Optimization of scalaBle rEaltime modeLs and functIonal testing for e-drive ConceptS

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Publishable Executive Summary

This document investigates different international (ISO & IEC) and European standards (JARI & SAE) regarding Lithium-ion batteries. The main focus of these standards are design, performance and safety issues and try to address all concerns regarding Li-ion battery usage in electric vehicles. Furthermore, this report addresses the stablished standards regarding batteries for second life application and possible reusability as the safety are the most important issue for second life energy storage systems.

1.1 Document Structure

The structure of document is as below:

- Introduction
- Li-ion battery standards
    - ISO and IEC standards
        - Design
        - Safety
        - Performance
    - JARI standards
    - SAE standards
- Second life standard for reusability

1.2 Deviations from original Description in the Grant Agreement Annex 1 Part A

1.2.1 Description of work related to deliverable in GA Annex 1 – Part A

Evaluation of existing international standards for lithium-ion batteries in battery electric vehicles.
Investigation on reliable and automated methods and procedures for parameter identification of physical and/or empiric models of batteries. Potential for international cooperation in establishing standard procedures should be explored.
Increased collaboration between firms and academia and other projects with similar research activities and further leverage the EV-development ecosystem in Europe.
-Assessment of existing standards IEC & ISO at cell and system levels
-Interaction with European and international standardization bodies (CEN-CENELEC, ISO, IEC, SAE, JARI, …)
-Analysis of legislation framework to verify current feasibility for reuse and second-life (e.g. integration with WEEE Directive; Safety issues etc.).

1.2.2 Time deviations from original planning in GA Annex 1 – Part A

There are no deviations with respect to the timing of this deliverable.

1.2.3 Content deviations from original plan in GA Annex 1 – Part A

There are no deviations from the Annex 1 – Part A with respect to the content.

2 Introduction:

Electric Vehicles (EVs), are expected to contribute effectively to the sustainable mobility. However, to allow a faster market penetration, standardization is extremely important. Indeed, for convenient and secure use of vehicle, various aspects of EVs should be standardized [1]. At a worldwide level, standardization is mainly under the competence of two institutions: The International Electrotechnical Commission (IEC), founded on 1906, and the International Organization for Standardization (ISO), founded on 1946. Compare to IEC, which is work on electric components and electric supply infrastructure, ISO considers an electric vehicle, as a whole. Regarding Lithium-Ion batteries, the standards focus on three main aspects: design, safety and performance aspects. The standards, developed for Lithium-ion batteries by ISO/IEC, are as below:

- **Electrically propelled road vehicles**: ISO/NP PAS 16898
- **Lithium batteries- battery pack and system level:** ISO 12405-1, 12405-2, 12405-3
- **Secondary lithium cells:** IEC 62660-1, IEC 62660-2

There are also some other standards relating to EVs batteries like JARI, SAE and CEN

In figure 1 standards of EVS batteries is shown.

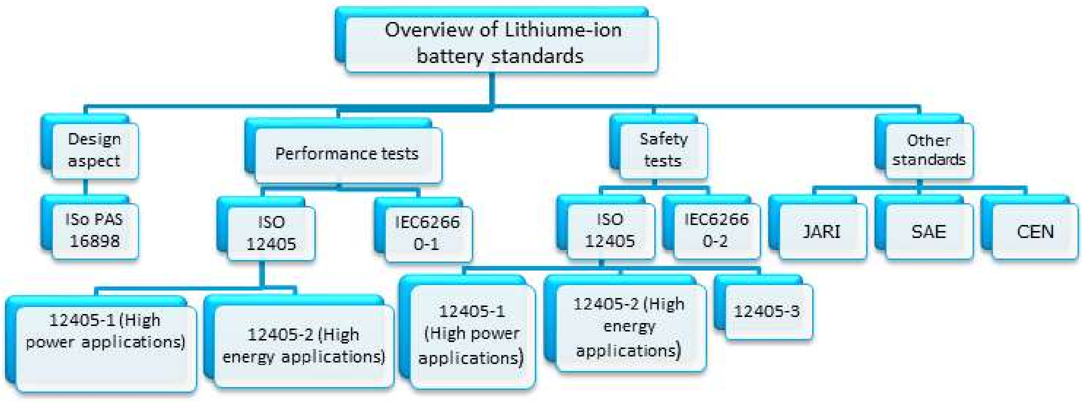


Figure 1 Standards of EVS batteries

3 Lithium-Ion Battery standards:

The Lithium-ion battery standards are considered as below:

- **ISO/NP PAS 16898:** The vehicle traction battery system as a large and very costly component of an electrically propelled vehicle has a huge influence on the vehicle design. Depending on vehicle dimensions and package constraints, the shape of battery packs and systems should follow a top-down procedure. The dimensional requirements on lithium-ion cells for automotive application are given by the battery system, which is influenced by the vehicle design. Therefore, ***ISO/NP PAS 16898***, was developed to focus on electrically propelled road vehicles battery system design. This standard check for the requirements on dimensions for lithium-ion cells for vehicle propulsion [2].
- **ISO 12405:** ISO 12405 specifies test procedures for lithium-ion battery packs and systems, to be used in electrically propelled road vehicles. The specified test procedures enable the user of this part of ISO 12405 to determine the essential characteristics of performance, reliability, and abuse of lithium-ion battery packs and systems. The user is also supported to compare the test results achieved for different battery packs or systems. Therefore, ISO 12405 specifies test procedures for lithium-ion battery packs and systems, to be used in electrically propelled road vehicles. The specified test procedures enable the user of ISO 12405 to determine the essential characteristics of performance, reliability, and abuse of lithium-ion battery packs and systems. The user is also supported to compare the test results achieved for different battery packs or systems. Therefore, the objective of ISO 12405 is to specify standard test procedures for the basic characteristics of performance, reliability, and abuse of lithium-ion battery packs and systems. ISO 12405 consists of the following parts, under the general title Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems:
  - **Part 1: High power applications**: This part of ISO 12405 specifies test procedures for lithium-ion battery packs and systems, to be used in electrically propelled road vehicles. The specified test procedures enable the user of this part of ISO 12405 to determine the essential characteristics of performance, reliability, and abuse of lithium-ion battery packs and systems. The user is also supported to compare the test results achieved for different battery packs or systems. [3]
  - **Part 2: High energy applications**: This part specifies the tests for high energy battery packs and systems. [4]
  - **Part 3: Test specification for lithium-ion traction battery packs and systems (Safety performance requirements):** This standard specifies test procedures for lithium-ion battery packs and systems, to be used in electrically propelled road vehicles. the specified test procedures enable the user of this standard to determine the essential characteristics of the safety performance of lithium-ion battery packs and systems
- **IEC62660:** This standard is to specify performance testing for automobile traction lithium-ion cells and batteries - batteries that basically differ from the other batteries including those for portable and stationary applications specified by the other IEC standards. For automobile application, it is important to note the usage specificity; i.e. the designing diversity of automobile battery packs and systems, and specific requirements for cells and batteries corresponding to each of such designs. Based on these facts, the purpose of this standard is to provide a basic test methodology with general versatility, which serves a function in common primary testing of lithium-ion cells to be used in a variety of battery systems. It includes two parts: IEC62660-1 and IEC62660-2, and it is associated with ISO 12405-1-and ISO 12404-2.
  - **IEC62660-1:** This part of IEC 62660 specifies performance and life testing of secondary lithium-ion cells used for propulsion of electric vehicles including battery electric vehicles (BEV) and hybrid electric vehicles (HEV) [5].
  - **IEC62660-2:** specifies the reliability and abuse testing for lithium-ion cells for electric vehicle application [6].

3.1 Design aspects:

3.1.1 ISO PAS[1] 16898 scopes:

This Publicly Available Specification (PAS) specifies a designation system as well as the shapes and dimensions for secondary lithium-ion cells for integration into battery packs and systems used in electrically propelled road vehicles including the position of the terminals and an over-pressure safety device (OPSD). It is related to *cylindrica*l, *prismatic* and *pouch* cells. The cell designation according to this PAS is intended to be applied to the cells used for electrically propelled road vehicles. This PAS does not apply to cells specifically used for mopeds, motorcycles, and vehicles not primarily defined as road vehicles, i.e. material handling trucks or forklifts. The cell dimensions listed in this PAS are recommended but not restricted for use in passenger cars up to 3,5 t. The inner design, the cell chemistry, the electrical characteristics and any further properties of the cells are not defined in this PAS.

3.2 Performance tests

A set of test procedures have been specified to determine the essential characteristics on performance of lithium-ion battery packs and secondary lithium-ion cells for propulsion of electric vehicles by ISO 12405 and IEC62660-1 respectively. Table 1 summarized the performance tests according to ISO 12405 and IEC62660-1

Table 1.Prformance tests according to ISO 12405 and IEC62660-1

Performance tests	
ISO 12405-1,2	IEC62660-1
Energy and capacity at RT Energy and capacity at different temperature and discharge rates Power and internal resistance No load SOC loss SOC loss at storage Cranking power at low temperature Cranking power at high temperature Cycle life	Power teste • Power density test • Regenerative power density Energy tests Storage tests • Charge retention test • Storage life test Cycle life tests • BEV cycle test • HEV cycle test Energy efficiency test • Test for cells of BEV application • Energy efficiency calculation for cells of HEV application

[1] Publicly Available Specification

3.2.1 Battery performance test procedures according to ISO 12405

According to ISO 12405, The test procedures should be considered to fulfill battery performance criteria.

- Energy and capacity at RT
- Energy and capacity at different temperature and discharge rates
- Power and internal resistance
- No load SOC loss
- SOC loss at storage
- Cranking power at low temperature
- Cranking power at high temperature
- Cycle life

3.2.1.1 Energy and capacity at RT

This test measures DUT capacity in Ah at constant current discharge rates corresponding to the suppliers rated 1C capacity in Ah (e.g., if the rated one-hour discharge capacity is 10 Ah, the discharge rate is 10 A). The one-hour rate (1C) is used as a reference for static capacity and energy measurement and as a standard rate for pack and system level testing. In addition, if applicable, the 10C and the maximum permitted C rate shall be performed for capacity determination to meet the high-power system application requirements. Discharge is terminated on supplier specified discharge voltage limits depending on discharge rates.

Test procedure:

Discharge phase:

- Constant current with the following discharge rates: 1C, 10C and the maximum C rate as permitted by the supplier (the maximum C rate corresponds with Imax).

Charge phase:

- Before starting the charge phase the DUT shall rest at least for 30 min or shall reach RT.
- The charge phase shall not be started until the temperature of the pack or system is fully equilibrated to the proper charge temperature, or a fixed equilibration period shall be used to allow for full equilibration of the DUT.
- After a discharge phase, the DUT shall rest at least for 30 min or shall reach RT before starting the charge phase.

The sequence of energy and capacity test at RT is summarized in table 2:

Table 2 Test sequence energy and capacity test at RT

Step	Procedure	Ambient temperature
1.1	Thermal equilibration	RT
1.2	Standard charge (SCH)	RT
1.3	Standard cycle (SC)	RT
2.1	Discharge at 1C	RT
2.2	Standard charge (SCH)	RT
2.3	Discharge at 1C	RT
2.4	Standard charge (SCH)	RT
2.5	Discharge at 10C	RT

2.6	Standard charge (SCH)	RT
2.7	Discharge at 10C	RT
2.8	Standard charge (SCH)	RT
2.9	Discharge at Imax	RT
2.10	Standard charge (SCH)	RT
2.11	Discharge at Imax	RT
2.12	Standard charge (SCH)	RT
3.1	Standard cycle (SC)	RT

All discharge tests shall be terminated at the suppliers' discharge voltage limits

3.2.1.2 Energy and capacity at different temperature and discharge rate

This test characterizes the capacity at different temperatures at three different constant current discharge rates. The different discharge rates shall be performed in a sequence before the ambient temperature is changed and the test shall be repeated after the new temperature is achieved. This test applies to battery packs and systems.

Test procedure:

After a discharge phase, the DUT shall rest at least for 30 min or shall reach the ambient temperature requirement before starting the charge phase. It should be considered that:

- All discharge tests shall be terminated at the suppliers' discharge voltage limits.
- The standard charge at the different temperatures shall be performed according to the supplier recommendation.
- The value for the C discharge rate shall be based on the rated capacity provided by the supplier and according to the 1C test results as described in test procedure 7.1 Energy and capacity test at RT, respectively.

A test sequence of energy and capacity at different temperature and discharge rates are specified in table 3:

Table 3 Test sequence energy and capacity test at different temperature and discharge rates

Step	Ambient temperature	Thermal equilibration
1.1	Thermal equilibration	RT
1.2	Standard charge (SCH)	RT
1.3	Standard cycle (SC)	RT
2.1	Thermal equilibration	40 °C
2.2	Standard charge (SCH) for top off	40 °C
2.3	Discharge at 1C	40 °C
2.4	Standard charge (SCH)	40 °C
2.5	Discharge at 1C	40 °C
3.1	Thermal equilibration	RT

3.2	Standard charge (SCH)	RT
3.3	Standard cycle (SC)	RT
4.1	Thermal equilibration	40 °C
4.2	Standard charge (SCH) for top off	40 °C
4.3	Standard charge (SCH)	40 °C
4.5	Discharge at 10C	40 °C
5.1	Thermal equilibration	RT
5.2	Standard charge (SCH)	RT
5.3	Standard cycle (SC)	RT
6.1	Thermal equilibration	40 °C
6.2	Standard charge (SCH) for top off	40 °C
6.3	Discharge at Imax	40 °C
6.4	Standard charge (SCH)	40 °C
6.5	Discharge at Imax	40 °C
7.1	Thermal equilibration	RT
7.2	Standard charge (SCH)	RT
7.3	Standard cycle (SC)	RT
8.1	Thermal equilibration	0 °C
8.2	Standard charge (SCH) for top off	0 °C
8.3	Discharge at 1C	0 °C
8.4	Standard charge (SCH)	0 °C
8.5	Discharge at 1C	0 °C
9.1	Thermal equilibration	RT
9.2	Standard charge (SCH)	RT
9.3	Standard cycle (SC)	RT
10.1	Thermal equilibration	0 °C
10.2	Standard charge (SCH) for top off	0 °C
10.3	Discharge at 10C	0 °C
10.4	Standard charge (SCH)	0 °C
10.5	Discharge at 10C	0 °C
11.1	Thermal equilibration	RT
11.2	Standard charge (SCH)	RT

11.3	Standard cycle (SC)	RT
12.1	Thermal equilibration	0 °C
12.2	Standard charge (SCH) for top off	0 °C
12.3	Discharge at Imax	0 °C
12.4	Standard charge (SCH)	0 °C
12.5	Discharge at Imax	0 °C
13.1	Thermal equilibration	RT
13.2	Standard charge (SCH)	RT
13.3	Standard cycle (SC)	RT
14.1	Thermal equilibration	-18 °C
14.2	Standard charge (SCH) for top off	-18 °C
14.3	Discharge at 1C	-18 °C
14.4	Standard charge (SCH)	-18 °C
15.1	Thermal equilibration	RT
15.2	Standard charge (SCH)	RT
15.3	Standard cycle (SC)	RT
16.1	Thermal equilibration	-18 °C
16.2	Standard charge (SCH) for top off	-18 °C
16.3	Discharge at 10C	-18 °C
16.4	Standard charge (SCH)	-18 °C
16.5	Discharge at 10C	-18 °C
17.1	Thermal equilibration	RT
17.2	Standard charge (SCH)	RT
17.3	Standard cycle (SC)	RT
18.1	Thermal equilibration	-18 °C
18.2	Standard charge (SCH) for top off	-18 °C
18.3	Discharge at Imax	-18 °C
18.4	Standard charge (SCH)	-18 °C
18.5	Discharge at Imax	-18 °C
19.1	Thermal equilibration	RT
19.2	Standard charge (SCH)	RT
19.3	Standard cycle (SC)	RT

3.2.1.3 Power and internal resistance

The power and internal resistance tests are intended to determine the dynamic power capability, the ohmic resistance for discharge and charge conditions as well as the OCV of the DUT as a function of SOC and temperatures according to a realistic load profile derived from vehicle driving operation. The test procedure combines the PNGV / Freedom Car "Hybrid Pulse Power Characterization Test" and the EUCAR "Internal Resistance, Open Circuit Voltage, and Power Determination Test". This test applies to battery packs and systems.

Pulse power characterization profile

The objective of this profile is to demonstrate the discharge pulse power (0,1 s, 2 s, 10 s, and 18 s) and regenerative charge pulse power (0,1 s, 2 s, and 10 s) capabilities at various SOC. The test protocol uses constant current at levels derived from the suppliers maximum rated pulse discharge current Imax with an upper limitation of 400 A. Only in case the DUT reaches the discharge voltage limit during discharge, the current shall be reduced such that the battery terminal voltage is maintained at the discharge voltage limit throughout the 18s discharge pulse. The current of the regenerative charge pulse shall be kept constant and shall be calculated as 75 % of the discharge pulse current. Only in case, the DUT reaches during charging the charge voltage limit, the current shall be reduced such, that the battery terminal voltage is maintained at the charge voltage limit throughout the 10s regenerative charge pulse. The test profile shall consist of an 18s discharge pulse followed by a 40 s rest period to allow the measurement of the cell polarization resistance. After the 40s rest period, a 10s charge pulse with 75 % current rate of the discharge pulse shall be performed to determine the regenerative charge capabilities. After the charge pulse, a rest period of the 40s shall follow. Table 4 and show pulse power characterization profile

Table 4 Pulse power characterization profile

Time Increment	Time cumulative	Current
0	0	0
18	18	Imax
40	58	0
10	68	-0,75 Imax
40	108	0

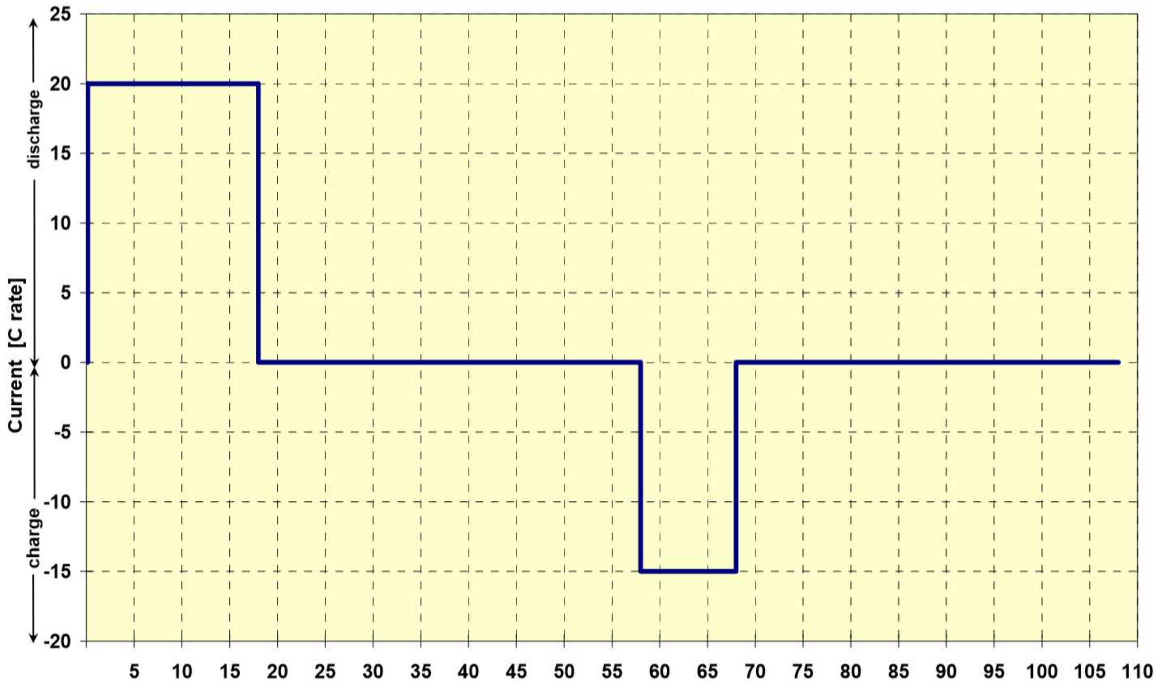


Figure 2 Pulse power characterization profile – current

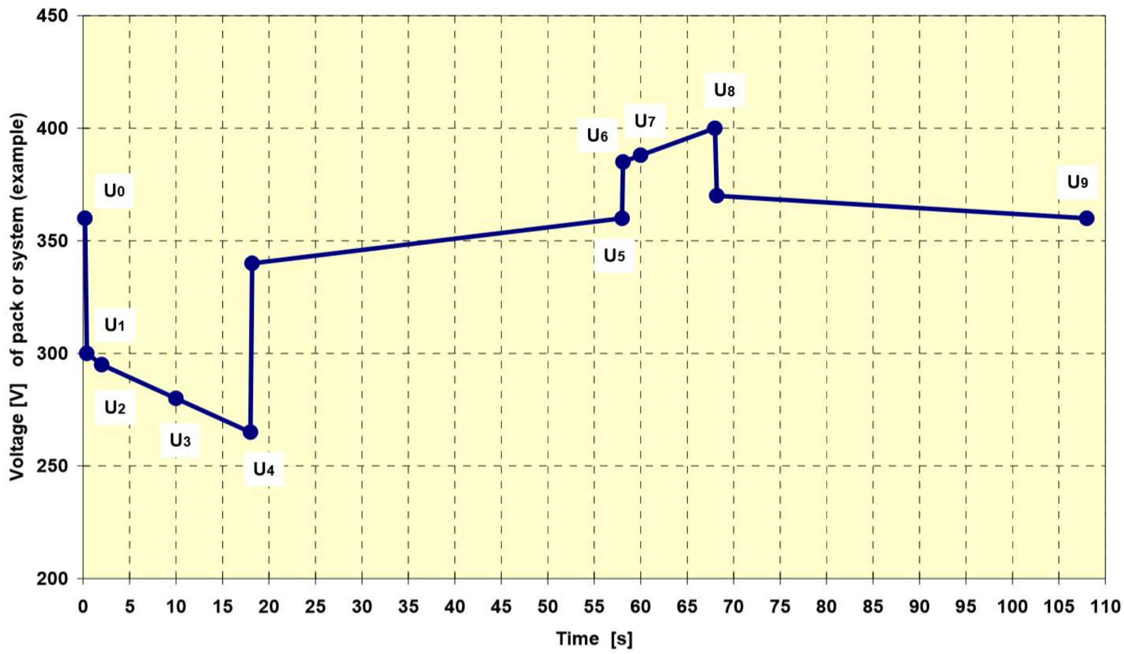


Figure 3 Pulse power characterization profile – voltage

3.2.1.4 No load SOC loss

The purpose of this test is to measure the capacity loss of a battery system if it is not used for an extended period. This test refers to a scenario that a vehicle is not driven for a longer period and therefore the battery system could not place on charge. The no-load capacity loss, if it occurs, may be due to self-discharge, which is normally temporary, or to other mechanisms that could produce permanent or semi-permanent loss of capacity. This test applies to battery systems only.

Test procedure:

The no-load capacity loss shall be measured with a complete and fully operational battery system. The BCU shall be supplied with the necessary auxiliary power (e.g. 12 V d.c. power supply) to be able to control necessary battery system functions during the rest period, e.g.:

- Battery system cell balancing
- Periodical BCU wake-up activities

NOTE: The no-load capacity loss rate[s] shall include any possible parasitic or operational discharge contribution of the cell balancing circuitry itself beyond the inherent self-discharge rate of the battery cells themselves.

The no-load capacity loss rate of the battery system shall be measured for three different rest periods and at two different temperatures. The battery system is discharged to 80 % SOC (or to a SOC agreed between supplier and customer) and then left at open circuit for a certain time. The BCU shall be able to perform control activities (e.g. cell balancing, regular wake-up activities, etc.). After the rest period, the remaining capacity shall be determined by a 1C discharge at RT.

The tests shall be performed in a temperature controlled test chamber at the given temperatures. Before each test cycle at a given temperature, the battery shall be kept at the test temperature for a minimum of 12 h. This period can be reduced if thermal stabilization is reached, specified as less than 4 K change among individual cell temperatures during an interval of 1 h.

Temperatures: RT and 40 °C. Standard cycle: To ensure that each test is done with the battery system in the same initial condition, a SC (see 6.2) shall be performed prior to each test. Discharge rate: Discharge the battery system to 80 % SOC (or to a SOC agreed between supplier and customer) at the 1C rate. Rest period: 24 h (1 day), 168 h (7 days) and 720 h (30 days).

Auxiliary Energy: The auxiliary energy consumption (e.g. 12 V d.c. level) for the BCU and, if required, for other battery system electronics shall be measured continuously and expressed in Wh for each rest period.

The test sequence:

- The first test sequence: Rest period at RT
- The second test sequence: Rest period at 40 °C (or higher according to an agreement between supplier and customer)

Table 5 Test sequence no load SOC loss at RT

Step	Procedure	Ambient temperature
1.1	Thermal equilibration	RT
1.2	Standard charge (SCH)	RT
1.3	Standard cycle (SC)	RT
1.4	Discharge 1C to 80 % SOC	RT
1.5	Rest period with open HV circuit for 24 h	RT
1.6	Standard cycle (SC)	RT
1.7	Discharge 1C to 80 % SOC	RT
1.8	Rest period with open HV circuit for 168 h	RT
1.9	Standard cycle (SC)	RT
1.10	Discharge 1C to 80 % SOC	RT
1.11	Rest period with open HV circuit for 720 h	RT
1.12	Standard cycle (SC)	RT

Table 6 Sequence no load SOC loss at 40 °C (or higher)

Step	Procedure	Ambient temperature
2.1	Thermal equilibration	RT
2.2	Standard charge (SCH)	RT
2.3	Standard cycle (SC)	RT
2.4	Discharge 1C to 80 % SOC	RT
2.5	Rest period with open HV circuit for 24 h	40 °C (or higher)
2.6	Thermal equilibration	RT
2.7	Standard cycle (SC)	RT
2.8	Discharge 1C to 80 % SOC	RT
2.9	Rest period with open HV circuit for 168 h	40 °C (or higher)
2.10	Thermal equilibration	RT
2.11	Standard cycle (SC)	RT
2.12	Discharge 1C to 80 % SOC	RT

2.13	Rest period with open HV circuit for 720 h	40 °C (or higher)
2.14	Thermal equilibration	RT
2.15	Standard cycle (SC)	RT

3.2.1.5 SOC loss at storage

The purpose of this test is to measure the capacity loss at storage of a battery system if it is stored for an extended period. This test refers to a scenario when the battery system is shipped from a supplier to a customer. This capacity loss at storage, if it occurs, may be due to self-discharge, which is normally temporary, or to other mechanisms that could produce permanent or semi-permanent loss of capacity. This test applies to battery systems only

Test procedure:

The capacity loss at storage behavior shall be measured with a complete and fully operational battery system. During the storage period, all battery system terminals shall be disconnected (e.g. HV connections, LV connection, cooling). The service disconnect device, if any, shall be disconnected. The capacity loss at storage of the battery system shall be measured after a 720 h (30 days) rest period at 45 °C ambient temperature with an initial SOC of 50 %. The remaining capacity after the storage period shall be determined by a 1C discharge.

The capacity loss at storage test shall be performed in a temperature controlled test chamber.

Temperature: 45 °C.

Standard cycle: To ensure that each test is done with the battery system in the same initial condition, a SC (see 6.2) shall be performed prior to the capacity loss at storage test.

Discharge rate: Discharge the battery system to 50 % SOC at the 1C rate.

Rest period: 720 h (30 days).

Auxiliary Energy: During the storage period, all connections at the battery system are disconnected.

Service disconnect: The service disconnect device, if any, shall be disconnected.

The test sequence for SOC loss at storage is summarized in table 7.

Table 7 Test sequence SOC loss at storage

Step	Procedure	Ambient temperature
1	Thermal equilibration	RT
2	Standard charge (SC)	RT
3	Standard cycle (SC)	RT
4	Discharge 1C to 50 % SOC	RT
5	Discharge 1C to 50 % SOC RT 5 Rest period for 720 h, all HV and LV terminals are disconnected, service disconnect is disconnected	45 °C
6	Thermal equilibration	RT
7	Standard cycle (SC)	V

3.2.1.6 Cranking power at low temperature

The cranking power test at low temperatures is intended to measure the power capability at low temperatures. The relevant temperatures shall be -18 °C and, if agreed between supplier and customer, also -30 °C. The aim is to generate a data basis for a time depending on power output at low temperatures. This test applies to battery systems only.

Test procedure:

The test for cranking power at -18 °C shall be performed at the lowest SOC level permitted as specified by the supplier according to the test sequence in Table 8.

Table 8 Test sequence cranking power at low temperature (-18 °C)

Step	Procedure	Ambient temperature
1.1	Thermal equilibration	RT
1.2	Standard charge (SCH)	RT
1.3	Standard cycle (SC)	RT
1.4	Discharge the fully charged DUT at a 1C discharge rate to 20 % SOC or the lowest SOC level allowable as specified by the supplier (minimum state of charge)	RT
1.5	Thermal equilibration	-18 °C
1.6	Set constant voltage of test bench to the lowest permitted system discharge voltage level according to the supplier recommendation for 5 s and monitor the power versus time profile. The maximum current shall not exceed the supplier specification.	-18 °C
1.7	Rest period with open HV circuit for 10 s	-18 °C
1.8	Repeat steps 1.6 to 1.7 twice	-18 °C
1.9	Thermal equilibration	RT
1.10	Standard charge (SCH)	RT

The sampling rate for test data during testing shall be ≤ 50 ms. If agreed between supplier and customer the test for cranking power shall also be performed at -30 °C at the lowest SOC level permitted as specified by the supplier according to the table 9.

Table 9 Test sequence cranking power at low temperature (-30°C)

Step	Procedure	Ambient temperature
2.1	Thermal equilibration	RT
2.2	Standard charge (SCH)	RT
2.3	Standard cycle (SC)	RT
2.4	Discharge the fully charged DUT at a 1C discharge rate to 20 % SOC or the lowest SOC level allowable as specified by the supplier (minimum state of charge)	RT
2.5	Thermal equilibration	-30 °C
2.6	Set constant voltage of test bench to the lowest permitted system discharge voltage level according to the supplier recommendation for 5 s and monitor	-30 °C

	the power versus time profile. The maximum current shall not exceed the supplier specification	
2.7	Rest period with open HV circuit for 10 s	-30 °C
2.8	Repeat steps 2.6 to 2.7 twice	-30 °C
2.9	Thermal equilibration	RT
2.10	Standard charge (SCH)	RT

The sampling rate for test data during testing shall be ≤ 50 ms.

Table 10 Voltage limits for cranking power at low temperature

Time increment [s]	Cumulative time [s]	Applicable DUT Voltage [V]
5	5	Lowest permitted system discharge voltage
10	15	Open HV circuit
5	20	Lowest permitted system discharge voltage
10	30	Open HV circuit
5	35	Lowest permitted system discharge voltage
10	45	Open HV circuit

3.2.1.7 Cranking power at high temperature

The test for cranking power at high temperature is intended to measure power capabilities at a high temperature of 50 °C or the maximum temperature specified by the supplier. The aim is to generate a data basis for a time depending on power output at high temperatures. This test applies to battery systems only.

Test procedure:
The test for cranking power at 50 °C shall be performed at the lowest SOC level permitted as specified by the supplier according to the test sequence in Table 11.

Table 11 Test sequence cranking power at high temperature (50 °C)

Step	Procedure	Ambient temperature
1.1	Thermal equilibration	RT
1.2	Standard charge (SCH)	RT
1.3	Standard cycle (SC)	RT
1.4	Discharge the fully charged DUT at a 1C discharge rate to 20 % SOC or the lowest SOC level allowable as specified by the supplier (minimum state of charge).	RT
1.5	Thermal equilibration	50 °C (or max. temperature specified by the supplier)
1.6	Set constant voltage of test bench to the lowest permitted system discharge voltage level according to the supplier recommendation for 5 s and monitor the power versus time profile. The maximum current shall not exceed the supplier's specification.	50 °C (or max. temperature specified by the supplier)
1.7	Rest period with open HV circuit for 10 s	50 °C (or max. temperature specified by the supplier)

1.8	Repeat steps 1.6 to 1.7 twice	50 °C (or max. temperature specified by the supplier)
1.9	Thermal equilibration	RT
1.10	Standard charge (SCH)	RT
1.11	Standard cycle (SC)	RT

The sampling rate for test data during testing shall be ≤ 50 ms.

Table 12 Voltage limits for cranking power at high temperature

Time increment [s]	Time cumulative [s]	Applicable DUT Voltage and Current [V] & [A]
5	5	Lowest permitted system discharge voltage and maximum permitted discharge current
10	15	Open circuit
5	20	Lowest permitted system discharge voltage and maximum permitted discharge current
10	30	Open circuit
5	35	Lowest permitted system discharge voltage and maximum permitted discharge current

the profile pulses according to Table 11 shall be performed for the full 5 s duration (even if the test power should be limited to stay within the minimum permitted discharge voltage) to permit the later calculation of the cranking power capability at high temperature.

Requirement

The results shall be delivered as a graphic presentation of power versus time profiles including current, voltage and temperature values.

3.2.1.8 Energy efficiency

The purpose of the energy efficiency test is to determine the battery system round trip efficiency by calculation from a charge balanced pulse profile. For high power application, the energy efficiency of the used battery system has a significant influence on the overall vehicle efficiency. It affects directly the fuel consumption and emission levels of a vehicle equipped with a battery system for high power application. This test applies to battery systems only.

Test procedure:

The test simulates the following driving situation: For acceleration, e.g. onto a highway or during an overtake process, the vehicle driver requests the maximum vehicle power (max. battery discharge power). Consecutively there is a cruising phase without battery performance for an assumed time of 40 s. After that, there is a regenerative braking period assumed for 10 s to recharge the battery. Of course, the actual demands will be different because the drive systems of the vehicle suppliers will differ, but for comparison reasons and evaluation of battery pack and systems it is a common base.
Conditions:

- RT, 40 °C, 0 °C
- 3 different SOC: 65 %, 50 %, 35 %
- 30 min rest period before each power pulse sequence application for equilibrium
- adequate rest period (see general conditions 5.1) after temperature change for thermal equilibration
- Current profile for energy efficiency characterization as described in Table 13:

Table 13 Energy efficiency test profile

Time increment [s]	Time cumulative [s]	Current
0	0	0
12	12	20C or Imax
40	52	0
16	68	-15C or -0.75 Imax
40	48	0

The charge balance (Ah) during this current profile pulse sequence shall be neutral. That means the recharged capacity shall be the same as the discharged capacity before. In case of voltage limitations and current degradations during the power pulse sequence, only the charge neutral periods shall be evaluated. This case shall be indicated clearly in the reported results.

Evaluation:

- Energy during discharge pulse: E_out [Wh]
- Energy during charge pulse: E-in [Wh]
- Determination of energy by integration of discharge/charge voltage and current over time during each pulse
- Energy efficiency, use calculation formula as follows:

Expected values are between 75 % and 90 %, depending on chemistry and system.

$$\boldsymbol{\eta} = \left| \frac{\int_{t_{start}}^{t_{end}} \boldsymbol{U}.\boldsymbol{I}_{discharge}.\,\boldsymbol{dt}}{\int_{t_{start}}^{t_{end}} \boldsymbol{U}.\boldsymbol{I}_{charge}.\,\boldsymbol{dt}} \right| \times \mathbf{100}\ (\%)$$

Table 14 Test sequence energy efficiency test

Step	Procedure	Ambient temperature
1.1	Thermal equilibration	RT
1.2	Standard charge SCH	RT
1.3	Standard cycle SC	RT
2.1	Discharge with 1C to SOC 65 %	RT
2.2	Rest period for 30 min with open HV circuit	RT
2.3	Energy efficiency test at SOC 65 %	RT
2.4	Discharge with 1C to SOC 50 %	RT
2.5	Rest period for 30 min with open HV circuit	RT
2.6	Energy efficiency test at SOC 50 %	RT
2.7	Discharge with 1C to SOC 35 %	RT

2.8	Rest period for 30 min with open HV circuit	RT
2.9	Energy efficiency test at SOC 35 %	RT
3.1	Standard cycle SC	RT
3.2	Thermal equilibration	40 °C
4.1	Discharge with 1C to SOC 65 %	V
4.2	Rest period for 30 min with open HV circuit	40 °C
4.3	Energy efficiency test at SOC 65 %	40 °C
4.4	Discharge with 1C to SOC 50 %	40 °C
4.5	Rest period for 30 min with open HV circuit	40 °C
4.6	Energy efficiency test at SOC 50 %	40 °C
4.7	Discharge with 1C to SOC 35 %	40 °C
4.8	Rest period for 30 min with open HV circuit	40 °C
4.9	Energy efficiency test at SOC 35 %	40 °C
5.1	Thermal equilibration	RT
5.2	Standard cycle SC	RT
5.3	Thermal equilibration	0 °C
6.1	Discharge with 1C to SOC 65 %	0 °C
6.2	Rest period for 30 min with open HV circuit	0 °C
6.3	Energy efficiency test at SOC 65 %	0 °C
6.4	Discharge with 1C to SOC 50 %	0 °C
6.5	Rest period for 30 min with open HV circuit	0 °C
6.6	Energy efficiency test at SOC 50 %	0 °C
6.7	Discharge with 1C to SOC 35 %	0 °C
6.8	Rest period for 30 min with open HV circuit	0 °C
6.9	Energy efficiency test at SOC 35 %	0 °C
7.1	Thermal equilibration	RT
7.2	Standard charge SCH	RT
7.3	Standard cycle SC	RT

The sampling rate for test data during testing shall be ≤ 50 ms.

3.2.1.9 Cycle life:

Additional to other aging factors (i.e. time, temperature), the energy throughput has a significant influence on the lifetime of a battery. For choosing a relevant aging profile concerning the energy throughput, the real conditions during driving shall be considered. That means the applied high C rates and SOC swing shall cover the vehicle demands in a proper way. Further, the usable SOC range shall be covered by the energy cycling test. This is important to get reliable and significant data for lifetime prediction. On the other hand, the battery system shall not be stressed too much. Therefore, the thermal management and monitoring of the battery system are mandatory, as well as certain rest phases are needed for equilibrium and cell balancing. This test applies to battery systems only.

Test procedure:

During the test it is needed, to maintain the DUT temperature by its cooling equipment within a temperature range between RT and 40 °C (i.e. RT during rest periods, certain higher during operation). If requested by the supplier, additional rest periods can be placed between the cycles to keep the DUT within the designated temperature range.

The cycle test is performed by combining two test profiles, one is the “discharge-rich profile” where the discharge amount is slightly larger than the charge amount, as shown in Table 16 and Figure 4, and another one is the “charge-rich profile” where the charge amount is slightly larger than the discharge amount, as shown in Table 17 and Figure 5.

The SOC swing range shall be defined by the customer otherwise the cycle test shall be performed between 30 % and 80 % SOC.

By combining the two profiles, the SOC swing range can be utilized over the cycling test. The cycle test shall be started from the upper limit of SOC with the discharge-rich profile and once the SOC reaches the lower limit or the battery voltage reaches the lower voltage limit specified by the supplier, the profile shall be switched to the charge-rich profile and continued until the upper SOC limit or voltage limit is reached.

The SOC limit for altering the profiles can be detected by one of the following:

- SOC calculated, i.e. by the BCU for a battery system test
- number of cycles (1,944 %/cycle of delta SOC)
- Ah counted by external measurement
- Battery voltage upper and lower limit defined by the supplier

After 22 h of cycling, 2 h of rest shall be taken to allow certain equilibrium within the cell chemistry and to bring all cells to a voltage balanced status (this will be normally performed by the integrated cell voltage balancing circuitry), followed by the performance check.

The test sequence for cycle life has been shown in table 15:

Table 15 Test sequence for cycle life test

Step	Procedure	Ambient temperature
1	Thermal equilibration	RT
2	Standard cycle	RT
3	Standard cycle (SC) for 1C capacity determination	RT

4	Standard discharge (SCH) to 80 % SOC or another upper limit SOC defined by customer	RT
5	Cycling by the discharge-rich profile until SOC 30 % or other lower limit SOC defined by the customer - Battery voltage reaches lower limit defined by the supplier	RT
6	Cycling by the charge-rich profile until SOC 80 % or other upper limit SOC defined by the customer - Battery voltage reaches upper limit defined by the supplier	RT
7	Repeat steps 5 and 6 for 22 h	RT
8	Each day after 22 h of cycling and at the end of the charge-rich profile: - the rest period for equilibration of cell voltages and temperature to be agreed between supplier and customer	RT
9	Every week after 7 days of cycling perform power test with the following test sequence: - Thermal equilibration - Standard charge (SCH) - Standard cycle (SC) - Pulse power characterization - Standard charge (SCH)	RT
10	Continue with step 4, but every two weeks continue with step 2 to perform 1C capacity determination	RT

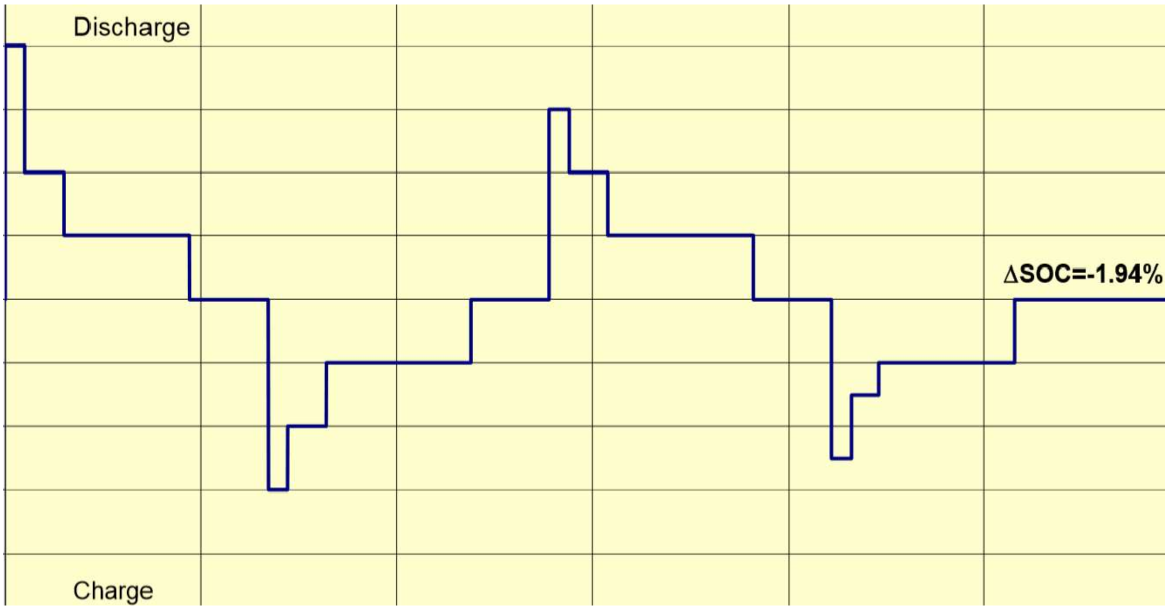


Figure 4 Current profile for cycle life test — Discharge-rich profile

Table 16 Times and current profile — Discharge-rich profile

Time increment [s]	Time cumulative [s]	Current [C-rate]	Delta SOC [%]
5	5	20	2,778
10	15	10	-5,556
32	47	5	-10,000
20	67	0	-10,000
5	72	-15	-7,917
10	82	-10	-5,139
37	119	-5	0,000
20	139	0	0,000
5	144	15	-2,083
10	154	10	-4,861
37	191	5	-10,000
20	211	0	-10,000
5	216	-12,5	-8,246
7	223	-7,5	-6,806
35	258	-5	-1,9444
42	300	0	-19,444

NOTE: Because of different time delays and slew rates of various battery testers which will be used, no shorter pulses than 5 s are defined. A requested C-rate according to Table 16 shall be limited to the maximum current specified by the manufacturer. If so, the corresponding time increment shall be increased in order to achieve the requested delta SOC value. This results in an increased cumulative time for the discharge-rich profile

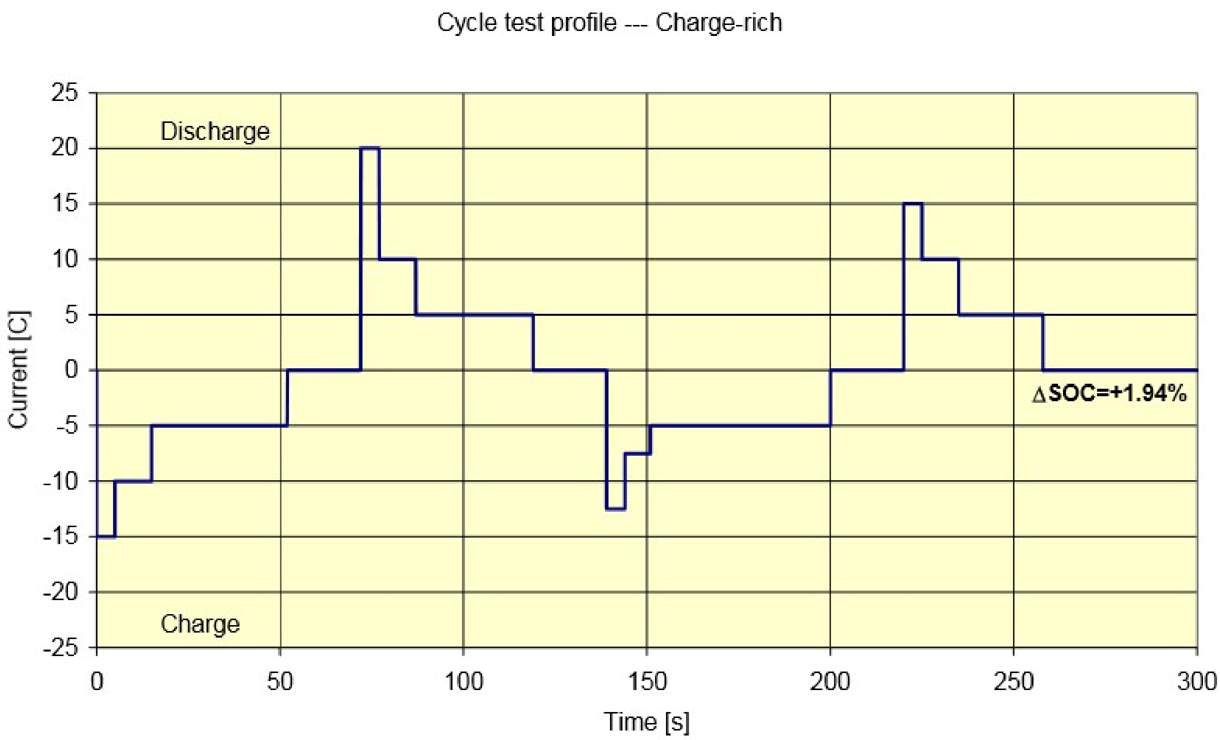


Figure 5 Current profile for energy cycle test — Charge-rich profile

Table 17 Times and current profile — Charge-rich profile

Time increment [s]	Time cumulative [s]	Current [C-rate]	Delta SOC [%]
5	5	-15	2,083
10	15	-10	4,861
37	52	-5	10,000
5	77	20	7,222
10	87	10	4,444
32	119	5	0.000
20	139	0	0.000
5	144	-12.5	1,736
7	151	-7.5	3,194
49	200	-5	10,000
5	226	15	7,917
10	235	10	5,139
23	258	5	1,944
42	300	0	1,944

NOTE: Because of different time delays and slew rates of various battery testers which will be used, no shorter pulses than 5 s are defined.
A requested C-rate according to Table 17 shall be limited to the maximum current specified by the manufacturer. If so, the corresponding time increment shall be increased in order to achieve the requested delta SOC value. This results in an increased cumulative time for the charge-rich profile.

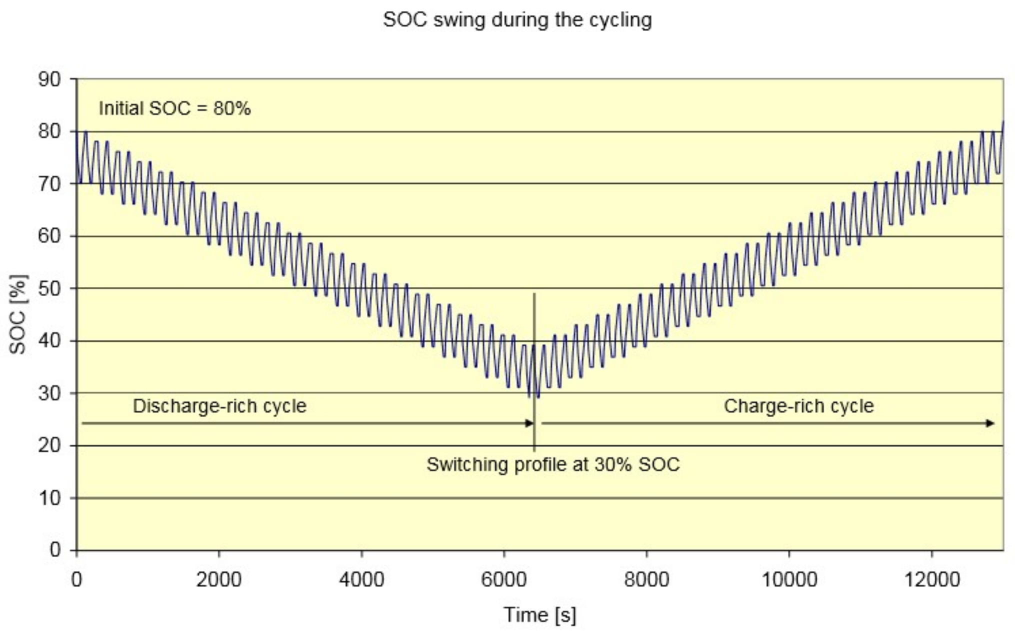


Figure 6 Typical SOC swing by two profiles combination

3.3 Safety aspects:

When it comes to battery safety, the tests below should be considered in both high-power applications and high energy applications. These tests are generated according to ISO 12405-1 and 12405-2 for lithium-ion battery package and IEC62660-2 for lithium-ion battery cells:

Table 18 Safety tests

Safety tests				
ISO 12405-1,2		IEC62660-2		
Electrical abuse tests	Reliability tests	Mechanical tests	Thermal tests	Electrical tests
• Short circuit protection • Overcharge protection • Over-discharge protection	• Dewing • Thermal shock • Mechanical vibration • Mechanical shock	• Vibration: • Mechanical shock: • Crush:	• High-temperature endurance: • Temperature cycling	• External short circuit • Overcharge • Forced discharged

3.3.1 Safety tests with respect to ISO 12405-2

3.3.1.1 Electrical abuse tests

3.3.1.1.1 Short circuit protection

The purpose of the short circuit protection test is to check the functionality of the overcurrent protection device. This device shall interrupt the short circuit current to prevent the DUT from further related severe events caused by a short circuit current.
This test applies to battery packs and systems.

Test procedure

The DUT shall be at RT, fully charged and under normal operating conditions (main contactors are closed, battery systems are controlled by the BCU). An appropriately sized conductor of (100 +0/-40) mΩ shall be used to apply a 'hard short' in less than one second for 10 min, or until another condition occurs that prevents completion of the test (e.g., component melting). The test shall be performed with integrated passive and no passive short circuit protection devices operational.
After the DUT has been shorted as described above, the observation of the DUT shall be continued for two hours. All functions of the DUT shall be fully operational as designed during the test. At pack level, the overcurrent protecting device (e.g. fuse) shall interrupt the short circuit current. At the system level, the short-circuit current shall be interrupted by the overcurrent protecting device (e.g. fuse) and/or by an automatic disconnect by the main contactors.
Data sampling, especially for DUT voltage and current shall be performed with an adequate sampling rate e.g. 0,1 ms for evaluation of the current shut-off function and the real short circuit current peak.
Requirement
Measured data shall include:

- DUT voltage, current, and temperature as a function of time.
- Isolation resistance between the DUT case and the positive and negative terminals before and after the test.

3.3.1.1.2 Overcharge protection

Test procedure:

The DUT shall be at RT, fully charged and under normal operating conditions with the cooling system operating (main contactors are closed, the battery system is controlled by the BCU). The test shall be performed with integrated passive circuit protection devices operational. Active charge control of the test equipment shall be disconnected.

- The DUT shall be charged at a constant current rate which is agreed by supplier and customer. The recommended constant charge current should be 5C.
- The upper limit for the power-supply voltage should be set not to exceed 20 % of the maximum battery system voltage.
- Charging shall be continued until the DUT interrupt the charging by an automatic disconnect of the main contactors
- The overcharge test shall be terminated when the SOC level is above 130 % or when cell temperature levels are above 55 °C. Limits for SOC and DUT cell temperature levels for terminating the overcharge protection test may be agreed between supplier and customer. Data acquisition/monitoring shall be continued for one hour after charging is stopped.

All functions of the DUT shall be fully operational as designed during the test. The BCU shall interrupt the overcharge current by an automatic disconnect of the main contactors into preventing the DUT against further related severe effects.
Data sampling, especially for DUT voltage and current shall be performed with an adequate sampling rate e.g. 100 ms for evaluation of the current shut-off function.

3.3.1.1.3 Over-discharge protection

Purpose
The purpose of the over discharge protection tests it is to check the functionality of the over discharge protection function. This device shall interrupt the over discharge current to prevent the DUT from any further related severe events caused by an over discharge current.
This test applies to battery systems only.
Test procedure
The DUT shall be at RT, fully charged and under normal operating conditions with the cooling system operating (main contactors are closed, the battery system is controlled by the BCU). The test shall be performed with integrated passive circuit protection devices operational. Active discharge control of the test equipment shall be disconnected.

- Perform a standard discharge. When reaching the normal discharge limits, discharging with 1C rate shall be continued.
- Discharging shall be continued until the DUT interrupt the discharging by an automatic disconnect of the main contactors.
- The discharge test shall be terminated manually if 25 % of the nominal voltage level or a time limit of 30 min after passing the normal discharge limits of the DUT have been achieved. Values for time and voltage limits for terminating the over discharge protection test may be agreed between supplier and customer.

NOTE: Nominal voltage is the voltage given by the supplier as the recommended operating voltage of their battery system. Voltage depends on chemistry, cell numbers and arrangement of cells.
Data acquisition/monitoring shall be continued for one hour after discharging is stopped.
All functions of the DUT shall be fully operational as designed during the test. The BCU shall interrupt the over discharge current by an automatic disconnect of the main contactors to prevent the DUT against further related severe effects.
Data sampling, especially at normal discharge limits and beyond for DUT voltage and current shall be performed with an adequate sampling rate e.g. 100 ms for evaluation of the current shut-off function.
Requirement
Measured data shall include:

- DUT voltage, current and temperature as a function of time
- Isolation resistance between the DUT case and the positive and negative terminals before and after the test

3.3.1.2 Reliability tests

3.3.1.2.1 Dewing (temperature change)

Purpose

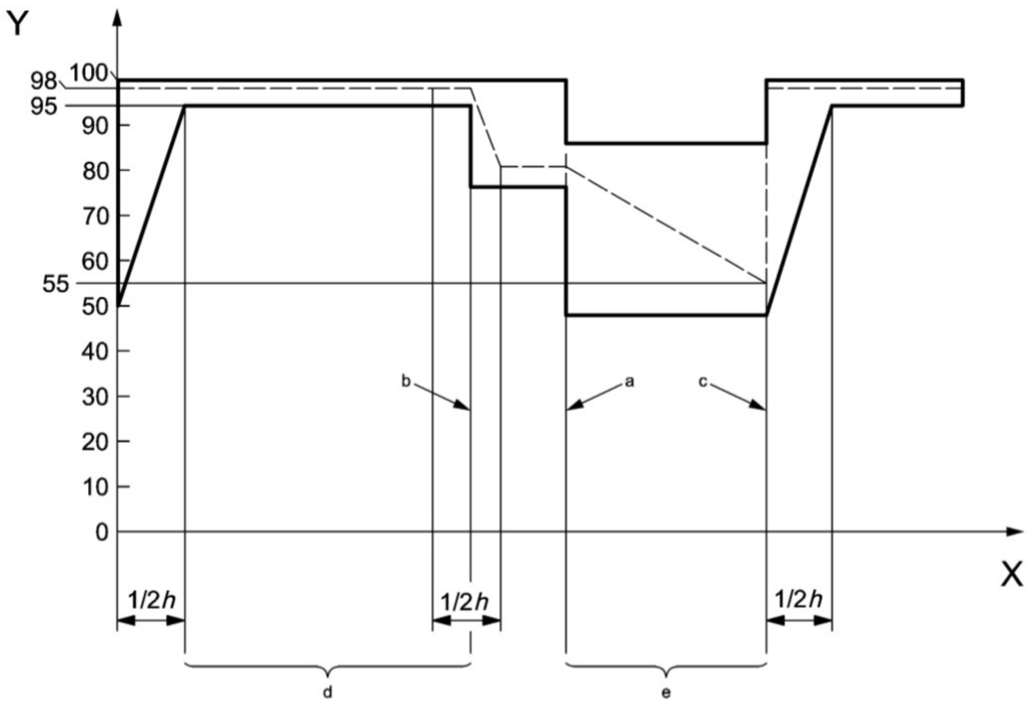
This test simulates the use of the system/component under high ambient humidity. The failure modes addressed, are an electrical malfunction(s) caused by moisture (e.g. leakage current caused by a printed circuit board which is soaked with moisture). An additional failure mode can be a breathing-effect which transports moisture inside the housing when the air inside the system/components cools down and ambient air with high humidity is drawn into the system/components. This test applies to battery packs and systems.

Test procedure

- Perform the test in reference to IEC 60068-2-30, Db, but: – Humidity and temperature profiles according to Figure 7
- Several cycles 5 Use operating mode 2.1 according to ISO 16750-1 during the complete test sequence.

If the temperature of the DUT exceeds the limits given by the supplier the DUT should be operated in an operating mode as agreed between customer and supplier.

NOTE The temperature and humidity profile is specified to generate dewing affected like in the vehicle environment.



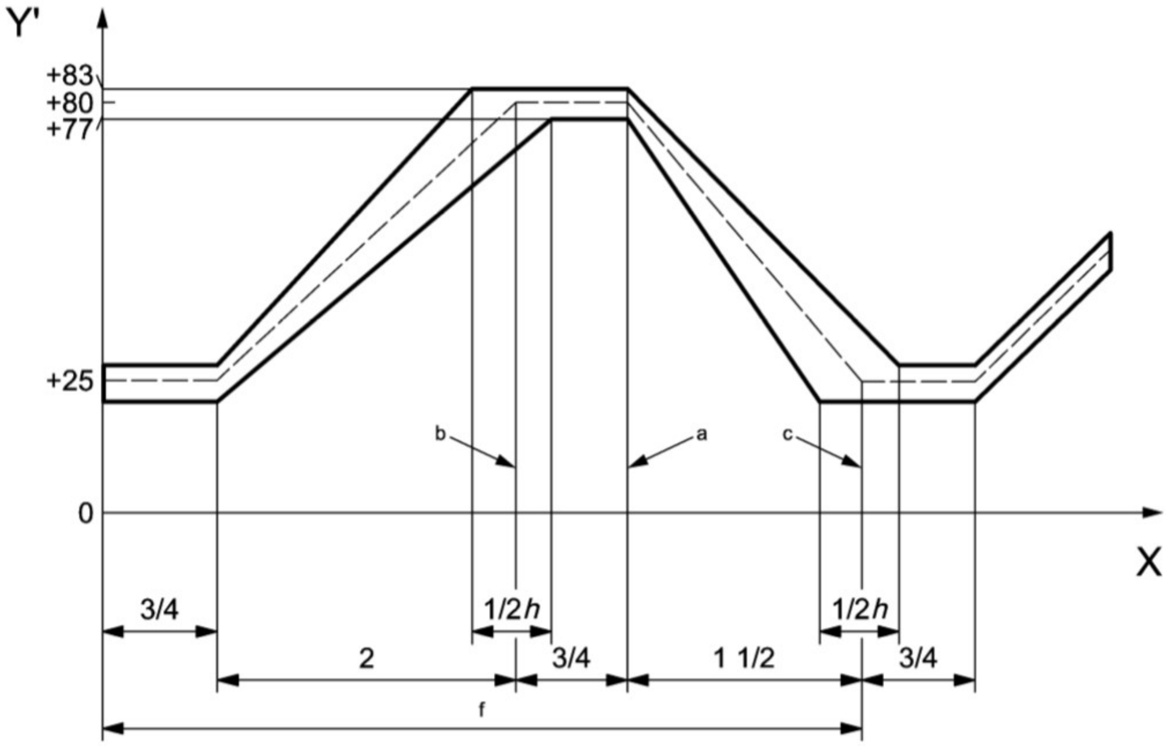


Figure 7 Dewing cycle

Y: Relative humidity in % RH
Y': Temperature in °C
X: Time
a: Start of temperature fall
b: End of temperature rise
c: Recommended set value humidity / temperature d: condensation
e: Drying
f: One cycle

Requirement
The functional status shall be class A as specified in ISO 16750-1.
Measured data shall include:

- Isolation resistance between the DUT case and the positive and negative terminals before and after the test.

3.3.1.2.2 Thermal shock cycling

Purpose
Thermal shock cycling is performed to determine the resistance of the DUT to sudden changes in temperature. The DUT undergo a specified number of temperature cycles, which start at RT followed by high and low-temperature cycling. The failure modes addressed are an electrical and mechanical malfunction(s) caused by the accelerated temperature cycling.
This test applies to battery packs and systems.
Test
Before thermal shock cycling, the DUT capacity shall be evaluated by performing two standard cycles (SC) according to 6.2. Adjust the SOC with a 1C discharge to 50 % before starting the thermal shock cycling profile.

With the DUT at 50 % SOC and at RT, contained in a closed volume and with all thermal controls disabled, thermally cycle the DUT with an ambient temperature between 85 °C or Tmax as specified between supplier and customer to -40 °C (the ambient temperature should be measured near the DUT). The time to reach each temperature extreme shall be 30 min or less. If it is logistically possible, given equipment limitations and safety considerations, the DUT can be moved between two test chambers each set at the opposite end of the temperature range. The DUT shall remain at each extreme for a minimum of one hour. A total of five thermal cycles shall be performed. After thermal cycling, inspect the DUT for any damage, paying special attention to any seals that may exist. Verify that control circuitry is operational.
After thermal shock cycling, the DUT capacity shall be evaluated by performing two standard cycles (SC) according to 6.2.
Measured data shall include:

- The voltage across the positive and negative terminals of the DUT during the test.
- Isolation resistance between the DUT case and the positive and negative terminals before and after the test.
- 1C capacity at RT before and after thermal shock cycling test (in each case 1C capacity of the 2nd standard cycle). 8.2.3 Requirement

The functional status shall be class A as specified in ISO 16750-1.

3.3.1.2.3 Vibration

Purpose
This test checks the DUT for malfunctions and breakage caused by vibration. The vibration of the body is random vibration induced by rough-road-driving as well as internal vibration of the power train. The main failures to be identified by this test are breakage and loss of electrical contact.
The vibration test is composed of two parts,

- Part 1 of the vibration test procedure is intended to test the behavior of the overall battery pack or system. Due to the big mass of this DUT the maximum test frequency is limited to 200 Hz, but the vibration test shall be performed in sequence in all three spatial directions.
- Part 2 of the vibration test procedure is intended to test separately the behavior of the electric and electronic devices with low masses (comparable to electric / electronic devices used in normal vehicle applications) including their mounting devices used in the battery pack or system. This test follows ISO 16750-3 for mounting areas on sprung masses (vehicle body).

This test applies to battery packs and systems

3.3.1.2.4 Mechanical shock

Purpose
This test is applicable to packs and systems intended to be mounted at rigid points of the body or on the frame of a vehicle.
The load occurs, e.g. when driving over a curb stone at high speed. The failure mode is a mechanical damage to components due to the resulting high accelerations. This test applies to battery packs and systems.
NOTE: This test may be performed using a battery pack sub-system
Test
The test shall be performed according to ISO 16750-3, or according to the test profile determined by the customer and verified to the vehicle application.
Acceleration from the shock in the test shall be applied in the same direction as the acceleration of the shock that occurs in the vehicle. If the direction of the effect is not known, the DUT shall be tested in all six spatial directions.

Table 19 Mechanical shock test-parameters

Procedure	Requirements
Operation mode of DUT	3.2

Pulse Shape	half-sinusoidal
Acceleration	500 m/s²
Duration	6 ms
Temperature	RT
Number of shocks	10 per test direction

Before mechanical shock testing, the DUT capacity shall be evaluated by performing two standard cycles (SC). Adjust the SOC with a 1C discharge to 50 % before starting the mechanical shock profile.
After mechanical shock testing, the DUT capacity shall be evaluated by performing two standard cycles.
Requirements:
The functional status shall be class A as specified in ISO 16750-1.
Measured data shall include:

- The voltage across the positive and negative terminals of the DUT during the test.
- Isolation resistance between the DUT case and the positive and negative terminals before and after the test.
- 1C capacity at RT before and after the test (in each case 1C capacity of the 2nd standard cycle

3.3.2 Safety tests with respect to IEC62660-2:

3.3.2.1 Mechanical tests:

- Vibration: This test is performed to characterize cell responses to vibration assumed in the use of vehicle
- Mechanical shock: This test is performed to characterize cell responses to mechanical shocks assumed in the use of vehicle
- Crush: This test is performed to characterize cell responses to external load forces that may cause deformation

3.3.2.2 Thermal tests

- High-temperature endurance: This test is performed to characterize cell responses to the high-temperature environment
- Temperature cycling: This test is performed to characterize thermal durability of the cell by exposing at low and high-temperature environment alternately to cause expansion and contraction of cell components

3.3.2.3 Electrical tests

- External short circuit: This test is performed to characterize cell responses to the external short circuit.
- Overcharge: This test is performed to characterize cell responses to overcharge
- Forced discharged: This test is performed to characterize cell responses to over discharge

3.3.3 Safety tests with respect to ISO 12405-3:

The objective of this standard is to specify standard test procedures for the basic characteristics of safety performance of lithium-ion battery packs and systems.

3.3.3.1 Mechanical tests

- **Vibration**: This test applies to battery packs and systems.
    - *Purpose*: Simulates a mechanical load on vibration derived from vehicle operation which a battery system will likely experience during its life.

- *Test procedure*: According to ISO 12405 clause 8.3
- *Requirements*: During the test and for a 1-hour post-test observation period, the battery system shall exhibit no evidence of venting or battery enclosure rupture, fire, or explosion, and shall maintain an isolation resistance of at least 500 Ω/V. Isolation measurement shall be done in accordance with ISO 6469-1.

- **Mechanical shock:** This test applies to battery packs and systems.
  - *Purpose:* Simulates a mechanical load on shock derived from vehicle operation which a battery system will likely experience during its life.
  - *Test procedure:* According to ISO 12405 clause 8.4
  - Requirements: During the test and for a 1-hour post-test observation period, the battery system shall exhibit no evidence of venting or battery enclosure rupture, fire, or explosion, and shall maintain an isolation resistance of at least 500 Ω/V. Isolation measurement shall be done in accordance with ISO 6469-1.
- **Drop test**: This test applies to battery packs and systems.
  - *Purpose*: Simulates a mechanical load during service operation when the battery system is removed from the vehicle.
  - *Test procedure:* According to ISO 16750-3
  - *Requirements*: During the test and for 1 hour post-test observation period, the battery system shall exhibit no evidence of fire or explosion.

3.3.3.2 Climatic tests

- **Thermal shock**: This test applies to battery packs and systems.
  - Purpose: Simulates a thermal load derived from vehicle operation which a battery system will likely experience during its life.
  - Test procedure: According to ISO 12405 clause 8.2
  - Requirements: During the test and for a 1-hour post-test observation period, the battery system shall exhibit no evidence of venting or battery enclosure rupture, fire, or explosion, and shall maintain an isolation resistance of at least 500 Ω/V. Isolation measurement shall be done in accordance with ISO 6469-1.
- **Dewing**: This test applies to battery packs and systems.
  - *Purpose:* Simulates a climatic load which causes dewing derived from vehicle operation which a battery system will likely experience during its life.
  - *Test procedure*: According to ISO 12405 clause 8.1
  - *Requirements:* During the test and for a 1-hour post-test observation period, the battery system shall exhibit no evidence of venting or battery enclosure rupture, fire, or explosion, and shall maintain an isolation resistance of at least 500 Ω/V. Isolation measurement shall be done in accordance with ISO 6469-1

3.3.3.3 Simulated vehicle accidents

- **Inertial load at vehicle crash**: This test applies to battery packs and systems.
  - *Purpose*: Simulates an inertial load which may occur during vehicle crash situation.
  - *Test procedure:* a) Battery pack or system test, <tbd> , b) Vehicle test, <tbd>
  - *Requirements*: During the test and for a 1 hour post-test observation period, the battery system shall exhibit no evidence of venting or battery enclosure rupture, fire, or explosion, and shall maintain an isolation resistance of at least 500 Ω/V. Isolation measurement shall be done in accordance with ISO 6469-1. The battery system shall be retained at its mounting locations and internal electrical components shall be retained at their mounting locations, when assessed during a post test inspection. Refer also to ISO 6469-1, ISO 6469-3 and applicable national and/or international standards and regulations.
- **Contact force at vehicle crash**: This test applies to battery packs and systems.
  - *Purpose:* Simulates a contact load which may occur during vehicle crash situation.
  - *Test procedure:* a) Battery pack or system test. The complete battery system shall be tested in a crush using a half cylinder with a diameter 150 mm. The tests shall be performed on the expected

vulnerable axes with a minimum force of 100 kN on the battery enclosure. It is not required that all test conditions are conducted on a single DUT. If vehicle structure is used as part or all of the battery enclosure, then that vehicle structure shall be included in the test. b) Vehicle test
  - *Requirements:* During the test and for a 1 hour post-test observation period, the battery system shall exhibit <no evidence of battery enclosure rupture/protection degree of at least IPXXD (according to ISO 20653)>, no fire, explosion or electrolyte spillage outside of the battery system enclosure and vent system

- **Water immersion**: This test applies to battery packs and systems.
- *Purpose:* Simulates a water immersion which may occur when a vehicle is flooded.
- *Test procedure:* According to ISO 16750-4
- *Requirements:* During the test, the battery system shall exhibit no evidence of battery enclosure rupture, fire, or explosion.
- **Simulated vehicle fire:** This test applies to battery packs and systems.
  - *Purpose:* Simulates a thermal load which may occur in a vehicle fire.
  - *Test procedure:* similar requirements of a test procedure for a fuel tank of ECE R34.
  - *Requirements*: During the test, the battery system shall exhibit no evidence of an explosion

3.3.3.4 Electrical tests

- **Short circuit:** This test applies to battery packs and systems.
  - *Purpose:* Simulates an external short circuit across the terminals of the battery system.
  - *Test procedure:* According to ISO 12405 clause 9.2
  - *Requirements:* During the test, the battery system shall exhibit no evidence battery enclosure rupture, of fire, or explosion. The battery system shall maintain an isolation resistance of at least 500 Ω/V. Isolation measurement shall be done in accordance with ISO 6469-1.

3.3.3.5 System failure tests

- **Overcharge protection:** This test applies to battery packs and systems.
  - *Purpose:* Simulates a system failure during charging of the battery pack or system.
  - *Test procedure:* According to ISO 12405 clause 9.3
  - *Requirements:* During the test, the battery system shall exhibit no evidence of venting or battery enclosure rupture, fire, or explosion. The battery system shall maintain an isolation resistance of at least 500 Ω/V. Isolation measurement shall be done in accordance with ISO 6469-1
- **Over-discharge protection**: This test applies to battery packs and systems.
  - *Purpose:* Simulates a system failure during discharge of the battery pack or system.
  - *Test procedure*: According to ISO 12405 clause 9.4
  - *Requirements*: During the test, the battery system shall exhibit no evidence of venting or battery enclosure rupture, fire, or explosion. The battery system shall maintain an isolation resistance of at least 500 Ω/V. Isolation measurement shall be done in accordance with ISO 6469-1
- **Loss of thermal control/cooling**: This test applies to battery packs and systems.
  - *Purpose:* Simulates a system failure of the thermal control/cooling of the battery pack or system.
  - *Requirements:* During the test, the battery system shall exhibit no evidence of venting or battery enclosure rupture, fire, or explosion

3.4 Other standards

3.4.1 JARI

This paragraph is aimed to introduce the reader to Japan rules for electric vehicle safety and standardization.
The main highlight is that the Japanese standard JIS D 5305-3 can be considered perfectly equivalent to the European standard ISO 6469-3 according to [14]. In the general the various articles of JIS D 5305-X are corresponding to the ISO 6469-X; according to [15] the JIS ones are classified as Modified (MOD) of ISO 6469.

Table 20 Comparison between ISO and JIS standardization normative.

ISO	JIS	Status
ISO 6469-1: ELECTRICALLY PROPELLED ROAD VEHICLES - SAFETY SPECIFICATIONS - ON-BOARD RECHARGEABLE ENERGY STORAGE SYSTEM (RESS)	JIS D 5305-1:2007 Electric road vehicles -- Safety specifications -- Part 1: Traction battery	MOD
ELECTRICALLY PROPELLED ROAD VEHICLES - SAFETY SPECIFICATIONS - PART 2: VEHICLE OPERATIONAL SAFETY	JIS D 5305-2:2007 Electric road vehicles -- Safety specifications -- Part 2: Functional safety means and protection against failures	MOD
ELECTRICALLY PROPELLED ROAD VEHICLES — SAFETY SPECIFICATIONS — PART 3: PROTECTION OF PERSONS AGAINST ELECTRIC SHOCK	JIS D 5305-3:2007 Electric road vehicles -- Safety specifications -- Part 3: Protection of persons against electric hazards	MOD

Therefore, the research has been enlarged considering JARI documents. Japan Automobile Research Institute (JARI) is a general incorporated foundation dedicated to automotive testing and research activities. As Japanese deliberation body working with ISO/TC22 (Road vehicles), ISO/SC21 (Electrically propelled road vehicles) and IEC/TC69 (EVs and electric industrial vehicles), JARI carries out drafting and commenting concerning ISO and IEC standards and Japanese JIS standards for EVs, hybrid electric vehicles (HEVs) and fuel cell vehicles (FCVs), and is also involved in standardization discussions at ISO/TC197 (hydrogen technology), IEC/TC21 (batteries), and IEC/SC23H (industrial plug and socket-outlets) in collaboration with associated organizations. JARI has submitted 10 new work item proposals for the international standards relating to automotive lithium-ion battery, DC charging system and similar items. Of these, four have been published as international standards (IEC 62660-1, IEC 62660-2, IEC 62196-2, IEC 62576), one has been published as a public specification (IEC/ISO PAS 16898), and three are scheduled for the final voting in 2013 (IEC 61851-23, IEC 61851-24, IEC 62196-3). In order to promote the wide use of electric vehicles, JARI is trying to have its views and experiences reflected in about 20 other international standards concerning lithium-ion battery pack and system, conductive charging, wireless charging, V2G communication, lightweight EV charging, etc. Some following proposals are the following:

1. JARI conducted high-temperature endurance tests for Li-Ion cell to verify the relevance of this test method. The International standard IEC 62660-2 for Li-Ion cell's safety evaluation tests declares that endurance test ends after the cell is held for 30 minutes at 130°C. However, JARI indicates that the test should be extended until the battery cools to room temperature because one cell ignited while cooling after the test [7].

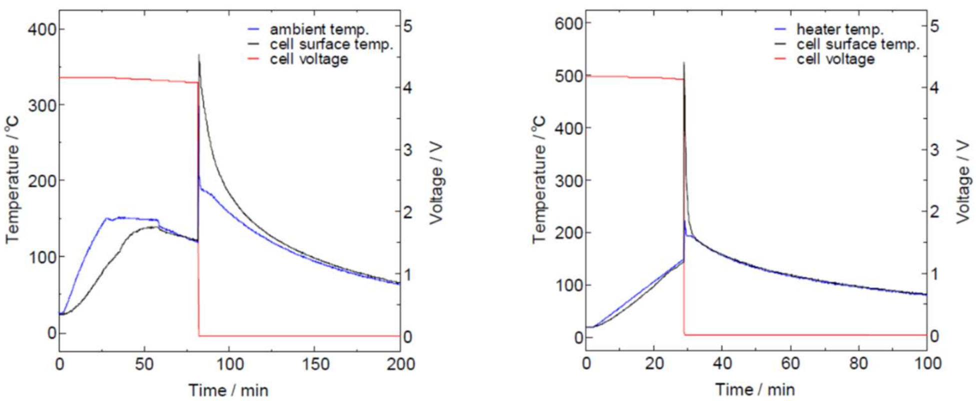


Figure 8 High-temperature endurance test for a prismatic cell conducted by oven (on the left) and by heater blocks (on the right).

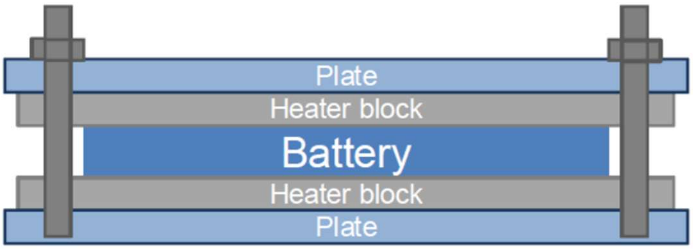


Figure 9 **Schematic view of high-temperature endurance test for battery conducted by heater blocks**

2. JARI analyzed three kinds of standard life tests (rectangular power pulse (IEC), 1C constant current (GB/T-1) and rectangular current pulse discharge (GB/T-2)) to evaluate the effects of test profiles on battery degradation. A Li-Ion cell for EV was used for the tests, which were conducted at 45°C. Faster degradation was observed in the GB/T-2 test. In the comparison of cell voltage distribution during the three kinds of cycle evolution life tests, the ratio at high voltage in GB/T-2 was largest of the three standards, clarifying the cathode/anode reaction region slip which was accelerated [8].

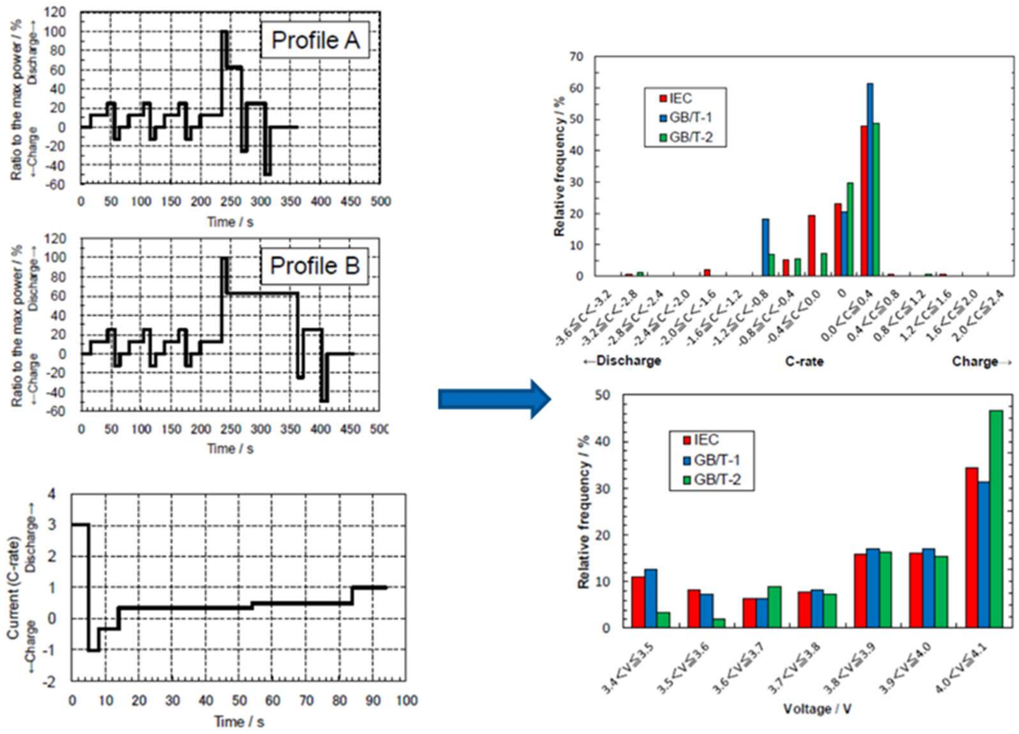


Figure 10 On the left two IEC cycle life test profile (upper) and GB/T-2 cycle life test profile (lower); on the right comparison of C-rate and voltage distribution during several cycle life test.

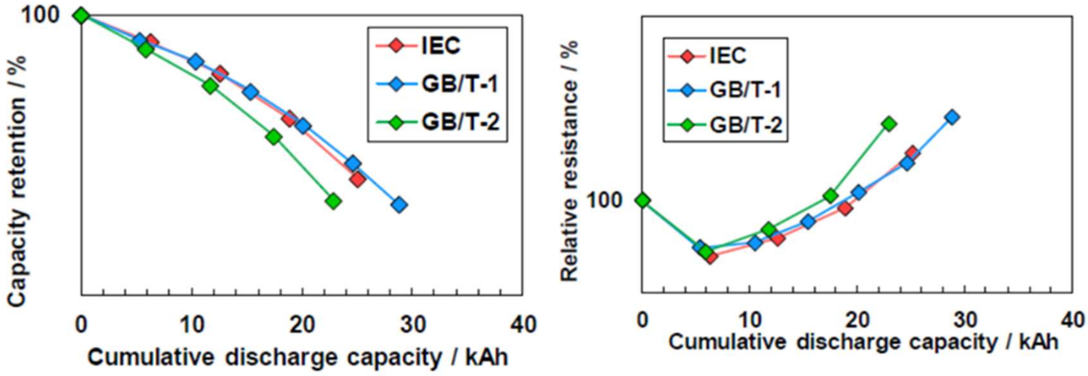


Figure 11 Comparison of capacity retention and relative resistance at 25℃ during the three kinds of cycle life test.

3. JARI found an alternative forced internal short circuit test (FISC) respect to the IEC 62660-3, which specifies safety requirements of Li-Ion cells for automobile applications. Alternative test method releases a ceramic nail with a Ni tip 30 seconds after the internal short has occurred. This alternative method is easier to conduct and obtains lower shorted layers than the original method, yet the method has almost the same event [9].

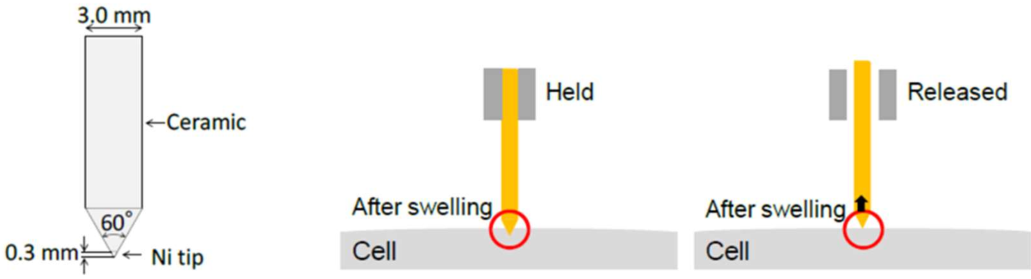


Figure 12 On the left schematic view of a ceramic nail with a Ni tip; on the right comparison of the nail tests after cell swelling.

4. JARI developed a simple current charge-discharge profile for Cycle Life Test (CLT). To verify the validity of this method, JARI measured the change of battery-cell performance (capacity and internal resistance) in an endurance cycle test by using a CLT profile and a reference profile (JC08, UDDS, NEDC). The result did not indicate any clear differences in cell performance among test profiles, although there was very little performance degradation (in particular for internal resistance) [10].
5. JARI conducted review investigation concerning international standards for electric vehicle battery and charging (IEC, ISO) [11], [12], [13]. However, such documents are available only in the Japanese language at the moment, so that a thorough examination is not possible.
6. JARI proposed a battery capacity estimation method to evaluate battery capacity in the real world from the collected data. Using this battery capacity estimation method, JARI evaluated the effect of temperature, SOC, discharge rate on capacity degradation. For the batteries evaluated in this study (always for Electric Vehicle), JARI confirmed that temperature was a major factor contributing to capacity degradation in the real world [14].

Vehicle classification	Area*1	Average temp.*2 [°C]	Average SOC [%]	Average discharge rate*3 [C]	Annual mileage [km]
High-1	Aichi	19.4	65.5	0.23	10,639
High-2	Saitama	19.4	72.7	0.23	9,859
High-3	Kanagawa	18.8	83.5	0.25	7051
Low-1	Ibaraki	15.9	54.9	0.26	11,728
Low-2	Tochigi	14.2	71.4	0.37	11,719
Low-3	Gunma	13.0	76.3	0.28	5,025

Vehicle classification	Area*1	Average temp.*2 [°C]	Average SOC [%]	Average discharge rate*3 [C]	Annual mileage [km]
High-1	Tochigi	16.5	96.3	0.33	8,847
High-2	Ishikawa	17.5	94.0	0.35	7,022
High-3	Saitama	18.0	91.1	0.23	7,243
Low-1	Saitama	18.2	65.1	0.23	8,409
Low-2	Chiba	18.3	59.6	0.26	11,869
Low-3	Ibaraki	15.9	54.9	0.26	11,728

Vehicle classification	Area*1	Average temp.*2 [°C]	Average SOC [%]	Average discharge rate*3 [C]	Annual mileage [km]
High-1	Ishikawa	17.5	94.0	0.35	7,022
High-2	Aichi	18.2	64.1	0.34	5,583
High-3	Akita	18.1	64.0	0.33	3,539
Low-1	Saitama	17.8	64.4	0.20	4,015
Low-2	Kyoto	18.8	67.7	0.18	6,786
Low-3	Kanagawa	18.1	74.2	0.17	4,787

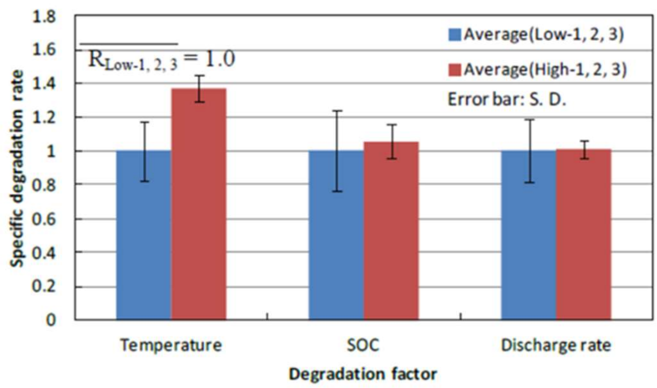


Figure 13 On the left usage conditions of Evs selected for evaluating the effects of temperature (upper), the SOC (middle) and the discharge-rate (lower) on capacity degradation; on the right comparison between specific degradation rates for each degradation factor (temperature, SOC, discharge-rate).

OTHER WORKS

1. JARI conducted fire tests on vehicles with Li-Ion batteries to collect data for examining measures to ensure safety during a vehicle fire. JARI found that the maximum heat flux 1 m from the vehicle and at a height of 1.2 m was 12 kW/m^2 when accompanied by battery combustion, which is not significantly greater than that of gasoline-powered vehicles [15].
2. JARI performed immersion tests of battery packs for electric vehicles using tap water and salt water to confirm the safety when an electric vehicle was submerged such as in floods. Although the discharge current during the immersion tests was different between two types of water, the battery did not present ignition or explosion. Therefore, the battery should remain safe even if water flows into the battery pack [16].

In [19] are described in detail test conditions for each battery level and in comparison, with international safety standards.

3.4.2 SAE

SAE (Society of Automotive Engineers) International is the premiere world resource for the design, manufacturing, operation, and maintenance of automobiles, aircraft, space vehicles, off-highway equipment, trucks, buses, trains, marine craft, engines, and self-propelled vehicles. The largest automotive and aerospace standards-setting body in the world, SAE offers technical information in the form of papers, books, magazines, meetings, conferences, professional development seminars, workshops, expositions, continuing education programs, and Internet products. SAE is committed to serving Society through its vehicle safety, maintenance, resource conservation, and education programs. SAE members are over 128.000 engineers and related technical experts in the aerospace, automotive and commercial vehicle industries. The basic skills of SAE International concern not only the production of non-normative scientific literature, but also the production of technical standards in the sectors mentioned previously. The SAE Technical Standards Development Program has been for nearly a century and is now, revising and producing new standards regarding aerospace, automotive, and commercial vehicle areas. Today's SAE standards product line includes almost 10.000 documents created through consensus standards development by more than 240 SAE Technical Committees with over 450 subcommittees and task groups. These works are authorized, revised, and maintained by the volunteer efforts of more than 9.000 engineers, and other qualified professionals from around the world. Additionally, SAE has 60 US Technical Advisory Group (USTAG's) to ISO Committees. Today battery SAE standards are extended on USA country and it is the editor of 10 battery standards published and 3 under development. Reference safety Li-Ion batteries standards more recent are the SAE J2464 (2009) and SAE J2929 (2013).

3.4.2.1 SAEJ2929 (Safety Standard for Electric and Hybrid Vehicle Propulsion Battery Systems Utilizing Lithium-based Rechargeable Cells)

This standard document is issued in February 2011 and revised in February 2013 (latest revised). SAE J2929 defines a minimum set of acceptable safety criteria for a lithium-based rechargeable battery system to be considered for use in a vehicle propulsion application as an energy storage system connected to a high voltage powertrain. The battery system is a completely functional energy storage system consisting of the packs and necessary ancillary subsystems for physical support and enclosure, thermal management, and electronic control. This standard is primarily focused, wherever possible, on conditions which can be evaluated utilizing the battery system alone. As this is a minimum set of criteria, it is recognized that battery system and vehicle manufacturers may have additional requirements for cells, modules, packs and systems in order to assure a safe battery system for a given application. So, the specific purpose of this SAE standard should assure that a battery system can safely be integrated into an electric or hybrid vehicle. Each battery safety procedure test (electrical, thermal, mechanical test typologies) is designed to assure that a single point fault will not result in fire, explosion, battery enclosure rupture, high voltage hazard, or flammable gas concentration shall not exceed the lower flammability limit in the air (to assess the presence of flammable gas, a spark source or gas concentration measuring device is required in the battery location of highest potential for gas leaks). If it is not measured flammable gas concentration, after test visual inspection of all cells must show no cell venting. These define the pass/fail criteria which are assigned to each test. Main references of SAE J2929 are the previous battery safety standard SAE J2464 [24], FMVSS 305 [25], UL2580 [26], UN Test Manual [27], and international standards ISO 12405 [28], [29], [30] IEC 62660 [31], [32].

Table 21 SAEJ2929 Safety test type for Li-Ion different battery level [33]

	Test	Cell	Module	Pack	Vehicle
Mechanical	Mechanical shock	X	X	x	x
	Drop			x	
	Penetration				
	Immersion			X	
	Crush/crash			X	X
	Rollover			X	
	Vibration	X	X	X	
Electrical	External Short Circuit			X	
	Internal Short Circuit				
	Overcharge/ over discharge			X	
Environmental	Thermal stability				
	Thermal shock and cycling	x	x	X	
	Overheat			X	
	Extreme cold temperature				
	Fire			X	
Chemical	Emissions			x	
	Flammability			x	

3.4.2.1.1 Electrical abuse tests

3.4.2.1.1.1 Electrical short circuit

Electrical short circuit test simulates a hard short circuit condition across the battery terminals (simulation of an external short circuit).

Test procedure:

The complete battery system is to be tested, in accordance with one of the following procedure test standard: UN Test Manual Test T.5 (External Short Circuit) [26] indicates a resistance of 100 mΩ; SAE J2464 Section 4.5.1 [23] (hard short circuit is used a resistance < 5 mΩ), or ISO 12405-1 [28] or ISO 12405-2 [29], Section 9.2, shown previously.

Exceptions/Clarifications:

All battery system electronic modules are to be connected and in the "operational" state during testing.

Differences with SAEJ2464, which disables or bypasses protection devices, is not be included in this SAE standard; so, protection devices are in the operational state.

Requirements:

The battery system shall exhibit no evidence of fire, battery enclosure rupture, explosion, or flammable gas concentration shall not exceed the lower flammability limit in the air.

3.4.2.1.1.2 Overcharge protection

This electrical abuse test simulates the condition where the battery charge device is no longer being controlled and the failure may allow the battery system to be overcharged.

Test procedure:

DUT is to be operated under a normal operating condition with the cooling system operating. The connection interface (e.g., main contactors) which connects the battery system to the charging device is to be controlled by the Battery Control Function. Integrated, passive circuit protection devices are operational. Active charge control (i.e., Charge/Discharge Control Function) shall be disabled/disconnected from the charging device. In Figure 14 is shown a battery component block system used for this test. DUT is charged at maximum possible charge rate for the application; if passive over-current circuit protection is below this current value, conduct test at maximum current compatible with the passive protection device. Continue charging until the charge device voltage is reached or the connection interface disconnects the battery from charge device.

Requirements:

During the test, and for a minimum 1-hour post-test observation period, the battery system shall exhibit no evidence of fire, battery enclosure rupture, explosion, or flammable gas concentration shall not exceed the lower flammability limit in the air.

3.4.2.1.1.3 Over-discharge protection

This electrical abuse test simulates the condition where the battery system discharge load is no longer being controlled and the failure may allow the battery system to be over discharged.

Test procedure:

DUT is to be operated under a normal operating condition with the cooling system operating. The connection interface (e.g., main contactors) which connects the battery system to the charging device is to be controlled by the Battery Control Function. Integrated, passive circuit protection devices are operational. Active discharge control (i.e., Charge/Discharge Control Function) shall be disabled/disconnected from the charging device. In Figure 15 is shown a battery component block system used for this test. DUT is discharged at a 1C rate for HEV/PHEV applications or a C/3 rate for V applications. Continue discharging until the connection interface disconnects the battery from discharge load or battery voltage reaches 0.0 V $\pm$ 0.2 V.

Requirements:

During the test, and for a minimum 1 hour post-test observation period, the battery system shall exhibit no evidence of fire, battery enclosure rupture, explosion, or flammable gas concentration shall not exceed the lower flammability limit in the air.

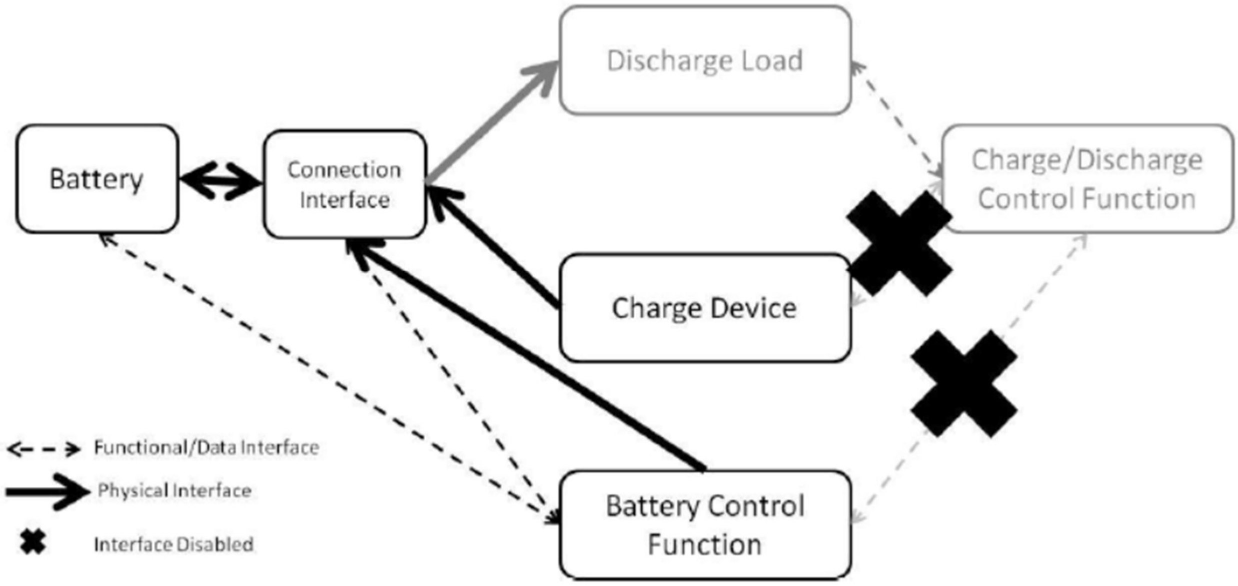


Figure 14. Overcharge test Block diagram.

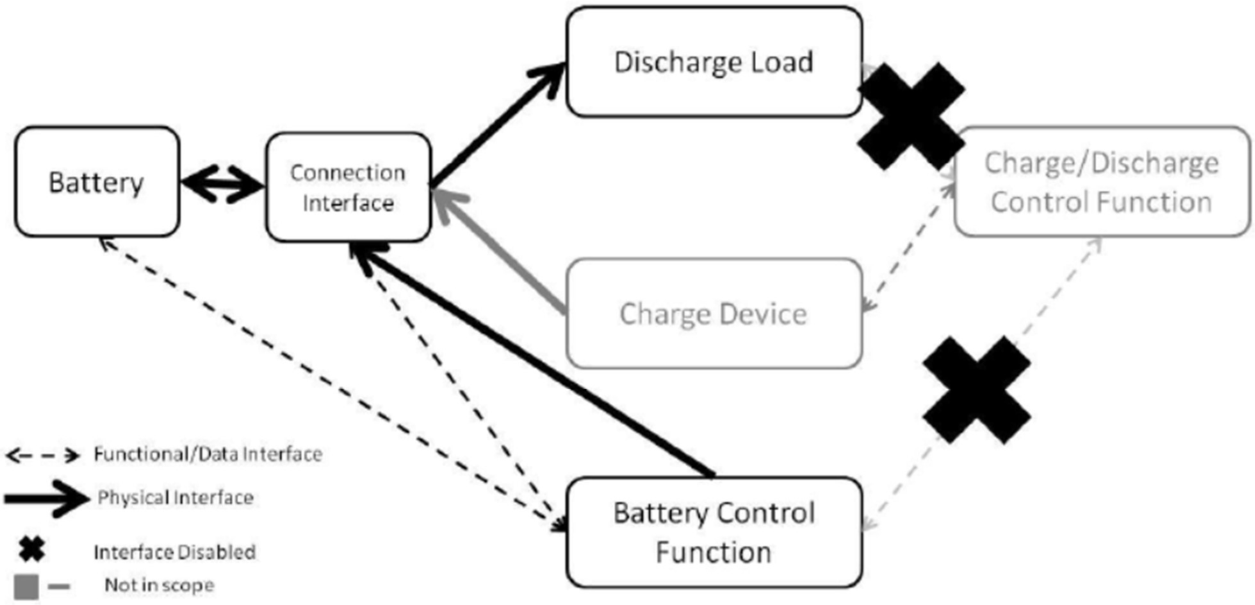


Figure 15 Over discharge test Block diagram

3.4.2.1.1.4 Thermal control system failure

This test simulates the condition where the battery system temperature control is no longer operating and the failure may lead to a battery system over temperature condition.

Test procedure:

DUT is to be tested in accordance with SAE J2464 Section 4.4.3 [23].
Exceptions/Clarifications:
DUT is to be operated under a normal operating condition with the cooling system disabled. Battery systems connection interface is to be controlled by the Battery Control Function. Integrated circuit protection devices are operational. Charge rate shall be the maximum normal rate for the DUT.
Requirements:
During the test, and for a minimum 1-hour post-test observation period, the battery system shall exhibit no evidence of fire, battery enclosure rupture, explosion, or flammable gas concentration shall not exceed the lower flammability limit in the air.

3.4.2.1.1.5 Protection against High Voltage Exposure

1. **Automatic Disconnects:**

This test verifies that the battery system shall be electrically disconnected from the vehicle high voltage system when commanded to do so, and at least one of the external terminals of battery system disconnects the battery cells within 5 s after actuation of automatic disconnect.

2. **Manual Disconnect:**

This test verifies that the battery system can be safely handled in the event of automatic disconnect failure, following one of these two options:
Option 1: Provide a method for manually removing any voltage between its positive and negative output terminals when assessed without connection to the remainder of the vehicle high voltage system. Measured voltage across all external battery terminal sets shall be less than 60 VDC within 5 s after the manual disconnect is actuated with the automatic disconnect (for example, contactors) closed.
Option 2: Provide finger-proof (IPXXB per ISO 20653 [32]) access to high voltage conductors.

3. **Protection against Direct High Voltage Contact**

This test verifies that the battery system does not expose users to high voltage hazard, following requirements of ISO 6469-3, Section 7.6 [33].

3.4.2.1.2 Environmental tests

3.4.2.1.2.1 Thermal shock

Thermal shock test simulates a rapid temperature change environment which a battery system will likely experience during its life.
Test procedure:
DUT is to be tested in accordance with thermal shock profile defined in SAE J2464, Section 4.4.4 [23] (max temperature 70 ℃ $\pm$ 2 ℃ or 5% of reading, and min temperature -40 ℃ $\pm$ 2 ℃ or 5% of reading; protection devices are disabled, so it is imposed hard testing conditions), or in accordance with UN Test Manual, Test T.2 (Thermal Test) [25].

Requirements:
Prior to the test, during the test and for a minimum 1-hour post-test observation period, the battery system shall exhibit no evidence of venting outside of battery enclosure or venting system, battery enclosure rupture, fire, or explosion, and shall maintain high voltage to ground isolation no less than 100 Ω/V. Isolation measurement is to be done in accordance with ISO 6469-1, Section 6.1.3 [34]; or equivalent. Post-test pack open circuit voltage shall be no less than 90% of the pre-test pack open circuit voltage. Post-test visual inspection of battery system internal components shall identify no evidence, as a result of the test, of cracked, damaged or loosened high voltage conductors which are part of the primary power current path.

3.4.2.1.2.2 Humidity/Moisture Exposure

This test simulates a temperature/humidity environment which a battery system will likely experience during its life.

Test procedure

DUT is to be tested in accordance with IEC 60068-2-30 [35] with a severity of 55 ℃ with 6 temperature cycles.

Requirements

Prior to the test, during the test and for a minimum 1-hour post-test observation period, the battery system shall exhibit no evidence of venting outside of battery enclosure or venting system, battery enclosure rupture, fire, or explosion, and shall maintain high voltage to ground isolation no less than 100 Ω/V. Isolation measurement is to be done in accordance with ISO 6469-1, Section 6.1.3 [34]; or equivalent. Post-test pack open circuit voltage shall be no less than 90% of the pre-test pack open circuit voltage. Post-test visual inspection of battery system internal components shall identify no evidence, as a result of the test, of cracked, damaged or loosened high voltage conductors which are part of the primary power current path.

3.4.2.1.2.3 Exposure to simulated Vehicle Fire

This test simulates exposure to a vehicle fire condition to verify that the battery system does not pose an additional risk due to the explosion.

Test procedure

DUT is to be subjected to a high-temperature heat and flame environment until the battery system is fully involved in the fire. DUT is surrounded by a steel wire mesh screen (annealed aluminum wire with a diameter of 0.25 mm and grid density of 6 to 7 wires per cm) in a way that no part of an exploding cell or battery can penetrate through the mesh. Wire mesh screen is placed no farther than 200 cm away from the DUT and extends 350 cm above the top surface of the DUT. The external heat and flame source is removed once that DUT is allowed to continue burning. The test is completed and post-test observation period begins when there is no longer visible flame. The responsible organization shall define the specific details of the test protocol. Useful references are SAEJ2464 Section 4.4.1 [23], ECE R34 (Annex 5, Sections 5.3-5.8) [15], SAE J2579 (Appendix C.8) [37], Korean KMVSS 18-3, Attachment 48 Section 48.6.7 [38], or FMVSS 304 Section 8.3 [39].

Requirements

During the test and for a minimum 1-hour post-test observation period, exploding component of DUT shall not penetrate wire mesh screen.

3.4.2.1.3 Mechanical abuse tests

3.4.2.1.3.1 Drop test

This test simulates the condition where battery system is removed from the vehicle and is dropped.

Test procedure:

DUT is to be tested in accordance with SAE J2424, Section 4.3.2 [23] with the following exceptions. DUT shall be oriented in such a way to represent the most likely impact orientation based on battery system size, shape, installation location and usage. The responsible organization shall develop and document the rationale for the selected orientation.

Exceptions/clarifications:

Surface type, when DUT is fallen, is to be:

- Horizontal flat surface;
- Integral and massive enough to be immovable;
- Rigid enough to be non-deformable under drop test;
- Sufficiently large to ensure that the DUT falls entirely upon the surface;

The drop height shall be the maximum distance which the battery system experiences when serviced according to documented procedure, but not less than 1 m. The test is conducted at battery SOC of 95-100% of the maximum level specified by the manufacturer/users for vehicle operations.
Requirements:
During the test and for a minimum 1-hour post-test observation period, the battery system shall exhibit no evidence of fire, or explosion.

3.4.2.1.3.2 Immersion test

This test simulates the condition in which vehicle is flooded with water.
Test procedure:
DUT is to be tested in accordance with SAE J2464, Section 4.3.5 [23], with the following exceptions/clarifications.
Exceptions/Clarifications:
At the start of test: all battery system electronic control modules are to be connected and in the operational power state; all contactors and all vehicle interface connections, including high voltage, low voltage, electronic signals, and thermal management system, are in place to simulate vehicle in use condition. DUT shall be fully submerged within 5 min following initial contact with the water.
Requirements:
During the test, the battery system shall exhibit no evidence of battery enclosure rupture, fire, or explosion.

3.4.2.1.3.3 Mechanical shock

This test simulates inertial loads which may occur during a vehicle crash situation.
Test procedure:
The test can be conducted at two different DUT levels: battery system-level or vehicle-level. For battery system-level, the test is to be conducted in accordance with one of the following options: UN Test Manual, Test T.4 (Shock) [26]; or SAE J2464, Section 4.3.1 [23], with some difference. For vehicle level, the test is to be conducted in accordance with FMVSS 305, Sections 6.1, 6.2, 6.3 [24].
Exceptions/Clarifications:
For battery system-level, the test is conducted in the positive and negative directions of the primary vehicle longitudinal and lateral axes, as installed, for a total of 4 separate evaluation conditions. Battery system shall be firmly secured to the test fixture. For vehicle-level, the test is conducted in front, rear and side impacts, as defined in FMVSS 305 [24]. Table 22 show at mechanical shock test procedure for each level. (battery SOC shall be 95-100% of the maximum which is possible during normal vehicle operation and battery temperature shall be 25 ℃ $\pm$ 5℃, or as specified in equivalent regionally applicable regulations).
Requirements:
During the test and for a minimum 1-hour post-test observation period, the battery system shall exhibit no evidence of battery enclosure rupture, fire, or explosion and shall maintain high voltage to ground isolation no less than 100 Ω/V. Isolation measurement is to be done in accordance with ISO 6469-1, 6.1.3 [34]. For vehicle level, the battery system shall be retained at its mounting location (per SAE J1766, Section 4.4.2 [40]).

Table 22 Mechanical shock test (similar in [20]).

	Battery system-level	Vehicle-level
Peak acceleration (g)/vehicle collision speed (km/h)	150 g for each level, or 50 g (if cell > 0.5 kg, or module or battery Pack > 12 kg), or 25 g (battery pack)	48 km/h or 54 km/h or 80 km/h
Direction of shock	Positive and negative directions of the primary vehicle longitudinal and lateral axes.	Front, rear and side part of vehicle.
Shock duration (ms)	6 ms for each level, or 11 ms (if cell > 0.5 kg, or module or battery Pack > 12 kg), or 15 ms (battery pack)	FMVSS 305

3.4.2.1.3.4 Battery Enclosure Integrity (Crash test)

This test simulates contact loads which may occur during a vehicle crash situation.
Test procedure:
The test can be conducted at three different DUT levels: Battery system-level in the Application-Specific case or Generic case or Vehicle-Level. For battery system-level, the test is to be conducted in accordance with SAE J2464, Section 4.3.6 [23] with some difference. In this case, following the crash, the battery pack shall be rotated about its longitudinal axis (as oriented in a vehicle application), with the axis kept horizontal, to each successive increment of 90°, 180°, and 270° at a uniform rate, with 90° of rotation taking place in a time interval of 1 to 3 minutes (rollover test). After reaching each 90° increment, the battery system is held in that position for 5 minutes. For vehicle system-level, the test is to be conducted in accordance with FMVSS 305, Sections 6.1, 6.2, 6.3 [24]. Battery SOC shall be 95-100% of maximum which is possible during vehicle operation and battery temperature shall be 25 ℃ $\pm$ 5℃.
Exceptions/Clarifications:
In Table 23 crash test for each level is shown.

Table 23 Battery Enclosure Integrity test (similar in [20]).

	Battery system-level (Application specific)	Battery system-level (Generic)	Vehicle-level
Crush speed	Is determined by the responsible organization.	5-10 mm/min	FMVSS 305
Crush force	Magnitude, direction and location are determined by the responsible organization.	100 kN	FMVSS 305
Crush plate type	Surface size and shape are determined by the responsible organization	Shown in Fig.3-3	FMVSS 305
Rollover test	Rotation of an increment of 90° in a time interval of 60-180 s. After this, DUT is held in that position for 300 s.	Rotation of an increment of 90° in a time interval of 60-180 s. After this, DUT is held in that position for 300 s.	Not specified

Note that in the crash test for a battery system-level (Application-specific), is responsible to make and document specification of crash test.

Requirements:

During the test and for a minimum 1-hour post-test observation period, the battery system shall exhibit no evidence of battery enclosure rupture, fire, or explosion and shall maintain high voltage to ground isolation no less than 100 Ω/V. Isolation measurement is to be done in accordance with ISO 6469-1, 6.1.3 [34]; or equivalent. For vehicle-level application, the battery system shall be retained at its mounting locations (per SAE J1766, Section 4.4.2 [40]).

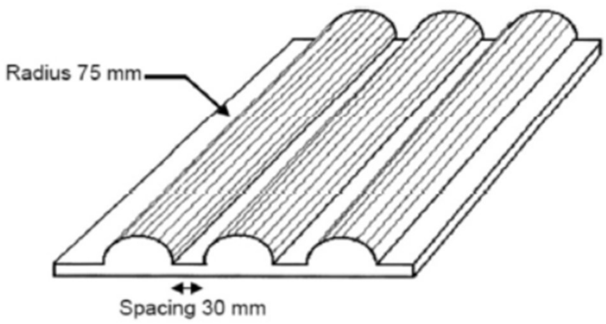


Figure 16 Surface shape of contact load [20].

3.4.2.1.3.5 Vibration test

This test simulates a vibration environment which a battery system will likely experience during its life.

Test procedure:

The test can be conducted at two different DUT level: Complete battery system or battery subsystem. For complete battery system, components or battery subsystem test is to be conducted in accordance with one of the following options: UN Test Manual, Test T.3 (Vibration) [26], or SAE J2380 [42], or a profile from the responsible organization which reflects the actual application. In the case of battery subsystems, the responsible organization shall define the specific components or subsystems to be tested. In the case complete battery system shall be tested as part of a vehicle level vibration test, where the battery is subject to conditions that are appropriate to the vehicle's operation, the responsible organization shall define appropriate vibration testing profile which reflects actual application.

Exceptions/Clarifications:

For single complete battery system, SOC shall be 95-100% of the maximum which is possible during normal vehicle operation, for battery system considered as a part of a vehicle level vibration test, battery SOC and temperature shall be that of normal vehicle operation for the ambient conditions during the vehicle test.

Requirements:

For complete battery system, requirements are the following: prior to the test, during the test and for a minimum 1-hour post-test observation period, the battery system shall exhibit no evidence of venting outside of battery enclosure or venting system, battery enclosure rupture, fire, or explosion, and shall maintain high voltage to ground isolation no less than 100 Ω/V. Isolation measurement is to be done in accordance with ISO 6469-1, Section 6.1.3 [34]; or equivalent. Post-test pack open circuit voltage shall be no less than 90% of the pre-test pack open circuit voltage. Post-test visual inspection of battery system internal components shall identify no evidence, as a result of the test, of cracked, damaged or loosened high voltage conductors which are part of the primary power current path. For battery subsystems, the components shall exhibit no evidence or fire or explosion during the test and for a minimum 1-hour post-test observation period. The responsible organization shall determine what, if any, additional test requirements are necessary, based on the component or subsystem tested.

3.4.2.1.3.6 Vibration test procedure by SAE J2380 (Vibration Testing of Electric Vehicle Batteries)

This document provides a test procedure for characterizing the effect of long-term, road induced vibration and shock on the performance and service life of electric vehicle batteries. During vibration test, either swept sine wave vibration or random vibration is typically used for the performance of such testing. This document focuses or random vibration. Vibration durability of battery modules or battery packs is tested, determining an appropriate cumulative number of shock pulses at various G-levels.

Test Equipment:

- Performance of this procedure requires a one- to three-axis table (or multi-axis table if DUT can only be vibrated in a particular physical orientation) capable of producing accelerations up to 1.9 G over the vibration spectra detailed in Figure 17, extending from 10 to approximately 200 Hz.
- Test fixtures are required to properly secure DUT to the shaker table (not specification about fixtures).
- Instrumentation capable of withstanding the vibration and monitoring battery conditions during vibration test.

Determination of Electrical Test conditions:
In accordance to the procedures in SAE J1798, section 4.4.1 [33].

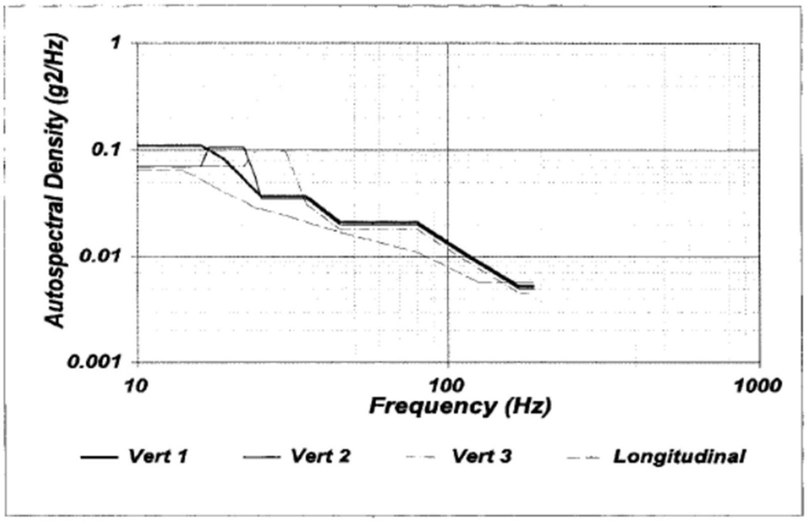


Figure 17 Random vibration test: vibration spectral density.

Test procedure:

1. Perform a sequence of Reference Performance Tests in accordance to SAE J1798 [33]: this test consists of a C/3 Constant Current Discharge, a Dynamic Capacity Test discharge to 100% of rated capacity, and a Peak Power discharge. During this test, DUT performance data based on this test sequence shall be acquired.
2. Charge the battery fully using the manufacturer’s recommended charge method.
3. For each of the vertical, longitudinal, and lateral axes of the battery, select the normal or alternative vibration test from Table 24, 25 and program the shaker table appropriately.
4. Mount the DUT so that it will be subjected to vibration along the appropriate axes, based on the manufacturer's recommended physical orientation.
5. Perform the programmed vibration for the required times, while battery depth-of-discharge is varied from 0% (full charge) to 80% (minimal charge) over the course of the vibration testing of a given battery. In based on shaker table type, two approaches are allowed:

- If a one- or two-axis vibration table is used, approximately two-thirds of the vertical axis testing should be done at full charge, followed by the longitudinal and lateral vibration at 40% DOD, and then the remaining vertical axis vibration at 80% DOD.
- If a three-axis table is used to perform all vibration regimes simultaneously, the total testing period can be divided into three intervals of roughly equal length. The first interval should be performed with the battery fully charged, the second interval with the battery at 40% DOD, and the third interval at 80% DOD.

It's noticeable that between these vibration intervals, DUT should be discharged at C/3 constant current until to reach 40% of rated capacity discharged.

6. Repeat the Reference Performance Tests in accordance to SAE J1798 and acquire DUT performance data.

Table 24 Vibration schedule for random vibration normal test.

Test Conditions Vibration Spectrum (Fig. 3-3)	Test Conditions SOC (%)	Accelleration (g rms)	Time (h)	Cumulative Time (h)
Vertical Axis vibration				
Vertical 1 spectrum (Fig. 3-4)	100	1.9	0.15	0.15
Vertical 1 spectrum (Fig. 3-4)	100	0.75	5.25	5.4
Vertical 2 spectrum (Fig. 3-4)	100	1.9	0.15	5.55
Vertical 2 spectrum (Fig. 3-4)	100	0.75	5.25	10.8
Vertical 3 spectrum (Fig. 3-4)	20	1.9	0.15	10.95
Vertical 3 spectrum (Fig. 3-4)	20	0.75	5.25	16.2
Longitudinal Axis vibration				
Longitudinal spectrum (Fig. 3-4)	60	1.5	0.09	16.29
Longitudinal spectrum (Fig. 3-4)	60	0.4	19.0	35.29
Longitudinal spectrum (Fig. 3-4)	60	1.5	0.09	35.38
Longitudinal spectrum (Fig. 3-4)	60	0.4	19.0	54.38
Lateral Axis vibration				
Longitudinal spectrum (Fig. 3-4)	60	1.5	0.09	54.47
Longitudinal spectrum (Fig. 3-4)	60	0.4	19.0	73.47
Longitudinal spectrum (Fig. 3-4)	60	1.5	0.09	73.56
Longitudinal spectrum (Fig. 3-4)	60	0.4	19.0	92.56

Table 25 Vibration schedule for random vibration alternative test.

Test Conditions Vibration Spectrum (Fig. 3-3)	Test Conditions SOC (%)	Acceleration (g rms)	Time (h)	Cumulative Time (h)
Vertical Axis vibration				
Vertical 1 spectrum (Fig. 3-4)	100	1.9	0.15	0.15
Vertical 1 spectrum (Fig. 3-4)	100	0.95	3.5	3.65
Vertical 2 spectrum (Fig. 3-4)	100	1.9	0.15	3.8
Vertical 2 spectrum (Fig. 3-4)	100	0.95	3.5	7.3
Vertical 3 spectrum (Fig. 3-4)	20	1.9	0.15	7.45
Vertical 3 spectrum (Fig. 3-4)	20	0.95	3.5	10.95
Longitudinal Axis vibration				
Longitudinal spectrum (Fig. 3-4)	60	1.5	0.09	11.04
Longitudinal spectrum (Fig. 3-4)	60	0.75	6.7	17.74
Longitudinal spectrum (Fig. 3-4)	60	1.5	0.09	17.83
Longitudinal spectrum (Fig. 3-4)	60	0.75	6.7	24.53
Lateral Axis vibration				
Longitudinal spectrum (Fig. 3-4)	60	1.5	0.09	24.62
Longitudinal spectrum (Fig. 3-4)	60	0.75	6.7	31.32
Longitudinal spectrum (Fig. 3-4)	60	1.5	0.09	31.41
Longitudinal spectrum (Fig. 3-4)	60	0.75	6.7	38.11

Reporting data acquisition and Test Termination Criteria:

Prepare a report detailing the actual vibration regimes applied, pre and post-vibration electrical performance data and any results of detailed component failure analysis to understand the adequacy of the battery design to withstand the vibration environments. Vibration testing shall be suspended or terminated if any observed component degradation produces conditions which are abnormal or outside the operating ranges of the battery as specified by the manufacturer. DUT conditions to be monitored are the follows:

- Loss of electrical isolation between the battery positive connection and the battery case and/or test equipment ground. The degree of isolation shall be verified regularly, e.g., daily, during any period of vibration testing to be 0.5 MΩ or greater (1.0 mA or less leakage at 500 V DC).
- Abnormal battery voltages indicating the presence of open- or short-circuit conditions.
- Unexpected resonance conditions within the battery, indicating failure of mechanical tie-down components.
- Abnormal temperature conditions indicating possible damage to battery cells or thermal management system components.
- Manufacturer's recommended measurements not listed above.

3.4.2.2 CEN/CENELEC/CEI

CEN (Comité européen de normalization, founded in 1961), is an association that brings together the National Standardization Bodies of 34 European countries. It aims to harmonize and produce technical standards in Europe in collaboration with national and supranational regulatory bodies such as ISO and IEC. CEN is one of three European Standardization Organizations (together with CENELEC and ETSI) that have been officially recognized by the European Union and by the European Free Trade Association (EFTA) as being responsible for developing and defining voluntary standards at European level. It is the responsible for standardization in all sectors, except the electronic committee (delegated to CENELEC) and the telecommunications sector covered by the ETSI (European Telecommunications Standards Institute). CENELEC (Comité Européen de Normalisation Electrotechnique, founded in 1973) is the European Committee for Electro-Technical Standardization and is responsible for standardization in the electro-technical engineering field. CENELEC prepares voluntary standards, which help facilitate trade between countries, create new markets, cut compliance costs and support the development of a Single European Market. CENELEC creates market access at European level but also at international level, adopting international standards wherever possible, through its close collaboration with the International Electro-Technical Commission (IEC), under the Frankfurt Agreement (17 October 2016).

CEI represents Italy in the activities of CENELEC and IEC. Consequently, CEI performs standardization and pre-standardization activities, in cooperation with the parties interested in the standardization process such as the publication of technical standards at the national level and endorsement of the international and European ones, including those harmonized according to European Directives and Regulations. So, CEN/CENELEC/CEI main purpose is to have the IEC, ISO or international standards adopted by member countries and to agree on common modifications, e.g. international battery standards IEC 62660.

4 Second-life

4.1 Second Life, Application to Stationary Energy Storage for Railway Applications.

In this section, a few suitable applications suitable for the reuse of partially degraded automotive battery packs will be described.
A suitable application is to install batteries in the proximity of railway infrastructures for energy exchange. There is a wide scientific literature concerning the application of stationary energy storage systems to railway applications, especially with DC electrification standards.
From an academic point of view this topic is quite mature; in **Error! Reference source not found.**26 there is a brief selection of scientific contributions produced in the last five years by known research groups.
In **Error! Reference source not found.**7 there is also a brief selection of known industrial suppliers that currently propose complete systems or subsystems devoted to this application.
Any product installed in a railway infrastructure is subject to a number of restrictions and regulations which are described in technical standards. Therefore, assuming that the second-use of energy storage system is still at its beginning, as a first attempt the examination of railway standards can be used to define a few elements to be assumed as a reference for specification, requisites and installation rules. Some related standards that should constraint and lead the implementation of energy storage systems are listed in **Error! Reference source not found.**.
In this relation it's not considered the application to railway vehicle energy storage systems mainly for three reasons:

- Application on vehicles is constrained by encumbrance and weight limitations that should clearly induce system designer to use, solutions with high-performance storage systems avoiding the usage of second-life batteries.
- Application to onboard vehicle system is more constrained by railway safety and interoperability standards and it's much more invasive depending on specific features of the vehicle on which the system has to be installed.
- If the case of intermittent/discontinuous power collection is excluded, fixed installation is often preferred in literature respect to mobile one also in terms of cost/benefit ratio.

Stationary energy storage systems for railway applications are typically composed by a storage unit connected to the overhead line. The stationary storage unit can be connected directly or more commonly through a static converter (typically a bi-directional step-up/step-down chopper).
Aims of these systems are substantially two:

- Stabilize voltage-load behavior on connected overhead line.
- Allow a bi-directional flux of power from and to the overhead line.

The main benefit of the proposed solutions should be briefly summarized in the following points:

- Improved Energy efficiency due to an extensive application of regenerative braking and to the possibility of reducing losses along the line.
- Reduction of line voltage fluctuations (increased life and reliability of connected components and sub-systems)
- Optimization of construction and maintenance of infrastructures, since installed storage systems often allow an optimization (reduction) of feeding substations both in terms of installed power and spacing along the line.

There is a wide and immediate applicability of this technology to DC electrified lines considering that almost all tramway and metro systems are fed with low-medium DC voltages (from 500V to 1500V where the most common value is a nominal line voltage of 750 V). This kind of local and urban transportation systems are still knowing a positive trend, especially in large urban areas. It should be also considered that the required voltage levels for urban transportation system are not too different from the current trend of automotive technologies where there are a lot of examples of vehicles with energy storage system working at 350-400 V of nominal voltage.
Also the size of energy storage systems especially for tramway applications should be limited to less than 1MWh (starting from a minimum size corresponding to about 200kWh) so also in terms of size a single storage unit should not too bigger respect to a corresponding electric automotive application where values between 30 and 200kWh are highly feasible.

As a consequence, it's not too complicate to foresee a possible application scenario in which a limited number of battery packs are revamped and re-used to assembly a storage-voltage stabilizing unit for a tramway line. Considering the typical extension of a tramway or a metro-line and the foreseen spacing of storage units along the line, it's highly feasible, that the application of this kind of technology to the urban transportation system of a medium size European town should involve the reuse of an equivalent battery capacity corresponding to a significant number of cars that should be affordable respect to the number of circulating vehicles in the same town.

Also as visible in Figure 18 Electrification Standards in Europe., DC electrification standard is still quite diffused on many railway networks corresponding to a large part of southern and eastern Europe including Russia and ex Soviet republic (which involve a large part of Asia and a consistent part of existing lines in the far east). Outside of Europe, it should be considered a mixed situation in which DC electrification is still widely diffused especially for conventional freight and passenger lines, while the application of alternate current lines is often devoted only to dedicated high-speed lines. This scenario is quite common in highly developed countries of far east like South Korea, Japan, and China.

For these reasons also, the application to a stationary storage system for conventional railways should represent a potential application for a second-life re-use of batteries.

It' interesting to notice that most of the important industrial player in the railway sector has released in a quite short period (less than ten years) have released new products trying to cover this potential application field as visible in the partial list (see Table 27 Industrial products to support railway infrastructures) in which only some of the most known proposals are described.

Also in terms of harmonization in terms of applicable standards the situation is relatively clear: in particular for the railway sector and in particular for standards concerning electric tractions systems Europe plays a central role: In particular, EC has developed a corpus of TSI (Technical Specifications for Interoperability) which fixes main specifications of railway systems for the countries of the European community. Also, TSI represents the reference for the corresponding detailed EN Standards which for each precise topic.

Another important technical reference is represented by the UIC association (Union Internationale des Chemins de Fer), originally an international association of the major European stakeholder of the railway sector which currently has gained a preeminent world role since also many extra-European countries and railway administrations has joined the association.

In Table 28 Main reference Standards coming from railway sector. there is a brief list of the most important Specifications and Standards affecting the application of energy storage systems to the railway sector.

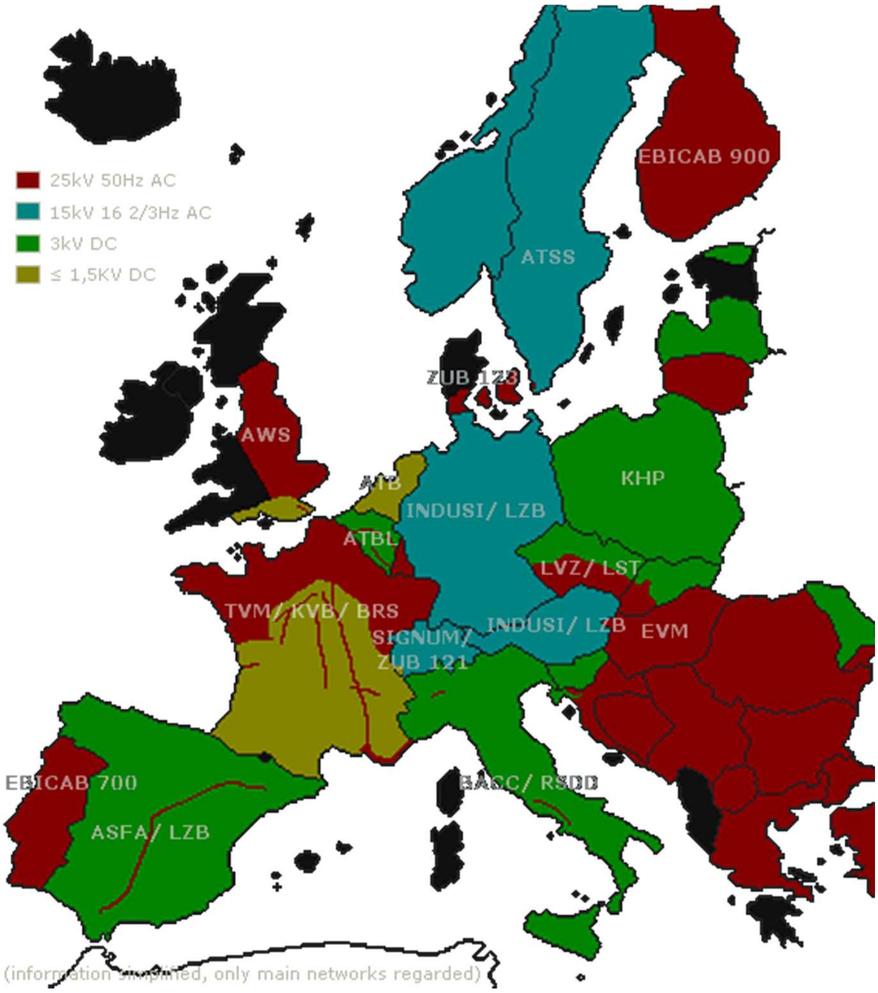


Figure 18 Electrification Standards in Europe.

This Map is not very recent and it should be referred to the year 2010-2012, since some further AC high-speed line has been constructed in the meanwhile as an example in Italy (http://www.bueker.net/trainspotting/voltage_map_europe.php)

Table 26 Brief list of publications regarding the use of energy storage system to support railway infrastructures with some comments and notes

Research Work	Storage Technology	Application
Barrero, R., Tackoen, X., Van Mierlo, J. Stationary or onboard energy storage systems for energy consumption reduction in a metro network (2010) Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 224 (3), pp. 207-225. DOI: 10.1243/09544097JRRT322	Both Lithium-ion and Super Cap are considered	Application to Metro Systems
González-Gil, A., Palacin, R., Batty, P. Sustainable urban rail systems: Strategies and technologies for optimal management of regenerative braking energy (2013) Energy Conversion and Management, 75, pp. 374-388. DOI: 10.1016/j.enconman.2013.06.039	Both supercap and various battery technologies	Application to Metro and Tramways systems

Pugi, L., Conti, R., Nocciolini, D., Galardi, E., Meli, E. A comprehensive tool for the optimization of traction and braking systems with respect to the application of energy storage devices (2015) International Journal of Railway Technology, 4, pp. 69-93	Generic Storage System	Application to both conventional and high-speed railways
Frilli, A., Meli, E., Nocciolini, D., Pugi, L., Rindi, A. Energetic optimization of regenerative braking for high-speed railway systems (2016) Energy Conversion and Management, 129, pp. 200-215. DOI: 10.1016/j.enconman.2016.10.011	Lithium-Ion Batteries	Regenerative Braking of High Speed and Conventional Railways

Table 27 Industrial products to support railway infrastructures

Industrial Product/Activity	Storage Technology	Application
ABB ENVLINE ESS™ https://library.e.abb.com/public/530732baf3dcfe42c1257e150048002b/ENVILINE%20ESS%20EN.pdf	Hybrid (batteries, supercap or batteries+supercap)	Tramway, Light Rails, Metro Railways and conventional systems
Maxwell-Voltage Stabilization Systems http://www.maxwell.com/solutions/transportation/rail/rail-voltage-stabilization-systems	SuperCap	Tramway, Light Rails, Metro Railways and conventional systems
Toshiba TESS™ http://www.toshiba.co.jp/sis/railwaysystem/en/products/power/tess.htm	Li-ion Batteries	Tramway, Light Rails, Metro Railways and conventional systems
Hitachi Rail B-Chop™ http://www.hitachi-rail.com/products/power_supply/equipment/feature03.html	Li-ion accumulators for automotive applications	Tramway, Light Rails, Metro Railways and conventional systems
Bombardier EnerGstor Wayside Energy Storage™ http://www.bombardier.com/content/dam/Websites/bombardiercom/supporting-documents/BT/Bombardier-Transportation-ECO4-EnerGstor-EN.pdf	SuperCap	Tramway, Light Rails, Metro Railways and conventional systems
Alstom-Saft Intensium™ https://www.saftbatteries.com/products-solutions/products/intensium%C2%AE-max-efficient-trackside-energy-storage?text=storage&tech=&market=342&sort=newest&submit=Search	Li-ion Batteries	Not only for railway system (Joint proposal Alstom-Saft) but general purpose platform for grid stabilization.
Siemens SITRAS HES™ https://www.siemens.com/press/pool/de/feature/2012/infrastructure-cities/rail-systems/2012-08-avenio/productinformation-sitras-hes-e.pdf	Hybrid (batteries, supercap or batteries+supercap)	Configurable, modular system both for onboard and wayside railway storage systems

General Electric Durathon™ for Public Transport http://www.apta.com/mc/rail/previous/2012/presentations/Presentations/Maroon-M-Sodium-Nickel-Energy-Storage-Technology-for-Rail-and-Public-Transportation.pdf	Proprietary Technology (Special Sodium Nickel Tech from older British rail studies)	Application to Rail System but more generally to grid Stabilization

Table 28 **Main reference Standards coming from railway sector.**

Reference Standard	Notes
Energy ENE TSI 1301/2014/EU Infrastructure INF TSI: 1299/2014/EU Locomotives and passenger rolling stock - LOC & PAS TSI 1302/2014/EU	*All these TSI (Technical Specification s for Interoperability) give reference to main system specifications and to the corresponding EN Standards /UIC FICHES
Noticeable int. Standards respect to TSI EN 50163 and IEC 60850	** EN Standards follows specifications and line guides of TSI these are some of the most known international standards defining electrification of railway lines
UIC Fiches (relevant for electrification and energy storage applications) • 50x-xx General Provisions Concerning Way and Works • 60x-xx (650-xx) General Regulations concerning electric traction lines (continuation) • 61x-xx Electric Traction • 66x-xx High-Speed Trains • 85x-xx Tractive Stock Parts • 87x-xx Electric Traction Fixtures • 93x-xx Exchange of Energy Consumption Data	***UIC (Union Internationale des Chemins de Fer) It's a worldwide association. UIC tech. regulations, the so-called Fiches are fundamental technical references for the formulation of EN Standards and also for the evolution of TSI. Many extra-European railway administration has Joined UIC which have gained a world dominant position in the definition of railway technical standards. Leaflets are de-FACTO standards for many railway applications influencing and regulating major technical development in the railway sector

4.2 Case study: Batteries in second-life use for Photovoltaic Energy Systems

Battery selection for off-grid and mini-grid energy systems should always be informed by relevant performance testing according to presiding international standards. Battery used in photovoltaic (PV) systems are regulated by international standard IEC 61427 (Secondary cells and batteries for renewable energy storage – general requirements and methods of test), the first part (IEC 61427-1 [47]) consists of battery use for photovoltaic off-grid Electrical Energy Storage (ESS) application, the second part (IEC 61427-1 [48]) consists in battery use for on-grid ESS application.

4.2.1 IEC 61427-1 (Secondary cells and batteries for renewable energy storage – general requirements and methods of test – Part 1: Photovoltaic off-grid application)

This part of the IEC 61427 series gives general information relating to the requirements for the secondary batteries used in photovoltaic energy systems (PVES, to supply a constant, variable, or intermittent energy to the connected load) and to the typical methods of test used for the verification of battery performances. This part deals with cells and batteries used in photovoltaic off-grid applications and it is applicable to all types of secondary batteries. In particular, this standard refers to Lead-acid, Nickel-Cadmium, Nickel Metal Hydride and Lithium-Ion batteries and cells typology. This standard does not include specific information relating to battery sizing, method of charge or PVES design.

4.3 The battery in second-life use in photovoltaic off-grid: Condition of use

4.3.1 Daily and seasonal cycle

In photovoltaic off-grid application, the battery is to be designed to supply energy under specified conditions for a period of time, typically from 3 days to 15 days without solar irradiation. In fact, for this application, the battery is normally exposed to a daily cycle as follows:

- Charging during daylight hours;
- Discharging during night-time hours.

Not only, but battery may be exposed to a seasonal cycle of its SOC as follows:

- Low solar irradiation period (e.g. winter period): in this period battery SOC can go down to 20% of the rated capacity or less.
- High solar irradiation period (e.g. summer period): in this period there is the possibility that the battery could be overcharged if is not controlled.

Typical daily usage results in a discharge between 2% to 20% of the battery capacity. But the battery is to be designed in based on its daily and seasonal cycle usage.

4.3.2 Typical charge and discharge currents

For PVES application, standard specifies the typical battery charge and discharge currents which may supply by PVES and deliver to load connected:

- Maximum charge current C/20;
- Average charge current C/50;
- Average discharge current as determined by the load: C/120;

But depending on the system design, the charge and the discharge current may vary in a wider range.

4.3.3 Storage period

Manufacturer's recommendations for storage shall be observed. In the absence of such information, the storage period may be estimated according to the climatic conditions as shown in Table 29.

Table 29 Limit values for storage conditions of battery for PV applications [47]

Battery type	Temperature range (°C)	Humidity (%)	Storage period for batteries	
			With Electrolyte	Without Electrolyte
Lead-acid	-20 to +40	< 90	Up to 12 months (depending of the design)	1-2 years (dry charged)
Nickel-cadmium	-20 to +50 (standard electrolyte) -40 to +50 (high density electrolyte)	< 90	Up to 6 months	1-3 years (fully discharged, drained and sealed).
Nickel metal hydride	-40 to +50	< 90	Up to 6 months	N/A
Lithium-Ion	-20 to +50	< 90	Up to 12 months	N/A

4.3.4 Operating temperature and humidity

Climatic conditions as environmental temperature and humidity may define the expected lifetime of the battery. Manufacturer's recommendations for operating temperature and humidity shall be observed. In the absence of such information, operating temperature and humidity may be estimated according to the climatic conditions as shown in Table 30.

Table 30 Limit values for operating temperature and humidity conditions of battery for PV applications [47]

Battery type	Temperature range (°C)	Humidity (%)
Lead-acid	-15 to 40	< 90
Nickel-cadmium	-20 to +45 (standard electrolyte)	< 90
	-40 to +45 (high density electrolyte)	
Nickel metal hydride	-40 to +45	< 90
Lithium-Ion	To be verified by the battery manufacturer	To be verified by the battery manufacturer

4.3.5 Physical protection and control

To overcome overcharge problem during a high solar irradiation period, this standard explains the correlation between maximum SOC and maximum charge voltage, which depending on temperature also. Moreover, it indicates that some regulators, e.g. in a lithium battery are cited the Battery Management System (BMS) electronic control, which control the overcharge and allow the battery voltage to exceed maximum charge voltage for a short period as an equalizing or boost charge. In this last case, charge voltage compensation shall be used according to the battery manufacturer instructions if the battery operating temperature deviates significantly from the reference temperature. Other physical protection shall be provided against consequences of adverse site conditions, for example:

- uneven distribution and extremes of temperature;
- exposure to direct sunlight (UV radiation);
- air-borne dust or sand;
- explosive atmospheres;
- flooding, water vapor condensation and sea water spray;
- earthquakes;
- shock and vibration (particularly during transportation);
- Monitor system that protects the lead-acid battery against deep discharge so to avoid capacity loss due to irreversible sulphitation or passivation effect.

4.4 The battery in second-life use in photovoltaic off-grid: General Requirements

4.4.1 Mechanical Endurance

Batteries for PV application shall be designed to withstand mechanical stresses during transportation and handling taking into account that PVES installations may be accessed via unpaved roads and installed by less qualified personnel. Manufacturer's instructions shall be observed, in particular for unpacked or not protected batteries. In case of specific requirements regarding mechanical stresses, such as earthquakes, shock and vibration, these shall be individually specified or referred to in a relevant standard. For lithium battery safety, it may refer to international standards ISO, IEC and SAE.

4.4.2 Charge Efficiency

In this standard, battery charge efficiency is defined as the ratio between the quantity of electricity (expressed in Ah) delivered during the discharge of a cell or battery and the quantity of electricity (expressed in Ah) necessary to restore the initial SOC under specific conditions, in accordance with IEC 60050-482-05-39 [49]. In the absence of this data provided by battery manufacturer, battery typology should assume the charge efficiency listed in Table 31.

Table 31 3 Battery charge efficiency at different SOC and reference temperature [26].

SOC (%)	Lead-Acid Efficiency cells (%)	Nickel-cadmium and Nickel metal hydride Efficiency cells (%)	Lithium-Ion Efficiency cells (%)
90 %	>85	>80	>>95
75 %	>90	>90	>>95
<50%	>95	>95	>>95

4.5 The battery in second-life use in photovoltaic off-grid: Battery test performance

Battery shall be characterized by its:

- Rated capacity;
- Endurance in cycling;
- Charge retention;
- Endurance in cycling in PV application (extreme conditions).

The accuracy of the measuring instruments and estimated parameters accuracy shall be in compliance with the relevant requirements of the applicable standards depending on the battery typology used and listed in Table 32

Table 32 Preparation to battery test performance: reference standards.

Battery typology	Battery sub-typology	Type of use	Reference Standard
Lead-Acid	Vented	Stationary	IEC 60896-11 [29]
	Valve-regulated	Stationary	IEC 60896-21 [30]
		Portable	IEC 61056-1 [31]
Nickel-Cadmium	Sealed	generic	IEC 60622 [32]
	Vented	generic	IEC 60623 [33]
	With partial gas recombination	generic	IEC 62259 [34]
	generic	portable	IEC 61951-1 [35]
Nickel metal hydride	generic	portable	IEC 61951-2 [36]
Lithium-Ion	generic	portable	IEC 61960-3 [37]
	generic	Industrial applications	IEC 62620 [38]

4.5.1 Capacity test procedure

Battery Capacity test shall be performed according to the applicable standards listed in Table 32. The verification of the rated capacity shall be performed using one long duration test and normal duration test, shown in Table 33. Two capacity tests consist of constant discharge current until the DUT reaches its low cut-off voltage.

Table 33 Capacity test specification.

Battery typology	Discharge C-rate current (Long duration test)	Discharge C-rate current (Normal duration test)	Final voltage (V)
Lead-Acid	C/120	C/10	1.85 (Long duration test) 1.80 (Normal duration test)
Nickel-Cadmium	C/120	C/5	1.00
Nickel metal hydride	C/120	C/5	1.00
Lithium-Ion	C/120	C/5	Not defined

4.5.2 Generic cycling endurance test procedure

The batteries shall be tested for generic cycling endurance according to the clauses, if any, of the applicable standards listed in Table 32.

4.5.3 Charge retention test procedure

The batteries shall be tested for charge retention according to the clauses, if any, of the applicable standards listed in Table 32.

4.5.4 Cycling endurance test in photovoltaic applications (extreme conditions)

In PV application, the battery will be exposed to a large number of shallow charge/discharge cycles but at different SOC. This test simulates this service under extreme conditions by submitting the battery at 40°C (extremely high temperature), to several aggregates of charge/discharge cycle each comprising 50 cycles at low SOC (Phase 1) and 100 cycles at high SOC (Phase 2). This standard indicates that one set of 150 aggregates cycle is approximately equivalent to 1-year service in a PV energy storage application.

Initialization:

- The DUT shall be selected, prepared and installed according to the applicable standard shown in Table 32.
- The test shall be carried out with a DUT composed of such a number of cells that its Open Circuit Voltage (OCV) is > 12 V.
- DUT shall meet or exceed the rated capacity value when tested for capacity test shown previously in Table 33;
- The test shall be started with the DUT is fully charged;
- DUT shall be brought to a temperature of 40°C $\pm$ 3°C, and stabilized at this temperature for 16 h.

Cycling Endurance Test:

Table 34 is shown Cycling Endurance Test composed of 50 charge/discharge cycles at low SOC and 100 charge/discharge cycles at high SOC. The DUT shall be maintained at 40°C $\pm$ 3°C throughout the two phases.

Table 34 Cycling Endurance Test

Test Phase	Sub-Test phase	Lead-acid and other batteries	Nickel-cadmium, nickel metal hydride and Lithium batteries
1^{st} Phase (Shallow cycling at low SOC)	(a.1)	Discharge the DUT with a current of C/10 for 9 hours	Discharge the DUT with a current of C/10 for 9 hours
	(b.1)	Recharge the DUT with a current of 1.03*(C/10) for 3 hours	Recharge the DUT with a current of 1.03*(C/10) for 3 hours
	(c.1)	Discharge the DUT with a current of C/10 for 3 hours	Discharge the DUT with a current of C/10 for 3 hours
Repeat (b) and (c) 49 times			

Full recharge DUT according to the manufacturer recommendations			
2^{st} Phase (Shallow cycling at high SOC)	(a.2)	Discharge the DUT with a current of 1.25*(C/10) for 2 hours	Discharge the DUT with a current of 1.25*(C/10) for 2 hours
	(b.2)	Recharge the DUT with a current of C/10 for 6 hours (For lead-acid batteries charge voltage limited to 2,40 V/cell unless otherwise specified by the manufacturer)	Recharge the DUT with a current of C/10 for 6 hours (For vented nickel-cadmium batteries charge voltage limited to 1,55 V/cell unless otherwise specified by the manufacturer)
Repeat (a.2) and (b.2) 49 times			
Residual Capacity Determination	Battery cooling	Cool down the DUT, under continued charge, to the temperature defined for a capacity test in the applicable standards as listed in Table 32, and then stabilized at this temperature for 16 hours	
	Normal Capacity Test	Discharge the DUT with a C/10 current to low cut-off voltage of 1.80 V/cells	Discharge the DUT with a C/10 current to low cut-off voltage of 1.00 V/cells for nickel-cadmium and nickel metal hydride batteries; for Lithium batteries low cut-off voltage is defined by the battery manufacturer.
	Long Capacity Test	If the residual capacity estimated is less of 80%, battery is fully recharged and is submitted to a long capacity test: discharge the DUT with a C/120 current to cell low cut-off voltage.	
If no condition of test termination (explained below) is encountered, recharge battery in accordance to the manufacturer's specifications and restart the cycle			

This standard indicates as requirements that the minimum number of completed cycling endurance test shall be not less than 3. Single cycle Test duration is about 1160 hour, so about 48 days.

The condition of Test Termination:

The cycling endurance test shall be considered terminated when one of these follows conditions is fulfilled:

- When during the discharge (c.1) of 1^{st} Phase, a battery with *n* cells reached the manufacturer's recommended minimum safe cell voltage (this standard specifies 1,5 V/cell for typical lead-acid battery, 0,8 V/cell for typical nickel cadmium or Ni-MH batteries, not specification regarding Lithium battery).
- When during the residual capacity determination phase, the determined capacity was found lower than 80 % of the rated capacity.
- The cycling endurance test shall be expressed in terms of completed phase cycles determined in Table 33 before a limit, as specified in the two test termination conditions above, was encountered together with the value of Long Capacity Test, as determined at the conclusion of the test.

4.6 The battery in second-life use in photovoltaic off-grid: Conclusions

Batteries in second-life are defined as batteries which have a residual capacity of 85-80% of the rated capacity. Internal resistance (Rint) of aged batteries is higher than a new battery and so battery efficiency decreases in time. Nevertheless, lithium batteries, especially LiFePO4 batteries, present a lower internal resistance, so an efficiency >> 95%. Analyzing three types of LiFePO4 batteries in the PV applications, shown in Table 35, where charge and discharge currents **C-rate are very little** (e.g. C/10), it is proven that efficiency of Lithium battery should remain >95%.

Table 35 Efficiency of lithium battery in second life.

Battery example	New cell		Aged cell (10*Rint)		Most Aged cell (20*Rint)	
CALB cell	Rint (mΩ)	1	Rint (mΩ)	10	Rint (mΩ)	20
	Capacity (Ah)	72	Capacity (Ah)	72	Capacity (Ah)	72
	1/C-Rate	10	1/C-Rate	10	1/C-Rate	10
	Charge Current (A)	3.6	Charge Current (A)	3.6	Charge Current (A)	3.6
	Nominal Voltage (V)	3.2	Nominal Voltage (V)	3.2	Nominal Voltage (V)	3.2

	Efficiency (%)	**99.8**	**Efficiency (%)**	**97.8**	**Efficiency (%)**	**95.5**
Winston cell	Rint (mΩ)	0.4	Rint (mΩ)	4	Rint (mΩ)	8
	Capacity (Ah)	160	Capacity (Ah)	160	Capacity (Ah)	160
	1/C-Rate	10	1/C-Rate	10	1/C-Rate	10
	Charge Current (A)	16	Charge Current (A)	16	Charge Current (A)	16
	Nominal Voltage (V)	3.2	Nominal Voltage (V)	3.2	Nominal Voltage (V)	3.2
	Efficiency (%)	**99.8**	**Efficiency (%)**	**98**	**Efficiency (%)**	**96**
A123 systems cell	Rint (mΩ)	4	Rint (mΩ)	4	Rint (mΩ)	4
	Capacity (Ah)	4.4	Capacity (Ah)	4.4	Capacity (Ah)	4.4
	1/C-Rate	10	1/C-Rate	10	1/C-Rate	10
	Charge Current (A)	0.44	Charge Current (A)	0.44	Charge Current (A)	0.44
	Nominal Voltage (V)	3.3	Nominal Voltage (V)	3.3	Nominal Voltage (V)	3.3
	Efficiency (%)	**99.9**	**Efficiency (%)**	**99.5**	**Efficiency (%)**	**98.9**

These results are computed in absence of self-discharge phenomena, which could prove to be important in battery efficiency estimation in the case of PV applications. Cycling Endurance test can be used not only to analyze the performance of lithium battery in second life, but also to analyze the relationship between residual capacity, internal resistance which varies during battery life and its electrical consumptions (Ah Throughput, number of charge/discharge cycles).

5 Risk Register

5.1 Risk register

Mention here the risks that are linked to this deliverable. See the list of risks on the OBELICS sharepoint:

Table 36

Risk No.	What is the risk	Probability of risk occurrence[2]	Effect of risk[3]	Solutions to overcome the risk
WPx.x	Describe here the risks!! And please refer to the section of the text in the document dealing with this.	Indicate the level	Indicate the level	Give a description how to overcome the risk / give here possible solution(s)

[2] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

[3] Effect when risk occurs: 1 = high, 2 = medium, 3 = Low

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8 Appendix A – Quality Assurance

The following questions should be answered by all reviewers (WP Leader, peer reviewer 1, peer reviewer 2 and the technical coordinator) as part of the Quality Assurance Procedure. Questions answered with NO should be motivated. The author will then make an updated version of the Deliverable. When all reviewers have answered all questions with YES, only then the Deliverable can be submitted to the EC.

NOTE: For public documents this Quality Assurance part will be removed before publication.

Question	WP Leader	Reviewer 1	Reviewer 2	Technical Coordinator
	NAME	NAME	NAME	Horst Pfluegl
1. Do you accept this deliverable as it is?	Yes / No (motivate)	Yes / No (motivate)	Yes / No (motivate)	Yes / (thorough overview of standards)
2. Is the deliverable completely ready (or are any changes required)?	Yes / No (motivate)	Yes / No (motivate)	Yes / No (motivate)	Yes / (chapter 5,6,7 to be completed)
3. Does this deliverable correspond to the DoW?	Yes / No (motivate)	Yes / No (motivate)	Yes / No (motivate)	Yes / Does correspond to D7.2 description
4. Is the Deliverable in line with the OBELICS objectives?	Yes / No (motivate)	Yes / No (motivate)	Yes / No (motivate)	Yes
a. WP Objectives?	Yes / No (motivate)	Yes / No (motivate)	Yes / No (motivate)	Yes
b. Task Objectives?	Yes / No (motivate)	Yes / No (motivate)	Yes / No (motivate)	Yes
5. Is the technical quality sufficient?	Yes / No (motivate)	Yes / No (motivate)	Yes / No (motivate)	Yes / very thorough investigation through all relevant standards