BY ORDER OF THE COMMANDER

SMC Standard SMC-S-017
13 June 2008

Supersedes:
New issue

Air Force Space Command

SPACE AND MISSILE SYSTEMS CENTER STANDARD

LITHIUM-ION BATTERY FOR SPACECRAFT APPLICATIONS

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **13 JUN 2008**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **SMC-S-017 (2008) Lithium-Ion Battery for Spacecraft Applications**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **USAF Space and Missile Systems Center**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**61**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

FOREWORD

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

2. This new-issue SMC standard comprises the text of The Aerospace Corporation report number TOR-2007(8583)-1.

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

Division Chief, SMC/EAE
SPACE AND MISSILE SYSTEMS CENTER
Air Force Space Command
483 N. Aviation Blvd.
El Segundo, CA 90245

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

James Horejsi, Col, USAF
SMC Chief Engineer

Contents

1. Scope

1.1 Purpose

This document establishes standards for the development, testing, storage, handling, and usage of lithium-ion batteries for military spacecraft. Compliance with this standard is intended to assure proper performance of batteries and to provide protection against pre-flight degradation and premature degradation during operational use on space, launch, and upper-stage vehicles.

1.2 Application

This report is intended for compliance in applicable military spacecraft acquisition and development to incorporate common requirements and practices necessary to assure successful lithium-ion battery operation during space missions. It is expected that battery piece parts, such as cell, cell-module, charge control electronics, bypass switch, heaters, temperature sensors, etc., are procured to lower-level qualification documents that define design, process, and quality controls, and qualification and acceptance test requirements.

1.3 Conflicts with Other Standards

In the event of conflict between this document and the AIAA Electrical Power Systems for Unmanned Spacecraft Standard[1] or the Space Battery Standard,[6] this document shall take precedence with regards to any battery-specific definition or requirement.

This page intentionally blank.

2. Definitions

2.1 Battery

A battery is an assembly of battery cells or modules, from a single-cell lot, electrically connected (usually in series) to provide the desired voltage and current capability. Generally, the cells are physically integrated into either a single assembly (or battery) or into several separate assemblies (or modules). The battery may also include one or more attachments, such as electrical bypass devices, charge control electronics, heaters, temperature sensors, thermal switches, and thermal control elements.

2.2 Battery Depth-of-Discharge (DOD)

The Battery Depth-of-Discharge (DOD) is the ratio of the number of watt-hours removed from a battery for a defined charge voltage-current profile, discharge load profile, and temperature profile to the battery rated (or nameplate) energy E(Wh), times 100. For a lithium-ion battery, the DOD must be specified at a state-of-charge (SOC) operation or a voltage that relates to SOC operation.

$$\text{Battery Depth-of-Discharge (\%)} = \left(\frac{E(Wh)_{REMOVED}}{E(Wh)_{RATED}}\right) X\ 100$$

NOTE: For batteries 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%.

2.3 Battery Energy

Launch, transfer orbit, and on-orbit battery energy and energy reserve requirements are flowed down from the Electrical Power Subsystem specification for the entire mission life. Battery energy is 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. The limits of integration are from the start of discharge to either the minimum power subsystem battery voltage limit, or the point at which the first cell reaches the lower cell voltage limit, or when the defined time duration is reached. This is a point-in-time energy value that is measured at a defined charge voltage-current profile, discharge load profile, and temperature profile. Battery discharge can be accomplished with constant-current discharge; however, constant power discharge is the preferred method if it more closely simulates spacecraft power.

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

2.4 Battery State of Charge (SOC)

The Battery State of Charge (SOC) is the ratio of the number of Wh present in a battery for a defined charge voltage-current profile, discharge load profile, and temperature profile to the rated energy E(Wh) of the battery, times 100.

$$\text{Battery State-of-Charge (\%)} = \left(\frac{E(Wh)_{PRESENT}}{E(Wh)_{RATED}}\right) X\ 100$$

2.5 Battery Capacity

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

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

2.6 Cell Activation

The addition of electrolyte to a battery cell constitutes cell activation and starts the clock on cell, module, and battery service life. It is used to define the start of battery shelf life.

2.7 Cell or Battery Cell

A cell is a single-unit device within one cell case that transforms chemical energy into electrical energy at characteristic voltages when discharged. Battery cells can be directly connected (usually in series) to form a battery. Battery cells can be connected in series or parallel to form a module; in such cases, the modules are connected (usually in series) to form a battery.

2.8 Cell Design

A cell design is built to one set of manufacturing control documents that define material composition, dimensions, quantity, process, and process controls for each component in the cell. A change in cell design is considered a different cell design that requires a separate qualification. A change in cell design includes, but is not limited to, the following:

(a) Positive electrode composition, raw material (including binder), loading density, foil, dimension, or process change

(b) Negative electrode composition, raw material (including binder), loading density, foil, dimension, or process change

(c) Electrolyte composition

(d) Separator composition or dimension

(e) Cell stack or cylindrical wrap dimension or compression

(f) Cell case size

(g) Change in cell or raw material manufacturing location

(h) Terminal seal

2.9 C/n Charge or Discharge Current (C-Rate)

The constant charge or discharge current for a battery is defined as C/n, or C-rate. C is the cell-level nameplate (or rated) capacity in ampere-hours (per vendor's criteria), and n is any value for elapsed time measured in hours. For example, a discharge current of C/2 for a 20 A-h rated cell is a discharge current of 10 A.

2.10 Cell Lot or Battery Cell Lot

A cell lot or flight battery cell lot consists of a continuous, uninterrupted production run of cells, which consists of anode, cathode, electrolyte material, and separator, from the same raw material sublots with no change in processes or drawings. A flight battery or lithium-ion cells produced in a single lot should be procured, stored, delivered, and tested together to maintain a flight battery or single lot definition.

It is the intent that all cells in a flight battery contain a single lot of cells that are all exposed to the same duration of temperature exposure and electrical cycles. Any deviation from this requirement will require a waiver. Factors that are important in obtaining a waiver include charge control architecture, capacity fade and resistance change as a function of temperature storage and electrical cycling, distribution of capacity fade, and resistance change demonstrated in life test.

2.11 Cold Storage

Cold storage, for batteries that are not in use, is long-term storage where the temperature and humidity environments are controlled, and temperature is below ambient temperature.

2.12 Energy Reserve

Total amount of usable energy in E(Wh) remaining in a battery, which has been discharged to the maximum allowed DOD under normal operating conditions to either the minimum power subsystem battery voltage limit, or first cell reaches lower cell voltage limit.

Note: Energy reserve provides enough energy to ensure positive energy balance during the maximum sun-outage time when a loss of attitude control occurs coincident 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 rare, deep discharges such as relocation with electric propulsion, or those that may occur in transfer orbit.

2.13 Maximum and Minimum Predicted Temperatures (MPT)

The maximum and minimum predicted temperatures are the highest and lowest temperatures that an item can experience during its service life, including all test and operational modes. The MPT are established by adding thermal uncertainty margins to the maximum and minimum model temperature predictions as defined in TR-2004(8583)-1.[2]

2.14 Maximum Expected Operating Pressure (MEOP)

The Maximum Expected Operating Pressure (MEOP) is the maximum pressure that pressurized hardware is expected to experience during its service life, in association with its applicable operating environments.

2.15 Module or Battery Module

A battery module is an assembly of series- or parallel-connected battery cells that are connected (usually in series) to form a battery.

2.16 Procurement Authority

The Procurement Authority is the agency responsible for spacecraft procurement.

2.17 Rated (or Nameplate) Battery Energy

The rated battery energy is the minimum guaranteed energy at beginning-of-life (BOL) for a defined range of mission charge control conditions, discharge load conditions, temperature profile, and minimum voltage requirement. The relationship that defines the rated battery energy is determined from the maximum power subsystem mission requirements and the real-time and accelerated-time database.

Rated battery 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. The limits of integration are from maximum allowable power subsystem charge voltage to either the minimum power subsystem battery voltage limit, or when the first cell reaches lower cell voltage limit.

BOL is at the completion of battery-level qualification, proto-qualification, or acceptance test. Rated battery energy may differ from the vendor's cell ratings, but can not be greater. Battery discharge may be accomplished with constant-current discharge; however, constant power discharge is the preferred method if it more closely simulates spacecraft power.

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

2.18 Service Life

The service life of a battery, battery module, or battery cell starts at cell activation and continues through all subsequent fabrication, acceptance testing, handling, storage, transportation, testing preceding launch, launch, and mission operation.

2.19 Shelf-Life Limit

Shelf-life limit for a battery, module, or cell is the maximum allowed time from cell activation to launch. This includes any time in cold storage.

2.20 Survival Temperature

Survival temperatures are the cold and hot temperatures over which a unit is expected to survive, either operationally or non-operationally. The unit must demonstrate that it can be turned on at theses temperatures and, although performance does not need to meet specification, the unit must not show any performance degradation when the environment or unit temperatures are returned to the operational or acceptance temperature range of the unit.

This page intentionally blank.

3. Development Testing

3.1 Development Testing

The objective of development testing is to identify problems early in the design evolution so that any required corrective actions can be taken prior to starting formal qualification. Development testing shall be conducted for a new or modified battery design, new or modified module design, new or modified cell design, new application, or new supplier of cell, module, or battery. Development testing should be used to confirm performance, structural margins, dimensional requirements, compatibility to pre-launch, launch and space environments, manufacturability, testability, maintainability, reliability, and compatibility with system safety. Development tests should be conducted, when practical, over a range of operating conditions that exceeds the design range to identify margins in capability. Operating conditions include temperature and charge control conditions.

3.2 Charge Control Testing

The battery shall be tested with flight-like charge control electronics to determine whether the charge control method and conditions are consistent with required battery performance throughout mission life. Control parameters to be used, such as voltage, temperature, current, and cell balancing capability shall be characterized sufficiently for a flight-type battery to demonstrate a charge control design that will meet the requirements for all vehicle operations, including sun periods and contingencies. Charge control electronic designs shall be validated during the life cycle test.

3.3 Thermal Control Testing

Thermal testing of a battery shall be performed to determine whether the thermal control method and provisions are consistent with and satisfy battery requirements. Control parameters to be used, such as temperature and temperature gradients, shall be characterized sufficiently for a flight-type battery to demonstrate a thermal control design that will meet the requirements for all mission conditions and vehicle operations, including sun periods and contingencies.

A variety of thermal tests may be performed to validate thermal characteristics and reduce the risk of thermal issues occurring during qualification test:

(a) Thermal characterization tests can be performed at the cell, module, or battery level, either in a calorimeter, thermal vacuum, or temperature-controlled environment, to aid in thermal model correlation. This data validates the cell-level thermal dissipation or quantifies the external temperatures and gradients as a function of charge/discharge conditions.

(b) A thermal conductance test can quantify the rate of heat transfer through a material or across an interface. Specific applications include measuring the directional conductivity in composites, the conductance across cabling, and verification of thermal blanket performance, or any other potentially significant heat conduction path, such as from the cell to the radiator or across battery-to-spacecraft interfaces.

(c) A thermal balance test at a unit level provides data for thermal model correlation and verifies the thermal control subsystem. This test verifies heaters, thermostats, flight thermistors, radiators, heat pipes, etc., and demonstrates temperature and heater margins.

3.4 Mechanical Test

The objective of mechanical development tests includes the validation of new technologies and design concepts, the correlation of analytical models, the quantification of requirements, and the reduction of risk. Typically, an engineering cell, module, or battery unit is exposed to simulated environments to assist in the evolution of conceptual designs to flight articles. Resonance searches of a unit should be conducted to correlate with a mathematical model and to support design margin or failure evaluations. When a unit's structural design is composed of advanced composites or bonded materials, development tests should be conducted as defined in TR-2004(8583)-1 paragraph 6.2.3.[2] Development tests and evaluations of vibration and shock test fixtures should be conducted prior to first use to prevent inadvertent over-testing or under-testing, including avoidance of excessive cross-axis response.

3.5 Transportation and Handling Tests

The battery unit is commonly packaged in a manner that will provide protection against damage from physical and environmental sources during transportation and handling. It is possible that additional design and test requirements may come from handling and transportation environments, which can expose the unit to greater structural loading due to handling orientation and worst-case shock and vibration environments. It is also necessary to consider that transportation can result in a high number of load cycles, causing fatigue or wear, even though the amplitude of the cycles may be low relative to flight loads. MIL-STD-810[3] provides guidance for defining transportation environments and test requirements.

Since these environments are difficult to predict, it is often necessary to conduct a handling and transportation development test to determine worst-case dynamic inputs. Such a test should use a development model of the item or a simulator that has at least the proper mass properties and is instrumented to measure responses of the item. In particular, a drop test should be conducted to demonstrate protection of the item in the handling apparatus and validate the design of the shipping container. The data should be sufficient to determine whether the environments are benign relative to the design requirements, improve the packaging protection design, or to provide a basis for an analysis to demonstrate lack of damage, or to define specific mechanical environmental levels for qualification and acceptance testing.

3.6 Safety Testing

Safety requirements for lithium-ion battery design, safety testing, and ground operation are primarily driven by Air Force Range Safety and Department of Transportation requirements. The effect of cell failure on battery reliability throughout life needs to be considered due to the potential of cell failure propagating to other cells or piece parts. Battery-level safety needs to be validated by test under all known failure modes, which includes at a minimum the following conditions: overcharge, over-discharge, over-temperature, over pressurization, internal cell short, and external cell short. Cell-level, module-level, or battery-level development testing that simulates battery mechanical and thermal design needs to evaluate the potential of one cell failure propagating to another cell or piece part within the battery. Safety tests should be conducted over a range of operating conditions that exceed the design limits to identify marginal capabilities and marginal design features.

This page intentionally blank.

4. Qualification Testing

4.1 Qualification Test

(a) Qualification tests shall be conducted to demonstrate that the design, manufacturing process, and acceptance program produce battery hardware that meets specification requirements with adequate margin to accommodate normal production variation, multiple rework, and test cycles.

(b) The qualification tests shall validate the planned acceptance program, including test techniques, procedures, equipment, instrumentation, and software.

(c) Each type of battery, module, or cell design that is to be acceptance tested shall undergo a corresponding qualification test.

(d) A qualification test specimen shall be exposed to all applicable environmental tests in the order of the qualification test plan.

4.1.1 Test Hardware

The battery and cell hardware subjected to qualification testing shall be produced from the same drawings, using the same materials, tooling, manufacturing process, and level of personnel competency as used for flight hardware. Ideally, a qualification battery, module, or cell would be randomly selected from a group of production items.

4.1.2 Qualification Test Levels and Duration

4.1.2.1 To demonstrate margin, the qualification environmental conditions shall stress the qualification hardware to more severe conditions than the maximum conditions that might occur during service life. Qualification testing, however, should not create conditions that exceed applicable design safety margins or cause unrealistic modes of failure. The qualification test conditions should envelop those of all applicable missions.

4.1.2.2 Qualification test levels and durations shall be consistent with those described in TR-2004(8583)-1.

4.1.3 Data Collection and Acquisition Rates

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

4.1.3.2 Voltage, current, and temperature data shall be recorded at rates and accuracy sufficient to verify compliance with test requirements and performance specifications.

4.1.3.3 During any dynamic environmental test, data shall be collected on strip chart recorders or at an acquisition rate of at least 10,000 samples per second to evaluate for intermittent dropouts.

4.1.4 Cell Matching Criteria

4.1.4.1 A document shall be written that defines the cell matching criteria for the flight lot and provides the data that supports the selection of a specific criterion.

4.1.4.2 Cell matching criteria for the flight battery shall be enveloped by the beginning-of-life performance of the qualification life test cells that utilized flight-like charge control for balancing during test.

4.1.4.3 The cell matching criteria shall include at minimum: capacity, charge retention, and resistance data at a defined voltage or state-of-charge.

4.1.4.4 To maximize cell matching throughout life, all flight cells within a battery series/parallel configuration shall be exposed to the same electrical and temperature test conditions. As an example, if one module of a battery is exposed to proto-qualification levels, the second module of the same battery should also be exposed to proto-qualification levels.

4.1.5 In-Process Inspections and Tests

4.1.5.1 Parts, wiring, or materials that cannot be adequately tested after assembly shall be subjected to in-process controls and in-process inspections during their manufacture.

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

4.1.6 Qualification (or Proto-qualification) Report

A qualification report shall be provided at the completion of qualification testing; it shall include the following items:

(a) End-Item Description
(b) Certificate of Conformance
(c) Closure of action items [Critical Design Review (CDR), Manufacturing Readiness Review (MRR), Test Readiness Review (TRR)]
(d) Engineering changes since CDR
(e) Hardware discrepancy reports
(f) Test discrepancy reports
(g) Deviations and Waivers
(h) Battery specification

(i) Battery qualification procedures
(j) Test Equipment Calibration Record
(k) Cell Selection Criteria Report
(l) Specification compliance verification report
Battery Unit Qualification Test Data
In-Process Inspections and Tests
Analyses supporting the requirement or waiver of qualification test [Shock, Static Load, Proof Pressure, Electromagnetic Compatibility (EMC) and Thermal cycling]
Component level burst pressure and proof pressure results, as applicable
Report correlating thermal test data with thermal model predictions
Safety data and analysis report
Radiation data and analysis report
High Reliability Parts (cell, electronic or mechanical devices) Qualification Report
(m) As built assembly level, interface control and wiring drawing
(n) List of as build drawings, manufacturing procedures and test procedures identifying revision that were used to build and test the qualification unit
(o) Age Sensitive Component Record
(p) Telemetry Coefficients for all analog telemetry
(q) Electronic copy of raw test data

4.2 Qualification Tests Required

Test	Spacecraft Application	Suggested Test Sequence	Section
Inspection (1)	R	1	4.2.1
Specification Performance (1)	R	2	4.2.2
Leakage (1)	R	3, 7,12	4.2.3
Shock	ER	4	4.2.4
Vibration or Acoustic (2)	R	5	4.2.5
Acceleration	ER	6	4.2.6
Thermal Cycle	R	8	4.2.7
Thermal Vacuum	R	9	4.2.8
Climatic	ER	10	4.2.9
Proof Pressure	R	11	4.2.10
Electromagnetic Compatibility	ER	13	4.2.11
Burst Pressure	R	14	4.2.10
Static Load	R	15	4.2.12
Life	R	ER	5.0
Safety	R	ER	4.2.13
Radiation	ER	ER	4.2.14

R Required
ER Evaluation Required
(1) Performed before and after each environmental test as appropriate
(2) Vibration or acoustic required, as appropriate, with the other discretionary.

4.2.1 Inspection

4.2.1.1 The battery unit shall be inspected before and after each environmental test to identify discrepancies as a result of qualification testing.

4.2.1.2 The battery unit shall be inspected, and measurements made to verify compliance with the specification. These include:

Configuration
Electrical, mechanical, thermal interfaces
Design and construction requirements
Weight
Dimensions
Clearances
Electrical isolation
Electrical continuity

4.2.1.3 The results of the inspections and measurements must be recorded in sufficient detail to determine significant changes in the condition of the battery unit post-environmental test.

4.2.1.4 Inspection of battery hardware following completion of qualification shall entail disassembly to the extent that wear and/or mechanical integrity can be confirmed by X-ray or DPAs. Qualification units that will be subjected to life test can be subjected to an abbreviated inspection sufficient to confirm viability to continue on to the life test, followed by a complete disassembly inspection at the conclusion of life testing.

4.2.2 Specification Performance

The specification performance tests verify that the electrical and mechanical performance of the battery unit meets the requirements of the unit specification. The following electrical tests are intended to characterize the battery qualification unit performance over the full voltage and temperature range. Paragraphs 4.2.2.1, and 4.2.2.3 through 4.2.2.6 shall be performed pre- and post-environmental tests.

4.2.2.1 Actual Battery Energy

4.2.2.1.1 The actual battery energy shall be measured at nominal charge and discharge rates, to maximum and minimum voltage levels, for each of the following five cases.

4.2.2.1.2 Multiple cycles shall demonstrate energy stability for each condition.

4.2.2.1.3 One or more test cycles shall simulate cell level tests.

4.2.2.1.4 Flight-like charge balancing can be active.

Maximum predicted operational temperature +10°C (Qual)
Maximum predicted operational temperature
Nominal predicted operational temperature
Minimum predicted operational temperature
Minimum predicted operational temperature –10°C (Qual)

4.2.2.2 Mission-Specific Performance Requirements

4.2.2.2.1 Mission-specific performance requirements shall be demonstrated at expected on-orbit temperatures:

Minimum charge and discharge rates
Nominal charge and discharge rates
Maximum charge and discharge rates
Pulse power cycles requirements

4.2.2.2.2 Electrical parameters should closely match intended usage (such as constant power discharges).

4.2.2.2.3 Requirements can be demonstrated as part of thermal vacuum tests.

4.2.2.3 Battery Charge Retention (Designed with active cell-level charge control)

4.2.2.3.1 Battery charge retention shall be measured in an open-circuit state starting at full state-of-charge for at least 7 days. The temperature should be at ambient, 20°C to 25°C.

4.2.2.3.2 Any charge control electronics or voltage monitoring devices shall be fully disconnected during the open-circuit period to minimize stray currents.

4.2.2.3.3 Cell voltages shall be monitored periodically over the test period, and the remaining energy shall be measured at the end of the test period.

4.2.2.3.4 Data should be comparable with cell- or module-level test data.

4.2.2.4 Battery Charge Retention (Designed with active battery-level charge control)

4.2.2.4.1 Battery charge retention shall be measured in an open-circuit state starting at full state-of-charge for at least 30 days. The temperature should be at ambient, 20°C to 25°C.

4.2.2.4.2 Any charge control electronics or voltage monitoring devices shall be fully disconnected during the open-circuit period to minimize stray currents.

4.2.2.4.3 Cell voltages shall be monitored periodically over the test period, and the remaining energy shall be measured at the end of the test period.

4.2.2.4.4 Data should be comparable with cell- or module-level test data.

4.2.2.5 Battery DC Impedance

The battery DC impedance shall be measured at the battery terminals at the nominal on-orbit cycling temperatures at high, mid and low states-of-charge.

4.2.2.6 Battery Reconditioning Circuit (as applicable)

Reconditioning circuit shall be demonstrated to be fully operational.

4.2.3 Leakage

4.2.3.1 The leakage test demonstrates the capability of pressurized components and hermetically sealed units to meet the specified design leakage rate requirements.

4.2.3.2 A battery-level leakage test shall be performed that meet the requirements set forth in TR-2004(8583)-1.

4.2.3.3 A leakage test shall be performed on the battery unit before and after environmental tests and at end of qualification testing to demonstrate that all hermetic seals meet the specified design leakage rate requirements.

4.2.3.4 An acceptable measurement technique is one that accounts for leak rate variations with hot and cold temperatures and has the required threshold, resolution, accuracy, and duration to detect any leakage equal to or greater than the maximum acceptable leak rate.

4.2.4 Shock

The battery unit will be exposed to qualification level operational and non-operational shock levels and shall show no performance or physical degradation. The operational shock qualification test demonstrates the ability of the unit to endure a limited duration of acceptance testing and then meet requirements during and after exposure to a margin over the maximum predicted vibration environment in flight. Guidance for the non-operational vibration test is provided in paragraph 3.5. An analysis may be performed to evaluate whether test levels are enveloped by other dynamic tests.

4.2.4.1 If the analysis shows that both non-operational and operational shock testing is <u>not</u> required as defined in paragraph 3.5 and TR-2004(8583)-1, paragraph 6.3.4.4, the analysis shall be documented and included as part of the qualification report.

4.2.4.2 If the analysis shows that a test <u>is</u> required, the shock test shall demonstrate the capability of the unit to survive qualification-level (operational and non-operational) shock environments.

4.2.4.3 The battery unit shall not demonstrate physical or performance degradation after exposure to qualification level non-operation shock environments as described in MIL-STD-810.

4.2.4.4 The battery unit shall not demonstrate physical or performance degradation during or after exposure to qualification-level operational shock testing as described in TR-2004(8583)-1.

4.2.4.5 Battery- and cell-level voltages (where applicable), current, and temperature shall be monitored continuously during all shock tests for failure or intermittent performance.

4.2.4.6 Relays shall not transfer and shall not chatter in excess of specification limits during the shock test.

4.2.4.7 A visual inspection, electrical isolation, and electrical performance test shall be performed before and after non-operational and operational shock testing. A leakage and charge retention test should be performed after non-operational and operational shock testing.

4.2.5 Vibration/Acoustic

The battery unit shall be exposed to qualification-level operational and non-operational vibration levels, and shall show no performance degradation. The operational vibration (or acoustic, if applicable) qualification test demonstrates the ability of the unit to endure a limited duration of acceptance testing and then meet requirements during and after exposure to a margin over the maximum predicted vibration environment in flight. Guidance for the non-operational vibration test is provided in paragraph 3.5.

4.2.5.1 The battery unit shall not demonstrate physical or performance degradation after exposure to qualification-level non-operation vibration environments as described in paragraph 3.5 and MIL-STD-810.

4.2.5.2 The battery unit shall not demonstrate physical or performance degradation during or after exposure to qualification-level operational vibration (or acoustic) testing as described in TR-2004(8583)-1.

4.2.5.3 During operational vibration testing, the battery unit shall be functionally sequenced through various operational modes to the maximum extent practical. This includes all primary and redundant circuits, and all circuits that do not operate during launch.

4.2.5.4 The vibration fixture shall be verified by test to uniformly impart motion to the unit under test and to limit the energy transfer, or crosstalk, from the test axis to the other two orthogonal axes.

4.2.5.5 Battery- and cell-level voltages (where applicable), current, and temperature shall be monitored continuously during all vibration tests for failure or intermittent performance.

4.2.5.6 Relays shall not transfer and shall not chatter in excess of specification limits during the vibration test.

4.2.5.7 A visual inspection, electrical isolation, and electrical performance test shall be performed before and after non-operational and operational vibration testing. A leakage and charge retention test should be performed after non-operational and operational vibration test.

Note: A leakage test and charge retention test shall be performed post-vibration test if acceleration test is not performed.

4.2.6 Acceleration

The acceleration test demonstrates the capability of the unit to operate during and after exposure to the qualification-level acceleration environment. An analysis can be performed to determine whether the acceleration environment is adequately enveloped by the unit-level qualification vibration test.

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

4.2.6.2 If the analysis shows that a test is required, the battery unit shall be attached, as it is during flight, to a test fixture and subjected to qualification-level acceleration in the appropriate direction per TR-2004(8583)-1 while operating.

4.2.6.3 Any acceleration test shall be performed with the battery under a discharge load, and both battery/cell voltages and current shall be monitored during the test.

4.2.6.4 A visual inspection, electrical isolation, and electrical performance testing shall be performed before and after acceleration testing. A leakage and charge retention test shall be performed after acceleration testing.

4.2.7 Thermal Cycle

The thermal cycle test imposes environmental stress screens in an ambient pressure environment to detect flaws in design, parts, processes, and workmanship. The thermal cycle qualification test demonstrates robustness of the electrical and electronic unit design, operation over the design temperature range, and the ability to function during subsequent performance testing.

4.2.7.1 A thermal cycle test shall be performed as described in TR-2004(8583)-1 that encompasses the range of thermal conditions expected during storage, prelaunch, and mission.

4.2.7.2 For qualification, the worst-case hot and cold temperatures shall exceed the maximum and minimum predicted temperatures and acceptance test temperatures by 10°C.

4.2.7.3 A minimum of 23 thermal cycles shall be applied. The number of thermal cycles can be reduced to six if all battery unit solder joints and electronic piece parts were previously exposed to qualification level thermal cycles.

4.2.7.4 Battery and cell voltage (where applicable) temperature, current, and heater status shall be continuously monitored during all portions of the test.

4.2.8 Thermal Vacuum

The thermal vacuum test demonstrates specification performance and survivability over combined thermal and vacuum conditions. The qualification thermal vacuum test demonstrates the ability of the unit to perform to specification limits in the qualification environment and to endure the thermal vacuum testing imposed on flight units during acceptance testing.

4.2.8.1 The qualification thermal vacuum test shall test the battery unit to 10°C beyond maximum and minimum predicted temperatures as defined in TR-2004(8583)-1.

4.2.8.2 For qualification testing, four thermal vacuum cycles shall incorporate the following on-orbit cases:

(1) Survival temperature (non-operational) cycle test

(2) Qualification-Level Hot Case (full-orbit operation until stability is obtained)

(3) Nominal Case (full-orbit operation until stability is obtained)

(4) Qualification-Level Cold Case (full-orbit operation until stability is obtained)

4.2.8.3 During the test, all primary and redundant heater operation, such as turn-off/on set points and heater duty cycle, shall be validated, as well as accuracy of flight temperature measurements, over-temperature switch, heat pipe performance, radiator sizing, and insulation effectiveness, if available.

4.2.8.4 The battery unit shall be instrumented with additional thermistors or thermocouples to fully validate cell-to-cell temperature gradients and gradients across individual cells.

4.2.8.5 During testing, battery and cell voltage (where applicable) and electrical and heater currents shall be monitored.

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

4.2.8.7 All thermal vacuum test results shall be correlated with the battery unit thermal model, validate specification performance requirements, and verify no intermittent behavior.

4.2.9 Climatic

An analysis can be performed to determine whether any of the climatic tests are required. If any of the tests are required, the test will demonstrate that the unit is capable of surviving exposure to various climatic conditions without excessive degradation, or operating during exposure, as applicable. Exposure conditions include those imposed upon the unit during fabrication, test, shipment, storage, preparation for launch, launch itself, and reentry, if applicable. These can include, but not be limited to, such conditions as humidity, sand and dust, rain, salt fog, and explosive atmosphere.

4.2.9.1 It is the intent that terrestrial natural environments not drive environmental design of flight hardware. To the greatest extent feasible, the flight hardware 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 battery handling procedures. Only those environments that cannot be controlled need be considered in the design and testing.

4.2.9.2 Any required tests shall conform to the methods given in TR-2004(8583)-1.

4.2.9.3 Degradation due to fungus, ozone, and sunshine shall be verified by design and material selection.

4.2.10 Pressure/Burst

The pressure test demonstrates adequate margin in the battery unit so that structural failure does not occur before the design burst pressure is reached, or excessive deformation does not occur at the maximum expected operating pressure, MEOP. For space vehicle batteries, pressure testing may be performed at a lower component level, such as cell or heatpipe.

4.2.10.1 Pressure testing shall comply with the requirements of AIAA S-080-1998[7] (metallic vessels) or AIAA S-081-2000[8] (composite-overwrapped vessels).

4.2.10.2 All pressure test results, whether performed at the component level (cell or heatpipe) and/or battery level, shall be included as part of the qualification report.

4.2.11 EMC

The electromagnetic compatibility test will demonstrate that the electromagnetic interference characteristics (emission and susceptibility) of the unit, under normal operating conditions, do not result in malfunction of the unit. It also demonstrates that the unit does not emit, radiate, or conduct interference, which could result in malfunction of other units.

4.2.11.1 An analysis based on TR-2004(8583)-1 and TOR-2005(8583)-1[4] shall be performed with respect to the compatibility of the battery with its EMC requirements.

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

4.2.11.3 Specific testing required by the analysis in 4.2.11 (a) shall be performed per TR-2004(8583)-1[2] and TOR-2005(8583)-1.

4.2.12 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). A static load test can be waived for metallic structures if the qualification-level static load paths are encompassed in an acceleration or vibration test and the test fixture accurately simulates spacecraft-level mounting points.

4.2.12.1 If the static load test is waived due to acceleration or vibration test configuration and levels, this analysis shall be documented and included as part of the unit-level qualification report.

4.2.12.2 Battery structures made of composite material or having adhesively bonded parts shall have a static proof load test performed per TR-2004(8583)-1 due to variability and uncertainty in the manufacturing process.

> Note: static load testing may be performed at the spacecraft level with a battery simulator of sufficient structural characteristics such that the objective of spacecraft-level test is not compromised.

4.2.13 Safety

Safety testing is required to satisfy Range Safety and Department of Transportation requirements specific for lithium-ion batteries. To support reliability analysis, the impact of cell failure propagating to other cells needs to be demonstrated by test to define battery reliability.

4.2.13.1 The battery design, safety testing, and ground operation shall comply with applicable range safety requirements; or necessary waivers shall be obtained and approved through Range Safety.

4.2.13.2 The battery design and safety testing shall comply with the applicable transportation requirements.

4.2.13.3 Battery-level safety testing shall validate battery-level safety against all known failure modes.

4.2.13.4 Battery-level safety shall be validated by test to the following conditions at a minimum: overcharge, overdischarge, overtemperature, over pressurization, internal cell short, and external cell short.

4.2.13.5 If a battery-level analysis is performed, cell-, module-, or battery-level development testing shall be provided that simulates battery mechanical and thermal design, and evaluates the potential of one cell failure propagating to another cell or piece part within the battery.

4.2.14 Radiation

The purpose of radiation testing is to determine the response of a device to the types of radiation and levels expected over mission life. At the battery level, an analysis may be performed that is supported by adequate component-level testing for all sensitive piece parts.

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

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

4.2.14.3 Component-level tests shall demonstrate performance before, during, and after exposure to quantify any degradation.

4.2.14.4 Post-radiation cell-level (or module-level) cycle testing shall quantify any degradation in performance due to radiation exposure.

5. Qualification Life Test

5.1 Life Expectancy Confirmation

5.1.1 Confirmation of battery life expectancy shall be based upon battery life testing or a combination of analyses and confirmation of the life expectancy of battery materials and components, such as module, cell, electrical bypass devices, heaters, strain gauges, temperature sensors, or thermal switches.

5.1.2 Confirmation of battery module life expectancy shall be based upon module life testing or a combination of analyses and confirmation of life expectancy of module materials and components, such as cell, electrical bypass devices, heaters, strain gauges, temperature sensors, or thermal switches.

5.1.3 Confirmation of life expectancy of battery cells shall be based on life testing as defined in paragraph 5.2.

5.1.4 Confirmation of life expectancy of battery components, other than battery cells, shall be based on life testing or similarity as defined in paragraph 4.10.1 of TR-2004(8583)-1.

5.2 Life Testing

5.2.1 Life testing of battery, module, or cell for service life expectancy confirmation shall be under a set of conditions that envelopes the conditions preceding launch, mission battery loads, charge control methods and conditions, and mission temperature.

5.2.2 Test equipment and fixtures shall maintain flight-like thermal and mechanical configuration, such as simulating flight-like temperature variations and external compression.

5.2.3 Test duration shall include a margin to demonstrate the required battery reliability and confidence level from the number of test samples.

5.2.4 Cell-level performance testing shall fully characterize beginning-of-life energy, resistance, charge retention, and leakage characteristics prior to initiating life test over the anticipated temperature range.

5.2.5 Life test samples may come from a cell lot different from the battery-level qualification lot and may not have completed full battery-level performance or environmental testing. Consideration should be given to performing cell-level qualification dynamic testing prior to initiating life test.

5.3 Real-Time Life Test

For spacecraft applications, a battery, module, or cell life test used to confirm life expectancy can be a real-time life test.

5.3.1 Real-time data shall be on-orbit data or data from real-time ground tests where the time, current, orbit state-of-charge, and temperature profiles of discharge and charge match those of the mission.

5.3.2 The data shall envelope flight-level cell matching criteria and incorporate flight-like charge control methods.

5.3.3 Data from real-time tests shall include electrical performance data and data from destructive physical analysis of tested cells.

5.4 Time-Accelerated Life Test

For spacecraft applications, a battery, module, or cell life test used to confirm service life expectancy can be a set of time-accelerated tests that envelopes the mission loads, charge control methods and conditions, and temperatures. The acceleration factor can have different values for storage, cycling, or different operational modes.

5.4.1 Acceleration Factor

5.4.1.1 The acceleration factor shall be confirmed by real-time life test data where the time, current, and temperature profiles of discharge and charge exactly match those of the mission.

5.4.1.2 Real-time data shall be on-orbit data or data from real-time ground tests that envelope flight-level cell matching criteria and incorporate flight-like charge control methods.

5.4.1.3 Data from real-time and accelerated tests shall include electrical performance data and data from destructive physical analysis of tested cells.

5.4.1.4 The acceleration factor shall be based on a sound analysis of data and shall not be greater than two.

5.5 Test Duration

Real-time and accelerated-life test duration shall include a margin to demonstrate the required battery reliability and confidence level from the number of test samples and failure rate characteristics.

5.5.1 Incomplete Life Test Data

Selection of a new cell design without real-time data demonstrating mission life increases risk to the spacecraft program. The following methods are ways to minimize program risk.

5.5.1.1 Pursuit of a dual-path approach with a more established design or technology.

5.5.1.2 Battery sizing with the new technology shall be designed with a greater end-of-life energy margin. A rationale for determining this factor shall be provided, and final approval shall be made by the procurement authority.

5.5.1.3 Results from destructive physical analysis of cells on real-time life test shall be provided to evaluate degradation modes prior to launch.

5.5.1.4 Time-accelerated test data can facilitate risk assessment as a method to define possible failure mechanisms and trends. Results from destructive physical analysis shall be provided.

5.5.1.5 The decision to include a new technology or design for a mission before there is sufficient data to conclusively verify mission life may be made, with the expectation that ground testing will continue until mission life with margin is demonstrated.

5.6 Sample Size

5.6.1 The real-time life test sample size shall provide a minimum of 90% confidence level at 88% reliability (or 20 cells) without failure. Other sample sizes can be used.

5.6.2 If the sample size, N, is not 20, the actual test duration without failure should be multiplied by a factor K for mission life expectancy. The reliability and confidence level shall remain at 90%/88% for a test with N samples without failure for duration KT.

5.6.3 If the failure probability function is not known, the use of a Weibull function is suggested to establish test durations. The beta shape parameter should be estimated from failure data of the most comparable cells and operational type conditions. As more data are accumulated, a failure probability function can be refined. See Reference 5 for guidance.

5.7 Life Test Sample Characteristics

5.7.1 Storage, and cycle test history shall be provided for each individual life test sample down to the cell level.

5.7.2 Cell-level (module-level and battery-level, as applicable) acceptance test data shall be provided that define at minimum individual cell energy to minimum usable voltages, charge retention, and impedance at defined conditions.

5.7.3 Beginning of test mission capacity and voltage profile measurements shall be provided that define total available energy at mission operating conditions to minimum usable voltage at the cell level, module level, and battery level, as applicable.

5.7.4 End of test mission performance measurements shall be provided as a point of comparison with 5.1.1.5 (b) and 5.1.1.5 (c) at the cell level, module level, and battery level, as applicable.

5.7.5 Periodic energy measurements can be performed during the life test to facilitate performance trending. If energy measurements are performed, capability for on-orbit reconditioning shall be available.

5.8 Manufacturing Control Documents

5.8.1 The life test cells shall be built to an approved set of manufacturing control documents, which defines the qualified cell design.

5.8.2 The procuring authority shall have the right to review manufacturing control documents to confirm that the flight lot cell design is identical to that of the life test cell.

6. Acceptance Test

6.1 Unit Acceptance Test

(a) Acceptance tests shall be conducted to demonstrate the acceptability of each flight battery, module, or cell to meet performance specification and demonstrate error-free workmanship in manufacturing.

(b) Acceptance testing is intended to stress screen items to precipitate incipient failures due to latent defects in parts, processes, materials, or workmanship.

(c) The acceptance test conditions shall envelop a composite of the worst-case applications.

(d) When a destructive test is to be performed, it shall be performed on representative cells from each flight lot.

6.1.1 Test Hardware

Each flight battery and cell hardware shall be subjected to acceptance testing and produced from the same drawings, using the same materials, tooling, manufacturing process, and level of personnel competency as used for the qualification hardware.

6.1.2 Acceptance Test Levels and Duration

6.1.2.1 To demonstrate workmanship, the acceptance environmental conditions shall stress the flight hardware to the maximum conditions expected for all flight events, including transportation and handling.

6.1.2.2 Acceptance test levels and durations shall be consistent with those described in TR-2004(8583)-1.

6.1.3 Data Collection and Acquisition rates

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

6.1.3.2 Voltage, current, and temperature data shall be recorded at rates and accuracy sufficient to verify compliance with test requirements and performance specifications.

6.1.3.3 During any dynamic environmental test, data shall be collected on strip chart recorders or at an acquisition rate of at least 10,000 samples per second to evaluate for intermittent dropouts.

6.1.4 Cell Matching Criteria

6.1.4.1 A document shall be written that defines the cell matching criteria for the flight lot and provides the data that supports the selection of a specific criterion.

6.1.4.2 Cell matching criteria for the flight battery shall be enveloped by the beginning-of-life performance of the qualification life test cells that utilized flight-like charge control for balancing during test.

6.1.4.3 The cell matching criteria shall include at minimum: energy, charge retention, and resistance data at a defined voltage or state-of-charge.

6.1.4.4 To maximize cell matching throughout life, all flight cells within a battery series/parallel configuration shall be exposed to the same electrical and temperature test conditions. As an example, if one module of a battery is exposed to proto-qualification levels, the second module of the same battery should also be exposed to proto-qualification levels.

6.1.5 Test Data Trending

Key battery performance parameters, such as charge retention, capacity, voltage under maximum load, and resistance, shall be monitored across successive manufacturing lots to identify possible performance degradation due to unanticipated material or manufacturing variation during acceptance testing.

6.1.6 In-Process Inspections and Tests

6.1.6.1 Parts, wiring, or materials that cannot be adequately tested after assembly shall be subjected to in-process controls and in-process inspections during their manufacture.

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

6.1.7 Flight Unit Buy-off Report (Acceptance Level)

A buy-off report shall be provided at the completion of acceptance test, which includes the following items:

(a) End-Item Description
(b) Certificate of Conformance
(c) Closure of action items [Critical Design Review (CDR), Manufacturing Readiness Review (MRR), Test Readiness Review (TRR)]
(d) Engineering changes since CDR
(e) Hardware discrepancy reports
(f) Test discrepancy reports
(g) Deviations and Waivers
(h) In-process inspection and test data

(i) Battery specification
(j) Battery acceptance test procedures
(k) Test Equipment Calibration Record
(l) Cell Selection Criteria Report
(m) Specification compliance verification report
    Battery Unit Acceptance Test Data
    Component level burst pressure and proof pressure results, as applicable
    High Reliability Parts (cell, electronic or mechanical devices) Buyoff Report
(n) As built assembly level, interface control and wiring drawing
(o) List of as build drawings, manufacturing procedures and test procedures identifying revision that were used to build and test the qualification unit
(p) Age Sensitive Component Record
(q) Telemetry Coefficients for all analog telemetry
(r) Electronic copy of raw test data

6.2 Acceptance Tests Required

Test	Spacecraft Application	Suggested Test Sequence	Section
Inspection (1)	R	1	6.2.1
Wear-in	ER	2	6.2.2
Specification Performance (1)	R	3	6.2.3
Leakage	R	4, 7,12	6.2.4
Shock	ER	5	6.2.5
Vibration or Acoustic (2)	R	6	6.2.6
Thermal Cycle	ER	8	6.2.7
Thermal Vacuum	R	9	6.2.8
Proof Pressure	R	10	6.2.9
Proof Load	ER	11	6.2.10
Electromagnetic Compatibility	ER	13	6.2.11

R Required
ER Evaluation Required
(1) Performed before and after each environmental test as appropriate
(2) Vibration or acoustic required, as appropriate, with the other discretionary.

6.2.1 Inspection

The battery unit will be inspected before and after each environmental test to identify discrepancies as a result of test.

6.2.1.1 The battery unit shall be inspected, and measurements made to verify compliance with the specification. These include:

Configuration
Electrical, mechanical, thermal interfaces
Design and construction requirements
Weight
Dimensions
Clearances
Electrical isolation
Electrical continuity

6.2.1.2 The results of the inspections and measurements must be recorded in sufficient detail to determine significant changes in the condition of the battery unit post environmental test.

6.2.2 Wear-in (Conditioning Cycles)

The wear-in test detects material and workmanship defects that occur early in the unit life and can also establish performance stability. An evaluation can be performed to determine whether additional wear-in cycles are required beyond those performed in the required acceptance tests.

(a) **Pressure.** Ambient pressure should normally 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 life cycles.

(d) **Conditions.** The unit shall operate under nominal electrical conditions.

(e) Wear-in cycles shall be demonstrated as part of the cycle life requirements.

6.2.3 Specification Performance

The specification performance tests verify that the electrical and mechanical performance of the battery unit meets the requirements of the unit specification. The following electrical tests are intended to characterize the flight battery performance over the full voltage and temperature range. Paragraphs 6.2.2.1, and 6.2.2.3 through 6.2.2.7 shall be performed pre- and post-environmental tests.

6.2.3.1 Actual Battery Energy

6.2.3.1.1 The actual battery energy shall be measured at nominal mission charge and discharge rates, to maximum and minimum voltage levels, for each of the following three cases.

6.2.3.1.2 Multiple cycles shall demonstrate energy stability within 1% for each condition.

6.2.3.1.3 One or more test cycles shall simulate cell-level tests.

6.2.3.1.4 Flight-like charge balancing can be active.

Maximum predicted operational temperature
Nominal predicted operational temperature
Minimum predicted operational temperature

6.2.3.2 Mission-Specific Performance Requirements

6.2.3.2.1 Mission-specific performance requirements shall be demonstrated at expected on-orbit temperatures:

Minimum charge and discharge rates
Nominal charge and discharge rates
Maximum charge and discharge rates

Pulse power cycles requirements

6.2.3.2.2 Electrical parameters should closely match intended usage (such as constant power discharges).

6.2.3.2.3 Requirements can be demonstrated as part of thermal vacuum tests.

6.2.3.3 Battery Charge Retention (Designed with active cell-level charge control)

6.2.3.3.1 Battery charge retention shall be measured in an open-circuit state starting at full state-of-charge for at least 7 days. The temperature should be at ambient, 20–25°C.

6.2.3.3.2 Any charge control electronics or voltage monitoring devices shall be fully disconnected during the open-circuit period to minimize stray currents.

6.2.3.3.3 Cell voltages shall be monitored periodically over the test period, and the remaining energy shall be measured at the end of the test period.

6.2.3.3.4 Data should be comparable with cell- or module-level test data.

6.2.3.4 Battery Charge Retention (Designed with active battery-level charge control)

6.2.3.4.1 Battery charge retention shall be measured in an open-circuit state starting at full state-of-charge for at least 30 days. The temperature should be at ambient, 20–25°C.

6.2.3.4.2 Any charge control electronics or voltage monitoring devices shall be fully disconnected during the open-circuit period to minimize stray currents.

6.2.3.4.3 Cell voltages shall be monitored periodically over the test period, and the remaining energy shall be measured at the end of the test period.

6.2.3.4.4 Data should be comparable with cell- or module-level test data.

6.2.3.5 Battery DC Impedance

The battery DC impedance shall be measured at the battery terminals at the nominal on-orbit cycling temperatures at high, mid, and low states-of-charge.

6.2.3.6 Battery Reconditioning Circuit (as applicable)

A reconditioning circuit shall be demonstrated to be fully operational.

6.2.4 Leakage

The leakage test demonstrates the capability of pressurized components and hermetically sealed units to meet the specified design leakage rate requirements.

6.2.4.1 A battery-level leakage test shall be performed that meet the requirements set forth in TR-2004(8583)-1.

6.2.4.2 A leakage test shall be performed on the battery unit before and after environmental tests, and at end of acceptance test, to demonstrate that all hermetic seals meet the specified design leakage rate requirements.

6.2.4.3 An acceptable measurement technique is one that accounts for leak rate variations with hot and cold temperatures and has the required threshold, resolution, accuracy, and duration to detect any leakage equal to or greater than the maximum acceptable leak rate.

6.2.5 Shock

The battery unit will be exposed to acceptance-level operational shock levels and shall show no performance or physical degradation. The operational shock test demonstrates the ability of the unit to meet requirements during and after exposure to a margin over the maximum predicted vibration environment in flight. An analysis may be performed to evaluate whether test levels are enveloped by other dynamic tests.

6.2.5.1 If the analysis shows that a test is required, the shock test shall demonstrate the capability of the unit to survive acceptance-level operational shock environments as defined in TR-2004(8583)-1.

6.2.5.2 The battery unit shall not demonstrate voltage, energy, or physical degradation during or after exposure to acceptance-level operational shock test.

6.2.5.3 Battery- and cell-level voltages (where applicable), current, and temperatures shall be monitored continuously during all shock tests for failure or intermittent performance.

6.2.5.4 Relays shall not transfer and shall not chatter in excess of specification limits during the shock test.

6.2.5.5 A visual inspection and functional performance test shall be performed before and after operational shock testing. A leakage and charge retention test should be performed after operational shock testing.

6.2.6 Vibration/Acoustic

The operational vibration (or acoustic) test demonstrates the ability of the unit to meet requirements during and after exposure to the maximum predicted vibration environment in flight and validates workmanship.

6.2.6.1 The battery unit shall be tested to operational acceptance vibration levels and durations as described in TR-2004(8583)-1.

6.2.6.2 The vibration fixture shall be verified by test to uniformly impart motion to the unit under test and to limit the energy transfer, or crosstalk, from the test axis to the other two orthogonal axes.

6.2.6.3 During vibration test, the battery unit shall be functionally sequenced through various operational modes to the maximum extent practical. This includes all primary and redundant circuits as well as all circuits that do not operate during launch.

6.2.6.4 The battery unit shall not demonstrate physical or performance degradation during or after test.

6.2.6.5 Battery- and cell-level voltages (where applicable), current, and temperature shall be monitored continuously during all vibration tests for failure or intermittent performance.

6.2.6.6 Relays shall not transfer and shall not chatter in excess of specification limits during the vibration test.

6.2.6.7 A visual inspection, and leakage and functional testing shall be performed before and after operational vibration testing. A charge retention test should be performed after operational vibration testing.

6.2.7 Thermal Cycle

The thermal cycle test imposes environmental stress screens in an ambient pressure environment to detect flaws in design, parts, processes, or workmanship. The thermal cycle test demonstrates robustness of the electrical and electronic unit design, operation over the design temperature range, and the ability to function during subsequent performance testing.

6.2.7.1 Thermal cycle testing shall be performed as described in TR-2004(8583)-1 and address the thermal conditions expected during storage, prelaunch, and mission. The burn-in test of TR-2004(8583)-1, paragraph 6.3.8.3 (d) can be eliminated to prevent excessive degradation.

6.2.7.2 A minimum of 10 thermal cycles shall be applied. The number of thermal cycles can be reduced to 3 if all the battery unit solder joints and electronic piece parts were previously exposed to acceptance-level thermal cycles as required by TR-2004(8583)-1.

6.2.7.3 The battery unit shall be tested to the maximum and minimum predicted temperatures.

6.2.7.4 Battery and cell voltage (where applicable), temperature, current, and heater status shall be continuously monitored during all portions of the test.

6.2.8 Thermal Vacuum

The thermal vacuum test demonstrates specification performance and survivability over combined thermal and vacuum conditions. The acceptance thermal vacuum test demonstrates the ability of the unit to perform to maximum predicted temperature environments and verifies workmanship, parts, materials, and processes.

6.2.8.1 The acceptance thermal vacuum test shall test the battery unit to maximum predicted temperatures as defined in TR-2004(8583)-1.

6.2.8.2 Four thermal vacuum cycles shall incorporate the following on-orbit cases:

(1) Survival temperature (non-operational) cycle test
(2) Maximum Predicted Hot Case (full orbit operation)
(3) Nominal Case (full orbit operation)
(4) Maximum Predicted Cold Case (full orbit operation)

6.2.8.3 During testing, all primary and redundant heater operation, such as turn-off/on set points and heater duty cycle, shall be validated, as well as accuracy of flight temperature measurements, over temperature switch, heat pipe performance, radiator sizing, and insulation effectiveness, if available.

6.2.8.4 The battery unit shall be instrumented with additional thermistors or thermocouples to fully validate cell-to-cell temperature gradients and gradients across individual cells.

6.2.8.5 During testing, battery and cell voltage (where applicable), and electrical and heater current shall be monitored.

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

6.2.8.7 All thermal vacuum test results shall validate specification performance requirements and no intermittent behavior.

6.2.9 Proof Pressure

The proof pressure test demonstrates adequate margin in the battery unit so that structural failure does not occur before the design burst pressure is reached, or excessive deformation does not occur at the maximum expected operating pressure, MEOP. For space vehicle batteries, pressure testing may be performed at a lower component level, such as at the cell or heat pipe level.

6.2.9.1 Acceptance testing proof pressure testing shall comply with the requirements of AIAA S-080-1998 (metallic vessels) or AIAA S-081-2000[8] (composite overwrapped vessels). Proof pressure testing shall be performed on each seal container in a flight battery.

6.2.9.2 Each flight lot of sealed containers shall have a qualification pressure cycle test and burst test performed as defined in paragraph 6.3.12.2 (b) of TR-2004(8583)-1.

6.2.9.3 All proof pressure test results, whether performed at a lower component level or battery level, shall be included as part of the unit buyoff report.

6.2.10 Proof Load

The proof load test demonstrates the adequacy of the battery structure to meet requirements of strength and stiffness, with the desired flight margin, when subjected to simulated critical environments predicted to occur during its service life (such as temperature, humidity, pressure, and loads). A proof load test can be waived for metallic structures if the acceptance-level proof load paths are encompassed in an acceleration or vibration test and the test fixture accurately simulates spacecraft level mounting points.

6.2.10.1 If the proof load test is waived due to acceleration or vibration test configuration and levels, this analysis shall be documented and included as part of the unit-level qualification report.

6.2.10.2 Battery structures made of composite material or having adhesively bonded parts shall have a proof load test performed per TR-2004(8583)-1 due to variability and uncertainty in manufacturing process.

6.2.11 EMC

The electromagnetic compatibility test will demonstrate that the electromagnetic interference characteristics (emission and susceptibility) of the unit, under normal operating conditions, do not result in malfunction of the unit. It also demonstrates that the unit does not emit, radiate, or conduct interference, which could result in malfunction of other units.

6.2.11.1 An analysis based on TR-2004(8583)-1 and TOR-2005(8583)-1 shall be performed with respect to the compatibility of the battery with its EMC requirements.

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

6.2.11.3 Specific testing required by the analysis in 6.2.11 (a) shall be performed per TR-2004(8583)-1 and TOR-2005(8583)-1.[4]

This page intentionally blank.

7. Handling, Storage and Maintenance

The requirements set forth in this section apply to the handling, storage, and maintenance of batteries during ground activities preceding pre-launch activities. These requirements need to be defined in the battery specification and/or battery storage and handling procedure so as to minimize preflight degradation.

7.1 Battery Storage and Handling

7.1.1 Battery handling, storage, and maintenance methods validated as part of development and/or qualification tests shall be documented in the battery storage and handling procedure.

7.1.2 Battery storage, handling, and maintenance methods shall be in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware.

7.1.3 An electrostatic discharge (ESD) control program shall be implemented to protect ESD-sensitive hardware on the battery as specified in MIL-STD-1686.[9] The battery ESD control program and procedures shall be approved by the procuring authority.

7.1.4 The maximum shelf life limit (cell activation through launch) shall be defined for the battery that includes the maximum exposure time to ambient temperature conditions. Records shall be maintained that document the temperature exposure and Cell-level state-of-charge of flight hardware on a daily basis.

7.1.5 Battery and/or cell inspection shall be performed following transportation. At a minimum, this shall include visual inspection of flight hardware, temperature, humidity, and shock sensors, and measurement of battery open-circuit voltage (and cell voltages where available) and isolation resistance.

7.1.6 At all times, batteries, modules, or cells shall be maintained within a controlled temperature and humidity environment to maximize battery life and prevent water condensation

7.1.7 When not in use, the batteries, modules, or cells shall be placed in cold storage, whenever practicable, at an appropriate state-of-charge.

7.1.8 Battery handling procedures shall allow for cold temperature storage or installation on spacecraft following completion of acceptance tests.

7.1.9 A connector saver shall be used during all testing prior to battery installation on the vehicle to avoid repeated connecting and disconnecting of the flight connector. The connector saver shall interface between the battery flight connectors and any mating test or ground support equipment cables.

7.1.10 Specialty storage containers shall be used during extended storage to provide physical protection. The container shall be designed to prevent damage during handling, transportation, and storage. Containers shall contain temperature, humidity, and shock indicators.

7.1.11 Batteries shall not be used for flight if the time between battery cell activation and launch exceeds the specified activated shelf life at the specified temperature conditions.

7.2 Battery Cell Maintenance

7.2.1 During storage and handling, voltage monitoring and periodic recharge, cell rebalancing, or reconditioning may be required to minimize degradation. Battery maintenance procedures shall define appropriate maintenance methods, monitoring frequency, and appropriate voltage, current, and temperature limits that were validated during development and/or qualification tests.

7.2.2 The maximum allowed self-discharge rate for cells and batteries during storage shall be specified. Cells or batteries exhibiting excessive self-discharge rates may indicate degradation.

7.2.3 Any equipment used to monitor, charge, or discharge batteries, modules, or cells shall be designed with a level of safety features similar to or greater than those available at the spacecraft level. Check-out of all maintenance equipment, software, and safety inhibits shall be performed before connecting flight hardware.

7.2.4 When discharged is the appropriate storage condition for a battery, the discharge of batteries to prepare for storage shall be accomplished with a battery conditioning module that will discharge the battery or individual cells at specified control rates.

7.2.5 As a safety feature, devices shall be incorporated into the design of battery conditioning modules to accommodate the discharge of the battery at any state-of-charge without causing any damage to the battery, including the prevention of any battery cell voltage from exceeding upper or lower voltage limits.

7.3 Records

7.3.1 Records documenting the flight accreditation status of batteries shall be maintained.

7.3.2 These records shall provide traceability from production of the battery, through final installation in the vehicle, and on through to launch.

7.3.3 The records shall indicate changes in battery location, status, use, storage time, or any conditions that could affect reliability or performance.

7.3.4 Time-correlated records shall be maintained indicating battery charge or discharge current, battery voltage, and temperature to a sufficient accuracy to allow an assessment of potential degradation.

7.4 "Not for Flight" Marking

7.4.1 Batteries that by intent, by usage, or by material disposition are not suitable for use in flight, and which could be accidentally substituted for flight or flight spare hardware, shall be red tagged or striped with red paint, or both, to prevent such substitution.

7.4.2 The red tag shall be conspicuous and marked "NOT FOR FLIGHT."

7.4.3 The red paint shall be material compatible, and the stripes unmistakable.

This page intentionally blank.

8. Pre-Shipment Verification

The requirements set forth in this section apply to check-out, performance verification, and shipment of flight batteries prior to installation on spacecraft. Battery testing should condition flight hardware to produce acceptable electrical performance while minimizing degradation. Battery handling, inspection, test, and transportation need to comply with all safety requirements.

8.1 Minimum Use of Flight Batteries during Vehicle Integration & Test

8.1.1 To maximize on-orbit performance, the actual batteries to be used for flight shall not be installed or used for vehicle-level integration or acceptance tests at the vehicle fabrication and assembly site, except as may be necessary for non-operational tests such as spin balance.

8.1.2 Test batteries that are equivalent in configuration to the flight batteries and that have passed battery flight-level acceptance tests, shall be used for space vehicle level integration and acceptance testing.

8.2 Removal from Storage

Safeguards shall be used to protect flight batteries from thermal shock or water condensation upon removal from cold storage.

8.3 Inspection

8.3.1 The manufacturer, part number, and serial number of the flight battery shall be verified for accuracy.

8.3.2 The records for each flight battery shall be reviewed and used to verify that flight batteries do not exceed their maximum shelf life or cycle life prior to mission use.

8.3.3 The flight battery shall be visually inspected for signs of handling damage or abuse.

8.3.4 The continuity and isolation of cells, connector pins ,and wires shall be verified, as applicable.

8.3.5 The operation of all monitoring or control circuits shall be verified, as feasible.

8.4 State of Health Verification

8.4.1 Test equipment used to monitor and electrically test the flight battery shall be equivalent to the charge equipment validated by qualification testing.

8.4.2 The open-circuit voltage of every cell shall be verified to be within the manufacturer's cell balanced requirements, as applicable. Cell rebalancing may be performed as required.

8.4.3 At a minimum, one standard capacity measurement shall be performed on the flight battery. Any mission pulse load requirement shall be demonstrated. This capacity test shall be identical to a capacity test performed during flight battery proto-flight or acceptance testing for trending purposes.

8.4.4 The charge retention rate following at least a seven-day stand period during final processing shall be verified to be within requirement.

8.4.5 Data shall be reviewed and trended with qualification or acceptance test data to verify that performance meets minimum beginning-of-life mission requirements.

8.5 Preparation for Shipment

Flight batteries may be installed in the vehicle before it is shipped to the launch site, or shipped separately and installed at the launch site.

8.5.1 The battery state-of-charge shall be set at an appropriate level to minimize degradation during transportation.

8.5.2 Individual cell voltages shall be verified to be within the cell-balanced voltage criteria. Cell rebalancing may be performed as required.

8.5.3 The battery shall be transported in a qualified shipping container (see paragraph 3.5) that provides physical protection. This container shall be designed to prevent damage during handling, transportation, or storage. Containers shall contain temperature, humidity, and shock indicators.

8.5.4 Batteries shall be maintained between –10°C and +25°C, if it is practicable to do so, during handling, transportation, and installation.

9. Pre-Flight Operations

The requirements set forth in this section apply to battery installation, check-out, and maintenance of batteries during spacecraft-level ground activities preceding launch. Battery processing should maintain flight hardware to produce acceptable electrical performance while minimizing degradation.

9.1 Battery Installation on Spacecraft

9.1.1 An easily attachable and removable non-conducting cover shall be used to protect any power, monitoring, and heater connectors that attach to the vehicle wiring harness prior to installation on the vehicle. Optionally, the cover may remain in place for some or all of the vehicle launch preparation, but shall be removed prior to launch.

9.1.2 For large lithium-ion batteries, a handling plate or fixture shall be used for installing the battery on the vehicle. The fixture shall protect the thermal and structural elements of both the battery and vehicle from damage. The handling plate shall be removed once the battery is installed on the vehicle.

9.1.3 The battery shall be electrically connected to the vehicle bus in a manner that prevents uncontrolled current and/or damage to connector pins.

9.1.4 After vehicle installation, the flight battery shall go through electrical checkout to verify operation of electrical charge and discharge path, nominal telemetry readings, and operation of reconditioning circuit, heaters, and any inhibit circuits.

9.1.5 Battery voltage (and cell or module voltage where available), current, and battery temperature shall be monitored after battery installation on the vehicle at a sufficient frequency and resolution to detect any cell-level anomaly, such as premature discharge.

9.1.6 Pass/fail criteria for battery state-of-charge, battery/cell voltage, and temperature shall be derived from prior development and qualification testing specific to the design and applied prior to and during the terminal countdown. These requirements may vary at different phases prior to launch.

9.1.7 Battery monitoring and handling shall be conducted in a manner that complies with vehicle, facility, and Range Safety requirements.

9.2 Battery Maintenance on the Spacecraft

9.2.1 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. Specific limits or frequency shall be defined for each aspect of battery maintenance.

9.2.2 When discharged is the appropriate storage condition for a battery, the discharge of batteries to prepare for storage shall be accomplished with a battery conditioning module that will discharge the battery or individual cells at specified control rates.

9.2.3 As a safety feature, devices shall be incorporated in the design of battery conditioning modules to accommodate the discharge of the battery at any state-of-charge without causing any damage to the battery or vehicle, including the prevention of any battery cell voltage reversals.

9.2.4 Battery monitoring and cycling shall be conducted in a manner that complies with vehicle, facility, and Range Safety requirements.

10. Launch and On-Orbit Operations

10.1 Battery Monitoring Preceding Launch

10.1.1 Battery voltage, module voltage (when applicable and available), cell voltage (when available), current, battery temperature, and module temperature (when applicable) shall be monitored periodically after battery installation on the vehicle up to the final terminal countdown.

10.1.2 These data shall be evaluated to provide state-of-health verification of the electrical systems prior to launch.

10.1.3 Pass/fail criteria shall be applied prior to and during the terminal countdown to abort the launch when malfunctions occur in launch-critical batteries.

10.2 Charge Control

10.2.1 Normal battery charging and control procedures, and contingency procedures shall be prepared based upon test data obtained during vehicle, battery, module, and cell development/ qualification tests.

10.2.2 These documented procedures shall be the basis for battery operations and controls at the launch site and while on orbit.

10.3 Temperature

10.3.1 Battery temperatures throughout the orbital lifetime shall be maintained in the appropriate range based upon test data obtained during vehicle, battery, module, and cell development testing.

10.3.2 Control and contingency procedure 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.

10.4 On-orbit Battery Monitoring

10.4.1 Space vehicle battery voltage, module voltage (when modules are part of a battery), cell voltage (when available), current, battery temperature, and module temperature (when modules are part of a battery) shall be monitored periodically during flight and during all sun (solstice) and eclipse operations.

10.4.2 These data, together with depth-of-discharge performance, shall be summarized, trended, and evaluated to provide performance trends and be a basis for on-orbit operations.

This page intentionally blank.

References

1. AIAA S-122-2006, “Standard, Electrical Power Systems for Unmanned Spacecraft.”

2. Aerospace Report No. TR-2004(8583)-1 (Rev. A), SMC-TR-04-17, “Test Requirements for Launch, Upper-Stage, and Space Vehicles,” 6 September 2006, Edwin Perl, editor.

3. DOD-MIL-STD-810, “Environmental Engineering Considerations and Laboratory Tests.”

4. Aerospace Report No. TOR-2005(8583)-1, “Electromagnetic Compatibility Requirements for Space Equipment and Systems,” 8 August 2005, M. W. Dunbar.

5. Aerospace Report No. TOR-2007(8583)-6690, “Weibull-Based Life Test Scenarios,” 30 May 2007, M. M. Cavanaugh.

6. Aerospace Report No. TOR-2004(8583)-5, “Space Battery Standard,” 1 October 2004, W., C,. Hwang.

7. AIAA 5-080-1998, “Space Systems—Metallic Pressure Vessels, Pressurized Structures, and Pressure Compnents.”

8. AIAA 5-081A-2000, “Standard for Space Systems—Composite Overwrapped Pressure Vessels (COPVs).

9. DOD-MIL-STD-1686, “Electrostatic Discharge Control Program for Protection of Electrical and Electronic Parts, Assemblies, and Equipment (Excluding Electrically Initiated Explosive Devices).”

SMC Standard Improvement Proposal

INSTRUCTIONS

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

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

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

3. Document Title	

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

5. Reason for Recommendation

6. Submitter Information

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

8. Preparing Activity

Space and Missile Systems Center
AIR FORCE SPACE COMMAND
483 N. Aviation Blvd.
El Segundo, CA 91245
Attention: SMC/EAE