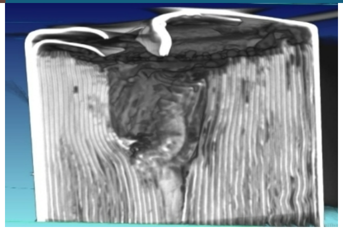
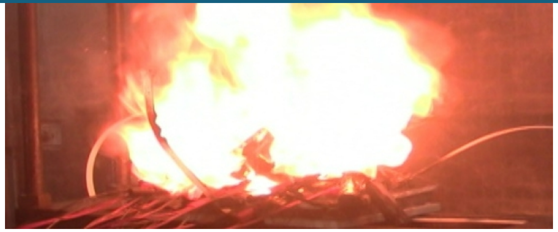
SAND2021-9216PE

Battery Energy Storage System Safety





SEPA Energy Storage Workshop

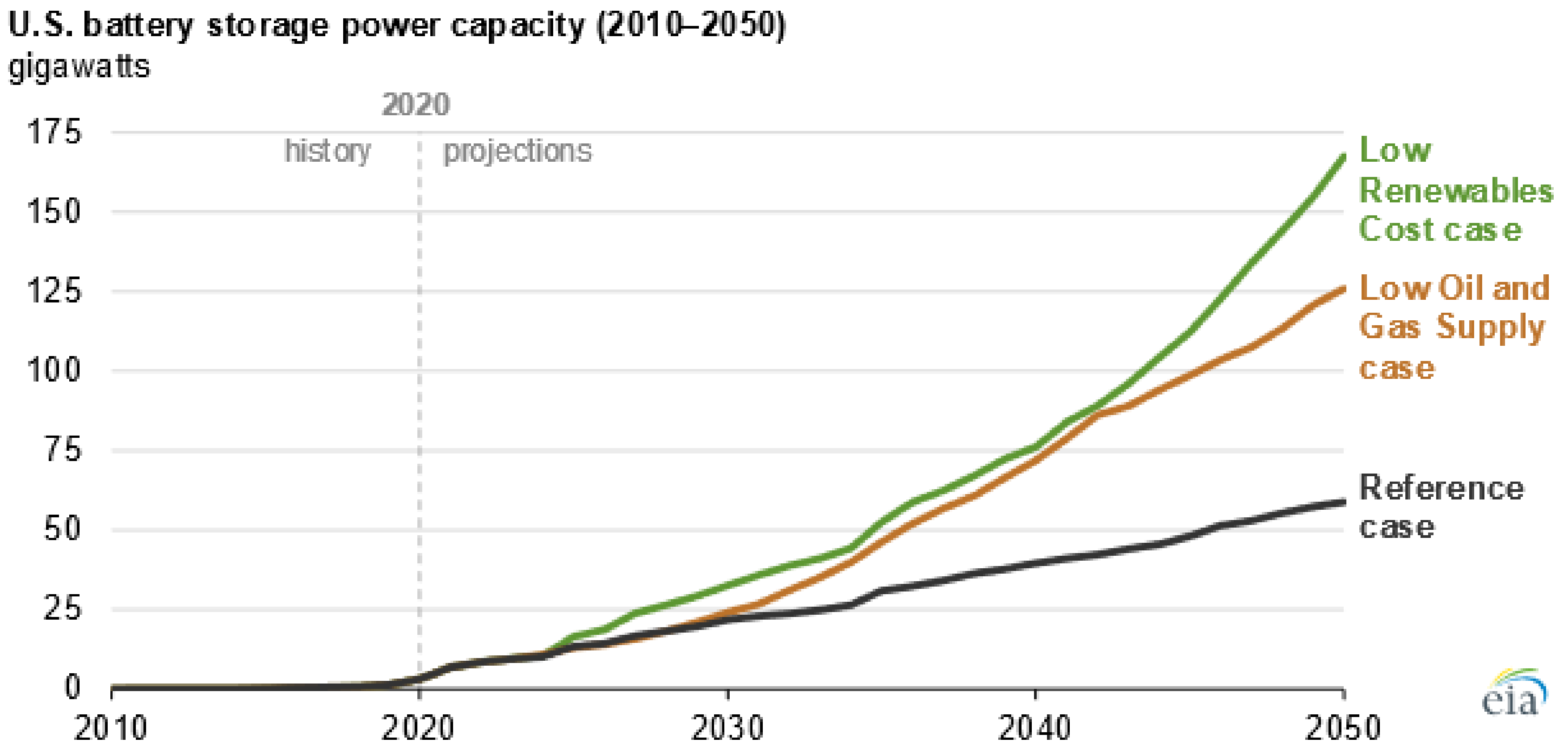
August 10, 2021

Joshua Lamb

jlamb@sandia.gov

Batteries will provide substantial grid-scale energy storage

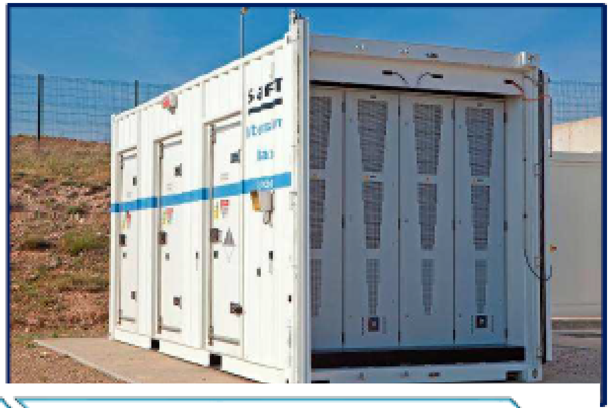
Energy Information Administration Annual Energy Outlook 2021 report projects 59 GW of battery energy storage on the grid by 2050 in the base case, 175 GW if more renewables



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2021*

https://www.eia.gov/todayinenergy/detail.php?id=47276

Impact and consequence of scale on safety

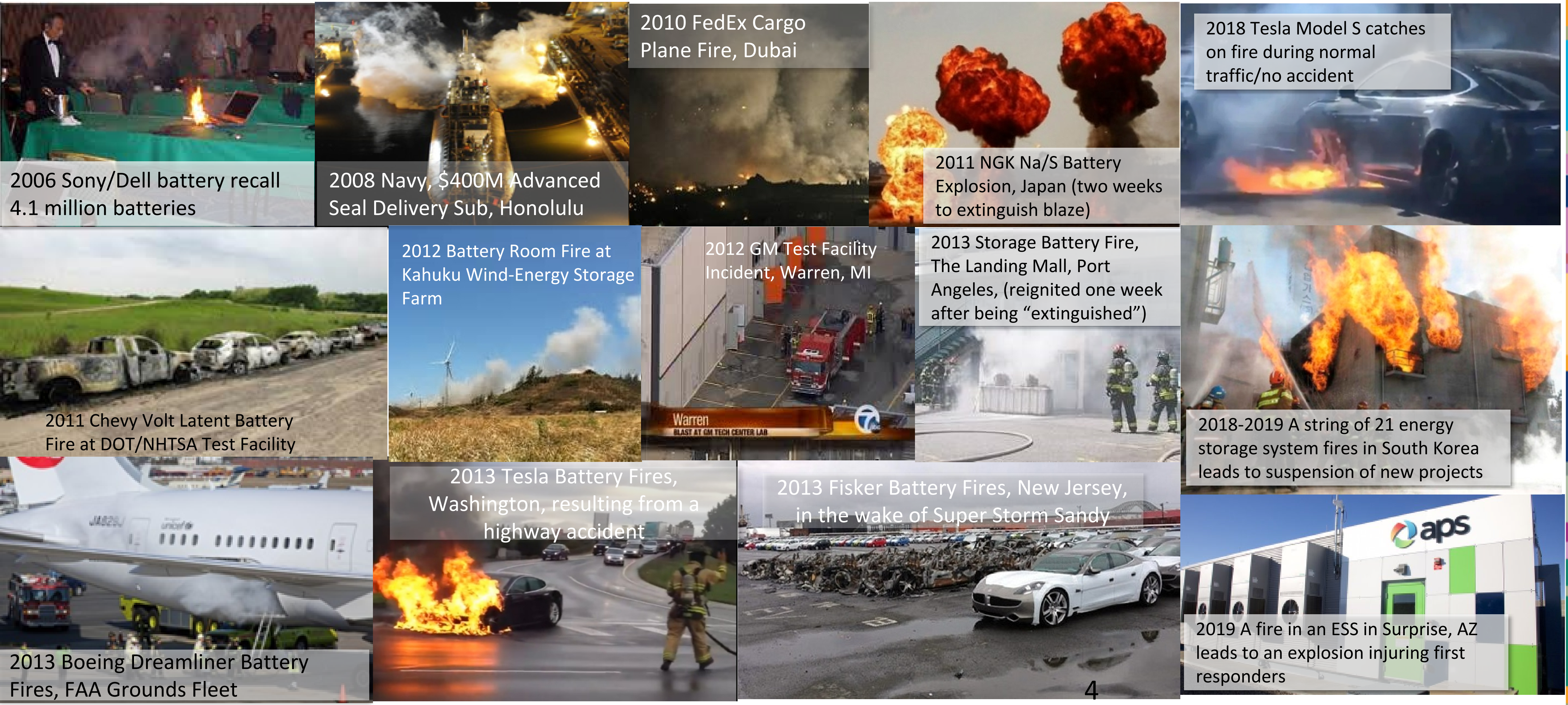


Consumer Cells (0.5-5 Ah) → Large Format Cells (10-200 Ah) → Transportation Batteries (1-50 kWh) → Utility Batteries (MWh)

Safety issues and complexity increase with battery size

Safety research is heavily focused on lithium-ion as the primary application ready technology. However many emerging technologies identified as promising for grid-scale storage are less well studied.

Grid ESS are the new frontier of energy storage safety



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)

2018 Tesla Model S catches on fire during normal traffic/no accident

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")

2018-2019 A string of 21 energy storage system fires in South Korea leads to suspension of new projects

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

2019 A fire in an ESS in Surprise, AZ leads to an explosion injuring first responders

ESS incidents typically make the news

Safety is critical to the widescale deployment of energy storage technologies.

Bloomberg

Bloomberg

Hyperdrive

Explosions Threatening Lithium-Ion's Edge in a Battery Race

By Brian Eckhouse and Mark Chediak
April 23, 2019, 4:58 PM MDT *Updated on April 24, 2019, 8:24 AM MDT*

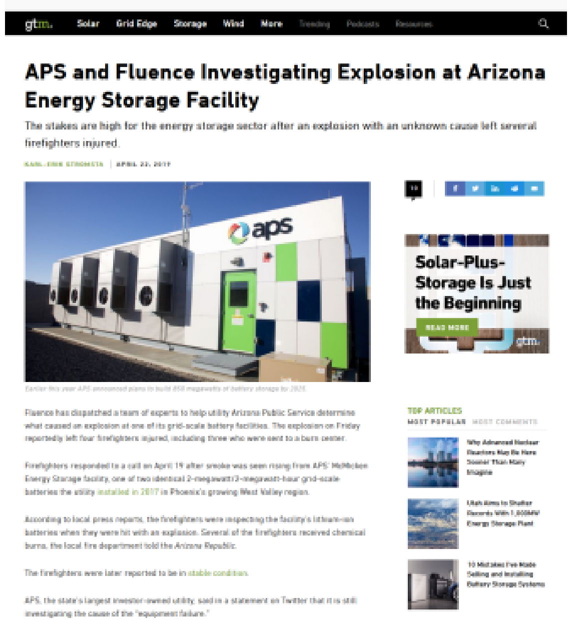
- Battery exploded at plant in Arizona; two others were shut
- Arizona utility regulator calls for 'thorough investigation'

Another lithium-ion battery has exploded, this time at an energy-storage complex in the U.S.

At least 21 fires had already occurred at battery projects in South Korea, according to BloombergNEF. But this latest one, erupting on Friday at a facility owned by a Pinnacle West Capital Corp. utility in Surprise, Arizona, marked the first time it has happened in America since batteries took off globally.

https://www.bloomberg.com/news/articles/2019-04-23/explosions-are-threatening-lithium-ion-s-edge-in-a-battery-race

Greentech Media



APS and Fluence Investigating Explosion at Arizona Energy Storage Facility

The stakes are high for the energy storage sector after an explosion with an unknown cause left several firefighters injured.

Fluence has dispatched a team of experts to help utility Arizona Public Service determine what caused an explosion at one of its grid-scale battery facilities. The explosion on Friday reportedly left four firefighters injured, including three who were sent to a burn center.

Firefighters responded to a call on April 19 after smoke was seen rising from APS' McMicken Energy Storage facility, one of two identical 2-megawatt/3-megawatt-hour grid-scale batteries the utility installed in 2017 in Phoenix's growing West Valley region.

According to local press reports, the firefighters were inspecting the facility's lithium-ion batteries when they were hit with an explosion. Several of the firefighters received chemical burns, the local fire department told the Arizona Republic.

The firefighters were later reported to be in stable condition.

APS, the state's largest investor-owned utility, said in a statement on Twitter that it is still investigating the cause of the "equipment failure."

https://www.greentechmedia.com/articles/read/aps-and-fluence-investigating-explosion-at-arizona-energy-storage-facility#gs.gpky5k

The Korea Times

Biz & Tech

Auto IT Game Manufacturing Retail & Food Energy

IT

Frequent fire raising concerns over safety of solar energy

A fire engulfs an energy storage system at a cement plant in Jecheon, North Chungcheong Province, Monday. / Courtesy of North Chungcheong Province Fire Service Headquarters

By Nam Hyun-woo

A series of fires in energy storage systems (ESSs) has been raising safety concerns, according to industry analysts, Tuesday.

With ESSs essential for optimizing energy efficiency, further accidents may compromise the feasibility of renewable power and hamper the government's bid to expand the use of cleaner energies.

According to the Ministry of Trade, Industry and Energy, it recommended individuals, companies and other organizations to stop using 584 uninspected ESSs across the country.

https://www.koreatimes.co.kr/www/tech/2018/12/133_260560.html

There is a tendency to use the availability heuristic when considering risk.

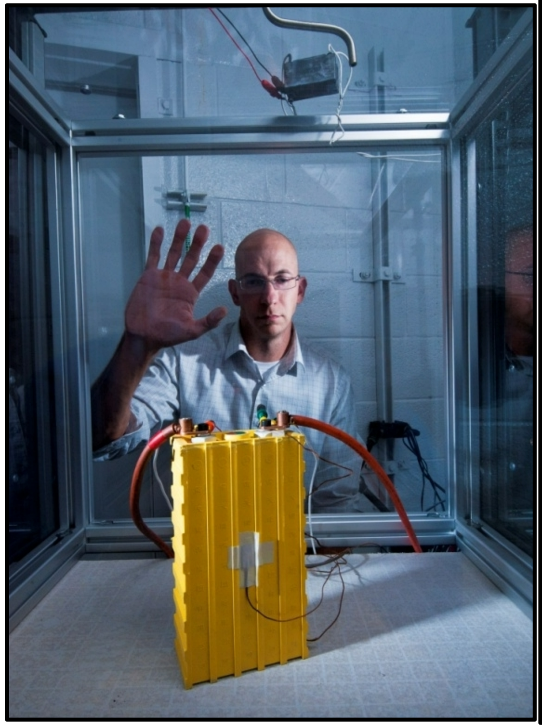
To avoid this, consider how many batteries continue to operate without problems every day.

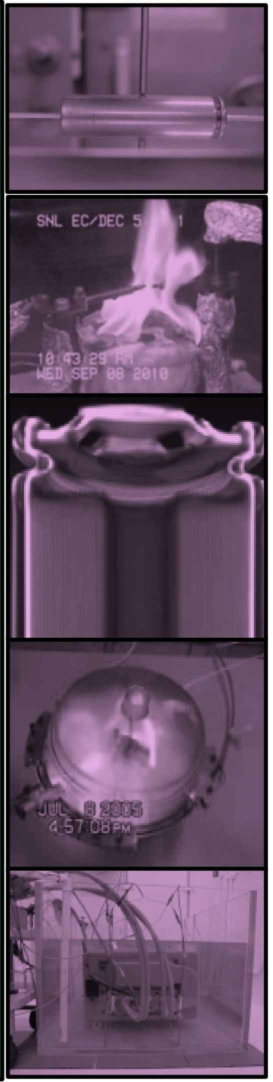
Dedicated facilities for battery testing

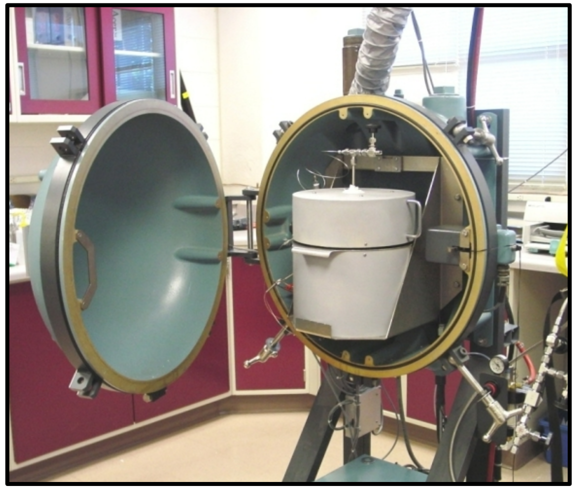
- Hundreds of independent channels for testing, from coin cells to kWh modules
- 150 uA to 2000 A current range capability
- R&D 100 Green Technology-awarded high-precision testers
- 70+ thermal chambers, ranging from 1.2 ft^3 to 25 ft^3
- –72°C to 95°C temperature capabilities
- Welding capabilities, including resistance, pinch, and spot
- Additional labs for materials characterization and 8000 ft^2 dry-room space for prototyping

World-class battery abuse lab (DOE Core facility)

- 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







Engineering Safety through Design - How to think about safety

The goal of safety engineering is to analyze, design, and document the safety of specific system.

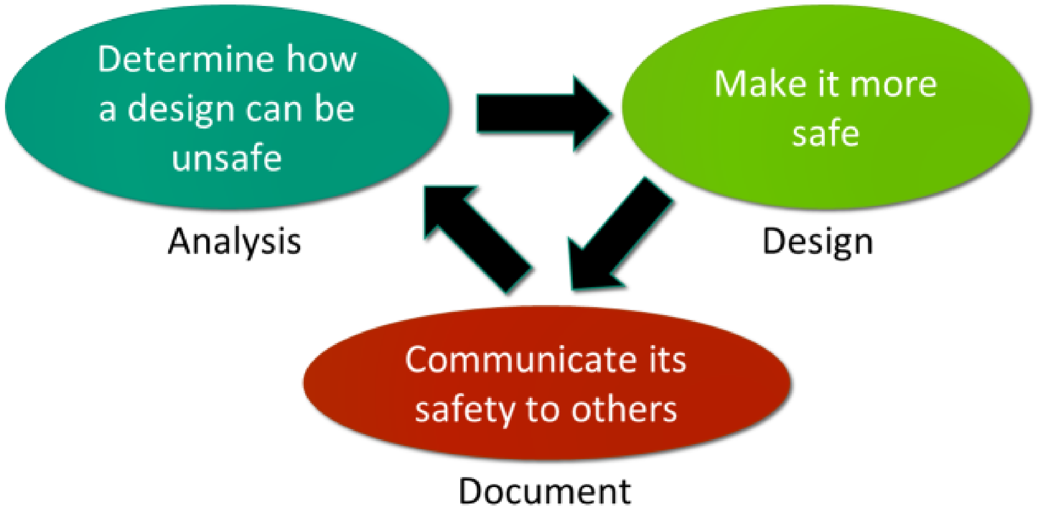
Common methods:

Probability Risk Assessment (PRA)

- Assumes that accidents happen because the stochastic components of a system fail.
- Analysis answers three questions: What can go wrong? How likely is that? How bad would that be?
- PRA Consists of a combination of Event trees and Fault trees

Systems Theoretic Process Analysis (STPA)

- Accidents occur when interactions violate safety constraints
- The system enforces these constraints using feedback control
- STPA consists of:
  - Safety control structures
  - Unsafe control actions
  - Loss scenarios



Mechanics of Thermal Runaway

How does thermal runaway start?

- Thermal, electrical, or mechanical "abuse"
- However, "abuse" thresholds are statistical properties and can change with time, usage, and environment

Thermal runaway measured via accelerated rate calorimetry (ARC)

1. **Self-heating onset temperature**
2. **Thermal runaway onset temperature**
3. **Total heat release (ΔT)**

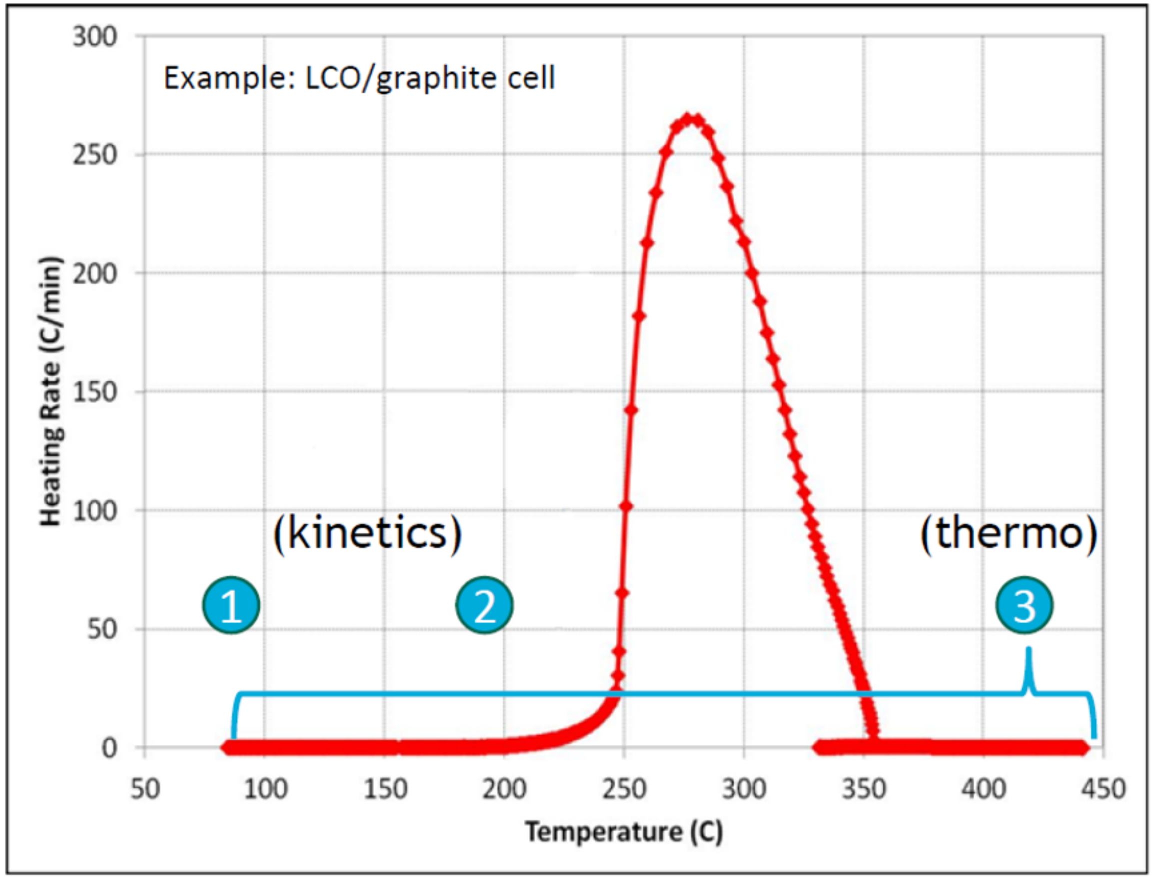
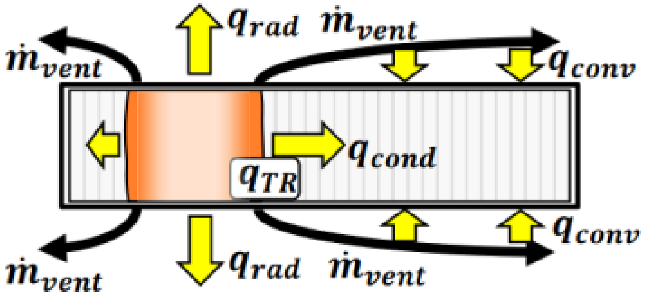


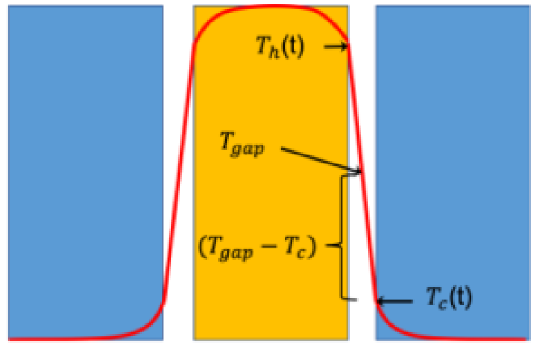
Figure Credit: Yuliya Preger https://custom.cvent.com/5B9EB96FC2FC4AC69710004DEF407285/files/f4910d8f6dec42fb8b312e3934da8826.pdf

Approaches to designing in safety



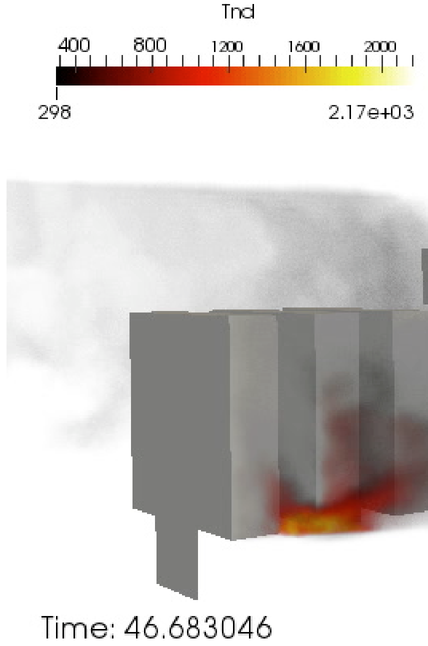
The current approach is to test our way into safety.

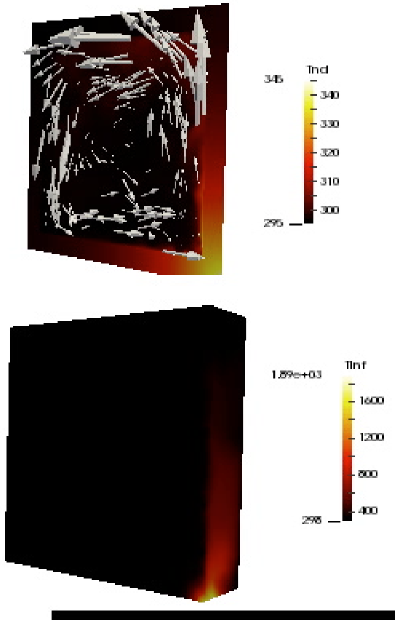
- Large system (>1MWh) testing is difficult and costly.

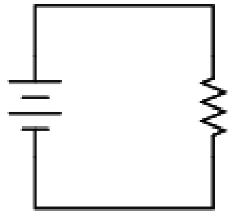


Supplement testing with predictions of challenging scenarios and optimization of mitigation

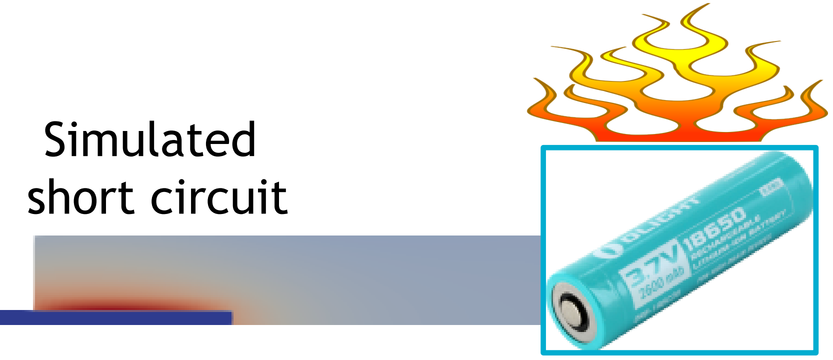
- Leverage world-class fire sciences, thermal modeling, and computing resources at SNL
- Develop multi-physics models to predict failure mechanisms and identify mitigation
- Build capabilities with small/medium scale measurements
- Still requires some testing and validation







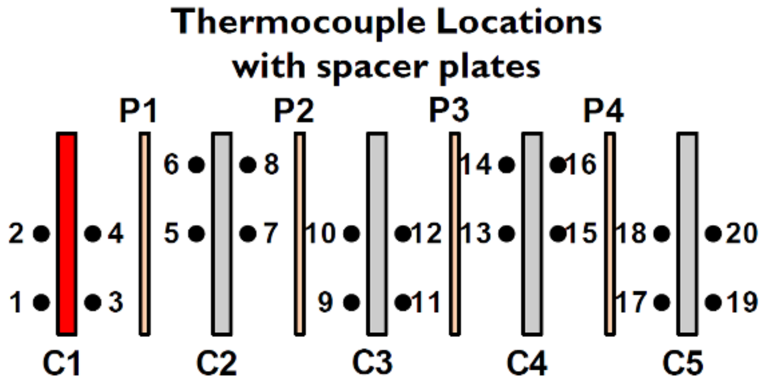
Simulated short circuit



Cell to Cell Propagation

Thermal runaway in one cell can drive nearby cells into thermal runaway depending on:

- **abuse thresholds,**
- **heat capacity,**
- **heat generation rate, and**
- **heat dissipation rate**



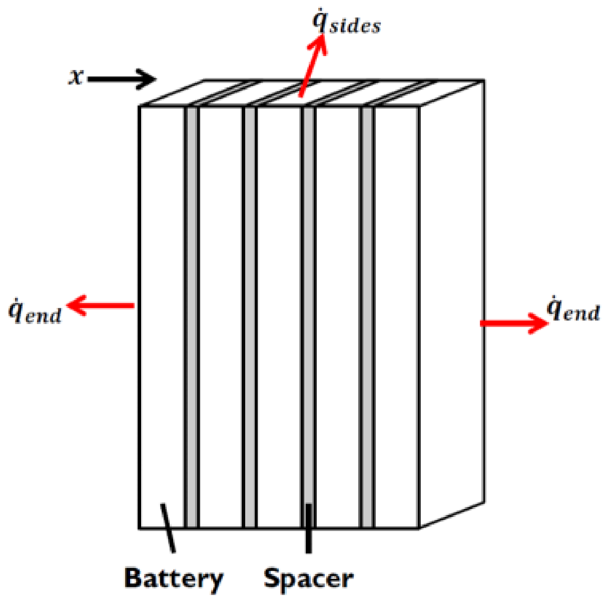
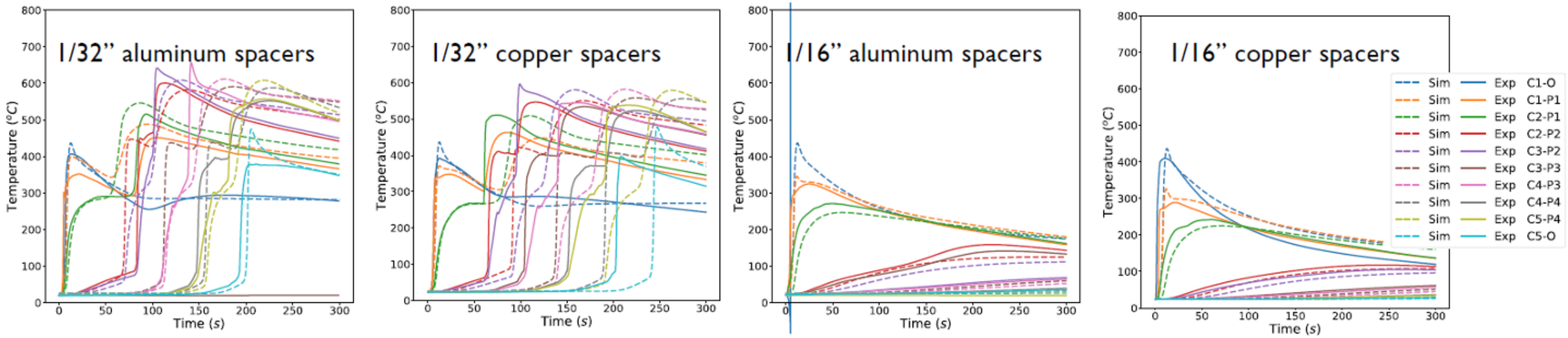


Figure Credit: John Hewson
https://www.sandia.gov/ess-ssl/wp-content/uploads/2021/ESSRF/Hewson_John.pdf

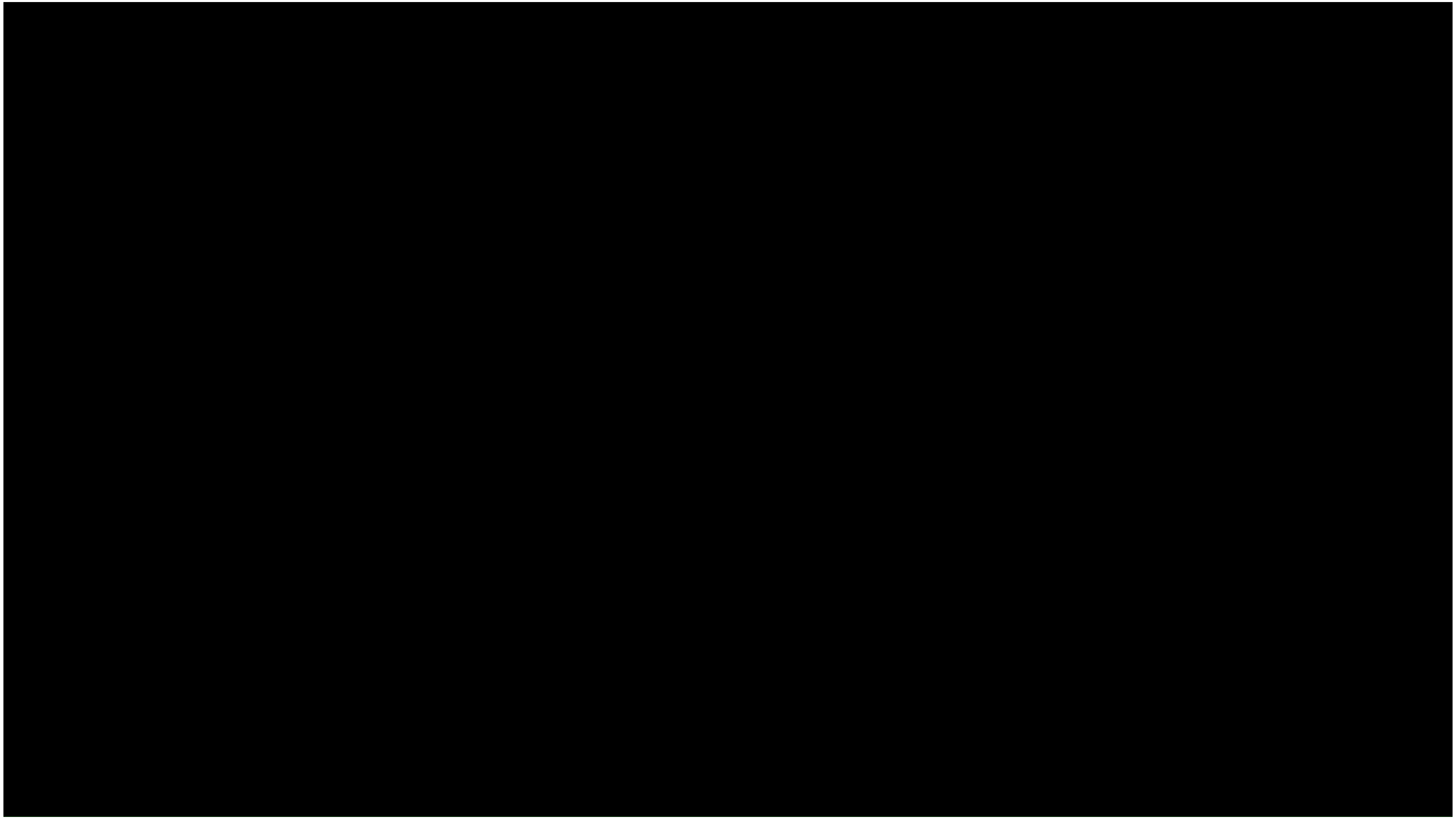
Model Based Testing

- Successful prediction over a range of reduced SOC and metallic inserts.
- Collectively add heat capacity & increase time delay for cell runaway.
- Prevent propagation for 30% increase in net heat capacity.



Kurzawski, A., et al. (2020). "Predicting cell-to-cell failure propagation and limits of propagation in lithium-ion cell stacks." Proc. Combust. Instit. 38.

An example of propagation testing



Different mitigation design strategies

Some of the design options available

- Prevent thermal runaway (e.g. non-lithium-ion chemistry)
- Limit the size (energy) of any one module
- Don’t put the battery in an enclosure
- Enclosure deflagration venting

Andrew F. Blum and R. Thomas Long Jr. “Hazard Assessment of Lithium Ion Battery Energy Storage Systems FINAL REPORT” Fire Protection Research Foundation, 2016, Available: https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Hazardous-materials/RFFireHazardAssessmentLithiumIonBattery.ashx

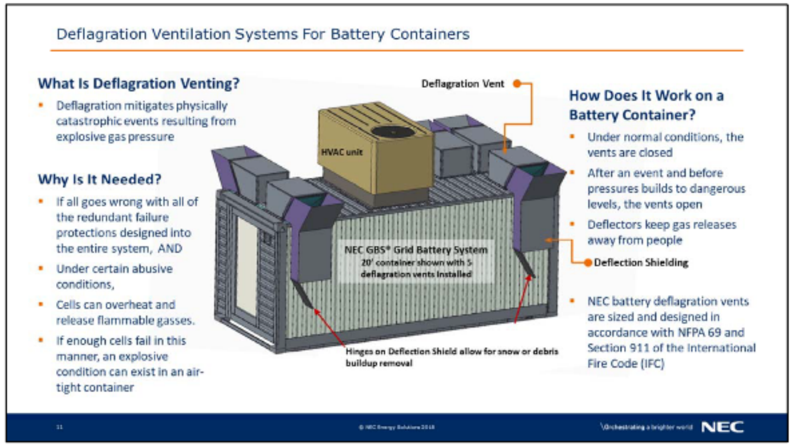
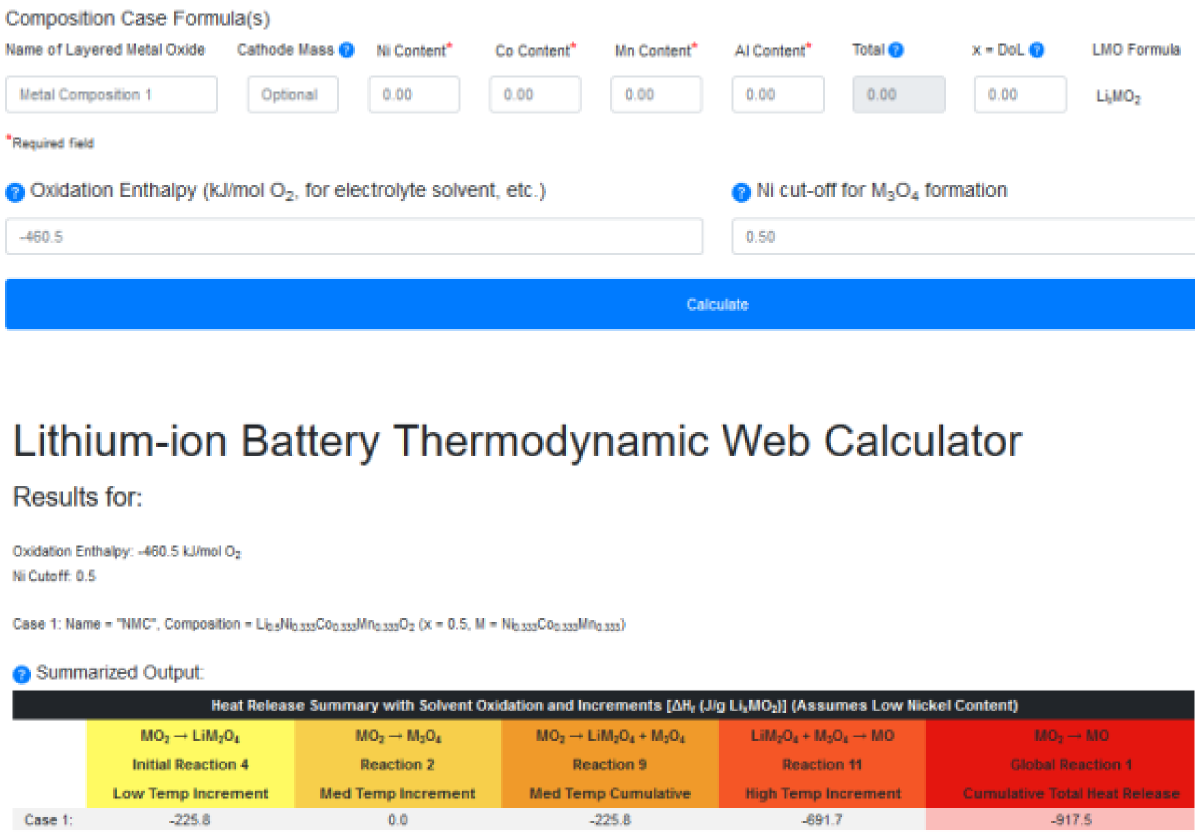


Figure source: https://share-ng.sandia.gov/ess/wp-content/uploads/2019/04/4a_Hoff_GSS-Safety-Overview-v15.6_MHOFF-with-Notes.pdf

Sharing battery safety tools with the community

Launched heat release calculator based on Li-ion battery materials composition



Composition Case Formula(s)

Name of Layered Metal Oxide	Cathode Mass	Ni Content*	Co Content*	Mn Content*	Al Content*	Total	x = DoL	LMO Formula
Metal Composition 1	Optional	0.00	0.00	0.00	0.00	0.00	0.00	Li_xMO_2

*Required field

Oxidation Enthalpy (kJ/mol O_2, for electrolyte solvent, etc.)

-460.5

Ni cut-off for M_3O_4 formation

0.50

Calculate

Lithium-ion Battery Thermodynamic Web Calculator

Results for:

Oxidation Enthalpy: -460.5 kJ/mol O_2

Ni Cutoff: 0.5

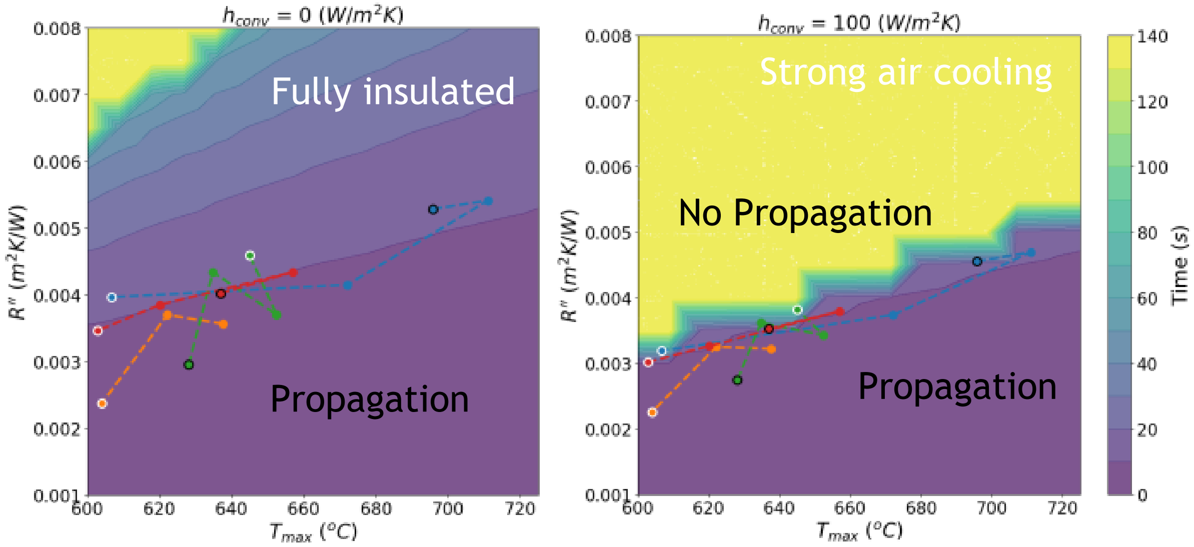
Case 1: Name = "NMC", Composition = $Li_{0.5}Ni_{0.333}Co_{0.333}Mn_{0.333}O_2$ (x = 0.5, M = $Ni_{0.333}Co_{0.333}Mn_{0.333}$)

Summarized Output:

Heat Release Summary with Solvent Oxidation and Increments [ΔH_r (J/g Li_xMO_2)] (Assumes Low Nickel Content)					
	$MO_2 \rightarrow LiM_2O_4$ Initial Reaction 4 Low Temp Increment	$MO_2 \rightarrow M_3O_4$ Reaction 2 Med Temp Increment	$MO_2 \rightarrow LiM_2O_4 + M_3O_4$ Reaction 9 Med Temp Cumulative	$LiM_2O_4 + M_3O_4 \rightarrow MO$ Reaction 11 High Temp Increment	$MO_2 \rightarrow MO$ Global Reaction 1 Cumulative Total Heat Release
Case 1:	-225.8	0.0	-225.8	-691.7	-917.5

Source: Randy Shurtz
https://www.sandia.gov/ess-ssl/thermodynamic-web-calculator/

Developing simulator of module-level thermal runaway propagation



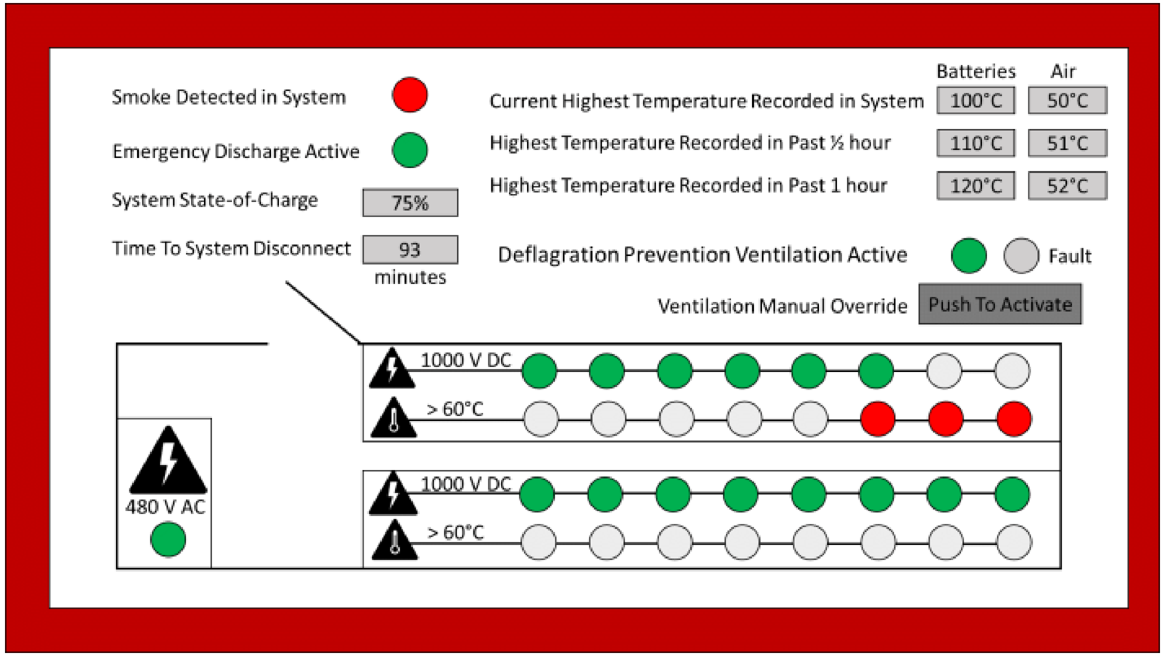
Source: Andrew Kurzawski

Safety critical information availability to firefighters

The system should include a durable, external display, accessible from a safe location, for firefighters to access the following information:

1. what percentage of the cells in the system have vented,
2. is the ventilation system working as expected,
3. what voltages are present in the system,
4. what the temperature trending history is internally,
5. what actions have been taken by the automated systems (e.g. fire suppression), and
6. the presence or absence of any gases in hazardous concentrations (including smoke).

Training should focus on hazard identification, determining safe entry, methods for limiting the spread of a battery fire, identifying when the best approach is to not put out the fire (letting hazardous stored energy be dissipated safely), and determining when it is safe to leave an incident site.



Example layout for an energy storage fire alarm control panel

From: https://www.sandia.gov/ess-ssl/wp-content/uploads/2020/09/Rosewater-

Ensuring Safety – Codes and Standards

Safety standards are developed through a consensus-based development process with diverse stakeholder participation.

Advantages:

- Broad agreement in the field
- Good at learning from past accidents

Disadvantages

- Slow to change (3-10 year revision schedules)
- Bad at preventing accidents before they happen

A few prominent examples are:

IFC – defines what safety standards shall be used in regions that have adopted it

UL 9540 – provides a hierarchy of safety standards for energy storage components, tests, and system integration

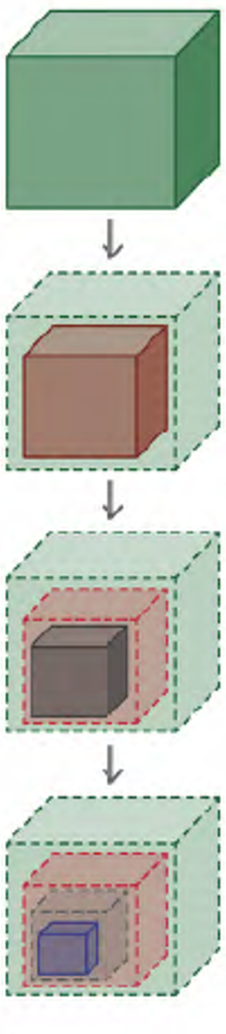
NFPA 855 – covers: installation, commissioning, O & M, emergency response, and decommissioning

Codes and Standards Update

Publication released quarterly

The following activities support that objective and realization of the goal:

1. Review and assess C/S which affect the design, installation, and operation of energy storage systems (ESS)
2. Identify gaps in knowledge that require research and analysis to provide data for technical committee inputs
3. Identify areas in C/S that are potentially in need of revision or enhancement and can benefit from activities conducted under research and development
4. Develop input for new or revisions to existing C/S through individual stakeholders, facilitated task forces, or through laboratory staff supporting these efforts



BUILT ENVIRONMENT

- iCodes – IFC, IRC, IBC
- IEEE – C2, SCC 18, SCC21
- NFPA 5000, NFPA 1, ISA

ENERGY STORAGE SYSTEMS

- UL 9540, MESA
- ASME TES-1, NECA
- NFPA 791

INSTALLATION / APPLICATION

- NFPA 855
- NFPA 70
- UL 9540 A
- IEEE C2
- IEEE 1635/ASHRAE 21
- IEEE P1578
- DNVGL GRIDSTOR
- FM GLOBAL 5-33
- NECA 416 & 416

SYSTEM COMPONENTS

- UL 1973
- UL 1974
- UL 810A
- UL1741
- CSA 22.2 No. 340-201
- IEEE 1547
- IEEE 1679 Series

Available: https://www.sandia.gov/energystoragesafety-ssl/

Acknowledgements

Funded by the U.S. Department of Energy, Office of Electricity, Energy Storage program. Dr. Imre Gyuk, Program Director.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia Battery Safety & Reliability Team

Loraine Torres-Castro, Jill Langendorf, Chris Grosso, Lucas Gray, Alex Bates — Abuse

Armando Fresquez, Reed Wittman — Testing

David Rosewater, Chris Searles — Codes & Systems

John Hewson, Andrew Kurzawski, Randy Shurtz — Thermal modeling

Software Development

Valerio De Angelis (SNL)

Early framework testers at CCNY: Sanjoy Banerjee, Jinchao Huang, Andreas Savva, Gautam Yadav

Front end: Sam Roberts-Baca (SNL)

Database: Mark Spoonamore (SNL)

Early site feedback: Matthieu Dubarry (HNEI)

Research Collaborations

Matt Paiss, Charlie Vartanian (PNNL)

Hsin Wang, Michael Starke (ORNL)

Abhishek Jaiswal (Arizona Public Service Electric)

Michael Hargather (New Mexico Tech)

National Institute of Technology and Evaluation, Japan

For questions about this presentation: jlamb@sandia.gov