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SPACE AND MISSILE SYSTEMS CENTER STANDARD

LITHIUM-ION BATTERY FOR LAUNCH VEHICLE APPLICATIONS

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FOREWORD

1. This standard defines the Government's requirements and expectations for contractor performance in defense system acquisitions and technology developments.

2. This new-issue SMC standard comprises the text of The Aerospace Corporation report number TOR-2007(8583)-2.

3. Beneficial comments (recommendations, changes, additions, deletions, etc.) and any pertinent data that may be of use in improving this standard should be forwarded to the following addressee using the Standardization Document Improvement Proposal appearing at the end of this document or by letter:

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4. This standard has been approved for use on all Space and Missile Systems Center/Air Force Program Executive Office - Space development, acquisition, and sustainment contracts.

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1. Scope

1.1 Purpose

This TOR establishes requirements and guidelines for the development, testing, storage, handling, and usage of lithium-ion cells and batteries for launch vehicle applications, including booster and upper stages. Compliance with this document is intended to assure a high-reliability product for achieving suitable battery performance during mission.

Lithium-ion-based batteries are an evolving technology that has seen little use in launch vehicles to date. They are attractive over the primary batteries more commonly used because full electrical performance, including voltage regulation and capacity, can be directly verified on the flight hardware prior to use. It is expected that these standards will require amendment as these batteries are used and lessons specific to the challenges of the lithium-ion technology are learned.

1.2 Application

This standard, along with the associated citations, is intended for reference in applicable launch vehicle specifications or other documents to incorporate common requirements and practices necessary to assure successful battery operation during launches to space.

1.3 Conflicts With Other Standards

The requirements herein are meant to augment and clarify those expressed in MIL STD 1540E regarding the use of lithium-ion batteries in launch vehicles. They have also been prepared so as not to conflict with launch site system safety requirements or Range Safety requirements for using lithium-ion batteries in flight termination systems. However, the appropriate range documentation should be consulted for any intended use of lithium-ion batteries at the launch site or in flight termination systems.

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2. Applicable Documents

MIL-STD-1540E, Aerospace TR-2004(8583)-1, “Test Requirements for Launch, Upper Stage, & Space Vehicles,” 31 Jan 2004.

Air Force 30th Space Wing Memorandum of 4 May 2005, “Joint 45 SW/SE and 30 SW/SE Interim Policy Regarding EWR 127-1 Requirements for System Safety for Flight and Aerospace Ground Equipment Lithium-Ion Batteries.”

Aerospace Report No. TOR-2004(8583)-5, “Space Battery Standard,” 1 Oct 2004.

Aerospace Report No. ATR-2005(9308)-1, “New PMP Technology Insertion Guidelines,” 5 July 2005.

Code of Federal Regulations, Part V Department of Transportation: 49 CFR sections 100-187.

UN Manual of Test and Criteria, Part III Sub-Section 38.3 Lithium Batteries.

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3. Definitions

3.1 Activation

The addition of electrolyte to a battery cell constitutes cell activation, and the earliest cell activated defines the start of the cell, module, or battery service life. Lithium-ion cells are activated at the manufacturing facility during cell production. Following activation, lithium-ion cells typically undergo several charge/discharge cycles to condition the surface of the electrodes and stabilize capacity.

3.2 Battery

A battery is an assembly of battery cells or modules electrically connected in series to provide the desired voltage and capacity. Generally, the cells are physically integrated into either a single assembly (or battery) or into several separate assemblies (or modules) connected in series. The battery may also include components such as charge control electronics, fuses, filters, isolation resistors, electrical bypass devices, heaters, temperature sensors, thermostats, thermal switches, thermal control devices, and pressure relief devices. These devices may be used to monitor the health of the battery and to prevent unsafe operation of the battery that would be detrimental to personnel or battery performance.

3.3 Calendar Life

The calendar life of a cell or battery is the maximum allowed period of use of the cell or battery as defined from the date of manufacture of the oldest cell in the battery.

3.4 Capacity

Battery capacity is measured in units of ampere-hour (for Ah capacity) and watt-hour (for Wh capacity).

3.4.1 Actual Capacity

Actual ampere-hour capacity for a specific condition is equal to the integral of the discharge current from the beginning of the discharge of a fully charged battery (i.e., charged to its maximum allowed upper-voltage limit under a nominal charge rate and temperature) until the lowest usable voltage limit is reached. Actual watt-hour capacity for a specific condition is equal to the integral of the product of discharge current and voltage from the beginning of the discharge of a fully charged battery until the lower usable voltage limit is reached.

$$C(Ah) = \int_{LowestVoltageLimt}^{MaximumChargeVoltageLimit} IdT$$

$$C(Wh) = \int_{LowestVoltageLimt}^{MaximumChargeVoltageLimit} IVdT$$

Actual battery capacity should be stated in both units to facilitate energy balance evaluations, thermal evaluations, and comparisons of different types of batteries.

For lithium-ion cells, the capacity measured can be strongly dependent on the end-of-charge voltage, discharge voltage limit, temperature during charging and discharge, and the current used during charging and discharging. Therefore, it is important to maintain these variables when comparing capacity changes as a function of cycle life and to choose values based on worst-case use during ground operations (for charging) and mission (for discharge).

3.4.2 Operational Capacity

The operational battery capacity is measured in units of ampere-hour and watt-hour. It is equal to the same integral of the values from the beginning of the discharge of a fully-charged battery until the lowest usable voltage limit is reached for mission charge control and load conditions. However, the upper and lower voltage limits may be more conservative than the limits allowed by the cell design in order to preserve cycle life and to meet minimum bus voltage limits. Therefore, the operational capacity is always less than or equal to the actual capacity of the cell or battery.

3.4.3 Rated Capacity

The rated (or nameplate) battery capacity is measured in units of ampere-hour and watt-hours. The rated battery capacity is provided by the battery or cell vendor and is typically less than the actual capacity. Manufacturers usually provide excess capacity over the rated value to compensate for variability within the manufacturing lot and capacity losses expected over the life of the battery.

3.5 Cell or Battery Cell

A battery cell is a single device within one cell case that transforms chemical energy into electrical energy at a characteristic voltage when discharged at a nominal rate. Battery cells are typically connected electrically in series to form a battery of the desired voltage. Battery cells may be connected in series or parallel to form a module to increase the capacity, voltage, and current capability beyond the limitations of the cell. In such cases, the modules are connected in series to form a battery.

3.6 Cell Design

A cell design constitutes those factors that result in unique cell performance, including the size and number of electrodes, type and porosity of the separators, composition and volume of electrolyte, the type of active material on the positive and negative electrodes, current collector alloy, cell terminal construction, and safety and heat transfer devices within the cells. Lithium-ion cells typically use either a wound construction of single, long, positive and negative electrode, or a prismatic construction of alternating positive and negative electrode plates.

3.7 Charge Cycle

A charge cycle is defined by recharge to an initial state of charge, following a discharge of a significant portion of the rated capacity of the cell or battery. Discharge may be the result of an electrical load or self discharge of the cell or battery.

3.8 Charge Life

The charge life of a battery is the length of time from completion of battery charging to a specified voltage limit until recharging is required to recover capacity losses due to self discharge.

3.9 Cold Storage

Cold storage is the long-term storage of cells/batteries that are not in use, where the temperature and humidity environments are controlled, and temperature is below ambient to reduce the rate of self discharge of the battery and to reduce age effects such as corrosion. Lithium-ion cells generally require a minimum storage voltage to prevent unrecoverable capacity losses and corrosion during storage.

3.10 Cycle Life

The cycle life of a cell or battery is the maximum number of charge cycles that a cell or battery can provide before irreversible performance losses occur such that the cell or battery can no longer meet performance requirements. The cycle life may vary with application and should be validated by qualification testing.

3.11 Electrolyte

The electrolyte provides a conductive path for lithium ions between the positive and negative electrodes. Lithium-ion cells typically use a flammable electrolyte consisting of a polycarbonate solvent and a lithium salt.

3.12 Maximum Predicted Environment (MPE)

The maximum predicted environment is the envelope of worst-case electrical, thermal, and dynamic conditions for the battery.

3.13 Manufacturing Lot

A manufacturing lot of cells is defined as a continuous, uninterrupted production run of cells that consists of anode, cathode, separator, and electrolyte material from the same raw material sub-lots with no change in manufacturing processes or drawings. Lithium-ion cells produced in a single lot should be procured, stored, delivered, and tested together to continue to constitute a single lot.

3.14 Module or Battery Module

A battery module is an assembly of series or series/parallel-connected battery cells. Multiple modules are connected to form a battery.

3.15 Negative Electrode

The negative electrode in lithium-ion cells is typically a carbon host material that intercalates lithium ions during charge into interstitial sites in the carbon matrix.

3.16 Open-Circuit Voltage (OCV)

The open-circuit voltage is the voltage of a cell or battery in the absence of any electrical load, including any small loads due to connection to the vehicle or test equipment and monitoring.

3.17 Positive Electrode

The positive electrode in lithium-ion cells is typically a metal-oxide material that intercalates lithium ions during discharge into interstitial sites in the metal-oxide matrix.

3.18 Primary Battery

A primary battery is not intended for recharge. It is delivered from the manufacturer at 100% state of charge and no longer has useful life following discharge to a low state of charge.

3.19 Rate Capability

The ability of a cell to maintain voltage at high currents is known as its rate capability. Lithium-ion cells achieve a high rate capability through high surface area electrodes, but rate capability may decline with age and cycle life.

3.20 Recharge Ratio (RR)

The recharge ratio is the amount of charge measured in ampere-hours delivered to a cell or battery during charge divided by the amount of charge removed during the discharge portion of the cycle. This number is often very close to 1.0 in well-conditioned lithium-ion cells. Chronic overcharge (RR > 1.0) typically shortens the cycle life of lithium-ion cells. Excessive amounts of overcharge may lead to safety concerns.

3.21 Secondary Battery

A secondary battery is designed to have a useful life following discharge and may be recharged to its initial capacity.

3.22 Solid Electrolyte Interphase (SEI) Layer

The solid electrolyte interphase is a film that forms on the positive and negative electrodes and is composed of solvent species, lithium salts, and lithium after activation. Initial cell conditioning is often performed by the manufacturer to preferentially form and stabilize the SEI layers. Properly formed SEI layers provide low rates of self discharge; however, changes to the SEI over the life of the cell often lead to an increase in impedance and a loss in capacity.

3.23 Self-Discharge

Self-discharge refers to the loss of cell or battery capacity and OCV that may occur with time during open-circuit conditions. Self-discharge is often partially or fully reversible following subsequent charge cycling of the cell. The rate of self-discharge is usually greater at higher temperatures.

3.24 Separator

The separator used in lithium-ion cells is a thin, porous polymeric material that is permeable to electrolyte and used to maintain physical and electrical isolation between the positive and negative electrodes.

3.25 Service Life

The service life of a battery, battery module, or battery cell starts at cell activation and continues through all subsequent fabrication, acceptance testing, handling, storage, prelaunch transportation, prelaunch testing, launch, and mission operation. The maximum service life of a cell or battery should be validated by test either through qualification testing or an age surveillance program on cells from the same manufacturing lot as flight batteries.

3.26 State of Charge (SOC)

The state of charge (SOC) of a battery is the ratio of the operational capacity [C(Ah) or C(Wh)] minus the capacity removed to the total operation battery capacity, expressed as a percentage.

$$\text{SOC} = \left(\frac{C_{\text{Operational}} - C_{\text{REMOVED}}}{C_{\text{operational}}} \right)$$

3.27 Unit

A unit is a functional item that is viewed as a complete and separate entity for the purposes of manufacturing, maintenance, and record keeping. A battery is considered a unit and is subject to the unit-level acceptance and qualification tests defined by MIL STD 1540E.

3.28 Voltage Reversal

Voltage reversal refers to a cell wherein the positive electrode is forced to a negative cell voltage relative to the negative electrode during discharge either by higher capacity cells in a battery string or by an external power source.

4. Design

4.1 Purpose

The intent of this section is to review the design and safety practices specific to developing a high-reliability lithium-ion battery for use in launch vehicles.

4.2 Identification and Traceability

All cells and batteries require an attached permanent label identifying the lithium-ion chemistry, the manufacturer, part number, serial number, manufacturer's rated capacity, and date of manufacture. Identification should permit traceability to the manufacturing plant, manufacturing lot, sub-assembly construction, delivery lots of the electrode and electrolyte components, and expiration date.

4.3 Cell Design

In general, lithium-ion cells consist of alternating positive and negative electrodes divided by a polymer separator. Electrodes and separator are contained by casing that is made hermetic after filling with electrolyte to prevent damage to the internal components by air. Each electrode must be mechanically and electrically connected to the cell terminals of the appropriate polarity. Metallic cell cases may be insulated from both electrodes, or at the same potential as the negative electrode. Positive terminals may be electrically isolated from metallic cases by means of a glass-to-metal seal.

4.3.1 Electrode and Electrolyte Materials

Lithium-ion cells typically are composed of a metal-oxide positive electrode, a carbon-based negative electrode, a permeable polymeric separator, and an electrolyte containing a lithium salt in an organic solvent. Both electrodes accept lithium atoms in the interstitial sites of their crystalline matrix, and electrical energy is stored when the carbon negative electrode is electrochemically charged with lithium atoms. When a load is placed across the cell terminals, the lithium ions spontaneously flow to the positive electrode where they deposit in the interstitial sites of the metal-oxide matrix. The electrolyte provides a conductive solution to facilitate the reaction, and thin metal foils, such as copper and aluminum, are used as current collectors in the electrodes. Because the inherent conductivity of intercalated lithium is relatively low, the thickness of each electrode is typically very thin to maximize the surface area for the reactions to occur. Both positive and the negative electrodes may contain a mixture of several compounds, including the lithium intercalation host material, binders for maintaining physical contact between the intercalation particles and the current collectors, and conductivity agents to lower the resistance between the intercalation particles.

A lithium-based chemistry that is not consistent with the above description may qualify as a New Technology. If so, then a review board should be convened by the program to assess whether a particular lithium-ion cell chemistry qualifies as a New Technology. Cell chemistries that qualify as a

New Technology may require additional testing to that recommended in this document, as discussed in Aerospace Report No. ATR-2005(9308)-1, “New PMP Technology Insertion Guidelines,” 5 July 2005.

In this standard, the definition of a manufacturing lot is used to maintain materials control of a design. Many different types of carbon materials, metal oxides, solvents, and salt compositions are in use today to make lithium-ion cells. The specific type used by a design depends chiefly on material availability, safety characteristics, performance characteristics, and cost. Although a specialty battery manufacturer may favor a specific electrode composition for a particular application, that manufacturer may not be able to control their raw material source or environmental conditions well enough to prevent significant changes in cell performance between manufacturing runs. Even minor materials changes have been known to impact cell capacity, internal cell resistance, self-discharge rate, and the onset of thermal runaway under abuse conditions.

4.3.2 Cell Voltage

Lithium-ion cells should produce suitable voltages at no less than the minimum requirements for the intended application (including line losses) for all discharge rates at expected minimum and maximum qualification temperatures. A cell’s ability to meet these requirements should not be compromised by preflight environments such as temperature, vibration, humidity, etc., or the calendar life or number of cycles applied to the cells prior to use. The voltages produced by the cells after an electrical load is applied should be stable. Cells should be designed to meet minimum voltage requirements through their calendar and cycle life.

Cell voltage is dependent on the state of charge, the current load applied to it, and temperature. Typically, cold temperatures are worst case for voltage performance under load; however, voltage losses can also occur at high temperatures. Specialty electrolytes may be used in some cell designs, which prohibit operation at higher temperatures. During cycling, cell voltage under specified conditions for current and temperature should be repeatable to permit state of health testing validation based on voltage under load.

4.3.2.1 Charge and Discharge Voltage Limits

The minimum and maximum cell voltages should be defined during the design phase. The health of most lithium-ion cells is typically critically dependent on the cell voltage limits used during charge and discharge. Excessively high voltages during charge may present safety issues as well as cause irreversible reactions that both reduce the amount of lithium available for charge and reduce the positive and negative electrode’s ability to store charge. Furthermore, unlike alkaline chemistries, cell voltages often may require careful control during discharge and be maintained above zero volts to prevent irreversible changes in the electrodes and side reactions with other cell components. For this reason, many lithium-ion cells are restricted between 2.7 and 4.2 V during operation and open-circuit stand.

4.3.2.2 Operating Voltage at Different States of Charge

Cells should meet operating voltage requirements at all states of charge expected for the application under worst-case conditions for current and temperature. Typically, both the positive and negative crystalline matrices undergo a series of minor crystalline phase transitions while lithium is introduced or extracted from the host matrix. Each crystallographic phase may have a different associated electrochemical potential and lattice conductivity, which could affect the internal resistance of the cell.

4.3.3 Cell Capacity

Cells should be designed to meet the minimum capacity requirements through their calendar and cycle life. Cell capacity should be stable when cycling under consistent temperatures and currents, and the capacity variation between charge cycles should be less than a pre-defined standard provided by the manufacturer. Capacity stability permits state of health validation and facilitates cell matching. When operating the cells following a long time of inactivity, several charge/discharge cycles may be needed before a stable capacity is achieved.

Cells should be selected to meet worst-case operational requirements with significant capacity margin to accommodate self-discharge from the last charge cycle and irreversible loss of capacity due to calendar life and accumulated charge/discharge cycles. Operational requirements include flight capacity to end of mission, all pre-flight checks after the last battery charge, monitoring loads during storage, check-out and after vehicle installation, integration testing, and contingency capacity due to launch aborts and holds. If elevated stand temperatures are expected after installation, then additional capacity margin may be needed to offset the more rapid self-discharge of the cells.

4.3.3.1 Impact of Temperature on Capacity

Cells should meet operational capacity requirements at worst-case current and temperature conditions for both charge and discharge. Cold temperatures tend to reduce charge acceptance and discharge capacity, whereas hot temperatures increase the rate of self-discharge and promote irreversible capacity loss through side reactions. Specialty electrolytes that prohibit high operation temperatures may be used for low-temperature applications.

4.3.4 Cell Charge Retention

For many types of lithium-ion cells, cell charge retention, or alternatively, cell self-discharge rate, is indicated by the loss in cell open-circuit voltage (OCV) with time under standard conditions. This property can be used to permit state-of-health validation and, if needed, cell matching. A consistent self-discharge rate is required to prevent the development of excessive cell-to-cell capacity imbalance over life. The degree of consistency required depends on the application and the charge balance strategy for the battery.

Similarly, the OCV of a lithium-ion cell may also vary with the state of charge of the cell. In some applications, this variation is used to verify the approximate state of charge of the cell prior to use. After charging, the loss in OCV with time is initially high, but typically attains a constant rate after about a day's stand at ambient conditions. The overall rate of self-discharge varies with temperature, and cold storage temperatures are effective in reducing the self-discharge rate.

For lithium-ion chemistries whose OCV is invariant with state-of-charge, discharge following long stand periods at different temperatures should be performed to quantify the rate of self-discharge.

4.3.5 Cell Service Life

The maximum service life for the cell shall be defined by the manufacturer, and shall exceed the projected needs of the application. The allowed service life shall be validated either through qualification testing or an age surveillance test performed on representative cells from the same manufacturing lot as flight batteries.

The cell design should consider the following guidelines for maximizing service life during the design phase.

4.3.5.1 Minimize Mission Charge Cycle Requirements

The intended mission application should minimize the number of cycles required of the cell for integration and test activities prior to flight. Over time and charge cycling, both electrodes and the electrolyte may suffer irreversible physical damage due to the large volumetric change of the electrode lattices. Portions of the metal-oxide lattice may transition to more stable crystalline phases that do not readily intercalate lithium ions. Similarly, exfoliation of carbon negative electrodes by the solvents in the electrolyte is commonly reported. Furthermore, the organic solvents and lithium salts may decompose, which may reduce solution conductivity and consume active lithium through side reactions.

4.3.5.2 Reduce Cell Storage Temperatures

Changes to the solid electrolyte interphase (SEI) layer on the positive and negative electrodes may cause a loss in capacity and voltage under load. SEI layer formation is facilitated during high-temperature storage, and it is recommended that lithium-ion cells be stored cold between periods of use to reduce the risk of SEI layer changes. The type of SEI layer formed, and its rate of growth, is dependent on the types of electrodes and electrolytes used in the cells.

4.3.5.3 Reduce Cell Contaminants

Contaminants picked up during cell manufacture also may have deleterious effects on cell performance and life. In particular, water contamination should be minimized.

4.4 Battery Design

A robust battery design should make provisions for mechanical stability, electrical continuity, and adequate heat flow management. For lithium-ion batteries, cell-level voltage monitoring, coupled with appropriate voltage limits during charge and discharge, is critical to reliable battery performance and safety.

4.4.1 Electrical Design

The electrical design of the battery should address cell-to-cell wiring, connections to the power harness, connections to ground systems, monitoring and bypass devices, isolation resistors, and if needed, heater blankets. The design should minimize the risk of leakage currents from the cell terminals to the battery case and electrostatic discharge. The design should also meet electromagnetic interference and compatibility requirements for the vehicle and provide filtering circuits if needed. Connectors should be designed to prevent mis-mating with the wiring harness.

4.4.1.1 Monitoring Devices

The battery should be designed so that voltage and temperature can be monitored during check-out, ground testing, post-installation monitoring, and battery charging, either by the battery or ground support equipment. Additional devices to monitor other parameters may be added as needed to adequately verify the state of health of the battery or its cells.

4.4.1.1.1 Cell Voltage Monitoring

Cell-level voltage monitoring circuitry is required during ground testing, charging, and state-of-health monitoring to verify that none of a battery's cells are at a voltage that is outside the range validated by qualification testing.

Cell-level data is required to adequately monitor battery health due to the large voltage variation that normally occurs in many types of lithium-ion cells from the fully charged condition (about 4.1 V) to the fully discharged condition (about 2.7 V). For example, a loss of 1.4 V in a nine-string battery could indicate that all cells fell 155 mV due to normal self-discharge, or that a single cell lost all useful capacity and is at 2.7 V. Insight to voltages at the cell level prevents misinterpretation of the voltage changes seen at the battery level.

4.4.1.1.2 Temperature Monitoring

Temperature monitoring circuitry is required to verify proper cell temperature during open-circuit stand, charging, and discharging. For designs with heaters, monitoring is needed so that the heater circuit can be disabled during an out-of-temperature condition.

4.4.1.1.3 Current Monitoring

Current monitoring is required during cell or battery charging and discharging, but may be provided by ground support equipment.

4.4.1.2 Circuitry for Charge Control

Circuitry for charge control, whether contained within the battery or external to it, is considered to be an integral part of a lithium-ion battery design. Changes in charge rate and temperature may impact battery capacity; therefore, battery charging equipment and standard test conditions should be developed in parallel with the battery design. The charging method selected, including any specialty charge equipment and software, should be validated during qualification along with the cells and battery.

4.4.1.2.1 Overcharge and Overdischarge Protection

For safety and performance reasons, charge control circuitry is required to protect cells from excessively high or low voltages. Unlike alkaline cells, there is no inherent overcharge protection in most lithium-ion cells, and any charge in excess of the amount accepted by the negative electrode invariably leads to a net capacity loss. Chronic overcharging of lithium-ion cells, even in small amounts, may significantly degrade the cycle life of lithium-ion cells.

For many cell designs, discharge beyond a minimum voltage limit (typically 2.7 V) causes irreversible capacity losses and may facilitate corrosion of the current collector on the negative electrode.

4.4.1.2.2 Cell State of Charge Balancing

For certain applications, cell balancing may be needed to reduce the cell-to-cell divergence in voltage and state of charge that accumulate with calendar life and number of charge cycles. Although cell balancing is routinely achieved in alkaline cells by overcharging all cells to a fixed recharge ratio, such an approach could be disastrous for lithium-ion batteries. Cell voltage monitoring during charge with bypass electronics to switch cells out of the charging circuit once the charge voltage limit is reached may be used to balance cells.

The amount of acceptable cell state-of-charge divergence for a battery design depends on the battery application, with the intended cycle life and capacity margin for the mission being the major drivers. Operation scenarios requiring a high cycle life with little capacity margin typically need both cell-level monitoring and cell-level charge control to prevent prohibitively large cell-to-cell imbalances. For batteries built with larger capacity margins, sufficient charge balance may be achieved by charging/discharging to the weakest cell, or by a similar algorithm based on the charge input/output per cycle.

4.4.1.3 Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC)

The battery should be designed such that any EMI generated by the battery under normal operating conditions does not result in a malfunction of the battery. Also, the battery should not emit, radiate, or conduct interference that could result in the malfunction of other flight hardware on the vehicle.

4.4.1.4 Electrostatic Discharge (ESD)

The battery design should minimize the risk of ESD between cells, charge control circuitry, switches, relays, monitoring devices, and safety devices.

4.4.2 Mechanical Design

The mechanical design should provide support to the cells and wiring such that they can withstand transportation, handling, and launch environments without damage or loss of performance. The mechanical strength margin of all structural components shall be per MIL STD 1540E.

Cells should be electrically insulated from one another prior to making electrical connections to the cell terminals. Cell terminals should be protected by design to reduce the risk of an accidental short due to processing or foreign object debris in the battery. Encapsulation methods should be considered for electronic components installed inside the battery case that cannot tolerate exposure to cell electrolyte in case of cell venting.

The method of mounting or sealing cells in a battery case should not obscure or impede the operation of any cell-level rupture disk. If a sealed battery case design is used, then the battery case is required to meet safety requirements per Appendix 1 because lithium-ion cells are capable of generating high pressures during an abuse situation such as overcharge.

4.4.3 Thermal Design

The thermal design of the battery should provide a uniform, consistent operating temperature during all aspects of operation to prevent inordinate drift in cell-to-cell state of charge or electrical performance and to prevent thermal runaway. Effective heat transfer solutions may be critical for certain lithium-ion cell designs, particularly for operation under space vacuum conditions. To achieve this goal, heater blankets, radiators, emissivity coatings, and phase change materials may be required.

4.5 Safety Design

Lithium-ion batteries present a greater number of safety concerns compared to alkaline batteries because lithium-ion batteries contain an organic, flammable electrolyte and may explode with heat and flame under abuse conditions. There is a high risk of fire if an electrolyte leak occurs. There is a high risk of explosive venting and burning in an overcharge or an over-temperature situation, which may cause neighboring cells in the battery to vent and burn. Sustained charge voltages greater than 4.6 V are expected to cause violent venting and fire in many types of lithium-ion cells.

To date, the chief safety concerns for lithium-ion batteries and cells are overcharge tolerance, reversal tolerance, response to over-temperatures, external short circuits, and tolerance to mechanical abuse such as drops.

4.5.1 Cell-Level Safety Devices

Under high-temperature conditions, all lithium-ion cells have the potential to generate pressure and act as an ignition source once rupture occurs. To protect personnel, all cells are required to contain a venting device such that the cell vents prior to fragmentation of the cell case during an abuse situation.

Commercial lithium-ion cells often contain a number of devices on or internal to the cell to benignly disable the cell in the event of an electrical overload or high temperature. Devices commonly used include: shutdown separators, resetable fuses, high- and low-voltage interrupt devices, thermal switches, and pressure switches. The use of these devices should be carefully considered. Reliance on an internal safety device for voltage or temperature control may require a large amount of verification testing during cell or battery acceptance to demonstrate that the device will not inadvertently disable the battery during flight.

4.5.1.1 Materials Safety Data Sheets (MSDS) for Cell Materials

The cell manufacturer is required to provide an MSDS for the cell design that identifies the solvents and salts within the cell in case of accidental release at the launch site. Specialty handling areas may be required at the launch site depending on the toxicity of the components.

4.5.2 Battery-Level Safety Devices

Cells, modules, and batteries should be designed to protect personnel in the event of electrical overcharging, reversal, short circuit, overtemperature, and over-pressurization conditions. Special handling protocols and tooling may be needed because lithium-ion batteries are usually charged during all phases of life. Additional interrupt devices may be needed for batteries that use parallel strings of cells in instances where individual cell-protect devices may be defeated.

The battery-level safety devices required by the Range Safety offices in charge of DOD launch ranges are summarized in Appendix 1. Appendix 2 lists preliminary requirements specific to lithium-ion batteries generated after EWR 127-1 was released. If a sealed battery design is used, a pressure relief device such as a burst disk or blow-out crimp seal is required so that the battery ruptures before it can explode. Sealed battery cases require a minimum 3:1 ultimate safety factor with respect to worst-case pressure build-up, and the pressure relief devices are required to operate at 1.5 times the worst case predicted maximum pressure. The user is advised to contact the appropriate launch site regarding updates to the design requirements summarized in Appendices 1 and 2.

4.5.3 Battery Charging and Discharge Equipment

The design of battery charge and discharge equipment should protect against accidental damage to the cells, module, or battery due to any reverse polarity, shorting, overcharging, thermal runaway, or high pressure generation. This can be achieved through circuit protection mechanisms such as:

- Plug/receptacle connectors designed to prevent reverse polarity
- Diodes to prevent reverse currents
- Bypass diodes to prevent overcharging
- Fuses to prevent high currents

Charging, discharging, and battery conditioning equipment should automatically shut down if any cell voltage becomes too high or too low. Equipment should be designed to monitor battery temperature and halt operation in the event of an over-temperature to prevent thermal runaway. Equipment is required to be two-fault tolerant during charging, discharging, and monitoring to prevent failures that could cause a hazardous condition to personnel or cause property damage.

4.5.4 Deep Discharge for Disposal

For launch site operations, lithium-ion cells and batteries should be designed so that they can be completely discharged to zero volts for disposal without presenting a hazardous condition such as cell reversal.

4.6 Storage Capability

For batteries installed in a vehicle for long periods prior to use, additional hardware either on or off the vehicle may be required for battery voltage monitoring and recharging in the stored condition to compensate for charge losses without removal of the batteries from the vehicle. Any equipment developed for this purpose should conform to the requirements in Subsections 4.4.1.2 and 4.5.3.

Active monitoring circuits may increase the rate of battery self-discharge. If monitoring circuits are to be connected to the batteries for a significant length of time during storage or check-out testing, the rate of discharge should be quantified by test and included in capacity margin analysis and the projected rate of self-discharge for the battery.

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5. Development Testing

5.1 Purpose

This section details the required and recommended tests and analyses that constitute good practice for lithium-ion battery development. Generally, the goal during the development phase is to characterize engineering parameters, gather data, and validate the design approach. Specifically, it is used to characterize the technology sufficiently to demonstrate that the design is stable, meets mission requirements, and contains enough margin over those requirements that there is high confidence for passing qualification testing.

Development tests are crucial for gathering the data necessary for defining pass/fail criteria for later acceptance and qualification testing. All data, results, and findings during the development phase should be thoroughly documented and available for review at later stages in the acquisition cycle.

5.2 Development Test Requirements

Development testing should demonstrate voltage, rate capability, capacity margins, life expectancy, thermal control requirements, structural margins, dimensional requirements, compatibility to pre-launch, launch and space environments, manufacturability, testability, maintainability, reliability, and compatibility with system safety. Unless otherwise noted, testing should be done at the battery level due to possible differences in temperature and electrical potential unique to each cell position in the battery.

Development tests should be conducted, when practical, over a range of operating conditions that exceeds the design range to identify margins in capability. Development testing should attempt to define the critical limits on major parameters when possible even when those limits exceed mission requirements.

5.2.1 Cell-Level Electrical Testing

5.2.1.1 Cell-Level Charge Retention Testing

Development testing should establish a standard method for measuring the rate of charge retention (or self-discharge) in cells for later cell matching and evaluation of cell health. Charge retention and self-discharge are strongly dependent on temperature; therefore, a consistent temperature should be used when assessing the state of health of a cell or battery. Insofar as the self-discharge rate of some designs is very slow, elevated temperature stand may be used when it otherwise presents no risk of damage to the cells. Testing should also determine the self-discharge rate under worst-case, hot-temperature predictions for use in capacity calculations to select battery recharging schedules and to show that there is sufficient capacity margin in the design.

Criteria for the maximum-allowed self-discharge rate should be derived based on anticipated mission requirements, capacity margin, and allowable cell-to-cell capacity divergence over life. This criteria can be used to screen cells during acceptance testing and, if needed by design, to match cells within a battery.

5.2.1.2 Cell Matching Strategy Development

Development activities should define the critical parameters to match cells within a manufacturing lot required to attain the desired battery performance. For example, the maximum range in self-discharge rate between cells tolerated by the capacity margin over operation requirements may suggest a matching strategy based on charge retention for applications that do not provide for cell balancing.

5.2.2 Battery-Level Electrical Testing

5.2.2.1 Conductivity and Connectivity

Isolation, connectivity, and conductivity between cells, battery pins, connections to the power harness, connections to ground, and case should be verified. The resistance between all battery connector pins should be at least 2 MΩ or greater when measured at 500 V prior to the installation of the cells.

The connectivity and conductivity of other components, such as isolation resistors, filters, monitoring devices, bypass devices, and heater blankets, should also be verified.

5.2.2.2 Voltage Verification

Following charging under standard conditions, batteries should demonstrate acceptable voltages for an appropriate duration at minimum and maximum currents under minimum and maximum qualification temperatures. For steady-state load applications, it is recommended that the battery meet minimum load voltage requirements at worst-case high currents, plus 10% current margin, and maximum load voltage requirements at worst-case low currents, minus 10% current margin. For pulse load applications such as firing pyrotechnic devices, it is recommended that the battery meet load voltage requirements for currents 50% greater than mission need, and for a 100% longer pulse duration.

Testing should be repeated throughout the entire operational state of charge for the battery. Pulse testing, in particular, should be performed at highest, lowest, and intermediate states of charge where internal cell impedance may be at a maximum. Any failure to produce an acceptable, well-regulated voltage at this stage should result in choosing a different cell.

5.2.2.3 Capacity Demonstration

Development testing should validate the end-of-charge voltage limit, end-of-discharge voltage limit, and charge/discharge temperatures chosen for the battery design. Once defined, these parameters should be consistently used to characterize capacity during acceptance testing and qualification to establish the state of health for the battery and to match cells for batteries. Development testing should demonstrate capacity stability during charge cycling.

Once stable, development batteries should be charged under worst-case charge conditions, and discharged under worst-case temperatures and current rates to demonstrate that the design meets its operation capacity needs with margin. Any failure to produce an acceptable capacity at this point should result in either choosing a different cell or battery design, or an evaluation of the thermal gradients and current leak paths in the battery.

5.2.2.3.1 Battery-Level Charge Retention Testing

The apparent cell self-discharge rates may be higher once cells are assembled in batteries. Self-discharge rates should be measured on cells as-installed in the battery, including any charge monitoring devices used for significant lengths of time during storage or check-out to determine the maximum rate of capacity loss for capacity margin calculations, and to develop state-of-health checks appropriate for the battery design.

5.2.2.4 Cycle Life Demonstration

Development testing should demonstrate that the battery produces acceptable capacity and voltage under worst-case loads following charge cycling at 100% depth of discharge for operational requirements, for the maximum number of cycles expected of the battery over life. A cycle-life margin of 100% is recommended for this demonstration.

Following these tests, sample cells should be inspected for signs of leakage and dissected to verify acceptable condition of the electrodes, internal tabs, and other cell components. Pitting, cracking, loss of cohesion, and films have been reported after cycle life testing on lithium-ion cells. Also, dissolution and pitting of copper current collectors may occur for cells exposed to very low states of charge.

5.2.2.5 Charge Control Testing

Development testing should validate that the charge control strategy coupled with the chosen cell matching strategy is adequate to control cell-to-cell variations within acceptable voltage limits for the required capacity. Charge control parameters such as voltage limits, temperature limits, current ranges, and use of bypass circuitry should demonstrate that the charge control design meets requirements for all operations, including contingencies.

Testing should demonstrate protection of cells from overcharge and overdischarge conditions. Testing should also verify conformance to the system safety requirements summarized in Appendix 2.2.1.

5.2.2.5.1 Charge/Discharge Equipment

Development testing should demonstrate that any specialty charge equipment developed for the lithium-ion batteries produces the desired uniform current and voltage levels necessary to condition the cells in the battery. Tests should verify that the equipment is two-fault tolerant for automatically aborting charging or discharging when either the voltage, current, or temperature limits are exceeded. The processing equipment should also revert to an open-circuit condition for all cells in the event of a power failure of either its main computer or its sub-assemblies.

The launch site requirements for fault tolerance and cell-level charge control per Appendices 1 and 2 should be demonstrated during development testing.

5.2.2.6 Monitoring Devices

The operation of voltage and temperature monitoring devices should be demonstrated by test. Any discharge of the battery caused by internal or exernal monitoring devices should be factored into the capacity analysis for the battery.

5.2.2 Mechanical Analysis and Testing

A combination of stress analysis and test should be performed to demonstrate that a battery design meets system and mission mechanical requirements with acceptable margin. For new designs, or existing designs previously qualified to lower maximum predicted environments (MPE), qualification-level shock and random vibration testing on a prototype unit should be performed. Cells should be inspected by X-ray prior to testing then re-inspected by X-ray or dissection after testing to determine whether internal components such as electrode tabs shifted, broke, or otherwise suffered mechanical failure. Any signs of electrolyte leakage or movement, or material failure should force a re-evaluation of the mechanical stability and possible redesign of the cells or battery.

Analysis should verify that the stresses due to worst mechanical loads are not excessive for the yield strengths of the materials and bonding strengths of any adhesives used.

5.2.3 Thermal Analysis and Testing

Proper thermal design of the battery should be validated both by analysis and by test at the battery level under flight-like environments during development. A combination of thermal stress analysis, chemical modeling, and test should be performed to demonstrate that a battery design will meet system and mission thermal requirements with qualification margin. Analysis should verify that the thermal stresses produced under the thermal extremes and electrical loads used during acceptance testing, qualification testing, mission, and storage do not produce severe gradients, and are not excessive for the yield strengths of the materials and bonding strengths of any adhesives used. Test should validate that the use of worst-case thermal ramp rates and temperatures during flight and during the placement and removal of the battery in cold storage do not cause excessive stresses within the cells or battery or cause electrolyte leakage. Test or analysis should be used to verify that the cell chemistry is not degraded by storage and prelaunch environments.

For new designs, or existing designs previously qualified to more benign thermal environments, thermal testing to acceptance, qualification, mission, or storage temperatures is strongly recommended to verify that no leakage or degradation of cells occurs.

5.2.3.1 Heater Testing

Development testing should demonstrate that any heater used on the battery is adequate to produce the necessary temperature range for use without causing severe thermal gradients across cells or across the battery. The operation of devices such as thermostats should demonstrate that the heater circuit disengages before an overtemperature condition is produced.

Testing should also demonstrate that the heater and related circuitry do not violate electromagnetic interference requirements when in operation.

5.2.4 Environmental Testing

For applications involving harsh environments such as humidity, altitude, salt fog, high radiation levels, UV exposure, etc., it is recommended that development activities address these environments by analysis or test to demonstrate design reliability prior to qualification testing.

5.3 Safety and Abuse Testing

The operation of all cell-level and battery-level safety devices should be validated by test during the development cycle. Tests should include any expected abuse scenarios, as well as those required by systems safety regulations. Range Safety regulations require that the fault-tolerant devices and subsystems of all non-exempt lithium-ion batteries and charging equipment safeguard against the conditions of overvoltage, overdischarge, high currents, and high temperatures. For new designs, the UN tests required by the Department of Transportation may be necessary.

5.3.1 Cell and Battery Venting Devices

The operation of all battery- and cell-level vents and burst disks should be validated and characterized to provide pass/fail criteria for acceptance and qualification testing. For sealed batteries, the 3:1 ultimate safety factor for worst-case pressure build-up prior to mechanical yielding should be validated by test or analysis.

5.3.2 Charging and Monitoring Equipment

Analysis and testing should demonstrate that charging and monitoring equipment at the launch site is two-fault tolerant against shorting, overcharging, overdischarging, and thermal runaway.

5.3.3 Deep Discharge for Disposal

Protocols developed for safely discharging a cell or battery to zero volts should be demonstrated during development testing.

5.4 Quality Assurance and Reliability

The goal of quality assurance is to ensure that manufacturing, handling, and conditioning processes are well controlled. Critical operations should be defined by the manufacturer and monitored. A plan for collecting and analyzing key production data by proven statistical process control methods should be developed. Statistical process controls should be implemented, including establishment of control limits and periodicity of data collection and analysis. A sequence of notification and approval for process, drawing, material changes, and discrepancy reporting should be derived for cell and battery production.

A quality assurance program is required to be in place prior to the manufacture of qualification test articles.

5.4.1 Process Margins

The tolerance range in critical processes should be evaluated with respect to impact on cell performance and life. Demonstration testing of the minimum and maximum limits of key processing parameters may be required to validate process margins.

5.4.2 Failure Modes Effects Analysis

A detailed consideration of the possible material, electrical, and mechanical failures that could occur as a result of all expected environments, handling, and operational scenarios should be developed. All possible failure mechanisms should be defined such that both the factors causing the failures, their impact on operation, and mitigation factors are understood.

Because lithium-ion batteries are a relatively new technology, it is particularly critical to perform exhaustive testing to expose the common failure modes for the chemistry. Ample margin is recommended in the above electrical, thermal, mechanical, and abuse tests to disclose the manner in which the cell or battery is most likely to fail.

6. Qualification Testing

6.1 Purpose

Qualification tests are conducted to demonstrate that the design, materials, and manufacturing processes used to produce battery hardware meet the specifications for the application with adequate margin. In addition, qualification validates the acceptance program, including the cell matching strategy, test protocols, test equipment, and software associated with battery charging and conditioning. The goal of this section is to review the qualification requirements for lithium-ion batteries as applied to launch vehicle use.

The qualification recommendations in this section are based on MIL STD 1540E requirements that define a battery as a unit and subject to unit-level qualification and acceptance tests. The reader is referred to MIL STD 1540E for a more detailed description of the more generic tests discussed below. As of this writing, this standard is consistent with, but does not envelop, the more stringent test requirements applicable to lithium-ion batteries used to power Range Safety flight termination systems, and the user is advised to contact the appropriate launch site regarding those requirements.

6.2 General Qualification Requirements

6.2.1 Qualification Test Hardware

Any qualification battery, module, or cell shall be representative of a manufacturer's construction methods and processes. It shall be verified that all subsequent flight assets are produced from the same drawings, materials, tooling, manufacturing processes, and level of personnel competency as was utilized for constructing the qualification hardware.

All cells in the qualification battery shall be from the same manufacturing lot. The cells selected should represent the widest performance variation allowed in flight batteries to validate the cell matching strategy used to group cells during acceptance testing per Subsection 7.3.2. All other components associated with the battery should be randomly selected from production hardware.

Only one qualification battery is required to demonstrate compliance with the qualification environments. However, in instances where testing is destructive or individual tests are mutually exclusive, additional batteries may be used to demonstrate performance under qualification conditions. When this is required, the test approach shall maximize the number of different environments applied to at least one of the batteries to demonstrate compliance to the composite environments.

6.2.1.1 Manufacturing Lot Restrictions

Cells may be considered to be from the same manufacturing lot if they were produced from a large continuous automated production run with materials from the same source, and if they were manufactured without interruption of the normal process sequence. Cell groups produced from different manufacturing plants shall be treated as different lots. Cells with non-continuous serial numbers or showing a break in their date of manufacturing time stamps should be evaluated for possible materials or manufacturing process changes.

For specialty and non-automated production lines, cells may be considered to be from the same lot if evaluation of the materials, travelers, work processes, and manufacturing quality standards establish that the cells were manufactured without interruption utilizing the same raw materials, drawings, processes, and qualified personnel, and that manufacturing processes were well-enough controlled to prevent significant variability within the lot.

6.2.2 Battery Conditioning Equipment

It is critical that qualification testing utilize the same battery processing equipment intended for flight hardware for battery conditioning, charging, and discharging. The type of battery charging equipment and charge control algorithms intended for use on flight hardware shall be developed or purchased prior to qualification testing so both the battery and the charging system are validated by the qualification test even if the charge equipment does not accompany the battery during flight.

6.2.3 Data Collection and Acquisition Rates

Voltage, current, and temperature data shall be recorded at rates sufficient to verify compliance with test requirements and performance specifications. High data acquisition rates of at least 1000 samples per second are recommended during the first second of load application while recording voltage and current levels during pulse loads for pyrotechnic applications. An acquisition rate of at least 10,000 samples per second is required during testing under dynamic environments for the duraton that maximum environments are applied to capture any loss of voltage or current due to mechanical damage of the electrode connections or internal wiring. Cell-level voltage measurements are recommended during battery charge and discharge to verify that cells remain within specified voltage limits.

In all instances, the numerical values for voltage, temperature, current, capacity, resistance, and pressure should be recorded when required instead of only indicating PASS or FAIL against a range of values provided by the test plan.

6.2.4 Qualification Test Failures and Anomalies

Qualification testing should immediately halt in the event of a test anomaly or failure. A failure condition is considered to be the inability of the battery to meet electrical, structural, or thermal requirements. An anomaly condition is considered to be a potential failure condition such as would result from a test discrepancy or an unanticipated battery response requiring further analysis. Unless the battery is in an unsafe condition, the test configuration should not be broken in the event of a failure or anomaly until a review team is convened.

6.2.5 Re-qualification of Battery Designs

Partial or complete requalification of a battery design may be required under the following circumstances:

- Change in parts, materials, or processes affecting the fit, form, or function of the battery;
- Change in parts, materials, processes, or design that changes the response of the battery, battery components, cells, or cell components to mechanical environments, thermal environments, physical environments, and electrical loads;
- Change in parts, materials, processes, or design that changes the rate of deterioration of the battery, battery components, cells, or cell components prior to, or during, use;
- Change in parts, materials, processes, or design that change the electromagnetic field generated by the battery (EMI/ESD);
- Change in prelaunch or mission maximum predicted environments for the battery;
- Change in transportation environments or shipping container;
- Change in storage environment;
- Change in prelaunch processing equipment or battery charger, including hardware and software modifications for charging and conditioning batteries prior to flight;
- Any anomaly or failure indicative of a potential failure mechanism not addressed during the original qualification testing.

In the event that a lithium-ion cell manufacturer is unwilling or unable to satisfy the requirements for maintaining stringent process, drawing, and raw material controls between manufacturing lots, repeat qualification and abuse testing is required for every follow-on manufacturing lot of lithium-ion cells after the battery is qualified.

The length of allowable use of a manufacturing lot of lithium-ion cells following successful qualification and acceptance testing shall follow the requirements of Subsection 6.4.

6.2.6 Protoqualification of Battery Designs

Protoqualification testing of batteries should be avoided because it assumes a higher risk to mission and reduces the ability to adjust to failures that may occur during testing. Protoqualification or re-use of qualification batteries for flight is also impractical because of requirements to dissect the battery and a sampling of cells after qualification testing. Any re-use of qualification battery cases shall verify that any venting devices on the battery case have not been damaged.

6.2.7 Qualification by Similarity

In general, a battery design “B” may be considered qualified by similarity to a battery design “A” already qualified for flight if all the following conditions apply:

- Battery "B" is a minor variation of battery "A". Any dissimilarities should be thoroughly analyzed and evaluated in terms of weight, electrical performance, mechanical configuration, thermal effects, and dynamic response;
- The cells in batteries "A" and "B" are from the same manufacturing lot per the requirements of Subsection 6.2.1.1;
- Every qualification environment required for battery "B" is equal to or less severe than the qualification environment s for battery "A;"
- Battery "A" has not been qualified by similarity or analysis.

6.3 Qualification Tests

Unless otherwise noted, qualification testing shall adhere to the requirements of MIL STD 1540E. Table 6.3 lists the qualification requirements required for lithium-ion batteries consistent with MIL STD 1540E. Safety testing consistent with launch range operational system safety requirements for lithium-based batteries has been included. Test conditions and environments shall stress the qualification hardware to more severe conditions than the maximum conditions expected during service life. However, testing should not cause unrealistic modes of failure. Qualification test conditions shall envelope the highest levels expected for all missions.

Prior to starting qualification testing, all cells and batteries should pass acceptance testing and any required wear-in processing. If cell matching is used, the cell group in the battery selected for qualification should represent the maximum range in matching criteria expected for the flight hardware to validate the cell matching strategy. Unless otherwise noted, the qualification test battery should be exposed to all applicable environmental tests in the order of their occurrence during the expected

Table 6.3 Qualification/Protoqualification Test Requirements for Launch Vehicle Batteries from MIL-STD 1540E. Items in bold-face are additional tests from those contained in MIL-STD 1540E.

Test	Qualification
Inspection	R
Thermal cycle	R
Thermal vacuum	R
Climatic/Humidity	ER
Shock	R
Vibration & Acoustic	R
Acceleration	ER
Performance specification (Functional)	R
Leakage	R
Pressure & Burst Pressure	R
Static Load	R
EMC/EMI	ER
Life	R
Safety Devices	**R**

R = Required, ER = Evaluation Required

application. For example, transportation environments should precede launch environments, diurnal thermal cycling should precede operational thermal cycling, etc.

Throughout qualification, the test batteries shall be maintained in the same orientation as expected during the actual application, including prelaunch stand and mission.

6.3.1 Inspection

Prior to qualification testing, batteries shall be inspected for general workmanship and signs of an anomaly such as corrosion or electrolyte leakage. Battery part number, manufacturer, serial number, and date of manufacturing shall be verified. Weight and critical dimensions shall also be verified.

Once qualification testing has been concluded, test batteries shall be re-inspected to verify that none of the cell or battery components have been stressed beyond their design limits by the qualification environments. In particular, visual and radiographic inspection (X-ray or N-ray) may be used to examine the integrity of all wiring external to the cells, the connectors, the tabs and wires inside the cell that connect the electrodes to the terminals, and the condition of potting and shimming materials.

Destructive physical analysis or its equivalent shall be performed on a sample of cells from the qualification battery following all environmental testing and operational testing to demonstrate that electrodes, separators, tab connections, safety features, and structural components internal to the cell have not been stressed beyond their design limits.

6.3.2 Thermal Cycle

Thermal cycle testing shall address the impact of thermal conditions expected during mission, prelaunch and storage.

6.3.2.1 Storage Temperature

A storage temperature test or analysis shall be performed to demonstrate that the battery will not be damaged by the maximum predicted high and low storage temperatures with margin (generally 10°C recommended). If analysis is done, a stress model should be generated to predict stress generated under worst-case hot and cold temperatures due to coefficient of thermal expansion mismatch and to validate that the worst-case rate of change from one thermal extreme to the other does not damage the battery. Analysis or test is also recommended to evaluate the capacity loss and rate capability loss during storage under worst-case high temperatures.

6.3.2.2 Non-Operational Thermal Cycling

Test or analysis shall demonstrate that the diurnal temperature variations expected after installation on the vehicle do not damage the battery mechanically or severely impact electrical performance. If testing is performed, it should be applied to the qualification battery prior to conducting the operational environmental tests. The number of thermal cycles applied and their duration at worst-case hot conditions should be consistent with the intended application.

6.3.2.3 Operational thermal cycling

Unless application restrictions apply, a minimum of 23 thermal cycles shall be applied in addition to the four cycles applied during thermal vacuum testing, with a minimum dwell of two hours at each thermal extreme. If the unit is exempt from thermal vacuum testing per MIL STD 1540E exemptions, then a total of 27 thermal cycles shall be applied. The worst-case high and low temperatures shall exceed the MPE and acceptance test levels by at least 10°C, and the rate of transition between hot and cold extremes shall not be slower than 1°C per minute or slower than the thermal transition rates expected during operation. Battery temperature and voltage shall be continuously monitored during all portions of the test.

During testing, a battery shall demonstrate the ability to meet electrical performance requirements per Subsection 6.3.8.3 following the minimum dwell period at both worst-case hot and cold conditions expected during mission on the first and last cycle, and at ambient temperatures before and after thermal cycling. Recharge of the battery may be done at temperatures intermediate to the thermal extremes if only intermediate temperatures are used during charging in the intended application.

6.3.3 Thermal Vacuum

Thermal vacuum test shall be designed to demonstrate the following under the combined environments of vacuum and worst-case high and low operational temperatures:

- Electrical performance requirements per 6.3.8.3 are met
- Structural integrity is maintained
- The battery is not susceptible to corona or arcing
- The battery adequately dissipates heat without air convection

Some of these goals may be met by analysis. A minimum of four thermal cycles shall be applied using thermal extremes that exceed the MPE and acceptance test levels by 10°C under vacuum. The total amount of time under vacuum shall envelope the maximum duration expected for the longest mission time planned. The battery shall be mounted in the thermal vacuum chamber in a manner similar to its installation on the vehicle or on a thermally controlled heat sink, and shall include any surface finish applied to the flight hardware to control emissivity. Battery temperature and voltage shall be continuously monitored during all portions of the test.

Batteries that are used during the ascent phase of flight shall be discharged at flight-level currents during the test, and monitored for arcing and corona while lowering pressure to vacuum levels and while at vacuum levels. For operation verification during the ascent mode, the pressure shall be reduced from atmospheric to 0.15 Torr in 10 min. For operation after ascent, the test vacuum levels should be consistent with the maximum service altitude and service duration.

Electrical performance tests per Subsection 6.3.8.3 shall be applied during both the hot and cold thermal extremes on cycles one and four. The rate of vacuum application should approximate the rate of pressure decay expected during flight.

6.3.4 Climatic/Humidity

6.3.4.1 Humidity

Unless a sealed battery design is used or batteries are otherwise protected from a relative humidity of greater than 55%, test or analysis shall be performed to demonstrate that the battery will not be damaged by the predicted relative humidity of the pre-flight environments. If required by application, humidity testing shall be done between 2°C and 35°C at no less than 95% relative humidity for two cycles, with humidity levels altered only after the target temperature has been reached. On cycle 3, the test unit shall be dried to less than 50% relative humidity and ambient temperature after the hot dwell, then raised to 90% relative humidity after establishing a 35°C temperature on cycle 4. After the cold portion of cycle 4, the battery may be dried again with ambient temperature air.

Functional testing per 6.3.8.3 shall be performed prior to the test, within 2 h of drying in cycle 3, and after a 1 h dwell at 35°C and 2°C (at 90% relative humidity) in cycle 4 to demonstrate acceptable performance.

6.3.4.2 Climatic Tests

Qualification testing to worst-case climatic conditions is recommended, depending on the exposure conditions imposed during fabrication, test, shipping, storage, launch preparation, launch, and re-entry. Climatic testing may be critical for reserve battery designs and for batteries installed on missiles or in silo environment early in its service life. It may also be necessary to demonstrate a benign battery response in an explosive atmosphere for usage in silos.

6.3.4.2.1 Rain

Unless a sealed battery design is used or batteries are otherwise protected from rain, test or analysis may be required to show that a battery exposed to rain during its service life will not be damaged. Rain testing demonstrating the adequacy of protective shelters, storage, or shipping containers may be required if exposure to rain is expected during shipping and handling.

6.3.4.2.2 Salt Fog

Unless a sealed battery design is used or batteries are otherwise protected from salt fog by shipping or storage containers, test or analysis may be required to show that a battery exposed to salt fog during its service life will not be damaged.

6.3.4.2.3 Dust and Sand

Dust and fine sand testing may be necessary for any battery design intended for long-duration storage in a silo or similar environment that is not protected by contamination control, protective covers, storage containers, or shipping containers. Testing should specify the humidity, sand composition, particle size, dust velocity, and test duration appropriate for the application.

6.3.4.2.4 Fungus Resistance, Ozone, Sunshine

Fungus resistance, ozone, and sunshine (UV) testing is recommended as warranted by the application, design, and material selection.

6.3.4.2.5 Explosive Atmosphere

If the lithium battery is expected to operate in an environment containing potentially explosive conditions, then it is necessary to demonstrate by test or analysis that venting of the battery will not cause ignition of the surroundings. Lithium-ion batteries typically contain a flammable electrolyte and may act as an ignition source in a vented condition, and are generally not recommended for operation in these environments.

6.3.5 Shock

Shock testing shall address the shock environments that occur during shipping, handling, and flight.

6.3.5.1 Transportation Shock

A transportation shock test shall be performed to demonstrate that the battery packaging is sufficient to protect the battery during transportation and handling. Batteries shall be tested in the shipping containers intended for flight batteries.

Typically, a drop test is performed with a battery packaged in its shipping container, and the assembly is dropped onto a concrete slab from a height equivalent to the maximum height of the container lifter used during transportation. The number of drops used is chosen based on the number of different container orientations possible (side, edge, top, bottom). Radiography of the battery and cells before and after this test is recommended to document the change in position of the internal components of the batteries.

6.3.5.2 Bench Shock

A bench handling shock test shall be performed to demonstrate that the battery and its cells will not be damaged by normal handling. Multiple free drops and pivot drops on the order of inches onto a wooden table of each side of a batteries are required to demonstrate that the design is sufficiently rugged to prevent damage.

6.3.5.3 Pyrotechnic Shock

Unless exempt per MIL STD 1540E, shock testing shall be performed to demonstrate that a battery can withstand the shock environment expected during launch with margin of 6 dB above MPE in each direction of each axis. A minimum of three shocks in each direction of each axis should be applied. Any isolators, grounding straps, brackets, and cabling used on the battery shall also be included in the test configuration, and cabling used to monitor battery voltage shall be equivalent to the one used in flight.

Shock testing shall be done with the battery under an operational discharge load to discern any performance anomalies. Both battery voltage and current shall be monitored during the application of each shock, with voltage data sampled at a rate of 10,000 times a second or faster.

6.3.6 Vibration and Acoustic

Vibration and acoustic testing shall address the dynamic environments that occur during shipping and flight. When testing is required, any isolators, grounding straps, brackets, and cabling used on the battery shall also be included in the test configuration, and cabling used to monitor battery voltage shall be equivalent to the one used in flight.

Acoustic, sinusoidal, and random vibration testing shall be performed with the battery under an operational discharge load to discern any performance anomalies, and both battery voltage and current should be monitored during the test, with voltage data sampled at a rate of 10,000 times a second or faster.

Testing under combined environments of vibration and worst-case temperature or pressure extremes should be evaluated as warranted by the design and intended use.

6.3.6.1 Transportation Vibration

A transportation vibration test shall subject the battery and cells to maximum predicted vibration levels during transportation. Analysis may be done in lieu of testing if it can be demonstrated that the random vibration levels for flight exceed the levels expected during transportation for all frequencies. However, care must be taken with this approach to validate that the longer duration of the transportation environment is adequately enveloped and that a sine component is not present in the transportation environment. If testing is warranted, batteries shall be tested in the shipping containers intended for flight batteries.

6.3.6.2 Acoustic

Test or analysis shall be performed to demonstrate that a battery can withstand the acoustic environment expected during launch with margin of 6 dB above MPE for 3 min in each axis.

6.3.6.3 Sinusoidal Vibration

Test or analysis should be performed to demonstrate that a battery can withstand the sinusoidal vibration component of the dynamic environment at a margin of 6 dB above MPE in each axis.

6.3.6.4 Random Vibration

Testing shall be performed to demonstrate that a battery can withstand the random vibration environment expected during launch for a minimum of 3 min in each axis at levels that are 6 dB above MPE from 20 to 2000 Hz.

6.3.7 Acceleration

Test or analysis shall be performed in both directions of all three orthogonal axes to demonstrate that a battery can withstand the acceleration environment expected during launch at levels that are 1.25 times the maximum predicted acceleration. If testing is required, any isolators used on the battery shall be included in the test configuration. Testing shall be done with the battery under a discharge load to discern performance anomalies, and both battery voltage and current shall be monitored during the test.

Often, analysis is used to demonstrate that the environments applied during shock testing exceed those of acceleration to justify deleting this requirement. However, testing should be considered if there is a risk of electrolyte migration under sustained acceleration that could negatively impact battery performance.

6.3.8 Performance Specification

Performance testing shall demonstrate all critical battery performance parameters and that all voltages are maintained within the manufacturer's recommended limits. Charging devices used during qualification testing shall be of the same design and use the same charge control algorithm as those intended for use on flight hardware to adequately duplicate the charge/discharge conditions expected during service. Every charge cycle applied to the battery during qualification testing shall be recorded, including the date applied.

When testing for baseline capacity measurements, it may be necessary to adhere to a standard set of charge and discharge rates, end-of-charge/discharge voltages, and charge/discharge temperature to maintain repeatability from cycle to cycle.

6.3.8.1 Continuity and Isolation

The isolation, connectivity, and conductivity between cells, battery pins, connections to the power harness, connections to ground, and case shall be measured to demonstrate acceptable continuity and isolation. The connectivity and conductivity of other components such as isolation resistors, monitoring devices, bypass devices, and heater blankets shall also be verified.

6.3.8.2 Charge Retention

The charge retention capability of the battery shall be tested to show that the rate of self-discharge of each cell in the battery is within acceptable limits for the design, that the capacity requirements are not violated, and that cell-to-cell divergence is within acceptable limits. The test shall measure both the loss in OCV and capacity during stand. Baseline testing shall establish cell and battery capacity under a standard set of charge/discharge temperatures and rates. Following charging, the battery shall stand under open-circuit conditions for a sufficient period of time to detect a significant loss in OCV at a linear rate with time, then discharged under standard conditions to calculate the capacity lost.

For lithium-ion cells and batteries, the first days after charge are accompanied by a greater OCV loss than subsequent days. Therefore, stand time shall be long enough to pass this initial transient so as not to overestimate the OCV and capacity losses as a function of time. Elevated temperatures may be applied to reduce the stand time, provided they are not detrimental to the cell chemistry and the battery is returned to standard conditions for discharge.

Capacity and voltage shall be verified after exposure to worst-case preflight temperatures. Batteries shall be maintained at maximum predicted non-operational temperatures under appropriate connect loads for the maximum duration allowed between charge cycles prior to capacity and voltage verification.

6.3.8.3 Electrical Performance

Electrical performance verifies that the battery can sustain the appropriate voltage levels for worst-case mission requirements for current and duration under qualification environments. It shall be applied multiple times throughout qualification testing to demonstrate compliance at different areas of the flight envelope. Results from these tests shall meet requirements and be within expectation for the design and manufacturing lot. During testing, battery and cell voltages shall be recorded along with discharge current and battery temperature to show that no single cell violates the manufacturer's recommendations for allowable voltage or the requirements for the electrical bus.

Due to potential impacts in battery performance caused by service life and manufacturing variability, it is recommended that pass/fail voltage criteria exceed mission requirements during qualification testing.

Current loads applied during steady-state and pulse discharge shall not be less than the worst-case loads expected during mission. Additionally, it is recommended that margin be applied to steady-state and pulse currents loads during qualification testing to accommodate changes during service life, manufacturing variability, and mission requirements. High-rate pulse loads shall be applied at the minimum and maximum states of charge, as well as at multiple intermediate states of charge where local maxima in internal impedance may occur due to phase changes within the electrodes.

At the end of electrical performance testing, the battery shall be discharged for capacity verification.

6.3.8.4 Heater Operation

Battery designs incorporating heaters shall be tested to demonstrate that operation will not degrade for the maximum number of heater cycles and heater time expected for mission and pre-launch activities. These tests, combined with the thermal cycling tests, shall demonstrate that the battery performance is not degraded beyond acceptable limits by the time spent at elevated temperatures.

6.3.9 Leakage

Following exposure to qualification environments, cells shall be inspected or tested for electrolyte leakage. It is recommended that vacuum application combined with a chemical sniffer be used to detect electrolyte leakage. For sealed batteries, a leak test shall be performed to demonstrate hermeticity.

6.3.10 Pressure and Burst Pressure

For hermetically sealed batteries, abuse testing or analysis shall be performed to demonstrate that structural failure of the battery case will not occur during failure scenarios that cause the lithium-ion cells to produce pressure and vent.

For unsealed battery designs, abuse testing shall be performed to demonstrate that cells vent before structural failure of the cells occurs.

For battery cases with a re-usable venting device or pressure relief mechanism, a proof pressure test shall be performed after exposure to all qualification environments to demonstrate that venting does not occur until 1.1 times the maximum expected operating pressures are exceeded, and that venting occurs prior to reaching the structural limit.

6.3.10.1 Non-Reusable Venting Devices

For cells and batteries using a rupture disk or similar non-reusable device, a burst pressure test shall be performed to demonstrate that the opening pressure of the device has not been compromised after exposure to qualification environments.

Any cell or battery failing to demonstrate proper opening of a non-reusable vent shall be cause for rejection of the battery or cell lot due to system safety requirements.

6.3.11 Static Load

Static load test and margin requirements are typically addressed by analysis, and the stresses applied during the other portions of qualification testing because batteries are not load-bearing structures. The design limits of the structural components within the battery should not be exceeded when the unit is exposed to the worst-case conditions of acceleration, vibration, pressure, preloads, and temperature. If static load testing is required, the static loads should be 1.25 times the limit load, and the structural components should withstand the applied loads without gross yielding, gross deflection, rupture, or collapse.

6.3.12 EMC/EMI

Test or analysis is required to show that the battery emission of EMI and susceptibility to EMI from surrounding units do not result in malfunction of the battery under expected operating conditions, including ground operations. Test or analysis shall verify that the battery does not emit, radiate, or conduct EMI, which could result in malfunction of other units. This is of particular concern for battery designs using heaters. A 12-dB test margin on EMC levels is required for qualification.

6.3.13 Mission Life and Cycle Life

The qualification battery shall satisfy all of its performance specifications following application of all environments plus the maximum number of operating charge and discharge cycles expected of the battery throughout its life, including margin to account for variability such as calendar life that cannot be simulated during qualification testing. Worst-case mission life shall be demonstrated after maximum stand at worst-case hot conditions to demonstrate acceptable rates of battery self-discharge. Cycle life includes all charge cycles applied during acceptance testing, storage, preflight testing, and flight. It is recommended that the total number of cycles applied to the qualification unit before final functional testing be at least twice the number of cycles expected over life.

The depth of discharge used to simulate a cycle on the test battery shall be 100% of the maximum depth of discharge expected during service. Cycling at depths of discharge that are less than actual service are not expected to generate the same magnitude of stresses on the electrode materials, which may expand, contract or undergo phase changes at different states of charge.

All mission life testing shall be done under electrical charge and discharge conditions that simulate ground processing loads including currents, charge control methods, and temperatures.

6.3.14 Safety Devices

The proper operation of all battery-level and cell-level safety devices installed in the battery, such as bypass circuitry, charge control circuitry, internal fuses, thermal switches, pressure switches, and voltage interrupt devices that are expected to safeguard personnel in the event of a battery anomaly, shall be verified to function correctly following exposure to qualification test environments.

Any cell or battery failing to demonstrate action of a safety device shall be cause for rejection of the battery or cell lot.

6.4 Service Life

Service life testing is required for all battery designs to demonstrate that the calendar life acquired over time does not degrade battery performance. For some lithium-ion designs, calendar life has been the cause of higher self-discharge rates, losses in rate capability, and a higher susceptibility to thermal runaway due to side reactions and SEI growth. Performance losses may vary widely, depending on the type of anode, cathode, and electrolyte composition involved and storage temperature.

6.4.1 Electrical Testing of Leader Batteries

For batteries that do not require qualification testing of every manufacturing lot, representative "leader" batteries from manufacturing lots made at or before the manufacturing date of the oldest battery in the flight inventory shall be electrically tested for performance at periodic intervals (such as every six months) until the maximum service life (and any extensions per Subsection 6.4.2) of the battery design is demonstrated. For batteries that require qualification testing for every manufacturing lot, electrical testing on a representative "leader" battery from each manufacturing lot in the flight inventory shall be performed.

6.4.2 Three-Year Life Extension

For batteries that are not flown within three years of passing qualification testing, additional testing is required using batteries either stored with the flight batteries or stored separately but exposed to the same storage environments (temperature, state-of-charge), cycle life history, and charge/discharge voltages. The purpose of the three-year life extension testing is to demonstrate that no significant structural or chemical deterioration of the battery has occurred.

The three-year life extension testing shall validate electrical performance, mechanical stability, operation of safety devices, seal integrity, and the battery's response to abuse conditions. The qualification tests listed below shall be repeated on the test articles representative of every manufacturing lot of flight hardware unless the battery design does not require qualification testing for every manufacturing lot.

- Electrical isolation and continuity (6.3.8.1)
- Pressure and burst pressure (6.3.10)
- Mission life and cycle life (6.3.13)
- Thermal cycling (6.3.2)
- Thermal vacuum testing (6.3.3)
- Shock and Vibration testing (6.3.5 & 6.3.6)
- Charge retention (6.3.8.2)
- Electrical performance (6.3.8.3)
- Structural integrity and condition of internal cell components after environments (6.3.1, 6.3.9)

Successful completion of the above tests shall provide an additional three-year period of use for the flight hardware.

6.4.3 Accelerated Testing

Accelerated testing is not recommended for launch vehicle application of lithium-ion batteries because accelerating factors that mimic both calendar life and cycle stresses are generally not available.

7. Acceptance Testing

7.1 Purpose

Acceptance tests are conducted to demonstrate that all cells and batteries meet minimum requirements for performance and workmanship in manufacturing, processes, and materials. Acceptance testing is intended to screen for defective parts, processes, materials, and workmanship by applying benign stresses that either result in failures or unexpected behavior of the battery or cell. Acceptance test conditions shall envelop a composite of the worst-case conditions for mission without overstressing the battery or exceeding the environments applied during qualification testing.

Unless otherwise noted, acceptance testing shall adhere to the requirements of MIL STD 1540E. As of this writing, these requirements are consistent with, but do not envelope, the more stringent test requirements applicable to lithium-ion batteries used to power Range Safety flight termination systems.

7.2 General Acceptance Test Requirements

7.2.1 Test Hardware

All flight articles and qualification test cells and batteries shall undergo acceptance testing. All cells screened and grouped for batteries shall be from the same manufacturing lot. All cells for a particular battery shall be from the same matched group per Subsection 7.3.2.

7.2.2 Test Location

Acceptance testing may be performed at the manufacturer site, contractor facility, battery storage site, or launch site.

7.2.3 Test Levels and Durations.

Acceptance environmental conditions shall stress the hardware to the maximum conditions expected for all flight events. Acceptance test levels shall be consistent with those in MIL-STD-1540E.

7.2.4 Test Data Trending

Baseline performance shall be established for critical battery performance parameters measured during acceptance testing, such as charge retention, capacity, and voltage under maximum loads. These parameters shall be monitored to identify possible performance degradation due to unanticipated manufacturing variation or unacceptably large manufacturing, design, or material variation during production of a lot or between manfacturing lots.

7.3 Acceptance Tests

The major components of acceptance testing are cell inspection, cell characterization, cell matching, manufacturing lot testing of venting devices, battery inspection, and battery performance testing. Table 7.3 lists the acceptance tests recommended for lithium-ion batteries used in launch vehicles. Note that, unlike the silver-zinc battery chemistry, there are no inherent limitations for lithium-ion batteries that precludes acceptance-level random vibration, thermal cycling, or thermal vacuum testing for acceptance.

Table 7.3. Acceptance Test Requirements for Launch Vehicle Batteries (MIL-STD 1540E). Items in bold-face are additional tests from those contained in MIL-STD 1540E.

Test	Acceptance
Cell Screening	**R**
Cell Matching	**ER**
Inspection	R
Wear-in	ER
Thermal cycle	ER
Thermal vacuum	R
Shock	ER
Vibration and Acoustic	R
Performance specification (Functional)	R
Leakage	R
Proof Pressure, Burst Pressure	R
Proof Load	ER
EMC/EMI	ER
Safety Devices	**R**

R = Required, ER = Evaluation Required

7.3.1 Cell Screening

7.3.1.1 Cell Inspection

Cell inspection shall verify the part number, serial number, manufacturing lot, and date of manufacture. It shall be verified that cells have been manufactured from the same lot from the same manufacturing plant. It may be necessary to verify that all cells have consecutive serial numbers to demonstrate that no gaps occurred during cell production that would invalidate the definition of a single manufacturing lot per 3.13.

Cells shall be clean and show no signs of electrolyte leakage. General workmanship shall be evaluated by noting any significant dents, scratches, loose parts, or signs of abuse. X-ray inspection may be required to verify that the cells received were manufactured per design specifications.

Each cell in a module or battery shall have a serial number indelibly marked that can be traced to the manufacturing lot for the cell. If not provided, it is advisable to mark all cells with a unique serial number to facilitate matching after electrical characterization.

7.3.1.1.2 Cell OCV

The OCV of all cells shall be checked and recorded. Batteries and cells may be shipped at a partial state of charge to meet Department of Transportation requirements.

7.3.1.2 Cell Characterization

The electrical characterization of cells is critical for demonstrating that performance meets expectations and to provide the data needed for grouping of cells into battery strings (if needed). Electrical performance tests should verify the following:

- Cell capacity
- Charge retention (self discharge rate)
- Cell voltage under a high discharge current at ambient temperature
- Cell voltage under a high discharge current at low temperature

Prior to measuring cell capacity, a number of standard charge/discharge cycles may be needed to stabilize the cell's capacity. It is recommended that cell capacity be stable to 1% or less over three consecutive charge cycles under standard conditions for charge voltage, discharge voltage, current, and temperature prior to judging the cell capacity.

Charge retention is an important cell performance parameter because cells with different rates of self-discharge are expected to diverge from one another over life unless cell-level charge control or some other type of cell balancing strategy is used. A charge retention test should measure both the loss in OCV and capacity during stand, following an initial discharge for capacity under standard conditions. This test may take on the order of a week to a month to evaluate due to the low self-discharge rate of the cells. Also, the self-discharge rate may be sensitive to cell state-of-charge and require several days to attain a constant value. Elevated stand temperatures may be used to reduce the stand time for the test, provided the temperatures are not detrimental to the cell chemistry.

The rate capability of the cell and the impact of low temperatures is an important performance parameter, particularly for applications requiring high sustained or pulse currents. It is recommended that high current loads be applied to the cells both at ambient and worst-case cold operational temperatures to document the individual characteristics of each cell and to reveal any critical design or manufacturing drift from prior production lots.

For all these tests, it is recommended that any cell that does not reach a stable capacity or that does not meet operational requirements during discharge testing be rejected.

7.3.2 Cell Matching

Cell matching based on cell capacity, impedance, and self-discharge rate may be needed for applications of lithium-ion batteries that have either high cycle life requirements or limited margin for capacity or rate capability. Cells that are not initially matched for capacity, or that suffer self-discharge at disproportionate rates, reduce the overall battery capacity over time and the number of charge discharge cycles applied. Cell balancing requires cell-level control circuitry because, unlike alkaline chemistries, lithium-ion batteries cannot be re-balanced by overcharge or overdischarge because both of these processes are typically abusive and may cause a safety incident.

Once characterized, cells shall be matched into a battery string such that any divergence in capacity over the service life due to initial cell capacity or differences in self-discharge rate can be accommodated by the design and its intended use. The priority of which variables from the electrical characterization tests are critical for matching depends on the margin in the design for its intended application. For example, cells with a high cycle life may require closer capacity matching, whereas cells with a long time between charge cycles may be better matched based on self discharge rate. Once matched into groups, cells shall be labeled with a group identifier.

Matched cell groups may contain a sufficient number of cells for multiple batteries. The matching criteria selected shall be validated by qualification testing. Qualification batteries should consist of cells showing the largest amount of allowed variance within the matching criteria to validate the other batteries built by the same criteria.

7.3.2.1 Post-Acceptance and Matching Cell Storage

Once characterized and matched, cells may either be built into batteries or placed in storage. Cells shall be stored per the manufacturer's recommended conditions for voltage and temperature. In general, humidity-controlled refrigerated storage is recommended to maximize the service life of the cells and batteries. Thermal shock during storage and removal should be minimized, with protective insulation and packaging. The dates for placement and removal of all cells from storage shall be logged.

During storage, voltage monitoring and periodic recharge may be required to keep the cell voltage within acceptable limits. A standard monitoring procedure should be developed, and records shall document the number of charges and time out of storage prior to use for each cell or battery.

7.3.3 Inspection

Battery inspection shall verify the battery part number, manufacturer, serial number, and date of manufacturing. The battery shall be visually examined for general workmanship and signs of abusive handling, such as cracks, loose wiring, defective connectors, damaged electronic components, and electrolyte leakage. In some instances, X-ray inspection may be required to verify that the items received are per the design requested by part number. Critical battery dimensions, such as foot print, height, and weight, should be verified.

After acceptance testing has concluded, all batteries shall be re-examined for signs of electrolyte leakage, corrosion, mechanical overstressing, and defects resulting from the acceptance test environments.

7.3.3.1 Cell OCV

The OCV of every cell in the battery shall be verified to be within acceptable manufacturing limits.

7.3.4 Wear-in

Functional testing shall be conducted as necessary to exercise any battery component requiring wear-in to provide smooth, consistent battery performance.

7.3.5 Thermal Cycle and Thermal Vacuum

Thermal vacuum testing, or a combination of thermal cycle and thermal vacuum testing, shall be performed to demonstrate that batteries cycled between the limits of the maximum predicted thermal environment will not be damaged. Analysis should be provided if vacuum testing is not performed to demonstrate that the effects of vacuum on battery case deflection, exposed seals, and thermal response are negligible.

If only thermal cycling is done, a minimum of 14 cycles shall be applied between the maximum and minimum predicted temperatures. Functional electrical testing per 7.3.8.3 shall be applied at the temperature extremes during the first and last cycles, and at ambient temperature before and after thermal cycling. Recharge of the battery may be done at temperatures intermediate to the thermal extremes. A minimum dwell of two hours at each thermal extreme is required during cycling, and the rate of transition between hot and cold extremes shall not to be less than 1°C per minute. Battery temperature and voltage shall be continuously monitored during all portions of the test.

If only thermal vacuum testing is done, a minimum of 14 cycles shall be applied between the maximum and minimum predicted temperatures after application of a vacuum consistent with the intended application. The battery shall be mounted in the thermal vacuum chamber in a manner similar to its installation on the vehicle or on a thermally controlled heat sink, and shall include any surface finish applied to the flight hardware to control emissivity. The total amount of time under vacuum shall envelope the maximum duration expected for the longest mission time expected. Functional electrical testing per 7.3.8.3 shall be applied at the temperature extremes during the first and last cycles, and at ambient temperature before and after thermal cycling. Recharge of the battery may be done at temperatures intermediate to the thermal extremes. A minimum dwell of two hours at each thermal extreme is required during cycling, and the rate of transition between hot and cold extremes shall not to be less than 1°C per minute. Battery temperature and voltage shall be continuously monitored during all portions of the test.

If both thermal cycling and thermal vacuum testing is performed, a minimum of 10 thermal cycles and 4 thermal vacuum cycles shall be applied between the minimum and maximum predicted temperatures. Functional electrical testing per 7.3.8.3 shall be applied at the temperature extremes during the first and last cycles, and at ambient temperature before and after thermal cycling during both test sequences. Recharge of the battery may be done at temperatures intermediate to the thermal extremes, and battery temperature and voltage shall be continuously monitored during all portions of the test.

If temperature extremes that exceed the minimum and maximum temperatures for operation are needed to verify workmanship, electrical testing may be done at intermediate temperatures, provided they envelop the operational predicted levels. However, temperature extremes that are beyond the manufacturer's recommendations for the cell should not be applied.

7.3.6 Shock

For applications that expose batteries to significant shock levels during mission, shock testing to MPE levels shall be applied once in both directions of each axis. Any isolators, grounding straps, brackets, and cabling used during flight shall also be included in the test configuration. Testing shall be performed with the battery under a discharge load to detect performance anomalies. Both battery voltage and current shall be monitored during the application of each shock, with voltage data sampled at least 10,000 times a second.

7.3.7 Vibration and Acoustic

Three-axis random vibration testing shall be performed to MPE levels from 20 to 2000 Hz for one minute per axis. Any isolators, grounding straps, brackets, and cabling used during flight shall also be included in the test configuration. Testing shall be performed with the battery under a discharge load to detect performance anomalies. Both battery voltage and current shall be monitored during the application of each shock, with voltage data sampled at least 10,000 times a second.

7.3.8 Performance Specification (Functional)

Performance testing shall demonstrate all critical battery performance parameters. Voltages and currents shall be maintained within the manufacturer's recommended limits to avoid damaging the cells. When testing for baseline capacity measurements, it is important to adhere to a standard set of charge and discharge rates, end-of-charge/discharge voltages, and charge/discharge temperature to maintain repeatability from cycle to cycle.

During all electrical testing, the calendar life and every charge/discharge cycle shall be recorded.

7.3.8.1 Continuity and Isolation

The isolation, connectivity, and conductivity between cells, battery pins, connections to the power harness, connections to ground, and case shall be measured to demonstrate acceptable continuity and isolation. The connectivity and conductivity of other components, such as isolation resistors, monitoring devices, bypass devices, and heater blankets, shall also be verified.

7.3.8.2 Charge Retention

The charge retention test shall demonstrate that the rate of self-discharge of each cell in the battery is within acceptable limits for the design and the capacity requirements for the mission, and that cell-to-cell divergence is within acceptable limits. The test measures both the loss in OCV and capacity during stand, and consists of an initial discharge to determine capacity under a standard set of charge/discharge temperatures and rate, followed by stand for a sufficient period of time for repeatable capacity and OCV loss. Elevated stand temperatures may be used to reduce the stand time for the test, provided that the temperatures are not detrimental to the cell chemistry, and that the battery or cell is returned to standard conditions for the discharge.

7.3.8.3 Electrical Performance

Electrical performance testing shall verify that the battery can sustain the appropriate voltage levels for worst-case mission requirements for current and duration under worst-case mission environments. It shall be applied multiple times throughout acceptance testing to demonstrate compliance at different areas of the flight envelope. Results from these tests shall meet requirements and be within expectation based on development data, qualification data, and data from other batteries from the same manufacturing lot for voltage and capacity. During testing, battery and cell voltages shall be recorded along with discharge current and battery temperature and verified to meet the requirements for the electrical bus.

Because of potential impacts in battery performance due to calendar time and cycling between acceptance testing and launch, it is recommended that pass/fail voltage criteria exceed mission requirements during acceptance testing.

Current loads applied during steady-state and pulse discharge shall not be less than the worst-case loads expected during mission. Additionally, it is recommended that margin be applied to steady-state and pulse currents loads during acceptance testing to accommodate performance changes due to calendar time and cycling between acceptance testing and mission use. High-rate pulse loads shall be applied at the minimum and maximum states of charge, as well as at multiple intermediate states of charge where local maxima in internal impedance may occur due to phase changes within the electrodes.

At the end of electrical performance testing, the battery shall be discharged for capacity verification. During testing under standard conditions for charge and discharge, battery capacity should be consistent to within 1%. Conditioning or battery cycling may be used to achieve capacity stability after delivery or storage. During acceptance testing, it is recommended that the total battery capacity exceed the maximum operational capacity requirement to provide a suitable capacity margin to compensate for losses due to calendar time and cycling between acceptance testing and mission use.

7.3.8.4 Heater Circuits

Any heater circuit used to control battery temperature shall be validated by demonstrating that the control hardware and software maintains the required temperature range for multiple cycles.

7.3.8.5 Specialty Circuits

Any specialty circuits or components used to monitor or condition the battery shall be tested to verify proper operation. This includes temperature, voltage, and current monitors, and any bypass circuitry needed to prevent over-charge or over-discharge to the cells.

7.3.9 Leakage

Following exposure to acceptance test environments, cells shall be inspected or tested for signs of electrolyte leakage. For sealed batteries, a leak test shall be performed to demonstrate hermeticity. A vacuum leak test may be used to demonstrate compliance.

7.3.10 Proof Pressure

For battery cases with re-usable venting devices, a proof pressure test shall be performed to demonstrate that venting does not occur until maximum expected operating pressures are exceeded, and that venting occurs at the design set point prior to reaching the structural limit.

7.3.11 Burst Pressure

For cells and batteries using a rupture disk or otherwise non-reusable device, a burst pressure test shall be performed on a statistically significant number of manufacturing lot samples to demonstrate that the opening pressure of the device meets requirements.

Any cell or battery failing to demonstrate proper opening of a non-reusable vent shall be cause for rejection of the battery case or cell lot due to system safety requirements.

7.3.12 Proof Load

Proof loads shall be applied to all structural components containing composite materials or adhesively bonded parts. Proof loads shall be applied to joined areas such as welded mounting feet and connectors to reveal any material, process, or workmanship defects at the time of battery acceptance testing or during manufacturing.

7.3.13 EMC/EMI

Unless the EMC characteristics of the battery or EMI environments for the battery have changed since qualification testing, EMC/EMI testing is typically not required for acceptance testing.

7.3.14 Safety Devices

The proper operation of all battery-level and cell-level safety devices installed in the battery, such as bypass circuitry, charge control circuitry, internal fuses, thermal switches, pressure switches, and voltage interrupt devices that are required to safeguard personnel in the event of a battery anomaly, shall be verified to function correctly for each manufacturing lot of cells.

8. Transportation, Storage, Handling Safety and Disposal

8.1 Purpose

The recommendations set forth in this section apply to the transportation, storage, handling safety, and disposal of batteries from the battery or module manufacturer to the launch site. Cells or modules may be stored prior to battery assembly to facilitate charge maintenance. Storage, handling, and conditioning should be chosen to minimize preflight degradation and comply with all safety requirements for the facility.

8.2 Transportation

Lithium-ion cells, modules, and batteries transported from the battery manufacturer to the contractor or launch site storage area shall be maintained within the cell manufacturer's recommended voltage, state of charge, and temperature limits during handling and transportation. Flight batteries may be installed in the vehicle before it is shipped to the launch site. However, the installed configuration shall maintain the cell manufacturer's requirements for temperature, voltage, and state-of-charge.

Vibration and shock loads during handling, transportation, and installation shall not exceed the maximum predicted levels used in qualification testing.

Transportation of the vehicle stage shall comply with Department of Transportation (DOT) regulations regarding the shipment of equipment and test articles containing lithium-ion batteries.

8.2.1 Transportation Safety Regulations

In the United States, the transportation of lithium-ion cells and batteries is regulated in Part 49 Section 173.185 of the Code of Federal Regulations (49 CFR Section 173.185) of the US hazardous materials regulations (HMR). The code addresses requirements for exceptions, battery safety testing, labeling, and packaging testing.

The UN safety tests typically performed to validate a cell design are not repeated for every manufacturing lot. Whether or not a cell or battery design that has previously passed the UN test requires revalidation due to small design and materials changes is left to the discretion of the cell or battery manufacturer. Furthermore, the eight UN tests should not be considered exhaustive in their validation of a "safe" design.

8.3 Storage

Batteries, modules, or cells that are not in test or being prepared for flight shall be placed in storage at an appropriate state of charge and maintained with temperature and humidity controls. A battery that is not in use shall not remain outside controlled storage for a period exceeding the manufacturer's recommendations unless addressed by qualification testing per Subsection 6.3.2.1. Cells and batteries may be stored at different points of the acquisition cycle, depending on whether or not acceptance testing and battery construction is done immediately after cell delivery.

8.3.1 Receiving Inspection

All lithium-ion cells, modules, and batteries shall be inspected per manufacturer's directions upon receipt at the launch site to verify that no abuse or anomaly occurred during transportation. A state-of-health check shall be performed on all cells, modules, and batteries to verify compliance with the manufacturer's recommendations for allowable storage voltage if not immediately prepared for mission use.

8.3.2 Storage Configuration

In general, refrigerated storage is recommended to maximize the service life of cells, modules, and batteries. It is recommended that humidity controls or desiccated storage be used to prevent condensation of water on cells and batteries. All lithium-ion cells, modules, and batteries shall be stored either in their shipping containers or in specialty storage containers prior to placement in long-term storage. These containers should be designed to protect the facility against the effects of electrolyte venting during storage, unless the storage facility uses a non-common or an inert gas air system.

8.3.3 Health Monitoring during Storage

During storage, voltage monitoring and periodic recharge may be required to maintain cell voltages within acceptable limits. The monitoring and recharge procedure used shall be equivalent to the charge processes used during acceptance testing and qualification.

The maximum allowed self-discharge rate for cells and batteries during storage shall be specified. Cells and batteries exhibiting excessive self-discharge rates should be evaluated for rejection because higher rates of self-discharge in lithium-ion cells may indicate irreversible losses in capacity and rate capability.

When cells and batteries are removed from storage, safeguards shall be used to minimize thermal shock and water condensation.

8.3.4 Storage Documentation

Storage records shall provide a time history of the storage temperature. Records shall be kept for each cell and battery documenting the dates for placement into storage, removal from storage, and the number of charge cycles applied during storage.

8.5 Handling Safety

Lithium-ion batteries usually contain flammable electrolytes that may be vented during an overcharge or high-temperature anomaly. Facilities where lithium-ion batteries are processed shall be designed to protect personnel and surrounding equipment from the effects of electrolyte venting. Safeguards, handling procedures, and emergency response procedures shall be developed to prevent or respond to the following conditions:

- Loose objects damaging or causing short circuits on cells or batteries
- Dropped cells or batteries
- Improperly connecting cells, modules, or batteries to electrical equipment
- Unexpected cell venting

8.5.1 Materials Safety Data Sheets

The manufacturer of a lithium-ion cell, module, or battery shall provide Materials Safety Data Sheets identifying the components used in their lithium-ion cells in case of electrolyte venting.

8.6 Disposal

Lithium-ion cells, modules, and batteries designated for scrap or disposal shall be discharged to zero volts prior to removal from the launch site. Specialty discharge equipment per Subsection 5.5.4 may be required to safely discharge lithium-ion cells, modules, and batteries to zero volts with minimal or tolerable cell reversal.

8.6.1 Shorting Plugs

After discharge to zero volts, shorting plugs shall be used to maintain a shorted condition across the terminals of battery and any cell terminal or conductive surface that can be easily accessed. Shorting plugs should be designed to prevent an inadvertent connection to a fully charged battery.

8.6.2 “Not for Flight” Marking

Batteries that by intent, usage, or material disposition are not suitable for flight shall be red tagged or striped with red paint, or both, to prevent substitution with a flight article. The red tag shall be conspicuous and marked ”NOT FOR FLIGHT.” The red paint shall be material compatible and unmistakable.

8.6.3 Disposal Regulations

Final cell and battery disposal processes shall follow EPA regulations for the destruction of hazardous materials.

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9. Pre-Flight Operations

9.1 Purpose

The requirements set forth in this section apply to operations and check-out of batteries during ground activities preceding launch. Battery processing should condition flight hardware to produce acceptable electrical performance while minimizing degradation. Processing shall comply with all safety requirements for the facility.

9.2 Initial Check-Out

9.2.1 Removal from Storage

Safeguards shall be used to protect flight batteries from thermal shock and water condensation upon removal from cold storage. Storage records shall be checked to verify that flight batteries have not exceeded their specified service life or allowed number of charge cycles.

9.2.2 Inspection

The manufacturer, part number, and serial number of the flight battery shall be verified. The flight batteries shall be visually inspected for signs of handling damage or abuse.

The continuity and isolation of connector pins and wires shall be verified. The operation of any monitoring or heater circuits shall be verified.

9.2.3 Record Verification

Records documenting the flight accreditation status of batteries shall be maintained. These records shall provide traceability from production of the battery, acceptance testing of cells, acceptance testing of the battery, through final installation in the vehicle, and on through to launch. The test and storage life shall be detailed and logged by serial number for each flight battery. The records shall indicate any changes in battery location, cycle number, status, use, or any conditions that could affect reliability or performance.

The records for each flight battery shall be reviewed to verify that flight batteries do not exceed their maximum service life, charge life, or cycle life prior to mission use.

9.3 State-of-Health Verification

Normal battery charging and control procedures, and contingency procedures shall be prepared based upon test data obtained during development testing, qualification, and acceptance testing.

It is recommended that the following battery state-of-health checks be accomplished within four weeks of launch at the launch site unless the battery is installed in the launch vehicle prior to delivery to the launch site. If a mission delay occurs after verification testing, it is recommended that these tests be repeated to validate an additional four-week period of use.

The OCV of every cell shall be verified to be within manufacturer's requirements prior to use. Any battery containing a cell that is out of specification for OCV should be scrapped.

The charge retention rate following at least a one-week stand period during final processing shall be verified to be within expectation.

The capacity of a flight battery shall be verified to maximum predicted performance requirements prior to use under standard or specified discharge conditions if battery recharging can be accomplished at the launch site. Battery capacity shall be within expectation and within manufacturer's recommendations. If needed, flight batteries may be electrically cycled to stabilize capacity, provided the total number of accumulated electrical charge cycles does not exceed the amount validated by qualification testing. Charging equipment shall be equivalent to the charge equipment validated by qualification testing.

The voltage under worst-case mission loads shall meet minimum mission requirements with margin during discharge, including any pulse loading required for mission. The margin in voltage shall be sufficient to offset additional drops due to operation under worst-case cold conditions.

The results from these preflight tests for charge retention, capacity, and voltage under load shall be compared to the battery acceptance data to identify any anomalies or unexpected performance. Batteries that do not meet expectation based on comparison to acceptance and age surveillance data, or that display anomalous performance, should be considered for rejection.

9.3.1 Post Health Test Monitoring

Battery voltage and individual cell voltages shall be monitored after successful completion of the state-of-health tests prior to vehicle installation at a sufficient frequency and resolution to detect a cell-level anomaly such a low-level short or premature discharge.

9.4 Vehicle Installation and Monitoring

9.4.1 Protective Hardware

An easily attachable and removable non-conducting cover shall be used to protect any power, monitoring, and heater connectors that attach to the vehicle wiring harness prior to installation on the vehicle. The cover shall remain in place on the battery at all times prior to vehicle installation, except during electrical testing.

A connector saver shall be used during testing prior to vehicle installation to avoid repeated connecting and disconnecting of the flight connectors. The connector saver shall be removed before vehicle installation or returning the battery to storage.

For large lithium-ion batteries, a handling plate should be used for testing and installation of battery on the vehicle. The handling plate should protect from damaging the battery and any other structural or thermal interface of the battery with the vehicle. The handling plate shall be removed when the battery is installed on the vehicle.

9.4.2 Pre-launch Battery Monitoring.

As a minimum, battery voltage, current, and battery temperature shall be monitored after battery installation on the launch vehicle up to the final terminal countdown. It is recommended that ground or telemetry systems also monitor battery module and cell voltages for higher reliability. However, if battery charging is done on the vehicle, then cell-level monitoring during charging is required. Data collection shall be at a sufficient frequency and resolution to detect a cell-level anomaly such as premature discharge. These data shall be evaluated to provide state-of-health verification of the electrical systems prior to launch. Pass/fail criteria shall be derived from prior development and qualification testing specific to the design, and applied prior to and during the terminal countdown to abort the launch should a malfunction occur in launch-critical batteries.

9.5 Post-Flight Analysis

After mission, all available battery, module, and cell voltages, currents, and temperatures from telemetry data shall be examined, trended, summarized, and compared to the expected performance based on qualification and acceptance testing and prior flight use. This activity is critical to detect any performance anomaly, to confirm the qualification status of the design for follow-on missions, and to identify early signs of an incompatibility between mission use and test requirements.

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Appendix 1—Summary OF EWR 127-1 Requirements for Batteries Brought to the Launch Site

[The following is a summary of EWR 127-1 battery-related system safety requirements that may apply to a lithium-ion battery, depending on its design. The reader is referred to the original document for the complete set of regulations and methods of compliance.]

A1.1 Safe Handling and Abuse Design Requirements —All Chemistries (EWR 127-1 chapter 3.14.1)

a. All batteries shall be capable of being easily electrically disconnected and/or removed.

b. Battery connectors shall be designed to prevent reverse polarity.

c. Diodes shall be used to prevent reverse current.

d. If a battery is not connected to the system, the battery terminals or connector plug shall be taped, guarded, or otherwise given positive protection against shorting.

e. Each battery shall be permanently identified with the following information: unit name, type of construction, manufacturer identification, part number, lot and serial number, and date of manufacture.

A1.2 Safe Handling and Abuse Design Requirements—All Batteries Containing Metallic Lithium (EWR 127-1 Chapter 3.14.1.6.2)

a. All lithium battery designs shall be reviewed and approved by Range Safety prior to arrival, usage, packing, storage, transportation, or disposal on the Ranges. (Batteries that have an Underwriter's Laboratory (UL) listing and are intended for public use are exempt.)

b. Thermistors or fuses shall be used for each battery output, and internal diodes shall be placed between each cell, unless proven by test that any single cell cannot be driven into reversal by the remaining cells. Cells in series shall have shunt diode protection, and parallel rows of cells shall have blocking diodes.

c. Each electrical safety device shall have a specific quality control program approved by Range Safety.

d. Safety-critical steps and processes shall be identified during development for the manufacturing process.

A1.3 Safety Test Requirements for Batteries containing Metallic Lithium (EWR 127-1 Chapter 3.14.4)

Unless otherwise agreed to by Range Safety, the following tests shall be performed prior to the use or storage of lithium batteries at the Ranges:

a. Lithium Battery Constant Current Discharge and Reversal Test

b. Lithium Battery Short Circuit Test

c. Lithium Battery Drop Test

A1.4 Safe Handling and Abuse Design Requirements—Flight Hardware Batteries (EWR 127-1 Chapter 3.14.3.3 & 3.12.4.1.6)

a. Flight battery cases shall be designed to an ultimate safety factor of 3 to l with respect to worst-case pressure build-up for normal operations.

b. Sealed batteries shall have pressure-relief capability unless the battery case is designed to a safety factor of at least 3 to 1 based on worst-case internal pressure.

A1.5 Safe Handling and Abuse Design Requirements—Battery Charging Equipment (EWR 127-1 Chapter 3.14.2.6)

a. Battery charging EGSE shall be current limited by design.

b. The battery charging rate shall not be able to initiate or sustain a run-away failure of the battery.

c. A temperature monitoring system shall be used in addition to other methods of charge control.

A1.6 Use of Components Containing Hazardous Materials (EWR 127-1 Chapter 3.10.4)

The following reporting requirements must be met when bringing components containing hazardous materials to the launch range:

a. A list of all hazardous materials on the flight system and those used in ground processing

b. A description of how and under what conditions each of these materials and liquids is used and in what quantity

c. A description of flammability and, if applicable, explosive characteristics, including test results provided or referenced

d. A description of toxicity, including Threshold Limit Value (TLV) and other exposure limits, if available

e. A description of compatibility, including a list of all materials that may come in contact with a hazardous liquid or vapor with test results provided or referenced

f. A description of electrostatic characteristics with test results provided or referenced, including bleed-off capability of the as-used configuration

g. A description of Personal Protective Equipment (PPE) to be used with the hazardous material and liquid, including type, make, and location

h. A summary of decontamination, neutralization, and disposal procedures

i. A Material Safety Data Sheet (MSDS) for each hazardous material and liquid on flight hardware or used in ground processing.

j. Description of any detection equipment, location, and proposed use

A1.7 Battery Storage and Processing Areas (EWR 127-1 Chapter 5.6.2.6)

a. Battery shops shall be designed in accordance with AFOSH 91-66 and Article 480 of the NEC.

b. Dedicated storage and processing areas for batteries that have the potential for venting hazardous fluids shall be designed with emergency eyewash and shower systems; dedicated water systems, floor drain and containment system for electrolyte spills; ventilation hood located directly above the battery charging area and vented to a safe location outside the facility; sufficient ventilation in the battery maintenance area to prevent accumulations of explosive vapor concentrations from exceeding 25% of the LEL; floors constructed of a material compatible with the battery electrolyte; battery racks constructed of a material resistant to corrosion due to contact with electrolyte; and separate areas for storage and servicing of batteries that have incompatible electrolytic solutions such as acid and alkaline

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Appendix 2—Summary of System Safety Requirements for Use of Lithium-Ion Batteries at the Launch Site

[The following is a summary of the Range Safety Interim System Safety Requirements for Lithium-ion Batteries and Chargers. The reader is referred to the original document for the complete text.]

A2.1 Applicability

Requirements apply to flight hardware or ground support equipment batteries without UL or MSA approval for the cells, batteries, and battery chargers approved specifically for the cell pack used.

Batteries not applicable to these system safety requirements are those used in UL- or MSA-approved appliances that have Li-Ion batteries as part of the certification. (Examples: batteries that are in cell phones and computers)

A2.2 System Safety Requirements

The standard battery safety requirements per EWR 127-1 are applicable, as well as the following additional requirements:

A2.2.1 Charging and Discharging

The following safeguards are required during cell or battery charging and discharging at the launch site:

a. Ground support equipment shall be two-fault tolerant during charging and discharging. During charge, cells may not exceed 4.4 V, and during discharge, cells may not be less than 0 V.

b. Individual cell monitoring and recording is required during charging and discharging. Cell voltages shall be recorded at least every minute for charge rates up to 1C, and every 10 s for charge rates up to 2C, and once a second for charge rates in excess of 2C. Charging data shall be reviewed for anomalies and verification of voltage limits.

c. Electrical ground support equipment for charging, discharging, and monitoring cells shall be intrinsically safe, and include provisions to prevent high heat, sparks, and high charge/discharge currents.

d. Discharge shall not take place below –20°C or above 60°C.

A2.2.2 High Pressure Protection

All cell designs shall provide protection against the generation of high pressure during abuse situation (examples: burst disks, heat-sealed pouches). These devices must adhere to the following requirements:

a. Battery and cell case design shall have a 3:1 burst pressure based on vent device operating pressure.

b. Cell pressure relief devices shall be demonstrated by test to show that the vent operates as intended, and the vent is adequate to prevent cell fragmentation.

c. Battery case design shall not impede cell vent operation. Battery design shall accommodate venting of all cells within the battery at the same time. Compliance to this requirement shall be demonstrated by test.

A2.2.3 Voltage Source Hazard

Batteries/cells shall be treated as always having a voltage potential; therefore, connection or disconnection of battery shall be considered an electrical personnel hazard and a ”spark” potential.

A2.2.4 Toxicity and Combustion Risk Evaluation

Batteries/cells shall be evaluated for toxic, reactive, flammable, and combustion materials. This evaluation shall include the products if the cell case vents. Evaluation must assume fratricide of all cells in a pack unless the design incorporates mechanical and thermal barriers between cells.

A2.2.5 Support Equipment Validation

Support equipment (ground or airborne) shall be verified to operate correctly, including all fault-tolerant devices or subsystems prior to connecting battery. Verification shall include inducing overvoltage/undervoltage/temperature extremes to the monitoring devices as intended when in use prior to connecting of the battery.

A2.2.6 Lithium-Ion Battery Storage

When not installed in ground support equipment or airborne hardware, storage of lithium-ion batteries shall be in an approved battery storage locations.

A2.2.7 Transportation

Transportation to the launch site shall meet DOT requirements. If not incorporated into flight hardware, batteries transported on publicly accessed roadways shall not exceed 50% of rated charge. If the lithium content exceeds 8.0 g per battery, transportation packaging shall have caution labels in accordance with 49 CFR 173.185.

Batteries transported incorporated into flight hardware shall be approved on a case-by-case basis.

SMC Standard Improvement Proposal

INSTRUCTIONS

1. Complete blocks 1 through 7. All blocks must be completed.
2. Send to the Preparing Activity specified in block 8.

NOTE: Do not be used to request copies of documents, or to request waivers, or clarification of requirements on current contracts. Comments submitted on this form do not constitute or imply authorization to waive any portion of the referenced document(s) or to amend contractual requirements. Comments submitted on this form do not constitute a commitment by the Preparing Activity to implement the suggestion; the Preparing Authority will coordinate a review of the comment and provide disposition to the comment submitter specified in Block 6.

SMC STANDARD CHANGE RECOMMENDATION:	**1. Document Number**	**2. Document Date**

3. Document Title	

4. Nature of Change
(Identify paragraph number; include proposed revision language and supporting data. Attach extra sheets as needed.)

5. Reason for Recommendation

6. Submitter Information

a. Name	**b. Organization**
c. Address	**d. Telephone**
e. E-mail address	**7. Date Submitted**

8. Preparing Activity

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