# Performance, Safety Characterizations and System Integration of a Large Lithium Thionyl Chloride Battery for Unmanned Undersea Vehicles

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**Abstract**
The Unmanned Undersea Vehicle (UUV) Program Office of NAVSEA (PMS403) is developing the first in a series of UUVs capable of extended autonomous missions, with launch and recovery by submarine. NSWC Carderock in conjunction with NUWC Newport, the prime contractor Boeing Corporation and the battery prime contractor HED Battery Corporation are conducting an integrated, parallel development and qualification of the non-rechargeable power source for the AN/BLQ-11 vehicle, also known as the Long-term Mine Reconnaissance System (LMRS). We will present an overview of the system, the vehicle design for non-rechargeable power, the battery and the performance requirements. We will describe the performance and safety testing being conducted and ongoing efforts to qualify the battery for internal carriage, launch and recovery by a submarine platform.

**System Overview and Description**
A detailed description of the AN/BLQ-11 unmanned undersea vehicle (UUV), and associated shipboard support equipments is beyond the scope of this paper. Details of the requirements may be obtained from a review of the A-Level System Requirements Specification (1). Suffice to say, the AN/BLQ-11 vehicle is a 21” format, 240” long device that is launched and recovered via a submarine torpedo tube. Presentations at other conferences have addressed detailed overviews of the AN/BLQ-11 system and its physical design. Approximately 20% of the vehicle length and weight is allocated to the stored electrical power system, referred to as the Energy Section. The Energy Section is designed to be a modular component of the AN/BLQ-11 vehicle to permit rapid change out and refit while in the torpedo room of a submarine.

**Energy Section Design**
The Energy Section design consists of a pressure hull, bulkhead plates, mounting hardware, battery cells, monitoring and control interface electronics, and active and passive safety devices. The pressure hull is required to permit operation at normal operating depths and carry structural loads during launch. The Energy Section maintains communication with the submarine platform whether stowed as a spare “battery” or installed to a vehicle. This communication assures comprehensive monitoring of all lithium batteries for the UUV while internal and external to the submarine.

The overall Energy Section is approximately 52” long and weighs nearly 700 pounds in air. The active components of the battery housed in the Energy Section weight just over 460 pounds.

The Energy Section must provide the UUV with at least 96 kWh of energy, including a 20% energy margin. The details of the Energy Section are listed in Table 1. Twenty-four lithium-thionyl chloride cells are connected in series to provide the energy requirements.

**TABLE 1: Energy Section Characteristics**

| | |
|---|---|
| Energy Section Weight | 694 lb |
| Energy Section Dim. | 21” diameter x 52” long |
| Nominal Discharge Power | 1300 Watts with 38 Amp transients |
| Peak Sustained Discharge Power | 2800 Watts with 38 Amp transients |
| Battery Weight | 462 lb |
| Battery OCV | 88 VDC |
| Battery Loaded Voltage | 70 to 82 VDC |
| Nameplate Capacity | 1200 Ah |
| Cell OCV | 3.67 |
| Cell Energy | 4.05 kWh |
| Battery Energy | 97.2 kWh (nameplate) |
| Planned Energy Use | 77 kWh |
| Cell Loaded Voltage | 3.30 to 3.45 VDC |
| Cell Weight | 17.6 lb |
| Cell Dimensions | 8” diameter by 4.98” tall |
| Module Dimensions | 8” diameter x 42” long |
| Battery Electrical Description | All cells wired in series, each cell is electrically fused, battery electrically and thermally fused. All cells individually monitored for voltage and temperature. Battery health status monitored and reported every second by vehicle onboard computer |

**Battery and Cell Design**
The present cell is a further optimization of the HED Battery Corporation’s Small Business Innovative Research (SBIR) effort (conducted through PMS-403 and NUWC Newport), and the additional Internal Research and Development (IRAD) funds pursued by Boeing during the prior phase of system development.

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The basic nature of these cell development efforts have been previous described (2, 3, 4).

Presently, the AN/BLQ-11 cell is a nominal name-plate of 1200 Ah with a delivered energy of 4kWh under a 20 Amp constant current discharge to 2.9 volts. Optimization during the present design phase included reduction of the electrolyte fill level to prevent hydraulic over-pressurization under abusive temperature extremes as well as strengthening of the cell case to increase robustness.

Each cell includes a 90-amp time-fuse assembly that is produced as an integral component of the cell. This fuse rating is approximately 2x the maximum anticipated current under use and is 33% above the maximum sustained current permitted by the inboard UUV branch fuses. Approximately 400 cells have been built under the current effort for performance and safety tests, quality assurance checks, and module and battery assembly deliverables.

Each Energy Section "Battery" consists of 24 cells. These cells are arrayed in the pressure hull as a triad of 8 cell stacks. These 8 cell stacks, or modules, are held together under compression by two end-plates held on a central mandrel. Cells are isolated from each other along the central rod by thermal conduction/mounting plates which are themselves electrically isolated from the hull by a thin layer insulator. The thermal conduction/mounting plates serve to passively connect the cells to the hull for conduction cooling to water and physically mount the cells to the hull by a compression provided by wedge-locks. Approximately 36, 8-cell modules are to be built and tested in the present effort.

Each cell is individually monitored electrically and thermally. These data are gathered by the Battery Monitor Electronics Assembly (BMEA) mounted in the energy section that operates with external power in storage, or on internal power when underway as part of the UUV. The BMEA transmits battery data via serial data-links to both torpedo room and internal vehicle computers, allowing the system to maintain a status and record of the battery characteristics during all phases of shipboard and mission usage. The total suite of battery data available to system operators include cell and energy section temperature, cell and battery voltage, energy section pressure, battery current, energy extracted, capacity extracted, and water leak detection.

The UUV is powered externally during pre-programming, requiring both diode isolation and charge detection control. The UUV and external power sources are diode isolated permitting a "soft-crossover" of power from the external power supply to the UUV battery during launch operations. Figure 1 and 2 are schematic and block diagrams of the battery and health monitor circuits.

Figure 1: Battery Block Diagram

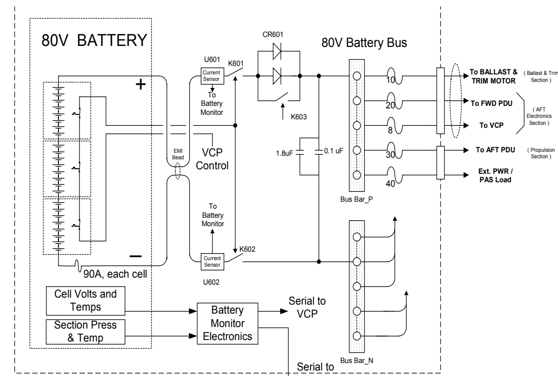
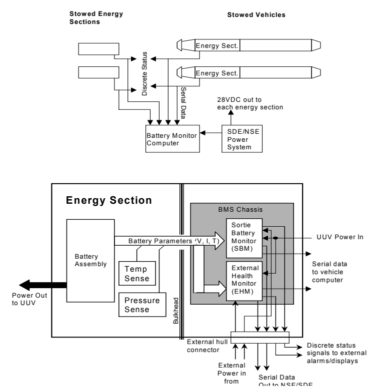



Figure 2: Monitoring System Block Diagram




**Development of a Combined Test Program**
The emphasis of the current test program is determination and verification of the safe operating envelope for the lithium battery as it will be used in the AN/BLQ-11 vehicle from a manned submarine launch platform. Verification of compliance to the environments of the A-Specification, specific contractor system performance characteristics, safe shipping characteristics to support Department of Transportation (DoT) cognizant authority (CA) adjudication and evolved test conditions based upon submarine stores handling logistics were overlaid to formulate a comprehensive test program. In addition, combinations of MIL-STD-810F, MIL-STD-167, NAVSEA Technical Manual S9310-AQ-SAF-010, and the "UN Regulations for the Transport of Dangerous Goods" were the principal specifications and requirements used to develop the joint test and evaluation plan. Discussion of the formulation of the test plan is covered in detail in another paper (5).

The unique nature and legacy heritage embodied by the HED Battery cell designs permitted a simplified safety test characterization program to be conducted. This test program relies heavily upon characteristics of the previous cell design and intensive cell-level verification of abuse tolerance and failure modes under abuse. This program emphasized cell-level tests, followed by module-level (8-cell assembly) tests for the traditional NAVSEA S9310-AQ-SAF-010 test series.

The design of the Energy Section and vehicle interfaces that acknowledged early on the potential hazard posed by the energy source were mirrored in the test plan at the cell and module levels. The concept of an "intelligent" open battery with live access data telemetry to the submarine crew is unique to this application. The ability to monitor the battery at all times while aboard the submarine has eliminated, reduced or altered some of the more extreme test series designed to understand the behavior of otherwise deaf and dumb battery powered applications.

The number of safety tests at the all-up battery, (or Energy Section level), are significantly reduced in comparison to other programs. Again this is due to the "intelligent" smart battery concept designed into the system. Significant portions of the test program at the all-up energy Section level evaluates the ability of the passive safety systems and software control to prevent the battery from operating in an unsafe manner.

**Performance Tests and Characterizations**
Performance tests have been conducted as part of the overall test program. These performance discharges have tested and examined the cell, module and battery capability of performing the mission requirements with sufficient energy to meet all requirements. Cell level tests have been conducted at both "constant" current and power conditions with transients to simulate mission load requirements. These tests have been conducted under various thermal conditions and after varying degrees of storage and handling. With exception of cells and battery stored under excessive temperature, no problems were observed with performance or start-up voltage delay under the designated load profiles.

Environmental conditioning and tests have been completed at the cell level. These tests have demonstrated that the cells are exceptionally robust physically and capable of withstanding the combined environments of the master requirements specifications.

Similar environmental and performance testing has been conducted at the module (8-cell) level. The tests conducted to date are demonstrating equivalent behavior to the cell data generated earlier.

Performance qualification of the cells as a battery assembly will be conducted on at least two articles prior to the start of in-water testing. These tests will also have fully operational software involvement and may be partial step-wise discharges to emphasize the verification of the software in a working environment.

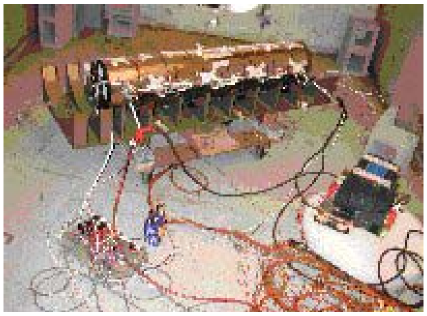
**Safety Tests and Characterizations**
Preliminary safety characterizations were conducted during the previous phase of the AN/BLQ-11 Energy Section development. These results were favorable and have been described previously (6). The test program currently underway is an expansion of the tests conducted during the previous work, and of prior test programs with a larger variation of the cell being evaluated for the AN/BLQ-11.

Significant progress was made in July of 2000 when fresh and spent cells were subjected to Mil-S-901 shock environments. This was a significant achievement as no cells of this size had ever undergone Mil-S-901 shock previously. Figure 3 shows a set of cells undergoing shock testing. The fresh cells were evaluated under various discharge conditions and found to be undamaged. Subsequent cell level tests have demonstrated the cells can withstand moderately extreme air-carriage vibration, thermal over-temperature. Forced reversal discharges, from C/30 to C/120 rates, even at low temperatures are tolerated to lithium exhaustion and appear stable even several weeks after cessation of the test. High reverse current (charging) has been demonstrated to be severely damaging, however the cells can withstand four hours of 30 amperes charge prior to venting. Voltage limited reverse current charge, on the order of 3.8 VDC is tolerated with milliampere current flow for 24 hours. Fully depleted cells have demonstrated ability to operate the 90-Amp fuse assembly. High-rate discharges (just below fuse values) do not adversely affect either fresh or discharged cells.

Figure 3: Cell 901 Shock Testing

Module tests are still ongoing. Testing completed to date indicate that the modules are capable of tolerating severe electrical abuse. Pseudo-adiabatic high rate discharges (approx. 80 amperes continuous) and short-circuits produce no adverse behavior. Modules have also been discharged under a 60-odd amp limit to simulate a worse-case test anomaly aboard a submarine limited by the UUV fuse panel with demonstration of passive/active safety devices. Modules have been discharged resistively to approximately zero volts (with 7 of 8 cells in reversal), with no hazardous behavior after recovery. Figure 4 shows a typical module test set-up at the NSWC facility.

Figure 4: Module Discharge Testing



Battery level tests are planned to be conducted in parallel with the last of the module level tests. The battery tests will include extensive testing of the active and passive safety devices, and will concentrate on performance behavior that is outside of the normal operating range to establish performance limits and demonstrate robustness in the operation of the battery.

Software based safety verification with live hardware is a critical step. Software development status is paralleling vehicle development and is not presently fully functional at the vehicle control level. Software and hardware to be used as modules are sitting in storage is ready and will be tested in conjunction with final battery level environmental tests and safety and performance tests.

As in the cell level tests, the demonstration of a fully functional electrical monitoring system after exposure to numerous Mil-S-901 shock pulses is considered a critical step. The battery, as a battery assembly does not need to function, but must remain safe.

**Platform Integration**

The integration and submarine certification of the AN/BLQ-11 with a lithium battery Energy Section is perhaps the single highest technical risk associated with the LMRS program and system performance goals. The Energy Section design, operation, and its overall compatibility with the platform have had continuous scrutiny from the onset of the program. Close coordination with the engineering and design oversight codes of Naval Sea Systems Command has been sought from the start. Numerous technical reviews and comments have been incorporated into the design of the battery, vehicle interfaces, and the nature and type of tests that the battery and vehicle will undergo.

The AN/BLQ-11 is the first program to attempt to put a lithium battery of this size into a submarine platform on a permanent carriage basis. Needless to say, a great deal of education and coordination has been needed and will be needed. The program is trailblazing the requirements and logics necessary to implement the hosting of such a system inboard.

Issues and requirements that must be addressed are firefighting, atmosphere control, casualty procedures, shock response, handling and load-out, refurbishment underway, and system start-up and depassivation. One of the critical elements of the platform integration is assuring the safety of the platform after a severe shock impulse to the various UUV battery sections. This is met by demonstrating safe performance and structural integrity of the cells and battery modules after exposure to the severe shocks applied under Mil-S-901. The Battery Health Monitor is also required to function after exposure to these shocks, so that the status of all the batteries may be ascertained and known at all times.

**Present Status of Test Program**

The battery tests are progressing with little variation from the original test plan outline developed. Minor extension of the test plan may develop from incorporation of Naval Sea System Command submarine engineering and design codes for other environments.

The currently planned test program should be completed by December 2002, with request for certification going forward for March 2003.

**Summary and Outlook**

The present cell and batteries are performing and functioning as designed under performance discharges and test verifications. The energy content of the battery meets all of the contractor and Program Office requirements for the AN/BLQ-11 operation. The safety-related behavior of the lithium thionyl chloride battery is being demonstrated as fault tolerant and robust. The suite of active and passive safety devices, and intertwined software interlocks provide a multilevel overlay of control, communication, intervention and protection over a robust design. No unexpected behaviors have been observed under cell and module level abuse and performance testing. The lithium-thionyl chloride battery for the AN/BLQ-11 should be able to demonstrate safe performance behavior suitable to meet the stringent requirements for submarine carriage.

**Acknowledgements**

The authors would like to acknowledge the funding and support of the Unmanned Undersea Vehicle Program Office (PMS-403).

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