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ScienceDirect
Journal of Power Sources 174 (2007) 575–578
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Short communication

Screening Li-ion batteries for internal shorts

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Available online 3 July 2007

Abstract

A Li-ion polymer pouch cell battery design for a spacesuit developed an internal short during ground storage. A detailed failure investigation found that native contamination was the most probable root cause as the failure mechanism was successfully replicated. Lessons learned are applicable to the implementation of most Li-ion cell designs for critical applications.
Published by Elsevier B.V.

Keywords: Li-ion; Internal short; Screening

1. Introduction

The extremely high cost of aerospace battery failures due to internal shorts make it essential that their occurrence be very rare, if not, eliminated altogether. With Li-ion cell/batteries, the potentially catastrophic safety hazard that some internal shorts present adds additional incentive for prevention. Prevention can be achieved by design, manufacturing measures, and testing.

Specifically for NASA's spacesuit application, a Li-ion polymer pouch cell battery design was in its final stages of production. One of the 20 flight batteries fabricated and acceptance tested developed a cell internal short, which did not present a safety hazard, but has required revisiting the entire manufacturing and testing process. Herein are the details of the failure investigation that followed to get to root cause of the internal short and the corrective actions that will be taken, which are lessons learned applicable to most Li-ion battery applications.

2. Spacesuit battery design

This 20 V, 37 Ah spacesuit battery consists of five-cell modules connected in series through a printed circuit board and housed in an aluminum box. Each cell module consists of five pouch cells (7.4 Ah) whose tabs are welded to a pair terminal blocks, which puts the five cells in parallel electrically. Each cell is roughly 100 mm × 75 mm × 9 mm and its electrochemistry consists of graphite, cobaltate, and $LiPF_6$ salt (Fig. 1). The cell design consists of a single anode, cathode, and two layers of separator laminated together as a ∼1 m × ∼100 mm cell. The substrate foils for the anode and cathode are laminated with active material only on one side. The laminated cell assembly is then z-folded 15 times into a ∼9 mm thick cell stack. The cell stack is then sealed in a plastic-aluminum laminate pouch material. The five cells are stacked and sealed in a similar plastic-aluminum laminate outer pouch. The fragile assembly is then placed in a mold to be potted with urethane foam to become a solid 37 Ah cell module brick. The entire battery assembly, including the cells, is designed and manufactured at Electrovaya Corp., in Mississauga, Canada. The cell and cell module acceptance was also performed by them, while the majority of the battery acceptance testing was done at NASA-JSC.

3. Current internal short controls

Each cell was manufactured and extensively screened for visual, physical, and other defects such as loss of hermeticity, soft shorts, high self-discharge rate, anomalous capacity and impedance performance. The cell modules acceptance consists of two capacity and impedance performance cycles. The battery acceptance consists of visual, physical, and capacity and impedance verifications before and after thermal cycling and random vibration testing.

With battery s/n 1010, all the verifications were completed in October 2005 and indicative of a healthy battery. After charging it to 30% SoC, the unit was placed in its shipping container until it was called to support a charger test in February 2006. This is when one of its cell modules was found to have an OCV of ∼10 mV while the other 4 modules where at their nominal 3.78 V (30% SoC).

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0378-7753/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.jpowsour.2007.06.245

Fig. 1. One of the five cells that make up a cell module.

Fig. 3. Damaged bottom corner of cell #5 on top of cell #4 with cell pouches removed.

4. Plausible root causes

Careful, deliberate, non-destructive, and destructive physical examinations (DPA) isolated the short to within one of the cell pouches within the defective cell module, specifically, the outer most cell #5 in the stack (Figs. 2 and 3). Specifically, both cell bottom corners show evidence of high heat-affected zones with their centers located very near the corners. There appears to be two “ground zeros” for the short, which when fed by the energy of all five cells caused intense heating, high enough to melt the copper foil (1084 °C) in microscopic locations (Fig. 4). This damaged the bottom corners of the adjacent cell #4. No evidence of separator failure or foreign object debris (FOD) was found to be root cause. This leaves electrode misalignment, native contamination, cold flow through the plastic-aluminum laminate, and pouch seal fold impingement as remaining possible root causes aggravated by the thermal cycling or/and vibration.

During the DPA, non-uniformities in the thickness of the urethane foam potting around the cell module were found in the layers adjacent to the affected bottom corners of cell #4 and #5. Thin and thick spots could have left the stack of pouch cells unsupported at the corners, allowing relative motion during vibration. This could have contributed to any of the four root causes mentioned earlier.

Vibration could have stressed the unsupported electrode substrate folds and cause them to tear (Fig. 5). This in turn could have damaged the separator and allowed misalignment of the electrode folds. Similarly, vibration could have caused some active electrode material to break loose and contaminate the substrate fold area, where no active material should be present. This contamination could have cause separator damage and a short. Also, impingement of the cell stack corner against the laminate pouch could have caused its plastic outer layers to cold flow until the folded cell stack made direct contact with the aluminum layer in the pouch. Two cold flow shorts to the pouch would be required for this mechanism, since the pouch is electrically isolated from the cell tabs. Alternatively, the folded pouch seal on the external edges and corners of the cells could have damaged the cell

Fig. 2. Five-cell stack of internally shorted cell module after outer pouch was removed. Note the heat-affected bottom corners of cells #4 and #5.

Fig. 4. Ground zero arc damage on the copper foil substrate on a torn side fold near the bottom corner of cell #5.

Fig. 5. Unfolded cell #5 stack showing the torn copper folds and ground zero of the internal short.

pouch laminate material at its corner where the pouch is drawn (stretched) to form a cup shape for the cell stack. This is particularly possible for cell #5, whose edge seal is doubly folded in the direction of cell #4 and its resultant corner seal fold can result in a very stiff and sharp point.

The key facts that any mechanism of this internal short must be consistent with are as follows:

(a) The 1 min/axis random vibration test was performed with battery OCV measurements made immediately before and after. No OCV variation between the two measurements exceeded ±1 mV. Battery was at 30% SoC.
(b) Nine days later, the battery was charged, discharged, and recharged to 30% SoC, with in-family individual cell module voltage performances throughout.
(c) The pre-test capacity cycling test was performed 13 days prior to the vibration testing and was very consistent with the post test capacity, which occurred ∼4 days after vibration testing.
(d) If two internal shorts developed during vibration, they must have been of high enough impedance to escape detection during the capacity cycling, and then, transitioned to low impedance shorts to cause the thermal damage on the corners of cell #4 and #5. These two shorts must have occurred at nearly the same time, or else, the first short would have consumed the cell module energy.
(e) No clear path of heat-affected zones exists between the two corners which would directly indicate that one caused the other.

5. Root cause validation

To validate the folded seal impingement theory, fully charged cells from the same lot as the flight lot were drop tested on their bottom corners from up to 1.5 m high. When the seal is folded as it the cell#5 configuration, the pouch is not breach, even though the corners of cells are very deformed. Surprisingly, no anomalous OCV decay occurred. When the cell seal is not folded, drops from over 60 cm cause corner pouch tears. Two-cell stacks representing cell#4 adjacent to cell#5 suffer no evidence for internal shorts even after drop impacts on their bottom edges from up to 1.5 m. Cell #4 was breached in the two-cell stacks only after 1.5 m drop, not after lower drops. These finding indicate that laminate pouch material is very durable and not fragile.

To validate the cold flow of the insulating plastic layers of the cell pouch, the insulation resistance of the laminate pouch material have been measured for over 21 days, while in contact with 0.45 cm diameter ball bearing down on the stretched corners of the pouch. These bearings were loaded with 150–1000 g weights. The insulation measurements were done 25 V. To date, not slightest evidence of cold flow has appeared. The design of the laminate does not appear to cold flow in conditions relevant to the Spacesuit application. Furthermore, it was determined by test that with good electrical contacts on a drawn cell pouch corners, the laminate is able to conduct 50 A through its aluminum layer without causing any visual heat effects in the middle section between the contacted corners. Thus, if cold flow at the cell corners is possible, then the resulting internal short could have left a heat-affected signature as seen in Fig. 2.

To validate the misalignment of the electrode theory, defects in the foam of engineering cell modules were introduced at the corners. These defective modules were assembled into engineering batteries and vibrated to levels 2dB higher than acceptance level. No anomalous decay in cell module OCVs has occurred after >150 days.

Attempts to replicate the native material contamination theory were done with foreign contamination. Specifically, pins, staples, and finally acupuncture needles were used in a set of trial and error experiments. Success in replicating the original damage (Fig. 3) was achieved when puncturing cells with a 0.15 mm diameter acupuncture needle on their edge where the current collectors are z-folded while under an argon flow and with the cells at 30% SoC. The steel needle was insert through a pre-made hole in the pouch on the side of the cell, such that the Al current collector was first punctured, then the two layers of separator, and

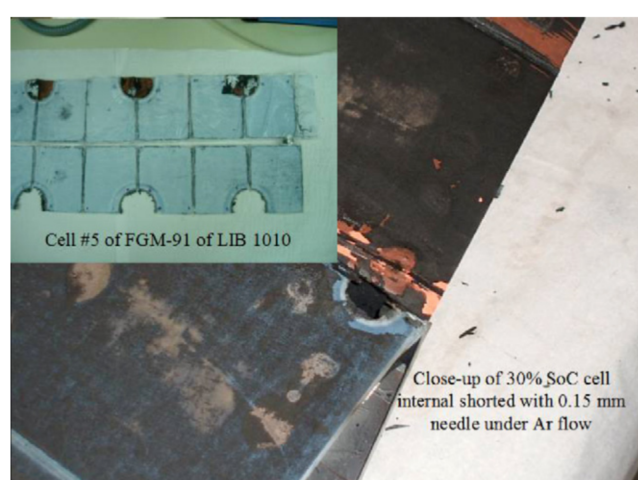

Fig. 6. Comparison of the damage caused the internal short in cell#5 (inset) and in a cell internally shorted with an acupuncture needle. Note the similarity of the localized damage.

then formed a short when it reached the graphite coated copper current collector. The short caused a small puff of smoke which quickly extinguished itself. The OCV of the cell dropped from 3.78 to <0.1 V in <15 h. The test was performed twice, once as a single cell test and another time as five cells in parallel. Subsequent DPA revealed mechanics of failure closely resembling the original damage shown in Fig. 3 and a comparison is shown in Fig. 6.

X-ray photoelectron spectroscopy was performed on inside layer of the composite laminate pouch corner that was adjacent to the bottom corner opposite ground zero. The presence of lithium was detected on surface the aluminum layer of the pouch. This is an indication of a possible Al–Li alloying resulting from an insulation defect that polarized the Al layer of the pouch to the negative electrode potential, since the copper negative current collector is the external wrap of the z-fold on that side of the cell electrode stack. This insulation defect could have gone undetected during cell fabrication and acceptance.

6. Corrective actions

The current acceptance screening for the internal shorts [1,2] is nearly adequate at the cell level, except for the lack of a pouch isolation resistance test from the cell terminals. Current procedures are inadequate at the cell module level because no thermal cycling or vibration is followed with capacity cycling tests with appropriate hold times. Screening for internal shorts only at the completed flight battery assembly level is a success-oriented approach, which is high risk when a failure is detected.

The proposed corrective actions are to perform thermal and vacuum cycling, random vibration, and charge/discharge cycling at the cell module level. This should be followed with capacity cycling tests that include hold times designed to detect high self-discharge and soft shorts. Short shorts are detected by fully discharging a cell module at 3.0 V to a 125 mA taper current and monitoring cell open circuit voltage on days 14 and 21. Any cell module whose voltage is declining between days 14 and 21 is rejected. At this low state of charge, a great majority of soft shorts will produce a measurable OCV decay. Once the cell modules are cleared for assembly into batteries, battery thermal cycling and vibration acceptance testing can be done at levels for detecting standard workmanship defects rather than the higher levels that had been used to screen for internal shorts.

7. Conclusions

The internal short that occurred in spacesuit lithium ion battery was most probably caused by native contamination in one bottom corner of a cell coupled with an insulation defect in the pouch adjacent to the opposite cell corner. This subtle internal short was not detected during the acceptance testing because it was very subtle (high impedance) during those tests and later transitioned into a low impedance short, causing localized damage. The difficultly the investigation had in replicating the failure supports the argument that these type of subtle, smart shorts are extremely rare. It also concludes that the acceptance tests were clearly inadequate and must be supplemented with more thermal, vacuum, and charge/discharge cycling to provide any latent workmanship defect a much greater probability of manifesting itself.

Acknowledgements

The author thanks the contributions of John Weintritt and Dan Hall of Jacobs Engineering Group and Rakesh Bhola and Jim Jacobs of Electrovaya to this failure investigation.

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