International Standard

ISO 17546

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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Contents

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 document 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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This document was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

This second edition cancels and replaces the first edition (ISO 17546:2016), which has been technically revised.

The main changes are as follows:

— updated 5.4 and Annex F.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document has been developed for the purpose of establishing the standard to obtain sustainable development and to prevent incidents of lithium-ion battery for space vehicles.

Lithium-ion batteries belong to the category of rechargeable batteries which are based on electrochemical systems. The batteries generally consist of lithium metal oxide for positive electrodes and carbon for negative electrodes. Lithium element exists in an ionic or quasi-atomic form within a lattice structure of each electrode material.

For battery developers and spacecraft system architects, this document leads the way to assessing 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 to prevent lithium-ion batteries (LIB) for space vehicles from having performance defects in orbit and incidents through the life cycle. The total life cycle of lithium-ion batteries consists of material manufacturing to deorbit after mission completion as shown in Figure 1.

Since lithium-ion batteries start to deteriorate just after cell activation during cell manufacturing of stage 1, the service life starts at that point. And it continues through cell testing, cell transportation of stage 2, battery manufacturing/testing of stage 3, battery transportation of stage 4. Eventually, the service life is regarded defined as the duration until deorbit which corresponds to the end of life of stage 9.

Clauses in this document address “performance”, “safety” and “logistics” according to each stage of the life cycle, and each requirement belongs to the shelf life of lithium-ion batteries. The shelf life means from cell activation to launch and does not exceed the shelf life limit. A battery whose shelf life exceeds the shelf life limit is judged to be non-conforming even if it is not used because the battery capacity is insufficient for the mission completion. In other words, the shell life is the period until launch while maintaining the battery capacity to complete required missions.

— Performance

Since LIB starts to degrade from activation, it is necessary to consider meeting the power requirement through the mission life; that is, to be unaffected from handling conditions (temperature) and usage conditions in orbit (temperature, cycle, current or power and depth of discharge). Also, the risk in orbit can be mitigated based on the life estimation; and with care unexpected degradation can be avoided throughout the whole life cycle.

— Safety

A complex risk assessment process that is easy to understand is established. The method was agreed internationally at ISO/IEC and is a traditional method for space use. LIB keeps 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 over-charge. The important thing is that the process, which can result in a hazardous situation, does not always immediately result in an incident. Because of these risks, LIB is considered hazardous at all times. The risk assessment becomes very important to cover a variety of environments during the handling or use and history of stress.

— Logistics

The most important aspect of assuring battery safety and space quality in transportation is to perform a life cycle assessment of performance and safety from a broad perspective.

Critical damage includes, for example, the temperature history (especially high uncontrolled temperature outdoors), shock/vibration, and electrical shorts. Also, to reflect the results of handling or usage, the measurement should be done. All the personnel with responsibilities for the development, design, and handling should survey and estimate the influence of their assessment spontaneously to improve the sustainable development of the space component.

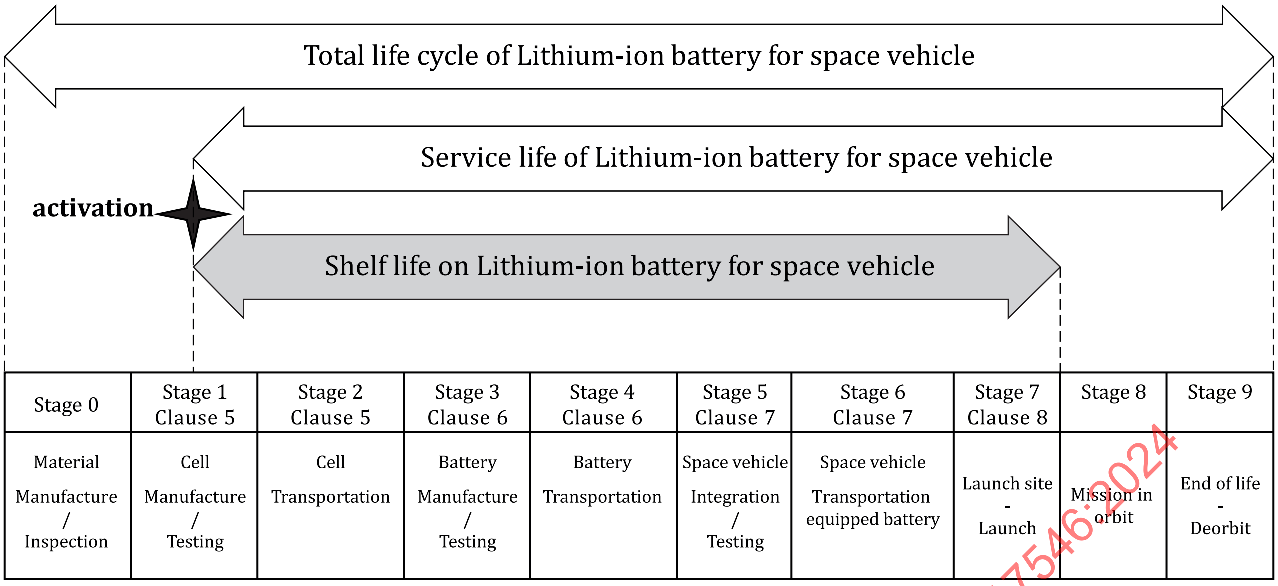

Figure 1 — Definition of life cycle stages of lithium-ion battery for space vehicle

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

1 Scope

This document specifies design and minimum verification requirements for lithium-ion batteries from the perspectives of performance, safety and logistics.

This document is applicable to battery assemblies for space vehicles and component cells of batteries, which are critical devices to be harmonized with standards and regulations for other industries. In addition, this document is applicable to component cells which are not designed for space vehicles but can be used in space.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. 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*

MIL-STD-1686, *ELECTROSTATIC DISCHARGE CONTROL PROGRAM FOR PROTECTION OF ELECTRICAL AND ELECTRONIC PARTS, ASSEMBLIES AND EQUIPMENT (EXCLUDING ELECTRICALLY INITIATED EXPLOSIVE DEVICES)*

3 Terms and definitions

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— IEC Electropedia: available at https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
activation
process of making an assembled *cell* (3.4) functional, by introducing an electrolyte at the manufacturing facility during cell production, which is used to define the start of *battery* (3.3) shelf *life* (3.19)

Note 1 to entry: See References [4], [5], [6] and [11].

3.2
aging
permanent loss of capacity due to repeated cycling or passage of time from *activation* (3.1)

Note 1 to entry: See Reference [6].

3.3
battery
two or more *cells* (3.4) which are electrically connected together, fitted with devices necessary for use, for example, case, terminals, marking and *protective devices* (3.26)

Note 1 to entry: A single cell battery is considered a “cell”[9].

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[4][5].

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 document, treated as batteries[9].

3.4
cell
single encased electrochemical unit (one positive and one negative electrode) which exhibits a voltage differential across its two terminals

Note 1 to entry: See Reference [9].

3.5
COTS cell
cell (3.4) mass-produced for terrestrial use by third parties such as distributors

Note 1 to entry: COTS cells have various kinds of types, 26650, 21700,18650, 17670, 18500, 18350, 17500, 16340, 14500, 10440 of cylindrical shape identified by external dimensions, and rectangular shape in metallic container, and thin pouch type.

3.6
dangerous phenomenon
phenomenon where a *lithium-ion battery* (3.20) is damaged

EXAMPLE *fire* (3.10), bust/*explosion* (3.8), *leakage* (3.18) of *cell* (3.4) electrolyte, *venting* (3.34), burns from excessively high external temperatures, *rupture* (3.28) of battery case with exposure of internal components, and smokes

3.7
disassembly
vent (3.34) or *rupture* (3.28) where solid matter from any part of a *cell* (3.4) or *battery* (3.3) penetrates a wire mesh screen (annealed aluminium wire with a diameter of 0,25 mm and grid density of 6 wires per centimetre to 7 wires per centimetre) placed 25 cm away from the cell or battery

Note 1 to entry: See Reference [9].

3.8
explosion
condition that occurs when a *cell* (3.4) container or *battery* (3.3) case violently opens and major components are forcibly expelled and the cell or battery casing is torn or split

Note 1 to entry: See References [12] and [14].

3.9
external short circuit
direct connection between positive and negative terminals of a *cell* (3.4) or *battery* (3.3) that provides less than 0,1 Ω resistance path for current flow

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.

Note 2 to entry: See Reference [9].

3.10
fire
flames emitted from the test *cell* (3.4) or *battery* (3.3)

Note 1 to entry: See References [9] and [12].

3.11
out-gassing
evolution of gas from one or more of the electrodes in a *cell* (3.4)

Note 1 to entry: See Reference [6].

3.12
harm
physical injury or damage to the health of people or damage to property or the environment

3.13
hazard
potential source of *harm* (3.12)

Note 1 to entry: The term hazard is qualified in order to define its origin or the nature of the expected *harm* (3.12) (e.g. electric shock hazard, crushing hazard, cutting hazard, toxic hazard, *fire* (3.10) hazard, drowning hazard).

3.14
hermetic seal
permanent air-tight seal

Note 1 to entry: See Reference [10].

3.15
intercalation
process where lithium-ions are reversibly removed or inserted into a host material without causing significant structural change to that host

Note 1 to entry: See Reference [11].

3.16
intended use
use of a product, process or service in accordance with specifications, instructions and information provided by the supplier

Note 1 to entry: See Reference [12].

3.17
internal resistance
opposition to the flow of current within a *cell* (3.4) or a *battery* (3.3), that is, sum of electronic resistance and ionic resistance with the contribution to total effective resistance including inductive/capacitive properties

3.18
leakage
visible escape of electrolyte or other material from a *cell* (3.4) or *battery* (3.3) or the loss of material (except battery casing, handling devices or labels) from a cell or battery such that the loss of mass exceeds specific values

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

Table 1 — Mass loss limit

mass M of cell	mass loss limit
$M < 1$ g	0,5 %
1 g $\leq M \leq$ 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:

$$L_{mass} = \frac{M_1 - M_2}{M_1} \times 100$$

where M_1 is the mass before test; M_2 is the mass after test; and L_{mass} is lost mass (%).

When mass loss does not exceed the values in Table 1, it is considered as “no mass loss”[9].

3.19
life
duration of maintaining a required performance [e.g. 50 % of beginning of life (BOL) capacity], estimated in years (calendar life) or in the number of charge/discharge cycle

Note 1 to entry: See Reference [6].

3.20
lithium-ion battery
rechargeable electrochemical *cell* (3.4) or *battery* (3.3) in which the positive and negative electrodes are both *intercalation* (3.15) 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

Note 1 to entry: See Reference [9].

3.21
load profile
illustration of the power needed from a *battery* (3.3) to support a given system, which is usually expressed by graphing required current versus time

Note 1 to entry: See Reference [11].

3.22
lot
group of components produced in continuous and uninterrupted production run with no change in processes or drawings

Note 1 to entry: See Reference [5].

[SOURCE: ISO 26871:2020, 3.1.40, modified — The preferred term "batch" has been removed; the definition has been editorially improved; note 1 to entry has been added.]

3.23
open circuit voltage
voltage across a lithium-ion *cell* (3.4) or *battery* (3.3) with no-load and no current in external circuit

Note 1 to entry: See References [6] and [9].

3.24
over-charge
charge past the manufacture’s recommended limit of voltage

3.25
over-discharge
discharging a *cell* (3.4) or *battery* (3.3) past the point determined by the cell supplier where the full capacity has been obtained

3.26
protective device
device which interrupts the current flow, blocks the current flow in one direction or limits the current flow in an electrical circuit

EXAMPLE Fuses, by-pass, diodes and current limiters.

Note 1 to entry: See Reference [9].

3.27
reasonably foreseeable misuse
use of a product, process or service in the way which is not intended by the supplier but which results from a readily predictable human behaviour

Note 1 to entry: See Reference [12].

3.28
rupture
mechanical failure of a *cell* (3.4) container or *battery* (3.3) case induced by an internal or external cause, resulting in exposure or spillage but not ejection of solid materials

Note 1 to entry: See Reference [9].

3.29
self-discharge
phenomenon due to *leakage* (3.18) current in open circuit at *cell* (3.4) and/or *battery* (3.3) level

3.30
shelf life limit
maximum allowed *life* (3.19) time from *cell* (3.4) *activation* (3.1) to launch when the *battery* (3.3) capacity before launch, which is deteriorated due to both preliminary charge and discharge and storage damage depending on temperature, can certainly complete all of subsequent missions on orbit

Note 1 to entry: See References [4] and [5].

3.31
space quality
high reliability required for vehicles and equipment built for space use

3.32
tailoring
process by which individual requirements of specifications, standards and related documents are evaluated and made applicable to a specific project by selection and, in some exceptional cases, modification of existing or addition of new requirements

Note 1 to entry: See ISO 27025.

[SOURCE: ISO 10795:2019, 3.237, modified — Note 1 to entry has been added.]

3.33
thermal runaway
uncontrollable condition whereby a *cell* (3.4) or a *battery* (3.3) overheats and reaches very high temperatures in very short periods (seconds) through internal heat generation caused due to an internal short or due to an abusive condition

Note 1 to entry: See Reference [6].

3.34
vent
release of excessive internal pressure from a *cell* (3.4) or *battery* (3.3) in a manner intended by design to preclude *rupture* (3.28) or *disassembly* (3.7)

Note 1 to entry: See References [9], [11] and [12].

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
COTS	commercial off the shelf
DOD	depth of discharge [6]
EOCV	end of charge voltage [7]
EODV	end of discharge voltage [7]
EOL	end of life [7]
FMEA	failure modes, effective analysis [7]
FTA	fault tree analysis
GEO	geosynchronous earth orbit
GTO	geosynchronous transfer orbit [6]
GSE	ground support equipment
IPA	iso-propyl alcohol
LAT	lot acceptance test
LEO	low earth orbit
LIB	lithium-ion battery
V_{oc}	open circuit voltage [6]
PTC	positive temperature coefficient
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 General

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

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

The cell contained in a battery is 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, may be tailored from UN38.3 and IEC 62281.

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

5.1.2 Test requirements

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

The design and manufacturing procedure shall be verified through the qualification test and be guaranteed with its test report.

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

Acceptance testing for lithium-ion cells 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;

f) internal resistance.

Some environmental and safety device testing, such as vibration, extreme thermal cycling, CID/PTC testing, includes acceptance tests. In each testing, the criteria are specified by the battery or cell manufacturer.

5.1.3 Test data trending [4]

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 check

b) cycle testing, vibration

c) thermal cycling

d) X-ray

e) impedance

f) LAT

g) electrical wear-out cycling.

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

Users 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 or others as deemed appropriate for the specific hardware and application[5][15][16].

Recommended test items of the component cell qualification for the space vehicle are specified. Examples are 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 include, but are not limited to, those specified in 5.1.5 to 5.1.10.

5.1.5 Leakage (hermetic) test

Each cell is tested for leakage in cell/battery acceptance test.

Criteria: The maximum leakage rate shall be low enough so that at the end of life, the remaining amount of electrolyte inside the cells is still compatible with the required performances of the cell. For example, the maximum helium gas leakage equivalent rate should not exceed, for example, $1,0 \times 10^{-6}$ Pa·m^3/s for a cell.

5.1.6 Safety tests

Each cell type 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.

5.1.7 Thermal/thermal vacuum test [5]

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

5.1.8 Mechanical environmental test

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

Examples of mechanical environment level for cells are described in Tables 2 to 4.

Table 2 — Sine vibration (sweep rate: 2 octave/min)

Axis	Qualification	
	Frequency Hz	Amplitude Acceleration
All axis	5 to 22 22 to 100	20 mm (double) 20 (9,8 m/s^2)

Table 3 — Random vibration (duration: 180 s per each axis)

Axis	Frequency Hz	Level
cell Z axis along the length of cell	20 to 50 50 to 300 300 to 450 450 to 700 700 to 1 000 1 000 to 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
cell X and Y axes for rectangular shape cell R axis for cylindrical shape in the plane of cell cross section	20 to 50 50 to 100 100 to 150 150 to 250 250 to 284 284 to 500 500 to 783 783 to 1 000 1 000 to 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 -12,43 dB / oct 0,1 $(9,8\ m/s^2)^2$ / Hz -3 dB / oct
	overall	21,19 $(9,8\ m/s^2)$ rms

Table 4 — Shock (three times per axis)

Axis	Frequency Hz	Acceleration (× 9,8 m/s^2)
All axis	200 1 400 4 000	24 4 200 4 200

5.1.9 Radiation test

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

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

For lot acceptance: DOD 100 %

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

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

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

Standard capacity measurements are performed before the life test and every 100 cycles.

5.1.11 Models for analysis

The following information shall be clearly defined by the battery supplier based on the cell suppliers' information for the battery design evaluation, if available; and their information is provided to the battery assembler.

Models are 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 General

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

The safety tests that 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[5].

5.2.2 Hazard description

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

Potential hazards which are the subject of this document are as follows[12][17]:

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.

5.2.3 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 is implemented at module or battery level. Typical examples of the protective devices for hazard control are described as follows.

a) 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, thereby breaking or opening the circuit.[11] Latching current limiters (externally resettable) also may be protective devices instead of fuses.

b) Current interrupt device (CID)

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

c) Positive temperature coefficient (PTC) device

A polymeric or ceramic element which has a very low resistance and conducts electricity with very little loss until 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[11].

d) 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[11]. The fusible link melts at specific currents, which then inhibits any hazardous occurrences during an external short condition.

e) 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.

f) 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 is designed to 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. 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.

g) 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.

5.2.4 Safety testing

It is presupposed that a safety test is conducted to comply with the transport regulation as specified in 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 tests such as vibration and shock tests in UN38.3 are merged or involved as equivalent test condition. Since toxicology assessment and report (independent materials usage and toxicological memos) are required for the following stage of battery level or space vehicle safety evaluation, destructive physical analysis (DPA) with electrolyte analysis may be necessary for space use[15].

5.2.5 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 over-charge 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 shall 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 are monitored during the tests.

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

For protection, all the testing are conducted in a protected room separate from the observer[14].

a) T1 high altitude test

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

b) T2 thermal test

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

c) 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 the vibration test for space qualification is much severer. Therefore, the vibration test in UN38.3 may be merged with the qualification vibration test. The fatigue stress is appropriately considered to set the duration time.

In space use, the vibration test is also considered as a screening test for internal short circuit risk and shall be performed mainly at the battery configuration level using the satellite and other spacecraft environments taking into account the amplification factors[16].

d) T4 shock

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

e) 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).

f) 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 result in an internal short circuit. Test conditions are different according to 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.

g) 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.

5.2.6 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 pressure to maximum expected operating pressure (MEOP) ratio with a margin up to 3:1; and case burst pressure to vent pressure with a margin exceeding 3:1.

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

   1) Pressurize the cell cases to P_i MPa·G while P_i 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 P_v 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 is observed at 0,5 MPa or less. Operating pressure of rupture plates of P_v is more than 3,0 times of P_i respectively.

5.3 Logistics

5.3.1 General

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

These requirements are defined in the cell specification and/or storage and handling procedure so as to minimize pre-flight degradation. Storage, handling, and maintenance methods are in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware[4].

Rough handling results in cells being short-circuited or damaged. This causes leakage, rupture, explosion or fire[13].

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. It is presupposed that the latest editions of these regulations are consulted prior to the transportation[13].

Manufacturers of cells (and batteries) should 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[12].

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[4].

b) Cell storage, handling, and maintenance methods shall be in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware[4].

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

   Records are maintained that document the temperature exposure and periodic cell-level SOC of flight hardware[4].

   For extended storage, physical protections are granted[4].

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[5].

e) At all times, cells shall be maintained within a controlled temperature and humidity environment to maximize battery life and prevent water condensation[4].

   High temperature of high humidity causes deterioration of the battery performance and/or surface corrosion[13].

   General cleanliness and contamination control requirements are addressed during the manufacturing and testing of flight cells. In addition, special precautions are 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 a 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[4].

5.3.3 Safety measure for handling

Annex D shall be followed 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.

5.4 COTS cells for space use

5.4.1 General

Cells designed for space applications have a clear genealogy from development to qualification, so battery and spacecraft system manufacturers can be assured of the high quality and intended performance of the cells. On the other hand, COTS cells are generally superior to space cells in terms of mass, speed of performance improvement, and cost, but they were not necessarily developed for space applications. In addition, since these cells are mass-produced for consumer use, cell configuration control is not strict and traceability is low, making it difficult to guarantee the same quality as that of space-use products. In order to apply COTS cells with these superior characteristics to space applications, evaluation tests of lot integrity and mission environment compatibility is conducted to confirm the space quality level.

5.4.2 Safety requirements

The safety requirements for COTS cells in space applications are basically the same as those for space cells.

It is presupposed that safety tests are conducted to comply with the transport regulation as specified in UN38.3 as a cell level or a battery one.

When charging the battery at the launch site, a charging system with an over-charge prevention function shall be prepared and able to detect abnormalities before charging.

If customers of space program require higher safety than UN38.3 safety tests, additional test items and their criteria shall be determined with the customers.

5.4.3 Lot integrity assessment

In general, the traceability of COTS cells tends to be uncertain because of their continuous mass production by cell manufacturers. Then “cell lots" are only defined by the unit of sale. Besides, COTS cells do not have a fixed customer at the time of manufacture, so minor changes that occur in the constituent materials or manufacturing process are not reported. Therefore, based on the criteria required by the battery and spacecraft system manufacturer, the lot integrity shall be confirmed by evaluation tests of all cells assembled in the flight battery. The lot integrity is evaluated based on the test results of open circuit voltage (V_{oc}), mass, capacitance, DC resistance, and AC resistance, as illustrated in the flowchart in Annex F, or the inspection report submitted by the cell manufacturer. Cells that do not pass the Criteria are excluded and not used for flights. And if the number of excluded cells is greater than a predetermined percentage (exclusion rate), no flight cell is selected from that lot. The above criteria and exclusion rate may be values agreed upon by the battery and spacecraft system manufacturer with their customers.

5.4.4 Mission conformance test

These tests are to confirm that the COTS cells are compatible with the mission environmental conditions. The parameters of each test are determined by considering loading conditions, environmental conditions, and duration of use, and are selected to suit the specific mission environment. Any cell from the lot that has passed the integrity test shall be selected for the mission environmental conformance test.

5.4.5 Charge and discharge test

When cells charged according to specific mission environment conditions are discharged under the same conditions, the resulting as discharge voltage, capacity and power are evaluated to satisfy mission requirements. Charging conditions include ambient temperature, charging current, charging time, charging upper voltage limit, and charging stop conditions. Discharge conditions include ambient temperature, discharge current or power, discharge time, discharge lower limit voltage, and depth of discharge.

5.4.6 Thermal vacuum test

The thermal vacuum test is conducted to confirm the hermetic integrity of the cell when subjected to thermal stress under conditions that cover the temperature range expected for the mission. Thermal environment applicability is evaluated based on changes in capacity, discharge voltage, charge voltage, and internal resistance before and after the test, and loss of hermetic integrity is confirmed by detecting vaporized electrolyte coming out from inside the cell in a vacuum environment.

5.4.7 Mechanical environment test

Sinusoidal vibration, random vibration, and shock mechanical environment tests encompass the vibration and shock levels expected on the mission. The mechanical environment test levels are based on the values shown in Table 2, Table 3, and Table 4. The mechanical environment applicability is evaluated based on the changes in capacity, discharge voltage, charge voltage, and internal resistance before and after the tests.

5.4.8 Cycle life test

Charge-discharge cycle tests are conducted in the temperature environment expected for the mission. Charging is performed at a constant current charge followed by a constant voltage transition at the upper voltage limit specified by the manufacturer until a certain time elapses.

After charging, the cells are discharged at a constant current until the voltage reaches the lower discharge limit voltage. The above charge/discharge cycle is repeated until the number of cycles reaches a predictable number for mission completion. The durability of the cell and the possibility of completing the mission are evaluated based on the rate of capacity decrease, the decrease in discharge voltage, and the increase in internal resistance before and after the charge/discharge cycles.

5.4.9 Storage life test

Lithium-ion cells deteriorate even when stored without charging and discharging. The amount of degradation during storage is evaluated by placing the cell under a constant environmental temperature for a long period of time, using SOC as a parameter. The durability of the cells and the possibility of completing the mission are evaluated based on the rate of capacity loss before and after storage, the decrease in discharge voltage, and the increase in internal resistance.

6 Battery

6.1 Performance

6.1.1 General

This subclause describes the minimum items of performance to satisfy for the fundamental requirement for the LIB for the space vehicles, maintaining space quality.

6.1.2 *C*/*n* charge or discharge current (c-rate)[4][5][6]

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.

6.1.3 Cut-off voltage

Endpoint voltage as specified by the manufacturer in discharge sequence.

6.1.4 Cycle

One cycle is usually one sequence of fully charging and fully discharging a rechargeable cell or battery.[9] 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 includes rest periods[13].

6.1.5 Depth of discharge (DOD)[4][5][6][13]

DOD is defined as the ratio of discharge capacity to fully charge capacity, and there are two ways definition of DOD: one is based on the quantity of electricity (in ampere-hours) and the other is on the basis of energy (in watt-hours).

$$D_c = \frac{C_d}{C_f} \times 100 \quad \text{or} \quad D_e = \frac{E_d}{E_f} \times 100 \qquad (1)$$

where D_c, C_d, and C_f are DOD, discharge capacity and fully stored charge capacity based on quantity of electricity and where D_e, E_d, and E_f are DOD, discharge energy and fully stored charge energy based on energy.

NOTE For batteries that are sub-charged, i.e., not recharged to full energy, DOD is the percentage of energy expended in a discharge from the sub charged point. For example, a battery that is sub charged to 70 % SOC and then discharge down to 40 % SOC is considered to have cycled over 30 % of its energy and the DOD is 60 %.

6.1.6 End of charge voltage

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

6.1.7 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 is 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.

$$E_d = \int (I_d \times V_d) \cdot dt \qquad (2)$$

where E_d, I_d, and V_d mean discharge energy, discharge current and discharge cell voltage as a function of time

6.1.8 Energy density

Quantity of energy stored by a cell or a battery per unit weight or unit volume. Typical units include watthours per kilo-grams (Wh/kg) for specific energy, watt-hours per litre (Wh/l) for volumetric energy. To be most useful, energy density is measured at a specific discharge rate and temperature[11].

6.1.9 Energy reserve [4][5]

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.

6.1.10 Fully charged [9][13]

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

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

6.1.11 Nameplate capacity

Nameplate capacity (Ah) is defined by battery module supplier considering the nominal capacity and the minimum guaranteed capacity. Battery supplier informs the nameplate capacity with nominal capacity to their user and associated conditions for definition.

6.1.12 Nominal capacity

Nominal capacity is defined as standard method for capacity measurement which is described in this document (see 6.1.16).

6.1.13 Nameplate energy [5][12]

Nameplate energy (Wh) is defined by battery module supplier considering the nominal energy and the minimum guaranteed energy. Battery supplier informs the nameplate energy with nominal energy to their user and associated conditions for definition. Nameplate energy in the watt-hour rating is marked on the battery module as the product of Nameplate capacity of Nominal discharge voltage according to the United Nations recommendation.

NOTE Nominal voltage is measured and defined by battery supplier.

6.1.14 Nominal voltage [9]

Approximate value of the voltage used to designate or identify a cell or battery. Nominal voltage is 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 represents average discharge voltage obtained during the nominal capacity test.

6.1.15 State of charge

SOC is defined as the ratio of charge capacity to fully charge capacity, and there are two ways definition of SOC: one is based on the quantity of electricity (in ampere-hours) and the other is on the basis of energy (in watt-hours).

$$S_c = \frac{C_d}{C_f} \times 100 \quad \text{or} \quad S_e = \frac{E_d}{E_f} \times 100 \tag{3}$$

where S_c, C_d, and C_f are SOC, charge capacity and fully stored charge capacity based on quantity of electricity and where S_e, E_d, and E_f are SOC, charge energy and fully stored charge energy based on energy.

The available capacity in a cell or battery expressed as a percentage of rated capacity[6].

6.1.16 Standard method for capacity measurement

Standard capacity is measured according to the following protocol[15].

a) Preparation

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

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 the representative temperature becomes stable, perform charging protocol according to the battery suppliers' definition.

d) After the representative temperature becomes stable, perform discharge with applicable protocol until the defined voltage limit is reached.

e) The measured discharge capacity is recorded as the nominal capacity.

6.1.17 Battery internal resistance (ohmic)

This measurement is performed as required.

The internal resistance of each battery is 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 (e.g. constant current discharge with 30 s), then calculating the $\Delta V/\Delta I$ 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.

6.1.18 Battery impedance

This measurement is performed as required.

The impedance of each battery is 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).

6.1.19 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 is performed using real-time and/or accelerated conditions.

It is recommended to perform the 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 per day of eclipse simulation and 135 d of solstice with or without plasma propulsion peak simulation.

For accelerated conditions of GEO profile, the number of charge/discharge cycles is accelerated from 1 cycle per day in eclipse season to 2 cycles, and a sun light season of 135 days is reduced to few days, and capacity degradation during a sunlight season is estimated by another calendar life tests.

6.1.20 For GEO simulated

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

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

b) 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.

c) 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.

d) 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 are 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.

6.1.21 For LEO simulated

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

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

c) CC; discharge current 0,5 C.

Balancing system is also included to the test, if applicable.

Standard capacity measurements are performed before life test and every 3,000 cycles or less.

6.1.22 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 is derived from the mission profile.

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

6.1.23 Battery general requirements [5][11]

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 is usually different from that of the individual cells. The cells aren't manufactured identically and each can 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) influences the performance as it affects the environment and temperature of the individual cells[18][19].

6.1.24 Electrical design

The 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 electro magnetic interference and compatibility requirements for the application. The battery charge control is required for LIB to avoid the hazards associated with over-charge and is 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.

6.1.25 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.

6.1.26 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 maximum operating pressure.

6.1.27 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 over-charged, 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.

6.1.28 Marking

Batteries shall be marked with the watt- hour rating on the outside case.

Marking is confirmed according to each mode of transport regulations[9].

6.1.29 Cell matching

Cell matching shall be performed regardless of the kind of cell selected or the passing of qualification/ acceptance testing, if there is no cell-balancing system within the battery.

6.1.30 Polarization testing (optional)

The electrochemical activity of a cell shall be 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) 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.

In this way, the cell SOC remains approximately the same at the end of the test as it was at the beginning of the test. Preferred SOC are 25 %, 50 %, and 75 %.

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.

6.1.31 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.

6.1.32 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 allow the engineer to identify deviations in cell behaviour.

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

By analysing the plotted data, performance differences can be 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 is 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 are plotted using the same scale values.

— The resulting voltage *versus* time curve is 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.

6.1.33 Cell matching criteria

A document is written that defines the cell matching criteria for the flight lot and provides the data that support the selection of a specific criterion depending on the cell design and supplier.

The cell matching criteria for the flight battery are enveloped by the beginning-of-life performance of the qualification life test cells that utilize flight-like charge control for the 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.

6.1.34 Contamination control

At all times, the battery shall be maintained within a controlled temperature and humidity environment to maximize battery life and prevent water condensation[4].

High temperature of high humidity causes deterioration of the battery performance and/or surface corrosion[13].

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

6.1.35 Test data trending [4]

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.

6.1.36 Flight verification acceptance testing [5]

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

Off-gassing/out-gassing tests are 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.

6.1.37 Assurance of the life estimation [8]

The following are the recommended measure to establish the 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 is 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 includes 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 is based on data and analysis to be provided to and approved by customer.

6.1.38 Parameter measurement tolerances

Battery shall be manufactured under parameter measurement tolerances.

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

6.1.39 Battery testing [5][15]

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

6.1.40 Development testing [4][15]

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 is 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 is 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 testing is 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.

6.1.41 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) are characterized sufficiently for a flight-type battery to demonstrate a charge control design that satisfies the requirements for all vehicle operations, including sun periods and contingencies.

Charge control electronic designs are validated during the life cycle test.

6.1.42 Thermal control testing

Thermal testing of a battery is 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, are characterized sufficiently for a flight-type battery to demonstrate a thermal control design that satisfies 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) A thermal characterization test is 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 condition.

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

6.1.43 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 are conducted prior to first use to prevent inadvertent over-testing or under-testing, including avoidance of excessive cross axis response.

6.1.44 Qualification test [4]

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[18].

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

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

A qualification test specimen is exposed to all applicable environmental tests in the order of the qualification test plan.

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

6.1.46 In-process inspections and tests

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

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

6.1.47 Data collection and acquisition rates

In all instances, the numerical values for voltage, temperature, current, capacity, and resistance are 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 conformity with test requirements and performance specifications.

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

6.2 Safety

6.2.1 General

Battery supplier ensures 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 are identified and implemented.

Potentially hazardous conditions, as well as hazardous procedures, are 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 are designed and constructed so 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 experiences.

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

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

Typical hazardous situations caused by an LIB become common knowledge; however, the LIB design or interface is analysed specifically case by case, due to the differential system architecture, supply chain, or chemistry[12].

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 is prevented by design.

— Temperature increases in the cell or battery are controlled by the design, e.g. by limiting the current flow.

— Lithium cells and batteries are designed to relieve excessive internal pressure or to preclude a violent rupture under conditions of transport.

— Lithium cells and batteries are 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 are equipped with effective means to prevent dangerous reverse current flow (e.g. diodes, fuses)[13].

— Technical requirements for battery design and operations should be according to ISO 24113.

— 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

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

These hazards are the results of risk assessment and analysis.

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

Potential hazards which are the subject of this document are as follows[12][17]:

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 life cycle shall be conducted as earlier phase of development of LIB.

FMEA is 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 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 is selected.

6.2.4 Fault tolerance

The fault tolerance of the battery is 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.

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 counts as a hazard control, dependant on cell design, capacity, complexity, charging and application. A cell failure is counted as one of the failures[5].

6.2.5 Hazard controls [5]

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 includes assessment of the battery hazard controls.

6.2.6 Over-current prevention

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

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

If the battery is tapped to provide different output voltages, each tap is protected with an overcurrent device.

If for practical reason (such as accuracy of measurements, power efficiency or reliability concerns), fuses or other protection cannot be used, a strict quality control is enforced during handling and operation on the battery to avoid any risk of over-current.

6.2.7 Over-voltage protection

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

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

Protective function automatically works 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.

6.2.8 Temperature/current management

The design of batteries 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.

6.2.9 Insulation and wiring

The insulation resistance between the positive terminal and externally exposed metal surfaces of the battery excluding electrical contact surfaces are 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 is such that adequate clearances and creepage distances are maintained between connectors.

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

6.2.10 Positive protection against accidental shorting

When the battery is not installed in a 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 are selected to prevent accidental battery turn-on. Switching devices are not used in the ground leg(s).

6.2.11 Venting

The battery cases and cell shall incorporate a pressure relief mechanism or shall be so constructed that they can relieve excessive internal pressure at a value and rate that can 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 are 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 is not 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 is designed to prevent case rupture or undirected venting except in applications where venting of any kind is not permitted. Housing for a battery assembly has a functional vent mechanism to preclude rupture.

6.2.12 Crew touch temperature requirements

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

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

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

6.2.13 Terminal contacts

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

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

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

6.2.14 Safety testing

It is presupposed that a safety test is conducted to comply with the transport regulation as specified in UN38.3 or other regulations (e. g. ICAO etc.) prior to the international transportation as a battery level. The tests manual and criteria specify the purpose and test measures.

If safety tests cannot be performed at battery level, a justification file is approved by transport authorities involved in the battery transport. This justification file is supported by safety tests at cell level, qualification tests at battery level, tests and design analysis of the packaging, and any relevant analysis (such as venting and hazard analysis).

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

6.2.15 Important test considerations

Some lithium batteries can explode 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 shall 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 are 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)[14].

For protection, all the testing are conducted in a protected room separate from the observer[14].

a) T1 high altitude test

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

b) T2 thermal test

This test shall be conducted to evaluate the ability to withstand a foreseeable thermal environment from UN38.3 for transportation. This temperature range is not considered as an operating temperature range. For space vehicle use, since this temperature range is wider than qualification test, this thermal test is conducted separately from the qualification test.

c) T3 vibration

This test shall be conducted to evaluate the ability to withstand the vibration environment during transportation.

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

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

d) T4 shock

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

e) 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.

f) T7 over-charge [9]

Typical failures: charger failure; protective circuit board failure.

Battery level: verify protective feature for over-charge/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 are representative of flight hardware configuration. Batteries not equipped with over-charge 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 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 over-charge of the battery assembly.

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

6.2.16 Thermal runaway propagation

Thermal runaway, a catastrophic failure mode of cells, may be triggered in the intended application and environment by overcharging, external short circuits, internal short circuits, and excessively high temperatures. When thermal runaway is initiated in a cell in the battery, the large amount of heat generated propagates to adjacent cells (thermal runaway propagation), resulting in secondary or tertiary thermal runaway of the cells. Therefore, thermal runaway propagation tests shall be conducted in battery designs for manned spacecraft with high safety requirements to quantitatively confirm the thermal runaway characteristics of a single cell and the heat transfer characteristics of cell-to-cell between assembled cells. It is important to understand the heat transfer characteristics of the entire battery and to verify that the design does not go into catastrophic failure mode.

6.2.17 Special provision

a) smaller population [11]

A smaller population of test units is 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.

b) alternative test units

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

c) 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), are used for safety testing, Alternate allocations of test units are possible. For example, a short-circuit.

6.2.18 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 General

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

Storage, handling, and maintenance methods are in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware[4].

Rough handling results in batteries being short-circuited or damaged. This causes leakage, rupture, explosion and/or fire[13].

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. It is presupposed that the latest editions of these regulations are consulted prior to the transportation[13].

Manufacturers of batteries 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[12].

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[4].

b) Battery storage, handling, and maintenance methods shall be in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware[4].

c) The maximum shelf life limit (cell activation through launch) is 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[4].

   Speciality storage containers are used during extended storage to provide physical protection[4].

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 (V_{oc}) and cell isolation resistance[4].

   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 are 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[5].

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[4].

   High temperature of high humidity causes deterioration of the battery performance and/or surface corrosion[13].

General cleanliness and contamination control requirements are addressed during the manufacturing and testing of flight batteries. In addition, special precautions are 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[4].

g) If necessary, an electrostatic discharge (ESD) control program shall be implemented to protect ESD sensitive hardware on the battery as specified in MIL-STD-1686.

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, has an adequate flame rating. External connectors forming part of the fire enclosure are 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[11].

6.3.3 Safety measure for handling

Annex D shall be followed for safe handling of lithium batteries.

6.3.4 Transportation

Common items to be considered are described in Annex E.

7 Battery onboard space vehicle

7.1 Performance

7.1.1 General

Flight batteries are 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 can be estimated as negligible or acceptable level, program management gives 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 are not 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 are used for space vehicle level integration and acceptance testing.

This clause describes the case that the flight batteries are installed in the space vehicle before it is transported to the launch site.

7.1.2 Basic design

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 maintains flight hardware to produce acceptable electrical performance while minimizing degradation.

— Variation between battery modules

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

  Actual capacity, impedance, heat generation, or EODV are 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 is close to the fixation point of battery panel, it is easy to interface to thermal control subsystems just as an interface temperature.

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

7.1.3 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 should be confirmed and shared early in the battery designing phase.

7.1.4 Temperature reference point of battery module

As described in 7.1.2, the 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.

7.1.5 Preparation for handling, transportation

During storage and handling, voltage monitoring and periodic recharge, cell rebalancing lead to minimize degradation.

Battery maintenance procedures define appropriate maintenance methods, monitoring frequency, and appropriate voltage, current, and temperature limits that are 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[4].

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

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

Time-correlated records are 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 inform battery manufacturer of the satellite and other spacecraft's end of life.

7.2 Safety

7.2.1 General

Battery suppliers ensure the safety of personnel and hardware throughout all phases of battery development, fabrication, assembly, testing, handling, storage and transportation[19].

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

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

7.2.2 Definitions of dangerous phenomenon

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

Hazardous events which are the subject of this document are as follows[12][17]:

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 equipment and devices prevent foreseeable incidents effectively. The remaining risk is 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 General

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 are defined in the battery specification and/or storage and handling procedure so as to minimize pre-flight degradation and hazard risk[4].

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 is removed prior to launch.

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

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

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

An easily attachable and removable non-conducting cover can 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 vehicles launch preparation but is removed prior to launch.

The battery is 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 goes 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 are 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 are derived from prior development and qualification testing specific to the design and applied prior to and during the terminal countdown. These requirements vary at different phases prior to launch.

Battery monitoring and handling are conducted in a manner that complies with vehicle, facility, and range safety requirements[4][8].

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 frequencies are 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 is accomplished with a battery conditioning module that discharge the battery or individual cells at specified control rates.

As a safety feature, devices are 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 are 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

8.1 General

Flight batteries are 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 can be estimated as negligible or acceptable level, program management gives 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 are not 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 are used for space vehicle level integration and acceptance testing.

This clause describes the case that the flight batteries are 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 standing point and the applicable range safety document have priority.

8.2 Performance

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

Battery testing condition maintain flight hardware to produce acceptable electrical performance as a health check after transportation[4].

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

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

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

8.3 Safety

Battery suppliers 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 are identified and implemented.

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

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

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 are the basis for battery operations and controls at the launch site and while on orbit.

8.4 Logistics

8.4.1 General

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 are defined in the battery specification and/or storage and handling procedure so as to minimize pre-flight degradation. Storage, handling, and maintenance methods are in accordance with practices that minimize safety hazards to personnel, facilities, and flight hardware[4].

Rough handling results in batteries being short-circuited or damaged. This causes leakage, rupture, explosion and/or fire[13].

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.

It is presupposed that the latest editions of these regulations are consulted prior to the transportation[13].

8.4.2 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[4].

8.4.3 Preparation for transportation

Flight batteries are installed in the space vehicle before transportation to a launch site, otherwise transported separately and then installed to the space one there.

8.4.4 SOC level for transportation

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

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

8.4.5 Container for transportation

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

Batteries are preferably maintained between −10 °C and +25 °C, if practicable to do so, during handling, transportation, and installation[4].

8.4.6 Battery testing (health checking after transportation)

Every GSE which is used for monitoring, charging and discharging of batteries is designed with a level of safety features similar to a space vehicle.

Every equipment, software, and safety inhibit are checked out under maintenance 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 flight connectors.

The connector saver is confirmed to interface between flight battery connectors and cables of ground support equipment by mating test.

8.4.7 Inspection

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

The records for each flight battery are 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 is visually inspected for signs of handling damage or abuse.

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

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

8.4.8 State of health verification

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

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

Pulse load requirement for any mission is demonstrated. The capacity of the test is identical to a capacity performed in the acceptance test for flight or proto-flight battery.

The charge retention rate following at least a seven-day stand period is verified to be within requirement.

All the data are reviewed and trended with qualification or acceptance test data to verify that performance meets minimum BOL mission requirements.

8.4.9 Battery storage at launch site

Batteries shall be placed in cold storage, whenever practicable, at an appropriate SOC when not in use[4].

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

8.4.10 Self-discharge rate

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 (from cell activation to launch) is defined for the battery that includes the maximum exposure time to ambient temperature conditions.

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

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

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

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

8.4.11 Protection under integration

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 is removed prior to launch.

8.4.12 Handling plate

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

8.4.13 Electrical connection

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

8.4.14 Electrical checkout

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.

8.4.15 Battery monitoring

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 self-discharge. Pass/fail criteria for battery SOC, battery/cell voltage, and temperature are derived from prior development and qualification testing specific to the design and applied prior to and during the terminal countdown. These requirements vary at different phases prior to launch.

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

8.4.16 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 are evaluated to provide state-of-health verification of the electrical systems prior to launch.

Pass/fail criteria is 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

According to the requirement of ISO 24113 and subsidiary defined detail measure, as a part of disposal actions, space vehicles equipped with lithium-ion batteries are designed and shall be planned to be operated as follows.

a) As a minimum, but not limited to, the component cell-voltages and temperature(s) shall be monitored in orbit to ensure the battery condition. disposal execution before end of life.

b) Assess the risk of producing debris caused by residual stored energy in the battery after disposal execution of spacecraft.

c) Batteries shall be passivated by control the state of charge to mitigate accidental break-ups risk after disposal execution of spacecraft. Discharge operation with electrical power consumption, self-discharge phenomena in battery cells, abandon charge operation after deep discharge by power consumption, and/or vent plug on the cell container or battery case are all effective measures.

NOTE All the lithium-ion batteries do not vent to break-up in any circumstances under 30 % state of charge. Some types of battery cell have higher SOC criteria of 50 %.

d) At the end of operations, battery charging shall not be possible.

Annex A
(informative)

Parameter measurement tolerances

A.1 General

The overall accuracy of controlled or measured values, relative to the specified or actual parameters, should be within the tolerances in A.2.

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[12].

Annex B
(informative)

Example of cell qualification test

B.1 General

This annex describes the example of qualification test for the cell that intends to apply to the space vehicle battery (See Figure B.1). The qualification program is adapted to cell design and size.