Exceptional service in the national interest

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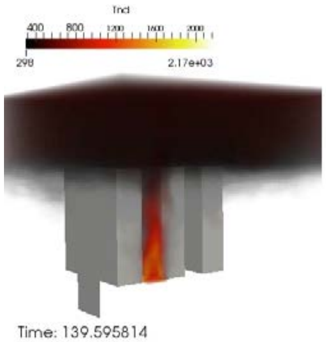


Battery Safety: Experiments, Modeling, and Codes and Standards

Amanda Dodd

(SNL POC's: Josh Lamb, John Hewson, Summer Ferreira)

The International FORUM of Fire Research Directors Annual Meeting
September 27, 2016

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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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)

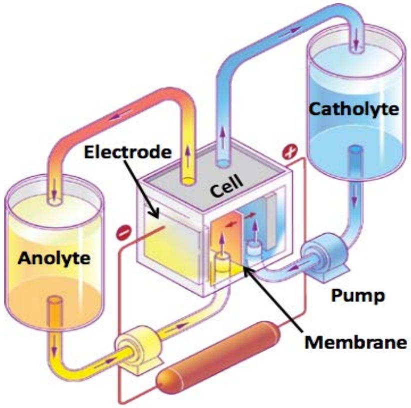
www.ford.com www.samsung.com www.saftbatteries.com

Safety issues should become paramount with increasing battery size

The 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

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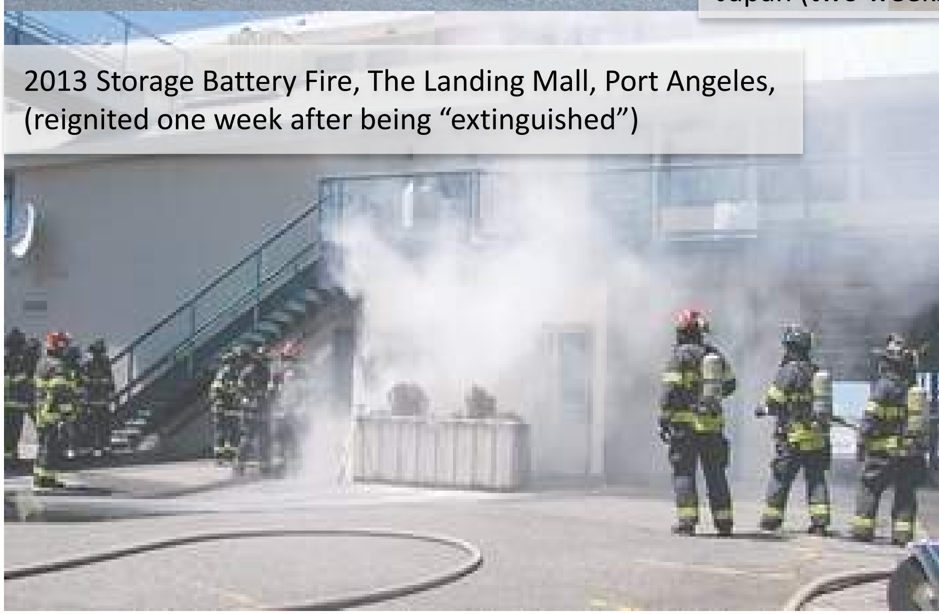
2011 Beacon Power Flywheel Failure

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

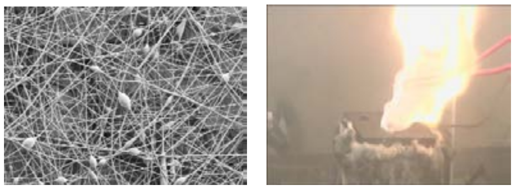
Battery Safety R&D Program at SNL

Sandia National Laboratories

Mission Statement: The Laboratory is committed to serving the energy storage community and the National interest with cutting edge research programs, the highest quality testing results, leadership in battery safety and reliability R&D

- Understanding failure mechanisms in cells and battery systems for the emerging global transportation and storage markets
- Safety evaluation of the next generation electrode materials for lithium-ion batteries
- Development of advanced materials and electrolytes that are abuse tolerant, non-flammable and can mitigate high rate thermal runaway reactions
- Develop testing and analytical techniques to better understand critical safety concerns with lithium-ion chemistries and large format cell designs
- Facilities include:
  - Battery Calorimetry Center
  - Battery Abuse Testing Laboratory
  - Cell Prototyping Facility
- Modeling Expertise and modeling capability
- Codes and Standards Expertise

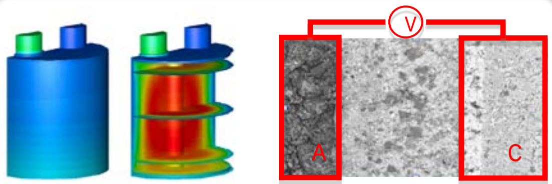
Battery Safety – Stationary Storage



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)

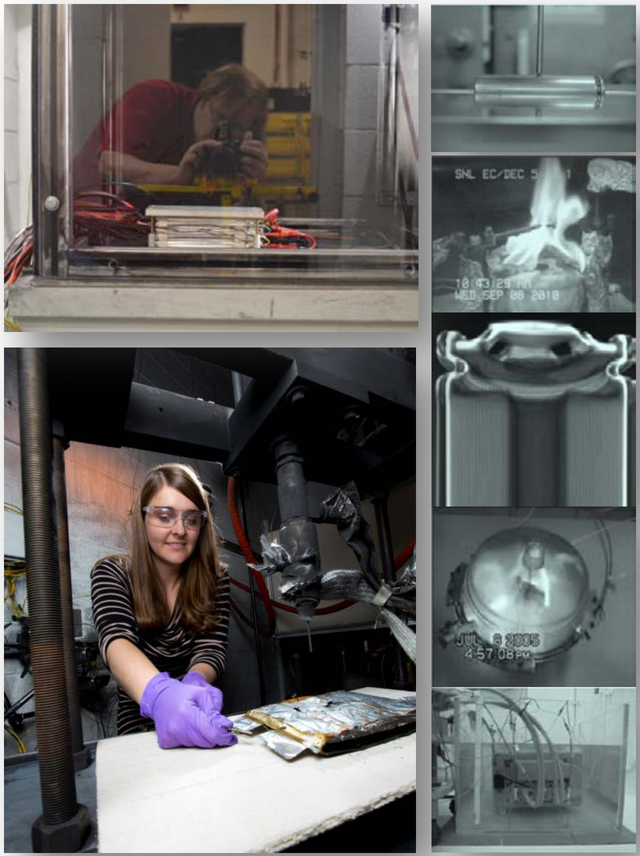


Simulations and Modeling
- Multi-scale models for understanding thermal runaway
- Validating failure propagation models
- Sierra Thermal Fluids and Fire Dynamic Simulations (FDS) to predict the size, scope, and consequences of battery fires

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)

Experimental Approach and Capabilities

Cell and Module Testing
Battery Abuse Testing Laboratory (BATLab)



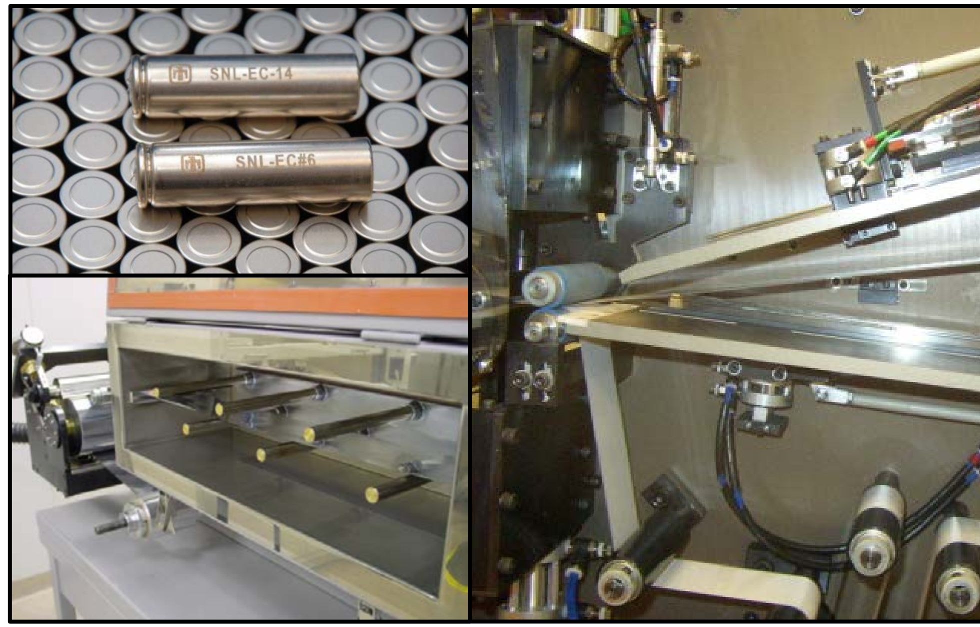
Battery Pack/System Testing
Thermal Test Complex (TTC) and Burnsite

Battery Calorimetry

Cell Prototyping Facility

Sandia National Laboratories

- The SNL cell prototyping facility is the largest DOE dedicated R&D facility equipped to manufacture small lots of lithium-ion cells of various sizes including 2032 coin cells, 18650s, D-cells, and prismatic cells
  - 1000 sq. ft. of dry room space in two separate dry rooms
  - Two prototype electrode coaters, 20-30 meter coating run capacity
  - Three 18650 cell winders
  - One multiformat cell winder for 18650, D-cell, and prismatic cell formats
  - Electrolyte filling and associated cell hardware and packaging equipment
  - 96 channels for battery performance testing and formation cycling

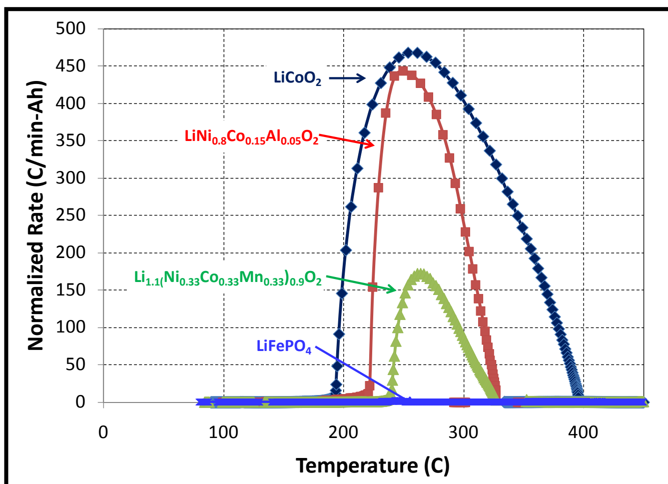


- Experience with numerous lithium-ion chemistries including natural and synthetic graphite anodes, $Li_4Ti_5O_{12}$, $LiCoO_2$, NMC, LFP, and spinel cathodes ($LiMn_2O_4$ and $LiNi_{0.5}Mn_{1.5}O_4$).

Battery Calorimetry Center

Sandia National Laboratories

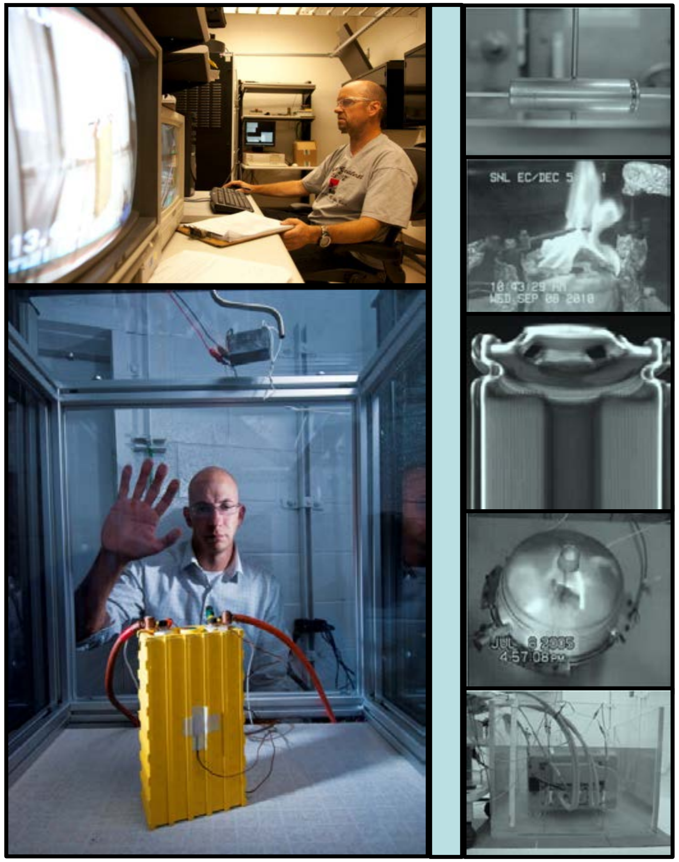
- One of the world's largest dedicated battery calorimetry facilities
- Six accelerating rate calorimeters (ARCs) for materials and cell-level measurements
  - Gas volume measurements for decomposition gas products
  - Quantitative gas analysis capabilities from ARC samples
  - Measurements on 1 to 150 Ah cells
- Two isothermal battery calorimeters
- Microcalorimetry for materials analysis
- Modulated DSC



Battery Abuse Testing Laboratory (BATLab)

Sandia National Laboratories

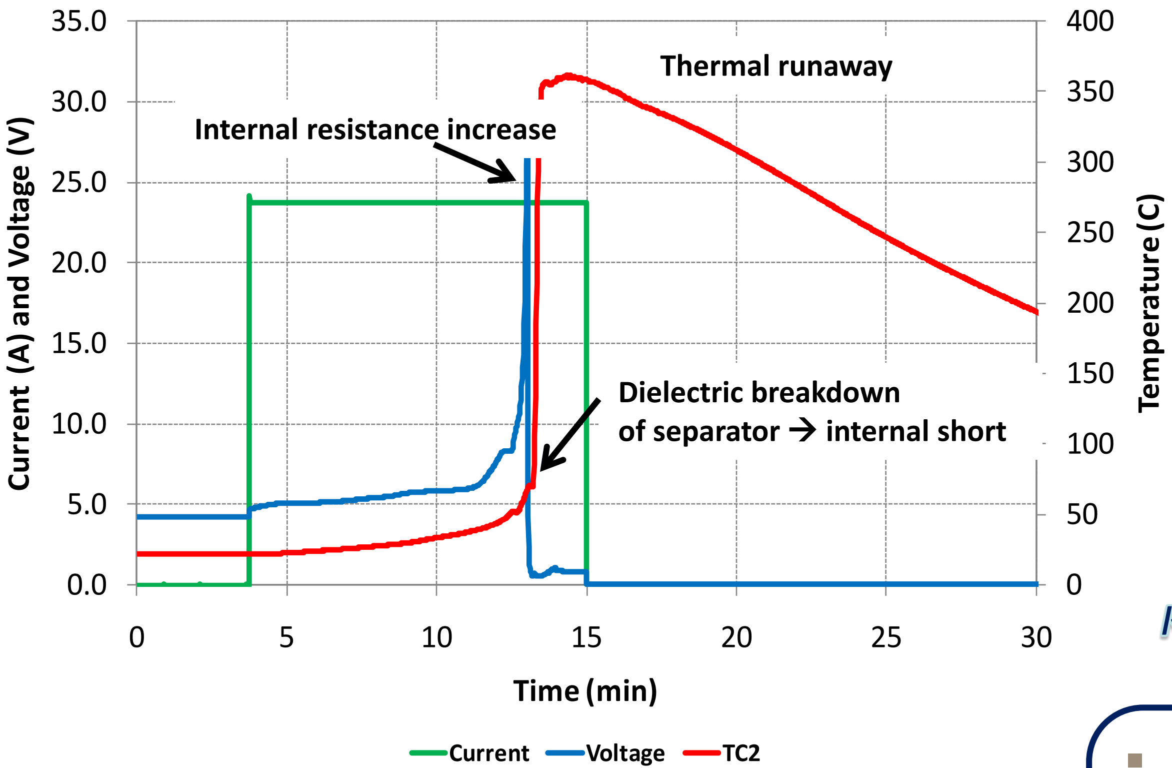
- Comprehensive abuse testing platforms for safety and reliability of cells, batteries and systems from mWh to kWh
- Mechanical abuse
  - Penetration
  - Crush
  - Impact
  - Immersion
- Thermal abuse
  - Over temperature
  - Flammability measurements
  - Thermal propagation
  - Calorimetry
- Electrical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



Abuse Testing

Sandia National Laboratories

12 Ah (~50 Wh) Cell Overcharge Abuse



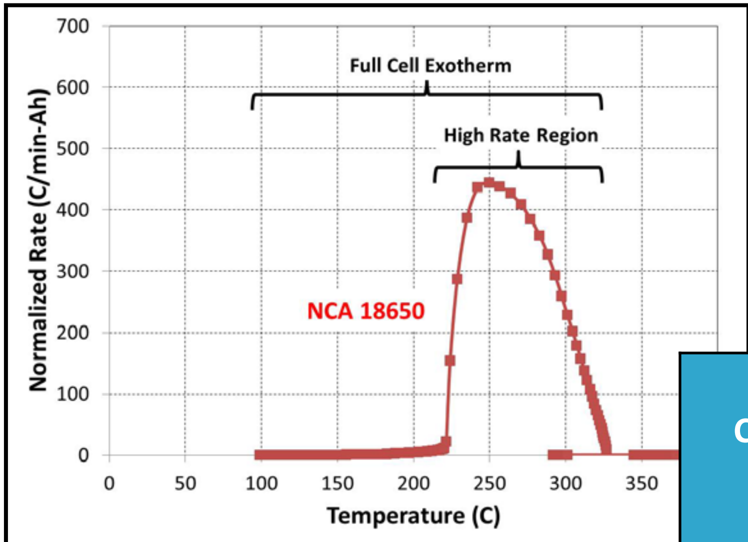
(Internal temperature limited due to ejection of cell contents)

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?

Characterizing Thermal Runaway



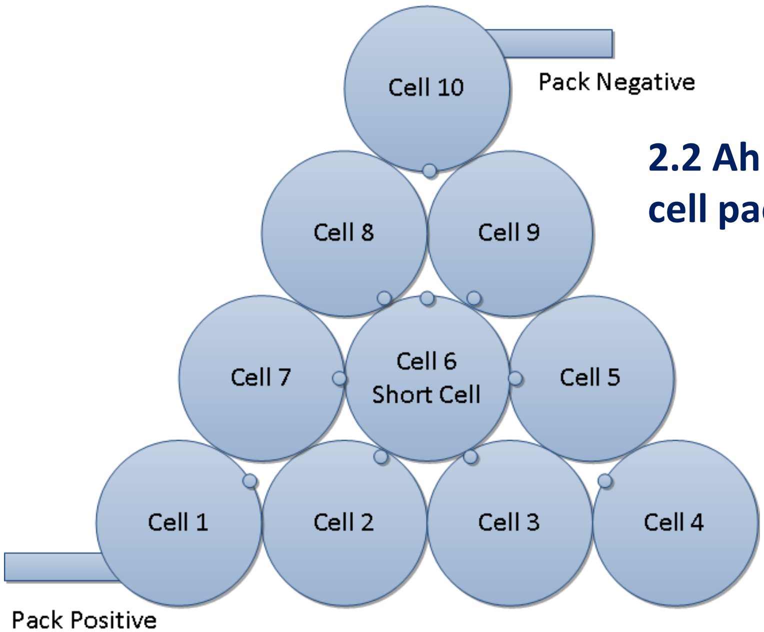
- *Full cell runaway enthalpy shows a significant amount of heat generation from even an LFP 18650 cell*
- *But that heat is generated at much different rates for the different cell types*

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

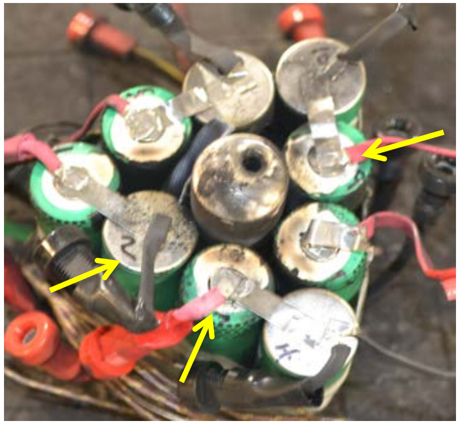
*ΔH based on dT (exotherm)
‡ΔH based on dT/dt (exotherm)

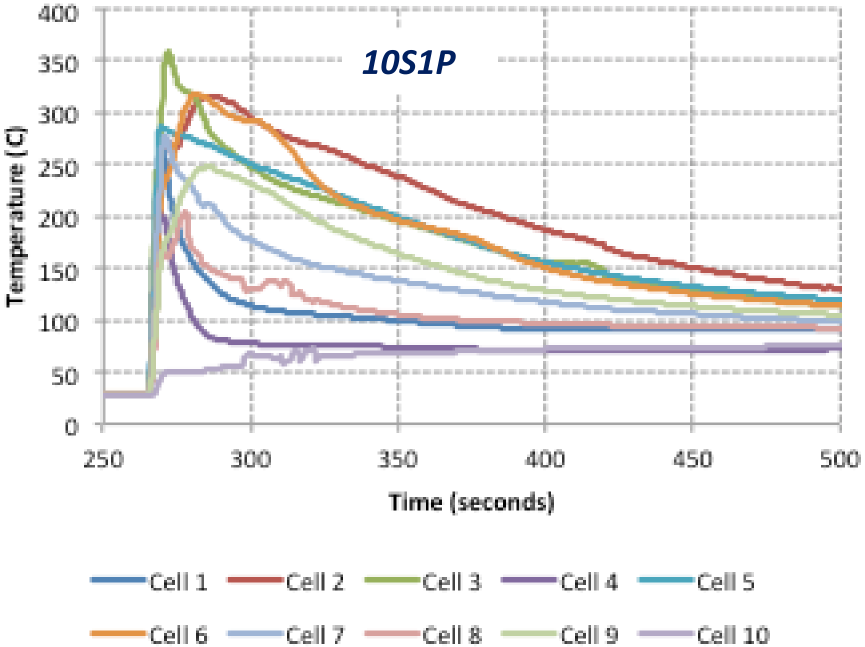
Data provide a quantitative measurement of the runaway enthalpy

Failure Propagation Testing



2.2 Ah CoO 18650 cell packs

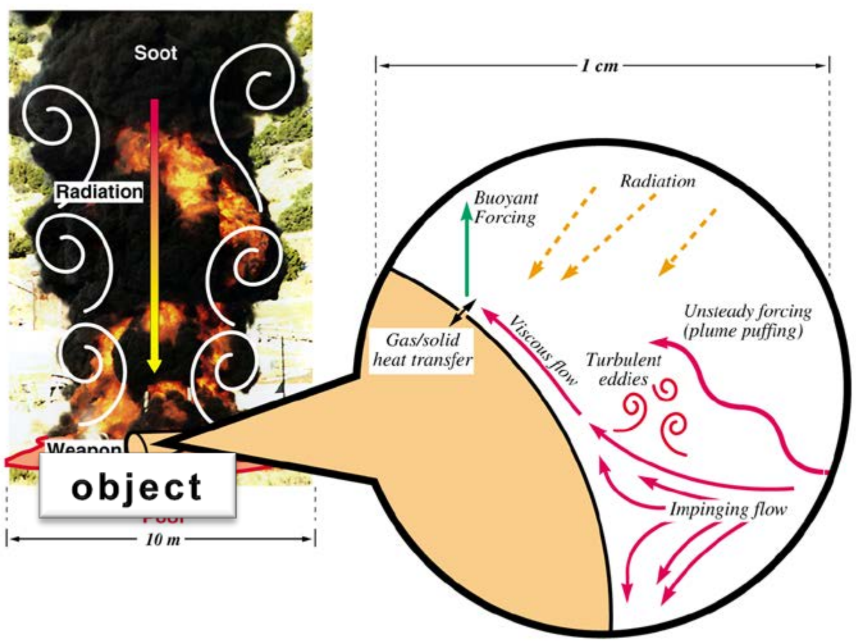




Limited propagation of the single point failure in the 10S1P pack

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



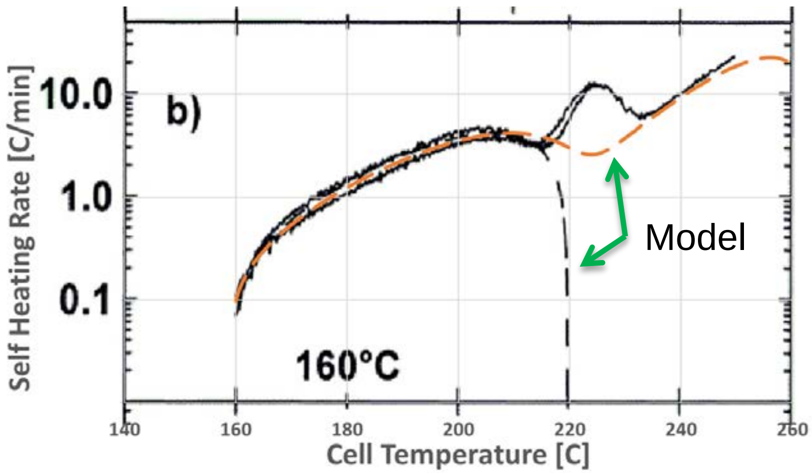
Heat transfer mechanisms in a fire

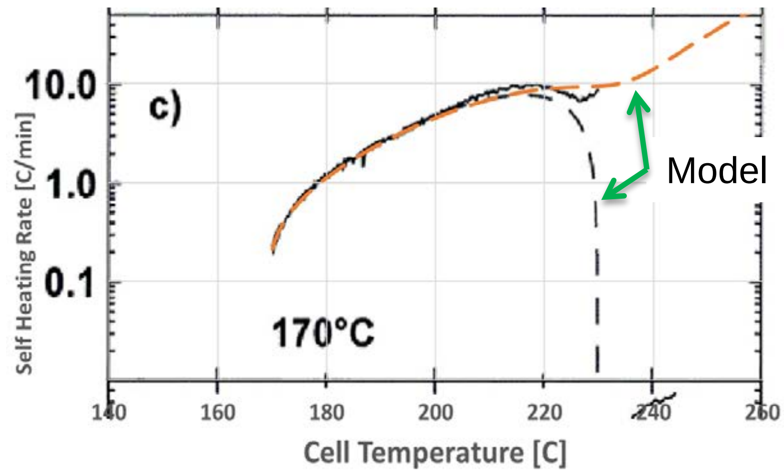
Physics:

- 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

Comparison of calorimetry measurements

- Calorimetry measurements inform and calibrate models for heat release rates
- Here, cathode heat release models are evaluated based on literature measurements



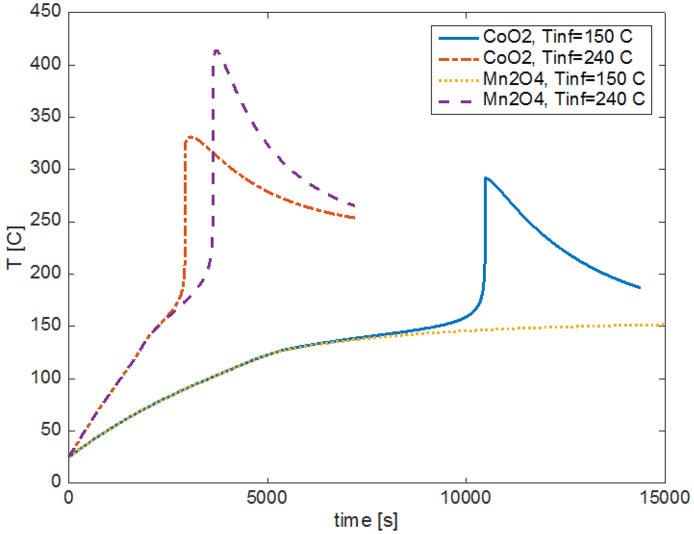


- Measurement from: MacNeil, D. D. and J. R. Dahn (2001). "Test of reaction kinetics using both differential scanning and accelerating rate calorimetries as applied to the reaction of LixCoO2 in non-aqueous electrolyte."
- Models based on Spotnitz, R. and J. Franklin (2003). "Abuse behavior of high-power, lithium-ion cells." Journal of Power Sources **113**(1): 81-100.

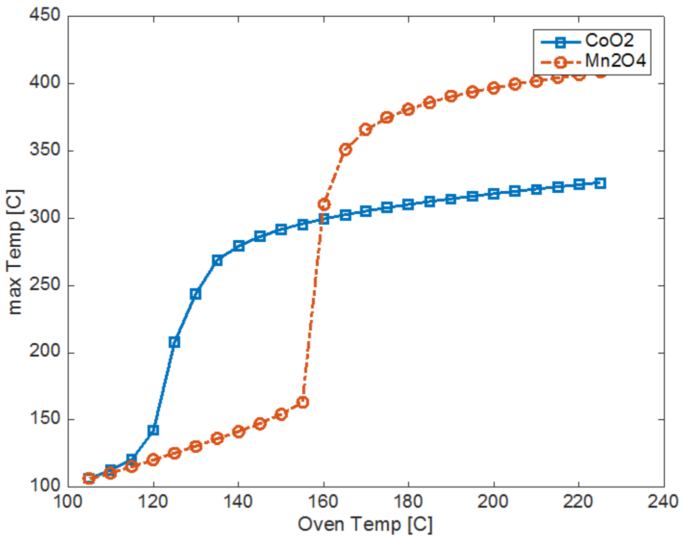
Modeling thermal runaway in lithium ion cells

- Evolution simulated using calorimetry-derived heating rates and lumped thermal mass
- Consider SEI decomposition, cathode-electrolyte reaction, electrolyte decomposition, anode-electrolyte reaction
- Fire environment modeled as an ambient temperature
- Bound thermal runaway versus heat dissipation

Temp. evolution two environ. temps., two cathode materials

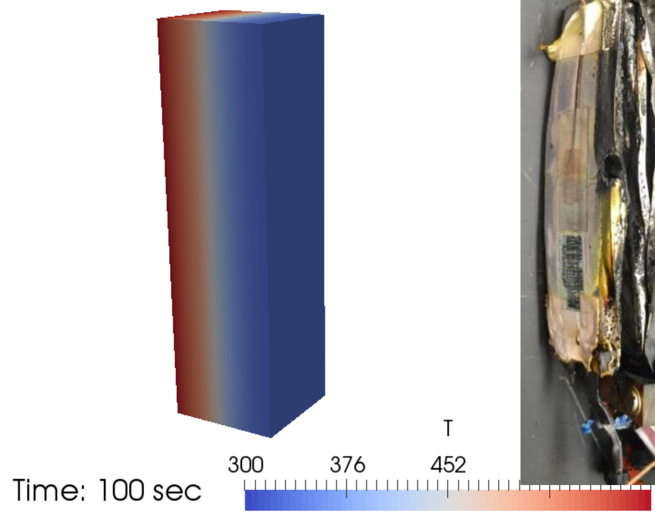


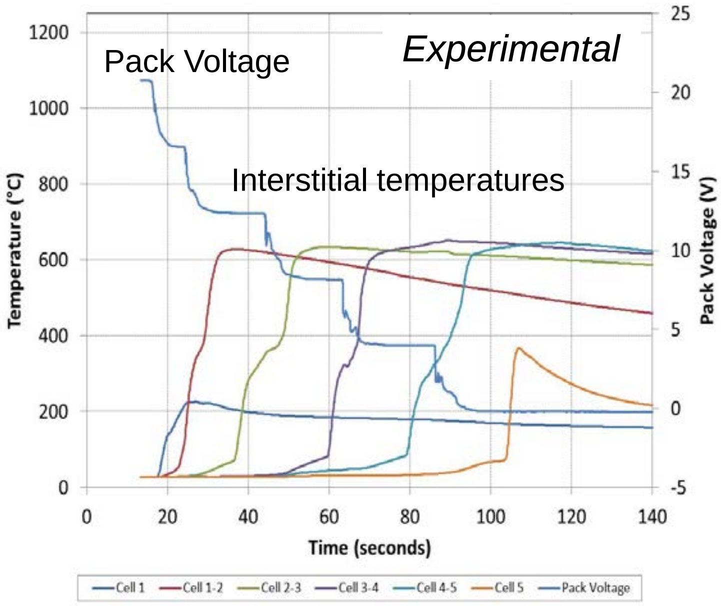
Max temp. observed versus environment (oven) temp.

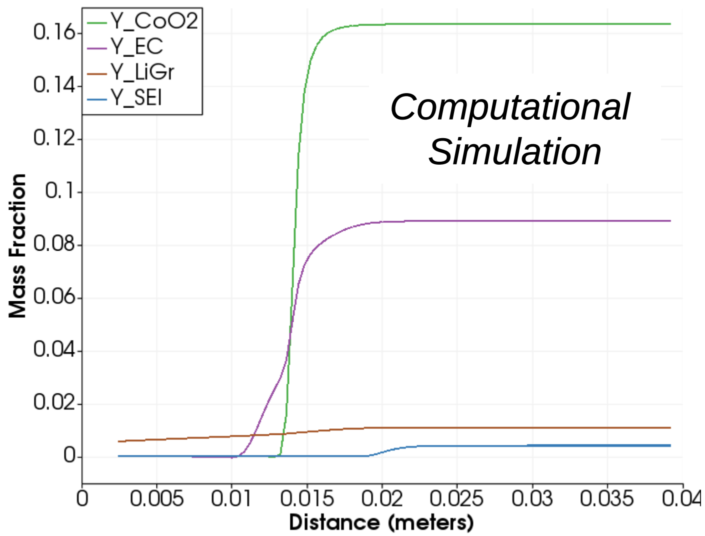


Propagation across multiple (5) cells

- Prediction and mitigation of cell-to-cell propagation is key to addressing risk.
- Here simulating propagation across series of pouch cells.
- Accurate measurements of highest temperature kinetics unavailable and need to be calibrated to get agreement.

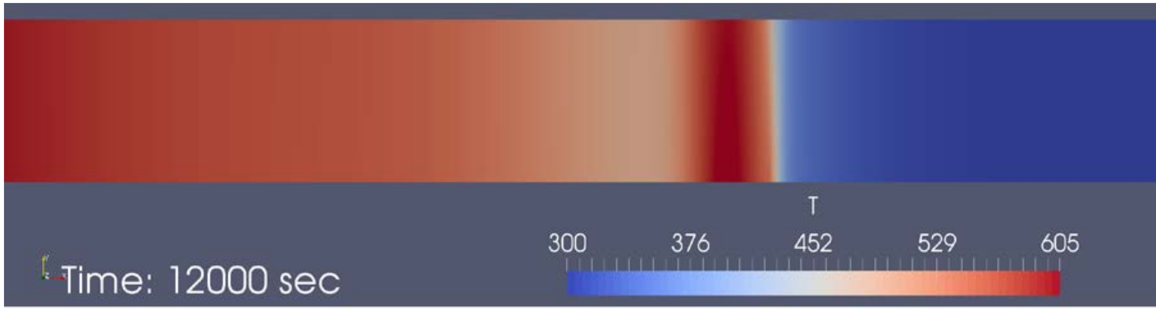


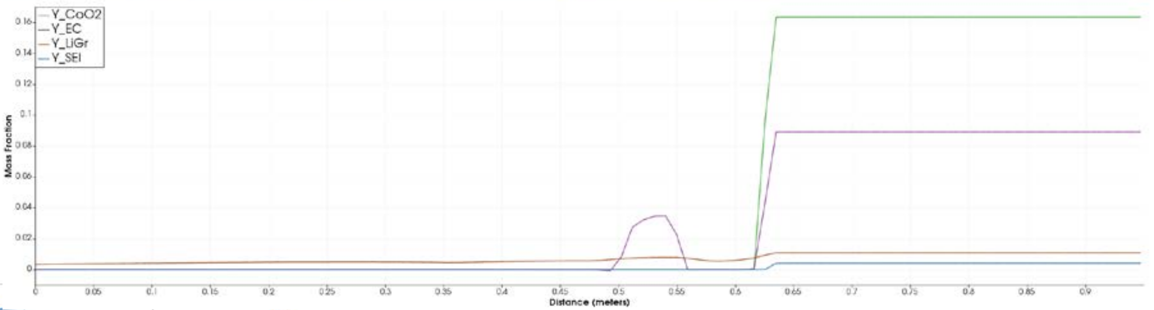


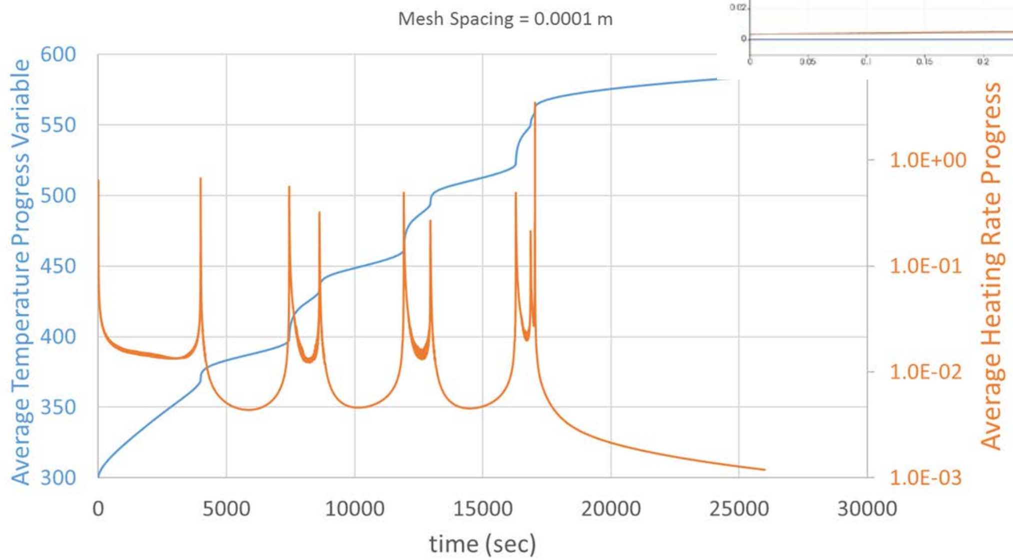


Pulsating Propagation at large scales

- Prediction and mitigation of cell-to-cell propagation is key to addressing risk.
- Here predictions include multi-step mechanism involving anode, cathode, electrolyte reactants.







- Propagation across a large pack (128 cells here) exhibits pulsating instabilities.

The Problem of Scale

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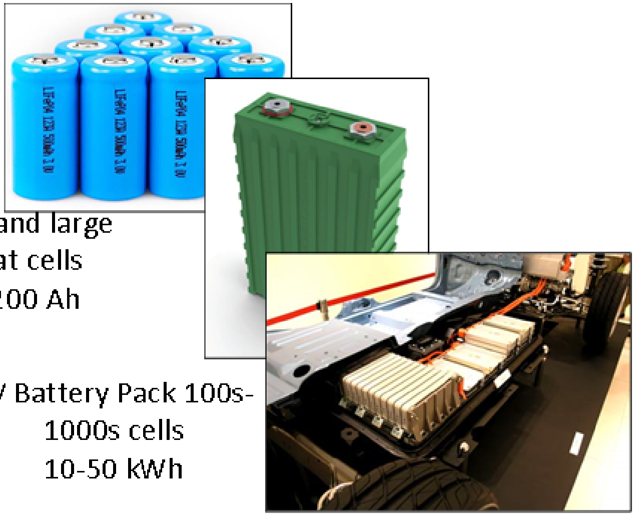
- Field failures of single cells are relatively rare
  - Failure rates as low as 1 in several million
- The number of cells used in the transportation and energy storage industries is potentially huge (billions)
- EV and PHEV batteries: 10-50 kWh
- Batteries for stationary storage applications: *O*(MWh)
- 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

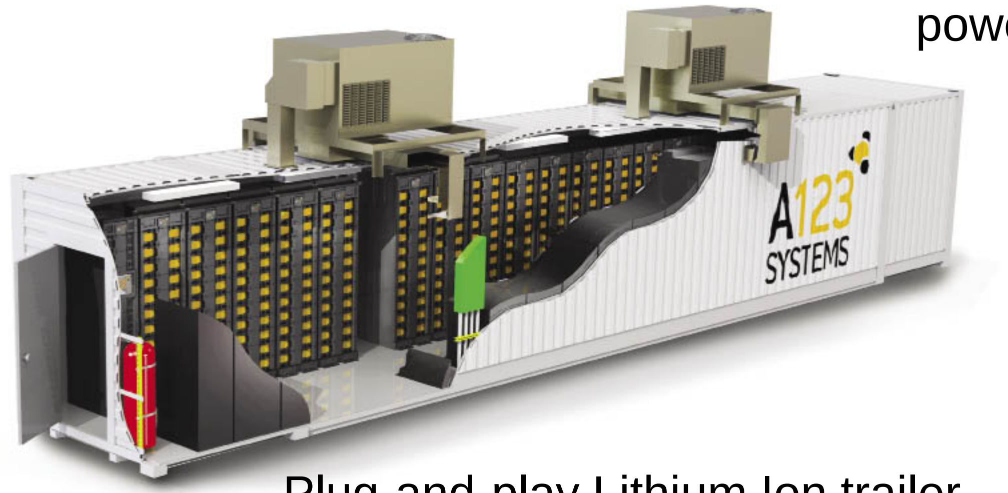


EV Battery Pack 100s-
1000s cells
10-50 kWh

Stationary storage
system 1000s or more
individual cells
MWh+

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

Failures at scale necessitate modelling



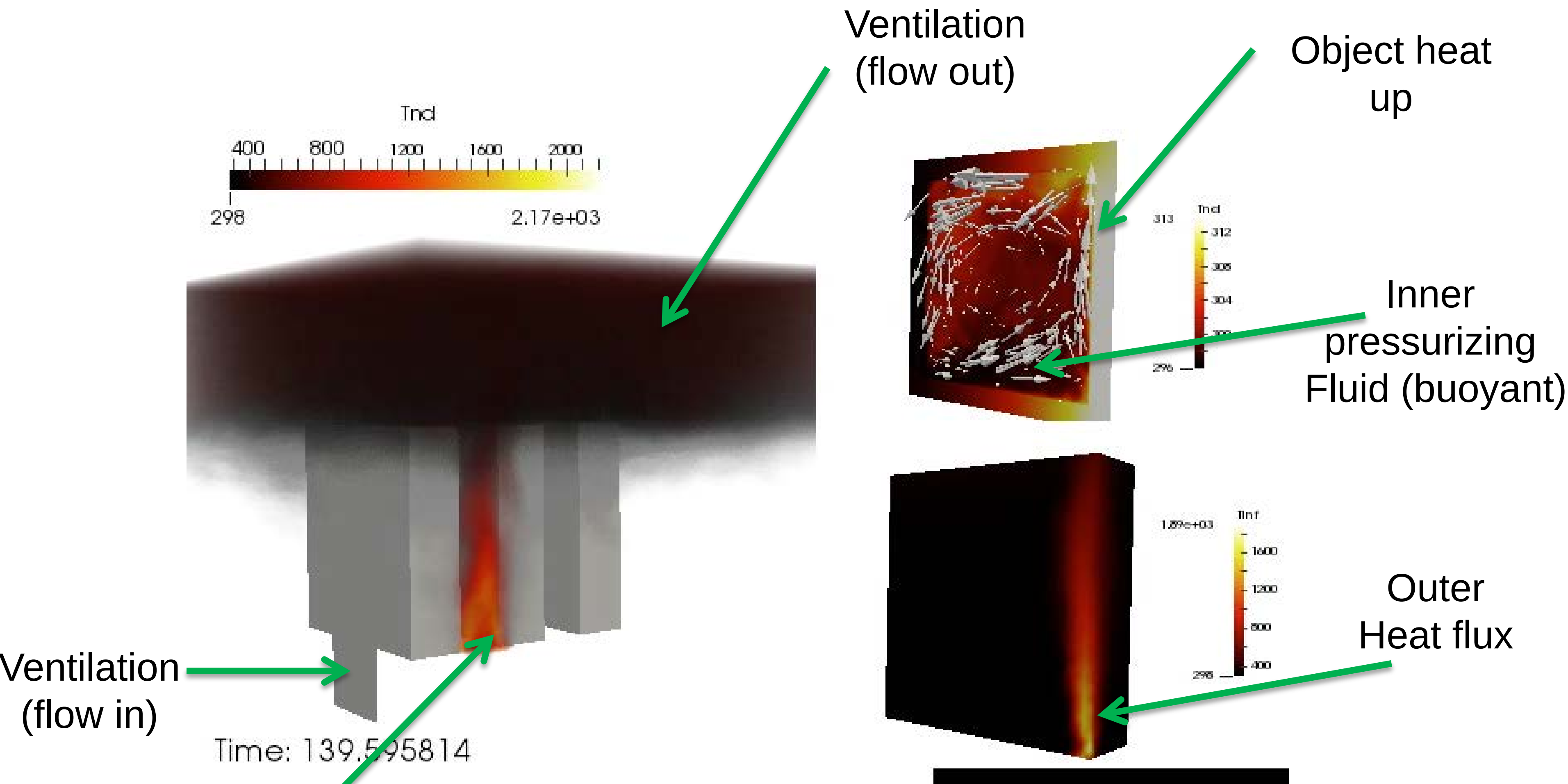
Plug-and-play Lithium Ion trailer

power conditioning system

racks of batteries

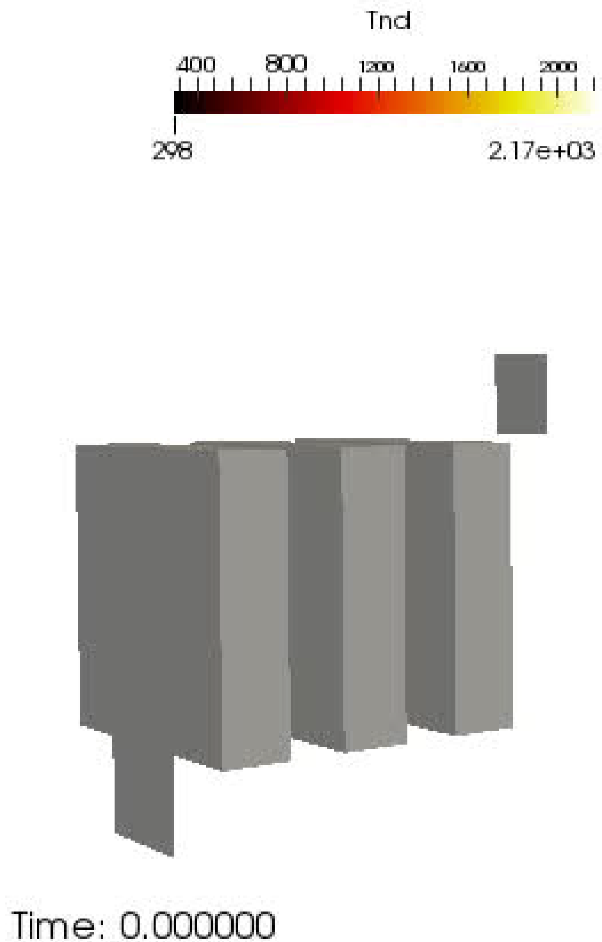
Lead acid Alaska facility designed to replace back-up diesel

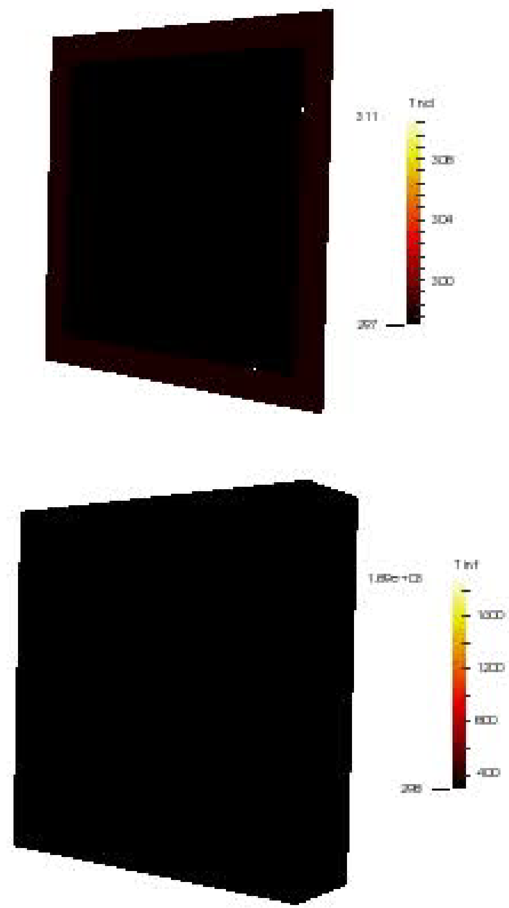
Simulation of Battery Fire Scenarios: effect of ventilation



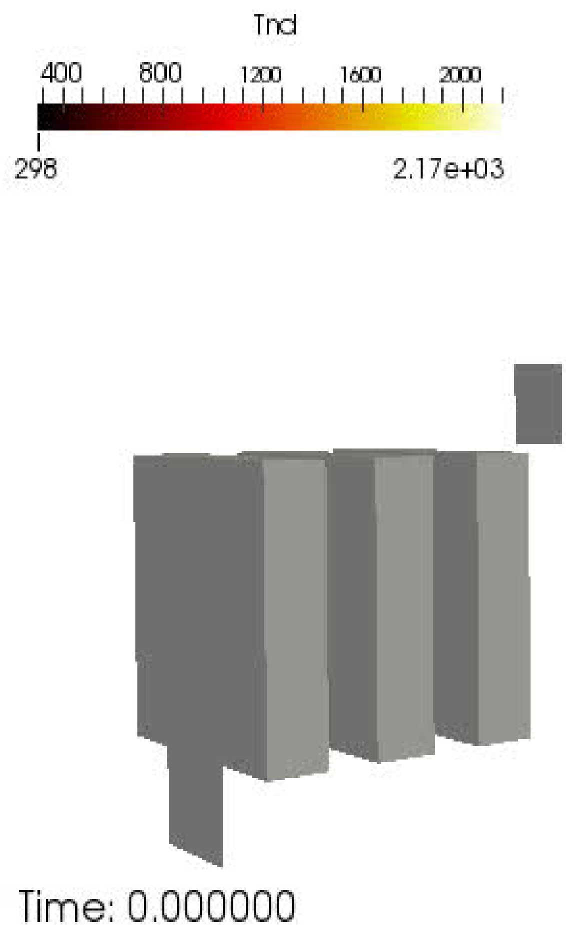
Fire modeled as a combustible hydrocarbon

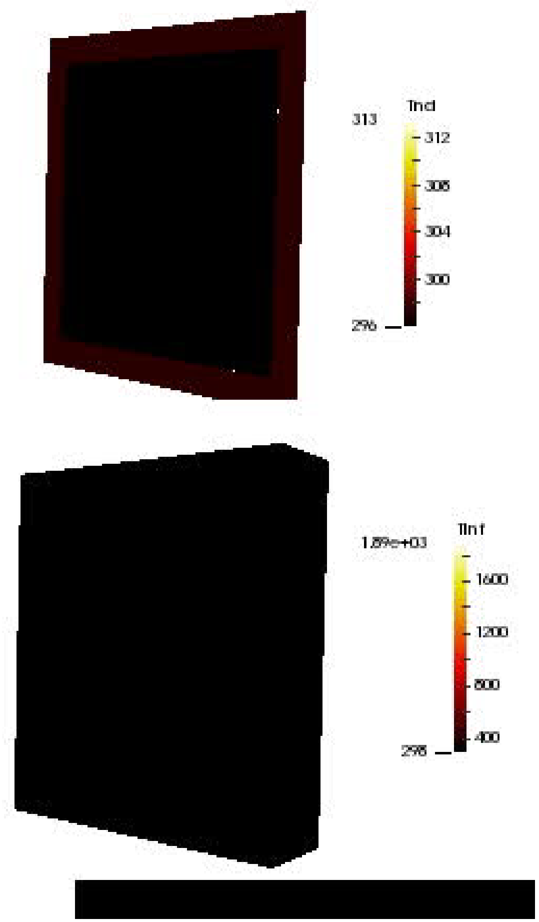
Ventilation effect on fire plume dynamics: No Ventilation



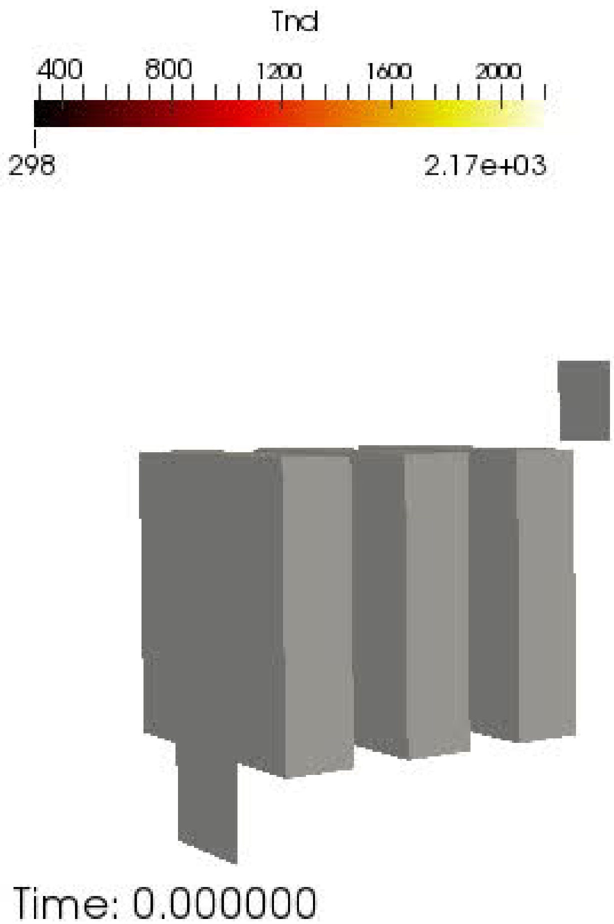


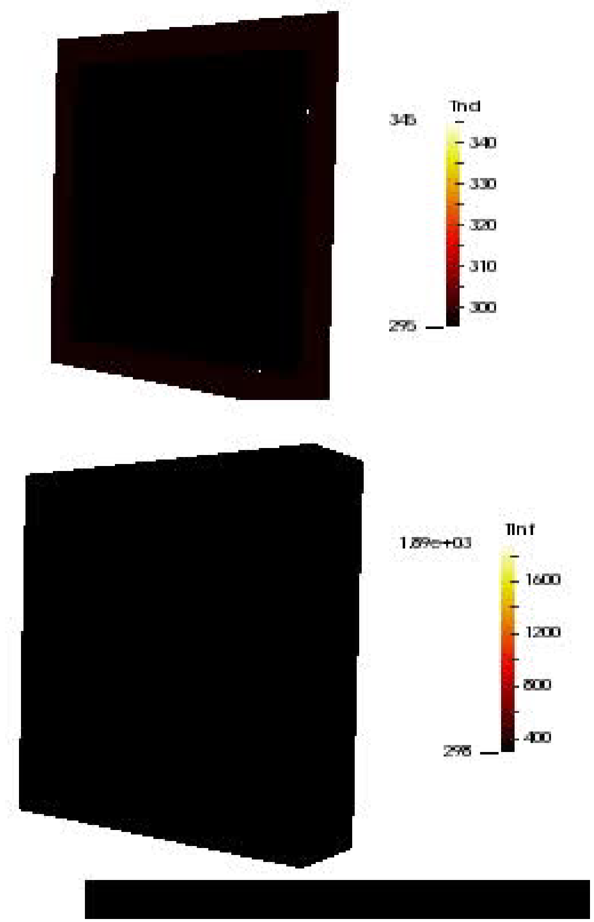
Ventilation effect on fire plume dynamics: 1 m/s ventilation



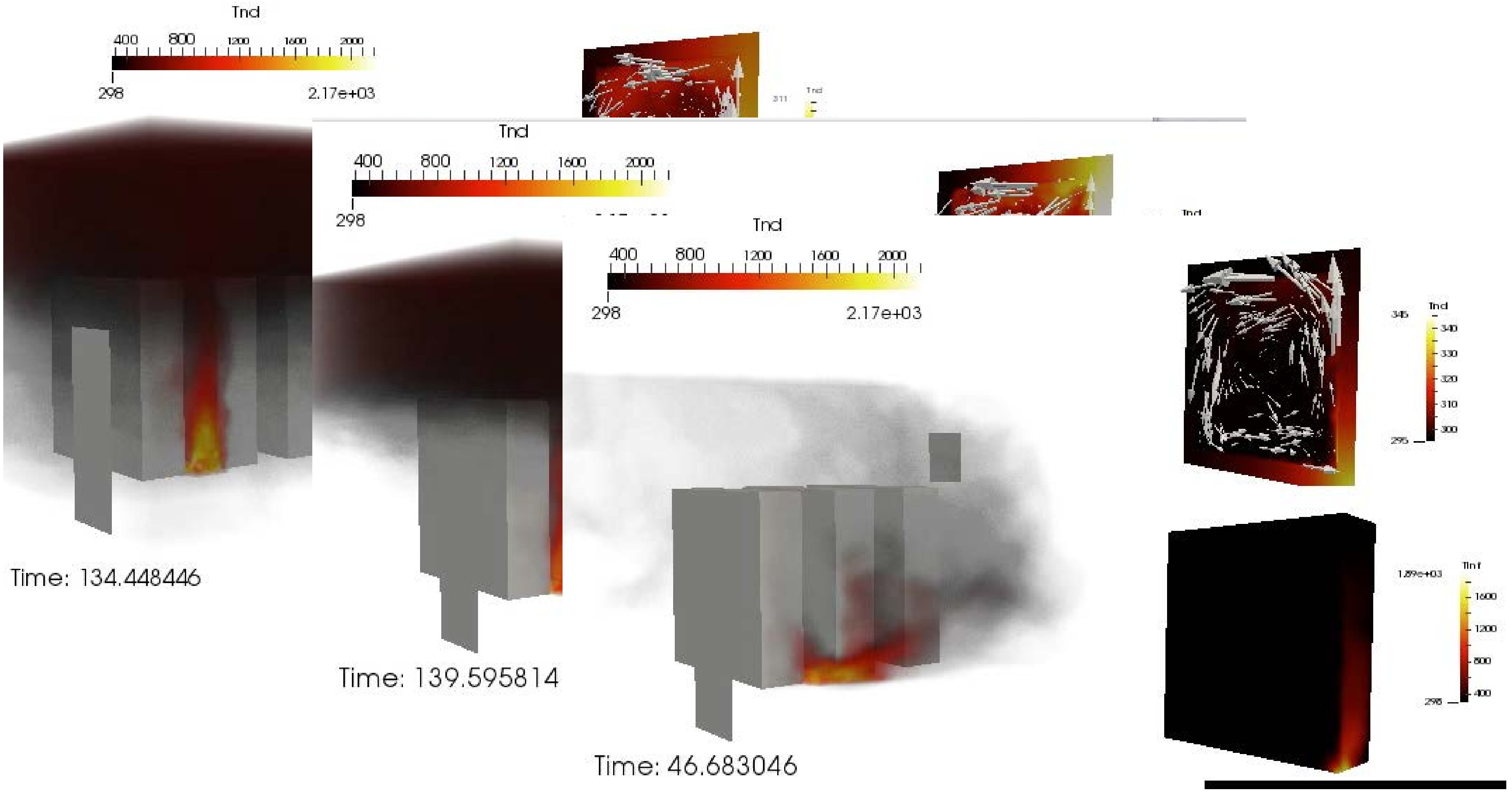


Ventilation effect on fire plume dynamics: 10 m/s ventilation



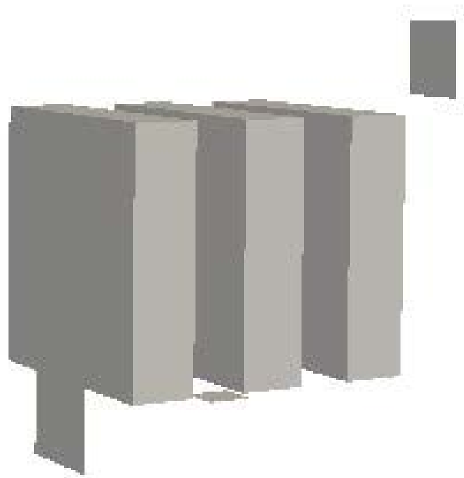


Plume dynamics

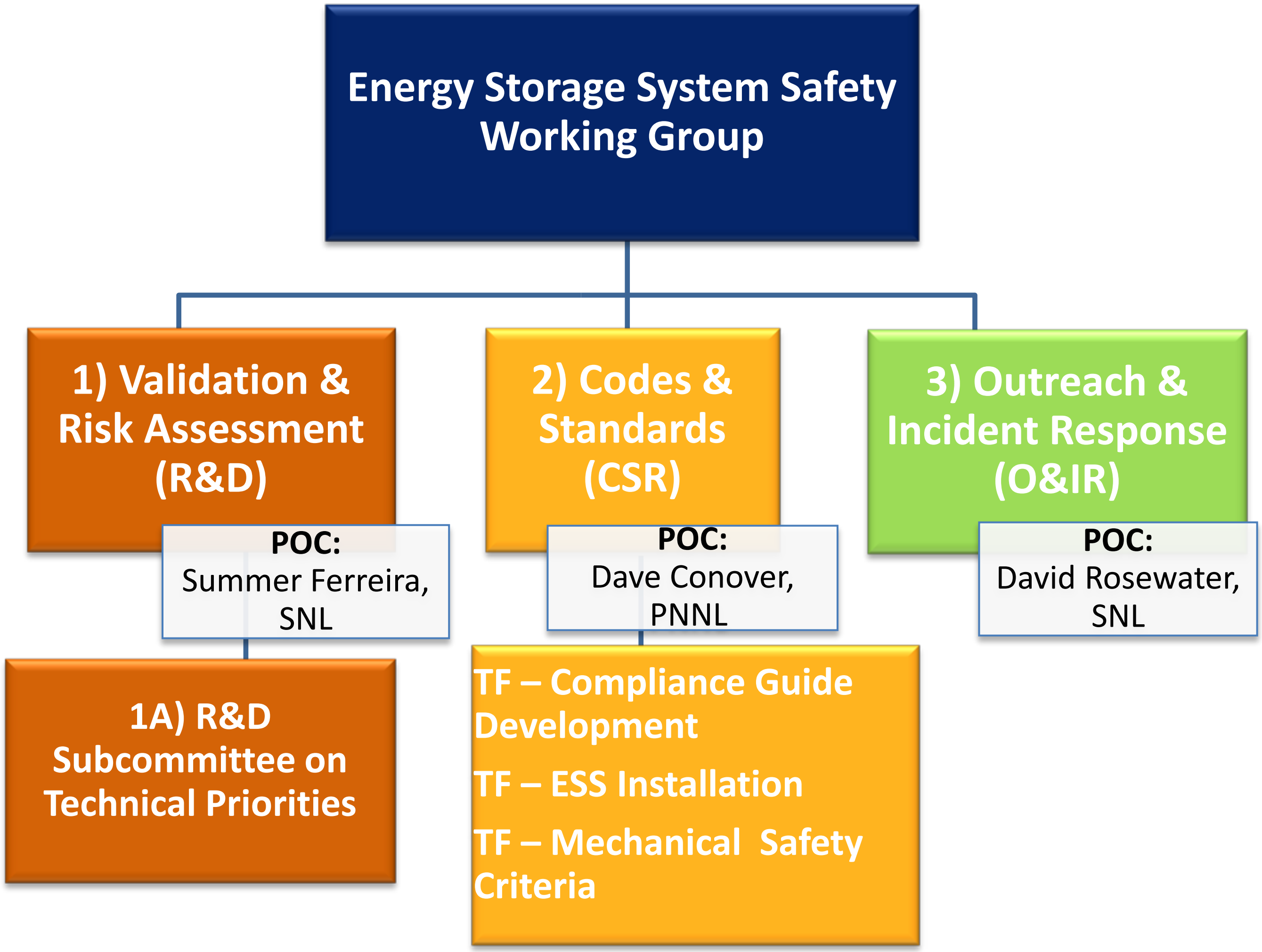


Three ventilation comparison still shot

Suppression

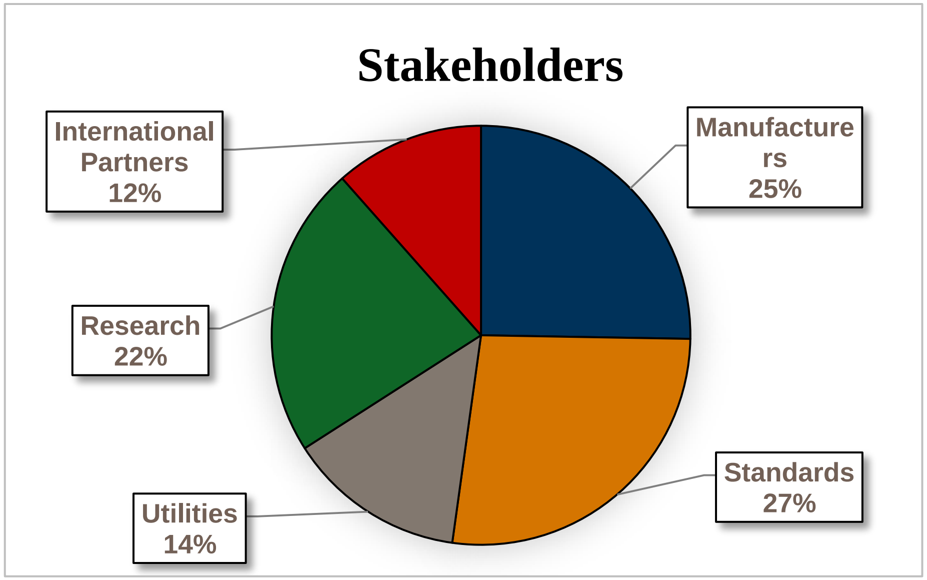


Codes and Standards/Outreach: Energy Storage Safety Working Group



Collaboration

- All interested and affected parties are encouraged to participate
- Communication is directly with stakeholders as well as key organizations representing specific types of stakeholders
- The makeup of the participants of each group span the industry:
  - Safety Validation and Risk Assessment
    - ✓ 110 on the distribution list, 30 average meeting attendance
    - ✓ 25 on the Priorities and Gap Assessment subcommittee
  - Codes and Standards
    - ✓ 108 on the distribution list, 35 average meeting attendance
    - ✓ 6 on the mechanical safety task force (drafted input to UL 9540)
    - ✓ 18 on the ESS Compliance Guide task force
    - ✓ 11 on the ESS Installation Pre-standard task force
  - Safety Outreach and Incident Response
    - ✓ 100 People on the distribution list, 30 average meeting attendance



Working Groups Address Safety Across the Board

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ESS Safety Topology

Research

Technical Development R&D

- Organize annual ESS Safety R&D Forum and in person meeting of the working groups
- Identify top R&D priorities and CSR gaps and conduct R&D to address:
  - Fire suppression testing and analysis
  - Thermal runaway research
  - System scale burn test
  - Commodity classif cation development
  - Fire and vent gas modeling and analysis

Codes and Standards

Design

Components

UL 489 (Circuit Breakers)
UL 810A (Electrochemical Capacitors)
UL 1642 (Lithium Batteries)
UL 1973 (Batteries for Stationary Applications)
UL 1974 (Second Use Batteries- DRAFT)
NFPA 791 (Recommended Practice and Procedures for Unlabeled Electrical Equipment)

Entire Energy Storage System

UL 9540 (Safety for ESS- DRAFT)
UL 3001 (Safety for Distributed Energy Generation and ESS)
ASME TES-1 (Molten Salt Thermal Energy Storage Systems)
NFPA 791 (Recommended Practice and Procedures for Unlabeled Electrical Equipment)

Installation & Commissioning

Systems Layout

IBC (Building Code)
NFPA 5000 (Building Code)
NECA 416 (ESS Installation)
NFPA 855 (ESS Installation)
IFC (Fire Code)
NFPA 1 (Fire Code)

Safety Systems

NFPA 850 (Electrical Generation)
NFPA 70 (Electrical Code)
IFC (Fire Code)
NFPA 1 (Fire Code)

Operations & Maintenance

Operations Sequence

NFPA 70 (Article 706)
IFC (Fire Code)
NFPA 1 (Fire Code)

Incident Response

Incident Response

NFPA 921 (Fire Investigations)
IEEE 979 (Guide for Substation FP)

Educational Outreach

Safety Outreach

- Development and dissemination of educational materials
- Cultivating partnerships with key stakeholder groups

Battery Safety R&D Program Support

Sandia National Laboratories

- The BATLab has had a number of partnerships over the years including cooperative research and development agreements (CRADA) and work for others (WFO) programs with industry and government agencies to study battery safety and reliability.
- DOE EERE Office of Vehicle Technologies (OVT) support: USABC/Testing Program, Advanced Battery Research (ABR) Program
- Interagency agreement work for others program with DOT/NHTSA to address state of stability and stranded energy issues
- US Council for Automotive Research (USCAR) program to provide experimental support of crash models
- Partnered with Ford in a DOT/NHTSA program to develop test protocols for EV battery systems. This involved testing from the cell level up to full size EV batteries.
- Partnering with PNNL for

Questions

- Additional Resources/Announcements
  - http://www.sandia.gov/ess/
- ESS Safety Forum – February 22-24, 2017
  - The call for papers is open
  - https://share.sandia.gov/ess/ess-safety-forum-2017

Acknowledgements

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- Pete Roth
- Jill Langendorf
- Lorie Davis
- Denise Bencoe
- Travis Anderson
- Chad Staiger
- Harry Pratt
- Tom Wunsch
- Leigh Anna Steele
- Bill Averill
- Dave Johnson
- Scott Spangler
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- Kyle Fenton
- Chris LaFleur
- Alice Muna
- Pam Cole (PNNL)
- Dave Conover (PNNL)

Battery Safety R&D Program at Sandia: ***http://energy.sandia.gov/?page_id=634***
DOE Office of Electricity and Energy Reliability
Office of Vehicle Technologies