
**Space systems — Space batteries
— Guidelines for in-flight health
assessment of lithium-ion batteries**

*Systèmes spatiaux - Batteries spatiales - lignes directrices pour
l'évaluation en vol de la santé des batteries lithium-ion*

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Foreword

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

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

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.

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Introduction

The charge and discharge cycle of a battery is not 100 % efficient, with each cycle side reactions can occur that eventually accumulate and cause degradation of the battery's performance. Understanding how the battery's performance changes throughout the mission is a subject of importance; and accurate determination of the battery's current SoH is essential in a large number of situations, for example:

- the routine assessment of battery performance to allow early detection of anomalies (by comparing its actual versus predicted performance);
- the setting of alarm thresholds to ensure adequate energy;
- detection of battery anomalies that can put at risk the spacecraft passivation and/or de-orbiting strategy;
- decisions regarding mission extension beyond initial target life;
- evaluating the remaining capability of a spacecraft upon occurrence of an anomaly;
- feedback to the battery manufacturer to improve the performance predictions.

However, it is often difficult to properly assess the in-flight status, due to various factors:

- Flight electrical load profiles differ significantly to load profiles used to characterize battery performance models and the battery's SoH; for example, the total available battery capacity, which is the most important parameter, is not directly accessible during flight since its simple measurement by full discharge of the battery goes against the spacecraft operational safety.
- The quality of the accessible data from telemetry is sometimes poor: insufficient telemetry resolution and/or accuracy, lack of synchronization between related parameters like current and voltage, possibly large load consumption fluctuations introducing a high level of noise, delivery of data under a form not easy to process, etc.
- The battery is operating in flight in a way that is generally very different from the test conditions at qualification or acceptance. As a consequence, if no in-flight assessment has been made at the beginning of life, the direct comparison between current in-flight status and available ground testing data can be difficult and in any case more difficult than a comparison with the initial in-flight behaviour.
- The battery is operated under time variant conditions in a large bandwidth of different time scales, e.g. switching heater circuits vs. variations of the charge profile and eclipse length for a LEO satellite with drifting orbit. Low frequency variations introduced by drifting orbits or seasons are considered for the computation of trends and averaging over several orbits.
- The processing of data to derive the health status is not straightforward and is usually performed by identifying the ageing parameters of a model. Therefore, the representativeness of this model is a key issue. In addition, even with a good model, the results are not always satisfactory.

Therefore, it has been found of interest to provide detailed information about the means currently used or envisioned to perform in-flight battery health assessment and to make recommendations to spacecraft builders, operation managers and batteries manufacturers that would make it easier. This is the subject of this document.

It is important to highlight that, according to the definition given in [3.1.1](#), assessing the health status allows to verify that the battery behaves as well as or possibly better than anticipated. It is not aimed at providing an evaluation of any sort of "absolute ageing" nor to predict further evolution, even if this can be the case with some methods and their on-board implementation.

Space systems — Space batteries — Guidelines for in-flight health assessment of lithium-ion batteries

IMPORTANT — The electronic file of this document contains colours which are considered to be useful for the correct understanding of the document. Users should therefore consider printing this document using a colour printer.

1 Scope

This document provides detailed information on the various methods of assessing the health status of lithium-ion space batteries in flight and makes recommendations to battery suppliers, spacecraft manufacturers and operators to ease this assessment.

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 17546, *Space systems — Lithium ion battery for space vehicles — Design and verification requirements*

3 Terms, definitions and abbreviated terms

3.1 Term and definitions

For the purposes of this document, the terms and definitions given in ISO 17546 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:
<https://www.iso.org/obp>

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

— IEC Electropedia: available at <http://www.electropedia.org/>

3.1.1

battery health

state of the battery, which is healthy if both the amount and the rate of degradation of its performance are lower than or equal to the predicted ones at the same time into the mission

3.2 Abbreviated terms

ADC	analogue to digital converter
BoL	beginning of life
CC	constant current
CV	constant voltage
DoD	depth of discharge
EIS	electrochemical impedance spectroscopy
EMF	electro-motive force (a.k.a. open circuit voltage)

EoC	end of charge
EoCV	end of charge voltage
EoD	end of discharge
EoDV	end of discharge voltage
EoL	end of life
ESA	European Space Agency
GEO	geostationary earth orbit
LEO	low earth orbit
NCA	nickel cobalt aluminium (lithium-ion cathode composition)
NIBHM	non-Intrusive battery health monitoring
SoC	state of charge
SoH	state of health
RTL	round trip loss

4 Overview

4.1 General

The SoH of a battery reflects its capability to fulfil the needs of a mission, i.e. whether the performance is at or above the expected level. Typically, the performance itself covers requirements such as;

- a) the capability to deliver and absorb a certain amount of energy, under a certain load profile and with a defined voltage range;
- b) the capability to deliver a certain power for a given duration, while maintaining a certain voltage.

Theoretically, assessing this SoH can be conceived as the simply monitoring the battery behaviour (e.g. the battery voltage) in the orbit and comparing it against previously set baselines but, in reality, it is far less straightforward.

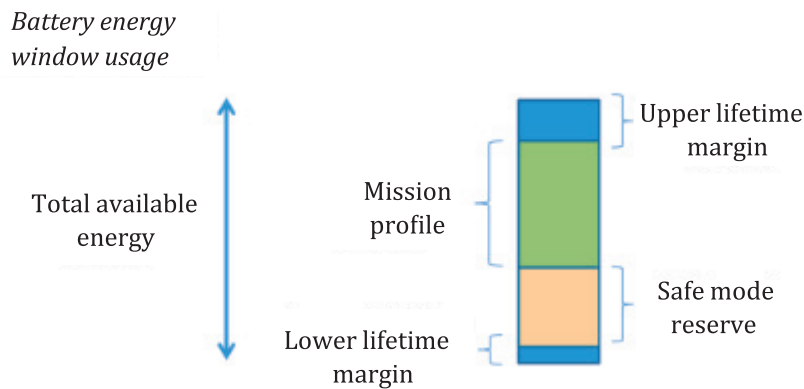


Figure 1 — Schematic of energy usage in satellite battery

As [Figure 1](#) shows, the deliverable energy a) of a battery is dependent on the mission phase and operational strategy. In many cases this not only shows characterizing the mission energy profile but also includes understanding the proportion of contingency energy, i.e. the energy needed to reach a safe mode, as part of the recovery of a major on-board failure. There is also some usable energy that will not be used at the extremes of SoC (to mitigate the accelerated lifetime degradation that occurs with repeated use of energy in these segment of the SoC window). As energy is not expected to be drawn from the contingency or protective margins of the battery in nominal operating conditions, observing energy in these segments is simply not possible during mission.

Pulsed power profiles in b) may occur for a duration too short to be captured by the telemetry. It is thus necessary to infer the health status from only the observable data, by estimating the value of the parameters driving the battery performance.

At a simplistic level, the capabilities of the battery can be expressed using the following fundamental formulae:

$$E = QV_N \quad (1)$$

where

E is the battery energy (Wh);

Q is the battery capacity (Ah);

V_N is the nominal voltage at which the charge is delivered (V).

$$V_T = V_{OCV} \pm IR \quad (2)$$

where

V_T is the terminal voltage (V); [ISO/TR 20891:2020](https://standards.iteh.ai/catalog/standards/iso/d47ea999-32ca-4ac3-b577-05b91ff896a9/iso-tr-20891-2020)

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V_{OCV} is the open circuit voltage of the battery (V);

I is the current in (or out) of the battery (A);

R is the resistance (or internal impedance) of the battery (Ω).

$$P = IV_{OCV} \pm I^2R \quad (3)$$

Where P is the power developed by the battery (W).

$$R = R_{\Omega} + R_{CT} + R_{dif} \quad (4)$$

where

R_{Ω} is the ohmic (electronic) resistance (Ω);

R_{CT} is the charge transfer resistance (Ω);

R_{dif} is the diffusion resistance (Ω).

From the formulae, it can be seen that the battery capacity and voltage (driving factor of a) above) and internal impedance (driving factor of b)) are the main contributors to the battery performance and

that the evolution of these factors through ageing leads to a reduction of both the operating voltage at a given discharged energy and the discharge rate^[7].

Other parameters, like self-discharge or diffusion time constant, are also quite sensitive to ageing but have, at most, a second order influence on the performance. This does not mean, though, that they cannot be useful indicators of the battery SoH.

It is worth noting that many parameters (such as resistance and SoC) have a temperature dependency, which should be considered when choosing a test temperature or interpreting telemetry data.

4.2 Battery capacity

The simplest and most direct way of measuring a battery capacity is to perform a full discharge at a known rate (the lower the current the less resistive effects that will be observed). Unfortunately, this is usually not compatible with safe operation of the spacecraft. Therefore, the difficulty of estimating the capacity depends on the way the battery is used on board.

On a GEO, the total number of eclipses over the lifetime is small and consequently the battery can be used at a relatively large DoD, in the range of 70 % to 80 %. In such operating conditions, most of the discharge curve is accessible directly via the telemetry and, given the large fraction of the orbit period that is devoted to charging, the battery has time to reach a stable state, usually taper under almost zero current.

Conversely, in a LEO, the very large number of eclipses forces to limit the operating DoD to values around 20 % and the quick succession of eclipse and sunlight regimes does not allow the battery to reach any steady state (here the diffusion plays a significant role). Furthermore, due to seasonal variations of the sun illumination and even more pronounced variations in the case of a drifting orbit, the repetitive profile of the battery state from orbit to orbit is not even converging towards a stationary profile. It is therefore much more difficult to observe directly a stable battery behaviour.

4.3 Battery impedance

4.3.1 General

A rechargeable intercalation battery functions by internal ion flow motivating external electron flow (discharge) or external electron flow motivating internal ionic movement (charge). When subjecting a cell to a flow of current, a chemical change occurs within it. This chemical change causes the build-up or dissipation of obstacles to the current. These obstacles are known as polarizations:

- a) Ohmic polarization is caused by ohmic internal resistance of the cell against the flow of the current. This ohmic resistance (R_{Ω}) consists of an electronic resistance and an ionic one.
 - The electronic resistance can be seen in positive current collectors (foil and electrode terminal), positive active materials, positive conductive materials, negative current collectors (foil and electrode terminal) and negative active materials. Contact resistance between positive current collector and positive active materials is also an electronic resistance because the oxide thin layer is formed on the surface of the aluminium current collector foil. Since the positive active material shows a characteristic in electronic conductivity similar to a semiconductor, mixed conductive material like carbon keep electronic network in positive electrode layer. On the other hand, negative current collectors made of copper and negative active materials made of carbon have lower electronic resistance than positive ones.
 - The ionic resistance is another component of ohmic polarization. The resistance makes obstacle against the transfer of Li-ion and counter anion in liquid electrolyte impregnated in consecutive micro-pores inside the positive electrode layer, negative electrode layer and porous separator.

This polarization usually has a very fast response time, i.e. in the order of milliseconds.

- b) Activation polarization is the potential difference needed to generate currents depending on the activation energy of electrode reaction. The activation energy has electrons transferred from

electrodes into electrolyte or from electrolyte into electrodes. In the case of charge reaction of positive electrode, for example, Li de-intercalated from solid active material inside is activated on the surface of particle, and thereafter is oxidized to Li-ion. The response can be in the order of 10 milliseconds to seconds.

- c) Concentration polarization denotes the voltage loss resulting from changes in the electrolyte concentration due to a flow of electrode reaction current through the electrode/electrolyte interface. The concentration polarization is equivalent to a difference of the thermodynamic potential, which is a function of concentration of electrode reaction species.
- d) Diffusion polarization is a kind of concentration polarization. The diffusion polarization occurs when electrode reaction species become insufficient at the electrode surface because of slow supply rate driven by concentration gradient. This polarization occurs at the positive and negative electrode surface, for example, when Li transfer from active material to electrode surface through solid phase by diffusion process, and the intercalation to active material is also accompanied by diffusion polarization. This response can be in the order of minutes to hours.

Therefore, it is preferable to speak about internal impedance than resistance and to consider the impedance spectrum (i.e. impedance module and phase versus frequency) as an appropriate way to get an insight onto these various polarizations. Its evolution with ageing can be a very effective qualitative health indicator^{[5][6]}. It may even, under certain conditions, allow prediction of the battery behaviour, at least in the short to medium term^[9]. The drawback is that the classical way of measuring it, by the sweeping in frequency of a sine excitation current, is not straightforward to implement on-board. The internal resistance, which can be seen as a reduced image of the impedance, is easier to access and is therefore also a parameter of interest.

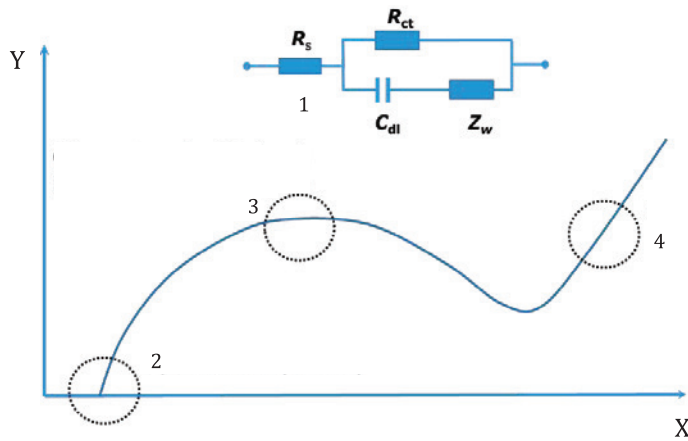
4.3.2 Electrochemical impedance spectroscopy (EIS)

In a Li-ion battery, the charge and discharge mechanism relies on several electronic and ionic processes for successful operation. These processes occur across a range of timescales from picoseconds to minutes and hours. By analysing the response of a battery to voltage or current with respect to time (or frequency of excitation), the behaviour of some of these processes can be separated and understood individually. In EIS, this is done by studying the output impedance signal from an applied sinusoidal current or voltage. The phase shift and magnitude of the output signal can then be used to determine the impedance.

Different internal mechanisms inside the battery can be linked to specific time domains and hence respond to specific excitation frequencies. By altering the frequency of the input current or voltage and investigating how the resulting phase shift (and impedance) changes with input frequency, the relationship between individual mechanisms and their individual impedances can be isolated and understood.

As a battery ages the performance characteristics alter. The process governing these performance characteristics can be traced back to changes in the internal electrochemical mechanisms. These changes (and the mechanisms responsible for them) can be observed via the changing impedance vs. frequency relationship with lifetime.

Typically, these results are displayed in a Nyquist plot where the impedance is separated into the real and imaginary components and the two components plotted on the X and Y axis respectively, as shown in [Figure 2](#).



Key

- X real (Z), $m\Omega$
- Y imaginary (Z), $m\Omega$
- 1 equivalent circuit
- 2 ohmic resistance (R_s) 0 phase shift (i.e. DC)
- 3 charge transfer (R_{ct}) and double layer (C_{dl}) region, Hz
- 4 Warburg impedance (Z_w) solid state diffusion region, mHz

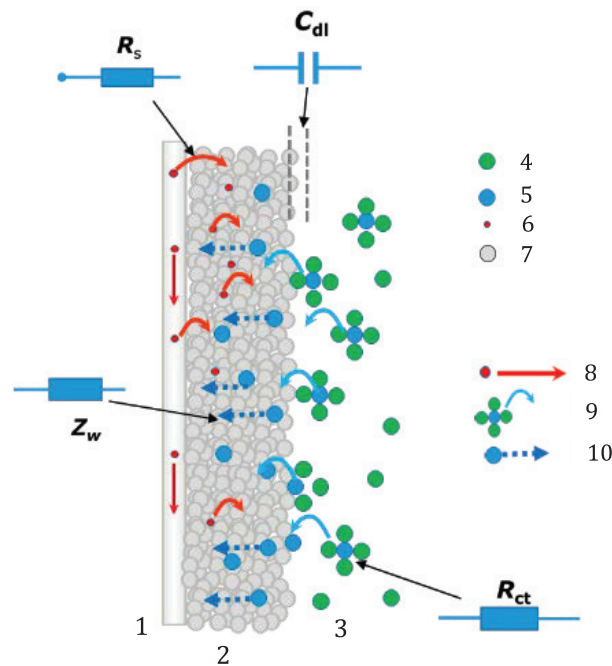
Figure 2 — Schematic of a Nyquist impedance plot

The key attributes of the battery can then be observed, and an equivalent circuit can be used to map the attributes to the physical behaviour inside the battery. [Figure 3](#) illustrates schematically.

Over time these attributes may change. This may be due to several factors such as;

- the introduction of surface layers, slowing down to electrolyte /electrode transfer, increasing resistance;
- poorer electrical connection between the electrode particles, increasing the electrical resistance;
- loss of surface area through pore clogging reducing etc.

Theoretically changes in the battery can be traced through changing impedance spectrum. The behaviour of the EIS spectrum is translated to changes in the individual elements in an equivalent circuit and characterized at each stage throughout the life of the battery.



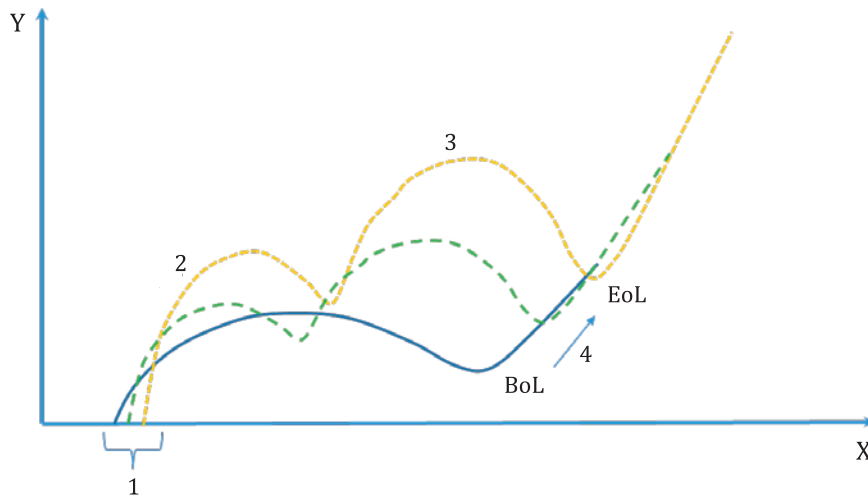
Key

- | | | | |
|---|----------------------|----|---------------------------------|
| 1 | current collector | 6 | electron |
| 2 | electrode | 7 | electrode particle |
| 3 | electrolyte | 8 | electron movement |
| 4 | electrolyte molecule | 9 | Li ⁺ charge transfer |
| 5 | Li ⁺ ion | 10 | Li ⁺ diffusion |

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<https://standards.iteh.ai/> **Figure 3 — Cell reaction processes and their corresponding equivalent circuit element** <https://standards.iteh.ai/standards/ISO/20891/2020>

In reality there is still some debate about some of the features observed in battery impedance spectra and their physical meaning (e.g. magnitude of specific contributions from surface layer mechanisms at the solid electrolyte interface). It can also be challenging to directly link an equivalent circuit based on impedance spectrum alone to observable charge and discharge behaviour at spacecraft level in [Figure 4](#). For this reason, EIS is primarily used as a powerful tool to qualitatively assess changes in battery but seldom used for quantitative modelling of battery behaviour over life.



Key

- X real (Z), $m\Omega$
- Y imaginary (Z), $m\Omega$
- 1 increasing ohmic resistance
- 2 introduction surface layer process
- 3 changing charge transfer resistance
- 4 ageing

Figure 4 — Schematic of charge state of Nyquist plot with time

4.4 Battery internal resistance

The battery internal resistance is commonly defined by the classic Kirchhoff relationship, with the resistance equal to the ratio of change in battery voltage to change in current that produced it. As mentioned in 4.3, the battery not being a pure resistor, the resistance measure is dependent on the timeframe of measurement; an instantaneous sampling of the change of voltage yields the resistance associated with the fastest mechanisms of resistances (electronic) while sampling over the course of seconds shows the additional contributions from charge transfer and diffusion mechanisms. Extending the resistance sampling time also sees the voltage change as a function of SoC (as per Formulae (2) and (4)). Thus, the measured value obviously depends on the delay between the current change and the voltage sampling. This is illustrated by Figure 5, which shows how large the difference between the values of a cell internal resistance measured by two different methods during the same cycle can be.

R_{int} via the ESTBC method is resistance determined by voltage drop with constant low load.

R_{int} via supplier method is determined by the voltage drop at the end of a higher magnitude current pulse.