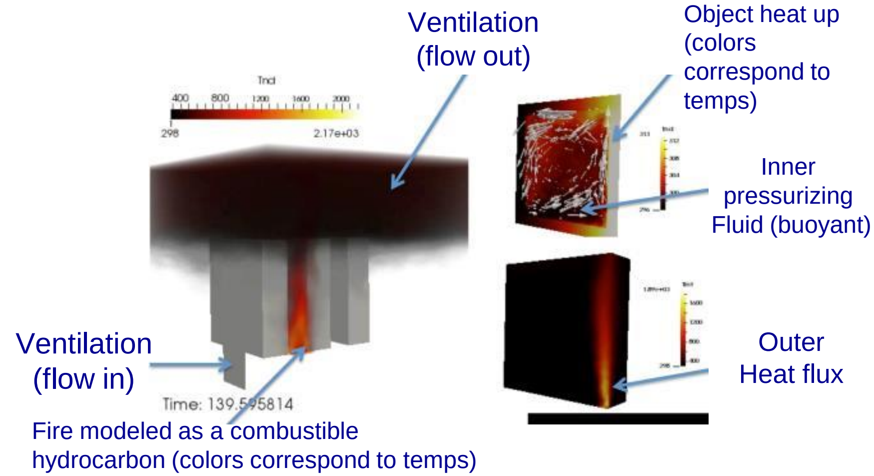
Electrochemical Energy Storage Abnormal Thermal Modeling

Modeling thermal events in cell

Model linking battery performance with thermal environment

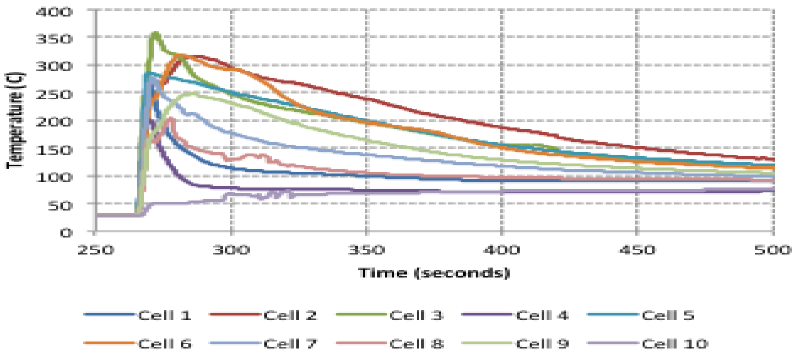


Model of fire propagation between storage packs



- Sandia has been using it's linked chemical / mechanical modeling capability to study failure in components through full systems.
- Predicting consequences of abnormal source terms
  - Heat transfer to adjacent cells
  - Toxic product distribution
- Understanding processes that ***limit and mitigate cascading failure***
  - Heat dissipation to reduce reaction rates
  - Means of limiting interaction of active materials, separate cells, etc.

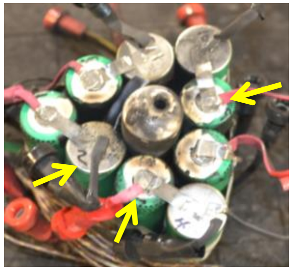
Electrochemical Energy Storage Abnormal Thermal Modeling

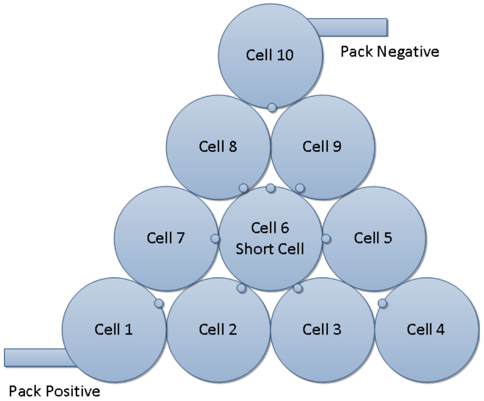


Status

- Began literature review of battery thermal runaway kinetics
- Compiled historical data from Sandia abuse lab
- Developed and validated tools to fit battery thermal runaway data to kinetic models
- Adapted Sierra tools to model battery thermal runaway chemistry
- Begun simulations to look at thermal interactions leading to runaway (contrast this with the previous simulations where the batteries did not release heat)
- Identified modeling and experimental needs for propagation of failure – cascading failure from a single thermal runaway

Electrochemical Energy Storage Abnormal Thermal Modeling



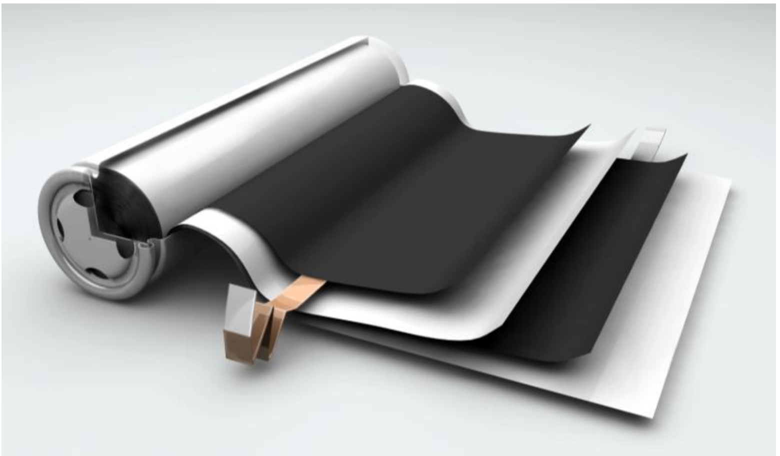


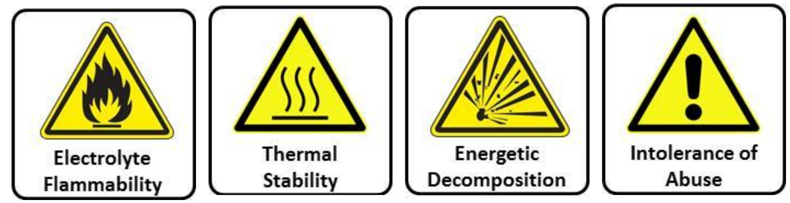
Next Steps

- Fit historical data from a variety of Li-ion battery chemistries (i.e. Sandia battery abuse lab and literature) to kinetic models (existing and improved forms).
- Model thermal interaction of battery packs in Sierra - predict thermal environment leading to cascading failure versus isolated failure.
- Integrate reacting thermal models of battery packs with fire models in Sierra to evaluate safety of representative geometries and scenarios.
- Predict contributions of battery thermal runaway to overall fire load and as source of hazardous products.

→ **Ultimate goal:** ***Predict criteria for cascading failure to aid in developing mitigation strategies.***

Safety Analysis and Model Validation of Electrochemical Storage in Abnormal Thermal Environments



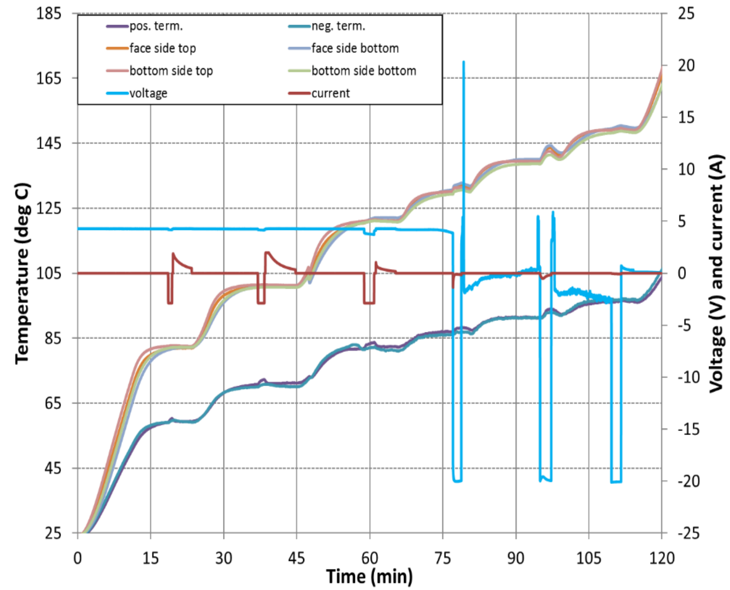


Several factors impact Li-Ion safety

Goal

- Develop a testing program to evaluate the thermal runaway conditions that may impact grid-level energy storage systems. Provide validated experimental data for thermal modeling efforts in parallel to this work.

Safety Analysis and Model Validation of Electrochemical Storage in Abnormal Thermal Environments



Status

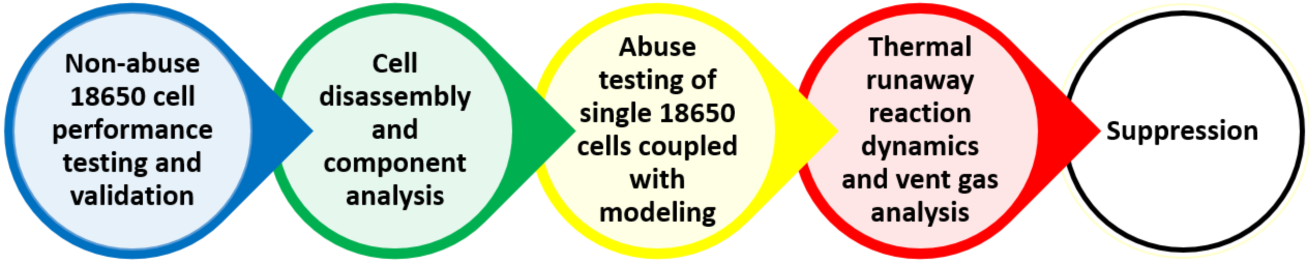
- Recent work determining temperature limits on discharge on 3 Ah LiCoO2 cells
- Above 130C, discharge becomes impossible and may accelerate runaway
- This impacts the ability to remove energy through discharge after the battery reaches unsafe temperatures
- Testing is underway examining the impact of state of charge on failure

Safety Analysis and Model Validation of Electrochemical Storage in Abnormal Thermal Environments

Next Steps

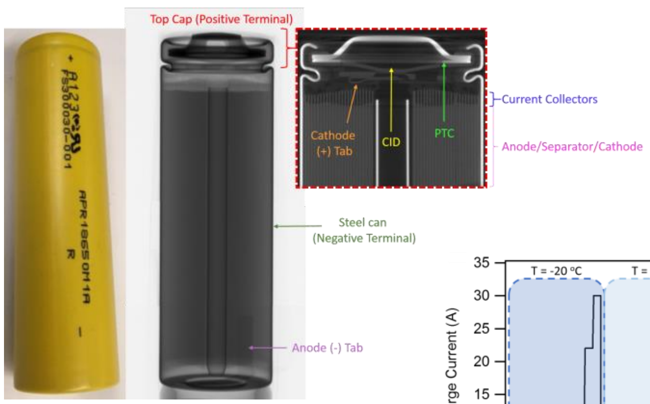
- Coupling discharge with cooling methods to arrest runaway
- Full exploration of impact of SOC on thermal runaway of multiple chemistries

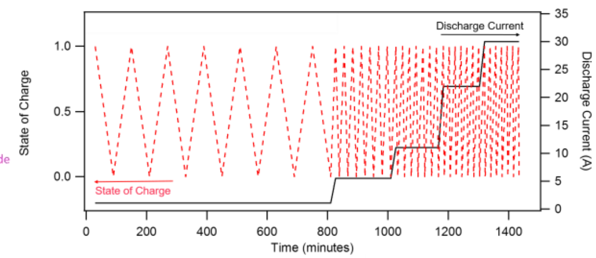
Fire Suppressant Analysis and Characterization

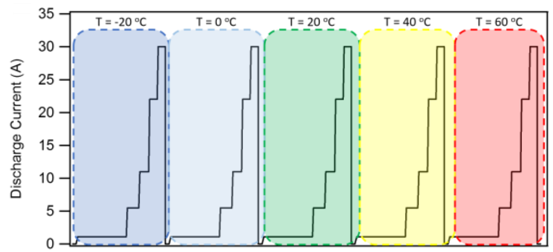


Project Goal: To gain detailed understanding of battery cell performance and failure with the ultimate goal of developing a novel suppressant chemistry or technique which can be applied to a wide variety of cell chemistries and installation environments. This understanding will help mitigate safety related risks associated with large installations typically seen in grid-level energy storage systems.

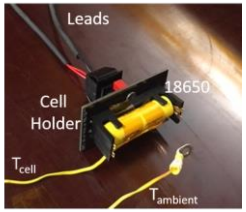
Fire Suppressant Analysis and Characterization







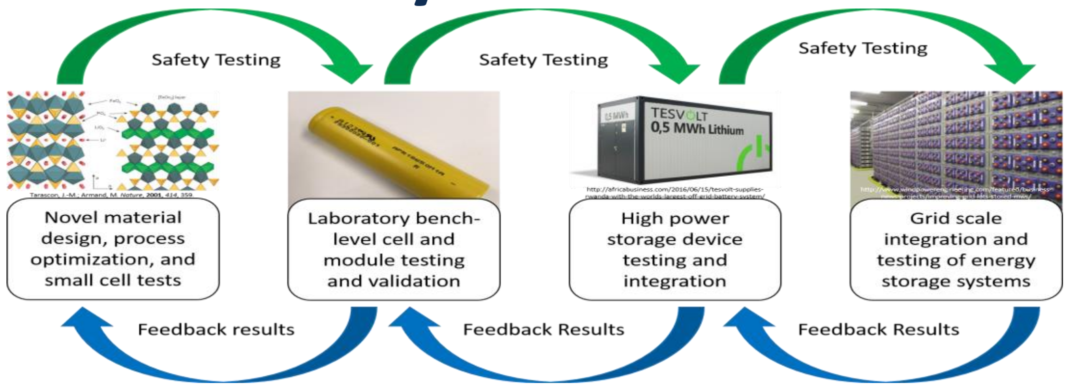
Chemistry	Nominal Capacity (mAh)	Nominal Voltage (V)	Δ T (°C)	Max Discharge Current (A)
LFP $LiFePO_4$	1100	3.3	-30 to 60	30
NMC $LiNi_{1-x-y}Mn_xCo_yO_2$	3000	3.6	-5 to 50	20
LCO $LiCoO_2$	2500	3.6	0 to 50	20
NCA $LiNi_{0.80}Co_{0.15}Al_{0.05}O_2$	2750	3.6	0 to 40	10



Status:

- Located and purchased commonly used and commercially available Li-ion 18650 cells of different chemistries (e.g. Lithium-Iron-Phosphate, Lithium-Nickle-Manganese-Cobalt-Oxide, Lithium-Cobalt-Oxide, and Lithium-Nickel-Cobalt-Aluminum-Oxide)
- Developed test plan for baseline cell characterization, non-abuse, and abuse testing of commercial 18650 Li-ion batteries.
- Began disassembly and characterization of cell components (electrolyte, etc.)
- Began non-abuse (i.e. within manufacturer suggested temperature and current limits), electrochemical performance testing on Lithium-Iron-Phosphate.

Fire Suppressant Analysis and Characterization



Next Steps:

- Continue to disassemble the commercial cells to elucidate the composition and morphology of cell components.
- Finish non-abuse base-line electrochemical performance testing on Lithium-Iron-Phosphate and move on to Lithium-Cobalt-Oxide, Lithium-Nickle-Magnesium-Cobalt, and Lithium-Nickle-Cobalt-Aluminum-Oxide.
- Study the electrochemical performance of 18650s under abuse temperatures and discharge currents to the point of failure.
- Understand how/when 18650 cell fail and any dependency on chemistry or test condition.
- Discover what gasses/liquids/particulates are released and in what quantity when a catastrophic failure occurs.
- Collaborate with the *Abnormal Thermal Modeling, Analysis and Model Validation Projects* → **Design a suppressant to either avoid catastrophic failure or mitigate the spread/effects of a cell failure to enable a battery pack to "fail gracefully".**

Improving battery safety

Sandia National Laboratories

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

Acknowledgment

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