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# Overview of battery safety tests in standards for stationary battery energy storage systems

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Contents

## Abstract

The newly approved Regulation (EU) 2023/1542 concerning batteries and waste batteries [1] sets minimum requirements, among others, for performance, durability and safety of batteries, covering many types of batteries and their applications. Batteries for stationary battery energy storage systems (SBESS), which have not been covered by any European safety regulation so far, will have to comply with a number of safety tests. A standardisation request was submitted to CEN/CENELEC to develop one or more harmonised standards that lay out the minimum safety requirements for SBESS. Batteries that have been tested according to the harmonized standards are presumed to be in conformity with the (requirements of) the Regulation.

This overview of currently available safety standards for batteries for stationary battery energy storage systems shows that a number of standards exist that include some of the safety tests required by the Regulation concerning batteries and waste batteries, forming a good basis for the development of the regulatory tests. Nevertheless, none of the standards covers all the tests listed in the Regulation. The current report provides a comparative analysis of safety tests in various existing standards and attempts to identify gaps to be addressed.

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# 1 Introduction

The newly approved Regulation (EU) 2023/1542 concerning batteries and waste batteries [1] sets minimum requirements for, among others, performance, durability and safety of batteries, covering many types of batteries and their applications. The aim is to ensure that only the sustainable, "green" and safe batteries are placed on the European market, reducing the environmental and societal impacts of battery materials sourcing, production and use including re-use and recycling.

Batteries are deployed in a wide range of applications ranging from portable consumer electronics to electric vehicles and stationary battery energy storage systems (SBESS). The regulation is aimed to ensure the safety of SBESS and defines such systems as follows [1]:

*"'stationary battery energy storage system' means an industrial battery* ([1]) *with internal storage that is specifically designed to store from and deliver electric energy to the grid or store for and deliver electric energy to end- users, regardless of where and by whom the battery is being used"*

SBESS can be found at many different positions of the power grid over a significant range of sizes and applications. In Front-of-Meter applications, they are used for storage of energy produced by intermittent and variable renewable power sources such as wind and solar that is not immediately used. In addition, batteries are used for capacity firming, load levelling, peak shaving and smoothing of the electricity production independent from the source of electricity [2]. SBESS are used for ancillary services and frequency control. During the distribution, they are used for load management, peak shaving and voltage control. In Behind-the-Meter applications, SBESS are used for off-grid solutions, back-up power and also peak shaving at home whereas commercial and industrial sites use SBESS besides off-grid solutions for load levelling, peak shift and uninterruptable power supply (UPS).

In a nutshell, the power of SBESS ranges from several kW up to tens of MW [2].

The most relevant chemistry for home SBESS and many other applications is the lithium-ion technology [3]. There are, however, other battery chemistries, whose current market shares are small [3] but whose market share are forecast to grow in the near future on a global scale [4] from 4 % in 2021 to 15% in 2021.

RWTH (Aachen Technical University) developed a tool to analyse all the battery energy storage installations in Germany [5]. Other battery chemistries than Li-ion are represented in various SBESS installations in Germany with a total power of 139 MW ([2]) leading to about 2.2% German market share [5]:

- Lead-acid (112 MW)
- Nickel-metal hydride (NiMH) (13 MW)
- Sodium-sulfur / Sodium-high temperature (Na HT) (13 MW)
- Flow batteries (1 MW)

Since Germany is the country with the highest population in the EU (status 2023) [6], these figures give a good indication about the relevant emerging battery chemistries on the SBESS market.

Article 12 of the Regulation concerning batteries and waste batteries (EU) 2023/1542 addresses safety of stationary battery energy storage systems. The compliance of battery systems with safety requirements is evaluated by performing the following tests listed in its Annex V:

- thermal shock and cycling
- external short circuit protection
- overcharge protection
- over-discharge protection
- over-temperature protection

[1] "The definition for an industrial battery is as follows [1]: *"'industrial battery' means a battery that is specifically designed for industrial uses, intended for industrial uses after having been subject to preparation for repurposing or repurposing, or any other battery that weighs more than 5 kg and that is neither an electric vehicle battery, an LMT [light means of transport] battery, nor an SLI [lighting and ignition] battery"*

[2] Status 5th October 2023

— thermal propagation protection
— mechanical damage by external forces
— internal short circuit
— thermal abuse
— fire test
— emission of gases ([3])

To meet the requirements set by the safety tests in the Regulation, battery manufacturers can prove the compliance with either a harmonised standard or with technical specifications issued by the European Commission itself. Harmonised standards are developed (or respectively, adopted from IEC/ISO) by recognised European standardisation bodies (CEN, CENELEC or ETSI) and also provide technical specifications for which - when fulfilled- compliance with requirements given in the corresponding EU regulatory text is presumed.

A standardisation request for the development of a harmonised standard was submitted by the European Commission to CEN/CENELEC on the 7th December 2021 [7].

A number of standards for the safety of SBESS exist [8–26]. However, not a single standard covers all the safety tests mentioned in Annex V of the Regulation [1].

The current report provides a detailed comparative analysis of safety tests in various existing standards and attempts to identify gaps to be addressed in the future, e.g. through a harmonised standard.

Even though batteries with external storage, i.e. batteries that have their energy stored in one or more attached external devices, e.g. flow batteries, are not in the scope of Article 12 of the new Regulation, for the sake of completeness and because flow batteries are used in SBESS, this report covers this type of battery systems as well.

[3] Although "emission of gases" appears as a separate test in the list of tests in Annex V of the Regulation, it is a requirement on all the tests mentioned before (see chapter 4)

# 2 Standards dealing with the safety of batteries for stationary battery energy storage systems

There are numerous national and international standards that cover the safety of SBESS. This analysis aims to give an overview on a global scale. However, many national standards are equivalent to international IEC or ISO standards (e.g. the Koran standard KS C IEC 62619 [27], the Australian standard AS IEC 62619 [28] and the Indian standard IS 17067:Part 5:Sec 2:2021 [29]). In that case, only the international standard is analysed. The standards are presented in the subchapters below.

The scope of this report is limited to standards that specifically address SBESS. However, for the thermal propagation test, the EV standards ISO 6169-1/AMD1:2022 [30] and GB 38031-2020 [31] were included in the scope for completeness. Ruiz et al. already published an analysis of safety standards for Li-ion batteries in electric vehicles (EVs) in 2018 [32].

## 2.1 Chemistry agnostic

— UL 1973:2022 “Batteries for Use in Stationary and Motive Auxiliary Power Applications” [8]

This standard defines requirements for battery systems used in stationary application including photovoltaic (PV), wind turbine storage or UPS. In addition, battery systems used in light electric rail (LER) applications for regenerative breaking of trains, vehicle auxiliary power (VAP) providing power for lighting and appliances and as back-up power in emergency situations, are also in the scope of this standard. This standard does not apply to batteries for traction power.

This standard contains a high number of battery safety and abuse tests that are mostly but not always chemistry agnostic. Alternative test protocols are included that are specific to certain battery chemistries.

— UL 9540A:2019 “Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems” [9]

In this standard, the battery is tested for its behaviour during thermal runaway and its fire and explosion hazard characteristics using the generated data for the design of fire and explosion protection of the installation. Although chemistry agnostic, this standard is rather relevant for batteries with flammable components. For flow batteries there is a specific procedure.

## 2.2 Lithium(-ion) chemistry

— IEC 62619:2022 “Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries, for use in industrial applications” [19]

This standard covers cells and batteries with lithium-ion chemistry in stationary (telecom, UPS etc.) as well as traction applications (forklift truck, golf cart, etc.), but not in road vehicles. It is an umbrella standard to IEC 63056:2020 [20] that deals with the safety of SBESS and other standards for industrial applications. This means that the requirements set out in this standard are common and minimum for all the applications.

— IEC 63056:2020 “Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems” [20]

This standard outlines the product safety requirements and tests for secondary lithium (i.e. Li-ion) cells and batteries with a maximum DC voltage of 1500 V for the use in SBESS.

— UL 1642:2020 “Lithium Batteries” [21]

This standards is about the safety of primary and secondary lithium batteries used as power sources. Not only lithium-ion but also metallic lithium and lithium-alloy batteries are in the scope. It is applicable to single cells and cells connected in parallel or in series. Although the SBESS are not explicitly mentioned, battery packs and “multicell installations” are in the scope of this standard which is the reason it is included in this analysis.

— VDE-AR-E 2510-50:2017-05 “Stationary battery energy storage systems with lithium batteries - Safety requirements” [22]

This German application rule deals with the safety of battery energy storage systems (BESS) containing lithium-ion batteries throughout its entire lifecycle. It is limited to applications in private households and small businesses. Medical applications are out of scope.

— GB 40165-2021 "Lithium ion cells and batteries used in stationary electronic equipment - Safety technical specification" [23]

This Chinese standard sets the basic safety requirements for stationary lithium-ion batteries. Batteries for uninterrupted power supply (UPS) and emergency power supply (EPS) are specifically mentioned in the scope of this standard. Therefore, the terminology can deviate from the original.

## 2.3 Nickel Metal Hydride chemistry

— IEC 63115-2:2021 "Secondary cells and batteries containing alkaline or other non-acid electrolytes - Sealed nickel-metal hydride cells and batteries for use in industrial applications - Part 2: Safety" [24]

This standard covers nickel-metal hydride cells and batteries and specifies tests and requirements for safe operation in industrial applications including the use in SBESS.

## 2.4 Lead acid chemistry

— EN 60896-21:2004 "Stationary lead-acid batteries - Part 21: Valve regulated types - Methods of test" [25]
EN 60896-22:2004 "Stationary lead-acid batteries - Part 22: Valve regulated types – Requirements" [26]

This standard with its parts 21 and 22 applies to valve regulated stationary lead-acid cells and monobloc batteries that are permanently connected to a load and a DC power supply (float charge application), not intended to be moved (static) and used in a stationary equipment such as battery rooms for telecom, UPS, utility switching or emergency power. It mainly contains tests designed to test the performance of the battery system. However, there are some tests related to its safety. It does not apply to lead-acid batteries used as engine starter batteries in vehicles, solar photovoltaic energy systems or general purpose applications. Part 21 contains the test themselves and part 22 contains the pass/fail criteria for the tests described in part 21.

## 2.5 Sodium High Temperature chemistry

— IEC 62984-2:2020 "High-temperature secondary batteries – Part 2: Safety requirements and tests" [10]

This standard includes safety requirements and test procedures for batteries with a minimum operating temperature of 100°C that are used for mobile and stationary use and whose rated voltage does not exceed 1500 V.

## 2.6 Flow Batteries

— IEC 62932-2-2:2020 "Flow battery energy systems for stationary applications – Safety requirements" [11]

Flow battery systems for stationary application including their installations with a voltage below 1500 V DC are in the scope of this standard. It addresses the safety hazards that are relevant to flow battery systems when they are used as intended. It includes indoor and outdoor as well as commercial and industrial application.

## 2.7 Standards addressing safety and functionality of protective and auxiliary systems

— IEC 62933-5-2:2020 "Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems" [33]

This standard considers safety aspects for the vicinity of grid-connected energy storage systems using an electrochemical storage subsystem. It gives key parameters for risk analysis and hazard identification of different use cases (residential, commercial, industrial and utility scale). It considers the hazards under normal and abnormal conditions for lithium-ion batteries, lead-acid batteries, nickel batteries, high temperature sodium batteries, flow batteries as well as lithium metal solid state batteries.

- IEC 62485-2:2010 “Safety requirements for secondary batteries and battery installations - Part 2: Stationary batteries” [13]

  This standard covers the measures and guidelines for auxiliary systems for protection against hazards from electricity, gas emission and electrolyte of lead-acid, NiCd and NiMH batteries that are used for example in telecom, power station operation or UPS. It does not contain abuse testing of batteries or their protective devices.

- IEC 62485-5:2020 “Safety requirements for secondary batteries and battery installations - Part 5: Safe operation of stationary lithium ion batteries” [14]

  This standard includes guidelines for protective equipment (e.g. overcurrent protective device) for the installation, use, maintenance and repair of stationary secondary lithium-ion batteries with up to 1500 V DC under normal and certain fault conditions (electricity, short-circuits, electrolyte, gas emission, fire, explosion). It does not contain abuse tests.

- EN 60896-11:2002 “Stationary lead-acid batteries - Part 11: Vented types – General requirements and methods of test” [15]

  This standard applies to stationary lead-acid batteries that are of vented type. It contains performance and endurance measurement requirements in order to create safety recommendations for battery installations. It does not contain battery safety or abuse tests.

- IS 17092:2019 “Electrical Energy Storage Systems: Safety Requirements” [16]

  This Indian standard deals with the safety of all kinds of electrical energy storage systems (including SBESS). It sets requirements for auxiliary systems and refers to UL 1973 for battery specific safety requirements.

- AS/NZS 5139:2019 “Electrical installations - Safety of battery systems for use with power conversion equipment” [17]

  This standard from Australia and New Zealand focusses on the installation and safety requirements for SBESS connected to power conversion equipment and installed in an enclosed space. It applies to systems with an energy between 1 kWh and 200 kWh. It does not apply to systems used for telecommunication, electric vehicles, portable equipment or UPS. It does not contain safety tests.

- GB/T 34866:2017 “Vanadium flow battery - Safety requirements” [18]

  This Chinese standard contains the safety requirements for auxiliary systems of vanadium flow battery systems (e.g. leakage collection trays or grounding system) to ensure a safe operation under normal condition and foreseeable misuse indoors and outdoors. It does not contain safety or abuse test requirements.

The domain of functional safety and security (e.g. ISO 13849 [34,35], IEC 62061 [36], ISO/SAE 21434 [37]) is beyond the scope of this report.

# 3 Analysis of safety tests required in the Regulation (EU) 2023/1542 concerning batteries and waste batteries

The Regulation concerning batteries and waste batteries [1] lists several safety tests that SBESS have to successfully pass (see chapter 1).

Besides the individual test criteria that are required by the nature of each test, common criteria are compared: the level of the device under test (DUT), the state-of-charge (SOC), the pass/fail criteria and their verification method. For these criteria, the report cites as close as possible the original terms in the standard. GB 40165-2021 was machine translated and therefore the translated terms can have a different meaning to the ones used in the rest of the standards. The actual meaning was then added in square brackets.

## 3.1 Level of integration

A battery consists of several sub-units at which safety testing could take place.

The regulation introduces terms for the level of assembly of a battery [1]

— <u>(Battery) cell</u>

"*'battery cell' means the basic functional unit in a battery, composed of electrodes, electrolyte, container, terminals and, if applicable, separators, and containing the active materials the reaction of which generates electrical energy*" [1]

— <u>(Battery) module</u>

"*'battery module' means any set of battery cells that are connected together or encapsulated within an outer casing to protect the cells against external impact, and which is meant to be used either alone or in combination with other modules*" [1]

— <u>(Battery) pack</u>

"*'battery pack' means any set of battery cells or modules that are connected together or encapsulated within an outer casing, to form a complete unit which is not meant to be split up or opened by the end-user*" [1]

— <u>Battery (system)</u>

"*'battery' means any device delivering electrical energy generated by direct conversion of chemical energy, having internal or external storage, and consisting of one or more non-rechargeable or rechargeable battery cells, modules or of packs of them, and includes a battery that has been subject to preparation for re-use, preparation for repurposing, repurposing or remanufacturing*" [1]

Among the standards, the term "battery" is interchangeable used along with the term "system"

In addition to the levels of assembly that match the definition in the regulation, an additional level of assembly is introduced by IEC 62619:2022 [19].

— <u>Cell block</u>

"*Group of cells connected together in parallel configuration with or without protective devices (e.g. fuse or positive temperature coefficient device (PTC)) and monitoring circuitry*

*Note 1 to entry: The cell block is not ready for use in an application because it is not yet fitted with its final housing, terminal arrangement and electronic control device.*"

For lead acid batteries, an additional level of assembly is used in EN 60896 standard series [15,25,26]:

— <u>Monobloc battery</u>

"*Secondary battery in which the plate packs are fitted in a multi-compartment container*"

Testing can be done at all the levels described above. However, testing at a lower level of integration is not always representative for the whole battery system which can have multiple layers of protection (similar to the "defence-in-depth" concept in nuclear safety [38]). Apart from the safety at cell level (e.g. intrinsically safer electrode materials or flame retardant electrolyte additives) the safety of a battery system can be increased by many other factors such as the BMS, temperature controls, protective devices or durable enclosures [39,40]. These protective measures can have a significant influence on the outcome of a safety test at system level.

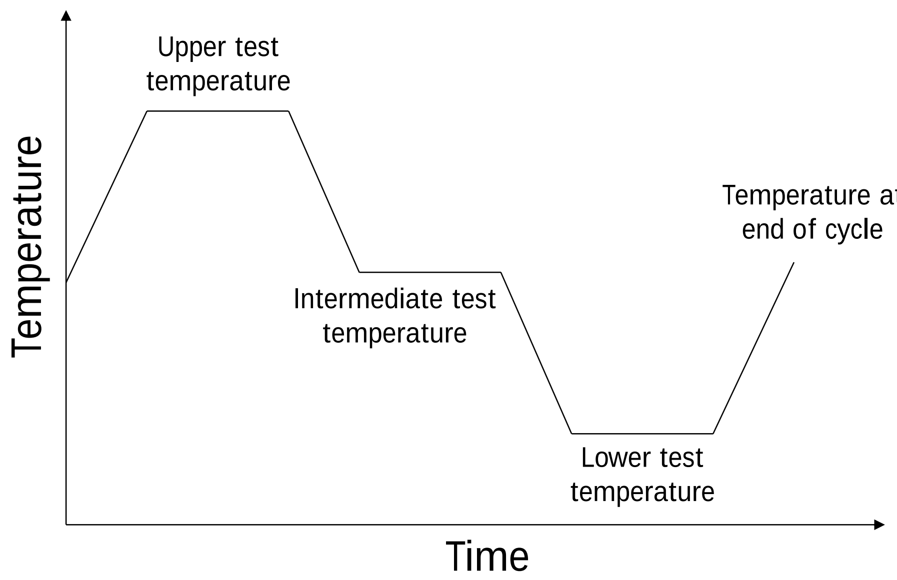
## 3.2 Thermal shock and cycling

Text of the Regulation [1]:

*"This test shall be designed to evaluate changes in the integrity of the battery arising from expansion and contraction of cell components upon exposure to extreme and sudden changes in temperature, and potential consequences of such changes. During a thermal shock, the battery shall be exposed to two temperature limits and held at each temperature limit for a specified period."*

Table 1 summarises the requirements for the tests in the standards that fit to the "Thermal shock and cycling" requirement in the Regulation that is cited above. The name of the test is not always the same. However, the sequence of steps to be followed is similar for all standards (see Figure 1). The DUT is heated to an upper test temperature, then the temperature is decreased to an intermediate test temperature (in all standards, this is close to room temperature) and subsequently to the lower test temperature. At the end of the cycle, the DUT is brought back to the temperature of the intermediate test temperature.

Figure 1. Test sequence for the one cycle in the test "Thermal shock and cycling"




*Source: JRC, 2023*

The first difference that can be extracted from the analysis of the different standards is the DUT. In IEC 63115-2 the test is and in GB 40165-2021 the test can be conducted at cell level whereas in the other standards the whole battery (system) is to be tested. This has implications for the outcome of the test. A cell might react differently compared to a whole battery system for several reasons. In a system battery cells and other components influence each other during a safety test (e.g. by dissipating heat to other cells and parts of the pack or active cooling by a thermal management system) while tests at cell level only take into account the individual cell and disregard these influences. This makes a direct comparison between cell- and system-level tests challenging.

The majority of the standards set the SOC criterion to "fully charged". This leaves it up to the manufacturer to set the upper charging voltage limit.

The time the DUT is held at a certain temperature varies from 1 hour (only for flow batteries) and 4 to 6 hours with a varying number of cycles.

The upper, intermediate and lower test temperatures are relatively similar except for Na high temperature batteries (higher) and flow batteries. This makes sense since Na high temperature batteries work at higher temperatures and flow batteries store their electrolyte externally in tanks which are not part of the DUT. GB 40165-2021 does not have an intermediate temperature step.

Only three standards include an observation time and two require a functionality check after the thermal shock and cycling test. All the standards have no fire and no explosion in common as pass/fail criteria. Apart from these two criteria the standards vary in stringency with regard to which pass/fail criteria apply. Moreover, often no verification method is stated, which leaves room for interpretation as to how the occurrence of a given phenomenon is to be verified. For IEC 63115-2 and IEC 62932-2-2 visual inspection is sufficient to verify the "no leakage" requirement, fire and explosion. In UL 1973 the pass/fail criteria shall be verified using a gas monitor to detect combustible vapour concentrations and toxic gas release (see chapter 4) and a dielectric voltage withstand test to exclude an electric shock hazard.

Table 1. Comparison of different standards for the test on "Thermal shock and cycling"

| Standard no. | UL 1642:2020<br>Temperature Cycling Test | UL 1973:2022<br>Thermal Cycling Test | UL 1973:2022<br>Cell temperature cycling | IEC 63115-2:2021<br>Temperature cycling | IEC 62932-2-2<br>Heat shock strength | GB 40165-2021<br>Temperature cycling |
|---|---|---|---|---|---|---|
| Battery chemistry/type | Li-ion | Li-ion, NiMH, FB | Na HT | NiMH | FB | Li-ion |
| DUT | Battery ([1]) | Battery system | Cell | Cell | Stack or sub-stack | Battery [cell] ([4]), cell block, module or pack |
| SOC | Fully charged | Fully charged | Fully charged | Fully charged | Not specified | Filled with electricity [charged] |
| Upper test temperature, hold time | Ramp to (70±3)°C within 30 min, 4 hours | Ramp to (75±2)°C within 30 min, 6 hours | Ramp to (85±2)°C within 30 min, 4 hours | Ramp to (70±5)°C, within 30 min, 4 hours | Stack: $T_{max}$+5°C ([2])<br>Liquid: $T_{min}$-5°C ([3])<br>1 hour | Ramp to (72±2)°C within 30 min, 6 hours |
| Intermediate test temperature, hold time | Ramp to (20±3)°C within 30 min, 2 hours | Ramp to (20±2)°C within 30 min, 2 hours | Ramp to (20±2)°C within 30 min, 2 hours | Ramp to (20±5)°C within 30 min, 2 hours | - | - |
| Lower test temperature, hold time | Ramp to (-40±3)°C within 30 min, 4 hours | Ramp to (-40±2)°C within 30 min, 6 hours | (Ramp to -40±2)°C within 30 min, 4 hours | Ramp to (-20±5)°C within 30 min, 4 hours | Stack: $T_{min}$-5°C<br>Liquid: $T_{max}$+5°C<br>1 hour | Ramp to (-40±2)°C within 30 min, 6 hours |
| Temperature at end of cycle, hold time | Ramp to (20±3)°C within 30 min | Ramp to (20±2)°C within 30 min | Ramp to (20±2)°C within 30 min | Ramp to (20±5)°C within 30 min, 2 hours | - | (20±5) ° |
| No. of cycles | 10 | 10 | 10 | 5 | 10 | 10 |
| Observation temperature and time | (20±5)°C, 24 hours | (25±5)°C, 24 hours | - | 24 hours | - | 12 hours |
| Functionality check | - | One full charge and discharge cycle at manufacturer's specifications | One full charge and discharge cycle at normal operating temperature | | | |
| Additional requirements | - | - | - | | Maximum inlet pressure applied | |
| Pass/fail criteria | No explosion<br>No fire<br>No leakage<br>No venting | No explosion<br>No fire<br>No leakage<br><br>No combustible vapour concentrations<br>No toxic vapour release<br>No electric shock hazard (dielectric breakdown)<br>No rupture<br>No loss of protection controls | No explosion<br>No fire<br><br>max. mass loss 0.1%,<br>for NaS: casing temperature equal or less than before the test | No explosion<br>No fire<br>No leakage | No leakage | No explosion<br>No fire<br>No leakage |
| Verification method | - | Visual inspection (rupture, leakage),<br>dielectric voltage withstand test (electric shock hazard),<br>gas monitoring (combustible vapour concentrations, toxic vapour release) | - | Visual inspection | Visual inspection | |

[1] In UL 1642 the term "battery" means "a single cell" or "a group of cells connected together either in series and/or parallel configuration"

[2] $T_{max}$: Maximum fluid temperature or ambient temperature (whichever is higher) of the stack

[3] $T_{min}$: Minimum fluid temperature or ambient temperature (whichever is lower) of the liquid

[3] For cell-level testing cell block or module are also acceptable as DUT, but cell is the preferential choice.

*Source: JRC, 2023*

## 3.3 External short circuit protection

Text of the Regulation [1]:

*"This test shall evaluate the safety performance of a battery when applying an external short circuit. The test can evaluate the activation of the overcurrent protection device or the ability of cells to withstand the current without reaching a hazardous situation (e.g. thermal runaway, explosion, fire). The main risk factors are heat generation at cell level and electrical arcing, which can damage circuitry or lead to reduced isolation resistance."*

As can be seen from this description, two different approaches can be taken: either the ability of the DUT to withstand harsh conditions of high current and heat generation or its ability to activate a protective mechanism. These two approaches are reflected in the names of the tests in the different standards (see Table 2).

During an external short circuit the two poles of the battery are connected with an external load of a certain resistance that is relatively low so that a high current can flow leading to a fast discharge of the DUT and heat generation. The external short circuit test conditions in the standards vary significantly from each other in terms of testing level (complexity of the DUT, i.e. system, module or even cell), SOC and external resistance (see Table 2).

Most of the standards listed in Table 3 recommend testing for external short circuit at room temperature, usually defined to be between 20±5°C and 25±5°C. Only in the UL 1642, the test is required to be conducted at higher temperature of 55±5°C. VDE-AR-E 2510-50:2017-05 and IEC 62984-2:2020 stipulate a test at (normal) operating temperature and conditions.

The external short circuit resistance has a high influence on the current that is flowing and hence the cell heating. The choice of resistance is therefore of importance for the outcome of the test. It also depends on what is tested: the protective device or the cell's ability to withstand a short circuit. Most of the standards require a fixed external resistance independent of the number of cells comprising a system. The external short circuit resistance applied in the different standards ranges from 5 mΩ to 100 mΩ. In battery systems with cells connected in series, the current in case of a short circuit increases with the number of cells at a fixed external short circuit resistance. Increasing the external short circuit resistance with the number of cells therefore makes sense to maintain comparability between cell and system level tests. For parallel-connected cells the current that flows from each cell is, however, a fraction of the total number of cells if the resistance is kept fixed. The external short circuit resistance should therefore decrease with the number of cells. Therefore, in IEC 63056:2020 the external short circuit resistance rightly increases with the number of cells connected in series and decreases with the number of cells connected in parallel.

There are also large differences in the termination criteria: after the temperature of the DUT has decreased to less than 20% of the temperature rise or after 6-24 hours (IEC 62619:2022, IEC 63056:2020 and IEC 63115-2:2021); after the current has decreased to 1 % of the nominal discharge rate (IEC 62984-2:2020); full discharge (UL 1973:2022, UL 1642:2020 and IEC 62932-2-2:2020); and after the protective device has been triggered (IEC 62984-2:2020, UL 1973:2022, UL 1642:2020, VDE-AR-E 2510-50:2017-05, IEC 62932-2-2:2020 and GB 40165-2021).

The pass/fail criteria set in all standards are "no explosion/bursting" and "no fire". Other criteria defined in some standards include "no rupture" (IEC 63056:2020 and IEC 62984-2:2020), "no (electrolyte) leakage" (IEC 62984-2:2020, UL 1973:2022 and IEC 62932-2-2), "no electric shock hazard" (IEC 62984-2:2020 and UL 1973:2022) and "no flammable/toxic gas emission/release" (IEC 62984-2:2020 and UL 1973:2022). UL 1973:2022 requires gas monitoring to exclude the release of toxic gas, combustible vapour concentrations and a dielectric voltage withstand test to exclude an electric shock hazard. In addition, IEC 62984-2:2020 introduces "no loss of protection controls" and GB 40165-2021 "no non-recoverable short-circuits" as a pass/fail criterion.

As the only standard in the list, UL 1973 requires a functionality check. This means that for the other standards it cannot be guaranteed that the test has not been destructive to a DUT.

Table 2. Comparison of standards for the test on "External short circuit protection"

| Standard no. | IEC 62619:2022 External short-circuit test | IEC 63056:2020 Protection against short circuit during transport and installation | IEC 62984-2:2020 Short circuit test | UL 1973:2022 Short circuit test | UL 1642:2020 Short-Circuit Test | VDE-AR-E 2510-50:2017-05 External short circuit | IEC 63115-2:2021 External short-circuit test | IEC 62932-2-2:2020 External short-circuit | GB 40165-2021 High temperature external short circuit | GB 40165-2021 Short circuit control |
|---|---|---|---|---|---|---|---|---|---|---|
| Battery chemistry/type | Li-ion | Li-ion | Na HT | Li-ion, NiMH, Pb acid, NiMH, FB | Li-ion | Li-ion | NiMH | FB | Li-ion | Li-ion |
| DUT | Cell or cell block | System or lower level if dismantled for transport | Batteries and modules | Cells connected in series only: cell or module<br>Also parallel connected cells: System | Battery (1) | Module, pack and system | Cell and battery | System | Battery [cell] (2), cell block or module | Battery system |
| SOC | Fully charged | Charged/discharged with 0.2C to SOC for installation and maintenance, if not specified: fully charged | 100% SOC | Fully charged | Fully charged | 100% SOC | Fully charged | Fully charged | Fully charged | Filled with electricity |
| Test temperature | (25±5)°C | (25±5)°C | Operating setpoint temperature | (25±5)°C | (20±5)°C and (55±5)°C | Maximum operating temperature for at least 12 hours (preconditioning), prior to the test: Normal operating conditions | (20±5)°C | 20 - 25°C. | (55±5)°C | (20±5)°C |
| External resistance | (30±10) mΩ | (30±10) mΩ x (no. of series connections divided by no. of parallel connections) or <5 mΩ (whichever is higher), not more than 100 mΩ in total | <5 mΩ | ≤20 mΩ | (80±20) mΩ (or more if an overcurrent device would be activated) | 20(+0 /-10) mΩ | (80±20) mΩ | ≤20 mΩ | ≤30 mΩ | (30±10) mΩ |
| Termination criteria (whichever comes first) | • 6 hours<br>• *T* of maximum temperature rise has declined by 80% | • 6 hours<br>• *T* of maximum temperature rise has declined by 80% | • Current decreases to less than 1% of the nominal discharge rates<br>• Activation of the short circuit protection | • 0% SOC<br>• Protection has operated<br>• Temperature of the module has reached steady state condition and 7 hours have elapsed | • Fire<br>• Explosion<br>• Complete discharge (<0.2 V) and the return to ±10°C of ambient temperature | • Short-circuit protection device has interrupted the circuit<br>• Venting, explosion or fire occurs | • 24 hours<br>• *T* declined by 20% after maximum temperature rise | • Battery is completely discharged<br>• the protective device was triggered<br>• the battery structure failed | • 24 hours<br>• *T* declined by 50% after maximum temperature rise | • BMS cut the circuit |
| Repetitions with same DUT | - | - | - | - | - | - | - | - | - | 2 |
| Observation temperature and time | - | - | - | - | - | Observation until no further change of the test result is to be expected | 1 hour after cell voltage is below 0.8 V and has decreased by <0.1 V in 30 min | - | - | 1 hour |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Functionality check | - | | | Operational DUTs undergo 1 charge and discharge cycle. | - | - | | - | - | - |
| Additional requirements | | | | If modules are intended to be replaced, this test has to be conducted at module level too. | If protective device was activated, test shall be repeated with the maximum load not to trigger the protective device. | | | | - | - |
| Pass/fail criteria | No explosion<br>No fire | No explosion<br>No rupture<br>No fire | No rupture,<br>No bursting<br>No fire<br>No electric shock hazard<br>no leakage<br>No loss of protection controls<br>No flammable/toxic gas emission | No explosion<br>No fire<br>No electric shock hazard<br>No leakage<br>No flammable/toxic gas release | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire<br>No electrolyte leakage | No explosion<br>No fire | No non-recoverable short-circuits |
| Verification method | - | - | - | Visual inspection (rupture, leakage), dielectric voltage withstand test (electric shock hazard), gas monitoring (combustible vapour concentrations, toxic vapour release) | - | - | - | - | - | - |

[1] In UL 1642 the term “battery” means “a single cell” or “a group of cells connected together either in series and/or parallel configuration”
[2] For cell-level testing cell block or module are also acceptable as DUT, but cell is the preferential choice.

*Source: JRC, 2023*

## 3.4 Overcharge protection

Text of the Regulation [1]:

*"This test shall evaluate the safety performance of a battery in overcharge situations. The main safety risks during overcharge are the decomposition of the electrolyte, cathode and anode breakdown, exothermic decomposition of the solid electrolyte interphase (SEI) layer, separator degradation, and lithium plating, which can lead to self-heating of the battery and thermal runaway. The factors affecting the outcome of the test shall, as a minimum, include, the charging rate and the finally reached state of charge. The protection can be ensured either by voltage control (interruption after reaching the limit charging voltage) or current control (interruption after exceeding maximum charging current). "*

In all the standards that include a test that deals with "overcharge", the functionality of the protective devices to control the voltage is tested. In addition, IEC 61619:2022, UL 1973:2022 and GB 40165-2021include a test for protective devices that control the current. All test conditions and requirements are summarised in Table 3.

Among the standards, the testing level varies from cell to system level.

Most of the standards require the test at ambient temperatures between 20 and 25°C. Only IEC 62984-2:2020 and UL 1973:2020 do not specify the test temperature.

The overcharging voltage varies from 10 % (IEC 62619:2022, IEC 62984-2:2020, UL 1973:2020 and GB 40165-2021) to 150 % (IEC 63115-2:2021) exceeding the upper limit charging voltage. IEC 62619:2022, UL 1973:2022 and GB 40165-2021 include another test ("Overcharge control of current", "High Rate Charge" and "Overflow charging control" respectively) in which the charging current is exceeded by 20 %. In principle, both tests are relevant for meeting the requirements of the Regulation.

IEC 62619:2022 relies completely on the protective device (or the BMS) to be triggered as termination criterion in both the cell level and the system level test.

The observation time is longest for IEC 62984-2 with 3 hours, many other standards stipulate 1 hour as observation time, while others do not specify this at all (see Table 3). Only UL 1973:2022 requires a functionality check after the test.

IEC 62984-2 and UL 1973:2022 are much more stringent in terms of pass/fail criteria. The whole structure must remain intact to pass the test whereas other standards allow, for example, leakage of electrolyte.

Table 3. Comparison of standards for the test on "Overcharge protection"

| Standard no. | IEC 62619:2022<br>Overcharge test | IEC 62619:2022<br>Overcharge control of voltage | IEC 62619:2022<br>Overcharge control of current | IEC 62984-2:2020<br>Overcharge | IEC 63115-2:2021<br>Overcharge test | UL 1973:2022<br>Overcharge test | UL 1973:2022<br>High Rate Charge | GB 40165-2021<br>Overcharge | GB 40165-2021<br>Overcharge control | GB 40165-2021<br>Overflow charging control |
|---|---|---|---|---|---|---|---|---|---|---|
| Battery chemistry/type | Li-ion | Li-ion | Li-ion | Na HT | NiMH | Li-Ion, NiMH, Pb acid, Na HT, FB | Li-Ion, NiMH, Pb acid, Na HT, FB | Li-ion | Li-ion | Li-ion |
| DUT | Cell or cell block | System | System | Batteries or modules | Cell and battery | Battery system | Battery system | Battery [cell] [1], cell block or module | Battery system | Battery system |
| SOC | Discharged at 0.2C to final voltage specified by manufacturer | Discharged at 0.2C to final voltage specified by manufacturer | Discharged at 0.2C to final voltage specified by manufacturer | Fully discharged | Discharged at 0.2C to 1.0 V | Fully discharged | Fully discharged | Filled with electricity | Discharged | Discharged |
| Test temperature | Ambient temperature | (25±5)°C | (25±5)°C | - | (20±5)°C | - | - | - | - | (20±5)°C |
| Overcharge condition | Maximum charge current until maximum voltage possible without triggering the protective device | Exceeding upper limit charging voltage by 10% at maximum charging rate | Charged with max. charge current+20% | Charged to 110% SOC at maximum charging rate | Charged to 250% of the rated capacity using charging method in according with IEC 63115-1:2020, 7.2 | Charged to 110% SOC at maximum charging rate | Charged with max. charge current+20% | Systems ≥3V: Maximum continuous charge current as specified by the manufacturer<br><br>Systems <3V; Charged to 1.5 times the maximum charged cap voltage specified by the manufacturer | Charged to 110% SOC at maximum charging rate | Charged with a current exceeding 20% max. charge current |
| Termination criteria (whichever comes first) | • Voltage and temperature reached steady state<br>• cell returned to ambient temperature | • BMS terminates charging | • BMS detects overcharging current and controls it to below max. charge current until DUT is fully charged | • 110% SOC reached, charging is terminated by protective circuitry<br>• Fail criteria is triggered | Temperature of the cell surface:<br>• reaches steady state (<10°C variation in 30 min) ; or<br>• has returned to ambient temperature | • 110% SOC reached<br>• charging is terminated by the protective circuitry<br>• fail criteria is triggered | • Charging terminated by protective device | • 1 h after passing max. voltage specified by the manufacturer; or<br>• battery temperature decreases by 50% of the maximum temperature rise | • 110% SOC reached<br>• charging is terminated by the BMS | Overcurrent detected by BMU/BMS and controlled to below maximum charging current |
| Repetitions with same DUT | - | - | - | - | | - | - | - | 2 | 2 |
| Functionality check | | | | | | DUTs undergo 1 charge and discharge cycle. | DUTs undergo 1 charge and discharge cycle. | - | - | - |
| Observation time | - | 1 hour | 1 hour | 3 hours | - | 1 hour | 1 hour | | 1 hour | 1 hour |
| Pass/fail criteria | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire | No fire<br>No electric shock hazard<br>No bursting,<br>No leakage<br>No rupture<br>No loss of protection controls<br>No flammable gas emission<br>No toxic gas emission | No explosion<br>No fire | No explosion<br>No fire<br>No electric shock hazard<br>No leakage<br>No rupture<br>No loss of protection controls<br>No combustible vapour concentrations<br>No toxic vapour release | No explosion<br>No fire<br>No electric shock hazard<br>No leakage<br>No rupture<br>No loss of protective controls<br>No combustible vapour concentrations<br>No toxic vapour release | No explosion<br>No fire | No non-recoverable short-circuits | No non-recoverable short-circuits |
| Verification method | - | - | - | - | - | Visual inspection (rupture, leakage), dielectric voltage withstand test (electric shock hazard),<br>gas monitoring (combustible vapour concentrations, toxic vapour release) | Visual inspection (rupture, leakage), dielectric voltage withstand test (electric shock hazard),<br>gas monitoring (combustible vapour concentrations, toxic vapour release) | - | | - |

[1] For cell-level testing cell block or module are also acceptable as DUT, but cell is the preferential choice.

*Source: JRC, 2023*

## 3.5 Over-discharge protection

Text of the Regulation [1]:

*"This test shall evaluate the safety performance of a battery in over-discharge situations. Safety risks during over-discharge include polarity reversal leading to oxidation of the anode current collector (Copper) and to plating on the cathode side. Even minor over-discharge can cause dendrite formation and ultimately short-circuiting."*

The testing level ranges from cell to system among the standards. For IEC 62619:2022, IEC 63056:2020 and GB 40165-2021 the test temperature is defined whereas UL 1973:2022 and UL 1642:2020 do not specify a test temperature. The SOC of the DUT ranges from fully charged to fully discharged. Tests that start with a DUT at a fully charged state will most likely cause more heat generation.

A controlled monitored discharge is to be conducted for most of the standards that include the over-discharge test (see Table 4). In UL 1642, however, a fully discharged cell is connected in series to other fully charged cells. Subsequently, the whole system is to be short-circuited. This, as well, leads to an over-discharge of the discharged cell. Though, the current that flows cannot be controlled – similar to an external short-circuit. This could lead to additional heating caused by the high current during discharge on top of that coming from the over-discharge test itself and hence to higher temperatures. The C-rate in which the batteries are over-discharged varies from 1.0 C (IEC 62619:2022, IEC 63056:2020 and GB 40165-2021) to maximum discharge rate specified by the manufacturer (UL 1973:2022) and uncontrolled discharge by short-circuiting a discharged cell with charged cells. Overcharging with a higher current leads to more heat generation that will likely affect the outcome of the test.

IEC 63056:2020 and UL 1973:2022 use the triggering of a protective device or the BMS as a termination criterion for the test whereas the other tests set minimum voltage criteria or a maximum discharging time and therefore check for an intrinsic capability of the DUT to withstand over-discharge.

Besides "no explosion" and "no fire" that is common in every standard, relying on the triggering of a protective device is also a pass/fail criterion for IEC 63056:2020. UL 1973:2022 has many more pass/fail criteria that also require gas monitoring as verification method for the presence of combustible vapour concentrations or toxic gas release. IEC 62619:2022 requires visual inspection after the test to check all pass/fail criteria. For the others, the verification method for the pass/fail criteria is not stated.

IEC 63056:2020 and UL 1973:2022 require an observation time after the test. In addition, UL 1973:2022 requires a functionality check.

Table 4. Comparison of standards for the test on "Over-discharge protection"

| Standard no. | IEC 62619:2022<br>Forced discharge test | IEC 63056:2020<br>Over-discharge control of voltage | UL 1973:2022<br>Overdischarge protection test | UL 1642:2020<br>Forced Discharge Test | GB 40165-2021<br>Forced discharge |
|---|---|---|---|---|---|
| Battery chemistry/type | Li-ion | Li-ion | Li-ion, NiMH, Pb acid, Na HT | Li-ion | Li-ion |
| DUT | Cell or cell block | Battery system | Battery system | Cell | Battery [cell] (3), cell block or module |
| SOC | Discharged at 0.2C to final voltage specified by manufacturer | Fully charged | Fully charged | Fully discharged | Discharged |
| Test temperature | (25±5)°C | (25±5)°C | - | - | |
| Over-discharge condition | Forced discharge at 1.0 C | Discharged at 0.2C to 30% of the rated capacity, then discharged at the specific maximum discharging current | Discharged with a constant discharge current/power at the specified maximum discharge rate | Cell is connected in series with fully charged cells of the same kind. Positive and negative terminal of the series are short-circuited with a resistance load of (80±20) mΩ | DUT is discharged with 1C. If maximum negative voltage is reached within 90min, the voltage should be maintained by reducing the current. |
| Termination criteria (whichever comes first) | • Discharging for 90 min<br>• target voltage reached (12):-<br>○ Number of protections or controls ≥2 or only one cell or cell block in the system:-$U_{max}$<br>○ Number of protections or controls ≤1: -($n$-1) x -$U_{max}$ | • BMS terminates discharging | • Passive protection device(s) are activated<br>• minimum cell voltage/maximum temperature protection is activated<br>• 30 min after reaching the normal discharge limit | • ≤0.2V has been reached<br>• return to ambient temperature (±10°C) | • Discharging for 90 min |
| Functionality check | - | - | DUTs undergo 1 charge and discharge cycle. | - | - |
| Observation time | - | 1 hour | 1 hour | - | -100 min |
| Pass/fail criteria | No explosion<br>No fire | No explosion<br>No fire<br>No cell voltages below their specific limits | No explosion<br>No fire<br>No electric shock hazard<br>No leakage<br>No rupture<br>No loss of protection controls<br>No combustible vapour concentrations<br>No toxic vapour release | No explosion<br>No fire | No explosion<br>No fire |
| Verification method | Visual inspection | - | Visual inspection (rupture, leakage), dielectric voltage withstand test (electric shock hazard),<br>gas monitoring (combustible vapour concentrations, toxic vapour release) | - | - |
| Additional requirements | - | Cooling system may remain functional. | - | - | - |

1 $U_{max}$: Upper limit charging voltage
2 $n$: number of cells connected in series
3 For cell-level testing cell block or module are also acceptable as DUT, but cell is the preferential choice.

*Source: JRC, 2023*

## 3.6 Over-temperature protection

Text of the Regulation [1]:

*"This test shall evaluate the effect of temperature control failure or failure of other features for protection against internal overheating during operation."*

Among the standards that include the over-temperature protection test, the testing level ranges from module to system (see Table 5 for comparison).

The heating method, initial/starting SOC and the temperature at the beginning of the test depend on the over-temperature test principle:

In IEC 62984-2:2020 that sets requirements for high-temperature cells, the heaters that heat the cells to the operating temperatures are required to be permanently on. This leads to a higher temperature than the normal operating temperature of the battery. DUT is required to be fully charged. The temperature of the test chamber is 25±5°C.

In UL 1973:2022, however, the heating is purely caused by charging of the fully discharged DUTs, while the cooling system is disabled. DUTs are preconditioned (7 hours at maximum operating temperature), discharged and charged at the maximum operating temperature. IEC 62619:2022 is similar to UL 1973:2022, except for the requirements on the test temperature, which are dependent on the SOC of the DUT (see Table 5). GB 40165-2021 has similar requirements to IEC 62619:2022 except that the DUT is externally exposed to higher temperatures instead of the cooling system being switched off.

What all the standards have in common is the triggering of the protective device as a termination criterion.

Both UL 1973:2022, IEC 62619:2022 and GB 40165-2021 require observation time of 1 hour. Only UL 1973:2022 stipulates a functionality check after the test.

Most of the standards have "no fire" and "no explosion" ("no bursting" in IEC 62984-2:2020) as pass/fail criteria. No non-recoverable short-circuits is set as a pass/fail criterion by GB 40165-2021. UL 1972:2022 and IEC 62984-2:2020 do not allow the emission of flammable or toxic gases, electric shock hazard and the rupture of the DUT. Only UL 1973:2022 states a verification method of the pass/fail criteria (gas monitoring) for combustible vapour concentrations and toxic gas release and electric shock hazard (dielectric voltage withstand test).

Table 5. Comparison of standards for the test on "Over-temperature protection"

| Standard no. | IEC 62984-2:2020<br>Overheating test | UL 1973:2022<br>Failure of Cooling/Thermal Stability System | IEC 62619:2022<br>Overheating control | GB 40165-2021<br>Overheating control |
|---|---|---|---|---|
| Battery chemistry/type | Na HT | Li-ion, NiMH, Na HT, Pb acid, FB | Li-ion | Li-ion |
| DUT | Battery/module | Battery system | System | Battery system |
| SOC | 100% | Fully discharged to the manufacturer's end of discharge condition | Discharged at 0.2C to final voltage specified by manufacturer | Discharged |
| Test temperature | (25±5)°C | $T_{max}$ (1) | (25±5)°C (0-50% SOC)<br>$T_{max}$ (1) +5°C (>50% SOC) | (25±5)°C (0-50% SOC)<br>$T_{max}$ (1) +5°C (>50% SOC) |
| Over-temperature condition | Internal heaters are turned on permanently until the safety cut-off temperature is reached or the temperature has reached a steady state in which it does not vary more than 1°C per hour. | 1. DUT charged at maximum charge rate with cooling/thermal stability system switched off until fully charged or operation of protective device is triggered.<br>2. After 7 h or thermally stable, the DUT is then discharged at the maximum discharge rate until end of discharge condition or operation of protective device | Charging at recommended current with cooling system disconnected | Charging at recommended current |
| Termination criteria | • After reaching safety cut-off threshold: Temperature has dropped below the minimum operating temperature<br>• In case of a self-resetting safety cut-off: 3 h or after 5 cut-offs, whichever is longer. | • End of discharge condition reached<br>• Operation of a protective device is triggered | • BMS terminates charging | • BMS/BMU (2) terminates charging |
| Repetitions with same DUT | - | - | - | 2 |
| Functionality check | - | DUTs undergo 1 charge and discharge cycle. | - | - |
| Observation time | - | 1 hour | 1 hour | 1 hour |
| Additional requirements | The temperature shall be measured every 10 s and plotted | Prior to the test, the DUT is fully discharged to the end of discharge condition specified by the manufacturer and then conditioned at the maximum operating temperature for 7 hours or until temperature change ≤2°C after 3 temperature measurements with 15 min interval | - | - |
| Pass/fail criteria | No bursting<br>No fire<br>No electric shock hazard<br>No leakage<br>No rupture<br>No emission of flammable/toxic gas | No explosion<br>No fire<br>No electric shock hazard<br>No leakage<br>No rupture<br>No toxic gas release<br>No combustible vapour concentrations<br>No loss of protection controls | No explosion,<br>No fire | No non-recoverable short-circuits |
| Verification method | - | Visual inspection (rupture, leakage),<br>dielectric voltage withstand test (electric shock hazard),<br>gas monitoring (combustible vapour concentrations, toxic gas release) | - | - |

1 $T_{max}$ : maximum operating temperature

2 The standard states that the BMS is sometimes called BMU (battery management unit)

*Source: JRC, 2023*

## 3.7 Thermal propagation

Text of the Regulation [1]:

*"This test shall evaluate the safety performance of a battery in thermal propagation situations. A thermal runaway in one cell can cause a cascading reaction throughout the entire battery which can be composed of numerous cells. It can lead to severe consequences including a significant gas release. The test shall consider the tests that are under development for transport applications by ISO and the UN (United Nations) Global Technical Regulation."*

ISO 6469-1/AMD1:2022 and GB38031:2020 are standards that establish safety requirements for electric vehicles, particularly focusing on the propagation of a thermal runaway event resulting from lithium-ion battery cell failures (see Table 6). These standards have been operational since 2020 and are currently undergoing a revision process. Although the application of these standards may vary, the methodologies outlined in the standards for EVs can provide helpful approaches and can be partially applicable for stationary applications.

For most of the standards, the DUT to be tested is a module or a battery system/pack. However, cell level testing is allowed by UL 9540A:2019 (see Table 7) if the thermal runaway cannot be induced in the cell.

Thermal propagation tests are usually performed on a fully charged DUT. Some standards, i.e., VDE-AR-E 2510-50:2017-05, specify that the DUT needs to be charged to its maximum operating voltage.

The temperatures for the test are defined slightly different in the listed standards: for IEC 62619:2022, UL 9540A:2019, IEC 62984-2:2020 and UL 1973:2022, the tests are to be performed at 25±5°C or 25±10°C. However, for VDE-AR-E 2510-50:2017-05, the test temperature is to be set to the maximum specified/operating temperature for the DUT, which may in some cases exceed 35°C.

Prior to commencing the test, the DUTs must be fully charged and allowed to stabilise. The stabilisation time is only specified in the UL 9540A:2019 and UL 1973:2022 standards.

Except for IEC 62984-2:2020 standard, which covers thermal propagation testing for sodium batteries, most standards outline the thermal propagation test using lithium-ion cells. UL 9540A:2019 standard does not refer to the battery chemistries to be tested.

All standards use a single cell to initiate the thermal runaway in the DUT. However, the selection of the specific cell to trigger the thermal runaway is not explicitly mentioned in most standards, except for UL 9540A:2019 and IEC 62984-2:2020, which offer brief guidelines to identify the initiation cell.

For effective monitoring of thermal propagation, it is advisable to install multiple thermocouples within the DUT. Among the standards, only IEC 62984-2:2020 provides more detailed guidelines for the exact location of thermocouples in the DUT.

The standards employ various trigger methods for inducing thermal runaway, including laser, heater, nail penetration, cell failure, among others. However, IEC 62619:2022, UL 9540A:2019 and IEC 62984-2:2020 standards provide a clear and detailed explanation of their primary trigger method; for example, IEC 62619:2022 adopts the laser method as a primary trigger method, while UL 9540A:2019 uses an external flexible heater and IEC 62984-2:2020 uses the cell failure technique to induce thermal runaway. On the other hand, UL 1973:2022 standard and VDE-AR-E 2510-50:2017-05 application rule offer more general information and brief explanations of the methods used to trigger thermal runaway in the battery system. Despite IEC 62619:2022 and UL 9540A:2019 specifying their main trigger method, they also mention alternative methods to initiate thermal runaway within the DUT; for example, they propose to use mechanical, overcharging, heating or nail penetration methods.

In most cases, the termination criterion is met when thermal runaway takes place within the DUT, resulting in an elevated temperature that subsequently stabilizes or begins to decrease after reaching its peak. Detecting thermal runaway requires data collection throughout the test using various recording methods. One common method is to observe the temperature increase, which all standards specify. Additionally, UL 9540A:2019 and VDE-AR-E 2510-50:2017-05 employ the monitoring of gases released from the DUT to detect thermal runaway. UL 1973:2022 and VDE-AR-E 2510-50:2017-05 standards propose additional verification methods to detect thermal runaway, such as monitoring voltage levels or using video recording.

Repeatability in the thermal propagation test is addressed by the standards IEC 62619:2022 and UL 9540A:2019 and it is not always explicitly specified in other standards. After a thermal runaway event, the observation period varies among standards. For instance, the IEC 62984-2:2020 standard recommends a short observation period of three hours, while the UL 1973:2022 standard suggests a longer observation period of one day. However, in some cases, the observation period is not clearly specified.

To prevent potential issues or hazards within the battery system, all standards provide safety guidelines related to the BMS with the exception of the UL 9540A:2019 standard.

When thermal runaway occurs within a battery, and the need arises to validate pass-fail criteria, a range of tests can be implemented to ensure the battery system complies with safety standards. These verification approaches aim to analyse the battery's behaviour under thermal runaway. A universally employed verification method across the various standards presented is the assessment of cell temperature profile. Moreover, the VDE-AR-E 2510-50:2017-05 application rule includes the use of thermographic videos to detect electrolyte leakage within the DUT. UL 9540A:2019 and VDE-AR-E 2510-50:2017-05 include visual verification approaches, they identify any indicators of unusual behaviour within the battery system, like swelling, venting, leakage, deformation, or re-ignition from thermal runaway. UL 9540A:2019 introduces an array of verification methods, including monitoring diverse gas types ($O_2$, CO, $CO_2$) released and assessing heat release rate during thermal runaway.

Most standards consider the absence of fire propagation, of battery rupture, or of explosion as the primary criteria for a successful test. However, standard UL 9540A:2019 does not define specific pass/fail criteria, instead it permits observation methods of potential damages within the battery system.

Table 6. Comparison of standards for the "Thermal propagation" test in automotive traction batteries

| Standard no. | ISO 6469-1/AMD1:2022<br>Thermal propagation test | GB38031:2020<br>Thermal propagation test |
|---|---|---|
| DUT | • RESS (Rechargeable Energy Storage System) level<br>• RESS subsystem level<br>• in-vehicle RESS level | • Secondary cell<br>• Battery pack<br>• Battery system (constituted by one or more battery packs) |
| SOC | ≥ 95% SOC | ≥ 95% SOC |
| Test temperature<br>Stabilisation time prior to test (stabilization of voltage and temperature) | Between 18°C to maximum permissible operating temperature<br>- | Above 0°C, a relative humidity of 10-90% and an atmospheric pressure of 86-106kPa |
| Trigger level | 1 cell | 1 cell |
| Type of battery (chemistry, design) | Li-ion<br>Pouch, cylindrical and prismatic cells | Li-ion<br>Pouch, cylindrical and prismatic cells |
| Selection of initiation cell | Intimate thermal contact between the heating element and the target cell surface<br>The selection of a single cell depends on the chosen trigger method and the RESS design | Center within the battery pack or surrounded by other secondary cells |
| Specification of thermocouples | Attach the thermocouples on the initiation module and on the adjacent modules | The position of temperature sensor shall be as near as possible to the short circuit point. The thermocouple is arranged at the side far away from the heat conduction |
| Preferred trigger methods | • Internal heater<br>• Localized rapid external heating<br>• Nail penetration | • External heating<br>• Nail penetration |
| Alternative trigger methods | - | - |
| Termination criterion | Set of criteria is met and last more than 3s for battery <130Wh/kg:<br>• Temperature rise dT/dt> 1K/s and temperature exceeding the thermal runaway onset temperature (determined by the cell manufacturer)<br>• Temperature exceeding the thermal runaway onset temperature with a rapid and distinct voltage drop<br>• Temperature exceeding the thermal runaway onset temperature with venting gas or smoke release<br>• Temperature rise dT/dt>1K/s and venting gas or smoke release and rapid voltage drop.<br><br>Set of criteria is met and last more than 0,5s for battery ≥130Wh/kg:<br>• Temperature rise dT/dt> 15K/s and temperature exceeding the thermal runaway onset temperature<br>• Temperature exceeding the thermal runaway onset temperature with a rapid and distinct voltage drop<br>• Temperature exceeding the thermal runaway onset temperature with venting gas or smoke release<br>• Temperature rise dT/dt>15K/s and venting gas or smoke release and rapid voltage drop. | • The trigger object produces a voltage drop, and the drop value exceeds 25% of the initial voltage and Temperature rise dT/dt≥1ºC/s, and last for more than 3s.<br>or<br>• Temperatures of monitoring points reach the maximum work temperature specified by the manufacturer and Temperature rise dT/dt≥1ºC/s, and last for more than 3s. |
| Detection of thermal runaway | In the RESS or RESS subsystem level:<br>• Occurrence of ejected solid material<br>• Failure of the BMS or signal faults<br>• Mass loss greater than its electrolyte mass of the initiated cell<br>• RESS or cell rupture<br>• Material formation indicating high temperatures;<br>• Specific reaction products;<br>• Current collector foil absence;<br>• Thermal decomposition of polymer materials. | • Temperature rise<br>• Voltage drop |
| Test repeatability | - | - |

| | | |
|---|---|---|
| Observation period | Minimum of 1 hour | 1 hour |
| Safety indication (BMS, warning indication) | • BMS<br>• Single cell voltages, temperatures, isolation faults<br>• Alarms to vehicle occupants<br>• Information screen<br>• Venting<br>• Cooling<br>• Gas permeability | • Thermal event alarm signal<br>• Manufacturers shall provide verification procedures and results documents for risk mitigation functions or characteristics of battery packs or system safety |
| Additional requirements | • A statement that the safety case of thermal propagation of the RESS is conducted according to the requirements of ISO 6469-1/AMD1:2022 shall be provided.<br>• Information shall be provided about the professionals who have constituted the practitioners 'team, their technical expertise and role. | • 5min prior to single cell thermal runaway causing thermal propagation therefore hazard in occupant compartment, battery pack or system shall provide a thermal event alarm signal<br>• Manufacturer shall provide the documents for description of battery pack or system safety: description of thermal event alarm signal and the technical documents for description of battery pack<br>• The testing body shall report technical documents for description of risk mitigation functions: procedure and result data of verification test |
| Pass/fail criteria | - | - |
| Verification methods | • Temperature recording (heating element and the target cell)<br>• Current and voltage recording of the target cell<br>• Video camera<br>• Audio (warnings)<br>• Multi-gas measurement<br>• BMS data recording<br>• Observation of: fire / explosion / smoke / rupture or damages within the DUT | • Temperature recording<br>• Voltage recording<br>• Alarm signal<br>• Photo<br>• External smoke<br>• Observation of fire or explosion |

Table 7. Comparison of standards for the "Thermal propagation" test in non-motive storage applications.

| Standard no. | IEC 62619:2022<br>Propagation test | UL 9540A:2019<br>Thermal runaway fire propagation | IEC 62984-2:2020<br>Cell failure propagation test | UL 1973:2022<br>Single Cell Failure Design Tolerance | VDE-AR-E 2510-50:2017-05<br>Internal short-circuit (propagation test) |
|---|---|---|---|---|---|
| DUT | Battery system | • Cell level<br>• Module level<br>• Unit level<br>• Installation level | Battery system | Battery system | • Cell block<br>• Module |
| SOC | Fully charged | 100% SOC | 100% SOC | Fully charged | Final voltage within the operating range |
| Test temperature | (25±5)°C | (25±5)°C | (25±10)°C | (25±5)°C | Maximum operating temperature |
| Stabilisation time prior to test (stabilization of voltage and temperature) | - | 1 hour for the Cell/Module level and 8 hours for the Unit/Installation level | - | | - |
| Trigger level | 1 cell | 1 cell | 1 cell | 1 cell | 1 Cell |
| Type of battery (chemistry, design) | Li-ion<br>Containing alkaline or other non-acid electrolytes | Li-ion<br>Flow battery | Na HT<br>(High-Temperature batteries whose rated voltage does not exceed 1500 V) | Li-ion<br>Na HT<br>Pb acid<br>NiMH | Li-ion |
| Selection of initiation cell | - | Shall present the greatest thermal exposure to adjacent cells | There should be 2 cells surrounding the target cell in every direction | - | - |
| Specification of thermocouples | Use multiple thermocouples | At least one thermocouple shall be located below the heater film at the centre of the cell surface and one near the positive cell terminals | Monitoring temperature at three different heights of the faulted cell: 10%, 50% and 90% of the total cell height from the top | Thermocouples attached to the central component cell or module. Temperature measurements shall be made with the measuring junction of the thermocouple held tightly against the component being measured. | Temperature sensors applied to adjacent cells or higher levels of the system |
| Preferred trigger method | Laser (parameters are set such that the initiation cell enters the thermal runaway within 10min) | External heater | Cell failure | Arbitrary (e.g., heating, nail penetration, internal defect, short circuit, overcharge) | • Overcharging<br>• Overheating<br>• Short-circuiting (≤5 mΩ)<br>• Overvoltage impulses<br>• Nail penetration<br>• Other methods recommended by the manufacturer |
| Alternative trigger methods | • Heating<br>• Overcharging<br>• Nail penetration | • Mechanical<br>• Overcharging, over-discharging<br>• Short-circuiting<br>• Alternate heating sources | - | - | - |
| Termination criterion | Thermal runaway | Maximum surface temperature<br>• Thermal runaway | • Thermal runaway- | Thermal runaway | No more reactions occur within the cell |
| Detection of thermal runaway | Rapid increase of cell temperature indicates a thermal runaway event | • Temperature rise<br>• Gas release (oxygen, carbon monoxide and carbon dioxide analysers)<br>• Weight loss shall be measured through the module<br>• -Visual inspection | Temperature rise | • External heater: rapid and uncontrolled heating<br>• Nail penetration: once the voltage of the failed cell drops by 500mV or the depth of penetration reaches half of the cell.<br>• Internal defect: effect on the charge /discharge cycling | • Rise of the cell temperature resulting in an increase of the temperature of adjacent cells<br>• Venting of gaseous electrolyte<br>• Burning of the cell<br>• Sparking and ignition of vented gas mixtures<br>• Explosion of the cell |

| | | | | | |
|---|---|---|---|---|---|
| Test repeatability | 3 times | 3 times | - | - | - |
| Observation period | 8 hours | - | 3 hours | 24 hours | - |
| BMS guidelines | Yes | No | Yes | Yes | Yes |
| Additional requirements | The battery system may be modified to facilitate the thermal runaway of the target cell. The modification should be minimized, and it shall not affect the thermal properties of the battery system. | • Surface temperature measurements along instrumented wall surfaces shall not exceed 60°C of temperature rise above ambient<br>• The surfaces temperature of modules within the target BESS units adjacent to the initiating BESS shall not exceed the temperature at which thermally initiated cell venting occurs | • The BMS shall prevent the battery from entering a hazardous state<br>• Heaters use to maintain the cells at specified operating temperatures shall be dimensioned for the current and voltage to prevent breakages and short circuit<br>• Temperature shall be monitored at 10, 50 and 90% of total height of the initiation cell | • Initiation cell is chosen that is expected most likely to lead to propagation.<br>• The number of cells that fail due to propagation from the triggering cell shall be documented<br>• Determination of potential for fire hazard: a gas monitor suitable for detecting 25% of the lower flammability limited of the evolved gases being measured | • Each module shall be equipped with a fire protection enclosure in accordance with DIN EN 62368-1 (VDE 0868-1)<br>• Cell defects shall only propagate within the module in which the thermal instability of the cell was intentionally caused<br>• A propagation from this module to an adjacent module shall be precluded by testing<br>• Hazards shall not propagate beyond the system boundaries<br>• The BMS shall ensure compliance with the permissible operating range of the cell. This requires the monitoring of different parameters: cells voltage; battery system current; cells temperature |
| Pass/fail criteria | No external fire from the battery system<br>No battery system case rupture | - | No external fire<br><br>No rupture of DUT enclosure exposing hazardous material<br><br>No electric shock hazard (dielectric breakdown)<br>No leakage (external to enclosure of DUT)<br>No bursting | No fire propagation from DUT<br><br>No explosion | No propagation from module to module<br><br>No hazards beyond the system boundaries |
| Verification methods | Temperature measurement | • Temperature measurement<br>• Gas monitoring ($O_2$, CO, $CO_2$)<br>• Voltage recording<br>• Heat release rate vs time<br>• Visual inspection<br>• Video<br>• Module weight loss<br>• Observation of re-ignition | Temperature measurement | • Temperature measurement<br>• Voltage recording<br>• Time recording from the start of applying the failure to the observable initiation of the cell failure should be recorded<br>• Video | • Temperature measurement<br>• Voltage recording<br>• Video<br>• Visual inspection |

*Source: JRC, 2023*

## 3.8 Mechanical damage by external forces

Text of the Regulation [1]:

*"These tests shall simulate one or more situations in which a battery is accidentally exposed to mechanical stresses and remains operational for the purpose for which it was designed. The criteria to simulate these situations should reflect real life uses. "*

This requirement is reflected in two scenarios:

— the battery system is impacted by an object while in place.

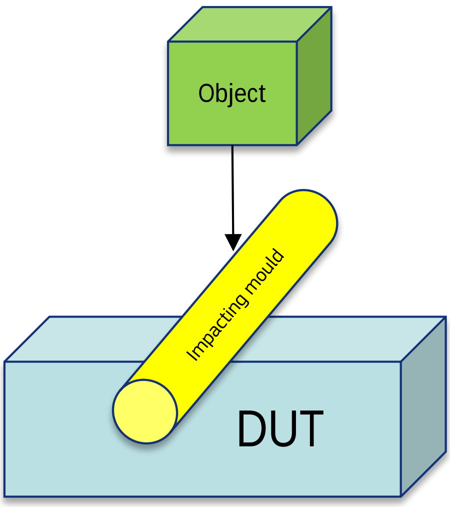
— the battery (system) is accidently dropped on the ground during installation or failure of its suspension

Standards include two different tests for these scenarios: the impact test (see chapter 3.8.1 and Table 8) and the drop test (see chapter 3.8.2 and Table 9).

### 3.8.1 Impact test

During the impact test, the DUT is subjected to an impact by either the object itself with a certain geometry and weight or a mould of a certain geometry that is impacted by an object of a certain weight (see Figure 2).

Figure 2. Illustration of the impact test in (IEC 62619:2022 and UL 1642:2020)




*Source: JRC, 2023*

The testing level of the DUT ranges from cell to system among the standards.

Apart from IEC 62619:2022, which requires a SOC of 50%, the DUT has to be fully charged.

UL 1973:2022 does not specify the level of assembly, all other standards require to test at cell (or cell block) level.

Two different testing approaches are taken. IEC 62619:2022 and UL 1642:2020 use a mould that is hit by a weight to distribute the impact to the whole battery cell whereas UL 1973:2022 impacts the DUT with the impact mass (535 g heavy sphere) directly (i.e. without an impacting mould) on several locations that could be exposed to an impact leading to more localised impacts. UL 1642:2020 requires the Round Bar Crush Test for cells with a capacity of 300 mAh and higher. In this test, the weight is not dropped onto the DUT but crushed with a certain crush force that depends on the shape of the DUT. GB 40165-2021 requires the squeeze test (similar to the crush test) for bigger cylindrical, pouch and prismatic cells.

The weight of the impacting object can have an influence on the outcome. E.g. in UL 1973:2022 the weight of the impacting object is almost one twentieth of that used in UL 1642:2020 and IEC 62619:2022. More information about the properties of the impacting object can be found in Table 8.

Only UL1973:2020 requires an observation time of one hour. “No explosion” and “no fire” are the pass/fail criteria that all the mentioned standards have in common. UL 1973:2022 lists more pass/fail criteria. Only UL 1973:2022 states the verification method of the pass/fail criteria: gas monitoring to verify the presence combustible vapour concentrations or toxic gas release and a dielectric voltage withstand test to exclude an electric shock hazard.

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### 3.8.2 Drop test

For the drop test the DUT varies from cell to system among the standards. IEC 62619:2022 even distinguishes between two types of drop tests, depending on the weight of a cell or a cell block (group of cells connected together but not ready for use in its final application). This similar approach is also taken in GB 40165-2021 where the drop conditions depend on the weight of the DUT.

The DUT is mostly fully charged. VDE-AR-E 2510-50:2017-05 and EN 60896-21+22 do not state an SOC and IEC 63056:2020 allows to adjust SOC to that for transport and maintenance, if specified.

The Drop Test experimental setup varies among standards. The cell is either dropped on a metal or concrete surface with different orientation depending on the standard (from the corner, the shortest edge or bottom down). The drop height depends on the weight of the DUT, but gradually decreases with the weight of the DUT from 1 m for small batteries to a couple of centimetres for heavier batteries. See Table 9 for precise values.

The amount of drop repetitions ranges from 0 to 2 times.

Most of the standards include an observation time (1-2 hours) to account for a delayed reaction. Interestingly, while IEC 62619:2022 required an observation time of 1 hour for the Drop Test, this is not necessary for the Impact Test.

The pass/fail criteria are different in every standard. “No explosion” and “no fire” are present in almost every standard (“no bursting” in IEC 62984-2:2020) except for EN 60896-21+22 for Pb acid batteries. UL 1973:2022 and VDE-AR-E 2510-50:2017-05 require many more pass/fail criteria to be met to pass the test. IEC 62619:2022 and IEC 63115-2:2021 state visual inspection as verification method. UL 1973:2022 requires air monitoring to verify combustible vapour concentrations or toxic gas release and EN 60896-21+22 a dielectric breakdown test to exclude presence of leakage. In addition, UL1973:2022 requires a dielectric voltage withstand test to exclude an electric shock hazard. GB 40165-2021 sets the presence of leakage as a pass/fail criterion only at system level.

Table 8. Comparison of standards for the "Impact" test as part of the test on "Mechanical damage by external forces"

| Standard no. | IEC 62619:2022<br>Impact test | UL 1642:2020<br>Impact Test | UL 1642:2020<br>Round Bar Crush Test | UL 1973:2022<br>Impact Test | GB 40165-2021<br>Heavy impact | GB 40165-2021<br>Squeeze |
|---|---|---|---|---|---|---|
| Battery chemistry/type | Li-ion | Li-ion | Li-ion | Li-ion, NiMH, Pb acid, Na HT | Li-ion | Li-ion |
| DUT | Cell or cell block | Cells (cylindrical, prismatic and pouch [1] ≤300 mAh) | Pouch cells (>300 mAh) | not specified | Cylindrical battery [cell] with diameter ≥18.0 mm | Cylindrical battery [cell] with diameter >18.0 mm, pouch cell, prismatic cell |
| SOC | Discharged at 0.2C to 50% of the rated capacity | Fully charged | Fully charged | Fully charged | Filled with electricity | Filled with electricity |
| Impact mould | Type 316 stainless steel bar | Bar | Round steel bar | - | Metal rod | Two plates |
| Dimensions of the impacting mould | at least 60 mm length or the longest dimension of the cell whichever is greater, (15.8±0.1) mm diameter | (15.8±0.1) mm diameter | (25±1) mm diameter | - | (15.8±0.2) mm diameter | - |
| Location to place the mould | Centre of the DUT | Centre of the DUT | Top of the DUT, perpendicular to the tab of the cell extending by at least 5 mm the width of the sample | - | Perpendicular the DUT | Vertical axis of cylindrical cells and broad surface of pouch cells and prismatic cells is placed between the two plates |
| Type of impacting object and weight | Weight, 9.1 kg | Weight, (9.1±0.46) kg | Crush plate | Steel sphere (50.8 mm diameter and 535 g in weight) | Weight, 9.1 kg | |
| Force of impact | - | - | Crush force 1-13 kN (depending on the cell width) | 6.8 J | - | Squeeze force (13±0.78) kN |
| Drop height | (610±25) mm | (610±25) mm | - | - | (610±25) mm | - |
| Location of impact | Centre of mould | Centre of the mould | - | any surface that could be exposed to an impact | Centre of the mould | - |
| Observation period | - | - | - | 1 hour | - | -1 hour |
| Additional requirements | Cells are to be impacted at both the longitudinal axis parallel to the flat surface and the axis perpendicular to it. Prismatic cells are to be impacted on both the narrow and the wide sides (one impact per DUT). | Prismatic cells are to be impacted at both the longitudinal axis parallel to the flat surface and the axis perpendicular to it (one impact per DUT). | Crushing direction of (90±1)° | For the side impacts the sphere shall be suspended by a cord. | - | Test terminated if voltage drops by 100 mV |
| Pass/fail criteria | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire<br>No combustible vapour concentrations<br>No toxic vapour release<br>No electric shock hazard<br>No leakage<br>No rupture<br>No loss of protection controls | No explosion<br>No fire | No explosion<br>No fire |
| Verification method | - | - | | Visual inspection (rupture, leakage),<br>dielectric voltage withstand test (electric shock hazard),<br>gas monitoring (combustible vapour concentrations, toxic gas release) | | - |

[1] UL 1642:2020 requires the Round Bar Crush Test for pouch cells with a capacity of more than 300 mA.

*Source: JRC, 2023*

Table 9. Comparison of standards for the “Drop” test as part of the test on "Mechanical damage by external forces"

| Standard no. | IEC 62619:2022<br>Whole Drop test | IEC 62619:2022<br>Edge and Corner Drop test | IEC 63056:2020<br>Drop test | IEC 62984-2:2020<br>Drop test | UL 1973:2022<br>Drop Impact test | VDE-AR-E 2510-50:2017-05<br>Drop Test* | IEC 63115-2:2021<br>Drop test | EN 60896-21+22<br>Stability against mechanical abuse of units during installation | GB 40165-2021<br>Fall down |
|---|---|---|---|---|---|---|---|---|---|
| Battery chemistry/type | Li-ion | Li-ion | Li-ion | Na HT | Li-ion, NiMH, Pb acid, Na HT | Li-ion | NiMH | Pb acit | Li-ion |
| DUT | Cell or cell block, battery system <20 kg | Cell or cell block, battery system ≥20 kg | System or lower level, if dismantled for transport | Battery or modules | Module/<br>component pack | Battery system and its components | Cell and battery | 2 cells or monobloc batteries | Battery [cell] (2), cell clock, module or pack |
| SOC | Fully charged | Fully charged | Fully charged or, if specified, SOC for installation or maintenance | 100% SOC | Fully charged | - | Fully charged | - | Filled with electricity |
| Drop height | <7 kg: 100.0 cm<br>7≤ mass <20kg:<br>10.0 cm | <50 kg:<br>10.0 cm<br>50 kg≤ mass <100 kg:<br>5.0 cm<br>≥100 kg:<br>2.5 cm | < 20 kg:<br>100 cm<br>20 kg ≤ mass<50 kg:<br>50 cm<br>50 kg ≤ mass < 100 kg:<br>5 cm<br>≥100 kg:<br>2.5 cm | Class 20:<br>20 cm<br>class 100:<br>100 cm<br>class 300:<br>300 cm (1) | ≤7 kg: 100 cm<br>>7 kg but ≤100 kg: 10 cm<br>>100 kg: 2.5 cm | ≤50 kg: 100 cm<br>≥50 kg mass <100 kg:<br>5.0 cm<br>≥100 kg:<br>2.5 cm | <50 kg: 10.0 cm<br>≥50 kg mass <100 kg:<br>5.0 cm<br>≥100 kg:<br>2.5 cm | <50 kg: 10.0 cm<br>≥50 kg mass <100 kg:<br>5.0 cm<br>≥100 kg:<br>2.5 cm | 2.5 cm to 100 cm |
| Repetitions with same DUT | 2 | 1 | <50 kg: 0 ≥50 kg: 1 | - | - | 2 | - | 1 | <20 kg: 0 ≥20 kg: 1 |
| Drop orientation | <7kg: random,<br>≥7kg: bottom down | Shortest edge and corner | < 7 kg:<br>random<br>7 kg ≤ mass<50 kg:<br>Bottom down<br>≥50 kg:<br>Shortest edge and adjacent corner | Corner down | most representative manner for handling or maintenance | ≤50 kg: shortest edge, corner and perpendicular onto front or rear<br>≥50 kg: Shortest edge and corner | Bottom down | Shortest edge down<br>Corner down | < 7 kg:<br>random<br>7 kg ≤ mass<50 kg:<br>Bottom down<br>≥50 kg:<br>Shortest edge and adjacent corner |
| Surface type | Flat (metal or concrete) | Flat (metal or concrete) | Flat concrete or metal floor | Concrete | Concrete or insulated metal | Concrete covered with a metal plate | Concrete or metal floor | Level concrete floor | Concrete or metal panel |
| Observation time | 1 hours | 1 hour | 1 hour | 3 hours | 1 hour | - | 1 hour | - | 1 hour |
| Additional requirements | - | - | - | Battery is heated to operating temperature if rated for handling, while operational otherwise to 70 - 80°C | - | Insulation resistance is measured before and after the test<br>≤50 kg: Test conditions of IEC 62619 apply | - | The DUT shall be dropped two times on the same edge or corner | - |
| Pass/fail criteria | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire | No fire<br>No bursting<br>No leakage | No explosion<br>No fire<br>No combustible vapour concentrations<br>No electric shock hazard<br>No leakage<br>No rupture<br>No loss of protection controls | No explosion<br>No fire<br>No venting<br>No hazardous surface temperatures<br>No ejected parts that may lead to injury of bystanders<br>No access to active parts above the protective low voltage | No explosion<br>No fire | No leakage | No explosion<br>No fire<br>No leakage (module) |
| Verification method | Visual inspection | Visual inspection | - | - | Visual inspection (rupture, leakage), dielectric voltage withstand test (electric shock hazard),<br>gas monitoring (combustible vapour concentrations, toxic gas release) | - | Visual inspection | Dielectric breakdown test, He leak and $H_2$ detector or<br>pH indicator (leak testing) | Visual inspection |

1 The drop height depends on the drop severity class reflecting mechanical requirements during handling and operation. Class 20 resembles falling from a pallet.
2 For cell-level testing cell block or module are also acceptable as DUT, but cell is the preferential choice.
Source: JRC, 2023

## 3.9 Internal short circuit

Text of the Regulation [1]:

*"This test shall evaluate the safety performance of a battery in internal short-circuit situations. The occurrence of internal short circuits, one of the main concerns for battery manufacturers, potentially leads to venting, thermal runaway, and sparking which can ignite the electrolyte vapours escaping from the cell. The generation of such internal short circuits can be triggered by manufacturing imperfections, the presence of impurities in the cells or dendritic growth of lithium, and is the cause of most in-field safety incidents. Multiple internal short circuit scenarios are possible (e.g. electrical contact of cathode/anode, aluminium current collector/copper current collector, aluminium current collector/anode) each with a different contact resistance. "*

There is only one standard that includes instructions for an Internal Short-circuit test (see Table 10). It uses a nickel particle as short circuit trigger that is placed into the cell before the test. The standard refers to clause A.5 and A.6 of IEC 62133-2:2017 [24] for the procedure to introduce the particle in different types of cells as well as the particle dimensions. The DUT is a discharged cell that is charged during the test conducted at 25°C to its upper charging voltage. Subsequently, the nickel particle that is already placed inside the cell is introduced with a special pressing equipment in between the electrode layers to cause a short-circuit. The termination criteria is a voltage drop or a certain press force on the cell.

Table 10. Standard for the test on "Internal short circuit"

| Standard no. | IEC 62619:2022<br>Internal short circuit test |
|---|---|
| Battery chemistry/type | Li-ion |
| DUT | Cell or cell block |
| SOC | Discharged at 0.2C to a specified final voltage |
| Test temperature | (25±5)°C |
| Short circuit trigger | Nickel particle (L-shape, height 0.2 mm, thickness: 0.1 mm, 1 mm long on each side), placed inside the cell during preparation[41] |
| Requirements | 1. DUT is charged to upper charging limit<br>2. Nickel particle is introduced with a special pressing equipment in between electrode layers after charging |
| Termination criteria | Voltage drop (>50 mV) or force of the press reached 800 N for a cylindrical cell and 400 N for a prismatic cell. |
| Pass/fail criteria | No fire |
| Verification method | - |

*Source: JRC, 2023*

## 3.10 Thermal abuse

Text of the Regulation [1]:

*"During this test, the battery shall be exposed to elevated temperatures (in IEC 62619 the temperature is 85°C) which can trigger exothermal decomposition reactions and lead to a thermal runaway in the cell."*

The majority of the standards that include this test require to test at cell level. IEC 62619:2022 and UL 1642:2020 prescribe testing at cell block and battery level, respectively.

Table 11 summarises the test conditions for the thermal abuse test. All standards require testing of a fully charged DUT. The test temperature varies among the standards. While IEC 62619:2022 requires 85°C, UL 1642:2020 and UL 1973:2022 require 130°C and more for batteries that have an operating temperature higher than 100°C. Considering that at 130°C more exothermic decomposition reactions can be triggered than at 85°C, it is reasonable that the test duration is reduced from 3 hours for exposure to 85°C to as little as 10 min for that at 130°C. In GB 40165-2021 the test duration is dependent on the amount of cells that are connected; more cells increase the test duration.

To test Ni metal hydride cells (IEC 63115-2:2021), the test temperature depends on the battery casing.

Only UL 1973:2022 requires an observation time of 1 hour.

Pass/fail criteria are the same for all tests, namely "no explosion" and "no fire", and no verification method is specified for these.

Table 11. Comparison of different standards for the test on "Thermal abuse"

| Standard no. | IEC 62619:2022 Thermal abuse test | UL 1642:2020 Heating Test | UL 1973:2022 Heating Test | IEC 63115-2:2021 Thermal abuse test | GB 40165-2021 Thermal abuse |
|---|---|---|---|---|---|
| Battery chemistry/type | Li-ion | Li-ion | Li-ion, Na HT, FB | NiMH | Li-ion |
| DUT | Cell or cell block | Battery ([1]) | Cell | Cell | Battery [cell] ([2]), cell block or module |
| SOC | Fully charged | Fully charged | Charged to manufacturer's specified upper limit charging voltage | Fully charged | Filled with electricity |
| Start temperature | (25±5)°C | (20±5)°C | (25±5)°C | (20±5)°C | (20±5)°C |
| Test temperature | 85°C | Batteries with operating temperature <100°C: (130±2)°C<br><br>Batteries with operating temperature >100°C: (30±2)°C above the manufacturer's maximum specified temperature<br><br>Lithium-metal batteries: (170±2)°C | Batteries with operating temperature <100°C: (130±2)°C<br><br>Batteries with operating temperature >100°C: (30±2)°C above maximum specified temperature= | Cell case:<br>Steel: (130±5)°C<br>Plastic (85±5)°C | (130±2)°C |
| Heating rate | (5±2)°C/min | (5±2)°C/min | (5±2)°C/min | (5±2)°C/min | (5±2)°C/min |
| Test duration | 3 hours | 10 min | ≤500 g: 10 min<br>>500 g : 30 min | 30 min | 1 cell: 1 hour<br>*n* cells: 1+(*n*-1)·0.1 hours |
| Observation period | - | - | 1 hour | - | - |
| Pass/fail criteria | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire | No explosion<br>No fire |
| Verification method | - | - | - | - | - |

[1] In UL 1642 the term "battery" means "a single cell" or "a group of cells connected together either in series and/or parallel configuration"
[2] For cell-level testing cell block or module are also acceptable as DUT, but cell is the preferential choice.

Source: JRC, 2023

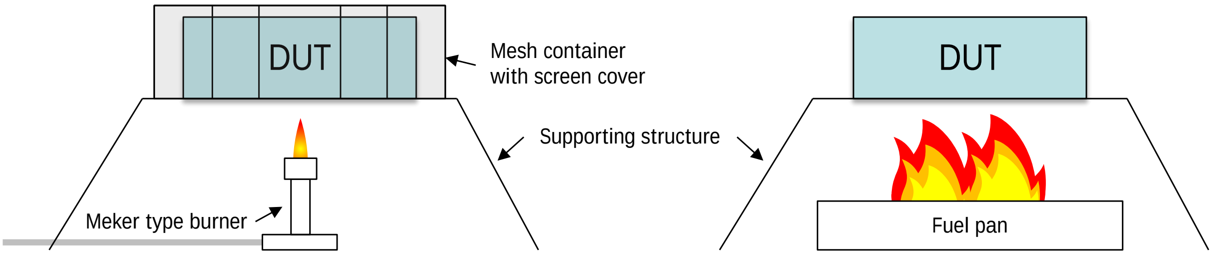
## 3.11 Fire test

Text of the Regulation [1]:

*"The risk of explosion shall be assessed by exposing the battery to fire."*

The principle of the fire test is similar among the standards. The DUT is placed above a fire that is produced in a certain way at a certain height for a certain time (see Figure 3). UL 1642:2020 requires an additional steel wire mesh container for the DUT to hold back possible projectiles.

Figure 3. Illustration of the fire test: On the left using a Meker type burner (required in UL 1642:2020) and on the right using a fuel pan (required in UL 1973:2022 and IEC 62984-2:2020)




*Source: JRC, 2023*

The test conditions for the fire test vary significantly among the standards (see Table 12). The DUT varies from cell to system among the standards. However, the DUT is either fully charged or at 100 % SOC.

The standards give a wide range of ambient test temperatures. UL 1973:2022 requires the test to be conducted free from wind or other environmental factors. In IEC 62984-2:2020 the test is conducted in the open air. In UL 1642:2020, the DUT is put in a steel wire mesh container with openings. UL 1973:2022 requires the test to be done in a protective test chamber. The placement of the DUT above the fire varies among the standards from 3.8 cm to 50 cm above the burner/fuel surface.

UL 1973:2022 and IEC 62984-2:2020 use heptane (or a similar liquid hydrocarbon) as fire source while UL 1642:2020 uses gas (e.g. butane). The heat flux of the combustion in a gas burner can only be comparable to a liquid hydrocarbon fire under a certain mass flow rate of gas [42]. UL 16420 does not specify a mass flow rate or gas during the test.

The fire test has different purposes depending on the battery chemistry that lead to different pass/fail criteria. In UL 1973:2022 and IEC 62984-2:2020 the cell is exposed to fire only for a certain amount of time whereas in UL 1642:2020 the cell is exposed to the fire until ignition, explosion or burning out. Consequently, the pass fail criterion for UL 1642 is merely that nothing shall have penetrated the protective wire mesh. In UL 1973 a battery that catches fire would also pass as long as it does not explode and projectiles stay within a perimeter of 1 m from the outer edge of the longest side of the DUT. The outcome of this test in UL 1973:2022 and UL1642:2020 is expected to be destructive. IEC 62984-2:2020 has stricter pass criteria (e.g. no rupture) that might come from the nature of the battery itself since the battery system has to withstand high temperatures during normal operation.

Table 12. Comparison of different standards for the "Fire test"

| Standard no. | UL 1973:2022<br>External Fire Exposure for Projectile Hazards Test | UL 1642:2020<br>Fire exposure test (Projectile Test) | IEC 62984-2:2020<br>External fire exposure test |
|---|---|---|---|
| Battery chemistry/type | Li-ion, NiMH, Na HT, FB | Li-ion | Na HT |
| DUT | Battery system | Cell and battery ([1]) | Battery/module |
| SOC | Fully charged | Fully charged | 100% SOC |
| Ambient temperature | 0 to 46°C | - | Ambient temperature, at least 0°C |
| DUT container | - | Steel wire mesh (20 openings per 25.4 mm and a wire diameter of 0.43 mm | - |
| Type of fire | Pool of burning heptane or similar hydrocarbon | Meker type burner | Pool of heptane |
| Fire container | Steel pan | Screen with a hole (102 mm diameter) in the centre | Steel pan |
| Placement of the DUT | Centred 50 cm on top of the fuel surface | 38 mm above the burner | Centred max. 10 cm on top of the fuel surface |
| Exposure time | 20 min | Until ignition, explosion or burning out | 30 min |
| Action after exposure | Hose down to represent a fire fighter response from discharge angle of 30° and a minimum discharge of 4.7 L/s from a nozzle with 38 mm diameter and a pressure of 517 kPa. | - | - |
| Observation time | 1 hour | - | DUT observed until surface temperature back to ambient temperature or at least 3 hours. |
| Additional requirements | Approx. 15.24 cm (6 inch) of water is added to the pan prior to adding the fuel for a consistent flame during the test | - | Water is added to the pan |
| Pass/fail criteria | No explosion<br>No projectiles outside a perimeter of 1 m | No part of DUT has penetrated the wire mesh | No fire<br>No bursting<br>No leakage<br>No rupture<br>No emission of flammable/toxic gas |
| Verification method | - | - | Visual inspection (bursting, fire, leakage) |

[1] In UL 1642 the term "battery" means "a single cell" or "a group of cells connected together either in series and/or parallel configuration"

*Source: JRC, 2023*

## 4 Emission of gases

Text of the Regulation [1]:

*"Batteries can contain significant amounts of potentially hazardous materials, for example highly flammable electrolytes, corrosive and toxic components. If exposed to certain conditions, the integrity of the battery could be compromised, resulting in the release of hazardous gases. Therefore, it is important to identify emissions of gases from substances released from the battery during tests: the risk of toxic gases emitted from non-aqueous electrolytes shall be properly taken into account for all safety parameters listed in points 1 to 10."*

Even though the measurement of the emission of gases appears in the list of safety tests in Annex V of the Regulation, it is a not a self-standing test but can rather be considered a requirement for all listed tests. Therefore, it can be concluded that the emission of toxic gases is to be set as pass/fail criterion for all tests and a proper verification method is needed. This has implications to the execution of the tests (e.g. execution in an enclosed environment). It is worth to mention that unlike for combustible vapour concentrations (in UL 1973:2022) – for which a concentration of a gas is to be measured – only the presence (the release) of toxic gases is to be determined. This results in other requirements on verification equipment.

UL 1973 contains a section on the determination of toxic emissions. It applies to those (destructive) tests that could result in toxic gas emissions. The potential of an exposure to these gases can be verified with this measurement. Established methods for determination of toxic emissions, cited in UL 1973:2022, are listed in Table 13. SESS systems that are placed in open air with natural ventilation or are equipped with a ventilation system are exempt from the determination of toxic gas emissions.

Table 13. Summary of information in UL 1973:2020 for the requirement "Emission of gases"

| Standard no. | UL 1973:2022<br>Determination of Toxic Emissions |
|---|---|
| Sampling procedure | Continuous sampling conducted in a closed test chamber of known volume during destructive tests |
| Exemptions | SESS that are installed outside or SESS that are equipped with a ventilation system to prevent exposure |
| Analysis methods | ASTM D4490 [43]<br>ASTM D4599 [44]<br>OSHA Evaluation Guideline for Air Sampling Methods Utilizing Spectroscopic Analysis [45]<br>NIOSH Manual of Analytic Methods [46] |

*Source: JRC, 2023*

Standards that deal with air monitoring provide general information and methods that can be relevant to verify the emission of gases:

— ISO 16000 - Indoor air [47]

  This series of standards deals with the identification and quantification of indoor air pollution. Relevant parts are

  - ISO 16000-1:2004 Indoor air — Part 1: General aspects of sampling strategy [47]
  - ISO 16000-5:2007 Indoor air — Part 5: Sampling strategy for volatile organic compounds (VOCs) [48]
  - ISO 16000-6:2021 Indoor air — Part 6: Determination of organic compounds (VVOC, VOC, SVOC) in indoor and test chamber air by active sampling on sorbent tubes, thermal desorption and gas chromatography using MS or MS FID [49]
  - ISO 16000-29:2014 Indoor air — Part 29: Test methods for VOC detectors [50]

— EPA Method TO-15 for the determination of VOC's (volatile organic compounds) in air Collected In Specially-Prepared Canisters and analysed by Gas Chromatography and Mass spectrometry [51]

— EPA Method TO-16 for Long-Path Open-Path Fourier Transform Infrared Monitoring Of Atmospheric Gases [52]

— EPA Methods TO-17 for the determination of VOC's in air using active sampling onto sorbent tubes [53]

— "Protection against internal ignition from external spark sources" test in EN 60896-21+22:2004 [25,26]

## 5 Other safety tests mentioned in the standards that are not required in Annex V of the Regulation (EU) 2023/1542

The Regulation (EU) 2023/1542 requires additional considerations on possible additional safety hazards not addressed in its Annex V and their successful mitigation for which state-of-the-art testing methodologies shall be used [1].

There are a number of safety tests described in various standards that are not mentioned in Annex V of the Regulation concerning batteries and waste batteries. It is worth to take a closer look at them. Table 14 gives an overview of these tests. The list may not be exhaustive. Some of them (e.g. "leakage test" or "valve operation") are specific to batteries with a certain chemistry and the resulting design. Others are specific to the environment in which the battery is operated or transported (e.g. "vibration" during transport on a bumpy road) and where it is installed (e.g. "enclosure stress at high temperatures" when the DUT is run in relatively hot regions or "support structure test" when it is suspended).

There are several reasons why the tests in Table 14 are not included in the Regulation (EU) 2023/1542. After the analysis of all the tests it can be concluded that

— Some of the features are already covered by testing the safety of the battery itself rather than its auxiliary system (e.g. drop test in case of a failing wall mount fixture).

— Since the safety of SBESS during their application is covered by tests listed in Annex V of the Regulation (EU) 2023/1542, tests that assess the transport capabilities (e.g. vibration) or safety during installation (e.g. Wall Mount Fixture) are not applicable.

— Tests specifically designed for flow battery systems are not relevant for the Regulation since it does not contain safety requirements for flow batteries. However, the safety of flow batteries might become relevant in future.

The safety tests required in Annex V of the Regulation (EU) 2023/1542 are based on Li-ion chemistry. Other chemistries, may require different safety tests for example on

— Leakage protection

— Pressure relief valves in case of pressure build-up

Table 14. Standardised tests addressing safety aspects that are not mentioned in Annex V of the Regulation.

| Test | Standards | Chemistries/ types | Description |
|---|---|---|---|
| Continuity test | UL 1973:2022 | Li-ion<br>NiMH<br>Pb acid<br>Na HT<br>Flow batteries | This test evaluates the continuity of the protective grounding and bonding system of the battery system that is intended to provide an electrically conductive path. The measured resistance between any two bonding connections shall be less than or equal to 0.1Ω and is measured with a milli-ohmmeter. |
| Dielectric Voltage Withstand Test | UL 1973:2022 | Li-ion<br>NiMH<br>Pb acid<br>Na HT<br>Flow batteries | This test evaluates the electrical spacing and insulation at high voltage to exclude an electrical breakdown or insulation failure within the DUT. A voltage is applied between the voltage circuits of the DUT and accessible non-current carrying but conductive part. No evidence of a dielectric breakdown (arcing, breakdown of insulation) shall be detected by the test equipment |

| | | | |
|---|---|---|---|
| Enclosure stress at high temperatures / Mold Stress Test | IEC 63115-2:2021<br>UL 1973:2022<br>GB 40165-2021 | Li-ion<br>NiMH<br>Pb acid<br>Na HT<br>Flow batteries | In this test, the enclosure of the DUT is tested for integrity at higher temperatures. The discharged DUT within an enclosure is exposed to temperatures moderately higher than the maximum operating temperature. Its integrity shall not be compromised. UL 1973:2022 includes an observation period after which the DUT is subjected to a dielectric voltage withstand test and is visually examined for signs of rupture and evidence of leakage. |
| Resistance to Moisture Test | UL 1973:2022 | Li-ion<br>NiMH<br>Pb acid<br>Na HT<br>Flow batteries | During the moisture resistance test the DUT's ingress protection rating in accordance with IEC 60529 or CAN/CSA-C22.2 No. 60529 is evaluated. It is tested whether the DUT can withstand exposure to moisture in its intended use. After the test, the DUT is subjected to one discharge and charge cycle (if still intact), an observation period, dielectric voltage withstand test, a visual inspection for signs of rupture and leakage. If venting is anticipated, combustible vapour concentrations shall be measured as well as the release of toxic gases. Other pass/fail criteria besides no dielectric breakdown, no rupture and no leakage are: no explosion, no fire, no combustible vapour concentrations and no toxic vapour release. |
| Salt Fog Test | UL 1973:2022 | Li-ion<br>NiMH<br>Pb acid<br>Na HT<br>Flow batteries | The DUT is exposed to salt fog conditions like near a marine environment according to IEC 60068-2-52. The DUT is fully charged. This test is not intended for DUTs that are not intended to be used near marine environments. After the test, the DUT is subjected to one discharge and charge cycle (if still intact), an observation period, dielectric voltage withstand test, a visual inspection for signs of rupture and leakage. If venting is anticipated, combustible vapour concentrations shall be measured as well as the release of toxic gases. Other pass/fail criteria besides no dielectric breakdown, no rupture and no leakage are: no explosion, no fire, no combustible vapour concentrations and no toxic vapour release. |
| Temperature and Operating Limits Check Test | UL 1973:2022 | Li-ion<br>NiMH<br>Pb acid<br>Na HT<br>Flow batteries | The DUT is tested for its ability to function reliably and safely under various environmental conditions (temperature) and operating scenarios (current, voltage) within its operational limits. After the test, the DUT is subjected to two charge and discharges cycles, an observation period, dielectric voltage withstand test and a visual inspection for signs of rupture and leakage. Other pass/fail criteria besides no dielectric breakdown, no rupture and no leakage are: no explosion, no fire, no combustible vapour concentrations and no toxic vapour release. This test is different to thermal shock and cycling as DUT is not subjected to extreme conditions. |
| Wall Mount Fixture / Support Structure / Handle Test | UL 1973:2022 | Li-ion<br>NiMH<br>Pb acid<br>Na HT<br>Flow batteries | In this test, the support structure of the battery system to be hung on the wall is tested. A force of three times the weight of the DUT is applied to the centre of the mounting apparatus and held for 1 min. There shall be no damage to the mounting apparatus. Nothing is stated on how to verify this criterion. |

| | | | |
|---|---|---|---|
| Imbalanced Charging Test | UL 1973:2022 | Li-ion<br>NiMH<br>Pb acid<br>Na HT | The test aims to ensure that the charging current is appropriately distributed among the cells of the DUT and any significant imbalances are prevented. All cells of a fully charged DUT are fully discharged except for one which is only partially discharged to create an imbalance. After (partial) discharging, the DUT is charged until end of charge condition. During the test combustible vapour concentrations shall be measured as well as the release of toxic gases. After the test, the DUT is subjected to one discharge and charge cycle (if still intact), an observation period, dielectric voltage withstand test, a visual inspection for signs of rupture and leakage. Other pass/fail criteria besides no dielectric breakdown, no rupture and no leakage are: no explosion, no fire, no combustible vapour concentrations and toxic vapour release. |
| Input | UL 1973:2022 | Li-ion<br>NiMH<br>Na HT<br>Flow batteries | The test aims to ensure that the battery system receives a stable and appropriate voltage level for charging. This helps prevent overcharging or undercharging, which can degrade battery performance and lifespan. Performing an input test within a battery system involves changing gradually the input parameters such as the voltage or the current and simultaneously monitoring the battery voltage, current and temperature response. When connected to an ac supply, the input current shall not exceed 110% of the rated/specified value of the device. |
| Leakage Current | UL 1973:2022 | Li-ion<br>NiMH<br>Na HT<br>Flow batteries | Leakage current testing helps ensure that there is no electric current flow within the battery system when it is not supposed to be active. The current limit shall comply with the protective touch voltage, touch current and protective conductor current test of UL 62368-1/CSA. Other pass/fail criteria are no hazardous behaviours such as leakage, electric shock or fire. |
| Overload Under Discharge /<br>Overload control | UL 1973:2022<br>GB 40165-2021 | Li-ion<br>NiMH<br>Na HT<br>Flow batteries | The purpose of tThis test helps assess how the battery system responds under conditions where the demand for energy exceeds its specified capacity. The fully charged DUT shall be discharged at a current equal to 90% of the rated overcurrent protection value of the BMS. Throughout the test, both the current and temperature are under constant observation. If required based upon installation, venting of toxic releases shall be continuously monitored during the test. The DUT shall be examined for signs of rupture and evidence of leakage as a pass fail/criteria. This test is different the over-discharge protection test as the DUT is not subjected to extreme conditions. |
| Push-Back Relief | UL 1973:2022 | Li-ion<br>NiMH<br>Na HT<br>Flow batteries | The purpose of this test is to determine if the strain relief of a non-detachable accessible cord provides adequate protection to connections and prevents hazardous displacement of internal wiring and connections as a result of push back. The supply cord shall be pushed back into the product under test in 25.4mm increments until the force to push the cord into the product exceeds 26.7 N. The test shall not lead to disconnection, short circuits, sparks, or any other hazardous conditions. |

| | | | |
|---|---|---|---|
| Strain Relief<br><br>(similar as Push-Back relief test) | UL 1973:2022 | Li-ion<br>NiMH<br>Na HT<br>Flow batteries | The strain relief test evaluates the mechanical integrity of the battery's connection under mechanical stress and prevents damage or displacement upon being pulled. The battery system provided with a strain relief shall withstand without damage to the conductors and without displacement, a direct pull of 156 N applied to the conductors for 1 min. As a result of the pull force, there shall be no damage or displacement of internal connectors. |
| Working Voltage measurements | UL 1973:2022 | Li-ion<br>NiMH<br>Na HT<br>Flow batteries | This The test purpose is to measure the working voltage of a battery system and helps prevent over-discharging within the DUT. The working voltage between live parts of opposite polarity, live and dead metal parts, live parts and a metal enclosure, and live and ground connections under both normal charging and discharging conditions is measured. The values obtained during the measurement shall be used to verify electrical spacing criteria. |
| Crush test | UL 1973:2022<br>UL 1642:2020<br>IEC 63115-2:2021 | -<br>Li-ion<br>NiMH | The DUT is crushed between two flat surfaces. It shall not catch fire nor explode. UL 1973:2020 requires more: gas monitoring to verify the absence of toxic vapour release and combustible vapour concentrations. This test is partially required and included in chapter 3.8 for certain DUT sizes. However, this test does not directly represent a scenario in which a damage caused by external forces to a SBESS can occur. |
| Shock test /<br>Mechanical shock/<br>Acceleration shock | UL 1973:2022<br>UL 1642:2020<br>IEC 63115-2:2021<br>GB 40165-2021 | -<br>Li-ion<br>NiMH | The DUT's capability to withstand shocks is assessed. The DUT is subjected to shocks due to acceleration in each of the 3 mutual perpendicular directions. It shall not catch fire nor explode. UL 1973:2020 requires more: gas monitoring to verify the absence of toxic vapour release and combustible vapour concentrations as well as a dielectric voltage withstand test and an examination for signs of rupture or leakage. |
| Vibration | UL 1973:2022<br>UL 1642:2020<br>IEC 63115-2:2021<br>GB 40165-2021 | -<br>Li-ion<br>NiMH | This test assesses the DUT's capability to withstand vibration during transport. The DUT is subjected to a harmonic motion. It shall not catch fire, explode or leak. UL 1973:2020 requires more: gas monitoring to verify the absence of toxic vapour release and combustible vapour concentrations as well as a dielectric voltage withstand test and an examination for signs of rupture or leakage. |
| Low pressure (altitude simulation) | UL 1642<br>IEC 63115-2:2021<br>GB 40165-2021 | Li-ion<br>NiMH | DUT is kept at sub-atmospheric pressure for a certain amount of time. It shall not explode or catche fire. |
| Reverse charge test | GB 40165-2021<br>IEC 63115-2:2021 | Li-ion<br>NiMH | DUTs are tested for The reverse charge test is conducted toto identify potential weaknesses in battery design. s to withstand a reverse charge. The DUT is subjected to a reverse charge for a certain time or until the BMS detects the reverse charge and interrupts the circuit. The pass/fail criteria for are no explosion and no fire (for IEC 63115-2:2021). |
| Abnormal charge | UL 1642:2020 | Li-ion | Discharged DUT is charged with a constant specified output voltage and three times the maximum charging current for 7h or until reaching end-of-charge condition The pass/fail criteria are: no explosion, no fire. |

| | | | |
|---|---|---|---|
| Protection for reverse connection | IEC 63056:2020 | Li-ion | One pack or module in a discharged DUT is connected in the opposite polarity. The fully charged DUT is discharged. One cell is disconnected and connected with the opposite polarity. Then, the DUT is charged until the safety protection stops the charging or it is fully charged. After an hour of rest period, the DUT is discharged again until lower discharge voltage followed by an hour of observation time. The pass/fail criteria are: no rupture, no fire, no explosion with no verification method stated. |
| Resistance to abnormal heat | IEC 63056:2020 | Li-ion | The integrity of the non-metallic building parts of the DUT is assessed in this test. Non-metallic parts are subjected to a The parts are impacted by a ball-shaped weight at elevated temperatures. They shall be resistant to the its impacts and the abnormal heat. |
| Reverse charge test | IEC 63115-2:2021 | NiMH | DUTs are tested for reverse charge test to identify potential weaknesses in battery designs to withstand a reverse charge. The DUT is subjected to a reverse charge for a certain time. The pass/fail criteria are no explosion and no fire. |
| High current tolerance | EN 60896-21+22:2004 | Pb acid | The DUT's capability to withstand high currents is assessed. The fully charged DUT is discharged at maximum discharge current and afterwards visually inspected internally (i.e. by opening the service caps) and externally for signs of enclosure melting (pass/fail criterion). |
| Protection against ground short propensity | EN 60896-21+22:2004 | Pb acid | DUT are tested to evaluate the adequacy of design features against ground shorts. The fully charged DUT is put into contact with a metallic surface. A voltage is applied between this metallic surface and a source. It shall remain in this position for 30 days or until a current flow is detected. The pass/fail criteria are no leakage (no verification method stated) and no ground short detected by the system. |
| Start-To-Discharge Test (for valve regulated systems) | UL 1973:2022 | Valve regulated (e.g. Pb acid) | In this test, the pressure relief valve is assessed by applying a pressure to it that is higher than the maximum working pressure. The pressure relief valve shall open in the range of 90-100% of its assigned start-to-discharge pressure setting. |
| Static force | UL 1973:2022 | Pb-acid | The purpose of this test is to determine if the DUT enclosure has sufficient strength to safely withstand a static force that may be applied to it. The fully charged DUT is subjected to a steady force of 250 N for 5 seconds on the top, bottom and sides. After the test, the DUT is subjected to one discharge and charge cycle (if still intact), an observation period, dielectric voltage withstand test, a visual inspection for signs of rupture and leakage. Other pass/fail criteria are: no explosion, no fire, no loss of protective controls, no combustible vapour concentrations and toxic vapour release. For the latter two gas monitoring should be applied iof deemed necessary. |
| Pressure release test (for valve regulated systems) | UL 1973:2022 | Valve regulated (e.g. Pb acid) | This test assesses the capability of the pressure release valve to work when submerged in mineral oil. The DUT (or for larger DUT only the pressure relief valve) is submerged in mineral oil and an increased charging current is applied causing gas formation. The test is passed if bubbles are only observed at the pressure relief valve. |

| | | | |
|---|---|---|---|
| Start-To-Discharge Test (for valve regulated systems) | UL 1973:2022 | Valve regulated (e.g. Pb acid) | In this test, the pressure relief valve is assessed by applying a pressure to it that is higher than the maximum working pressure. The pressure relief valve shall open in the range of 90-100% of its assigned start-to-discharge pressure setting. |
| Cell abnormal charging | UL 1973:2022 | Na HT | Discharged DUT is charged at maximum charging current (constant current) to maximum abnormal charging voltage, Charging charging is continued (constant voltage) for 7h. There shall be no fire and no explosion. |
| Immersion test | IEC 62984-2:2020 | Na HT | Optional test to ensure safety when the battery is flooded. The fully charged DUT is immersed 0.15 m deep into a 0.15 m deep container of sea water (NaCl solution) for a minimum of 2 hours until the temperature of the DUT drops below 50°C followed by an observation period of 3 hours. Pass/fail criteria are: no bursting, no fire, no leakage, no rupture (bulging allowed) with no verification method stated. |
| Electrolyte blockage test | UL 1973:2022 | Flow batteries | This test evaluates the DUT's ability to withstand an overcharge condition caused by a blockage of the electrolyte pumping system. Further details are not given. |
| Hydraulic pressure test | UL 1973:2022 | Flow batteries | This test is to assess the electrolyte containment vessel during a pressure build-up (e.g. 1.5 times the maximum pressure) with an inactive pressure relief device. Pass/fail criteria are: no burst, no leak, no rupture, no fracture and no permanent deformation. A verification method is not stated. |
| Insulation resistance | UL 1973:2022 | Flow batteries | This test shall ensure that the energised electrolyte fluids that travel through the system are insulated. The insulation resistance of the DUT is measured by high impedance (MΩ) while applying a high voltage between the live parts of the DUT and accessible conducting parts for a certain time. The resistance shall be greater than 1 MΩ. |
| Leakage test | UL 1973:2022<br>IEC 62932-2-2:2020 | Flow batteries<br>Flow batteries | The DUT enclosure's capability to hold the liquid even at a higher pressure than specified is tested during the leakage test. The DUT is subjected to a fluid pressure higher than the maximum fluid pressure (e.g. 1.5 times in UL 1973:2022). No visible leakage shall occur. Other pass/fail criteria are: no explosion, no fire, no combustible vapour concentrations, no toxic vapour release, no rupture and no loss of protection controls. A verification method is not clearly stated. |

*Source: JRC, 2023*

# 6 Gap analysis

## 6.1 Availability of standards containing test required by the Regulation

There are several standards available that describe some of the required tests. Table 15 lists the tests and shows which standard exists for the relevant chemistries for SBESS. There is not a single standard that covers all the tests required by the Regulation. A harmonised standard will have to be inspired by different international, national and industry-association authored standards.

Table 15. Safety standards listed in the Regulation on batteries and waste batteries for different battery chemistries

| Chemistry | Lithium-ion | NiMH | Lead-acid | Na HT | Flow batteries |
|---|---|---|---|---|---|
| Thermal shock and cycling | UL 1973<br>UL 1642<br>GB 40165 | UL 1973<br>IEC 63115-2 | | UL 1973 | UL 1973<br>IEC 62932-2-2 |
| External short circuit protection | UL 1973<br>UL 1642<br>VDE-AR-E 2510-50<br>IEC 62619<br>IEC 63056<br>GB 40165 | UL 1973<br>IEC 63115-2 | UL 1973 | UL 1973<br>IEC 62984-2 | UL 1973<br>62932-2-2 |
| Overcharge protection | UL 1973<br>IEC 62619<br>VDE-AR-E 2510-50<br>IEC 62619<br>GB 40165 | UL 1973<br>IEC 63115-2 | UL 1973 | UL 1973<br>IEC 62984-2 | UL 1973 |
| Over-discharge protection | UL 1973<br>UL1642<br>VDE-AR-E 2510-50<br>IEC 62619<br>IEC 63056<br>GB 40165 | UL 1973 | UL 1973 | UL 1973 | |
| Over-temperature protection | UL 1973<br>IEC 62619<br>GB 40165 | UL 1973 | UL 1973 | UL 1973<br>IEC 62984-2 | UL 1973 |
| Thermal propagation protection | UL 1973<br>UL 9540A<br>IEC 62619<br>VDE-AR-E 2510-50 | UL 1973<br>UL 9540A | UL 1973<br>UL 9540A | UL 1973<br>UL 9540A<br>IEC 62984-2 | UL 1973<br>UL 9540A |
| Mechanical damage by external forces | UL 1973<br>UL 1642<br>IEC 62619<br>IEC 63056<br>VDE-AR-E 2510-50<br>GB 40165 | UL 1973<br>IEC 63115-2 | UL 1973<br>EN 60896-21+22 | UL 1973<br>IEC 62984-2 | |
| Internal short circuit | IEC 62619 | | | | |
| Thermal abuse | UL 1973<br>UL1642<br>IEC 62619<br>GB 40165 | IEC 63115-2 | | UL 1973<br>IEC 62984-2 | UL 1973 |
| Fire test | UL 1973<br>UL 1642 | UL 1973 | | UL 1973<br>IEC 62984-2 | UL 1973 |
| *Emission of gases* ([1]) | *UL 1973* | *UL 1973* | *UL 1973* | *UL 1973* | *UL 1973* |

1 The emission of flammable and toxic gases is to be considered for every safety test in Annex V. Hence, the "Emission of gases" test cannot be considered as a test on its own.

*Source: JRC, 2023*

## 6.2 Applicability to different battery types and chemistries

Lithium-ion batteries are covered by the highest number of standards.

For lead acid batteries, the number is significantly lower. For “Thermal shock and cycling”, the “internal short circuit” test, the “thermal abuse” and the “fire test” there are no specifications that are explicitly made for lead acid batteries. In addition, the applicability of all the tests listed in Annex V to battery chemistries that do not contain a flammable electrolyte remains questionable and other, more specific safety tests not listed in Annex V, might make more sense. According to the regulation, the assessment of additional hazards not addressed in Annex V is the duty of the manufacturer. However, the Commission remains empowered to amend the parameters in Annex V over time to follow technical and scientific progress [1].

For battery chemistries with a high volume of (aqueous) electrolyte, other test that challenge the DUT’s ability to withstand a pressure build-up or to prevent a leakage might be relevant as well. Possible additional tests were discussed in chapter 5.

## 6.3 Applicability to batteries for second-life application

In the Regulation concerning batteries and waste batteries [1] the second life of a battery is considered:

“*The technical documentation shall be reviewed if a battery is prepared for re-use, prepared for repurposing, remanufactured or repurposed.*”

In the case of a SBESS this can be a battery that is e.g. repurposed by extracting it from a car and using it for stationary application. There can be different levels of modification (e.g. re-using the whole pack or exchanging modules or cells in it). Used batteries are often unique in terms of usage history and state-of-health (SOH), which makes type approval safety testing prior to their second life through (potentially) destructive tests not feasible. In the worst case, after changing the configuration of packs and modules that subsequently consist of heterogeneous cells, safety tests on module and pack level passed by type testing in the battery’s first life might not be valid/relevant for its second life and additional safety tests might be needed for every single battery before its use in a second life application can be allowed.

There are a few standards that deal with the second life of a battery:

— SAE J2997 (under preparation since 2012): “Standards for Battery secondary use” [54]

  This standard is in preparation and further information is not available.

— IEC 62933-5-3:2023 “Electrical energy storage (EES) systems - Part 5-3: Safety requirements for grid-integrated EES systems – Performing unplanned modification of electrochemical based system” [12]

  This part of IEC 62933 deals with the unplanned modification of SBESS, which also includes the modification of a battery system to be re-used or repurposed. The standards contains safety considerations, requirements and processes for adequate selection of batteries, their safety characterisation, system design, monitoring and operation. Destructive safety testing does not appear in this standard. The safety is estimated by several parameters of the battery’s first life and the current state of deterioration (e.g. measured by electrochemical impedance spectroscopy). During operation the battery’s SOC range shall be narrowed for energy and power intensive application by increasing the lower and reducing the upper voltage limit. For back-up power application, only the upper voltage limit needs to be reduced.

— UL 1974:2018: “Standard for Evaluation for Repurposing Batteries” [55]

  UL 1974:2018 lays out testing requirements for assembled repurposed batteries. The standard requires the battery to be suitable for its intended end use application and the cells inside the battery to be from the same model and the same manufacturer. In the case of the end use application being a SBESS, it shall be tested for the requirements published in UL 1973 with samples used for testing being representative for the worst case state of health using actual repurposed cells. UL 1974:2018 does not give more information what a representative (homogenous) sample is. Some information that can be used to find a homogenous sample could be obtained from the battery passport (e.g. state-of-health or dismantling information) [1]. For the requirement to comply with the tests outlined in UL 1973, UL 1974 does not specifically exclude destructive tests which means that even after having found a sufficient number of DUTs that can be considered representative, they would not be able to be used after the safety testing. A more practical solution would be preferred, but at the moment it does not exist.

# 7 Conclusions

From the analysis of the existing safety standards the following conclusions can be drawn:

— There is an international or national standard or application rule for every test that is required in Annex V of the Regulation EU) 2023/1542 concerning batteries and waste batteries [1].

— There are significant and numerous differences among existing safety standards, which can have an impact on the outcome of the test and hence on what is considered safe:

- The investigated standards and application rules show a large variation in device under test complexity level (from a single cell to a full system) and test conditions (e.g. test temperature, device under test state-of-charge, test procedure and the observation time after the test, to name a few).

- The pass/fail criteria, if defined, vary widely in stringency among the standards. "No explosion" and "no fire" are the two most commonly adopted pass/fail criteria for tests in all standards, but some standards contain additional pass/fail criteria.

- In many cases, no verification method is specified for a given pass/fail criterion, leaving some freedom of interpretation of the test outcome to the test performer.

- A requirement to monitor emissions of toxic gases in all tests, stipulated by art. 12 of the Regulation [1], would essentially introduce a new pass/fail criterion for all safety tests. Nevertheless, as no verification method is recommended, it can be difficult implement this criterion in practice. Chapter 4 gives an overview of guidance documents and standards for determination of emissions of toxic gases.

This shows that for a harmonised application of the Regulation in the field, standardisation bodies will have to make considerations regarding the choice of the most fit-for-purpose standard(s) to be followed for a given test.

— The safety tests listed in Annex V of the Regulation [1] address the typical safety risks of Li-ion batteries. Besides the tests that are required by the Regulation [1], the analysed standards list additional tests that are often specific for certain battery technologies (e.g. flow batteries) and/or battery designs (e.g. valve-regulated lead-acid batteries). These additional tests can be relevant for the safety of the batteries with these chemistries and should be considered in the future discussions to refine the Regulation.

— The Regulation requires safety testing to be performed for both factory-new and second-life batteries. Destructive safety testing of batteries for second-life application remains impractical. So far, second life batteries are only considered in two standards (UL 1974:2018 Standard for Evaluation for Repurposing Batteries and IEC 62933-5-3: "Electrical energy storage (EES) systems - Part 5-3: Safety requirements for grid-integrated EES systems – Performing unplanned modification of electrochemical based system") and a commonly accepted approach to safety testing of second life batteries that is compliant with the safety requirements in the Regulation is still to be developed. The safety testing approach and the extent of reverification for second-life batteries may depend on the application. As field experience with second-life applications steadily grows, it is expected to feed into the standardisation process.

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## List of abbreviations and definitions

| | |
|---|---|
| ASTM | American Society for Testing and Materials (USA) |
| BESS | Battery energy storage system |
| BMS | Battery management system |
| BMU | Battery management unit |
| CEN | Comité Européen de Normalisation |
| CENELEC | Comité Européen de Normalisation Électrotechnique |
| DUT | Device-under-test |
| EMC | Electromagnetic compatibility |
| EPA | Environmental Protection Agency (USA) |
| EV | Electric vehicle |
| FB | Flow battery |
| He | Helium |
| IEC | International Electrotechnical Commission |
| ISO | International Organization for Standardization |
| LER | Light electric rail |
| Li-ion | Lithium-ion |
| Na HT | Sodium high temperature |
| NiMH | Nickel-metal Hydride |
| NIOSH | National Institute for Occupational Safety and Health (USA) |
| OSHA | Occupational Safety and Health Administration (USA) |
| Pb acid | Lead acid |
| SEI | Solid electrolyte interphase SEI |
| SBESS | Stationary battery energy storage system |
| SOC | State-of-charge |
| SOH | State-of-health |
| SVOC | Semi-volatile organic compounds |
| UL | Underwriters Laboratories |
| UN | United Nations |
| VAP | Vehicle auxiliary power |
| VOC | Volatile organic compounds |
| VVOC | Very volatile organic compounds |

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