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Physical and chemical analysis of lithium-ion battery cell-to-cell failure events inside custom fire chamber

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HIGHLIGHTS

- A 5-m^3 decompression chamber was re-purposed into a fire test chamber.
- Single- and multi-cell lithium-ion batteries were abused to the point of failure.
- Failure events were studied via optical, infrared, chemical, and thermal means.
- Surrogate 18650 cells were constructed and tested in multi-cell packages.
- Gas analysis was performed, along with temperature and heat flux measurements.

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ABSTRACT

A 5-cubic meter decompression chamber was re-purposed as a fire test chamber to conduct failure and abuse experiments on lithium-ion batteries. Various modifications were performed to enable remote control and monitoring of chamber functions, along with collection of data from instrumentation during tests including high speed and infrared cameras, a Fourier transform infrared spectrometer, real-time gas analyzers, and compact reconfigurable input and output devices. Single- and multi-cell packages of $LiCoO_2$ chemistry 18650 lithium-ion batteries were constructed and data was obtained and analyzed for abuse and failure tests. Surrogate 18650 cells were designed and fabricated for multi-cell packages that mimicked the thermal behavior of real cells without using any active components, enabling internal temperature monitoring of cells adjacent to the active cell undergoing failure. Heat propagation and video recordings before, during, and after energetic failure events revealed a high degree of heterogeneity; some batteries exhibited short burst of sparks while others experienced a longer, sustained flame during failure. Carbon monoxide, carbon dioxide, methane, dimethyl carbonate, and ethylene carbonate were detected via gas analysis, and the presence of these species was consistent throughout all failure events. These results highlight the inherent danger in large format lithium-ion battery packs with regards to cell-to-cell failure, and illustrate the need for effective safety features.

1. Introduction

A key capability gap in assuring safe use of lithium-ion batteries is adequately protecting against the full range of impacts and consequences on neighboring cells in a large battery pack as one cell undergoes failure. While models do exist for commercial and Department of Energy (DOE) applications such as automotive batteries [1–4], their use of experimental data to capture the impact on nearby cells of high temperatures, gas venting, fire, and shrapnel due to cell failure as related to military and shipboard applications has been limited. A predictive capability is needed to accurately determine a maximum credible event (MCE) for battery behavior and to extrapolate cell behavior to full scale battery systems used on military platforms, which will ultimately reduce cost in testing

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and certification.

Higher-level models that predict different aspects of platform impact, e.g. fire spread [5] and structural damage [6], will need modifications (i.e. additional modules) to describe and predict the consequences of catastrophic lithium-ion battery failure effects. These required modifications should be possible with upgrades that enable a more accurate description of battery casualty and can be directly fed into models. Conversely, lower-level thermo-electrochemical models and studies exist for describing the internal condition inside a single cell [7–10]. These models describing the internal chemistry and microstructure of individual cells have provided valuable insights into the sources of cell failure, but fail to extend to multiple cells. Thus, there is a knowledge gap between single cell and large format lithium-ion battery failure.

Reports of detailed testing to measure the impact of a single cell failure on nearby cells for military applications have been limited [11,12]. Because there are several different ways in which the failure of a single cell may spread to neighboring cells, a number of parameters must be measured to adequately document what conditions cause failure to spread. Therefore, it is necessary to develop a scientific and experimental infrastructure to investigate cell-to-cell failure propagation in lithium-ion batteries and provide robust experimental data for computational models. In this study, an environmental fire test chamber, outfitted with various instrumentation for remote video monitoring and data acquisition, was used to conduct lithium-ion battery failure tests for both single- and multi-cell packages. Physical and chemical analyses were performed in conjunction with recorded videos from both high speed and infrared cameras to characterize and evaluate failure events, and the data collected is intended for future use in predictive thermo-electrochemical models for lithium-ion battery failure.

Table 1
Detectable gases and concentration ranges monitored by the two ZRE real-time gas analyzers (Low Range and High Range).

Gas	Molecular formula	Low range ZRE	High range ZRE
Carbon dioxide	CO_2	0–5%	N/A
Carbon monoxide	CO	0–200 ppm	0–1000 ppm
Sulfur dioxide	SO_2	0–500 ppm	0–1000 ppm
Oxygen	O_2	0–25% (paramagnetic)	0–25% (fuel cell)
Methane	CH_4	N/A	0–500 ppm

2. Experimental

The US Naval Research Laboratory (NRL) has a 5-m^3 (177 ft^3) two-man decompression chamber that has been re-purposed as an environmental fire test chamber located at the Chesapeake Bay Detachment (CBD) facility in Chesapeake Beach, Maryland, and Fig. 1 shows an image along with diagrams of the chamber after its conversion and re-purposing. Numerous custom modifications were carried out to enable the study of lithium-ion battery cell-to-cell failure propagation. Bulkheads along the sides of the chamber (Fig. 1B) were tailored for input/output of both communication signals and physical gases to accommodate the use of various analytical instruments. In previous experiments, gas sampling canisters and sorbent tubes have also been used within the chamber to test for the presence of various acids and other hazardous chemicals [11]. Two reconfigurable embedded control and acquisition systems (CompactRIOs, cRIO-9014/cRIO-9025, National Instruments) were implemented to remotely control and monitor chamber functions (lights, power switches, exhaust fan, mixing fan and vent valve), as well as collect temperature data from K-type thermocouples (Omega). Data was acquired via a gigabit-enabled local area network (Gig-E LAN) and remote functions were controlled and programmed using LabVIEW (National Instruments).

Two cameras, one high speed (HS) and one infrared (IR), were placed inside the chamber for video analysis of battery failure events. Both cameras were connected directly to the remote desktop computer using 150-ft Cat6 Ethernet cables to provide high fidelity connections and prevent packet loss issues (dropped frames) that could arise from shared communication over the Gig-E LAN. The cameras were also placed inside separate metal enclosures to protect against potentially harmful fluids expelled during battery failure. The HS camera (HiSpec1, Fastec Imaging) enclosure was fitted with a transparent soda lime glass window to allow video imaging, and the camera was equipped with a 28 mm zoom lens (Nikkor f/2.8D, Nikon). The IR camera (A300, FLIR Systems) enclosure was affixed with a 2 mm-thick ZnSe window (Edmund Optics) which is transparent to IR light. Both enclosures with cameras inside were mounted on lab jacks and adjusted to focus on

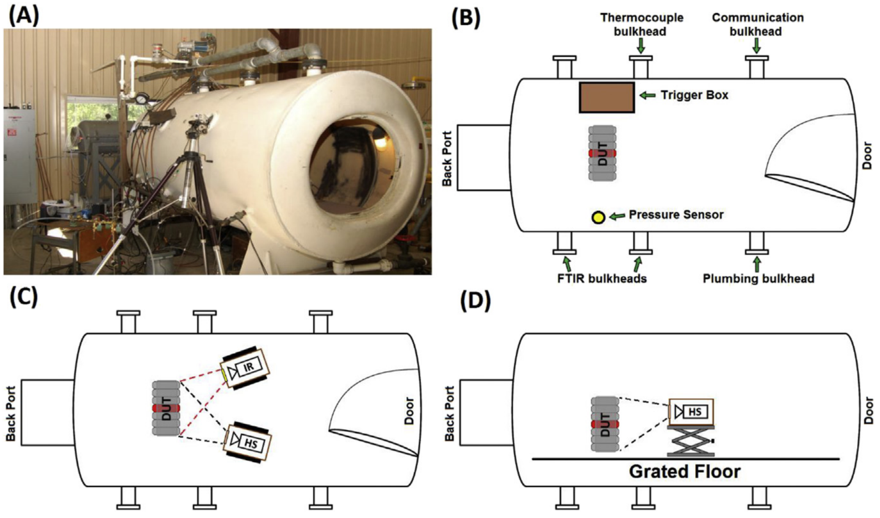

Fig. 1. (A) Photograph of two-man decompression chamber re-purposed as an environmental fire test chamber; (B) top view diagram of chamber indicating locations and functions of bulkheads, back and front ports, pressure sensor, trigger box, and device under test (DUT); (C) top view and (D) side view diagrams showing relative locations of high speed (HS) and infrared (IR) cameras during tests.