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Lithium-ion Battery Standard for Spacecraft Applications

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14. ABSTRACT

This standard provides specific lithium-ion battery and cell-level requirements for design, manufacturing, testing (development, qualification, and acceptance), storage, handling, and usage of lithium-ion batteries utilized in government spacecraft applications. It is intended to ensure specified performance of batteries and to provide protection against degradation preflight and during operational use on space vehicles. These requirements and practices are intended for compliance in government unmanned spacecraft development and/or acquisition programs utilizing either configuration-controlled cells or commercial off-the-shelf (COTS) cells. The requirements may be tailored based on project-specific acquisition situation/environment, design complexity, design margins, vulnerabilities, technology state of the art, in-process controls, mission characteristics/criticality, lifecycle cost, number of vehicles involved, prior usage, and acceptable risk.

15. SUBJECT TERMS
Energy storage; Cell; Battery; Lithium-ion; Li-ion; Spacecraft; Standard

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Document History

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–	The Aerospace Corporation Technical Operating Report TOR-2007(8583)-1, *Lithium-Ion Battery Standards for Spacecraft Applications*. • Initial release • Also published as SMC-S-017 (2008)	June 30, 2007
Stakeholder Review 1a	TOR-2016-01667 and Rev A, *Stakeholder Review of Updated Lithium Ion Battery Standard for Spacecraft Application* • Major update and stakeholder consensus review • Also published as DRAFT SMC-S-017 (2017). Limited Distribution • Clarified definitions and requirements language, including reduction of redundant or prescriptive clauses • Updated to current references • Refined requirements flow from SMC-S-016 • Added general requirements consistent with current industry practices for: o Cell and battery design o Manufacturing o Quality o Safety • Addressed cell-level workmanship requirements in o Manufacturing o Cell design o Cell-level testing	April 5, 2016 December 9, 2016
Stakeholder Review 1b	Also published as DRAFT SMC-S-017 Rev A (2018). Limited Distribution • Clarified application as parallel-series configurations with cell balancing only • Consolidated “procurement authority approval” clauses into overarching tailoring and approval clauses for implementation flexibility and consistency with MIL/industry standards • Reformatted/revised definitions for editorial consistency and added missing definitions	Internal working paper

<table>
<tr><th>Rev No.</th><th>Description of Change</th><th>Effective Date</th></tr>
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Updated key definitions and associated requirements for clarity and implementation flexibility, including

Cell and Battery Lot
Cell Formation (formerly Cell Activation)
Foreign and Native Object Debris (FOD/NOD)
Thermal Runaway
Vision System

Updated technical requirements including

Modified cell/production to remove time duration
Replaced x-ray 20-micron resolution with minimum feature size resolution
Clarified Manufacturing Contamination Control Plan criteria for FOD/NOD size
Added vision system as alternative to x-ray

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<tr><td>Stakeholder Review 2</td><td>
TOR-2016-01667-Rev B and -Rev C, Stakeholder Review of Updated Lithium-Ion Battery Standard for Spacecraft Application.

Major rewrite directed by Aerospace senior management and Aerospace internal review

Reformatted document to segregate cell from battery requirements
Added/updated key definitions for clarity, including;

Cell lot or battery cell lot
Commercial-off-the-shelf cell lot
Configuration controlled cells
Current interrupt device
Open circuit voltage
Positive temperature coefficient device
Venting
In-family/out-of-family

Refined requirements language, throughout, for completeness, accuracy, clarity, and implementation flexibility
Added general requirements section to consolidate existing standard practice requirements (’ilities)
Added section for Commercial Cells
Updated Configuration Controlled Cell (formerly Custom Cell) section
Added Battery Design section to consolidate existing requirements
Refined requirements to ensure consistency with industry practices and implementation options for

x-ray
destructive physical analysis
thermal runaway testing
cell selection

Ensured consistency with referenced standards

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Rev No.	Description of Change	Effective Date
	• Aligned requirements with current programs of record using draft SMC-S-017 (2017) and/or draft SMC-S-017- Rev A (2018) • Transitioned Electrical Power System requirements for Li-Ion Batteries to separate document – tailoring of AIAA S-121A	
This Document	TR-RS-2021-00017 Also published as SMC-S-017 (2021)	February 28, 2021

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Note

Throughout this document there are references to other paragraphs/sections of this document.

- Paragraph – refers to the specific paragraph number that is specified.
- Section – refers to all paragraphs subsumed under the specified section number.

1. Scope

1.1 Purpose

This document provides specific lithium-ion battery and cell-level requirements for design, manufacturing, testing (development, qualification, and acceptance), storage, handling, and usage of lithium-ion batteries utilized in government spacecraft applications. This standard is intended to ensure specified performance of batteries and to provide protection against degradation preflight and during operational use on space vehicles.

1.2 Application

This document provides requirements and practices necessary to ensure successful lithium-ion battery operation during space missions and is intended for compliance in government unmanned spacecraft development and/or acquisition programs utilizing either configuration-controlled cells or commercial off-the-shelf (COTS) cells.

1.3 Requirements Tailoring

The requirements contained herein may be tailored with the Procurement Authority concurrence based on each project-specific acquisition situation/environment, design complexity, design margins, vulnerabilities, technology state of the art, in-process controls, mission characteristics/criticality, lifecycle cost, number of vehicles involved, prior usage, and acceptable risk. Tailoring may include deletion of non-applicable requirements, modifications to requirements/criteria, or alternative analyses/tests/criteria.

All tailoring of requirements must achieve the intent of the requirements in this Standard and must be consistent with the Procurement Authority's mission needs and risk posture. As part of the tailoring process, technical rationale with supporting data for each tailored requirement must be documented.

Tailoring rationales should include risk assessment per the process detailed in MIL-STD-882 [3]. If the baseline requirements in this Standard are not tailored by the contract, the requirements of this document stand as written.

1.4 Approvals

All products specified in this standard (e.g., test plans, test methodology, manufacturing documents, inspection and test data, etc.) are subject to procurement authority concurrence/approval as specified by contract.

1.5 Data Records

Documented information such as data and associated records shall be created, updated, stored, and retained in accordance with industry best practices such as SAE AS9100 (including SMC tailoring), SAE International AS6500, and SAE International EIA 649-1.

Documented information must be:

a. Created and updated to ensure appropriate identification/description, format, and review/approval for suitability and adequacy

b. Controlled to ensure availability and suitability for use when needed

c. Protected from loss of integrity or confidentiality

Documented information of external origin shall be controlled consistent with these requirements and interorganizational agreements.

Documented information that comprises evidence of conformity/compliance shall be protected from intentional or unintentional alterations.

2. Definitions

Anode

Cell electrode that gives up electrons to an external circuit and is oxidized during an electrochemical reaction of discharge.

Battery

An assembly of battery cells, cell banks, or modules electrically connected to provide the desired voltage, current, and capacity capability.

Note: The battery may also include one or more assemblies, such as electrical bypass devices, charge control electronics, heaters, temperature sensors, thermal switches, and thermal control elements which are attached to the battery or cells. In a battery, the cells and assemblies are often enclosed within a case or other structural element, to enable attachment to spacecraft structure. Connectors and harnesses are included for power and telemetry command and sense.

Battery Beginning-of-Life Capacity

The capacity measurement at completion of battery-level qualification, protoqualification, or acceptance test (see SMC-S-016/TR-RS-00016 for definitions).

Battery Capacity

The integral of the discharge current, where I_d is a positive value. The battery (or cell) capacity is measured in units of ampere-hours (Ah). Integration limits are from the start of discharge to either the minimum cell voltage, minimum power subsystem battery-voltage limit, the point at which the first cell reaches the lower cell voltage limit, or the defined time duration is reached.

$$\text{Battery Capacity (Ah)} = I_d\,dt$$

Note 1: For the purpose of qualification and acceptance test, battery voltage limits are when the first cell reaches the manufacturer’s recommended maximum and minimum recommended voltage.

Note 2: This is a point-in-time capacity value measured at a defined charge voltage-current profile, discharge load profile, and temperature profile. The battery capacity may be different than the capacity measured at a cell level due to different test conditions.

Battery Energy

The integral of the product of discharge current and voltage, where I_d (a positive value) is the discharge current, and V_d (a positive value) is the discharge voltage. Integration limits are from the start of discharge to either the minimum cell voltage, minimum power subsystem battery-voltage limit, the point at which the first cell reaches the lower cell voltage limit, or when the defined time duration is reached.

$$\text{Battery Energy (Wh)} = I_d\,V_d\,dt$$

Note 1: For the purpose of qualification and acceptance test, battery voltage limits are when the first cell reaches the manufacturer’s recommended maximum and minimum recommended voltage.

Note 2: This is a point-in-time energy value that is measured at a defined charge voltage-current profile, discharge load profile, and temperature profile. The battery energy may be different than the energy measured at a cell level due to differences in test conditions.

Cathode	Cell electrode that accepts electrons from the circuit and is reduced during the electrochemical reaction of discharge.
Cell Formation	One or more electrical cycles that create the initial solid-electrolyte interphase on the electrode surface just after electrolyte is added to the cell. Note: Cell formation begins just after electrolyte is added to the cell, constitutes cell activation, and starts the clock on cell, module, and battery service life. Where the cell lot is made up of multiple formation batches, the service life clock starts with the earliest formation batch. It is also used to define the start of battery shelf life.
Cell Bank	Two or more cells electrically connected into a parallel string.
Cell Bypass Switch	A device used to provide an alternate parallel low-impedance path around a cell. Note 1: Cell bypass allows the battery charge and discharge to continue in the presence of a failed or degraded cell, continues after a cell has reached its end of charge or end of discharge voltage limit, and when in the presence of a failed or degraded cell, thereby avoiding a single-point failure. Note 2: A bypass switch creates a short around the failed cell, which results in rapid dissipation of any remaining energy. See also "cell isolation switch."
Cell Design	A set of manufacturing control and fabrication specifications that define material composition, dimensions, quantity, process, specialized tooling, and process controls for each component in the cell manufactured at a specific location.
Cell Isolation Switch	A device that provides a make-before-break transition during actuation to provide an alternate low-impedance path around a cell, once activated, so that battery charge and discharge continues in the presence of a failed or degraded cell, thereby avoiding a single-point failure. Note: Once the switch is activated, the cell is electrically in an open state. See also "cell bypass switch."
Cell Lot or Battery Cell Lot (Configuration Control Designs)	All cells manufactured in a single or multiple production run manufactured from the same anode, cathode, electrolyte, and separator material sublots with no change in processes, drawings, or tooling, and within a defined production run or time period.
Cell or Battery Cell	A unit device consisting of an anode and cathode within a single case that transforms chemical energy into electrical energy at characteristic voltages

	when discharged. Various form factors exist for the case including cylindrical and prismatic.
Cell and Battery Service Life	The duration, spanning all activities from cell formation through end of life, that the cell and battery are expected to perform within specification limits. Note: This starts at cell formation and continues through all subsequent fabrication, acceptance testing, handling, storage, transportation, prelaunch testing, all phases of launch, orbital operations, disposal, reentry or recovery from orbit, refurbishment, retesting, and reuse that may be required or specified.
C/n Charge or Discharge Current (C-Rate)	The constant charge or discharge current for a battery where C is the cell- level nameplate (or rated) capacity in ampere-hours (per the vendor's criteria) and n is any value for elapsed time measured in hours. Note: For example, a discharge current of C/2 for a 20 Ah-rated cell is a current that is half the capacity or 10 A.
Cold Storage	A controlled, monitored, and measured environment below room temperature (typically 0 deg C) with controlled humidity used to store cells, modules, and batteries at a state of charge that preserves service life when not in use.
Commercial-off-the-shelf (COTS) Cell Lot	A group of cells manufactured within one day as verified by the individual cell lot date code stamp. The cell lot is to be procured and delivered as one group of cells and subsequently stored and tested together to maintain a single lot definition. The cell lot may be procured directly from the cell vendor or through a retail establishment with traceability to cell vendor.
Configuration-Controlled Cells	Any cell design wherein any change to the cell dimensions, materials, assembly processes, or tooling requires notification of the procurement authority and where complete visibility into manufacturers' design, manufacturing processes, and product control can be reviewed for acceptance. Qualification test is completed at least once for each cell chemistry, design, cell size (capacity), supplier, and manufacturing location.
Current Interrupt Device (CID)	A built-in nonresettable pressure valve that disables the electrical path through the cell when the pressure internal to the cell is too high (for example, above 180 psi).
Depth of Discharge (DOD)	The proportion to which a battery is discharged relative to its total capacity. Note 1: The ratio of the number of amp-hours or watt-hours removed from a battery and/or cell for a defined charge voltage-current profile, discharge load profile, and temperature profile to the battery/cell-rated (or nameplate) capacity C(Ah) or energy E(Wh) times 100. For a lithium-ion battery, the DOD needs to be specified at a state of charge (SOC) operation or a voltage that relates to SOC operation.

$$\text{DOD (Ah) (\%)} = \left(\frac{C(Ah)_{REMOVED}}{C(Ah)_{RATED}} \right) \text{X 100}$$

$$\text{DOD (Wh) (\%)} = \left(\frac{E(Wh)_{REMOVED}}{E(Wh)_{RATED}} \right) \text{X 100}$$

Note 2: For batteries/cells that are subcharged, i.e., not recharged to full energy, DOD is the percentage of energy expended in a discharge from the subcharged point. For example, a battery that is subcharged to 70% SOC and then cycled down to 40% SOC is considered to have cycled over 30% of its energy, and the DOD is 30%.

Design Range	Environmental and electrical extreme conditions at which the cell and/or battery meets design and performance requirements. Electrical and thermal control, usually as validated by qualification testing, are included.
Destructive Physical Analysis (DPA)	A systematic, logical, detailed examination of parts and complex materials during various stages of disassembly, conducted on a sample of completed parts from a given manufacturing lot, wherein parts and/or materials are examined for design and workmanship characteristics as well as defects that may not show up during normal screening tests. Note: The purpose of this examination is to compare the item with the approved configuration baseline and to detect anomalies or defects that may be pervasive to the production lot such that they could cause, at some later date, part and/or material failure in performance or reliability requirements. DPA is also used to assess the effects of environments and to verify that battery and cell subcomponents have not been stressed beyond their design limits.
Electrode	Either the cathode or anode in the cell.
Energy Reserve	The remaining usable energy in Wh in a battery after discharge to the maximum DOD under normal operating conditions Note: Energy reserve provides margin to ensure positive energy balance during the maximum sun-outage time when a loss of attitude control occurs coincidently with the end of the longest eclipse or combination of eclipses (Earth and lunar) before normal recharge. Energy reserve may also be used for other infrequent, deep discharges such as relocation with electric propulsion or those that may occur during launch, transfer, early orbit operations, and other operational discharge events.
Foreign Object Debris (FOD)	A substance, debris, or article that is alien to the cell or battery.
Formation	The initial electrochemical cycling of the cell that forms a stabilized solid electrolyte interphase (SEI) layer on the electrode surface.

In-Family	Operation or performance that is within specification limits and is within expected values (range) from previous samples, i.e., the behavior does not differ significantly from that previously observed for the same or similar equipment (even if the behavior meets specifications). Additionally, the mechanism underlying two or more events must be the same for the set of events to be considered in-family.
Maximum Expected Operating Pressure (MEOP)	The maximum pressure which the pressurized cell or battery is expected to experience during its service life in association with its applicable operating environments. Note: Included are the effects of applicable operating environments, maximum ullage pressure, fluid head due to vehicle quasi-steady and dynamic accelerations, water hammer, slosh, pressure transients and oscillations, temperature, operating variability of regulators or relief valves, and chemical side reactions in battery cells.
Module or Battery Module	An assembly of cells or cell banks connected in series.
Native Object Debris (NOD)	A substance, debris or article inherent to the cell that is not in its intended place. Note: Examples include dust or flakes from electrodes, metallic particles from weld/crimp processes, or other cell piece parts found in unintended locations.
Open-Circuit Voltage (OCV)	The difference in potential between the terminals of a cell or battery in the absence of any measurable external current flow.
Out of Family	Operation or performance that does not conform to performance requirements, does not meet specification limits, or is outside expected values from previous samples and experience. Performance may be within both specification and tolerable limits but can be out of family if the parameter values either differ from previous samples or if the trend line indicates that performance is headed away from previous samples, indicating the possibility of unidentified underlying failure modes. If after analysis and other engineering activities, including the identification of mechanism and root cause and a worst-case analysis, a determination is made that the requirements should be changed to include the behavior, then by definition the behavior becomes in-family from that time onward, otherwise it remains out-of-family.
Overcharge	The process of charging a cell above its allowed maximum voltage as defined by the cell manufacturer.
Overdischarge	The process of discharging a cell or battery below a specified minimum voltage.

Positive Temperature Coefficient (PTC) Device

An internal protective device used in some cells (typically small COTS cells) to provide hazard protection against high currents or short circuits external to the cell. When the device is exposed to a high current condition, a conductive polymer within the PTC heats up and changes phase to make the device become several orders of magnitude more resistive. After the short or high current condition is removed, the PTC returns to its electrically conductive state. Once activated, PTCs will activate at lower temperatures and currents during subsequent activations.

Procurement Authority

The government organization responsible for spacecraft procurement.

Production Run

A group of configuration-controlled cells manufactured within a defined time period from the start of first cell electrode mixing through completion of cell formation (either continuously from start to finish) or uninterrupted continuous batches through each manufacturing step, using the anode, cathode, electrolyte material, and separator from the same raw material sublots. (See also Cell Lot definition).

Rated (or Nameplate) Battery or Cell Capacity/Energy

The minimum ampere-hours (or watt-hours) of a battery or cell specified at the beginning of life (BOL) for a defined range of charge control conditions, discharge load conditions, temperature profile, and minimum discharge voltage.

Note: Although actual measured capacity (energy) can, and does, exceed manufactured nameplate, the rated battery/cell capacity cannot exceed the cell manufacturer rated capacity. This capacity is typically defined at a C/2 discharge rate.

Rated battery/cell capacity (Ah) is less than or equal to the integral of the discharge current after charging, where I_d is a positive value. There are three limits: 1. maximum cell-charge voltage; 2a and b. maximum power subsystem charge to (either) a. minimal cell voltage *or* b. minimum power subsystem battery-voltage limit; or 3. when the first cell reaches lower cell voltage limit.

$$\text{Rated Capacity (Ah)} \leq \; I_d \; dt$$

Rated battery/cell energy is less than or equal to the integral of the product of discharge current and voltage, where I_d, a positive value, is the discharge current, and V_d, a positive value, is the discharge voltage. There are three limits: 1. maximum cell-charge voltage; 2a and b. maximum power subsystem charge to (either) a. minimal cell voltage *or* b. minimum power subsystem battery-voltage limit; or 3. when the first cell reaches lower cell voltage limit.

$$\text{Rated Energy (Wh)} \leq \; I_d \, V_d \; dt$$

Shelf-Life Limit	The maximum timespan from cell formation to launch, including any time in cold storage that is permissible to ensure battery/cell performance over service life.
Short Circuit (Short, Cell Short, or Battery Short)	An electrical circuit that allows a current to travel along an unintended path with no or below normal electrical impedance that can be internal or external to a cell and/or battery.
Spacecraft (aka Space Vehicle)	Integrated set of subsystems and units, including their software, capable of supporting a specified mission. Note: These terms are sometimes used to refer to a satellite, which generally includes the integrated bus and payloads.
State of Charge (SOC)	The proportion to which a battery is charged relative to its total capacity. Note: The ratio of the number of C(Ah) or E(Wh) present in the battery/cell for a defined charge voltage-current profile, discharge load profile, and temperature profile to the rated capacity or energy of the battery/cell times 100 expressed in terms of ampere-hours or watt-hours.

$$\mathrm{SOC(Ah)} = \left(\frac{C(Ah) - C(Ah)_{REMOVED}}{C(Ah)_{\mathrm{RATED}}} \right) \times 100$$

$$\mathrm{SOC(Wh)} = \left(\frac{E(Wh) - E(Wh)_{REMOVED}}{E(Wh)_{RATED}} \right) \times 100$$

Survival Temperature (Battery or Cells)	Hot and cold temperature extreme conditions at which the cell and/or battery can be exposed and still meet the design and performance requirements after exposure. Includes defined electrical and thermal control, usually as validated by qualification testing. Note: The survival temperature limits are specified as nonoperational (e.g., when in storage) and/or operational (e.g., anomalous on-orbit operation or dead bus) because the battery is by nature always on. For an operational survival limit, the unit survival is the demonstration that the unit will operate at the survival limit. The unit does not need to meet performance to specification at these temperatures; however, it cannot show any performance degradation when the unit is returned to the operational or acceptance temperature range. For a nonoperational survival limit, unit survival is the demonstration that the unit will be taken to the survival limit with the unit off (or in standby mode) and show no performance degradation when the unit is returned to the functional or performance temperature range. Battery life tests and analyses need to quantify degradation resulting from survival temperature and durations.

Thermal Runaway	An accelerating release of heat inside a cell due to a series of uncontrollable exothermic reactions manifesting in an increase in cell temperature that exceeds the ability of the thermal control system to maintain cell temperature.
Venting	The act of releasing liquid, particulates, or gas from a cell due to the buildup of excessive internal pressure. Visual observation of leakage, detection of the components used in the electrolyte, or measurable weight loss indicates venting.
Vision System	A calibrated image-based inspection technique that has a perceptivity of the device's internal components, with resolution capable to allow for critical design and manufacturing inspection (such as separator thickness), that creates and compares information to a mechanical template, specified dimensions, color variations, and/or other criteria attributes.

3. General Requirements

3.a. The requirements in this section shall apply to the battery, cell, and piece parts used for battery unit-level qualification and acceptance.

3.b. Whenever the Quality Assurance and/or Manufacturing Control requirements below and in Section 4 cannot be contractually invoked for the cells selected and used, the cells shall be defined, qualified, and acceptance tested like commercial-off-the-shelf (COTS) cells as specified in Section 5.

3.1 Quality Assurance

The battery, cell, and piece part manufacturers shall implement a quality assurance program in accordance with SAE International AS9100 [25] and SMC-S-003 [18].

3.2 Manufacturing Control

The battery, cell, and pieces parts intended for use in life test, qualification, and flight hardware shall be manufactured in accordance with SAE AS6500 [17] and as follows:

3.2.1 Manufacturing qualification processes shall be validated prior to use, baselined, and maintained under document control.

3.2.2 Subsequent changes to the qualified drawings, materials, tooling, and processes shall be evaluated to ensure they do not require requalification.

3.2.3 Compliance with the documented process controls, inspection requirements, and general workmanship requirements shall be verified and data maintained.

3.2.4 Records of process measurements and variability shall be maintained throughout the build.

3.3 Reliability/Failure Modes

3.3.1 A reliability analysis shall be performed for the battery, cell bank, cells, and piece parts in accordance with SMC-S-013 [23] and analyzed for the potential of failure propagation to other cells or battery components.

3.3.2 All catastrophic and single-point failures shall be documented with mitigation plans while considering the entire set of mission phases and conditions, and approved by the procurement authority.

3.4 Space Debris

The battery shall meet the orbital debris requirements as specified by the U.S. government's National Space Policy of the United States of America [9], U.S. government's Orbital Debris Mitigation Standard Practices [10], Air Force Instruction 91-217 [11], DOD Instruction No. 3100.12 [12], DOD Directive, No. 3100.10 [13], or as directed by the Procurement Authority.

4. Configuration-Controlled Cell Requirements

The requirements of this section shall be applied on all configuration-controlled cells and cell lots as defined in Section 2 and paragraph 7.2.5.6 for use in characterization/development, qualification, or flight lot acceptance.

a. The cell design shall be described by a set of manufacturing drawings and documents that define material composition, dimensions, quantity, process, specialized tooling, process controls, and inspections for each component in the cell manufactured at a specific location and be made available for review and approval.

b. Two-way traceability shall be maintained where documentation demonstrates a solid chain of custody from incoming materials to final assembly and vice versa.

c. Periodic independent audits shall be performed of tool calibration, certificates of compliance, and/or analysis to meet required specifications for composition, impurities, and properties of materials and components.

d. Any change to the cell or cell component dimensions, material, composition, quantity, processes, tooling, process control, inspections or manufacturing location shall be made available in advance of change for review and acceptance within spacecraft-level contractual requirements.

e. Qualification test shall be completed at least once for each configuration-controlled cell chemistry, design, cell size (capacity), supplier, and manufacturing location/facility.

f. Each flight cell lot shall go through acceptance tests to validate performance and workmanship.

4.1 Cell Characterization/Development Testing

The objective of development testing is to identify problems early in the design evolution so that any required corrective actions will be taken prior to starting formal cell qualification or battery-level critical design review (CDR). Development testing characterizes cell-level margins and performance over a range of operating environmental conditions, including:

a. Temperature
b. Discharge and charge control
c. Structural margins
d. Dimensional requirements
e. Compatibility to prelaunch
f. Launch and space environments
g. Cycle life stability (200 cycles minimum)
h. Manufacturability
i. Testability
j. Maintainability
k. Reliability
l. Compatibility with safety requirements

4.1.1 Cell Electrical Performance Characterization

Cell-level development testing shall be conducted to establish a high probability that the battery-level electrical performance requirements can be met, unless data is provided to prove the following requirements have been met.

a. Electrical capacity, impedance, and energy tests shall be characterized over both nominal and off-nominal temperature ranges, charge-discharge currents, and voltage limits to establish battery-level performance requirements and margins for both beginning and end of life.

b. Cell-level charge conditions (voltage and current) shall be characterized at worst-case expected dead bus recovery temperatures to define and verify an appropriate dead bus recovery approach for the applicable power subsystem.

c. Charge retention at the cell level shall be assessed per Section 4.4.3.5 at temperatures consistent with operating, test, and storage temperatures at both 100% state of charge and storage state of charge.

d. Charge retention at the cell level shall be assessed per Section 4.4.3.5 and compared with a similar test run for 14 days to verify that the cell-to-cell variation in voltage decay rate at day 6 to 7 versus day 13 to 14 is statistically unchanged (i.e. any outlier cells can be correctly identified). If voltage decay repeatability is not verified, test duration of Sections 4.4.3.5, 7.3.2.3, and 9.13 shall be increased to a duration that validates repeatability.

e. The specific test method adopted for the above electrical tests shall be defined and the data documented in time-stamped format and maintained throughout future testing for trending purposes.

4.1.2 Cell Pressure Evaluation

The cell maximum expected operating pressure (MEOP) shall be established for the cell design by measuring and validating beginning-of-life cell pressure and for any further pressure growth over the expected operational cycle life based on worst-case design limits and process controls.

4.1.3 Cell Thermal Characterization

A thermal characterization test at the cell level shall be performed, either in a calorimeter, thermal-vacuum, or temperature-controlled environment. Data from these tests measure and validate the cell-level thermal dissipation or quantify the external temperature and gradient as a function of charge/discharge conditions.

4.1.4 Cell Safety

Safety requirements for the lithium-ion cell design, safety testing, and ground operation shall meet Air Force Range Safety AFSPCMAN 91-710 [14] and Department of Transportation (DOT) requirements [15]. In addition:

4.1.4.1 Cell design, manufacturing processes and quality control measures shall be taken to reduce the likelihood and/or severity of safety risk during nominal or inadvertent abusive operation or handling.

4.1.4.2 Cell-level safety shall be validated by test under known cell failure modes that include at minimum the following conditions: overcharge, overdischarge into reversal, over temperature to thermal runaway, overpressurization, internal cell short, and external cell short.

4.1.4.2.1 Safety tests shall establish the threshold where a cell becomes unsafe over a range of charge/discharge voltages, currents, temperatures, and cell state of charge.

4.1.4.2.2 The nonhazardous or hazardous consequences of abusive conditions shall be characterized in terms of the effects on cell performance and any impact to the cell's surrounding environment.

4.1.4.2.3 The evaluation criteria shall include at minimum:

a. cell voltage, current and temperature profile measurements during test
b. time to unsafe threshold
c. products vented/ejected from the cell
d. measurement and/or video of flames/hot gases exiting the cell

4.1.4.2.4 The data from safety testing shall be documented and available for program reference.

4.1.4.2.5 When available, a videorecording of the safety test shall be provided as part of the end- item data package.

4.1.5 Cell Thermal Runaway

4.1.5.1 Cell thermal runaway shall be mitigated by cell design, battery design, battery cell controls limits, battery charge/discharge inhibits for both ground and on-orbit operations,, manufacturing processes and controls, and cell handling procedures.

4.2 Cell Manufacturing Requirements

Cell manufacturing intended for use in life test, qualification, and flight hardware shall be in accordance with SAE AS6500 [17] and as follows:

4.2.1 All critical manufacturing steps shall be verified by inspection and/or test with inspection/test data recorded and maintained.

4.2.2 Inspection and in-process controls of anode/cathode manufacturing shall be implemented to verify that coating composition, thickness, weights, and dimensions meet manufacturing specification requirements.

4.2.3 Records of process measurements and variability shall be maintained throughout the build.

4.2.4 Process controls shall be implemented to assure lot-to-lot variation and rejection rates for critical processes (such as coating, die-cutting, slitting, pressing, electrode winding/assembling, electrolyte, electrolyte filling, postfilling voltage stabilizing, weld/crimp stepping, leak testing, and formation) are within family and acceptable manufacturing limits for the design.

4.2.5 The processes, in-process controls, and criteria shall be qualified per Section 3.2.

4.2.6 Compliance with the documented process controls, inspection requirements, and general workmanship requirements shall be verified and the data retained under configuration control.

4.2.7 The cell stack assembly shall conform to minimum overlap dimensions of the negative electrode relative to the positive electrode, and the separator shall extend beyond the positive and negative electrodes with margin as established by the cell manufacturer.

4.2.7.1 The specific separator dimension shall be documented in the Manufacturing Control Plan and/or end-item data package.

4.2.7.2 The introduction of FOD from equipment or process shall be prevented.

4.2.7.3 The cell stack assembly process shall prevent introduction of contaminants (such as dust, flakes) into the cell stack.

4.2.8 The Manufacturing Contamination Control Plan shall specify control of FOD and NOD, and include at least the following provisions:

4.2.8.1 There shall be no FOD or NOD of size equal to or greater than the total thickness of the material used to separate positive electrode from negative electrode that could be mobile and capable of bridging nonconnected conducting elements.

Note: If any individual cell contains FOD or NOD external to the cell stack (and not in a region of compression) that exceeds the dimensional requirements of 4.2.8.1, that cell may be exposed to proto-qualification vibration test to demonstrate no movement of the FOD or NOD based on pre and post vibration x-rays.

4.2.8.2 Manufacturer shall have an effective method to collect all loose material produced during cell production. Methods may include vacuum, magnetic, or other effective method.

4.2.9 The manufacturer shall maintain process controls within specified limits during cell assembly, such as twisting, bending, wrinkling, tearing, and the generation of loose particles.

4.2.10 The manufacturer shall have an effective test method applied to all cells to detect nonconforming cell stacks, such as high-voltage dielectric test (high-pot), voltage test, or resistance/impedance test.

4.2.11 Following completion of cell formation cycles, the cells should rest at open-circuit voltage for at least 30 days before the start of qualification or acceptance tests to allow time for the solid electrode/electrolyte interface to be formed.

Note: A reduced time period can be suggested as part of tailoring if data is provided that shows the mV/day drop for all cells in the lot are within 3 sigma of the lot mean.

4.2.12 All cells shall be inspected and in-process control data verified at the following points; additional inspection points may be established as appropriate:

a. Electrode fabrication (mixing, coating, pressing, slitting, drying, and punching)
b. Stacking or winding process
c. Tab to terminal weld
d. Case insertion
e. Electrolyte activation/degas
f. Final cell

4.3 Cell Manufacturing Screens

4.3.1 Cell Case Pressure Tests

For all pressure tests defined below, the cells shall be under flightlike compression as per battery design. When flightlike configuration does not impart compression, compression is not required.

4.3.1.1 Cell Maximum Expected Operating Pressure

As part of cell qualification, the cell pressure shall be measured on at least two cells at beginning of life and documented.

4.3.1.1.1 Pressure growth over lifecycle testing shall be measured to evaluate worst-case end-of-life pressures.

4.3.1.1.2 An analysis shall be performed to document the cell design MEOP for worst-case operating/handling conditions and design/manufacturing tolerances and processes.

4.3.1.2 Proof Pressure

All of the cell cases intended for use in the life test, qualification, and/or flight cell lots shall be proof pressure tested per SMC-S-016/TR-RS-2014-0016 [1] and the following to demonstrate margin in the cell design so that structural failure does not occur before the design burst pressure is reached and/or excessive deformation does not occur at the maximum expected operating pressure:

4.3.1.2.1 Each cell case (100% of cases) of either sealed containers (<100 psi MEOP) or pressurized vessels (>100 psi MEOP) shall be subjected to one proof pressure test at 1.25 MEOP minimum for five minutes in accordance with AIAA S-080A-2018 (metallic vessels) [4] or AIAA S-081B-2018 [5] for composite overwrapped vessels.

4.3.1.2.2 Cell dimension, case material, and welds shall be inspected before and after test to verify structural failure, leakage, or excessive deformation does not occur.

4.3.1.2.3 Following the proof pressure test, all cells shall have a hermeticity test performed to demonstrate the cell leak rate is not greater than an equivalent of 1.0 x 10-6 std cc/sec of helium leak rate at MEOP.

4.3.1.3 Cell Case Burst Test

Following proof pressure test, a minimum of two cell cases from each lot shall go through a pressure burst test to verify the design burst pressure is at least 3.0 times the MEOP.

4.3.1.3.1 Any cell pressure relief vent shall be securely sealed.

4.3.1.3.2 Cell burst pressure and location of burst shall be documented.

4.3.1.4 Cell Case Burst/Cycle Test (MEOP >100 psi)

Following proof pressure test, a minimum of two cell cases from each lot shall go through the pressure cycle test: four times the number of predicted operating cycles to MEOP, or 50 cycles, whichever is greater. After demonstrating no burst, increase pressure to actual burst of vessel as follows:

4.3.1.4.1 A minimum of two cell cases, selected from the sample lot subjected to the pressure cycle test, shall verify the design burst pressure is at least 3.0 x the MEOP.

4.3.1.4.2 Any cell pressure relief vent shall be securely sealed.

4.3.1.4.3 Cell burst pressure and location of burst shall be documented.

4.3.1.5 Pressure Relief Device

For cells using a pressure relief disk or similar one-time-use vent device, a vent test shall be performed on at least two cell cases per lot of rupture disks.

4.3.1.5.1 Cell dimension, case material, and welds shall be inspected before and after test to verify structural failure, leakage, or excessive deformation does not occur (excluding rupture disk).

4.3.1.5.2 Cell case shall demonstrate a minimum ratio of vent pressure to MEOP of 1.5:1.

4.3.1.5.3 Cell cases shall demonstrate a minimum ratio of burst pressure to vent pressure of 1.5:1.

4.3.1.6 Case to Terminal Electrical Isolation

Verify case to terminal electrical isolation (both positive and negative) on each cell prior to electrolyte activation.

4.3.2 Cell Identification and Traceability

4.3.2.1 In a cell lot, all cells shall be uniquely identified with a serial number assigned at electrode stacking or winding (not to be repeated within the lot) and included in the cell case marking.

4.3.2.2 All cells within the cell lot shall be traceable to the individual cell production run.

4.3.2.3 Cell serial number traceability shall be maintained through cell buy-off.

4.3.3 Visual Inspection

All cells shall be inspected at 1X to 10X magnification and meet the criteria below:

a. The cell assembly (electrodes, separator, insulator, and tabs) contains uniform compression to maintain the cell dimensions within cell manufacturer’s drawing tolerance and to prevent interference that can induce a burr or damage to cell core or stack.

b. Electrode stack contains no wrinkling, tearing, and/or deformation and the alignment of the cell stack/jelly roll is within allowed tolerances.

c. The positive electrode is covered by the active material of the negative electrode and is within acceptable tolerance and cell manufacturer design criteria.

d. The separator extends beyond the positive and negative electrodes with margin and within cell manufacturer design criteria.

e. Tabs or connections within the electrical path are not loose or broken (including partially broken).

f. Tab positioning is within cell manufacturer design limits and prevents electrode damage or short circuits.

g. Tab lengths and strain relief are within cell manufacturer design criteria.

h. Corrosion is not present on cell materials.

i. No contamination is present beyond specifications of the Manufacturing Contamination Control Plan.

j. Weld/crimp alignment meets the acceptable cell manufacturer design criteria.

k. Cell case cleanliness, scratches, and dents meet cell manufacturer design criteria.

l. Cell safety devices, such as current interrupt, temperature control devices, and/or vents, are correctly installed and meet cell manufacturer design criteria.

4.3.4 X-ray Inspection

a. All qualification and flight cells shall be subjected to an x-ray inspection, computerized tomography (CT), or equivalent vision system of the sealed cell to ensure electrode integrity and prior to cell selection approved by the prime contractor using the contractor-developed pass/fail criteria.

b. To ensure control of manufacturing processes and handling of components, the images shall be made available at the original resolution prior to cell selection.

4.4 Cell Qualification and Acceptance Inspections and Tests

4.4.1 Configuration-Controlled Cell General Requirement

4.4.1.1 Configuration-controlled cell lot qualification inspection and tests shall be performed without cell failure unless a failure review board arrives at a root cause from cell failure and corrective actions are implemented based on findings with procurement authority approval.

4.4.1.2 Configuration-controlled cell lot acceptance inspection and tests shall be performed on 100% of the delivered cells without cell failure unless a failure review board arrives at a root cause from cell failure and corrective actions are implemented based on findings with procurement authority approval.

4.4.1.3 Cell test conditions (voltage limits, temperature range, test duration, state of charge, and charge/discharge currents) shall encompass the range of battery usage and qualification conditions for the cells.

4.4.1.4 Compressive force on cells shall match conditions for subsequent battery-level tests as specified in Sections 7 and 9.

4.4.1.5 The electrical measurements in this section shall be documented and shown to be within statistical process control and specification values throughout qualification and acceptance test for each cell over the test sequence.

4.4.1.6 Time-stamped data shall be recorded for each cell serial number at least every 30 seconds, unless stated otherwise.

4.4.1.7 Test current, voltage, impedance, ampere-hours, and temperature shall be measured and recorded for all tests with the following accuracies, unless stated otherwise: $\pm$1%, $\pm$0.1 mV, $\pm$0.01 mohms, $\pm$0.1 mAh and $\pm$2 deg C, respectively.

4.4.1.8 After completion of the qualification and/or acceptance tests, an end-item data package shall be made available for review and approval.

Table 1. Configuration-Controlled Cell Qualification and Acceptance Testing

Inspection or Test	Cell Qualification	Cell Acceptance	Suggested Test Sequence	Paragraph
Cell MEOP	R	n/a	1	4.3.1.1.1
Burst/Cycle (per case lot)	R	R	2	4.3.1.3/4.3.1.4
Relief Pressure (per disk lot)	R	R	3	4.3.1.5
Proof Pressure	R	R	4	4.3.1.2
Helium Leak	R	R	5	4.3.1.2
Case to Terminal Isolation (pre-activation)	R	R	6	4.3.1.6
Inspection	R	R	7,24	4.4.2
X-ray (1)	R	R	8	4.3.4
Cell Capacity	R	R	9,20	4.4.3.1
DC Impedance	R	R	10,21	4.4.3.3
AC Impedance	R	R	11,22	4.4.3.4
Cell Charge Retention	R	R	12,23	4.4.3.5
Cell Differential Voltage	R	R	13	4.4.3.6
Shock	R	ER (Note 5)	14*	4.4.5
Vibration	R	R (Note 5)	15*	4.4.6
Acceleration	ER	n/a	16*	4.4.7
Thermal Cycle	R	n/a	17*	4.4.8
Thermal Vacuum/Leakage (2)	R (4.4.9 and 4.4.4.1)	R (4.4.4.2 only)	18*	4.4.9/4.4.4.1/4.4.4.2
Cell Mission Specific Capacity	R	R	19	4.4.3.2
Radiation	R	n/a	25*	4.4.10
Lifecycle Test	R	n/a	26	4.4.11
Flight Lot Cycle	R	R	27	4.4.12
Cell DPA (3)	R	R	28	4.4.13
Safety Devices (4)	R	R	29	4.4.14
Safety	R	n/a	30	4.4.15
Shipment OCV	R	R	31	4.4.16

R: Required
ER: Evaluation Required by contractor
* Inspection (4.4.2) and specification performance (4.4.3.1.c, 4.4.3.3, 4.4.3.4 and 4.4.3.5) performed before and after test.
(1) Cell x-rays may be performed at the end of cell acceptance in this series of tests.
(2) Thermal vacuum/leakage test should be the last test in the environment test sequence.
(3) Perform DPA on one control cell, one cell postshock/vibration test (qualification only), one cell postradiation test (qualification only), and one following completion of flight lot cycle test.
(4) Safety device test for internal cell PTC, CID, fuses, etc., if applicable
(5) Environmental tests performed on sample cells from flight lot per 4.4.12 and 9.24.

4.4.2 Cell Inspection

Each cell shall be inspected and measurements made and recorded before and after the qualification/acceptance test to verify compliance with the specification and cell drawings as defined below:

a. Verify all dimensions in uncompressed state.

b. Verify cell mass.

c. Visually inspect the exterior of each cell and verify there are no out-of-spec conditions, such as dents, scratches, stains, bulging, corrosion, cracks, or abnormal markings.

d. Inspect all welds and verify there are no cracks, corrosion, pits, scratches, dents, burrs, or discontinuity outside of manufacturer's specification using a magnification of 10X.

e. Verify there has been no electrolyte leakage per paragraph 4.4.4.

f. Measure and record cell voltage.

g. Verify electrical isolation between both positive and negative terminal and case is within specified requirements.

h. Verify cell case marking.

4.4.3 Cell Electrical Tests

4.4.3.1 Cell Capacity or Energy

The cell capacity or energy shall be verified to meet specification when measured at specified maximum charge conditions to the manufacturer's maximum specified charge voltage, followed by a C/2 discharge rate to the manufacturer's minimum voltage level for each of the following five temperature conditions:

a. Maximum qualification temperature (acceptance temperature +10 deg C), qualification test only
b. Maximum acceptance temperature
c. Design operating point acceptance temperature
d. Minimum acceptance temperature
e. Minimum qualification temperature (acceptance temperature –10 deg C); select appropriate charge-discharge rates to simulate expected on-orbit rates at cold temperatures, qualification test only

4.4.3.1.1 The cell shall achieve capacity/energy stability within 1% for two consecutive cycles, up to three cycles maximum, for each temperature condition.

4.4.3.2 Cell Mission-Specific Capacity

Mission-specific performance requirements, if not covered by paragraph 4.4.3.1, shall be verified after subjecting the cell to the following conditions, at expected on-orbit temperatures to manufacturer's maximum and minimum specified voltages:

a. Minimum charge and discharge rates
b. Design operating charge and discharge rates
c. Maximum charge and discharge rates
d. Pulse power requirements

4.4.3.3 Cell DC Impedance

The DC impedance of each cell shall be measured at the cell terminals at the design operating temperatures at 95%, 50%, and 20% states of charge via a step current change during discharge for 30 seconds or longer and documented to show it meets the application-specific internal impedance requirements.

4.4.3.4 Cell AC Impedance

AC impedance shall be measured at 1,000 hertz and be documented for each cell at a defined state of charge and meet the cell manufacturer's specification requirements.

4.4.3.5 Cell Charge Retention

4.4.3.5.1 A charge retention test shall be performed on each cell at 20 ±2 deg C in an open-circuit state starting at 100% state of charge to screen out potential internal shorts while electrode stack is under the highest mechanical force and at a region with the highest voltage sensitivity.

a. Test duration shall be a minimum of seven days for cells intended for battery designs with an active cell-level charge balance circuit.

b. Test duration shall be a minimum of 30 days for cells intended for battery designs without cell-level charge balance for the before and after environmental (mechanical and thermal) test verification. In between environmental tests, test duration can be reduced to seven days.

4.4.3.5.2 Cell open-circuit voltage and temperature measurements shall be taken at least every 24 hours ±1 hour postcharge termination for the total period and be within established criteria for open-circuit voltage drop.

4.4.3.5.3 The cell capacity or energy shall be verified to be within established criteria when measured using a C/2 discharge rate to the minimum allowed voltage level following the cell capacity or energy test in paragraph 4.4.3.1.

4.4.3.5.4 Time-stamped data shall be provided for the entire charge and discharge periods of the charge retention test.

4.4.3.6 Cell Differential Voltage Test

The data from this capacity test shall be used for a differential capacity analysis to assure there have been no cell chemistry changes. Data from this test will be used to verify uniformity across all cells, that the cells are healthy and similar to cells used for qualification test and qualification life test. This test only needs to be performed once as part of the qualification and acceptance tests.

4.4.3.6.1 The test shall be performed at the design operating temperature.

4.4.3.6.2 Starting from a fully discharged state, each cell shall be charged at the C/20 rate to the cell vendor's maximum specified voltage (with no taper charge), and 15 minutes open circuit.

4.4.3.6.3 Each cell shall be discharged at the C/20 rate to the cell vendor's minimum specified voltage.

4.4.3.6.4 Cell voltage, current, and temperature shall be measured and recorded at least every 30 seconds, with charge and discharge capacity documented.

4.4.3.6.5 The data shall be used to perform a differential capacity analysis per TOR-2019-00829 [26].

4.4.3.6.5.1 Differential analysis of the voltage data shall be performed based on voltage, apparent OCV, and DC resistance to indicate how these parameters depend on SOC.

4.4.3.6.5.2 Cells that exhibit differential voltage, apparent OCV, or DC resistance indications at any SOC that are outside ±3 sigma of the median value shall be documented and excluded from flight battery use.

4.4.3.7 Cell Outliers

The lot of cells shall be screened to remove ±3 sigma outliers for the following minimum performance parameters: charge retention (open-circuit charge decay), mass, impedance, and discharge capacity.

4.4.3.7.1 After removing outlier cells, the resultant ±3 sigma range for the following parameters as a percentage of the mean (±3 sigma range/mean) shall not exceed the following unless reviewed and accepted by the Failure Review Board:

a. Charge retention OCV (end of test) <1%
b. Mass <2%
c. Capacity <5%
d. DC impedance <15%

4.4.3.7.2 If the total number of cells that fail the qualification criteria is greater than 15% of the lot, then the lot shall be rejected.

4.4.4 Cell Leakage

Each cell shall be tested before and after environmental tests and at end-of-acceptance testing by a litmus test (pH paper test) or equivalent to verify that there is no electrolyte leakage.

4.4.4.1 During the qualification thermal vacuum test of Section 4.4.9, a leakage test on each shall be performed using a residual gas analyzer to verify that the cell meets the specified design cell leakage rate to satisfy mission life requirements.

4.4.4.2 For acceptance test, all flight cells shall be placed in a vacuum to at least 10-5 Torr for a minimum of 12-hours where the cell temperature is cycled at least once between the survival, minimum, and maximum acceptance temperature limits and is performed using a residual gas analyzer per paragraph 4.4.9.4 to verify that the cells meet the specified design cell leakage rate to satisfy mission life requirements.

4.4.4.2.1 Cell weights shall be measured before and after test to identify which cell, if any, experienced a leak.

4.4.5 Shock

The cells shall be exposed to specified shock levels per SMC-S-016/TR-RS-2014-0016 [1] and AIAA S-110-2005 [24] (qualification, 6 dB; flight lot proof test, 3 dB) in each direction along each of the three orthogonal axes (qualification, applied three times; flight lot proof test, applied one time), and the following, to verify no physical damage and/or degradation in performance, and to verify the cell design and workmanship:

4.4.5.1 The generation of shock environmental conditions shall encompass the range of all ground, launch, ascent and on-orbit conditions including transportation, handling, and storage, using the methods stated in SMC-S-016/TR-RS-2014-0016 [1].

4.4.5.2 Shock tests shall be performed to equivalent battery levels at the cell interface when mounted in a flightlike condition per SMC-S-016/TR-RS-00016 [1]. Note: A transfer function between the battery base and the cell base is typically required to define appropriate cell dynamic environments and that cell boundary conditions need to be representative of the cell mounting configuration in the battery to produce representative test results.

4.4.5.3 Starting at 90% SOC, the cells shall be discharged at C/10 rate, or the expected launch SOC and discharge loads, during the shock test.

4.4.5.4 Individual cell voltages and currents shall be monitored continuously during all shock tests, at a rate defined in paragraph 7.2.4.3, for failure or intermittent performance.

4.4.5.5 Cell voltages shall not experience negative voltage transients in excess of either twice the signal noise imparted by the test environment or 15 mV, whichever is smaller. If baseline test noise or transients are expected to exceed requirements, a simulation test shall validate the baseline levels.

4.4.5.6 A visual inspection, electrical isolation, and leakage test per Section 4.4.2 and specification performance tests per paragraphs 4.4.3.1.c, 4.4.3.3, 4.4.3.4, and 4.4.3.5 shall be performed before and after the operational shock testing, with individual cell results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

4.4.5.7 Deviation from performing shock testing shall be in accordance with SMC-S-016/TR-RS-2014-0016 [1] and rationale documented.

4.4.6 Random Vibration

The vibration test shall be performed per SMC-S-016/TR-RS-2014-0016 [1] and AIAA-S-110-2005 [22] on the cells at the specified vibration environment (qualification, 6 dB; flight lot proof test, 3 dB) in three orthogonal axes for a duration of three minutes per axis (qualification) or two minute per axis (flight lot proof test) and the following:

4.4.6.1 The qualification vibration environments shall encompass the full range of ground, launch, ascent, and on-orbit conditions, including transportation, handling, and storage, using the methods stated in SMC-S-016/TR-RS-2014-0016 [1].

4.4.6.2 Vibration tests shall be performed to equivalent battery levels at the cell interface while mounted in a flightlike condition per SMC-S-016/TR-RS-00016 [1].

Note: A transfer function between the battery base and the worst-case cell response in the battery pack is required to define appropriate cell-level dynamic environments, and cell fixturing (boundary) conditions must be realistic to conservative representation of worst-case conditions imposed by the battery pack. Replication of minimum state-of-charge and minimum imposed pressures and locations like that used in pack assembly along with performance of vibration testing at launch minimum state-of-charge is typically needed during single cell tests.

4.4.6.3 Starting at 90% SOC, the cells shall be discharged at C/10 rate, or the expected launch SOC and discharge loads, during the vibration test.

4.4.6.4 Cell-level voltages, current, and temperature shall be monitored continuously during the entire vibration test at a rate defined in paragraph 7.2.4.3 for failure or intermittent performance.

4.4.6.5 Cell-level voltages shall not experience negative voltage transients in excess of either twice the signal noise imparted by the test environment or 15 mV, whichever is smaller. If baseline test noise or transients are expected to exceed requirements, a simulation test shall validate the baseline levels.

4.4.6.6 A visual inspection, electrical isolation, and leakage test per Section 4.4.2 and specification performance test per paragraphs 4.4.3.1.c, 4.4.3.3, 4.4.3.4, and 4.4.3.5 shall be performed before and after operational vibration testing, with individual cell results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

4.4.6.7 Before and after vibration x-rays (computer tomography scan for qualification) shall be performed on three cells to verify workmanship requirements and compared to verify no movement, breakage, or damage internal to the cell was caused by the mechanical environments.

Note: If an acceleration test is performed, x-rays should be performed after completion of the test.

4.4.6.8 At least one cell with worst-case capacity, resistance, or charge retention degradation shall undergo DPA per Section 8.12 to verify that the cell continues to meet requirements after environmental dynamic testing per paragraph 4.4.13.3.

Note: If an acceleration test is performed, DPA should be performed after completion of the test.

4.4.7 Acceleration

As applicable, a cell-level acceleration test shall begin at a prelaunch SOC and discharge state during the test per SMC-S-016/TR-RS-2014-00016 [1], AIAA-S-110-2005 [22], and the following, to verify no physical damage and/or degradation in performance occurs as a result of acceleration test, and to validate workmanship.

4.4.7.1 The acceleration test shall verify the capability of the cell to operate during and after exposure to the qualification-level acceleration environment, at least 1.25 times the maximum predicted acceleration, for at least a duration of five minutes in both directions of the three perpendicular axes of test.

4.4.7.2 An analysis shall be performed to determine whether the acceleration environment is addressed by the cell-level qualification vibration test.

4.4.7.2.1 If the analysis shows that the acceleration test is encompassed by the vibration test, the analysis shall be fully documented and included as part of the cell-level qualification report.

4.4.7.2.2 If the analysis shows that an acceleration test is required, it shall be performed.

4.4.7.3 The acceleration test shall be performed with the cell under a discharge load, with cell voltages, temperature, and current continuously monitored during the test at a rate defined in paragraph 7.2.4.3 for failure or intermittent performance.

4.4.7.4 Cell voltages shall not experience negative voltage transients exceeding twice the signal noise imparted by the test environment or 15 mV, whichever is smaller. If the baseline test noise or transients are expected to exceed requirements, a simulation test shall validate the baseline levels.

4.4.7.5 Cell level x-ray and DPAs shall be performed per paragraphs 4.4.6.7 and 4.4.6.8.

4.4.7.6 A visual inspection, electrical isolation, and leakage test per Section 4.4.2 and specification performance tests per paragraphs 4.4.3.1.c, 4.4.3.3, 4.4.3.4, and 4.4.3.5 shall be performed before and after the operational shock testing, with individual cell results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

4.4.8 Thermal Cycle

The cell thermal cycle testing shall be per SMC-S-016/TR-RS-2014-0016 [1] and the following:

4.4.8.1 The cell shall be mounted in a fixture that simulates flightlike thermal interface and cooling paths.

4.4.8.2 Cell temperature shall be used to verify that minimum temperature, maximum temperature, and minimum thermal ramp rates have been achieved.

4.4.8.3 The cells shall be exposed to 23 thermal cycles to the maximum and minimum specified battery temperatures that encompass the qualification range of thermal conditions expected during all ground, launch, ascent, and on-orbit operation conditions, including transportation, handling, and storage, per below:

Cycle 1 – Survival temperature range (nonoperational)

Cycles 2–23 – Qualification temperature range (Qual = +10 deg C of acceptance)

4.4.8.4 During the first and last operational qualification hot and cold temperature soak a functional capacity test shall be performed on the cells by starting at the maximum defined cell voltage and then discharging at a C/2 rate to the minimum cell voltage criteria, followed by a recharge to maximum voltage using the appropriate temperature-defined charge currents.

4.4.8.5 The cell SOC shall be maintained at 50% for the survival cycle and within 90%-100% SOC for the remainder of the thermal cycle test.

4.4.8.6 Cell voltage, temperature, and current shall be continuously monitored during all portions of the test to validate specification performance requirements and to verify no intermittent behavior.

4.4.8.7 A visual inspection, electrical isolation, and leakage test per paragraph 4.4.2, and specification performance tests per paragraphs 4.4.3.1.c, 4.4.3.3, 4.4.3.4, and 4.4.3.5 shall be performed before and after thermal cycle test, with individual cell results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

4.4.9 Thermal Vacuum

The cell thermal vacuum test shall be per SMC-S-016/TR-RS-2014-0016 [1] and the following:

4.4.9.1 The cells shall be exposed to a minimum of four thermal vacuum phases as outlined below, with the last three phases simulating maximum on-orbit mission depth-of-discharge operation, and demonstrate that the state of charge and temperature balance are maintained within a 24-hour period and/or achieve thermal stability

a. TV Phase 1: Survival temperature (nonoperational) cycle test
b. TV Phase 2: Worst-case hot (24-hour orbit operation, minimum)
c. TV Phase 3: Design operating case (24-hour orbit operation, minimum)
d. TV Phase 4: Worst-case cold (24-hour orbit operation, minimum)

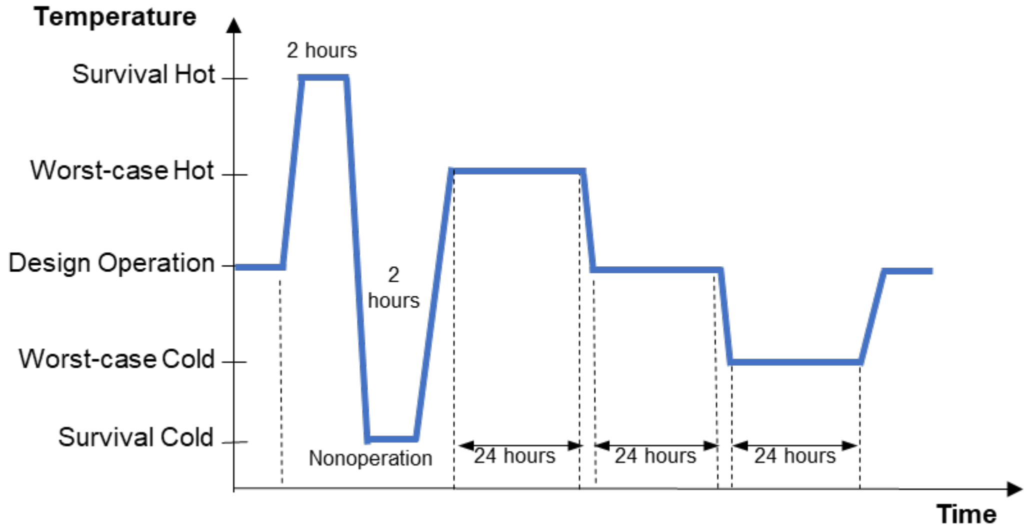

Figure 1. Configuration-controlled cell thermal vacuum test.

4.4.9.2 For cell qualification, the worst-case hot and cold test temperatures shall exceed the maximum and minimum acceptance temperatures by +10 deg C.

4.4.9.3 Cell voltage, temperature, and current shall be continuously monitored during all portions of the test to validate specification performance requirements and verify no intermittent behavior.

4.4.9.4 A residual gas analyzer shall scan every minute during the thermal vacuum test with a capable gas detector tuned to detect volatile electrolyte solvents in the cell with a threshold and accuracy to verify no cell leakage occurred.

4.4.9.5 A visual inspection, electrical isolation, and leakage test per Section 4.4.2 and specification performance tests per paragraphs 4.4.3.1.c, 4.4.3.3, 4.4.3.4, and 4.4.3.5 shall be performed before and after the thermal vacuum test, with individual cell results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

4.4.10 Radiation

A total of six cells shall be tested for radiation and survivability to verify that the requirements are met for the types of radiation and levels expected over spacecraft service life.

4.4.10.1 A visual inspection, electrical isolation, and leakage test per Section 4.4.2 and specification performance tests per paragraphs 4.4.3.1.c, 4.4.3.3, 4.4.3.4, and 4.4.3.5 shall be performed before and after the radiation test, with individual cell results documented to verify that any physical damage and/or performance degradation occurring as a result of the environmental test can be demonstrated to meet specified mission requirements.

4.4.10.2 A cell-level DPA shall be performed per Section 8.12 on at least one cell postradiation test to verify that any design or material impacts as compared with the control cell DPA per paragraph 4.4.13.4 can be demonstrated to meet specified mission requirements.

4.4.10.3 Postradiation test, five cells shall be included as part of a realtime lifecycle test per Section 4.4.11 to quantify any excessive degradation in performance degradation throughout the lifecycle due to radiation exposure.

4.4.11 Cell Realtime Lifecycle Test

Realtime life testing shall be conducted, per Section 8, on each cell chemistry, design, supplier, and manufacturing location used in each battery design, application, and environment.

4.4.12 Flight Lot Lifecycle Test

A sample of six cells from each lot shall be lifecycle tested per Section 9.24.

4.4.13 Cell DPA

4.4.13.1 A cell-level DPA per Section 8.12 shall be performed on at least one control beginning-of-life cell for qualification and each cell lot to verify cell design and workmanship are as expected and meet the manufacturing requirements. The control DPA may be performed at the same time as the DPA in paragraph 4.4.13.2 by storing the cell at open-circuit voltage.

4.4.13.2 A DPA shall be performed per Section 8.12 for each cell lot following the flight lot cycle test as defined in Section 9.24.

4.4.13.3 A DPA per Section 8.12 shall be performed on at least one worst-case cell from paragraph 4.4.6.9 postqualification shock/vibration/acceleration test to verify no movement, breakage, or internal damage to the cell was caused by the environments.

4.4.13.4 A DPA shall be performed per Section 8.12 following qualification radiation test as defined in paragraph 4.4.10.2.

4.4.14 Safety Devices

Safety devices that are included within the cell, such as fuses, current interrupt, and/or positive temperature coefficient devices, shall meet the requirements of SMC-S-009 [7], SMC-S-010 [19], and per sections 5.4.11.3 and 5.4.11.4.

4.4.15 Safety Tests

The safety tests of sections 4.1.4 and 4.1.5 shall be performed from cells built as part of the qualification lot.

4.4.16 Shipment OCV Test

4.4.16.1 Prior to shipment or cell selection and/or matching, the open-circuit voltage of each cell shall be measured to $\pm$0.1 mV and recorded with date/time stamp and temperature.

4.4.16.2 Each cell voltage shall be remeasured to $\pm$0.1 mV at least 90 days later (can be postshipment) and shall be recorded with date/time stamp and temperature. Any cell measurement not within family and/or specified values shall be deselected prior to battery cell selection

.

5. Commercial Cells

5.1 Process for Using COTS Cells in Space Batteries (informative)

COTS lithium-ion battery cells are used in some cases to fabricate space batteries. These cells are built by many commercial suppliers to meet the needs of worldwide consumer electronics applications. The chemistry, design, cell size, level of quality control, performance, and many other features key to space batteries can therefore vary considerably depending on where and how the cells were made. COTS cells are typically built using a continuous manufacturing process and a higher level of automation with the expectation that there is statistical uniformity within a purchased lot. Because these cells are often distributed by second- and third-party sources, it is very important to verify the traceability of these cells to a single cell supplier production run, based on both COTS cell lot documentation and test data.

COTS Li-ion cells are most commonly made in a cell size termed "18650," which is 18 mm in diameter and 65 mm in height, between the typical "AA" and "C" battery cell size. These cells can vary from about 2 Ah to 3.5 Ah in capacity, depending on design and targeted application. Other COTS cell sizes are also sometimes used in space batteries, such as the 26650 cell size, which is larger than the 18650 cell size. A desirable feature of COTS cells is that the standardization of cell physical sizes can allow several types of cells (potentially made by different manufacturers) to be considered for use in any given application.

Many COTS applications electrically configure the cell in a series: parallel connection without external electronics that maintain cell balance, bypass failed cells, prevent excess charge currents or voltage, and/or prevent excessive discharge currents, unlike configuration-controlled cells. This requires the cell performance to be extremely well matched to prevent cell divergence over life. Safety protection devices, such as PTC, CID, and/or fuses, are built into the cells so that in the event of divergence of one or more cells or strings over life, the cell(s) will fail benignly if any excessive charge/discharge currents or voltages occur.

The qualification time for COTS cell lots can be time intensive, so it is advantageous to procure large numbers of cells in a lot to support multiple programs. The number of qualification cells, 231 cells, is based on achieving 0.99 reliability at the cell level with 90% confidence. If qualification is to be performed on smaller COTS cell lots for a single program, a reduced number of cells with abbreviated testing can be considered to satisfy lower cell reliability per procurement authority approval via the normal tailoring process.

Figure 2 provides a process flow of the requirements for use of COTS cells in space batteries. When the requirements of Figure 2 are satisfactorily met, cells from the lot may be selected for fabrication into a space battery for battery qualification per Figure 3 and finally for flight battery acceptance per Figure 4.

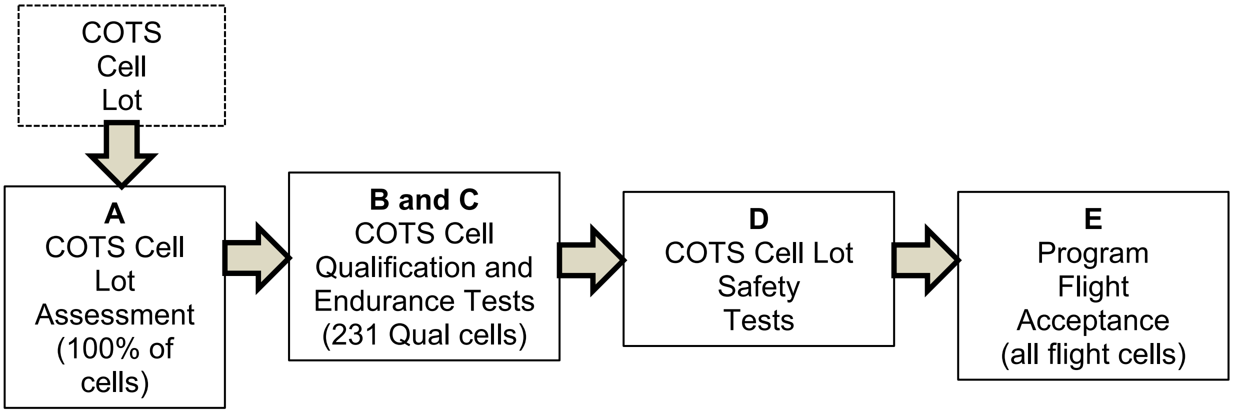

Figure 2. Cell-level testing to verify COTS cell lots for space batteries.

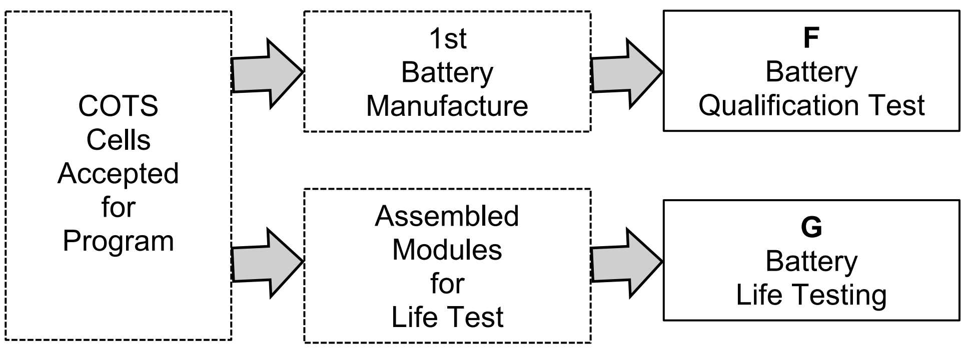

Figure 3. Battery-level qualification and life testing using COTS cells.

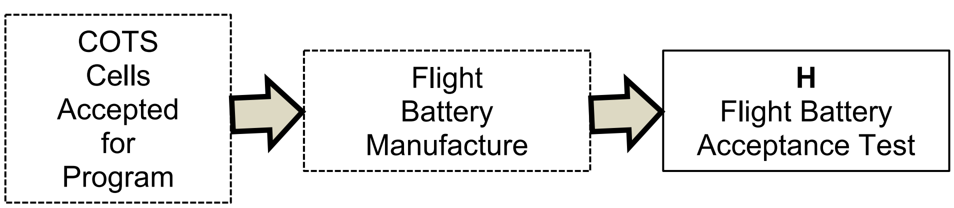

Figure 4. Flight battery-level acceptance testing using COTS cells.

The acquisition of COTS cells and their use in a space-qualified battery includes:

A. COTS Cell Lot Assessment. This assessment provides preliminary inspection and electrical data, including self-discharge rates, that are used to screen cells and COTS cell lots for space use prior to committing the lot to qualification test.

B. COTS Cell Lot Qualification. For the COTS cell lot procured, based on lot date code, these qualification tests determine if a given COTS cell type is spaceworthy. This includes a variety of tests to determine if the COTS cell lot should continue down the sequence of tests which will qualify it for space battery use. These tests are intended to demonstrate that the cell meets worst-case performance and environments, contains safety features with standard margins relative to the intended space application, and matches the requirements of the manufacturer's specification sheet.

C. COTS Cell Lot Endurance Tests. Endurance testing for COTS cell lots is performed to determine the rate of degradation with time and cycle count. The data serve the following purposes:

1. Support the design of a battery that can provide the required electrical performance at the end of life (EOL)
2. Demonstrate the performance degradation rates within the COTS cell lot is sufficiently consistent to allow the cells to remain balanced in voltage and capacity for a typical space mission duration
3. Compare degradation rates to other cell types
4. Determine the effect of environment on long-term performance
5. Characterize the effects of various storage conditions on degradation rates and operational life.

D. COTS Cell Lot Safety Tests. Safety testing serves to ensure the cells are safe under normal circumstances and after feasible mishandling events. They characterize the operation of safety devices and develop understanding of nonhazardous consequences of abuse in terms of the effects on battery performance.

E. Program Flight Cell Acceptance. This includes mission-specific tests intended to detect workmanship defects and to verify that the functional and performance requirements of the mission are met. Acceptance tests verify that the flight cells are acceptable for battery manufacture or cell delivery.

F. Battery Qualification: The first battery made for a mission using each lot of COTS cells for the mission is subjected to qualification testing to verify expected operation and performance over worst-case conditions to which it could be exposed.

G. Battery Life Qualification: Life tests to verify mission capability shall be done at a module level to realistically simulate battery electrical and thermal charge/discharge conditions, which may contain either the actual number of parallel strings or a statistically significant number of parallel strings if the battery is very large. This is required because the life of COTS batteries can be controlled by cell-to-cell divergence in the cell strings, which can only be tested and verified in realistic modules that contain a number of parallel-connected series strings of cells.

H. Flight Battery Acceptance: Once a COTS cell lot has been qualified, the lot has been accepted, and the selected cells have met program acceptance requirements, the cells continue into the battery fabrication process. This process is illustrated in Figure 4 and involves selection of the cells for the various strings to be built into the battery according to the sizing requirements of the mission. Following battery fabrication for a mission, each flight battery is acceptance tested to verify workmanship and expected performance over the required operational profile.

5.2 COTS Cell General Requirements

5.2.1 Each cell shall contain markings that identify the manufacturing date or manufacturing date code as affirmed by the manufacturer that verifies all cells in the COTS cell lot were built within the same 24-hour period.

5.2.1.1 If a manufacturer produces a cell at more than one factory, each cell package shall have a distinctive marking to identify it as the product of a particular factory.

5.2.2 The physical and performance characteristics as specified by the original cell vendor shall be documented and at minimum include the following:

a. Cell maximum discharge pulse current (at defined duration)
b. Manufacturing location
c. Cell model number
d. Cell vendor
e. Cell voltage, maximum and minimum
f. Cell maximum continuous charge and discharge current
g. Cell chemistry (anode, cathode, electrolyte)
h. Cell capacity (at defined test conditions)
i. Cell mass
j. Cell dimensions
k. Electrical/thermal conditions that activate safety devices
l. Cell safety certification(s) (e.g., IEC, UL, UN)
m. Any other available data that defines expected cell performance or safety characteristics

5.2.3 COTS cell lot assessment, inspections, tests, and analyses shall be performed on all cells from each lot procured per Section 5.3, with any cell performance falling outside 3 sigma discarded from the COTS cell lot and further use, and supporting documentation provided.

5.2.4 COTS cell lot endurance testing shall be performed per Section 5.4.10 with supporting documentation provided along with semiannual updates (i.e., every six months) until test completion.

5.2.5 Program acceptance inspections, tests, and analyses shall be performed to demonstrate all COTS flight cells selected from the COTS cell lot for batteries for a given mission meet all requirements per Section 5.5, with supporting documentation provided.

5.2.6 The first battery using each lot of COTS cells for a mission shall be subjected to qualification testing per Section 7 to verify expected operation and performance over worst-case conditions to which it could be exposed, including nonoperational survival environments.

5.2.7 Battery life qualification tests to verify mission capability shall be done at a module level per Section 8 utilizing a module containing either the actual number of parallel strings or a statistically significant number of parallel strings if the battery is very large.

5.2.8 Each flight battery shall be acceptance tested per Section 9 following battery fabrication for a mission to verify workmanship and expected performance over defined program operational ranges.

5.2.9 Test current, voltage, impedance, ampere-hours, and temperature shall be measured/calculated and recorded for all tests with the following accuracies unless stated otherwise: ±1 mA, ±0.1 mV, ±0.01 mohms, ±0.1 mAh, ±2 deg C.

5.2.10 All the cells in the COTS cell lot shall be subjected to the cell lot assessment, cell lot qualification, flight cell acceptance test, and test sequence as outlined below in Table 2, unless otherwise noted, to validate the cell construction, manufacturing, quality, performance, mechanical uniformity, and ability to survive space environments.

Table 2. COTS Cell Assessment, Qualification, and Acceptance Testing

Inspection or Test	Cell Lot Assessment	Cell Lot Qualification	Flight Cell Acceptance	Suggested Test Sequence	Paragraph
Visual Inspection Screen	R	R	R	1	5.3.1
Leakage Screen	R	R	R	2	5.3.2
Weight Screen	R	R	R	3	5.3.3
Dimension Screen	R	R	R	4	5.3.4
Cell Isolation Test	R	R	R	5	5.3.5
X-ray (2)	R	R	R	6	5.3.6
Initial OCV	R	R	R	7	5.3.7
AC Impedance	R	R	R	8	5.3.7
Standard Electrical Screen	R	R	R	9	5.3.7
Cell Vendor Capacity	R	R	R	10	5.3.8
Cell OCV Screen (<10% SOC)	R	R	R	11	5.3.9/5.3.12
Cell Differential Voltage Analysis		R	R	12	5.3.10
Cell Electrical and Charge Retention (100% SOC)	-	R	-	13	5.4.2
Vibration	-	*R	-	14	5.4.3.1
Shock	-	*R	-	15	5.4.3.2
Thermal Cycle	-	*R	-	16	5.4.3.3
Thermal Vacuum/Leakage (1)		*R		17	5.4.3.4
Radiation (2)		*R		18	5.4.4
Humidity (2)		R		19	5.4.5
Weld (2)		R		20	5.4.6
DPA (2)		R		21	5.4.7
Chemical Analysis (2)		R		22	5.4.8
Electrical Characterization (2)		R		23	5.4.9
Endurance Tests (2)		R		24	5.4.10
Safety Tests (2)		R		25	5.4.11
Life Test (2)		R		26	8.0
Standard Electrical Test			R	27	5.5.2.1
Mission Capacity Test, design temp			R	28	5.5.2.2
Mission Capacity Test, max temp			R	29	5.5.2.3
Mission Capacity Test, min temp			R	30	5.5.2.4
Cell Charge Retention			R	31	5.5.2.5
Thermal Vacuum - Leakage			R	32	5.5.2.6
X-ray (2)			R	33	5.5.2.7
Terminal Isolation			R	34	5.5.2.8
Visual Inspection			R	35	5.5.2.9

R: Required
* Inspection (Section 5.4.1) and specification performance (Section 5.4.2) performed before and after test.
(1) Thermal vacuum test should be performed as the last environment test as defined in Table 2.
(2) Refer to test paragraph 5.4 for required quantity of cells.

5.3 COTS Cell Lot Assessment Requirements

The following inspections, tests, and analyses shall be done on all cells procured in a single COTS cell lot from a single manufacturer's date code to determine if further lot qualification and flight use are justified. Note: Cell x-ray inspection may be performed on <100% of the cell lot as defined in paragraphs 5.3.6.1 and 5.3.6.2.

5.3.1 Visual Inspection Screening

5.3.1.1 All cell shipping containers shall be inspected upon receipt for signs of damage during handling and/or shipping with any damage documented and traceable to cell serial number or barcode.

5.3.1.2 All cells shall be individually identifiable (e.g., unique serial number or barcode) to enable traceability throughout all stages of testing or use in flight batteries which reference the COTS cell lot. The label or barcode can replace the cell case insulator/wrapper provided by the cell manufacturer.

5.3.1.3 Pass/fail criteria for labeling, dents, scratches, stains, contamination, package damage, or other factors shall be established and rationale provided.

5.3.1.4 All cells shall be visually inspected at 10X magnification or greater, with any of the following documented, including traceability to cell serial number or barcode: dents, scratches, stains, contamination, corrosion, or other factors that could complicate welding tabs to the cell.

5.3.1.5 All cells shall be inspected after case insulator/wrapper is removed and after completion of electrical cycling, at 10X magnification or greater for any dents, scratches, stains, contamination, corrosion, or other factors that could complicate welding tabs to the cell or impact cell performance, documented with traceability to cell serial number or barcode.

5.3.1.6 Any cell that does not meet the pass/fail criteria shall be excluded from qualification tests and flight battery use.

5.3.2 Leakage Test

5.3.2.1 A litmus (pH paper) test or equivalent shall be performed on each cell to verify that terminals, crimp/welds, and fill port of all cells are sealed and there is no electrolyte leakage.

5.3.2.2 Cells with indication of leakage shall be excluded from qualification tests and flight battery use.

5.3.3 Weight Inspection

5.3.3.1 Each cell shall be weighed without wrapper to an accuracy of ±0.001 grams, and the weight shall be documented by cell serial number or barcode.

5.3.3.2 Cells that are outside ±3 sigma of the mean weight value for the entire COTS cell lot and/or outside cell manufacture specification shall be documented and excluded from qualification tests and flight battery use.

5.3.4 Dimensional Inspection

5.3.4.1 The total length, length to the cell shoulder, and two perpendicular diameter measurements at each end and at the middle of the cell shall be measured and documented for each cell, by cell barcode, without the cell wrappers.

5.3.4.2 Cells that are outside ±3 sigma of the mean dimensional value for the entire COTS cell lot and/or outside cell manufacture specification shall be documented and excluded from qualification tests and flight battery use.

5.3.5 Terminal-to-Case Isolation

5.3.5.1 Terminal-to-case isolation shall be measured and documented on each cell to verify that the isolation is greater than 10 MΩ, as applicable.

5.3.5.2 Any cell with terminal-to-case isolation less than 10 MΩ shall be documented and excluded from qualification test and flight battery use.

5.3.6 X-ray Inspection

5.3.6.1 Cell-level x-rays shall be performed on at least 10% of the COTS cell lot (with >250 cells/lot), or on at least 25 cells minimum (with <250 cells/lot), to verify the contractor-developed pass/fail criteria, including at a minimum the criteria below:

a. The cell assembly (electrodes, separator, insulator, and tabs) contains uniform compression and is free of interference that can induce a burr or damage to the cell core or stack.

b. Electrode stack/jellyroll contains no wrinkling, tearing, out-of-family misalignment, and/or deformation.

c. The active positive electrode is covered by the active material of the negative electrode and is within acceptable tolerance.

d. The separator extends beyond the positive and negative electrode with margin.

e. Tabs or connections within the electrical path are not loose or broken (including partially broken).

f. Tab positioning prevents electrode damage or short circuits.

g. Tab lengths are of sufficient length with strain relief.

h. Metallic plating or corrosion is not visible on cell materials.

i. No FOD/NOD or other contamination is present.

j. Weld/crimp alignment is uniform.

k. Cell case cleanliness, scratches, and dents are determined to be within acceptable criteria.

l. Cell safety devices such as current interrupt devices, temperature control devices, and/or vents are correctly installed and not impeded.

5.3.6.2 If any of the x-rayed cells in paragraph 5.3.6.1 fail any criteria in (a) - (l), then either the whole lot is rejected or only cells that are screened by x-ray for items (a) – (l) are acceptable for qualification testing or for use in flight batteries.

5.3.7 Standard Electrical Screening

Electrical screening measurements shall be performed on each cell to verify performance and provide COTS cell lot statistical variability of OCV, AC impedance, and capacity at a controlled temperature of 20 deg C to aid in identification of counterfeit cells.

5.3.7.1 The initial OCV of each cell shall be measured and documented.

5.3.7.2 The 1 kHz AC impedance measurement shall be measured and documented at a defined state of charge that is consistent for all measurements for trending purposes.

5.3.7.3 Each cell shall be discharged at C/10 to the manufacturer's minimum voltage.

5.3.7.4 A standard capacity measurement shall be performed for each cell, consisting of recharge at C/10 to full recharge per the manufacturer's maximum voltage, and full discharge at C/10 to the manufacturer's minimum voltage. A C/20 charge/discharge rate may be used in lieu of the C/10 charge/discharge

5.3.7.5 An additional standard capacity measurement shall be performed on each cell, per paragraphs 5.3.7.3 and 5.3.7.4, that ends with the cell in the discharged condition.

5.3.7.6 Current, cell voltage, and temperature shall be recorded at least once per 30 seconds.

5.3.7.7 Each cell charge and discharge capacity for each capacity cycle shall be documented.

5.3.7.8 The cells that are outside ±3 sigma of the median value initial OCV, AC impedance, charge capacity, and discharge capacity during each capacity cycle shall be documented and excluded from qualification tests or flight battery use.

5.3.8 Cell Vendor Capacity Test

A capacity measurement shall be performed to verify each cell meets the cell vendor's performance specification at a controlled temperature.

5.3.8.1 Each cell shall be fully charged and discharged to the manufacturer's defined charge/discharge rates and maximum /minimum voltage profile. The desired cycle should resemble a charge rate of C/5, discharge rate of C/2, and controlled temperature that represents the designed operating temperature.

5.3.8.2 Current, cell voltage, and temperature shall be measured and recorded at least once per 30 seconds.

5.3.8.3 Each cell charge and discharge capacity shall be documented.

5.3.8.4 The cells that are outside ±3 sigma of the median value for initial OCV, charge capacity, and discharge capacity shall be documented and excluded from qualification tests or flight battery use.

5.3.9 Cell OCV Screening

All cells shall be screened for OCV trends during storage to establish self-discharge trends based on OCV decay rates when at ≤10% state-of-charge.

5.3.9.1 All cells shall be discharged at C/10 to the cell vendor's minimum voltage requirement. If required, charge cells to no higher than 10% state of charge.

5.3.9.2 All cells shall be stored in a temperature-controlled environment where the chamber temperature is measured and documented at least once every 24 hours.

5.3.9.3 Cell open-circuit voltage measurements shall be taken at 168 hours ±1 hour and at 30 ±0.04 days after achieving the designated state of charge.

5.3.9.4 Cells that are outside ±3 sigma of the median value for OCV decay rate shall be documented and excluded from COTS cell lot qualification and flight battery use.

5.3.10 Cell Differential Voltage Analysis

The following data analysis shall be performed per TOR-2019-00829 [26] to provide assurance that all cells in the COTS cell lot were manufactured similarly, and to increase confidence that no counterfeit cells, repurposed cells, or cells from different lots are retained for flight batteries:

5.3.10.1 Differential analysis of the voltage data from the second capacity cycle during standard electrical screening of Section 5.3.7 shall be performed based on voltage, apparent OCV, and DC resistance to indicate how these parameters depend on SOC.

5.3.10.2 Cells that exhibit differential voltage, apparent OCV, or DC resistance indications at any SOC that are outside ±3 sigma of the median value shall be documented and excluded from COTS cell lot qualification and flight battery use.

5.3.11 Statistical Lot Uniformity

To ensure only COTS cell lots with adequate performance uniformity are considered for flight use, after removing outlier cells, the resultant ±3 sigma range for the following parameters as a percentage of the mean (±3 sigma range/mean) shall not exceed the following:

a. Initial and screening OCV <1%
b. Mass <2%
c. Capacity <5%
d. DC and AC resistance <15%

5.3.11.1 If more than 3% of the cells in the COTS cell lot fail the leak test, the entire COTS cell lot shall be scrapped.

5.3.11.2 If the total number of cells that fail the acceptance screening criteria, including outliers, is greater than 15% of the lot, then the COTS cell lot shall be rejected for flight use.

5.3.11.3 If the COTS cell lot exhibits bimodal or other distribution functions that may indicate manufacturing changes during the COTS cell lot production or possible mixed cell lots, the lot shall be rejected for flight use.

5.3.11.4 The COTS cell lot assessment report that documents the statistical data and number of outliers for each test parameters shall be available for review.

5.3.12 Flight Cell Screening/Storage

The cells from the lot assessment that meet the statistical requirements and are not used for COTS cell lot qualification test shall be stored in a temperature-controlled environment at a SOC <10% to minimize cell degradation. This test can be a continuation of the test initiated in Section 5.3.9.

5.3.12.1 The storage chamber shall contain temperature and humidity sensors that maintain the chamber at the appropriate controlled temperature and humidity where the chamber temperature and humidity are monitored and recorded at least once per day.

5.3.12.2 At minimum the initial and final OCV measurement with date/time stamp shall be documented for each cell at a defined temperature.

5.3.12.3 Cells that are outside ±3 sigma of the median value for OCV decay rate shall be documented and excluded from COTS cell lot qualification and flight battery use.

5.3.12.4 Records shall be maintained and available for review on each flight cell inspection, electrical screening test/analysis, and storage data.

5.4 COTS Cell Qualification Requirements

A minimum of 231 qualification cells shall be randomly selected from the entire COTS cell lot for the testing specified below to verify they meet inspection and performance requirements, and to identify the COTS cell lot cell-to-cell variation.

a. To maintain cell lot consistency, all 231 cells should be tested simultaneously, otherwise, any cell not under test for >5 days shall be maintained in cold storage at < 50% SOC.
b. A reduced number of cells with abbreviated testing can be considered to satisfy lower cell reliability with Procurement Authority approval.

5.4.1 Inspection Tests

5.4.1.1 Visual inspection shall be performed as previously performed in paragraph 5.3.1.4 and Section 5.3.4 and documented for each cell at a minimum of 10X magnification prior to and after each environmental test to verify no physical damage and no statistical change in dimensions occurred following the environmental test.

5.4.1.2 Terminal-to-case isolation shall be performed as previously performed in Section 5.3.5 and documented on each cell before and after environmental test to verify statistically unchanged cell isolation following each environmental test compared to the initial measurement, as applicable.

5.4.1.3 A litmus (pH paper) test or equivalent shall be performed as previously performed in paragraph 5.3.2 and documented on each cell prior to and after each environmental test to verify terminals, crimp/welds, and fill port of all cells are sealed and there is no electrolyte leakage following each environmental test.

5.4.2 Electrical Tests

5.4.2.1 Each cell shall complete one standard capacity cycle per Sections 5.3.7 and 5.3.10 following each environmental test, and demonstrate the cell capacity, AC impedance, and internal resistance are statistically unchanged when compared to the initial screening standard capacity cycles.

5.4.2.2 Each cell shall complete a charge retention test prior to and following each environmental test and demonstrate that open-circuit voltage decay rate and retained capacity are statistically unchanged compared to the initial charge retention test.

5.4.2.2.1 The cell charge retention test shall be performed at 20 ±2 deg C in an open-circuit state starting at 100% state of charge on each cell.

5.4.2.2.2 Cell open-circuit voltage measurements shall be taken at 168 hours ±1 hour and at

30 ±0.04 days postcharge completion for the initial before environmental test and after the final environmental test.

5.4.2.2.3 After the open-circuit period, the cell shall be discharged at C/10 rate to the manufacturer's minimum voltage and the capacity recorded.

5.4.2.2.4 The charge retention test open-circuit duration per paragraph 5.4.2.2.2 can be reduced to 168 hours ±1 hour except for first pre-environmental test and final postenvironmental test.

5.4.3 Environmental Testing

Launch and space battery operation can include environments for which COTS cells have not been specifically designed. A range of environmental tests are required to validate the ability of the cell design to survive these environments.

5.4.3.1 Vibration Test

The cells shall survive the vibration environment expected from launcher rocket motors, structural resonances, and aeroacoustics inputs when in a flightlike fixture and interface, and the following, without physical damage and/or performance degradation, and to validate cell design and workmanship

Note: A transfer function between the battery base and the cell base is typically required to define appropriate cell dynamic environments, and cell boundary conditions need to be representative of cell mounting configuration in the battery to produce representative test results.

5.4.3.1.1 All qualification cells shall be subjected to random vibration at 6 dB above the acceptance level typically encountered in a battery structure for 3 minutes in each of the three axes as defined in SMC-S-016/TR-RS-2014-0016 [1] and AIAA S-110-2005 [22].

5.4.3.1.2 Starting at 90% SOC, the cells shall be discharged at C/10 rate during the vibration test.

5.4.3.1.3 Individual cell voltages and currents shall be monitored at a rate defined in paragraph 7.2.4.3 during the vibration test.

5.4.3.1.4 During vibration, the cell voltage shall not experience negative voltage transients in excess of either twice the signal noise imparted by the test environment or 15 mV, whichever is smaller.

5.4.3.1.5 Inspection and electrical tests shall be performed and documented on each cell per Sections 5.4.1 and 5.4.2 before and after vibration test to verify that no physical damage and/or performance degradation occurred as a result of the environmental test.

5.4.3.1.6 Computer tomography x-ray scan shall be performed, before and after environmental tests, on three cells to verify workmanship requirements of Section 5.3.6 and compared to verify no movement, breakage, or damage internal to the cell was caused by the vibration environments.

5.4.3.1.7 At least two cells with worst-case capacity, resistance, or charge retention degradation shall undergo DPA per Section 5.4.7 to verify that they continue to meet requirements after environmental testing.

5.4.3.2 Shock Testing

The cells shall survive physical shock due to the detonation of pyrotechnic bolts used for launcher separation when in a flightlike fixture and interface without physical damage and/or degradation in performance, and in order to validate cell design and workmanship after previously passing vibration testing.

Note: A transfer function between the battery base and the cell base is typically required to define appropriate cell dynamic environments, and cell boundary conditions need to be representative of cell mounting configuration in the battery to produce representative test results.

5.4.3.2.1 All qualification cells shall be subjected to shock environments at 6 dB above the acceptance level typically encountered in a battery structure for three times in each direction along each of the three orthogonal axes as defined in SMC-S-016/TR-RS-2014-0016 [1] and AIAA S-110-2005 [22].

5.4.3.2.2 Starting at 90% state of charge, the cells shall be discharged at C/10 rate during the shock test.

5.4.3.2.3 Individual cell voltages and currents shall be monitored at a rate defined in paragraph 7.2.4.3 during the shock test.

5.4.3.2.4 During shock, the cell voltage shall not experience negative voltage transients in excess of either twice the signal noise imparted by the test environment or 15 mV, whichever is smaller.

5.4.3.2.5 Inspection and electrical tests shall be performed and documented on each cell per Sections 5.4.1 and 5.4.2 before and after shock testing to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

5.4.3.2.6 Computer tomography x-ray scans shall be performed, before and after environmental tests, on three cells to verify workmanship requirements of Section 5.3.6 and compared to verify no movement, breakage, or damage internal to the cell was caused by the shock environments.

5.4.3.2.7 At least two cells with worst-case capacity, resistance, or charge retention degradation shall undergo DPA per Section 5.4.7 to verify that they continue to meet requirements after shock testing.

5.4.3.3 Thermal Cycle Test

The cells shall survive exposure to thermal cycles that encompass the range of the survival temperature extremes without physical damage and/or performance degradation, and in order to validate cell design and workmanship, after passing the vibration/shock tests.

5.4.3.3.1 All qualification cells shall be subjected to 23 thermal cycles when held at open circuit after charging to 100% state of charge per SMC-S-016/TR-RS-2014-0016 [1].

5.4.3.3.2 The first thermal cycle shall encompass a nonoperating survival temperature limit of at least $\pm$10 deg C of the qualification temperature limits, or maximum survival temperature limits of the cell design.

5.4.3.3.3 The remaining 22 hot-cold thermal cycles shall encompass qualification temperature limits of at least ±10 deg C of acceptance temperature limits.

5.4.3.3.4 Cell temperature shall be used to verify minimum temperature, maximum temperature, and minimum thermal ramp rates have been achieved.

5.4.3.3.5 During the first and last operational qualification hot and cold temperature soak, a functional capacity test shall be performed on the cells by starting at the maximum defined cell voltage and then discharging at a C/2 rate to the minimum cell voltage criteria, followed by a recharge to maximum voltage using appropriate temperature defined charge currents.

5.4.3.3.6 The cell SOC shall be maintained at 50% for the survival cycle and within 90%-100% SOC for the remainder of the thermal cycle test.

5.4.3.3.7 Individual cell voltages, currents, and temperatures shall be continuously monitored during the thermal cycle test and demonstrate no intermittent behavior.

5.4.3.3.8 Inspection and electrical tests shall be performed and documented on each cell per Sections 5.4.1 and 5.4.2 before and after thermal cycle test to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

5.4.3.3.9 Computer tomography x-ray scan shall be performed before and after environmental tests on three cells to verify workmanship requirements of Section 5.3.6 and compared to verify no movement, breakage, or damage internal to the cell was caused by the thermal cycle environments.

5.4.3.3.10 At least two cells with worst-case capacity, resistance, or charge retention degradation shall undergo DPA per Section 5.4.7 to verify that they continue to meet requirements after thermal cycle testing.

5.4.3.4 Thermal Vacuum (TVAC) Test

All qualification cells shall survive exposure to specified qualification-level thermal vacuum cycles per SMC-S-016/TR-RS-2014-0016 [1] while operating without physical damage and/or performance degradation, and to validate cell design and workmanship after previously passing thermal cycle test.

5.4.3.4.1 The first thermal vacuum phase shall encompass a nonoperational survival temperature limit of at least ±10 deg C of the qualification temperature limits while held at open-circuit voltage at 100% state of charge.

5.4.3.4.2 The remaining three thermal phases shall encompass qualification temperature limits of at least ±10 deg C of acceptance hot and cold temperature limits and design operating temperature, as specified below, with operational electrical cycles starting at 100% SOC with discharge to 20% SOC at a C/2 discharge rate followed by operational charge to 100% SOC for each 24-hour phase.

a. TV Phase 1: Survival hot-cold temperature (nonoperational)
b. TV Phase 2: Worst-case hot (24-hour orbital operation, minimum)
c. TV Phase 3: Design operating case (24-hour orbital operation, minimum)
d. TV Phase 4: Worst-case cold (24-hour orbital operation, minimum)

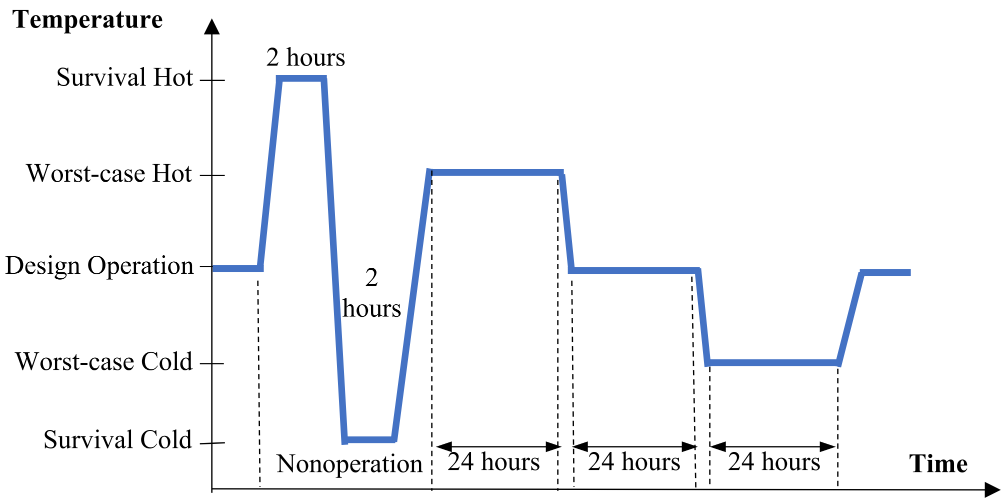

Figure 5. COTS cell qualification thermal vacuum test.

5.4.3.4.3 Individual cell voltages, currents, and temperatures shall be continuously monitored during all portions of the TVAC test to validate specification performance requirements and verify no intermittent behavior.

5.4.3.4.4 A residual gas analyzer shall scan every minute during the thermal vacuum test with a capable gas detector tuned to detect volatile electrolyte solvents in the cell with a threshold and accuracy to verify no cell leakage occurred.

5.4.3.4.5 The mass of each cell shall be measured before and after TVAC test at a minimum accuracy of ±0.001 grams to verify the mass is within 0.2% of the initial COTS cell lot screening value.

5.4.3.4.6 Inspection and electrical tests shall be performed and documented on each cell per Sections 5.4.1 and 5.4.2 before and after thermal vacuum test to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

5.4.3.4.7 Computer tomography x-ray scan shall be performed before and after environmental tests on three cells to verify workmanship requirements of Section 5.3.6 and compared to verify no movement, breakage, or damage internal to the cell was caused by the thermal cycle environments.

5.4.3.4.8 At least two cells with worst-case capacity, resistance, or charge retention degradation shall undergo a DPA per Section 5.4.7 to verify that they continue to meet requirements after TVAC testing.

5.4.3.4.9 Helium leak test shall be performed on at least five cells following TVAC test to verify the helium leak rate is $<10^{-6}$ cc/sec.

5.4.4 Radiation Test

Cells shall be exposed to worst-case expected radiation environment to verify acceptable physical degradation and/or impact on cell performance over life in accordance with SMC-S-014 [16].

5.4.4.1 A total of 10 cells shall be exposed to radiation environment while at 100% SOC and 20 deg C.

5.4.4.2 During radiation test, the cell voltage, current, and temperature shall be continuously monitored to verify no intermittent behavior.

5.4.4.3 The mass of each cell shall be measured before and after radiation test, at a minimum accuracy of ±0.001 grams, to verify the mass is within 0.2% of the initial COTS cell lot screening value.

5.4.4.4 Inspection and electrical tests shall be performed and documented on each cell per Sections 5.4.1 and 5.4.2 before and after the radiation test to verify no physical damage and/or performance degradation occurred as a result of the radiation test.

5.4.4.5 Computer tomography x-ray scan shall be performed before and after environmental tests on three cells to verify workmanship requirements of Section 5.3.6 and compared to verify no movement, breakage, or damage internal to the cell was caused by the thermal cycle environments.

5.4.4.6 At least two cells with worst-case capacity, resistance, or charge retention degradation shall undergo DPA per Section 5.4.7 and verified to meet requirements.

5.4.4.7 Eight cells shall be included as part of the lifecycle test in Section 5.4.10.3 to verify there is no statistical difference in lifecycle performance in cells with and without radiation exposure.

5.4.5 Humidity Testing

A minimum of 20 cells shall be tested to MIL-STD-810H, METHOD 507.6 [27], exposing the cells to 60 deg C maximum, or the cell vendor's maximum allowed storage temperature, and 95% humidity environment for 10 days per Procedure II to verify cell corrosion resistance.

5.4.5.1 No cell shall show any corrosion on the external surface of the cell at a minimum of 10X magnification following the test.

5.4.6 Weld Qualification

A production weld schedule as designated by the cell vendor shall be verified for welding tabs onto the external cell positive and negative cell terminals or surfaces without impacting the function of safety devices or vents.

5.4.6.1 A minimum of 10 cells shall be verified as having acceptable weld quality for both the positive and the negative lead connections as defined in paragraphs 5.4.6.2 through 5.4.6.4.

5.4.6.2 Weld strength for both positive and negative external cell connections shall be verified by performing a pull test.

5.4.6.2.1 A shear pull test shall be performed to demonstrate that the tab material or tab terminal tears prior to weld joint separation.

5.4.6.3 Weld penetration integrity for both positive and negative external cell connections shall be verified by cross-section analysis.

5.4.6.4 Safety tests performed in Sections 5.4.11.1, 5.4.11.3, and 5.4.11.4 shall utilize cells containing electrical tab welds performed per the qualified weld process to verify the weld heat affected zone has not compromised the operation of the vent or safety devices.

5.4.7 Destructive Physical Analysis (DPA)

A DPA shall be performed on three randomly selected cells prior to any environmental test to physically assess the cell design, manufacturing uniformity, workmanship, and any internal defects or out-of-family characteristics.

5.4.7.1 Dimensions of each cell shall be verified to be within manufacturer's specification prior to DPA.

5.4.7.2 Each cell shall be internally inspected using CT or high-resolution x-ray imaging to assess for any unusual features in the cells prior to disassembling them during DPA. Any features detected in the x-ray images should, if possible, be located and visually documented during cell disassembly.

5.4.7.2.1 Before and after the environmental test, x-rays shall be compared to verify that no movement, breakage, or damage internal to the cell was caused by the environment.

5.4.7.2.2 Safety devices shall not be tripped or be impaired.

5.4.7.3 The electrodes shall be removed from the cell to visually inspect 100% of the electrode surface, documenting signs of defects, damage, lithium plating, anode or cathode surface features such as spots or delamination, or other out-of-family characteristics.

5.4.7.3.1 The anode electrode shall overlap the cathode in all places.

5.4.7.3.2 The separator shall extend beyond the electrode with margin.

5.4.7.3.3 The electrode active material shall be uniform and not flaky or delaminating.

5.4.7.3.4 For prismatic cell designs, the anode and cathode plate count shall be consistent.

5.4.7.4 The DPA shall verify that the most common sources of internal cell shorts are not present, which at a minimum includes the following:

5.4.7.4.1 Shorts induced via charge/discharge or thermal extremes, which can cause the deposition of metallic dendrites of copper and/or lithium upon cycling, leading to separator stress to the point of failure

5.4.7.4.2 Separator defects or damage during manufacture or assembly

5.4.7.4.3 Electrode defects (e.g., metallic burrs), nonuniformity, and/or degradation

5.4.7.4.4 Tab/lead defects, fatigue, or inadequate isolation

5.4.7.4.5 Misalignment of electrodes and separators during winding/stacking

5.4.7.4.6 Separator shutdown/pore closure

5.4.7.4.7 Impurities, contaminants, FOD, or NOD

5.4.7.4.8 Plastic seal or glass-to-metal seal failure that compromises its electrical isolation function

5.4.7.5 The internal electrical path welds or connections shall be visually inspected to verify they are secure and do not show evidence of breakage or tearing or loss of electrical isolation (e.g., tab to foil, tab to bussing, bussing to terminal).

5.4.7.5.1 The joint strength of the internal cell welds or connections shall be measured and documented for each electrical interface, such as a tab that connects to anode electrodes, cathode electrodes, positive terminals, and negative terminals as well as any other electrical interface to provide a statistical basis for comparison to postenvironment strength measurements.

5.4.7.5.2 After each test, the joint strength shall be measured and documented for each weld type to verify that postenvironment weld strength measurements are within ±3 sigma of the mean values determined in paragraph 5.4.7.5.1.

5.4.7.6 Internal part measurements shall be performed on each individual component from the cell, including the weight and dimensions (thickness, length, and width) to enable various density calculations and to verify uniformity of electrodes throughout the stack.

5.4.7.7 After each environmental test, the internal cell components and electrode shall not shift, break, or tear as a result of performance, environmental, or life test.

5.4.7.8 Photographic documentation shall be available for each cell DPA.

5.4.8 Chemical Analysis

Following DPA, the following analyses shall be performed on a minimum of three cells to characterize cell materials and to verify uniformity of the materials and construction:

5.4.8.1 X-ray powder diffraction analysis shall be performed on the anode and cathode material to characterize crystalline structure of cell materials.

5.4.8.2 Scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy analysis shall be performed on the cathode, anode, separator, foil, electrical tab/connection, case material, etc., to characterize material type and dimensions.

5.4.8.3 Gas chromatograph – mass spectrometry shall be performed on the electrolyte to characterize electrolyte solvents and ratios.

5.4.8.4 Particle size distribution in the electrodes shall be characterized by an analysis method such as SEM imaging.

5.4.8.5 Fourier transform infrared spectroscopy analysis shall be performed on all insulating materials, including separator and the cell header seal and organic materials such as binders to characterize material types.

5.4.8.6 Case plating thickness on the cell shall be characterized using an analysis method such as SEM imaging, as applicable.

5.4.9 Electrical Characterization

Electrical characterization shall comprise measurement of the cell electrical behavior over the range of operating conditions in which a battery is required to operate. Significant performance deviation could indicate a nonuniform COTS cell lot.

5.4.9.1 A minimum of eight cells shall be characterized at each condition. One or more groups of eight cells can be used to satisfy these tests.

5.4.9.2 Individual cell or cell module voltage, current, and temperatures shall be continuously measured and recorded over the range of rates and temperatures specified by the cell manufacturer.

5.4.9.3 The discharge temperatures shall include: -15 deg C, 0 deg C, 10 deg C, 20 deg C, 40 deg C, and 60 deg C. This range may be narrowed to be consistent with the cell manufacturer specification at the extremes if necessary. At cold temperatures, the cells may be recharged at a higher temperature prior to reducing the temperature for the discharge.

5.4.9.4 At least one discharge cycle shall be performed for each of the following discharge rates: 10C, 5C, 2C, C/1, C/2, and C/10 at each of the temperatures defined in paragraph 5.4.9.3. The highest discharge rate should not exceed the maximum specified by the cell manufacturer.

5.4.9.5 Prior to each discharge, the cell shall be charged to the maximum voltage specified by the manufacturer at a C/10 rate, followed by a taper to C/100.

5.4.9.6 The direct current internal resistance (DCIR) shall be determined at each temperature as a function of SOC, based on the difference between cell voltage during recharge and the cell voltage at the same SOC during discharge.

5.4.9.7 The apparent OCV shall be determined at each temperature as a function of SOC based on correcting the C/10 recharge voltage for the observed DCIR offset.

Table 3. Electrical Characterization Test Matrix (Cells May Be Used for Multiple Tests)

Discharge Rate	-15 deg C	0 deg C	10 deg C	20 deg C	40 deg C	60 deg C
10C	8 cells	8 cells	8 cells	8 cells	8 cells	8 cells
5C	8 cells	8 cells	8 cells	8 cells	8 cells	8 cells
2C	8 cells	8 cells	8 cells	8 cells	8 cells	8 cells
C/1	8 cells	8 cells	8 cells	8 cells	8 cells	8 cells
C/2	8 cells	8 cells	8 cells	8 cells	8 cells	8 cells
C/10	8 cells	8 cells	8 cells	8 cells	8 cells	8 cells

5.4.10 Endurance Testing

Endurance testing shall be performed to measure the performance of lithium-ion cells related to permanent changes associated with time and electrical cycling. Endurance test reports summarizing cell/module performance and key performance trends shall be updated on at least an annual basis.

5.4.10.1 Capacity Fade Due to Storage

This long-term storage test shall assess the effect of various temperatures and SOC levels on cell capacity.

5.4.10.1.1 A standard capacity measurement per Section 5.4.2 shall be performed at ambient temperature on each cell prior to starting the storage test.

5.4.10.1.2 Fifteen cells at minimum shall be charged to each of the following state of charge levels at ambient temperature: 5%, 30%, 50%, 75%, and 100%.

5.4.10.1.3 Five cells at minimum shall be stored at each of the following controlled temperatures: 0 deg C, 20 deg C, and 40 deg C for each SOC.

5.4.10.1.4 After 3 months, 6 months, 1 year, and annually after that, each cell shall be removed from storage and brought to ambient temperature for capacity characterization using two standard capacity cycles per Section 5.4.2.

5.4.10.1.5 Following completion of the capacity measurement cycles, each cell shall be charged back to its specified storage SOC and placed back into storage at its specified temperature.

5.4.10.1.6 Individual cell voltage, currents, and temperatures shall be continuously measured and recorded throughout all nonstorage portions of the testing.

5.4.10.1.7 This test shall be performed for a minimum of five years or until cell capacity degrades to 80% of the manufacturer's rated capacity.

Table 4. Test Matrix for the Storage Capacity Fade Test

Test Conditions	5% SOC	30% SOC	50% SOC	75% SOC	100% SOC
0 deg C	5 cells	5 cells	5 cells	5 cells	5 cells
20 deg C	5 cells	5 cells	5 cells	5 cells	5 cells
40 deg C	5 cells	5 cells	5 cells	5 cells	5 cells

5.4.10.2 OCV Decay During Storage

This test shall be conducted to assess the effects of long-term storage on the open-circuit voltage of a cell starting at various SOC levels.

5.4.10.2.1 A minimum of five cells shall be charged to each of the following SOC: 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. As an option, a minimum of 12 cells shall be charged to each of the following SOCs: 25%, 50%, 75%, and 100%.

5.4.10.2.2 Cells shall be stored in a temperature-controlled chamber at 20 deg C and temperature recorded at least daily.

5.4.10.2.3 The OCV of each cell shall be measured and recorded on at least a monthly basis.

5.4.10.2.4 The minimum duration of this test shall be 365 days or until cell reaches the minimum discharge voltage threshold.

5.4.10.2.5 The OCV decay rates of all the cells shall be trended with time.

Table 5. Test Matrix for OCV Decay During Storage

Test Conditions	5% SOC	10% SOC	20% SOC	30% SOC	40% SOC	50% SOC	60% SOC	70% SOC	80% SOC	90% SOC	100% SOC
20 deg C	5 cells	5 cells	5 cells	5 cells	5 cells	5 cells	5 cells	5 cells	5 cells	5 cells	5 cells

5.4.10.3 Accelerated Lifecycle Test

An accelerated lifecycle test shall be conducted to assess the cycle life capability of the cell type for relatively high-stress operational conditions in the series strings that will be utilized in batteries. A 40%

DOD is selected for this reason, along with relatively high C/2 charge and discharge rates. The data from this test will provide a relative indication of life capability and a baseline for comparison to future COTS cell lots.

5.4.10.3.1 Cells shall be wired into 8S modules for cycling, with one module from cells tested through environment and another from cells tested through environments and radiation.

5.4.10.3.2 Within each of these sets of cells, the cell capacities, the initial voltages, and the OCV decay rates shall be matched as performed for flight batteries.

5.4.10.3.3 The modules shall be cycled in a thermal chamber set to 20 deg C, with continuous monitoring and recording of the module voltage, temperatures, and current.

5.4.10.3.4 The discharge time shall be 0.8 hour to represent a 40% DOD at a C/2 discharge rate, and the peak recharge rate will be C/2 for 1.2 hours, giving 12 cycles per day.

5.4.10.3.5 The peak recharge voltage for each module shall be 8 times the maximum specified cell voltage.

5.4.10.3.6 After 750 cycles, a standard capacity discharge per Section 5.4.2 shall be performed to a minimum of 24 volts and the data reviewed to determine if continued cycling is warranted.

5.4.10.3.7 Cycling shall continue beginning at the recharge part of the cycle and continued until a maximum module voltage of 8 times the maximum specified cell voltage is reached.

5.4.10.3.8 After the first recharge following standard capacity check, cycling shall be briefly stopped to allow individual cell voltages to be probed, providing cell SOC balance information.

5.4.10.3.9 Additional capacity discharges per paragraphs 5.4.10.3.6 to 5.4.10.3.8 shall be done at least annually to trend performance until only 80% of the manufacturer's rated capacity is remaining.

5.4.10.4 Lifecycle Test at 100% DOD

This test shall be conducted to assess the performance fade rate of the cells postenvironmental test under very high-stress cycling conditions and is intended to provide comparative endurance trend rates across COTS cell lots for verification purposes and across cell types.

5.4.10.4.1 Ten cells shall be equally distributed between the two test temperatures of 20 deg C and 40 deg C.

5.4.10.4.2 Each cell shall be charged at a C/2 peak rate to the manufacturer's maximum specified voltage for the cell, and then allowed to have the current taper for a total charge time of 2.4 hours (120% total charge return capability with no taper).

5.4.10.4.3 Each cell shall be discharged at a C/2 rate to the manufacturer's minimum specified voltage for the cell, providing 100% of the cell capacity capability.

5.4.10.4.4 Cycling shall be continued and the capacity discharge trended until the capacity drops to less than 80% of the manufacturer's rated capacity or to a lower level as needed.

5.4.10.4.5 Individual cell voltage, currents, and temperatures shall be continuously measured and recorded throughout the test.

5.4.10.4.6 At least two cells with worst-case capacity, resistance, or charge retention degradation shall undergo DPA per Section 5.4.7 and verified to meet requirements.

5.4.11 Safety Testing

Lithium-ion cells can be hazardous if mishandled. Therefore, COTS lithium-ion cells incorporate multiple safety mechanisms to reduce the risk of dangerous failures. Safety testing serves the following purposes:

1. Ensure the cells are safe to use under normal circumstances and after feasible mishandling events.
2. Characterize the operation of safety devices to allow comparisons to be made for future COTS cell lot procurements.
3. Understand the nonhazardous consequences of abuse in terms of the effects on battery performance. These tests are typically done in a containment chamber to safely contain energetic events that may occur.

Safety testing shall be conducted as specified below.

Note: Any prior documented DOT/UN and UL test results on the cell design that meet the cell safety test requirements and criteria in Section 5.4.11 may be presented to the procurement authority for consideration as partial fulfillment of these test requirements. In all cases, the cell vent and burst tests in 5.4.11.1 and verification of weld qualification in paragraph 5.4.6.4 shall be conducted.

5.4.11.1 Vent and Burst Tests

This test assesses the functionality of the safety vent mechanism and its relationship to cell can failure. Cells shall contain electrical tabs welded per the qualified weld process to verify the weld heat affected zone has not compromised the operation of the vent.

5.4.11.1.1 At least three cells shall be instrumented via case penetration to record internal pressure. Each cell shall be pressurized at a rate of 5 ± 1 psi with dry nitrogen while holding for a minimum of 5 seconds at each step until the cell pressure relief vent mechanism opens.

5.4.11.1.2 At least two cells with the pressure relief vent securely sealed shall be instrumented to record internal pressure. Each cell shall be pressurized at a rate of 5 ±1 psi with dry nitrogen while holding for a minimum of 5 seconds at each step until the case bursts.

5.4.11.1.3 The criteria to pass this test shall be a minimum measured case burst pressure of at least three times the maximum measured cell vent pressure.

5.4.11.1.4 Photographs shall be taken of each cell postpressure relief test and burst test, and provided as part of the end-item data package.

5.4.11.2 Overdischarge Test

At least two cells, starting at 100% SOC, shall be discharged at a C/2 rate, sequentially overdischarging to each of the following final discharge voltages: 0.0, -0.5, -1.0, -1.5 volts, then discharging for at least 3 hours below minimum specified voltage for cell to achieve overdischarge to 150% of rated capacity.

5.4.11.2.1 Cell voltage current and temperature shall be measured during each test and documented.

5.4.11.2.2 Overdischarge shall be limited to 3 hours maximum duration if any cell does not reach the desired final voltage.

5.4.11.2.3 Cells passing this test shall exhibit no disassembly, leakage, venting, or fire within 7 days after the test.

5.4.11.2.4 Pictures of each cell shall be taken following safety test completion and provided as part of the end-item data package.

5.4.11.3 Overcurrent Test

Series-connected cells shall be discharged at a high rate through a low external resistance to simulate a short circuit as defined below to evaluate the operation of the cell and the safety devices used in many COTS cells.

5.4.11.3.1 Cells shall contain electrical tabs welded per qualified weld process to verify the weld heat affected zone has not compromised the operation of the vent.

5.4.11.3.2 The overcurrent test shall be performed on Ns1p modules, where N is the maximum number of series cells that will potentially be connected in individual strings within a flight battery.

5.4.11.3.3 Pack voltage, current, and temperature on each cell shall be measured during the entire test, and for at least 6 hours after the application of the short circuit and then documented.

5.4.11.3.4 Prior to applying the overcurrent, each module shall be fully charged to N times the maximum cell voltage allowed by the cell manufacturer.

5.4.11.3.5 At least two modules shall be subjected to a 50-mΩ short circuit starting at -10 deg C and at +20 deg C, and three modules starting at +40 deg C will be subjected to 10-mΩ, 50-mΩ, and 100-mΩ short circuits.

5.4.11.3.6 Packs passing this test shall exhibit no temperatures exceeding 170 deg C, cell or pack disassembly, venting, or fire during test and within 6 hours after test completion.

5.4.11.3.7 Pictures of each cell string shall be taken following completion of safety test and provided as part of the end-item data package.

5.4.11.4 Overcharge Test

This test shall be conducted by charging cells beyond the nominal 100% SOC until failure to assess the operation of the Current Interrupt Device (CID) protection system, as defined below, with at least one cell fully charged to the maximum voltage specified by the manufacturer.

5.4.11.4.1 Cells shall contain electrical tabs welded per qualified weld process to verify the weld heat affected zone has not compromised the operation of the vent.

5.4.11.4.2 Each cell shall be overcharged at the specified rate and starting temperature until either the cell fails (CID opens and current drops to zero) or until 200% overcharge has been reached while continuously monitoring cell voltage, current, and temperature.

5.4.11.4.3 Cells that have only been screened shall be overcharge tested starting at 0 deg C and at 40 deg C at each of the overcharge rates of C/10 and 2C.

5.4.11.4.4 Cells that have only been screened shall be overcharge tested starting at 20 deg C/ambient at each of the overcharge rates of C/10, C/2, C, 2C, and 6C (or all rates up to the maximum current specification from cell manufacturer).

5.4.11.4.5 Cells that have completed environmental test shall be overcharge tested starting at 20 deg C at each of the overcharge rates of C/10, C, and 2C.

5.4.11.4.6 A cell shall pass this test if the CID opens and the cell case shows no signs of disassembly, venting, and fire within 7 days after test.

5.4.11.4.7 Pictures of each cell shall be taken following safety test completion and provided as part of the end-item data package.

Table 6. Overcharge Test Conditions

Test Temperature	Environmental Test?	C/10 charge rate	C/2 charge rate	C charge rate	2C charge rate	6C charge rate
0 deg C	No	X			X	
20 deg C	No	X	X	X	X	X
40 deg C	No	X			X	
20 deg C	Yes	X		X	X	

5.4.11.5 Internal Short Circuit Test

The COTS cell lot shall be tested to demonstrate the severity of an internal short circuit event.

5.4.11.5.1 A internal short circuit shall be induced on five individual cells that are at 100% state of charge and stabilized to 20 deg C.

5.4.11.5.2 Cell voltage current and temperature shall be measured during each test and documented.

5.4.11.5.3 The evaluation criteria of the short circuit event shall include, at minimum, maximum cell temperature achieved, time to maximum temperature and duration of event, products vented/ejected from the cell, and video of flames/hot gases exiting the cell.

5.4.11.5.4 Internal short circuit may be initiated and triggered within a cell by either a thermal or mechanical method. Thermal method involves heat exposure to damage the separator that insulates the anode and cathode. The mechanical methods involve crushing, penetrating, and/or shock forces applied to the cell. More advanced methods involve implanting defects into a cell either during manufacture or afterward and triggering the short by mechanical or thermal means.

5.4.11.5.5 Measures shall be taken to reduce the likelihood and/or severity of an internal short circuit event to a level acceptable to the program/project.

5.4.11.5.6 A video recording of the entire safety test shall be conducted and provided as part of the end-item data package.

5.4.11.6 Heating Test

A minimum of five cells at 100% SOC and five cells at 50% SOC shall be heated in a temperature-controlled chamber from 20 deg C $\pm$5 deg C to 130 deg C at a rate no higher than 5 deg C $\pm$2 deg C per minute, then held at 130 deg C $\pm$2 deg C for 10 minutes without fire or explosion.

5.4.11.6.1 Each cell voltage and temperature shall be continuously monitored during the entire test to verify voltage stability.

5.4.11.6.2 The cells shall be cooled back to ambient and visually inspected and photographically documented.

5.5 COTS Cell Acceptance Test Requirements

The data reviews and tests specified below shall be performed on all flight cells to validate they meet mission performance requirements and that cell performance uniformity meets cell matching criteria validated by mission life tests.

5.5.1 COTS Cell Lot Data Review

5.5.1.1 COTS Lot Shipment

Documentation shall be provided to demonstrate all qualification and flight cells were procured and shipped together as one group of cells and flight cells were subsequently stored and tested as a group.

5.5.1.2 COTS Lot Uniformity

Documentation shall be provided to validate that the COTS cell lot meets the statistical cell screening uniformity requirements of sections 5.2 and 5.3, including total number of rejected cells for each specific test.

5.5.1.3 COTS Lot Qualification

Documentation shall be provided to validate that all the COTS cells passed qualification test requirements of Sections 5.2 and 5.4.

5.5.1.4 COTS Cell Qualification

Any qualification test originally completed for the COTS cell lot in Section 5.4 that did not verify program-specific battery-level qualification test margin described per Section 7 shall be qualified to the appropriate levels and demonstrated to meet requirements.

5.5.1.5 Flight Cell Assessment Data

Documentation shall be provided of the original assessment data per Section 5.3 for all flight cells to validate that they met all requirements within statistical uniformity.

5.5.1.6 Flight Cell OCV Trend

Documentation for each flight cell OCV trend per Section 5.3.12 shall be provided for the entire storage period, which is at least three months to validate the cells meet the statistical uniformity requirements for cell matching as demonstrated in mission life tests.

5.5.1.7 Flight Cell Age

Time at launch from cell manufacture shall be less than 5 years.

5.5.1.8 Flight Cell End-Item Data Package

After completion of the acceptance tests of Section 5.5, an end-item data package shall be submitted for review and approval.

5.5.2 COTS Acceptance Tests

5.5.2.1 Flight Cell Capacity Test

Each cell shall complete two standard capacity cycles per Section 5.3.7 to validate capacity, voltage, resistance performance, and statistical uniformity requirements following open-circuit voltage storage of Section 5.3.12.

5.5.2.2 Flight Cell Mission Capacity Test (Design Operating Temperature)

Each cell shall complete two electrical cycles that represent the maximum charge and discharge rates expected during flight battery use and meet capacity, voltage, and resistance performance and statistical uniformity requirements.

5.5.2.2.1 The two electrical cycles shall electrically cycle between the maximum and minimum voltage levels defined by the cell vendor, utilizing taper charge as implemented for flight battery usage to bring the cells to a full SOC prior to discharge.

5.5.2.2.2 The two electrical cycles shall be performed at the on-orbit battery operational temperature within ±2 deg C.

5.5.2.2.3 Current, cell voltage, and temperature shall be measured and recorded at least once per 30 seconds.

5.5.2.2.4 DC resistance shall be determined as a function of SOC from the difference between the cell charge and discharge voltages during the second cycle per Section 5.3.10.

5.5.2.2.5 Apparent OCV shall be determined as a function of SOC during the second cycle by interpolating between the charge and discharge voltages to zero current per Section 5.3.10.

5.5.2.2.6 The cells that are outside ±3 sigma of the median value charge capacity, discharge capacity, DC resistance, or apparent OCV during the second cycle shall be documented and excluded from flight battery use.

5.5.2.3 Flight Cell Mission Capacity Test (Maximum Temperature)

The capacity test cycles of Section 5.5.2.2 shall be performed at the battery level maximum acceptance temperature for each cell and meet specified requirements.

5.5.2.4 Flight Cell Mission Capacity Test (Minimum Temperature)

The capacity test cycles of Section 5.5.2.2 shall be performed at the battery level minimum acceptance temperature for each cell and meet specified requirements.

5.5.2.5 Flight Cell Charge Retention Test

Cell charge retention shall be measured at 20 deg C in an open-circuit state starting at 100% SOC for at least 30 days on each cell.

5.5.2.5.1 All cells shall be stored in a temperature-controlled environment where the chamber temperature is measured and documented at least every 24 hours.

5.5.2.5.2 Cell open-circuit voltage shall be measured and recorded with time stamp at 168 ±1-hour and at 30 ±0.04 days postcharge termination.

5.5.2.5.3 Cells that are outside ±3 sigma of the median value for OCV decay rate shall be documented and excluded from flight battery use.

5.5.2.6 Flight Cell Leakage Test

Each cell shall be placed in vacuum to at least 10^{-5} Torr for a period of at least 12 hours where the cell temperature is cycled at least once between the survival, minimum and maximum acceptance temperature limits.

5.5.2.6.1 A residual gas analyzer shall scan every minute during the vacuum test with a capable gas detector tuned to detect volatile electrolyte solvents in the cell with a threshold and accuracy to verify no cell leakage occurred.

5.5.2.6.2 The mass of each cell shall be measured to an accuracy of 0.001 grams before and after vacuum test to verify the mass is within 0.2% of the initial COTS cell lot screening value.

5.5.2.7 Flight Cell X-rays

5.5.2.7.1 All cells selected as flight cells shall have cell level x-rays performed to verify that they meet the criteria of paragraphs 5.3.6.1a through l if one or more of the qualification cell x-rays failed to meet the requirements of Section 5.3.6.

5.5.2.7.2 If all qualification cells exposed to x-ray in Section 5.3.6 met criteria, all flight cells shall have closeout x-rays taken and available for review at cell buy-off or prior to flight battery cell matching.

5.5.2.8 Flight Cell Isolation

Terminal-to-case isolation shall be measured and documented for each cell following acceptance electrical and leakage tests to verify cell isolation is greater than 10 MΩ, as applicable.

5.5.2.9 Flight Cell Visual Inspection

Each cell shall be visually inspected at 10X minimum for dents, scratches, stains, contamination, corrosion, or other factors that could complicate welding tabs to the cell or impact cell performance and verified to be within established criteria of paragraph 5.3.1.3 following completion of all acceptance tests.

6. Battery Design Requirements

6.1 Battery Design

The following battery-level design requirements shall be implemented and verified.

6.1.1 The battery shall have appropriate labels that identify battery chemistry, Ah capacity, battery voltage, part number, date of manufacture, and manufacturer's identity.

6.1.2 Each cell, power harness, and cell-to-cell interconnects shall be isolated from the battery surface by at least two layers of electrical insulating material that endures all phases of battery assembly and environments through end of life (i.e., materials used must resist tear and cold flow squeeze down loss of thickness over life).

6.1.3 Battery wiring, power leads, and cell-to-cell interconnects shall be sized appropriately with margin for current and heat-carrying capability based on the worst-case currents and temperatures expected for the design.

6.1.4 All battery and cell voltage sense lines shall have a fuse or be otherwise protected in the event of an external short.

6.1.5 Enclosed battery housing shall be designed to leak before burst can occur.

6.1.6 Cell vent orientation shall also be considered to protect the battery from additional damage in the event of cell venting.

6.1.7 Contact between dissimilar metals within the battery shall be protected against galvanic corrosion.

6.1.8 The output power of any battery heater shall be designed such that they do not initiate thermal runaway of the battery cells in the event of a heater malfunction.

6.1.9 Isolation barrier, such as wraps and coatings used inside the battery housing shall not react with electrolyte and be compatible with mission environmental requirements.

6.1.10 The battery system shall be operated in a way that preserves measurably positive margins in operating voltage, current, temperature, and cycle life versus the manufacturer's limits for the cell design.

6.1.10.1 For a battery designed without available cell voltage monitoring, the maximum battery charge voltage during ground test, qualification test, acceptance test, and on-orbit operation shall be no greater than the following:

Maximum battery voltage = (# cells in series string) x (cell vendor's maximum cell voltage – 0.020V)

6.1.11 Cell restraint/retention within the battery pack shall utilize an effective independent mechanical cell restraining system and not rely only on friction to prevent cells from moving during dynamic environmental testing.

6.2 Predesign Development Tests

The objective of development testing is to identify problems early in the design evolution so that any required corrective actions will be taken prior to starting formal qualification or battery-level CDR.

6.2.1 Each battery and cell bank design, supplier, and manufacturing location shall be validated for intended application and environments through developmental testing outlined below for each cell chemistry, design, supplier, and manufacturing location. Existing development data may be used to substantiate the requirements below.

6.2.2 Development testing characterizes the battery, cell-bank and cell-level performance, structural/thermal margins, dimensional requirements, compatibility to prelaunch, launch, and space environments, manufacturability, testability, maintainability, reliability, and compatibility with requirements.

6.2.3 Development tests are conducted at the battery, cell bank, cell string, and cell level over a range of operating conditions including temperature, discharge, and charge control that exceeds the design range to verify margins in capability to define threshold limits.

6.2.4 Each battery and cell design, supplier, and manufacturing location shall be verified to be appropriate for the intended application and environments through developmental testing outlined in Section 6.3 through Section 6.9 for each cell chemistry, design, supplier, and manufacturing location. Existing development data may be used to substantiate the requirements in Sections 6.3 through 6.9.

6.3 Battery Electrical Performance

The following battery-level development testing shall be conducted to verify the battery-level electrical performance requirements, unless data is provided to verify that these requirements have been met.

6.3.1 Electrical capacity, impedance, and energy tests shall be characterized over a temperature range of at least ±10 deg C outside the qualification temperature range to characterize battery operation, charge-discharge currents, and voltage performance/limits to define the basis for battery-level performance requirements and margins for both beginning and end of life.

6.3.2 Battery, cell bank, or cell-level charge conditions (voltage and current) shall also be characterized at temperatures following worst-case cold soak to simulate dead bus recovery.

6.3.3 Charge retention at the battery level shall be conducted at temperatures consistent with operating, test, and storage at both 100% state of charge and storage state of charge with and without charge balance circuitry attached (see Section 7.3.2.3 for durations).

6.3.4 The specific test method adopted for the above electrical tests shall be defined, documented, and maintained for execution during subsequent future testing for trending purposes.

6.4 Battery Charge Control Testing

The charge control electronics shall be tested to determine whether the charge control method and conditions are appropriate to maintain battery performance for the intended application throughout service life.

6.4.1 Battery, cell, or cell bank voltage, temperature, current, shall be measured to characterize cell balancing capability for a flightlike battery to demonstrate a charge control design that meets the requirements for all vehicle operations, including sun periods, launch, transfer, and early orbit operation.

Note: For battery designs using COTS cells without available cell balancing electronics, cell level voltages may not be available.

6.4.2 Charge control designs and cell balancing electronic designs (as applicable) shall be validated during the life test (see paragraph 8.3.2).

6.5 Battery Thermal Control Characterization and Testing

Thermal characterization tests at the cell, cell bank, and/or battery level shall be performed to verify the battery thermal control design over mission life.

6.5.1 Battery-level thermal analysis shall validate temperature limits are not exceeded with worst-case end-of-life impedance growth.

6.5.2 Cell thermal dissipation, worst-case hot and cold temperatures, and thermal gradients shall be measured as outlined below to demonstrate the battery thermal control design meets the requirements for all mission conditions and vehicle operations and orientations, including sun periods, safe mode, launch, transfer, and/or early orbit operation. Thermal development tests that may be used to obtain this data include:

a. Perform a thermal characterization test at the cell, cell bank, and/or battery level in a temperature-controlled environment, such as a calorimeter or thermal vacuum chamber. Data from these tests measure and validate the cell-level thermal dissipation or quantify the external temperature and gradient as a function of charge/discharge conditions.

b. Perform a thermal conductance test to quantify the heat transfer through materials and/or across interfaces. Specific measures may include the directional conductivity in composites, the conductance across cabling, terminal/interconnect interfaces, thermal blanket performance, or any other potentially significant heat conduction path, including the cell to the radiator or across battery-to-spacecraft interfaces.

c. Perform a thermal balance test at the battery level, which can provide steady-state and/or transient data for thermal model correlation and validate the battery thermal control design. This test verifies functionality, operation, and performance of heaters, thermostats, flight thermistors, radiators, heat pipes, and heat generation during bypass operations, and demonstrates temperature and heater margins.

6.6 Battery Mechanical Test

The mechanical tests shall be performed to determine whether the proposed technology and design concept are consistent with required battery performance throughout the service life.

6.6.1 The battery mechanical design shall be characterized as outlined below for all intended environments including resonance, vibration, shock, acceleration, and pressure/vacuum to validate that the structural design meets the requirements for all mission conditions and vehicle operations, including sun periods and contingencies.

6.6.1.1 Resonance searches of a battery shall be conducted to correlate with a mathematical model and to support design margin or failure evaluations.

6.6.1.2 When a battery's structural design includes advanced composites or bonded materials, development tests shall be conducted as specified in paragraph 6.2.3 of SMC-S-016/TR-RS-2014-00016 [1].

6.6.1.3 Vibration and shock test fixtures shall be characterized prior to first use to prevent inadvertent overtesting or undertesting including avoidance of excessive cross-axis response.

6.6.1.4 A sample of three cells minimum shall be selected for cell-level computed tomography (CT) x-ray before and after environment tests at the cell level per paragraph 4.3.4 and post-test DPA per Section 8.12.

6.6.1.5 Pressure testing shall be conducted on battery enclosures with pressure relief valves or pressure relief mechanisms per SMC-S-016/TR-RS-2014-0016 [1] and Section 7.3.10 of this document.

6.6.1.6 The placement of the cell vents shall be verified to not be impeded by other cells or battery subcomponent or impact other cells, electronics, harness, or battery structure should venting occur.

6.7 Transportation and Handling Tests and Requirements

Handling and transportation environments shall be defined to ensure they do not exceed the battery design limits and meet the following requirements:

6.7.1 The battery shall not be exposed to excessive structural loading due to handling orientation and worst-case shock and vibration environments.

6.7.2 Handling and transportation loading environment shall be considered in the structural design of the hardware, and not result in load cycles causing fatigue or wear, even though the amplitude of the cycles may be low relative to flight loads. SMC-S-016/TR-RS-2014-00016 [1] and AIAA-S-110-2005 [22] provide guidance for defining transportation environment, design, and test requirements.

6.7.3 Test data shall be used in the analysis per AIAA-S-110-2005 [22] to (1) determine whether the environments are benign, relative to the design requirements, (2) provide a basis for improving the packaging protection design or to otherwise provide a basis for an analysis to demonstrate that damage has not been incurred during transportation or handling, and (3) define specific mechanical environmental levels for qualification and acceptance testing.

6.8 Safety Testing

Safety requirements for the lithium-ion battery design, safety testing, and ground operation shall meet Air Force Range Safety AFSPCMAN 91-710 [14] and Department of Transportation (DOT) requirements [15] and space debris requirements specified in Section 3.4 of this document.

6.9 Failure Mode Analysis and Test

6.9.1 Due to potential catastrophic effects of a cell failure, the cell, cell bank, and battery shall be analyzed for all potential failure modes and the potential of cell failure propagating to other cells or piece parts in accordance with SMC-S-013 [23].

6.9.2 A battery-level analysis shall be performed where cell-, cell bank-, or battery-level development testing is used to evaluate the potential of one-cell failure cascading failure. Cell-level development testing should inform the battery-level analysis.

6.9.3 If cell development characterization or safety tests result in thermal runaway unmitigated by battery design, system control, or operational procedures, the following characterization tests shall be performed:

6.9.3.1 The lowest testability level shall be based on the battery design and encompass the maximum parallel cell configuration and include relevant harness, piece parts, and battery case.

6.9.3.2 The preferred test method is a vacuum environment.

6.9.3.3 Each cell and key component (e.g., relay, diode, electronics, harness, bypass switch) shall have a minimum of one thermistor for the test to monitor temperature. If a flight thermistor is not available, each cell and key component shall have a minimum of one thermistor added for the test to monitor cell/component temperature.

6.9.3.4 Battery terminal (positive and/or negative) to battery chassis isolation shall be measured to verify that electrical isolation is maintained throughout the test and no additional current paths are created.

6.9.3.5 Electrical isolation between battery chassis and all electrical components (e.g., cell, cell harness, piece parts, etc.) shall be measured continuously throughout the test.

6.9.3.6 The test article shall be stabilized at worst-case hot temperatures prior to initiating the thermal runaway test.

6.9.3.7 The cell location selected as the thermal runaway trigger cell shall be based on being the most likely cell position that will lead to thermal propagation to surrounding cells in the test battery or module.

6.9.3.8 The test shall be monitored for at least 24 hours after triggering the cell into thermal runaway to assess for cell-to-cell propagation.

6.9.3.9 Any propagation of cell or cell bank thermal runaway shall not affect more cells, cell banks, or batteries than allowed by battery design redundancy nor degrade the mechanical structure or spacecraft functionality.

6.9.3.10 The remaining cells and cell banks shall be verified to be fully operational during and following the cell or cell bank thermal runaway test unless spacecraft is designed with battery-level redundancy.

6.9.3.11 Cell or cell bank thermal runaway shall not result in any remaining cell or cell bank, harness, or other assembly exceeding specified survival temperature and vendor maximum recommended temperature limit.

6.9.3.12 Cell or cell bank thermal runaway shall not result in debris external to battery case.

6.9.3.13 Any debris, vapors, flame, or other contaminate generated external to the battery resulting from a failure shall be analyzed to quantify other system-level impacts of a battery or battery component failure scenario.

6.9.3.14 A video recording of the entire safety test shall be conducted for at least 24-hours and provided as part of the end-item data package.

7. Battery Qualification (Protoqualification) Testing

7.1 Qualification testing shall be conducted on a single battery or battery module (see Note below) to demonstrate that the intended flight design, manufacturing process, and acceptance program produce battery hardware, test techniques, procedures, equipment, instrumentation, and software that meet specification requirements with the margin to accommodate normal production variation, multiple rework, and test cycles per SMC-S-016/TR-RS-2014-00016 [1] and the additional requirements below:

7.1.1 The qualification battery shall undergo a corresponding test as outlined in Sections 7.3.1 through 7.3.15, and Section 8.

7.1.2 All subsequent changes in the battery, cell, or piece-part design (or process including change in supplier or manufacturing location) shall be evaluated to determine if it is considered a different battery, cell, or piece-part design that requires requalification.

7.1.3 One qualification battery shall be exposed to all applicable environmental tests in the order of the qualification test plan specified in Section 7.3 and per the test level margins and durations specified in Table 6.3-3 in SMC-S-016/TR-RS-2014-00016 [1].

7.1.4 Pass/fail criteria shall be established for all cell in-process inspections and tests as well as all battery qualification inspections and tests based on the design and intended application, and verified during battery qualification.

7.1.5 Test plans and procedures shall be documented in detail to provide a framework for identifying and interrelating all the individual tests and test procedures needed, and to meet the requirements defined in SMC-S-016/TR-RS-2014-00016 paragraphs 4.8.1 and 4.8.2 [1].

7.1.6 When an existing battery design has identical cell and piece-part designs and applications that previously completed qualification test, battery protoqualification testing can be used to substantiate the requirements below using the protoqualification environmental test levels and durations as specified in SMC-S-016/TR-RS-2014-00016 [1] with supporting qualification data.

7.1.7 The qualification battery shall have previously undergone a corresponding test as outlined in Sections 7.2 through 7.3.15 and Section 8.

7.1.8 Protoqualification testing shall meet the requirements and criteria defined within Sections 7 and 8 except with test level margins and durations as allowed per Table 6.3-3 in SMC-S-016/TR-RS-2014-00016 [1].

7.1.9 When protoqualification test is substituted for qualification test, qualification data and reports shall be supplied.

Note: For the purpose of qualification, when the battery is made up of multiple identical modules mounted separately on the spacecraft, the module can be substituted for the battery.

7.2 Qualification Test

7.2.1 Test Hardware

7.2.1.1 The battery and cell hardware subjected to qualification testing shall be produced in the same manufacturing facility, from the same cell and battery design, using the same level of parts, materials, tooling, manufacturing process, and level of personnel competency as used for flight hardware. If possible, a qualification battery or module should be randomly selected from a group of flight items.

7.2.1.2 Cells subjected to qualification test within the battery shall be from the same cell design as used for Section 8 life qualification tests and/or changes from that design shall be identified and qualified. (Document control verification for COTS cells is not normally assessable to the cell purchaser.)

7.2.1.2.1 COTS cells subjected to qualification test shall also be from the same flight COTS cell lot.

7.2.1.3 All cells in the qualification battery shall be from a single cell lot (may consist of one or more production runs) or a single COTS cell lot as defined in Section 2.

7.2.1.3.1 In a cell lot, all cells shall be uniquely identified with a serial number assigned at electrode stacking or winding (not to be repeated within a lot) and included in the cell case marking (or lot date code for COTS cells).

7.2.1.3.2 All cells within the cell lot shall be traceable to the individual cell production run (or lot date code for COTS cells).

7.2.1.3.3 Cell serial number traceability shall be maintained through battery build and test.

7.2.1.4 Piece parts that are included within the battery, such as resistors, capacitors, diodes, heaters, relays, fuses, bypass switches, and circuit board assemblies, shall meet the requirements of SMC-S-009 [7] and SMC-S-010 [19].

7.2.1.5 Any electronic assembly that is attached to or assembled as part of the battery shall meet SMC-S-016/TR-RS-2014-00016 [1] qualification requirements for an electrical and electronic unit prior to installation on a battery.

7.2.1.6 Additional instrumentation beyond flight battery design (e.g., thermistors) can be added during qualification test to validate the design.

7.2.1.7 Battery and cell-voltage accuracy used for charge control and cell balancing shall be verified to meet voltage accuracy requirements of AIAA S-122/T [24] at the end of qualification test.

7.2.2 Qualification Test Levels and Duration

7.2.2.1 Qualification test levels and durations shall be per SMC-S-016/TR-RS-2014-00016 [1].

7.2.3 Qualification Retest

Battery qualification retest shall meet the requirements of SMC-S-016/TR-TS-2014-00016, paragraph 4.3.2.3 (4.3.3.3 for protoqualification) [1] and is also applicable when the manufacturer and/or manufacturer location changes.

7.2.4 Data Collection and Acquisition Rates

7.2.4.1 Numerical values for voltage, temperature, current, capacity, and impedance shall be recorded and assessed by indicating PASS or FAIL against a range of values provided in the approved test plan.

7.2.4.2 Cell (or cell bank) and battery voltage, current, and temperature measurements shall be monitored and recorded at rates within a contractor-established allowable experimental uncertainty that supports the test success criteria. Note: For battery designs using COTS cells without cell-balancing electronics, cell voltage measurements are typically not available.

7.2.4.3 The cell (or cell bank), battery voltage, and current shall be electrically monitored during any dynamic environmental test and be collected at an acquisition rate of at least 10,000 samples per second to evaluate for intermittent dropouts. Note: For battery designs using COTS cells without cell-balancing electronics, cell voltage measurements are typically not available.

7.2.4.4 Temperature measurements shall be from temperature sensors mounted on cells and key piece parts inside the battery (e.g., relays, diodes, bypass switches, electronics, harness).

7.2.5 Cell Matching Criteria

7.2.5.1 For each battery design, the cell matching criteria shall be defined, documented, and applied on all qualification, life test, and flight batteries.

7.2.5.2 Cell matching criteria for the battery shall be the same as or tighter than that used for the qualification life test cells.

7.2.5.3 The cell matching criteria shall include at a minimum: capacity, energy, charge retention, impedance at a defined voltage or state of charge, and temperature.

7.2.5.4 The cell lot (or COTS cell lot) shall be procured, stored, tested, and delivered together to maintain a flight battery cell lot for a shipset or single lot definition.

7.2.5.5 To maintain cell matching throughout life, all the cells within a battery shall be exposed to the same electrical current and all cells within a battery exposed to the same thermal environment.

7.2.5.6 All cells in the battery shall be from a single cell lot (may consist of one or more production runs) or single COTS cell lot as defined in Section 2 and the following:

7.2.5.6.1 For configuration control cell lots the maximum period of time the cell lot build shall span, defined as electrode mixing to cell activation, is to be documented and verified by lifecycle performance test.

7.2.5.6.2 An acceptable lifecycle performance test shall include cells built spanning the maximum specified production run and cell lot time period consisting of realtime, accelerated, or worst-case cycling over a duration that demonstrates similar and stabilized performance.

7.2.5.6.3 The cell lot (or COTS cell lot) shall be verified to have statistically unchanged performance from the lot used for life qualification tests.

7.2.6 In-Process Inspections and Tests

7.2.6.1 All critical processes as defined in SAE AS6500 [25] for battery manufacturing shall be performed in accordance with documented AS6500-compliant in-process controls and inspections.

7.2.6.2 The processes, in-process controls, and criteria shall be qualified per Section 3.2.

7.2.6.3 Compliance with the documented process controls, inspection requirements, and general workmanship requirements shall be verified and data maintained.

7.2.7 Qualification Documentation

Buy-off documentation shall be provided at the completion of cell qualification test and battery qualification test and include the following items:

a. Battery and cell lot (or COTS cell lot) electronic copy of the end-item data package
b. Battery and cell lot (or COTS cell lot) certificate of conformance
c. Battery and cell lot (or COTS cell lot) closure of action items from critical design review, manufacturing readiness review, and test readiness review
d. Battery and cell lot (or COTS cell lot) engineering changes since CDR
e. Battery and cell lot (or COTS cell lot) hardware discrepancy and failure analysis reports
f. Battery and cell lot (or COTS cell lot) test discrepancy and failure analysis reports
g. Battery and cell lot (or COTS cell lot) deviations and waivers
h. Battery and cell lot (or COTS cell lot) in-process inspection and test data
i. Battery and cell (or COTS cell lot) specifications
j. Battery and cell qualification procedures, as-run
k. Battery and cell lot (or COTS cell lot) test equipment calibration record
l. Battery and cell lot (or COTS cell lot) travelers
m. Cell lot or COTS cell lot summary and attribute in-process data
n. Cell selection and matching criteria report
o. Specification compliance verification report
p. Battery and cell lot (or COTS cell lot) qualification test data
q. Battery and cell lot (or COTS cell lot) acceptance test data
r. COTS cell lot assessment test data
s. Battery and cell development data, as applicable
t. Test data and analyses supporting the requirement or waiver of qualification test for shock, static load, climatic environments, proof pressure, electromagnetic compatibility (EMC), and thermal cycling
u. Battery and cell lot (or COTS cell lot) burst pressure, vent rupture pressure, proof pressure, and pressure cycling results, as applicable
v. Battery and cell report correlating thermal test data with thermal model predictions
w. Battery and cell safety data, videos, and analysis report
x. Battery and cell radiation data and analysis report
y. High-reliability parts (cell, electronic, or mechanical devices) buy-off and qualification report
z. Battery and cell level as built assembly level, interface control and wiring drawing (Note: For COTS cell lots, cell-level drawings may not be available)
aa. Battery- and cell-level list of build drawings, manufacturing procedures and test procedures identifying revision that were used to build and test the qualification battery (Note: For COTS cell lots, cell-level manufacturing and build data may not be available)
bb. Battery- and cell-level age-sensitive component record
cc. Telemetry coefficients for all analog telemetry
dd. Electronic format of cell- and battery-level raw test data
ee. Electronic format of cell- and battery-level raw life test data
ff. All cell x-rays performed as uncompressed TIFF files
gg. DPA results from before and after qualification environmental test, life test, or other investigation
hh. High-definition photographs of battery and cell during inspections and DPAs
ii. Battery and cell-voltage calibration report (Note: For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are generally not available)
jj. Battery and cell inspection and test products, and handling procedures.

7.3 Qualification and Protoqualification Tests

The qualification or protoqualification battery shall be subjected to the tests outlined below.

Table 7. Qualification and Protoqualification Testing

Test	Spacecraft Application	Suggested Test Sequence	Paragraph
Inspection/Leakage	R	1,14	7.3.1
Specification Performance	R	2,13	7.3.2
Shock	ER	3*	7.3.4
Vibration	R	4*	7.3.5
Acceleration	ER	5*	7.3.6
Thermal Cycle	R	6*	7.3.7
Thermal Vacuum/Leakage (1)	R	7*	7.3.8/7.3.3
Climatic Environments	ER	8**	7.3.9
Proof Pressure (2)	R	9**	7.3.10
Electromagnetic Compatibility	ER	10	7.3.11
Static Load	ER	11	7.3.12
Burst Test (2)	R	12	7.3.10
Safety	R	15*	7.3.13
Radiation	ER	16*	7.3.14
Life	R	17*	8.0
Failure Modes	R	18*	7.3.15

R: Required
ER: Written and approved evaluation required by contractor
* Inspection (7.3.1) and specification performance (7.3.2.1.1.c, 7.3.2.3, 7.3.2.4 and 7.3.2.5) performed before and after test.
** Inspection (7.3.1) performed before and after test.
(1) Thermal vacuum test should be performed as the last environmental test.
(2) 100% proof pressure and qualification lot sample burst test is required at the cell level. Battery-level proof or burst test required only if design enclosure contains a pressure relief valve.

7.3.1 Inspection

7.3.1.1 The battery shall be inspected, and measurements made before box closeout and postqualification test to verify compliance with the specification.

a. As-built vs. as-designed configuration
b. Electrical, mechanical, thermal interfaces
c. Design and construction requirements
d. Weight
e. Dimensions
f. Clearances
g. Condition of hardware (damage)
h. Electrical isolation
i. Electrical continuity
j. Finish
k. Fastener tightness torques or visual inspection of staked fasteners
l. Identification markings
m. Cleanliness
n. Workmanship
o. Electrolyte leakage
p. Condition of vent disks when included in the design
q. Temperature sensors

7.3.1.2 Inspection of battery hardware following completion of qualification shall entail disassembly to the extent that wear and/or mechanical integrity can be confirmed. For qualification battery to be subjected to life test, an abbreviated inspection (e.g., removal of battery case top) may be performed to inspect electrical connections before life test and disassembly inspection at the conclusion of life testing.

7.3.1.3 The battery shall be inspected before and after each environmental test to identify discrepancies resulting from testing or test conditions, including:

a. Condition of hardware (damage)
b. Electrical isolation
c. Electrical continuity
d. Fastener tightness torques or visual inspection of staked fasteners
e. Cleanliness
f. Roll test – 360-degree rotation while mounted on trunnion (after mechanical environmental test only)
g. Electrolyte leakage
h. Condition of vent disks when included in the design

7.3.1.4 The results of the inspections and measurements shall be recorded in detail to determine significant changes in the condition of the battery after each environment test.

7.3.2 Specification Performance

The specification performance tests shall verify that the electrical and mechanical performance of the battery meets the requirements of the battery specification.

a. Battery discharge during ground testing shall simulate the in-flight spacecraft power system operation. Note: This may be accomplished with constant current discharge; however, constant power discharge is the preferred method if it more closely simulates spacecraft power.

b. The electrical testing specified shall characterize the battery qualification performance over the full voltage and temperature range unless otherwise stated.

c. Sections 7.3.2.1.1.c, 7.3.2.3, 7.3.2.4, and 7.3.2.5 shall be performed to fulfill the specification performance element of qualification/protoqualification testing, before and after environmental testing.

7.3.2.1 Battery Capacity (or Energy)

7.3.2.1.1 The battery capacity or energy shall be measured at specified charge conditions to the maximum charge voltage, with cells in a balanced state, followed by a C/2 discharge rate to the minimum voltage level, for each of the following five temperature conditions:

a. Maximum qualification temperature (acceptance temperature +10 deg C)
b. Maximum acceptance temperature
c. Design operating point acceptance temperature
d. Minimum acceptance temperature
e. Minimum qualification temperature (acceptance temperature –10 deg C)

Note 1: Select appropriate charge-discharge rates to simulate expected on-orbit rates at cold temperatures.

Note 2: Protoqualification temperatures are acceptance temperature ±5 deg C.

7.3.2.1.2 The battery shall achieve capacity/energy stability within 1% for two consecutive cycles, up to three cycles maximum, for each temperature condition specified in paragraph 7.3.2.1.1.

7.3.2.1.3 If the battery capacity test conditions are different than the cell level, an additional capacity cycle shall be performed using the cell-level conditions for comparison.

7.3.2.2 Mission-Specific Performance Requirements

7.3.2.2.1 Electrical parameters shall meet intended usage (such as constant power discharges)

7.3.2.2.2 Mission-specific requirements, if not included in the conditions specified by paragraph 7.3.2.1, shall be verified at expected on-orbit temperatures following cell balancing (as applicable) to maximum and minimum voltages:

a. Minimum charge and discharge rates
b. Design operating charge and discharge rates
c. Maximum charge and discharge rates
d. Pulse power requirements

7.3.2.3 Battery Charge Retention

Battery charge retention shall be measured at 20 deg C in an open-circuit state starting at 100% state of charge to screen out potential internal shorts while electrode stack is under the highest mechanical force and at a region with the highest voltage sensitivity.

7.3.2.3.1 Any charge control electronics or voltage monitoring devices mounted on the battery shall be electrically disconnected to the maximum extent possible to eliminate/minimize parasitic current leakage.

7.3.2.3.2 Cell or cell bank open-circuit voltage measurements shall be periodically taken at least every 24 hours ±1 hour postcharge termination for a total period of 168 hours for designs that contain cell balancing electronics or 30 days for designs without cell-balancing electronics and be within established criteria for open-circuit voltage drop.

7.3.2.3.2.1 For battery designs using COTS cells without available cell balancing electronics, battery voltage measurement may be used in lieu of cell voltage measurements.

7.3.2.3.3 The battery capacity or energy shall be measured using a C/2 discharge rate to the minimum allowed voltage level following the cell or cell bank voltage measurement in paragraph 7.3.2.3.2 and be within established criteria.

7.3.2.3.4 Charge retention data measured before and after battery-level environmental tests shall meet the design requirements and verify that charge retention does not degrade from the previous cell, cell bank, or battery-level test data.

7.3.2.3.5 Time-stamped data shall be provided for the charge retention test starting at the beginning of charge through end of discharge.

7.3.2.4 Battery Impedance

The battery impedance shall be measured at the battery terminals at the nominal on-orbit cycling temperatures at 95%, 50%, and 20% states of charge via a step current change during discharge for 30 seconds or longer and shown to meet design requirements.

7.3.2.4.1 The impedance shall be measured and data recorded before and after all environmental tests.

7.3.2.4.2 A beginning-of-life impedance pass/fail criteria shall be defined that accounts for end-of-life expected impedance growth and worst-case temperatures.

7.3.2.5 Battery Functional

Any battery circuit or harness path not operating during the above capacity cycles shall be demonstrated to be fully operational at maximum currents (such as dead-bus protection circuit and each cell-balance circuit, relay operation, heater circuit, and conditioning circuit).

7.3.3 Battery Leakage

The battery leakage test, per SMC-S-016/TR-RS-2014-00016 [1], shall be performed using a residual gas analyzer to verify that the pressurized components and hermetically sealed units meet the specified-design battery leakage rate in a thermal vacuum test.

7.3.3.1 The battery shall be inspected before and after environmental tests, and at end-of-qualification testing to verify that there is no electrolyte leakage.

7.3.3.2 A residual gas analyzer shall be used during the entire thermal vacuum test with a capable gas detector, threshold, resolution, accuracy, and duration to detect any electrolyte leakage.

7.3.4 Shock

The battery shall be exposed to specified qualification-level shock applied three time in each direction along each of the three orthogonal axes per SMC-S-016/TR-RS-2014-0016 [1], AIAA-S-110-2005 [22], and the following to verify no physical damage and/or degradation in performance occurred as a result of shock test and to validate workmanship:

7.3.4.1 The generation of qualification environmental requirements shall encompass the range of all ground, launch, ascent, and on-orbit conditions, including transportation, handling, and storage using the methods stated in SMC-S-016/TR-RS-2014-0016 [1] and AIAA-S-110-2005 [22].

7.3.4.2 The battery shall be exposed to qualification shock levels, 6 dB (3 dB for protoqualification) above acceptance environment while discharging starting at 90% SOC.

7.3.4.3 Starting at 90% SOC, the cells shall be discharged at C/10 rate, or the expected launch SOC and discharge loads, during the shock test.

7.3.4.4 (Section number reserved)

7.3.4.5 Battery-, cell-, or cell bank-level voltages, currents, and temperatures shall be monitored continuously at the lowest level possible for the battery design during all shock tests at a rate specified in paragraph 7.2.4.3 for failure or intermittent performance.

7.3.4.5.1 For battery designs using COTS cells without cell-balancing electronics, cell voltage measurements are typically not available.

7.3.4.6 Cell- or cell bank-level voltages shall not experience negative voltage transients in excess of either twice the signal noise imparted by the test environment or 15 mV, whichever is smaller.

7.3.4.6.1 For battery designs using COTS cells without available cell balancing electronics, battery voltage measurements may be used in lieu of cell voltage measurements.

7.3.4.6.2 If baseline test noise or transients are expected to exceed requirements, a simulation test shall validate the baseline levels.

7.3.4.7 Relays and mechanical switches shall be monitored to ensure they do not transfer or chatter in excess of specification limits during the shock test.

7.3.4.8 As part of safety verification, continuous battery terminal (positive and/or negative) to battery chassis isolation shall be monitored at a rate defined in paragraph 7.2.4.3 during the shock test to verify that electrical isolation between battery chassis and all electrical components (e.g., cell, harness, piece parts, etc.) is maintained within specification requirements throughout the test.

7.3.4.9 Visual inspection and tests per Section 7.3.1 and specification performance tests per sections 7.3.2.1.1.c and 7.3.2.3 through 7.3.2.5 shall be performed before and after nonoperational and operational shock testing with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

7.3.4.10 Deviation from performing shock testing shall be in accordance with SMC-S-016/TR-RS-2014-0016 paragraph 6.3.4.4.

7.3.5 Random Vibration

The battery shall be exposed to specified qualification-level random vibration (hereafter referred to as vibration) on each axis per SMC-S-016/TR-RS-2014-00016 [1], AIAA S-110-2005 [22], and the following to verify no physical damage and/or degradation in performance occurred as a result of vibration test, and to validate workmanship.

7.3.5.1 The generation of qualification vibration requirements shall encompass the range of all ground, launch, ascent, and on-orbit conditions, including transportation, handling, and storage, using the methods stated in SMC-S-016/TR-RS-2014-0016 [1].

7.3.5.2 The battery shall be exposed to qualification vibration levels 6 dB (3 dB for protoqualification) above acceptance environment with discharge starting at 90% SOC.

7.3.5.3 Starting at 90% SOC, the cells shall be discharged at C/10 rate, or the expected launch SOC and discharge loads, during the vibration test.

7.3.5.4 The battery functional performance shall be continuously monitored while discharging at launch electrical load during exposure to qualification-level vibration testing at a rate defined in paragraph 7.2.4.2, including all primary and redundant circuits that operate during launch.

7.3.5.5 Battery- and cell- or cell bank-level voltages, currents, and temperatures shall be monitored continuously for failure or intermittent performance during all vibration tests at a rate defined in paragraph 7.2.4.3.

7.3.5.5.1 Note: For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

7.3.5.6 Cell- or cell bank-level voltages shall not experience negative voltage transients exceeding twice the signal noise imparted by the test environment or 15 mV, whichever is smaller.

7.3.5.6.1 If the baseline test noise or transients are expected to exceed requirements, a simulation test shall validate the baseline levels.

7.3.5.6.2 For battery designs using COTS cells without available cell-balancing electronics, battery voltage measurements may be used in lieu of cell voltage measurements.

7.3.5.7 Relays and switches shall be monitored to verify they do not transfer or chatter in excess of specification limits during the vibration test.

7.3.5.8 As part of safety verification, isolation between the battery terminal (positive or negative) and the battery chassis shall be monitored at a rate specified in paragraph 7.2.4.3 during the vibration test to verify that electrical isolation between the battery chassis and all electrical components (e.g., cell harness, piece parts, etc.) is maintained within specification requirements.

7.3.5.9 Visual inspection and tests per Section 7.3.1 and specification performance tests per sections 7.3.2.1.1.c and 7.3.2.3 through 7.3.2.5 shall be performed before and after nonoperational and operational vibration testing with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

7.3.6 Acceleration

As applicable, the battery acceleration test shall begin at a prelaunch SOC and discharge state during the test per SMC-S-016/TR-RS-2014-00016 [1], AIAA-S-110-2005 [22], and the following to verify no physical damage and/or degradation in performance occurs as a result of acceleration test and to validate workmanship.

7.3.6.1 The acceleration test shall verify the capability of the battery to operate during and after exposure to the qualification-level acceleration environment, at least 1.25 times the maximum predicted acceleration, for at least a duration of five minutes in both directions of the three perpendicular axes of test.

7.3.6.2 An analysis shall be performed to determine whether the acceleration environment is addressed by the battery-level qualification vibration test.

7.3.6.2.1 If the analysis shows that the acceleration test is not required, the analysis shall be fully documented and included as part of the battery-level qualification report.

7.3.6.2.2 If the analysis shows that an acceleration test is required, it shall be performed.

7.3.6.3 The acceleration test shall be performed with the battery under a discharge load, with battery/cell voltages, temperature, and current continuously monitored during the test at a rate defined in paragraph 7.2.4.3 for failure or intermittent performance. Note: For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

7.3.6.4 Cell- or cell bank-level voltages shall not experience negative voltage transients exceeding twice the signal noise imparted by the test environment or 15 mV, whichever is smaller.

7.3.6.4.1 If the baseline test noise or transients are expected to exceed requirements, a simulation test shall validate the baseline levels.

7.3.6.4.2 For battery designs using COTS cells without available cell balancing electronics, battery voltage measurements may be used in lieu of cell voltage measurements.

7.3.6.5 Relays and switches shall be monitored to verify they do not transfer or chatter in excess of specification limits during the acceleration test.

7.3.6.6 As part of safety verification, isolation between the battery terminal (positive or negative) and the battery chassis shall be monitored at a rate defined in paragraph 7.2.4.3 during the acceleration test to verify that electrical isolation between the battery chassis and all electrical components (e.g., cell, harness, piece parts, etc.) is maintained within specification requirements.

7.3.6.7 Visual inspection and tests per Section 7.3.1 and specification performance tests per sections 7.3.2.1.1.c and 7.3.2.3 through 7.3.2.5 shall be performed before and after acceleration testing with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

7.3.7 Thermal Cycle

The thermal cycle qualification test demonstrates robustness of the battery design over the design temperature range and the ability to function during subsequent performance testing. The battery thermal cycle test shall be per SMC-S-016/TR-RS-2014-0016 [1], as defined for electrical and electronic units, and the following to verify no physical damage and/or degradation in performance as a result of thermal cycle test, and to validate battery workmanship.

7.3.7.1 A thermal cycle test shall encompass the range of thermal conditions expected during all ground, launch, ascent, and on-orbit operation and survival conditions including transportation, handling, and storage.

7.3.7.2 For battery qualification, the worst-case hot and cold test temperatures shall exceed the maximum and minimum acceptance temperatures by ±10 deg C (±5 deg C for protoqualification).

7.3.7.3 The qualification battery shall be exposed to a minimum of 23 thermal cycles (20 cycles for protoqualification), in air and/or vacuum. The number of thermal cycles can be reduced to six (three for protoqualification) if all the battery solder joints, electronic piece parts, any sensitive bonds/interfaces subject to coefficient of thermal expansion (CTE) mismatch, and any part that requires environmental stress screening were exposed to 23 thermal cycle (20 cycles for protoqualification) over a temperature range of +71 deg C and –34 deg C (+66 deg C and –29 deg C for protoqualification) prior to battery qualification-level thermal cycles.

7.3.7.3.1 The first temperature cycle shall be at the specified survival temperature range.

7.3.7.4 Battery and cell or cell bank voltage, temperature, current, and heater status shall be continuously monitored during all portions of the test to validate specification performance requirements and verify no intermittent behavior. Note: For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

7.3.7.5 A representative cell temperature shall be used to verify minimum temperature, maximum temperature, and minimum thermal ramp rates have been achieved.

7.3.7.6 Any electronic assembly that is attached to or assembled as part of the battery shall be exposed to the full qualification-level thermal cycles and temperature levels as required by SMC-S-016/ TR-RS-2014-00016 [1], prior to installation on the battery.

7.3.7.7 As part of safety verification, isolation between the battery terminal (positive or negative) and the battery chassis shall be monitored during the thermal cycle test to verify that electrical isolation between battery chassis and all electrical components (e.g., cell, harness, piece parts, etc.) is maintained within specification requirements.

7.3.7.8 Visual inspection and tests per Section 7.3.1 and specification performance tests per Sections 7.3.2.1.1.c and 7.3.2.3 through 7.3.2.5 shall be performed before and after thermal cycle testing, with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

7.3.8 Thermal Vacuum

The qualification thermal vacuum test demonstrates the ability of the battery to perform to specified qualification environmental levels and to endure the thermal vacuum testing imposed on flight battery during acceptance testing.

The battery thermal vacuum testing shall be performed per SMC-S-016/TR-RS-2014-0016 [1] and the following to verify no physical damage and/or degradation in performance as a result of thermal vacuum test, and to validate battery workmanship.

7.3.8.1 The worst-case hot and cold test temperatures shall exceed the maximum and minimum acceptance temperatures by ±10 deg C (±5 deg C for protoqualification).

7.3.8.2 Four thermal vacuum phases shall be performed as specified below with simulation at hot, design operating, and cold temperature phases.

a. TV Phase 1: Survival temperature range (nonoperational)

b. TV Phase 2: Qualification hot case (24-hour operation, minimum)

c. TV Phase 3: Design operating point case (24-hour operation, minimum)

d. TV Phase 4: Qualification cold case (24-hour operation, minimum)

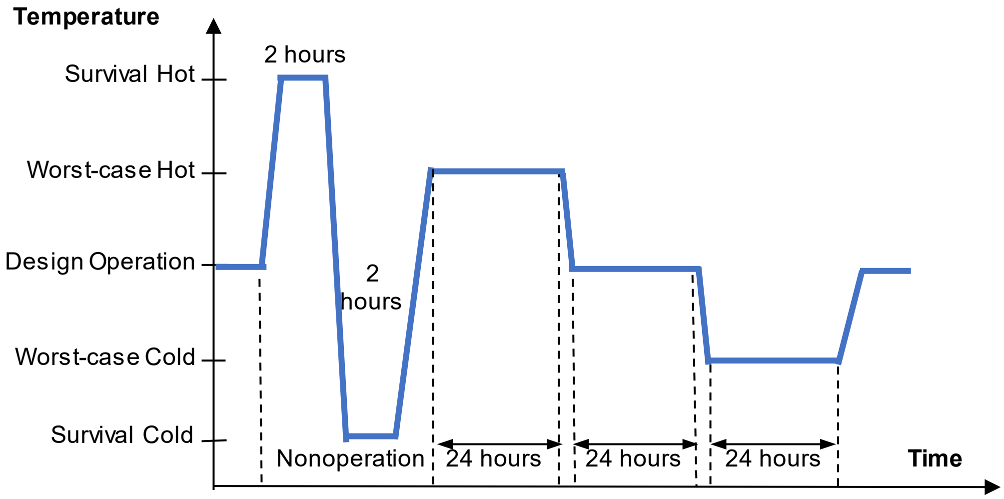

Figure 6. Qualification thermal vacuum test.

7.3.8.3 The battery shall be assessed by test and/or analysis to validate the thermal interfaces and control system. Additional thermistors or thermocouples may be temporarily installed to supplement existing flight temperature sensors to measure cell-to-cell temperature gradients.

7.3.8.3.1 Temperature gradients across individual cells shall be within 5 deg C.

7.3.8.3.2 Temperature gradients within a cell bank shall be within 3 deg C at similar locations on the cell.

7.3.8.4 Battery and cell or cell bank voltages, temperatures, currents, and heater status shall be continuously monitored during all portions of the test to validate specification performance requirements and verify no intermittent behavior. Note: For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

7.3.8.5 A leakage test per Section 7.3.3 shall be performed with a residual gas analyzer that scans with at least once-a-minute frequency throughout the thermal vacuum test and with a capable gas detector tuned to detect volatile electrolyte solvents in the cell with a threshold and accuracy to verify no cell leakage occurred.

7.3.8.6 A thermal balance test shall be performed in vacuum to provide data necessary to verify the analytical thermal model and verify the capability of the thermal control design to maintain specified operational temperature limits.

7.3.8.7 All primary and redundant heater operations shall be validated, such as turn-off/on set points, heater duty cycle operation, flight temperature measurements, overtemperature switch accuracy, heat-pipe performance, radiator sizing, and insulation effectiveness (if present during the test) shall be validated.

7.3.8.8 As part of safety verification, isolation between the battery terminal (positive or negative) and the battery chassis shall be monitored during the thermal vacuum test to verify that electrical isolation between the battery chassis and all electrical components (e.g., cell, harness, piece parts, etc.) is maintained within specification requirements.

7.3.8.9 Visual inspection and tests per Section 7.3.1 and specification performance tests per Sections 7.3.2.1.1.c and 7.3.2.3 through 7.3.2.5 shall be performed before and after thermal vacuum testing with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

7.3.9 Climatic Environments

Climatic tests shall be performed on battery and cell bank/cells in accordance with SMC-S-016/TR-RS-2014-0016 [1], paragraph 6.3.10.

7.3.9.1 An analysis shall assess exposure conditions imposed upon the battery during fabrication, test, shipment, storage, preparation for launch, launch, and reentry, if applicable.

7.3.9.2 The climatic analysis shall be documented, including rationale for any climatic tests that are not required.

7.3.9.3 Climatic environment that cannot be controlled shall be addressed by design and testing.

7.3.9.4 The battery, cell banks, and/or cells shall be protected from the potentially degrading effects of extreme terrestrial natural environments by procedural controls and special support equipment, as provided for in the contractor's battery handling procedures.

7.3.9.5 If any of the climatic environment tests are required based on the analysis, the test shall verify that the battery is capable of surviving exposure to various climatic environmental conditions without excessive degradation, or operating during exposure, as applicable.

7.3.9.6 Battery design and materials selection shall be verified by analysis or test to prevent material degradation due to fungus, ozone, and sunshine.

7.3.9.7 Visual inspection and tests per Section 7.3.1 and specification performance tests per Sections 7.3.2.1.1.c and 7.3.2.3 through 7.3.2.5 shall be performed before and after qualification climatic environmental testing with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

7.3.10 Pressure/Burst

Pressure testing shall be conducted on battery enclosures with pressure relief valves or pressure relief mechanisms per SMC-S-016/TR-RS-2014-0016 [1] and as specified below. Note: For cell-level pressure/proof pressure tests, see Sections 4.3.1 and 5.4.11.1 of this document; for other component (e.g., heat pipes) pressure testing, see SMC-S-016/TR-RS-2014-0016 [1].

7.3.10.1 The proof pressure/pressure tests shall demonstrate margin in the battery so that structural failure does not occur before the design pressure is reached and/or excessive deformation does not occur at the maximum expected operating pressure.

7.3.10.2 For battery cases with a reusable venting device or pressure relief mechanism, a proof pressure test shall be performed after exposure to all qualification environments to demonstrate that venting occurs at the design set point, which is greater than 1.25 maximum expected operating pressure.

7.3.10.3 For batteries using a rupture disk or similar nonusable device, a burst test shall be performed after exposure to all qualification environments to demonstrate that the device bursts at pressures greater than 1.25 but less than 1.5 maximum expected operating pressure.

7.3.10.4 All pressure/burst test results shall be included as part of the qualification report.

7.3.10.5 For battery cases with a reusable vent device, a visual inspection and tests per Section 7.3.1 shall be performed before and after qualification pressure/burst testing with results documented to verify that no physical damage occurred as a result of the test.

7.3.11 EMC

EMC compatibility of the battery shall be per SMC-S-016/TR-RS-2014-0016 [1], AIAA S-121A and SMC-T-008 [2], MIL-STD-461 [21], and the following:

7.3.11.1 The battery EMC compatibility shall be evaluated by analysis to verify the margin.

7.3.11.2 The EMC analysis shall be documented and included within the qualification report.

7.3.11.3 If the required margin is not met, an electromagnetic compatibility test shall be conducted to verify that the electromagnetic interference characteristics (emission and susceptibility) of the battery, under normal operating conditions, will not result in malfunction of the battery in support of a request for waiver.

7.3.11.4 If the required margin is not met, an electromagnetic compatibility test shall be conducted to verify that the battery does not emit, radiate, or conduct interference, which could result in malfunction of other units in support of a request for waiver.

7.3.12 Static Load

The structural static load test demonstrates the adequacy of the battery structure to meet requirements of strength and stiffness, with the desired qualification margin, when subjected to simulated critical environments predicted to occur during its service life (such as temperature, humidity, pressure, and loads). The battery static load testing shall be performed per SMC-S-016/TR-RS-2014-0016 [1] and AIAA-S-110-2005 [22].

7.3.12.1 An analysis shall be performed and documented to determine the limit load expected for the application.

7.3.12.2 Visual inspection and tests per Section 7.3.1 shall be performed before and after qualification static load testing, with results documented to verify no physical damage occurred as a result of the test.

7.3.13 Safety

Safety requirements for the lithium-ion battery design, safety testing, and ground operation shall meet Air Force Range Safety AFSPCMAN 91-710 [14] and Department of Transportation (DOT) [15] requirements.

7.3.14 Radiation

The battery shall be evaluated to determine the response of a device to the types of radiation and levels expected over spacecraft service life.

7.3.14.1 A battery-level analysis shall be performed consistent with SMC-S-014 [16] that is supported by component-level testing for all sensitive piece parts.

7.3.14.2 The battery shall meet mission performance requirements over life after exposure to predicted worst-case mission radiation environments.

7.3.14.3 The battery-level radiation analysis and supporting component-level tests shall be included as part of the qualification report.

7.3.14.4 Piece-part-level tests shall verify performance before, during, and after radiation exposure to quantify any degradation.

7.3.14.5 A visual inspection, electrical isolation verification, electrical performance, and leakage verification shall be performed before and after qualification radiation testing, with results documented on all piece parts to verify no physical damage and/or performance degradation occurred as a result of radiation test.

7.3.14.6 Cell-level verification shall be performed per Section 4.4.10 or 5.4.4.

7.3.15 Failure Mode Verification

To verify battery performance during inflight operation, the analyses and tests in this section shall be performed.

7.3.15.1 A battery-level analysis shall be performed where cell-, cell bank-, or battery-level development testing is used to evaluate the potential of one-cell failure propagating to another cell or piece part within the battery as well as any system or spacecraft-level impact over mission life.

7.3.15.2 Battery-level performance shall be verified under all unmitigated battery and battery component failure modes, which includes at a minimum the following conditions:

a. Overcharge
b. Overdischarge into reversal
c. Overtemperature
d. Overpressurization
e. Internal cell short
f. External cell/battery short

7.3.15.3 Any contamination as a result of a failure shall be analyzed to quantify other system-level impacts of a battery or battery component failure scenario and verified to comply with Section 3.4.

7.3.15.4 On-orbit battery operation shall satisfy the on-orbit monitoring and safety fault handling and responses per AIAA S-122/T [24].

8. Life Test

Realtime life testing of battery service life expectancy shall be conducted (on each cell design) as required by SMC-S-016/TR-RS-2014-00016 [1] paragraph 6.3.14 and as below under designed worst-case failure conditions of redundant cells that encompass the range of the intended application, conditions preceding launch, launch dynamic environments, mission battery loads, charge control methods and conditions, and mission temperature.

8.1 Life Expectancy

8.1.1 Battery life expectancy shall be determined based upon battery life testing or on a combination of battery cell bank, battery cell string, and/or cell life tests that are configured and tested in a flightlike manner (thermal, mechanical, and electrical), and analyses that confirm the life expectancy of battery materials and components, such as module, cell, electrical bypass devices, heaters, strain gauges, temperature sensors, or thermal switches.

8.1.1.1 For COTS cell lots, life testing shall be done on a cell series string, which consists of a minimum of two parallel strings of n series connected cells, where n is the number of cells to be connected in series in the intended flight battery series strings.

8.1.2 The life test shall expose the battery, cell bank, cell string, or cells to worst-case on-orbit temperature variations, charge profile, and electrical loads with electrical, mechanical, and thermal configuration matching the battery design.

8.1.2.1 Worst case on orbit temperature variations include minimum temperature, maximum temperature, temperature range, number of cycles, and time at temperature, as applicable, when the battery contains failure modes related to thermomechanical fatigue and/or time at temperature.

8.1.3 Test duration shall encompass mission life, the required battery service life reliability, and confidence level based on the number of test samples used.

8.1.4 The cells used in the life test shall be from a single cell lot (which may consist of one or more production runs), as defined in Sections 2 and 7.2.5.6, and of the same design as the qualification cells used in the qualification battery.

8.1.4.1 For COTS cells, the cells used in the life test shall be from a single COTS cell lot as defined in Section 2, where the qualification cells used in the qualification battery and flight cells are from the same COTS cell lot.

8.2 Cell Characterization Before and After Life Test

8.2.1 Three randomly selected cells from the life test cell lot shall be exposed to cell interface protoqualification-level shock and vibration test using simulated flightlike cell fixturing/mounting prior to the life test.

8.2.2 Cell-level DPA shall be performed in accordance with Section 8.12 at the following:

a. Beginning-of-life test on at least one control cell to verify cell design and workmanship are as expected

b. Completion of battery life test on at least one cell that was exposed to shock and vibration environments to verify the cell design performed as expected

8.2.3 X-ray inspection shall be performed per Section 5.3.6 on:

a. All cells selected for life test prior to shock and vibration test of 8.2.1 to verify that they meet design and workmanship requirements

b. Three randomly selected cells (at a minimum), after the protoqualification mechanical tests, to verify no movement, breakage, or damage internal to the cell was caused by the mechanical environments

8.3 Realtime Life Test

8.3.1 Realtime data shall be from realtime ground tests on a sample of cells per Section 8.8 where the time, current, orbit state of charge, temperature profiles and gradients of discharge, charge and periods of balancing/open circuit encompass the range of the mission.

8.3.1.1 For a COTS cell lot, test sample size in the life test series–parallel module shall be per Sections 8.1 and 8.8.

8.3.2 The test shall encompass the range of the cell matching criteria and use the same charge control and cell balancing methods as intended to be used for flight battery.

8.3.3 Internal cell pressure shall be monitored and measured on at least three cells via a calibrated strain gauge or pressure transducer to quantify pressure growth over the life test.

8.3.3.1 For COTS cell lots, cell internal pressure monitoring during the life test is not typically performed.

8.3.4 An electronic copy of all life test data shall be maintained.

8.3.5 Life test status reports shall be updated yearly, at minimum.

8.4 Accelerated Life Test

As risk mitigation for spacecraft applications, a battery, cell bank, cell string, or cell accelerated life test can be used to confirm service life expectancy per TR-2006(1445)-1 [8]. This will be a set of accelerated tests that encompass the range of the mission loads, charge control methods and conditions, and temperatures with electrical, mechanical, and thermal configurations matching the battery design. The acceleration factor can have different values for storage, cycling, or different operational modes.

8.4.1 Acceleration Factor

8.4.1.1 The life acceleration factor shall be confirmed by realtime life test data on a sample of cells per Section 8.8 where the time, current, and temperature profiles of discharge and charge match those of the mission.

8.4.1.1.1 For COTS cell lot, a cell series–parallel module shall be per Sections 8.1 and 8.8.

8.4.1.2 The time acceleration methods shall be based on an analysis of data. Cell sample size, defined in Section 8.8, can be spread across multiple test conditions as long as the number of cells per test is at least five cells.

8.4.1.3 The time acceleration shall not be greater than two to ensure that failure modes are the same for realtime and accelerated tests.

8.4.1.4 An electronic copy of all life test data shall be maintained.

8.4.1.5 Life test summary reports shall be updated yearly, at minimum.

8.5 Ground Storage Realtime Life Test

A second realtime life test per Section 8.3 shall be conducted following the maximum specified ground storage period, if the storage period was not captured within paragraph 8.3.1.

8.6 Test Duration

Realtime and accelerated life test duration shall encompass mission life to verify the required battery reliability and confidence level, based on the number of test samples and failure-rate characteristics.

8.7 Incomplete Life Test Data

When sufficient realtime life test data is not available for acceptable risk per TR-2006(1455)-1 [8], one or more of the measures defined below shall be used to minimize program risk:

a. Dual-path approach with a more established design or technology

b. Battery sizing with a greater end-of-life energy margin

c. Destructive physical analysis on a limited number of cells from the realtime life test to evaluate degradation modes prior to launch

d. Accelerated testing to facilitate failure mechanisms and performance loss trends with destructive physical analysis to verify loss mechanisms

e. Parallel on-orbit flight use with realtime ground testing to provide data for making on-orbit adjustments until service life with margin is accomplished

8.8 Cell Sample Size

8.8.1 The life test sample size shall provide a minimum of 88% reliability with 90% confidence (or 20 cells) without failure. If other sample sizes are used, follow the rules below to establish the test duration based on sample size.

8.8.1.1 If the sample size, n, is not 20, the actual test duration without failure, T, shall be multiplied by a factor, K, for service life expectancy.

8.8.1.2 The confidence and reliability level shall remain at 90% over 88% for a test with n samples, without failure for duration KT.

8.8.1.3 If the failure probability function is not known, the use of a Weibull function shall be used to establish test durations.

8.8.1.4 The beta shape parameter for the Weibull function shall be estimated from failure data of the most comparable cells and operational type conditions. As more data is accumulated, a failure probability function will be refined. See TOR-2007(8583)-6690 [3] for guidance.

8.9 Life Test Sample Data

8.9.1 Storage as well as cycle-test history and data shall be provided for each individual life test sample at the cell level.

8.9.1.1 For a COTS cell lot, these data shall be provided at the cell series–parallel module level.

8.9.2 Cell-level (or cell bank-level and battery-level, as applicable) capacity, charge retention, and impedance acceptance tests shall be performed at the conditions defined in Sections 7.3.2.1.1.c and 7.3.2.2 through 7.3.2.5.

8.9.3 An additional 1,000 hertz impedance test shall be performed on each cell prior to life test at a state of charge where prior data is available for comparison.

8.9.4 Periodic capacity/energy and impedance measurements per paragraph 8.9.2 (on a yearly basis minimum) shall be performed during the life test to facilitate performance trending.

8.9.5 End of test capacity/energy and impedance measurements shall be conducted to repeat paragraph 8.9.2 tests at the cell level (or cell bank level and battery level as applicable).

8.9.6 An electronic copy of the life test data shall be maintained and summarized as part of the yearly update.

8.10 Manufacturing Control

8.10.1 The life test cells shall be built to a qualified set of manufacturing processes and in-process controls as intended for the flight cells.

8.10.1.1 For COTS cell lot, the life test series–parallel module shall be built to a qualified set of manufacturing processes and in-process controls.

8.10.2 These processes shall be maintained under document control to define the qualified cell design.

8.10.2.1 For COTS cell lot, all processes shall be maintained under document control to define and control the life test cell series–parallel module design.

8.10.3 Subsequent changes to qualified manufacturing processes shall be evaluated to ensure they do not require requalification of the qualified cell design.

8.10.3.1 For COTS cell lot, subsequent changes to the qualified processes shall be evaluated to ensure they do not require requalification of the qualified life test series–parallel module design.

8.10.4 Manufacturing control documents shall be verified per paragraph 7.4 to ensure that the qualification and life test cells are of the same design.

8.10.4.1 For COTS cell lot, qualification data shall be reviewed to verify that the cells used in each flight battery matches the performance measured for the cells used in the life test series–parallel module.

8.11 Life Test Criteria

8.11.1 The contractor shall define the pass/fail criteria for realtime (and accelerated life test if applicable) based on the mission profile and power subsystem architecture and battery specification requirements for the following at both beginning of life (BOL) and end of life (EOL):

a. Self-discharge (voltage decay) rate
b. Internal impedance
c. End-of-discharge voltage
d. Capacity
e. Cell pressure (not typical for COTS cells)
f. Battery/cell temperature range

8.11.2 The realtime test (and accelerated life test, if applicable) shall have periodic inspections performed to verify the following conditions:

a. Cell-voltage (for COTS cells: cell-module-voltage) profiles shall not show evidence of lithium plating voltage signature.

b. Cells shall not show signs of electrolyte leakage.

c. Cell/battery electrical connection points shall be free of contamination and oxidation.

d. Electrical path within the battery and cells shall remain secure and not result in an open path or partially opened path during any test event.

e. Safety devices shall not show signs of being tripped or impairment.

f. All battery electronic piece parts, harness, and structure shall operate within expected limits without degradation.

g. Cell interfaces and compression torque shall remain in specification as applicable.

h. There shall be no loss of electrical isolation between components operating at different voltages within the battery or module.

8.12 DPA

A cell-level destructive physical analysis shall be performed to visually assess the cell design, workmanship, and performance characteristics, and detect degradation by opening the cell and inspecting individual plates/separators within the stack as well as other cell components. For COTS cells, refer to Sections 5.4.7 and 5.4.8.

8.12.1 Prior to disassembly, a cell shall not show evidence of electrolyte leakage.

8.12.2 Prior to disassembly, the external case dimensions shall be verified to be within drawing tolerances.

8.12.3 Internal and external cell components shall meet visual inspection criteria of paragraph 4.4.2.

8.12.4 Safety devices shall not be tripped or impaired.

8.12.5 All electrical connections shall be secure and not show evidence of breakage or tearing (tab to foil, tab to bussing, bussing to terminal, or isolation loss).

8.12.6 Internal and external components shall not shift, break, or tear as a result of environmental or life test or flight lot cycle test.

8.12.7 Cell case, terminals, and internal leads shall not show signs of corrosion, fatigue, and loss of terminal preload.

8.12.8 Cell/stack inspection shall meet the requirements of the Manufacturing Contamination Control Plan inside the cell at 1X to 10X magnification.

8.12.9 100% of the electrode stack shall be visually inspected for the following:

a. Anode and cathode coating dimensions, weight, and thickness shall be verified for uniformity.

b. The electrode stack shall show no evidence of electrode nonuniformity, spots, lithium plating, or delamination.

c. The anode electrode shall overlap the cathode in all places. Note: Lithium plating at electrode edges is evidence of insufficient electrode overlap.

d. The electrode cylindrical roll or plate stack shall not show evidence of telescoping, plate shifting, or misalignment beyond tolerance limits.

e. The separator shall show no signs of shutdown/pore closure and shall extend beyond both electrodes with margin.

f. Anode and cathode plate count (prismatic) and foil dimensions (prismatic/jellyroll) shall be verified.

8.12.10 The DPA shall document any evidence of cell design or material changes, or changes in manufacturing processes as compared with qualification cell DPA.

8.12.11 Internal cell pressure shall be measured and validated to be within MEOP after accounting for expected pressure growth over mission life.

8.12.12 The DPA results shall be compared with other previous DPAs performed on the cell design, such as prior lots or beginning-of-life cells, to evaluate degradation characteristics.

9. Battery Acceptance Test

Acceptance testing is intended to stress screen items to precipitate incipient failures due to latent defects in parts, processes, materials, or workmanship. All acceptance tests shall be per SMC-S-016/TR-RS-2014-0016 [1] and as specified below:

a. Battery acceptance tests shall verify the acceptability of each flight battery, module, piece part, or cell to meet specification performance and verify quality of workmanship in manufacturing.

b. The acceptance test conditions shall encompass the range of a composite of the worst-case applications.

c. Each flight battery shall be exposed to all applicable environmental tests in the order of the acceptance tests planned per Section 9.7.

d. Pass/fail criteria shall be established for all cell in-process inspections and tests as well as all battery acceptance-level inspections and tests based on the design (intended application) and as verified during battery qualification.

e. Test plans and procedures shall be documented in detail to provide a framework for identifying and interrelating all of the individual tests and test procedures needed and meet the requirements defined in SMC-S-016/TR-RS-2014-00016, Sections 4.8.1 and 4.8.2 [1].

9.1 Battery Acceptance Test

9.1.1 Test Hardware

9.1.1.1 Each flight battery shall be subjected to acceptance testing and the following:

a. Produced in the same factory, from the same drawings, using the same parts, materials, tooling, manufacturing process, and level of personnel competency as used for the qualification hardware

b. Built to a qualified set of manufacturing processes and in-process controls

9.1.1.2 Cell serial number traceability shall be maintained through battery build and test.

9.1.1.3 Piece parts that are assembled into the battery, such as resistors, capacitors, diodes, heaters, relays, fuses, bypass switches, and circuit board assemblies, shall meet the requirements of SMC-S-009 [7] and SMC-S-010 [19].

9.1.1.4 Any electronic assembly that is attached to or assembled as part of the battery shall meet SMC- S-016/TR-RS-2014-00016 [1] acceptance requirements for an electrical and electronic unit prior to installation on the battery.

9.1.1.5 Additional instrumentation beyond flight battery design (e.g., thermistors) can be added during acceptance test to validate workmanship.

9.1.1.6 Battery and cell or cell-pack voltage accuracy used for charge control and cell balancing shall be verified to meet AIAA S-122-2007 [20, 24] at the end of acceptance test. Note: For battery designs using COTS cells, cell balancing is typically not available.

9.1.2 Design Control

9.1.2.1 The flight battery, cell, and piece-part designs shall be the same as the qualified and life tested design.

9.1.2.2 All subsequent changes since qualification in the battery, cell, or piece-part design or processes from the qualified and life tested design (including change in supplier or manufacturing location) shall be evaluated in advance of battery, cell, or piece-part build to determine if it is considered a different design that requires requalification.

9.2 Acceptance Test Levels and Duration

9.2.1 Acceptance test levels and durations shall be per SMC-S-016/TR-RS-2014-00016 [1] and as defined herein.

9.2.2 To verify workmanship, the acceptance environmental conditions shall stress the flight hardware to the maximum acceptance-level conditions expected for all flight events, including transportation and handling, but not less than the minimum workmanship levels defined by this standard.

9.3 Data Collection and Acquisition Rates

9.3.1 Numerical values for voltage, temperature, current, capacity, and impedance shall be recorded and assessed by indicating PASS or FAIL against a range of values provided by the test plan.

9.3.2 Battery and cell or cell-pack voltage, current, and temperature measurements shall be made and recorded at rates within a contractor-established allowable experimental uncertainty that supports the test success criteria. Note: For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

9.3.3 Battery and cell or cell-pack voltage and current shall be electrically monitored during the dynamic environmental test and collected at an acquisition rate of at least 10,000 samples per second to evaluate for intermittent dropouts. Note: For battery designs using COTS cells without available cell balancing electronics, battery voltage measurements can be used in lieu of cell voltage measurements.

9.3.4 Temperature measurements shall be from temperature sensors mounted on cells and key piece parts inside the battery (e.g., relays, diodes, bypass switches, electronics, and/or harness).

9.4 Acceptance Retest

Battery-level retest shall meet the requirements of SMC-S-016/TR-TS-2014-00016, paragraph 4.3.4.3 [1].

9.5 Cell Matching Criteria

9.5.1 For each battery design, the cell matching criteria shall be defined, documented, and applied on all qualification, life test, and flight-battery units.

9.5.2 Cell matching criteria for the battery shall be the same or tighter than that used for the qualification life test cells.

9.5.3 The cell matching criteria shall be based on program qualification tests and include at a minimum the following: capacity, energy, charge retention, impedance at a defined voltage or state of charge, and temperature.

9.5.4 The cell lot (or COTS cell lot) shall be procured, stored, tested, and delivered together to maintain a flight battery cell lot for a shipset or single lot definition.

9.5.5 To maintain cell matching throughout life, all the cells within a battery shall be exposed to the same electrical current, and all cells within a battery shall be exposed to the same thermal environment.

9.5.6 All cells in the flight battery shall be from a single cell lot (may consist of one or more production runs) or single COTS cell lot as defined in Section 2 and the following:

9.5.6.1 For configuration-control cell lots, the maximum period of time the cell lot build shall span, defined as electrode mixing to cell activation, is to be documented and verified by lifecycle performance test.

9.5.6.2 An acceptable lifecycle performance test shall include cells built spanning the maximum specified production run and cell lot time period consisting of realtime, accelerated, or worst-case cycling over a duration that demonstrates similar and stabilized performance.

9.5.7 The flight cell lot shall be verified to have statistically unchanged performance from the lot used for qualification tests.

9.5.8 Flight COTS cell lot shall be from the same cell lot used for qualification and lifecycle test, and have statistically the same performance as the qualification cells.

9.6 Flight Battery Unit Documentation (Acceptance Level)

Buy-off documentation shall be separately provided at the completion of cell acceptance test and battery acceptance test and include the following items:

a. Battery and cell lot (or COTS cell lot) electronic copy of end-item data package

b. Battery and cell lot (or COTS cell lot) certificate of conformance

c. Battery and cell lot (or COTS cell lot) closure of action items from CDR – first flight lot only, MRR, and TRR

d. Battery and cell lot (or COTS cell lot) engineering changes since CDR

e. Battery and cell lot (or COTS cell lot) hardware discrepancy and failure analysis reports

f. Battery and cell lot (or COTS cell lot) test discrepancy and failure analysis reports

g. Battery and cell lot (or COTS cell lot) deviations and waivers

h. Battery and cell lot (or COTS cell lot) in-process inspection and test data

i. Battery and cell lot (or COTS cell lot) specification changes

j. Battery and cell lot (or COTS cell lot) acceptance test procedures as run

k. Battery and cell lot (or COTS cell lot) test equipment calibration record

l. Battery and cell lot (or COTS cell lot) travelers

m. Cell lot or COTS cell lot summary and attribute in-process data

n. Cell selection and matching criteria report

o. Specification compliance verification report

p. Battery and cell lot (or COTS cell lot) acceptance test data

q. COTS cell lot assessment test data

r. Battery and cell development data

s. Battery and cell lot (or COTS cell lot) burst pressure, proof pressure, and pressure cycling results, as applicable

t. Battery report correlating thermal test data with qualification thermal test data

u. High-reliability parts (cell, electronic, or mechanical devices) buy-off report

v. Battery and cell-level as-built assembly-level interface control and wiring drawing
Note: For COTS cell lots, cell-level drawings may not be available

w. Battery and cell-level list of build drawings, manufacturing procedures, and test procedures identifying revision used to build and test the acceptance unit
Note: For COTS cell lots, cell- level manufacturing and build data may not be available.

x. Battery and cell-level age-sensitive component record

y. Battery-level telemetry coefficients for all analog telemetry

z. Electronic format of cell and battery test raw data

aa. All cell x-rays as uncompressed TIFF file

bb. Cell lot DPA results

cc. Electronic format of raw flight lot cycle-test data

dd. High-definition photographs prior to and after battery enclosure, cells during inspections, and DPAs

ee. Battery and cell-voltage calibration report
Note: For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

ff. Battery and cell specification, inspection, and test procedures and handling procedures

9.7 Acceptance Tests Required

The flight batteries shall be subjected to all the tests outlined below:

Table 8. Battery Acceptance Testing

Test	Spacecraft Application	Suggested Test Sequence	Paragraph
Inspection	R	1,13	9.8.1
Wear-in	ER	2	9.9
Specification Performance	R	3,12	9.10 thru 9.15
Leakage	R	4	9.16
Shock	ER	5*	9.17
Vibration	R	6*	9.18
Thermal Cycle	ER	7*	9.19
Thermal Vacuum/Leakage (1)	R	8*	9.20/9.16
Proof Pressure (2)	R	9**	9.21
Proof Load	ER	10**	9.22
Electromagnetic Compatibility	ER	11	9.23
Flight Lot Cycle Test (3)	R	14*	9.24
Safety	R	15	9.25

R: Required
ER: Evaluation Required by contractor
* Inspection (Section 9.8) and specification performance (paragraph 9.11.1.b and Sections 9.13 through 9.15) performed before and after test
** Inspection (Section 9.8) performed before and after test
(1) Thermal vacuum tests should be performed as last environmental test
(2) 100% proof pressure and lot qualification sample burst test at the cell level as required per Sections 4 or 5; battery level required only if design enclosure contains a pressure relief valve
(3) Test performed on spare cells from the flight cell lot

9.8 Inspection

9.8.1 The battery shall be inspected and measurements made prior to box closeout and postacceptance test to verify compliance with the specification. These include:

a. As-built vs. as-designed configuration
b. Electrical, mechanical, thermal interfaces
c. Design and construction requirements
d. Weight
e. Dimensions
f. Clearances
g. Condition of hardware (damage)
h. Electrical isolation
i. Electrical continuity
j. Finish
k. Fastener tightness torques or visual inspection of staked fasteners
l. Identification markings
m. Cleanliness
n. Workmanship (including roll test)
o. Electrolyte leakage
p. Condition of vent disks when included in the design
q. Temperature sensors

9.8.2 The results of the inspections and measurements shall be recorded in detail and assessed to determine significant changes in the condition of the battery, following each environmental test.

9.8.3 The battery shall be inspected before and after each environmental test to identify discrepancies as a result of the test as follows:

a. Condition of hardware (damage)

b. Electrical isolation

c. Electrical continuity

d. Fastener tightness torques or visual inspection of staked fasteners

e. Cleanliness

f. Roll test – 360 degree rotation while mounted on trunnion (postmechanical environmental test only)

g. Electrolyte leakage

h. Condition of vent disks when included in the design

9.9 Wear-in (Electrical Cycles)

9.9.1 The wear-in test (battery charge and discharge cycles) detects material and workmanship defects that occur early in the battery life and establishes performance stability. An evaluation shall be performed by the contractor to determine whether additional wear-in cycles are required beyond those performed in the required acceptance tests.

9.9.2 If required, wear-in test shall adhere to the following:

a. Pressure – Ambient pressure shall be used
b. Temperature – Temperature representative of the operational environment shall be used
c. Duration – The wear-in test shall not exceed 5% of the total expected service lifecycles
d. Conditions – The battery shall operate under nominal electrical conditions

9.10 Specification Performance

The specification performance tests shall verify that the battery meets the requirements of the battery specification.

a. Battery discharge during ground testing shall simulate the in-flight spacecraft power system operation. This will be accomplished with constant-current discharge; however, constant power discharge is the preferred method if it more closely simulates spacecraft power.

b. The electrical testing specified in this section shall characterize the flight battery performance over the full voltage and temperature range unless otherwise stated.

c. Sections 9.11 through 9.15 shall be performed to fulfill the specification performance element of acceptance testing before and after environmental testing, as specified in Table 8.

9.11 Battery and Cell Capacity (or Energy)

9.11.1 The battery capacity or energy shall be measured at specified charge conditions to the maximum charge voltage, with cells in a balanced state, followed by a C/2 discharge rate to the minimum voltage level, for each of the following three temperature conditions:

a. Maximum acceptance temperature
b. Design operating point acceptance temperature
c. Minimum acceptance temperature

9.11.2 The battery shall achieve capacity/energy stability within 1% for two consecutive cycles, up to three cycles maximum, for each temperature condition.

9.11.3 If the battery capacity test conditions are different than the cell level, an additional capacity cycle shall be performed using the cell-level conditions for comparison.

9.12 Mission-Specific Performance Requirements

Electrical parameters shall meet intended usage (such as constant power discharges)

9.12.1 Mission-specific requirements, if not included in the conditions specified by paragraph 9.11.1, shall be verified after subjecting the battery to the following conditions at expected on-orbit temperatures following cell balancing (as applicable) to maximum and minimum voltage limits:

a. Minimum charge and discharge rates
b. Design operating charge and discharge rates
c. Maximum charge and discharge rates
d. Pulse power requirements

9.13 Battery Charge Retention

Battery charge retention shall be measured at 20 deg C in an open-circuit state starting at 100% state of charge to screen out potential internal shorts while electrode stack is under the highest mechanical force and at a state-of-charge with the highest voltage sensitivity.

9.13.1 Any charge control electronics or voltage monitoring devices mounted on the battery shall be electrically disconnected to the maximum extent possible to eliminate/minimize parasitic current leakage.

9.13.2 Cell or cell bank open-circuit voltage measurements shall be periodically taken at least every 24 hours ±1 hour postcharge termination for a total period of 168 hours for designs that contain cell balancing electronics or 30 days for designs without cell-balancing electronics and be within established criteria for open-circuit voltage drop.

9.13.2.1 For battery designs using COTS cells without available cell balancing electronics, battery voltage may be used in lieu of cell voltage measurements).

9.13.3 The remaining battery capacity or energy shall be measured using a C/2-per-hour discharge rate to the minimum-allowed voltage level following the cell or cell bank open-circuit voltage measurements and verified to be within the established criteria.

9.13.4 Charge retention before and after environment testing shall meet the design requirements and the results compared to verify that charge retention does not degrade from previous cell, cell bank,
or battery-level test data.

9.13.5 Time-stamped data shall be provided for the entire charge retention test starting at beginning of charge through the end of discharge.

9.14 Battery Impedance

9.14.1 A beginning-of-life impedance pass/fail criteria shall account for end-of-life expected impedance growth and worst-case temperatures.

9.14.2 The battery impedance shall be measured at the battery terminals at the nominal on-orbit cycling temperatures at 95%, 50%, and 20% states of charge via a step current change during discharge for 30 seconds or longer and shown to meet the design requirements.

9.14.3 The impedance shall be measured and data recorded before and after all environmental tests.

9.15 Battery Functional

Any battery circuit or harness path not operating during the above capacity cycles shall be verified to be fully operational at maximum current (such as dead-bus protection circuit, relay operation, and each cell- balance circuit, heater circuit, and conditioning circuit).

9.16 Battery Leakage

During the thermal vacuum test, a battery leakage test per SMC-S-016/TR-RS-2014-00016 [1] shall be performed to verify that the pressurized components and hermetically sealed units meet the specified design battery leakage rate as verified during battery qualification.

9.16.1 The battery shall be inspected before and after environmental tests and at end of acceptance testing to verify that there is no electrolyte leakage.

9.16.2 A residual gas analyzer shall be used during the entire thermal vacuum test with a capable gas detector, threshold, resolution, accuracy, and duration to detect any electrolyte leakage per Section 9.20.

9.17 Shock

When applicable, the battery shall be exposed to specified acceptance-level shock in each direction along each of the three orthogonal axes per SMC-S-016/TR-RS-2014-0016 [1] and AIAAS-110-2005 [22] and the following to verify no physical damage and/or degradation in performance occurs as a result of shock test, and to validate workmanship:

9.17.1 The generation of acceptance environmental requirements shall encompass the range of all ground, launch, ascent, and on-orbit conditions, including transportation, handling, and storage using the methods stated in SMC-S-016/TR-RS-2014-0016 [1].

9.17.2 Starting at 90% SOC, the cells shall be discharged at C/10 rate, or the expected launch SOC and discharge loads, during the shock test.

9.17.3 Battery- and cell- or cell-bank-level voltages currents and temperatures shall be monitored continuously during all shock tests at a rate defined in paragraph 9.3.3 for failure or intermittent performance.

9.17.3.1 For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

9.17.4 Cell- or cell-bank-level voltages shall not experience negative-voltage transients in excess of either twice the signal noise imparted by the test environment or 15 mV, whichever is smaller.

9.17.4.1 For battery designs using COTS cells without available cell balancing electronics, battery voltage measurements may be used in lieu of cell voltage measurements.

9.17.4.2 If baseline test noise or transients are expected to exceed requirements, a simulation test shall validate the baseline levels.

9.17.5 Relays and mechanical switches shall be monitored to ensure they do not transfer or chatter in excess of specification limits during the shock test.

9.17.6 As part of safety verification, continuous battery terminal (positive and/or negative) to battery chassis isolation shall be monitored during the shock test to verify that electrical isolation between battery chassis and all electrical components (e.g., cell, harness, piece parts, etc.) is maintained within specification requirements throughout the test.

9.17.7 Visual inspections and tests per paragraph 9.8.3 and specification performance test per paragraph 9.11.1.b and Sections 9.13 through 9.15 shall be performed before and after the operational shock testing with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

9.17.8 Deviation from performing shock testing shall be within accordance to SMC-S-016/TR-RS-2014-0016.[1]

9.18 Random Vibration

The vibration test shall be performed per SMC-S-016/TR-RS-2014-0016 [1] and AIAA-S-110-2005 [22] on the battery at specified acceptance-level vibration in three orthogonal axes for a duration of one minute per axis and the following to verify no physical damage and/or degradation in performance occurs as a result of random vibration test, and to validate workmanship.

9.18.1 The generation of acceptance environmental requirements shall encompass the range of all ground, launch, ascent, and on-orbit conditions, including transportation, handling, and storage using the methods stated in SMC-S-016/TR-RS-2014-0016 [1].

9.18.2 Starting at 90% SOC, the cells shall be discharged at C/10 rate, or the expected launch SOC and discharge loads, during the shock test.

9.18.3 Battery- and cell- or cell-bank-level voltages, currents, and temperatures shall be monitored continuously during the entire vibration test at a rate defined in paragraph 9.3.3 for failure or intermittent performance.

9.18.3.1 For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

9.18.4 Cell- or cell-bank-level voltages shall not experience negative voltage transients in excess of either twice the signal noise imparted by the test environment or 15 mV, whichever is smaller.

9.18.4.1 For battery designs using COTS cells without available cell balancing electronics, battery voltage measurements may be used in lieu of cell voltage measurements.

9.18.4.2 If baseline test noise or transients are expected to exceed requirements, a simulation test shall validate the baseline levels.

9.18.5 Relays and switches shall be monitored to verify they do not chatter in excess of specification limits during the vibration test.

9.18.6 As part of safety verification, continuous battery terminal (positive and/or negative) to battery chassis isolation shall be monitored at a rate defined in paragraph 9.3.3 during the vibration test to verify that electrical isolation between battery chassis and all electrical components (e.g., cell, harness, piece parts) is maintained within specification requirements throughout the test.

9.18.7 Visual inspections and tests per paragraph 9.8.3 and specification performance test per paragraph 9.11.1.b and Sections 9.13 through 9.15 shall be performed before and after operational vibration testing, with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

9.19 Thermal Cycle

The battery thermal cycle testing shall be per SMC-S-016/TR-RS-2014-0016 [1] and the following to verify no physical damage and/or degradation in performance occurs as a result of thermal cycle testing, and to validate workmanship.

9.19.1 An analysis shall be performed to determine if the unit can be defined as an electrical/electronic unit or a non-electrical/non-electronic unit.

9.19.2 The battery shall be exposed to a minimum of 14 thermal cycles unless all the electrical/electronic parts/unit interfaces subject to coefficient of thermal expansion (CTE) mismatch and any part that requires environmental stress screening were subjected to 14 thermal cycles prior to installation on the battery, at which point only one thermal cycle is required.

9.19.3 Any non-electrical/non-electronic unit containing only metallic materials (screwed or bolted together) shall require only one thermal cycle.

9.19.4 The thermal cycle test shall be performed to the maximum and minimum battery acceptance temperatures that encompass the range of thermal conditions expected during all ground, launch, ascent, and on-orbit operation conditions, including transportation, handling, and storage.

9.19.5 Any electronic assembly that is attached to or assembled as part of the battery shall be exposed to the full-acceptance-level thermal cycles (14 cycles) and temperature levels (-24 deg C to +61 deg C) as required by SMC-S-016/TR-RS-2014-00016 [1] prior to integrating them into the battery.

9.19.6 Battery and cell or cell pack voltages, temperatures, currents, and heater status shall be continuously monitored during all portions of the test to validate specification performance requirements and to verify no intermittent behavior.

9.19.6.1 For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

9.19.7 A representative cell temperature shall be used to verify minimum temperature, maximum temperature, and minimum thermal ramp rates have been achieved.

9.19.8 As part of safety verification, continuous battery terminal (positive and/or negative) to battery chassis isolation shall be monitored during the thermal cycle test to verify that electrical isolation between battery chassis and all electrical components (e.g., cell, harness, and piece parts) is maintained within specification requirements throughout the test.

9.19.9 Visual inspections and tests per paragraph 9.8.3 and specification performance test per paragraph 9.11.1.b and Sections 9.13 through 9.15 shall be performed before and after thermal cycle test, with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test and to verify workmanship.

9.20 Thermal Vacuum

The battery thermal vacuum test shall be performed per SMC-S-016/TR-RS-2014-0016 [1] and the following to verify no physical damage and/or degradation in performance occurs as a result of the thermal vacuum testing, and to validate workmanship.

9.20.1 For acceptance testing, four thermal vacuum phases shall be performed as outlined below, with the last three phases simulating battery on-orbit mission functional operation, and demonstrate that the state of charge and temperature balance are maintained within a 24-hour period and/or achieve thermal stability.

a. TV Phase 1: Survival temperature range (nonoperational)
b. TV Phase 2: Worst-case hot (24-hour orbit operation, minimum)
c. TV Phase 3: Design operating case (24-hour orbit operation, minimum)
d. TV Phase 4: Worst-case cold (24-hour orbit operation, minimum)

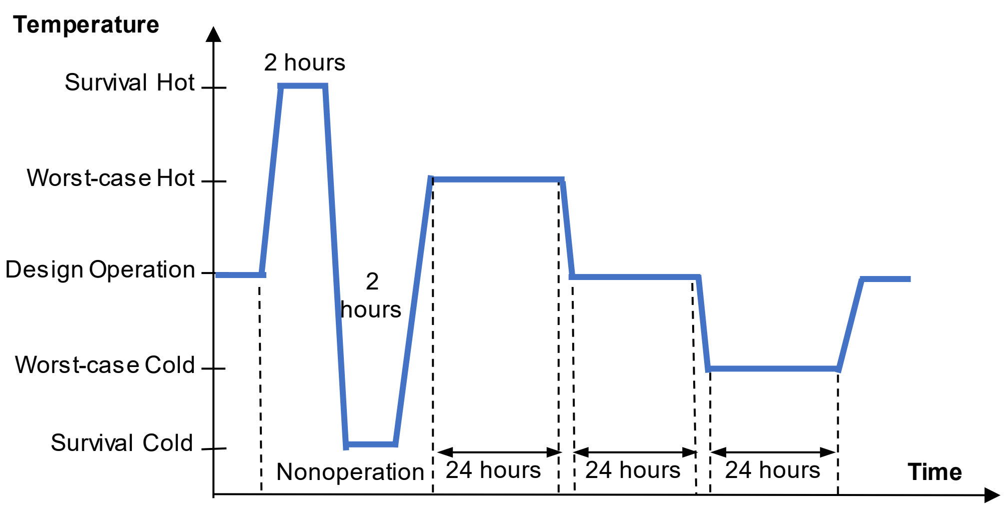

Figure 7. Battery acceptance thermal vacuum test.

9.20.2 All primary and redundant heater operations shall be validated, such as turn-off/on set points and heater duty cycle operation, flight temperature measurement, overtemperature switch accuracy, heat pipe performance, radiator sizing, and insulation effectiveness, if available during the test.

9.20.3 Cell-to-cell temperature gradients shall be measured with existing flight temperature sensors to validate the thermal interfaces and control system and verified to be within 5 deg C across individual cells by test and analysis for the battery. If battery enclosure design allows for additional thermistors or thermocouples they can be temporarily installed to supplement existing flight temperature sensors for cell temperature gradient measurement.

9.20.4 Cell-to-cell temperature gradients at same location within a parallel circuit or series string when cell balancing is unavailable shall be within 3 deg C by test and analysis.

9.20.5 Battery and cell or cell-bank voltage, temperature, currents, and heater status shall be continuously monitored during all portions of the test to validate specification performance requirements and verify no intermittent behavior.

9.20.5.1 For battery designs using COTS cells without available cell balancing electronics, cell voltage measurements are typically not available.

9.20.6 The thermal balance test results shall be compared to the analytical thermal model and previous battery performance.

9.20.7 A leakage test per Section 9.16 shall be performed with a residual gas analyzer that scans with at least once-a-minute frequency throughout the thermal vacuum test, and with a capable gas detector tuned to detect volatile electrolyte solvents in the cell, with a threshold and accuracy to verify no cell leakage occurred.

9.20.8 As part of safety verification, continuous battery terminal (positive and/or negative) to battery chassis isolation shall be monitored during thermal vacuum test to verify that electrical isolation between battery chassis and all electrical components (e.g., cell, harness, piece parts, etc.) is maintained within specification requirements throughout the test.

9.20.9 Visual inspections and tests per paragraph 9.8.3 and specification performance test per paragraph 9.11.1.b and Sections 9.13 through 9.15 shall be performed before and after thermal vacuum test, with results documented to verify no physical damage and/or performance degradation occurred as a result of the environmental test.

9.21 Proof Pressure

Pressure testing shall be conducted on battery enclosures with pressure relief valves or pressure relief mechanisms per SMC-S-016/TR-RS-2014-0016 [1] and as specified below. Note: For cell-level pressure/proof pressure tests, see Section 4.3.1 or 5.4.11.1; for other component (e.g., heat pipes) pressure testing, see SMC-S-016/TR-RS-2014-0016 [1].

9.21.1 The proof pressure/pressure tests shall demonstrate margin in the battery so that structural failure does not occur before the design pressure is reached, and/or excessive deformation does not occur at the maximum expected operating pressure.

9.21.2 For battery cases with a reusable venting device or pressure relief mechanism, a proof pressure test shall be performed after exposure to all acceptance environments to demonstrate that venting occurs at the design set point, which is greater than 1.25 times the maximum expected operating pressures.

9.21.3 For batteries using a rupture disk or similar one-time-use device, a burst test shall be performed on a statistically significant number of flight lot rupture disk samples to demonstrate that the opening pressure of the device meets the requirements.

9.21.4 All proof pressure/pressure test results shall be included as part of the acceptance report.

9.21.5 Visual inspections and tests per paragraph 9.8.3 shall be performed before and after proof pressure test, with results documented to verify no physical damage occurred as a result of the test.

9.22 Proof Load

A battery proof load test is conducted for all structural units made of composite materials or having adhesively bonded parts. The proof load test is intended to detect material, process, and workmanship defects that could lead to structural failure. The battery structural testing shall be performed per
SMC-S-016/TR-RS-2014-0016 [1] and AIAA-S-110-2005 [22] as applicable.

9.22.1 Visual inspections and tests per paragraph 9.8.3 shall be performed before and after proof load test with results documented to verify no physical damage occurred as a result of the test.

9.23 EMC

EMC compatibility of the battery shall be performed per SMC-S-016/TR-RS-2014-0016 [1] as applicable, and as further specified in the SMC-S-008 [2] and MIL STD 461 [21].

9.23.1 The electromagnetic compatibility test shall verify that the electromagnetic interference characteristics (emission and susceptibility) of the battery, under normal operating conditions, do not result in malfunction of the battery.

9.23.2 The electromagnetic compatibility test shall verify that the battery does not emit, radiate, or conduct interference, which could result in malfunction of other units.

9.23.3 Radiated emission test shall be performed on all batteries capable of generating emissions.

9.23.4 Acceptance tests shall be performed when there is less than 12 dB qualification margin or the radiated emissions requirement is more stringent than 10 dB µV/m or the units have a passive intermodulation requirement.

9.24 Flight Lot Cycle Testing

Flight lot cycle testing, as specified below, shall be performed on a minimum of five randomly selected spare cells from each flight lot that completed cell-level acceptance testing to validate the performance and workmanship of each cell flight lot. For programs with multiple cell lot deliveries that occur over multiple years, flight lot cycle test frequency may be reduced to once every two years when the cell design has significant flight heritage and proven reliability. For COTS cell lots, flight lot cycle testing is satisfied within Section 5.

9.24.1 Three of the five flight lot cycle test cells shall be exposed to flightproof-level shock/vibration test prior to the flight lot cycle test that represents flightlike levels at the cell interface and mounting surface per SMC-S-016/TR-RS-00016 [1] and Section 4.4.5/4.4.6 of this document.

9.24.2 The flight lot cycle test shall repeat any previously performed accelerated cycle test (temperature, currents, voltage, depth-of-discharge, and number of cycles) for performance comparison.

9.24.3 Cell-level capacity, charge retention and impedance acceptance tests that most closely represent on-orbit operation shall be performed before and after cycle test as well as annually, at conditions previously performed for acceptance test in order to generate performance trends.

9.24.4 The first two cycles and last two cycles of the flight lot cycle test shall be performed at C/20 charge and discharge rates to vendor's maximum and minimum voltage thresholds to identify issues such as irreversible chemical changes, electrode delamination, lithium plating, and/or undisclosed design change.

9.24.5 Flight lot cycle testing shall be initiated right after flight cell selection to maximize the amount of data collected prior to spacecraft launch.

9.24.6 Postflight lot cycle test x-rays shall be performed on three cells to verify workmanship requirements of paragraph 4.3.4 and compared to cell x-rays before environmental testing to verify no movement, breakage, and/or damage internal to the cell was caused by the mechanical environments.

9.24.7 Following completion of flight lot cycle test, at least one of the test cells shall go through a destructive physical analysis to verify that the cell design meets the criteria of Section 8.12. The DPA can be performed prior to completion-of-life test (prior to launch) as required.

9.24.8 Flight lot cycle test progress and results shall be reported on at least a six-month basis.

9.24.9 Flight lot cycle test results shall show statistically unchanged performance from the qualification accelerated life test.

9.25 Safety

The flight battery design, qualification and acceptance tests, safety testing, and ground operation shall comply with Section 7.3.15, AIAA S-122/T [24], AFSPCMAN 91-710 [14], and DOT lithium-ion battery regulation(s) [15].

9.25.1 Any waivers to the AFSPCMAN 91-710 [14] or DOT [15] requirements shall be obtained and approved through their respective government agencies (range safety and/or DOT) as required.

9.25.2 A test of all reusable vent devices on cells and battery cases shall be verified to meet specification requirements for opening and closing pressures per Section 9.21.

10. Handling, Storage and Maintenance

The requirements in this section apply to the handling, storage, and maintenance of batteries, cell modules, cell banks, and cells during ground activities preceding prelaunch activities. These requirements shall be specified in the battery specification and/or battery storage and handling procedure to minimize preflight degradation per AIAA S-122-2007 and its tailoring [20, 24] and the following:

10.1 Battery/Cell Bank/Cell Storage and Handling

10.1.1 Validated data from development and qualification tests shall be used to develop documented handling, storage, and maintenance procedures in all phases of battery handling for:

a. State of charge
b. Voltage monitoring
c. Periodic recharge
d. Cell rebalancing/conditioning
e. Temperature and humidity conditions

10.1.2 The storage, handling, and maintenance procedures shall minimize safety hazards to personnel, facilities, and flight hardware.

10.1.3 Handling procedures shall document the steps necessary to place cell, cell bank, and batteries into cold-temperature storage or for installation on the spacecraft following completion of acceptance tests.

10.1.4 An electrostatic discharge (ESD) control program shall be implemented to protect ESD-sensitive hardware on the battery as specified in MIL STD 1686 [6] or other equivalent documents.

10.1.5 The maximum shelf-life limit shall be defined for the battery, including the maximum exposure time to ambient, cold-storage temperature and humidity conditions.

10.1.6 Batteries, cell banks, or cells shall be maintained within a controlled temperature and humidity environment at all times to maximize battery life and prevent water condensation. Consider the use of bagging or other methods to reduce possibility condensation upon removal from cold storage.

10.1.7 When not in use for greater than three months, the batteries, cell banks, or cells shall be placed in cold storage at a state of charge for the storage conditions and planned storage duration unless validated by qualification life test data/analysis to show the battery meets intended service life.

10.1.8 Cell or cell bank voltages shall be measured and recorded no less than every 30 days during cell, cell bank, and battery storage to identify low-voltage cells or cell banks before they violate the minimum voltage threshold due to self-discharge.

a. For COTS cells, any cell that drops to an unacceptably low voltage during open-circuit stand may be recharged if the cells are within the statistical self-discharge distribution of the lot; otherwise the cell shall be rejected.

b. For modules or batteries using COTS cells, voltage shall be measured and recorded no less than every 30 days during storage to identify low voltage before they violate the minimum voltage threshold due to self-discharge.

10.1.9 Connector savers shall be used for all testing to interface the battery flight connectors and any mating test or ground support equipment cables.

10.1.10 Specialty containers shall be used during extended storage and transportation to provide physical protection to prevent damage during handling, transportation, and storage.

10.1.11 Shipping containers shall contain sensors to measure temperature, humidity, and mechanical shock during shipping of cells, cell banks, and batteries.

10.1.12 Batteries shall not be used for flight if the time between battery cell formation and launch exceeds the specified shelf-life limit for the battery under the specified temperature conditions unless verified by the qualification life test data/analysis and recent battery performance data, and approved by a waiver/deviation.

10.1.13 Inspection of batteries and/or cells shall be performed following transportation per Section 11.3.

10.1.14 Storage and handling records shall be maintained and periodically assessed to verify that the storage plan, methods, and conditions have been met.

10.2 Battery, Cell Bank, and Cell Maintenance

10.2.1 Voltage monitoring, periodic recharge, cell rebalancing, and conditioning shall be performed in accordance with the approved/established battery handling and storage procedures, to minimize degradation.

10.2.2 Maintenance procedures shall define maintenance methods and equipment; monitoring frequency; and voltage, current, and temperature limits as validated during development and/or qualification tests.

10.2.3 Cell balancing shall be completed prior to capacity measurement. This requirement does not apply for batteries using COTS cells that are not designed with cell balancing.

10.2.4 The maximum allowed voltage decay rate for cells, cell banks, and batteries shall be defined, based on development test and life test database and verified by measurement for each cell, cell bank, and battery before and after shipping and at least every 30 days during storage as well as battery-level manufacturing, and following completion of cell acceptance through launch.

10.2.5 No cell, cell bank, cell module, or battery exhibiting out-of-specification or out-of-family voltage decay rates shall be used in a flight battery. The cells (or cell bank) in a lot or battery may be recharged or balanced to prevent a cell from dropping to an unacceptably low voltage during open-circuit stand if all the cells are within the 3-sigma statistical self-discharge rate distribution for the lot; otherwise unacceptably low voltage cells outside the 3-sigma distribution shall be rejected.

10.2.6 Any equipment used to monitor, charge, or discharge batteries (cell banks or cells) shall be designed with a level of safety features similar to or greater than those available at the spacecraft level.

10.2.7 Checkout of all maintenance equipment, software, and safety inhibits shall be performed before connecting flight hardware.

10.2.8 Redundant safety inhibits and devices shall be incorporated into the battery conditioning modules to prevent damage to the battery or vehicle, prevent any battery cell voltage from exceeding upper- and lower-voltage limits for all battery states of charge, and prevent maximum charge or discharge currents and temperatures from exceeding specification limits.

10.3 Records

10.3.1 Records documenting the flight accreditation status of batteries shall be maintained for five years postlaunch unless otherwise specified in the contract.

10.3.2 These records shall provide traceability from production of the battery through final installation in the vehicle and on through to launch.

10.3.3 The records shall indicate changes in battery/cell location, status, use, storage time, charge maintenance, or any conditions that could affect reliability or performance.

10.3.4 Time-correlated records shall be maintained indicating battery, cell bank, cell charge or discharge current, battery voltage, and temperature with accuracy to allow an assessment of potential degradation when discharging, recharging, cell-balancing, and electrical performance testing is performed.

10.4 'Not for Flight' Hardware

10.4.1 Battery and battery hardware that by intent, by usage, or by material disposition are not suitable for use in flight shall be clearly identified as nonflight (e.g., a red tag, striped with red paint) to prevent such substitution with flight or flight-spare hardware.

10.4.2 The red tag shall be conspicuous and marked "NOT FOR FLIGHT."

10.4.3 The red paint shall be material compatible, and the stripes highly visible and unmistakable.

10.4.4 All nonflight hardware used during manufacture of the battery shall be accounted for and removed prior to flight.

11. Verification for Shipment

The requirements in this section apply to checkout, performance verification, safety, and shipment of flight batteries prior to installation on spacecraft. Battery testing shall verify flight hardware to produce acceptable electrical performance while minimizing degradation per AIAA S-122-2007 and its tailoring [20, 24], manufacturer's assessment that the battery is safe for its intended use, and the following:

11.1 Safety

Battery handling, inspection, test, and transportation shall comply with the approved battery handling procedures and all safety requirements, including range safety [14] and DOT [15].

11.1.1 All existing sources of data, including manufacturer safety assessments, existing safety test data, and mishap risk assessments, shall be provided.

11.2 Removal from Storage

Flight batteries shall not be subjected to thermal shock or water condensation upon removal from cold storage prior to shipping.

11.3 Inspection

Inspection of flight battery shall be performed prior to shipping, repeated after shipping and prior to installation on spacecraft.

11.3.1 The manufacturer, part number, and serial number of the flight battery shall be verified for accuracy.

11.3.2 The records for each flight battery shall be reviewed to verify that flight batteries do not exceed their maximum shelf-life limit prior to mission use and will not exceed the maximum cycle life prior to completion of mission.

11.3.3 The flight battery shall be visually inspected for signs of handling damage or abuse.

11.3.4 The battery and cell or cell bank (as applicable) open-circuit voltage shall be documented and verified to be within specification limits, and data trending does not indicate an out-of-family cell or cell bank performance.

11.3.5 The continuity and isolation of cells, connector pins, and wires shall be verified, as applicable.

11.3.6 The operation of all monitoring or control circuits shall be verified, as feasible.

11.3.7 The condition of any venting device on the battery housing shall be inspected to verify that it meets the design criteria.

11.3.8 Temperature, humidity, and mechanical shock levels shall be documented during shipment and verified to be within handling requirements after shipment.

11.3.9 The battery, by inspection, shall be verified not to contain cells that are leaking electrolyte.

11.4 State-of-Health Verification

State-of-health verification as defined below shall be performed after removal from storage and prior to shipping for spacecraft integration.

11.4.1 Test equipment used to monitor and electrically test the flight battery shall be equivalent to the charge equipment which was validated by qualification or acceptance testing.

11.4.2 The open-circuit voltage of every cell or cell bank shall be verified within the battery-handling cell-balance requirements specified by the battery handling plan, as applicable. Cell rebalancing will be performed as required.

11.4.3 One standard capacity measurement, at a minimum, shall be performed prior to shipment from storage or prior to spacecraft integration and verified on each flight battery to be within 3% of the prior test performed during flight battery protoqualification or acceptance testing for trending purposes.

11.4.4 The charge retention rate following at least a seven-day stand period at 100% state of charge shall be performed and verified to be within requirements.

11.4.4.1 Cells, cell banks, or batteries exhibiting out-of-specification or out-of-family voltage decay rates shall not be used in a flight battery.

11.4.5 State-of-health data shall be reviewed and trended with qualification or acceptance test data to verify that performance meets minimum beginning-of-life mission requirements.

11.5 Preparation for Shipment

Flight batteries can be installed in the vehicle before it is shipped to the launch site or shipped separately and installed at the launch site.

11.5.1 The battery state of charge shall be at a level that minimizes degradation during transportation and maintains cell voltages above the cell low-voltage limit throughout transportation as specified by the battery handling plan.

11.5.2 Individual cell voltages shall be verified within the cell-balanced voltage criteria and rebalanced if needed. For batteries using COTS cells, individual cell voltages and cell balancing may not be available.

11.5.3 The battery shall be transported in a qualified shipping container that provides physical protection to prevent damage during handling, transportation, or storage.

11.5.3.1 The shipping containers shall contain sensors to measure temperature, humidity, and mechanical shock during shipping.

11.5.4 Batteries shall be maintained between –10 deg C and +30 deg C during handling, transportation, and installation.

11.6 Minimum Use of Flight Batteries during Vehicle Integration and Test

11.6.1 To maximize on-orbit performance, batteries used for flight shall not be installed or used for spacecraft-level integration or acceptance tests at the vehicle fabrication and assembly site, except as necessary for nonoperational tests such as spin balance or when the requirements of paragraphs 11.6.3 and 11.6.4 are met.

11.6.2 Test batteries that are equivalent in configuration to the flight batteries and that have passed battery flight-level acceptance tests, shall be used only for space vehicle-level integration and acceptance testing.

11.6.3 As an option, when the flight battery is used for vehicle-level integration, the qualification life-test data/analysis and battery replacement plan (availability of spare battery in the event of flight battery damage during vehicle-level integration) shall prove that it can meet service life and launch schedule, respectively.

11.6.4 If flight batteries are installed on the vehicle prior to completion of spacecraft environmental test one standard capacity measurement shall be performed pre- and postenvironmental test as well as postshipment to launch site to verify that performance meets minimum beginning-of-life mission requirements.

12. Preflight Operations

The requirements in this section apply to battery installation, checkout, safety, and maintenance of batteries during spacecraft-level ground activities preceding launch. Battery processing shall maintain flight hardware to produce acceptable electrical performance while minimizing degradation, per AIAA S-122-2007 and its tailoring [20, 24] and the following:

12.1 Safety

Battery installation, handling, and maintenance shall comply with the approved battery handling procedures and all safety requirements, including range safety [14] and DOT [15].

12.2 Battery Installation on Spacecraft

12.2.1 An easily attachable and removable nonconducting 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.

12.2.1.1 The cover should remain in place for some or all of the vehicle launch preparation and shall be removed prior to launch.

12.2.2 For large lithium-ion batteries, typically over 40 pounds, a handling plate or fixture shall be used for installing the battery on the vehicle.

12.2.2.1 The fixture shall protect the thermal and structural elements of both the battery and vehicle from damage.

12.2.2.2 The handling plate shall be removed once the battery is installed on the vehicle.

12.2.3 When electrically connecting the battery to the spacecraft bus, the difference between the spacecraft bus voltage and the battery voltage shall be within predetermined limits that are sufficiently small to limit surge currents to levels that will not result in damage to components or connector pins.

12.2.4 Battery voltage and cell and/or cell bank voltage, current, and temperature shall be monitored after battery installation on the vehicle at a frequency and resolution to detect a cell-level anomaly, such as premature discharge. For batteries designed with COTS cells, cell voltages may not be available.

12.3 Battery Maintenance on the Spacecraft

Battery maintenance procedures shall be in place that allow for periodic maintenance of battery state of charge, periodic cell balancing, and battery charge/discharge after vehicle installation, as required.

12.3.1 Specific limits or frequency shall be defined for each aspect of battery maintenance with a minimum frequency for battery capacity measurements of 6 months or as defined paragraph 11.6.4 when a test battery is not used.

12.3.2 The battery conditioning module shall be used to discharge the battery at a controlled current to prepare the spacecraft for storage instead of allowing the battery to self-discharge.

12.3.3 Any ground support equipment used to monitor, charge, or discharge a battery shall be designed with a level of safety features similar to or greater than those available at the spacecraft level.

12.3.4 Redundant safety devices and inhibits shall be incorporated in the battery conditioning module to prevent damage to the battery or vehicle and prevent any battery/cell voltage from exceeding upper- or lower-voltage limits for all battery states of charge, and prevent maximum charge or discharge currents and temperatures from exceeding specification limits.

12.3.5 Checkout of all maintenance equipment, software, and safety inhibits shall be performed before connecting flight hardware.

12.3.6 Maximum and minimum criteria for battery state of charge, battery voltage, cell or cell bank voltage, charge-discharge current, temperature, and maximum cell-voltage dispersion shall be derived from prior verification and qualification testing that is specific to the design and mission, and used to monitor battery health after battery installation through to terminal countdown. For batteries designed with COTS cells, cell voltages may not be available.

13. Launch and On-Orbit Operations

The requirements in this section apply to battery launch, on-orbit battery operation, orbital maintenance, orbital-data trending, and orbital safety. Battery operation shall maintain flight hardware in an operational state by producing acceptable electrical performance while minimizing degradation per AIAA S-122-2007 [20, 24] and its tailoring and the following:

13.1 Battery Monitoring Preceding Launch

Battery voltage, cell or cell bank voltage, current, and cell temperatures shall be measured periodically after battery installation on the vehicle, up to the final terminal countdown, to verify state of health of the electrical systems prior to launch.

13.1.1 Battery data, listed below, shall be evaluated and compared against the maximum and minimum criteria that is specific to the design and mission. These data shall be used to monitor battery health after battery installation through to terminal countdown, to abort the launch when malfunctions occur in launch-critical batteries.

a. Battery state of charge
b. Battery voltage
c. Cell or cell bank voltage
d. Cell or bank temperature
e. Maximum cell-voltage dispersion

13.2 Charge Control

13.2.1 Battery charging-and-control procedures and contingency procedures shall be prepared based upon test data obtained during vehicle, battery, cell bank, and cell development/qualification tests.

13.2.2 Documented procedures shall be the basis for battery operations and controls at the launch site and while on orbit.

13.2.3 Battery or individual cell voltages and charge currents shall not exceed manufacturer's recommendation (accounting for measurement tolerances) unless validated by test and impact to mission life.

13.3 Temperature

13.3.1 Battery temperatures throughout the orbital lifetime shall be maintained with a temperature range previously established from vehicle, battery, cell bank, cell development, and life testing.

13.3.2 Control and contingency procedures to maintain battery temperature within the required range shall be the basis for battery operations and control while at the launch site and on orbit.

13.4 Cell Balancing

Prior to launch, all cell or cell bank voltages shall be within the designed tolerance.

14. Applicable Documents

Unless otherwise specified, the following specifications, standards, and handbooks (of the revision in effect at the time of invitation to bid the government acquisition activity) form part of this document to the extent specified herein. In the event of conflict between this document and the referenced documents below, this document shall take precedence.

Documents not identified by revision or date shall be the latest issue in effect.

1. SMC-S-016 (2014), *Test Requirements for Launch, Upper-Stage and Space Vehicles* (originally published as Aerospace Report No. TR-RS-2014-00016).

2. SMC-S-008 (2008), Electromagnetic Compatibility Requirements for Space Equipment and Systems (originally published as TOR-2005(8583)-1).

3. Aerospace Report No. TOR-2007(8583)-6690, *Weibull-Based Life Test Scenarios*, May 30, 2007, M. M. Cavanaugh.

4. AIAA-S-080A-2018, Space Systems—Metallic Pressure Vessels, Pressurized Structures, and Pressure Components.

5. AIAA-S-081B-2018, Standard for Space Systems—Composite Overwrapped Pressure Vessels (COPVs).

6. MIL-STD-1686, Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies, and Equipment (Excluding Electrically Initiated Explosive Devices).

7. SMC-S-009 (2013), Parts, Materials, and Processes Control Program for Space Vehicles (also published as TOR-2006(8583)-2336).

8. Aerospace Report No. TR-2006(1455)-1, *Lithium-ion Life Expectancy Verification Guidelines for Transformational Satellite Communication System (TSAT)*, November 25, 2005, W. H. Hwang.

9. U.S. Government, National Space Policy of the United States of America.

10. U.S. Government, Orbital Debris Mitigation Standard Practices.

11. Air Force Instruction 91-217, Space Safety and Mishap Prevention Program.

12. DOD Instruction No. 3100.12, *Space Support*.

13. DOD Directive No. 3100.10, *Space Policy*.

14. AFSPCMAN 91-710, Range Safety User Requirements.

15. DOT Lithium-ion Battery Regulation(s), 49 Code of Federal Regulations Parts 171, 172, 173.

16. SMC-S-014 (2010), *Survivability Program Management for Space* (originally published as TOR-2008(8583)-8164).

17. SAE AS6500, Manufacturing Management Program.

18. SMC-T-009 (2018), Space and Launch Requirements Addendum to AS9100D Quality Management Systems.

19. SMC-S-010 (2013) Technical Requirements for Electronic Parts, Materials, and Processes Used in *Space Vehicles* (originally published as TOR-2006(8583)-2336).

20. AIAA S-122-2007, Electrical Power Systems for Unmanned Spacecraft.

21. DOD MIL-STD-461G, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment.

22. AIAA S-110-2005, Space Systems – Structures, Structural Components, and Structural Assemblies.

23. SMC-S-013 (2008), Reliability Program for Space Systems.

24. SMC-T-012 (2020), *Lithium-Ion Battery Tailoring for AIAA S-122-2007, Electrical Power Systems for Unmanned Spacecraft* (originally published as TR-RS-2020-00030).

25. SAE International AS9100, Quality Management Systems – Requirements for Aviation, Space, and Defense Organizations.

26. Aerospace Report No. TOR-2019-00829, *Differential Capacity Analysis and Apparent OCV Analysis Methods for Lithium-Ion Cell*s, May 15, 2019.

27. DOD MIL-STD-810H, *Test Method Standard*.

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