Navy Safety Testing of Lithium Ion Batteries for the Battlespace Preparation Autonomous Underwater Vehicle (BPAUV)

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Abstract

Lithium Ion batteries have key performance characteristics that frequently make them the chosen power source for Autonomous Underwater Vehicle (AUV) applications. Their high gravimetric energy density results in substantial savings in both volume and weight, which can increase payload capacity and improve the mobility of the vehicle. However, as with all energy dense storage systems, safety must be engineered into the design of the battery at all levels. All lithium batteries that are fielded by the United States Navy are evaluated for safety in accordance with NAVSEA Instruction 9310.1b and the Technical Manual S9310-AQ-SAF-010. This paper describes the safety tests conducted on the Battlespace Preparation Autonomous Underwater Vehicle (BPAUV) lithium ion battery. Results of BPAUV sub-module and battery tests conducted by NSWC Carderock are also presented.

Introduction

A significant number of critical Naval missions can be met or enhanced using AUV technology. The Navy UUV Master Plan[1] highlights the following areas that could be addressed with this technology: Intelligence, Surveillance, Reconnaissance, Mine Countermeasures, Tactical Oceanography, Communications, Navigation, and Anti-Submarine Warfare. Advantages of using AUVs include (but are not limited to): multiplication of force, cost savings, and removal of personnel from harm's way. One of the critical sub-systems for determining overall performance and mission capability of a UUV is the power system.

Battlespace Preparation Autonomous Underwater Vehicle (BPAUV)

BPAUV Mission and Capabilities

Bluefin Robotics initially developed the BPAUV under sponsorship of the Office of Naval Research (ONR). The vehicle was designed to carry out a mission of covertly gathering accurate bathymetry and bottom classifications using acoustic sensors in the early stages of Battlefield preparation. Many successful demonstration missions have been completed and the overall vehicle design has been refined over the past 6 years through an evolutionary process of improvement. As a direct result of these years of demonstration and development, this AUV has been chosen as one of a group of systems that will be fielded aboard the Littoral Combat Ship (LCS) to support the mine countermeasure mission of this future platform.

The BPAUV shown in Figure 1 is designed to gather bathymetry and bottom classification for various mine countermeasure missions. Once deployed, the vehicle operates independently of its deployment platform following a set of pre-programmed mission directives. After surveying up to 8 sq nautical miles per dive (during dive durations of up to 18 hours) using dead-reckoning-based navigation and high-resolution side scan sonar, the vehicle returns to a pick up location with 10 cm by 7.5 cm sonar data, bathymetry and physical oceanography data. After recovery, the vehicle can be rapidly turned around on ship and re-deployed with a new mission and batteries.

Figure 1. BPAUV during deployment

BPAUV Power Supply Design

An important design feature of BPAUV is the free-flooded architecture; this provides true modularity through field swappable components. Use of a pressure tolerant battery system completely obviates the need for operators to service the O-rings and seals normally associated with batteries housed in pressure vessels. While historically, the down time associated with battery charging was the main limiting factor affecting fast turnaround times, pressure tolerant batteries remove this limitation by providing the ability to replace 7kWh of battery energy in under 15 minutes. This feature has created a new operational paradigm: while the vehicle searches, the spare batteries are

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[1] The Navy Unmanned Undersea Vehicle (UUV Master Plan of 20 April 00

charging in preparation for the next mission, making back-to-back search and classify missions a practical reality.

Key parameters used to compare energy storage are the Wh/L or Wh/kg. Both are important metrics that limit the amount of energy that can be floated or contained within a pressure vessel. An alternative metric is the Whrs per neutral Kg, which is best suited to compare cells and batteries used in underwater vehicles. Simply put, this metric includes all flotation required to make the energy system neutrally buoyant. After examining the trade off between housing cells in pressure vessels and encapsulating battery packs for direct immersion, it was determined that the latter metric is the most suitable for this application.

With historical hydrodynamic information gleaned from previous vehicle designs using Silver/Zinc batteries, Bluefin engineers combined the many design parameters of energy requirements, handling, safety, system integration, charging, shipping and logistics to determine that the optimum energy configuration for the BPAUV was that of two 3.5kWh batteries weighing in at around 31kg each (see Figure 2). In the final analysis, the batteries have a dry specific energy capacity of 116 Wh/kg and a neutral energy density of 105Wh/kg using 300 meter rated foam flotation.

Figure 2. BPAUV batteries

Bluefin Robotics Corporation originally developed pressure tolerant batteries under a Navy funded Small Business Innovative Research (SBIR) contract. Since then, over 60 batteries packs have been made and installed on many AUVs. The battery packs used in BPUAV were first granted limited safety approval for use in Navy experiments in 2003. Also in 2003, Bluefin upgraded the design by using better cells from another vendor, improved production processes, and implemented a second tier of testing and tracking in addition to vendor qualification. The battery pack is composed of a group of lithium ion polymer cells, which have been connected in a series/parallel combination and encapsulated in urethane. The battery total energy is approximately 3550 Watt-hours (Wh) with a nominal voltage of 29.6V and a demonstrated vehicle run time of 18 hours.

The battery includes an intelligent battery board controller that facilitates safe charging and discharging, as well as conditioning and monitoring vital statistics for the battery. The battery board also implements several protection mechanisms in hardware and firmware to protect the battery, the vehicle and the user from damage. The battery assembly itself is designed to operate in water; it does not need any other pressure vessel or casing to protect it from the environment.

The BPAUV battery design is described using some unique terminology. A unit of eight (8) cells connected in parallel is called a quanta. Each quanta has a pair of heavy-gauge positive leads and a pair of heavy-gauge negative leads. A unit of three (3) quanta connected in parallel is called a brick. A battery is composed of eight (8) bricks connected in series.

Navy Testing of the BPAUV Lithium Ion Battery

Overview of Navy's Lithium Battery Safety Testing

The Naval Surface Warfare Center (NSWC) Carderock, Code 616, conducted safety testing on the above described BPAUV battery design in accordance with the Navy's Lithium Battery Safety Program as described in Technical Manual S9310-AQ-SAF-010[2]. Tests included crush, short circuit, over-discharge, over-charge, high temperature abuse and electrical safety device (ESD). A small sub-population of bricks was aged to approximately 100% of the projected cycle life, and then abuse tests were repeated on them.

Tests were conducted on quanta, bricks and full-size batteries. The quanta and half of the bricks that were tested were not fully encapsulated. Use of some minimally-encapsulated quanta and bricks allowed for visual documentation of cell-level responses to the intended abuse conditions. Those results may then be compared with the fully-encapsulated bricks and production batteries under the same test conditions. Thus, the complete battery safety test program generates 1) a greater understanding and documentation of cell-level responses, 2) data that quantify the effects of the encapsulant, and 3) an accurate documentation of the end-item reaction to a given abuse condition. Use of sub-modules is also an accepted means to a more cost-effective and comprehensive test program.

Quanta-Level Safety Tests

The following tests were conducted on BPAUV quanta: crush, short circuit, over-discharge, over-charge, and high temperature abuse. Quanta contain no integrated safety devices and are not fully encapsulated. Verification cycles were performed on each quanta prior to conducting any abusive tests. All quanta performed normally during the verification cycles, delivering on average 40.5 Ah.

Short Circuit Test: Two short circuit tests were conducted on fully charged BPAUV quanta. Each quanta was short-circuited through a resistance of approximately 3 milliohms for a minimum time interval of 24 hours. The external

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[2] NAVSEA Technical Manual S9310-AQ-SAF-010, "Batteries, Navy Lithium Safety Program Responsibilities and Procedures" of 19 Aug 04

short was applied through a Joslyn Clark relay connected to the quanta with AWG 4 and AWG 10 wire. A peak current of 588 A was recorded using a Fluke model 87 digital multimeter (DMM) in the first test.

When the first test resulted in a single negative lead connecting to the quanta burning open, the instrumentation was changed to use both quanta leads to carry the short circuit current. This test also generated a peak current of 624 A, and the same benign result of a burned open lead.

Crush Test: The same quanta that were used for the short circuit tests were subjected to a series of crush tests. The first quanta was crushed in a hydraulic press using a triangular metal bar. This quanta vented and caught fire after only a slight deformation of the end cell that was exposed to the crushing force. Figure 3 is a snapshot from the video taken after the crush test of the quanta using this setup. The second quanta was hit with a 10 pound weight dropped from 4 feet, and it survived multiple strikes in 3 orientations before it vented and caught fire.

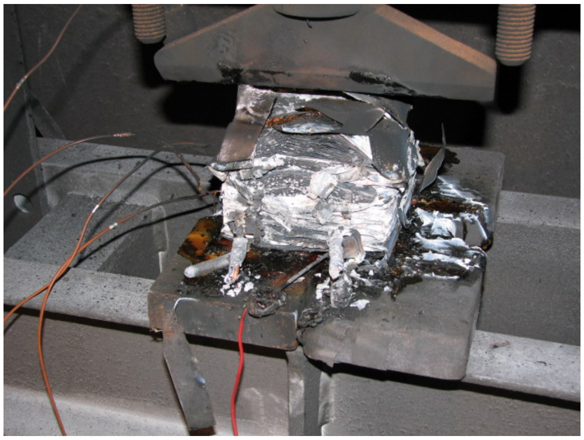

Figure 3. Quanta Crush Test on Serial Number Q8

Over-charge Test: In the over-charge test, the quanta were discharged at a nominal constant current rate of 20 A using a Kikusui electronic loader, model PLZ603W until the battery voltage dropped to 3 V. After discharge, the quanta were allowed to rest for one-half hour, and then charged abusively at 10 A to 5.25 V using a Kepco power supply, model ATE 6-100M, until the charging current dropped below 0.02 A or battery failure occurred. This test was conducted twice. The first time the quanta was freestanding in air. The second time, the quanta had Plexiglas plates affixed to each flat-sided face, and the entire unit was taped in an effort to make the asset more representative of an encapsulated battery.

The BPAUV lithium ion quanta responded to the over-charge abuse as expected. Cells vented with smoke and quickly caught fire. The maximum temperature recorded on the quanta (prior to initial cell venting) during over-charge testing was 91°C.

Over-discharge Test: In the over-discharge test, one quanta was discharged abusively into voltage reversal at a rate of 20 A for 2.5 hours using a circuit with both a Kikusui electronic loader, model PLZ603W, and a Kepco power supply, model ATE 6-100M. At the end of the discharge, the quanta voltage was –2.3 V. The maximum temperature recorded on the outside of the quanta during this test was 100°C. The BPAUV quanta responded benignly to over-discharge abuse. No cells vented in response to this test, and the final physical result was slight but discernable swelling of cells, and inoperability of the quanta.

High Temperature Abuse Test: The high temperature abuse test was conducted on two quanta. One quanta was fully charged, and the other was fully discharged at the time of the test. A single, 225 W heating plate was affixed directly on the outermost cell of the quanta, and Plexiglas endplates were taped onto the pack to provide additional structure. The quanta were instrumented with thermocouples at various locations adjacent to the heating plate, and also opposite it. The voltage applied to the heating element was controlled with a Variac variable auto-transformer. Each quanta was heated at a rate of approximately 5°C per minute up to a maximum temperature of 500°C.

Approximately 50 minutes after the test on the fully charged quanta was started, a large temperature rise was measured. The thermocouple measuring closest to the heating element read 340°C just prior to this temperature raise. The thermocouple farthest from the heating element measured 57°C. Shortly thereafter, the quanta began to vent and caught fire. In the test with the fully discharged quanta, the end result was cell venting with much smoke, but no fire. The temperatures increases for this test were more gradual and the heating element was used continuously to deliver heat to further the abuse throughout the quanta.

Brick-Level Safety Tests

The following tests will be conducted on BPAUV bricks: aging cycles, short circuit, over-discharge, over-charge, and high temperature abuse. Like quanta, bricks contain no integrated safety devices. Two sub-populations of bricks will be tested in this evaluation: 1) bricks with minimal encapsulant and a significant exposure of individual cells to air, and 2) bricks that have been fully encapsulated in urethane in a manufacturing process that is similar to the full-size batteries. Verification cycles were performed on each brick prior to conducting any abusive tests. Three bricks have been subjected to verification cycles to date and all have performed acceptably, delivering on average 123 Ah. The data presented below summarize the brick-level testing that was complete as of the submission date for this paper. All of the bricks tested to date are from the first sub-population, and have minimal encapsulant and exposed cells.

Aging Cycles: As noted previously, four bricks were aged by repeated charge/discharge cycling prior to their use in abuse tests. The goal of the aging effort was to complete approximately 100% of the projected cycle life (200 cycles) of the BPAUV battery on bricks. The aging cycles consisted of taper charging the bricks at 25 A and 4.2 V for 5 hours, discharging them at 30 A to a cutoff voltage of 3 V, and then holding them at open circuit voltage for 30 minutes before repeating. A data plot showing this aging cycle on a brick is shown in Figure 4. At the date of submission of this paper, all four bricks had achieved over 150 cycles. Based on the first 100 cycles, an average capacity fade of 2.67% from their initial value of 122.9 Ah was observed.

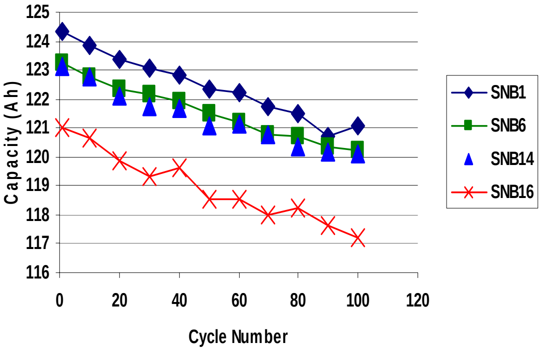

Figure 4. Aging Cycle Data on BPAUV Brick

Over-charge Test: In this test, the bricks were discharged at a nominal constant current rate of 30 A using a Kikusui electronic loader, model PLZ603W until the battery voltage dropped to 3 V. After discharge, the quanta were allowed to rest for one-half hour, and then charged abusively at 25 A to 5.25 V using a Kepco power supply, model ATE 6-100M until the charging current dropped below 0.02 A or battery failure occurred. This test regime is comparable to a scaled up version of the over-charge test that was conducted on the quanta. As in the second quanta test, the brick had Plexiglas plates affixed to each flat-sided face, and the entire unit was taped in an effort to make the asset more representative of a fully potted battery.

As expected, the bricks responded to over-charge much as the quanta did. Cells vented with smoke and quickly caught fire. The maximum temperature recorded on the brick prior to thermal runaway was 104°C. Qualitatively, the test engineer noted that the force of the event may have been somewhat greater than with the quanta, but he attributed that to a more successful encapsulating of the brick using the endplates and tape. The onset of the event was not significantly accelerated by the greater energy content of the brick versus the quanta, nor was the maximum temperature significantly greater. Figure 5 is a snapshot from the video taken during the over-charge test of BPAUV brick Serial Number (S/N) B11.

Figure 5. Brick Over-charge Test on S/N B11

Battery-Level Safety Tests

The following tests will be conducted on BPAUV batteries: Electrical Safety Device (ESD) test, short circuit, over-charge, and high temperature abuse. No battery-level testing was complete as of the submission date of this paper. Evaluation of the effect of a worst-case battery event on a fully encapsulated battery installed in a BPAUV housing will be documented. Verification of the reliable performance of the battery safety electronics will be critical to support recommendation for safety approval of the BPAUV battery design.

Conclusions

Safety tests on the quanta and bricks completed to date have generated expected results based on the electrochemistry and construction of the battery subassemblies. Test results from both quanta and unencapsulated bricks indicate that over-discharge and short circuit abuses would produce benign responses from the BPAUV battery, regardless of the presence of safety devices. Over-discharge typically resulted in limited bulging or swelling of the battery pack in-situ, also a benign failure mode. The test results to date indicate that a worst-case battery event with a BPAUV lithium ion battery would likely result from abusive over-charge or high temperature abuse. It is worthwhile to recall that the electronic controls within the battery that are specifically designed to prevent abuse over-charge would have to be circumvented or fail to create the possibility of this hazard occurring in the field. Additionally, the dedicated charging station has safety cut outs that prevent overcharge of the batteries if the battery electronic systems fail.

Repetition of the brick-level safety tests on bricks that have been fully encapsulated will determine if the encapsulation decreases the magnitude of the overall battery event in worst-case failures. The completion of the Electrical Safety Device tests on the full battery will be critical to verifying that the internal protection circuitry is successful in protecting the battery against over-charge.