Safety Testing of Lithium Ion Batteries for Navy Devices

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ABSTRACT

Lithium ion battery technology is being introduced into power supplies used by our Armed Forces for a variety of applications. In many cases, the same cells and design parameters that support commercial battery packs are being used in military battery packs. This approach is expected to result in a major decrease in the total life cycle cost of the equipment these batteries support.

On June 13, 1991, NAVSEA issued INST9310.1B1 [1], which states that all lithium battery powered equipment must undergo safety evaluation and approval prior to fleet use. This safety program governs a process whereby approvals are issued for lithium batteries to be used in specific equipment on ground facilities, surface combatants, air combatants, and/or submarines. The Naval Ordnance Safety and Security Activity (NOSSA) manages the program. The chief technical advisors are Code 644 at NSWC Carderock Division and Code 609A at NSWC Crane Division.

This paper describes three battery designs that incorporate lithium ion technology, and the results of battery safety tests conducted in accordance with Navy requirements.

HAND-HELD RADIO (HHR) BATTERY

Boeing North America and Bren-Tronics, Inc. developed a lithium ion battery design for use in a hand-held emergency radio shown in Figure 1. This battery consists of six Sanyo model number UR18650P cells arranged in a two-in-parallel by three-in-series configuration. The cells were connected to a printed circuit board (PCB), and this subassembly was placed in a Xenoy housing measuring 2.8 inches high × 1.7 inches wide × 3 inches tall (Figure 1). The battery housing included a state of charge indicator and a small pressure release vent. The HHR battery pack as tested had a 3 Ampere-hour (Ah) capacity rating with a nominal voltage of 12.6V.

There were two internal safety devices in each Sanyo UR18650P cell: a positive thermal coefficient (PTC) device and a current interrupt device. Safety devices in the HHR battery included a thermal fuse (104°C), resettable thermal cutoff (70°C), and charge protection electronics monitoring battery voltages and current.

ADVANCED WEAPON SIGHT (WS) BATTERY

The United States Army developed and procured a lithium ion battery for use in an advanced weapon sight system, shown in Figure 2. The WS battery pack consisted of six Moli 18650 lithium ion cells in a two-in-series by three-in-parallel configuration. The cells were attached to two printed circuit boards, one mounted on the top of the cells and one mounted on the top of the battery case. The cells were arranged in the battery case with half of the cell vents facing down and the other half facing up. These cells were then potted into the bottom of the battery case. The WS battery pack as tested had a
Ampere-hour (Ah) capacity rating with a nominal voltage of 8.4V.

Safety devices in the WS battery pack included a 7A fuse, a 120°C, 5A thermal fuse; and overcharge and over discharge protection circuits. Internal, cell-level safety devices included a PTC and a vent mechanism.

**UNMANNED UNDERWATER VEHICLE BATTERY**

Woods Hole Oceanographic Institute (WHOI) developed a semi-autonomous unmanned underwater vehicle (UUV) that can perform shallow-water reconnaissance. WHOI contracted with SAFT America, Inc. to design and manufacture a lithium ion battery to power this UUV as shown in Figure 3. From one to four UUV battery packs can be installed in the vehicle, where they are electrically connected in parallel. The batteries can be charged without opening the vehicle.

The cells used in these UUV batteries were SAFT model MP 176065 lithium ion cells with a normal voltage of 4.1 V. Each cell included a vent and a low-pressure circuit breaker. Each UUV battery contained 14 cells. Two cells were connected in parallel, and seven of these cell pairs were connected in series. Thus a nominal, fully charged battery voltage was 28.7V. The capacity ranged between 9 and 11 Ah, depending on discharge rate. Each of the cell pairs had a thermal fuse that opens at 84°C (+0; -3 Celsius degrees) and is rated at 15 amperes.

Within each UUV battery, the string of seven cell pairs was divided into two groups. In the string, the negative-most four cell pairs formed the first group, and the positive-most three cell pairs formed the second group. Each group had its own protection circuit and its own end-of-discharge diode. The string had one 15 ampere, “Slo-Blo” fuse (218015 Littelfuse or 0034.3129 Schurter). Each battery also had an SMBus (Smart Bus) integrated circuit (IC). Each UUV battery also contained a DC-DC converter that has an input of 32 VDC and an output of 28.7 VDC at 1 A that was used to charge the battery. This converter was made to order by VICOR.

**BATTERY SAFETY TEST RESULTS**

NSWC Carderock, Code 644 conducted safety testing on the three above described battery designs in accordance with the Navy’s Lithium Battery Safety Program as described in Technical Manual 9310-AQ-SAF-010 [2]. Tests included short circuit, over discharge, overcharge, thermal abuse, and electrical safety device (ESD). It should be noted that short circuit, over discharge, and overcharge tests were conducted with all battery-level safety devices bypassed. For each of the battery designs, tests were conducted both on fresh batteries and on batteries that were aged or used to approximately 50% of their projected cycle life.

**HHR Battery**

Under worst-case conditions of thermal abuse, all of the HHR batteries vented, but only one of the three HHR batteries tested under these conditions caught on fire. During the overcharge tests, no visible damage to the batteries was recorded on video. However, post-test inspection of the batteries revealed that cells in two of the batteries vented and released electrolyte into the battery housings. All other electrical abuse conditions resulted in benign outcomes. Safety device functions were verified over multiple cycles in the ESD tests. No variations were noted between the behavior of the new and used batteries. Thus, under testing conducted in accordance with Navy lithium battery requirements, the HHR lithium ion battery was characterized as having a good overall safety rating.

**WS Battery**

The WS battery performed safely during short circuit, ESD, over discharge and overcharge. During these tests, the WS battery did not vent or produce flames. The battery exhibited only moderate temperature rises during these tests. No variations were noted between the behaviors of the new and used batteries. The thermal abuse test resulted in all batteries...
HHR: Overcharge test SN115

![Graph showing temperature, voltage, and current vs. time during an overcharge test on the HHR battery]

**Fig. 4. Temperature, voltage, and current vs. time during an overcharge test on the HHR battery**

TWS: Overcharge Test on SN11

![Graph showing temperature, voltage, and current vs. time during an overcharge test on the WS battery]

**Fig. 5. Temperature, voltage, and current vs. time during an overcharge test on the WS battery**

HHR: Thermal Abuse Test SN105

![Graph showing temperature, voltage, and current vs. time during a thermal abuse test on the HHR battery]

**Fig. 6. Temperature and voltage vs. time during a thermal abuse test on the HHR battery**

The safety tests conducted on the SAFT lithium ion UUV battery resulted in benign reactions to most abuse scenarios. The safety devices and internal protection circuitry demonstrated success in protecting the battery against overcharge, over discharge, and short circuit. Even when safety devices were bypassed, there were no UUV battery ventings in response to these abuses. The thermal abuse test results indicated that external exposure to temperatures over approximately 160°C could result in batteries venting, and possibly a fire if there is an ignition source for the spilled electrolyte. No variations were noted between the behavior of the new and used batteries. Thus, under testing conducted in accordance with Navy lithium battery requirements, the UUV lithium ion battery was characterized as being acceptable for Navy use.

**DISCUSSION**

The size and chemistry of the component cells, as well as the basic designs of the battery packs, influenced the safety test results described. For example, of the three battery designs described, only the HHR battery vented during overcharge testing. This venting was benign and remained internal to the battery case. However, given the flammability of the electrolyte, the potential for fire was present.

The overcharge tests on the HHR batteries were conducted at the nominal charge rate of approximately 2.5A to an over voltage of 14.5V (15% over voltage) for 4.5 hours (150% normal duration). Figure 4 illustrates the temperature, voltage, and current data collected during an overcharge test on the HHR battery. The overcharge tests on the WS battery were conducted at the nominal charge rate of approximately 4A to an over voltage of 9.0 to 9.4V (10-15% over voltage) for 6 hours (150% normal duration). Figure 5 illustrates the temperature, voltage, and current data collected during an overcharge test on the WS battery. Thus, at the cell level, the HHR cells were

<table>
<thead>
<tr>
<th>Short Circuit</th>
<th>Over Charge</th>
<th>Over Discharge</th>
<th>ESD</th>
<th>Thermal Abuse</th>
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<tr>
<td>HHR Battery</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>V</td>
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<tr>
<td>WS Battery</td>
<td>B</td>
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<tr>
<td>UUV Battery</td>
<td>B</td>
<td>B</td>
<td>B</td>
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B = Benign Result
V = Venting of Cell
F = Fire

*(#) indicates number of events*
exposed to only a slightly higher over voltage of approximately 0.13V at a slightly lower charge current by about 70mA. It is unlikely that this small difference in test parameters could be the sole cause of the variation in battery behavior observed during these tests. Therefore, we conclude that the Sanyo UR18650P cell may be more susceptible to venting in response to overcharge than the Moli 18650 cell.

The overall results of the thermal abuse tests were more violent for the WS battery than for the HHR battery. In addition to all of the WS batteries catching fire (as opposed to one out of three of the HHR batteries), all of the WS batteries generated flying debris when they vented. This result is interesting given that both batteries contain six 18650-type cells. Additional tests were conducted to verify that the heating methods used in the tests were not the cause of this variation in results. Two possible conclusions were reached: 1) the Moli 18650 cells vented at higher pressure and create a more energetic reaction to heat when compared to the Sanyo UR18650P cell; or 2) the packaging of the cells in the WS battery interfered with the cells venting and caused them to vent more violently then they would without the presence of the potting. It is also possible that the observed reaction was a combination of these two conditions. However it would seem that the second condition is the least likely given that venting did occur just prior to the rapid disassembly. Figure 6 shows results from HHR thermal abuse testing and Figure 7 shows results from WS thermal abuse testing.

CONCLUSION

The battery safety test results described demonstrate acceptable safety behavior for a lithium battery that will be fielded for use in a Naval application. Reliable performance of safety devices, both at the battery and at the cell level, is an essential characteristic. Other safety test results must be evaluated in the context of the system enclosure and keeping in mind the deployment methods to make a final recommendation concerning the safety approval of a battery.

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REFERENCES