LITHIUM BATTERY SAFETY IN SUPPORT OF OPERATIONAL FIELDING OF UNMANNED UNDERWATER VEHICLES
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Abstract
Lithium-ion batteries provide significant advantages over lead-acid, nickel cadmium, and silver zinc electrochemistries for use in Unmanned Underwater Vehicles (UUVs). Lithium-ion batteries with high energy densities provide significant benefits in weight, volume and extended mission durations. However, dormant and operational hazards increase with higher overall system energy density. To assure that the risks associated with all lithium batteries fielded in Navy applications have been characterized and accepted appropriately, the Navy employs a structured and tailored lithium battery safety program. This paper will review the Navy’s lithium battery safety program and discuss its implementation with respect to a variety of lithium-ion battery designs for use in UUVs. It will cover both general lithium battery safety testing and platform specific requirements for both shipboard and submarine deployments.

Introduction
A significant number of critical Naval missions can be met or enhanced using UUV 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 UUVs 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.

The predominant technology in use today for UUV power is lithium-ion batteries. Lithium-ion batteries provide significant advantages over lead-acid, nickel cadmium, and silver zinc electrochemistries for use in unmanned vehicles. Lithium-ion batteries with high energy densities provide significant benefits in

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\(^1\) The Navy Unmanned Undersea Vehicle (UUV) Master Plan of 20 April 00

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Figure 1. Comparison of Delivered Energy for Various Battery Electrochemistries\(^2\)

Lithium-ion batteries are a form of stored chemical energy. The desired output from any battery is

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\(^2\) Handbook of Batteries, Fourth Edition, David Linden and Thomas B. Reddy
controlled release of electrical power in the form of current and voltage. However, lithium metal and lithium-ion batteries are also capable of generating undesired release of their stored energy, typically in the form of excessive heat, fire, release of toxic or noxious chemicals, and even high pressure events that look like explosions. The bulk of the energy release from lithium-ion batteries occurs when the battery fails in an oxygen atmosphere, as the electrolytes are typically quite flammable. Early (1970-1980’s) deployments of lithium primary (non-rechargeable) batteries by the United States military service resulted in some unprecedented safety incidents, including personnel injuries, and even loss of life, in extreme cases. A thermal runaway event in 2008 with a large lithium-ion battery resulted in the complete loss of a submersible system, although no personnel were injured.

The Navy’s Lithium Battery Safety Program

Technical Authority
In the mid 1980’s, the Department of Defense issued a policy requiring that lithium battery hazards would have to be managed if the technology was going to be utilized by the military services. OPNAV 5100.8G, CH-2 of 24 May 89 established the Naval Sea Systems Command (NAVSEA Code 665) as the responsible agent within the Navy for management and implementation of a lithium battery safety program. Various reorganizations within NAVSEA resulted in the transition of the cognizant authority for lithium battery safety to the Naval Ordnance Safety and Security Activity (NOSSA). The Commander of NAVSEA Command is still the designated technical authority for lithium battery safety within the Department of the Navy (DON). NOSSA executes the Naval lithium battery safety program as an element of the overall DON explosives safety program.

Policy
NAVSEA Instruction (INST) 9310.1b of 13 June 1991 is the current policy document for the Navy’s lithium battery safety program. As of the writing of this paper, an update to this instruction was in final routing for signature, and the official release of NAVSEA INST9310.1c is anticipated to occur in late 2011. Therefore, this paper will reference the content of the revised 1c version of the document.

This instruction defines the process in terms of the scope of the program, as well as the roles and responsibilities of the various parties who must participate in the process. NAVSEA INST9310.1c applies to all Navy and Marine Corps activities who deal with the intended use or transport of lithium batteries and lithium battery-powered systems on Naval facilities, ships and aircrafts. Materials to which this instruction applies include: all non-rechargeable and rechargeable, active, thermal and reserve lithium batteries, as well as all equipment powered by lithium electrochemical power sources, throughout all phases of the life cycle of such systems.

The Naval Surface Warfare Center Carderock Division (Code 616) and the Naval Surface Warfare Center Crane Division (GXS), under the direction of NOSSA, act as lead Navy activities and technical agents in the execution of the lithium battery safety program. All Naval Systems Commanders (SYSCOMs), Program Executive Officers (PEOs), Project Managers (PMs), and any research and development activities conducted are responsible for implementing the lithium battery safety program within their cognizant material support area; assuring that lithium battery safety criteria are incorporated in the design of lithium batteries. Each Navy lithium battery safety review is specific to a given battery, application/system, concept of operations (CONOPS) and deployment platform.

A second document, NAVSEA Technical Manual (TM) S9310-AQ-SAF-010 of 15 July 10 provides additional guidance in the implementation of the policy set forth in NAVSEA INST 9310. In addition to documenting the Navy’s lithium battery approval process, TM S9310 also includes: (1) recommendations for designing safe lithium batteries, (2) recommendations for storage, transportation, packaging, and conditions, (3) disposal guidelines, and (4) recommendations for general emergency response procedures appropriate for most lithium and lithium-ion batteries.

Testing Protocols
One of the major policy contributions of NAVSEA TM S9310-AQ-SAF-010 is the testing protocols listed in chapter 11 of the document. Testing requirements for lithium batteries are organized by and specific to the following battery types:

1. Primary (non-rechargeable)
2. Secondary (rechargeable)
3. Reserve (liquid and thermal)

Chapter 11 of the TM describes the minimum test asset count, and identifies and describes minimum tests required. However, specific test programs for each given battery and application combination are developed from combining this guidance with battery and system design parameters.
For previously reviewed, tested and authorized battery/system combinations, an initial evaluation of the Safety Data Package describing the battery and system by the NOSSA technical agent supports the determination of required testing. Focused, “delta” test programs are usually used to repeat only the tests needed to determine the impact of any changes in battery or system design, or to address additional or changed platform integration issues.

Lithium battery safety testing conducted in accordance with NAVSEA TM S9310-AQ-SAF-010 has two basic goals. The first is to validate the performance of the battery’s safety devices under likely and/or typical abuse conditions. Both short circuit and high rate discharge into voltage reversal tests are run on primary batteries to achieve this goal. If the candidate system uses a rechargeable battery, these tests include short circuit and a high-rate overcharge/overdischarge.

The second goal of the Navy’s lithium battery safety testing protocol is to quantify the response of the battery to some worst-case abuse conditions. In these tests, all battery-level safety devices must be removed or bypassed so that data can be gathered on the worst possible failures that can occur with the battery/system. Tests include high temperature abuse, charging (for primary batteries) or overcharging (for secondary batteries), and sometimes physical abuse exposures like nail penetration, bullet penetration, impact and crush tests.

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**Platform Integration Requirements**

**Concurrence Requirements for Specific Platform Carriage and Use**

For any program whose system contains a lithium battery system to be deployed, transported, or recharged on a surface ship, aircraft, or submarine; specific concurrence from the technical authority for the platform in question must be secured prior to the issuance of a lithium battery approval by NOSSA. Naval aircrafts platform concurrence concerning design and suitability for any system that will be deployed or transported on Naval aircrafts is provided by NAVAIRSYSCOM CODE AIR 4.4.5.2. Naval forces afloat platform concurrence concerning design and suitability for any system that will be deployed or transported on Navy surface ships or submarines is provided by NAVSEASYSCOM CODE SEA 05Z. Military Sealift Command (MSC) platform concurrence concerning design and suitability for any system that will be deployed or transported on MSC vessels is provided by COMMSC N7.

**Overview of Technical Manual SG270-BV-SAF-010**

In 2011, NAVSEA issued a second technical manual designed to be implemented in conjunction with NAVSEA TM S9310-AQ-SAF-010 for those high energy systems, including lithium batteries, that are intended for use aboard Naval surface and subsurface platforms. The “High Energy Storage System Safety Manual,” NAVSEA TM SG270-BV-SAF-010, defines the NAVSEA process used to characterize hazards associated with high energy storage systems; to ensure the programs using these systems have implemented appropriate hazard mitigations. This provides maximum assurance that failures of these systems can be safely mitigated to avoid endangering Navy platforms and personnel. The manual is intended to address all chemical energy storage systems, including fuel cells. However, at present the manual focuses most specifically on lithium primary and rechargeable battery systems.

The manual relies on a rigorous system safety approach that has been tailored for large, high-energy battery systems to define requirements for a given battery system. Depending on system engineering choices made early in design development, and on risk mitigation strategies adopted, the test requirements section of the manual will need to be selectively invoked and tailored as applicable to the specific design, CONOPs, and hazard mitigations for a given battery system. The applicability of the specific test paragraphs given in the manual are determined based on the System Safety Program Plan.
(SSPP), from the specific hazards identified in the program’s Preliminary Hazard Assessment (PHA), System Hazard Analysis (SHA) and software safety analysis, and from the mitigations proposed for each hazard. The sponsoring program office must work with NAVSEA and NOSSA to establish a Test Plan (TP) that defines which of the tests in the manual are required and how these tests will be conducted, based on the hazards and mitigations identified for the program.

The testing described in NAVSEA TM SG270-BV-SAF-010 is based on validating a lithium battery’s safety characteristics against known design attributes for shipboard carried systems. Specifically this means containing severe negative output from the battery, thus limiting consequences to personnel and platforms. Testing is separated into characterization of failure modes and effect by demonstration and then validation of mitigation of failure effects on platform structures.

The testing targets validation of mitigations to a lithium battery Maximum Credible Event (MCE). Data from the Worst Case Event (WCE) is included as part of the risk analysis so that all possible severities of outcomes have been given consideration. Acceptance of residual risk must be addressed (and documented) by the appropriate technical and programmatic authorities. The use of proven Battery Management Systems (BMS) is desired. Thus the testing also focuses on demonstrating reliability and redundancy or inherent fault tolerance of the BMS. Automated and validated warning systems constitute a desired characteristic of a ship carried design. In addition, validated fire suppression and ventilation tactics, and systems that are compatible with the platform capabilities and personnel are crucial. These tests focus on MCE level as demonstrated by test or simulation, based on system and host platform safety precepts for operability.

**Example Application – REMUS 600 UUV**

The REMUS 600 UUV is a commercially available, mid-size UUV produced by Hydroid, Inc. Variants of this device have been under evaluation by a variety of Navy sponsors for the last six years. The system uses a large lithium-ion power source, and has therefore undergone evaluation multiple times to support limited lithium battery safety approvals. However, updated safety characterization and platform integration evaluation is required prior to authorizing the unrestricted fielding of this UUV variant aboard Naval platforms.

The earliest Navy uses of the REMUS 600 UUV were in demonstration events like AUV Fest, and test and evaluation programs associated with Analysis of Alternatives (AoA) or development of operational requirements efforts. Navy sponsors like the Office of Naval Research (ONR) and the Underwater Explosives Ordnance Disposal Program Office (PMS-EOD), provided request letters and Safety Data Packages drafted in accordance with NAVSEA TM S9310-AQ-SAF-010 to support these limited approvals. Risk mitigation relied on a thorough review of the battery and systems design, specialized safety training and procedures, and limiting the location and exposure of the batteries to Navy personnel.

![Photo of a lithium battery pack](image)

**Figure 3. REMUS-600 UUV**

To support less restrictive lithium battery safety approvals and begin the safety characterization of the REMUS-600 lithium-ion battery design, lithium battery safety testing in accordance with NAVSEA TM S9310-AQ-SAF-010 was conducted on REMUS-600 battery sub-modules in 2005. The test suite includes short circuit, overcharge, over-discharge, electrical safety device evaluation, and thermal abuse tests. At least one of each type of safety test has been completed. Tests that were conducted with the safety devices intact within the battery assembly verified appropriate function of those devices in response to over-current, over-voltage and under-voltage conditions. In short circuit tests conducted without assembly level safety devices, the cell-level Positive Temperature Coefficient devices (PTCs) limited the current. Internal leads also failed in these tests, and no cells vented. Overcharge tests with safety devices bypassed resulted in cell venting, although the battery pack did not catch fire. The thermal abuse test resulted in rapid, vigorous, cell venting with flame,
which consumed the full battery assembly. However, none of the individual venting occurred with sufficient force to generate shrapnel from the battery pack.

After a history of successful test and demonstration efforts with the REMUS-600 UUV, multiple program offices made independent acquisition decisions that have resulted in this vehicle transitioning into a small number of independent programs. At this time, an updated test program is planned for 2012 to characterize any changes in the battery safety performance that could result from the evolution of the design since 2005, and to address the requirements of NAVSEA TM SG270-BV-SAF-010. Planned tests to be conducted in accordance with NAVSEA TM S9310-AQ-SAF-010 include validation of the performance of the Electrical Safety Devices (ESDs) in the latest battery sub-module design, which employs new electronics from the version tested in 2005, as well as evaluation of the high current devices as required by the 2010 update of the TM. Overcharge and thermal abuse tests will be repeated for comparison with 2005 results, characterizing the performance of the sub-modules under these abuse conditions with the higher capacity cells that are currently in use.

Platform integration safety testing will focus on determining failure points in the energy section housing of the UUV, potential for propagation of sub-module battery failures throughout the energy section of the hull, and characterization of the energy and heat release in both MCE and WCE type conditions. Finally, planned mitigation strategies involving hull separation and fire suppression and containment methods will be validated in an all-up vehicle configuration. Doctrine and supporting precepts for the test protocols will address a variety of planned use conditions and platforms. These mitigation validation tests will include limitation of propagation of one battery sub-module failure to another sub-module within a given vehicle, and prohibit propagation of failures between separate vehicles in a common operations area.

Conclusions
The primary function of the Navy’s lithium battery safety program is to minimize risk to personnel and platforms while allowing the use of lithium batteries to advance our military capabilities through the approval process managed by NOSSA. NAVSEA INST 9310.1b and TM S9310-AQ-SAF-010 define the policy, process, and procedures used to meet this goal. For ship-deployed systems that employ large format lithium batteries, there are additional hazard definition and mitigation requirements, as given in NAVSEA TM SG270-BV-SAF-010.