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HIGH-ENERGY STORAGE SYSTEM SAFETY MANUAL

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NOTICE TO USERS OF THIS MANUAL

This manual is intended to define the processes necessary to characterize the safety hazards and risks associated with integration and use of lithium batteries aboard Navy platforms, as well as the processes by which these hazards and risks are evaluated and adjudicated by Naval Sea Systems Command (NAVSEA) Ship Design and Engineering Services (NAVSEA 05). Users are urged to report instances where the manual does not achieve this objective. Additionally, recommendations to correct errors, deficiencies, or omissions are invited.

Users of this manual may provide feedback to the Technical Manual Maintaining Activity (TMMA). All recommendations of a routine nature are to be made using the Technical Manual Deficiency Evaluation Report (TMDER) forms found at the front of this manual. Submit completed TMDER forms by using the preaddressed portion of the form or by connecting to the Naval Systems Data Support Activity web site: https://nsdsa2.phdnswc.navy.mil and selecting TMDER. Follow the instructions for generating a TMDER.

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CHAPTER 1 – INTRODUCTION

1-1 PURPOSE.

This manual defines the NAVSEA 05 process to characterize hazards associated with high energy storage systems, to ensure programs using these systems have implemented appropriate hazard mitigations, and thereby to provide maximum reasonable assurance that failures of these systems can be safely mitigated to avoid endangering Navy platforms or Navy personnel. This manual is invoked within the framework of NAVSEA TM S9310-AQ-SAF-010 and provides the NAVSEA platform concurrence process that precedes final Naval Ordnance Safety and Security Activity (NOSSA) lithium battery approval for platform use. The requirements herein address system reliability and durability only as these aspects are related to safety. The focus of the initial issue of this manual is lithium battery systems. Future high-energy systems such as fuel cells and hybrid technologies will be addressed by invoking comparable requirements that are appropriately tailored to those technologies.

1-2 BACKGROUND.

Modern warfighting systems increasingly rely on large, high-density energy sources as the basis for new operational concepts. Given the current state of the art, energy storage can represent extreme danger to personnel and platforms in the event of uncontrolled release of energy in various forms. Recent high-profile failures point to the need to establish higher safety and reliability standards for these energy systems. A multi-disciplined approach is provided here for that purpose and includes traditional risk-assessment activities along with specific technical and test requirements to ensure safety. NAVSEA TM S9310-AQ-SAF-010 defines the overall Navy lithium battery safety program and also provides cell- and battery-level testing and analysis of the battery itself. This document, NAVSEA TM SG270-BV-SAF-010, and the NAVSEA 05 lithium battery process contained herein emphasize hazard characterization for NAVSEA platform-specific environments that have a bearing on casualty prevention and recovery

In conventional Acquisition Category (ACAT) programs, established formal risk-assessment processes are required and defined (reference DoD 5000.2 series). The recent development history of advanced undersea warfighting concepts shows a trend away from traditional formal Research and Development (R&D) and acquisition project control and toward a flexible, collaborative, and innovative project management environment. With regard to safety and reliability, this environment raises new challenges. The number of interfaces between participating organizations has increased, resulting in greater likelihood of misunderstandings in regard to critical project responsibilities. Also, the trend of less stability in project funding and scheduling can reduce continuity of safety and testing programs associated with projects. This acknowledgement of the current climate of technology-development projects is addressed throughout this manual. The intent is to provide consistent standards of hazard assessment, design, testing, Quality Assurance (QA), and accountability for all projects, regardless of size or degree of formality.

1-3 SCOPE OF REQUIREMENTS.

1-3.1 GENERAL SCOPE.

This manual provides the technical and administrative requirements necessary to ensure safe operation of lithium battery systems on Navy platforms. Where appropriate, requirements have been written that are unique to this manual. However, direction herein is in conjunction with, and does not supersede nor call into question, requirements from other Department of Defense (DoD) and Navy standards that are used wholly or partially to accomplish the objective.

1-3.2 APPLICABILITY TO NAVY SYSTEMS.

These requirements are structured to assess and mitigate risk at the earliest possible stages of system development, permitting inherently low-risk approaches and those that are not intended for platform use to proceed with minimal additional testing and analysis beyond that required by NAVSEA TM S9310-AQ-SAF-010. The applicability of the requirements of NAVSEA TM SG270-BV-SAF-010 includes all lithium batteries used, carried, or intended for use or carrying on Navy platforms, both as stand-alone batteries and as systems incorporating lithium batteries. Specifically included are Deep Submergence Systems operated from Navy platforms. For those lithium batteries not within the scope of this manual, NAVSEA TM S9310-AQ-SAF-010 applies.

1-3.3 APPLICABILITY TO NAVY PROGRAMS.

The applicability of the requirements of this manual includes all lithium high energy programs or projects intended for eventual Navy platform operation, regardless of the formal standing of those programs or projects as acquisition, R&D, or temporary systems. These requirements shall be invoked by contract or, in the case of non-acquisition projects, by the applicable tasking documents. Many systems requiring high-energy density sources have been developmental items either from the Navy R&D community or vendor internal R&D. These projects lie outside the DoD acquisition framework, and equivalent acquisition-type processes must be adapted for non-acquisition projects in selected areas (e.g., configuration control, system validation, Government access to records). These areas have direct or indirect bearing on system safety and reliability. It is the intent of this manual, within applicable projects, to require that R&D and developmental projects shall analyze and characterize high energy system safety and safety risk with a level of rigor equivalent to that imposed by the standard DoD acquisition process. Early-stage Science and Technology (S&T) projects as well as later-stage S&T projects and R&D projects that are not yet on a clear transitional path to a Navy acquisition program or Navy platform use will be briefed to NAVSEA 05 annually to assess the likelihood of Navy program office interest and the need to invoke TM SG270-BV-SAF-010.

1-3.4 CONCURRENT REQUIREMENTS OF NAVSEA TM S9310-AQ-SAF-010.

NAVSEA TM SG270-BV-SAF-010 addresses platform-specific hazards and risk evaluations. However, the program manager shall ensure other non-platform personnel and non-platform hazards and risk evaluations are fully characterized NAVSEA TM S9310-AQ-SAF-010, either prior to or in parallel with this process. The program office, NAVSEA 05, and NOSSA shall communicate and collaborate early in the program to define test objectives and Test Plans (TPs) that satisfy the needs of both NAVSEA TM S9310-AQ-SAF-010 and NAVSEA TM SG270-BV-SAF-010 while avoiding unnecessary duplication of tests.

1-3.5 EXCEPTIONS.

NAVSEA TM SG270-BV-SAF-010 and the NAVSEA 05 large lithium battery hazard characterization and safety approval process does not include or address the following areas:

- Nuclear energy systems under the cognizance of NAVSEA 08.
- Any area of responsibility already covered by NOSSA and NAVSEA TM S9310-AQ-SAF-010.
- Batteries with total stored electrical energy less than 1 kWh (kilowatt hour) per single battery pack or a system with total stored electrical energy less than 2 kWh that are already covered by NOSSA and NAVSEA TM S9310-AQ-SAF-010.

1-3.6 DEPARTURES FROM SPECIFICATION.

In the event a specific requirement of this manual is not met for any reason, the non-compliance will be documented and submitted by the System Developer to the Program Office for approval. The program Office shall ensure TWH concurrence with the non-compliance. The format used shall be in accordance with the system contract and specifications in effect.

1-3.7 USE OF PREVIOUSLY APPROVED BATTERIES.

As required by NAVSEA TM S9310-AQ-SAF-010, an activity using a previously approved lithium battery in its approved application/system/environment shall ensure configuration management is imposed on the battery, system, and environment in accordance with MIL-HDBK-61 (series) or an appropriate commercial standard such as ISO 10007. During the life of the battery and the system, any Class I battery change must be coordinated with NOSSA technical agents in order to initiate an updated safety review and approval. In addition to the usual definition, a Class I change shall be defined, for the purposes of this manual, as any change affecting safety characteristics of the battery, such as cell manufacturer, type, method of fabrication, material changes, insulation, circuit load changes greater than 10%, battery packaging, etc. Furthermore, any changes to the Concept of Operations (CONOPS), storage, or system change that may alter the risks associated with the battery shall be reported to a NOSSA technical agent in order to initiate an updated safety review and approval.

An activity seeking to use a previously approved lithium battery in a different application, system, or environment shall contact a NOSSA technical agent for review. Additional testing may be required by NOSSA and NAVSEA 05Z, depending on the risks associated with use of the lithium battery in the new application or system. To facilitate this review, the activity seeking approval shall identify any and all changes made to allow use of the lithium battery in the new application or system, including but not limited to:

- Differences in battery or component design.
- Changes to battery or component manufacturing processes, facilities, or vendors.
- Modifications to battery/system CONOPS, host environment, usage profiles, storage conditions, or transport conditions.

1-3.8 PROCESS SCOPE AND BOUNDS.

The scope of the hazard characterization and safety approval process will consider and take into account battery system characteristics such as the following:

- Specific energy, energy density, and chemistry.
- Magnitude and rate of energy release in any form (thermal, pressure, mechanical).
- Release of toxic or corrosive chemicals under any condition of storage, use, or failure.
- CONOPS that either increase or mitigate hazards or risks.
- Aggregate effects of multiple batteries, multiple systems incorporating batteries, or co-located stored energy (e.g., flasks, fuel tanks, etc.).
- Total stored energy (electrical, chemical, etc.).
- Level of control and software involved.

Based on these characteristics, platform suitability will be determined.

1-3.9 HISTORICAL DATABASE.

NAVSEA 05, in collaboration with NOSSA and NSWC, will develop and maintain a historical database of Navy-tested lithium battery types. The database will be periodically updated with new test results as they emerge from various Navy programs. This database will serve as an aid in evaluating battery hazards, platform risks, and platform suitability, and in developing Preliminary Hazard Lists (PHLs), Preliminary Hazard Analyses (PHAs), and Safety Critical Criteria (SCC) for new programs. This database will also be useful in selecting batteries for use on new-design and back-fitting batteries that become obsolete. This database can be used for developing TPs as required and where appropriate might be used to avoid unnecessary additional testing. The database will be accessible to all DoD projects/programs (see Appendix A for additional details).

1-3.10 PERIODIC TECHNOLOGY PEER REVIEWS.

The state of lithium battery technology and the scope and requirements of this manual will be reviewed every two years by an independent panel of experts comprising representatives from various branches of government, military, national laboratory, industry, and academia, as appropriate and as assigned by NAVSEA, to ensure the most current perspectives on the safe limits of lithium battery technology are understood and that risk evaluation processes and mitigation strategies and tactics are updated accordingly.

1-4 MANUAL ORGANIZATION AND USE.

The variety of operational concepts associated with lithium battery systems is extremely diverse, spanning Unmanned Underwater Vehicles (UUVs), Underwater Autonomous Vehicles (UAVs), manned submersibles, carry-on systems, and organic ship system functions, to name a few. This precludes a "one size fits all" approach to invoking requirements appropriate to specific battery systems and applications. Consequently, this manual relies on a rigorous system safety approach that has been tailored for large, high-energy battery system safety 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 of Chapter 5 of this manual are determined based on the System Safety Program Plan from the specific hazards identified in the program's PHA, System Hazard Analysis (SHA), and software safety analysis, and from the mitigations proposed for each hazard. The program office shall work with NAVSEA and NOSSA to establish a Test Plan (TP) that defines which of the tests in Chapter 5 are required, based on the hazards and mitigations identified for the program.

Once identified and agreed to in the TP, applicable tests from Chapter 5 can be satisfied by test or in some cases by similarity where comparable testing has already been completed, verified, and documented with NAVSEA involvement and concurrence. Furthermore, the applicability of the specific test paragraphs in Chapter 5 might also be dependent on test results. For example, if the design can be conclusively confirmed to be non-propagating with respect to cell-level failures, thereby eliminating or mitigating certain potential hazards identified in the original PHA, then certain system-level casualty characterization tests outlined in this manual and identified in the program's original TP might be deemed to be no longer necessary. In such cases where the applicability of the required tests might change during development, TP revisions are acceptable (presuming NAVSEA concurs).

In summary, it is the objective of this manual to reduce the required number of hazard characterization tests to a minimum, while simultaneously providing a thorough characterization of the impacts and risks associated with hazardous failure of the battery. Within this construct, it is important to re-emphasize that:

- Based on the hazard analyses, specific tests outlined in Chapter 5 may or may not be deemed applicable to a given program.
- Tests that are deemed applicable to a given program might be satisfied by similarity if comparable data is available, if NAVSEA concurs.
- Tests deemed applicable early in the development might later be deemed unnecessary as test data is collected, if NAVSEA concurs.

1-5 DOCUMENT HIERARCHY.

Silence of this document with respect to other contractually invoked requirements does not relieve designers and fabricators from meeting all invoked requirements. In cases of conflicting requirements, the conflict shall be addressed in writing to NAVSEA 05 for resolution. The general hierarchy of documents is:

1. This manual and S9310-AQ-SAF-010.
2. Temporary Alteration to Active Fleet Submarines, NAVSEA S9070-AA-MME-010, Technical Manual for Temporary Submarine Alterations.
3. System specifications.
4. Drawings.
5. Other specifications and standards.
6. Contract or tasking agreement.

CHAPTER 2 – ORGANIZATION AND ROLES

2-1 PROGRAM MANAGER/PROGRAM OFFICE.

The program manager/program office is the DoD program office that is responsible for the development and fielding of the system that includes a large lithium battery that impacts a Navy platform. For purposes of these requirements, program managers also include non-acquisition programs, R&D programs, combined (joint) programs, and technology evaluation projects that may fall outside DoD 5000.2 processes. Note: NAVSEA programs require a Platform Integration Agent (PIA) per paragraph 2-9 of this manual.

2-2 SYSTEM DEVELOPER.

The system developer is the prime activity in designing, building, and integrating a system that includes a large lithium battery. Note that in this context the battery is considered to be a subsystem or a component within the broader system. The system could, for example, be a vehicle or device that the Navy seeks to integrate with a Navy platform. In some cases, a Government activity can be assigned as a system developer.

2-3 TEST ACTIVITY.

The test activity is an organization assigned with testing the large lithium battery and its components in order to characterize the hazards associated with failure of the battery. The test activity may be assigned to be the system developer, warfare center, or an independent activity.

2-4 NAVSEA 05 TECHNICAL WARRANT HOLDERS (TWHs).

NAVSEA 05 TWHs are vested with Navy-wide decision authority, responsible for engineering operational and safety assurance of systems that are integrated within or on Navy platforms. They are responsible for technical standards, specifications, and policy in their areas. Signature authority for specific technical products may be delegated by the TWH as established in written agreements. With respect to the lithium battery safety approval process, NAVSEA 05 is responsible for providing platform concurrence to NOSSA concerning design and suitability for any system that will be deployed or transported on Navy surface ships or submarines.

2-5 NAVAL ORDINANCE SAFETY AND SECURITY ACTIVITY (NOSSA).

NOSSA is the NAVSEA organization that executes the Navy Lithium Battery Safety Program as an element of the overall Department of the Navy (DON) Explosives Safety Program. The scope of the NOSSA program is lithium batteries of all sizes and all applications (including shore-side applications). NOSSA is responsible for directing and coordinating efforts of all Navy technical offices in regard to lithium battery safety and for providing written concurrence and recommendations for any use, based on a review of the safety design, analysis, and tests conducted. NOSSA executes the overall DON explosives safety program and is TWH for weapons systems, ordnance, and explosives -- safety and security.

2-6 NAVSEA WARFARE CENTERS.

NAVSEA Warfare Centers are assigned In Service Engineering Agent (ISEA) responsibilities for various warfare systems, including lithium batteries. They function as centers of technical expertise and are the major Navy test activities for lithium batteries. Warfare Centers also assume project management duties when directed by program offices.

2-7 PROGRAM SPONSORS.

Program sponsors are DoD warfare resource management offices funding system development. For cooperative programs between DoD and other Government departments, the program sponsor is defined as lead agency for the joint program.

2-8 NAVY PLATFORM.

A vessel owned, leased, or operated by the Navy. Specifically included are manned Deep Submergence Systems. Specifically excluded are range support craft operating within U.S. territorial waters. Platform impact includes situations where the Navy platform is host to ancillary vehicles containing large lithium batteries.

2-9 PLATFORM INTEGRATION AGENTS (PIAs).

All systems containing lithium batteries within the scope of this manual for use on Navy platforms will have an assigned PIA. Unless otherwise specifically approved by NAVSEA 05Z34, the PIA will be the platform major program office in NAVSEA. PMS-394 will act as PIA for all submarine classified special systems. PMS-399 will act as PIA for special warfare support systems on submarines.

2-10 BATTERY CELL VENDORS.

Battery cell vendors provide battery cells to system vendors for use in assembling battery modules or entire systems.

2-11 BATTERY SYSTEM VENDORS.

The battery system vendor is the entity tasked with design and production of a specific battery system, usually including Battery Management Systems (BMSs), electrical components, container, control system, and vehicle/system interfaces. In some instances, the battery system vendor and battery cell vendor are one-in-the-same, requiring no distinction.

2-12 HIGH ENERGY CHEMICAL STORAGE SAFETY OFFICE (HECSSO).

HECSSO is the office established within NAVSEA 05 (NAVSEA 05Z34) to specifically address safety aspects of large lithium batteries and other energy-dense systems. In addition to managing the requirements contained in this manual, HECSSO executes development projects aimed at advancing safety and performance of batteries.

2-13 HIGH ENERGY SYSTEM SAFETY STEERING GROUP (HESSSG).

HESSG is an executive oversight group whose members include selected NAVSEA major program managers and deputy warranting officers. This group meets on a semi-annual basis to assess status and progress of HECSSO efforts. The group provides high-level coordination of programs (both R&D and acquisition) and resources. The secretary of HESSSG is the HECSSO program manager. HESSSG membership includes PMS399, PMS394, PMS406, PMS500, ESO, SEA 05P, SEA 05Z. Additional member to support emergent programs will be assigned by SEA 05Z.

2-14 INTERNAL INDEPENDENT PEER REVIEW TEAM (IIPRT).

NAVSEA 05 provides periodic independent assessments of recommendations to use or prohibit use of large lithium battery systems on a case-by-case basis as assigned (funded) by NAVSEA. NAVSEA 05 will determine the level of IIPRT involvement on a case-by-case basis in accordance with the attendant levels of risk. Upon completion of the Chapter 3 process within NAVSEA, and prior to submitting a concurrence or recommendation to NOSSA, the IIPRT will review the hazard characterizations, mitigations, and assumptions and advise the NAVSEA decision authority. This IIPRT comprises Navy technical experts in energy systems and safety that are not directly affiliated with HECSSO. The IIPRT members will be chosen from the broad range of capabilities available in the Navy within branches such as the Office of Naval Research (ONR), the Naval Research Laboratory (NRL), the Naval Postgraduate School, and the Deep Ocean Simulation Facility (DOSF) at the Naval Facilities Engineering Service Center (NFESC). The IIPRT will be consulted on new designs as appropriate to aid the NAVSEA Warfare Centers (see paragraph 2-6) in the task of evaluating the hazards of new designs. The IIPRT also will conduct periodic reviews with panels of experts from outside the Navy, as required in paragraph 1-3.9, in order to maintain currency on the safety and hazard mitigation aspects of lithium technology.
IIPRT assessments will documented in reports distributed to HESSG members.

2-15 SYSTEM SOFTWARE SAFETY ACTIVITY (SSSA).

The NAVSEA 05 TWH for Control Systems is the SSSA, responsible for assessing the safety level and severity of software applications associated with Lithium batteries and their systems. The SSSA maintains configuration control of the software and works with program management on assessing changes to the software and assessing the need for future upgrades and testing of the associated battery software. Upgrades to system software are coordinated through the SSSA, inclusive of evaluation, testing, installation testing, etc. The SSSA is responsible for compliance with requirements of Fly by Wire and Navel Vessel Rules. The SSSA reviews and approves all software safety-related tasking and direction.

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CHAPTER 3 – SAFETY CERTIFICATION PROCESS

3-1 PROCESS DESCRIPTION.

This chapter defines the NAVSEA 05 process for providing platform concurrence in coordination with the NOSSA lithium battery safety approval process defined by NAVSEA TM S9310-AQ-SAF-010.

3-1.1 PROCESS FLOW.

The NAVSEA 05 risk characterization and safety approval process is depicted at its top level in Figure 3-1 As depicted in the figure, the process engages and coordinates the efforts of the key stakeholders.

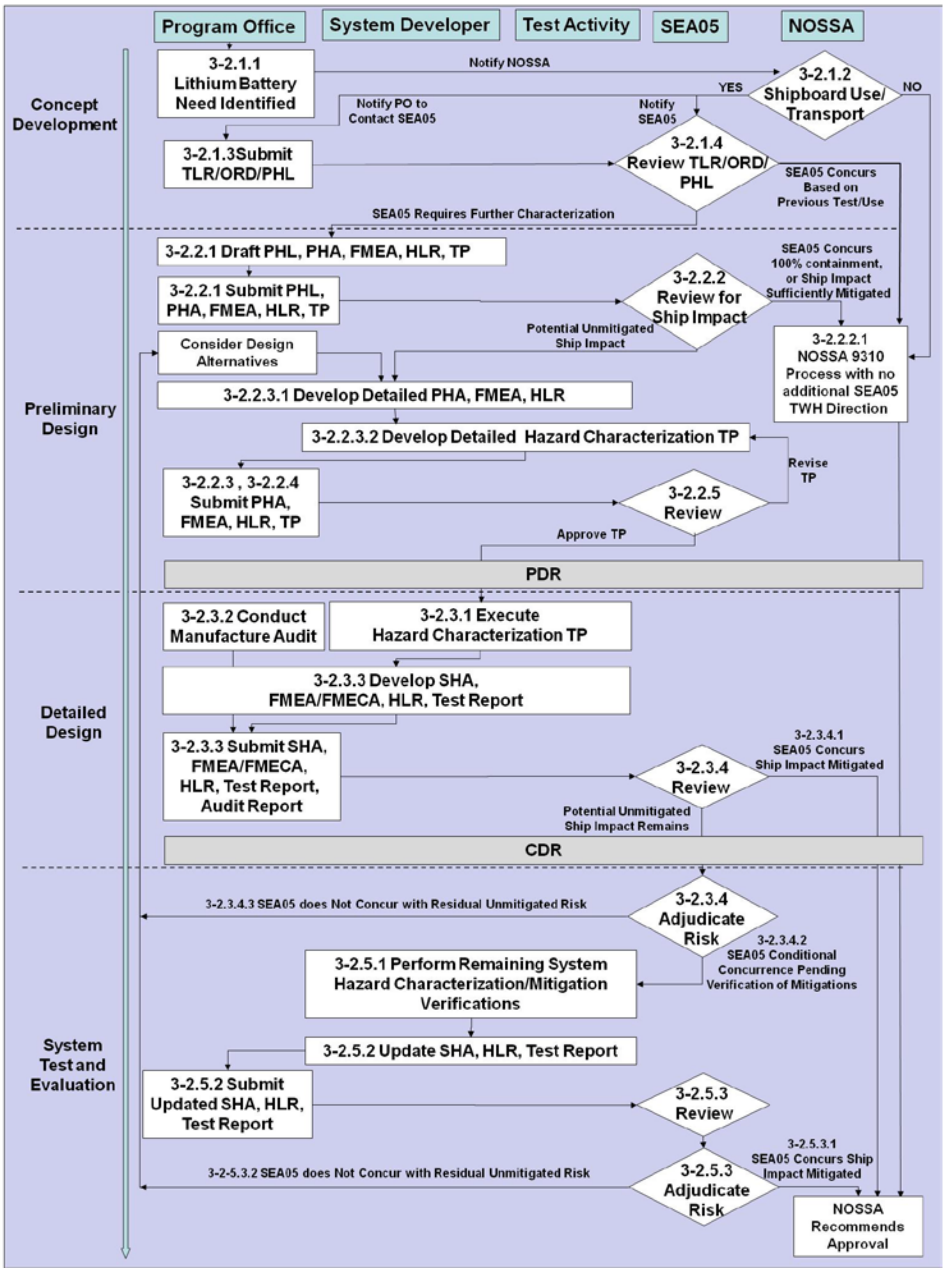

Figure 3-1. Top-level Process Flow Diagram for NAVSEA 05 Large Lithium Battery Risk Characterization and Approval Process.

3-1.2 PROCESS PHASES.

When systems are deemed to have NAVSEA platform integration hazards, the hazard characterization and safety approval process shall apply to all phases of system development including:

- Concept Development Phase.
- Engineering Design Phase.
- Manufacturing and Production Phase.
- Test and Evaluation Phase.
- Operational and Support Phase.

Within each phase, the program manager shall implement policies that drive the early and continued evaluation, characterization, and communication of hazards and risks to NAVSEA 05 and to other required decision authorities for adjudication and approval.

3-1.3 PROCESS MILESTONES.

Hazard characterizations and timing of hazard communications shall support acquisition program milestone requirements and shall generally conform to the guidelines described in this manual.

3-2 ACQUISITION PHASES, ACTIVITIES, AND BENCHMARKS.

Note that the following discussions refer to activities and documentation related to Preliminary Hazard List (PHL), Preliminary Hazard Analysis (PHA), System Hazard Analysis (SHA), and Hazard Log Record (HLR). Detailed descriptions of these documents and their content are included for reference in Appendix A.

3-2.1 CONCEPT DEVELOPMENT PHASE.

3-2.1.1 Engagement of NOSSA and NAVSEA 05 During Concept Development.

During the Concept Development Phase and upon identification of the need for a lithium battery that could impact Navy personnel, facilities, systems, or platforms, the program manager shall inform NOSSA of the potential need for a lithium battery. This contact shall be made regardless of whether the program originates or is managed from inside or outside of NAVSEA. The program office shall provide to NOSSA all information necessary for NOSSA to determine whether the lithium battery will, under any circumstance during its lifetime, be carried, used, or transported aboard a Navy platform in any configuration (e.g., as a standalone (spare) cell, or within a battery system).

3-2.1.2 NOSSA Review and Determination of Navy Ship Involvement.

NOSSA will review the information provided by the program office. If NOSSA determines the lithium battery will never be carried aboard a Navy platform, then NOSSA shall document this determination and proceed with hazard characterizations and assessments according to standard procedures defined in NAVSEA TM S9310-AQ-SAF-010, with no NAVSEA 05 involvement. If NOSSA determines the lithium battery will, in fact, be carried aboard a Navy platform at any point in its lifetime, then NOSSA shall contact the platform program office and NAVSEA 05, which will then engage in the process described in this manual.

3-2.1.3 System Requirements Submittal.

The program office shall submit the program's Top Level Requirements (TLRs), Operational Requirements Documents (ORD), including CONOPS, PHL, and/or equivalents (for non-ACAT programs) to NAVSEA 05 for review. A copy of the request letter and data package required by NAVSEA TM S9310-AQ-SAF-010 and submitted to NOSSA as part of the initial contact and review under 3-2.1.1 shall be included in the submittal for NAVSEA 05 review.

Prior to submittal, the program office shall ensure:

- Proper identification and consideration of safety hazards and risk mitigations are evident and incorporated into the system concept, ORD, TLR, CONOPS, and PHL
- Proper consideration has been given to energy source Analysis of Alternatives (AOA) and technology choices prior to concluding that a lithium battery is the most suitable choice.
- Proper consideration has been given to energy source weight and volume allocations, to battery location and environment, and to battery CONOPS.
- The potential need for software control of safety critical battery control and monitoring functions has been identified and risks are appropriately included in the PHL.
- Proper SCC has been established to help evaluate any software contained within the system design.

3-2.1.4 Requirements Validation.

NAVSEA 05 will review the ORD, TLR, CONOPS, PHL, and SCC and perform a requirements validation in accordance with the independent TWH process to ensure the requirements are reasonable and achievable while maintaining sufficient safety margins and considering the expected operating environment and CONOPS. Full advantage should be taken of the historical data. An assessment of available batteries shall be conducted prior to the start of a new program to qualify a new battery cell or system. All requirements are reviewed to determine safety critical involvement.

3-2.1.5 Engagement of NAVSEA 05 for Programs Beyond Concept Development.

For existing or legacy programs that are beyond the Concept Development Phase, NAVSEA 05 will revisit and review the program's TLR, ORD, CONOPS, PHL, and SCC or equivalents to ensure proper consideration has been given to energy source selection and to hazards and mitigations at the most fundamental levels of CONOPS and requirements, as described above for an ACAT program.

3-2.1.6 Program Management & System Safety Plans.

The Program Management Plan (PMP), shall include tasks, milestones, deliverables funding requirements, funding source(s), and a battery acquisition strategy that addresses and emphasizes battery safety at all stages, from system engineering trade studies to select the best battery and cell technology, to standards and acceptance criteria for design, manufacture, and qualification/test.

The System Safety Plan (SSP) shall identify how the system safety concerns will be addressed for hazards related to both hardware and software.

The program office shall meet with NAVSEA 05 and its affected TWHs, as applicable, to develop a plan of action to perform the PHA, BCCT, Hazard Mitigation Tests (HMT) if required, and the final SHA. This plan of action shall be integrated into both the PMP and SSP. NAVSEA 05 shall review the battery-relevant portions of the PMP and SSP, and shall work with the program manager to reach concurrence on the battery-related development approach. The PMP shall include a specific schedule for program office submittal and NAVSEA 05 review of required documentation. The specific schedule shall be agreed to by the program manager and technical authority.

3-2.1.7 Memorandum of Agreement (MOA).

The program manager shall develop and publish an MOA that clearly defines and communicates the roles and responsibilities of all stakeholders that will be involved with the development, manufacture, test, integration, use, and maintenance of the lithium battery during the execution and life of the program.

3-2.1.8 Documentation Requirements.

All program decisions, design data, tests, and evaluations that have a bearing on the hazard characterization and safety of the lithium battery and the system shall be documented. This documentation shall be retained in a program library/archive maintained by the program office and shall be available for recovery and reference over the entire life of the program.

The Hazard Log Record (HLR) shall be the top-level document that summarizes the status and history of each hazard on a separate form/record, including failure mode and effects, mitigations, and associated risk assessments. An example of an HLR is provided in Appendix A. Any pertinent documentation that supports or has a bearing on the information summarized in the HLR is referenced in the HLR. The HLR provides a concise and expedient vehicle for stakeholders to communicate and document the status of each hazard as well as any agreements among stakeholders regarding risk assessments, and approvals of any tests or analyses that have been completed or are planned to verify mitigations. The HLR is updated any time new information becomes available during the program's evolution.

3-2.1.9 Independent Oversight.

NAVSEA 05 shall define responsibilities for independent oversight of the design, quality, and safety processes during system development and qualification. These responsibilities shall be documented in the MOA.

3-2.2 ENGINEERING DESIGN PHASE: PRELIMINARY DESIGN.

3-2.2.1 Initial Documentation Requirements.

Within 90 days after the start of the Engineering Design Phase and at least 60 days prior to Preliminary Design Review, the program office shall submit the following to NAVSEA 05 for review:

- A draft of the battery Preliminary Hazard Analysis (PHA), characterizing the hazards and risks related to the lithium battery.
- A preliminary set of Hazard Log Records (HLRs) that summarize and baseline the Hazard Risk Index (HRI), failure mode, and failure effects for each hazard identified in the PHL and PHA.
- A draft top-level Functional Failure Modes and Effects Analysis (FMEA) for the battery and its system interfaces.
- A draft Hazard Characterization Test Plan (TP) that outlines tests that will be performed to characterize the battery hazards. The program office and system developer shall collaborate with NAVSEA 05 and NOSSA to establish a TP that defines which of the tests in Chapter 5 of this manual are required, based on the hazards and mitigations identified for the program. Tests required to satisfy the needs of both NAVSEA TM S9310-AQ-SAF-010 and of this manual (NAVSEA TM SG270-BV-SAF-010) shall be identified, while avoiding unnecessary duplication of efforts. NAVSEA 05 may approve selected portions of this draft TP (e.g., cell-level characterization tests) at this stage to allow hazard characterization to begin as early as possible.
- A draft software hazards, Critical Function (CF), and Best Practices (BP) list (see Appendix A).

The draft PHA, draft FMEA, and preliminary HLR shall be projected based on what is commonly known about the failure modes and effects of the lithium battery under consideration, with attention to the battery's specific chemistry, size, and intended use. The draft software hazards, CF, and BP list shall document all high-level system safety concerns that may have software impact within the system.

3-2.2.2 NAVSEA 05 Review of Draft PHA, FMEA, HLR, and Software Hazards, CF, and BP List.

NAVSEA 05 will review the draft PHA, FMEA, HLR, and software hazards, CF, and BP list; verify their content and accuracy; and make a determination regarding the existence of, or potential for, hazards and risks associated with integration, transport, storage, or use of the system on a Navy platform.

3-2.2.2.1 Systems with No Platform Hazards.

If NAVSEA 05 review of the draft PHA, FMEA, HLR, and software hazards, CF, and BP list does not identify any platform-related hazards or risks, the program will be referred to NOSSA for continued evaluation, tracking, and approval, using existing NOSSA processes in accordance with NAVSEA TM S9310-AQ-SAF-010. NOSSA and the program office shall continue to evaluate system safety and hazards during system development and shall re-engage NAVSEA 05 if battery–based, platform-related hazards or risks arise. In this case, NOSSA shall monitor and guide the continued refinement of the draft TP.

3-2.2.2.2 Systems with Platform Hazards.

If NAVSEA 05 review of the draft PHA, FMEA, HLR, and software hazards, CF, and BP list does identify the potential for platform-related hazards or risks, NAVSEA 05 and the program office shall document and communicate the potential for such risks to the next-higher level of decision authority to solicit feedback and to establish expected levels of risk tolerance. In this case, both NAVSEA 05 and NOSSA shall continue to review and monitor key program safety documentation and shall guide the refinement of the Hazard Characterization TP as described in paragraphs 3-2.2.3 to 3-2.2.5 below.

3-2.2.3 Detailed Documentation Requirements.

If NAVSEA 05 review of the draft PHA, FMEA, HLR, and software hazards CF, and BP list does identify the potential for platform-related hazards or risks, the program office shall develop and submit the following to NAVSEA 05 at the Preliminary Design Review:

- A detailed battery PHA that explores each hazard in greater depth to further validate HRI estimates and to explore mitigation approaches.
- Updated HLR with updated HRI estimates and any design or procedural mitigations the system developer plans to implement for each identified hazard.
- A functional FMEA detailed to the functional component level (i.e., one level above the parts level). The functional FMEA shall define failure modes and effects (hazards) for all phases of battery use, transport, and storage (see Appendix A).
- An updated and detailed Hazard Characterization TP that fully defines the tests that will be performed to characterize the battery hazards.
- Results of any material or cell-level hazard characterization testing performed during the preliminary design.
- A detailed list of software-related Safety Requirements (SRs) establishing how the software hazards, CF, and BP list will be evaluated and verified (see Appendix A).
- Software computer program level or Computer Software Configuration Item (CSCI)-level hazards, CF, and BP (see Appendix A).
- Software CSCI-level Software Criticality Hazard Matrix (SCHM) ranking (see Chapter 6).

3-2.2.3.1 Responsibilities for PHA, FMEA, HLR, and Software Hazards, CF, and BP List.

In all cases, the PHA, FMEA, HLR, and software hazards, CF, and BP list and SCHM rankings shall be the ultimate responsibility of, and shall be performed by, the system developer with program office review and oversight, and shall include all potential failure modes and hazards at the component, subsystem, system, and platform levels.

The program office shall ensure the system developer solicits, analyzes, and incorporates all information required from any sub-tier contractors or Government entities that may be involved in the design, development, manufacture, test, evaluation, and integration of the lithium battery into the system.

3-2.2.3.2 Responsibilities for TPs.

The TPs shall be the responsibility of, and shall be developed by, the test activity in collaboration with NAVSEA 05 and the system developer. In the event the system developer also serves as the test activity, the program manager shall ensure the system developer’s test activity is sufficiently independent of the system developer’s program management activity to provide unbiased participation in the development and execution of the TP, operating in the same independent fashion as the system developer’s safety officer or QA officer would be expected to operate.

3-2.2.4 Legacy Programs.

For existing or legacy programs, the program office will be required to submit a PHA, FMEA, HLR, and software hazards, CF, and BP list, and a summary of safety and hazard characterization tests already performed for NAVSEA 05 review. NAVSEA 05 may require additional characterization tests and a revised TP and test procedures, depending on the results of their review.

3-2.2.5 NAVSEA 05 Review and Approval.

TPs will be subject to selective NAVSEA 05 review and approval. When selected by NAVSEA for review, specific TP shall be submitted 30 days prior to the intended start of the test

3-2.3 ENGINEERING DESIGN PHASE: DETAILED DESIGN.

3-2.3.1 Hazard Characterization Test Execution.

Upon approval of the Hazard Characterization TP or any of its elements by NAVSEA 05, the test activity shall perform the required hazard characterization tests. Note that execution of the various levels of test outlined in the TP should be coordinated with the program phase. For example, materials-level and cell-level hazard tests are recommended as early as the System Preliminary Design stage. Module and prototype battery assembly-level hazard tests are suggested no later than the Detailed Design stage. System-level hazard tests might extend into the Test and Evaluation Phase. In any case, the objective shall be to perform the characterization tests at the earliest possible point in the development, with the objective of reducing schedule and cost risk.

3-2.3.2 Manufacturing Audits.

The program office shall conduct audits and inspections of the intended battery system/cell manufacturer's production facilities during the Detailed Design stage unless the selected battery system/cell vendor is "current" regarding its NAVSEA manufacturing audit status (see Chapter 7). Additional independent manufacturing audits performed by independent industry experts shall be performed in those situations where residual safety risk cannot be fully mitigated to a low level. Where foreign manufacture of cells prevents factory audits, other Objective Quality Evidence (OQE) shall be developed to ensure manufacturing quality is maintained. NAVSEA 05 or its agent will engage in the program's manufacturing audits as appropriate to ensure an understanding of the levels of safety risk associated with the manufacturing process and the resulting product.

The manufacturing audit shall be the responsibility of the program office, with participation by NAVSEA 05 or its representative in an independent oversight role.

3-2.3.3 Documentation Requirements.

The program office shall develop and submit the following to NAVSEA 05 30 to 60 days prior to Critical Design Review (CDR) for review and approval:

- A test report that details the results of the tests performed to characterize battery hazards.
- A final SHA, characterizing all hazards and risks related to the lithium battery and its integration and use in the system. The SHA shall include all hazards associated with the battery, including those during Operations and Support phases, unless otherwise captured in a separate Operating and Support Hazard Analysis (O&SHA). The SHA shall record each potential battery-related hazard on a separate HLR for tracking and adjudication. By reference to design documentation and associated analyses, the SHA and HLR shall fully detail the design and/or procedural mitigations the system developer will implement for each identified hazard. The SHA shall include fully supported failure probability estimates, severity estimates, and final HRI values for all identified hazards in accordance with guidance in Appendix C.
- As part of the SHA, a final functional FMEA detailed to the functional component level (i.e., one level above the parts level).
- As part of the SHA, a Failure Modes Effects and Criticality Analysis (FMECA) at the parts level for any electronics hardware whose failure results in an HRI of 9 or less (i.e., HRI of 9 or more severe).
- Updated HLR containing updated HRI estimates based on results of hazard characterization tests and hazard analyses, and results of mitigation tests.
- A manufacturing audit report summarizing any deficiencies identified at the intended manufacturer's facility and the corrective actions that must be implemented to correct those deficiencies.
- A Software Safety Requirement/Verification Requirements (SR/VR) plan establishing how the software-related systems will be evaluated (see Appendix A).

The SHA, FMEA, FMECA, HLR, and SR/VR plan shall be the responsibility of, and shall be performed by, the system developer, with program office review and oversight.

The program office shall ensure the SHA, FMEA, FMECA, HLR, and SR/VR plan incorporates the analyses of all potential failure modes and hazards identified by the test activity, the system developer, sub-tier contractors, and by Government entities, any of whom are involved with the design, development, manufacture, test, evaluation, and integration of the lithium battery into the system.

3-2.3.4 NAVSEA 05 Reviews.

NAVSEA 05 will review the design documentation, test report, SHA, FMEA, FMECA, HLR, SR/VR plan, and the program manager's Verification of Requirements (see section 7-4) and will make a determination of acceptance of residual risk. Section 7-4 allows use of alternative accountability systems to capture outstanding liabilities that are necessary for risk acceptance but cannot be completed as of the NAVSEA/NOSSA system-use recommendation. In these cases, alternative accountability systems must provide positive confirmation when actions are completed. For example, if a specific risk is accepted based on implementation of a procedure that can only be verified at sea with the battery system active, completion of these actions may not be possible before NAVSEA recommendation for system use. In that case a Sea Trial Test Agenda or Consolidated Ship's Maintenance Plan might serve as the alternate accountability system.

3-2.3.4.1 Systems with Platform Risk Acceptable to NAVSEA 05.

If the residual risk is acceptable to NAVSEA 05, then NAVSEA 05 will concur with the NAVSEA/NOSSA system-use recommendation. For record purposes, NAVSEA 05 shall document the concurrence and acceptance of residual risk by all parties in a formal letter to the Program Office in accordance with section 6-5.

3-2.3.4.2 Systems with Platform Risk Conditionally Acceptable to NAVSEA 05.

At this stage, NAVSEA 05 and/or NOSSA might provide only conditional concurrence or a letter of intent to concur, with final concurrence pending completion of any remaining hazard characterization tests and/or system evaluation tests in the Test and Evaluation Phase.

3-2.3.4.3 Systems with Platform Risk Unacceptable to NAVSEA 05.

If there is significant residual risk, and NAVSEA 05 Technical Authority determines the residual risk is unacceptable, NAVSEA 05 will then withhold concurrence and recommend one or more risk-acceptable alternatives to the program manager. The program manager may elect to implement one of the acceptable alternatives provided by NAVSEA 05 or may propose other alternative approaches. In either case, the program office will be required to re-enter the process at the appropriate step (PHA, TP, SHA), depending on the extent of the required design changes. NAVSEA 05 shall document any non-concurrence with residual risk in a formal letter to the program office in accordance with section 6-5.

3-2.4 MANUFACTURING AND PRODUCTION PHASE.

3-2.4.1 Manufacturing Oversight.

The program office or its qualified representative shall monitor cell and/or battery production and QA processes during the Manufacturing and Production Phase, with participation by NAVSEA 05 or its representative in an independent oversight role.

3-2.4.2 Materials Control and Traceability.

The program office, via the system prime and/or procuring activity, shall ensure the cell/battery vendors establish a material control program to provide an identification-and-control process for materials and associated components used in Lithium battery systems. This material control program shall ensure the correct material is installed in lithium battery systems and in installations aboard ship, and that such material is traceable to records of OQE. It shall provide for the procurement, receipt inspection, characterization, sample archiving, storage, installation, and verification of material during construction, test, overhaul, repair, and alteration of battery systems

3-2.4.3 Independent Quality Verification.

Special measures taken to verify material and product quality, such as Destructive Physical Analysis (DPA) or X-ray tomography of cell samples, shall be performed by an independent entity other than the manufacturer (see Chapter 7 for additional requirements and techniques).

3-2.4.4 Documentation and Reporting of Deficiencies.

The program office shall document any deficiencies or anomalies observed during manufacture of the cells or batteries, and report those deficiencies to NAVSEA 05 along with any potential impacts to the SHA and its HRI assessments.

3-2.5 TEST AND EVALUATION PHASE.

3-2.5.1 Completion of Remaining Tests.

The program manager shall ensure all tests in the TP that may have been delayed to the Test and Evaluation Phase are completed. (Note that delay of the completion of certain tests to this phase may be required due either to the duration of the tests, as might be true for long-term cycle tests for emergent defects, or to the availability of assets, or for system-level integration tests.) The program manager shall further ensure all testable software Verification Requirements (VRs) are tested as part of the testing effort. The testing of software VRs can be incorporated into the general tests, or special safety tests can be generated and executed.

3-2.5.1.1 System Verification.

System verification will be in accordance with section 7-4.

3-2.5.2 Updated SHA and HRI.

The program manager shall update the SHA, HLR, and HRI assessments based on results of any tests performed and completed in the Test and Evaluation Phase, and submit the results to NAVSEA 05 for review and approval in accordance with section 6-5.

3-2.5.3 NAVSEA 05 Reviews.

SEA05 will review the final test report, SHA, and HLR, and adjudicate the residual risk as follows:

3-2.5.3.1 Tests that Confirm Platform Risk Assessments from CDR.

If tests and evaluations in this phase confirm the SHA and HRI assessments provided and documented at CDR, then NAVSEA 05 will provide final concurrence to NOSSA for Navy approval. For record purposes, NAVSEA 05 shall document the final concurrence and acceptance of residual risk by all parties in a formal letter to the program office in accordance with section 6-5.

3-2.5.3.2 Tests that do not Confirm Platform Risk Assessments from CDR.

If tests and evaluations in this phase identify hazards or risks that exceed those established in the SHA and HRI assessments provided at CDR, then NAVSEA 05 will provide new guidance to the program office.

3-2.6 OPERATIONAL AND SUPPORT PHASE.

3-2.6.1 Continued Battery System Surveillance.

During the Operational and Support (O&S) Phase, the program manager shall ensure field support activities perform continual battery system surveillance, test, and data analyses to identify changes or developing conditions that might bear upon the risk and safety of the system. Continual validation of battery charging procedures and practices shall be maintained by the operational forces, and any abnormalities shall be reported to the program office and to NAVSEA 05.

3-2.6.2 Events Forcing a Change in Hazard and Risk Assessments.

During O&S, if events occur or conditions change that could have a bearing on the safety of the battery and system, the program manager shall immediately implement appropriate operating restrictions, shall inform NAVSEA 05, NOSSA, and the appropriate decision authorities, and shall submit a System Trouble Report. For Trouble Reports with a safety impact, the actual mishap/hazard shall be documented along with additional factors or conditions necessary for mishaps to occur. The program office shall re-evaluate and update the system SHA and HRI assessments, and develop a corrective action plan. All results shall be presented to NAVSEA 05 and NOSSA for review and further direction.

3-2.6.3 In Service System Operational Review

Based on complexity of the battery system or operational history, NAVSEA may elect to perform an on-site System Operational Review per paragraph 7.5.1.

3-2.7 NAVSEA 05 REVIEW OF TROUBLE REPORTS.

NAVSEA 05 and the SSSA will review each Trouble Report for potential safety impacts, and will provide guidance to the program office regarding the continued use of the lithium battery and system.

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CHAPTER 4 – DESIGN PRECEPTS

In addition to the design guidance provided in NAVSEA TM S9310-AQ-SAF-010, this chapter defines additional guidance for the design of lithium battery systems where use on Navy platforms is anticipated. Failure to meet one or more of these functional safety requirements may necessitate alternative risk mitigation efforts, or result in residual risk that must be accepted by increasing levels of authority.

4-1 PREVENTION/MITIGATION OF ENERGY RELEASE.

The battery system shall be designed in such a manner that the unexpected, uncontrolled release of energy in any form (thermal, mechanical, or electrical) is mitigated to a point acceptable by the appropriate authority.

4-1.1 THERMAL ENERGY RELEASE.

The battery system shall be constructed in such a manner that it either insulates cell-level thermal events to prevent thermal failure propagation to adjacent cells, or such that it conducts heat away from adjacent cells and modules with sufficient speed and efficiency to prevent sympathetic cell failure and propagation. The ability to prevent cell failure propagation shall be verified by test in accordance with section 5-2 of this manual, at the temperature extremes of the intended usage and/or storage environments. A detailed thermal analysis may be necessary, using an appropriate computational model to further ensure that in the event of cell thermal runaway, propagation from one cell or module to another is mitigated for the various possible modes of operation (e.g., with battery in air or in water). Such analyses should also be used to determine the fidelity of temperature sensors placed at various locations for the early detection of thermal runaway.

4-1.1.1 Thermal Impact.

Provisions shall be made to accommodate and mitigate – in a safe manner – the thermal impact of all ejecta (solids, gases, particulate, aerosols, etc.) from a battery failure that may be released to the platform. Gases venting from burning lithium cells may include a variety of hazardous materials, including Hydrogen Fluoride (HF). Furthermore, these gases are hot enough and corrosive enough to cut through a variety of construction materials. Therefore, a conscious effort shall be made by designers to prevent the direct impingement of hot gases from cell vents on critical structural components of Navy platforms in the event of a battery fire. Furthermore, the thermal impact caused by combustion or explosion of any flammable ejecta shall be mitigated.

4-1.2 MECHANICAL/PRESSURE/KINETIC ENERGY RELEASE.

Catastrophic failure of a lithium-based battery will result in the evolution of large volumes of gases. For battery systems housed within pressure vessels, these gases must be either safely contained or relieved such that the pressure vessel itself does not become a hazard.

Upon characterization of the gas volumes and heat generated by a battery failure, an analysis shall be performed to determine if the pressure vessel meets the PASS requirements of Table I of NAVSEA

TM S9310-AQ-SAF-010 (Aug 2004 Rev).

For battery systems housed within pressure vessels that do not meet the Pass/Fail requirements of Table I of NAVSEA TM S9310-AQ-SAF-010 (Aug 2004 Rev), detailed mitigation plans shall be developed and verified to prevent a hazardous release of pressure.

The pressure vessel shall incorporate intentional failure points/mechanisms to prevent material failure of the housing itself. The mechanisms shall be designed to release the volumes of gas expected based on testing detailed within this manual. Examples of pressure relief devices include, but are not limited to:

- Belleville washers on pressure vessel bulkhead fasteners.
- Urethane springs on pressure vessel bulkhead fasteners.
- Shear-pin bolts on pressure vessel bulkhead fasteners.
- Pressure relief discs/ports/flapper valves on the pressure vessel.

The pressure relief mechanism chosen in the design shall be evaluated and tested to ensure particulates or other materials released during a battery failure will not cause failure/blockage of the pressure relief mechanism. Note: Lithium cells can eject up to half of their mass as particulate during failure, and can eject larger pieces of internal components (e.g., current collector foils) as well.

Provisions shall be made to accommodate and mitigate the mechanical impact of all ejecta (solids, gases, particulate, aerosols, etc.) released to the platform during a battery failure. Furthermore, the mechanical impact caused by combustion or explosion of any flammable ejecta shall be mitigated.

4-1.3 ELECTRICAL ENERGY RELEASE.

Battery systems shall be designed with mitigations to limit the release of electrical energy resulting from a battery failure.

The battery system shall be designed such that failure of any battery component does not create an electrical short circuit that causes cell failure, cell failure propagation, or other hazards, including uncontrolled release of energy in any form. Battery cables, connectors, and interconnects must be secure and capable of withstanding fire without creating loose power cables inside battery bottles and housing.

The battery system shall be designed such that short circuit paths that can be created by inadvertent operator error or system faults are mitigated via the use of electrical interruption devices and/or physical designs/layouts that prevent operator injury and catastrophic damage to the cells or battery.

Electrical Safety Devices (ESDs) (e.g., contactors, fuses, circuit breakers, diodes, Positive Temperature Coefficient [PTC] Devices, Current Interrupt Devices [CIDs], etc.) shall be tested and proven at voltages and currents that can be encountered during operation or during failure. Failure of such electrical devices shall not permit or create catastrophic cell or battery failure. The behavior and failure of such devices at the intended system voltages, currents, and operating environments shall be tested and well understood before acceptance and implementation as a system safety device.

In addition to software-based and user-initiated overvoltage/overcharge protection, to the extent possible, the battery shall be designed with passive hardware-based overvoltage/overcharge protection.

4-1.4 INADVERTENT ENVIRONMENTAL STRESS OR ABUSE.

Design requirements for tolerance to inadvertent abuse such as drop, impact shock, electrical abuse, thermal abuse etc., shall be established and reviewed by the program office and NAVSEA 05.

4-2 BATTERY MANAGEMENT SYSTEM (BMS).

4-2.1 BATTERY MONITORING.

For the purposes of this manual, the design goal of the BMS is to provide effective detection and mitigation of any condition that can lead to energetic or catastrophic failure of the battery. The battery system shall be equipped with an automated BMS capability that is commensurate with the potential hazards and levels of risk posed to the platform by failure of the battery.

The BMS shall provide, to the operator and to any automated battery control system and/or platform damage control system, all data necessary to assess the health of the battery and to make real-time decisions regarding control, continued use, and failure response/mitigation. The BMS shall be capable of providing data during all operational phases of charge, discharge, and open circuit, and during non-operational phases, including storage and handling, as appropriate.

Examples of data and capabilities that may be required include but are not limited to:

- The capability to monitor the temperature of cells and detect the presence of anomalous heating within a cell.
- The capability to monitor individual cell voltages and detect individual cell voltage excursions.

- For battery systems housed within a vessel, the capability to monitor ambient air/gas temperature and detect air/gas temperature excursions.
- For battery systems housed within a pressure vessel, the capability to monitor the pressure within the vessel and detect pressure excursions.
- For battery systems housed within a pressure vessel, the capability to monitor and detect the potential for a combustible environment.
- For battery systems housed within a pressure vessel and intended for underwater use, the capability to monitor and detect seawater leakage.
- The capability to provide both audible and visual alarms to the operator.
- The capability to report alarm status information to an area of the platform that is continuously manned and monitored.
- The capability and algorithms to determine State of Charge (SOC) of the battery and of individual cells.
- The capability to detect and report battery system and cell self-discharge characteristics.

Primary battery systems greater than 1 kWh shall contain a battery monitoring system.

4-2.2 BATTERY CONTROL.

Via a combination of operator input and automated intervention, the BMS shall be capable of safely securing the battery system and limiting potential damage to the host platform.

4-2.3 CONTROL OF BATTERY CHARGE (FOR RECHARGEABLE BATTERIES).

The operator shall be capable of manually halting charge or discharge of the battery system at any time. The BMS shall be capable of automatically halting charge and discharge based on critical sensor readings (e.g., cell temperature, voltage, pressure, current, etc.).

Battery charging shall be a closely monitored evolution where an operator is required to monitor battery charging outputs either in real time or through an automated charging system. Verbatim compliance to all charging precautions and approved initial conditions (wet or dry environment, specific volume flows surrounding the charge, etc.) shall be required. Software specifically designed for charging shall be installed and tested only by an approved activity and shall have NAVSEA-approved documentation for any changes. The SSA shall ensure battery charging software changes are approved and comply with the software safety requirements of this manual.

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CHAPTER 5 – TESTING AND ANALYSES

All lithium batteries are subject to the standard safety test protocols in NAVSEA TM S9310-AQ-SAF-010, which include but are not limited to: short circuit, ESD testing, overcharge, over-discharge, and thermal abuse. The program office and system developer shall collaborate with NAVSEA 05 and NOSSA to establish a TP that defines which casualty characterization tests in Chapter 5 of this manual are required, based on the hazards and mitigations identified for the program. Tests required to satisfy the needs of both NAVSEA TM S9310-AQ-SAF-010 and this manual (NAVSEA TM SG270-BV-SAF-010) shall be identified, to avoid unnecessary duplication of efforts. Furthermore, the database being compiled by NAVSEA 05 should also be used to avoid unnecessary additional testing in those situations where sufficiently similar batteries have already been characterized.

The applicability of the specific test paragraphs of Chapter 5 of this manual derive directly from the System Safety Program Plan, from the specific hazards identified in the program's PHA and SHA, and from the mitigations proposed for each hazard.

NAVSEA TM S9310-AQ-SAF-010 tests may be conducted as precursory events or in parallel with the tests required by this manual as shown in Figure 5-1.

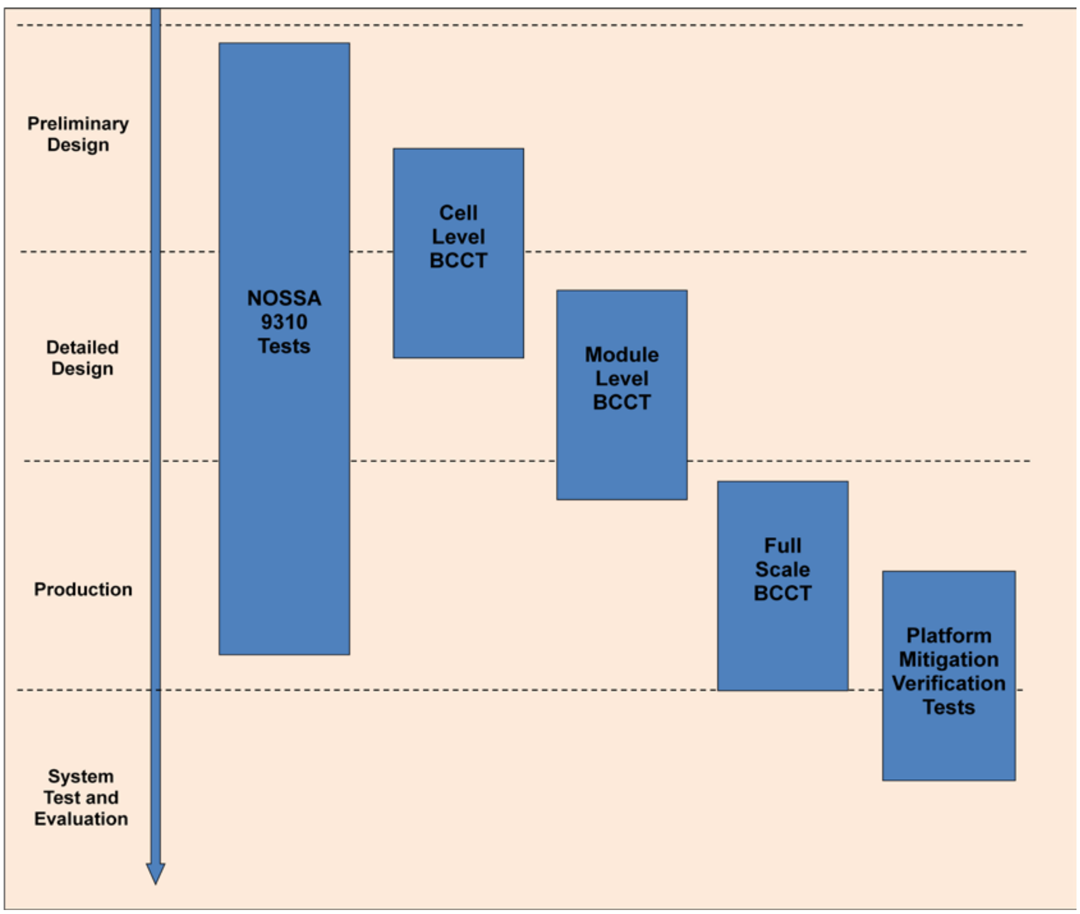

Figure 5-1. Notional Phasing and Coordination of Tests Called out by NAVSEA TM S9310-AQ-SAF-010 and NAVSEA TM SG270-BV-SAF-010.

5-1 GENERAL REQUIREMENTS.

NAVSEA TM SG270-BV-SAF-010 testing is necessary to characterize the hazards (corrosive and toxic gas production, heat release rates, debris ejection, pressure transients, propagation risk, etc.) from individual cells, groupings of cells, and batteries and in turn, to understand the risks that these hazards pose to personnel, systems, and platforms carrying or associated with the battery. Tests shall be conducted on individual cells; groupings of cells such as cell branches, modules, or Lowest Replaceable Units (LRUs); and full-scale batteries as defined in the TP and approved by NAVSEA 05.

NAVSEA TM SG270-BV-SAF-010 testing is designed to characterize the impact to the platform of the Worst Credible Event (WCE) involving a lithium battery casualty, and to evaluate the planned mitigation techniques. Battery testing shall be conducted in three categories:

- Cell and Battery Casualty Characterization Testing (BCCT) (see paragraph 5-3).
- Platform Characterization and Mitigation Testing (see paragraph 5-4).
- Platform Level Survivability/Recoverability and Environmental Testing (see paragraph 5-5).

The parameters of these tests shall be determined on a case-by-case basis as justified by the PHA, SHA, CONOPS, battery size and energy content, battery chemistry, and the potential sympathetic and collateral damage that a battery casualty may cause to the host platform.

Note: Test characterizations discussed in this section are intended to address all potential hazards and risks associated with the battery, the system, and the platform during any phase of use. For example, while the size, energy content, and chemistry of the battery are some of the most important drivers in characterizing failure energetics, it may also be important to include battery “shipping” or “packaging” material in casualty characterization tests because of the potential for such materials to act as fuel in the event of a fire. Also, in some battery chemistries, aerosols of organic electrolytes may be produced. The characterization of these aerosols is important, as they may present their own unique flammability or explosion hazards. The objective, therefore, is to characterize all relevant hazards, whether directly or indirectly associated with the battery.

5-1.1 TEST PLAN (TP) APPROVAL.

A TP shall be developed to address the known and unknown (or previously uncharacterized) hazards posed by the battery and system to personnel and to Navy facilities and platforms. This TP must be approved by NAVSEA 05 and/or their technical agents prior to execution. Tests to determine the platform hazards may be conducted without NAVSEA 05 pre-concurrence, but such tests are done at the risk that the data may be rejected or that additional tests may be required. The Platform Characterization and Mitigation section of the TP may be expected to evolve and undergo revision based on the emerging results of BCCT testing. All revisions to the TP must also be approved by NAVSEA 05 and/or their technical agents prior to execution.

5-1.2 TP CONTENT.

The PHL, PHA, SHA, FMEA, CONOPS, and any hazards and mitigations defined therein shall be used to determine the scope of the required tests, test methodologies, and test conditions. Hazards and failure modes identified in those documents shall be used to determine any data that must be gathered – whether specifically cited and required by this manual or not – to understand and characterize the behavior and potential risks of a battery casualty, both mitigated and unmitigated. Special consideration shall be given to the TP for any hazard determined to have an unmitigated HRI of 17 or lower.

Tests shall be conducted at the cell, module, LRU, full-scale assembly and system levels, as necessary to characterize the rate and magnitude of any heat, effluents, or ejecta generated by a cell or battery casualty. Chemical composition and quantities of gases or vapors evolved shall be characterized.

Tests shall subject assets to potential electrical, mechanical, and thermal influences that can cause significant battery events or failures. The potential for inadvertent environmental abuse such as mechanical shock or crushing events shall also be considered, and where not already covered under NAVSEA TM S9310-AQ-SAF-010, shall be included in the TP as agreed upon by the program manager and NAVSEA 05. For example, uncontrolled dropping, puncture, or crushing by a forklift or by handling/loading equipment are examples of events that are not explicitly covered by NAVSEA TM S9310-AQ-SAF-010, but may be expected to occur with some, albeit low, frequency in shipboard environments.

The TP shall include the type and number of tests to be performed, the test conditions, orientation, and criteria for each proposed test, and the number of assets required. The TP shall define the data collection methods proposed, any test fixtures and equipment required, the location and facilities proposed, and the conceptual instrumentation arrangements and test layouts. The TP shall highlight and justify any off-scale, modularized, partial, or non-directly comparable test methods and test facilities proposed in lieu of required full-scale tests.

5-1.3 TEST CONDITIONS.

The TP shall address all aspects of CONOPS for system and battery support across the full life cycle. The full life cycle includes system development; system test and evaluation; system use and deployment; shipboard carriage, storage, maintenance, and handling of spares and replacement units; and disposal. Where not specifically directed otherwise by the TP, tests shall be performed under standard local environmental conditions. Non-ambient test conditions shall be given consideration and shall be included when driven by the CONOPS across the full life cycle. Temperature, pressure, and humidity shall be noted and recorded for each test in the test report.

5-1.4 SCALE AND FIDELITY.

When approved by NAVSEA, full-scale BCCT and platform-level survivability/ recoverability and environmental testing may be conducted at a reduced scale from whole batteries and systems (e.g., at the module scale or LRU scale) provided there is sufficient information to enable scaling factors to be accurately applied to the test results. When reduced scales are used, the reduction of fidelity and any potential underestimations of experimental error and/or scaling error shall be analyzed, discussed, and accounted for in the test report. When off-scale testing is conducted, the error associated with the off-scale test, and the error imparted by test facilities that are not fully comparable to the intended platform use, shall be assessed to the more severe levels. In other words, if the test system error of measurement is 10 percent of the total measurement, the hazard characterization shall be reported at the UPPER/HIGHER value. These results may be used to calibrate and validate predictive models.

5-1.5 SPECIAL CONDITIONS.

Unique test configurations and conditions beyond the tests described herein may be required to characterize special hazards where they are a concern, such as hull overpressure and underwater implosions or concussions. Where CONOPS/Logistics require recovery/storage/handling of systems at partial SOC, special testing at partial SOC may be required for lithium primary and secondary batteries to assess and characterize the hazards posed at cell-level and module-level to support final hazard analyses.

5-2 TEST METHODS AND REQUIREMENTS.

This section outlines general test methods and data-collection requirements. The methods outlined here shall be applied selectively to the various levels of cell, intermediate (LRU, module), or full-scale battery tests as appropriate to accomplish the required hazard characterization at that scale (i.e., not all tests listed in section 5-2 apply to all levels of test). Table 5-1 demonstrates how the hazard characterizations described below might apply to the various stages and levels of test.

Note that section 5-2 defines “what” tests may be required for a given application. Additional details regarding “how” these tests should be executed (e.g., the test techniques and the specifics of the measurements required for each characterization) are included in Appendix B.

Table 5-1. Hazard Characterizations Potentially Applicable to Different Levels of Test.

Battery Casualty Hazard Characterization Test	Cell-Level BCCT	Intermediate Module-Level BCCT	Full-Scale Assembly-Level BCCT	Platform Hazard Characterization and Mitigation Verification
5.2.1.2 Quantitative Off-Gas Production Analysis.	X			
5.2.1.2.1 Real-time and Continuous Monitoring of Gases.	X			
5.2.1.2.2 Grab Samples for Toxic and Corrosive Gases.	X	X	X	X
5.2.1.3 Volatile Off-Gas Ignition.	X	X	X	X
5.2.1.4 Thermal, Volumetric, and Pressure Impacts of Off-Gas Ignition.		X	X	X
5.2.1.5 Gas Velocity Measurements.		X	X	X
5.2.1.6 Heat Release Rate and Thermal Flux.	X	X	X	X
5.2.1.7 Pressure and Pressure Transients.	X	X	X	X
5.2.1.8 Incandescent Debris and Shrapnel.	X	X	X	X
5.2.1.9 Aerosol Analysis.	X			
5.2.1.10 Smoke Generation.		X	X	X
5.2.1.11 Metal and Material Exposure.	X	X		
5.2.1.12 Cell Failure Propagation Tests.		X	X	X
5.2.1.13 Mitigation Verification Tests.		X	X	X

5-2.1.1 Cell and/or Battery Failure Initiation Requirements.

Tests shall be designed to reliably initiate a cell and/or battery failure. The method of initiation of the cell and/or battery failure shall be determined from the PHA and should represent the WCE. The method of failure initiation shall be fully described in the TP and shall be approved by NAVSEA 05.

5-2.1.2 Quantitative Off-gas Production Analysis.

Cell and/or battery failure shall be initiated, causing the cell and/or battery to undergo thermal runaway with gaseous release.

Off-gas analysis shall be performed to fully characterize the quantity of gas produced, the rate of gas production, and the composition of the gas produced. Two methods shall be used to measure gas composition:

- Real-time online analysis to characterize bulk generation and decay rates of key bulk gas constituents.
- Whole gas analysis on grab samples to characterize finer details of gas component ratios and trace materials that might be toxic or corrosive.

Additional details on methods, techniques, accuracy required, and types of gases expected are included in Appendix B.

Hazard characterization tests and the corresponding gas analyses shall be conducted in both air environments and in inert environments if the battery is packaged or housed in such an environment, unless otherwise agreed to by NAVSEA 05.

5-2.1.3 Volatile Off-gas Ignition Requirements.

Where the battery electrolyte contains an organic solvent or other liquid that might exothermically react or combust upon contact with air, a triggerable gas ignition device shall be included in the test setup to provide a means of reliably igniting the vapors, fumes or aerosols produced by a battery venting.

In all mitigated and unmitigated BCCT characterizations, tests shall be conducted with the ignition device operated in both the ENABLED (active) and SECURED (off) mode to contrast the variability in results both with and without ignition and combustion of off-gasses produced by a battery failure. If a system produces potentially flammable gases and aerosols but these do not normally ignite during the casualty event, these gases SHALL BE triggered to evaluate the potential explosiveness of fuel-air mixtures. Tests shall be initially conducted with the ignition system SECURED. If the failure event itself does not automatically trigger combustion of the gases vented from the cell or battery module, tests shall then be conducted with the ignition source enabled and operating to acquire the necessary data from the secondary combustion of fumes, gases and aerosols.

5-2.1.4 Thermal, Volumetric, and Pressure Impacts of Off-gas Ignition.

A significant portion of the thermal casualty assessment is based on the sensible and radiant heat released from combustible sources in the area of the casualty. Hazard characterization tests and assessments shall therefore quantify the potential sensible and radiant heat from combustion of flammable gases or aerosols released from the battery, as described below.

Hazard characterization tests and assessments shall also quantify the amount of additional gas volume created by the battery casualty, and to characterize the “breathing” associated with the combustion processes. Dynamic pressures shall be measured during these test events, and estimates shall be provided regarding the total volume of gases produced in excess of the primary volume of gases released from the battery.

5-2.1.5 Gas Velocity Measurements.

When required by NAVSEA, the gas velocity of the casualty exiting the shipboard compartment shall be recorded. The gas volume, pressure, and temperature can be useful in determining how quickly gases may spread to other compartments of a ship. Additional details on methods, techniques, and accuracy required are included in Appendix B.

5-2.1.6 Heat Release Rate and Thermal Flux.

The heat release rate shall be characterized for the battery system under question. Characterization tests shall be devised to quantify the total heat released to the platform during battery failure, either as radiant heat, or as sensible heat due to conduction, convection, or combustion of evolved gases and/or aerosols. Additional details on methods, techniques, accuracy required, and special guidance for partially or fully oxygen starved environments are included in Appendix B.

5-2.1.7 Pressure and Pressure Transients.

Pressure transients may be produced by a cell or battery undergoing a casualty. Hazard characterization tests shall measure absolute pressure and rapid pressure transients within the test chamber or test compartment during test. Additional details on methods and accuracy required are included in Appendix B.

5-2.1.8 Incandescent Debris and Shrapnel.

Cells and batteries undergoing induced casualty failures may produce shrapnel and eject incandescent particles. Fragmentation of battery cases under casualty conditions shall be considered a potential hazard for co-located equipment. Cell and battery module tests shall therefore include witness plates, impact plates, and video coverage of the gas-analysis tests to assess impact of these ejecta on co-located equipment, if this has not already been accomplished during NAVSEA TM S9310-AQ-SAF-010 tests. Additional details on methods and accuracy required are included in Appendix B.

5-2.1.9 Aerosol Analysis.

A battery that contains an organic electrolyte or other flammable liquid may produce an aerosol that (depending on the particle size) could form an explosive-air mixture. This extends to electrolyte-solvent solutions that in a liquid state would not normally be characterized as flammable. Therefore, when required by NAVSEA, or recognized as a casualty failure mode, aerosol analysis shall be conducted. Additional details on aerosol measurements and the analyses required are included in Appendix B.

5-2.1.10 Smoke Generation.

The density of the smoke shall be determined and recorded in percent transmittance or extinction factor. Measurements shall be made using American Society for Testing and Materials (ASTM) standards or comparable methods.

5-2.1.11 Metal and Material Exposure.

When required by NAVSEA, representative metal and composite material coupons shall be prepared by cleaning and distributing in the chamber. After exposure during characterization tests, they are rinsed, weighted and visually inspected, to help determine the post-fire cleanup that would be necessary and the systemic material damage that would be caused by a casualty.

5-2.1.12 Mitigation Verification Tests.

Mitigation tests shall be conducted to verify that proposed mitigations are effective. Mitigation testing may be appropriate at the cell level, the module level, the full-scale assembly level, and at the platform integration level.

5-2.1.13 Cell Failure Propagation Tests.

Propagation tests shall be conducted to determine the effects of a critical failure of one cell to neighboring cells and/or from one grouping of cells to neighboring groupings of cells. The tests shall be conducted in a fashion that simulates the real system's physical constraints (i.e., cell/sub-system module spacing and orientation, free volume, packing material, wiring, etc). The PHA and CONOPS shall be evaluated to determine the best triggering event. Intermediate-scale tests may be conducted to understand the potential propagation hazards prior to testing at full-scale or in simulated platform compartments and enclosures. The goal of every program is to prevent cell to cell propagation.

5-3 BATTERY CASUALTY CHARACTERIZATION TEST (BCCT).

It is the objective of this general test series to subject the cells and battery in question to their worst-case failure scenario(s) in order to characterize the maximum unmitigated risk to the system, platform, and personnel. It is the intent of the unmitigated BCCT to cause and ascertain the unmitigated failure events and behaviors of batteries and battery systems described in the PHA and SHA. Tests which produce effects less severe than worst-case events may also be necessary and shall be outlined in the TP.

The results of the unmitigated tests shall be used to formulate and assess potential risk mitigation, firefighting, and casualty recovery techniques.

Tests shall be conducted on individual cells, groupings of cells, and full-scale batteries and systems to provide an accurate representation of the casualty.

5-3.1 CELL-LEVEL BCCT AND ANALYSES.

Tests shall be conducted in a sealed chamber to collect and analyze evolved gases and to measure the thermal effects of a casualty at the cell level. The results shall be further evaluated and used to provide data scalable to intermediate and a full-scale battery tests. The by-products of a cell casualty can be toxic or corrosive and as such need to be analyzed in order to appraise the hazard to platform and personnel.

The tests outlined in Table 5-1 may be required at the cell level.

5-3.2 INTERMEDIATE-LEVEL BCCT AND ANALYSES.

Intermediate-level testing may be conducted to increase fidelity and scalability of the data. Intermediate-level testing includes any testing that is more than one cell and less than a full-scale battery. Examples of intermediate groupings are cell branches, LRU, or sub-system modules. A properly crafted TP can utilize intermediate-level testing to greatly increase fidelity. The greatest benefit of intermediate-level testing is the ability to test for cell-to-cell propagation at a level less than full scale.

Intermediate-level tests may also include cell- and battery-level mitigation testing. This testing may be used as a design and verification aid. The mitigations explored at this level of test are those implemented within the battery itself, and might include variations in design parameters such as cell orientation and spacing, SOC, thermal barriers between cells, packaging of intermediate groupings, etc.

The tests outlined in Table 5-1 may be required at the intermediate or module level.

5-3.3 FULL-SCALE BATTERY AND SYSTEM-LEVEL BCCT.

While some scaling can be conducted using the single cell and intermediate-level test data, further unmitigated and mitigated BCCT shall be conducted on full-scale batteries and systems in their storage/operational configurations in order to gauge the true hazards to the system, platform, and personnel. In the event that full-scale batteries and systems cannot be used, modules or sub-modules shall be used in environments that are representative of the physical constraints and CONOPS of the actual system (materials of construction, packing materials, free volume inside packaging, co-located ordnance/flammable material, under pressure, etc) when approved by NAVSEA 05.

Mitigation techniques that are implemented on or within the battery itself (i.e., on or within the cell, intermediate assembly, or full-scale battery) shall be tested and evaluated at the full-scale during BCCT to verify their effectiveness. Examples might include variations in cell orientation and spacing, reduced SOC, thermal barriers between cells, packaging of intermediate groupings, etc. Verification test shall re-confirm all aspects of gas production, heat release, pressure effects, ejecta, etc., with mitigations in place.

Full-scale characterization tests shall be conducted in an appropriate enclosed space capable of representing the actual usage/stowage environment under controlled conditions to acquire and allow modeling of the hazard characteristics of a battery-system-platform interaction during a fire event. Test enclosures and full-scale tests shall simulate the nature and physical layout of the platform space, the sensitivity and criticality of the space, and other potential failures in the space. Examples of test space criticality and potential platform impact include but are not limited to: platform interaction with items in the torpedo room, lockout/lock-in chambers, dry deck shelters, external stowage trunks, and large-diameter tube stowage. The use of mock items or simulations (e.g., ordnance, valving, hydraulic piping, high-pressure gas bottles and feeds, personnel, personnel protective equipment) shall be considered based on location, size, and nature of the battery and system.

The tests outlined in Table 5-1 may be required at the full-scale battery assembly level.

5-4 PLATFORM-LEVEL HMT.

When identified by the TP or PHA, platform-Level HMT shall be conducted to develop and verify effectiveness of platform-level mitigation strategies and capabilities such as detection/alarms, automatic extinguishment/control, isolation/segregation, and casualty response procedures.

5-4.1 ENTRY CRITERIA.

At this stage, the following tasks shall have been completed to serve as the basis of the HMT:

- Hazards shall have been identified by the PHA.
- Level of unmitigated hazard shall have been quantified by the BCCT.
- Performance requirements of the mitigation technique shall have been defined.
- Potential mitigation techniques shall have been identified.
- A test methodology shall have been developed.

5-4.2 HAZARD MITIGATION TECHNIQUE SELECTION AND DEVELOPMENT.

Potential mitigation techniques identified during the PHA may include segregation, the use of storage containers, the installation of an early warning fire detection system, the installation of a fast response fire suppression system, manual intervention, or other techniques. If fresh water is used for firefighting a high-voltage system, it must be shown that explosive gas pockets are not formed. These techniques shall be assessed in terms of feasibility, ship impact and cost. Analyses must also demonstrate that the mitigation techniques do not introduce a secondary hazard. When higher level risks cannot be accepted by the TWH without evaluation of further mitigation, a technique or combination of techniques shall be selected for further development and testing.

5-4.3 HAZARD MITIGATION EFFECTIVENESS.

Based on the discussions between the program manager, system developer, and NAVSEA 05, the safety TP shall include verification tests to assess the effectiveness of the proposed mitigation technique(s) and to quantify the resulting exposures produced during the test scenario. These exposures include the likelihood for fire spread, heat exposures to vital equipment, ordnance, and personnel, and chemical (toxic or corrosive gas) exposures to equipment and personnel. The tests shall be designed to challenge the mitigation technique(s). The tests may focus on a specific parameter identified during the PHA as undesirable or unacceptable. The effectiveness of the hazard mitigation technique(s) shall be evaluated versus the unmitigated BCCT tests conducted previously. The TP (including hazard mitigation test rationale) shall be approved by NAVSEA 05 prior to conducting the tests.

5-5 PLATFORM-LEVEL SURVIVABILITY/RECOVERABILITY AND ENVIRONMENTAL TESTING.

Other tests as required by the program’s system specification may have a bearing on the safety and the design of the battery and its integration onto the platform. The following list is not exhaustive, but provides examples of scenarios where an environmental insult traceable to a system specification may induce a casualty of a battery system producing unexpected effects and results. NAVSEA and the program office shall review and agree upon the need for additional tests in this category, with consideration given to the impacts on platform and personnel under such conditions.

- Implosion.
- Hydrostatic crush.
- MIL-S-901 (shipboard shock).
- 40-foot drop.
- Bullet/fragmentation penetration.
- Fast cook-off/slow cook-off.
- MIL-STD-167 (shipboard vibration).

CHAPTER 6 – METHODOLOGY FOR RISK CHARACTERIZATION TAILORED TO LITHIUM BATTERIES

6-1 GENERAL GUIDELINES FOR TAILORING OF MIL-STD-882C METHODOLOGIES.

The program manager shall tailor MIL-STD-882C guidance to the evaluation, mitigation, and tracking of the unique hazards and risks of lithium batteries, where such batteries are part of the system.

The program manager shall ensure specific reference and detail regarding the safety risks and risk reduction/management requirements for the lithium battery are included in the Systems Safety Program Plan and in the system Risk Management Plan.

The program manager shall further ensure that each safety hazard, risk, and mitigation related to the lithium battery are addressed and documented in the PHA, SHA, and HLR as called out in other sections of this manual.

Without a specific waiver from the program manager, warnings, cautions, procedures, and training shall not be the only risk control and reduction methods for Category I or II hazards.

At a minimum, the unacceptable conditions defined in MIL-STD-882C, Appendix C, Section 70.1.1 shall apply to lithium batteries and systems including lithium batteries. The program manager shall impose other restrictions as necessary to ensure system safety.

The acceptable conditions defined in MIL-STD-882C, Appendix C, Section 70.1.2 shall apply to lithium batteries and systems that include lithium batteries.

6-2 GENERAL HAZARD MITIGATION AND TRACKING GUIDANCE FOR LITHIUM BATTERIES.

The ability to detect hazards and failure modes of lithium batteries with sufficient certainty and sufficient time to take effective action to prevent the hazard's occurrence shall be emphasized. Certain failure modes of lithium batteries including but not limited to development of internal cell shorts, development of ground faults, loss of electrical isolation, and mechanical failures that cause physical damage can all lead to rapid thermal runaway in lithium batteries, and therefore thorough consideration shall be given to such failure modes and the true effectiveness of the mitigating features and actions proposed to reduce the likelihood and severity of an occurrence.

6-2.1 DOCUMENTATION OF HAZARDS AND MITIGATIONS.

Hazards and mitigations shall be identified, documented, analyzed, and evaluated in various documents called out in this manual, including the SSP, RMP, PHL, PHA, SHA, FMEA, FMECA, fault tree analysis (if required), and O&SHA.

6-3 HRI ESTIMATES.

Section 6-3 describes battery-specific approaches that tailor MIL-STD-882C guidance to the unique objective of estimating probability, severity, and risk of potentially catastrophic battery failures (i.e., those battery failures that can result in safety hazards). This section focuses on the risk-assessment model and the processes that shall be used to evaluate and bring closure to hazard causal factors that are dependent upon battery hardware and dependent in whole or in part upon any underlying battery monitoring and control software.

Per MIL-STD-882C, HRI estimates shall be based upon a structured analysis of hazard severity and failure probability. Resulting Hazard Severity and Failure Probability estimates shall be ranked and compared in the standard Hazard Risk Matrix to arrive at an HRI value, as shown in Figure 6-1.

Hazard Risk Index						
			Hazard Category			
			I	II	III	IV
			Catastrophic	Critical	Marginal	Negligible
Frequency	A	Frequent	1	3	7	13
	B	Probable	2	5	9	16
	C	Occasional	4	6	11	18
	D	Remote	8	10	14	19
	E	Improbable	12	15	17	20

HRI	Mishap Risk Category	Decision Authority
1-5	High	ASN(RDA)
6-9	Serious	Program Executive Office
10-17	Medium	NAVSEA System Program Manager
18-20	Low	System Designer, System Prime Conractor

Figure 6-1. Sample Hazard Risk Assessment Matrix.

Figure 6-1 includes suggested decision authorities for various levels of HRI related to lithium battery hazards. Decision authorities shall be further tailored based on the ACAT and Milestone Decision Authority (MDA) in accordance with NAVSEAINST 5000.8.

Lithium battery-specific rules and methods for estimation of failure probability and of hazard severity are provided in Appendix C. These rules shall be implemented in developing inputs for the HRI analysis.

Where software failure can cause, allow, or contribute to a specific hazard's or mishap's occurrence, the probability of software failure shall be incorporated, along with the probability of all other contributing component failures, in the calculation of the overall probability of the hazard/mishap's occurrence. Fault tree analysis (as described in Appendix C) may be required to properly account for the contribution of the software failure probability to hazard/mishap probability. For each hazard that is associated with a software failure, the severity estimate for that hazard is taken directly from the system hazard's HRI severity.

6-4 SOFTWARE HAZARD CRITICALITY MATRIX (SHCM) ASSESSMENT.

For each CSCI or software functional area, the program manager shall perform an SHCM assessment of each software function and categorize the specific software and its functional modules into the defined categories. Figure 6-2 describes the categories and process for determining an SHCM index.

The purpose of the SHCM assessment is to determine the level of rigor required for the development and the test/verification of each CSCI. The SCHM assessment can aid the program manager in estimating the amount of resources necessary to perform software safety analysis on a functional area, and can also be used to indicate the potential for software safety risk to the program manager, program executive office, and Assistant Secretary of the Navy, Research, Development, and Acquisition, as appropriate. If an actual software hazard is identified during testing or analysis, the actual hazard's severity and probability shall be calculated using the HRI table defined in Figure 6-1 and described in section 6-3.

			Hazard Category			
			I	II	III	IV
			Catastrophic	Critical	Marginal	Negligible
Software Control Category	I	Autonomous	1	1	3	5
	II a	Semiautonomous (Control)	1	2	4	5
	II b	Semiautonomous (Data/Display)	1	2	4	5
	III a	Permissive (Control)	2	3	5	5
	III b	Permissive (Data/Display)	2	3	5	5
	IV	No Control	3	4	5	5

SHCM Index	Description
1	**High Risk** - Detailed requirements and structured design to Software Standard IEEE 12207, Low Cyclomatic complexity. Significant analysis and testing required, including 100% Basis Path.
2	**Medium Risk** - Detailed requirements, design, and code analysis required, with sufficient testing to ensure safety implementation
3-4	**Moderate Risk** - High-level requirements, design, and code analysis and testing as needed.
5	**Low Risk** - Acceptable

Figure 6-2. Sample Software Hazard Criticality Matrix.

Definitions of Software Control Categories are shown in Table 6-1.

Table 6-1. Software Control Categories.

Category	Description	Control Description
I (A)	Autonomous	Software exercises autonomous control over potentially hazardous hardware systems, subsystems or components without the possibility of intervention to preclude the occurrence of a hazard. Failure of the software or a failure to prevent an event leads directly to a hazard's occurrence.
IIa (Ba)	Semi-Autonomous (Control)	Software exercises control over potentially hazardous hardware systems, subsystems, or components allowing time for intervention by independent safety systems to mitigate the hazard. However, these systems by themselves are not considered adequate.
IIb (Bb)	Semi-Autonomous (Data/Display)	Software item displays information requiring immediate operator action to mitigate a hazard. Software failures will allow or fail to prevent the hazard's occurrence.
IIIa (Ca)	Permissive (Control)	Software item issues commands over potentially hazardous hardware systems, subsystems or components requiring human action to complete the control function. There are several redundant, independent safety measures for each hazardous event.
IIIb (Cb)	Permissive (Data/Display)	Software generates information of a safety critical nature used to make safety critical decisions. There are several redundant, independent safety measures for each hazardous event.
IV (D)	No Control	Software does not control safety critical hardware systems, subsystems or components and does not provide safety critical information.

6-5 RISK ADJUDICATION AND ACCEPTANCE.

6-5.1 NAVSEA INTERNAL REVIEW PROCESS.

The recommendation to use a large lithium battery on a Navy platform will normally be made at the NAVSEA 05 (chief engineer) level. In specific applications, NAVSEA 05 may delegate this authority to NAVSEA 05Z.

The program manager is responsible for assembling the necessary supporting documentation into a review/decision package. If requested by NAVSEA 05Z or NAVSEA 05, the program manager shall prepare a briefing and present it to NAVSEA 05 in support of the review process. The review package will be forwarded to NAVSEA 05 via NAVSEA 05Z. The package shall contain:

- A concise technical description of the system and its CONOPS.
- All closed HLR or Hazard Disposition forms that document acceptance of residual risk at the appropriate level, as defined in NAVSEAINST 5000.8.
- A statement from the TWH recommending concurrence and confirming all technical requirements have been met.
- List of any unresolved issues.
- Documentation of any required conditions or limits attendant to the recommendation for use (e.g., in-service inspections or performance confirmations). Note: It is desirable, so far as possible, to make recommendations without conditions.
- A signature sheet for record purposes.

Once NAVSEA 05 concurs with the recommendation for use, the TWH will provide a document (memo) to NOSSA and the program manager. A copy will be sent to the lithium battery database custodian (see paragraph 1-3.80). This correspondence will clearly state all conditions or limits placed on use of the battery system. The program manager will ensure conditions and/or limits are captured in a liability tracking/accountability system and communicated to operators and ISEAs.

In the event NAVSEA 05 does not concur with the program manager recommendation, one or more technically acceptable alternatives must be provided by NAVSEA 05 to the program officer in accordance with NAVSEAINST 5400.97B.

A concurrence recommendation for a specific battery application shall not be extended to any additional applications without a written notification to the battery TWH (NAVSEA 05Z34). Use of an existing concurrence as a precedent for additional approvals beyond the scope of the original concurrence, without additional NAVSEA 05 review and approval, is prohibited.

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CHAPTER 7 – QUALITY ASSURANCE

7-1 RECORDS.

For projects that involve more than a single program manager and system developer as part of the development strategy, a written agreement shall be executed prior to preliminary design start that assigns responsibilities and accountability for all actions needed to comply with this manual. This agreement will be approved by the program manager, with an informational copy sent to NAVSEA 05Z. Subsequent to initial approval, changes will be agreed to by all parties and documented in revisions to the original agreement.

7-1.1 OQE.

Compliance with all design, test, production and safety program requirements in this manual shall be documented and retrievable for audit. This documentation, associated with specific battery system, will be retained by the prime contractor for seven years or the life of the system – whichever is greater. Specifically included are purchase orders, deficiency reports, discrepancy reports, departures from specification, and general correspondence. The program manager will retain records of TLRs (preliminary system performance goals), system specification approval, detailed design approval, verification of requirements, and acceptance of the system for Initial Operating Capability (IOC).

7-1.2 TROUBLE REPORTS.

Significant incidents that occur during battery testing or operation will be reported in a timely manner to NAVSEA 05Z34 and the program manager.

It is the responsibility of the program manager to ensure timely and complete reporting of incidents. Incidents include but are not limited to: 1) exceeding any operational parameters, 2) failure or compromise of any battery safety devices, 3) other anomalous behavior with any safety implications.

7-2 COMMERCIAL BATTERY CELL AND MATERIAL VENDORS.

Vendors of raw materials used in multi-cell battery systems and vendors of individual battery cells shall have a fully implemented QA program meeting ISO 9000 series or equivalent standards. Where foreign manufacture of cells prevents prime contractor supplier factory audits, alternate but compatible OQE shall be developed to ensure manufacturing quality is maintained, and may include product sampling and inspection. Examples of techniques that may be useful to verify quality include: X-ray tomography; DPA; Radiography; X-ray Diffraction (XRD); Fourier Transform Infrared Spectroscopy (FTIR); Gas/Liquid Chromatography with Mass Spectrometry (GCMS/LCMS); Electrochemical Impedance Spectroscopy (EIS); weights, dimensions, and digital photography; Scanning Electron Microscopy (SEM); Energy Dispersive Analysis with X-rays (EDAX); and Differential Scanning Calorimetry (DSC).

7-3 BATTERY SYSTEM PRIME CONTRACTOR.

Includes both commercial and Government activities tasked with battery system development.

7-3.1 REQUIREMENTS.

- The system prime contractor shall have a QA plan that meets ISO 9000 series or equivalent standards.
- The battery system prime contractor shall have a formal configuration control process in accordance with EIA-649-A, National Consensus Standard for Configuration Management,or an appropriate commercial standard such as ISO 10007. This process shall be sufficient to document approval of all changes to issued drawings and test procedures subsequent to design approval or production. Any changes classified as major per MIL-STD-792 will be submitted to the program manager for approval. All other changes shall be approved by the prime contractor. At the point of Government acceptance of the battery system (normally coincides with IOC), the prime contractor will provide the MA with documentation of the “as built” configuration of the system, which consists of all drawings with applicable revisions and ancillary documents such as engineering change notices, liaison action reports, and engineering reports.
- The system prime and/or procuring activity shall ensure the cell/battery vendors establish a material control program to provide an identification and control process for materials and associated components used in lithium battery systems. This material control program shall ensure the correct material is installed in lithium battery systems and in installations aboard ship, and that such material is traceable to records of OQE. It shall provide for the procurement, receipt inspection, characterization, sample archiving, storage, installation, and verification of material during construction, test, overhaul, repair, and alteration of battery systems.

- Only test and inspection devices included in an ongoing calibration program shall be used in fabrication and testing of battery systems.
- Soft\ware developers shall follow standard software development processes of the Institute of Electrical and Electronics Engineers Inc., IEEE/EIA 12207.0-1996. The software development process shall be identified in a software development plan approved by the program manager with concurrence from NAVSEA 05Z. Any software autonomous functions that can cause a battery failure mode shall be identified to the program manager. Level of software requirements linked/driven by HRI in accordance with Chapter 6.

7-3.2 AUDITS.

For activities engaged in battery system development, a periodic safety and QA audit will be conducted by NAVSEA 05Z. The purpose of such audits is twofold: 1) verify that Government requirements bearing on the safety and reliability of battery systems are being correctly implemented by design and production activities, and 2) confirm sufficient quality and safety infrastructure is present to ensure compliance with requirements.

The audit team shall be provided with unlimited access to the manufacturing/assembly process and to all documents relating to the manufacturing/assembly of the particular batteries of interest. The Government shall retain all rights to information obtained and any documents generated by the Government or contractors pertaining to the audit and its findings.

The nominal periodicity will be one year between the initial two audits and every two years thereafter. Based on results, periodicity is subject to adjustment by NAVSEA 05Z. Appendix D is a baseline audit plan and standard operating procedure. The audit plan is intended to be tailored for specific programs or projects. Alternative auditing processes and methodologies (NASA, commercial) may be used to fulfill the nominal two year periodicity requirement subject to specific NAVSEA 05Z approval. Any such allowance of alternative auditing processes shall include one or more NAVSEA technical representatives on the team.

Responses to audit findings will be submitted to NAVSEA 05Z in accordance with Appendix D. NAVSEA 05Z is the acceptance authority for corrective actions and will generate correspondence (nominally every eight weeks) to provide closure status and assess progress. Audited activities are responsible for maintaining accurate internal finding status and documentation of finding resolution.

7-3.3 PRIME CONTRACTOR CELL ACCEPTANCE TEST AND ACCEPTANCE CRITERIA.

Regardless of whether the prime contractor purchases cells from a subcontractor or manufactures his/her own cells in-house, performance of cells shall be verified by the prime contractor prior to assembling cells into battery modules or battery systems, as specified below.

7-3.3.1 Physical Inspection.

All cells should be physically inspected for improper welds and seals, electrolyte leakage, correct labeling and identification markings, and correct dimensions.

7-3.3.2 Capacity.

The capacity of each cell should be tested using the discharge rates expected during use of the cell or under manufacturer recommendations if charge/discharge rate exceed recommended use. The cell’s capacity should be within tolerances necessary to meet the requirements of the application without producing hazards associated with imbalance of the cells during discharge or charge (for rechargeable cells), and without producing undue stress on the system (heat, physical) through any balancing electronics that might be employed. Failure of the cell to provide the necessary capacity will disqualify the cell for use.

7-3.3.3 Open Circuit Decline.

Each cell will be charged to full capacity, and after 24 hours the Open Circuit Voltage (OCV) will be checked. The cell will then be left on open circuit for a period necessary to accurately determine the open circuit capacity decline rate. Any cell that has a capacity decline rate beyond acceptable limits shall be rejected. Acceptable limits for open circuit decline will be a function of the cell size or capacity, the cell impedance, and the conditions of test (e.g., temperature and maximum voltage at start of test), and therefore shall be defined on a case-by-case basis by the manufacturer, with NAVSEA concurrence. Alternate test methods may be used, with NAVSEA concurrence.

7-3.4 CELL MATCHING.

Any battery that contains cells that are not charged individually shall be matched by the manufacturer before battery assembly. Within the acceptable limits of capacity and open circuit decline noted above, the criteria for cell matching for the battery assembly shall be further defined and driven by the expected CONOPS, and shall be based on cell parameters that influence the ability to maintain cell balance under the expected CONOPS (e.g., self discharge rate, impedance, capacity, etc.).

7-4 BATTERY SYSTEM VERIFICATION OF REQUIREMENTS.

Prior to system IOC of a specific battery system, the program manager shall conduct an independent verification that will confirm compliance with all specifications and tests invoked by the Government. The program manager shall submit a software Safety Analysis Report (SAR) that documents all of the software safety analyses, the verification of each VR in the system, and a safety recommendation on whether to certify the computer programs undergoing safety analysis. In addition, the program manager shall confirm that all outstanding actions bearing on the safe operation of the battery system have been resolved (e.g., deficiency reports, departures from specifications, open job orders, and incomplete test procedures). Items that have been approved for deferral past IOC shall be transferred to an alternate life cycle accountability system with specific due dates. All deferred items will be reviewed for aggregate effect by the program manager prior to operational approval. This verification shall be certified by letter to NAVSEA 05Z.

7-5 BATTERY SYSTEM OPERATIONAL PHASE.

Navy personnel shall follow the Joint Fleet Maintenance Manual, COMFLTFORCOMINST 4790.3, when accomplishing maintenance on lithium battery systems. Maintenance work shall be accomplished via Controlled Work Procedures.

7-5.1 IN SERVICE SYSTEM OPERATIONAL REVIEW

If appropriate, due to complexity or service record of the battery system, NAVSEA will conduct an on site operational review of the battery system to examine maintenance and operating records and, operator training and qualification,

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APPENDIX A – LITHIUM BATTERY-SPECIFIC CONTENT FOR HAZARD ANALYSES (PHA, SHA), FMEA, FMECA, HAZARD LOGS/RECORDS, SAFETY CRITICAL CRITERIA, AND SOFTWARE ANALYSES

A-1 HAZARD LOG AND RECORDS.

A Hazard Log comprising a collection of Hazard Records similar to the one shown in Figure A-1 shall be compiled and used as the master file to track, control, and communicate the technical and approval status of each hazard. A Hazard Record summarizes the key information relating to a specific hazard, including present status and history, failure mode and effects, mitigations, and associated risk assessments. Any pertinent information from the PHA, SHA, or other documentation that supports or bears upon the information summarized in the Hazard Record is referenced in the Hazard Record. The Hazard Log provides a concise and expedient vehicle for stakeholders to communicate and document the status of each hazard, as well as any agreements among stakeholders regarding risk assessments, and approvals of any tests or analyses that have been completed or are planned to verify mitigations. The Hazard Log is updated any time new information becomes available during the program's evolution. The Hazard Log and Hazard Records shall be placed under configuration control at the beginning of the Preliminary Design Phase, and shall contain as a minimum:

- Description of each hazard, to include associated HRI.
- Status of each hazard and control.
- Traceability of resolution on each Hazard Log item from the time the hazard was identified to the time the risk associated with the hazard was reduced to a level acceptable to the MA, including any interim approvals issued and the issuing authority.
- Identification of residual risk.
- Action person(s) and organizational element.
- The recommended controls to reduce the hazard to a level of risk acceptable to the MA.
- References to supporting design documentation, analyses, test data, etc., that verify the effectiveness of each recommended control or mitigation.
- The signature of the MA accepting the risk and thus effecting closure of the Hazard Log.

Hazard Record

Original Identification Date:

Project:

System:

SHA Ref:

Subsystem:

Preparer:

Record#:

Assembly:

Reviewer:

Component:

Designer:

History ID/Rev. Date	Status (Open/ Closed)	Risk Assessment:		HRI	Rating (Acceptable/ Unacceptable	Comments
		Severity	Probability			

Hazard Description:

Failure Mode:

Failure Effects:

Mitigating Actions:

Reference:

Approval & Date:

Remarks:

Approval: Program Manager ______________________ Authorized SignatureDate

Approval: NAVSEA ______________________ Authorized SignatureDate

Figure A-1. Sample Hazard Record.

A-2 HAZARD ANALYSES (PHA, SHA).

A-2.1 GENERAL.

The overall objectives of the Hazard Analysis Program are to identify and evaluate hazards posed by the battery, to assess potential impacts to the system, platform, and personnel, and to evaluate the effectiveness of mitigations. The program office shall perform a PHA early in the program and an SHA later in the program as the system design matures and as results of BCCT and HMT become available.

Ultimately, the SHA shall verify the system compliance with system safety requirements and shall identify all hazards associated with subsystems, interfaces, and faults. The SHA will assess the risk associated with the total system design, including software. It will recommend actions necessary to eliminate identified hazards and/or control their associated risk to acceptable levels.

Hazard analyses shall be conducted following the requirements of MIL-STD-882.

A-2.2 CONTENT.

The hazard analysis shall include an overview of the primary components, interfaces, and functions of the system using the lithium battery (or batteries). The hazard analysis shall further describe the battery type, its characteristics, quantities to be stored or used, expected handling and usage protocols, intended platform or platforms, and specific locations of use, transport, or storage aboard the platform(s). Surrounding compartments adjacent and above the compartment containing the battery shall also be identified. The temperature ranges of the compartment during both storage and use shall be declared. If the battery system in question is to be charged onboard the platform, this shall be noted and the location of the battery during charging shall be declared. The hazard analysis shall identify planned co-location of the battery with other systems using similar batteries, co-location with flammable, combustibles or thermally sensitive materials, or co-location with ordnance (e.g., battery stowage in the torpedo room co-located with ordnance).

The hazard analysis shall include the results of any hazard or casualty characterization tests that may have already been performed on the battery.

A-2.3 HAZARD ANALYSIS ELEMENTS.

The hazard analysis should include the following elements:

- Characterize application, handling, and storage arrangements.
- Investigate fuel loading/chemical composition of the battery.
- Review historical usage and loss data.
- Perform FMEA.
- Evaluate environmental constraints, including operating environment.
- Identify possible casualty scenarios causing the basis of the threat.
- Identify how the battery reacts during each casualty scenario and quantify potential hazards to equipment and ship's personnel.
- Define hazard severity, probability, and HRI (see Chapter 6 and Appendix C of this manual).
- Develop application- and hazard-specific mitigations.
- Define test method(s) to characterize hazards and verify effectiveness of mitigations.
- Update the SHA, based on test results.
- Final risk assessment and submittal for program approval.

Each of these elements is described in detail as follows:

A-2.3.1 Characterize Application, Handling, and Storage Arrangements.

The conditions associated with the use, maintenance, and storage of the battery shall be characterized to serve as baseline conditions for the hazard analysis. The conditions to be characterized include compartment size, dimensions, configuration (contents/load-outs), ventilation, accessibility and fire protection features (detection, suppression, insulation), if any. Important parameters include contents of adjacent spaces, potential ignition sources, manning, and proximity of hazardous or energetic material or systems such as flammable or combustible liquids, oxidizers, high pressure systems, ammunition and explosives, or vital equipment.

A-2.3.2 Investigate Fuel Loading/Chemical Composition of the Battery.

Battery equivalent fuel loading and oxidant content, including all construction materials, and including packaging materials if relevant, shall be defined prior to testing. This information shall be used to scope and develop test measurements required to characterize associated hazards. For example, the presence of an oxidizer in the battery will require additional testing to quantify the heat released by the battery during combustion (i.e., oxygen calorimetry will not provide an accurate measurement). Results from NAVSEA 9310-AQ-SAF-010 lithium battery safety tests should be incorporated, if available and applicable. The chemical composition shall also be used to predict the type of compounds that will be produced during combustion, which in turn will define the types of gas concentration measurements required during the test.

A-2.3.3 Review Historical Usage and Loss Data.

A review of the usage and fire loss history of similar batteries shall be conducted to help quantify the hazards. “Similar” batteries may be those used on U.S. Navy ships, in other DoD or Government applications, or even in commercial applications where data is pertinent and can be verified. Important areas to focus on when conducting this review include cause/origin of the fire, fire severity, fire loss (injury, loss of life, and cost), and effectiveness of mitigation systems and/or manual interventions.

A battery database being compiled by NAVSEA 05 for Navy battery applications should be utilized to the extent possible to support the hazard analyses. The database will be populated with the following information, as data become available:

Cell level:

- Manufacturer.
- Chemistry.
- Size and weight.
- Voltage.
- Charge/discharge rates.
- Capacity.
- Energy density.
- Safety devices.
- Mitigations.
- Testing and results.

Battery level:

- Assembling company, if different from cell manufacturer.
- Configuration of cells and modules.
- CONOPS.
- Size and weight.
- System energy density.
- System voltage.
- Mitigations.
- Testing and results.
- Field usage data.
- Fire loss data.
- Risk assessments.

This data will be useful in defining the failure modes and potential hazards and impacts for a program that proposes to use a lithium battery. Furthermore, if the proposed battery and its application are sufficiently similar to an example already in the database, then certain testing might be precluded if already performed, when approved by NAVSEA 05.

A-2.3.4 Perform FMEA.

FMEA shall be performed to understand and document how the battery can fail and what the impacts of the various failure modes will be. In the context of this manual, the objective of the FMEA is to identify those failure modes that result in potential safety hazards and to estimate their potential impacts. Additional discussion on FMEA is provided in section A-3 below.

A-2.3.5 Evaluate Environmental Constraints, Including Operating Environment.

Characterize environment and environmental stresses, including but not limited to: potential shock, vibration, drop, physical damage, ship motion, extreme temperatures and humidity, electromagnetic effects, and radiation that may affect the battery. These will be considered for all aspects of the battery life, from manufacturing to installment, operation, maintenance, and disposal.

A-2.3.6 Identify Possible Casualty Scenarios Forming the Basis of the Threat.

The information collected during the tasks above shall be used to develop the potential casualty scenarios that could result under conditions of storage, transport, or use. These scenario(s) shall be used to define the potential hazards, to identify the hazard characterization tests required (see Chapter 5), to define the test methodology, and to develop mitigation systems and techniques.

The hazard analysis shall include immediate hazards created by electrical, mechanical, and thermal abuses, and by excessive environmental conditions (e.g., scenarios involving local fire, MIL-S-901 mechanical shock, MIL-STD-167 vibration, transient exposure to seawater, operator or maintainer error, overcharge, etc). The PHA shall also include hazards that may emerge over time (e.g., scenarios involving emergent internal defects or wear-out failure modes).

A-2.3.7 Identify How the Battery Reacts During a Casualty Scenario and Quantify Potential Hazards to Equipment and Ship's Personnel.

The hazard analysis shall characterize the expected reactions of the battery during the casualty scenario (e.g., combustion, explosion, arcing, ejection of hot gases, fluids, or solids, etc.) and assess potential hazardous impacts to the host ship and personnel. Impacts should include the likelihood of fire spreading to adjacent equipment or compartments, of heat sufficient to damage vital equipment, of potential for initiation of nearby ordnance, of injury to personnel from toxic gas, and of chemical deterioration of equipment. The potential for the battery assembly to injure or kill personnel or to damage structures and equipment (e.g., due to battery pressure vessel explosion, where applicable, or battery cell explosion/fire) must also be addressed. This information should be used in planning the battery casualty characterization tests described in Chapter 5 of this manual.

A-2.3.8 Define Hazard Severity, Probability, and HRI.

Risks associated with a casualty involving the battery shall be assessed in accordance with Chapter 6 and Appendix C of this manual. This process results in an HRI based on assignment of severity and probability to each hazard.

A-2.3.9 Develop Application- and Hazard-specific Mitigations.

NAVSEA 05 will require that mitigations be developed for any safety hazards with severity level of "Critical" or "Catastrophic." Potential risk mitigation techniques, component design changes, or other (procedures, equipment, and fire protection features) should be identified. These may include segregation, the use of storage containers, the installation of an early warning fire detection system, the installation of a fast-response fire suppression system, and manual intervention.

Mitigation requirements can vary depending on the application and on the intended platform. Mitigations must therefore be application-specific (e.g., surface ship vice submarine, submarine host vice diving platform, open ocean vice under ice). Mitigation methods may be limited by the intended application and platform. For example, casualty mitigation for a battery on a surface ship may allow for aggressive firefighting methods and ventilation of smoke and toxic gasses overboard. However, the same mitigation techniques may not meet the requirements for a submarine atmosphere where gases cannot be vented overboard and where firefighting may be more limited.

A-2.3.10 Define Test Method(s) to Characterize Hazards and Verify Effectiveness of Mitigations.

Tests shall be defined to characterize the hazards (BCCT) and verify the effectiveness of the mitigations (HMT). The hazard analysis shall be updated with information from these tests as they are completed. Severity levels, probabilities, and HRIs shall be revised to reflect the result of these tests

A-2.3.11 Update the SHA based on Test Results.

The SHA will update and extend the battery-level PHA, and shall include the results and findings of the BCCT and HMT. The SHA shall compare the initial risk and residual risk to the host ship in accordance with Chapter 6. Comparing these two risks provides a measure of the effectiveness of the proposed mitigation technique(s).

At this point in the program, the following tasks should have been completed and will serve as the basis for the final SHA.

- The required level of hazard mitigation has been achieved.
- Potential additional mitigation techniques have been identified and tested or have been proposed.
- The final configuration for use on the ship has been identified.
- The exposures produced during a casualty when the battery/battery pack is installed in the proposed configuration have been quantified.

The SHA should document any resulting restrictions on battery location, safety equipment or procedures. Upon completion of HMT, the NAVSEA 05 TWH shall identify recommendations for refinements to battery stowage locations, safety equipment, and safe practices aboard the host ship. These recommendations may include but not be limited to: segregation, the use of storage containers, the installation of an early warning fire detection system, the installation of a fast response fire suppression system, and manual intervention.

A-2.3.12 Final Risk Assessment and Submittal for Program Approval.

The residual risks associated with a fire in the battery in the proposed application shall be documented and submitted to the appropriate level of programmatic authority for approval.

A-3 FAILURE MODES AND EFFECTS ANALYSIS (FMEA).

A-3.1 FMEA PROCESS.

FMEA shall be initiated as an integral part of early design process and incorporated into the PHA. The FMEA shall be updated as necessary to reflect design changes during the development. The FMEA shall be used to identify failure modes that may result in safety hazards. The following discrete steps shall be used in performing the FMEA:

- Define the system to be analyzed. Narratives of the system should include descriptions of each component in terms of functions to be performed.
- Construct functional block diagrams that illustrate the operation, interrelationships, and interdependencies of the functional components. All system interfaces shall be indicated.
- For each functional component or interface, identify all potential failure modes, their root cause, and their effects at the local level, the system level, and platform level by mission phase. Also identify any potential effects to personnel and environment.
- Evaluate each failure mode in terms of the worst-case hazard that may result. Estimate the probability that the event can and will occur, and the potential impact or severity.
- Identify failure detection methods, and record planned mitigations for each failure mode.
- Identify corrective design or other actions required to eliminate the failure or control the risk.
- Recommend hazard mitigations for unacceptable or undesirable risks.
- Estimate the effects of corrective actions and mitigations.
- Document the analysis, summarize any safety hazards that could not be corrected and mitigated by design, and identify the special controls which are necessary to reduce failure risk.

A-3.2 FMEA RISK ASSESSMENT.

The risk (HRI) associated with each component shall be determined using the risk evaluation system described in Chapter 6.

A-3.3 FMEA REPORT.

The results of the FMEA and other related analyses shall be documented in a report that identifies the level of analysis, summarizes the results, documents the data sources and techniques used in performing the analysis, and includes the system definition narrative, resultant analysis data, and worksheets. Interim reports shall be available at each design review to provide comparisons of alternative designs and highlight high-risk failure modes, potential single-failure points, and proposed design corrections. The final report shall reflect the final design and provide identification of the failure modes and single-point failures that could not be eliminated from the design.

A-3.4 FMEA SUMMARY.

The report shall contain a summary that provides the system developer's conclusions and recommendations based on the analysis. The system developer's interpretation and comments concerning the analysis and the initiated or recommended actions for the elimination or reduction of failure risks shall be included. A design evaluation summary of major problems detected during the analysis shall be provided in the final report. A list of items omitted from the FMEA shall be included, with rationale for each item's exclusion.

A-3.5 FMEA WORKSHEET.

A separate worksheet for each item with an HRI of 9 or less will be included in the FMECA. The worksheet will contain at minimum:

- In listed format: preparation date, preparer(s) name and title, item name, probability of failure, failure mode, and associated risk.
- In narrative format: function, failure mode description, possible causes, failure detection, system impact, mission impact, surroundings impact (e.g., storage area, host platform), mitigations, and recommendations.

A-4 FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA).

A-4.1 FMECA PROCESS.

FMECA is a bottom-up approach that expands upon the existing FMEA and includes a quantitative risk Criticality Analysis (CA). CA is a procedure to rank a failure mode according to the severity and probability of occurrence. A FMECA may not be applicable to all components of the battery, but it is appropriate for safety-critical electronics (e.g., battery management electronics) where a CA can be conducted utilizing reliable electronic component failure rate data. The FMECA results should be presented in a worksheet similar to the FMEA, with the additional CA included.

A-5 SYSTEM REQUIREMENTS DECOMPOSITION INTO ASSOCIATED SOFTWARE ANALYSES AND REQUIREMENTS.

A-5.1 SAFETY CRITICAL CRITERIA (SCC).

Unlike hardware, software does not fail due to wear-out or damage. Software fails due to flaws in the design and/or implementation, as well as its ability to handle Abnormal Conditions and Events (ACE). Therefore, it is important to establish the SCC early in the development so the system architecture and design can take the safety issues into consideration. The SCC is a joint effort between the Navy, the developer, and safety personnel to determine the safety concerns for the system.

A-5.2 SYSTEM CRITICAL FUNCTIONS (CFs), HAZARDS, AND BEST PRACTICES (BPs).

A system CF list, hazard list, and BP list are created that document all high-level system safety concerns that may have software impact within the system. The system hazard list is a list of hazards that have system involvement and may or may not have software involvement. The system hazard list comes primarily from the PHA analysis. The system CF list is a list of functions whose correct performance is essential to the safe operation of the system. CFs usually respond to and/or control an actual or potential hazardous condition as opposed to preventing hazardous conditions. BPs are concerns with the development process and generation characteristics of the software rather than implementation of specific requirements. Check summing, strong data typing, and data initialization are examples of safety BPs.

A-5.3 COMPUTER PROGRAM CFs, HAZARDS, AND BPs.

System CFs, hazards, and BPs are examined to determine which ones are applicable to a specific computer program. Computer Program Critical Functions (CPCFs) are developed by taking the system-level CFs and determining which ones apply to each software program or CSCI. After determining a subset list of system CFs that apply, that subset list is expanded and further defined into more specifically derived CPCFs for each CSCI. The same process is used to determine computer program hazards and computer program BPs for each CSCI in the system.

A-5.4 SOFTWARE SAFETY REQUIREMENTS(SSRs).

SSRs are generated to document the specific concerns around each of the CPCFs, hazards, and system BPs. These SRs are the guidance for the safety analysis team. SRs are also used by the developers to ensure they are taking into account all the safety issues during the development of the system. Once the SRs are complete, a certification kickoff meeting is held with all pertinent parties to ensure consensus on the SRs and what safety tasks will be completed so each SR is met.

A-5.5 SOFTWARE SAFETY VERIFICATION REQUIREMENT (VR) DEVELOPMENT.

As software design features are further developed, VRs are created to give the code analyst and tester further insight into what must be verified for each SR. The number of VRs under any given SR will vary, depending on the complexity of the SR. Each VR will define the specific design details that must be verified for the SR and how that verification will be accomplished (test, analysis, etc.). Any VRs that are not capable of being verified through test must be verified through code analysis. Certain VRs might be verified by simple code inspection. For VRs that must ensure something does not happen, a fault tree or critical flow analysis approach may be required.

A-5.6 SOFTWARE SAFETY TEST/VERIFICATION.

During the Test and Evaluation Phase, all VRs must be verified to complete the safety analysis effort. The software safety test team shall document how each VR was verified and the results of the verification.

APPENDIX B – BATTERY CASUALTY CHARACTERIZATION (BCCT) TEST METHODS AND REQUIREMENTS

This appendix provides additional detail and guidance regarding test methods and data collection requirements for casualty characterization tests called out in Chapter 5.

B-1 CELL AND/OR BATTERY FAILURE INITIATION REQUIREMENTS.

Tests shall be designed to reliably initiate a cell and/or battery failure. The method of initiation of the cell and/or battery failure shall be determined from the PHA and should represent the WCE. Multiple methods may be used to initiate a cell casualty, and the method chosen will depend on the cell chemistry, cell failure response, and the hazard the casualty poses (as determined from the PHA/CONOPS). Potential methods to initiate a cell casualty include, but are not limited to: thermal abuse, overcharge, and puncture or crush. The use of a specialized donor cell that is purposely constructed to simulate a cell casualty due to a latent or emergent manufacturing defect (e.g., via an internal cell short initiated either external or internal to the cell) shall be used if available.

B-2 QUANTITATIVE GAS PRODUCTION ANALYSIS.

Cell and/or battery failure shall be initiated until the cell and/or battery undergoes thermal runaway with gaseous release. The test apparatus or compartment shall be capable of withstanding the pressures created from the rapid failure and disassembly of a cell and/or battery.

The chemical species released are expected to vary under different burning conditions, particularly with variations in the oxygen concentration. A comprehensive approach requires an initial qualitative study to assess the nature of the expected chemical species and relative concentration ranges. This will be followed by a targeted analysis that will provide quantitative results. Conditions will be varied to determine how changes in the burning conditions alter the chemical species that are released.

Gas analysis shall be performed to fully characterize the quantity of gas produced, the rate of gas production, and the composition of the gas produced. Two methods shall be used to measure gas composition:

- Real-time online analysis to characterize bulk generation and decay rates of key bulk gas constituents.
- Whole-gas analysis on grab samples to characterize finer details of gas component ratios and trace materials that might be toxic or corrosive.

B-2.1 REAL-TIME AND CONTINUOUS MONITORING OF GASES.

Oxygen (O_2), Carbon Monoxide (CO), and Carbon Dioxide (CO_2) shall be monitored and recorded real-time during the experiment. Real-time monitoring of other gases (e.g., Hydrogen [H_2], light hydrocarbons) may also be appropriate and will be determined on a case-by-case basis in the development of the TP by the test activity, with NAVSEA concurrence.

For cell-level tests, continuous sampling, based on cell chemistry, shall be conducted at a rate sufficient to characterize the evolution and decay of active species. A recommended real-time sampling rate is no less than once every five seconds. Chamber pressures shall also be recorded.

For intermediate-level and full-scale battery tests, gas analyses may be limited to real-time specific gas sensing and analysis using industrial-level, gas-specific sensors (i.e., not research-level trace gas sensitivity).

B-2.2 GRAB SAMPLES FOR TOXIC AND CORROSIVE GASES.

For cell-level tests, atmospheric grab samples from the chamber shall be taken prior to the start of the test, for a baseline. Samples shall also be taken periodically during the test at a rate sufficient enough to characterize the progression of the event. It should be noted that samples may be required to be taken more frequently to support rapid battery events, as identified in the TP. Atmospheric grab samples for toxic gases will be acquired from the test chamber during battery testing in accordance with EPA guidelines for determination of toxic organic compounds in ambient air (EPA/625/R-96/010b), specifically methods TO-14, TO-15, and TO-17. Other techniques and protocols may be used when these protocols are industrial, medical or Navy standards and have been accepted for use as part of the TP. Examples other technique protocols include the National Institute for Occupational Safety and Health (NIOSH) and American Society for Testing and Materials (ASTM), or techniques developed for specific gas analysis.

Atmosphere samples shall be acquired and analyzed retrospectively to determine their chemical components. Analytic methods shall be selected based on the significant gas products expected for the specific battery chemistry being tested. Sampling systems shall be compatible with and be non-reactive with the materials to be measured, or the measurements must be completed in a time period that will minimize the loss of material by surface reactions. Depending on the cell chemistry, H_2, hydrocarbons and organic vapors, CO_2, CO, O_2, and HF may be expected during a fire but will likely not be the only chemical compounds generated. Battery by-products often contain Hydrochloric Acid (HCl), Carbon Tetrachloride (CCl_4), Hydrogen Sulfide (H_2S), and Sulfur Dioxide (SO_2). Additional gas products from high-temperature chemical reaction are expected and will be governed by the source cell or module chemical makeup and design. Partial decomposition of the battery could lead to the formation of some moderate molecular mass organics and polymeric species.

Corrosive gas production shall be determined to assess impact on the environment, component, and system materials and the host ship or vessel. The need for corrosive gas evaluation will depend on battery chemistry. Most corrosive gases are highly reactive by nature and make qualitative and quantitative analysis difficult. The type of testing to be performed should be adequate to provide needed data to allow hazard assessments. Real-time testing can be expensive and difficult, but it provides a much more complete picture of the timeline for generation of corrosive gas than end-of-test analysis. Corrosive gas analysis performed at the end of the test will provide data concerning the total amount of corrosive gas generated and is much less expensive or time-consuming.

NOTE: Sealed test chambers shall have sufficient humidification to allow full hydrolysis of all inorganic releases from a battery, unless otherwise directed and approved in the TP.

NOTE: The chamber atmosphere should be re-circulated at a rate that allows homogenous sampling unless such chamber circulation would hinder accurate analysis of expected hazards. Chamber circulation methods should be carefully considered to avoid biasing the sample away from expected actual environmental conditions. For example, circulation of the chamber atmosphere might properly represent shipboard ventilation but may not adequately represent battery storage in a poorly ventilated area. For poorly ventilated areas, consideration should be made concerning use of two sampling ports (one high and one low).

B-2.3 VOLATILE OFF-GAS IGNITION REQUIREMENTS.

The gaseous materials released from most lithium and lithium-ion batteries include combustible organics. Where the battery electrolyte contains an organic solvent or other liquid that might exothermically react or combust upon contact with air, a triggerable gas ignition device shall be included in the test setup to provide a means of reliably igniting the vapors, fumes or aerosols produced by a battery venting in all mitigated and unmitigated BCCT tests.

Tests shall be conducted with the ignition device operated in both the ENABLED (active) and SECURED (off) mode to contrast the variability in results both with and without ignition and combustion of off-gasses produced by a battery failure. If a system produces potentially flammable gases and aerosols but these do not normally ignite during the casualty event, these gases SHALL BE triggered to evaluate the potential explosiveness of fuel-air mixtures. Tests shall be initially conducted with the ignition system SECURED. If the failure event itself does not automatically trigger combustion of the gases vented from the cell or battery module, tests shall then be conducted with the ignition source enabled and operating, to acquire the necessary data from the secondary combustion of fumes, gases, and aerosols.

B-2.4 THERMAL, VOLUMETRIC, AND PRESSURE IMPACTS OF OFF-GAS IGNITION.

A significant portion of the thermal casualty assessment is based on the radiant heat released from combustible sources in the area of the casualty. Hazard characterization tests and assessments shall therefore quantify the potential radiant heat from combustion of flammable gases or aerosols released from the battery.

Hazard characterization tests and assessments shall also quantify the amount of additional gas volume created by the battery casualty, and to characterize the “breathing” associated with the combustion processes. Dynamic pressures shall be measured during these test events and estimates provided regarding the total volume of gases produced in excess of the primary volume of gases released from the battery.

B-2.5 GAS VELOCITY MEASUREMENTS.

When required by NAVSEA, the gas velocity of the casualty shall be recorded. The gas volume, pressure, and temperature can be useful in determining how quickly gases may spread to other compartments of a ship. Gas velocities shall be measured using differential pressure gages capable of 0.01” to 10” water column pressure differential measurements, or when a test chamber has a dedicated outlet and exhaust system, a density independent anemometer system may be used to determine the velocity through a dedicated opening. These data shall be acquired at 1 Hz minimum data rate.

B-2.6 HEAT RELEASE RATE (HRR).

The heat release rate shall be characterized for the battery system under question. Heat generation can occur by a variety of mechanisms, including but not limited to:

- Chemical heat due to internal electrochemical discharge reactions.
- Chemical heat due to chemical reactions between internal components inside a failing cell or battery.
- Chemical heat due to combustion of flammable cell internal components (electrolyte, separator, etc.).
- Chemical heat due to combustion of flammable battery components (cell restraints, cables, etc.).
- Resistive heat due to internal and/or external short circuit current flow.

Characterization tests shall be devised to quantify the total heat released to the platform during battery failure, either as sensible heat or as radiant heat.

Depending on the battery chemistry, characterization may involve calculation of fuel loadings being derived from internally oxidized fuels. When characterized by test, the atmospheric oxygen level shall be maintained to support effective combustion of fuel vapors, since depletion of oxygen in the global test environment will lead to under estimating the heat release rate, and a corresponding underestimation of the mitigation requirements. For some specific battery chemistries, overcharging can lead to the liberation of oxygen that generates an oxygen-enriched atmosphere in the vicinity of the battery, greatly affecting the burning rate, possibly making suppression more difficult. Such characteristics shall be accounted for. When a battery or battery system will be operating in an oxygen-deficient environment (e.g., a purged/inerted housing), special provisions shall be made to characterize the open (free air) HRR and thermal flux history in addition to that expected under the oxygen-deficient conditions, unless otherwise agreed to by NAVSEA 05. Heat release rates and measurements shall be scaled based on the battery.

B-2.6.1 Thermal Flux History.

Both radiometers and calorimeters shall be positioned a safe distance from the batteries yet close enough to capture the radiative, conductive, and convective heat emitted. The radiometers and calorimeters should be sized depending on the size of the battery being tested. For fires this would typically be in the ranges of 0-1, 0-5, or 0-10 BTU/ft2 sec. Large-scale systems may produce 100 BTU/ft2 events or greater. Data rates shall be 1 Hz minimum. As a minimum, the HRR calorimetry system used must be capable of less than a 10 percent error.

B-2.7 PRESSURE AND PRESSURE TRANSIENTS.

Pressure transients may be produced by a cell or battery undergoing a casualty. Hazard characterization tests shall measure absolute pressure and pressure transients within the test chamber or compartment during test. The pressure release may range from a moderate and sustained pressure rise due to low-rate combustion, to a rapid deflagration of battery components internal to the cell(s). The pressure release can be sudden and abrupt, stemming from a sudden failure of battery cell cases or battery pressure containment vessels. In the event of a sudden pressure transient, the data collection rate of any continuous monitoring device shall be sufficient to capture it, and/or the continuous method shall be supplemented by single-use devices which will capture or indicate a peak (transient) value. Specialized shock wave explosive transient recording is not required and is subject to erroneous analysis.

B-2.8 INCANDESCENT DEBRIS AND SHRAPNEL.

Cells and batteries undergoing induced casualty failures may produce shrapnel and eject incandescent particles. Fragmentation of battery cases under casualty conditions shall be considered a potential hazard for co-located equipment. Cell and battery module tests shall therefore include witness plates, impact plates, and video coverage of the gas analysis tests to assess impact of these ejecta on co-located equipment and personnel, if this has not already been accomplished during NAVSEA TM S9310-AQ-SAF-010 tests. Impact force assemblies may be used to determine lethal radius of shrapnel and debris.

NOTE: The use of shrapnel and incandescent ejecta debris protection for sampling and analysis equipments may cause shifts in other wise free “atmosphere” interactions by increasing the local reaction temperatures and reducing quenching of the cell casualty “fireball.” When such a reaction is expected (e.g., oxyhalide cells or high-temperature reactions from lithium-metal primary batteries using carbon monofluoride or manganese dioxide) within a protective shield, tests shall be conducted with the shield in place and removed with protection of equipment accomplished by the best means possible. Preference to gas accumulation space shall be given to the condition that most replicates the potential system failure modes. If mitigation techniques use open air storage, although a battery may be stored in a system, the set of tests shall include both constrained and open cell/battery-module casualty gas analysis.

B-2.9 AEROSOL ANALYSIS.

When required by NAVSEA or recognized as a casualty failure mode, aerosol analysis shall be conducted. Aerosols of electrolyte or supporting fluids in pressure-compensated battery systems pose hazards that depend on the battery chemistry and design. A battery that contains an organic electrolyte may produce an aerosol that (depending on the particle size) could form an explosive-air mixture. This includes electrolyte-solvent solutions which in a liquid state would not be characterized as flammable. The flammability rating, aerosol chemistry, particle size with respect to human exposure, and what is adsorbed and absorbed on and in the aerosol shall be determined.

B-2.9.1 Flammability and Flash Point Rating.

The flammability and flash point of the electrolyte shall be determined, to put the electrolyte on a comparative scale with other flammable liquids such as Diesel Fuel Mixture (DFM), hydraulic fluid, and kerosene. The resulting analysis will be used to provide guidance on how to deal with an aerosol exposure.

B-2.9.2 Aerosol Characteristics.

Aerosol production shall be determined. Vapor analysis will not give an indication of the hazard of an aerosol. Two issues are the size of the particles with respect to human exposure, and what is adsorbed and absorbed on and in the aerosol. Knowing the nature of the aerosol will give indication of the gas-free engineering required.

B-2.10 SMOKE GENERATION.

The density of the smoke shall be determined and recorded in percent transmittance or extinction factor. Measurements shall be made using ASTM standard or comparable methods. Systems that are calibrated prior to use are acceptable, (e.g., an Optical Density Meter [ODM]). Multiple wavelength and location monitoring may be used at the test facility's preference. Monitoring of extinction values at various heights in the test facility may be used to identify behavior.

B-2.11 ELECTROMAGNETIC EFFECTS/RADIATION PRODUCTION.

When the battery can be located in the vicinity of ordnance that is sensitive or susceptible to electromagnetic radiation, tests may be required to determine the electromagnetic radiation generated by a battery casualty. The use of inductive loops to assess emission may be used.

NOTE: The use of electrically excited casualty modes may induce apparent EMI/RFI/HEMP/HERO measurements and potentials. Isolation of these effects may require the use of non-electrical thermal measurement systems. Caution shall be used when reporting "EFI/RFI" effects unless secondary measurements are made to isolate the formation of radiative events.

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APPENDIX C – LITHIUM BATTERY-SPECIFIC METHODS AND RULES FOR ESTIMATION OF FAILURE PROBABILITY AND HAZARD SEVERITY

C-1 BATTERY-SPECIFIC METHODS TO ESTIMATE FAILURE PROBABILITY.

In general, the intent of this section is to focus on the probability of hardware and/or software failures that can cause catastrophic failure of a cell or battery, with uncontrolled and/or unexpected release of energy. Performance failures, such as failure to meet capacity requirements or cycle life requirements due to other "graceful" degradation modes, while also important, are not discussed in this section. Where failure to meet such a performance requirement can result in a safety hazard for the system (e.g., loss of life or equipment), these types of hazards shall be addressed as part of the SHA and System Reliability Analysis and battery-specific tests (in addition to those called out in this document) and shall be performed as needed to ensure the performance reliability of the battery over its intended life is maintained through the application of appropriate levels of redundancy and margin.

C-1.1 BATTERY-SPECIFIC RULES FOR FAILURE PROBABILITY.

When estimating battery failure probability as input into the HRI analysis, the following general and battery-specific rules shall apply:

- The probability that a failure and its associated hazard will be present or created during the planned life expectancy of the system shall be described in potential occurrences per unit of time, events, and population, as appropriate.
- Estimates of failure probability shall be ranked into categories as shown in Table C-1. Failure rate levels shown in Table C-1 are derived from MIL-STD-882C and represent the maximum failure rates permissible for each category. The system program manager shall re-evaluate the failure probabilities in each category in Table C-1, shall determine whether more conservative failure probability requirements are required in each category (i.e., whether lower permissible failure probabilities are required), and shall impose such requirements if warranted. In no case shall the permissible failure probabilities be increased above those shown in Table C-1.

Table C-1. Failure Probability Levels and Maximum Allowable Failure Rates.

Description	Level	Environment, Safety, and Health Result Criteria	Fleet or Inventory
Frequent	A	Likely to occur often in the life of the item, with a probability of occurrence greater than 10^{-1} in that life.	Continuously experienced.
Probable	B	Will occur several times in the life of an item, with a probability of occurrence less than 10^{-1} but greater than 10^{-2} in that life.	Will occur frequently.
Occasional	C	Likely to occur sometime in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life.	Will occur several times.
Remote	D	Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life.	Unlikely, but can reasonably be expected to occur.
Improbable	E	So unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life.	Unlikely to occur, but possible.

- Estimates of battery-related failure probability shall not be lower (i.e., shall not be more optimistic) than what is proven and supported by test, inspection, or other OQE.
- The objective in the Hazard Analysis is to estimate the "WCE." The primary objective in estimating the probability of failure shall therefore be to estimate the highest credible failure probability, and not the lowest credible failure probability.
- Calculation of a range of failure probabilities that includes the highest and lowest credible failure probabilities is acceptable, and sometimes informative, but in all cases the highest credible failure probability shall be calculated, communicated, and used in HRI estimates and in decisions where acceptance of residual risk is required.
- For Commercial/Off the Shelf (COTS) battery cells, manufacturer test data, and commercial use data can be used to estimate failure probability. However, because the safety of a cell is directly

related to a specific manufacturer's design and manufacturing QA process, one manufacturer's data shall not be used to calculate and represent the probability of failure for another manufacturer's cells, unless additional verifications are done to prove that the cells and manufacturing processes of one manufacturer are comparable to another.

- Because the safety of a battery cell is directly related to the conditions and environment of its use, manufacturer's commercial use data or other test data shall not be used to directly estimate catastrophic failure probability unless the conditions and environment of use for the targeted application are proven to be equal to, or less stressful than, those for the manufacturer's commercial data.
- Estimates of catastrophic failure probability for primary lithium batteries can be derived from test data. Activation and discharge test of a primary battery renders it unusable for further cycle tests. Therefore, the test of a large number of samples can be required to develop acceptably low failure probability estimates using only this approach. For COTS primary lithium batteries that are sold commercially, representative commercial test data may be used to augment the data pool, under the limitations noted above.
- Rechargeable batteries are often subject to "wear out" failure modes that can result in "emergent defects" which may not manifest themselves until after many hundreds of cycles or years of use. Estimates of catastrophic failure probability for rechargeable batteries can be calculated from cycle test data, but to estimate the probability of failure due to emergent defects, test samples must be tested for at least as many cycles as the expected field use in order to provide valid results (e.g., 100 cells tested for 10 cycles is not the same as 10 cells tested for 100 cycles).
- Effect of Mitigations**:** For primary and rechargeable cells, additional reductions in catastrophic failure probability estimates may be applied if mitigations that reduce probability of a catastrophic failure are implemented, and if the effectiveness of those mitigations (i.e., the probability of failure of the mitigation itself) can be quantified and properly factored into the fault tree analysis described below. Mitigating methods to reduce failure probability, if proven and verified, might include:
  - X-ray tomography examination of cells to detect and characterize the frequency and magnitude/size of manufacturing defects and contaminants inside cells that can lead to catastrophic failure modes. This method is non-destructive and can be applied to 100 percent of cells intended for field service, when program requirements warrant, in order to reduce residual risk. In the fault tree analysis, the probability of failure of the X-ray examination mitigation shall be estimated and adjusted based on the resolution of the X-ray equipment, the percentage of the fielded cells examined, and the probability of operator oversight/error.
  - DPA of cells to detect and characterize the frequency and magnitude/size of manufacturing defects and contaminants inside cells that can lead to catastrophic failure modes. This method is destructive and can only be applied to representative samples from cell production lots. In this approach, the frequency and magnitude of defect data collected on the sample cells shall be used to calculate a probability distribution that is normalized to some representative design or manufacturing feature of the cell (e.g., the cumulative square area of electrode material in the sample cells if normalizing the frequency of debris or defects between electrodes, or the number of welds in the cell if normalizing weld defects). This normalized value shall then be extrapolated to the battery level (e.g., cumulative area of electrode materials in the fielded system, or cumulative number of welds) to calculate the probability and size of defects possible in the fielded system. Note that this approach will result in some real probability of larger defects and contaminants than observed in any of the cells undergoing DPA.
  - Manufacturing process quality control audits to verify manufacturing methods and controls that reduce the probability of cell or battery defects and contaminants.
  - Additional stress screening tests applied to cells for service, such as accelerated life tests to prove that cells are robust against emergent defects. Examples may include excess vibration tests and extended cycle tests.
- In calculating failure probability, a parametric approach to fault tree analysis shall be used and shall consider all relevant parameters that could bear upon the probability of failure, including but not limited to: cell and battery design, safety critical software design and complexity,

manufacturing processes and quality control, operator error, ancillary equipment failure, and unintended stresses related to the usage environment.

- Where required, for each identified battery failure hazard, the final event (e.g., thermal runaway) shall be analyzed to determine the various different fault pathways that can lead to the final event. Two logic gates are used in fault tree analysis. The "OR" gate is used where any one of the input events can, in and of itself, cause the output event. Fault or failure probabilities for each input event in the "OR" functions are added together to estimate the probability of the output event. The "AND" gate is used where the output event occurs only when all of the input events occur first. Probabilities for each input event in an "AND" function are multiplied together to estimate the probability of the output event.
- Pathways that are defined entirely by "OR" functions constitute potential single-point failures.
- When mitigating features are implemented, the mitigation is normally the "AND" function with the fault it seeks to mitigate. The probability that the mitigation itself will fail must be estimated and included in the analysis to determine the mitigated probability of the output event.
- An example of a top-level fault tree analysis is shown in Figure C-1 for three of the failure modes that can lead to thermal runaway in a rechargeable lithium-ion battery. Note that the fault tree analysis clearly identifies an internal cell short and abuse as potential single-point failures.
- Fault trees are further developed for each of the three failure modes in Figure C-2, Figure C-3, and Figure C-4.
- NOTE: Figures Figure C-1 through C-4 are meant to serve as examples of how a fault tree is constructed and are not to be interpreted as exhaustive representations of all potential faults and linkages.
- As shown in Figure C-2 through Figure C-4, the potential cause of a fault can be traced back as far as necessary (e.g., back to the raw material defects, back to manufacturing process quality issues, back to system design flaws, back to subpar test and verifications of hardware and software, etc.) to determine the probability that a defect might be present in the cell or battery or operating procedures, etc. In this fashion, the fault tree analysis provides the method by which data from manufacturing audits, inspections, and other mitigating activities can be folded into the estimate of failure probability.

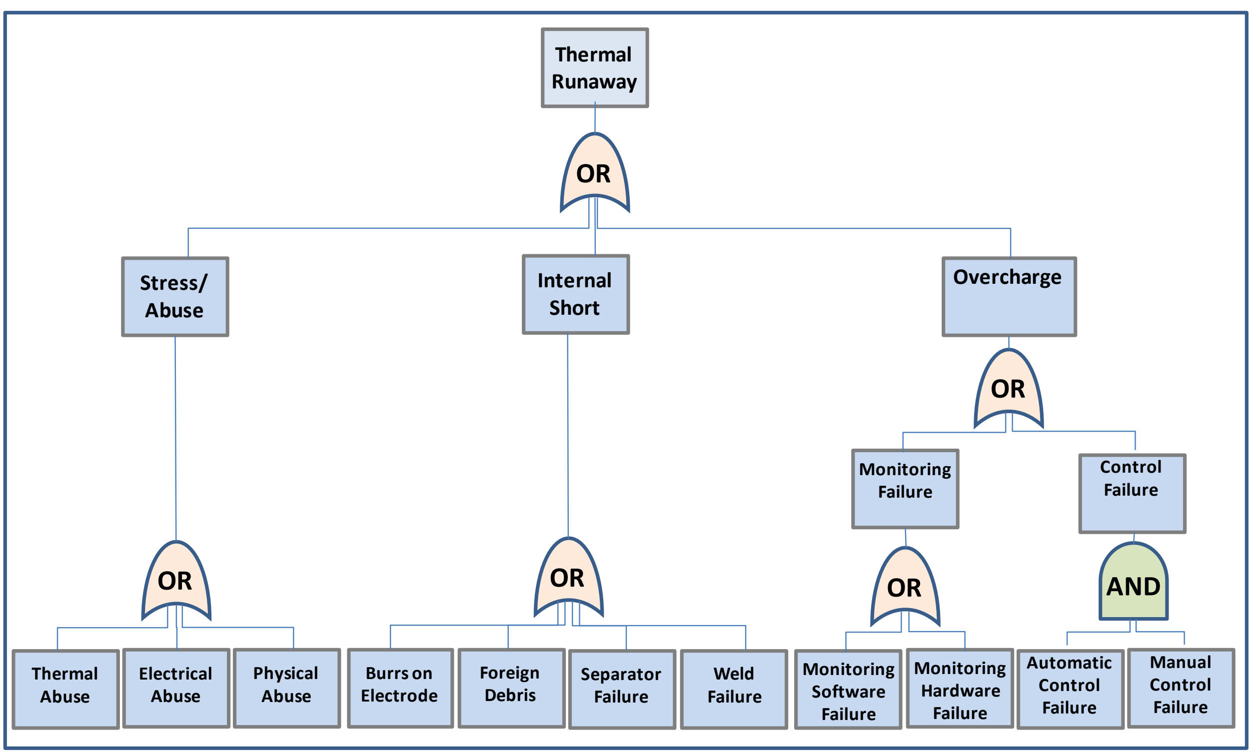

Figure C-1. Example of Top-level Fault Tree Analysis for Rechargeable Lithium-Ion Battery.

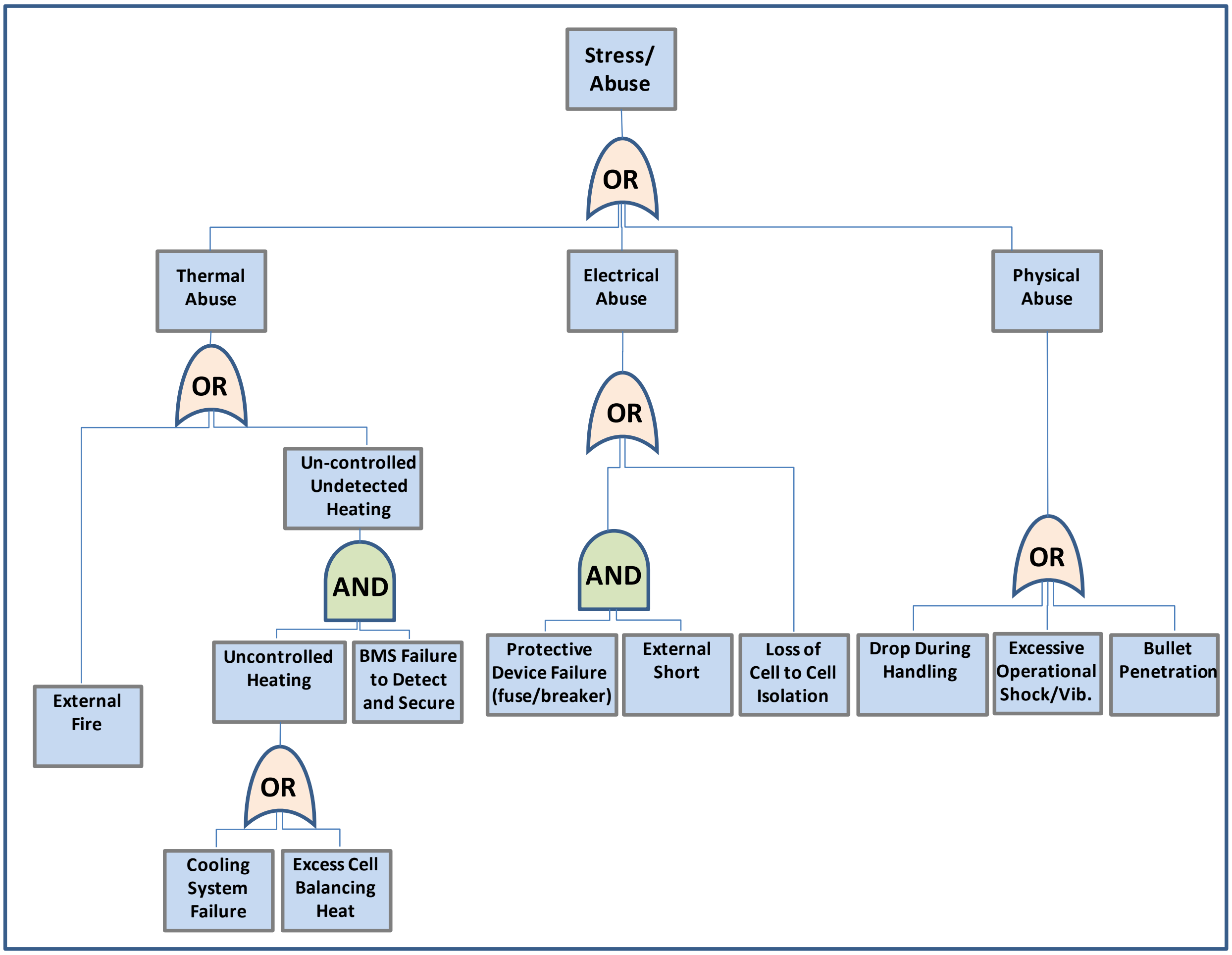

Figure C-2. Extension of Stress/Abuse Leg of Fault Tree Analysis for Rechargeable Lithium-Ion Battery.

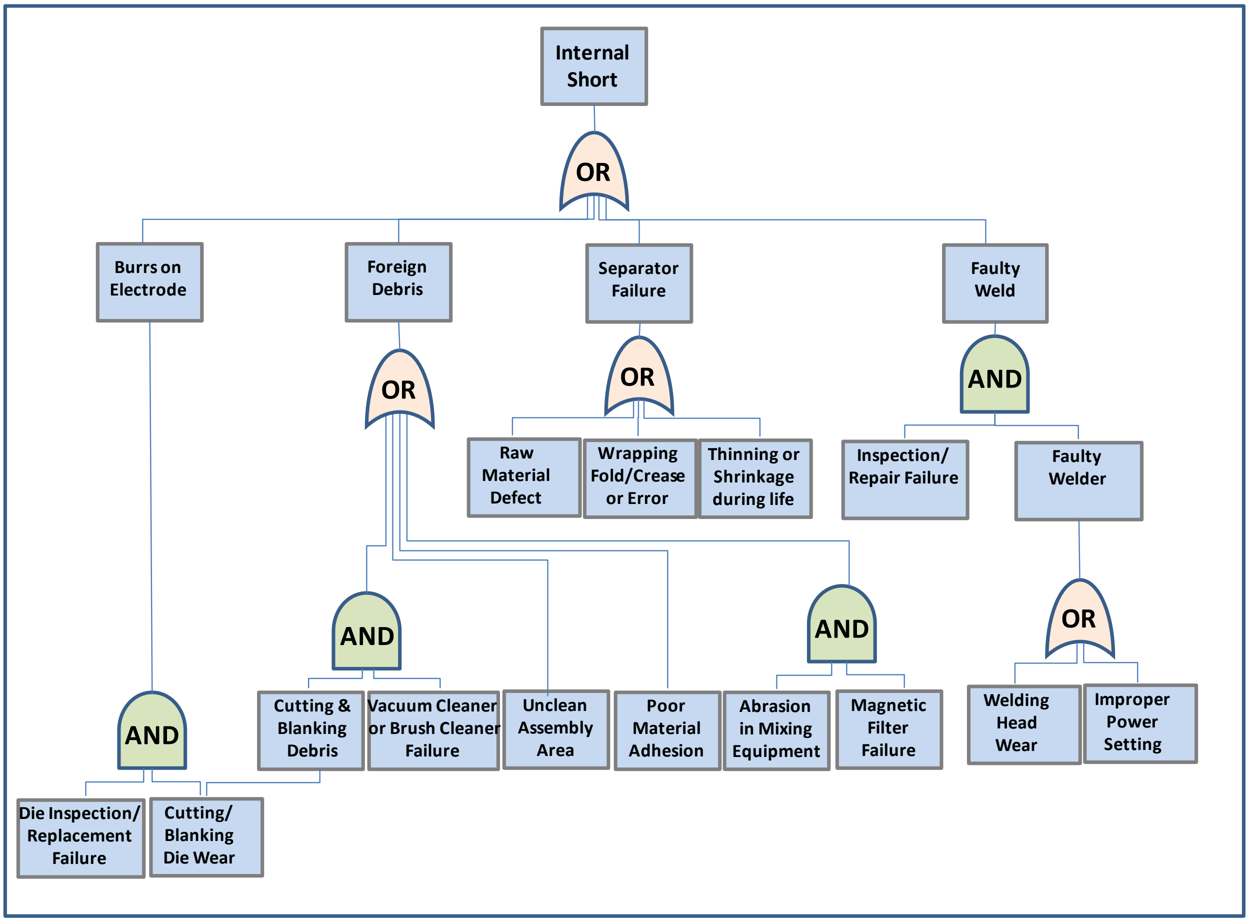

Figure C-3. Extension of Internal Short Leg of Fault Tree Analysis for Rechargeable Lithium-Ion Battery.

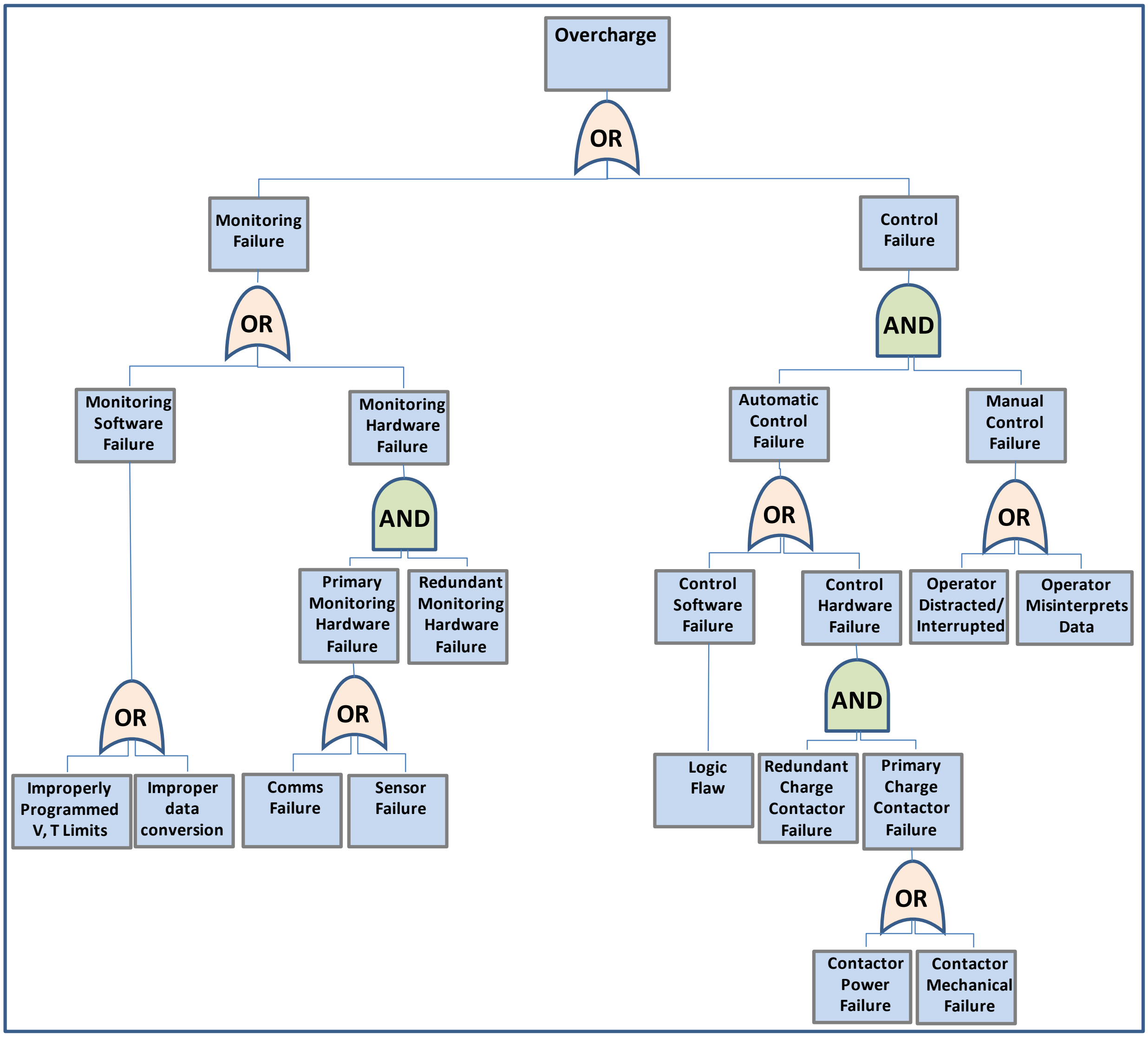

Figure C-4. Extension of Overcharge Leg of Fault Tree Analysis for Rechargeable Lithium-Ion Battery.

C-2 BATTERY-SPECIFIC METHODS FOR HAZARD SEVERITY ESTIMATES.

Hazard severity categories shall be defined as in Table C-2 for WCE that can result from personnel error, environmental conditions, design inadequacies, procedural deficiencies, and system, subsystem, or component failure or malfunction related to the battery.

Table C-2. Hazard Severity Categories from MIL-STD-882.

Description	Category	Environment, Safety, and Health Result Criteria
Catastrophic	I	Could result in death, permanent total disability, loss exceeding $1 million, or irreversible severe environmental damage that violates law or regulation.
Critical	II	Could result in permanent partial disability, injuries or occupational illness that may result in hospitalization of at least three personnel, loss exceeding $200,000 but less than $1 million, or reversible environmental damage causing a violation of law or regulation.
Marginal	III	Could result in injury or occupational illness resulting in one or more lost work day(s), loss exceeding $10,000 but less than $200,000, or mitigatible environmental damage without violation of law or regulation where restoration activities can be accomplished.
Negligible	IV	Could result in injury or illness not resulting in a lost work day, loss exceeding $2,000 but less than $10,000, or minimal environmental damage not violating law or regulation.

For each battery-related failure mode, hazard severity ranking shall be estimated based on the cell and battery testing and analyses outlined in Chapter 5. Hazard severity rankings shall be reviewed by the program manager and by NAVSEA 05 to ensure agreement that the severity rankings properly represent the WCEs.

Unless otherwise directed by the program manager, hazard severity rankings in the “Negligible” category will normally not require fault tree analysis to estimate failure probability.

Hazard severity rankings in the “Marginal” category may require fault tree analysis, and the level of analysis shall be determined by the program manager and NAVSEA 05.

Hazard severity rankings in the “Critical” and “Catastrophic” categories shall require fault tree analysis to quantify probability, if the decision authorities justify their decisions based on such probability estimates.

NOTE: Each software-dependent hazard takes its severity from the system hazard's severity category. The software severity categories are identical to the HRI severity categories shown in Figure 6-2 and Table C-2. The software risk also categorizes severity versus the SCC (i.e., level of software functional autonomy or lack of user interactive control), as shown in Table 6-1.

For primary and rechargeable cells and batteries, reductions in hazard severity estimates may be applied if mitigations that reduce the severity of a catastrophic failure are implemented, and if the effectiveness of those mitigations can be proven through test. In such cases, the probability of failure of the mitigation itself shall be quantified and properly factored into the fault tree analysis described above. Mitigating methods to reduce severity, if proven and verified, might include:

- Automated fire suppression systems.
- Modifications of CONOPS to reduce stored energy and the exposure of personnel, equipment, and platform to the effects of a failure.
- Efforts to reduce severity by preventing cell or battery failure propagation, as for example might be accomplished by providing adequate separation between multiple batteries in stowage.

APPENDIX D – BATTERY INTEGRATOR ON-SITE SURVEY PLAN AND STANDARD OPERATING PROCEDURE

D-1 FUNCTIONAL AREAS SUBJECT TO REVIEW.

- QA plan and procedures.
- Material control process.
- In-process demonstrations.
- Configuration control, including drawing and document revision control.
- Work planning and control process.
- System Safety Program.
- Management oversight.
- Test execution and control.
- Non-destructive testing.
- Instrument calibration.
- Plant/process cleanliness.

D-2 SURVEY STANDARD OPERATING PROCEDURES.

D-2.1 PRE-SURVEY ACTIVITIES.

Surveys will be scheduled by mutual agreement between the program manager and the applicable battery developer. The survey will be announced at least two weeks in advanced by NAVSEA letter, which will also identify the team members and any special administrative support needed. Survey teams will be staffed by one team leader and four to eight team members. Team members will have backgrounds in QA or engineering, with experience in complex battery design and specifications, and manufacturing. The activity being surveyed will arrange for badging prior to team arrival.

D-2.2 ON-SITE SURVEY ACTIVITIES.

Surveys will normally be scheduled for Tuesday through Thursday of the agreed-upon week. Upon team arrival, the activity will provide a one- to two-hour overview of the local processes and practices and will identify specific points of contact. The team leader will hold a brief meeting before close of business each day to summarize progress and identify emergent issues needing assistance to resolve. The team leader will convene an out brief to summarize findings and present a draft survey report on the final day of the survey. The team leader will provide the activity a draft set of cards (findings) prior to departure.

D-2.3 POST-SURVEY ACTIVITIES.

A soon as practical upon return to NAVSEA (Friday or Monday after survey) the team leader will brief the findings to NAVSEA 05Z and the system program manager. He/she will also provide an overview assessment as to the health of the activity safety and QA processes and any major systemic problems. The team leader will incorporate comments resulting from this brief and produce a final report for issue by NAVSEA 05Z letter.

D-2.4 SURVEY FINDINGS.

Findings will be one of two types: non-compliance issues or program improvements:

- Non-compliance findings document lack of compliance with either government requirements or implementing local procedures and processes. All non-compliance findings require a formal response from the activity to NAVSEA that provides an assessment of root cause of the finding, corrective action taken to resolve the problem, and corrective action taken that will prevent recurrence. Resolution of non-compliance findings will be tracked individually by the audited activity, with status reporting to NAVSEA every six weeks.
- Program improvement findings are items that team members recommend for increased program efficiency, better consistency, or more refined interpretations of requirements. Program improvement items require a written response from the surveyed activity, but there is flexibility

as to how the activity assesses the item and whether auditor recommendations are adopted. If the activity desires to implement a program improvement they feel justifies an equitable adjustment of the contract, the appropriate change clauses of the contract must be complied with before implementation of the change.

Survey findings will be documented one finding to a survey card (see Figure D-1) and cards will be uniquely numbered to allow tracking of finding resolutions. Each card will contain a concise one- or two-sentence statement of the finding and a narrative discussion of the finding. The discussion will include reference to the specific requirement violated and citing the specific documents the team member reviewed in determining the non compliance. The discussion will also contain a statement of whether the team member thinks the finding is an isolated case or part of a systemic problem. The cards will include the team members name and the name of the activity personnel with whom the finding was reviewed.

D-2.5 STAFFING OF SURVEY FINDINGS.

Once a team member has identified a finding, he/she will promptly draft the associated survey card. It is the team member's responsibility to review the finding with the cognizant activity's point of contact and document the name of the person on the survey card. The card will then be turned in to the team leader for processing. Once the team leader has edited the card, a designated activity management representative will initial that he/she has read and understands (but not necessarily agrees with) the finding. In cases where the team member and the activity point of contact cannot agree as to the validity of a finding, adjudication will be attempted by the team leader and the management representative. If agreement can still not be reached, the draft card will be briefed to NAVSEA.

Upon completion of immediate corrective action and establishment of long-term corrective action (if appropriate), these actions will be documented and endorsed by the activity QA manager. The response will then be forwarded to the NAVSEA 05Z survey team leader for approval. The team leader will be responsible for obtaining proper reviews within NAVSEA program and technical offices to support acceptance of the corrective action. NAVSEA 05Z will provide documentation of acceptance or rejection of survey correctives actions. In the event the Government rejects an activity response, the basis for the rejection will be documented, along with actions considered necessary to accept the response when resubmitted.

Card No. ____

NAVSEA High-Energy System Safety Survey
Activity Name
Survey Dates

Team Member ______
Team Leader ______
Activity _______

Functional Area: Team Member (s):

Reviewed With:

Category: (Noncompliance or Program Improvement)

Reference:

(a)

(b)

Observation:

Discussion:

Activity Corrective Action Submitted:_________________ Date ______

NAVSEA Acceptance of Corrective Action:____________Date_______

Figure D-1. Survey Card.

D-3 AUDIT AREAS.

Examples of processes and controls that should be evaluated during a manufacturing audit of a lithium-ion cell manufacturing facility are listed below. Auditors should collect in-process samples and take measurements to characterize compliance at all stages of production.

- Degree of Statistical Process Control (SPC).
- Frequency and level of integration of Quality Control checks.
- Shared anode and cathode production equipment and potential for cross-contamination.
- Processes that use metal-to-metal contact, and therefore provide the potential to create metal particulate.
- Control of particulate transfer by clothing, shoes, hair, tools, or other items that may enter/leave clean areas.
- Particulate and metallic contamination levels in production areas and in or around production equipment.
- Particulate and metallic monitoring and cleaning operations (magnets, brushes, vacuums) at the parts level, and the resulting contamination levels observed in the finished product.
- Production-area humidity and airborne particulate control systems and procedures.
- Moisture control for cell components prior to and during cell assembly, filling, formation, and sealing.
- Moisture control of any tools or materials that come into contact with cell components prior to or during cell assembly.
- Viscosity, thickness, drying, coating uniformity, and weight-loading controls during electrode coating operations.
- Handling and temporary storage of electrode rolls, separator rolls, or other components and potential for damage during such operations.
- Cutting and blanking operations and controls/inspections that ensure burrs, flakes of active materials, and current collector debris are not present in the final assembly.
- Separator application methods and equipment and the potential for folds, creases, misalignment, and improper tension levels.
- Welding operations and the potential for debris or splatter.
- Rework and repair procedures.
- Tracking of frequency of non-conformances and scrap/reject rates, and integration and use of this data to drive corrective action processes.
- Failure analysis processes and integration with corrective action processes.
- Continuous Improvement Process philosophy and commitment at all employee levels.
- Level of operator training and proficiency.
- Level of operator authority to identify, label, and scrap non-conforming material.

APPENDIX E – GLOSSARY OF ACRONYMS AND DEFINITIONS

ACRONYM LIST

ACAT	Acquisition Category
ACE	Abnormal Conditions and Events
ACN	Advance Charge Notice
AOA	Analysis of Alternatives
ASN(RDA)	Assistant Secretary of the Navy, Research, Development, and Acquisition
ASTM	American Society for Testing and Materials
BCCT	Battery Casualty Characterization Tests
BMS	Battery Management System
BP	Best Practices
BTU	British Thermal Unit
CA	Criticality Analysis
CCl_4	Carbon Tetrachloride
CDR	Critical Design Review
CID	Current Interrupt Device
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CF	Critical Function
COTS	Commercial/Off the Shelf
CONOPS	Concept of Operations
CPCF	Computer Program Critical Functions
CSCI	Computer Software Configuration Item
DDS	Dry Deck Shelter
DFM	Diesel Fuel Mixture
DoD	Department of Defense
DON	Department of the Navy
DOSF	Deep Ocean Simulation Facility
DPA	Destructive Physical Analysis
DSC	Differential Scanning Calorimetry
DSS	Deep Submergence System
EDAX	Energy Dispersive Analysis with X-rays
EFI	Electric Field Intensity
EIS	Electrochemical Impedance Spectroscopy
EMI	Electromagnetic Interference
ESD	Electrical Safety Device
FA	Failure Analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes Effects and Criticality Analysis
FT	Fourier Transform
FTIR	Fourier Transform Infrared Spectroscopy
GCMS/LCMS	Gas/Liquid Chromatography with Mass Spectrometry
H	Hydrogen

ACRONYM LIST (Cont)

H_2S	Hydrogen Sulfide
HCl	Hydrochloric Acid
HECSSO	High Energy Chemical Storage Safety Office
HEMP	High-altitude Electromagnetic Pulse
HERO	Hazards of Electromagnetic Radiation to Ordnance
HESSSG	High Energy System Safety Steering Group
HF	Hydrogen Fluoride
HLR	Hazard Log Records
HM&E	Hull, Maintenance, and Electrical
HMT	Hazard Mitigation Tests
HRI	Hazard Risk Index
IIPRT	Internal Independent Peer Review Team
IOC	Initial Operating Capability
ISEA	In Service Engineering Agent
ITP	Index of Technical Publications
kWh	Kilowatt hour
LRU	Lowest Replaceable Unit
MA	Managing Authority
MDA	Milestone Decision Authority
mm	Millimeter
MOA	Memorandum of Agreement
NFESC	Naval Facilities Engineering Service Center
NAVSEA	Naval Sea Systems Command
NIOSH	National Institute for Occupational Safety and Health
nm	Nanometer
NOSSA	Naval Ordnance Safety and Security Activity
O&SHA	Operating and Support Hazard Analysis
OCV	Open Circuit Voltage
ODM	Optical Density Meter
O-Level	Organizational Level (of maintenance)
ONR	Office of Naval Research
OQE	Objective Quality Evidence
ORD	Operational Requirements Documents
O_2	Oxygen
PEO	Polyethylene Oxides
PHA	Preliminary Hazard Analysis
PHL	Preliminary Hazard List
PIA	Platform Integration Agent
PTC	Positive Temperature Coefficient
QA	Quality Assurance
R&D	Research and Development
RFI	Radio Frequency Interference
S&T	Science and Technology
SAR	Safety Analysis Report

ACRONYM LIST (Cont)

SCC	Safety Critical Criteria
SEAL	Sea, Air, and Land
SEM	Scanning Electron Microscopy
SHA	System Hazard Analysis
SHCM	Software Hazard Criticality Matrix
SO_2	Sulfur Dioxide
SOC	State of Charge
SPC	Statistical Process Control
SR/VR	Safety Requirements/Verification Requirements
SSGN	Submersible, Ship, Guide, Nuclear
SSA	Software Safety Activity
SSP	System Safety Plan
SSR	Software System Requirements
SSSA	System Software Safety Activity
TLR	Top Level Requirement
TMDER	Technical Manual Deficiency/Evaluation Report
TMMA	Technical Manual Maintaining Activity
TP	Test Plan
TWH	Technical Warrant Holder
UAV	Underwater Autonomous Vehicle
UUV	Unmanned Underwater Vehicle
VR	Verification Requirement
WCE	Worst Credible Event
XRD	X-ray Diffraction

LIST OF DEFINITIONS

B

BATTERY CELL VENDOR – Vendor that provides cells as raw materials for use in assembling battery modules or entire systems.

BATTERY CASUALTY CHARACTERIZATION TESTS – Tests designed to determine the likelihood, severity, and by-products of a battery failure. Tests are conducted at multiple levels, from individual cells to full-scale batteries.

BATTERY MANAGEMENT SYSTEM (BMS) – An electronic system designed for a secondary (rechargeable) battery that monitors the charging cycle to protect the individual cells of a battery from overcharging. A BMS may also be used to control/monitor discharge of individual cells in either a primary (non-rechargeable) or secondary (rechargeable) battery. Also known as Battery Monitoring Systems.

BATTERY MONITORING DEVICE – Provides detection and mitigation of any condition with potential for causing energetic or catastrophic failure of the battery.

BATTERY SYSTEM VENDOR – The entity tasked with design and production of a specific battery system, usually including BMS, electrical components, container, control system, and vehicle/system interfaces.

C

CELL – An individual unit of a battery consisting of a container, anode, cathode, separator, and electrolyte.

CHROMATOGRAPHY WITH MASS SPECTROMETRY (GCMS/LCMS) – An analytical chemistry technique that combines the physical separation capabilities of liquid chromatography with the mass-analysis capabilities of mass spectrometry to detect and identify chemicals in complex mixtures.

COMPUTER SOFTWARE CONFIGURATION ITEM (CSCI) – A group of software elements treated as a single entity by a configuration management system.

D

DEEP SUBMERGENCE SYSTEM (DSS) – Those systems and components that, when working together, provide the capability for manned underwater operations. Elements may include a manned vehicle, shore training facilities, designated support equipment, those systems that are a temporary or permanent part of a submarine and which are used to disembark or recover personnel, such as Dry Deck Shelter (DDS) or Lockout Trunk, and handling equipment.

DESTRUCTIVE PHYSICAL ANALYSIS (DPA) – The systematic, detailed examination of electronic components, systems, and materials. Tests are conducted at joint DoD-approved laboratories for the performance of DPA, FA, and CA.

DIFFERENTIAL SCANNING CALORIMETRY (DSC) – Thermoanalytical technique in which the difference in the amount of heat required to increase the temperature of a sample and reference is measured as a function of temperature. The term DSC also describes the instrument allowing precise measurement of heat capacity.

LIST OF DEFINITIONS (Cont)

E

ELECTROLYTE – The conductive material within a battery that allows charged species to move between anode and cathode so that the cell reaction may proceed and ionic current will flow. Most electrolytes are liquid and are solutions of an ionic material (e.g., salts or acids, such as potassium hydroxide or sulfuric acid) in a poor/non-conductive solvent (e.g., water). Non-liquid examples are PEO plastics that have been doped with lithium salts, or various ceramics or glasses doped with sodium or lithium oxides and hydroxides. Liquid, non-aqueous electrolytes are limited to molten, ionic salt mixtures, which require no additives to improve conductivity (usually operated at high temperatures), or mixtures of covalent organic or inorganic solvents, which require the addition of ionic salt additives.

ENERGY DENSITY – The quantity of energy stored by a battery per unit weight or unit volume; typical units include watt-hours per pound or watt-hours per cubic inch. To be most useful, energy densities must be measured at a specific discharge rate and temperature.

ENERGY DISPERSIVE ANALYSIS WITH X-RAYS (EDAX) – A variant of X-ray fluorescence spectroscopy used for chemical characterization of a sample via a high-energy beam of charged particles focused onto the sample.

F

FOURIER TRANSFORM (FT) – Transformation of one complex-valued function of a real variable into another. FT decomposes a function into rhythmic functions and refers to both frequency domain and the formula for transforming one function into another.

FOURIER TRANSFORM INFRARED SPECTROSCOPY (FTIR) – A measurement technique where spectra are collected based on measurements of radiative sources. The term reflects that an FT is required to turn raw data into the actual spectrum.

FULL-SCALE BATTERY – For the purposes of this manual, a full-scale battery is a complete battery system as it would be employed in its intended system, including all of its cells, intermediate-level groupings, electronics, wiring, housing, safeties, and mitigations.

FULL-SCALE BCCT – Battery Casualty Characterization Tests conducted with full-scale batteries.

H

HAZARD RISK INDEX (HRI) – Estimates based on structured analysis of hazard severity and failure probability, ranked and compared with the standard Hazard Risk Matrix to arrive at an HRI value.

HIGH ENERGY CHEMICAL STORAGE SAFETY OFFICE (HECSSO) – The office established within NAVSEA 05 (SEA 05Z34) to specifically address safety aspects of large lithium batteries and other energy-dense systems.

HIGH ENERGY SYSTEM SAFETY STEERING GROUP (HESSSG) – An executive oversight group whose members include selected NAVSEA major program managers and deputy warranting officers. The group meets on a semi-annual basis to assess status and progress of HECSSO efforts.

I

INFRARED SPECTROSCOPY – The study of the interaction of matter with an infrared radiation, using electromagnetic waves from the long-wavelength limit of visible light (800 nm) to the shortest microwaves (1mm).

LIST OF DEFINITIONS (Cont)

I (Cont)

INTERMEDIATE-LEVEL/GROUPING – For the purposes of this manual, this is an intermediate-level battery or grouping consisting of a packaged collection of cells, multiples of which are necessary to create a full-scale battery. May also be called modules, submodules, or LRUs.

INTERNAL INDEPENDENT PEER REVIEW TEAM (IIPRT) – An independent peer review composed of Navy technical experts in energy systems and safety who are not directly affiliated with HECSSO.

IN SERVICE ENGINEERING AGENT (ISEA) – The maintenance activity for electronic, ordnance, and HM&E systems and equipment engineering support.

K

KINETIC ENERGY – Energy needed to accelerate the body of a given mass from rest to its current velocity.

L

LOWEST REPLACEABLE UNIT (LRU) – For the purposes of this manual, an LRU is the smallest collection of cells or intermediate-level battery that can be replaced during O-Level maintenance.

M

MAINTENANCE – Any service or upkeep required to repair and/or re-evaluate the battery or system and its performance, including but not limited to non-operational charging, discharging, physical inspection, disassembly, reassembly, and calibration of BMS components.

MASS SPECTROMETRY (MS) – Analytical technique that measures the mass-to-charge ratio of charged particles to determine particle mass or elemental composition of a sample or molecule, and for detailing the chemical structure of molecules in chemical compounds.

MITIGATION VERIFICATION TEST – Verification of the effectiveness of platform-level mitigation strategies and capabilities such as detection/alarms, automatic extinguishment/control, isolation/segregation, and casualty response procedures.

N

NAVSEA 05 – Decision authority responsible for engineering operational and safety assurance of systems integrated within or on Navy platforms. With respect to the lithium battery safety approval process, NAVSEA 05 is responsible for providing platform concurrence to NOSSA concerning design and suitability for any system that will be deployed or transported on Navy surface ships or submarines.

NAVSEA TECHNICAL WARRANT HOLDER (TWH) – Responsible for technical standards, specifications, and policy in their areas Navywide. Signature authority for specific technical products may be delegated by the TWH as established in written agreements.

NAVSEA WARFARE CENTERS – Centers of technical expertise that are assigned ISEA responsibilities for various warfare systems. The warfare centers are the major Navy test activity for lithium batteries.

NAVAL ORDNANCE SAFETY AND SECURITY ACTIVITY (NOSSA) – NAVSEA organization responsible for direction and coordination of all Navy technical offices in regard to lithium battery safety and for providing written concurrence and recommendations for use, based on review of safety design, analysis, and testing.

LIST OF DEFINITIONS (Cont)

N (Cont)

NON-OPERATIONAL TRANSPORT – Movement of the battery or system from one location to another while in a non-operating state.

O

OBJECTIVE QUALITY EVIDENCE (OQE) – A statement of face – either quantitative or qualitative – pertaining to the quality of a product or service, based on observation, measurement, or tests that can be verified.

P

PLATFORM – A vessel owned or leased by the Navy. Specifically excluded are range support craft operating within U.S. territorial waters. Platform impact includes situations where the Navy platform is host to ancillary vehicles containing large lithium batteries.

PLATFORM-LEVEL HAZARD MITIGATION AND VERIFICATION TESTS (HMT) – Tests conducted after the BCCT tests have determined the hazard to the platform in order to assess the effectiveness of the platform's mitigation techniques.

PLATFORM INTEGRATION AGENT (PIA) – Provides project oversight for systems containing lithium batteries for use on Navy platforms. Unless specifically approved by NAVSEA 05Z34, the PIA is the platform major program office in NAVSEA.

PRESSURE-RELEASE DEVICE – A failure-point mechanism designed to prevent material failure of the battery housing by releasing controlled volumes of gas.

PRIMARY BATTERY – A battery designed to be discharged only once (i.e., it is NOT designed to be recharged). Also called a non-rechargeable battery.

PROGRAM MANAGER/PROGRAM OFFICE – Responsible for development and fielding of systems that include large lithium batteries impacting Navy platforms. For the purposes of this manual, program managers also include non-acquisition programs, R&D programs, joint programs, and technology evaluation projects that may fall outside of DoD 5000.2 processes.

PROGRAM SPONSOR – DoD warfare resource management office for funding system development. The program sponsor serves as the lead agency for joint programs.

PROPAGATION – When the failure of a single cell or battery leads to the failure of neighboring cells or batteries, most commonly because of thermal or electrical energy transfer, known as cascading.

R

RADIOGRAPHY – Technique for producing photographic interior images or opaque specimens through radiation by gamma ray, X-ray, neutrons, or changed particles.

S

SAFETY CRITICAL CRITERIA (SCC) – Criteria defined by the program office and NAVSEA 05 that must be met to mitigate safety hazards and the severity of a mishap.

SCANNING ELECTRON MICROSCOPY (SEM) – A type of electron microscope that images the sample surface by scanning with a high-energy beam of electrons in a raster scan (rectangular) pattern.

LIST OF DEFINITIONS (Cont)

S (Cont)

SECONDARY BATTERY – A battery in which the electrochemical reaction is thermodynamically reversible and is designed to be recharged after use. May also be referred to as a rechargeable battery.

SOFTWARE SAFETY ACTIVITY (SSA) – Responsible for assessing the safety level and severity of software applications associated with lithium batteries and their systems. The SSA maintains configuration control of the software and works with program management in assessing changes to the software and the need for future upgrades and testing of associated battery software.

SPECIFIC ENERGY – The ratio of the energy output of a cell or battery to its weight (see Energy Density).

STORAGE – Stowage of a battery system or systems in the designated area on the naval vessel while not in use.

SYSTEM DEVELOPER – The prime activity in the design, building, and integration of systems that include large lithium batteries.

SYSTEM-LEVEL BCCT – BCCT tests conducted with a full-scale battery configured on its intended system, or a representative mock-up thereof.

T

TEST ACTIVITY – The organization assigned with testing large lithium batteries and their components to characterize hazards associated with battery failure. The test activity may be assigned to be the system developer, warfare center, or independent activity.

THERMAL RUNAWAY – Any discharge or charge condition in which a battery's internal temperature buildup continues until a cell/battery failure occurs. Typical causes of thermal runaway events can be forced discharge of electrodes that are insufficiently wetted by electrolyte, or excessive discharge currents, as in an internal or external short circuit.

TEST PLAN (TP) – A document that specifies battery system testing required to mitigate risks as defined in the PHA and SHA.

U

USE – The action of exercising the battery or system, including but not limited to operational periods such as charge, discharge, open circuit periods, or operational transport.

W

WORST CREDIBLE EVENT (WCE) – The event that combines maximum severity with highest probability.

X

X-RAY DIFFRACTION (XRD) – The scattering of X-rays by matter, with accompanying variation in intensity due to interference effects. Used in solid-state chemistry to determine atomic arrangements in matter.

X-RAY TOMOGRAPHY – The use of energy waves to generate images on the inside of objects from a series of two-dimensional X-ray images taken around a single axis of rotations