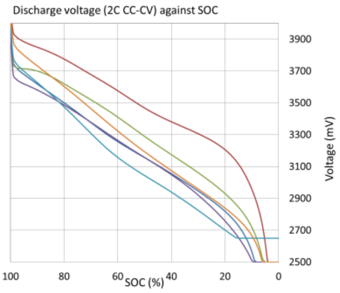
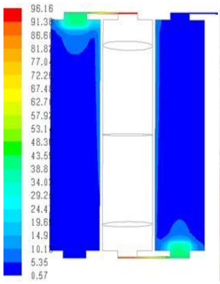
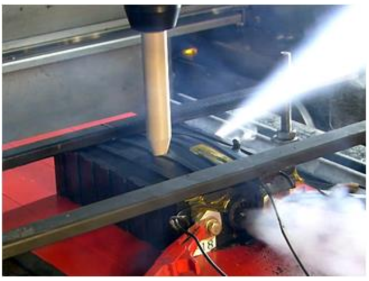
Draft White Paper

Test methods for improved battery cell understanding

Version 3.0







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Introduction

Background

The three European projects eCAIMAN, FiveVB and SPICY enable the next generation of competitive Li-ion batteries to meet customer expectations – made in Europe. The projects pursue the optimisation of the electrochemistry to hone parameters critical to customer acceptance: cost, safety aspects, resistance to high power charging, durability, recyclability, as well as consideration of scale-up for manufacturing. The ageing mechanisms of such cells, test procedures and the development of standards are also examined.

The European Commission has asked to collaborate that resulted in a common workshop of the projects and the preparation of a white paper on a joint standardisation effort. Topics can include the standardisation of cell specifications, the standardisation of tests for specific use cases, and the standardisation of physical components.

Goal

[The following goals are formulated in the meeting minutes of the 24M workshop]

1. Goal is to have a white paper with test methods that are valuable for the workshop partners. Objective is to have more insight in battery performance, ageing effects and safety aspects and suitability of the tests for battery modelling. This is a kind of round robin test, but also increases the total characterisation since the specific projects have different use cases like battery swelling and voltage hysteresis by using silicon particles.
2. The white paper can be handed to the EC and the standardisation bodies. It should include comments, changes, etc. to current standards keeping in mind the future developments on the sector. Should be signed by all partners to show commitment and have high relevance.
3. The white paper can also directly be used for standardisation. Since standardisation follows mostly a democratic bottom-up approach, a national mirror committee of the EN TC21 and IEC TC21 has to bring the white paper to one of both given standardization committees. The other countries involved in the white paper can then express their interest in this standardization project. Once seven agree, the standardization can start.
4. The white paper can be the base for a testing and modelling Wiki platform would be of high interest among academic and RTO partners.

Approach

The focus is on understanding the behaviour of battery cells.

In the goal section the generic topics are formulated for test methods:

- battery performance,
- ageing effects,
- safety aspects.

The test methods can envisage:

- Methods that are valuable for many battery cell types.
- Methods that examine specific behaviour stemming from new battery materials.

The test methods can have several applications:

- The direct measurement results describe the battery behaviour on the tested topic.
- The measurement results are suitable for the mathematical modelling of batteries.

For every proposed test method an inventory is given if (parts of) it exists in standards like published by IEC, ISO and CENELEC and what the most-used approach is.

Set-up

For each test method in this white paper the following structure is systematically used:

Test method name	the test name as most often used for the test type.
Test intention	what is the purpose of the test, including if it is valuable for many batteries or for a specific property: the 'why'.
Application(s)	is the test for direct use of the results, is it for modelling or for both?
Test approach	this describes how the test procedure is supposed to test for the identified intention (i.e. the 'how').
Test equipment	this involves probably a battery tester but maybe more is needed like a heat camera or a temperature chamber.
Test procedure	this describes the actual test procedure in a stepwise manner. It also indicates any pass-fail criteria linked to the executed test steps if applicable. If the procedure is identical to a test in a standard only a reference can be given. The test procedure can be repeated for several versions. Also test extensions can be given for specific purposes, like measuring cell swelling and heating.
Test duration	an indication of the period that the test procedure needs.
Difference with similar methods in standards or common practice	a description if deviations in the test procedure exist and the reason.
Post-processing	how the results can be used? What steps after the test have to be added in data processing to come to valuable results? In case of modelling, how the results enter into possible models?
Example	a typical example of a test lapse and the final result.

At the end preferable test-schemes can be given for e.g. short check-up test and extended check-up test.

Glossary

Definitions

C-rate	the current corresponding to a 1 h discharge.
I_t-rate	the current that corresponds to the declared capacity by the manufacturer.
C_n	the rated capacity with n being the time base in hours

Abbrevations

SOC	State of charge (%)
DOD	Depth of discharge (%)
EIS	Electrochemical impedance spectroscopy
BOL	Beginning of life
MOL	Mid of life
EOL	End of life
SOH	State of health

DUT	Device under test
CC	Constant current
CV	Constant voltage
I_{max}	The maximum allowed current according to the datasheet

Introductory topics about battery cell testing

Freedom in reference capacity: C-rate and I_t-rate

For battery tests the current is mostly expressed in a relative manner, i.e. in terms of the battery capacity. However, the capacity is not a fixed value. It is dependent on the current profile. Mostly, a constant current discharge is used that discharge the battery in a certain amount of hours. This is the definition of the rated capacity C_n, with n being the time base. Usual rated capacities for Li-ion batteries are:

- C_5 for portable and industrial applications (IEC 61960, IEC 62620)
- C_3 for BEV application (IEC 62660-1, ISO 12405-2)
- C_1 for HEV application (IEC 62660-1, ISO 12405-1)

To prescribe the needed currents in a test, several standards do not use C-rates, what refers to the capacity corresponding to a full discharge in exactly 1 h. However, they use I_t-rates, where I_t refers to the capacity as measured according to the time base prescribed by the standard (the n in C_n). So, this could be read as a C_n-rate. C_n must not be confounded with C/n, what refers to a current of 1/n of the 1 h capacity.

For good comparison of test results, the cell capacity has to be determined in the same manner for all tested cells. If that is e.g. the 5 h discharge capacity, then the I_t-rate can be used. If the cells have different time bases for the declared capacity or when no time-base is given in the datasheet, then it is better to use the 1 h capacity. This can be derived from the capacity test as given in the white paper by interpolation of the test results. Fortunately, the capacity of Li-ion cells is at room temperature hardly depending on the current: less than 5% difference between the 5 h and 1 h discharge, by experience. This is much less than for other battery chemistries like lead and NiMH. This stated, it appears that some cell manufacturers are too optimistic about the cell capacity. They declare a capacity that even cannot be reproduced by a 100 h discharge. A 10% difference between the declared capacity and the 1 C capacity can be found for Li-ion cells in practice.

Originally, the I_t-rate definition is found in IEC 61434 ‘Guide to designation of current in alkaline secondary cell and battery standards’. It had to solve the unit problem that exists between capacity (Ah) and current (A). The definition adds that the C_n capacity is divided by 1 [h], so that the resulting unit becomes [A].

The white paper uses the C-rate as basis. It can be replaced by an I_t-rate. Even if the time bases of the cells are not equal, this should not lead to large mismatches in the current from the 10% capacity difference given above. This can be checked by the capacity test. If the difference becomes above 10% then the capacity test should use the 1 h capacity (calculated by interpolation) and be repeated. This capacity has to be used for the other tests as well in that case.

This document puts an emphasis on the C_{25} capacity since it hardly depends on the growth in resistance during ageing in contrast with the C_1 capacity. So, it represents better the available battery capacity. It can be obtained relatively quickly by continuing the CC discharge with a CV discharge until a cut-off current of C/25.

Data acquisition

The results of the test methods have to be stored. Different methods exist.

Fixed interval

A common way is to store all measurement parameters with a fixed sampling rate like every second. This method is easy to implement and easy to plot since no time dependent X-axis is needed. Also, battery models for BMS systems, often prefer data with a fixed time step. The method has two inconveniences. It leads to a high amount of data, since to cover the dynamic behaviour of measurement signals a tiny time interval has to be taken. In periods of little change in signal, still a lot of data is captured. For transient and highly dynamic signals a short time step (like 1 s) can still be too slow to capture the complete dynamics.

Event-based

In event-based datalogging, data is stored when a threshold in value change for a given parameter is surpassed. This can be every 20 mV change for the voltage sensor and every 100 mA change for the current sensor. Most battery test machines accept C-rate as criterion, like 0,01 C change. The advantage is that all phenomena are captured with the resolution that you give, up to the fastest sample rate of the test machine, e.g. every 1 ms. If no points are captured, then the signals are stable within the required resolution. A disadvantage is that for plotting the data, the time axis has to be taken into account. For battery modelling, the data may need a resampling to fixed time interval.

Combination

A combination of both methods is the usual way. A slow time interval is taken, like 1 min, combined with event-based data acquisition. For graphs this can be nicer since in long periods with hardly a change, still some data points become visible. Also, if the resolution was incidentally chosen too coarsely, then still some data is captured.

Example

In Figure 1 the difference becomes clearly visible for a 10 s discharge pulse. In A the data is captured every second: most data points lie away from the pulse. In B the data is captured event-based with as criteria: 1 mV for the voltage and 0,01 C for the current. Most data is around the pulse. The fact that data exists before the pulse is due to the additional fixed time interval of 1 min (the combined method). In A the 10 s pulse is captured in 11 points, whereas in B 114 points are captured: the voltage slopes are very well visible.

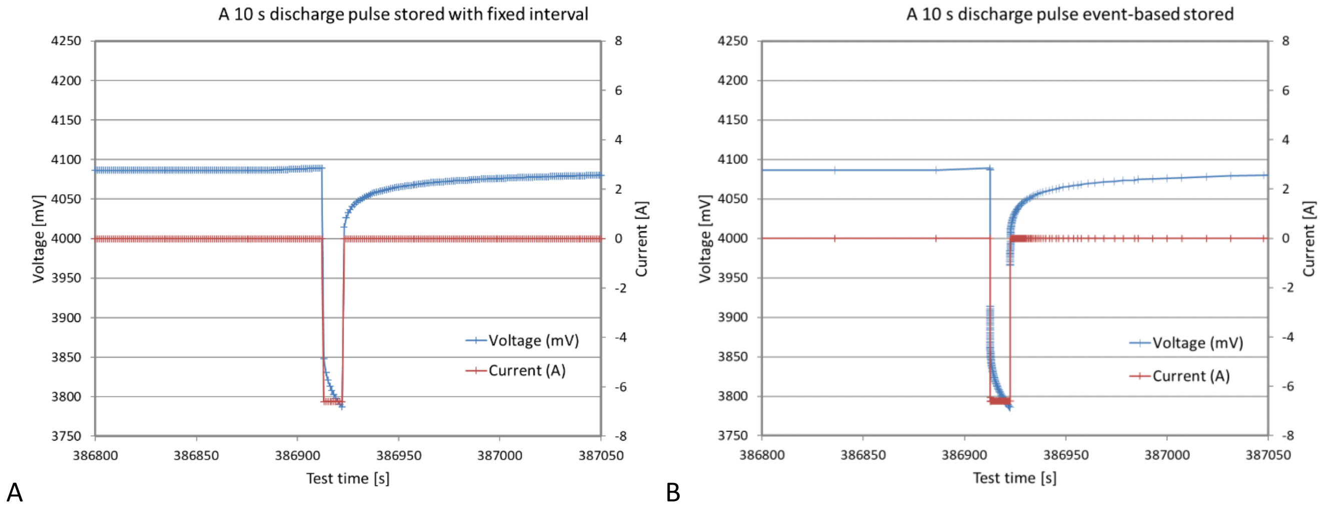

Figure 1: data acquisition via fixed interval versus event-based capturing. In A every second the voltage is sampled. In B data is sampled via the combined method that uses mainly criteria on the change in parameter values.

The sudden drop in voltage at the pulse onset is less deep (180 mV) in B than in A (240 mV) since it is quicker captured: the used test machine can store every 1 ms a data point, making it 1000 times quicker than in A. To determine the ohmic resistance of the cell, this may be advantageous. From A the ohmic resistance is 36 mΩ and from B it is 28 mΩ. The used resolution in B may be over-precise and can be diminished: even using 5 mV change would have let to a more precise pulse shape than in A. In the shown time frame, in A 250 points are captured and in B 440. Capturing data over a longer time, containing rest periods, will favour the combined method for data storage efficiency.

Air flow and controlled temperature

[eCAIMAN, AIT (H.Popp)]

When conducting tests on batteries, often several ambient temperatures are of interest, e.g. to determine low temperature performance or to gain temperature dependent data for modelling. Also in standards many temperatures are prescribed. Hence, often temperature chambers are used to fulfil this requirement. Normally circulation of air is needed to pass it over the coolers and heating elements. For the test equipment this usually means a forced convection rather than a natural convection which might be the desired one. Especially with forced convection in temperature chambers fan speed, shadowing effects and position in the chamber can lead to both different temperatures as well as dissimilar air flow rates. This can lead to following differences in heat transfer[2]:

- natural convection: $\alpha = 4 \ldots 15\ \mathrm{W/(m^2 \cdot K)}$
- forced convection: $\alpha = 10 \ldots 100\ \mathrm{W/(m^2 \cdot K)}$.

Despite having an overlapping region, these values differ significantly and may lead to different results especially during thermal characterization. Additionally, the value for the climatic chamber is an average value, local values can differ. Figure 2 shows a distribution of temperature sensors within a climatic chamber during calibration and Table 1 shows the according temperatures. The ambient temperature value set is 0°C and the mean deviation over all sensors is 0. It can be seen

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[2] M. Rudolph et. al, Batteries Conference, Nice, France, 2014

that the temperature within the camber deviates by 1.2 K in this case. This is a high quality climatic chamber from a well-known manufacturer. Temperature distribution in cheaper temperature or climatic chambers might vary more.

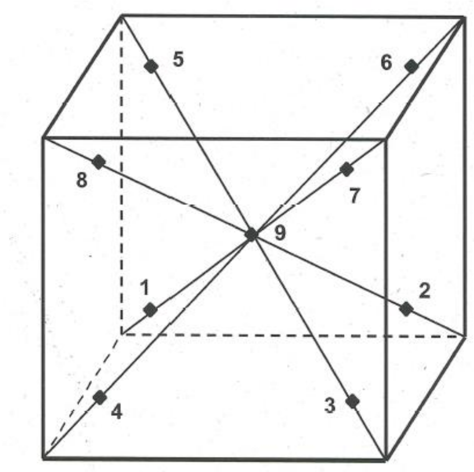

Figure 2. Spatial distribution and numbering of temperature sensors in climatic chamber.

Table 1. Measured temperatures in chamber.

Sensor (#)	1	2	3	4	5	6	7	8	9
Mean Value (°C)	-0.1	-0.8	0.4	0.0	-0.4	0.1	0.4	0.1	0.1
Std. deviation over time (K)	0.1	0.2	02.	0.1	0.2	0.1	0.1	0.1	0.1
Deviation from set value (K)	-0.1	-0.8	0.4	0.0	-0.4	0.1	0.4	0.2.	0.1

When thermal comparability needs to be ensured it is favourable to place the DUT in positions where similar conditions can be found. If this is not possible with normal setup additional fans can be placed to force comparable convection on all DUT equally.

Cell pressure equipment

[It might also be interesting to mention the existing cell pressure equipment and their use. Especially for modern, swelling, anodes it is important.]

DOE Test manual PHEV (2014)
https://inldigitallibrary.inl.gov/sites/sti/sti/6308373.pdf

3.1.3 Pressure control
Unless otherwise specified in a device-specific test plan, pouch or prismatic cell pressure should be established by placing the device between two plates with four to six bolts around the edges that are tightened using torque specifications provided by the manufacturer (or finger tightened if no specification is provided). Preferably, spacers between the two plates should be used to ensure a sufficient gap between the plates. As a general practice, once the pouch pressure has been set, the device should be placed in an environmental chamber and left undisturbed for the duration of the test period. The devices should occasionally be visually inspected periodically for any signs of swelling or leaking.

Explaining and interpreting typical data sheets

[Proposed by AIT (H.Popp)]

Figure 3 to Figure 5 show the sections of a typical datasheet. In this case it is from a very frequently used cell for portable devices: a Panasonic NCR18650B[3]. There is no standard or no common agreement which information a datasheet has to include. Depending on the manufacturer, the supplier, the field of intended application, the cell and even the customer the datasheet will look different which also makes them hard to compare. The following sections aim to help to understand the values provided by the manufacturer. Additional understanding can be also gained when reading the corresponding sections in this document.

General data

Figure 3 shows the general data section of the datasheet. Under "Features & Benefits" the type of cell (in this case it is a high energy density cell), the benefits and the field of application are given.
For experienced users the composition of the cell is also of interest but not included in this case. Some datasheets provide this information e.g. that the cell comprises a NMC cathode and a graphite anode.

Specifications

Rated capacity: It is the minimum capacity for discharge which can be achieved. However, the time base to derive the capacity is not given (see also the section 'Freedom in reference capacity'). It is only mentioned that the ambient temperature for the rated capacity test is 20°C. Although the rated capacity for cylindrical cells is often the 5 h capacity, the plots in Figure 5 let believe that it is about the 1 h capacity.

Nominal voltage: Mean voltage achieved during the discharge that leads to the rated capacity (called the standard discharge).

Capacity: Again a minimum value is provided. This one is higher because of the test being performed at 25°C. Also the typical value is given that is the expected value for this cell type.

Charging: States the standard charge method according to the manufacturer. In this case it is with a C/2 rate based on the typical capacity up to 4.2V with the charging time limited to 4h. Considering an empty cell this would account for approximately 2 h of CC charging and then 2 h of topping at 4.2V with CV charging. Note that also other charging strategies can be possible when imposing special boundaries, like a cut-off current. Contact the manufacturer if necessary.

Weight: In this case the maximum weight is stated. Also median weight is common.

Temperature: Values for charge, discharge and storage are given. These are the absolute maximum (or minimum) ratings on the surface of the cell.

Energy density: Volumetric and gravimetric energy density; in this case calculated for the worst case scenario with minimum capacity at 25°C and maximum dimensions / mass. It is to be expected that real values will be better.

Dimensions: Technical drawing of the cell with dimensions of cell and tabs.

Other typical values which are not found in this datasheet are:

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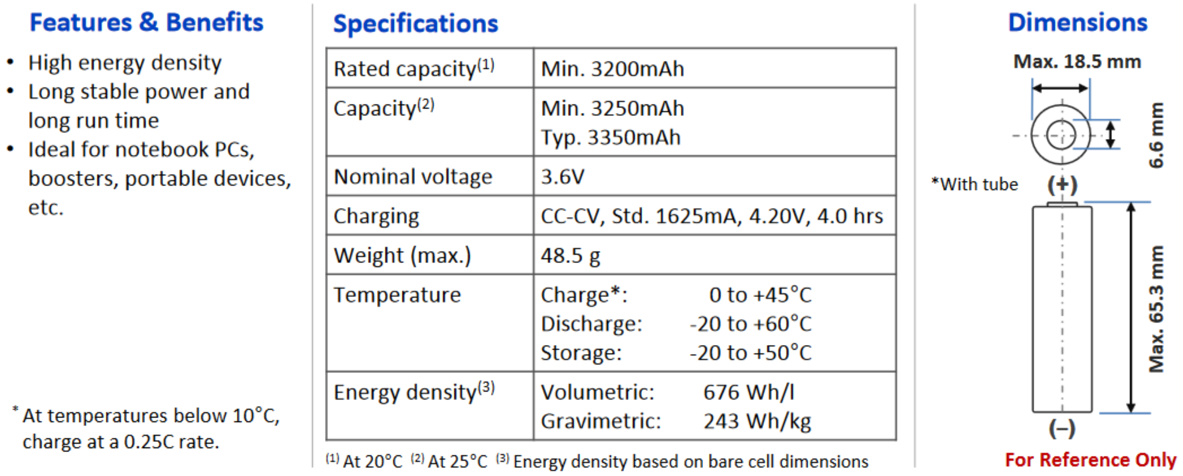
[3] http://www.batteryspace.com/prod-specs/NCR18650B.pdf

- Internal resistance
- Peak power (charge/discharge)
- Maximum continuous and peak current (amplitude and duration of peak current)
- Voltage limits (also voltage limits for peak power possible)
- Power density (volumetric / gravimetric)
- Material thickness (important for the corresponding connector tabs that can be used in case of resistive welding).



Features & Benefits

- High energy density
- Long stable power and long run time
- Ideal for notebook PCs, boosters, portable devices, etc.

* At temperatures below 10°C, charge at a 0.25C rate.

Specifications

Rated capacity(1)	Min. 3200mAh
Capacity(2)	Min. 3250mAh Typ. 3350mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1625mA, 4.20V, 4.0 hrs
Weight (max.)	48.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density(3)	Volumetric: 676 Wh/l Gravimetric: 243 Wh/kg

(1) At 20°C (2) At 25°C (3) Energy density based on bare cell dimensions

Dimensions

For Reference Only

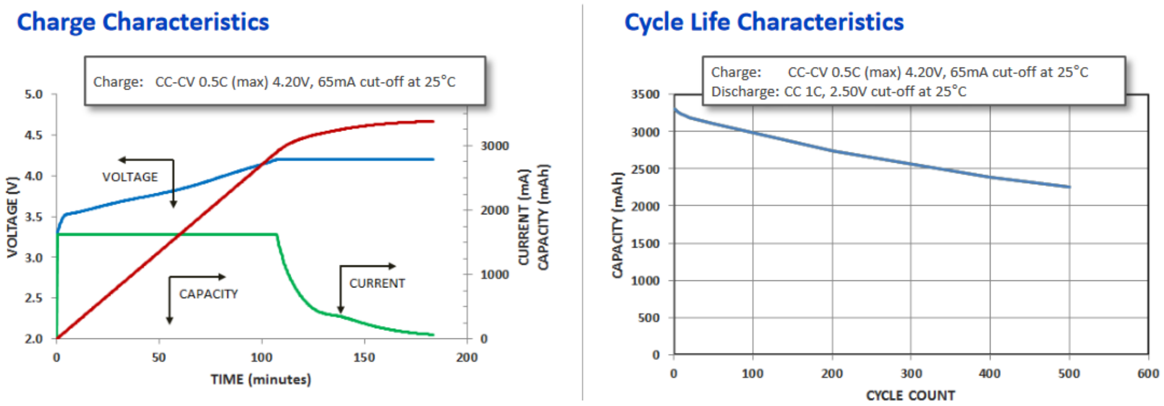
Figure 3: General data section in the data sheet of the Panasonic NCR18650B cell.

Charge characteristics

Figure 4 (left) shows a typical charging curve from empty to full state with the standard charging procedure. It can be seen that the CC charging phase takes 105 min and that the new cell is considered as fully charged at around 180 min (3h) taking a cut-off current into account (C/50). This is different from the charge prescription in the general section. The standard charge up to 4 h can be necessary then when the cell is aged and has higher internal resistance.

Cycle-life characteristics

Figure 4 (right) shows the cycle-life for the cell. In this case the capacity degradation is illustrated over the cycle count. The cell is cycled with full cycles, so the DOD is 100%. In other cases also cycle-life for smaller discharge windows, e.g. DOD 80 % or at different currents or temperature levels can be given.

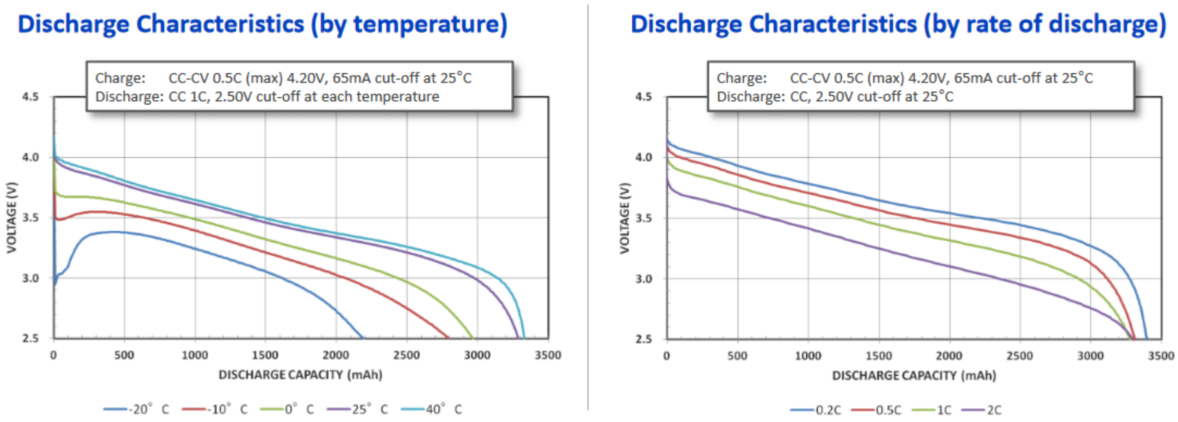

Charge Characteristics

Cycle Life Characteristics

Figure 4: Characteristics for charging and cycle life.

Discharge characteristics

Figure 5 (left) shows the discharge characteristics for several ambient temperatures. The C-rate for discharge is kept constant and the temperature is varied. As the electrical performance of a battery cell is strongly dependent on its temperature this is very helpful to estimate the cell performance at the intended operational temperature. It can be seen that at the lowest temperature level only two third of the capacity can be extracted in CC-mode. Figure 5 (right) shows the discharge characteristics by discharged current. The temperature is kept constant while the C-rate is varied. Due to the internal resistance the lower voltage limit is reached earlier with higher discharge currents meaning that less charge can be withdrawn. For more information see also Figure 8 and the corresponding section. In some cases also additional plots can be found which e.g. give the internal resistance or the power capability as function of the SOC.


Discharge Characteristics (by temperature)

Discharge Characteristics (by rate of discharge)

The data in this document is for descriptive purposes only and is not intended to make or imply any guarantee or warranty.

Figure 5: Discharge characteristics.

Battery cell performance

Preconditioning test

[This test item is elaborated by: *project SPICY, VITO, Grietus Mulder*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Test intention

The preconditioning test must verify that the capacity of the cells are stable, since during the first cycles of a new cell its capacity can increase or the cell performance may quickly deteriorate due to a production failure.

Application(s)

The application is for the rest of the test programme: to make sure that the cell has a stable start.

Test approach

The cell is charged- and discharged three times with the rate as defined in the standard cycle and the measured capacity is evaluated. If the differences in discharged capacity are more than 2% then the cycles are continued up to ten times maximally.

Test equipment

The needed equipment is:

- a battery cell tester with sufficient current capacity for high C-rates;
- temperature sensors.

Test procedure

- The cell must have been long enough in the laboratory that the cell temperature is at ambient temperature. Since the test is about comparing the capacity stability, no exact temperature has to be defined as long as it is stable (±2°C).
- The cell is charged with the rate recommended by the manufacturer, continued by a constant voltage charge as prescribed by the manufacturer with a cut-off current as given in the standard cycle.
- 30 min idling.
- The cell is discharged until the minimum prescribed voltage by the manufacturer with the rate as given in the standard cycle test method.
- 30 min idling.
- The cell is recharged with the rate recommended by the manufacturer, continued by a constant voltage charge as prescribed by the manufacturer with a cut-off current as given in the standard cycle.
- 30 min idling.
- This is repeated three times.
- The cell temperature is followed up and must be within the allowed limits as prescribed by the manufacturer.
- If the subsequent capacity readings alter more than 2%, then the test is repeated with a maximum of 10 discharges.

Test duration

The test duration is 8 h assuming a discharge rate of 1 C and charge rate close to C/2, up to two days for 10 cycles.

Difference with similar methods in standards or usual practice

The preconditioning test is called capacity test in the Battery Test Manual For Electric Vehicles (2015), INL/EXT-15-34184.

The preconditioning test is described in:

ISO 12405-1: Preconditioning test (3 cycles with a 2 C discharge or current suggested by the manufacturer. Room temperature is 25±2°C. 3% capacity change is allowed in consecutive cycles).

ISO 12405-2: Preconditioning test (3 cycles with a 0.3 C discharge. Room temperature is 25±2°C. 3% capacity change is allowed in consecutive cycles).

Battery Test Manual For Electric Vehicles (2015), INL/EXT-15-34184: (3 cycles with a 0.3 C discharge. Ambient temperature of 30°C. 2% capacity change is allowed in consecutive cycles).

The difference is in the discharge rate and in the stability criterion. This is taken as 2% since the stability is important to compare test results like in the capacity test (i.e. is the variation in capacity due to a continued conditioning or due to a different C-rate?).

Post-processing

No post-processing is necessary.

Example

In Table 2 the results of a preconditioning test is given for 5 cells. Per cell the capacity is hardly changing. In this case the difference between cells is substantial.

Cell	1C	discharge	capacity (Ah)	Difference
	Cycle 1	Cycle 2	Cycle 3	(3 comp. to 2)
1	8,84	8,91	8,91	0%
2	9,22	9,21	9,17	0,5%
3	9,19	9,21	9,18	0,4%
4	8,80	8,80	8,79	0,1%
5	9,46	9,37	9,31	0,6%
Difference	8%	6%	6%	

Table 2: Results of preconditioning test. The cell capacities are stable. The differences between cells are quite high.

Standard cycle

[This test item is elaborated by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Test intention

This test exists to derive the C_1 cell capacity and to follow up the capacity change over time. The discharge is continued with a CV discharge to obtain the C_{25} capacity what hardly depends on the growth in resistance during ageing in contrast with the C_1 capacity. The test may be used to obtain the declared capacity by the manufacturer.

Application(s)

The test result is used to follow up the cell capacity during its life. The emphasis is put on C_1 and C_{25} capacity. If it is important to compare the capacity of this standard cycle with the declared capacity, then not a 1 C discharge should be applied but the prescribed I_t-rate by the datasheet. See the section 'Freedom in reference capacity: C-rate and I_t-rate' for an explanation.

Test approach

The test discharges the cell with a current corresponding to the capacity as given by the manufacturer, leading to a 1 h discharge, until the minimally prescribed voltage by the manufacturer. It is continued in CV mode until the current reaches C/25.

Since for most Li-ion cells the C_1 capacity is not given, the current must be based on the declared capacity. From experience there can be 10% difference between this capacity and the C_1-capacity (the latter being smaller). The battery cell will then discharge in less than an hour. Consequently, the measured capacity is then strictly-speaking not the C_1-capacity. Since the difference of this capacity and the real C_1-capacity can only be a fraction of the earlier given 10% difference, the difference between the found capacity and the real C_1 capacity is maximally 2 %. If the declared capacity has to be found and followed up then a current must be applied that is found by dividing the declared capacity and its corresponding time span: the I_t-rate (see the section 'Freedom in reference capacity: C-rate and I_t-rate' for an explanation).

Test equipment

The needed equipment is:

- a battery cell tester;
- a cell temperature sensor.

Test procedure

- The room temperature has to be 25±2°C.
- Place the cell in the room and wait sufficiently long that it is acclimated.
- Discharge the cell until the prescribed minimum voltage by the manufacturer, using a current corresponding the C_1 or the rated capacity. If the rated capacity must be followed up, use the I_t-rate from the datasheet.
- The cell is charged with the rate recommended by the manufacturer, continued by a constant voltage charge as prescribed by the manufacturer with a cut-off current of C/25.
- 30 min idling.
- The cell is discharged until the prescribed minimum voltage by the manufacturer, using a current corresponding the C_1 or the rated capacity. If the rated capacity must be followed up, use the I_t-rate from the datasheet.
- Continue discharging at constant voltage until the current reaches C/25.
- 30 min idling.
- The cell is recharged with the rate recommended by the manufacturer, continued by a constant voltage charge with a cut-off current of C/25.
- 30 min idling.

Test duration

Around 8 h.

Difference with similar methods in standards or usual practice

The method is according to the standards as long as the nominal or standard current rate is left open to the manufacturer. The standards differ in this rate as given in Table 3. The standard cycle in the white paper also contains an extension, i.e. the CV discharge until C/25. The advantages are that it gives the slow rate capacity and that it is almost independent of the cell resistance.

Standard	*Test name*	*Discharge rate*	*Temperature*
ISO 12405-1	Standard cycle	1 I_t	
ISO 12405-2	Standard discharge	I_t/3 or by specified manufacturer	
IEC 62660	Capacity	I_t/3 for BEV application and 1 I_t for HEV application	20±5°C
IEC 61690	Discharge performance at 20°C	I_t/5	20±5°C
IEC 62620	Discharge performance at 25°C	I_t/5	25±5°C
DOE battery test manual for plug-in hybrid electric vehicles (2014)	Static capacity test	10 kW	30±5°C
DOE battery test manual for electric vehicles (2015)	Static capacity test	I_t/3	30±3°C

Table 3: Test names and conditions for the standard cycle.

Post-processing

No post-processing is necessary.

Example

Table 4 shows the result of the standard cycle for 3 cells. For 2 brands, the C25-capacity is smaller than the declared capacity by the manufacturer.

Cell	*Declared capacity [Ah]*	*Found C_1 capacity [Ah]*	*Measured C_{25} capacity [Ah]*
Brand 1	3,3	3,21	3,41
Brand 2	3,4	3,06	3,34
Brand 3	3,5	3,22	3,38

Table 4: The test results for the standard cycle for three cells.

Capacity test

[This test item is elaborated by: *project SPICY, VITO, Grietus Mulder*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Test intention

The primary test intention is obtaining the cell capacity and energy content as function of C-rate and temperature. Much more information can be obtained from this test, especially when several charge rates are used, like the (fast charge) efficiency, Peukert exponent and the voltage curves.

Application(s)

The test results like capacity, energy content, maximum temperature, cycle efficiency, can be used directly as key data of the battery cell. The voltage graphs and the heating behaviour can be used to verify battery models.

Test approach

The test is a constant current discharge until a prescribed minimum voltage. It may be continued by a constant voltage discharge until a cut-off current. The charge always exists of a constant current charge until a prescribed maximum voltage followed by a constant voltage charge down to a cut-off current. The test is repeated for several C-rates and can be performed at several temperatures. The C-rate is based on the C_1 capacity. Since for most Li-ion cells the C_1 capacity is not given, the current must then be based on the declared capacity leading to multiples of I_t-rate. See also the standard cycle where the same approach is used.

Test equipment

The needed equipment is:

- a battery cell tester with sufficient current capacity for high C-rates;
- temperature sensors;
- temperature chamber.

Optionally:

- forced air flow;
- heat camera.

Test procedure

The test applies several current rates and temperatures. Also a distinction between always applied values and optional values is made.

(Dis)charge rates

Always: 1/5; ½; 1; 2 C (or I_t)
Optional 5; 10 C (or I_t) and I_{max}.

The same rate is used for both discharge and charge up to the maximum allowed charge rate by the manufacturer. The charge is continued at constant voltage, as prescribed the manufacturer, until the current has decreased to the charge rate used in the slow discharge test being C/25.

The discharge can optionally be continued by a constant voltage discharge until C/25. This is interesting to observe whether the total capacity (measured in the slow discharge test) is accessible. It is also interesting for the heating behaviour that often peaks around this area and for (electrochemical) battery modelling. hearth

To prevent overheating, especially at currents above 1 C, it may be necessary to cool the battery cells with help of a forced air flow. If the cells are in a temperature chamber this flow is probably existing anyway.

The current rates that are always necessary cover the rates given for consumer cells (1/5 C) up to usual fast rates (2 C). For dynamic applications the optional high rates can be applied.

Temperatures

Always: 5, 25, 45°C.
Optional: low temperatures: 0, -10 and -20°C at discharge. For charge the lowest permitted temperature according to the manufacturer has to be used if this is higher than the applied ambient temperature during discharge.

The battery behaviour is very temperature depending due to the chemical reactions and the transport phenomena inside the battery cell. Especially for electrochemical modelling, where the temperature influence is fitted to the measurement data, measurements at several temperatures are necessary. Since most battery applications lie between 5 and 45°C this is the necessary range. For consumer and outdoor batteries a (sub)zero temperature range may be needed.

Step-by-step procedure

1. For the data acquisition during the test a measurement every minute and for every 10 mV change, every 0.05 C change and for every 0.2 K change is recommended. See also the section ‘Data Acquisition’.
2. If this test has been preceded by the standard cycle within 48 h before then the battery cell can be assumed to be fully charged. Else a discharge and charge have to be performed with the conditions as given in the standard cycle.
3. A rest of 60 min is applied.
4. The discharge at constant current is applied until minimum allowed cell voltage. The rates to be applied are defined above.
5. Optionally, a constant voltage discharge is applied at the minimum allowed voltage until C/25.
6. A rest of 60 min is applied.
7. The charge at constant current is applied until the maximum allowed cell voltage. The rates to be applied are defined above.
8. A constant voltage charge is applied at the maximum allowed voltage until C/25.
9. A rest of 60 min is applied
10. The test is repeated for every current rate.

The cell temperature is measured and must be within the allowed limits as prescribed by the manufacturer.

After changing the temperature according to the above described list, at least two hours is waited before starting a discharge. For thick high capacity cell more time may be needed. The equivalent holds if the battery cell has to be heated before charging is allowed.

If the voltage relaxation after (dis)charge is important, e.g. to find the EMF, then the rest time may be increased or a relaxation criterion can be introduced like less change than 5 mV/h.

A heat camera can be used, especially for high rates like 2 C and more to find the hot spots in the battery cell and maybe in the wires attached to the battery.

Test duration

The test at one temperature takes approximately 24 h. Repeating the test for three temperatures takes 3.5 days.

Difference with similar methods in standards or usual practice

The capacity test consisting of full discharges and recharges of a battery are also called ‘energy and capacity test’, ‘energy efficiency test at fast charging’ as well as ‘discharge performance’ in the standards.

Test standards that comprise a capacity test are:
IEC 62660-1: capacity test (I_t/3 for BEV application or 1 I_t for HEV application, at 0, 25 and 45°C).
ISO 12405-1: energy and capacity test at room temperature and at other temperatures (1 I_t, 10 I_t and maximum current at RT, 40°C 0°C, -18°C; each cycle at a specific temperature is followed by a cycle at RT resulting in 28 cycles).
ISO 12405-1: energy and capacity test at room temperature and at other temperatures (0.33 I_t, 1 I_t, 2 I_t and maximum current at RT, 40°C, 0°C, -10°C and -25°C).
Energy efficiency test at fast charging (two specific charge rates, i.e. 1 I_t and 2 I_t).
IEC 62620: discharge performance (0.2 I_t, 1 I_t, 5 I_t and 10°C, 0°C, -10°C, -20°C).

The standards show a wide variety in discharge rates from 0.2 I_t up to 10 I_t. The longest range is prescribed in ISO/DIS 12405-2 with a series of four C-rates.

The main difference in the proposed capacity test method is the charge rate. All standards prescribe the charge rate prescribed by the manufacturer, apart from the specifically designed ‘energy efficiency test at fast charging’. This is unnecessary, as many cells are allowed to be charged at higher rates (up to the maximum allowed charge rate by the manufacturer). It is interesting to include charge behaviour into the capacity test. A distinguishing quality that can be found during charging a battery is the SOC of a battery when it attains the maximum allowable voltage. At that moment charging switches to constant voltage charging. Due to the reduced current, the charging time increases to obtain a 100% SOC. So, the higher the SOC before attaining the maximum voltage, the quicker a cell is charged.

Post-processing

From the energy and capacity discharge and charge data the cycle efficiencies can be calculated as well as the coulombic efficiency. The average (dis)charge voltage can be calculated.

The very known Peukert constant is in neither of the mentioned standards although a discharge series makes its calculation possible. From the Peukert equation the 1 h capacity can be calculated so that the capacity declared by the manufacturer (I_t) can be replaced by true capacity (C) in the tests. Notwithstanding that the Peukert constant is close to 1 for most of the lithium batteries, it is still considered as an interesting aspect. At high C-rates the capacity can, unexpectedly, increase due to an involved temperature effect. If it is only one point, then it has to omitted from the calculation.

The Peukert formula can be derived by plotting the discharge time against the current and adding a power law trend line. In Excel the coefficients can directly be calculated using:

Peukert exponent =-INDEX(LINEST(LOG(*time vector [h]*);LOG(*current vector [A]*));1) [1a]
Peukert capacity =10^(INDEX(LINEST(LOG(*time vector [h]*);LOG(*current vector [A]*));2)) [1b]

For a wanted discharge time, the corresponding capacity can now be calculated by:

$$capacity = \left(\frac{time\ [h]}{Peukert\ capacity}\right)^{\frac{-1}{Peukert\ exponent}} \cdot time\ [h] \qquad [2]$$

From the tests at sub-zero temperature, the temperature can be deduced where the battery cell reduces to 70% of the 25°C capacity. This is also done in IEC 61960-3.

The discharge and charge voltage curves can be plotted against battery capacity and against state of charge. For the latter the battery capacity as found in the slow discharge profile has to be taken. This information is of high interest for battery modelling.

Example

In the example the major results are shown of capacity test with a LFP cell. Unfortunately the charge rates were not taken identical to the discharge rate. Also, no constant voltage discharge has been applied. The prescribed currents are used and I_{max} (3 I_t) has been added. The voltage measurement is shown in Figure 6 against time and Figure 7 A against capacity. For the charge curves the capacity is calculated by adding the previous discharge capacity. The transition to constant voltage charging appears for 1 I_t at 95% SOC. Figure 7 B shows the temperature increase. This cell is hardly warming up, even at 3 I_t. Figure 8 shows the Peukert equation derived by a power law trend line.

Figure 9 compares the capacities as function of discharge rates for two brands with identical shape and almost identical capacity at 1/25 I_t. In these tests a constant voltage discharge has been applied. It appears that the C_{25} capacity can be recovered for all discharge rates. The second brand is losing a lot of capacity at rates above 1 I_t.

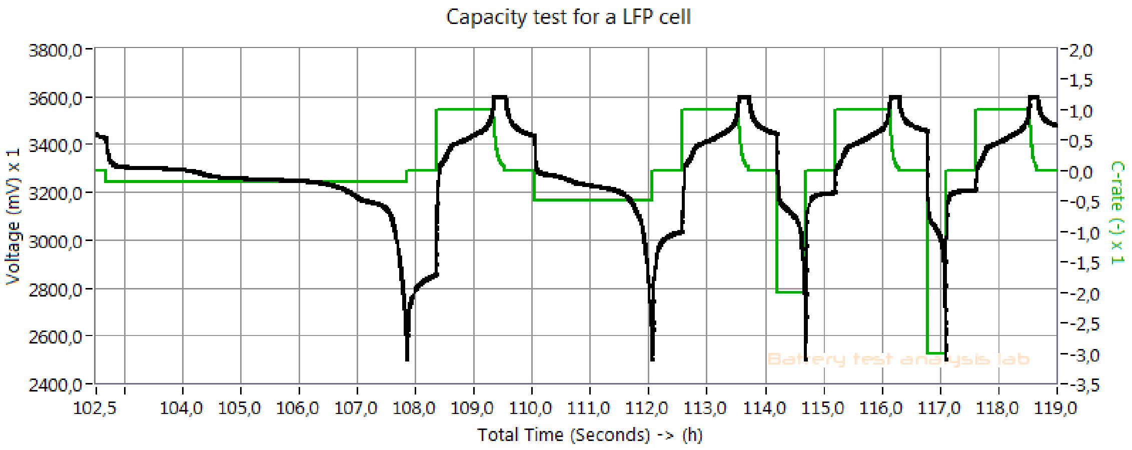


Figure 6: The capacity test against time. The cell voltage and the C-rate is shown.

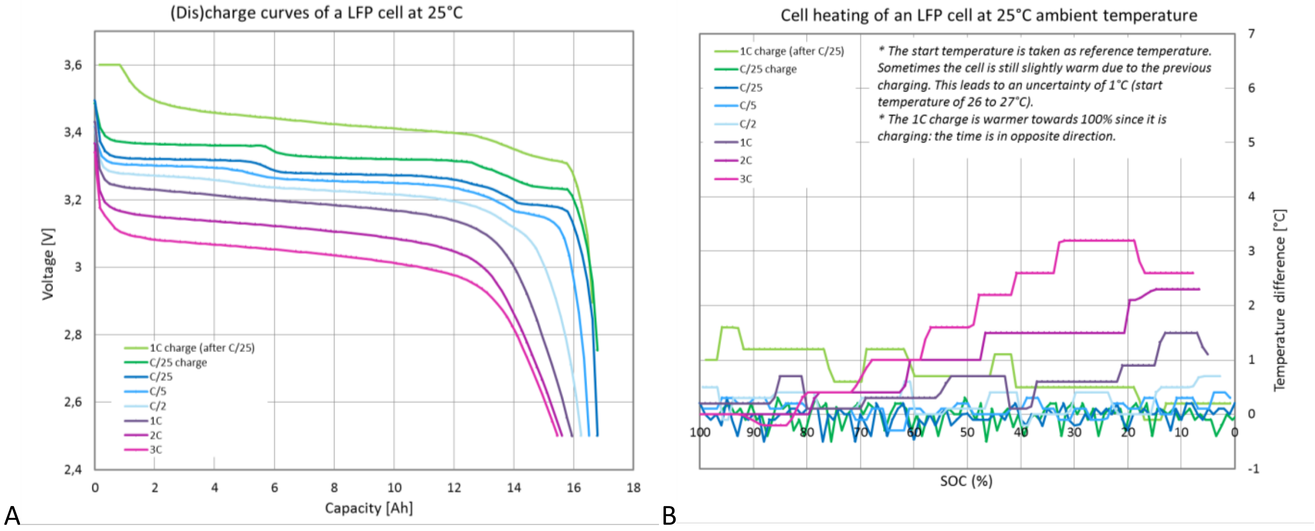


Figure 7: (A) the discharge and charge curves against capacity. (B) the temperature increase against SOC.

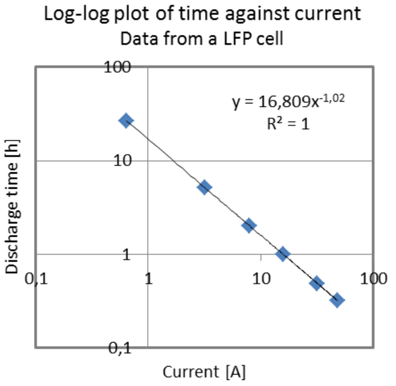


Figure 8: Derivation of the Peukert equation.

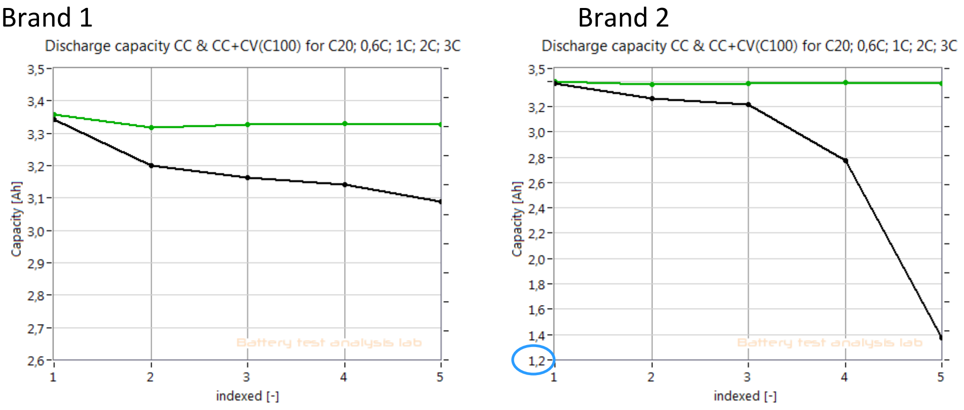


Figure 9: The effect of discharge rate (written in the graph titles) on the capacity for two brands. Also the result of the CC-CV discharge is shown leading to the C_{25} capacity (green).

Low C-rate cycle / Slow (dis)charge curve

[This test item is elaborated by: *SPICY, VITO, G.Mulder*]

Test intention

This test derives the cell capacity at low rate and to provides the low rate voltage curves, both for charge and discharge, that are used for cell modelling. It is mostly useful for battery modelling. The discharge rate is so slow that the increase in battery cell resistance has no influence on the capacity.

Application(s)

The test result can be directly used. The cell discharge and charge voltage curves are necessary for battery cell modelling. It is the input for the Incremental capacity analysis and the Differential capacity analysis. The charge and discharge curve can be averaged to get an idea of the cell EMF.

Test approach

In the test a cell is discharged and charged with C/25,.

Test equipment

The needed equipment is:

- a battery cell tester.

Test procedure

1. For the data acquisition during the test a measurement every minute and for every 1 mV change, and for every 0,2 K change is recommended.
2. The battery cell is tested at 25±2°C. It is acclimated sufficiently long in the test room.
3. The battery cell has to be charged as described in the standard cycle, maximally 48 h before.
4. The cell is discharged

Test duration

4 days.

Difference with similar methods in standards or usual practice

The method does not exist in standards.

Post-processing

The supposed EMF can be derived from the test by averaging the slow charge and discharge curve.

Comparison with EMF after pulse tests

Incremental capacity analysis (Dubarry)
Differential capacity analysis (Jeff Dane)

Example

To be inserted

Constant power discharge test

[This test item is elaborated by: Spicy project, Mikel Arrinda]

Test intention

The Constant Power Discharge test is designed to determine battery capacity and energy during a constant power discharge.

Application(s)

The test results (capacity and energy content) can be used directly as key data of the battery cell. The voltage graphs and the heating behaviour can be used to verify battery models. The effect of the temperature on the energy density can be characterised.

Test approach

The test consists on discharging charged cells at constant power values until cut-off voltage, several times at different discharge powers, where the discharge power values are set between maximum and minimum power rates that the cell can provide continuously. The procedure is repeated for different ambient temperatures. The cutoff voltage, maximum and minimum currents and temperature must also remain within the limits specified by the manufacturers.

Test equipment

In order to perform the test, the following equipment is needed:

- battery cell tester;
- temperature or climate chamber;
- temperature sensors.

Test procedure

The test described below covers a full parametrization of the power capability of the cell.

Discharge Power rates

Default power values are those required to remove 75%, 50%, 25% of battery energy in one hour (discharge to rated capacity or termination limits) limited up to the maximum allowed discharge rate by the manufacturer.

Temperatures

Recommended: 5, 25, 45°C.
Optional: low temperatures: 0, -10 and -20°C at discharge. For charge the lowest permitted temperature according to the manufacturer has to be used.

The battery behaviour is very temperature depending due to the chemical reactions and the transport phenomena inside the battery cell. Since most battery applications lie between 5 and 45°C this is the necessary range. For consumer and outdoor batteries a (sub)zero temperature range may be needed.

Step-by-step procedure

1. For the data acquisition during the test a measurement every minute and for every 20 mV change, every 0.05 C change and for every 0.2 K change is recommended.
2. The battery cell has to be charged as described in the standard cycle, maximally 48 h before.

3. A rest of 60 min is applied. For the data acquisition a measurement every minute and for every 20 mV change and for every 0.05°C change is recommended.
4. The discharge at constant power is applied until minimum allowed cell voltage. The rates to be applied are defined above.
5. A rest of 60 min is applied.
6. The charge at constant current is applied until the maximum allowed cell voltage. The rates to be applied are defined by the manufacturer (nominal current rate).
7. A constant voltage charge is applied at the maximum allowed voltage until the rate prescribed in the slow discharge test.
8. A rest of 60 min is applied
9. The steps 3, 4, 5 and 6 are repeated another 2 times (the constant power discharge is performed 3 times).
10. The test is repeated for every power rate.

The cell temperature is followed and must be within the allowed limits as prescribed by the manufacturer.

After changing the temperature according to the above described list, two hours is waited before starting a discharge. The equivalent holds if the battery cell has to be heated before charging is allowed.

If the relaxation after (dis)charge is important, e.g. to find the EMF, then the rest time may be increased or a relaxation criterion can be introduced like less change than 5 mV/h.

A heat camera can be used, especially for power rates higher than the nominal ones.

Test duration

In case only one temperature and one power rate is investigated, the duration of the entire procedure depends mainly on the applied power rate.

$$Test\ duration \approx \left(3 \cdot \frac{Nominal\ Power\ Rate}{Selected\ Power\ Rate}\right) + 3$$

Difference with similar methods in standards or usual practice

The same kind of test procedure can be also identified in manuals and guides which are public available and introduced by organization or committees, e.g.:

- *USABC Electric Vehicle Battery Test Procedures Manual.* The manual describes the Constant Power Discharge Test, which is analogous to the procedure introduced above. In this case, the test intention differs from the test intention explained here:

  > "The purpose of this testing is to perform a sequence of constant power discharge/charge cycles that define the voltage versus power behavior of a battery as a function of depth of discharge. This testing characterizes the ability of a battery to provide a sustained discharge over a range of power levels representative of electric vehicle applications. Constant power discharges are similar to constant speed vehicle operation in their effect on a battery."

Post-processing

Specific data deliverables include plots of voltage vs. time and current vs. time. The obtained energy throughput and capacity throughput are health indicators of the cell.

Example

There are different examples on-line. An example is available in:
http://www.richtek.com/Design%20Support/Technical%20Document/AN024
Here the constant power discharge test is performed in order to confirm that fuel gauge can provide accurate SOC report at different load conditions (Figure 10 and Figure 11).

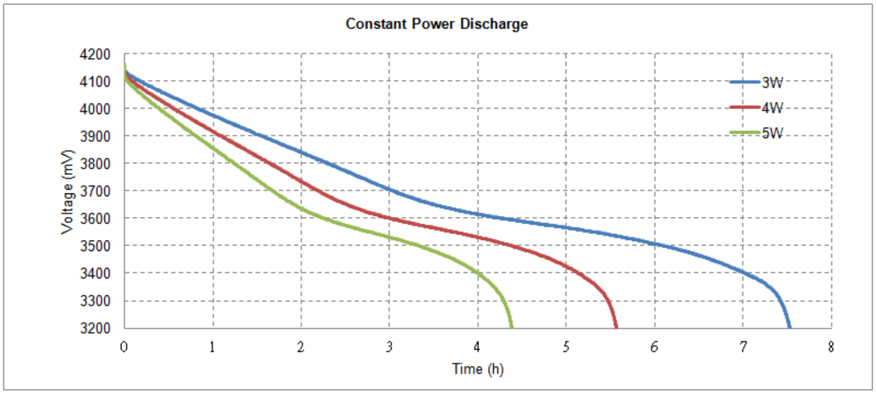


Figure 10: Voltage vs time plot using 3W, 4W and 5W constant power discharging rates until voltage <3.2v.

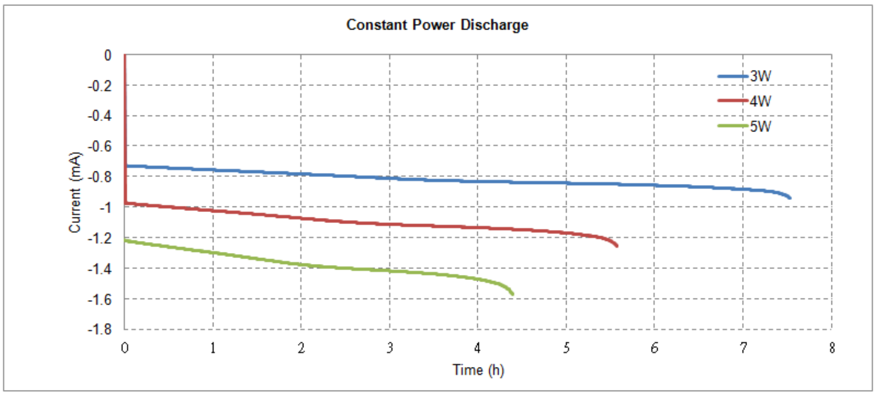


Figure 11: Current vs time plot using 3W, 4W and 5W constant power discharging rates until voltage <3.2v.

Another example is available in:
https://www.ecig.eu/pavblog/blog?id=22
Here different constant power discharge rates are applied to a group of 18650 Li-ion cells (Figure 12). The capacity throughout and energy throughout are used to compare the different 18650 tested cells in terms of capacity and energy. The capacity loss after testing is also provided (Figure 13).

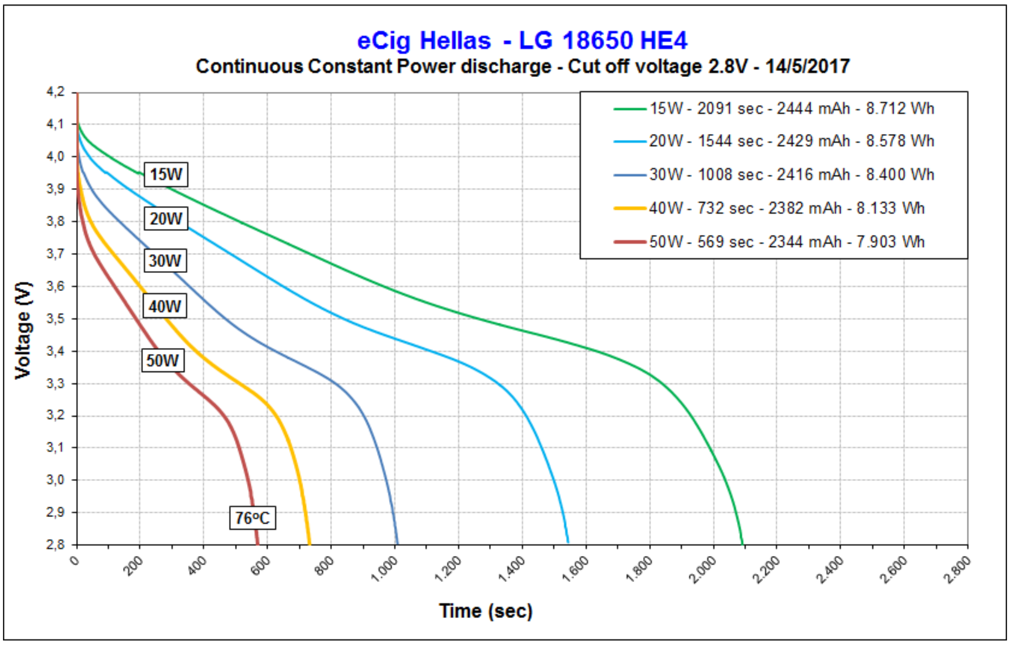
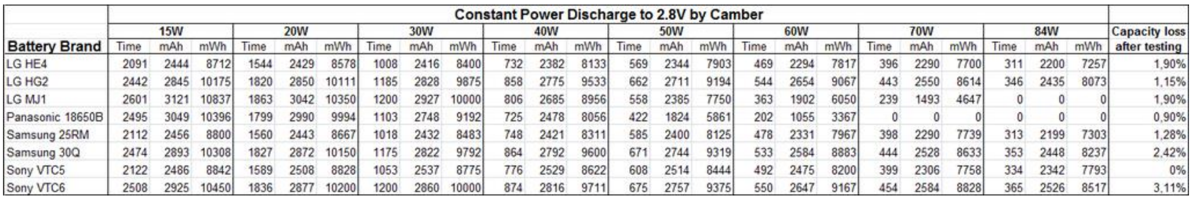


Figure 12: The LG 18650 HE4 Li-Ion cell (2500 mAh and 9.25 Wh) is tested at different constant power discharge rates.



	Constant Power Discharge to 2.8V by Camber																								
	15W			20W			30W			40W			50W			60W			70W			84W			Capacity loss after testing
Battery Brand	Time	mAh	mWh	Time	mAh	mWh	Time	mAh	mWh	Time	mAh	mWh	Time	mAh	mWh	Time	mAh	mWh	Time	mAh	mWh	Time	mAh	mWh	
LG HE4	2091	2444	8712	1544	2429	8578	1008	2416	8400	732	2382	8133	569	2344	7903	469	2294	7817	396	2290	7700	311	2200	7257	1,90%
LG HG2	2442	2845	10175	1820	2850	10111	1185	2828	9875	858	2775	9533	662	2711	9194	544	2654	9067	443	2550	8614	346	2435	8073	1,15%
LG MJ1	2601	3121	10837	1863	3042	10350	1200	2927	10000	806	2685	8956	558	2385	7750	363	1902	6050	239	1493	4647	0	0	0	1,90%
Panasonic 18650B	2495	3049	10396	1799	2990	9994	1103	2748	9192	725	2478	8056	422	1824	5861	202	1055	3367	0	0	0	0	0	0	0,90%
Samsung 25RM	2112	2456	8800	1560	2443	8667	1018	2432	8483	748	2421	8311	585	2400	8125	478	2331	7967	398	2290	7739	313	2199	7303	1,28%
Samsung 30Q	2474	2893	10308	1827	2872	10150	1175	2822	9792	864	2792	9600	671	2744	9319	533	2584	8883	444	2528	8633	353	2448	8237	2,42%
Sony VTC5	2122	2486	8842	1589	2508	8828	1053	2537	8775	776	2529	8622	608	2514	8444	492	2475	8200	399	2306	7758	334	2342	7793	0%
Sony VTC6	2508	2925	10450	1836	2877	10200	1200	2860	10000	874	2816	9711	675	2757	9375	550	2647	9167	454	2584	8828	365	2526	8517	3,11%

Figure 13: Comparison of LG, Samsung and Sony 18650 Li-ion cells (2500 mAh and 9.25 Wh) applying constant power discharge tests at 15W, 20W, 30W, 40W, 50W, 60W, 70W and 80W power discharge rates.

Dynamic stress test

Test intention

The intention is to evaluate the performance of the battery for automotive application. This specific regime can effectively simulate dynamic discharging and can be implemented with equipment at most test laboratories and developers. More information about this test can be found on: “ELECTRIC VEHICLE BATTERY TEST PROCEDURES , rev 2, USABC”

Application(s)

For driving-cycle testing of USABC batteries, the initial SFUDS profile was modified into the Dynamic Stress Test (DST). The intention of this test is clearly to evaluate the battery performance specifically for automotive application.

Test approach

The test consits of applying constant power steps to the battery. This defined power profile is scaled to the technology, size and characteristics of the cell under test. The test starts with a battery fully charged and the DST is normally applied continuously. This discharge regime is continued until either the end-of-discharge point specified in the test plan or inability to follow the test profile within a battery limit, whichever occurs first, has been reached. End-of-discharge is normally specified as: (a) the rated capacity in A·h, for performance or Reference Performance Tests; or (b) 80% of the rated capacity in A·h, for baseline life cycle tests

Test equipment

In order to perform the test, the following equipment is needed:

- battery cell tester;
- temperature or climate chamber;
- temperature sensors.

Test procedure

The comprehensive test described below covers a full parametrization of the power capability of the cell which can be considered as a trade-off between full behaviour understanding and time consume. The procedure can be shorted based on the different applications. Some hints on how to adapt the procedure based on different cases are given at the end of this section.

100% of DST power definition

There might be three different options to calculated the 100% of power for later use in the profile:

i) USABC goal: in general, 100% on this table is intended to be 80% of the USABC peak power goal (at 80% DOD) for a technology;. As an example, if this profile is scaled to 80% of the USABC midterm goal of 150 W/kg, it would have a peak power of 120 W/kg and an average power of 15 W/kg. A lower power version of this profile may be used for testing batteries that cannot be operated at the nominal peak power requirement. The test is designated DSTn, wherein is the scaled peak power value in W/kg.

ii) Using manufacturing data: however, the test may be performed based on manufacturer's ratings in some cases. Taking this data as a reference, the peak power is calculated by multiplying the nominal voltage by the maximum rate.

iii) Using Peak Power test (Using Procedure #3 from USABC BATTERY TEST PROCEDURES MANUAL, rev2. The peak power test is to be performed at 10 depths-of-discharge, from 0% DOD to 90% DOD in 10% intervals, during a single discharge. These DOD values are achieved by successively discharging the battery from a fully charged state to each % DOD at the Base Discharge Rate (see Terminology on next page). After the 90% DOD step sequence is performed, the battery is to be discharged at the Base Discharge Rate to 100% of its rated capacity (assuming this can be done without exceeding other discharge limits.) This test is performed with no regenerative energy applied to the battery.

   At each specified DOD, discharge the battery for 30 seconds at the High Test Current (see Terminology on the next page.). The same current values are used at all 10 DOD levels. However, the battery must remain above the Discharge Voltage Limit during each step, even if the step current has to be reduced. (Discharge Voltage Limit is established only once at beginning of life; see Terminology.) Note that the battery is to be discharged for 30 seconds at the Base Discharge Rate before applying the first (0% DOD) High Test Current step. The equations used for maximum power calculation are described below. The measured power at 50% of SoC or DoD is taken as reference for the rest of the test.

$$R = \frac{\Delta V}{\Delta I} = \frac{V_2 - V_1}{I_2 - I_1}$$

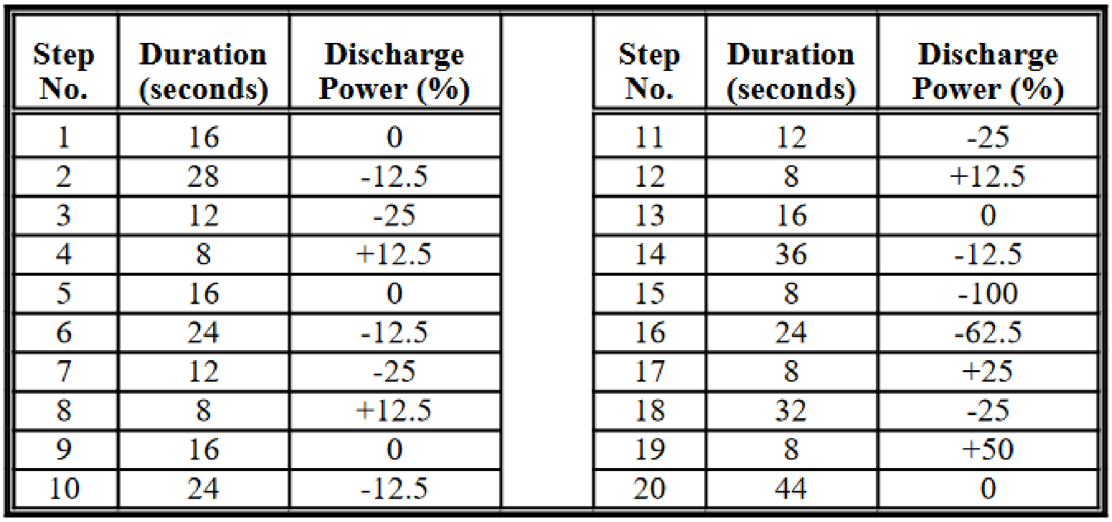
$$V_{IRFREE} = V - IxR$$

$$I_{base} = \left(12 * C_{nom} + I_{high}\right)/35$$

$$P = \min\left\{\frac{-2}{9}\frac{V_{IRFREE}^2}{R}, -V_{LowLmit}\frac{V_{IRFREE} - V_{LowLmit}}{R}, I_{MAX}(V_{IRFREE} + RxI_{MAX})\right\}$$

Step-by-step procedure

The battery will be charged and temperature stabilized in accordance with the manufacturer's recommended procedure or as otherwise specified in the test plan. Commencing from full charge, the battery will be discharged by applying the scaled DST power profile. The 360 second DST test profiles are repeated end-to-end with no time delay (rest period) between them. The maximum permissible transition time between power steps is 1 second, and these transition times are included in the overall profile length (i.e., a DST test profile is always 360 seconds long). This discharge regime is continued until either the end-of-discharge point specified in the test plan or inability to follow the test profile within a battery limit, whichever occurs first, has been reached. End-of-discharge is normally specified as: (a) the rated capacity in A·h, for performance or Reference Performance Tests; or (b) 80% of the rated capacity in A·h, for baseline life cycle tests. The end-of-discharge point is based on net capacity removed (total A·h - regeneration A·h).



Step No.	Duration (seconds)	Discharge Power (%)		Step No.	Duration (seconds)	Discharge Power (%)
1	16	0		11	12	-25
2	28	-12.5		12	8	+12.5
3	12	-25		13	16	0
4	8	+12.5		14	36	-12.5
5	16	0		15	8	-100
6	24	-12.5		16	24	-62.5
7	12	-25		17	8	+25
8	8	+12.5		18	32	-25
9	16	0		19	8	+50
10	24	-12.5		20	44	0

Figure 14: DST power profile defined by USABC for battery evaluation

Data acquisition. 500ms constant sample time should be sufficient since the main purpose of this test is to evaluate the performance of the battery for automotive application.

Test duration

The duration of single DST cycle is constant, 360 second. If the cycle is applied continuously to the battery, approximately the duration can be calculated as follows:

1. Chargin and temperature stabilization : $t_1 = 2h$
2. DST cycle : $t_2 = Wh_{cell} / (P_{max}/8)h$
3. Cell stabilization: $t_3 = 1h$

The test duration should be calculated using $t_1 + t_2 + t_3$

Difference with similar methods in standards or usual practice

FUDS (USABC battery test manual, rev 2)- a second-by-second dynamic regime calculated using the FUDS vehicle time- velocity profile with a hypothetical electric van having a peak power demand of 111 W/kg and average power of about 10 W/kg. The actual profile used for testing, sometimes referred to as FUDS79, is derived by artificially limiting the peak power demand to 79 W/kg. This "clipped" power profile can then be scaled to any desired maximum power demand.

Post-processing

The are some equations that need to be calculated before implementing the test, specially for 100% of Power rate calculation and subsequents levels.
For Post-processing and bearing in mind the objective of this test, it is interesting to track the discharged capacity and the energy over the lifetime. Specific data deliverables include the value of the maximum power step, the number of profiles completed, the capacity of the test unit (both gross and net A·h and kW·h), and any deviations from the procedure (e.g. reduced regen limits, where they are encountered and the capacity where such reductions are not in effect.) Note that the designation DSTn should be used to report the scaled peak power level for a DST test e.g., DST 120 indicates a test scaled to 120 W/kg.

Example

In Figure 15 it is shown the response of a NMC cell under 3 consecutive DST cycles. Since the duration of one cycle is 360 seconds, the completion of three cycles is 1080 seconds long.

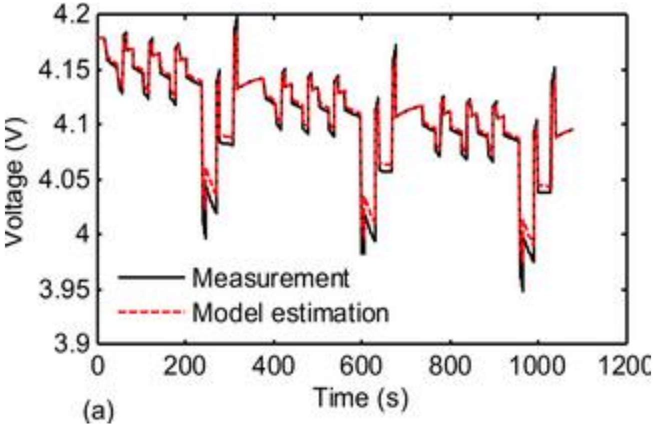


Figure 15: NMC cell discharge under DST profile.

As aforementioned, it is interesting to track the discharged capacity or the energy over the lifetime of the battery. In SPICY project this specific cycle was applied every check test to different cells. Some of them they were cycled at different conditions and some other ones stored at different conditions.
Error! Reference source not found. –a shows the evolution of the discharged capacity under DST versus capacity retention. The cells were cycled at 5ºC and at different charging rates: 0.3C, 1C and at 2C. The discharge rate was kept constant at 1C. According to the results the discharged capacity was lower for those cells charged at higher C rate, as a consequence of bigger impedance rise induced by a higher charging rate.
Similarly, **Error! Reference source not found.** –b shows the evolution of the same indicator for those cells stored at different SoC (30%, 65% and 100%) but at the same ambient temperature. According to these results, in this particular aging, the discharged capacity was identical in all the cells, for the same capacity retention respect to the initial value.

Pulse test

[This test item is elaborated by: Spicy *project, Cidetec, Andrea Marongiu*]

Test intention

The pulse test is known in different standard also as Hybrid Pulse Power Characterization (HPPC) test. Its goal is the analysis of the power capability of the investigated battery under different conditions, i.e. charge and discharge, current rate, ambient temperature and state-of-charge (SoC).

Application(s)

The results can be applied for:

1. Parametrization of an equivalent electric circuit model for the reproduction of the electric battery behavior. Each of the obtained pulse can be fitted with a combination of passive elements, in general resistors and capacitors.
2. Parametrization of battery state detection algorithms for different roles, i.e. state of charge, power prediction, state of health etc.

Test approach

The test consists in exciting the battery with constant current pulses of a defined duration for different current rates in directions, charge and discharge, after a defined relaxation time. The procedure is repeated for different values of SoC and for different ambient temperature. The pulses must always remain within the limits specified by the manufacturers, in term of cutoff voltage, maximum and minimum currents and temperature.

Test equipment

In order to perform the test, the following equipment is needed:

- battery cell tester;
- temperature or climate chamber;
- temperature sensors.

Test procedure

The comprehensive test described below covers a full parametrization of the power capability of the cell which can be considered as a trade-off between full behaviour understanding and time consume. The procedure can be shorted based on the different applications. Some hints on how to adapt the procedure based on different cases are given at the end of this section.

Step-by-step procedure

The test procedure can resumed as followed:

1. The battery is placed inside a climate/temperature chamber and the temperature is set at 23 °C. A rest period of 3 h is set in order to obtain battery acclimatization.
2. The battery is fully charged by applying a constant current procedure as defined by the manufacturer (datasheet) until the cut-off voltage is reached. Thereafter a constant voltage process is applied at cut-off voltage until the current has decreased to a value smaller than C/25 or C/50 (number to be adapted based on the characteristic of the battery tester) or until the time is bigger than 2 h.
3. A rest of 30 min is applied.
4. The battery is discharged at constant current is applied until minimum allowed cell voltage. The current applied is 0.5C and can be adjusted based on the datasheet. The obtained full discharge capacity (Ah-throughput) defines the total actual battery capacity which is considered for the calculation of the SoC during the rest of the procedure.
5. The battery is fully charged following the same procedure described at point 2.

6. The temperature of the climate/temperature chamber is set to the investigated temperature. A rest period of 6 h is set in order to obtain battery acclimatization.
7. The battery is discharged at constant current of 0.5C with a depth-of-discharge (DoD) of 5% (SoC variation of 10% calculated with the battery capacity measured at point 4). The process is interrupted if the cutoff voltage is reached.
8. A rest period of 1 h is set.
9. The battery is discharge with a constant current rate of I_1 for duration of 18 s of until the cut-off voltage is reached.
10. A rest period of 60 s is set.
11. The battery is charged with a constant current rate of I_1 for a duration of 18 s or until the cut-off voltage is reached.
12. A rest period of 60 s is set.
13. Repeat the points 9 to 12 of the current rate I_m for m = 1,2,…n.
14. Repeat the points 7 to 13 until the SoC is equal to 10% or until the cut-off voltage is reached.
15. The temperature of the climate/temperature chamber is set to 23 °C. A rest period of 6 h is set in order to obtain battery acclimatization.
16. Repeat the points 5 to 15 for all the selected and chosen temperatures.

Data acquisition. The following data acquisition methods can be applied:

- Points 3, 8, 10, 12: a measurement every minute or every 20 mV change or every 0.5 °C change is recommended.
- Points 2, 4, 5, 7 : a measurement every 5 s or every 20 mV change or every 0.5 °C change is recommended. Adaptation of the voltage variations for the data acquisition should be modified based on the characteristics of the battery chemistries, e.g. in case of LFP|G or LFP|LTO configuration a variation of 5 mV or smaller should be considered.
- Points 9, 11: a measurement every 10 or 20 ms (if this sample time is not possible, then the minimum allowed by the battery tester should be set) or every 3 mV change or every 0.5 °C change is recommended.

Procedure adaption and variants

The procedure described above can be modified based on the application and on the available testing time setting the following parameters.

Current rates. In case of limited time, only one current rate (point 13) can be investigated. In case of different current rates, these have to be adapter based on the type of cell (high power or high energy) and on the data released by the manufacturer. For the sake of simplicity, in a general case current rates of 0.2C, 1C and 5C can be considered for the charge and discharge pulses at points 9 and 11 (when these values are within the limits specified by the manufacturer).

Temperature. Generally, at least three temperatures should be investigated: one value in normal range (23-25 °C), one in hot/warm range (40-45 °C) and one in the cold range (0-10 °C). Especially the last value has to be adapted based on the limits specified by the manufacturer, together with charge current rate, in order to avoid fast degradation due to lithium plating).

SoC. The value of the DoD used in the procedure at point 7 is 5%. In case of limited time this could be increased to 10%. A value below 5% does not give additional information and only increase the time of test.

Pulse duration. The duration of the pulses can be adapted based on the considered application. The values indicated at points 9 and 11 can be considered feasible for electric vehicle and plug-in hybrid electric vehicle applications. In some cells, the use of pulses of 30 s duration can allow, independently of the current rate, to analyse part of the relaxation dynamics, and to use a more comprehensive model approach, as explained in the next sections. In case of hybrid application, where more power is requested in a shorter time period, pulses smaller than 10 s could also be employed (e.g. 5 s).

Test duration

In case only one temperature and one current rate is investigated, with pulses tested every 10% SoC, the duration of the entire procedure is approx. one day.

Difference with similar methods in standards or usual practice

Similar test procedure as the one described above can be found in norms and standard already published and promulgated. Regarding the norms, the example of pulse test can be found in:

- *IEC 62660-1 - Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 1: Performance testing.* In the section of related to the power test, different pulses in charge and discharge with different current rates are applied for the determination of the cell power capability. Some differences can be found in the duration fo the pulses, magnitude of the used current and relaxation time.
- *ISO 12405-2 - Electrically propelled road vehicles - Test specification for lithium-Ion traction battery systems – Part 2: High energy applications.* The norm describes a pulse power characterization profile, which is very similar to the procedure introduced above. Differences can be found again in the duration of the pulses, magnitude of the current and relaxation times.

Moreover, the same kind of test procedure can be also identified in manuals and guides which are public available and introduced by organization or committees, e.g.:

- *U.S. Department of Energy Vehicle Technologies Program - Battery Test Manual For Low-Energy Energy Storage System for Power-Assist Hybrid Electric Vehicles.* The manual describes the hybrid pulse power characterization test, which is analogous to the procedure introduced above.

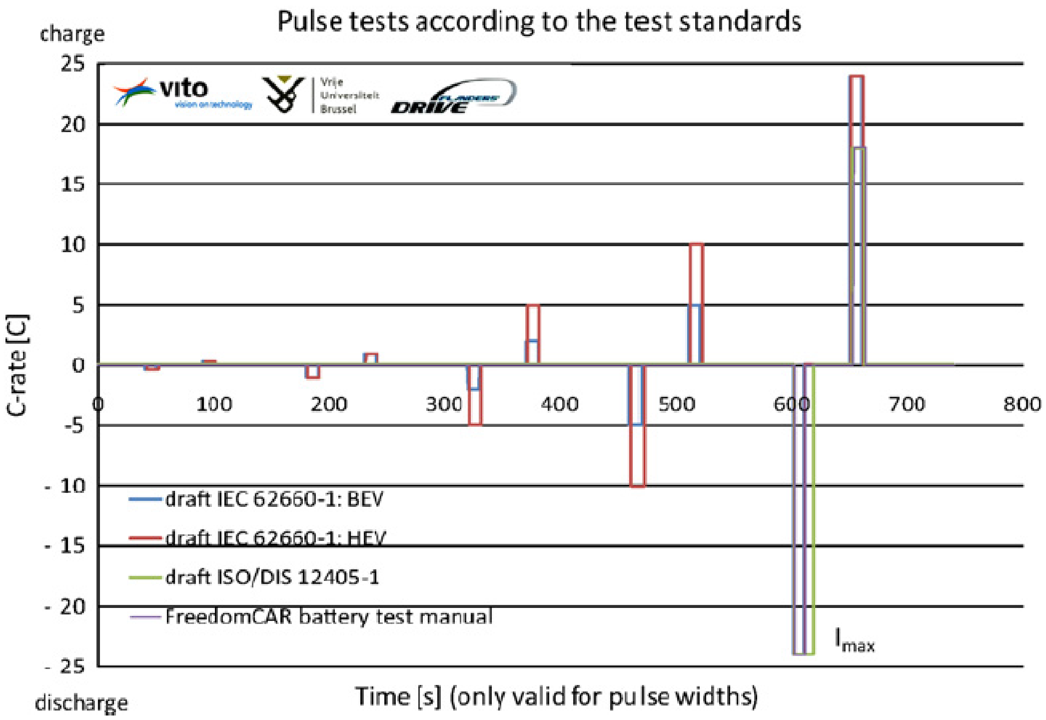


Fig. 2. Pulse trains as found in the pulse tests in the standards. The time between pulses is not visualised according to the standards.

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Post-processing

The Post-processing of the obtained data can be carried out in two different manners:

1. From the entire test data, the single pulses are extracted in terms of battery voltage and current. For each pulse, different resistance values can be evaluated, as shown in Figure 16:

$$R_{discharge\ 18\ s} = \frac{V_1 - V_4}{I}$$

$$R_{discharge\ 10\ s} = \frac{V_1 - V_3}{I}$$

$$R_{discharge\ 2\ s} = \frac{V_1 - V_2}{I}$$

   The same analysis has to be carried out for the charging process, for all the measured SoC, for each temperature and for the different current rates.

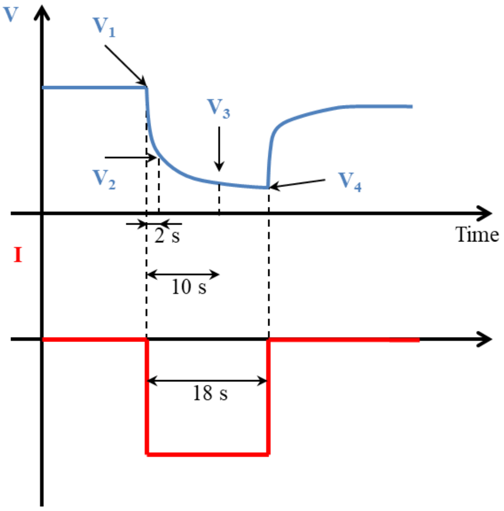


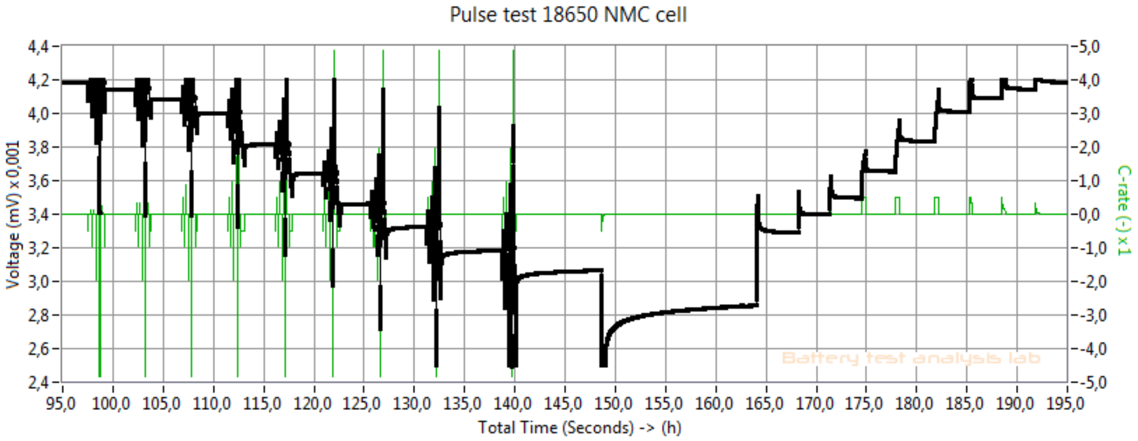
Figure 16: Representation of the battery current and voltage for a pulse excitation during the discharge process for a defined SoC.

2. From the entire test data, the single pulses are extracted in terms of battery voltage and current. Each pulse can be then fitted with an equivalent electric circuit model. The characteristic and structure of the circuit depends on the duration of the pulses and on the application. Generally for pulses of limited duration (below 20 s) a resistance in series with an R|C branch can be considered as a suitable choice. For some specific batteries and application, in case of pulses of 30 s duration, the use of equivalent electric circuit model of second order (two R|C branches) might allow the use of a single model valid for different current rates. This means that only pulses with one current rate has to be performed. The fitting procedure can be carried out by means of software such as Excel© or Matlab©.

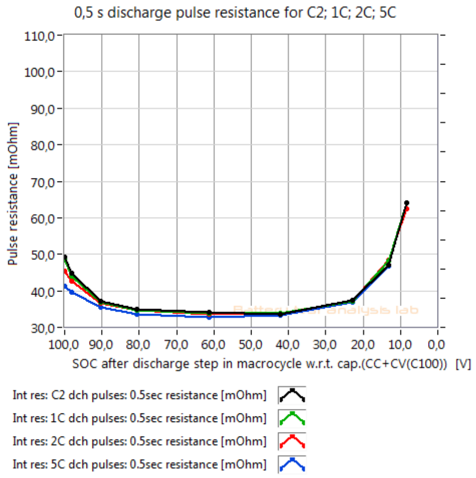
Example

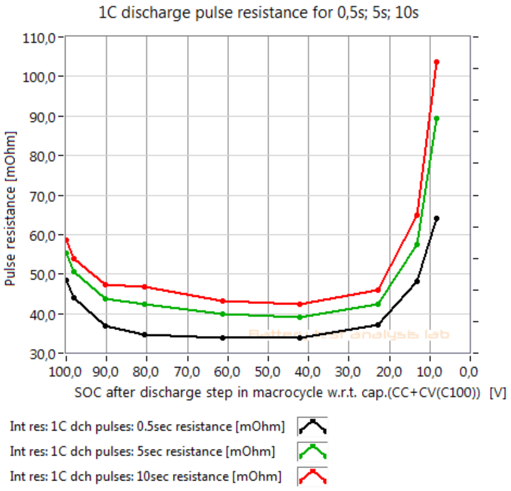
To be inserted. Current graphs are not fully in line with the test set-up.

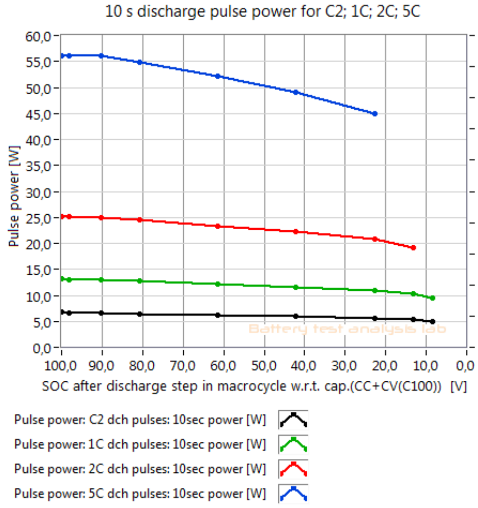
Pulse test:

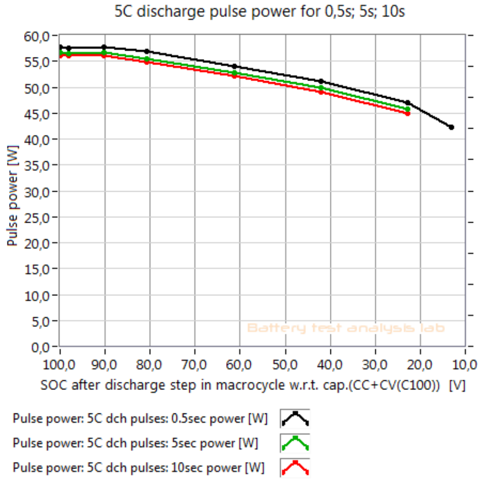


Results for pulse resistance and power:

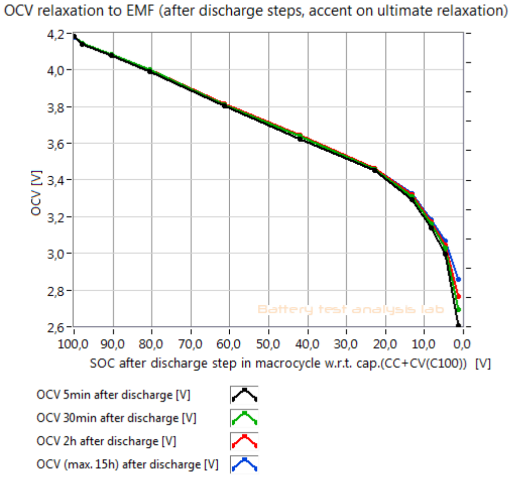


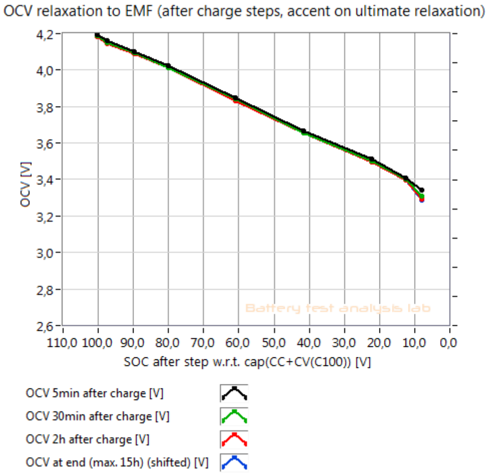




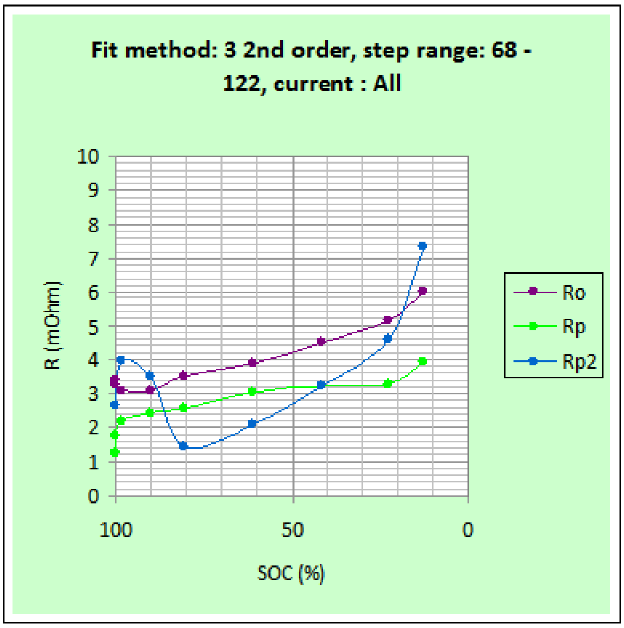


OCV relaxation from rest time (if period is long enough):





RC model that fits the data:



Thermal characterisation

[FiveVB, Philip Kargl (ViF), Wolfram Kohs (AVL)]

Test intention

The aim of this test is the determination of the heat distribution a cell is developing on its surface in operation.

Application(s)

The heat a cell is developing is an important input for thermal models, and the data are needed for conceptioning an appropriate cooling system for the cells in a module resp. in a battery pack.

Test approach

A cell is equipped with temperature sensors, thermally insulated as good as possible and then charged and discharged with defined currents.

Test equipment

Temperature sensors, a data logger, insulation material, a potentiostat or cycling system.

Test procedure

The cell to be tested is equipped with temperature sensors, the sensors should cover the whole surface, so that no blind spots remain. The assembly is then thermally insulated as good as possible, one could think of a pseudo-adiabatic setup. Only the cables needed are remaining imperfections; and even those can also be equipped with temperature sensors to calculate the heat flow / losses.
The cell is then charged and/or discharged with a defined current and the heat resp. more exactly the heat distribution on its surface is logged.

A second step is striping the insulation of the bottom of the cell and attaching it to a thermostated metal plate. The experiment is then repeated, the metal plate simulating a cooling system at

different temperatures, the resulting temperature gradient being logged. Further thermal information can be elaborated by using an arrangement of cells, and also by using an insulation which is similar to the final housing of the module.
If the cooling is intended to be done via the busbars, an analogous approach can be made.

Test duration

Difference with similar methods in standards or usual practice

No similar methods in the standards.

Post-processing

From the obtained temperature curves, an estimation of the different heat sources and sinks in the cell can be made **[1]**.
For this estimation, a reference point of the cell is chosen and the temperature of this point is taken as temperature for the whole cell. The temperature curve of this point can be used as reference for a 0D thermal model:

$$c_{h,cell}\frac{dT}{dt} = q_{irr} + q_{rev} + q_{cool}$$

q_{irr}, q_{rev} and q_{cool} are the heat contributions due to Joule heating, heating due to the electrochemical reaction and cooling. $c_{h,cell}$ is the heat capacity of the cell.

a. For an estimation of q_{cool} the cell is heated to a defined temperature. After this temperature is reached, the cell cools down back to the ambient temperature. The temperature curve is recorded. In this cooling region the contributions of q_{irr} and q_{rev} are zero and the temperature change is only due to cooling.

$$q_{cool} = \alpha(T - T_{ext})$$

α is the heat transfer coefficient, T_{ext} is the external temperature. If the heat capacity of the cell is known, this parameter can be obtained by fitting the calculated curve to the measurement.

b. q_{rev} can be estimated by cycling a profile with a charge and a discharge of the same current and the same length with enough rest time in between so that the cell reaches the thermal equilibrium after each cycle. The sign of q_{rev} depends on the direction of the current (heats during discharge; cools during charge). If one analyses the difference in temperature between the charge and the discharge cycle one can get an estimation for q_{rev}.

c. If q_{rev} and q_{cool} are known also the contribution of q_{irr} can be estimated from the temperature curve. Alternatively it can be estimated from the difference between cell voltage and OCV (overpotential). Therefore, an additional OCV measurement is required.

$$q_{irr} = I(U - U_{ocv})$$

Due to the simplifications this approach can only deliver a qualitative estimation of the heat sources in the cell.

[1] K. Onda, H. Kameyama, T. Hanamoto, K. Ito, *Journal of The Electrochemical Society*, **150** (3) A285-A291 (2003)

Example

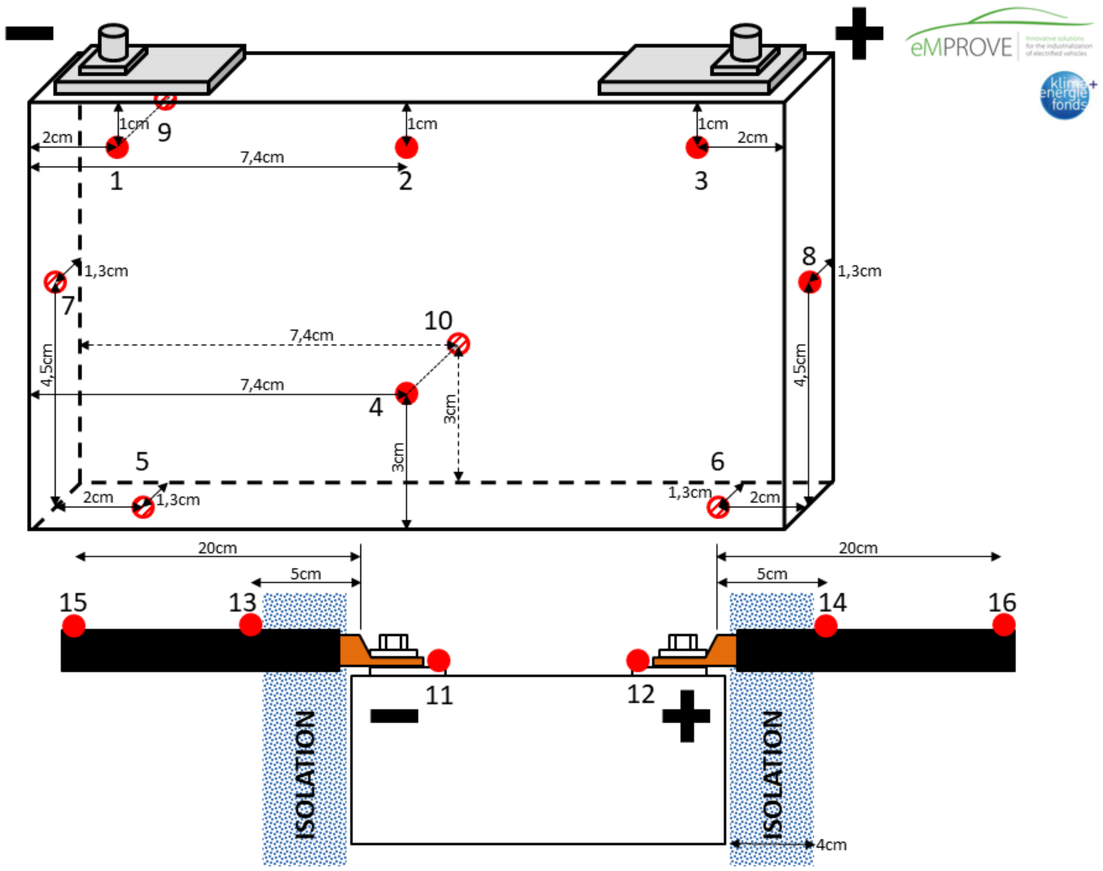


Figure 17: Example for an arrangement of temperature sensors on a prismatic cell.

Electrochemical impedance test

[This test item is elaborated by: Spicy *project, KIT, Arianna Moretti*
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Test intention

The test aim to obtain the cell impedance response and to monitor the variations occurring at different SOC and SOH. The break-down of the total impedance of the cell permits to obtain informations, without cell disruption, about contact and electrolyte resistance, charge transfer and interfacial resistances, transport limitations. The total impedance spectra can be analised qualitatively comparing the variations of the resistance values extrapolated from real axis intercept. Quantitative analysis can be performed via the construction of an equivalent circuit which permits to fit mathematically the different feature of the spectra.

Application(s)

The total impedance of the cell, and its break down into different contributions, can be used to examine the internal battery dynamics (e.g. charge transfer reaction on electrode/electrolyte interface and transport limitation in solid and liquid phase) to follow up the aging behaviour.

Test approach

The measurements are done at open circuit condition and performed at the BOL, MOL and EOL.
The EIS spectra are acquired at different SOC, from 100% to 0%. Between this two limits the cell is discharged at constant current to the desired SOC limiting the passed charge using the as reference tha value obtained from the Low C-rate cycle / Slow (dis)charge curve test described above.

Test equipment

The needed equipment is:

- a frequency response analyser preferably integrated in the battery cell tester to avoid to disconnect/connect cell.
- temperature controlled chamber.

Test procedure

The following describes the “loop” used to perfom the test:
Initial status: the cell is at 100%SOC

- Step 1- The cell is left to rest for 1 hour.
- Step 2- The complex impedance spectra is then acquired using the parameters reported below.
- Step 3- After the measurement the cell is let to rest for 10 minutes.
- Step 4-The cell is then discharged at 1 C to a value of 20% SOC lower than the previous one.

The cycle (from Step 1 to 4) is repeated until the last spectra at 0% SOC is recorded.
The 0%SOC is reached under constant current regime followed by a period of constant voltage until the current decays to a value lower than C/20. At any time it is recommended to limit the discharge step duration with not only the charge passed but with minimum voltage as well.

The parameters adopted for complex impedance spectra acquisition are the following:
Mode: potentiostatic
Amplitude: 5 mV_{rms}
Frequency range: from 10 kHz down to 10 mHz
Number of points for decade: 5-6

It can be recommended to minimize or control the impedance of the test leads such as the contribution of battery tester, cables, cell holder.

Test duration

In total, the test takes approximately 8 hours. The acquisition of each impedance spectra takes 12 minutes .

Difference with similar methods in standards or usual practice

A potentiostatic electrochemical impedance test is described in
IEC TS 62607-4 series on key control characteristics in nanomanufacturing Part 4-1: Cathode nanomaterials for nano-enabled electrical energy storage - Electrochemical characterisation, 2-electrode cell method.

It is specifically for coin cells filled with nanomaterials. However, no specificity to these materials seems to be given. A signal amplitude of 10 mV is prescribed and a frequency range of 100 kHz down to 10 mHz.

Three differences exist:

- The test described here in the white paper starts with 10 kHz. Going higher does normally not reveal battery behaviour, but shows only the cabling inductance.
- The signal seems higher with 10 mV but this is close to 5 mV_{rms}.
- The standard does not prescribe SOC levels.

Post-processing

Figure 18 reports the voltage vs time profile obtained following the procedure described above. The cell is discharged from 100%SOC to 0%SOC using 20% SOC steps. After the cell equilibration for 1h the complex impedance spectra is acquired as shown by the red trace representing the scanned frequencies.

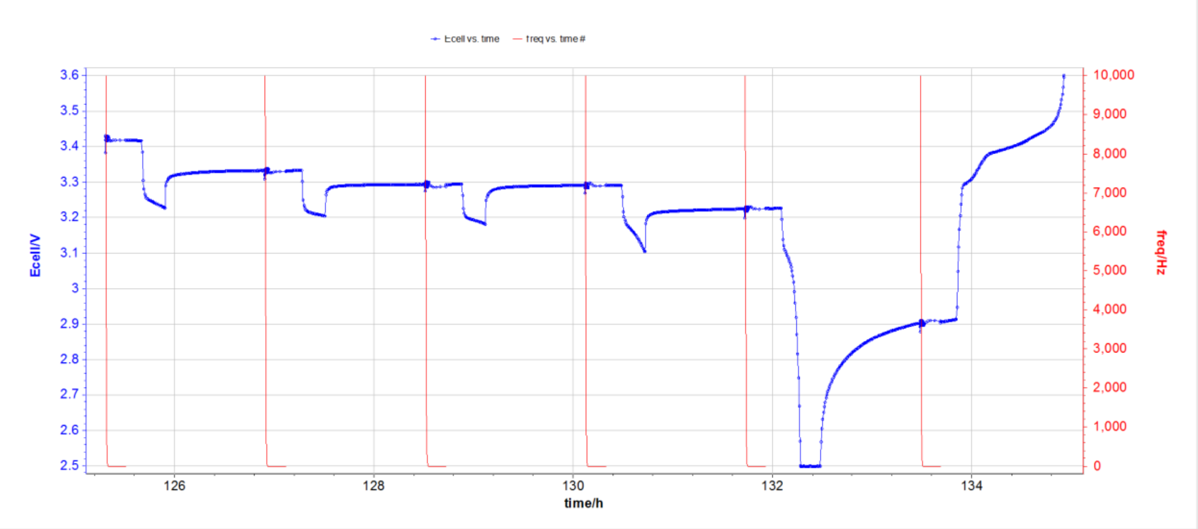


Figure 18: Representation of the test procedure result: in blue the voltage vs time trace and in red the scanned frequencies showing the points at which the impedance spectra where collected for the different SOC values.

The typical variation of the spectra, represented as Nuquist impedance, with SOC is reported in Figure 19a. The spectra are characterized by an inductive part at high frequency (>130 Hz), a semicircle and linear tail at low frequency. As can be better appreciated in Figure 19b, the intercept with the real axis is attributed to the sum of the contribution coming from the electrolyte, the contact resistance (between the porous electrodes and current collectors) and the external circuit and connections. The latter may vary when different set-up (cell holder, cables connections, instrument) are used. The semicircle resistance Rsc is attributed to fast interfacial phenomena like charge transfer while the resistance at low frequency Rt is dominated by the solid state diffusion. The total resistance, Rtot, is the sum of both.

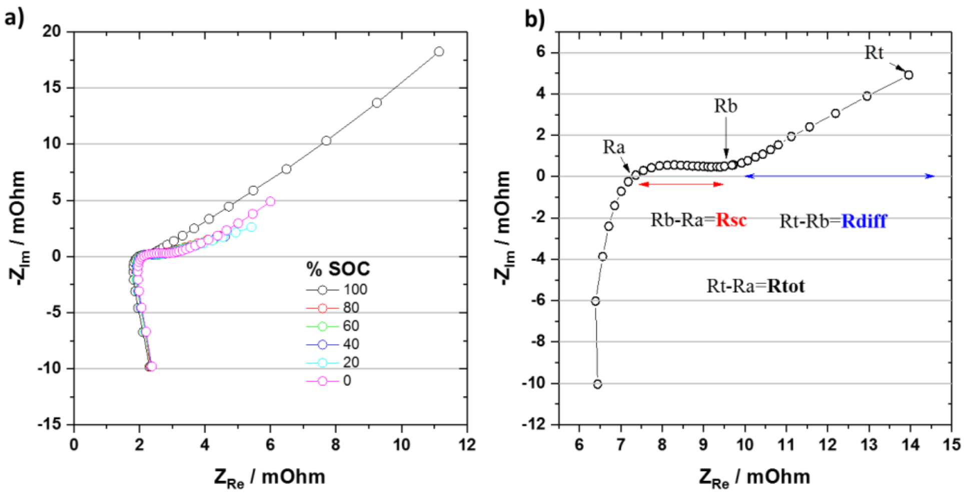


Figure 19: Nyquist impedance. a) variation of the spectra with cell SOC and b) break-down of impedance contributions.

The qualitative analysis can be done extrapolating the values of Ra (intercept with x-axis), Rb (intercept of the semi-circle with x-axis) and Rt (last point measured) and calculating the Rtot, Rsc and Rdiff. The procedure is certainly affected by operator experience and the quality of the recorded spectra. It may be helpful to keep track for each extrapolated point of the corresponding frequency value and to use it as a reference for multiple spectra analysis. Note that this requires the spectra to be collected with the same points per decade.

Quantitative analysis can be performed using different dedicated software applications which require the construction of a suitable equivalent circuit. Basically the electrochemical reactions at the electrodes are represented by a capacitor (interfacial capacitance), a resistance (for the charge transfer) and a Warburg resistance (to take into account the diffusion limitations). Additionally the resistance of the electrolyte (Ra) and an inductive component (to account for test leads) are included. A simple equivalent circuit is reported in Figure 20. More complicate circuits can be built up to fit the spectra, but the number of component should be kept as low as possible.

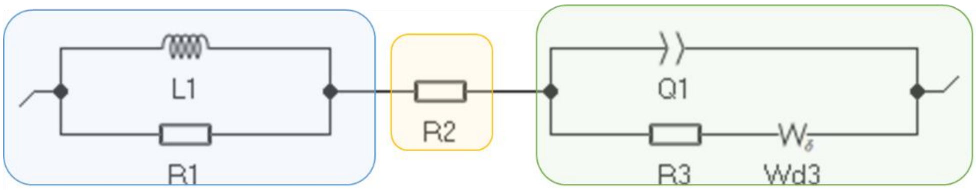


Figure 20: Example of equivalent circuit to fit the cell spectra. The blue part model the inductive component, the yellow the electrolyte resistance and the green the reactions at the anode and cathode.

Example

Figure 21 shows an example of the qualitative analysis performed on a cell aged by cycling at different rates. Panel a compares the total resistance (Rtot) at the BOL and EOL for different values of SOC. Panel b reports the variation of the resistance attributed to electrolyte Ra (containg the contribution of the test load, considered to be constant). An example of the break-down of Rtot in

Rsc and Rdiff contributions, expressed as % for simplicity of visualization, and their variation with SOC and SOH, is reported in panel c.

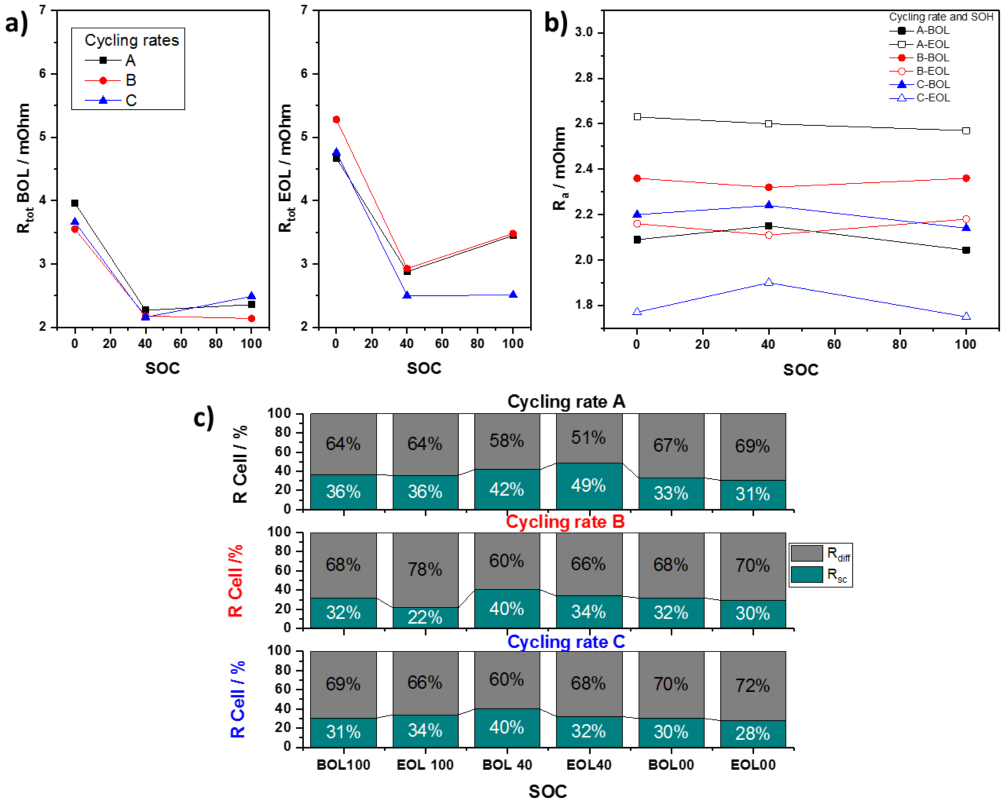


Figure 21: Example of qualitative analysis results. The cells were aged at different cycling rates. BOL and EOL express the SOH while the number the SOC at which the EIS spectra was measured.

Thermal impedance test

[This test item is elaborated by: *project SPICY , TUM, Yao Wu*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Test intention

The primary test intention is to obtain thermal parameters, mainly cell heat capacity, cell thermal conductivity and heat exchange between the cell's surface and the environment due to radiation and convection. It has great advantages over calorimeter measurements and heat-flux or Xenon-Flash measurements due to its low cost and non-destructive test.

Application(s)

Heat capacity, thermal conductivity and heat exchange with the environment of the cell are important parameters for the thermal modelling and the thermal design of battery systems to maximize battery lifetime and avoid safety problems.

Test approach

The test induces a sinusoidal heat generation inside the cell by applying a sinusoidal current with charge and discharge half cycles to it. The current frequencies should stay in the millihertz range, typically between 0.1 mHz and 10 mHz. For each chosen excitation frequency, the surface temperature of the cell is recorded. The same process is repeated for several frequencies.

Test equipment

The needed equipment is:

- a battery cell tester with sufficient current capacity for high C-rates;
- an IR thermopile sensor;
- temperature chamber;
- a measurement setup to minimize the contact area between the cell and the setup.

Optional:

- a thermal camera to verify the homogeneous surface temperature of the cell

Test procedure

Step-by-step procedure

1. The cell is connected to the measurement setup and put into a temperature chamber with 25°C. Wait for at least 3 hours until the cell temperature is stable and identical to the ambient temperature.
2. A sinusoidal current excitation is applied to the cell with alternating charge and discharge periods every 3 s. The cell’s state of charge remains constant. The heat excitation is recorded as Q(ωt).
3. The cell surface temperature is recorded by the IR thermopile sensor as T(ωt).
4. The thermal impedance can be calculated as $\frac{T(\omega t)}{Q(\omega t)}$.
5. The process is repeated for several excitation frequencies between 0.1 mHz and 10 mHz. Themal impedances for different frequencies result in a characteristic impedance spectrum.
6. A cell thermal model based on the finite difference method is created to simulate the above measurements.
7. A least-squares optimization is applied to adapt the heat capacity, the thermal conductivity and convective heat exchange coefficient until the best agreement is achieved between the measurement and the simulation. The final parameter values are considered as the real parameters of the cell.

Test duration

The test takes approximately 1 hour for 10 mHz and 8 hours for 0.1 mHz. The complete test takes approximately 24 hours.

Difference with similar methods in standards or usual practice

No similar methods in the standards.

Post-processing

The thermal impedance Z_{th} of a lithium-ion cell represents the temperature response T(ωt) to a sinusoidal heat excitation Q(ωt) and is defined in the frequency domain as follows:

$$Z_{th}(\omega t) = \frac{T(\omega t)}{Q(\omega t)} = \frac{\hat{T} \cdot e^{j(\omega t + \varphi_T)}}{\hat{Q} \cdot e^{j(\omega t + \varphi_Q)}} = \frac{\hat{T}}{\hat{Q}} \cdot e^{j(\varphi_T - \varphi_Q)}, \qquad \omega = 2\pi f \quad (1)$$

The surface temperature and heat loss in Eq. 1 are approximated by an analytical expression in the following equation:

$$y(t) = O + A_1 \sin(2\pi f t + \alpha_1) + A_2 \sin(4\pi f t + \alpha_2) \qquad (2)$$

Here, f is the test frequency, O is the offset, A_1 and A_2 are the amplitudes and α_1 and α_2 are phase angles. Thus, the thermal impedance can be expressed based on the first harmonics (f) as follows:

$$Z_{th,1}(j\omega) = \frac{A_{1,T}}{A_{1,P}} \cdot e^{j(\alpha_{1,T} - \alpha_{1,P})} \qquad (3)$$

Example

In the example the major results are shown of a cylindrical 18650 lithium ion cell. Fig. 6 shows the excitation current signal used to generate heat in the cell and its voltage and temperature outputs. For different cell types, the current shoud be adjusted to produce an appropriate amount of internal heat. The thermal impedance of the cell is measured at several frequencies between 0.1 mHz and 10 mHz, as presented in Fig. 7.

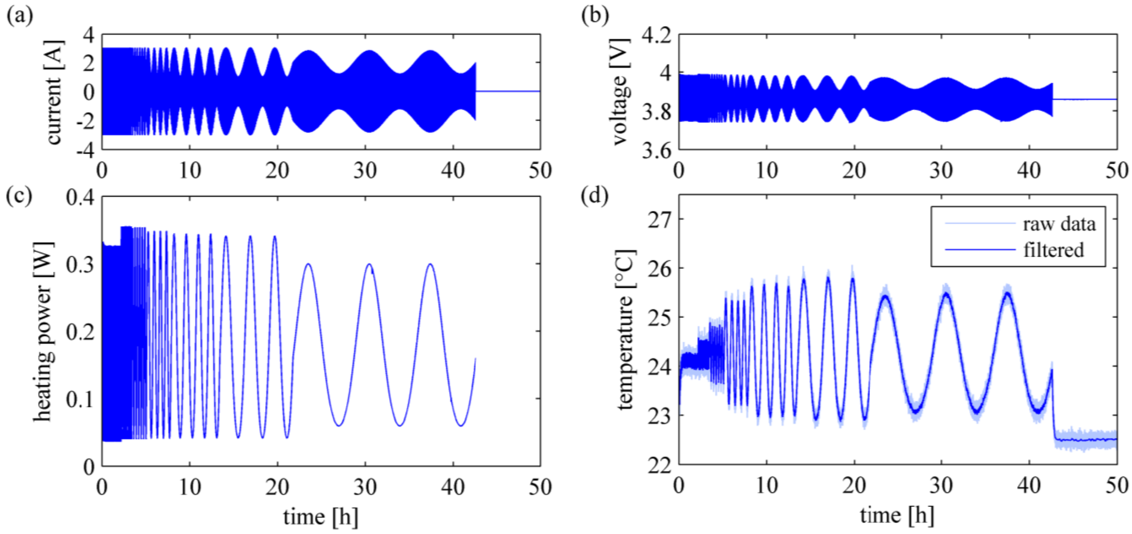


Figure 6: Measurement data of a thermal impedance experiment including (a) current, (b) terminal volatge, (c) computed heat loss, and (d) surface temperature (raw and filtered data)

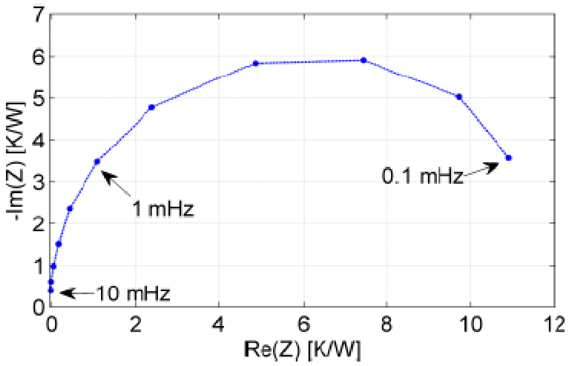


Figure 7: Typical TIS spectrum of a cylindrical 18650 Li-ion cell

A finite differences thermal model should be built according to the cell geometry. Fig. 8 is an example of the 18650 cell, with the following heat balance equations:

$$C_{p\_i} \cdot \dot{T}_i = Q_{i-1,i} - Q_{i,i+1} + P_{v_i} \qquad i \in [1, N-1] \tag{4}$$
$$C_{p\_N} \cdot \dot{T}_N = Q_{N-1,N} + P_{v_N} - Q_{rad} - Q_{conv} \tag{5}$$

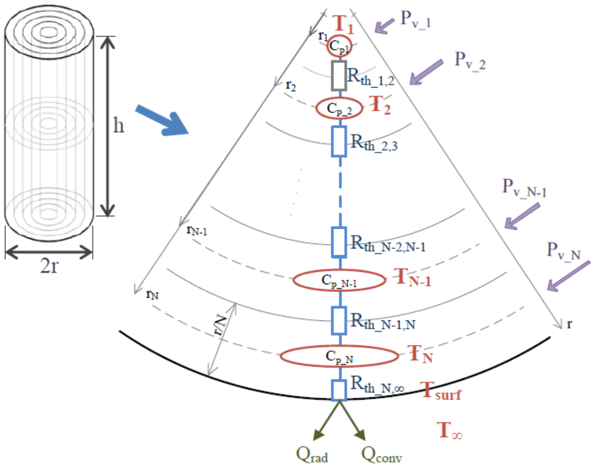


Figure 8: Discretization of a cylindrical battery for finite differences simulation and reduction to a radial 1D heat transfer problem

After a least-squares optimization routine, the heat capacity, thermal conductivity and convective heat exchange coefficient are adjusted to achieve the best agreement between simulation and measurement. The thermal parameters are listed in Tab. 1.

Table 1: Thermal parameter identification based on the thermal impedance measurement

	Parameter Identification
Heat Capacity (J/K)	43.6±0.2
Thermal Conductivity (W/mK)	3.2±0.5
Heat Exchange with Environment (W/m^{2}K)	27.8±0.1

Quasi-static thermal tests

[This test item is elaborated by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

[This test item is elaborated by: *project {FiveVB, VUB, Gert Berckmans*]

Test intention

The goal of this test is to quantify the perpendicular swelling of a battery cell throughout its SoC range. Due to the inter- and de-calation of lithium-ions is the electrode particles, the electrodes expand resulting in a swelling of the battery cell. The swelling consists out of two main types: reversible and irreversible. The reversible swelling can be used to predict possible SoC while the irreversible swelling can give an indication about the aging.

Applications

When designing a battery pack, it is critical to know the battery swelling to ensure a safe design of the battery pack. Additionally, swelling can give an indication about SoC and SoH.

Test approach

The swelling measurements are done at regular time intervals and can be done simultaneously with a capacity test. During a capacity test the swelling is measured.

Test equipment

The same test equipment as in a capacity test is required. Additionally, a digital dilatometer synchronised with the battery tester is required.

Test procedure

Similar as in a capacity test

Test duration

Similar as in a capacity test

Difference with similar methods in standards or usual practice

No similar methods in the standards.

Post-processing

No special Post-processing required

Example

This is an example of the swelling of an NMC pouch cell during a capacity test.

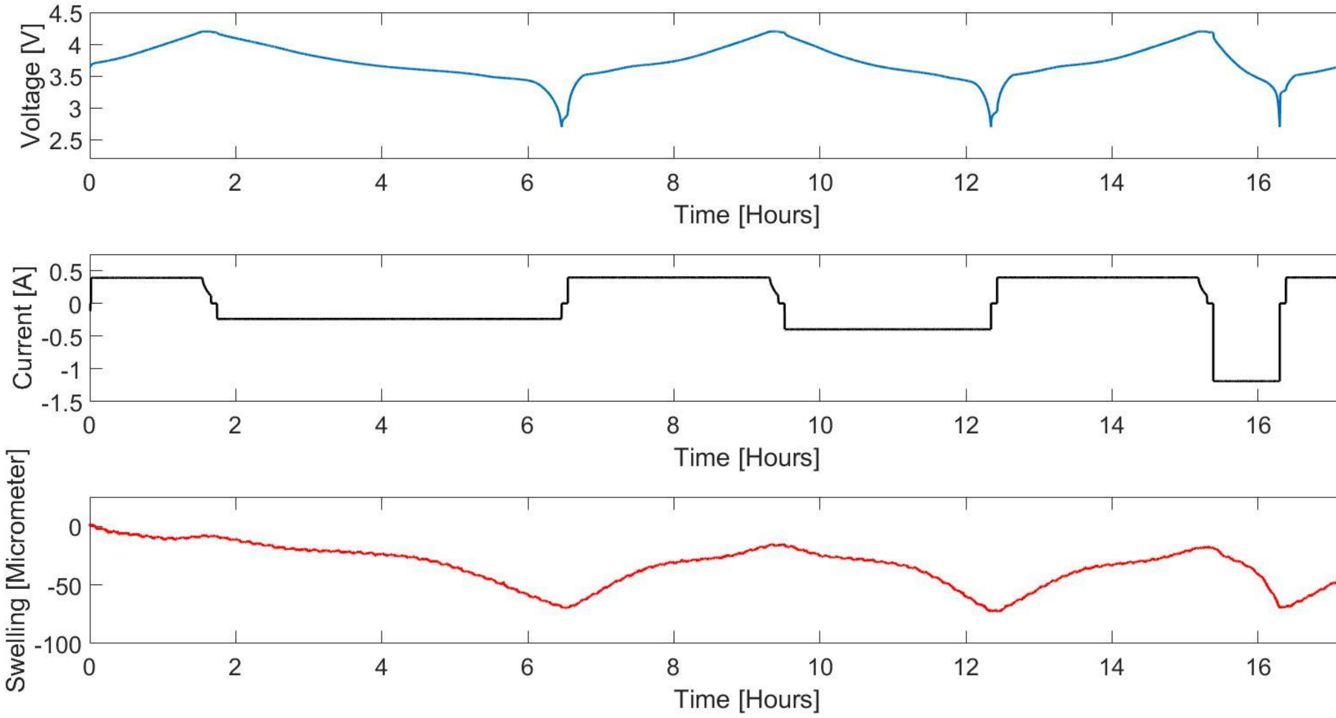


Figure 22: Voltage, current and swelling behaviour of a NMC pouch cell.

Drive cycle

[This test item is elaborated by: *project {FiveVB, VUB, Gert Berckmans*]
Think about following categories:

- *Car Drive cycle*
- *Motor Drive cycle*
- *Bus Car Drive cycle*
- *Heavy duty Car Drive cycle*

We can make a list here and classification.

Test intention

The goal of these tests is to link battery lifetime with an amount of kilometres driven. This can be achieved by cycling batteries with c-rates used during a realistic driving profile. The two most used standard driving profiles are the New European Driving Cycle (NEDC) and Worldwide harmonized Light vehicles Test Procedures (WLTP) class 3.

Applications

For car manufacturers and consumers it is more useful to express the battery lifetime in kilometres rather than in amount of cycles at a certain c-rate.

Test approach

This is an aging test for a battery.

Test equipment

- battery cell tester;
- temperature or climate chamber;
- temperature sensors.

Test procedure

Step	Action	Current (A)	Limit
1	Standard charge	C/3	End of charge voltage
2	Pause		30 min
3	NEDC/WLTP profile		End of discharge voltage
4	Standard charge	C/3	End of charge voltage
5	Repeat step 2-5		End of life

Test duration

Since it is a cycling test, the test will endure until the end of life of a battery is reached.

Difference with similar methods in standards or usual practice

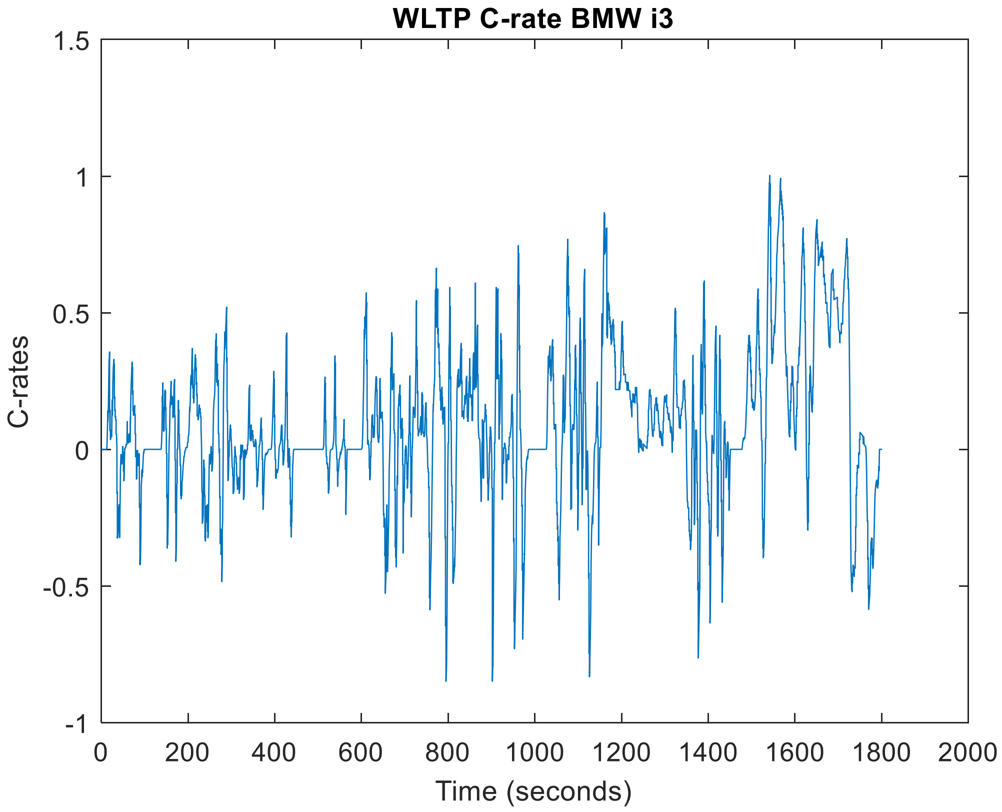
A none constant c-rate is used during cycling in order to represent a realistic driving profile.

Post-processing

Similar to other cycling profiles

Example

An example of the c-rates during a WLTP of a BMW i3 is shown



Preferable test schemes

[This test item is elaborated by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]
To be elaborated

In the standards canbe found:
FreedomCar:
https://inldigitallibrary.inl.gov/sites/sti/sti/6308373.pdf
Reference Performance Test (RPT) – periodic interruptions during calendar and cycle life aging to gauge degradation in the test article (see Section 3.13). Degradation rates are established by comparing results from the RPTs during life testing with respect to the initial RPT performed immediately prior to the start of life testing (usually referred to as RPT0).

http://www.uscar.org/commands/files_download.php?files_id=67
7.2 CORE PERFORMANCE TESTS (REQUIRED)
NOTE: Core Performance Tests are to be performed on all test units unless specifically
exempted in writing by the USABC Program Manager, in

https://www.energy.gov/sites/prod/files/2016/06/f32/es201_bloom_2016_p_web.pdf
USABC Reference Performance Test consists of 2 capacity cycles, peak
power pulse test at 10% DOD increments and full DST cycle. The cells are
characterized using these performance tests every 50 cycles
• China Reference Performance Test consists of 1 capacity cycle and 10
second discharge pulse at 50% DOD. The performance of the cells were

characterized using these performance tests every 25 cycles

Ageing effects

Cycle life test

[This test item is elaborated by: *project SPICY, VITO, K.TRAD*
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Test intention

The objective of a life cycle test is to assess a cell's lifetime under specific use conditions. A cell's lifetime can be expressed in many ways but the most common is the number of cycles. During this test the use conditions that have an effect on the cell's lifetime are varied which means the current, the environmental temperature, the voltage window and of course time. To ideally know the effect of each parameter, every parameter should be varied independently of the others. But practically this would lead to a big test matrix. In real application, a combination of the different parameters is observed. Design of Experiment (DOE) can help to investigate a broad parameter set with manageable effort.

Applications

The life cycle test is often necessary to deliver the lifetime info needed to be communicated in the cell's datasheet. It allows a quick identification of the suitability of a certain cell for a specific application for which lifetime is a crucial requirement. It also allows a comparison between different cell technologies and different brands.

The results of the life cycle tests are exploited to perform ageing modelling which maybe be used in state of health (SOH) estimation.

Test approach

The test consists of applying a specific current or power profile at different temperatures and within different voltage windows. The applied profile can be continuous or varying *e.g.* continuous fixed current or a varying current profile from a real application. When using a continuous current, the charge or discharge C-rate can be varied.

To follow the evolution of the cell's behaviour, the ageing test is regularly interrupted to perform a reference performance test at room temperature.

The basic reference performance test of a standard cycle, a rated capacity test and a pulse test. Other tests can be added but the test should be designed to be as short and consistent as possible to not degrade more the cell.

Test equipment

The needed equipment is:

- a battery cell tester with sufficient current capacity to realize periodical battery performance tests ;
- temperature chamber ;

Test procedure

A test matrix is designed where the different parameters are varied. The variation of parameters depends on the purpose of the ageing test. Indeed if a certain application is for example temperature dependant then the test would be more focused on investigating the effect of the environmental temperature.

After the preconditioning test, a cell first undergoes a performance test which becomes the reference to follow the performance evolution. The cell is then thermally stabilised at the testing temperature for 8 hours. The test is afterward started with the selected ageing profile. As discussed above, the life cycle test is interrupted often to perform a check-up test.
The ageing test is ended when the end of life criteria is reached.

Test duration

The aging test duration depends on:

- the objective of the test: for example the test may run several months to have enough data for modelers.
- on the ageing test conditions: some test conditions may be too harsh and end the ageing test faster than expected.
- on the availability of the testing infrastructure

Often the tests are stopped at a specific SOH which represents the end of life default value which is 80%SOH. :

Difference with similar methods in standards or usual practice

To be inserted.

Post-processing

Life cycle ageing test results are synthetized by analysing cell characteristics evolution (capacity, resistance, …) versus Ah throughput or equivalent cycle or ageing time.

Example

In the Spicy project, the objective of the life-cycle test is to assess and compare the different chemistries implemented in the different cell generations. As the end user requirement for this project is PHEV, the test conditions were designed to fulfil this requirement in terms of current C-rates. In addition, one of the objectives is to evaluate the cell's charging capabilities, only the charge C-rate and temperature are varied (see table below). Every test is carried on 2 cells.

Charge C-rate Temperature	**C1**	**C2**	**C3**
T1			
T2			
T3			

Drive cycle

[eCAIMAN, AIT (H.Popp)]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

In chapter 'driving cycle' on p. **Error! Bookmark not defined.** the details of driving cycle testing are explained. In this chapter driving cycles for analysis of ageing is discussed.

Test intention

Goal is to determine the behaviour and the degradation progress of the cell under load conditions which are assumed to be closer to real application as constant current cycling (see ‘cycle life tests’ p. **Error! Bookmark not defined.**).

Application(s)

Accelerated life cycle testing under conditions closer to reality. During regular check-up tests a basic set of operational parameters like capacity, resistance and power capability are determined; thus providing a progress of this data throughout the cycle life of the DUT.

Data can be used to estimate product lifetime or lifetime till a replacement of the battery is needed. Additionally data for the battery management system is delivered to keep precise SOX determination over lifetime. If a thermal management is considered it should be able to handle the higher dissipation of heat during later phases where the battery already has higher losses due to increases in internal resistance.

Test approach

Most of the tests found in the standards are based on a power and / or current step profile. It features different load scenarios depending on the application. Basically it is distinguished between battery electric vehicles (BEV) and (Plug-In) Hybrid-Electric-Vehicles (HEV). The first ones usually feature an energy rich cycle while the latter is more demanding in terms of power. For easier implementation on test benches usually these cycles reflect some artificial simplified profile which provides an approximation to real life driving cycles. Besides standards mostly by OEM testing specific demanding power profiles derived from vehicle application to battery level are tested to give an even more realistic approximation.

Test equipment

The needed equipment is:

- A programmable battery cell tester;
- temperature sensors;
- temperature chamber.

Test procedure

The tests apply several current or power levels for driving (also charge pulses for regenerative breaking) while the main charging is always kept constant. Based on the standard also different temperature levels can be required.

Current and Power Levels

For check-up tests at the beginning, during cycling and at the end of the test same specifications as in ‘battery cell performance’ which can be seen starting from p. **Error! Bookmark not defined.** apply. While for BEV the power or current normally peak at the nominal value of the cell during the currents for HEV testing are much higher and peaks up to 20 times the nominal current can be tested.

Temperatures

To speed up testing (accelerated life cycle testing) in some standards the test temperature is 45°C where others hive a range between 25 and 40°C whichever suits the operating point of the vehicle best.

Step-by-step procedure

Figure 23 shows exemplarily the flow diagram of a driving cycle test. Usually they begin with an initial check-up of values to define a starting point for further reference. Afterwards, cycling starts. In this case 100 cycles are performed before an intermediate characterization test is performed. To save time and to minimize the influence of the characterization on the cell these tests are often reduced compared to the initial check-up. Another criterion for going to the check-up test could be time e.g. every 28 days. After characterization it is decided if cycling continues. In this case this is done as long as the measured capacity is over 0.8 times the initial capacity. This value can vary from standard to standard. For some applications it might also be of interest to define a end of test criteria over the increase in resistance or a maximum number of cycles, or as often the case the limited availability of the test bench.

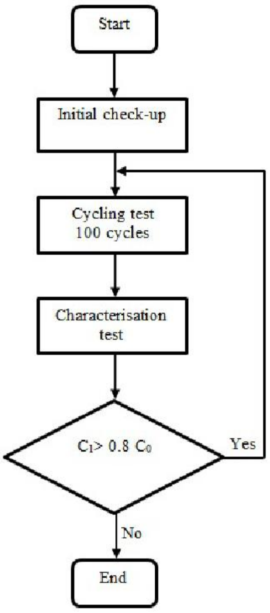


Figure 23. Example of flow diagram for driving cycle life testing.

Test duration

Most standards define end of test criteria which can vary depending on the cell performance. Maximum limit is often 6 months.

Difference with similar methods in standards or usual practice

Standards that contain driving cycle life tests can also include standard constant current cycle life test. In this section only driving cycle life tests are discussed.

Test standards that comprise a capacity test are:
IEC 62660-1: Different profiles for both BEV and HEV testing,.
ISO 12405-1: Profiles for high power batteries (HEV).
ISO 12405-2: Profiles for high energy batteries (BEV).
DOE-INL/EXT-15-34184: Profiles similar to IEC 62660-1.

Post-processing

Post-processing of the data is usually done by using the data from the initial and intermediate tests. Typically the decrease of the capacity and the increase of the internal resistance are of interest. Both can be depicted over e.g. total charge throughput or (equivalent) cycles, providing the progress of these values over the cycle life time.

Example

In this example a BEV and a PHEV test on a large scale NCA/G cell are shown. The cells were cycled in a SOC window like shown in Table 5. This means that the DOD of the BEV is 80% and of the PHEV 70% which is typical. The window may be shifted in some other cases and standards.

Table 5. SOC window of cells for driving cycle life.

SOC Range	EV application	PHEV application
Max SOC	100 %	95%
Min SOC	20%	25%

For both profiles the charging was kept the same. CC charge till U_{SOC} (OCV at according SOC) and then a CV phase at U_{SOC} till I<0.05C. Before the discharge was performed half an hour of idle time for thermal relaxation was given. The profiles for discharge can be seen in Figure 24. They simulate minor load like found in city traffic and higher ones like for accelerating to freeway speed. Also idle phases and pulses from regenerative breaking are included. Peak value for BEV profile is 1.2C and for PHEV it is 5C for discharge, and for charge it is -0.6 for BEV and -2.4 for PHEV. In total the profiles are discharge rich, so the batteries SOC is decreasing with every cycle.
The cycles were performed till the lower SOC limit shown in Table 5 was reached.
Check-up tests were performed every 14 days of cycling.

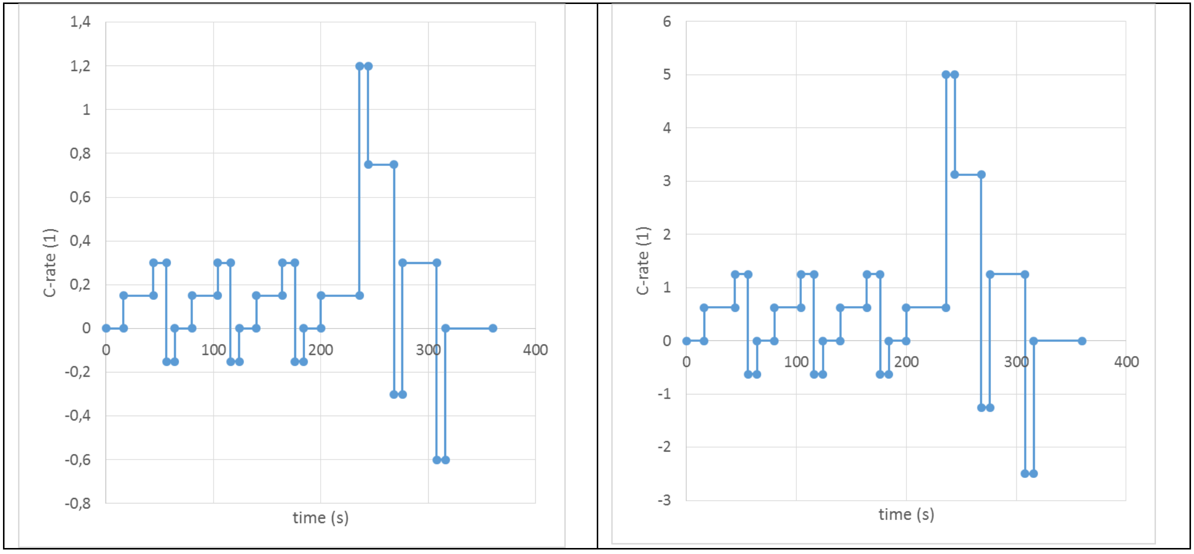


Figure 24. BEV profile (left) and PHEV profile (right) for driving cycle life testing.

Figure 25 shows the results of the cycling tests for both driving cycle types. Ambient temperature in this case was 45°C. The graph indicates the relative capacity (actual capacity divided by initial capacity) over the number of full equivalent cycles (discharged charge divides by initial capacity). Cells were cycled in strings. The bump in capacity is when the weakest cell of the string was removed for post mortem analysis. It can be seen that the BEV cell, despite the lower peak and RMS values shows higher degradation, most likely because of the broader DOD window including full charge.

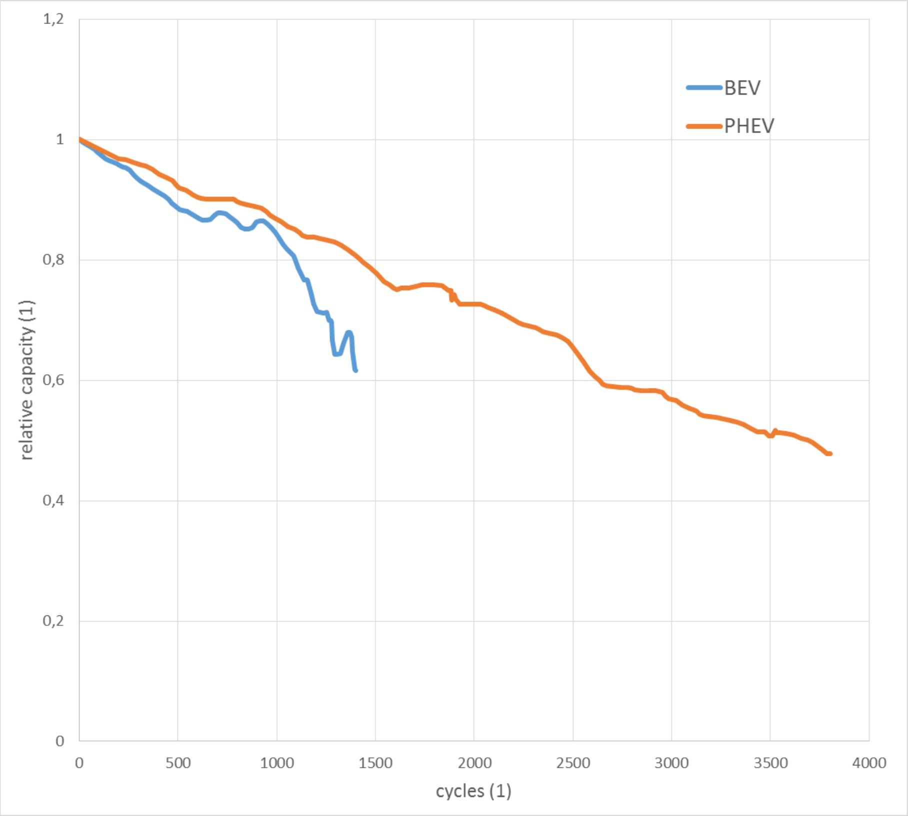


Figure 25. Capacity over cycles for a NCA/G large scale cell with BEV (blue) and PHEV (orange) profile at 45°C ambient temperature.

In this case testing was done over a certain period of time. This is why the cycling does not end at a specific relative capacity value.

Calendar ageing test (battery under rest)

[This test item is elaborated by: *SPICY, CEA, M. MONTARU, R.TESSARD, A. DELAILLE, E. LEMAIRE*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Test intention

The primary test intention is evaluating cell characteristics evolution after long storage periods in open circuit state; the cells are disconnected during rest phases (without voltage supplied from a test channel), with the advantage of no test channel in use.
In order to evaluate storage conditions impact, several tests are performed at different storage conditions (SOC, Temperature) among a specific experience plan. These storage conditions are chosen in order to be representative of useful life conditions in target applications.

Applications

The test results like capacity versus storage duration can be be used directly to compare different battery technology or different generations of same technology. They can also be used :

- to realize a sensitivity analysis when several ageing conditions are realised,
- to parametrize calendar ageing model which will be able to simulate calendar ageing in real usage.

It is also possible to evaluate :

- charge retention defined as the fraction of full capacity available from a battery under a specified set of conditions, after the battery has been stored for a given amount of time.
- self-discharge defined as the ratio between reversible capacity loss during storage and storage duration.

Test approach

The test consists in storing cells at different temperatures and SOC level for long storage periods and evaluate periodically battery performance with a check-up test at 25°C. Before storage periods, cells are fully charged and discharged to the target SOC at 25°C. Then, cells are stored in temperature chamber. After specific duration, cells are fully discharged before to realize a new check-up test.

The target SOC could be attained by different manner :

- discharge fixed charge quantity defined as a certain percentage of reference capacity. The reference capacity could be defined as :
    - the indicated capacity provided by the manufacturer;
    - the average capacity measured on fresh cells batch.
    - the capacity measured during the previous battery performance test.
- discharge until a specific voltage is attained with a CC+CV phase.

Test equipment

The needed equipment is:

- a battery cell tester with sufficient current capacity to realize periodical battery performance tests ;
- temperature chamber ;
- compression plate if necessary.

Test procedure

Calendar conditions

The general calendar aging conditions to perform, in particular for benchmarking purpose, are presented in Table 5.

Temperature SOC	45°C
65	P1
100	P2

Caption : 🟩 General conditions priority P1 then P2

Table 6: Usual calendar ageing conditions.

Other conditions are defined below to perform extended characterizations for calendar aging tests on Li-ion cells, i.e. for modeling purposes (Table 6). These conditions can be adjusted wisely according to the behavior known of the tested cells, or according to the specifications of the targeted application.

Temperature SOC	25°C	45°C	60°C
30	P4	P3	P4
65	P3	P1	P3

100	P4	P2	P4

Caption : 🟩 General conditions priority P1 then P2
🟨 Additional conditions priority P3
🟦 Additional conditions priority P4

Table 7: Calendar ageing conditions.

In order to track correctly performance evolution and reduce the number of check-up tests, the storage duration can be adapted among calendar conditions (Table 7). The time period should also be aadjusted as needed so that the irreversible losses between two CU are less than or equal to a certain percentage of capacity: default value = 5%.

Temperature	Check-up periodicity
45°C	6 weeks
60°C	4 weeks
25°C	8 weeks

Table 8: Storage duration between periodical check-up.

In order to assess , the test are reproduced for each calendar condition on 2 or 3 cells depending on batch number.

Step-by-step procedure

1. Check battery performance with check-up test protocol at 25°C;
2. Put cells to the target SOC at 25°C ;
3. Put cells in the temperature chamber set at the target temperature for predefined duration;
4. Put the cell at 25°C for 5h ;
5. Realize residual discharge until minimum voltage;
6. Go back to step 1 until end of test criteria is reached.

Test duration

The aging test duration is:

- At least 6 months;
- Stopped at a certain SOH, default value is: SOH <= 80%;
- Stopped after a certain duration of test: default value is = 12 months;
- Advantageously extended beyond the above criteria depending on the availability of testing equipment and the test purpose, but not beyond SOH=50%;
- Stopped before reaching the previous criteria if visible mechanical degradation (excessive swelling, electrolyte leakage, etc.).

The SOH may be defined from an initial reference capacity or an initial reference energy, the above criteria advantageously correspond to a criterion depending on the capacity (so that the SOH defined with respect to an energy is potentially lower than the above indicated values).

Difference with similar methods in standards or usual practice

Other standards differ with the proposition by the experience plan conditions choosen (Table 8).

	IEC 62660-1:2010	QC/T 743-2006	DOE-INL/EXT-15-34184	Proposition
Level	Cell			

Check-up periodicity	checkup every 42 days at 25°C ±2K			cf. Table 8
T	tested at 20°C ±2K	tested at 20°C ±5K	minimum of 3 different test temperatures is recommended	cf. Table 7
SOC	100% for BEV 50% for HEV	33%	Specified by manufacturer or application	
End of test criteria	after 3 repetitions	after 5 repetitions	End of test is application specific. Recommendations e.g. insufficient energy or capacity to finish check-up or too few values achievable by HPPC test.	default value : *SOH <= 80%; *duration >= 12 months

Table 9: SPICY Gen0 calendar ageing conditions.

Post-processing

Calendar ageing tests results are synthesised by analysing cell characteristics evolution (capacity, resistance, …) versus storage duration in calendar conditions.
it is also possible to evaluate :

- charge retention defined as the fraction of full capacity available from a battery under a specified set of conditions, after the battery has been stored for a given amount of time.
- self-discharge defined as the ratio between reversible capacity loss during storage and storage duration.

Example

In SPICY project, the first test generation Gen 0 has realised 3 calendar conditions at 45°C at SOC 30%, 65% and 100%. The capacity evolution during this test is represented in Fig. *27*.

Temperature **SOC**	**25°C**	**45°C**	**60°C**
30		X2	
65		X2	
100		X2	

Table 10: SPICY Gen0 calendar ageing conditions.

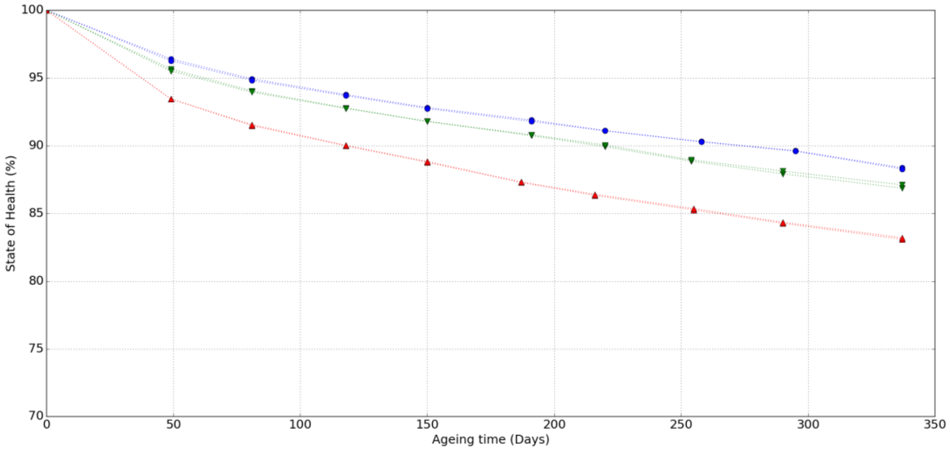


Figure 26: Gen0 SOH evolution during calendar tests at 45°C – SOC 30%, 65% and 100%.

Constant voltage test (battery maintained at a certain voltage)

[This test item is elaborated by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Preferable test schemes

[This test item is elaborated by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Safety aspects

[This chapter follows currently the division as given in http://mat4bat.eu/wp-content/uploads/2017/02/MAT4BAT_D5.1_M31_v1.pdf.]

Automotive Li-ion battery cells are used with complex current profiles, including high currents, in combination with a wide temperature range and road vibrations etc, which may affect the safety during ageing. Battery should be tested with different levels of ageing, e.g. fresh and after EOL (e.g. 70-80% SOH).

Mechanical

Vibration

[FiveVB, Wolfram Kohs]

Test intention

This test ought to simulate the vibration load which a battery system/cells in an electric vehicle will likely experience during its/their life. The mechanical stability and endurance to mechanical stress of the overall system, welding, screws, … is to be tested. The test aims not only on the cells, but also on the sensitive parts of the supplementary systems of a module/pack, e.g. cooling, control circuitry, electrical insulations, …

Application(s)

In most of the standards, vibration tests are defined for battery packs and modules; aiming on the detection of breakage and loss of electrical connections within these devices. Other failures which the vibration tests aim for are insulation problems.

Test approach

Vibration profiles from the car industry are used to test the batteries/cells stability.

Test equipment

A shaker is needed, there are different models which can work in one, two or all three axes. Also, the weight in combination with the acceleration a shaker can handle, can be an important factor.

Test procedure

The cells are usually fully charged when tested. For the vibration profiles if not defined directly, SAE J2380:2013 and IEC 60068-2-64:2009 are often cited, or are referred to indirectly, in most of the evaluated standards.

Test duration

The duration is depending on the shaker used, as the vibration profiles for three axes motion are shorter, than for one or two axes.

Difference with similar methods in standards or usual practice

UN38.3 seems to be most widespread used, it asks for a vibration profile covering 7 to 200 Hz with a peak acceleration of 8 g_n, 3 h in each direction.

For automotive applications also SAE J2380:2013 is of interest.

Post-processing

Mentionable is the approach of combining vibration tests, with life cycle testing to determine the effects of vibration on battery life (SAE J2380:2013, FreedomCAR:2015).

Example

Vibrationtest of a pouch cell according to EN 60068-2-64; all example material was contributed form the H2020 Greenlion project GA Nr. 285268.

Type of vibration:	Random, wide-band
Frequency range:	10 - 2000 Hz

Intensity of Acceleration:

Frequency [Hz]	**Intensity PSD $((m/s^2)^2/Hz)$**
10	20
55	6,5
180	0,25
300	0,25
360	0,14
1000	0,14
2000	0,14

RMS-value of Acceleration:	30,4 m/s2
Duration of test:	8 h

Test in 3 axes

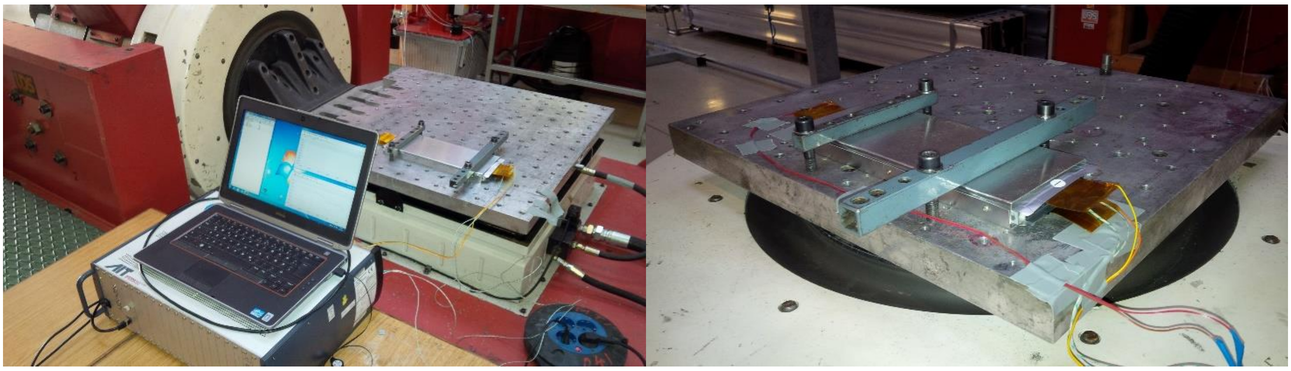
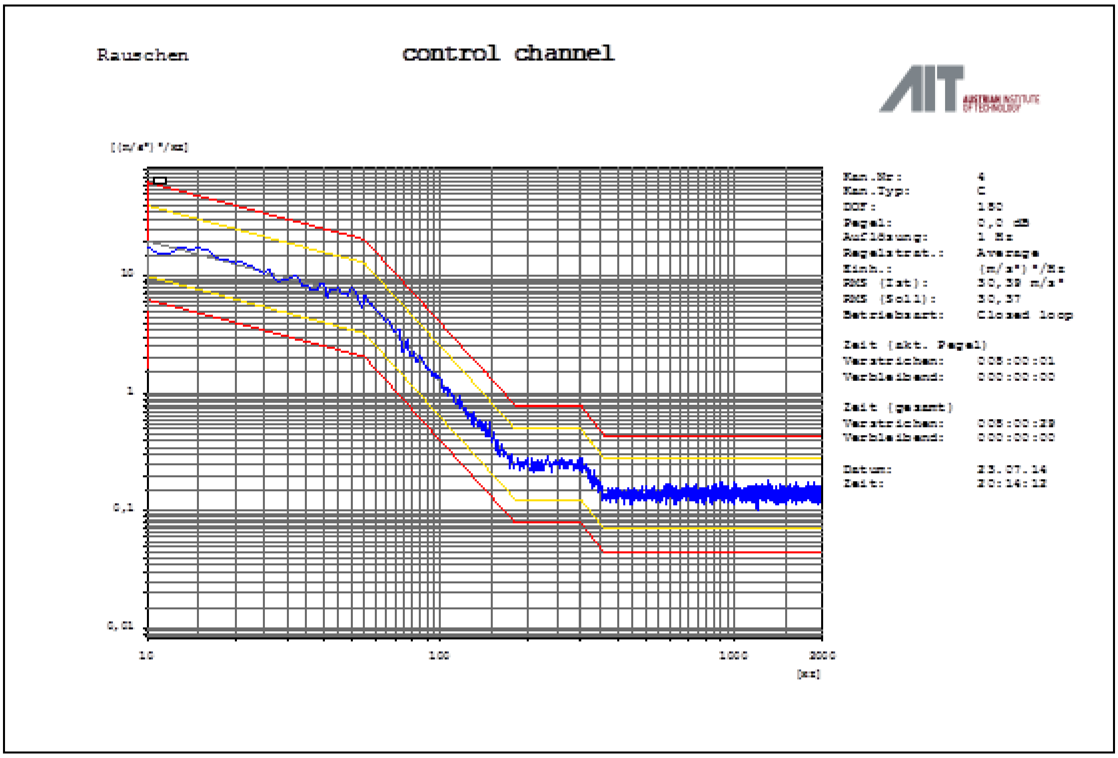


Figure 27: Monitoring equipment (left) and test setup in Z-axis of the specimen (right).



C:\VcpNT\Daten\2014\4314 EDT Green Lion\X_10-2000Hz_27,8ms2_003.rrn

Figure 28: Recorded vibration data from the test in x-axis.

Vibration equipment, electrodynamic vibration exciter LDS V864 HT-440 consisting of:

Device	Manufacturer	Type	Ser. No.
Vibration exciter	LDS	V864-440T	S 2395-001/1
Slip table	LDS	HBT 600	S 2395-001/1
Amplifier	LDS	DPA35/40K	S 2395-005/1
Control Hardware Control Software	m+p m+p	VibPilot VP8 VibPilot Rev.2.12	C14T20002
Control Computer	Dell	Optiplex	
Accleration sensor	Kistler	8202B1100M1	C193722
and the necessary auxiliary devices.			

Monitoring equipment:

Device	Manufacturer	Type	Ser. No.
Integr. acceleration sensor	Brüel & Kjaer	2513	1699636
acceleration sensor	Brüel & Kjaer	4384	1683736

Mechanical Shock

[FiveVB, Wolfram Kohs]

Test intention

This test aims on simulating the mechanical shock which is applied on cells under the internal load of a crash situation.

Application(s)

The test is applied on packs, modules and cells. At cell level the safety performance/mechanical stability (no rupture, no venting) is primarily of interest, but also insulation values, the inner resistance and other parameters.

Test approach

Most of the standards demand fully charged cells for this test. The devices are fixed on the testing machine and exposed to one, or several acceleration pulses.

Test equipment

The tests are regularly done with shaker systems, the weight in combination with the acceleration a shaker can handle, can be an important factor.

Test procedure

The description here follows UN Test Manual 38.3:2016: SOC = 100 %, a half sine pulse of 6 ms and 150 g_n peak acceleration (11 ms and 50 g_n for cells with a mass >500 g) is applied to the cells, three shocks in every orientation, a total of 18 shocks.

Test duration

Depending on the number of pulses, and a post observation period, the test may be considered to take about 1 h.

Difference with similar methods in standards or usual practice

Most of the standards evaluated are referring for this test to UN Test Manual Transport of Dangerous Goods 38.3 (SAE J2464, SAE J2929; IEC 62660-3 and UL2580 refer to IEC 62660-2, the latter with a minor variation describes a part of the tests of UN Test Manual Transport of Dangerous Goods 38.3).
Beside these, only ECE-R100.02 describes mechanical shock tests, however the acceleration values required are less demanding.

Post-processing

A post observation period is described in some of the standards, the capacity before and after the test might be measured, also the deformation if there is some, insulation and inner resistance can be of interest, …

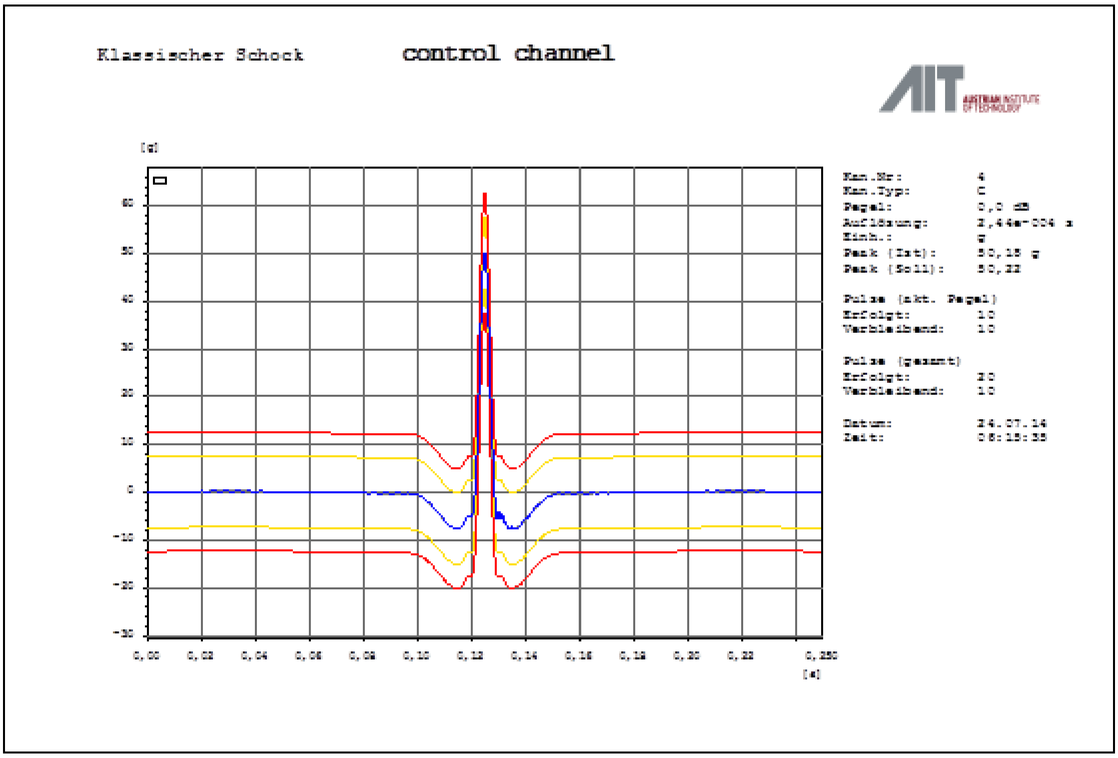
Example

Shock test of a pouch cell according to EN 60068-2-27, all example material was contributed form the H2020 Greenlion project GA Nr. 285268.

Pictures of the shaker and the control equipment used for this test can be found in Figure 27, the equipment is also detailly listed above.

Shape:	half-sine
Acceleration amplitude:	50 g
Duration:	6 ms

Test in 3 axis
10 shocks per test direction



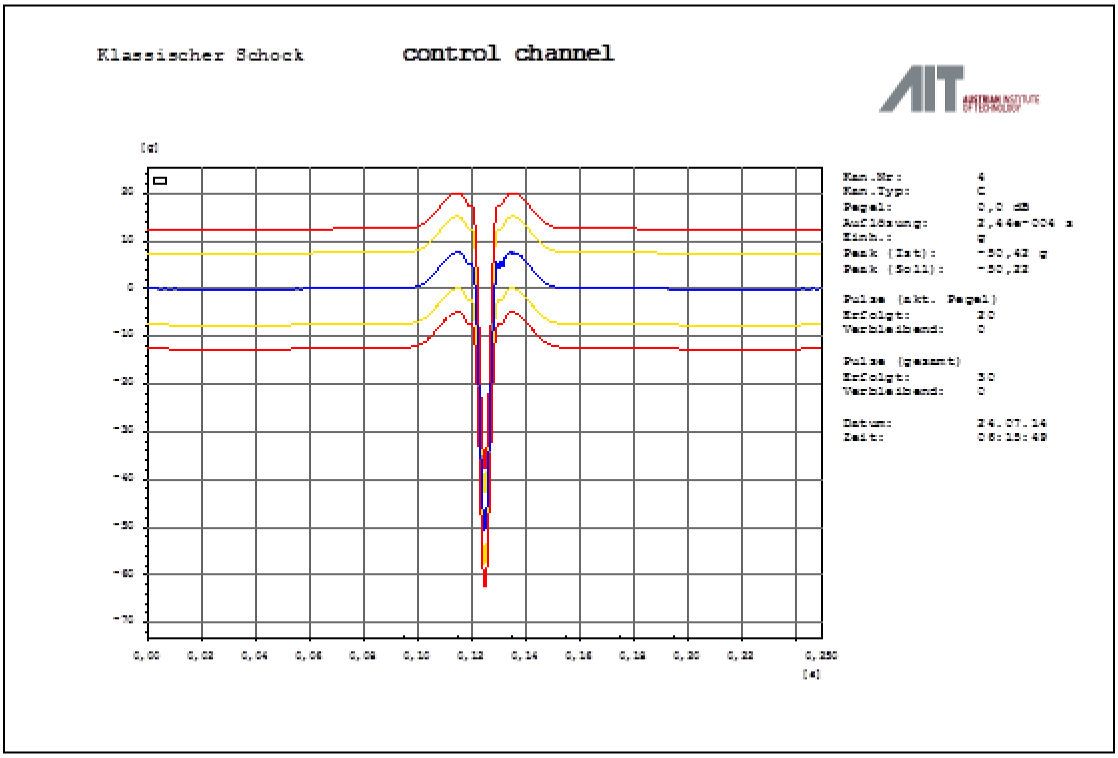
Kan.Nr: 4
Kan.Typ: C
Pegel: 0,0 dB
Auflösung: 2,44e-004 s
Einh.: g
Peak (Ist): 50,18 g
Peak (Soll): 50,22

Pulse (akt. Pegel)
Erfolgt: 10
Verbleibend: 10

Pulse (gesamt)
Erfolgt: 20
Verbleibend: 10

Datum: 24.07.14
Zeit: 08:15:35

C:\VcpNT\Daten\2014\4314 EIT Green Lion\50g_6ms+10-10_001.rsa



Kan.Nr: 4
Kan.Typ: C
Pegel: 0,0 dB
Auflösung: 2,44e-004 s
Einh.: g
Peak (Ist): -50,42 g
Peak (Soll): -50,22

Pulse (akt. Pegel)
Erfolgt: 20
Verbleibend: 0

Pulse (gesamt)
Erfolgt: 30
Verbleibend: 0

Datum: 24.07.14
Zeit: 08:15:48

C:\VcpNT\Daten\2014\4314 EIT Green Lion\50g_6ms+10-10_001.rsa

Figure 29: Shock profile in x-direction, both in positive and negative way.

Drop

[FiveVB, Wolfram Kohs]

Test intention

This tests aims on a service situation, in which a battery is removed from a vehicle and accidentally dropped.

Application(s)

Although from its intention rather applied on module and packs, the test is in some standards also mentioned for single cells. The results give a first impression of the stability and tightness of a cells construction.

Test approach

The test is done by dropping cells, modules and packs from a defined height onto a flat floor. Often more than one drop is asked for.

It has to be mentioned that this test is only mentioned in few standards, also UN38.3 does not ask for this test.

Test equipment

Standard test laboratory, the release of toxic gases as well as flammable gases should be measured with appropriate gas measurement system.

Test procedure

The standards are very similar, SOC 100 % and ambient temperature (i.e. 25 °C), the test objects shall be dropped off 1.5 m onto a floor made of concrete, terminal facing downwards; QC/T 31485:2015.
Varying from this, QC/T 743:2006 mentions a wooden floor of 20mm, and a drop for each side.
Varying from said, UL2580:2016 asks for one drop for all three directions off 1.0 m onto a concrete floor.

Test duration

From the test description, including a post observation period of 1 h, the test with some preparation and follow-up activities can be assumed to need 1-2 h.

Difference with similar methods in standards or usual practice

See test procedure.

Post-processing

A post observation period of 1 h is mentioned in the standards, evaluation of video material, insulation measurements, determination of the inner resistance, …

Example

An example picture of a drop testing device, and of some data of a drop test is given in Figure 30Figure 30: Drop testing setup according to FreedomCar and experimental data, Hybrid Commercial Vehicle (HCV) project..

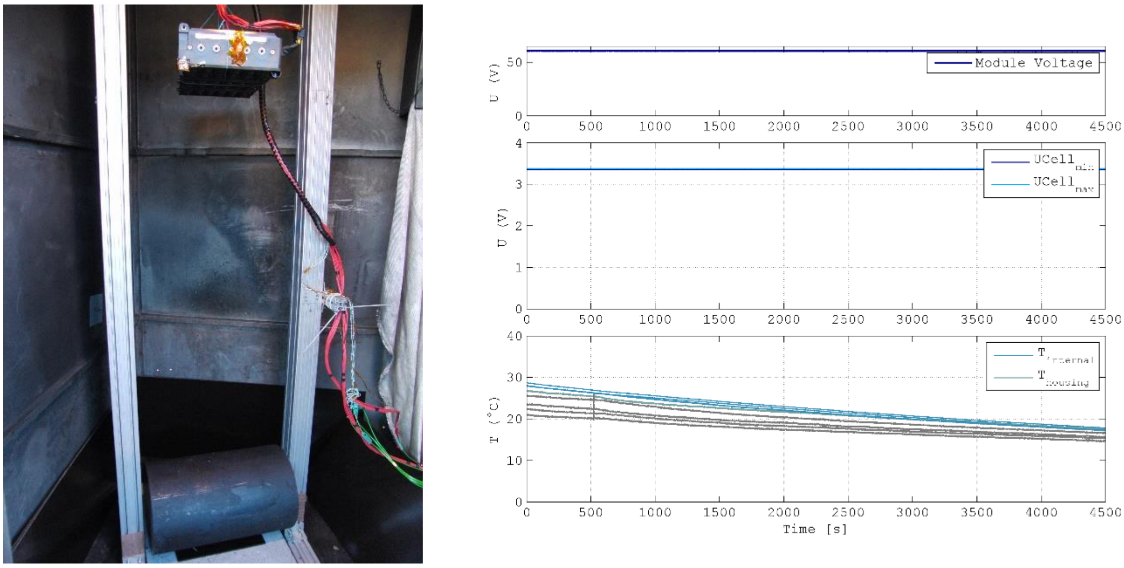


Figure 30: Drop testing setup according to FreedomCar and experimental data, Hybrid Commercial Vehicle (HCV) project.

Cell impact / Crush

[FiveVB, Wolfram Kohs]

Crush and cell impact are described together as they are hardly to separate from their aim. Only UN38.3 has two separate tests described for crush and cell impact.

Test intention

These tests aim at the situation of a vehicle crash, where the battery casing is damaged.

Application(s)

The results allow an evaluation of a device's mechanical stability respectively its safety.

Test approach

Tests are described for cells, modules, packs, and on vehicle level. The device to be tested is typically crushed between a resistance, which in case of cells is a flat surface, and a so-called crush plate resp. a cylindrical crush tool.

Test equipment

Abuse facilities, a hydraulic press with adjustable speed and preferable adjustable maximal load, camera system, temperature sensors, data logger for potential and resistance, distance/position sensors, …

Test procedure

SAE J2464:2010 and FreedomCAR:2015 describe a procedure which, with small variations, is found in most of the other standards. A cylindrical crushing tool, half the test cells average diameter (FreedomCAR); resp. with a diameter comparable to that of the cylindrical cells one (SAE J2464) should be used.

The test is done in two steps, first crush to 85 % of the original height/diameter and hold there for 5 min. SAE J2464 mentions a crush speed of 0.5 to 1 mm/min for cells. Then, go on up to a deformation of 50 % of the initial dimension, or stop as the force exceeds 1000 times the mass of the cell. Hold again for 5 min. The cells to be tested shall be fully charged.

Test duration

No indications are given about the duration of the tests. From practical experience at 1.5 h can be considered as reasonable.

Difference with similar methods in standards or usual practice

IEC 62660-2 differs from the above in using a semi-circular bar, or sphere or hemisphere as crushing tool. No crushing speed is defined, the test ends if one of the conditions is met: a voltage drop of one third of the original cell voltage, a deformation of ≥15 %, or the force exceeding 1000 times the cells mass.
IEC 62660-3 is similar to IEC 62660-2 but additionally defines a crush speed of ≤6 mm/min, UL2580 also refers to IEC 62660-2.

GB/T 31485 differs from SAE J2464/FreedomCAR in defining the semi-cylinder’s radius to be 75 mm, a crushing speed of 5 ± 1mm/s, and end condition of the cells potential is 0 V, the deformation is 30 %, or the force exceeding 200 kN.

QC/T 743 (2006) differs from SAE J2464/FreedomCAR in defining a crush head of min. 20 cm^2, however no further geometric recommendations are made. No force, no crush speed is given, the end conditions are battery case cracks, or short circuit with 0 V.

UN Test Manual 38.3 describes two different procedures for crush and impact, both differing from the standards discussed above.
Impact: Position a cell with a steel bar on it, lay the bar across the centre of the cell. The steel bar having a diameter of 15.8 ± 0.1 mm and a length of min 60 mm. Then drop a mass 9.1 ± 0.1 kg of a height of 61 ±2.5 cm onto the centre of cell/steel bar.
Crush: Use two flat surfaces, the crushing speed 1.5 cm/s, the end condition being the force exceeding 13 ± 0.78 kN, the cells voltage dropping by 100 mV, or the deformation exceeding 50 %.

Post-processing

Deformation, mass losses, composition and flammability of vented gases, heat generation, cell potential, insulation, and other parameters may be evaluated – depending on what happened in the test.

Example

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Penetration

[eCAIMAN, Hartmut Popp]

Test intention

This tests aims to simulate a short circuit within the cell; a failure which could be caused by the growth of dendrites or by the intrusion of foreign matter during a crash. It is according to SAE J2464:2009.

Application(s)

Relevant for all applications as dendrite growth can also take place for stationary applications. It is commonly exerted on cell level, on parallel connection of cells and modules.

Test approach

The cell in most cases is charged to SOC 100%. Short circuit in the cell is forced by a conductive steel rod.

The release of toxic gases as well as flammable gases should be measured with appropriate gas measurement system.

Test equipment

The needed equipment is:

- Hydraulic press with adjustable speed or special nail penetration unit;
- Nail
- Temperature sensors
- Data logger for voltage and temperature.
- Gas measurement equipment

Test procedure

- Charge cell to SOC 100% with standard charge
- Wait for thermal equilibrium at room temperature
- Penetrate the DUT with a mild steel (conductive) rod. The orientation of the penetration shall be perpendicular to the cell electrodes.
- For cell: Diameter of Rod 3mm, Rod End Type Tapered to a sharp point, Rate of Penetration 8 cm/s or greater, Minimum Depth of Penetration Through cell.
- For Module/Pack: Diameter of Rod 20mm, Rod End Type Tapered to a sharp point, Rate of Penetration 8 cm/s or greater, Minimum Depth of Penetration Through 3 cells or 100 mm whichever is greater.
- The DUT should be observed for a minimum of 1 h after the test with the rod remaining in place.

Test duration

Test duration for actual test is under 1 min. Depending on the standard the cell has to be monitored afterwards for at least 1h.

Difference with similar methods in standards or usual practice

The penetration test is described in:

SAE J2464:2009:	Reference in this case (see above)
SAND 2005-3123:	Same as SAEJ2464:2009.
QC/T 743-2006:	Test is called “prick test” there. Speed of nail during penetration and also the diameter of the nail are different for this test.

Post-processing

No post-processing is necessary.

Example

In this example a nail penetration test is exemplarily shown on a cylindrical cell of 26650 format and a LFP cathode combined with a graphite anode.

Figure 31 shows the cell in the test frame during the nail penetration test. The test frame in this case is to stabilize the cell and it has a hole on the top and on the bottom to guide the nail trough the cell. There is also dedicated equipment which is solely for the purpose of nail penetration tests on cylindrical cells. For those no frame is needed.
Additionally it can be seen that there are 2 thermocouples in the setup. One takes the cells surface temperature and the other on is placed close to the venting unit to detect venting and to determine the temperature of the exhaust. Voltage measurement takes place during the test too.

Figure 31: Cylindrical cell in test-frame during nail penetration test.

Figure 32 shows the bottom of the cell. One can see that the nail went through the cell and electrolyte is dripping off it.

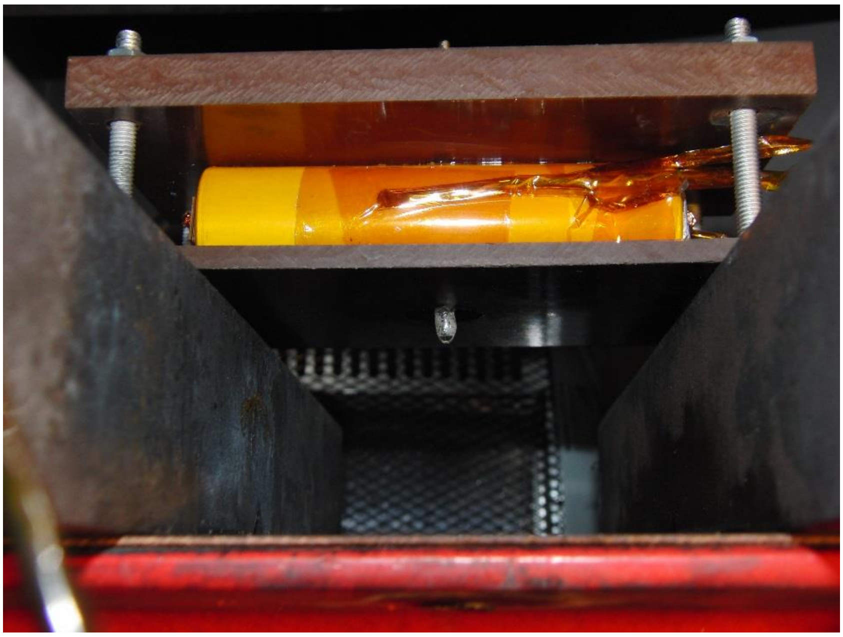

Figure 32: Bottom view of cylindrical cell during nail penetration test.

Figure 33 shows the measured values during the test. It can be seen that the cell voltage immediately drops to 0 when the cell is penetrated (see value displacement). Within the first seconds the cell heats to close to 100°C and then the temperature is decreasing. The temperature increase on the venting is only caused by heat radiated from the cell.

In total this is a satisfying result as the cell did not vent or catch fire during this very demanding abusive test.

It is recommended by the authors to monitor the data at least with 10Hz to have detailed resolution for further processing and plotting. Additionally to these values also the force needed to drive the nail through the cell can be of interest.

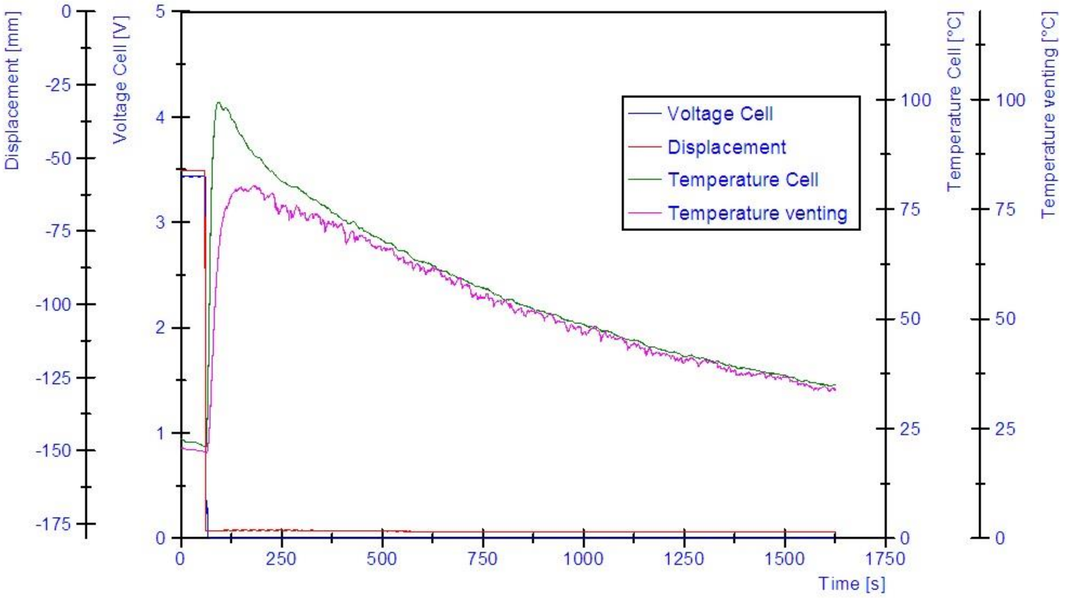

Figure 33. Measurements during nail penetration test.

Note (I):
This test is discussed by experts because of its problems for repeatability. Depending various values like precision of the tip, the material and the variation in speed when hitting the cell very different results can be observed; from almost no reaction to cell fire. Improvements and efforts towards higher reproducibility are made.

Note (II):
This test can be much more challenging for the cell when parallel strings are tested, as the other cells power the short circuit in one cell too, leading to much higher power and most of the time worse results.

Roll-over

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Thermal

Temperature cycling

[FiveVB, Wolfram Kohs]

Test intention

This test ought to simulate the rapid temperature change environment which a battery system/cells will likely experience during its/their life. The test aims not only on the cells, but also on the sensitive parts of the supplementary systems of a module/pack, e.g. seals, control circuitry, electrical insulations, …

Application(s)

The test is applied to find mechanical and electrical malfunctions caused by the temperature changes. The results allow improvements, resp. the test is a quality control.

Test approach

The devices to be tested are exposed to rapid temperature changes. The lower temperature is mostly defined as -40 C, whereas the standards list varying upper temperatures, and also varying time limits for the temperature changes.

In some of the standards, a functionality check, i.e. a capacity determination, before and after the thermal cycling is mentioned. However, this makes only sense if the upper temperature limit is 60 °C. Beyond, the cells chemistry will get damaged.

Test equipment

A climate chamber of appropriate volume is needed, which ought to be capable to perform the temperature changes in time.

Test procedure

UN 38.3:2013: Fully charged cells are thermally cycled between +72 °C and -40 °C. The maximum time for each temperature change is 30 min, each temperature extreme shall be held for 6 h, resp. 12 h for large cells (>500 g). Ten cycles shall be made.

Test duration

The longest test duration seems to be 240 h; IEC 62660-2:2010, no preparation and post observation or characterisation times included.

Difference with similar methods in standards or usual practice

The standards evaluated and describing temperature cycling tests for single cells are listed below, with the experimental differences included, Table 11. The number of temperature cycles depends on the individual standard, in some of them a capacity determination before and after the temperature cycling is additionally described.

Table 11: The standards describing temperature cycling tests, with upper and lower temperature extreme, time within the temperature changes ought to be performed,

time the cells should be held at each temperature extreme, number of temperature cycles to be made, and capacity determination to be made or not.

	T_{max}	T_{min}	t_{change}	t_{hold}	cycles	cap. det.
SAE J2464	70 °C	-40 °C	≤15 min	≥60 min	5	Yes
IEC 62660-2*	85 °C	-40 °C	130/150 min	110/90 min	30	No
IEC 62660-2**	65 °C	-20 °C	130/150 min	110/90 min	30	Yes***
ECE-R100.02	60 ± 2 °C	-40 ± 2 °C	≤30 min	≥6 h	5	Yes
FreedomCAR	80 °C	-40 °C	15 (30) min	≥60 min	5	Yes
GBT 31485	85 °C	-40 °C	130/150 min	110/90 min	5	No
UN Test 38.3	72 ± 2 °C	-40 ± 2	≤30 min	≥6 (12) h	10	No

Remarks:

* Test without current profiles.

** Test with electrical operation.

*** From the electrical characterisation, a capacity determination might be derivable, however its results are likely not comparable to the results from simple running normal charging/discharging cycles before and after the temperature tests.

IEC 62660-3 is not mentioned in the table above as for this test it only refers to IEC 62660-2, so does UL2580:2016.
ECE-R100.02 demands an SOC >50 %, FreedomCAR an SOC of 50 %, IEC 62660-2 an SOC of 80 % for HEV cells resp. 100 % for BEV cells, the other standards demand fully charged cells for this test.

Post-processing

Beside the capacity determination before and after the test, insulation values, changes of the inner resistance, and similar parameters might be of interest.

Example

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High temperature endurance

[FiveVB, Wolfram Kohs]

Test intention

This test aims on the reaction of lithium-ion cells on a nearly devastating high temperature.

Application(s)

This test is usually applied on single cells. The results allow a risk assessment of different cell chemistries, cell types, sizes and of cells from different manufacturers.

Test approach

The cell to be tested is heated to a defined temperature which is then held for a defined time. The cell´s reactions are observed. There are several standards, the test procedures differ slightly in details.

Test equipment

Abuse facilities are needed for these tests. An explosion-proof oven like system with a fine temperature control is needed, a ventilation for the gases eventually vented by the cell and a possibility to film the test setting. The temperature of the cell and the oven ought to be closely monitored. The cell´s potential might be logged.

Test procedure

A fully charged cell (SOC 80 % for HEV cells) is heated with 5 °C/min to 130 °C, this temperature is held for 30 min; IEC 62660-2:2010 and IEC 62660-3:2016.

Test duration

Preparation and follow-up activities not included the test seems to take about 1-2 h. …

Difference with similar methods in standards or usual practice

GB/T 31485:2015 is identical to the description from above, but asks generally for fully charged cells.
QC/T 743:2006 more simply asks for heating a cell of SOC 100 % up to 85 °C and holding this temperature for 120 min.

From its aim differing is the test of FreedomCAR:2005 - it asks to store cells with at a SOC of 20 %, 50 %, and 100 % at a temperature of 40 °C, 60 °C, and 80 °C over a period two month. Before and after the test the cells capacities shall be tested with three cycles each, during the test the cells shall be tested weekly with two cycles at room temperature.

Post-processing

Temperature curves, cell potential, isolation values, eventually venting temperature, and cell deformation can be evaluated.

Example

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Thermal control check

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Fire test

[eCAIMAN, Fredrik Larsson/RISE, FiveVB, Wolfram Kohs]

Test intention

The aim of the fire test is to assess the fire characteristics of the battery by exposing the battery to an external propane fire or similar source. The fire characteristics assessment should include e.g. the time of ignition (instant or delayed), oxygen access levels, heat release rate / combustion heat, total heat release / total combustion energy, toxic gas emissions, and the risk of cell case explosion and/or gas explosion. The fire resistance of the battery from an external fire exposure will also be assessed by this test.

Applications

The test is usually applied on modules and battery packs, or on vehicle level using the final mounting conditions; however, the test is also described for single cells. The results allow a risk assessment of different cell types, sizes, and chemistries.

Test approach

A battery is exposed to flames and high temperatures under defined conditions for a defined time, and the battery´s fire characteristics are studied.

Test equipment

Abuse facilities are needed for these tests, a fire place with a burner system, an appropriate dimensioned ventilation system, video cameras, temperature sensors, gas measurement equipment, e.g. FTIR, GC-MS, for analysing the composition of the vented gases, particularly analysis of toxic and flammable compounds.

Some of the released gas compounds can be very reactive and difficult to detect. Furthermore, in case of gases are collected and later analysed, the results can differ from the gas present at the test moment. Therefore, online time-resolved quantitative gas emission measurement gives the best measurement results.

The battery should be weighted before and after the test.

Test procedure

The battery is placed on wire gratings with an external propane burner beneath. The external burner should be active as long as the battery generates heat (is still combustible) and thereafter active for an additional minutes, e.g. 5 or 10 minutes.

Test duration

No duration is mentioned, the test itself seems rather short, the preparation before and the cleaning afterwards are likely much more time demanding.

Difference with similar methods in standards or usual practice

In UL 1642:2012 the test is done using a Bunsen burner, i.e. propane/butane is likely to be used as fuel, although it is not mentioned explicitly.
Two other standards are relevant - ECE-R100.02:2013 describes a test using a fuel fire with direct flames for 70 sec, and so called indirect flames (a sheet is partially covering the fire) for another 60 sec.
FreedomCar:2005 describes a test setup which might be considered as indirect working. The cell to be tested is placed inside of a cylinder/tube. Inside it is painted in a way to simulate a black body. The apparatus is heated up to 890 °C within 90 sec, the cell is exposed to this temperature for 10 minutes.

General remark:
The current standards on the topic of fire testing are rather limited. There are more possibilities.

Post-processing

A post observation time to let everything cool down. Battery potential measurements are mentioned, the electrical resistance between the positive terminal and the cell case might be evaluated, videos can be made, analysis and flammability of gases should be studied. The fire characteristics assessment should include e.g. the time of ignition (instant or delayed), heat release rate / combustion heat, toxic gas emissions, and the risk of cell case explosion and/or gas explosion.

Example

An example photo of a fire test of an array of pouch cells is given in Figure 34.

Figure 34: Example picture of a fire test of lithium-ion batteries performed at RISE Research Institutes of Sweden. In this example, the pouch cells were mechanically tightened together using steel wires and placed on a wire gratings with a propane burner underneath.

Propagation of thermal runaway

[FiveVvito\wkohsNot tested on cell level.

Rapid charging and discharging

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Thermal stability (ARC)

[FiveVB, Wolfram Kohs]

Test intention

This test aims on determining the thermal stability limits of lithium-ion cells. A nearly identical testing procedure is found in FreedomCar:2005 and SAE 2464:2009.

Applications

The test results allow the definition of a safety temperature limit of a cell / the onset temperature of a thermal runaway. Also, the risk potential of a cell can be evaluated. The results also allow comparisons between different cell chemistries and cell manufacturers.

Test approach

Fully charged cells are slowly heated up until venting and later a thermal runaway occurs.

Mentionable is the approach not only to test new cells, but also cells at mid-life and EOL. Also, overcharged cells if still working can be tested.

Test equipment

Abuse facilities are needed for these tests. An explosion-proof oven like system with a fine temperature control is needed (for small cells a calorimeter might be useable), ventilation is necessary for the gases vented by the cell and a possibility to film the test setting. The temperature of the cell and the oven ought to be closely monitored.

Test procedure

Starting from their normal operating temperature a fully charged cell is heated up in steps of 5 °C using a heating ramp of 5-10 °C/min. Each temperature plateau is then held for 30 min. If an exothermic reaction (>1.0 °C/min) starts stop heating and monitor the temperature of the cell until it stabilises again (then proceed with the heating), or the temperature exceeds 300 °C (200 °C in FreedomCar) plus operating temperature of the cell, or thermal runaway or venting occurs.
If a thermal runaway happened, redo the program with 2 °C steps and a pause time of min. 1 h at each temperature plateau to further redefine the thermal stability limit of the cell. This can be done starting from the last stable temperature plateau before the thermal runaway happened (or starting from 10 °C below the onset of the reaction, FreedomCar).

Test duration

No typical duration is mentioned in the standards, from the program description 2-3 days seem necessary. The test repetitions can be assumed to need less time.

Difference with similar methods in standards or usual practice

In FreedomCAR:2005 a second, alternative method is included by applying a thermal ramp on the cells. The temperature is increased at a constant rate, and the cells temperature is closely monitored and compared with the temperature of the heating system. The onset of a thermal runaway is indicated when the temperature difference between cell and heating system changes.

Post-processing

Evaluation of temperature profiles of oven (calorimeter) and cell are mentioned, analysis and flammability of gases vented is an option, the onset temperature of cell venting is of interest, analysis of the self heating processes might be evaluated.

Example

A setup for a thermal stability test is shown in Figure 35, the related test data can be found in Figure 36. The test was conducted in an adapted laboratory drying cabinet, which is quite suitable for small cells.

The test was started at 80 °C, 5 °C steps of 30 min were applied, the thermal runaway started at approximately 130 °C, a maximum temperature of 550 °C was recorded, though no severe reaction took place, test object was a cylindrical 5 Ah cell.

Figure 35: Test setup for a thermal stability test, and photo of the same setup after the test.

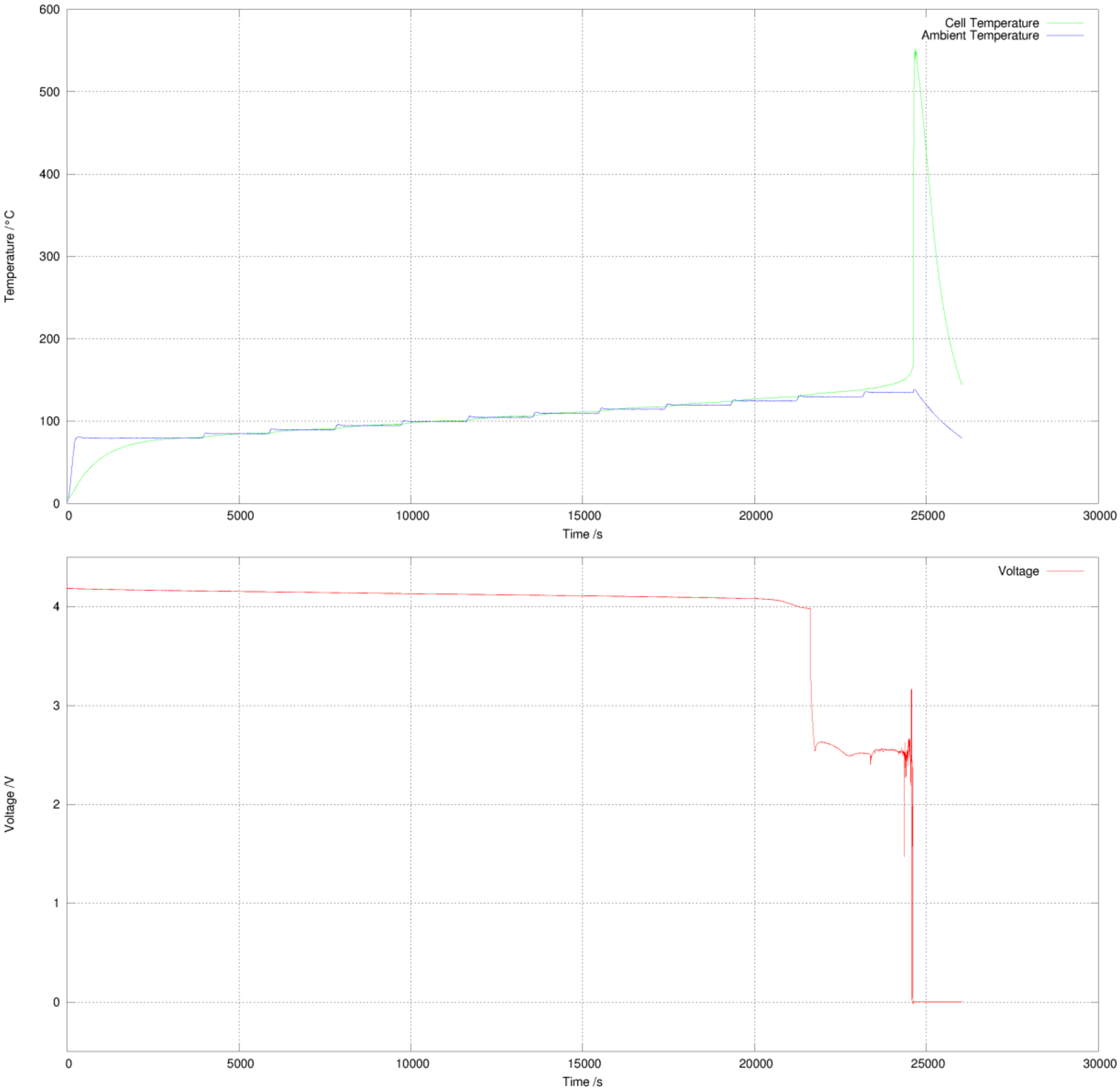

Figure 36: Progress of cell potential and temperature of the thermal stability test from above.

Electricity

External short circuit

[eCAIMAN, AIT (H.Popp)]
[This test item is reviewed/ further deepened by: *project {eCAIMAN, SPICY, FiveVB}, institute, people*]

Test intention

Goal is to determine the behaviour of the cell subjected to an external short circuit. This is an abusive out of operation test to investigate cell and system safety under extreme conditions. External short circuits could happen for example in a vehicle crash or due to false maintenance action.

Application(s)

Performed on all levels from cell to full system. As it is a very plausible fault condition it is integrated in most standards and is interesting for all kind of vehicles as well as for transport of the system and also stationary application.

Test approach

Normally the test is conducted on a fully charged device under test, as this is the worst case scenario. A hard short circuit is to be established leading to very high currents. This either triggers the internal overcurrent detection device (fuse) or causes high thermal stress in the cell.

Test equipment

The needed equipment is:

- A short circuit device which can handle currents up to 100 times the nominal current of the device under test. Including all the cables, connectors and measurement devices like shunt resistance. All should be generously dimensioned to minimize short circuit resistance[4].
- Current measurement device with very high sampling rate which can handle up to 100 times the nominal current of the cell.
- The release of toxic gases as well as flammable gases should be measured.

Test procedure

- Adjust the SOC of cell to 100 % in accordance with 5.3.
- Adjusted cell as above shall be stored at room temperature, and be then short-circuited by connecting the positive and negative terminals with an external resistance for 10 min. A total external resistance shall be equal to or less than 5 mΩ as agreed between the customer and the manufacturer.

---

[4] Most standards require a short circuit resistance of <5mΩ. Customer requirements are often more demanding. Short circuit resistances of <250μΩ are a practical value.

Test duration

Test duration usually is very short. Often the short circuit has to be maintained for 1 h or 10min plus 1h observation time.

Difference with similar methods in standards or usual practice

Test standards that comprise a capacity test are:
UN38.3: Test is conducted at 55°C, short circuit is maintained for 1h.
IEC62281: Similar to UN38.3 but with other period of observation.
IEC62133: Similar to UN38.3 but with different sample number.
IEC62660-2: Short circuit held for 10 min, then 1h observation time.
ISO12405-3: On pack level. Short circuit resistance less than 100mΩ.
SAEJ2929: Similar to UN 38.3.
SAND2005: Short circuit within 1s. Additional test where a resistance similar to the DC resistance of the cell shall be used but at least higher than 10mΩ.
QC/T743: On module or higher. Test can be conducted with resistance of 1/10 or DC resistance of module or less than 5mΩ. Second test where parts of the module are subjected to short circuit. Temperature is the highest operation voltage.
UL2580: Similar to IEC62660-2 but different requirements.
DOE-INL/EXT: On system level with short circuit resistance of <=20mΩ. Additionally test with current 15% below the rated value of the protection device.

Post-processing

Often the removed charge and the voltage after removing the short circuit are of interest.

Example

In this example a PHEV Module is short circuited. According to ISO12405-3. Internal protection is removed.
Figure 37. Shows the module with the electrical connectors. It is mandatory to ensure good electrical conductivity.

Figure 37. Module with electrical connection and thermal sensors before the test (Hybrid Commercial Vehicle (HCV)).

Figure 38 shows the short circuit equipment. It includes a 20kA current transformer and a 10kA shunt. This dual system is for backup in case one measurement is not satisfying. Also there is the high current automated switch on the right. Sampling rate of current and voltage was 20kHz and 10Hz on the temperature sensors. This is important as the test itself usually only lasts a few seconds.

Figure 38: Short circuit equipment.

Figure 39 shows the measurements during the test. It can be seen that the current exceeds 3000A in the beginning but then quickly declines. As soon as the short circuit is established the voltage drops to a few mV. When the short circuit is removed after 10 min the voltage recovers. Temperature wise it can be seen that there are peak temperatures close to 70°C at the spots. The module did not vent, catch fire or explode.

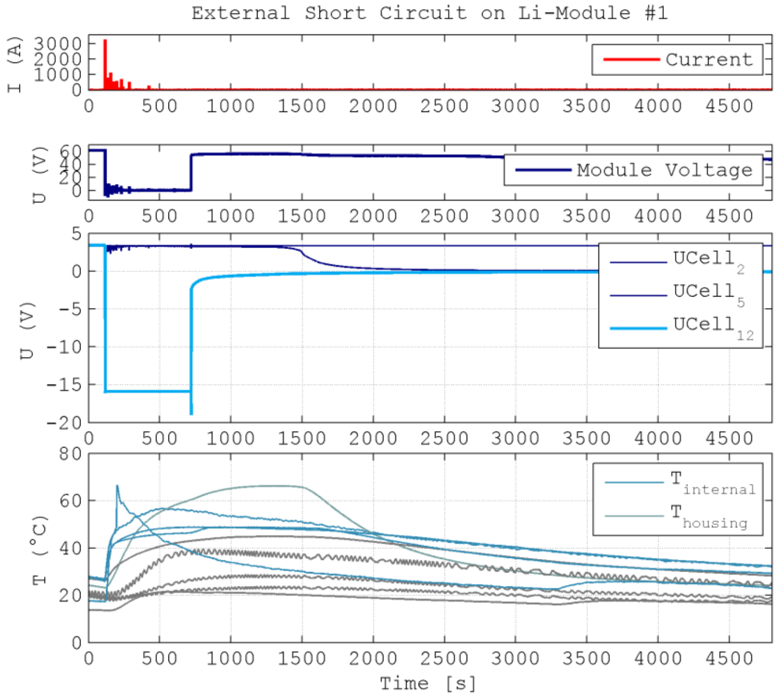

Figure 39. Results of short circuit test (HCV).

Figure 40 shows the casing after the test. It can be seen that the case melted a little during the test. This is an indicator that the maximum temperatures at some spots were higher than on those spots measured in Figure 39. However, this is a minor issue and the module has passed the test requirements.

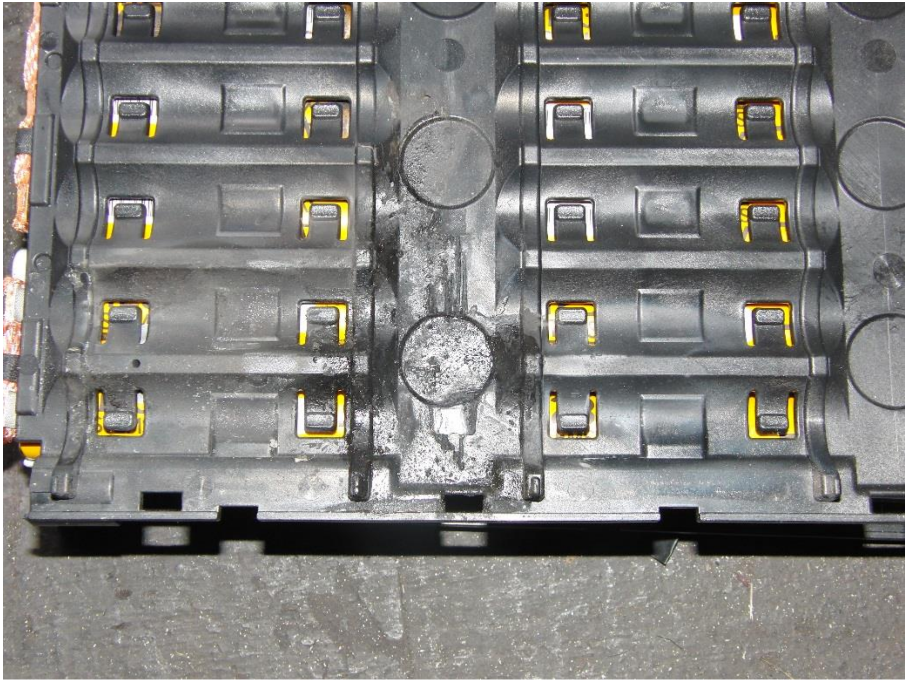

Figure 40. Case after short circuit test (HCV).

Internal short circuit

To be inserted

Overcharge

[FiveVB, Wolfram Kohs]

Test intention

This test is performed to study a cell´s response to accidental overcharge caused by BMS malfunction or similar. The test is usually applied on single cells, however there are similar tests for modules and packs.

Application(s)

The reaction of cells, the hazard potential, resp. if there, the cells security devices can be evaluated with the results. The vulnerability of different cell chemistries to overcharge can be studied.

Remark: Some of the standards, depending on the aim of the test, demand an inactivation of the security devices to test a worst-case scenario.

Test approach

Cells are overcharged under defined conditions; the cells behaviour being closely monitored.The release of toxic gases as well as flammable gases should be measured.

Test equipment

Potentiostat or cycling system, camera system, thermal camera, data logger for temperature, ev. GC/MS or similar for gas analysis in case of venting or rupture. …

Test procedure

The tests generally start at an SOC of 100 % and are done at ambient temperature. The different charging currents and end criteria are varying strongly between the standards and are therefore summarized in Table 12. The experiments however end, if the protection devices interrupt the test, or if there is a thermal runaway or venting.

Table 12: From the different standards, the following test conditions have been collected. The tests generally start at an SOC of 100 %.

	I	stop criteria
SAE J2464:	1C, or I_{max} (3C)	SOC 200 %
IEC 62660-2	1C (BEV), 5C (HEV)	$U = 2 * U_{max}$, or SOC 200 %
IEC 62660-3	1C (BEV), 5C (HEV)	$U = 1.2 * U_{max}$, or SOC 130 %
ECE-R100.02	≥C/3	SOC 200 %
QC/T 743	1C	$U \geq 5$ V, t = 90 min
QC/T 743*	3C	$U > 10$ V
GB/T 31485	1C	$U \geq 1.5 * U_{max}$, t = 60 min
UN Test 38.3	$I = 2 * I_{max}$	$U = 2 * U_{max}$

Remark:

* QC/T 743 describes two charging methods.

Test duration

The test itself can be considered to need 1-2 h, preparation and follow-up work not included.

Difference with similar methods in standards or usual practice

See test procedure.

Post-processing

Additionally to the mentioned above the deformation of the cell is maybe of interest, or if externally fixed the forces evolving.

Example

An example for a test setup for an overcharge experiment is given in Figure 41, the data from this test are shown in Figure 42 . The pouch cell, without any safety devices finally did not react in a gentle way.
Test object was a 84 Ah pouch cell, the final SOC was 193 %, the maximum temperatures recorded during the runaway reached 550°C.

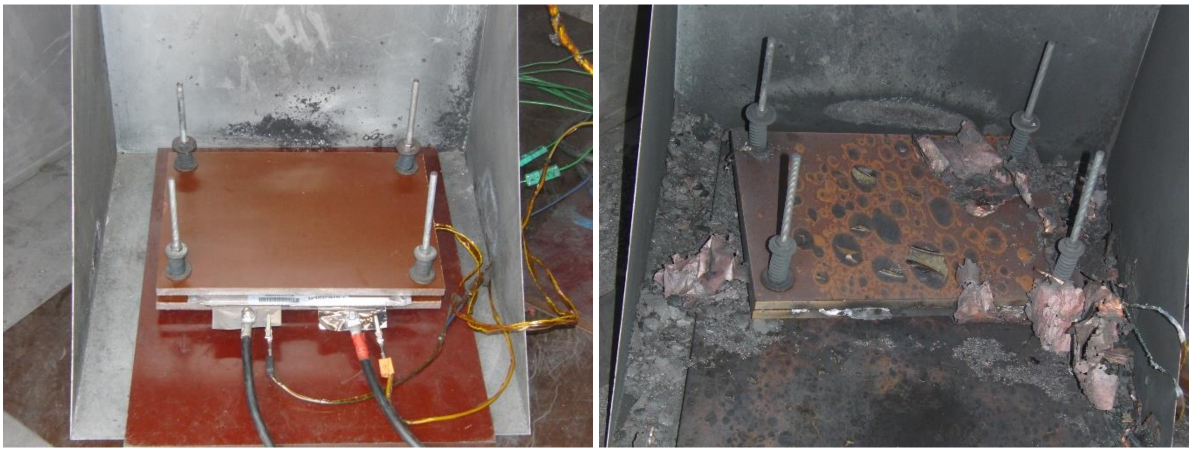

Figure 41: Test setup, and test result of an overcharge test of a pouch cell with a capacity of 84 Ah.

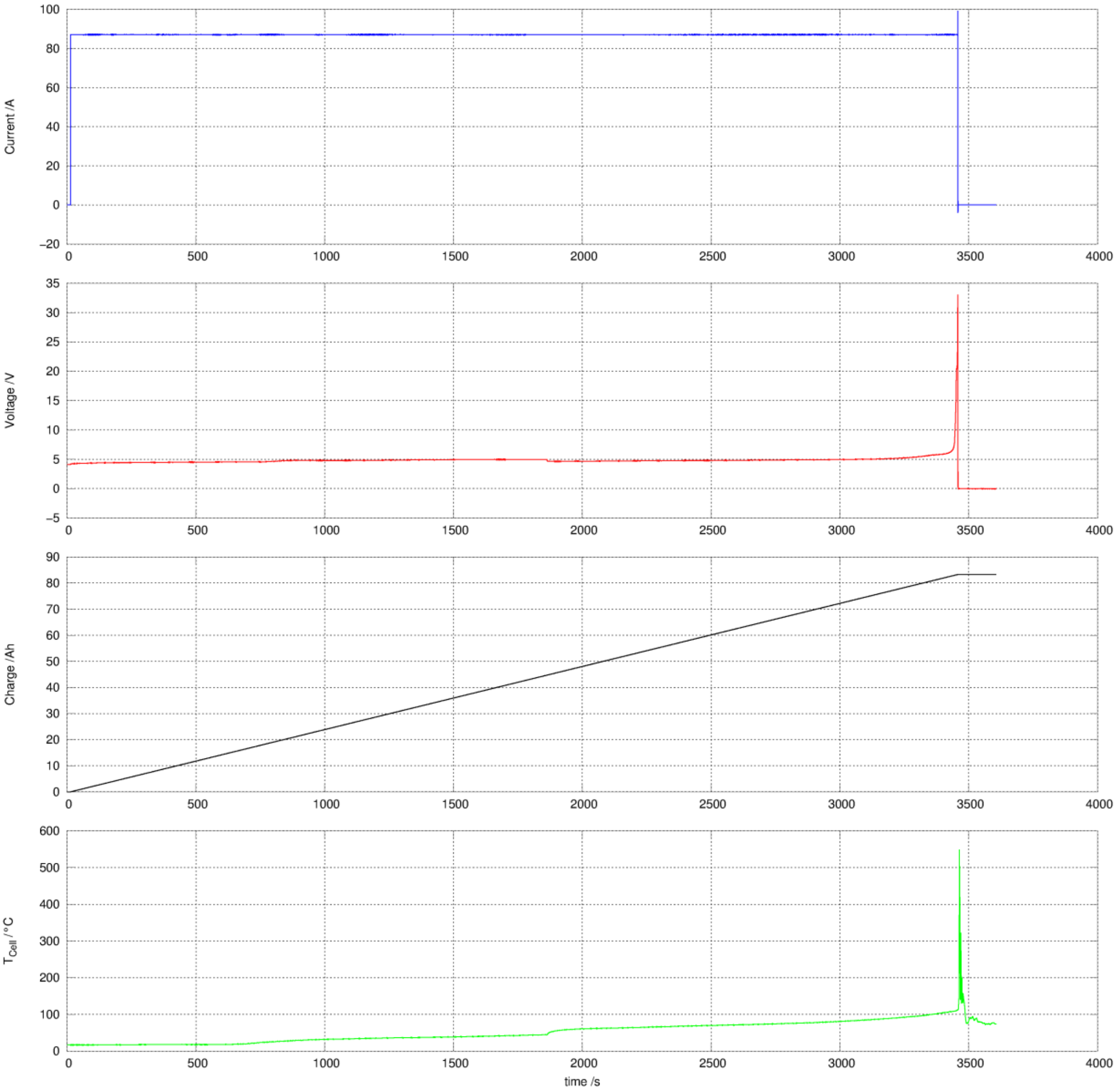

Figure 42: Progress of the current, cell potential, cell capacity (>100 % SOC) and cell temperature of the overcharge test mentioned before.

Forced discharge

[FiveVB, Wolfram Kohs]

Test intention

The purpose of this test is to verify the behaviour of a cell, and if there, the performance of over-discharge protection devices in case of deep discharge caused by BMS failure or similar. The test is applied on single cells, there are tests with similar intentions for modules and packs.

Application(s)

The results allow an estimation of a cell´s hazard potential. Also, an evaluation of different cell chemistries, cell designs, and safety devices is possible.

Remark: Some of the standards, depending on the aim of the test, demand an inactivation of the security devices to test a worst-case scenario.

Test approach

Cells are discharged under defined conditions beyond their lower potential limit. The reactions occurring are closely observed.

Test equipment

A potentiostat or cycling system is needed, a camera system, a data logger for the cell temperature, ev. GC/MS or similar for gas analysis in case of venting or rupture.

Test procedure

The tests start at different SOC´s. The corresponding discharging conditions and end criteria are varying strongly between the individual standards and are therefore listed in Table 13: From the different standards, the following test conditions have been collected. The tests generally start at an SOC of 100 %.Table 13. The experiments however end, if the protection devices interrupt the current, or if there is a thermal runaway or venting. The tests are done at ambient temperature.

Table 13: From the different standards, the following test conditions have been collected. The tests generally start at an SOC of 100 %.

	I	stop criteria
SAE J2464:	SOC 100 %, $I = I_{max}$ until SOC = -100 %, hold U for 30 min	$U = -U_{max}$
IEC 62660-2	SOC 0 %, 1C	t = 90 min
IEC 62660-3	SOC 0 %, 1C	$U \leq 0.25 * U_{nominal}$ or t = 30 min
ECE-R100.02	≥C/3	$U \leq 0.25 * U_{nominal}$
QC/T 743	SOC 100 %, C/3	U = 0 V
GB/T 31485	SOC 100 %, 1C	t = 90 min
UN Test 38.3	$I = I_{max}$	SOC -100 %

Test duration

Depending on the exact test procedure chosen and the cells reaction, 1 to about 5 or 6 h can be estimated for the test, preparation and follow-up work not included.

Difference with similar methods in standards or usual practice

See test procedure.

Post-processing

Deformation of cell case, maybe analysis of gases vented, progress of cell potential and temperature, and other parameters may be of interest.

Example

Imbalanced Charge

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Overcharge voltage control check

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Overcharge current control check

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Over-discharge current control check

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Environmental

Altitude simulation

[FiveVB, Wolfram Kohs]

Test intention

This standard aims on simulating an air transport under low-pressure conditions, the test is usually applied on single cells. Any loss of electrolyte during transport ought to be prevented. The test is found in UN Test Manual Transport of Dangerous Goods 38.3:2016and GB/T 31485:2015.

Applications

The test results allow a direct evaluation of a cell systems tightness. The results might also be useful to study the cell casings behaviour in respect of a later possible increase in cell pressure which might occur in its lifetime. Therefore, it is recommended to check for deformations of the cells case.

Test approach

Fully charged cells are exposed to a defined negative pressure and the cells reaction is observed.

Test equipment

A vacuum drying oven and a controllable vacuum pump are basically what are needed for this test. Vacuum chambers or air pressure chamber might be more sophisticated.

Test procedure

The cells have to be charged fully before starting the test, SOC = 100 %. The cells are placed in a vacuum chamber/air pressure chamber and a pressure of ≤11,6 kPa is applied for a minimum of 6 h. The test shall be performed at room temperature 20 °C ± 5 °.
Neither leakage, rupture nor venting should occur, nor disassembly, explosion or fire.

Test duration

The standards ask for a testing duration of minimally 6 h, more is possible.

Difference with similar methods in standards or usual practice

There are only minor differences between the compared standards, the charging procedures are differing minimally, room temperature is defined as 20 °C ± 5 °C in UN 38.3, resp. 25 °C ± 5 °C in GB/T 31485, the former describes another test criteria in the cells potential after the test being at least 90 % of the cells potential at the start of the test, while the later asks for a post observation period of the cells.

Post-processing

A post observation time of 1 h is defined in GB/T 31485:2015. The cell deformation occurring might be of interest.

Example

Humidity

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Dewing

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Immersion

[FiveVB, Wolfram Kohs]
Not tested on cell level.

~~Salt spray~~ / salt water immersion

[FiveVB, Wolfram Kohs]

Test intention

This test should reflect a situation in which an electric vehicle is flooded. As a worst-case scenario, a situation with salt water is taken into account. Most of the standards consulted describe this test for modules and packs; testing cells is mentioned in FreedomCAR:2005 and GB/T 31485:2015.

Applications

The severity of an accidental situation with water can be evaluated from the results. A short circuit of the cells is possible, hazardous gases can evolve, also loss of electrical isolation is a topic.

Test approach

Salt water immersion testing includes totally submerging cells and observing the reactions occurring.

Test equipment

A container with salt water is needed, the size of the container being big enough to guarantee all of the cell can be submerged. As hazardous gases can evolve, a fume hood or a sufficient ventilation is needed.

Test procedure

Fully charged cells are placed under water, T = 25 °C, use a sea water type composition = 35 g/l NaCl. An observation time of minimally 2 h is defined. No explosion and no fire should occur.

Test duration

The standards ask for an observation time of minimally 2 h.

Difference with similar methods in standards or usual practice

There are only minor differences between the compared standards, the charging procedures are differing minimally. FreedomCAR:2005 additionally mentions some optional parameters that could be measured during the test: temperature of cell, potential and insulation values before and after the test, chemical analysis and flammability of vented gases.

Post-processing

A post observation time of 1 h is also optionally mentioned in FreedomCar:2005, the corrosion of the cells casing could be investigated.

Example

The setup for an immersion test can be quite simple. For small cells a beaker glass is appropriate, a temperature sensor and a monitoring camera, see Figure 43. A ventilation is recommended as hazardous gases evolve due to the corrosion reactions.

As a recommendation, due to the electrically induced corrosion reaction lots of OH^- is formed, and the increasing pH could change, falsify the further corrosion. Therefore, a surplus of water, i.e. a big beaker glass should be used.

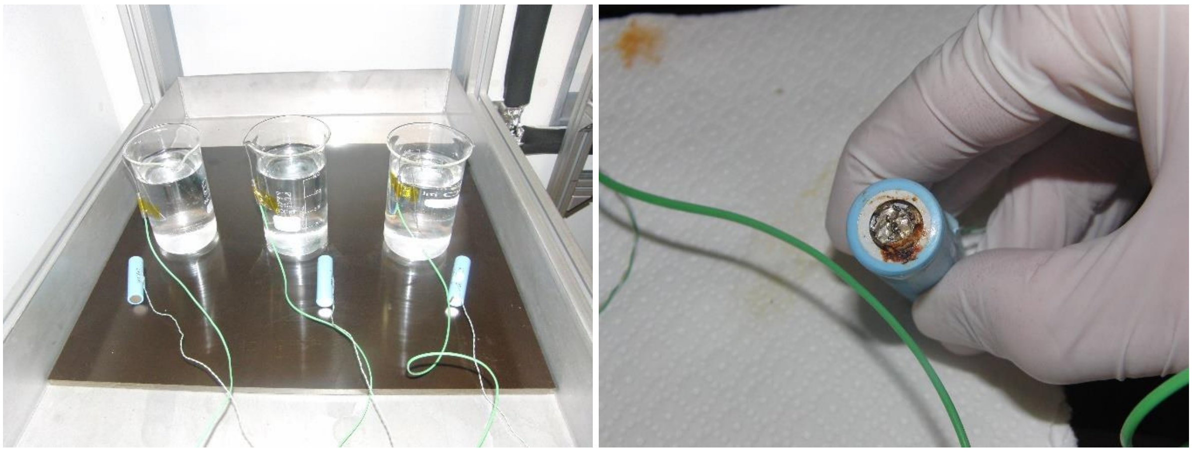

Figure 43. Setup for salt water immersion testing of small 18650 type cells. The outer casing of the positive terminal was destroyed, the inner casing remained okay, test time 2 hours.

Rain test

[FiveVB, Wolfram Kohs]
No standards found concerning this topic, there is only one remark for transport: …keep outside from rain, QC/T 743:2006 – sounds rather reasonable.

Electromagnetic susceptibility

[FiveVB, Wolfram Kohs]
Not tested on cell level.

Separator shutdown integrity test

[FiveVB, Wolfram Kohs]

Test intention

This test aims on evaluating the efficiency of a shutdown separator at elevated temperatures.

Applications

The results provide an understanding of the failure propagation resistance of cells in case of a single cell failure in their neighbourhood.
Also, the ability of a damaged cell (or a cell under abuse) to inactivate itself before going into a runaway can be evaluated.

Test approach

A cell is heated up and the cell impedance, resp. to be more precise current and potential are monitored closely.

Test equipment

Temperature sensor, potentiostat, data logger, oven or similar.

Test procedure

Shutdown separator testing is mentioned in SAE J2464:2009 and USABC Lithium Battery Separator Shut Down Test Procedure:2003. The test described in J2464 consists of two parts, determining the shutdown temperature, and testing the shutdown efficiency.
(I) Using a power supply, with a maximum voltage less than one volt greater than the cell voltage, a current of 5 mA is applied on a cell while heating the cell up. Shutdown is reached when the current drops and the voltage increases.
An exact heating rate is not defined in J2464, but in the USABC test description 10 °C/min are mentioned.
(II) The cell shall be heated to at least 5 °C above the shutdown temperature. After the temperature has stabilised for 10 min an overvoltage of ≥20 V shall be applied, with a current limit of <1C. The voltage shall be maintained for ≥30 min, or until the separator fails.

Remark:
It should be noted, that USABC describes characterisation of the shutdown properties of separators in a sophisticated, but also rather experimental way. From its description, it is intended for separator manufacturers, or more general RD.

Test duration

The test can be assumed to need about 2 h, preparation and follow-up work not included.

Difference with similar methods in standards or usual practice

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Post-processing

Failure propagation modelling might be possible with the results.

Example

Tests at module level

In the battery test standards some tests exist that are not described in this document. These tests are not possible at cell level.

These tests are:

- Roll-over
- Thermal control check
- Propagation of thermal runaway
- Rapid charging and discharging
- Imbalanced Charge
- Overcharge voltage control check
- Overcharge current control check
- Over-discharge current control check
- Humidity
- Dewing
- Immersion
- Salt spray
- Rain test
- Electromagnetic susceptibility

Discussion

To be inserted

Recommendations to specific test standards

To be inserted

Conclusion

To be inserted

Appendix A Battery test methods in international standards

Short overview of standards that have test methods for batteries.
This appendix can refer to the tables given in ‘BatteryStandards.info’

To be inserted

Appendix B Summary of the contributing projects

Info text on eCAIMAN, SPICY, FiveVB.

To be inserted