

SAFETY EVALUATION OF TWO COMMERCIAL LITHIUM-ION BATTERIES FOR SPACE APPLICATIONS

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ABSTRACT

Lithium-ion batteries have been used for applications on the Shuttle and Station for the past six years. A majority of the li-ion batteries flown are Commercial-off-the-Shelf (COTS) varieties. The COTS batteries and cells were tested under nominal and abusive conditions for performance and safety characterization. Within the past six months two batteries have been certified for flight and use on the Space Station. The first one is a Hand Spring PDA battery that had a single prismatic li-ion cell and the second is an Iridium satellite phone that had a two-cell pack with prismatic li-ion cells.

INTRODUCTION

In recent years, lithium-ion batteries are used widely in portable electronic equipment. The batteries have higher energy densities, lower self-discharge and long calendar and cycle life compared to other rechargeable battery chemistries. With the increased power demands from portable electronic equipment, the batteries have increased in energy and power with almost no changes in dimension, consequently increasing the hazards associated with high-energy systems. After the first use of a Canon li-ion battery for space applications, a few COTS li-ion batteries¹⁻³ have been tested and used for Shuttle and Station applications and several COTS li-ion cells have been tested for the same purpose⁴⁻⁷. A portion of the typical tests performed on these batteries to qualify and certify them for flight and use for space applications is described in this paper.

The Hand Spring PDA is powered by a single cell battery. The battery (3.6 V and 1.5 Ah) has a prismatic li-ion cell and a protective "smart" circuit board. The Iridium satellite phone has a two-cell pack battery. The battery pack (3.6 V and 1.9 Ah) has li-ion prismatic cells and a protective "smart" circuit board. The protective circuit boards have an integrated circuit (IC) chip that constantly monitors the current and voltage of the cells in the packs and activates MOSFET switches when the pack is subjected to off-nominal conditions. The tests conducted on the batteries included functional characterization as well as their tolerance to abusive conditions.

EXPERIMENTAL

The Hand Spring PDA and the Iridium satellite phone lithium-ion batteries were tested and qualified

for flight at the Energy Systems Test Area at NASA-JSC. The tests carried out on them on the battery level were charge / discharge cycles at different temperatures, overcharge, overdischarge, short circuits, vacuum and vibration. The cells were tested for overcharge, overdischarge and external short circuit. The batteries and cells also underwent vacuum leak checks and vibration tests on qualification and flight acceptance levels. The tests were carried out using several models of the BT 2000 series of the Arbin Test Stations or a Kepco Model BOP20-10 power supply and a Hydra Data Logger Model 2620A. The vibration test was carried out on a Ling Model 335B shaker, driven by a Ling Model 8036 power amplifier. This was controlled by a Spectral Dynamics model 2552B system, running Random software (version 3.7.1) with the Solaris 2.6 Sun operating system on a Sun Sparc5 workstation.

RESULTS AND DISCUSSION

The Hand Spring PDA (HSP) and Iridium Satellite Phone (ISP) lithium-ion batteries underwent the following tests. The results of the tests are discussed following a description of the test conditions.

a. Temperature: The batteries were charged and discharged in the respective device at temperatures of 10 °C (50 °F) and 32 °C (90 °F), as required for certification of in-cabin flight batteries. During the process, the battery temperature should not exceed 45 °C, the touch temperature limit for usage.

(i) HSP li-ion battery: The battery was tested at the two environmental conditions of 10 °C and 32 °C. The charge and discharge was carried using the HSP. The batteries powered the HSP for 140 minutes and 200 minutes at 10 °C and 32 °C, respectively. Almost no change in temperature was observed during the charge and discharge process at 10 °C and there was a 2 °C rise in temperature during both the charge and discharge process at 32 °C. No issues with high temperatures were encountered during this test.

(ii) ISP li-ion battery: The battery was charged and discharged in the ISP at environmental temperatures of 10 °C and 32 °C. The time of discharge was 204 and 222 minutes respectively. The temperature of the battery pack was 1.5 °C and 4.0 °C higher than the chamber temperature during charge and discharge, respectively for the 32 °C run and no changes for the

other. The temperatures recorded did not exceed the touch temperature limits.

a. Overcharge:

The overcharge test was performed to determine the safety characteristics and tolerance of the batteries and cells respectively.

(i) HSP li-ion battery:

Three fully charged batteries were subjected to an overcharge condition by charging with a current of 0.75 A to 12 V. The battery shut down at 4.4 V indicating that the overcharge protection MOSFET switch had been activated. The maximum temperature recorded was below 29 °C. The battery recovered after it was placed on the PDA and discharged. A post charge/ discharge cycle showed that the battery was fully functional with no changes in capacity when compared to the pre-test discharge capacity.

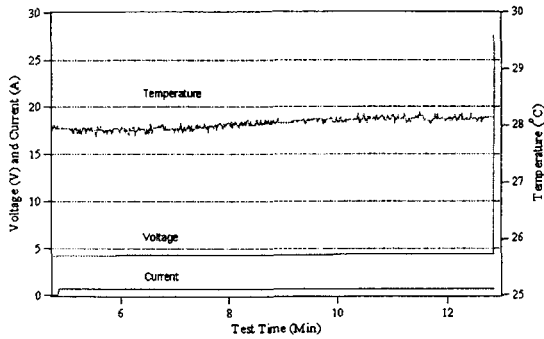


Figure 1. Overcharge test on a HSP li-ion battery with 0.75 A and 12 V limit.

Overcharge of fully charged cells without the circuit board using a charge current of 0.75 A caused the cell to vent and explode above 5.0 V. Fire and smoke were observed during this test.

(ii) ISP li-ion battery:

The overcharge test was performed on a fully charged battery with a current of 1 A to 12 V. The battery shut down at 4.35 V indicating that the MOSFET switch had been activated.

Fully charged cells were charged with a current of 0.5 A to 6 V, for 6 hours. Once the voltage reached 6.0 V, the current tapered down. The cells displayed swelling and could not be discharged but did not show any signs of venting or leakage.

Another set of fully charged cells was then subjected to higher currents (> 2.0 A) with a 12 V limit for 12 hours. Under these conditions, the cells vented and caught on fire almost at the 12 hour limit (Figure 2).

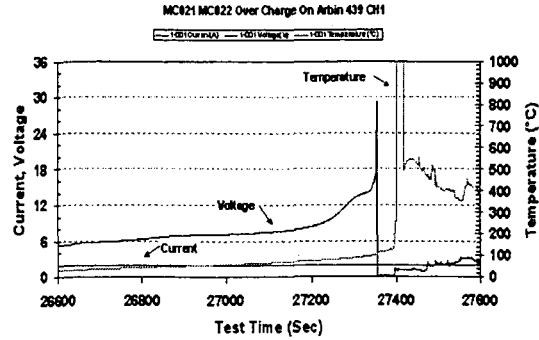


Figure 2. Overcharge test on a ISP li-ion cell with 2 A and 12 V limit.

b. Overdischarge:

The overdischarge test was conducted on both batteries to determine the characteristics of the safety features in the batteries.

(i) HSP li-ion battery:

The fully charged HSP li-ion batteries were discharged using a 1.5 A current and a voltage limit of 1.0 V. The discharge of the battery was stopped at 2.3 V due to the activation of the under voltage MOSFET switch. The maximum temperature recorded on the battery pack was 34 °C. The MOSFET switch was reset after it was placed in the PDA at which point it went into a charge mode.

Fully charged cells were discharged into reversal, with a current of 1.5 A. The minimum voltage obtained was -0.8 V (Figure 3) and the highest temperature recorded was 55 °C. Although the cells did not vent or explode, they were unusable after the test.

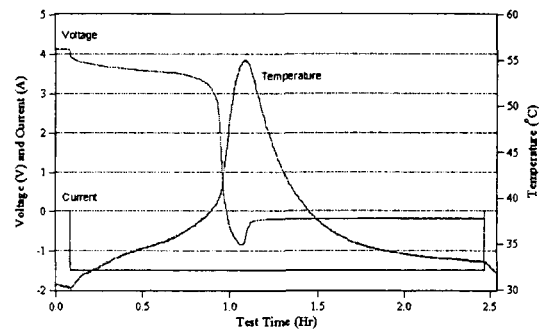


Figure 3. Overdischarge-into-reversal test on a HSP li-ion cell using a current of 1.5 A.

(ii) ISP li-ion battery:

The overdischarge test was performed on fully charged batteries using a current of 1.0 A. The undervoltage cutoff switch was activated at 2.45 V. The batteries did not show any signs of venting or leakage and recovered when placed on the PDA for charge.

Fully charged cells were overdischarged to 0 V with a current of 0.5 A, and then subjected to a charge and discharge cycle and found to be functional. Fully charged cells were then subjected to overdischarge into reversal until 150 % of the original capacity was extracted from the battery using 0.5 A current. The minimum voltage obtained was -1.5 V and the maximum temperature recorded was about 35 °C. The cells did not vent or smoke but were not functional after the test.

c. External Short Circuit:

This test was carried out on the batteries and cells to determine the safety features of the batteries under short circuit conditions and to determine the tolerance of the cells to short circuit condition.

(i) HSP Li-ion Battery:

Fully charged batteries were subjected to an external short condition using a load of 50 mohms. The data was collected at a rate of 1 kHz for the first few seconds to determine the maximum current achieved during the hard short. A current spike of almost 20 A was observed which dropped instantaneously to 0 A as the protective MOSFET switch was activated. The maximum temperature recorded on the battery was 30 °C. The switch was reset when the battery pack was placed on the PDA for charge. The batteries were fully functional after this test.

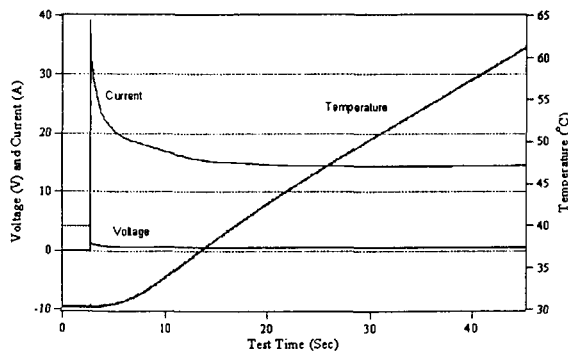


Figure 4. External Short Circuit test on a HSP li-ion cell with a load of 50 mohms.

Fully charged cells were subjected to a hard external short using a load of 50 mohms. Data collection was at 1 kHz rate for the first few seconds. A current spike of 39 A on the msec time scale was observed and the maximum temperature recorded was 103 °C. No venting or leakage of the cells was observed but the cells were non-functional after the test.

(ii) ISP Li-ion Battery:

Fully charged batteries were subjected to a hard external short using a load of 50 mohms. The

MOSFET switch was activated instantaneously safing the battery. The switch is reset after the battery is placed in the satellite phone for charge. Fully charged cells were subjected to a hard short with a load of 50 mohms. An instantaneous spike of 50 A was observed at a data collection rate of 1 kHz. Under the slow speed data collection method for the same test, the maximum current spike is not easily captured (Figure 5). The maximum temperature observed was 120 °C. The cells were non-functional after the test but no venting or fire had occurred.

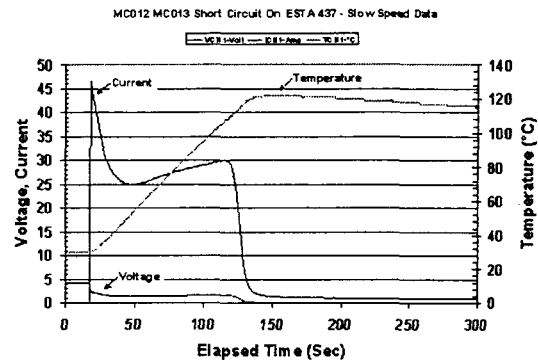


Figure 5. External Short Circuit Test on a ISP li-ion cell (slow speed data collection).

d. Crush Test:

The batteries are crushed to simulate an internal short caused due to the presence of foreign particles in the cells as part of a manufacturing defect. Under a launch vibration environment, these particles can be loosened enough to cause an internal short during the vibration process or during a charge/discharge process after the launch. The cells are crushed just enough to cause deformation without penetration and their tolerance to internal short is determined.

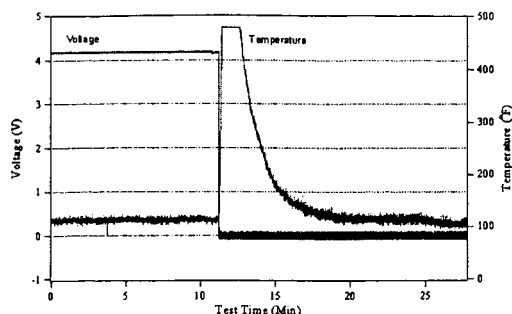
(i) HSP Li-ion Battery:

Fully charged cells from the HSP li-ion battery were crushed using a rod along the center of the flat portion of the cells. The cells experienced a drop in voltage when the internal short occurred and exploded almost instantaneously (Figure 6).

(ii) ISP Li-ion Battery:

The fully charged cells were crushed to simulate an internal short by causing a deformation without penetration. All the cells exploded violently, when the internal short occurred and the results were similar to that of the HSP prismatic li-ion cell.

Figure 6. Crush Test on a HSP li-ion cell to simulate an internal short.



f. Vibration:

Fully charged HSP and ISP li-ion batteries were subjected to a qualification vibration spectrum with a frequency of $0.1 \text{ g}^2/\text{Hz}$ for 15 minutes in each of the three independent x, y, and z axes. No changes in OCV (open circuit voltage) or capacity was observed after the vibration. All the flight batteries were subjected to a vibration spectrum with a frequency of $0.067 \text{ g}^2/\text{Hz}$ for one minute in each of the three independent axes. The qualification and flight batteries showed no change in functional performance after the test.

g. Vacuum Test:

Fully charged HSP and ISP li-ion batteries were subjected to a vacuum test to a level of approximately 0.1 psi for six hours. The rate of depressurization was 8 psi/minute and the rate of repressurization was 9 psi/ minute. The batteries displayed no change in functionality after the vacuum test. All flight batteries undergo the same level of vacuum exposure and checked for functionality.

h. Sneak Circuit Analysis:

(i) HSP li-ion Battery: The protective circuit board was tested independent of the battery to verify its functionality. The abuse conditions were imposed on the board using power supplies in the absence of the cells. The overvoltage switch activated at 4.3 V, the undervoltage switch activated at 2.4 V and the overcurrent switch activated at 2.3 A. Only one level of overcharge protection was present on the circuit board in spite of the cell being intolerant to overvoltage conditions. Hence analysis of the charging circuitry on the PDA was performed and determined that two more levels of protection were present in it with the voltage and current regulator to prevent the batteries from going into an overvoltage condition.

(ii) ISP Li-ion Battery:

The overvoltage switch activated at 4.34 V, the undervoltage switch activated at 2.5 V and the overcurrent switch activated at 3.6 A. It was also determined that there were redundant overcharge/overvoltage switches as the cell was not tolerant to an overcharge condition. One of the switches was removed and it was found that the other

switch prevented the battery from being abused. When the second switch was removed, the battery behaved like a dead battery and would not receive charge or discharge.

CONCLUSIONS

The Hand Spring PDA and Iridium Satellite phone li-ion batteries were qualified for launch and use on the Station. The Iridium Satellite phone li-ion battery was independently two-failure tolerant to catastrophic hazards. The Hand Spring PDA battery was not two-failure tolerant to all the catastrophic hazards due to the presence of only one level of protection for the overcharge condition. The battery depended on the PDA charging circuitry for additional levels of protection. The Hand Spring PDA and li-ion battery are currently on Station for crew use.

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