NASA Engineering and Safety Center-supported Battery Study

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In the past 2 years, we performed extensive studies to understand the limitations of the protective devices internal to 18650 lithium-ion (Li-ion) cells. Cylindrical 18650 Li-ion cells, especially those with the cobaltate cathode, are equipped with a positive temperature coefficient (PTC) and a current interrupt device (CID). Testing of multi-cell battery configurations indicates that these devices do not always provide protection when cells are in series and/or parallel configurations. A comprehensive test program carried out by the NASA team showed that the PTCs have voltage limitations and spontaneously ignite when activated under high-voltage conditions. Although the CID devices do not cause this failure, they do not protect against it when the internal reaction is too rapid, especially when it involves the evolution of oxygen (at high voltages) and activation of the PTC at the same time.

Introduction

Lithium-ion commercial off-the-shelf (COTS) cells have been tested at Johnson Space Center to determine state-of-the-art characteristics with respect to both performance and safety. We tested these cells as a subset of the flight battery certification processes as well as stand-alone cells obtained from cell manufacturers. The COTS Li-ion cells of the cylindrical type (e.g., the 18650s) have internal protective devices such as the PTC and the CID.

These internal protective devices have been extremely reliable at a single-cell level, preventing the cell from reaching a hazardous condition 100% of the time. However, test programs in the past 5 years have indicated that batteries built with cylindrical COTS cells in multi-cell configurations (i.e., series and/or parallel) have experienced thermal runaway under various test conditions. Analysis of test data indicated the two major causes for thermal runaway are overvoltage and external short conditions. Further investigation on series cell strings confirmed the existence of this problem. We observed that the internal protective devices were either not protecting as expected or were themselves causing the hazards that we encountered. Confirmed evidence exists of PTC ignition above its withstanding (i.e., threshold) voltage, but overcharge catastrophes are not well understood. Hence, we initiated this study to understand the causes for thermal runaway in high-voltage and high-capacity battery modules, and to determine the limitations of the cell internal protective devices.

Experimental

Tests carried out on single cells, four-cell series strings, four-cell parallel banks, 14-cell series strings, and 16-cell parallel banks included: single-cell PTC-withstanding voltage tests, CID tests on cell header assemblies and single cells, research for a suitable diode, and tests on various lengths and sizes of cell strings and banks. A last set of tests included testing cells in parallel configurations under external short-circuit and overcharge conditions. We performed these tests with Sony® 18650 cells of 1.5 Ah capacity. A summary of the tests is provided in Table 1. The cells were, at first, removed from the Canon camcorder batteries. Initial tests indicated that the cells had been compromised during their removal from the packs, however, and that the results were more catastrophic in nature. After these observations, we used fresh single cells for the tests. For the cell combinations, we varied the limits to determine the tolerance and limitations of the protective devices. All string and bank configurations had the cells arranged in a single-row (i.e., fence-post) type and laid flat. The tests were all off-nominal to determine the limitations of these internal devices, and the Sony cells removed from the Canon camcorder batteries were purely used as a test vehicle.

Description	Volts	Amps	Load (Ohm)
Single-cell overcharge	12	1.5	
4P overcharge, 48V, 6A	48	6	
4P overcharge, 12V, 6A	12	6	
4P overcharge, 12V, 4A	12	4	
16P overcharge, 48V, 24A	48	24	
16P overcharge, 12V, 24A	12	24	
16P overcharge, 12V, 12A	12	12	
Single-cell external shorts			50
16P external short			2

Table 1. *Summary of tests.*

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Summary of results and conclusions

The test program provided valuable results on the limitations of both the PTCs and the CIDs that are internal to small cylindrical Li-ion cells. Tripping cell PTCs irreversibly increases their electrical resistance by as much as a factor of 2. Compromised or high-resistance PTCs cause catastrophic failures under overcharge conditions. The CID either did not protect or underwent incomplete opening and reset under overcharge conditions when the current and/or voltage limit values (i.e., 48V and 6A for a bank of four cells, or 48V and 24A for a bank of 16 cells) caused uncontrollable heating or PTC ignition (figures 1 and 2).

Fig. 2. *Cell 4 after the 4P overcharge test with 6A and 48V limit.*

We are making the following recommendations to provide guidance in designing the battery modules that use these cells in high-voltage and high-capacity configurations: (a) The PTC that is withstanding the voltage and trip current should be determined for the cell to be used in the battery design, by testing, as cells from different manufacturers will have different PTC ratings and this information is not provided in a cell specification. (b) Cell screening for the battery build for engineering, qualification, and flight-testing should not cause inadvertent activation of the PTC. (c) The CID activation and protection from overcharge catastrophes should be confirmed by test in the actual flight battery configuration, if the CID is used as a level-of-safety control. (d) These tests should be run at the module size for which the CID is being used as a safety control.

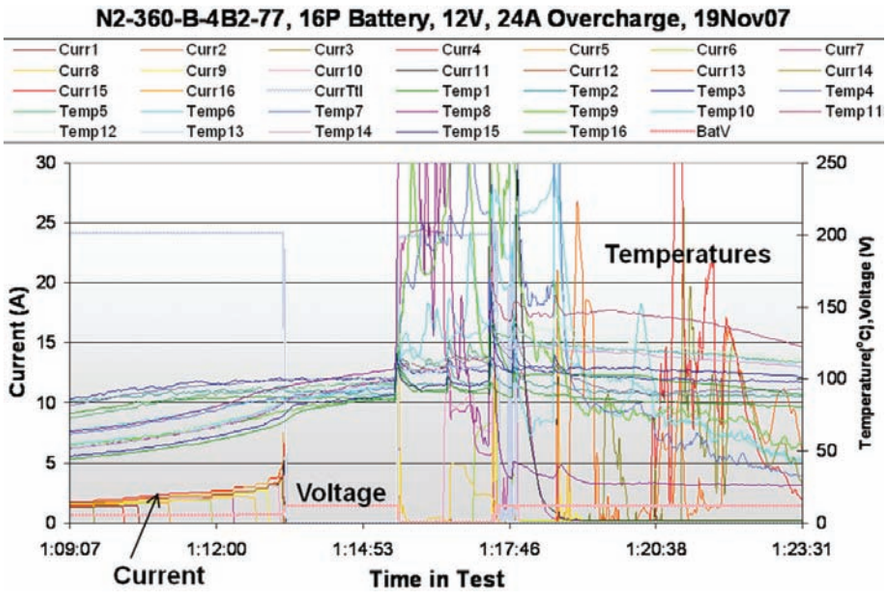

Fig. 1. *Overcharge test on 4P bank of Sony® Li-ion cells using 6A current with a 48V limit.*

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