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Space engineering

Li-ion battery testing handbook

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
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Foreword

This Handbook is one document of the series of ECSS Documents intended to be used as supporting material for ECSS Standards in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards.

The material in this Handbook is defined in terms of description and recommendation how to organize and perform the work of lithium-ion battery testing.

This handbook has been prepared by the ECSS-E-HB-20-02A Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

Disclaimer

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Introduction

Energy storage is required aboard almost all spacecraft. Batteries are the most common energy storage device. Batteries provide electrical power when power from solar arrays is temporarily unavailable or insufficient due to eclipses, payload peak loads, before solar panels are deployed or in case of emergencies or special manoeuvres. Batteries are tested in order to assess their performance and their suitability to meet mission requirements. This issue of the document does not include the battery management subsystem testing.

In order for a new cell or battery system to be accepted for a spacecraft mission, it is essential not only to have hardware which is qualified for a good beginning of life performance but also to have hardware whose performance changes with cycle life are well understood and predictable by appropriate models. For this reason the availability of comprehensive test data is very important.

The present handbook aims at providing practical and helpful guidelines for Li-ion cell and battery testing (testing conditions, required information, reporting) during the development and qualification of space equipment and systems. This document has been derived from requirements from ECSS-E-ST-20C and its purpose is to support the use of ECSS-E-ST-20C.

This Handbook gathers battery testing experience, know-how and lessons-learnt from the European Space Community.

1 Scope

This Handbook establishes support the testing of Li-ion battery and associated generation of test related documentation.

This handbook sets out to:

- summarize most relevant characterisation tests
- provide guidelines for Li-ion battery testing
- provide guidelines for documentation associated with Li-ion cell or battery testing
- give an overview of appropriate test methods
- provide best practices

2 References

ECSS-S-ST-00-01C	ECSS System - Glossary of terms
ECSS-E-ST-10-03C	Space engineering - Testing
ECSS-E-ST-10-04C	Space engineering - Space environment
ECSS-E-ST-20C	Space engineering - Electrical and electronic
ECSS-Q-ST-20-08C	Space product assurance - Storage, handling and transportation of space hardware
ECSS-Q-ST-70-02C	Space product assurance - Thermal vacuum outgassing test for the screening of space materials
IEC 62281 2013-08	Safety of primary and secondary lithium cells and batteries during transport
ST/SG/AC.10/11/rev5	United Nations Transport of Dangerous Goods UN manual of Tests and Criteria, Part III, subsection 38.3
JSC-20793 Rev.B April 2006	Crewed Space Vehicle Battery Safety Requirements

3 Terms, definitions and abbreviated terms

3.1 Terms from other documents

For the purpose of this document, the terms and definitions from ECSS-S-ST-00-01 apply, in particular for the following terms:

acceptance	**lot**	**quality control**
applicable document	**model**	**reliability**
assembly	**nonconformance**	**requirement**
bakeout	**outgassing**	**review**
calibration	**procedure**	**safety**
catastrophic	**process**	**specification**
environment	**product assurance**	**standard**
failure	**project**	**supplier**
handbook	**qualification**	**traceability**
hazard	**quality**	**validation**
inspection	**quality assurance**	**verification**

3.2 Terms specific to the present document

3.2.1 accelerated test

test designed to shorten cycle life test to estimate the average cell or battery lifetime at normal operating conditions

NOTE Temperature, SoC, cycle profile are sources of test acceleration.

3.2.2 activation

introduction of electrolyte in an assembled cell at the manufacturing facility during production

NOTE This is used to define the start of the cell shelf-life. The formation process is also part of the activation.

3.2.3 aging

permanent change in characteristics and performance due to repeated use or the passage of time

NOTE Permanent changes include loss of capacity and energy, increase in resistance.

3.2.4 battery

one or more cells (or modules) electrically connected to provide the required operating voltage, current and energy storage levels

3.2.5 battery management subsystem

electronics circuitry preventing cell or battery operation outside of specified voltage, current and temperature ranges, and managing cell-to-cell unbalance

NOTE It also includes cell or module of cells bypass circuits when deemed necessary by FMECA outcomes.

3.2.6 calendar loss

permanent degradation of electrical performance due to time after activation

NOTE Reversible effects such as self-discharge are not included in the calendar loss.

3.2.7 capacity

amount of charge available expressed in ampere-hours (Ah)

NOTE 1 Cell or battery (Ah) = $\int I_d.dt$. It is the integral of the discharge current, between start of discharge and cut-off voltage or other specified voltage or specified duration.

NOTE 2 The capacity of a cell or battery is determined by a number of factors, including the cut-off voltage, discharge rate, temperature, method of charge (i.e. current, end-of-charge voltage) and the age and life history of the cell or battery.

3.2.8 capacity retention

fraction of the rated capacity available from a cell or battery under specified conditions of discharge after it has been stored for a certain time period at a specified temperature and state of charge in open circuit

3.2.9 cell can

cell packaging

3.2.10 cell building block or brick

sub-assembly unit, which consists of identical electrically connected cells

NOTE Building blocks (or bricks) are connected together to form a module or battery.

3.2.11 cell electromotive force

difference of potentials which exists between the two electrodes of opposite polarity in an electrochemical cell under open circuit steady state conditions

3.2.12 cell reversal

reverse polarity of a cell during discharge

3.2.13 cell terminal

electrical contacts to connect the cell

3.2.14 cell type

cell chemistry, cell size and cell can geometry

3.2.15 charge rate

amount of current applied to a cell or battery during the charge

NOTE This rate is commonly expressed as a fraction of the nameplate capacity of the battery. For example, C/2 or C/5.

3.2.16 cycle life

<CONTEXT: cell or battery> number of cycles under specified conditions, that a cell or battery can undergo before failing to meet its specified performance criteria

3.2.17 cycle loss

gradual and irreversible degradation of electrical performance due to electrical cycling

3.2.18 deperm

demagnetisation of battery

3.2.19 depth of discharge (DoD)

ampere–hour removed from a battery expressed as a percentage of the nameplate capacity whatever the initial state of charge

3.2.20 depth of discharged energy (DoDE)

Watt-hours removed from a cell or battery, expressed as a percentage of nameplate energy, whatever the initial state of charge

3.2.21 discharge rate

amount of current delivered by a cell or battery during the discharge

NOTE This rate is commonly expressed as a fraction of the nameplate capacity of the battery. For example, C/2 or C/5.

3.2.22 energy

watt-hours available when the battery that has been discharged from a specified end-of-charge voltage to a selected cut-off voltage, under specified conditions

NOTE 1 Cell or battery (Wh) = $\int IdVd.dt$. It is the integral of the product of discharge current and voltage. The limits of integration are the start of discharge and the cut-off voltage or other specified voltage.

NOTE 2 Typical conditions can include:

- Temperature and thermal control
- Charge and discharge profiles

NOTE 3 The SI unit for energy is joule (1J = 1 W.s), but in practice, battery energy is usually expressed in watthours (Wh) (1 Wh = 3600 J)

3.2.23 energy reserve

energy available in a cell or battery when discharged from the maximum DoD or voltage cut-off expected under nominal operation to the minimum end-of-discharge voltage

3.2.24 internal resistance

opposition to the flow of electric current within a cell or battery expressed as the sum of the ionic and ohmic resistances of the cell components

3.2.25 maximum charge current

maximum continuous DC charge current allowed by the cell manufacturer under specified conditions

NOTE Usually expressed as C rate.

3.2.26 maximum discharge current

maximum continuous DC discharge current allowed by the cell manufacturer under specified conditions

NOTE Usually expressed as C rate.

3.2.27 maximum end-of-charge voltage (EOCV)

voltage determined by the cell or battery manufacturer which expresses the highest voltage limit up to which the cell can be charged without causing a hazard

3.2.28 minimum end-of-discharge voltage (EODV)

voltage determined by the cell or battery manufacturer which expresses the lowest voltage limit down to which a cell can be discharged without causing a hazard

3.2.29 module

set of any number of identical cells, electrically connected

NOTE Modules are connected appropriately to form the battery. A module is a deliverable mechanically distinct item, as opposed to cell brick.

3.2.30 nameplate capacity

available ampere-hours (Ah) under conditions defined by the cell manufacturer

NOTE 1 These conditions include:

- nominal charge current, method, ambient temperature and duration
- nominal cut-off voltage
- nominal discharge current and ambient temperature

NOTE 2 The term “**nominal capacity**” is synonymous.

3.2.31 nameplate energy

available watt-hours (Ah) under conditions defined by the cell manufacturer

NOTE 1 These conditions include:

- nominal end-of-charge voltage
- nominal charge current, method, ambient temperature and duration
- nominal discharge current and ambient temperature
- nominal end-of-discharge voltage

NOTE 2 The term “**nominal energy**” is synonymous.

3.2.32 nominal capacity

see “**nameplate capacity**” 3.2.30

3.2.33 nominal energy

see “**nameplate capacity**” 3.2.31

3.2.34 nominal end-of-charge voltage

characteristic end-of-charge voltage specified by the cell or battery manufacturer

NOTE This parameter is used for nameplate capacity checks.

3.2.35 nominal end-of-discharge voltage

characteristic end-of-discharge voltage specified by the cell or battery manufacturer

NOTE This parameter is used for nameplate capacity checks.

3.2.36 nominal operating voltage range

characteristic operating voltage range of a cell or battery defined by the manufacturer

3.2.37 open-circuit voltage (OCV)

cell or battery voltage measured under 0 (zero) A condition

NOTE This voltage is often associated to the electromotive force (EMF) when reaching a steady state.

3.2.38 overcharge

cell or battery charged beyond the maximum end-of-charge voltage (EOCV)

3.2.39 overdischarge

cell or battery discharged below the minimum end-of-discharge voltage (EODV)

3.2.40 protective devices

devices which interrupt or reduce the current flow to the affected cell or string to prevent hazardous failure

NOTE Examples of protective devices are fuses, diodes, by-passes, pressure switches and hazardous limiters.

3.2.41 rated capacity

minimum capacity guaranteed by the battery manufacturer on delivery under specified conditions

NOTE As conditions specified by the cell manufacturer can differ from those specified by the battery manufacturer, the battery capacity specified by the battery manufacturer is used.

3.2.42 rated energy

minimum energy guaranteed by the battery manufacturer on delivery under specified conditions

3.2.43 self-discharge

reversible capacity decrease while no current is flowing to an outside circuit, due to internal chemical reactions

3.2.44 shelf-life

duration of storage from the date of activation, under specified conditions, at the end of which a cell or battery still retains the ability to give a specified performance

3.2.45 specific energy

energy available, expressed in Wh/kg, under specified conditions

NOTE 1 Specific conditions include temperature, charge and discharge rates, cut-off voltages.

NOTE 2 Gravimetric energy is synonymous.

3.2.46 state of charge (SoC)

available capacity of the cell or battery, expressed as a percentage of its capacity at that time, where the capacity is measured at a low current such that the terminal voltage approximates the EMF

NOTE This value can be derived from the Open Circuit Voltage of the cell or battery, following determination of the cell characteristic EMF versus SoC curve.

3.2.47 taper charge

charge method that reduces progressively the charging current as the cell or battery voltage is maintained at a constant value

3.2.48 terminal voltage

voltage measured between cell or battery terminals

3.2.49 test item

single cell, string of cells in series or parallel, module, building blocks or battery

3.2.50 venting

release of excessive internal pressure from a cell or battery in a manner intended by design to preclude rupture or disassembly

3.2.51 volumetric energy

energy available by volume unit under specified conditions

NOTE Expressed in Wh/l.

3.2.52 working voltage

typical voltage range of a battery

3.3 Abbreviated terms

For the purpose of this document, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	Meaning
AC	alternating current
AIT	assembly, integration and test
AITP	assembly, integration and test plan
BOL	beginning-of-life
CC	constant current
CDR	critical design review
COTS	commercial off-the-shelf
CV	constant voltage
DC	direct current
DoD	depth of discharge
DoDE	depth of discharge energy
DRD	document requirements definition
EMF	electromotive force
EOCV	end-of-charge voltage
EODV	end-of-discharge voltage
EOL	end-of-life
ESA	European Space Agency
GEO	geostationary orbit
LEO	low Earth orbit
Li-ion	Lithium-ion
OCV	open circuit voltage
SoC	state of charge
TPRO	test procedure
TSPE	test specification

4
Cell or battery testing

4.1 Introduction

Each cell or battery used in space application undertakes different tests i.e. acceptance, qualification. These tests are detailed with a supporting test plan, associated procedures (containing test criteria and test method) and test report.

A battery is made of electrically connected cells, strings or modules. Single cells are electrically connected to build a string of cells. The strings are then connected to form a building-block. The building blocks are further assembled to make a module. Then the modules are assembled in a battery. And the tests mentioned in this document are performed on different test items that can be either single cell, string, building-block, module or full battery. Few examples are given in the Figure 4-1 to Figure 4-4.

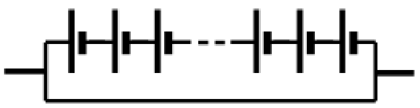

Figure 4-1: String of n cells connected in series (called n s 1p string)

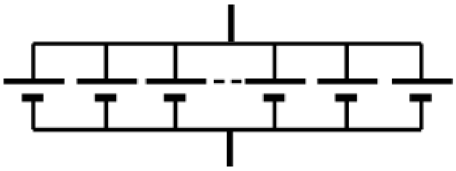

Figure 4-2: String of m cells connected in parallel (called a 1s m p string)

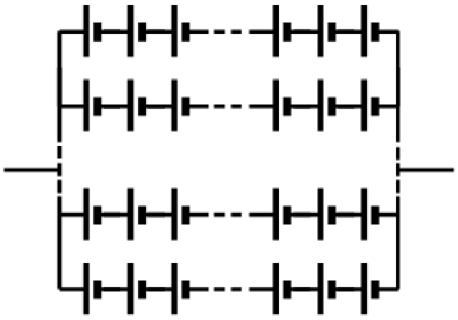

Figure 4-3: A module made of cells connected in series and parallel (n s m p module)

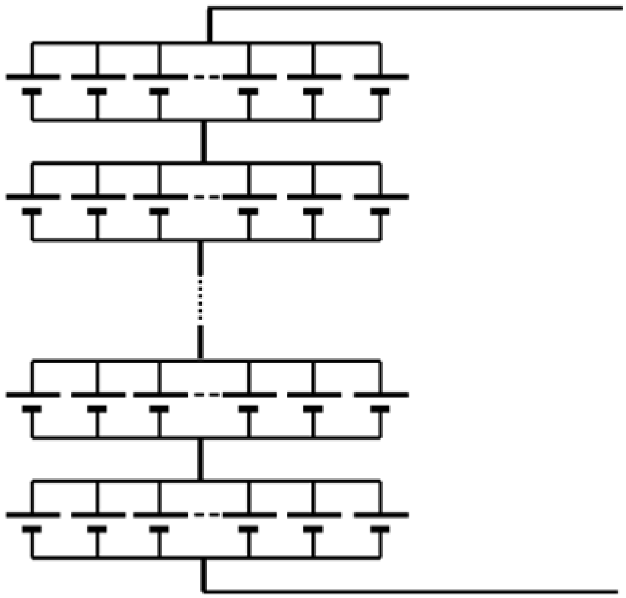

Figure 4-4: A module made of cells connected in parallel and series (n p m s module)

4.2 Test documentation

4.2.1 Test plan and test procedures

The Test plan (see Annex A) details the cell or battery characteristics under test, the test criteria and the test conditions.

The test procedure gives all test methods used and the different steps for the execution of the tests given in the plan to measure and validate the batteries or cell characteristics.

4.2.2 Test report

The tests items and test conditions are recalled in the test report. Test data and test data analysis are provided. All the NCRs related to test item and their disposition are also described in the report.

Individual test reports can be provided to cover the major test topics:

- Electrical tests
- Environmental tests
- Life tests
- Safety tests

For example in the environmental tests report, the test conditions together with specific details on the test set-up (i.e. connection, thermal control, equipment used, accelerometers type and location), the test data and the test data analysis are provided separately typically in the form of spreadsheets.

4.3 Tests

4.3.1 Initial electrical characterisation tests

The objectives of the initial cell or battery electrical characterisation tests are to:

- Establish the appropriate test parameters consistent with accepted technology limitations and requirements for the target application,
- Verify the initial capabilities of the life test cells.

4.3.2 Standard capacity and energy measurements

The objectives of the these tests are: to measure the capacity and energy of the test item under specific conditions in order to observe capacity and energy loss upon testing.

The capacity and energy measurements test, at a given temperature consist of a discharge to the nominal end-of-discharge voltage, followed by a recharge using the manufacturer's recommended procedure, and a constant current or power discharge at a specified rate to the manufacturer's recommended cut-off voltage.

The following information are detailed prior to the measurements:

- Charging protocol, e.g. Constant Current – Constant Voltage, Taper, Rest period conditions
- Charge current
- EOCV
- Taper charge conditions
- Discharge protocol (constant current or constant power)
- Discharge current or power
- EODV or specified cut-off voltage
- Temperature

Current, Voltage, Temperature are measured versus time and capacity and energy are calculated.

Temperature management and control are detailed in the test plan and test report.

4.3.3 Internal resistance measurement

The objectives of this test is to characterise the test item and to assess the evolution of the internal resistance upon cycling.

The impact of ionic and ohmic resistance can be evaluated by applying pulses during discharge (e.g. capacity check) or current interruption at several points along the discharge curve.

Using Ohm's law, the total cell internal resistance can be calculated by dividing the change in voltage by the change in current.

The measurement conditions are specified with the test results i.e.: SoC, temperature, charge and discharge current, pulse current, pulse duration, measurement time (or current interruption duration), sampling.

4.3.4 AC impedance measurement

The objective of the this test is to characterise the test item.

The AC impedance measurement gives a range of impedance value as a function of frequency (i.e. 0,01 kHz to 100 kHz).

The impedance is measured at a specified SOC and at a specified temperature.

4.3.5 Self-discharge test

The objective of this test is to assess the reversible and irreversible capacity losses, over a significant duration, as part of the qualification.

The self-discharge rate of cell or battery is evaluated by performing first a standard capacity measurement then by discharging the battery to a specific SoC, at a given temperature, and monitoring the cell open-circuit voltage for a long period (e.g. 30 days). After this rest period, the cell or battery is discharged to the nominal EODV, and a standard capacity measurement is performed again.

This test provides information on the self-discharge rate of the cell or battery and on the irreversible capacity loss.

4.3.6 Charge retention test

The objectives of this test is to measure the charge retention of a cell, for example as part of acceptance or state of health evaluation.

The charge retention is evaluated by stopping the cell or battery charge at a specific SoC, generally at ambient temperature, and monitoring the cell or battery open-circuit voltage evolution for a given period to be defined by the manufacturer - typically from few hours up to few days.

4.3.7 Cell rate capability

The objective of this test is to assess the impact of temperature and charge and discharge currents on the performance of a cell or battery.

Cell or battery rate capability is characterised by performing capacity measurements at different charge and discharge currents and different temperatures.

After stabilising the cell at a specified temperature, a residual discharge is performed. The cell is charged and discharged at a given rate, to cut-off voltages specified by the cell manufacturer. The same test, is repeated at different currents and temperatures.

4.3.8 Cell EMF measurement

The objective of this test is to characterise the cell.

The cell EMF measurement is obtained by a slow charge and discharge cycle at a given temperature.

After stabilising the temperature, a residual discharge is performed. Then the cell is charged at a low rate (C/50 or less) to maximum EOCV indicated by manufacturer, followed by a discharge at a low rate (C/50 or less) to minimum EODV indicated by the manufacturer. The measurements are taken at appropriate steps (i.e. x% capacity steps) and a relaxation time of at least 4 hours to 6 hours (x proposed: 5 %, 10%).

4.3.9 Battery magnetic moment measurement

The objective of this test is to measure the magnetic moment of a battery.

There are three components in the battery magnetic moment:

1. Static moment, which is inherent due to the presence of magnetic materials,
2. Dynamic moment due to the field induced by drawing power from the battery,
3. Induced magnetic moment under external field.

As a magnetic moment is a vector, the worst case magnetic moment occurs when all components act in the same direction and are superimposed.

For 1. the static moment is measured after the battery has been discharged at its maximum rate as the static moment will be then maximal.

For 2. the dynamic measurement is taken while the battery is discharged through a resistor at its maximum rate.

For 3. the battery magnetic moment is measured before deperm, when the battery is unpowered Then after applying a demagnetising field on each axis for a given time, the unpowered battery magnetic field is measured again.

4.3.10 Battery corona testing

The objective of this test is to verify the absence of Corona effect for high voltage battery.

For a high voltage battery (>200 V), a corona test is carried out.

The battery is placed in a vacuum chamber at 20 °C. A power supply is connected between the battery negative power connection and the ground reference point. The power supply is switched on and the pressure is decreased down to 10^{-3} mbar at a rate specified by the manufacturer and agreed by the customers specified rate.

The absence of arcing is shown by the absence of fluctuations of the power supply voltage throughout the all battery corona test.

4.4 Environmental tests

4.4.1 Objectives

The objectives of the environmental tests are to:

- Establish the technology limitations and verify the suitability of the cell or battery for the target application and mission,
- Verify the initial capabilities of the cells or module.

4.4.2 Mechanical tests: vibration (low level sine, random, sine) and shock

The objectives of the these tests are to validate the design and the manufacturing of the test item.

Mechanical environment tests are performed in accordance with the mission environmental profile.

The test item, i.e. cell, cell bricks or building block, battery module or battery is fully described in the test specification.

If single cells or cell building blocks are tested, they are installed in a jig mechanically representative of the cell and building block installation in the module or battery. The input levels are adapted to take into account possible amplification due to the module or battery packaging.

The cell or battery is tested in the 3 orthogonal axis at a specified SoC under load and for a specified duration.

Low level Sine vibration testing is performed before and after random vibration and shock tests.

The sequence of the tests, to be agreed by all involved parties, can be for example: low level sine → Sine → low level sine → random vibration → low level sine → shock → low level sine.

The test data collection: battery SoC, discharge or OCV, temperature, accelerometers location are detailed. The raw test data are provided to the customer.

4.4.3 Thermal vacuum test

The objectives of this test is to verify the cell or battery suitability under vacuum conditions at low and high temperatures.

The battery is subjected to a thermal vacuum test according to the mission profile.

In the test plan, the different temperatures are specified, the temperature increase or decrease rate, the dwell time between the temperatures and the number of cycles required. Table 4-1 provides a typical template for recording the test conditions.

Table 4-1: Thermal vacuum tests conditions

	Operational Temperatures		Non-operational Temperatures		Number of cycles	Dwell Time
	Minimum	Maximum	Minimum	Maximum		
Acceptance						
Qualification						
Tolerance						

The cell or battery charge and discharge cycling conditions are specified in accordance with the mission profile.

Bake-out of cells or batteries is not carried out as this can damage the test item.

NOTE For the majority of applications involves vacuum, however, for crewed mission, the test is performed at ambient pressure.

4.4.4 Leak test

The objective of this test is to verify the absence of cell electrolyte leakage under vacuum

Each cell and complete battery is placed in a vacuum chamber and exposed to a specified vacuum level in order to let it outgass (for outgassing see ECSS-Q-ST-70-02C) before starting the leak test. After this first step that eliminates gases coming from test item, the vacuum is lowered to 10^{-6} mbar (~ 10^{-6}

torr). The vacuum chamber can be equipped with a mass spectrometer to detect any chemical release from the cell or battery due to leak. If no mass spectrometer is used, the cells are wiped after vacuum with a pH paper to detect the leak of electrolyte.

4.4.5 Hermeticity test (Helium test)

The objective of this test is to measure the cell can hermeticity.

The hermeticity of the cell can is evaluated by a helium test.
Helium is injected into the cell can and the leak rate is measured. The leak rate test pass criteria is given as less than 10^{-5} mbar/l/s.

NOTE The "hermeticity test" is called "leak test" in ECSS-E-ST-10-03.

4.4.6 Radiation test

The objective of this test is to assess the impact of radiation on the test item.

The radiation tests are performed using a radiation dose enveloping all foreseen mission environments.

NOTE ECSS-E-ST-10-04 has further information on space environment.

The radiation test can be performed prior life tests or during life tests.

4.5 Life tests

4.5.1 Objectives

The objectives of the life tests are to:

- Establish the technology limitations and verify requirements for the target application,
- Establish long term performance and degradation factors to be applied for battery sizing and performance calculations

A fully representative life test is performed on the selected cell type. A sufficient number of cells is used to encompass design or process variability.

4.5.2 Calendar tests (survivability test)

In order to evaluate the irreversible capacity loss and internal resistance variation due to calendar effect, i.e. calendar loss, some calendar tests are performed.

The cells are stored at different temperatures and different SoC. Regular capacity checks are performed and results plotted to present the capacity loss trend.

4.5.3 Cycling tests

4.5.3.1 General

In order to evaluate the capacity loss due to cycling effect, i.e. cycle loss, cycling tests in different conditions are performed.

NOTE Different conditions of cycling tests can include temperature, discharge/charge rate, DoD, EOCV,EODV, charging conditions.

4.5.3.2 Constant DoD or DoDE

The objectives of these tests are to assess the test item degradation upon cycling.

For constant DoD or DoDE cycling test, the cell or battery is cycled at a specified temperature, to a given DoD or DoDE. The typical test steps are the following:

- Charge at a specified current for a specified duration to an EOCV defined by the battery supplier.
- Discharge at a specified current, to the desired DoD or DoDE.
- Standard capacity check performed before starting the test and repeated intermittently as deemed appropriate according to other test parameters.

4.5.3.3 Mission profile, including micro-cycling (ripple)

4.5.3.3.1 Parameters

For each mission profile, the following parameters are specified:

- Temperature and thermal environment (base plate, thermal chamber,
- Charge method and duration,
- Discharge method and duration,
- Regular standard capacity checks to assess the aging (capacity fade) trend.

4.5.3.3.2 GEO test profile

GEO profile can be simulated using period of 45 eclipses, and period of solstice. The GEO test can be accelerated by shortening this solstice period and reducing the charge period (by lowering the taper duration and increasing the charge current up to C/5).

- It is recommended to select a temperature representative of the thermal environment expected during the mission.
- Charge: constant current or constant power- constant voltage, with a charge current < C/5, to a specified EOCV, and a given duration.
- Discharge: Constant current or constant power, for different duration (the typical eclipses duration for a GEO profile is given in Table 4-2: there are a total of 45 cycles with longest eclipse of 72 minutes at cycle 23).
- Plasma Propulsion Simulation cycle can be added to the GEO profile.
- For the specified days in solstice use a constant voltage given by the battery supplier.
- The GEO life test can be performed with the battery management subsystem.

Standard capacity measurements are performed prior to starting the cycling and repeated regularly during the test e.g. every two seasons (actual/simulated).

Table 4-2: GEO eclipse cycles

Cycle number	Duration in minutes
1	21
2	29,37
3	35,55
4	40,58
5	44,82
6	48,5
7	51,72
8	54,58
9	57,13
10	59,4
11	61,42
12	63,23
13	64,84
14	66,26
15	67,5
16	68,58
17	69,51
18	70,26
19	70,9
20	71,38
21	71,73
22	71,93
23	72
24	71,93
25	71,73
26	71,38
27	70,9
28	70,28
29	69,51
30	68,58
31	67,5
32	66,26
33	64,84
34	63,23
35	61,42
36	59,4
37	57,13
38	54,58
39	51,72
40	48,5
41	44,82
42	40,58
43	35,55
44	29,37
45	21

4.5.3.3.3 LEO test profile

A LEO profile can be very different depending on the mission. Nevertheless, a generic real time LEO profile consists of repeating 90 minutes cycles as follows: 60 minutes charge and 30 minutes discharge.

- It is recommended to select a temperature profile representative of the thermal environment expected during the mission. The thermal control of the test sample is well detailed in the test plan.
- Charge: CC-CV at a specified current (with possibly ripple), for one hour to a specified EOCV.
- Discharge: CC at a specified current, or constant power for 30 minutes.

Standard capacity measurements are performed prior to and after the cycling test, and regularly during the test e.g. every few hundreds cycles.

4.5.3.4 Real time tests

The objectives of these tests are to assess the test item degradation due to charge-discharge cycling and to calendar effect.

The life tests is performed without any acceleration.

Charge and discharge profiles are fully representative of the mission requirements. Such approach has the advantage to assess the capacity loss due to cycling and the capacity loss due to the calendar effect.

For battery in orbit, the capacity available at EOL is used for DoD evaluation instead of nameplate capacity. The capacity used is then be clearly specified.

4.5.3.5 Accelerated tests

Mission duration can be long, typically 15 years for a GEO mission, 12 years for a LEO mission. Real time tests can be too long to qualify a cell type. Thus it can be necessary to perform accelerated tests and to extrapolate the capacity loss using models.

Tests can be accelerated by different methods: shortening solstice period, increasing charge and discharge rate, increasing the temperature.

The acceleration of the tests and its effect on the cell aging are assessed fully in order to avoid over-testing the cells.

4.5.3.6 Wear-out tests

The wear-out tests are short-duration life tests performed to verify the performance of cell lots to get confidence in the ability of the cell to fulfil the mission requirements, and to identify early on any issue due to materials or process change impacting performance.

Accelerated conditions are applied for such tests. The battery supplier proposes a wear-out test to demonstrate the performance of the cells to be used in their manufacture of the battery. Data from this wear-out test provides a trend analysis, with results being obtained for each of the different lots used.

Such wear-out tests are part of the Lot Acceptance Test (see test applicability matrix in clause 5).

4.6 Safety tests

4.6.1 Objectives

The objectives of these tests are to characterise the test item's safety protections.

The potential hazards of li-ion cell or battery are:

- Venting
- Fire
- Burst
- Explosion
- Electrolyte leakage.

Detailed descriptions of the hazards associated with different battery chemistry are given in reference document: Crew vehicle battery safety requirements, JSC-20793 Rev B April 06.

The objectives of the cell or battery safety tests are to:

- Establish the technology limitations,
- Verify the safety features at cell or battery level.

4.6.2 Overcharge

The objective of this test is to characterise the test item behaviour under overcharge conditions.

The cell or battery overcharge test is performed at ambient temperature (e.g. 20 °C). The cell or battery is charged to an EOCV greater than the EOCV recommended by the manufacturer, at a specified current. The cell or battery is maintained at the delta EOCV until a non-hazardous failure mode occurs (either disconnection or closed-circuit failure), such that further overcharge is either impossible or is not leading to hazardous events such fire or explosion.

Battery overcharge test depends on the battery design and a detailed test procedure is provided by the manufacturer.

4.6.3 Overdischarge

The objective of this test is to characterise the test item behaviour under overdischarge conditions.

The cell or battery overdischarge test is performed at ambient temperature (e.g. 20 °C). The cell or battery is discharged to a EODV lower than the EODV recommended by the manufacturer, at a specified current, without hazardous events occurring.

The cell can be forced to reversal to assess the cell behaviour in such conditions.

4.6.4 Short-circuit test

4.6.4.1 Objective

The objective of this test is to characterise the test item behaviour under short-circuit conditions.

4.6.4.2 External short-circuit

The cell or battery is tested for external short-circuit by applying a conducting path of sufficiently low resistance between the positive and the negative terminals to simulate an inadvertent short-circuit (e.g. accidental contact made with metallic tools). In the test the short circuit is maintained until the cell or battery can be demonstrated to be safe (e.g. cells without PTC discharge fully without a fire or explosion event). Test data includes the recording of the temperature, the voltage and the current. The maximum current under short conditions is measured.

In the event of a battery failure the test is deemed to be unsuccessful.

4.6.4.3 Internal short-circuit

This test is performed at cell level and is covered by the ST/SG/AC.10/11/rev5 United Nations Transport regulations. A crush or penetration test can be used to simulate an internal short.

4.6.5 Vent and burst tests

4.6.5.1 Objectives

The objectives of these tests are to measure the vent and burst pressure of the cell can.

These tests are performed using hydraulic oil or another incompressible fluid. Pressuring metallic containers with gas leads to very hazardous conditions on rupture (explosion with shrapnel).

NOTE There is no test performance loss through the use of hydraulic fluid for this test.

4.6.5.2 Vent test

An empty cell can, equipped with its safety vent, is pressurised with hydraulic oil or another incompressible fluid until the safety vent operates. This test gives the vent pressure of the can.

4.6.5.3 Burst test

The burst test is performed on empty cell cans where the vent mechanism is either not present or by some means disabled. The test is performed up to can burst and give the value of the can burst pressure.

The cell can is slowly pressurised by hydraulic oil (or another incompressible fluid) up to the point of can burst. Cell can is fitted with multiple distortion gauges when it is necessary to record the distortion at different locations.

4.6.6 Protective devices

The objectives of these tests are to characterise the protection devices of the test item.

The performance of protective devices included at cell or battery level is characterised by tests:

- Electrical fuse,
- Current Interrupt Device or Circuit breaker,

- Positive thermal coefficient (PTC) device,
- Vent,
- Shutdown separator,
- Thermal fuse,
- Bypass,
- Mosfet.

The protective devices are characterised in detail as they are part of the characteristics of the cells and ultimately of the battery.

4.7 Storage, handling, transport, AIT

4.7.1 General

Storage, handling and transportation is undertaken in compliance with requirements from the ECSS-Q-ST-20-08.

4.7.2 Storage and maintenance conditions

The cell or battery storage and maintenance conditions are detailed in the User Manual. The conditions specified minimize the irreversible capacity loss due to storage. The shelf-life of the cell or battery is indicated in the User Manual.

4.7.3 Handling

The battery handling methods are detailed in the User Manual to minimize safety hazards to personnel and facilities, and to ensure correct use of batteries under AIT.

4.7.4 Transport

Safety tests are performed prior to transportation as specified in ST/SG/AC.10/11/rev5 "United Nations Transport of Dangerous Goods UN manual of Tests and Criteria, Part III, subsection 38.3" regulation.

4.7.5 Assembly Integration Test (AIT)

During the AIT program, the use of the flight battery is minimized as specified in ECSS-E-ST-20C, clause 5.6.4.

At start of the AIT campaign, a battery health check (defined by spacecraft manufacturer and approved by battery manufacturer) or capacity check is performed. The same check is performed at the end of the AIT campaign. One of the two tests (health or capacity) are performed in order to evaluate the battery health status before and after the spacecraft test campaign. During AIT and storage phase, the OCV is checked regularly to ensure the battery performance prior integration and prevent need for further testing (such a restricted access to the battery).

5 Test applicability matrix

The Table 5-1 summarises the tests applicable to different phase of a programme: lot acceptance tests, acceptance and qualifications test.

Table 5-1: Test applicability matrix

Test	Cell			Battery	
	Lot acceptance	Acceptance	Qualification	Acceptance	Qualification
Standard capacity and/or energy measurements	x	x	x	x	x
Internal resistance measurement	x	x	x	x	x
AC impedance measurement	x		x		x
Self-discharge test	x		x		x
Charge retention test				x	x
Cell rate capability	x		x		
Cell EMF measurement	x		x		
Battery magnetic moment measurement					x
Battery corona test					x
Low level sine vibration test	x		x	x	x
High level sine vibration test			x		x
Random vibration test	x		x	x	x
Shock test	x		x		x
Thermal vacuum test	x		x	x	x
Leak test	x		x	x	x
Hermeticity test	x		x	x	x
Radiation test			x		
Calendar tests			x		
Real time cycling tests			x		x
Accelerated cycling tests			x		x
Wear-out cycling tests	x		x		
Overcharge test	x		x		x
Overdischarge test	x		x		x
Short-circuit test	x		x		x
Vent test	x		x		
Burst test	x		x		
Protective devices tests	x		x		x
Balancing system test		x	x	x	x

Annex A (informative) Test plan

The following content is an aid for implementing the test specification (TSPE), the test plan (AITP) and the test procedure (TPRO) reported as DRDs inside the ECSS-E-ST-10-03, for the case of Li-ion batteries and cells testing:

Cell or battery characteristics under test:

- nameplate and nominal capacity
- nominal EOCV, maximum EOCV
- nominal EODV, minimum EODV
- temperature range
- nominal voltage range
- specific and volumetric energy
- shelf-life
- mass
- dimension
- protective devices
- storage conditions
- maximum current pulses (amplitude and duration)
- balancing system
- voltage isolation
- thermostat

Test criteria:

- test duration
- frequency
- sinusoidal vibration amplitude input
- random vibration acceleration power spectral density (g2/Hz),
- shock levels
- radiation levels
- vacuum levels
- measurement accuracy of the voltage, current, temperature and time

Test conditions:

- temperature
- charge and discharge rate
- applied EOCV
- applied EODV
- constant current, constant power profile or other specific profiles
- taper condition
- connectivity
- voltage monitoring
- temperature monitoring
- temperature management and control
- sensors positions
- test equipment (e.g. accelerometers, measuring tools including calibration)

Specific to the life tests plan, the following aspects are detailed:

- the test items (i.e. cells, module or battery) description
- the test conditions
  - temperature
  - charge and discharge rate
  - EOCV
  - EODV
  - constant current or constant power profile
  - taper conditions
- description of the test set-up
  - connection
  - thermal control
  - equipment used