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Space systems — Lithium ion battery for space vehicles — Design and verification requirements

Systèmes spatiaux — Batteries à ions lithium pour véhicules spatiaux — Exigences de vérification et de conception

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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The committee responsible for this document is ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

This International Standard has been developed for the purpose of addressing the standard to obtain sustainable development and to prevent incident of lithium ion battery for space vehicle.

For battery developer and spacecraft system architects, this International Standard leads the way to assess the whole life cycle “from electrolyte filling to the end of the mission in space” and to clarify what is considered in the battery design phase and the processes to reach the appropriate verification.

It is important for lithium ion battery (LIB) for space vehicle to prevent performance defect in orbit and incident through the life cycle.

The three objectives in the life cycle, which are “performance”, “safety”, and comfortable “logistics”, aim to realize more reliable, more safe, and high efficient means at the same time for development of space vehicle batteries.

We address each objective as follows.

Performance

“How to estimate the life degradation at end of life”

Since LIB starts to degrade from activation, the consideration to meet the power requirement through the mission life is needed, that is, unaffected from handling conditions (temperature) and usage conditions in orbit (temperature, cycle, current or power and depth of discharge). Also, the risk in orbit could be mitigated based on the life estimation and unexpected degradation could be carefully avoided throughout the whole life cycle.

Safety

Here, we establish a complex risk assessment process that is easy to understand. The method was agreed internationally at ISO/IEC and is a traditional method for space use.

LIB needs to keep some amount of the SOC to avoid significant capacity degradation, so that the specific consideration and care for handling are required because of potential hazard source.

It is well known that LIB has specific risks with higher voltage when compared to other power sources and no saturation characteristic for overcharge.

The important thing is that the process, which can result to a hazardous situation, does not always immediately result to an incident. Because of these risks, LIB is considered hazardous at all times. The risk assessment needs to become very important to cover a variety of environment during the handling or use and history of stress.

Logistics

“How to bring the demand close to the general requirements to guarantee the safety and space quality”

From a wide-ranging point of view, the most important thing is to conduct life cycle assessment against performance and safety. For example, temperature history (especially high temperature history when cell is kept outdoors, where temperature is not controlled) and shocks/vibrations that cell receives during transport and electrical short when handling. Also, to reflect the results of handling or usage, measurement is needed.

All the personnel who owed responsibility of development, design, and handling are desired to survey and estimate the influence of their assessment spontaneously to improve for sustainable development of space component. As a result, a third party can evaluate the validity of the design and verification.

Space systems — Lithium ion battery for space vehicles — Design and verification requirements

1 Scope

This International Standard specifies design and minimum verification requirements for lithium ion rechargeable (including lithium ion polymer) batteries for space vehicles.

Lithium ion secondary electrochemical systems use intercalation compounds (intercalated lithium exists in an ionic or quasi-atomic form within the lattice of the electrode material) in the positive and in the negative electrodes.

The focus of this International Standard is on “battery assembly” and cell is described as “component cells” to be harmonized with other industrial standards and regulations.

“Performance”,” safety”, and “logistics” are the main points of view to specify.

This International Standard does not address “disposal” or “recycle”; however, some recommendations regarding disposal are suggested.

1.1 Life cycle

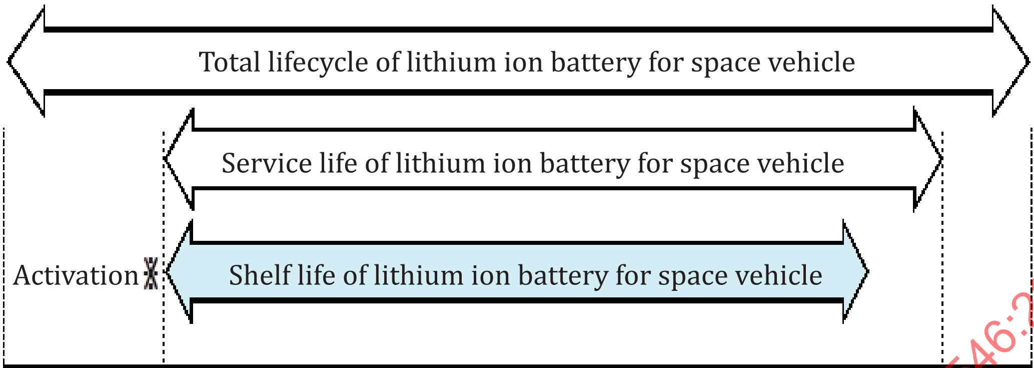
The service life of a battery starts at cell activation and continues through all subsequent fabrication, acceptance testing, handling, storage, transportation, testing preceding launch, launch and mission operation.

The scope of this International Standard addresses the shelf life, from cell activation to launch, although the life design and evaluations of the battery on the ground need to accommodate to the whole mission life in space.

Each article in this International Standard addresses “performance”, “safety”, and “logistics”, according to the each stage of lifecycle.

NOTE Stages 3 and 5 include storage period which induce some performances verifications.

Table 1 — Life cycle of lithium ion battery for space vehicle



Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9
Material Manufacture/ Inspection	Cell Manufacture/ Testing	Cell Trans-porta-tion	Battery Manufacture/ Testing	Battery Trans-porta-tion	Space vehicle Integration/ Testing	Space vehicle transportation equipped battery	Launch site ~Launch	Mission in orbit	End of life ~Deorbit

1.2 Performance

Evaluation items and methods of application for battery used for space vehicle is explained. The focus of the applicability is on the performance characteristics at the end of life (EOL).

The scope of the performance addresses terminology for the basic performance, typical usage (charge and discharge profile), quality assurance, testing method.

1.3 Safety

This International Standard follows the principle of ISO/IEC Guide 51.

Classify the hazards while normal usage through the lifecycle and provide rationale for the dangerous phenomenon, such as fire, burst/explosion, leakage of cell electrolyte, venting, burns from excessively high external temperatures, rupture of battery case with exposure of internal components, and smokes. Typical risk analysis, hazard analysis and fault tree analysis (FTA) through the battery life cycle is suggested in this International Standard. Hazard control method is distributed and tailored into each stage of life cycle, to harmonize with other industrial standards.

The safety test involves the items of "United Nations UN Manual of Tests and Criteria, Part III, sub-section 38.3, (UN38.3)" or UL1642. Necessary minimum safety precaution is described as Lithium Ion Battery for Space Vehicle.

Technical requirements are intended to reduce the risk of fire or explosion when lithium batteries are used in space vehicle. The final acceptability of these batteries is dependent on their use in a space vehicle that complies with the requirements applicable for range safety or payload safety.

These requirements are also intended to reduce the risk of injury to persons due to fire or explosion when prior to the launch site, transportation, battery testing and manufacturing.[11]

1.4 Logistics

In this International Standard, "logistics" means not only physical distribution or transportation but also descriptions on how to handle and care for and configuration (status or conditions of hardware and desirable environment) by each stage of lifecycle.

Descriptions of logistics contain the precautions for "manufacture", "assembling", "handling", "testing", "storage", "packing" and "transportation".

The scope of the logistics addresses the miscellaneous important precaution and rationale to maintain the performance and safety as a space vehicle battery, to harmonize with other industrial standards and regulations. Although, each item of relevant compliances is referred to the original document because each document or regulation is revised independently.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 24113, *Space systems — Space debris mitigation requirements*

IEC 61960, *Secondary cells and batteries containing alkaline or other non-acid electrolytes — Secondary lithium cells and batteries for portable applications*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
accelerated test
test designed to shorten the controlled environmental test time with respect to the service use time by increasing the frequency of occurrence, amplitude, duration, or any combination of these of environmental stresses during service use[7]

3.2
activation
process of making an assembled cell functional, by introducing an electrolyte at the manufacturing facility during cell production, which is used to define the start of battery shelf life[1][2][3][8]

3.3
aging
permanent loss of capacity due to repeated cycling or passage of time from activation[3]

3.4
battery
two or more cells which are electrically connected together, fitted with devices necessary for use, for example, case, terminals, marking and protective devices

Note 1 to entry: A single cell battery is considered a "cell".[6]

Note 2 to entry: A battery may also include some or more attachments, such as electrical bypass devices, charge control electronics, heaters, temperature sensors, thermal switches, and thermal control elements.[1][2]

Note 3 to entry: Units that are commonly referred to as "battery packs", "modules", or "battery assemblies" having the primary function of providing a source of power to another piece of equipment are, for the purposes of this International Standard, treated as batteries.[6]

3.5
calendar loss
degradation of electrical performances due to passage of time after activation

3.6
cell
single encased electrochemical unit (one positive and one negative electrode) which exhibits a voltage differential across its two terminals[6]

3.7
dangerous phenomenon
fire, burst/explosion, leakage of cell electrolyte, venting, burns from excessively high external temperatures, rupture of battery case with exposure of internal components, and smokes

3.8
disassembly
vent or rupture where solid matter from any part of a cell or battery penetrates a wire mesh screen (annealed aluminum wire with a diameter of 0,25 mm and grid density of 6 wires per cm to 7 wires per cm) placed 25 cm away from the cell or battery[6]

3.9
effluent
liquid or gas released when a cell vents or leaks[6]

3.10
explosion
condition that occurs when a cell container or battery case violently opens and major components are forcibly expelled and the cell or battery casing is torn or split[9][11]

3.11
external short circuit
direct connection between positive and negative terminals of a cell or battery that provides less than 0,1 ohm resistance path for current flow[6]

Note 1 to entry: An external short circuit occurs when a direct connection between the positive and negative terminals is made where the connection resistance is sufficiently low enough to higher than rated current flow through the cell.

3.12
fading
degradation of electrical performances due to cycling

Note 1 to entry: It is evaluated through life test and wear out test.

3.13
fire
flames are emitted from the test cell or battery[6][9]

3.14
gassing
evolution of gas from one or more of the electrodes in a cell[3]

3.15
harm
physical injury or damage to the health of people or damage to property or the environment

3.16
hazard
potential source of harm

Note 1 to entry: The term hazard is qualified in order to define its origin or the nature of the expected harm (for example, electric shock hazard, crushing hazard, cutting hazard, toxic hazard, fire hazard, drowning hazard).

3.17
hermetic seal
permanent air-tight seal[7]

3.18
intercalation
process where lithium ions are reversibly removed or inserted into a host material without causing significant structural change to that host[8]

3.19
intended use
use of a product, process or service in accordance with specifications, instructions and information provided by the supplier[9]

3.20
internal resistance
opposition to the flow of current within a cell or a battery, that is, sum of electronic resistance and ionic resistance with the contribution to total effective resistance including inductive/capacitive properties

3.21
leakage
visible escape of electrolyte or other material from a cell or battery or the loss of material (except battery casing, handling devices or labels) from a cell or battery such that the loss of mass exceeds the values in Table 2

Note 1 to entry: Mass loss means a loss of mass that exceeds the values in Table 2.

Table 2 — Table of mass loss limit

Mass M of cell	Mass loss limit
M < 1 g	0,5 %
l g ≤ M ≤ 75 g	0,2 %
M > 75 g	0,1 %

Note 2 to entry: In order to quantify the mass loss, the following procedure is provided:

$$\text{Mass loss (\%)} = \frac{(M1 - M2)}{M1} \times 100$$

where

M1 is the mass before the test and M2 is the mass after the test.

When mass loss does not exceed the values in Table 2, it shall be considered as “no mass loss”.[6]

3.22
life
duration of maintaining a required performance (e.g. 50 % of BOL capacity), estimated in years (calendar life) or in the number of charge/discharge cycle[3]

3.23
lithium ion battery
rechargeable electrochemical cell or battery in which the positive and negative electrodes are both intercalation compounds (intercalated lithium exists in an ionic or quasi-atomic form with the lattice of the electrode material) constructed with no metallic lithium in either electrode[6]

3.24
load profile
illustration of the power needed from a battery to support a given system, which is usually expressed by graphing required current versus time[8]

3.25
lot
continuous, uninterrupted production run with no change in processes or drawings[2]

3.26
open circuit voltage
difference in electrical potential voltage between the terminals of a cell or battery measured when the circuit is open (no-load condition) and no external current is flowing[3][6]

3.27
overcharge
charge past the manufacturer's recommended limit of voltage

3.28
over discharge
to discharge a cell or battery past the point determined by cell supplier where the full capacity has been obtained

Note 1 to entry: Continuous discharging of a cell or battery below zero volts causing voltage reversal is defined as forced discharge.[3]

3.29
probability of occurrence
theoretical distribution that measures of how likely it is that some event shall occur[7]

3.30
protective devices
devices such as fuses, by-pass, diodes and current limiters which interrupt the current flow, block the current flow in one direction or limit the current flow in an electrical circuit[6]

3.31
reasonable foreseeable misuse
use of a product, process or service in the way which is not intended by the supplier but which results from readily predictable human behaviour[9]

3.32
rupture
mechanical failure of a cell container or battery case induced by an internal or external cause, resulting in exposure or spillage but not ejection of solid materials[6]

3.33
self-discharge
phenomenon due to leakage current in open circuit at cell and/or battery level

3.34
shelf life limit
maximum allowed time from cell activation to launch, which includes any time in storage, whatever the temperature storage conditions[1][2]

3.35
space quality
high reliability required for vehicles and equipments built for space use

3.36
tailoring
process of choosing design characteristics/tolerances and test environments, methods, procedures, sequences and conditions, and altering critical design and test values, conditions of failure, etc., to take into account the effects of the particular environmental forcing functions to which material normally is subjected during its life cycle[7]

3.37
thermal runaway
uncontrollable condition whereby a cell or battery shall overheat and reach very high temperatures in very short periods (seconds) through internal heat generation caused due to an internal short or due to an abusive condition[3]

3.38
vent
release of excessive internal pressure from a cell or battery in a manner intended by design to preclude rupture or disassembly[6][8][9]

4 Symbols and abbreviated terms

BOL	beginning of life
C	capacity, expressed in ampere hours (Ah)
CC/CV	constant current/constant voltage
CID	current interrupt device
DOD	depth of discharge[3]
EOCV	end of charge voltage[4]
EODV	end of discharge voltage[4]
EOL	end of life [4]
FMEA	failure modes, effective analysis[4]
FTA	fault tree analysis
GEO	geosynchronous earth orbit
GTO	geosynchronous transfer orbit[3]
GSE	ground support equipment
IPA	iso propylic alcohol
LAT	lot acceptance test
LEO	low earth orbit
LIB	lithium ion battery
MSDS	material safety data sheet[8]
OCV	open circuit voltage[3]
PTC	positive temperature coefficient

QA quality assurance[4]

SOC state of charge

UN38.3 United Nations UN Manual of Tests and Criteria, Part III, 38.3

5 Cell

5.1 Performance

5.1.1 Purpose

This subclause describes the electro-chemical performance as a single cell in harmony with other standards.

Each article specifies the items that shall be necessary to verify when specific cells are to be assembled into the battery for space vehicle.

The cell contained in a battery shall be described as a component cell and a cell whose contents are enclosed within a sealed flexible pouch rather than a rigid casing is expressed as “pouch cell”.

The definitions of the size of cell, such as a small or large format, shall be tailored from UN38.3 and IEC 62281.

Recommended cell qualification test items are specified and the requirement for quality assurance of flight cells shall be addressed.

5.1.2 Terminology

For the purposes of understanding requirement of cell performance, the following terms and definitions apply.

Cell operating region

The conditions during charging and discharging in which the cell operates within its voltage and current and temperature range as specified by the cell manufacturer. See Figure 1 for a graphic representation of the cell operating region.[11]

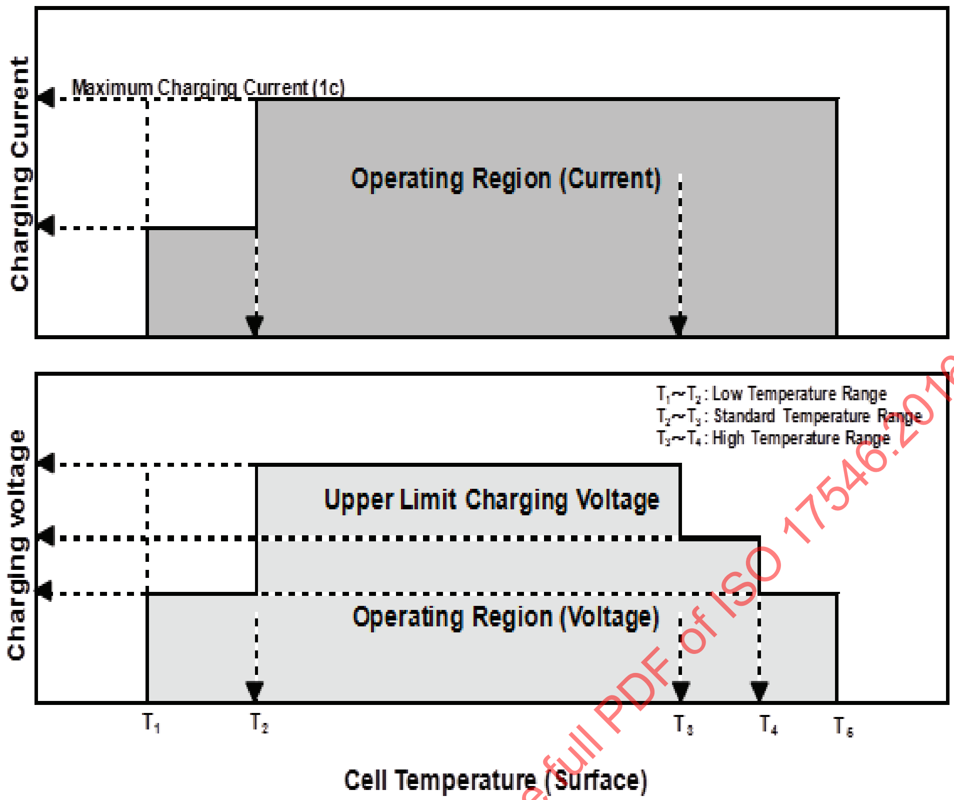


Figure 1 — Diagram representing an example of a cell operating region (e.g. from the Battery Association of Japan)

Maximum charging current for safety aspect

The maximum charging current in the cell operating region, which is specified by the cell manufacturer for the safety reason.[11]

Charging current limits for performances

The charging current limits in the cell operating region, which is specified by the cell manufacturer for the performances reason, shall not exceed the maximum charging current.

5.1.3 Requirement for quality assurance

Cells shall be manufactured under a quality management programme specified in United Nation Recommendation (see Annex E).

Acceptance tests shall be performed on cell level before the cells are installed in the battery-powered flight hardware.

Acceptance testing for Li-ion cells shall include as a minimum: a) visual inspection; b) leak check; c) dimensions and weight measurement; d) open circuit voltage; e) self-discharge, capacity or energy tests; e) internal resistance. Some environmental and safety device testing such as vibration, extreme thermal cycling, CID/PTC testing, etc. include acceptance test. In each testing, criteria shall be specified by the battery manufacturer.

Test data trending[1]

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

Additional tests are carried out as for example: a) closed circuit voltage checks; b) cycle testing, vibration; c) thermal cycling, d) X-ray; e) impedance; f) LAT; g) electrical wear-out cycling.

Off-gassing/out-gassing tests shall be required for materials compatibility. Any cell displaying any evidence of electrolyte leakage fails these tests.

Users shall verify that all cells intended for flight use are within the designated shelf life based on the cell manufacture date as specified in the Limited Life Items data.

The overall accuracies of controlled or measured values are commonly specified in Annex A.

5.1.4 Cell qualification test

Standard cell qualification test includes functional checkout (operational, cycle), environmental (i.e. vibration, thermal, thermal vacuum, radiation) and safety as stated in 5.2.1 or others as deemed appropriate for the specific hardware and application.[2][12][13]

Recommended test items of the component cell qualification for the space vehicle are specified. Examples are attached in Annex B.

For the space use, critical items for evaluations are hermetic test, safety testing, mechanical environment test, radiation, life cycling data and thermal/thermal vacuum test. The typical test method and criteria are specified, but not limited to, as follows or described rational for evaluation.

Leakage (hermetic) test

Each cell shall be tested for leakage in cell/battery acceptance test

Criteria: The maximum helium gas leakage equivalent rate shall not exceed $1,0 \times 10^{-6}$ $Pa \cdot m^3/s$.

Safety Tests

Each cell shall be subjected to over-charge, over-discharge, and over-current (short circuit testing) to ensure the cell does not result in a scenario where flame or fire exists.

Thermal/thermal vacuum test[2]

Cells shall be tested in an environment that encompasses the intended application as possible. Thermal environment, in particular, is a factor that significantly affects how a battery shall perform. Qualification temperature ranges shall encompass the mission temperature ranges and shall have a range sufficient to stress the hermeticity of the cell. The cells shall also experience a vacuum environment to determine the integrity of the cell hermetic seal.

Mechanical environmental test

Mechanical environment tests including sine and random vibrations and shock tests values shall encompass all possible space mission profile.

Examples of mechanical environment level for cells are described as follows.

Table 3 — Sine vibration

	Qualification	
Axis	Frequency/Hz	Amplitude/ Acceleration
All axis	5–22 22–100	20 mm (double) 20 (9,8 m/s²)

Sweep rate: 2 octave/min.

Table 4 — Random vibration

Axis	Frequency/Hz	Level
Along the length of the cell Cell Z axis	20–50 50–300 300–450 450–700 700–1 000 1 000–2 000	+6 dB/oct 0,2 (9,8 m/s^2)^2/Hz +12 dB/oct 1,0 (9,8 m/s^2)^2/Hz −19,43 dB/oct −3 dB/oct
	Overall	23,68 (9,8 m/s^2) rms
In the plane of the cell Cross section Cell X and Y axes for rectangular shape Cell R axis for cylindrical shape	20–50 50–100 100–150 150–250 250–284 284–500 500–783 783–1 000 1 000–2 000	+6 dB/oct 0,1 (9,8 m/s^2)^2/Hz +17,1 dB/oct 1,0 (9,8 m/s^2)^2/Hz −12 dB/oct 0,6 (9,8 m/s^2)^2/Hz −12 dB/oct 0,1 (9,8 m/s^2)^2/Hz −3 dB/oct
	Overall	21,19 (9,8 m/s^2) rms

Duration time: 180 s per each axis.

Table 5 — Shock

Axis	Frequency/Hz	Acceleration (x9,8 m/s^2)
All axis	200 1 400 4 000	24 4,200 4,200

Three times per axis.

Radiation test

Cells shall be exposed to the cumulative radiation dose, as a minimum, as specified for the mission environment.

Life cycle test

Life tests shall be performed for lot performance verification and for mission lifetime demonstration.

The life test for lot performance evaluation purpose shall be also included in a lot trend analysis. The supplier shall propose a representative wear out life test using accelerated conditions for current and cycle duration. The total energy (or capacity) degradation shall be checked after a defined number of cycles. An example of test procedure is given hereafter.

a) **For lot acceptance: DOD 100 %:**

1) Temperature T_{bat} (°C) (T_{amb}/T_{bat}): defined by battery supplier typically at ambient temperature);

2) CC/CV; Charge current 0,5 C (A)/EOCV: V_{ch} (V): defined by battery supplier;

3) CC; Discharge current 0,5 C (A) to EODV: V_{disch} (V): defined by battery supplier.

Standard capacity measurements shall be performed before life test and every 100 cycles.

5.1.5 Models for analysis

The following information shall be clearly defined by battery supplier based on cell suppliers' information for the battery design evaluation, if available, and their information shall be provided to battery assembler. Models shall be correlated with on-ground and on-orbit experimental data, where available.

a) **Heat generation and thermal model**

To evaluate worthiness of thermal design of the battery.

b) **Structural model**

To evaluate worthiness of structural design of strength and stiffness of the battery.

c) **Life (aging) model**

To evaluate worthiness of electrical power storage performance with appropriate margin through the life cycle.

5.2 Safety

5.2.1 Purpose

The purpose of this Clause is to clarify the dangerous phenomenon of independent cell and equipped safety features. Necessary test items for safety are provided.

The safety tests that shall prove two-fault tolerance to catastrophic hazard are performed as part of a qualification test program and repeated for each newly purchased lot of the same battery.[2]

5.2.2 Definitions and control of dangerous phenomenon

Hazard description

This subclause identifies the potential hazard when a cell shall be treated independently. See Annex C.

Potential hazards which are the subject of this International Standard are as follows:[9][14]

a) fire;

b) burst/explosion;

c) leakage of cell electrolyte;

d) venting;

e) burns form excessively high external temperatures;

f) rupture of battery case with exposure of internal components;

g) smoke.

Protective devices as a hazard control

For the purpose of hazard control, some protective devices shall be equipped within a cell. Although these protective devices are reliable in single cell use, it is necessary to evaluate their ability within a multi-cell battery. In case of multi-cell battery, delivery protection device shall be implemented at module or battery level. Typical example of the protective devices for hazard control shall be described as follows.

— **Electrical fuse**

A protective device containing a piece of metal that melts under heat produced by an excess current in a circuit and latching current limiters(ex), thereby breaking or opening the circuit[8]. Latching current limiters (externally resettable) also may be protective device instead of fuses.

— **Current interrupt device (CID)**

The CID is activated when the cells build up excessive pressure that usually occurs when the cells are overcharged to voltages close to or above 5 V.

— **Positive temperature coefficient (PTC) device**

A polymeric or ceramic element which has a very low resistance and conducts electricity with very little loss until a critical temperature or current range is reached. Upon reaching a predefined critical range, the internal resistance of the PTC increases exponentially, preventing the continued flow of current by the driving voltage applied. Resistance increase is typically five to six orders of magnitude over a temperature range of 25 °C. Upon cooling below the critical temperature range, resistance of the PTC device recovers to nearly the same resistance as originally found.[8]

— **Thermal fuse**

A fusible link electrical element that conducts current while it is below a critical threshold temperature. Once this threshold temperature is exceeded, the current-carrying capacity of the thermal fuse is irreversibly terminated, typically by melting a circuit breaker element allowing a spring to disconnect the circuit.[8]

— **By-pass device**

A by-pass device is used to irreversibly by-pass cell package or strings at battery level when voltage or temperature over passed the operating range.

— **Vent plug/rupture plate**

Most cells contain a vent mechanism, which is designed to release internal pressure in a benign manner in order to prevent any violent rupture of the battery case. The vent is often an intentionally weakened part of the cell case, which shall pop open before the case ruptures violently. A leak before burst design is also used to prevent any risk of violent rupture of the cell case.

— **Shutdown separator**

The shutdown separator is activated when the cells reach a certain temperature that causes a meltdown of the middle polyethylene-layer of the three-layer separator.

Large cells consist of the shutdown separator, vents, and a fusible link to the electrode as levels of protection. The shutdown separator is activated when the cells reach temperatures of close to 130 °C. The fusible link melts at specific currents, which then inhibits any hazardous occurrences during an external short condition. The vent typically operates above 1,03 MPa and the vent can sometimes be a level of protection to a catastrophic hazard but the cells typically do not perform after venting.

5.2.3 Safety testing

Mandatory safety test shall be conducted for the transport regulation as specified in “United Nations Transport of Dangerous Goods UN Manual of Tests and Criteria, Part III, subsection 38.3” (UN38.3) in case of the international transportation as a cell level. The manual of tests and criteria specify the purpose and test measures.

Considering the space qualification tests, some safety test such as vibration and shock in UN38.3 shall be merged or involved as equivalent test condition. Since toxicology assessment and report (independent materials usage and toxicological memos) shall be required for the following stage of battery level or space vehicle safety evaluation, destructive physical analysis (DPA) with electrolyte analysis shall be necessary for space use.[12]

Important test considerations

Some lithium ion cells or batteries are capable of exploding when the tests are conducted out of the cell design limits: mainly overcharge or over temperature ranges.

It is important that personnel be protected from the flying fragments, explosive force, sudden release of heat, and noise that results from such explosions.

The test area is to be well ventilated to protect personnel from possible harmful fumes or gases.

As an additional precaution, the temperatures on the surface of the battery casings shall be monitored during the tests.

All personnel involved in the testing of lithium batteries are to be instructed never to approach a lithium battery while the surface temperature exceeds 90 °C (194 °F) and not to touch the lithium battery while the surface temperature exceeds 45 °C (113 °F).

For protection, all the testing shall be conducted in a protected room separate from the observer.[11]

T1 High altitude test

This test shall be specifying the ability to withstand in low pressure during air transportation, to evaluate integrity and hermetically seal. For space vehicle use, this test shall be merged with thermal vacuum test.

T2 Thermal test

This test shall be specifying the ability to withstand in foreseeable thermal environment from −40 °C to 72 °C during transportation. For space vehicle use, since this temperature range is wider than qualification test, this thermal test shall be conducted separately from qualification test.

T3 Vibration

This test shall be conducted to evaluate the ability to withstand the vibration environment during transportations. For space vehicle use, the acceleration level of vibration test for space qualification is much severer. Therefore, the vibration test in UN38.3 shall be merged with qualification vibration test. Fatigue stress shall be appropriately considered to set the duration time.

In space use, the vibration test is also considered as screening test for internal short circuit risk and shall be performed mainly at battery configuration level using the satellite and other spacecraft environments taking into account the amplification factors.[13]

T4 Shock

This test shall be conducted at battery configuration level to evaluate the ability to withstand shock environment during transportations. For space vehicle use, the acceleration level of shock test for space qualification is much severer. Therefore, the vibration test in UN38.3 shall be merged with qualification shock test.

T5 External short circuit test

Typical failures	: inadvertent shorting across terminals; hard-blow/thermal fuse failure, if used.
Cell level	: external hard short is deliberately imposed on the cell under carefully controlled conditions.

Test conditions of external short in accordance with UN 38.3 in forces (e.g. less than 0,1 Ω at 55 °C ± 2 °C).

T6 Internal short circuit test (impact/crush)

Presence of impurities (metal burrs, particles, dust) that are dislodged due to vibration (manufacturing defect) are common causes of short circuits simulated mechanical abuse from an impact or crush that results in an internal short circuit. Test conditions are different by the shape of cell case or dimension.

When assembling batteries which consist of lithium-ion cells procured from other countries, it is necessary to use the cells that passed the UN 38.3 test by the original cell manufacturer.

T8 Over discharge test

Typical failures : low-voltage cut off (in equipment) failure; protective circuit board failure.

Test condition : each cell shall be forced discharged at ambient temperature by connecting it in series with a power supply at an initial current equal to the maximum discharge current specified by the manufacturer.

Optional test

The following tests are considerable for the option.

a) **High temperature and heat-to-vent**

Temperature tolerance on cells and determination of thermal runaway temperatures.

Requires cells be well instrumented with thermal and pressure measuring devices.

b) **Vent and burst pressure test (only for cell designed with vent system)**

Design criteria: vent/burst pressure ratio ≤3,0.

Vent pressure test shall be performed as per the following example, on a basis of two cell cases that has completed pressure cycling test and one cell case that is not used for pressure cycle test.

1) Pressurize the cell cases to Pi MPa·G while Pi means initial pressure.

2) Leave the cell cases for 1 min.

3) Confirm that there is no crack on rupture plate.

4) Add 0,05 MPa G to cell cases.

5) Leave the cell cases for 1 min. If crack on rupture plate occurs during 1 min, record the value of pressure as Pv MPa G.

6) Otherwise, repeat 4) and 5) until rupture plate operation.

7) Record the value of pressure at rupture plate operation.

Criteria: No crack on rupture plate shall be observed at 0,5 MPa or less. Operating pressure of rupture plates of Pv shall be more than 3,0 times of Pi respectively.

5.3 Logistics

5.3.1 Purpose

The requirements set forth in this Clause apply to the handling, storage, maintenance and transportation of cells during ground activities preceding pre-launch activities.

These requirements shall be defined in the cell specification and/or storage and handling procedure so as to minimize pre-flight degradation. Storage, handling, and maintenance methods shall be in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware.[1]

Rough handling results in cells being short-circuited or damaged. This causes leakage, rupture, explosion or fire.[10]

Regulations concerning international transport of lithium ion batteries or cells are based on the recommendation of the United Nations Committee of Experts on the Transport of Dangerous Goods.

Each country or region's law or regulations and/or directives follows. Therefore, prior to the transportation, the latest editions of these regulations shall be consulted.[10]

Manufacturers of cells (and batteries) shall ensure that equipment manufacturers and, in the case of direct sales, end-users are provided with information to minimize and mitigate these hazards.

It is the equipment manufacturer's responsibility to inform end-users of the potential hazards arising from the use of equipment containing secondary cells and batteries. See Annex C.[9]

5.3.2 Cell manufacturing, storage and testing

a) Cell handling, storage, and maintenance methods validated as part of development and/or qualification tests shall be documented in the storage and handling procedure.[1]

b) Cell storage, handling, and maintenance methods shall be in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware.[1]

c) The maximum shelf life limit shall be defined for the cell that includes the maximum exposure time to ambient temperature conditions.

   Records shall be maintained that document the temperature exposure and periodic cell-level SOC of flight hardware.[1]

   For extended storage, physical protections shall be granted.[1]

d) Recommended conditions for visual inspection of flight hardware are as follows.

   1) Inspection of the cells is performed to show that it is free from all visible contamination such as fingerprints, particles, corrosion products, metal chips, scale, oil, grease, preservatives, adhesives, and any foreign material.

   2) Ultraviolet inspection, special lights and mirrors considered aids to visual inspection shall be used.

   3) Components and cleaning materials shall only be handled with clean plastic gloves.

   4) Cell to cell and cell to case junctions are sealed with insulation material (tape, specific cap, etc.) The exterior shall be thoroughly cleaned with IPA immediately prior to packaging for shipment.

   5) The packaging material in contact with the cell is sterile or thoroughly cleaned with IPA prior to use.[2]

e) At all times, cells shall be maintained within a controlled temperature and humidity environment to maximize battery life and prevent water condensation.[1]

   High temperature of high humidity causes deterioration of the battery performance and/or surface corrosion.[10]

   General cleanliness and contamination control requirements shall be addressed during the manufacturing and testing of flight cells. In addition, special precautions shall be taken during final assembly to limit the numbers of trapped micro debris in the cell.

f) When not in use, cells shall be placed in low temperature environment as mentioned by the cell supplier, whenever practicable, at an appropriate SOC (defined and qualified by the cell supplier) to reduce storage degradation effects.[1]

5.3.3 Safety measure for handling

The following are requirements for safe handling of lithium ion batteries:

Common items to be considered are described in Annex D.

5.3.4 Cell transportation

Common items to be considered for transportation throughout the life cycle are described in Annex E.

6 Battery

6.1 Performance

6.1.1 Purpose

This subclause describes the minimum items of performance to satisfy for the fundamental requirement for the LIB for the space vehicles, maintaining space quality. The focusing issue here is the terminology for the LIB for space use. The importance is addressed into the evidences for life estimation, from the stand point of mission assurance.

6.1.2 Terminology

For the purposes of understanding requirement of battery performance, the following terms and definitions apply.

C/*n* charge or discharge current (C-Rate)[1][2][3]

The constant charge or discharge current for a battery is defined as C/*n*. C is the cell-level nameplate 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 Ah rated cell is a discharge current of 10 A.

Cut-off voltage

Endpoint voltage as specified by the manufacturer in discharge sequence.

Cycle

Usually one cycle is one sequence of fully charging and fully discharging a rechargeable cell or battery.[6] This is used mainly for full energy or capacity checks. On the other hand, one cycle of batteries such as LEO operation is a sequence with a partial charge (EOCV limit) and limited discharge (low DOD), which is defined as one partial cycle (e.g. discharge from SOC = 100 % to 80 % and charge from SOC = 80 % to 100 %).

Set of operations that is carried out on a secondary (rechargeable) cell or battery and is repeated regularly in the same sequence.

These operations consist of a sequence of a discharge followed by a charge or a charge followed by a discharge under specified conditions. This sequence shall include rest periods.[10]

Depth of discharge(DOD)[1][2][3][10]

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 nameplate energy E(Wh), times 100. For a lithium-ion battery, the DOD shall be specified at a state-of-charge (SOC) operation or a voltage that relates to SOC operation.

$$\text{Battery DOD (\%)} = \frac{E(\text{Wh})_{\text{REMOVED}}}{E(\text{Wh})_{\text{NAMEPLATE}}} \times 100 \quad (1)$$

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 %.

End of charge voltage

Highest charging voltage in the cell-operating region. This value is specified by the battery manufacturer taking into consideration the life requirement. In some cases, it is necessary to define an end of charge voltage value lower than the value of cell manufacturers' definition for the nameplate capacity, to limit the capacity degradation.

Energy

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 start of discharge to either the minimum battery voltage limit or when the first cell reaches the lower cell voltage limit or when 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 shall be accomplished with constant current discharge; however, constant power discharge is the preferred method if it more closely simulates spacecraft power. This is also sometimes called watt-hour capacity.

$$\text{Energy (Wh)} = \int (I_d \times V_d) \cdot dt \quad (2)$$

Energy density

Quantity of energy stored by a cell or a battery per unit weight or unit volume. Typical units include watt-hours per kilo-grams (Wh/kg) for specific energy, watt-hours per liter (Wh/l) for volumetric energy. To be most useful, energy densities shall be measured at a specific discharge rate and temperature.[8]

Energy reserve[1][2]

Total amount of usable energy in watt-hours 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 when the first cell reaches the lower cell voltage limit.

Fully charged[6][10]

Rechargeable cell or battery which has been electrically charged to its end of charge voltage as specified by manufacturer.

Fully discharged[6][10]

Rechargeable cell or battery which has been electrically discharged to its end point voltage as specified by manufacturer.

Nameplate capacity

Nameplate capacity (Ah) shall be defined by battery module supplier considering the nominal capacity and the minimum guaranteed capacity.

Battery supplier shall inform the nameplate capacity with nominal capacity to their user and associated conditions for definition.

Nominal capacity

Nominal capacity shall be defined as standard method for capacity measurement which is described in this International Standard (see 6.1.3).

Nameplate energy[2][9]

Nameplate energy (Wh) shall be defined by battery module supplier considering the nominal energy and the minimum guaranteed energy. Battery supplier shall inform the nameplate energy with nominal energy to their user and associated conditions for definition.

Nameplate energy in the watt-hour rating shall be marked on the battery module by permanent method with the following definition according to the United Nations recommendation:

$$\text{Nameplate energy (Wh)} = \text{Nameplate capacity (Ah)} \times \text{Nominal voltage (V)} \quad (3)$$

NOTE Nominal voltage is measured and defined by battery supplier.

Nominal voltage[6]

Approximate value of the voltage used to designate or identify a cell or battery.

Nominal voltage shall be defined and informed by cell supplier based on the capacity measurement with the conditions of end of charge voltage and cut off voltage.

Nominal voltage shall represent average discharge voltage obtained during the nominal capacity test.

State of charge

Ratio of the number of Ah or Wh present in a battery for a defined charge voltage-current profile, discharge load profile, and temperature profile to the rated energy E (Ah or Wh) of the battery, times 100.[1]

$$\text{Battery SOC (\%)} = \frac{E\,(\text{Ah or Wh})_{\text{PRESENT}}}{E\,(\text{Ah or Wh})_{\text{RATED}}} \times 100 \quad (4)$$

The available capacity in a cell or battery expressed as a percentage of rated capacity.[3]

6.1.3 Basic performance

Standard method for capacity measurement

Standard capacity shall be measured according to the following protocol.[12]

a) Preparation

The following information shall be clearly defined by battery supplier based on cell suppliers' recommendation prior to the measurement of capacity. Their information shall be provided to their end user:

1) charging protocol; CC-CV or CC-CC;
2) applicable design value of constant charge current;
3) end of charge voltage;
4) charge end condition; charge current ratio, e.g. C/100, or charge duration time, e.g. 8 h;
5) discharging protocol; constant current or constant power;
6) applicable discharge current;
7) lower voltage limit at the end of discharge;

8) temperature representative point as thermal control reference.

b) Discharge remaining energy with applicable constant discharge current until lower voltage limit.

c) After representative temperature come into stable, perform charging protocol according to the battery suppliers' definition.

d) After representative temperature come into stable, perform discharge with applicable protocol until defined voltage limit.

e) Measured discharge capacity shall be recorded as nominal capacity.

Battery internal resistance (ohmic)

This measurement shall be performed as required.

The internal resistance of each battery shall be determined at 2 SOC values (e.g. 10 % and 90 %) for the operational representative temperature which is specified by battery manufacturer, using a short duration pulse technique, then calculating the ΔV/ΔI values. It is noticed that the battery internal resistance is depending on the cell and battery design but also on the measuring techniques. Internal resistance values evolve considering the SOC, the time to perform the measurement.

Battery impedance

This measurement shall be performed as required.

The impedance of each battery shall be measured at a specified SOC value for the operational representative temperature which is specified by battery manufacturer, using a specific analyser with frequency range in adequacy with mission specification (typically range from 10 Hz to 100 kHz).

6.1.4 Life test demonstration

Battery qualification includes life test demonstration which is performed at cell level and/or battery configuration level depending on the mission.

The following conditions are the typical usage for the space vehicle use.

The life tests for qualification or life demonstration shall be performed using real time and/or accelerated conditions.

It is recommended to perform life test on hardware that have been submitted to vibration testing and/or radiation environment.

For GEO profile, real-time corresponds to repeated, up to 30 times at least (corresponding to 15 years), eclipse periods with 45 d, 1 cycle/day of eclipse simulation and 135 d of solstice with or without plasmic propulsion peak simulation.

In accelerated conditions, the solstice period is reduced from 135 d to a few days and the eclipse period is shortened by using 2 cycles per day.

a) **For GEO simulated**

The GEO simulated, eclipse profile uses periods of 45 cycles with the GEO eclipse profile.

1) Temperature T_{bat} (°C) (thermal chamber temperature regulation/T_{bat}: defined by battery supplier). The temperature has to be representative of the thermal environment seen during the mission by the battery. 15 °C or 20 °C shall be the reference temperature.

2) CC (constant current) or CP (constant power)/CV; charge current from C/5 to C/10/duration 22,825 h/EOCV: V_{ch} (V): defined by battery supplier.

3) CC or CP; discharge/duration: GEO profile with 1,175 h max achieved at day 23rd of the eclipse up to 70 % to 80 % DOD.

4) Days of solstice period with CV charge to EOCV defined by the supplier.

The GEO life test is performed using the selected balancing system for the battery, if applicable.

Standard method for capacity measurements shall be conducted before life test and periodically: after each or two seasons period up to season 30th, at minimum.

For LEO, mission profiles are different depending on the satellite type. However, the standard real-time corresponds to repeated 90 min cycles: 60 min charge and 30 min discharge.

b) **For LEO simulated**

1) Temperature T_{bat} (°C) (thermal chamber temperature regulation/T_{bat}: defined by battery supplier).

2) CC/CV ; charge current 0,3 C to 0,5 C/EOCV: V_{ch} (V): defined by battery supplier.

3) CC; discharge current 0,5 C.

Balancing system shall be also included to the test, if applicable.

Standard capacity measurements shall be performed before life test and every 1,000 cycles or less.

c) **For launch vehicle: simulate ground storage and usage at launch phase**

The launch vehicle missions are specific to the type of launcher and the battery function. The profile shall be derived from the mission profile.

If batteries are used for flight termination system, tracking system, or telemetry system, mission profile of batteries shall include abnormal conditions to ensure the safety functions.

6.1.5 Design requirements

General requirements[2][8]

The design of a multi-cell battery shall ensure electrical continuity, mechanical stability, and adequate thermal management. The battery shall provide both the energy/capacity and current required within the voltage limits of the application. The performance of the cells in a multi-cell battery shall usually be different than the performance of the individual cells. The cells cannot be manufactured identically and each may encounter a somewhat different environment in the battery.

The design of the multi-cell battery (such as packaging techniques, material of structure, insulation, and potting compounds, connecting, safety components) shall influence the performance as it affects the environment and temperature of the individual cells.[15][16]

Electrical design

Battery electrical design shall minimize the risk of leakage currents from the cell terminals to the battery case or cell voltage monitoring circuitry and electrostatic discharge and shall meet all EMI and compatibility requirements for the application. Battery charge control is required for LIB to avoid the hazards associated with overcharge and shall be developed along with battery design.

Batteries and battery structure shall be designed to survive all environmental conditions of a mission or application. This includes launch/abort/landing loads, transportation, and handling environments. Mounting or sealing of cells in a battery case does not interfere with cells vents or rupture plate.

Thermal design

Battery designs that retain the heat dissipated by the cells improve performance at low temperatures. On the other hand, excessive build-up of heat can be injurious to the battery's performance, life, and safety. The battery thermal design shall maintain an optimal temperature range for all the cells in the battery within the expected environmental conditions.

Mechanical design

Battery mechanical design shall be in accordance with the launch site requirements and the customer from mechanical margins which include the burst pressure versus the max operating pressure.

Cell-to-cell balancing mechanisms

During charging, differences in individual cells lead to differing voltages in cell groups. Some cells are undercharged, with a result of decrease in the overall battery capacity. Conversely, some cells are overcharged, with the result of cell damage, shortening of life cycle, or the creation of safety issues. In order to achieve a uniform SOC, consideration shall be given to, including a cell-to-cell balancing mechanisms for use during battery charging systems.

Marking

Batteries manufactured after 31 December 2011 shall be marked with the watt- hour rating on the outside case.

Marking shall be confirmed according to each mode of transport regulations.

(Reference [6])

6.1.6 Requirement of quality management

Cell screening tests[2]

This subclause provides a summary of the screening tests that shall be performed to match cells for use in a battery system.

Cell matching

Cell matching shall be performed regardless of the battery chemistry chosen or the qualification/acceptance testing to be performed, if there is no cell-balancing system.

Polarization testing (optional)

The electrochemical activity of a cell is determined periodically by measuring its voltage-current relationship using polarization.

The proposed method to perform the polarization test is as follows.

These tests are performed by applying the required current (five or six different current settings within the capabilities of the cell used shall be chosen) in charge mode for about 20 s and then in discharge mode for about 20 s.

NOTE Exceeding the rated current carrying capability of a given cell leads to permanent damage even for short-term exposures such as this. Choose test current density values carefully.

In this way, the cell SOC shall remain approximately the same at the end of the test as it was at the beginning of the test. This test shall be done at 25 %, 50 %, and 75 % SOC.

The degree of linearity of the plotted data (voltage as a function of current density) indicates whether the electrode is exhibiting kinetic or concentration polarization effects.

Kinetic effects and poor mass transport properties are evidenced by nonlinearity at low and high current densities.

The internal resistance of the cell can be calculated by determining the slope of the discharge curves at each of the SOC.

Cell resistance can also be measured with an impedance bridge at 1,000 Hz.

This measurement generally is in good agreement with the resistance calculated from the slope of the voltage-current relationship.

Self-discharge rate test

This simple test involves stopping during charge and/or discharge cycles at specific intervals (usually based on SOC) and observing the rate of decay for a fixed time interval (e.g. 72 h).

Usually 25 %, 50 %, 75 % or 100 % SOC are chosen for convenience. Cells with steeper decay rates shall be eliminated from consideration.

Tailoring screening tests

Screening tests shall be tailored to individual cell types (Capacity/energy checks, weight measurement, internal resistance checks, voltage profile, self-discharge). A series of combination cycles shall allow the engineer to identify deviations in cell behaviour.

For example, 1,5 Ah lithium ion cells shall be cycled in the following way for screening purposes.

By analysing the plotted data, performance differences are easily seen. Begin with a C rate charge at anything from C/1 to C/10 to a maximum of 4,2 V. Then switch the cell to open circuit (or wait state) for a short period of time (usually for several minutes, the same wait time shall be used for all cells of the same type). At the end of the wait state, observe and note the voltage decay and then do the following special discharge:

— discharge at C/1 for 1 min, then without hesitation, switch to a C/10 discharge down to 2,4 V. All graphical data shall be plotted using the same scale values;

— the resulting voltage versus time curve shall be an upward sloping charge curve with the expected peaks, followed by a self-discharge dip or notch, attached to a steep downward curve that abruptly turns upward caused by the reduction in the discharge rate;

— the difference between the C/1 discharge and the upturn resulting from the abrupt decrease in discharge rate allows the internal resistance of the cell to be determined. Finally, after the initial rise, the discharge curve decreases back down into a more typical slope;

— continue to test the cells in question for about 50 cycles. After about 50 of these special cycles, analyse the data to pick out the cells which are assembled into a string of cells.

Cell matching criteria

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 depending on the cell design and supplier.

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.

The cell matching criteria shall include capacity and resistance data at a defined voltage.

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 is also exposed to proto-qualification levels.

Contamination control

At all times, battery shall be maintained within a controlled temperature and humidity environment to maximize battery life and prevent water condensation.[1]

High temperature of high humidity causes deterioration of the battery performance and/or surface corrosion.[10]

General cleanliness and contamination control requirements shall be addressed during the manufacturing and testing of flight battery. In addition, special precautions shall be taken during final assembly to limit the numbers of trapped micro debris in the battery.

Test data trending[1]

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

Flight verification acceptance testing[2]

Acceptance testing for Li-ion batteries include visual inspection, vacuum/leak check, dimensions and weight measurement, open circuit voltage and closed circuit voltage checks, cycle testing, vibration, and thermal cycling or capacity tests at different temperatures.

Off gassing/out-gassing tests shall be required for materials compatibility. Any cell displaying any evidence of electrolyte leakage fails these tests.

Users shall verify that all batteries intended for flight use are within the designated shelf life based on the cell manufacture date as specified in the Limited Life Items data.

Assurance of the life estimation[5]

The following are the recommended measure to establish of life estimation. It is important not to depend on the numerical model of life prediction too much:

a) life testing of battery for service-life expectancy confirmation shall be conducted under a set of conditions that envelope the mission battery load range, charge-control methods and conditions, and temperatures through all mission modes and states;

b) test duration shall include margin to demonstrate the required battery reliability and confidence level from the number of test samples;

c) for cases where a time-acceleration factor has been established and validated by previous life-test results, the established acceleration factor is used;

d) for cases where a time-acceleration factor has not been established by previous test results to be valid for the mission duration and conditions, the time-acceleration factor shall be based on data and analysis to be provided to and approved by customer.

Requirement for quality assurance

Battery shall be manufactured under a quality management programme.

The overall tolerances of controlled or measured values are commonly specified in Annex A.

Battery testing[2][12]

Typical testing includes functional checkout (operational, cycle), environmental (i.e. vibration, thermal, thermal vacuum), electromagnetic compatibility, power quality, or others as deemed appropriate for the specific hardware and application.

The vibration spectrum varies depending on the cell construction and tolerance of the cell to internal shorts. The information for vibration testing is provided in the section on short circuit hazards below.

The safety tests that shall prove two-fault tolerance to catastrophic hazard are performed as part of a qualification test program and repeated for each newly purchased lot of the same battery.

Development testing[1][12]

The objective of development testing is to identify problems early in the design evolution so that any required corrective actions shall 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 shall 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 shall 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.

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 (if required) shall be characterized sufficiently for a flight-type battery to demonstrate a charge control design that shall meet the requirements for all vehicle operations, including sun periods and contingencies.

Charge control electronic designs shall be validated during the life cycle test.

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 shall meet the requirements for all mission conditions and vehicle operations, including sun periods and contingencies.

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

a) thermal characterization tests shall 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 shall quantify the rate of heat transfer through a material or across an interface. Specific applications include measuring the directional conductivity 9 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-space vehicle 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 thermistor, radiators, heat pipes, etc., and demonstrates temperature and heater margins.

Mechanical test

The objective of mechanical development tests includes the validation of new technologies and design concepts, the correlation of analytical models, if exists, 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 shall be effective to be conducted to correlate with a mathematical model and to support design margin or failure evaluations.

Development tests and evaluations of vibration and shock test fixtures shall be conducted prior to first use to prevent inadvertent over-testing or under-testing, including avoidance of excessive cross axis response.

Qualification test[1]

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.[15]

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.

Qualification test levels and duration

To demonstrate margin, the qualification environmental conditions shall stress the qualification hardware to more severe conditions than the maximum conditions during service life.

Qualification testing, however, shall not create conditions that exceed applicable design safety margins or cause unrealistic modes of failure. The qualification test conditions shall envelop those of all applicable missions.

In-process inspections and tests

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

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

Data collection and acquisition rates

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.

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

During any dynamic environmental test, data shall be collected on strip chart recorders or at a sufficient acquisition rate to evaluate for intermittent dropouts.

6.2 Safety

6.2.1 Purpose

Battery supplier shall ensure the safety of personnel and hardware throughout all phases of battery development, fabrication, assembly, testing, handling, storage and transportation.

All precautionary measures to prevent the inadvertent venting of an individual cell or assembled combination of cells shall be identified and implemented.

Potentially hazardous conditions, as well as hazardous procedures, shall be identified in a manner easily observed by personnel.

The safety of secondary batteries requires the consideration of two sets of applied conditions as follows:

a) intended use;

b) reasonably foreseeable misuse.

Cells and batteries shall be so designed and constructed that they are safe under conditions of both intended use and reasonably foreseeable misuse; it is expected that the misuse of cells or batteries fails to function following such experience.

They shall not, however, present significant hazards. It is also expected that cells and batteries subjected to intended use shall not only be safe but shall continue to be functional in all respects.

Based on the principle of ISO/IEC Guide 51 and ISO 12100, appropriate risk analysis shall be conducted by supplier considering whole life cycle.

Typical hazardous situation caused by an LIB becomes common knowledge; however, the LIB design or interface shall be analysed specifically case by case, due to the differential system architecture, supply chain, or chemistry.[9]

Lithium ion cells and batteries are categorized by their chemical composition (electrodes, electrolyte) and internal construction (bobbin, spiral, stacking).

They are available in various shapes. It is necessary to consider all relevant safety aspects at the battery design stage, recognizing the fact that they differ considerably, depending on the specific lithium system, power output and battery configuration.

The following design concepts for safety are common to all lithium ion cells and batteries:

— abnormal temperature rise above the critical value defined by the manufacturer shall be prevented by design;

— temperature increases in the cell or battery shall be controlled by the design, e.g. by limiting the current flow;

— lithium cells and batteries shall be designed to relieve excessive internal pressure or to preclude a violent rupture under conditions of transport;

— lithium cells and batteries shall be designed so as to prevent a short-circuit under normal conditions of transport and intended use;

— lithium batteries containing primary and secondary cells or strings of cells connected in parallel shall be equipped with effective means to prevent dangerous reverse current flow (e.g. diodes, fuses, etc);[10]

— in order to comply with ISO 24113, the main requirements for batteries and operations are as follows:

  — performance monitoring during mission in orbit to be able to engage end of life operations while battery is capable of these operations;

  — assessment of the risk of producing debris after end of life. This point can be merged with assessment of burst risk during the operating life cycle of cells and battery.

6.2.2 Definitions of dangerous phenomenon

Hazard description

This subclause identifies the hazardous event when a battery shall be treated independently.

These hazards are the results of risk assessment and analysis.

Example of risk analysis to identify such hazards is described in Annex C.

Potential hazards which are the subject of this International Standard are as follows:[9][14]

a) fire;

b) burst/explosion;

c) leakage of cell electrolyte;

d) venting;

e) burns form excessively high external temperatures;

f) rupture of battery case with exposure of internal components;

g) smoke.

6.2.3 Technical requirement

Technical requirements for battery safety design are described as follows.

Risk analysis through the lifecycle shall be conducted as earlier phase of development of LIB.

FMEA shall be done for all battery designs. All cell safety devices (such as rupture plate, current interrupt devices, positive temperature coefficient devices, fuses, and switches, relays, by-passes and diodes) incorporated into the battery design shall have their failure modes and reliabilities included in the overall battery failure and reliability analysis, since they increase the number of failure scenarios.

Whenever a choice exists between different risk-levels associated with chemistry, capacity, complexity, charging and application, the option that presents the minimum risk while meeting the performance requirements of the mission shall be selected.

Fault tolerance

The fault tolerance of the battery shall be evaluated as part of the battery design evaluation.

Batteries and their systems shall be inherently safe through the selection of appropriate design features or the use of appropriate safety devices, as fail operational/fail safe combinations to eliminate the hazard potential.

Since lithium-based cells/batteries have a high specific energy and hazard potential, they shall be at least two-fault tolerant to any catastrophic failure.

Catastrophic failure definition:

Hazards are considered as catastrophic when the consequence belongs to one of the following categories:

— loss of life, life-threatening or permanently disabling injury or occupational illness, loss of an element of an interfacing manned flight system;

— loss of launch site facilities or loss of system;

— long-term detrimental environmental effects.

Most lithium-based cell electrolytes present corrosive, toxic, or flammability hazards. With appropriate lot-verification testing, tolerance of lithium cells to certain types of abuse shall count as a hazard control, dependant on cell design, capacity, complexity, charging and application. A cell failure is counted as one of the failures.[2]

Hazard controls[2]

A battery design includes controls for potential battery hazards.

Battery design considerations shall be given to the structural integrity of the cell and battery housings, the possibility of gas generation, pressure, and/or electrolyte leakage, the prevention of short circuits and circulating currents, the possibility for high battery temperatures, over-discharging, and assurance of proper charging techniques. The battery evaluation shall assess the battery hazard controls.

Over-current prevention

Each battery having high energy density used as a power source shall contain a suitable over-current device.

Devices shall either go to the open-circuit position if the battery is discharged at an excessive rate, e.g. fuse or relay, or shall limit the current flow to a safe level, e.g. positive thermal coefficient (PTC) device. Batteries shall be over-current protected in the ground lead of each series string. Each separate circuit shall be protected.

If the battery is tapped to provide different output voltages, each tap shall be protected with an over-current device.

Over-voltage protection

Each battery shall have integrated overvoltage (over-charge) protection.

These protections shall disconnect the battery from the charging source or shunt current to avoid each cell not to be over-charged.

Protective function shall be automatically worked and not require operator action, when arming function, if any, is ON.

For example, the over-voltage protection within a battery may be providing a voltage monitoring signal to the spacecraft such that the spacecraft controller eliminates the charging function. The over-voltage protection may be a combination of battery and spacecraft electronics.

Temperature/current management

The design of batteries shall be such that abnormal temperature-rise conditions are prevented.

Where necessary, means shall be provided to limit current to safe levels during charge and discharge.

Insulation and wiring

The insulation resistance between the positive terminal and externally exposed metal surfaces of the battery excluding electrical contact surfaces shall be dependent on the battery design and established by the supplier.

Internal wiring and its insulation shall be sufficient to withstand the maximum anticipated current (using the de-rating rules for the wires of ECSS-Q-ST-30-11, for example), voltage and temperature requirements.

The orientation of wiring shall be such that adequate clearances and creepage distances are maintained between connectors.

The mechanical integrity of internal connections shall be sufficient to accommodate conditions of reasonably foreseeable misuse.

Positive protection against accidental shorting

When the battery is not installed in space vehicle, the leads or connector plug shall be taped, guarded, or otherwise designed or provided with positive protection against accidental shorting.

Power switches in the end item shall be selected to prevent accidental battery turn-on. Switching devices shall not be used in the ground leg(s).

Venting

Battery cases and cell shall incorporate a pressure relief mechanism or shall be so constructed that they shall relieve excessive internal pressure at a value and rate that shall preclude rupture, explosion and self-ignition. If encapsulation is used to support cells within an outer case, the type of encapsulate and the method of encapsulation shall neither cause the battery to overheat during normal operation nor inhibit pressure relief.

Cell or battery vents shall not be blocked if venting is considered as a measure of fault tolerance. If potting is essential, ensure that venting shall not be obstructed and that the potting does not adversely affect battery thermal management.

A vent path for the toxic and corrosive and/or flammable vent products shall be designed to prevent case rupture or undirected venting except in applications where venting of any kind is not permitted. Housing for a battery assembly shall have a functional vent mechanism to preclude rupture.

Crew touch temperature requirements

Hardware which shall be touched by crewmembers shall have surface temperatures not exceeding 45 °C for continuous contact, shall have warning labels for surface temperatures between 45 °C and 50 °C and shall have protective measures above 50 °C.

If a battery or cell under charge/discharge operation shall be touched by a crewmember, the battery shall incorporate additional protection to prevent the battery and/or cell temperature from exceeding this 45 °C limit even if the environmental temperature is around 45 °C.

If the battery or cell shall not be directly touched but is located near a surface that shall be touched, temperature controls shall be incorporated to prevent excessive battery or cell heat from transferring to the touchable surface.

Terminal contacts

Terminals shall have clear polarity marking on the external surface of the battery. The size and shape of the terminal contacts shall ensure that they carry the maximum anticipated current. When battery shall be delivered, the connector types shall also be detailed in an electrical interface drawing document.

In order to avoid improper connection, manufacturers shall find different keying or other means.

External terminal contact surfaces shall be formed from conductive materials with good mechanical strength and corrosion resistance. Terminal contacts shall be arranged so as to minimize the risk of short circuits.

6.2.4 Safety testing

Mandatory safety test shall be conducted for the transport regulation as specified in UN38.3 prior to the international transportation as a battery level. The tests manual and criteria specify the purpose and test measures.

Considering the space qualification tests, some safety test such as vibration and shock specified in UN38.3 shall be merged or involved as equivalent test condition.

Important test considerations
Some lithium batteries are capable of exploding when the tests are conducted.
It is important that personnel be protected from the flying fragments, explosive force, sudden release of heat, and noise that results from such explosions.
The test area is to be well-ventilated to protect personnel from possible harmful fumes or gases.
As an additional precaution, the temperatures on the surface of the battery casings shall be monitored during the tests.
All personnel involved in the testing of lithium batteries are to be instructed never to approach a lithium battery while the surface temperature exceeds 90 °C (194 °F) and not to touch the lithium battery while the surface temperature exceeds 45 °C (113 °F).[11]
For protection, all the testing shall be conducted in a protected room separate from the observer.[11]

T1 High altitude test

This test shall be specifying the ability to withstand in low pressure during air transportation, to evaluate integrity and hermetically seal. For space vehicle use, this test shall be merged with thermal vacuum test.

T2 Thermal test

This test shall be specifying the ability to withstand in foreseeable thermal environment from UN38.3 for transportation. This temperature range shall not be considered as an operating temperature range.

For space vehicle use, since this temperature range is wider than qualification test, this thermal test shall be conducted separately from qualification test.

T3 Vibration

This test shall be conducted to evaluate the ability to withstand the vibration environments during transportations.

For space vehicle use, the acceleration level of vibration test for space qualification is much more severe. Therefore, the vibration test in UN38.3 shall be merged with qualification vibration test. Fatigue stress shall be appropriately considered to set the duration time.

In space use, the vibration test is also considered as screening test for internal short circuit risk.

T4 Shock

This test shall be conducted to evaluate the ability to withstand shock environment during transportations. For space vehicle use, the acceleration level of shock test for space qualification is much more severe. Therefore, the vibration test in UN38.3 shall be merged with qualification shock test.

T5 External short circuit test

Typical failures : inadvertent shorting across terminals; hard-blow/thermal fuse failure.

Battery level : external hard short is deliberately imposed on the battery under carefully controlled conditions.

Test conditions of external short are dependent of the cell and battery design and shape.

T7 Overcharge[6]

Typical failures : charger failure; protective circuit board failure.

Battery level : verify protective feature for overcharge/over-voltage.

When a cell or battery type is to be tested in accordance with UN38.3, the number and condition of cells and batteries of each type to be tested shall be representative of flight hardware configuration.

Batteries not equipped with overcharge protection that are designed for use only in a battery assembly, which affords such protection, are not subject to the requirements of this test.

When cells that have passed all applicable tests are electrically connected to form a battery assembly in which the aggregate lithium content of all anodes, when fully charged, is more than 500 g, or in the case of a lithium ion battery, with a watt-hour rating of more than 6,200 watt-hours, that battery assembly does not need to be tested if it is equipped with a system capable of monitoring the battery assembly and preventing short circuits or over discharge between the batteries in the assembly and any overheat or overcharge of the battery assembly.

Test procedure:

It is the battery manufacturer's responsibility to propose test procedure that covers the overcharge depending on the design and the model mainly in case of very large batteries. This test shall not be done on a flight model to avoid additional degradation.

Special provision

— **Smaller population**[8]

A smaller population of test units shall be acceptable for safety evaluation that involves revisions to battery designs that have previously been tested in accordance with same condition or the use of previously tested batteries in new systems or applications.

— **Alternative test units**

In some tests, individual cells, subsections, and/or partially populated batteries shall be substituted as test units for large batteries. The use of alternative test unit and configurations shall be justified by the battery supplier.

— **Multiple use of test units**

Test units that have been subjected to environmental compliance test such as shock, vibration, and humidity exposure, that did not result in discharge of the battery (or when the battery is recharged to its full capacity), shall be used for safety testing, Alternate allocations of test units are possible. For example, a short-circuit.

Description for necessary information for system safety review

Since toxicology assessment and report (independent materials usage and toxicological memos) shall be required for the system safety review of battery level or space vehicle safety evaluation, destructive physical analysis (DPA) with electrolyte analysis is necessary.

6.3 Logistics

6.3.1 Purpose

The requirements set forth in this subclause apply to the handling, storage, maintenance and transportation of batteries during ground activities preceding pre-launch activities.

These requirements shall be defined in the battery specification and/or storage and handling procedure so as to minimize pre-flight degradation.

Storage, handling, and maintenance methods shall be in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware.[1]

Rough handling results in batteries being short-circuited or damaged. This causes leakage, rupture, explosion and/or fire.[10]

Regulations concerning international transport of lithium ion batteries or cells are based on the recommendation of the United Nations Committee of Experts on the Transport of Dangerous Goods. Each country or region's law or regulations and/or directives follows. Therefore, prior to the transportation, the latest editions of these regulations shall be consulted.[10]

Manufacturers of batteries shall ensure that equipment manufacturers and, in the case of direct sales, end-users are provided with information to minimize and mitigate these hazards. It is the equipment manufacturer's responsibility to inform end-users of the potential hazards arising from the use of equipment containing batteries. See Annex D.[9]

6.3.2 Manufacture/assembly storage and testing

a) Battery handling, storage, and maintenance methods validated as part of development and/or qualification tests shall be documented in the storage and handling procedure.[1]

b) Battery storage, handling, and maintenance methods shall be in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware.[1]

c) 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 SOC of flight hardware on a daily basis.[1]

   Speciality storage containers shall be used during extended storage to provide physical protection.[1]

d) Cell and battery inspections shall be performed according to the following as a minimum: visual inspection of flight hardware, temperature, humidity, and shock sensors and measurement of battery open-circuit voltage and cell isolation resistance.[1]

   1) An inspection of the cells and battery is performed to show that it is free from all visible contamination such as fingerprints, particles, corrosion products, metal chips, scale, oil, grease, preservatives, adhesives, and any foreign material.

   2) Visual inspection is performed with or without magnification with adequate vision and light conditions. Ultraviolet inspection, special lights and mirrors are considered aids to visual inspection.

   3) Components and cleaning materials shall only be handled with gloves.

   4) Cell to cell and cell to case junctions are sealed with insulation material. The packaging material in contact with the cell or battery is sterile or thoroughly cleaned with IPA prior to use.[2]

e) At all times, cells and batteries shall be maintained within a controlled temperature and humidity environment to maximize battery life and prevent water condensation.[1]

   High temperature of high humidity causes deterioration of the battery performance and/or surface corrosion.[10]

   General cleanliness and contamination control requirements shall be addressed during the manufacturing and testing of flight batteries. In addition, special precautions shall be taken during final assembly to limit the numbers of trapped micro debris in the battery.

f) When not in use, batteries shall be placed in cold storage, whenever practicable, at an appropriate SOC in accordance to the handbook procedure delivered by the supplier.[1]

g) If needed, an electrostatic discharge (ESD) control program shall be implemented to protect ESD sensitive hardware on the battery as specified in MIL-STD-1686.9.

h) Preventing method for unexpected discharge.

   An external battery connector shall be constructed to prevent inadvertent short circuiting of its terminals. Examples of methods to prevent inadvertent short-circuiting include recessing the terminals, providing circuitry that prevents inadvertent short circuiting, providing covers over the terminals, use of keyed connectors, and the like.

Insulating material for external battery connectors, outside the enclosure, shall have an adequate flame rating. External connectors forming part of the fire enclosure shall be minimized.

For partially used batteries intended for reuse and batteries awaiting disposal, protect battery connectors or terminals from inadvertent short circuits. Examples of protection methods include use of non-conductive tape, terminal plugs, or individual plastic bags.[8]

6.3.3 Safety measure for handling

The following are requirements for safe handling of lithium batteries:

See Annex D.

6.3.4 Transportation

Common items to be considered are described in Annex E.

7 Battery onboard space vehicle

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

When the batteries have the enough power reserve margins and the degradation during the system integration and test shall be estimated as negligible or acceptable level, program management shall give the priority to evaluate the workmanship of space vehicle system, installed the flight battery.

On the other hand, 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 for non-operational tests.

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.

This Clause describes the case that the flight batteries shall be installed in the space vehicle before it is transported to the launch site.

7.1 Performance

7.1.1 Purpose

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

7.1.2 Basic performance

— **Variation between battery modules**

In case of equipped more than one battery, the variations of some parameters shall be considered and appropriately managed to maximize battery performance in orbit.

Actual capacity, impedance, heat generation, or EODV shall be different by manufacturing variations.

— **Reference point of thermal control on battery module**

Typically, thermal reference point in the battery used to be set on the representative surface of cell directly or around the battery base plate.

When in case that the reference point of thermal control of the battery set on the cell surface, it is preferred to precise control directly as a cell temperature. Instead, the case that the reference point shall be near the fixation point of battery panel, it is easy to interface to thermal control subsystems just as an interface temperature.

The decision criteria exists in the program situation how much accurate to control the battery temperature and heat dissipation characteristics of the battery.

7.1.3 Design requirement

— **Electrical ground bonding**

To avoid the potential float, the battery used to be electrically bonded to the space vehicle body through the battery case. However, outer surface of the battery case shall be insulated to prevent outer short circuit. Information of specifications for ground bonding is recommended to be confirmed and shared early in the battery designing phase.

— **Temperature reference point of battery module**

As described in 7.1.2, temperature reference point of the battery shall set on the surface of the cell directly or on the base plate according to the battery thermal characteristics and demand of thermal control subsystem.

7.1.4 Preparation for handling, transportation

During storage and handling, voltage monitoring and periodic recharge, cell rebalancing shall 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.

The maximum allowed self-discharge rate for cells and batteries during storage shall be specified. Cells or batteries exhibiting excessive self-discharge rates indicate degradation.[1]

Records

Records documenting the flight accreditation status of batteries shall be maintained at minimum up to the launch date and for the entire satellite and other spacecraft life. These records shall provide traceability from production of the battery, through final installation in the vehicle, and on through to launch.

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

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.

Satellite and other spacecraft operator shall inform battery manufacturer of the satellite and other spacecraft's end of life.

7.2 Safety

7.2.1 Purpose

Battery supplier shall ensure the safety of personnel and hardware throughout all phases of battery development, fabrication, assembly, testing, handling, storage and transportation.[16]

All precautionary measures to prevent the inadvertent venting of an individual cell or assembled combination of cells shall be identified and implemented.

Potentially hazardous conditions, as well as hazardous procedures, shall be identified in a manner easily observed by personnel.

7.2.2 Definitions of dangerous phenomenon

Hazard description

This subclause identifies the hazardous event when battery shall installed onboard into space vehicle (see Annex C).

Hazardous event which are the subject of this International Standard are as follows:[9][14]

a) fire;

b) burst/explosion;

c) leakage of cell electrolyte;

d) venting;

e) burns form excessively high external temperatures;

f) rupture of battery case with exposure of internal components;

g) smoke.

7.2.3 Technical requirement

Battery shall be designed to reduce risks through cell life cycle, in accordance with battery development risk assessment. Moreover, reliable protective equipments and devices shall prevent foreseeable incidents effectively. The remaining risk shall be clearly identified and informed in the handling manual or directly cautioned by effective markings or labels on the battery case.

7.3 Logistics

7.3.1 Purpose

The requirements set forth in this subclause apply to the handling, storage, and maintenance of batteries during ground activities preceding pre-launch activities. These requirements shall be defined in the battery specification and/or storage and handling procedure so as to minimize pre-flight degradation and hazard risk.[1]

7.3.2 Safety measure for handling

Common items to be considered are described in Annex D.

7.3.3 Integration to the space vehicle

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 remains in place for some or all of the vehicle launch preparation but shall be removed prior to launch.

As needed to assist in installation or general battery handling operations, a handling device (frame or similar structural support) shall be used after the battery is assembled and prior to installation of the battery on the vehicle.

The handling device shall protect from damaging the battery and any other structural or thermal interface of the battery with the vehicle.

The handling plate shall be removed when the battery is installed on the vehicle.

An easily attachable and removable non-conducting cover shall protect the battery's terminals and connectors to the vehicle wiring harness after its assembly until just prior to its installation on the vehicle.

Optionally, the cover remains in place for some or all of the vehicle launch preparation but shall be removed prior to launch.

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

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 cell balancing circuit, heaters, and any inhibit circuits.

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.

Pass/fail criteria for battery SOC, 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 shall vary at different phases prior to launch.

Battery monitoring and handling shall be conducted in a manner that complies with vehicle, facility, and range safety requirements.[1][5]

7.3.4 Battery maintenance on the space vehicle

Battery maintenance procedures shall be in place that allow for periodic maintenance of battery SOC, 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.

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 shall discharge the battery or individual cells at specified control rates.

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

Battery monitoring and cycling shall be conducted in a manner that complies with vehicle, facility, and range safety requirements.

7.3.5 Battery transportation equipped in space vehicle

Common items to be considered for transportation throughout the life cycle are described in Annex E.

Items in descriptions are shipper's responsibility, packing instructions, label and marking, and relevant regulations per transportation mode.

8 Launch site

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

When the batteries have the enough power reserve margins and the degradation during the system integration and test shall be estimated as negligible or acceptable level, program management shall give the priority to evaluate the workmanship of space vehicle system, including the flight battery.

On the other hand, 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 for non-operational tests.

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.

This Clause describes the case that the flight batteries shall be transported separately and installed at the launch site.

All the activities at launch site are strictly controlled by system safety program of the range authority. Therefore, the descriptions in this Clause are the general consideration from engineering stand point and the applicable range safety document shall have priority.

8.1 Performance

8.1.1 Purpose

The requirements set forth in this subclause apply to check-out, performance verification of flight batteries prior to installation on spacecraft.

Battery testing shall condition flight hardware to produce acceptable electrical performance as a health check after transportation.[1]

8.1.2 Degradation calculation in launch site

At the launch site, most of the sequence shall be dedicated to the launch preparations of space vehicle. Therefore, the batteries onboard vehicle shall be sustained as a floating charge condition near the fully charge situation at room temperature, approximately a couple of month.

Since the battery capacity/energy slightly degrades by their condition, battery engineer shall reflect such condition into the life estimation and inform space vehicle system appropriately.

These data, together with life test, shall be summarized, trended, and evaluated to provide performance trends and be a basis for on-orbit operations.

8.2 Safety

8.2.1 Purpose

Battery supplier shall ensure the safety of personnel and hardware throughout all the phases in launch site.

All precautionary measures to prevent the inadvertent venting of an individual cell or assembled combination of cells shall be identified and implemented.

Potentially hazardous conditions, as well as hazardous procedures, shall be identified in a manner easily observed by personnel.

The battery safety control program and procedures shall be approved by the range authority.

8.2.2 Definitions of dangerous phenomenon

Typical concerning points are the same as battery (see 6.2.2).

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.

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

8.3 Logistics

8.3.1 Purpose

The requirements set forth in this subclause apply to the handling, storage, maintenance and transportation of batteries during ground activities preceding pre-launch activities.

These requirements shall be defined in the battery specification and/or storage and handling procedure so as to minimize pre-flight degradation. Storage, handling, and maintenance methods shall be in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware.[1]

Rough handling results in batteries being short-circuited or damaged. This causes leakage, rupture, explosion and/or fire.[10]

Regulations concerning international transport of lithium ion batteries or cells are based on the recommendation of the United Nations Committee of Experts on the Transport of Dangerous Goods. Each country or region's law or regulations and/or directives follows.

Therefore, prior to the transportation, the latest editions of these regulations shall be consulted.[10]

8.3.2 Safety measure for handling

Common items to be considered are described in Annex D.

As a safety feature, devices shall be incorporated into the design of battery conditioning modules to accommodate the discharge of the battery at any SOC without causing any damage to the battery, including the prevention of any battery cell voltage from exceeding upper or lower voltage limits.[1]

8.3.3 Preparation for transportation

Flight batteries shall be installed in the vehicle before it is transported to the launch site or transported separately and installed at the launch site.

The battery SOC shall be set at an appropriate level to minimize degradation during transportation. Approximately less than 50 % SOC shall be recommended.

Individual cell voltage shall be verified to be within the cell-balanced voltage criteria, if connector is available. Cell rebalancing shall be performed as required.

The battery shall be transported in a qualified shipping container 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 and or recorders.

Batteries shall be maintained between −10 °C and +25 °C, if it is practicable to do so, during handling, transportation, and installation.[1]

8.3.4 Battery testing (health checking after transportation)

Any GSE 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.

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.

Inspection

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

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.

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

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

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

State of health verification

The open-circuit voltage of every cell and/or cells pack shall be verified to be within the manufacturer's cell balanced requirements, as applicable. Cell rebalancing shall be performed as required.

At a minimum, one standard capacity measurement shall be performed on the flight battery, as feasible.

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.

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

Data shall be reviewed and trended with qualification or acceptance test data to verify that performance meets minimum BOL mission requirements.

8.3.5 Battery storage at launch site

When not in use, the batteries shall be placed in cold storage, whenever practicable, at an appropriate SOC.[1]

During storage and handling, voltage monitoring and periodic recharge, cell rebalancing, or reconditioning shall 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.

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

The maximum shelf life limit (cell activation through launch) shall be also defined for the battery that includes the maximum exposure time to ambient temperature conditions.

Records

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

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

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

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.

8.3.6 Integration to the space vehicle

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 remains in place for some or all of the vehicle launch preparation but shall be removed prior to launch.

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.

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

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 cell balancing circuit, heaters, and any inhibit circuits.

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.

Pass/fail criteria for battery SOC, 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 shall vary at different phases prior to launch.

Battery monitoring and handling shall be conducted in a manner that complies with vehicle, facility, and range safety requirements.

8.3.7 Battery monitoring preceding launch

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

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

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

9 Mission in orbit and end of life

In order to comply with ISO 24113, the main requirements for space vehicle having batteries and operations are as follows:

— performance monitoring during mission in orbit to be able to engage various kinds of operations while battery is capable of these operations before end of life;

— assessment of the risk of producing debris of batteries after end of life.

Annex A
(normative)

Parameter measurement tolerances

A.1 General

The overall accuracy of controlled or measured values, relative to the specified or actual parameters, shall be within these tolerances.

A.2 Measurement tolerances

a) ±5 mV for cell voltage/±0,5 % for battery voltage

b) ±1 % for current

c) ±3 °C for temperature

d) ±1 % for duration up to 1 h/±1 min for duration higher than 1 h

e) ±1 % for dimension

f) ±5 % vacuum pressure

g) ±5 % acceleration

h) ±2 % frequency vibration

These tolerances comprise the combined accuracy of the measuring instruments, the measurement use, and all other sources of error in the test procedure.[9]