On-Demand Cell Internal Short Circuit Device

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Abstract: A device implantable in Li-ion cells that can generate a hard internal short circuit on-demand by exposing the cell to 60°C has been demonstrated to be valuable for expanding our understanding of cell responses. The device provides a negligible impact to cell performance and enables the instigation of the 4 general categories of cell internal shorts to determine relative severity and cell design susceptibility. Tests with a 18650 cell design indicates that the anode active material short to the aluminum cathode current collector tends to be more catastrophic than the 3 other types of internal shorts. Advanced safety features (such as shutdown separators) to prevent or mitigate the severity of cell internal shorts can be verified with this device. The hard short success rate achieved to date in 18650 cells is about 80%, which is sufficient for using these cells in battery assemblies for field-failure-relevant, cell-cell thermal runaway propagation verification tests.

Keywords: cell internal short circuit; Li-ion; safety; thermal runaway; on-demand shorting device.

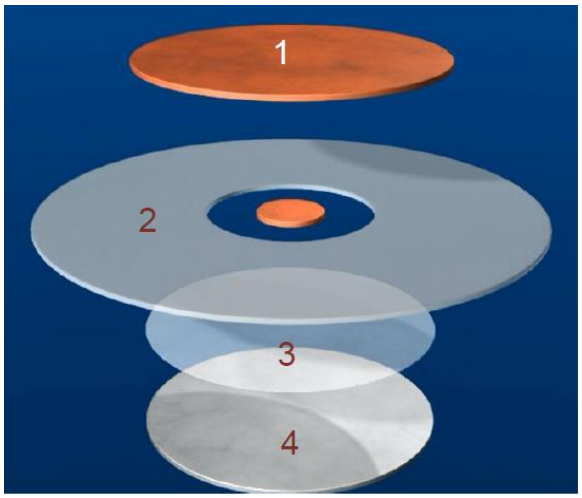
Introduction

Despite significant design maturity and extensive quality controls measures taken during manufacture since the commercialization of Li-ion cells, catastrophic cell internal shorts still occur periodically even in cells from reputable manufacturers. To replicate this, the Battery Association of Japan[1] has established a cell internal short circuit test that involves disassembling a charged 18650 cell and implanting a strategically placed metallic defect, rewinding the jellyroll, closing the cell, and cycling it to induce the short circuit. In addition, Barnett[2] has demonstrated the latency potential of defect induced cell internal shorts at escaping detection during cell screening and becoming catastrophic with more cycling. Quee[3] has reported on prolonged mechanical stress studies that cell void volume declines with repeated cycling as the density of the electrodes degrades. Therefore, sole reliance on prevention measures to mitigate the hazards of cell internal shorts is not sufficient for NASA. In battery designs over 80Wh, NASA battery safety requirements[4] for manned applications require an assessment by tests and analyses of the severity of a single cell thermal runaway event, and if catastrophic, a scoping of the design changes that could be implemented to appreciably reduce severity.

The challenge that our device addresses is how to induce a cell internal short circuit on-demand inside a battery in a way that is relevant to the conditions of such field failures. Traditional cell abuse tests, that electrically overcharge or thermally overheat cells, generally provide a uniform temperature distribution that is not present during a defect induced cell internal short. Cell abuse tests that mechanically crush or penetrate the cell enclosure yield a more localized and relevant internal short, however, these methods often breach the cell enclosure and are difficult to implement in a battery without significant alterations to the design and departure from relevant field failure conditions.

Design

The key feature of our device is an insulating wax layer compatible with Li-ion electrolytes and which melts at about 60 °C. The resulting low profile device shown in Fig.1 can be implanted in wound and in parallel electrode during cell assembly without impacting cell formation or subsequent acceptance testing.



Top to Bottom:
1. Copper Pad
2. Battery Separator with Copper Puck
3. Wax – Phase Change Material
4. Aluminum Pad

Figure 1. On-Demand Internal Short Circuit Device Design

Using conventional foils, the device thickness is less than 100 microns. As currently designed, the diameters of the metal pads are 11mm. For implantation, a hole > 11mmm is made in the native cell separator to allow a place for the device between anode and cathode materials. The device's and cell's separator layers overlap and are bonded together to secure the location of the device. With a good estimation of the wet electrode thickness and thicker pads, the design of the device can be optimized to achieve current collector-to-current collection shorts or electrode active material-to-current collection shorts, with the former shown in Fig. 2. This allows the 4 internals short circuit combinations to be achieved. The size of the copper puck determines the resistance and current carrying capacity of the device during the initial stages of the short.

The key component of the device is a thin, uniform, and complete wax layer in contact area of the copper puck and aluminum pad. These coated layers are achieved with a spin coating process developed at NREL. During the activation of the device, the thin liquid wax layer is wicked into the separator away from the path of the short. The wound radial pressure of jellyroll electrodes along with the interference fit of the copper puck help ensure good contact between the layers of the device and with the electrodes. With stacked electrode cell designs as in the pouch cells tested, external pressure is required to be maintained on the cell stack to reliably achieved hard shorts.

One caution in assembling these devices is preventing metallic burrs on the pads and the puck. These were found in earlier versions of our device and believed to have caused cell formation charge failures or premature activations. Using chemically etched metallic pads with edges that are free of burrs resolved this issue.

Experimental

To date, our device has been implanted in one 18650 and two pouch cell designs with nominal capacities of 2.4, 3.0, and 8.0Ah. After implantation and prior to electrolyte filling, insulation resistance tests are done to ensure the device is properly insulated. In addition, we find it prudent to perform a destructive device activation test on a sample of dry cells to verify that the device will achieve the anticipated hard short resistance.

Our latest trials with the 18650 cell design had less than 10% formation or cell acceptance failures. Subsequent capacity cycling for 20 cycles at C/10, C/2 and C-rates found negligible capacity or DC resistance impact of the device in comparison to nominal control cells.

To achieve current collector shorts, the active material of the electrode you want to bypass is manually removed in a circular spot with a solvent to expose the underlying current collector. The exposed area needs to be large enough to accommodate the diameter of the thicker pad of the device to ensure good device pad-to-collector contact.

Our latest trials with the 18650 cell design were done with two separator designs (shutdown and non-shutdown) and two short types (collector-to-collector (as shown in Fig.2) and anode active material-to-aluminum collector).

Results

Fig.3 shows typical cell voltage and temperature profiles from a hard short achieved during device activation that lead to thermal runaway. This result was achieved with a collector-to-collector short with a non-shutdown separator. The cell was fully charged and placed in an oven where its temperature was raised about 1 °C per minute. We have found that higher ramp rates lead to less consistent device activations, presumably due to uneven wax melting resulting from large temperature gradients in the cell. Once the cell and device are soaked at > 60°C, activation of the device typically causes a very steep cell voltage decline to near zero and very rapid cell skin temperature rise to the 600-700°C range or gets there with an intermediate pause at the 120-150°C range where separator meltdown occurs. Heating causes cell pressure to rise, open the cell current interrupt device (CID), the cell vent ruptures, and violent venting with flames, sparks, and electrolyte and

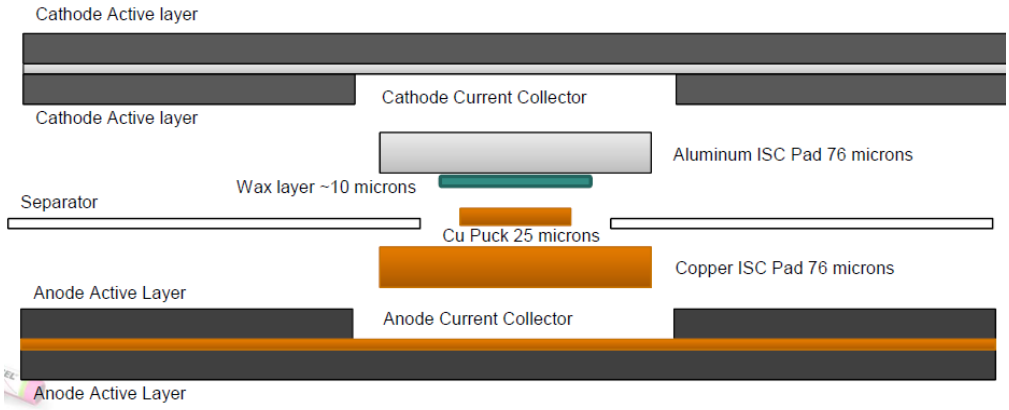


Figure 2. Design of ISC Device for a collector-to-collector cell internal short circuit.

electrode material venting results.

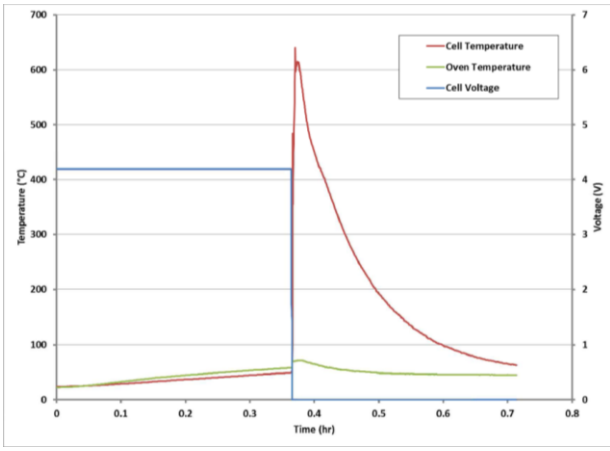


Figure 3. Typical voltage and temperature profiles during a cell hard short activation with collector-collector device[5]

In contrast, Fig.4 shows the typical cell voltage and temperature profiles with the same type of short circuit device but with the cell design equipped with a shutdown separator. Once the device activates the short, the cell voltage immediately drops and cell skin temperature rises abruptly to about 120°C and then safely cools down. Upon destructive disassembly of the cell jellyroll, we found significant portions of the anode were fully charged (Fig.5).

Figure 5. Unwound jellyroll showing significant portions of anode to be still charged (gold spots).[5]

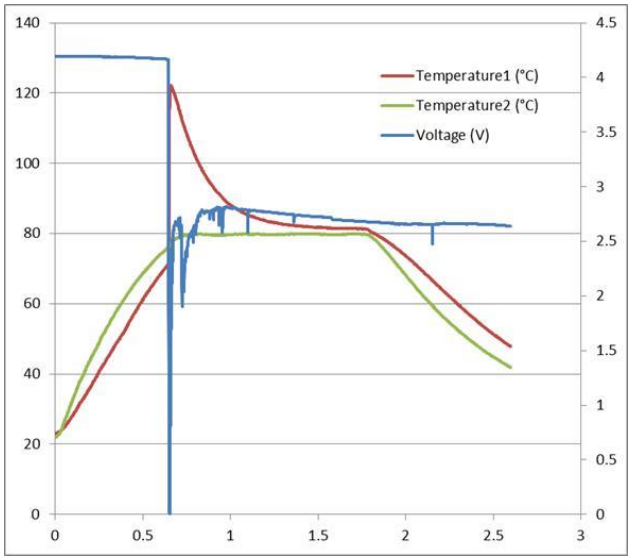


Figure 4. Typical profiles for cell with shutdown separator[5]

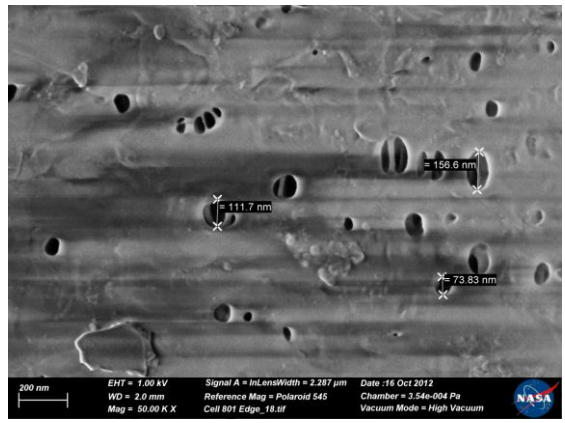


Figure 6. SEM micrograph of separator after shutdown.

Subsequent examination of the separator adjacent to the charged portions of the anode showed very significant porosity loss when compared to nominal separator by scanning electron microscope (Fig.6). The shutdown feature of the separator activates at about 130°C and restricted enough ion flow to shut down the short circuit and prevent the cell from going into thermal runaway. This result was confirmed on numerous repeat runs.

When testing the anode active material-to-cathode collector short, the shutdown separator did not prevent the cell from going into thermal runaway. The catastrophic result was the same with both types of separators. This result was confirmed with multiple repeated runs.

Furthermore, our testing of shorts that involved the cathode active material indicates that these types of shorts lead to benign soft shorts and are typically not hazardous. This is due to the lower electrical conductivity of the cathode.

Discussion

Why are anode-to-aluminum shorts not impeded from driving the cell into thermal runaway by the shutdown separator? This is consistent with the fact that the shutdown separator has been widely used in the industry for over a decade and cell lot recalls are still happening. Case in point is the Sony recall of 2006 which was attributed to this type of short[6]. The BAJ then adopted this short as a method for testing worst case cell internal shorts. Many manufacturers have since then implemented the best practice of insulating as much of their exposed aluminum collectors as practical. Santhanagopalan et. al.[7], were the first to compare the four different types of cell internal shorts with inserting shorting particles and their results agree with ours. Similarly, Barnett et. al.[8] used this type of short to demonstrate the latency potential of cell internal shorts.

Conclusions

The on-demand internal short circuit device has been demonstrated to be very useful in determining which types of short circuits are most hazardous and the effectiveness and limitations of cell safety features (like shutdown separator). Note that the results herein should not be taken as a guarantee that shutdown separator will prevent thermal runaway in all cases of collector to collector shorts.

Furthermore, when a manufacturer determines that in his designs active-active shorts are less hazardous than cathode collector shorts, this suggests that metallic defects embedded in the active electrode material to be more important to mitigate than defects that rests on the surface of the electrodes. This implies that a manufacturer should focus more on having defect-free mixing, coating, and calendaring processes to prevent building cells with embedded metallic defects that could lead to latent catastrophic cell internal shorts. After the calendaring process, the electrode active material has solidified and any metallic defect that gets into the cell assembly processes is less likely to get embedded and bridge to the current collector. Conversely, these results also indicate that embedded metallic defects in the cathode that could bridge to the aluminum collector present the most risk.

Acknowledgements

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