NAVY LITHIUM BATTERY SAFETY

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INTRODUCTION

Lithium batteries are electrochemical reactors that transform chemical energy into electrical energy on demand. Lithium metal batteries were first marketed in early 1970, primarily for military use. They have a very high gravimetric and volumetric energy density compared to all other batteries – five to ten times the energy of other battery systems. The reactive nature of the lithium chemistry can lead to energetic failure due to such insults as crushing, penetration, vibration, overheating, and/or manufacturing defects leading to internal shorts.

Lithium primary (i.e. non-rechargeable) batteries include both active and reserve batteries. Reserve batteries remain in an inactive condition until needed, at which time the electrolyte is introduced into the cell. The shelf life of lithium reserve batteries can be measured in decades, so they have been widely used in munitions systems for short bursts of power during deployment of a projectile. Liquid reserve batteries use an electrolyte that is a liquid at ambient temperatures, and reserved in a separate reservoir. Thermal reserve batteries use an electrolyte that is a solid at ambient temperatures and must be melted by an energetic material to activate the battery. Improvements in shelf life of active lithium primary batteries has led to a reduction in use of reserve batteries in some weapons systems, with a concomitant increase in potential hazards due to the presence of an activated cell in the article.

Lithium secondary (i.e. rechargeable) batteries are increasingly being used in weapon systems and platforms. These batteries are capable of delivering high rates of high power discharge capability with a high energy density and specific energy. Their long shelf life, long cycle life, and lack of a memory effect have made them attractive as a propulsion option for future unmanned underwater and aerial vehicles and weapons systems. However, like primary lithium batteries, due to the use of flammable organic electrolyte they can degrade at high temperature, and can undergo thermal runaway when crushed or otherwise damaged. Thermal runaway can also result from overcharging, overdepletion, or shorting. The result in both primary and secondary cells can be venting of toxic, flammable gases and a large energetic reaction (fire and explosion).

The potential for installed proximity of lithium primary and secondary batteries to weapons systems and for personnel exposure, require careful analysis and testing to determine the proper

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hazard classification of weapons systems and other military equipment using lithium batteries. This paper discusses the United States (U.S.) Navy approach to risk mitigation in the use of such batteries.

BACKGROUND

The Department of Defense experienced multiple mishaps during the 1970's and early 1980's, primarily in the application of primary cells using soluble cathode chemistry. Specific chemistries of concern were lithium-sulfur dioxide (Li-SO2), lithium-thionyl chloride (Li-SOCL2), and lithium-sulfuryl chloride (Li-S02CL2).

In response, the Navy established a lithium battery safety program in 1982 within a unit of the Naval Sea Systems Command responsible for explosives safety throughout the U.S. Navy and Marine Corps. (Currently this organization is the Naval Ordnance Safety and Security Activity (NOSSA), the authors' affiliation). The program includes lithium batteries and all lithium battery powered equipment/systems through the entire life cycle of such systems[3].

Batteries can detonate, deflagrate, pressure rupture, and thermal runaway to explosion.[4,5] The nature of the explosive reaction and the physical conditions required to initiate and propagate it vary with the specific electrochemical system employed and the physical design and application of the battery.

Recent mishaps with lithium batteries include the following. Manufacturing defects in limited-run, large format secondary batteries, including foreign objects and residue from manufacturing processes, such as cutting of current collector sheet material, causing an eventual internal short. Damage to batteries during transport and post-deployment handling causing an internal or external short.

All lithium batteries and lithium battery powered equipment and systems must be reviewed, tested (if deemed necessary during the system review), and formally approved before units are used by Navy and Marine Corps personnel and/or introduced into the Fleet as a service item.

Unique aspects of the Navy's program include a requirement for review and approval of ALL lithium batteries above a defined size threshold, and a requirement to consider the system application of the battery in the review process. Batteries are not given approval for general use, but for a specific application. Table 1 below illustrates the broad range of Navy battery applications, including weapons.

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[3] NAVSEA Instruction 9310.1B, "Naval Lithium Battery Safety Program", 19 June 1991

[4] Freeman, C., "The Relation of Batteries to Explosives", NSWC TR 80-455, Naval Surface Weapons Center White Oak Laboratory, Silver Spring, Maryland (September 1980).

[5] Carpenter, B. and D. Kieffner, "Test Report - The Mass Reaction Hazards of Lithium Primary Batteries", EDD 609 04-115, Crane Division, Naval Surface Warfare Center, 15 October 2004

Table 1: NAVY APPLICATIONS REQUIRING ELECTROCHEMICAL POWER SOURCES

Guided missiles	Memory backup
Bombs	Depth charges
Mines	Aircraft
Fuzes	Telemetry
Guided projectiles	Surveillance buoys
Torpedoes	Sonobuoys
Underwater targets	Sound sources
Submarines	Acoustic transponders
Swimmer delivery vehicles	Field communications
Unmanned Underwater Vehicles	Laser designators
Unmanned Aerial Vehicles	Countermeasures
Explosive Ordnance Disposal Robots	Night vision
Medical equipment	Weapons handling equipment

LITHIUM BATTERY SAFETY PROGRAM

The Navy's lithium battery safety program (LBSP) is structured around four steps[6]:

1. Submission of a Safety Data Package by the requesting program manager.
2. Safety Testing of the battery by LBSP approved personnel.
3. Safety Review of the data package and test results by the LBSP's designated technical agents.
4. Approval: formal recommendation, by the LBSP manager, for approval of the proposed battery's use by the requesting program manager.

1. Safety Data Package (SDP). A data package addressing the battery and intended system in which it will be used must be submitted to the LBSP for review. The following are presented as a sample of the required data. The SDP may be a living document with multiple revisions when battery development is part of the overall acquisition program.

A. General information.

For all batteries:

Manufacturer, model number and/or part number.
Electrical description (voltage, ampere-hour capacity, and nominal load profile).
Integral electrical safety devices.
Operating life (shelf and functional).
Physical dimensions and description.
Marking.

[6] Naval Sea Systems Command Technical Manual S9310-AQ-SAF-010, "TECHNICAL MANUAL FOR BATTERIES, NAVY LITHIUM SAFETY PROGRAM RESPONSIBILITIES AND PROCEDURES", 19 August 2004.

Yield pressure.
Material Safety Data Sheets.
Discharge rate.

For rechargeables only:

Rated cycle-life.
Discharge and recharge rates.

For thermal reserve batteries:

Case temperature information.
Complete temperature profile from activation to battery cool down.

For liquid reserve batteries:

Method of activation.
Expected activated life before self-depletion.

B. System description:

Description of System Purpose & Function.
Diagram of the system's overall mechanical interfaces showing battery proximity to other equipment and energetic devices.
Battery installation (mounting, seals, electrical connectors).
Battery housing/container, strength, and free volume.
Safety features or venting mechanisms.
Load profile of the system.
Block diagram of system showing interfaces to the battery (electrical and physical) and fuses, blocking diodes, and external power interface).
Charger and charge control mechanism, if applicable.
Description of other controls or mechanisms to enhance battery safety, such as a Battery Management System (BMS), software shutdown mechanism, etc.

C. Logistical and Operational Use Data:

Packaging.
Storage requirements, from delivery to disposal.
Transportation methods.
Disposal information.
Operational use scenario, including:

A complete description of how the system/batteries will be handled and used; what platform(s) (e.g. submarines, ships, and
aircraft) will carry or deploy the system; location of recharging operations, if applicable; description and location of recovery operations, ashore and afloat, if applicable; number of units

anticipated to be used; the battery change out/replacement plan, including number of batteries needed to support system during deployment, and in what storage configuration.

D. The SDP also includes requirements for information on any functional, environmental and safety test data available, any applicable safety testing program plan or completed test data, and, summarized results from the system safety program.

2. Safety Testing. The Navy has developed a series of abuse tests to demonstrate the maximum credible event in the event of a system failure. The test philosophy is to provoke the worst-case battery response to determine if the response is acceptable based on the system and platform requirements. Every attempt is made to minimize cost and schedule impacts and still obtain enough data to effectively support making risk assessments.

Batteries are tested inside a complete system, or a battery inside sufficient system components to simulate the battery/system interactions. Although ideally, every type of battery deployed would be tested, this is not always practical or warranted. Some examples follow. Commercial off-the-shelf cells and batteries below 2 Ampere-hours are exempt from testing, with Underwriter's Laboratories (UL) approval as an additional factor. UL-approved Lithium-ion "laptop" type batteries are exempted, as long as they are under 18 volts and 100 watt-hours. Solid cathode "coin cells" are exempted, as long as they are under 1 Ampere-hour capacity and 3 volts.

Larger batteries are often custom-made or limited production, very expensive, and unique. There are also many small variations in these special batteries. In many cases testing is deferred or exempted if data is available for the same cells used to make these large batteries, in similar battery pack configurations. However lack of testing data will usually result in a battery approval with limitations and restrictions in use.

All batteries must also comply with the Hazardous Material Regulations[7] requirement for testing in accordance with Section 38.3 of the UN Test Manual[8] in addition to any Navy-specific testing.

The following tests are included in the Navy's LBSP.

Active Non-rechargeable Battery Tests.

Constant Current Discharge & Reversal Test.
Short Circuit Test.
High Temperature Test.
Charging Test.
Electrical Safety Device Test.

Thermal Battery Tests.

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7 Title 49 Code of Federal Regulations Parts 171–180

8 United Nations, "Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, Fourth Revised Edition, Amendment 2", ST/SG/AC.10/11/Rev.4/Amend.2, 2007.

Unactivated Environmental Tests.
High Rate Discharge Test
High Temperature Test.
Open Circuit Test.
Charging Test

Liquid Reserve Battery Tests.

Unactivated Environmental Test.
Unactivated High Temperature Test.
Activated Constant Current Discharge & Reversal Test.
Activated Short Circuit Test.
Activated Open Circuit Test.
Electrical Safety Device (ESD) Test with High Temperature Preconditioning.
Charging Test.

Rechargeable Battery Tests.

Short Circuit Test.
Overcharge/Discharge Test.
Overdischarge/Charge Test.
High Temperature Test.
Electrical Safety Device Test.
Aging Safety Test.

3. Safety Review. The Navy's designated technical agents for performing the review of the technical data and test results on lithium batteries are the Naval Surface Warfare Center Carderock Division (Code 616) in Bethesda Maryland, and the Naval Surface Warfare Center Crane Division (Code GXS) in Crane, Indiana, under the direction of NOSSA.

There is an ongoing trend toward ever-larger lithium battery power sources. In the wake of a November 9 2008 fire[9] aboard a developmental lithium battery-powered mini-submarine using a very large lithium battery powered propulsion system, the Navy placed special emphasis on two aspects of the LBSP: "Platform Concurrence", and an overarching system safety program in accordance with MIL-STD 882.

Many batteries have the potential for use, deployment, transport, or storage on a Naval surface ship, submarine, or aircraft. Small batteries may be included in rechargeable communications systems. Large batteries may be part of an unmanned underwater vehicle deployed from a surface ship. Platform concurrence refers to the process of providing a summary of the proposed battery application to the designated engineering authority for the specific ship, submarine, or aircraft platform class that will need to carry the battery or battery-powered system, and receiving written concurrence for the proposed action. The Naval authorities responsible for ship/submarine and aircraft engineering are Naval Sea Systems Command Headquarters, and Naval Air Systems Command Headquarters, respectively.

[9] http://www.navytimes.com/news/2009/07/navy_seal_minisub_072709w/

Obtaining concurrence from the platform owner has, in the past, been part of the technical agent role, and has been a relatively informal notification process. However, for ship and submarine platforms, the Navy is developing a robust assessment program to determine the suitability of any large form battery system (over 1 kWh) for deployment and use. This assessment program includes additional testing to determine thermal heat loads, off-gas and smoke volumetric and compositional analysis for firefighting and personnel protection, and specific hazards analysis requirements to supplement the general requirements of MIL-STD 882. The additional testing and analysis requirements are in addition to the standard Navy safety tests described earlier, which only demonstrate the worst case.

The requirement for a MIL-STD 882 system safety program is particularly apt in the case of lithium batteries to be included in weapons systems. Some weapon system articles under development contain enough lithium batteries to affect the hazard classification. For example, if a large battery in an article fails thermal testing before the main charge, the resulting low-order deflagration may result in the production of fragments by a weapon designed to be non-fragmenting. This is a relatively new area of concern. All Navy weapons systems are subject to review by the Weapon System Explosives Safety Review Board (WSESRB), and representatives from the Lithium Battery Safety program sit on the board as required to address emerging battery safety issues.

4. Approval. Based upon a recommendation from the technical agent reviewing the data package, and with confirmed platform concurrence, the LBSP program issues a formal approval letter. The letter is issued in the form of a recommendation, by the safety program to the requesting program manager, to take the proposed action. This action may be to proceed to the next program developmental or testing milestone, to purchase or deploy equipment, to begin charging on a new platform, etc. Ultimate authority for approval for the use of battery systems lies with the program manager, following receipt of the NOSSA letter.

U.S. Navy Lithium Battery Safety Program

John Dow
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Naval Ordnance Safety and Security
14 July 2010


NAVSEA
NAVAL SEA SYSTEMS COMMAND
Undersea Warfare Center
EMATT
MK30 MOD 2
MK30 MOD 1
REMUS
MARV
21UUV
NMRS
MRUUV FLT1
LMRS
U.S. NAVY
MRUUV FLT2
MTV
MANTA
Autonomous Undersea Vehicles

Unmanned Aerial Vehicles

RAVEN B

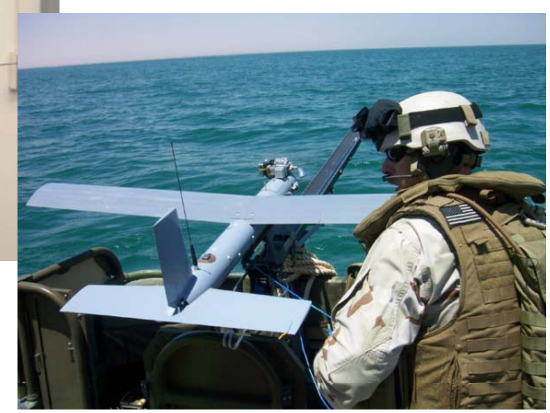
Switchblade

Scan Eagle

Dragon Eye

Wasp

Voyeur



Silver Fox

Lithium batteries

- **Electrochemical reactors that transform chemical energy into electrical energy on demand.**
- **High gravimetric and volumetric energy density.**
- **Five to ten times the energy of other battery systems.**
- **Primary (active and reserve).**
- **Rechargeable (mostly lithium ion).**

Li Batteries are energetic

- Teactive nature of the lithium chemistry can lead to energetic failure.
- Insults include crushing, penetration, vibration, overheating, and/or manufacturing defects leading to internal shorts.

FAA: 109 Mishaps

Aviation Incidents Involving Smoke, Fire, Extreme Heat or Explosion

6 hurt as battery erupts at Raynham plant

By Nandini Jayakrishna, Globe Correspondent | August 14, 2009

Electronic cigarettes cause FedEx MD-11 fire

By Kieran Daly on August 26, 2009 5:14 PM | Permalink | Comments (0) | TrackBacks (0) | ShareThis

Electronic what???? Yup, cigarettes, and I had never heard of them until today. Perhaps you had.

Well you've probably heard about the FedEx MD-11 incident at Minneapolis-St Paul on 14 August. After landing the crew had a lower forward cargo fire warning. They discharged the halon bottles and called the

Star Bulletin

Halt to battery cargo urged

A burned package on an isle flight is cited as an example of the risks c

By Gary T. Kubota

POSTED: 01:30 a.m. HST, Aug 26, 2009

A burned package aboard a flight shipment discovered in Honolulu is one of the reasons why the Air Line Pilots Association is calling for a suspension of cargo carrying lithium-ion batteries.

Primary (non-rechargeable) I

- **Reserve batteries:**
  - Remain in an inactive condition until needed.
  - Long shelf life.
  - Liquid reserve: liquid electrolyte is stored in a separate reservoir and mechanically introduced to activate battery..
  - Thermal reserve: solid electrolyte is melted by squib to activate battery.

Primary (non-rechargeable) II

- **Active batteries.**
  - Shelf life improvements leading to more use in weapons systems.
  - Increase in potential hazards due to use of activated cells in the article, toxic gases and fire in event of mishap.

Secondary (rechargeable)

- Increasingly being used in weapon systems and platforms.
- High rates of high power discharge capability.
- High energy density and specific energy.
- Long shelf life, long cycle life, and lack of a memory effect.
- UUVs, AUVs, UAVs can use very large batteries with multiple cells.

Disadvantages

- **Flammable organic electrolyte.**
- **Degradation at high temperature.**
- **Thermal runaway when crushed, damaged, overcharged, overdepleted, or shorted.**
- **Venting of toxic, flammable gases and energetic reaction (fire and explosion)**
- **Additional hazards if used in proximity to explosives and personnel.**

Safety Program Background

- Multiple mishaps in 1970's and 1980's with active primary cells:
  - Lithium-sulfur dioxide (Li-SO_2)
  - Lithium-thionyl chloride (Li-$SOCL_2$)
  - Lithium-sulfuryl chloride (Li-$S0_2CL_2$).
- Safety program established in 1982 within NAVSEASYSCOM.
- Program executed by NOSSA as an element of the explosives safety program.

Scope of Safety Program

- Lithium batteries and all lithium battery powered equipment/systems through the entire life cycle of such systems.
- Batteries must be reviewed and formally approved in the context of each application.
- Before used by Navy and Marine Corps personnel and/or introduced into the Fleet as a service item.

Key aspects of program

- Review and approval of ALL lithium batteries above a defined (very low) size threshold.
- Consider the system application of the battery in the review process.
- Batteries are not given approval for general use, but for a specific application.
- Navy-specific testing program.

Navy battery applications (including ordnance)

- Guided missiles
- Bombs
- Mines
- Fuzes
- Guided projectiles
- Torpedoes
- Underwater targets
- Submarines
- Swimmer delivery vehicles
- Unmanned Underwater Vehicles
- Unmanned Aerial Vehicles
- Explosive Ordnance Disposal Robots
- Medical equipment
- Memory backup
- Depth charges
- Aircraft
- Telemetry
- Surveillance buoys
- Sonobuoys
- Sound sources
- Acoustic transponders
- Field communications
- Laser designators
- Countermeasures
- Night vision
- Weapons handling equipment

Four steps to battery approval.

- **Submission of a Safety Data Package by the requesting program manager.**
- **Safety Testing of the battery by LBSP approved personnel.**
- **Safety Review of the data package and test results by the LBSP's designated technical agents.**
- **"Approval": formal recommendation, by the LBSP manager, for approval of the proposed battery's use by the requesting program manager.**

Safety Data Package (SDP)

- **Technical data on battery and system**
  - Detailed battery Description
  - System description including charging and safety features.
  - Logistical and operational use data.
  - MIL-STD 882 System Safety Plan information.
  - Any existing test data.

Safety Testing

- In addition to required UN testing.
- Demonstrates worst-case / maximum credible event
- Battery tested inside system, subsytem, or model
- Naval Sea Systems Command Technical Manual S9310-AQ-SAF-010

Active (Non-rechargeable) Battery Tests.

- **Constant Current Discharge & Reversal Test.**
- **Short Circuit Test.**
- **High Temperature Test.**
- **Charging Test.**
- **Electrical Safety Device Test.**

Thermal Battery Tests.

- **Unactivated Environmental Tests.**
- **High Rate Discharge Test**
- **High Temperature Test.**
- **Open Circuit Test.**
- **Charging Test**

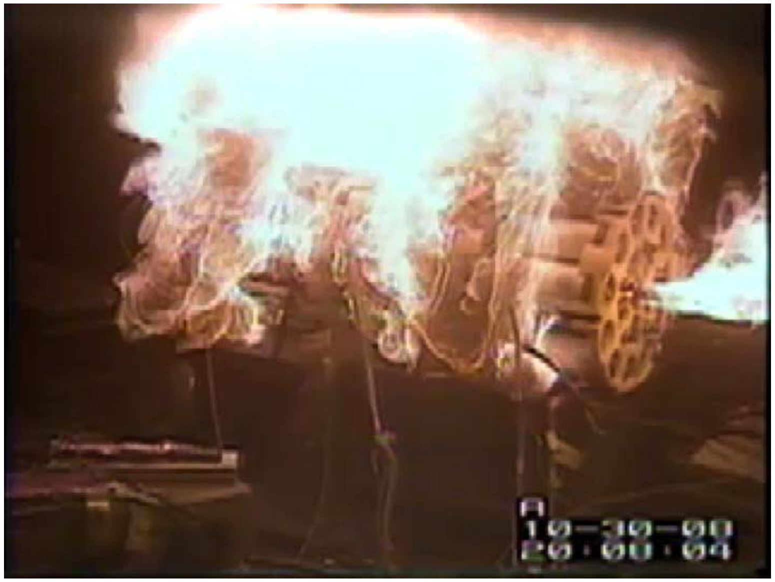
Liquid Reserve Battery Tests.

- **Unactivated Environmental Test.**
- **Unactivated High Temperature Test.**
- **Activated Constant Current Discharge & Reversal Test.**
- **Activated Short Circuit Test.**
- **Activated Open Circuit Test.**
- **Electrical Safety Device (ESD) Test with High Temperature Preconditioning.**

Rechargeable Battery Tests.

- Short Circuit Test.
- Overcharge/Discharge Test.
- Overdischarge/Charge Test.
- High Temperature Test.
- Electrical Safety Device Test.
- Aging Safety Test.

Typical test results



Typical test result

Safety Review

- **Navy designated technical agents**
  - Activities at Bethesda MD and Crane IN
  - Platform concurrence required
    - Ships and Submarines: NAVSEASYSCOM
    - Aircraft: NAVAIRSYSCOM
    - Military Sealift Command