Detecting Lithium-Ion Cell Internal Faults In Real Time

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Li-ion cell thermal-runaway failures can occur due to poor cell or battery-pack design (electrochemical or mechanical), manufacturing flaws, external abuse, and poor charger or system design. Fortunately, a procedure for detecting future failures shows promise.
Internal cell faults continue to lead to thermal runaway failures in Li-ion battery packs used in the field. Though these events are rare, the proliferation of Li-ion-powered consumer electronics has increased the risk for an event occurring on an aircraft, or at a similarly inauspicious location or time.

The average business traveler may be carrying anywhere from two to five Li-ion-battery packs (notebook pack, spare notebook pack, phone battery, camera battery, MP3 player battery, etc.) each time he or she travels. Since battery packs for notebook computers usually contain six to 12 higher-capacity cells (2,000 to 3,000 mAh each), the result of an event in a notebook pack is potentially more severe than an event with a single cell-phone battery pack.

After three incidents in the summer of 2009 involving fires or smoldering of packages containing Li-ion batteries in aircraft cargo holds, the Air Line Pilots Association (ALPA) has called for a ban on bulk shipments of lithium batteries — and products containing those batteries — from passenger and cargo planes.

“The evidence of a clear and present danger is mounting,” states an August 25, 2009 press release distributed by ALPA. “We need an immediate ban on these dangerous goods to protect airline passengers, crews, and cargo…ALPA calls on the agencies charged with protecting the public from hazardous materials to issue an immediate ban on lithium battery shipments to protect airline passengers, crews and cargo until the proper safety regulations are in place and can be enforced.”

The rate of notebook computer recalls due to Li-ion battery faults has apparently decreased since 2007, however they do continue to occur. For example, in May of 2009, a major notebook PC OEM announced a recall of 70,000 notebook computer battery packs.

CURRENT ATTEMPTS TO THWART CELL THERMAL RUNAWAY

Cell thermal runaway failures can occur for a number of reasons, including poor cell design (electrochemical or mechanical), cell manufacturing flaws, external abuse of cells (thermal, mechanical, or electrical), poor battery-pack design or manufacture, poor protection design, and poor charger or system design. The IEEE 1625 and 1725 standards committees have recently focused on conveying the concept that Li-ion battery pack safety is a function of the entirety of the cell, pack, system design, and manufacture. Each of the above aspects has a role to play in ensuring pack safety.

For notebook computers with mature pack and protection designs, Exponent has observed that the most common causes of field failures are internal cell faults that are directly related to cell design flaws, cell manufacturing flaws, or user abuse. For example, we have observed cell thermal runaway failures resulting from internal cell faults caused by contamination (either by materials foreign to the battery or loose pieces of battery material itself), manufacturing-induced electrode damage (scratches, punctures, tears, active material displacement), burrs on electrode tabs, weld spatter from cell lead attachment points, wrinkles or kinks in windings or tabs, electrode misalignment, poorly aging electrodes, post-manufacturing mechanical damage to cells, and cell thermal abuse.

Cell manufacturers continue to work toward designing safer cells, through modifications of cell components (e.g. changes in the cell separator, cell chemistry, etc.), and through improvements in manufacturing practices (e.g. eliminating contaminants, improving the uniformity of processing, etc.). The industry as a whole has also spent considerable effort in developing a collection of standards for improving the safety of Li-ion cells and battery packs (most recently the IEEE and BAJ efforts).

However, even the most respected cell manufacturers' cells have suffered field incidents. In addition, there are a number of new battery manufacturers whose technology and manufacturing approaches are not as advanced or mature as those of traditional suppliers. With the ever-increasing demand for Li-ion cells, these newer manufacturers' cells are increasingly entering the U.S. market in a variety of consumer electronic devices.

Individual cell manufacturers are arguably in the best position to make cell-design and process improvements in their own manufacturing lines to improve cell safety. However, we believe that a system-level approach to detect incipient failures with battery-pack electronics has the potential for reducing the rates of thermal runaway failures and thus could represent a significant contribution to battery safety.

Commercially available notebook battery packs have redundant-protection devices in place to prevent cell overcharging and other potentially damaging or unsafe conditions (charging at high temperatures, charging at high rate when cell voltage is low, etc.). These devices work by monitoring pack voltage, block voltage, current, and temperature in one or more locations within the battery pack.

DETECTING THERMAL RUNAWAY BEFORE IT HAPPENS

At present there is no pack-protection circuitry in commercial use that is designed to continuously monitor the cells for the symptoms of a latent incipient internal cell fault before such a fault causes thermal runaway. Until recently, the ability to detect incipient faults sufficiently early enough to prevent cell thermal runaway has been considered impossible or, at best, impractical. This is most likely a result of the difficulty in simulating faults similar to those that happen in the field, as well as the cell cycling regimes used during simulations.

However, our failure analysis studies, testing associated with our various failure analysis efforts, and testing conducted as a part of the work done for the Mobile PC Extended Battery Life Working Group (EBLWG) — an industry group that facilitates cooperation between cell, notebook, and protection electronics manufacturers — indicates that there are a number of early failure symptoms that might be effectively exploited to identify packs that are likely to suffer thermal runaway failures if left unmitigated. Such symptoms include:

- Excessive block (cell) voltage drop during extended rest periods, indicating high self-discharge rates consistent with micro-shorting (typical cycling programs used for testing to date do not include extended rest periods between charge and discharge steps, although these are common in actual usage of battery packs)
- Long taper-current charging times consistent with dissipation of charge current in a micro-short
- Noisy voltage profiles during charging and discharging (indicating the formation of transient micro-shorts)
- Cell heating during cell charging, particularly near the end of charging
- Charge capacity higher than discharge capacity beyond the typical charge efficiency losses
- Cell-charge/discharge inefficiency change

Exhaustive exploration of detection approaches for a wide variety of internal faults would require significant collaboration with battery manufacturers to produce cells with known faults (e.g. specific contaminants in pre-determined locations). However, in a project sponsored by the Mobile PC Extended Battery Life Working Group, Exponent has accomplished some preliminary rounds of testing that have proved productive.

ANALYZING THE TESTS

In the first round of tests, commercially available Li-ion cells were obtained and faults within the cells were induced through repeated cell overdischarge to induce copper dissolution and subsequent plating. Also, high-rate charging with slight overcharge was used to induce mild lithium plating. As a result, cells either did not develop faults, or failed by triggering designed safety features (charge interrupt devices), before developing an internal flaw that could be monitored over extended cycles.

AN ALTERNATE APPROACH

An alternate approach that involved the use of coin cells, provided the best data. In this approach, a coin cell and a commercially available prismatic cell were connected in parallel.

The coin cell was fabricated with a deliberately induced flaw (contaminant, slit separator, bare region of copper, etc.) using material harvested from a commercial prismatic cell identical to those used in testing. Since the coin cell was made of the same active components as the commercial prismatic cells and was of negligible capacity, the coin cell, once placed in parallel with a prismatic cell test sample, was recognized as part of the prismatic cell from an external electronics monitoring perspective (*Fig. 1*).

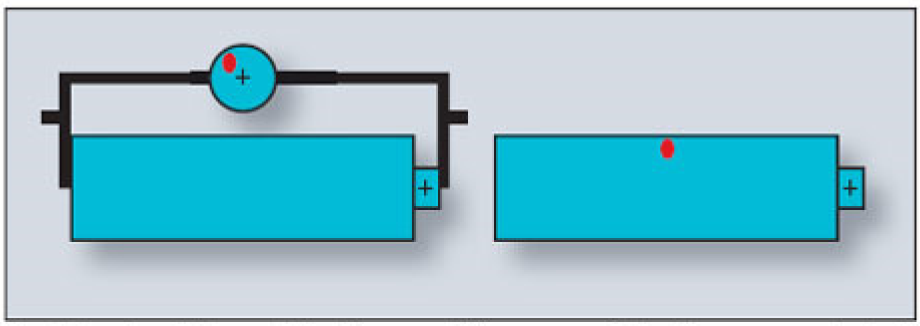

Fig. 1. A coin cell in parallel with a complete commercial cell appears equivalent to a slightly larger single commercial cell.

Since the prismatic cell used in this testing was undamaged, it accurately simulated the bulk of a micro-shorting cell's electrode. The coin cell simulated a relatively isolated region of micro-shorting. For a fault in the coin cell to be detectable, it had to be sufficiently active to affect the voltage or current draw of the normal full cell.

Any detectable abnormalities in the voltage or current measurements in the coin-cell / prismatic cell pair could be directly attributable to the fault in the coin cell alone. In comparison, variations in the signals produced in the overdischarge or high-rate charging tests might be the result of both large-scale electrode degradation as well as individual faults.

Coin-cell/prismatic-cell combinations were cycled prior to fault initiation, and their behavior was compared to that of a full cell cycling alone. The two systems were effectively indistinguishable. Faults were activated in the coin cells by compressing these cells. Cell voltages would often drop at the time of compression consistent with shorting, and then recover when the external stress was removed from the coin cell.

Thermocouples placed on the coin cells would register heat releases sufficient to quickly raise the cell temperature by several degrees after fault activation (in some cases more than 20 hours after the fault activation). In the interim, the cell exhibited measurable behaviors indicating an incipient fault such as:

- Elevated self-discharge rate observed during rest periods
- Extended taper-current times
- Charge capacity higher than discharge capacity

[Fig. 2](#), [Fig. 3](#), [Fig. 4](#), [Fig. 5](#), and [Fig. 6](#) show the results from one of the coin-cell tests. In this test, the heat release occurred approximately 23 hours after the fault was activated by compression of the coin cell (denoted as short-induced in the figures). Prior to the heat release, the cell exhibited enhanced self-discharge rates that manifested as voltage drops during post charge and post discharge rest periods, increased taper-current times, and diverging charge vs. discharge capacities.

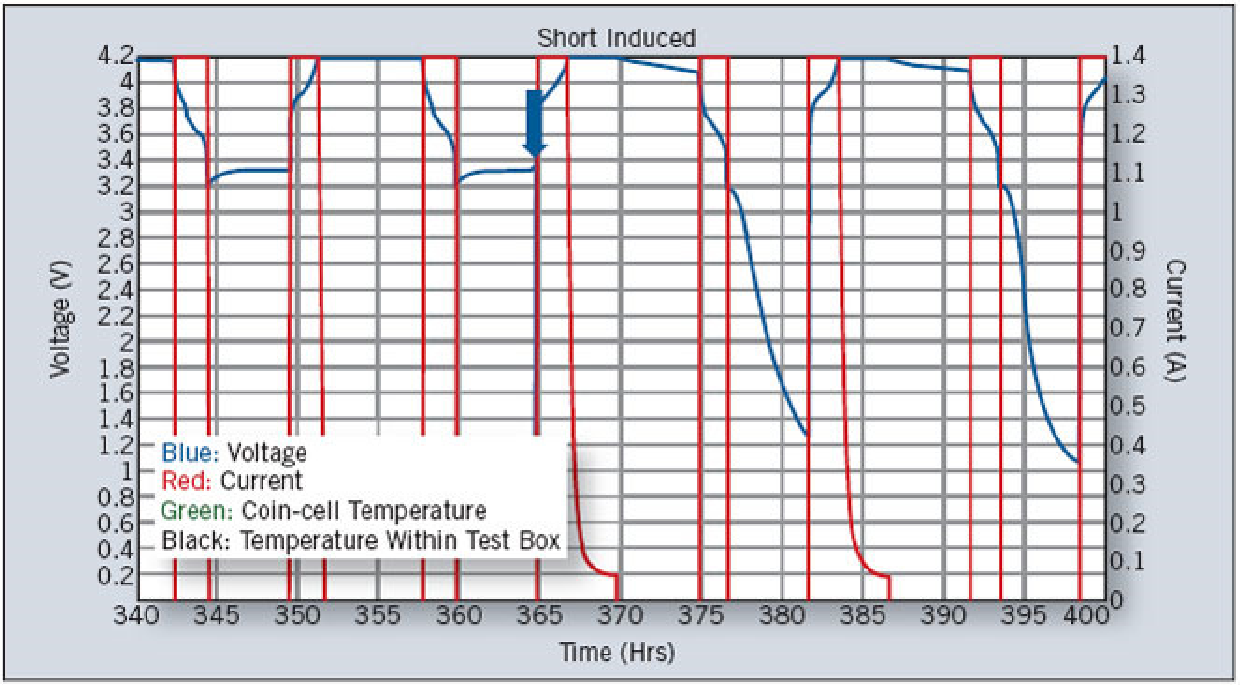

Fig. 2. Voltage and current traces of a full-cell/coin-cell combination before and after a short has been activated (short induced).

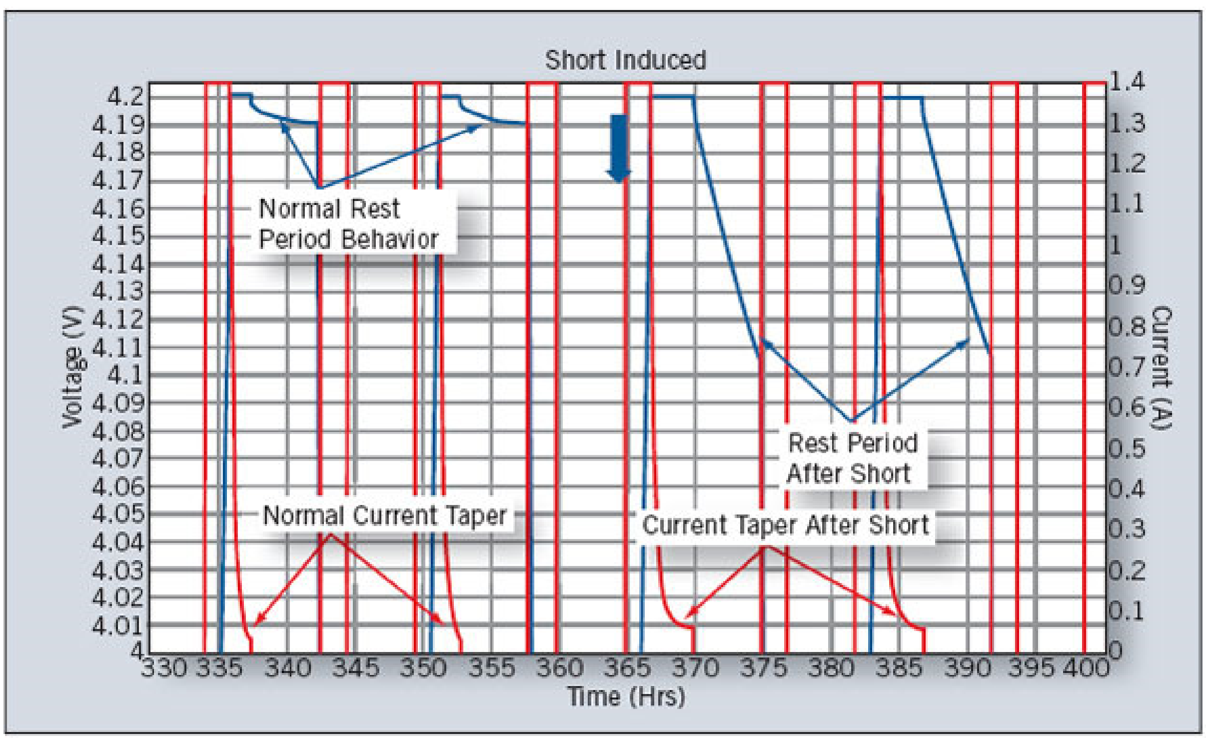

Fig. 3. Detailed view of the high-voltage behavior of the full-cell/coin-cell combination, showing the effect of an enhanced self-discharge rate caused by short activation on a fully charged cell resting voltage and taper-current periods.

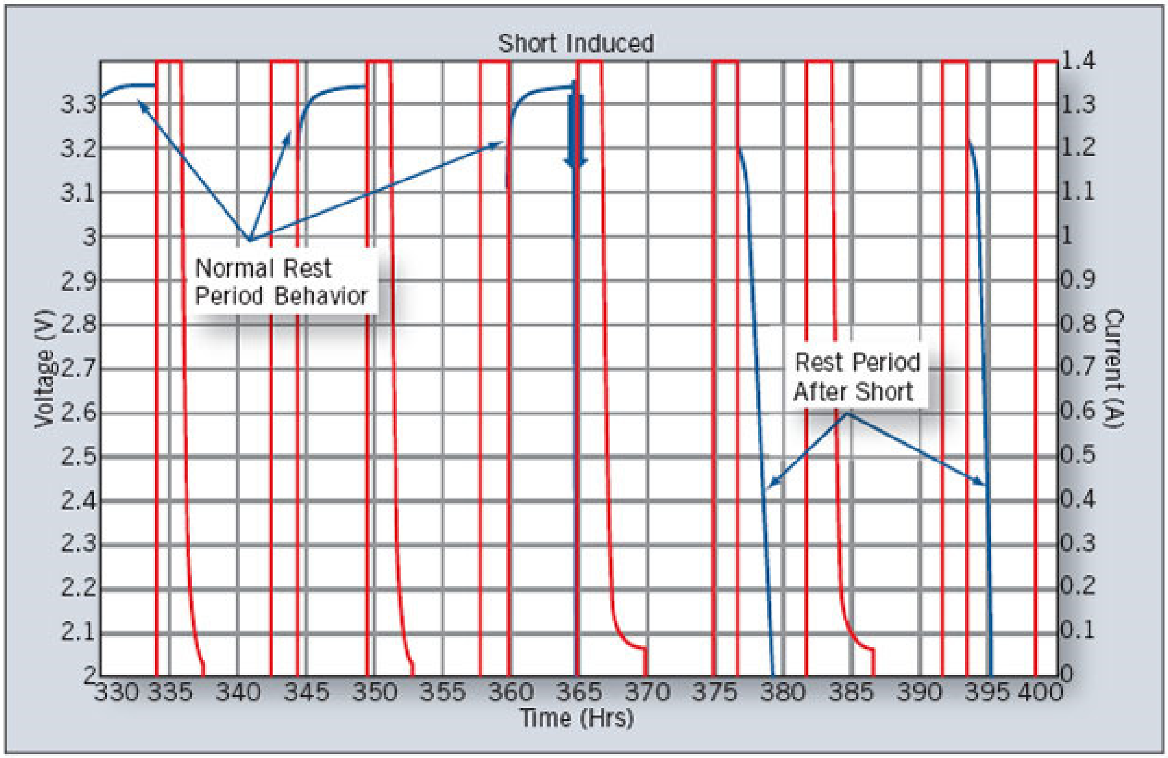

Fig. 4. Detailed view of the low-voltage behavior of the fuel-cell/coin-cell combination showing the effect of an enhanced self-discharge rate caused by short activation on discharged cell resting voltage.

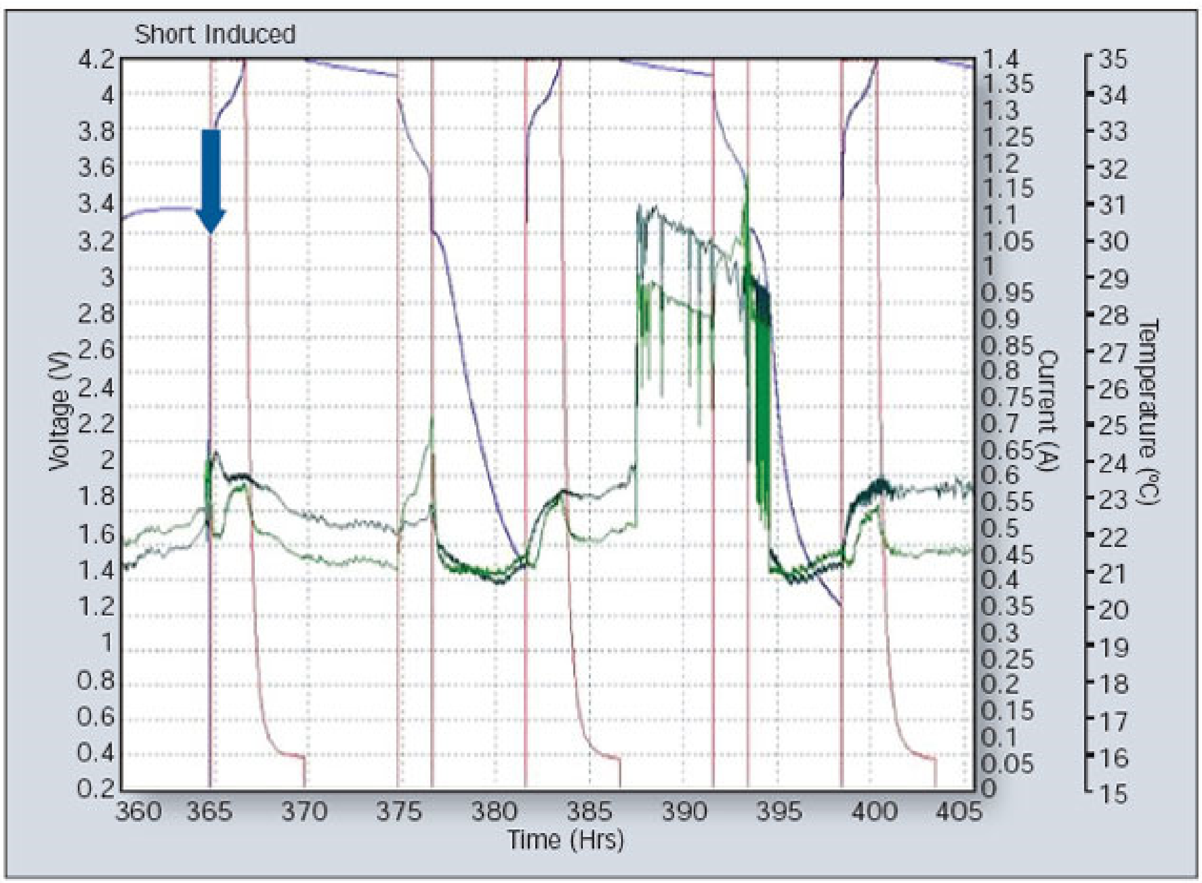

Fig. 5. Coin-cell temperature evolution after short activation; heat release occurs more than 20 hours after short activation, during a charged-cell rest period.

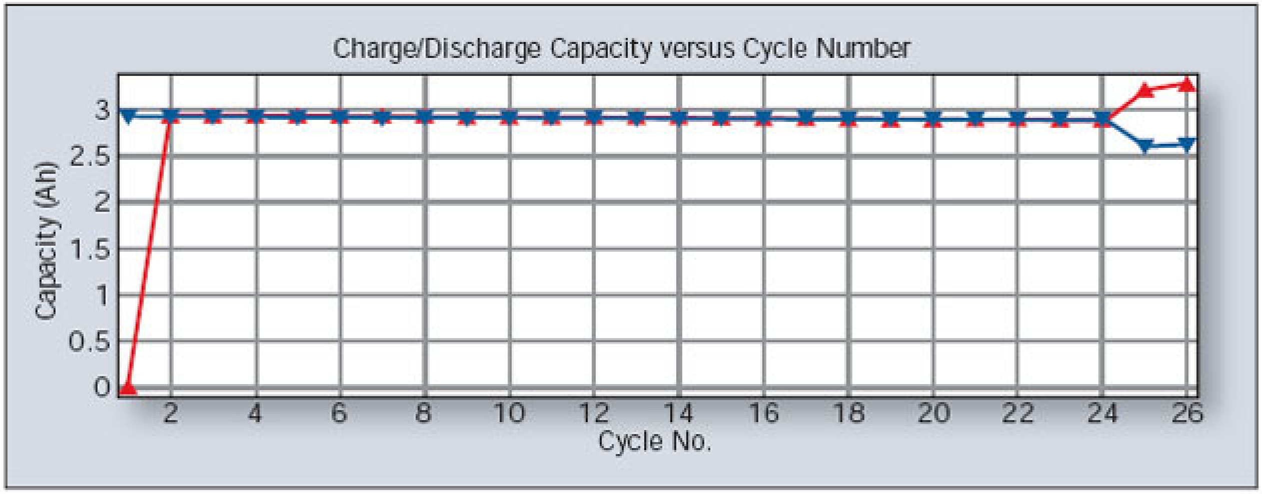

Fig. 6. Charge vs. discharge capacity of the full-cell/coin-cell combination: values begin to diverge after short induced.

TESTING: ROUND TWO

In a second round of testing, we obtained commercially manufactured cylindrical 18650 cells with manufacturing flaws that had been identified as counterfeit cells. Some of these cells had readily apparent manufacturing flaws.

For example, the cell in *Fig. 7* exhibits anode cathode misalignment — anode should overhang cathode to prevent lithium plating, subsequent lithium dendrite growth, and micro-shorting. This type of misalignment has been implicated in cell thermal runaway failures.

Fig. 7. X-ray of an 18650 Li-ion cell with misaligned electrodes.

We cycled these cells (this time without parallel connected coin cells) with a cycling program designed to simulate a Li-ion cell in a laptop battery pack under more realistic field conditions. The cycling program included:

- Extended rest periods at the end of both charge and discharge
- A secondary taper-charge step after the rest period at full charge that is used to simulate the presence of another cylindrical 18650 cell in parallel with the test cell that could provide current to a fault were it to develop
- Periodic partial charges and discharges rather than full charge/discharge cycles.

Though none of the cells tested in this manner went into thermal runaway, cell behaviors similar to those observed in the coin-cell tests consistent with micro-shorting were present. [Fig. 8](#) is an example of current and voltage profiles for one of the cycled cells.

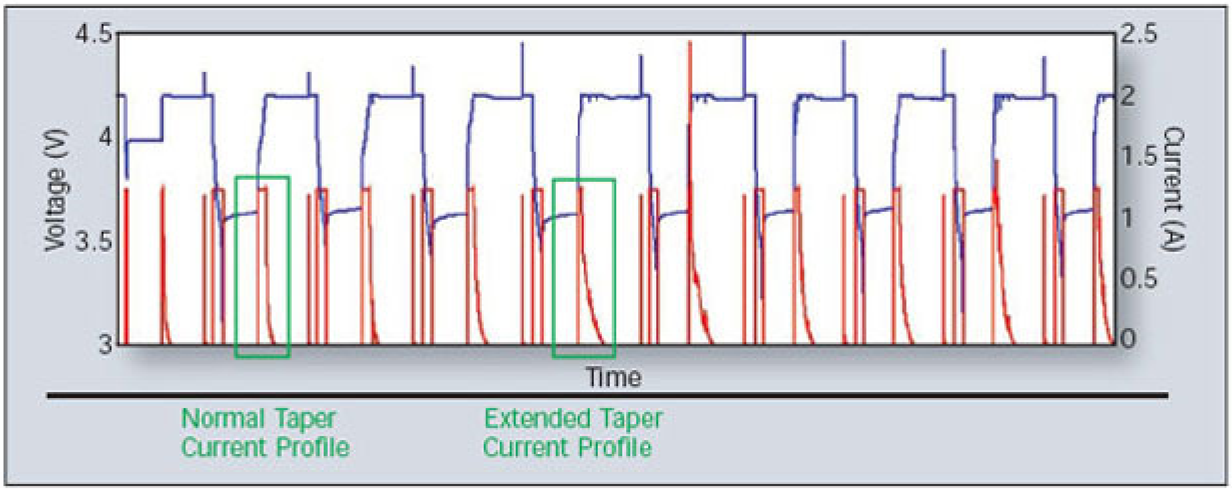

Fig. 8. Cycling data for a cycled 18650 cell. Taper current times are extended in some cycles.

MICRO-SHORTING

In these profiles we see evidence of micro-shorting occurring during both the constant current and constant voltage portions of the charging step. We also see extended-charge taper-current times occurring for some cycles, although we do not see evidence of any durable shorts that result in an elevated self discharge rate.

[Fig. 9](#) is an overlay of current profiles for all charge cycles made on the cell, with the greatest apparent winding misalignment made to date. Similarly, [Fig. 10](#) is an overlay of the voltage profiles for all charge cycles made to date on the same cell. The high variability of both current and voltage profiles indicates that micro-shorting has occurred regularly in the tested cell.

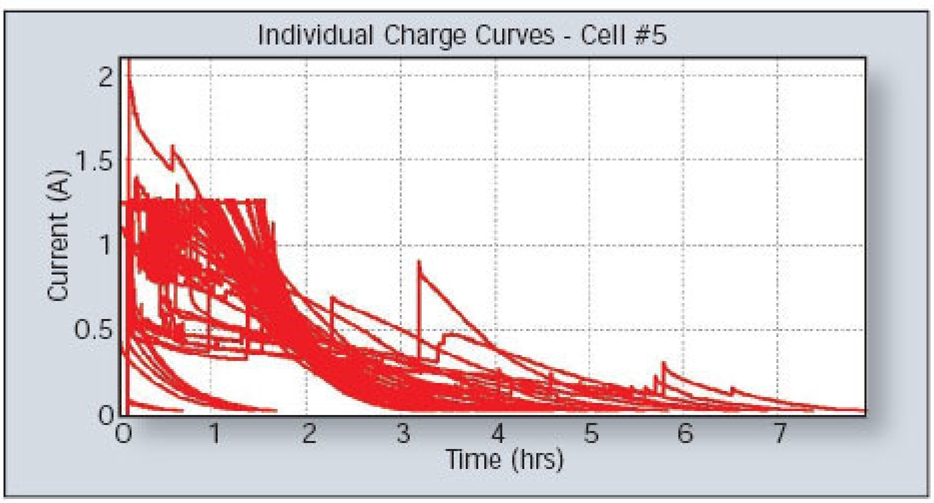

Fig. 9. Overlaid charge current profiles for an 18650 cell showing evidence of micro-shorting.

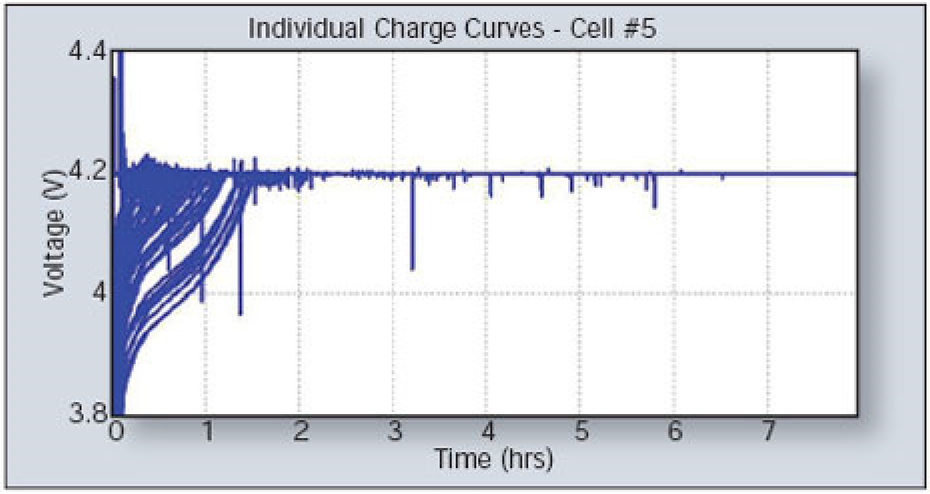

Fig. 10. Overlaid charge voltage profiles for an 18650 cell showing evidence of micro-shorting.

Though the coin-cell and cylindrical 18650 cell data demonstrates that detection is possible, further testing is required to:

- Confirm that similar behavior is detectable in full-scale cylindrical, prismatic, and polymer cells and packs, from a variety of different manufacturers
- Confirm that similar behavior is detectable in cells that have been exposed to field conditions and discernable from normal cell-aging behavior
- Begin to develop threshold values for normal vs. incipient fault performance that can be applied in practical battery protection systems

Exhaustive testing in collaboration with battery manufacturers that have produced cells with known faults (e.g., specific contaminants in pre-determined locations) is ideal, but very time consuming. Many cell faults do not develop into thermal runaway events for years.

Additionally, due to the remaining unknowns surrounding fault development in the field, testing may not produce fully applicable results. Using cells from block-imbalanced battery packs might reduce the development time of a usable data set that can provide a starting point for selecting protection thresholds for future battery-pack protection electronics.