INTEGRATED MODELING AND EXPERIMENTAL APPROACH FOR EVALUATING RISKS IN LARGE BESS

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PROJECT PROFILE

Topic: Safety & Reliability
Vertical: Safety & Reliability
Strategic Pathway: Stabilize
Integrated Modeling and Experimental Approach for Evaluating Risks in Large BESS
Project start and finish: FY25-FY26

PROBLEM

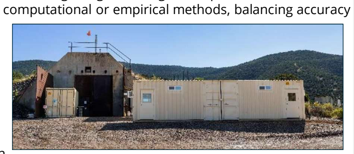
Background & Significance Large-scale Battery Energy Storage Systems (BESS) are essential for grid stability. Recent incidents (e.g., Moss Landing, McMicken) demonstrate severe risks from cascading thermal runaway failures and explosions.
Problem Statement Lack of accurate, validated models and experimental data to predict module-to-module propagation, explosion dynamics, and hazardous gases from battery fires. Thermal runaway involves complex, multi-scale multiphysics phenomena that are difficult to model and test.
Motivation & National Need Growing deployment of BESS increases urgency to improve safety and reliability. Enhancing public safety, infrastructure resilience, and regulatory compliance aligns with the DOE/OE strategic goal to "Catalyze onshore production and availability of critical grid components, such as high-voltage transformers, large-scale energy storage, and grid power electronics to reduce reliance on foreign suppliers."
Current Solutions & Limitations Existing models are often simplistic or computationally expensive, limiting practical use in system design. Empirical data is limited, restricting understanding of failure mechanisms and mitigation strategies. Very few large-scale tests have produced accessible data due to the proprietary restrictions of commercial designs.
Objectives Develop and validate high-fidelity and reduced-order ejecta and propagation models. Conduct large-scale experiments to generate critical data on failure propagation, explosion dynamics, and battery offgassing. Provide reliable predictive tools to support safer BESS design, standards development, and emergency response.
Main Milestone Successfully complete Large Scale Battery Abuse test!

H. Branson-Potts, Moss Landing *Los Angeles Times*, May 22, 2026.

APPROACH

Sandia National Laboratory's Open-Air Outdoor Pad & Pool Fire Capabilities

Methodology Overview This project combines high-fidelity modeling with large-scale experiments to study thermal runaway in Battery Energy Storage Systems (BESS). We develop first-principles ejecta models validated with experimental data and create reduced-order models for fast system-scale safety assessments. Multiphysics system-scale models simulate energy flow and failure propagation, validated against experiments and international data. Large-scale module-to-module explosion tests provide critical validation data. Hazardous gases and plume behavior are measured to inform safety guidelines.
Why This Approach Integrating modeling and experiments overcomes limits of purely computational or empirical methods, balancing accuracy and efficiency. This enables practical design exploration and a comprehensive understanding from cell-level ejecta to system-scale impacts.
Unique Lab Capabilities-Build on Previous Work Sandia's Battery Abuse Testing Lab supports safe, large-scale thermal runaway and explosion testing. Advanced modeling, precise instrumentation, and partnerships with international labs enable robust validation and gases analysis.



Sandia National Laboratory's Mobile Battery Abuse Testing Laboratory with sensor technology for gas, temperature, voltage and in-situ gas analysis with FTIR and process Mass Spectroscopy instrumentation

Sandia National Laboratory's Battery Testing at the Burnsite Igloo—54ft deep X 24ft wide X ~14ft high

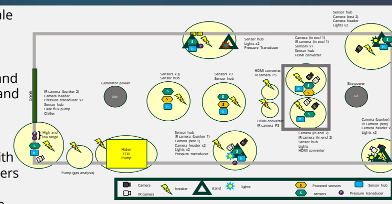
Large-Scale Experimental Testing Our Battery Abuse Testing Laboratory at Sandia (shown on the left) is equipped to safely conduct large-scale module-to-module propagation and explosion dynamics tests. This project's experimental setup includes multiple battery modules arranged within a 24-inch polycarbonate enclosure, instrumented with high-precision pressure sensors, thermal imaging cameras, and gas analyzers. Controlled overcharge and other abuse conditions are applied to initiate thermal runaway in a single cell, allowing observation of propagation dynamics, pressure wave behavior, and explosion risks. These experiments generate critical datasets for model validation and safety standards development.

Hazardous Gases and Plume Evolution Assessment We measure the types, concentrations, and temporal evolution of hazardous gases released during thermal runaway events, including toxic gases such as hydrogen fluoride (HF) and carbon monoxide (CO). Plume dispersion is characterized under varying ventilation and environmental conditions to inform safety buffer zones and environmental compliance. This task supports the development of guidelines for battery fire gas management and enhances public health protections.

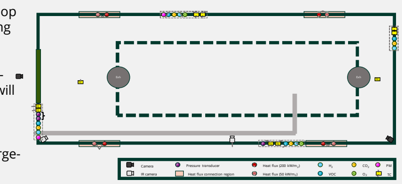
314Wh LFP CATL Prismatic Cell

RESULTS

Experimental Test Setup Designed a large-scale module-to-module propagation and explosion dynamics test rig replicating real-world BESS failure scenarios. Instrumented with high-precision pressure sensors, thermal cameras, and gas analyzers to capture detailed propagation and off-gassing data. Safety protocols and environmental controls established to enable repeatable, controlled testing.
Modeling Collaboration Close coordination with modeling teams to align experimental parameters with simulation inputs, ensuring relevant and comparable data. Preliminary simulations guide test design by identifying critical conditions and parameters to investigate. Iterative feedback loop established to refine models based on upcoming experimental observations.
Anticipated Outcomes Experimental data will validate and calibrate high-fidelity and reduced-order ejecta and propagation models. Results will improve understanding of pressure wave dynamics, failure propagation, and hazardous gases. Data will support development of safety guidelines and design recommendations for large-scale BESS.

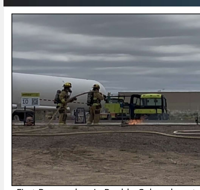


Experimental Set-up and Surrounding Area Test Power Needs



Experimental Test and Surrounding Area Sensor Set-up

CONCLUSIONS & IMPACT



First Responders in Pueblo Colorado put out a Lithium-Ion Battery Fire

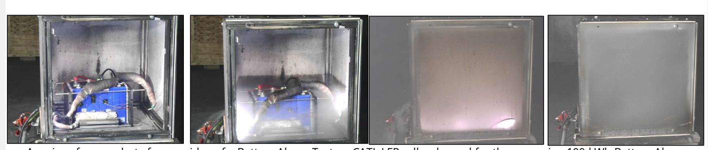
The development of a robust test platform and close integration with modeling efforts position this project to deliver critical, validated data on thermal runaway propagation, explosion dynamics, and hazardous gases in large BESS. Success will provide system designers, regulators, and first responders with reliable tools and data to improve safety protocols, design criteria, and emergency response strategies. Near-term impacts include the establishment of standardized testing methods and validated models that reduce uncertainty in risk assessments. Long-term, this work supports wider adoption of energy storage technologies by enhancing public safety and regulatory confidence, potentially accelerating deployment. Benefits include improved predictive accuracy of failure propagation models by up to 30%, faster design iteration cycles enabled by reduced-order models, and data-driven guidelines that can inform codes and standards development. This project advances grid resilience and contributes to safer, more reliable energy infrastructure.

Some of the Thermocouples that have been assembled for the 100kWh test

Burnsite Igloo Test Set-up with 100kWh Batteries inside modules, inside racks, inside the battery energy storage system test enclosure

FUTURE DIRECTIONS

For the remainder of the project, we will execute the planned large-scale module-to-module propagation and dynamics tests, collecting detailed data on pressure waves, thermal behavior, and hazardous gases. This experimental data will be used to validate and refine our high-fidelity and reduced-order models, ensuring their accuracy and reliability for system-scale safety assessments. We will also continue close collaboration between experimental and modeling teams to iteratively improve test designs and simulation fidelity. Looking ahead, this research will expand to include additional battery chemistries and configurations, enabling broader applicability of the models and safety guidelines. We aim to develop real-time monitoring and predictive tools based on validated models to support early failure detection and emergency response. We plan to disseminate this research to inform the development of effective codes and safety protocols for construction and response to battery energy storage system disasters.



A series of screenshots from a video of a Battery Abuse Test on CATL LFP cells, planned for the upcoming 100 kWh Battery Abuse Test. The cells were overcharged until the initiating cell underwent thermal runaway. The first screenshot (left) shows the cells before overcharging, all at 100% state of charge. The middle-left screenshot, at about 30 minutes, shows explosive vapor filling the enclosure with laminar flow vapor exiting on the left. The middle-right screenshot, at 58 minutes 15 seconds, captures thermal runaway with vapor, smoke, and electrolyte filling the 24-inch polycarbonate test cube. The final screenshot (right) shows the aftermath.

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