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Electrically propelled road vehicles — Safety specifications —

Part 1:
Rechargeable energy storage system (RESS)

AMENDMENT 1: Safety management of thermal propagation

Véhicules routiers électriques — Spécifications de sécurité —

Partie 1: Système de stockage d'énergie rechargeable (RESS)

AMENDEMENT 1: Management de la sécurité de la propagation thermique

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Foreword

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This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 37, *Electrically propelled vehicles*.

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Electrically propelled road vehicles — Safety specifications —

Part 1: Rechargeable energy storage system (RESS)

AMENDMENT 1: Safety management of thermal propagation

Introduction

Insert a new clause “Introduction” as follows:

> With the rapid development of the electric vehicle industry, its core component, the rechargeable energy storage system (RESS), has increasingly attracted attention, especially the safety requirements of RESS have raised a large interest within the public. This document specifies the general safety requirements for the RESS of electrically propelled road vehicles.
>
> This document also focuses on the safety performance of the lithium-ion battery. One central safety issue for lithium-ion battery systems is the potential for propagation of a thermal runaway event due to a cell thermal failure. For this purpose, this document provides methods for testing thermal runaway risk mitigation to support the development of vehicle and system safety concepts.
>
> The document primarily provides a tool kit for vehicle and RESS manufacturers to evaluate their product safety in terms of thermal propagation. It should enable RESS and/or vehicle manufacturers to get a deeper knowledge of the system behaviour in case of an internal failure of a single cell. Combined tests on cell and system level based on this document will provide comparable results about the RESS safety.
>
> Since it does not contain neither pass or fail criteria for thermal propagation, it is not foreseen to be used for homologation purposes.

Scope

Add the following paragraph after the first paragraph.

> Specifically, for lithium-ion based RESS, this document specifies demonstration methods for thermal runaway risk mitigation in case of a cell failure leading to an internal short circuit, including the collection of associated data. It also specifies a selection of different test methods for thermal propagation. The selected tests can be carried out at vehicle level or for RESS and RESS subsystem if appropriate.

Terms and definitions

Add the following additional terminological entries in Clause 3:

3.31
functional unit
entity of hardware or software, or both, capable of accomplishing a specified purpose

[SOURCE: ISO/IEC 2382:2015, 2121310, modified — Notes to entry were removed.]

3.32
internal short circuit
isolation failure inside a cell

Note 1 to entry: Formation of internal short circuits in a single cell may have different causes. The severity of the internal short circuit depends on the nature of the short and what parts of the cell that are involved. Some examples of potential causes of internal short circuit to consider are listed below:

— manufacturing defect involving foreign object debris (i.e. particles deposited on the electrode surfaces during cell manufacturing);

— manufacturing defect due to misalignment of electrode active material and separator;

— separator pinholes and creasing;

— separator shrinkage;

— electronically conductive burrs;

— current collector insulation flaws;

— lithium metal deposition at charging due to intercalation limitations;

— copper corrosion and formation of copper dendrites during cell operation;

— mechanical deformation of the cell, e.g. denting of the cell packaging during manufacture or deformation of the electrode coil or stack resulting from cycling.

3.33
operational design domain
specific operating domain(s) in which the RESS (3.22) is designed to operate, including but not limited to voltage/SOC (3.26) range, current range, temperature range, environmental conditions, and other domain constraints

3.34
safety case for thermal propagation of the RESS
argument that the safety requirements for the RESS (3.22) are complete and satisfied by evidence compiled from the work product of the safety activities during development

Note 1 to entry: Safety case for *thermal propagation* (3.37) of the RESS means in this document that a logical and hierarchical set of work products that describe risks in terms of hazards presented by the RESS in case of an *internal short circuit* (3.32) and the subsequent thermal energy release within the RESS, and which sets expectations and guidance for future performance, if hazards are controlled successfully.

3.35
target cell
cell in which *thermal runaway* (3.38) is initiated

3.36
thermal event
condition (event which occurs) when the temperature within RESS (3.22) rises significantly or is higher than the maximum operating temperature (3.17) as defined by the supplier (3.27) or customer (3.6)

Note 1 to entry: Depending on the situation (e.g. amount of heat generation compared to heat dissipation) a thermal event may or may not lead to a *thermal runaway* (3.38).

3.37
thermal propagation
transfer of thermal energy generated from *thermal runaway* (3.38) of a single cell to adjacent cells, which results in the thermal runaway of other cells in a RESS (3.22) or any assembly of RESS components

3.38
thermal runaway
heat generation caused by uncontrolled exothermic reactions inside the cell

Clause 5

Add a new subclause after 5.6 as follows:

5.7 Thermal propagation requirements

5.7.1 General

Thermal propagation requirements apply only to a lithium-ion RESS or RESS subsystem used for the propulsion of electric vehicles. Internal short circuit is a condition that can cause thermal runaway in a cell with subsequent thermal propagation in a RESS or RESS subsystem and which is not considered in other standards. Internal short circuit can be caused by contamination through the manufacturing process, by several events during operation and by aging (see 3.32).

The variety of lithium-ion technologies and the different cell construction types do not allow the definition of one single test method that covers all conditions in a safe, comparable, and reproducible way. This document provides three approaches to evaluate safety performance against thermal propagation for a RESS or RESS subsystem.

5.7.2 Safety performance of RESS

Safety performance of a RESS or RESS sub-system shall be considered by one of the following approaches:

1) demonstrating system robustness against a thermal failure of one cell to limit or withstand propagation effects by choosing test methods as specified in 6.7;

2) employing appropriate detection systems to identify early markers indicating a latent fault in a cell and demonstrate risk mitigation by the system safety approach detailed in Clause 7.

Clause 6

Add the following subclauses after 6.6 as follows:

6.7 Thermal propagation test

6.7.1 General

This subclause provides test methods to demonstrate the behaviour of a RESS or RESS subsystem in case of internal short circuit or thermal runaway caused by failure of a single cell. It also provides the test methods to generate measurement data which can be used to evaluate the safety performance of a RESS or RESS subsystem. The test method should be selected according to the intended test purpose and the possibilities for implementing the trigger method. Installation of a second trigger source may be performed by the test agency but is not required. A guidance for method selection based on cell type and test cases is given in Table 9.

Table 9 — Guidance for method selection

Trigger method	Applicable cell type (limitations provided in relevant clauses)	Application at RESS subsystem level	Application at RESS level	Application at vehicle level	Remarks
Internal heater	Any cell type	Yes	Yes	Yes	Cell manufacture is the only one to be able to introduce the internal heater inside the cell before electrolyte filling.
Localized rapid external heating	Any cell type	Yes	Yes	Yes	Heating element parameter may vary depending on different battery chemistries or cell type choices
Nail penetration	Any cell type	Yes	Yes	Yes	This trigger method cannot be applied to any position in a RESS or RESS subsystem. Can only be applied to the cells located in the outer perimeter of the pack.

NOTE 1 All trigger methods have intrinsic limitations and are state-of-the-art. Additional trigger methods can be developed as appropriate.

NOTE 2 These test methods are developed for lithium-ion RESS and vehicles using such RESS but are also applicable to other battery chemistries and future electric vehicle energy storage technologies and lithium-ion technology for other applications/industries. Using these methods outside of existing lithium-ion battery chemistries or manufacturing methods for electric vehicles, requires further validation to determine the suitability of the method is necessary.

If not otherwise specified, the tests described apply to the RESS or RESS subsystem referred to as device under test (DUT) in the following text. All methods utilize the initiation of thermal runaway in a target cell.

6.7.2 Target cell selection

For target cell selection, the number of adjacent cells, cell packaging, and the distance between cells in proximity to the potential target cell shall be considered. Installation of a trigger for the chosen target cell shall not impede the functionality of the original cell or RESS design and its safety features, such as venting, cooling, battery management system, gas permeability, spacing between cells or other components and thermal barriers.

In the field, a single cell thermal runaway may occur in any cell location within the RESS. For externally applied triggers, force may be required to maintain the method in proximity to the target cell and this may dictate the choice of the target cell. Target cell selection should follow a worst-case scenario in terms of thermal propagation.

Examples of conditions to consider are:

— thermal couplings to other cells and to RESS cooling mechanisms;

— thermal insulation around cells;

— geometrical aspect of electrical configuration, e.g. series or parallel connections;

— venting paths inside the RESS;

— configuration of battery management sensors and sampling rate.

Determination of the worst-case scenario may require preliminary tests, calculations or analysis, considering RESS or RESS subsystem design, cell capacity/chemistry/designs, or cooling system.

The selection of a single cell within the DUT depends on the chosen trigger method and the RESS design and shall be agreed between the customer and supplier.

If the intended application scenario is deemed not to have been covered by the tests, then repeating the test procedure with cells in different locations that represent the likely thermal environments and relationships within the RESS may be considered.

NOTE Placing the chosen trigger between battery cells using the existing RESS construction is sufficient but placing the trigger on an edge cell requires additional support structure and forces to maintain adequate contact between the target cell and trigger.

6.7.3 Test conditions

The test is conducted in either a suitable indoor or an outdoor environment. In case of outdoor testing there shall be no precipitation for the duration of the test. Immediately prior to the test commencing, wind speed shall be measured at a location which is no more than 5 m from the DUT and the average wind speed over 10 min shall be less than 28 km/h. It shall be ensured that the results are not affected by gusts of wind. Gusts shall not exceed 36 km/h when measured over a period of 20 s. Test set up should consider the impact of features such as shielding screens or walls which may create excessive funnelling affects during test execution.

The test should be carried out under the conditions as described in 6.1 with the following exceptions:

— charge the DUT to maximum permissible SOC from the battery management system, or a specific value of SOC as agreed between the customer and supplier;

— maintain the RESS temperature between 18 °C to maximum permissible operating temperature;

— maintain a humidity between 10 % and 90 %;

— maintain the atmospheric pressure between 86 kPa – 106 kPa.

For test procedure on vehicle or RESS level, necessary function of the thermal management, battery management and any other battery control systems, shall be operational during the test. For guidance for thermal cooling power estimation see Annex E.

In addition to those presented previously in this subclause, the following conditions should be met for this method:

— to ensure that the DUT is tested at the appropriate SOC according to this subclause, preconditioning of the DUT should be performed as follows

— discharge the DUT at a constant current of 0,2 It A, down to the specified final voltage

— charge the DUT to test SOC according to the method specified by the manufacturer.

NOTE 1 Charging and discharging currents for the tests are based on the value of the rated capacity (Cn Ah). These currents are expressed as a multiple of It A, where: It A = Cn Ah/1 h (see IEC 61434).

NOTE 2 The RESS which cannot be discharged at a constant current of 0,2 It A can be discharged at the current specified by manufacturer.

6.7.4 Evidence criteria of thermal runaway occurrence in target cell

6.7.4.1 Evidence criteria of thermal runaway occurrence in the target cell and other cells

For battery cells with an energy density of less than 130 Wh/kg, evidence of occurrence for thermal runaway during propagation test is provided if one of the following sets of criteria is met and last more than 3 s:

— temperature rise d*T*/d*t* >1 K/s and temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer;

or

— temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer with a rapid and distinct voltage drop;

or

— temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer with venting gas or smoke release at least one post disassembly analysis criteria in 6.7.4.2;

or

— temperature rise d*T*/d*t* > 1 K/s and venting gas or smoke release and rapid and distinct voltage drop.

For battery cells with an energy density equal to or greater than 130 Wh/kg, evidence of occurrence for thermal runaway during propagation test is provided if one of the following sets of criteria is met and last more than 0,5 s:

— temperature rise d*T*/d*t* >15 K/s and temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer;

or

— temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer with a rapid and distinct voltage drop;

or

— temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer with venting gas or smoke and at least one post disassembly analysis criteria in 6.7.4.2;

or

— temperature rise d*T*/d*t* > 15 K/s with venting gas or smoke release and a rapid and distinct voltage drop.

NOTE The energy density of a cell is calculated according to IEC 62660-1:2018, 7.6.3.1.

Rapidly changing technologies will require adjustment of the above given parameters, because the parameter 130 Wh/kg to distinguish large or small energy densities of cells has been determined from existing data.

6.7.4.2 Post-test disassembly analysis observations

The following indicators can be considered as supportive evidence of occurrence for thermal runaway:

— occurrence of ejected solid material;

— failure of the BMS or signal faults (if the BMS is still active). Logged faults in the BMS shall be analysed. Thermal runaway indicators shall be specified and documented if required.

The following indicators are post-analysis criteria as evidence of whether a thermal runaway has occurred in the target cell and whether this has resulted in thermal propagation in the RESS or RESS subsystem:

— mass loss greater than its electrolyte mass of the initiated cell;

— RESS or cell rupture;

— RESS deformation;

— material formation indicating high temperatures (e.g. molten and re-solidified aluminium or copper);

— specific reaction products such as e.g. metallic nickel or cobalt, lithium-aluminium oxide;

— current collector foil absence (partial or total);

— thermal decomposition of polymer materials, e.g. separator, isolation material.

6.7.5 Data recording and measurement

6.7.5.1 General advice

Unless otherwise specified in the test methods, the information, documents and data as listed in 6.7.5 shall be provided. Measurement accuracy mentioned in this document shall apply.

6.7.5.2 Recorded data and measurements

The following information shall be recorded during the test, during the observation period and shall be presented in the test report.

All data measurement systems shall be referenced to the same starting time and shall be recorded for an observation period of at least 1 h.

At the RESS and RESS subsystem level the following information shall be recorded:

— identification of test method, chosen trigger method and description of test setup used;

— test conditions (e.g. ambient temperature, SOC, other pre-conditioning parameters);

— battery management system live-data, if available (e.g. single cell voltages, temperatures, isolation faults, other warnings) recorded at a rate that matches the systems' maximum output rate;

— temperature of the target cell [°C];

— temperature of one adjacent cell (if possible);

— independent measurement of DUT voltage as a function of time and if possible, include the BMS pack voltage for comparison;

— voltage of the target cell (if possible);

— video and audio recording including indication of a time stamp of any observable system state change during test (such as defined in 6.7.5.3);

— condition of DUT at the end of test supported by photographs (before and after test) or video;

— temperature of vented gas [°C] exiting the RESS;

— attach thermocouples, not only on the initiation module, but also on the surfaces of adjacent modules, if possible, to observe thermal propagation between modules;

— additional temperature measurement with distributed sensors at the battery surface and at the venting port (if applicable);

— at the end of the test measure the isolation resistance on RESS or RESS subsystem level.

At the vehicle level, the information recorded shall be the same as the RESS level in addition to:

— warning indications or alarms to vehicle occupants.

The following data may be provided as additional information:

— infrared temperature video,

— weight loss of target cell,

— multi-gas measurement inside the vehicle for relevant flammable and toxic gases e.g. CO, H_2, CH_4 and VOCs levels by agreement between customer and supplier. In that case, the measurement method and result shall be reported.

NOTE It is possible to stop the test before the observation period at any time for the safety of personnel and test facilities.

6.7.5.3 Test events and outcome description

During the test, observation of at least the occurrences of the following events should be noted:

— deformation,

— venting,

— leakage,

— smoking,

— rupture,

— fire,

— explosion.

Table 10 can be used for guidance to report the test outcome.

Table 10 — Possible test outcomes

Scenario	Description	Effect
0	Target cell was not triggered to thermal runaway by the chosen trigger.	
1	Target cell thermal runaway was successfully initiated by chosen trigger method.	There is no thermal event of target cell. System controls and mitigations have stabilized the cell.
2	Target cell thermal runaway was successfully initiated by chosen trigger method.	Thermal runaway occurs in target cell, but there is no propagation to adjacent cells.
3	Target cell thermal runaway was successfully initiated by chosen trigger method. Propagation is observed.	Target cell is destroyed by thermal runaway. Propagation occurs in adjacent cells but does not spread beyond cell-block or module.
4	Target cell thermal runaway was successfully initiated by chosen trigger method. Propagation is observed.	Target cell is destroyed by thermal runaway. Propagation occurs in adjacent cells, cell-blocks or modules but is arrested so that no full pack thermal propagation occurs.

Table 10 *(continued)*

Scenario	Description	Effect
5	Target cell thermal runaway was successfully initiated by chosen trigger method. Propagation is observed.	Target cell is destroyed by thermal runaway. Propagation occurs in adjacent cells, cell-blocks or modules but is not arrested so that full pack thermal propagation occurs.

6.7.6 Triggering of the DUT through an internal heater

6.7.6.1 Introduction and method specification

This test method relies on an internal, localized short circuit inside the cell created by a local heater. The purpose of this test is to create a thermal runaway through the creation of a hole in the separator of the triggered cell. The hole comes from the local melting of the separator induced by the local heater.

6.7.6.2 Test description

6.7.6.2.1 Trigger method description

The heater is a resistor made of a tungsten flat spiral (Figure 5). The coil is wrapped in one layer of separator with similar melting temperature as the cell separator.

The important parameters of the resistor heater are

— thickness of heating filament: see Figure 5,

— resistance: (200 ± 5) mΩ,

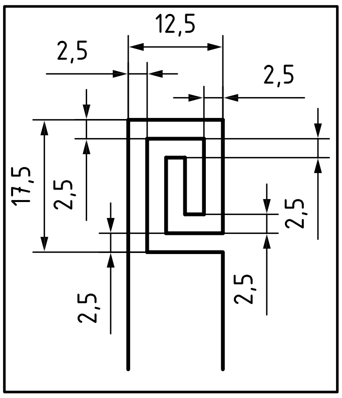
— heating power: from 50 watts to 200 watts between 10 s and 120 s to the cell,

— the entire heating area shall be located on the separator.

The resistance, power and duration shall be adjusted according to the electrochemistry and the size of the cell.

NOTE Energy is only released in the tungsten portion of the device since the external leads do not generate significant heat and, therefore, this additional energy does not influence the outcome of the test.

Dimensions in millimetres



NOTE The wire diameter is usually 0,1 mm to 0,3 mm.

Figure 5 — Example of an internal heater flat spiral of tungsten

6.7.6.2.2 DUT preparation

The heater is inserted in the connected electrode stack or jelly roll before cell sealing with the following steps. These steps are adapted for cylindrical and prismatic cells. A similar internal heater can be used for pouch cells with an adapted sealing principle.

Step 1: Two holes are drilled into the cover to allow the electrical feedthrough of the heater from inside the cell to the outside (Figure 6).

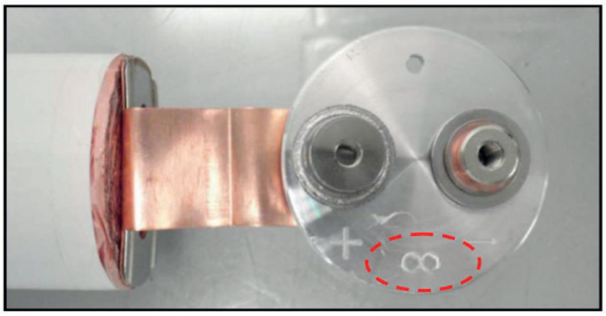
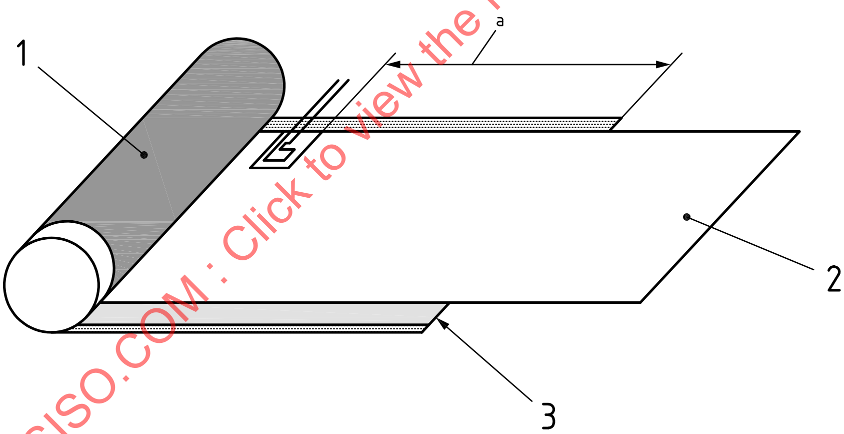


Figure 6 — Example of specific holes in cover for heater connection

Step 2: Unroll the separators and the electrodes to insert the heater.

Step 3: Locate the heater on the last wrap of electrode (Figure 8). The heater should be placed between the outermost negative and positive electrodes for the cell, if possible (see Figures 7, 8 and 9). The location should be determined between the customer and supplier.

Avoid unrolling a larger part of the jelly roll, since this can lead to damage of the jelly roll. Use an outer stack in case of stacked layers.



Key

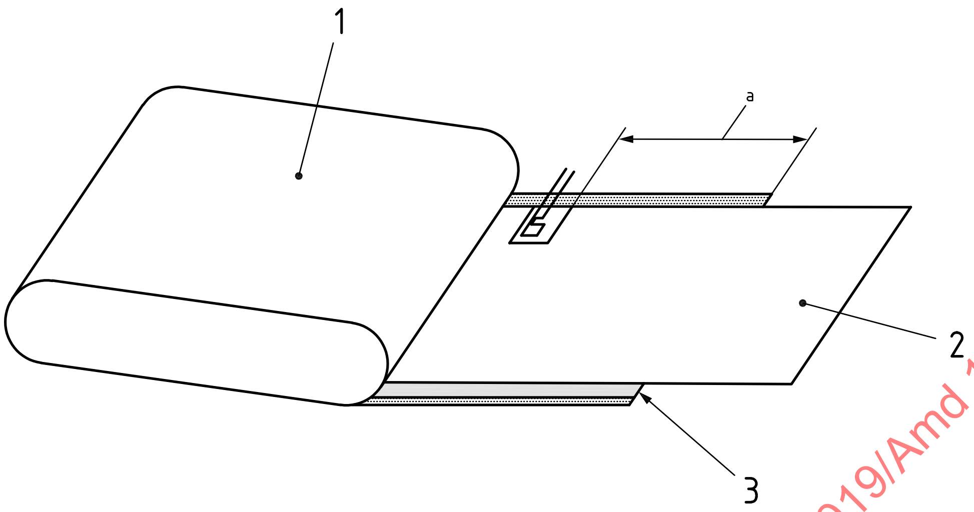
1 positive electrode

2 separator

3 negative electrode

[a] 180 mm from end of positive electrode and 15 mm from end of negative electrode, tolerance ±5 mm.

Figure 7 — Example of heater location inside the cylindrical cell



Key

1 positive electrode

2 separator

3 negative electrode

a 180 mm from end of positive electrode and 15 mm from end of negative electrode, tolerance ±5 mm.

Figure 8 — Example of heater location inside the prismatic cell

Figure 9 — Example of heater located on the last lap of negative electrode

Step 4: Wind the jelly roll with the heater (see Figure 10).

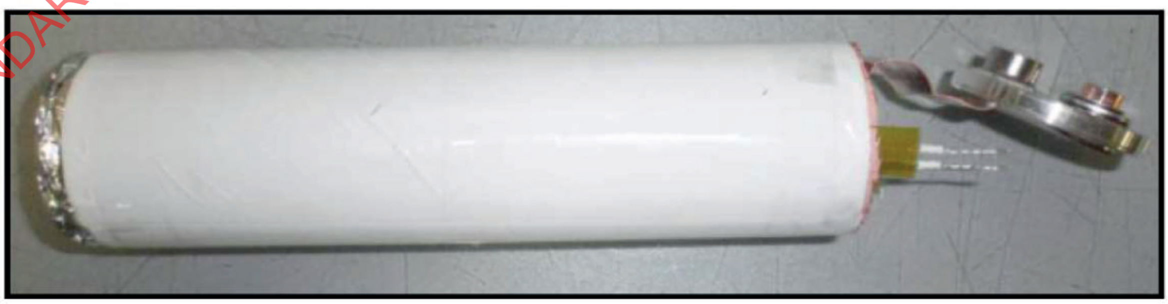


Figure 10 — Example of jelly roll equipped with heater

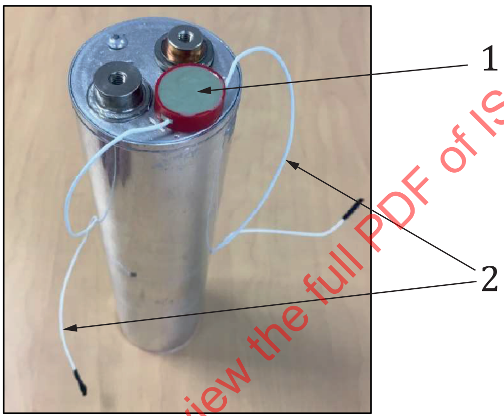
Step 5: Insulate the heater supply wires from the other parts of the cell. They are directed through the specific holes in the cover (see Figure 11). Assemble the lithium-ion cell according to standard manufacturing processes (e.g. electrolyte filling, cover welding).

All wires used in the RESS or RESS subsystem shall be electrically isolated. Furthermore, it should be ensured that no electrolyte or gases can leak out through the space between the wire strand and the wire insulator.

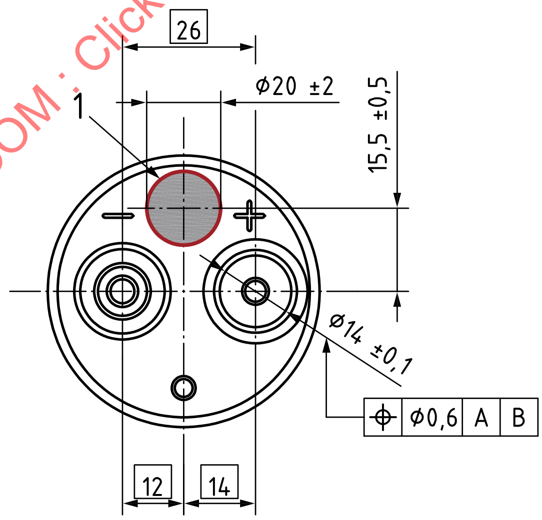
Selection of resin is critical as the strength of seal shall be greater than any installed vent of the cell. Furthermore, it should be ensured that no electrolyte or gases can leak out through the space between the wire strand and the wire insulator.

After cell cover welding, obtain the final sealing of the cell by adding a resin at the interface of the heater supply wires terminals and the cover. Perform the formation of the prepared cell in a designated chamber for that particular purpose. Ensure the sealing of the hole in the cell by using a resin (e.g. epoxy glue). After it is completely dry, carry out a helium test to check the sealing before filling the cell with electrolyte (see Figure 12).

NOTE 1 When the helium test is successful, cells are ready to be filled and formed.



a) picture



b) illustration

Key

1 resin for sealing of the heater supply

2 supply wires of the heater

Figure 11 — Example of finished cell with heater

Figure 12 — Example of cell before filling with electrolyte

Assemble the prepared cell inside the RESS or RESS subsystem according to the standard configuration.

If the modified cell is integrated into a RESS subsystem, without connecting wires (temperature sensor and internal power supply), some module modification may be necessary. Create a hole with sufficient diameter on the RESS or RESS subsystem case for all wires, thermocouple, voltage sensor, and so on. Fill in the hole of an initiation module with heat-resistant resin to prevent the inflow of oxygen or flame to escape from the hole during the test.

Connect the heater terminals by a dedicated connection box to the power supply.

Re-assemble and seal the DUT. Connect all wires of the heater, thermocouples and voltage sensors to the outside of the RESS or RESS subsystem though a hole in the RESS casing and seal the holes with heat-resistant resin (see Figure 13).

a) internal view

b) external view

Figure 13 — Example of RESS sub system with target cell

NOTE 2 In Figure 13 b), the circle indicates where the wires of the heater of the thermo-couplers are connected to the RESS.

6.7.6.2.3 Test procedure

The test procedure consists of the following steps:

— checking and connecting the heater;

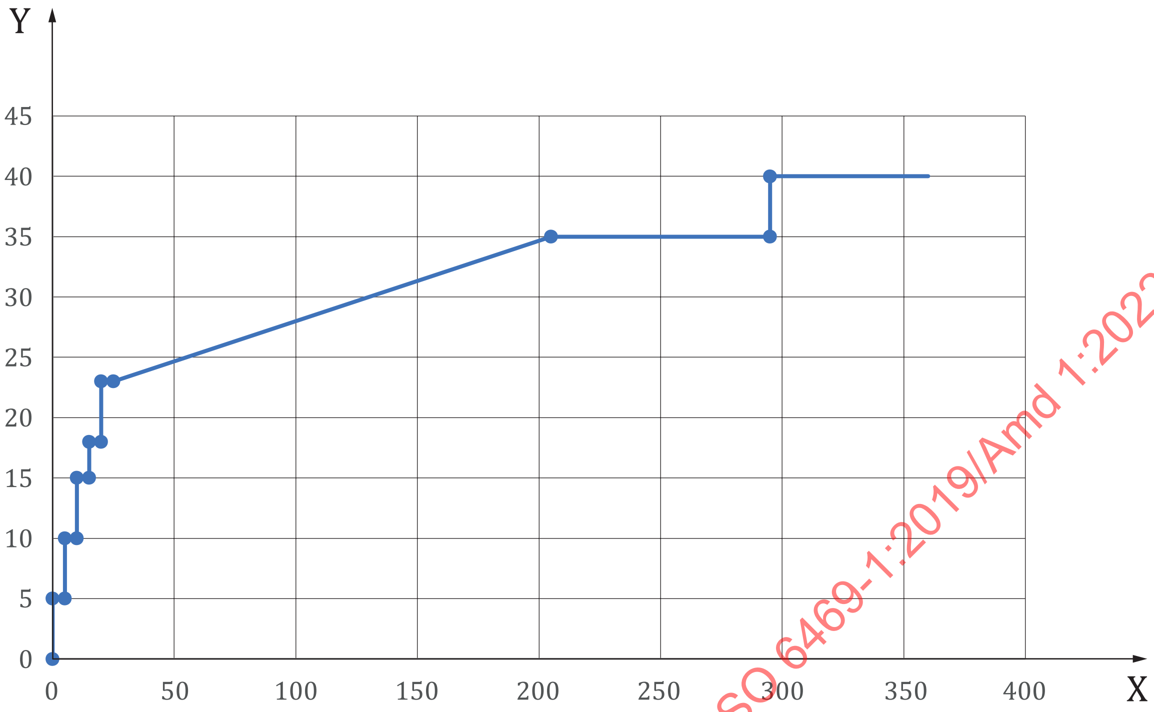
— checking heater resistance;

— applying the heater current profile specified in Table 11 and Figure 14 until thermal runaway;

— discontinue the heating sequence when thermal runaway has been confirmed according to the criteria in 6.7.4;

— continue the measurements until the cell temperature decreases to 60 °C.

NOTE Stepwise heating avoids breaking the heating wire.



Key

X time [s]

Y current [A]

Figure 14 — Current profile for heater

Table 11 — Current profile for heater

Time [s]	Current [A]
0	0
0	5
5	5
5	10
10	10
10	15
15	15
15	18
20	18
20	23
25	23
205	35
295	35
295	40
360	40

6.7.6.2.4 Data collection and recording specific to the method

Annex D provides an example for reporting and presenting test results.

In addition to those presented in 6.7.5, the following data should be collected for this method:

— heater power supply current [A];

— heater power supply voltage [V].

6.7.7 Triggering of the DUT through localized rapid external heating

6.7.7.1 Introduction and method specification

The DUT is a RESS, a RESS subsystem or a vehicle.

This test is performed by applying heat to the external surface of one target lithium-ion battery cell within the RESS via an external heater until thermal runaway is achieved with minimal increase in temperature of the adjacent lithium-ion battery cell(s) prior to thermal runaway within the target cell. The increase of temperature of adjacent cell(s), prior to thermal runaway in the target cell, shall remain below the maximum operating or storage temperature (whichever is higher) for the RESS. The native cooling strategy (if installed), battery control unit (BCU) and any other battery control systems, which are necessary for the test, shall be operational during the test. The heater selection, installation and operation shall be performed with minimal invasiveness to the original un-modified RESS and RESS subsystem operation. The test may be conducted at a vehicle level whereby the response of the vehicle level detection and/or safety system (warning symbols, alarms), tenability of the vehicle and effect on surrounding environment could be evaluated.

The method has the following two limitations.

1) The target cell shall have a sufficiently exposed surface area to mount the heating element on its surface. As such, some cell positions within a RESS may not be suitable for potential target cells. Significant modification of the RESS to accommodate surface mounting of the element for a given cell position may alter the RESS functionality or its native safety system and may lead to an inaccurate result.

2) If the heating element is inserted between two cells, then thermal runaway may be initiated in two cells simultaneously unless sufficient thermal insulation or barriers are added that does not impede natural RESS functionality.

6.7.7.2 Test description

6.7.7.2.1 Trigger method description

The trigger method applies a high-powered heat pulse, locally, to the external surface of the target lithium-ion cell. The successful implementation of the method requires the application of sufficient power to the chosen heating element to achieve, at a minimum, the set temperature, but it shall also not apply so much power that there is a premature heating element failure nor a side wall failure of the target cell prior to thermal runaway.

This method has been demonstrated to provide high reproducibility and high repeatability for initiating single cell thermal runaway within the RESS system and sub-systems. The heating device should be a resistive heating element, or other suitable heating device/technology capable of delivering the target parameters. Target parameters for the heating element are listed in Table 12. Table 12 was developed using pouch, prismatic and cylindrical cells designed for application in electrically propelled vehicles using high energy lithium-ion battery chemistries. Different battery chemistries or cell type choices (especially large prismatic cells) require variations to the target parameters.

Since thermal runaway conditions will be different for each cell type/chemistry/cell construction, etc., the test method shall be tailored based on those cell properties, such as capacity, format and chemistry.

These adjustments may be established through single-cell/small group of cells characterization testing (see 6.7.7.3.1) using the chosen heating device. External heating methods that do not meet the listed criteria may have significant deficiencies (adjacent cell heat up, significant RESS or RESS subsystem modifications, activating RESS level safety mechanisms to prevent thermal excursions/runaway).

Table 12 — Heating element selection guide – Target Parameters

Parameter	Value	Reasoning
Heating element material	Ni-chrome with an isolating barrier or another suitable resistive heating material	Achieve high temperatures and prevent element failures Isolating material may include alumina, ceramic, or fiberglass.
Thickness [mm]	<5	Minimize introduction of foreign objects, some RESS designs may require a thinner heating element.
Area	As small as possible, but no larger than 20 % of the surface area of the targeted face of the target cell	Concentrate heat to the smallest feasible area on the cell surface.
Heating Rate [°C/s]	≥15	Similar to heating rates observed within thermal runaway conditions to minimize adjacent cell or RESS preheating. [a]
Maximum heater temperature [°C]	100 °C > chosen heater setpoint temperature	Heater shall maintain integrity at the chosen operating temperature and take into account temperature deviations from heater element to thermocouple upon application of high power. [b]
Control method for heater	Thermostatic closed loop	Avoids undesirable test results, such as heating element burnout, elevated heating element temperature, battery cell sidewall ruptures due to high element temperature. [c]

[a] Ideally the heating rate is measured directly by a thermocouple on the chosen heater.

[b] This temperature may need adjustment for other chemistries and potentially other cell construction techniques (cell sidewall ruptures).

[c] Using a low voltage power source for the heating element will require higher currents (thicker wires), while a higher voltage source will require more resistant isolating material and higher levels of user safety while implementing the test.

6.7.7.2.2 DUT preparation

The DUT may be the full RESS, the RESS subsystem or the in-vehicle RESS with minimum modifications to the original un-modified DUT. Defined cooling/safety strategy and the battery management system used within the RESS and RESS subsystem shall be fully operational. The coolant flow could be null or active depending on the BMS. Any manipulation of RESS components, such as thermal barriers, cooling plates/channels, electrical connections, and cell to cell spacing shall be kept at a minimum and be reported. As the localized rapid heating method is externally activated, some minimal level of modification may be tolerated, but the original sealing capability of the RESS shall not be compromised through the introduction of the heating element.

For minimum modifications, all cell connecting busbars, tab welding, safety relevant components, BMS software should be maintained and un-compromised within the DUT according to their delivery stage.

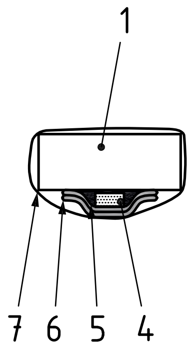
The installation of the chosen heating element should only modify the RESS by permitting electrical and thermocouple connections to the heating element. These connections shall provide greater seal integrity than the other connectors in the RESS.

Any leakage in the pack shall be through the pre-existing seals rather than through the connections for the chosen heating element or sense wiring.

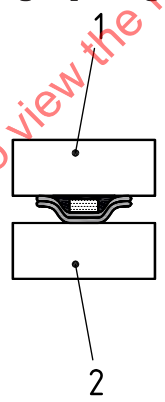
Instrumentation of the RESS or RESS subsystem shall also be kept at a minimum.

The chosen heating element shall be set to avoid contact to any RESS assembly surface except for the target cell. Intimate thermal contact between the heating element and the target cell surface is important for the successful application of this method. Thermal contact between the heating element and target cell may be improved through various methods [avoiding air gaps, addition of a heat transfer paste and applying pressure (which should be maintained throughout the test)].

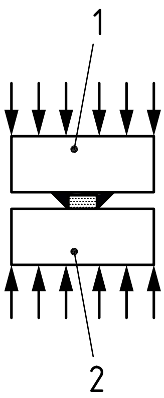
A sample of potential heater application methods are shown in Figure 15 and the applied method is dependent on the RESS or RESS subsystem design. In many cases, there is insufficient clearance to adequately thermally insulate the cells adjacent to the target cell, moreover the addition of insulation may have more disadvantages (additional foreign material may interfere with the RESS designed clearances and thermal management) than advantages (more realistic single-cell thermal runaway initiation). Maintain a contact pressure for the heating element on the target cell during the test to ensure contact and optimal heat transfer, see also Figure 15.



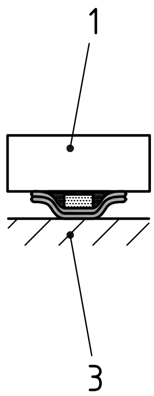
a) RESS with large spacings between cells



b) centre cell fixed spacing (e.g. prismatic cells)



c) centre cell compressed modules (e.g. pouch cells)



d) edge cell

Key

1 target cell
2 adjacent cell
3 battery enclosure wall
4 heating element
5 heat transfer paste
6 ceramic paper
7 wire or high-temperature tape

Figure 15 — Methods to apply pressure on the heating element to maintain heating element contact to target cell throughout the test

For selection of key 3 in Figure 15:

a) heating element may trigger two thermal runaway events simultaneously (or nearly simultaneous) and should only be selected if other options are not feasible; and

b) a thermal insulator on the adjacent cell could be used as long as it does not influence the native thermal management system of the RESS.

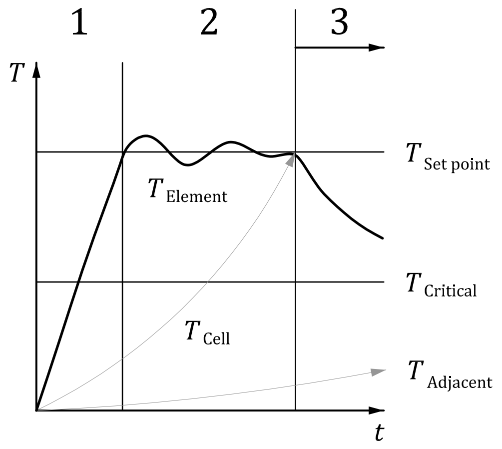
For implementation in vehicle level tests, the vehicle should be agnostic to the insertion of this trigger method into the RESS, any pass required through the vehicle body should be minimized.

NOTE 1 Nickel plated brass IP68 cable glands provides suitable sealing in most applications.

NOTE 2 Using a heat transfer paste having a thermal conductivity of >2 W/(mK) with an operating temperature >500 °C, while applying pressure of approximately 20 kPa usually provides good results.

6.7.7.2.3 Test methodology

The heating methodology shall follow the following temperature/time profile:



Key

1 phase 1 ramp

2 phase 2 soak

3 power off

NOTE This is a sample profile for the localized rapid external heating test methodology. The thermal runaway of the target cell occurs during the ramp or soak phase in the actual test.

Figure 16 — Heating methodology profile for the localized rapid external heating test

A temperature controller (i.e. thermostat) should be utilized to track the temperature/time profile as shown in Figure 16 via closed loop control. This approach necessitates the inclusion of a heating element temperature sensor, ideally located on the heating element. Temperature feedback minimizes undesirable test results such as element burnout and cell sidewall failures.

Parameters to use with this test methodology for typical lithium-ion battery cells for electric vehicles are shown in Table 13 as a guideline. The customer and supplier shall agree on specific values. Heating element setpoint temperature is dependent on cell chemistry, and manufacturing design and shall be above the critical temperature which is necessary to initiate thermal runaway reactions. The heating rate and soak times are dependent on the thermal conductivity of chosen cell and its design/chemistry. Measures shall be taken to ensure a maximum heat transfer effectiveness into the cell, such that there is a minimum time and minimum total energy input into the system to achieve a single cell thermal runaway. The maximum time allowed for the first thermal runaway event shall be agreed between the manufacturer and the test lab (see soak time in Table 13). The effect of the heat generated by the heating element on the adjacent cells or chosen RESS architecture shall be minimized and shall be lower than the maximum operating temperature of the RESS or RESS subsystem.

NOTE It is anticipated that RESS designs using a cell with a thicker cell wall will require a longer soak time than those RESS designs using cells with a pouch bag design.

Table 13 — Typical heater parameters for implementation of localized rapid external heating methodology

Parameter	Pouch cell	Cylindrical 18650/ 21700	Prismatic[a]	Remarks
Heating rate of the element [°C/s][b]	15 to 50	15 to 25	10 to 25	These values are based on: 1. heat capacity/mass/ volume of the target cell (including cell wall material choice/thickness and internal components); 2. thermal resistance, yield strength and melting point of cell wall; 3. installation effectiveness (heat transfer paste, applied contact pressure) throughout the test.
Set point [°C][c]	500	350	600	
Soak time phase and power off condition	Heating until thermal runaway is achieved or until total energy input into the heater exceeds 20 % of target cells' maximum rated energy.			Heating until thermal runaway is achieved within 5 min. If any active REESS safety system is inoperable, prior to conducting the test, it is not necessary to agree upon a maximum time limit.

a For large volume and/or thick-walled cells, the relative heating area may need to be increased, due to the constraints on the maximum set point, but should not be increased beyond the value listed in Table 9.

b It is important to note that heating rate is dictated by the chosen heating element and controller capabilities (rapid temperature feedback). It is preferable to use as high a heating rate as possible but to not exceed set point temperature by more than 10 %.

c Measurement should occur directly on the element and that at high heating rates/applied power the hottest point on the element may not be at the measurement point for some element designs.

6.7.7.2.4 Test procedure

Carry out the following steps to implement this method at the RESS level.

- Configure and prepare the heating element to initiate the setpoint temperature, heating rate and soak time (see 6.7.7.2.4, Table 12).
- Begin recording temperature and battery management system data.
- Begin sending power to the heating element.
- Open relay to heater after:
  - a predetermined maximum heating period, or
  - a total energy input to the heater that is >20 % of target cell energy, or
  - after 5 min of heating if any active system is inoperable (for example cooling), or
  - earlier, based on thermal runaway detection criteria in the target cell given in 6.7.4.
- If a thermal runaway reaction occurs:
  - monitor and observe until the maximum temperature of all temperature measurements, drops below 60 °C, then continue recording for an additional 1 h.
- If a thermal runaway reaction does not occur:
  - monitor and observe for a minimum of 1 h.

Carry out the following steps to implement this method at the vehicle level.

- Instrument the RESS as outlined above and connect all cooling/communication and high voltage lines and reinstall RESS into vehicle.

- Connect to CAN-bus or other vehicle monitoring system to collect data about battery management system.
- Install video camera inside vehicle cabin to record video (dashboard/information screen) and audio (warnings) from vehicle during test if applicable.
- Perform multi-gas measurement according to 6.7.5.2 if applicable.
- Turn vehicle “on”.
- Begin recording temperature and battery management system data.
- Begin sending power to the heating element.
- Open relay to heater after:
  - a predetermined maximum heating period, or
  - a total energy input to the heater that is > 20 % of target cell energy, or
  - after 5 min of heating if any active system is inoperable (for example cooling), or
  - earlier, based on thermal runaway detection criteria in the target cell given in 6.7.4.
- If a thermal runaway reaction occurs:
  - monitor and observe until the maximum temperature of all temperature measurements, drops below 60 °C, then continue recording for an additional 2 h.
  - external vehicle/RESS temperatures may be viewed through IR cameras.
- If a thermal runaway reaction does not occur:
  - monitor and observe for a minimum of 2 h.
- Turn vehicle “off”, wait 24 h with remote monitoring of test vehicle to ensure no further thermal reactions.

6.7.7.2.5 Data collection and recording specific to the method

In addition to those presented in 6.7.5, the following data should be collected at the RESS and vehicle levels for this method:

- heating element temperature,
- target cell temperature,
- current and voltage of the target cell during heating.

6.7.7.2.6 Method specific test conditions

In addition to those presented in 6.7.3, the following condition should be met for this method:

- maintain heating element contact pressure to the target cell before thermal runaway.

6.7.7.3 Test application and necessary modifications

6.7.7.3.1 Subsystem level testing

The use of this test method relies on quickly and effectively heating up a single cell into thermal runaway within a RESS and RESS subsystem. To ensure the test is conducted efficiently, a preliminary test on a single cell or a small number of cells should be performed using a modified cooling strategy (if desired). This subsystem level test permits the refinement of test parameters (heating rate, target temperature, dwell time) for the specific cell used in the chosen RESS design, which vary (from those shown in Tables 12 and 13) upon change of cell chemistry and cell size/construction. A subsystem test also refines the trigger method placement within the chosen RESS cells. Modifications required for subsystem level testing should mimic those found in the RESS to obtain an accurate test result relative to that obtained at a RESS test level. Any subsystem level testing should follow the guidelines presented in 6.7.7.2.2 to 6.7.7.2.4 for cell selection and modifications such that they may be implemented during subsequent RESS and vehicle level tests. It is important that any subsystem level test replicate the configuration, orientation, thermal conditions of the potential future RESS/vehicle level test.

6.7.7.3.2 RESS testing

The RESS testing with this method shall be performed with all necessary RESS systems under full operation, especially if that component potentially contributes to thermal propagation performance. The native cooling strategy within the anticipated vehicle shall be duplicated in RESS or RESS subsystem testing to achieve meaningful and comparable test results.

NOTE It is not clear how the results of a test at RESS level convey to a full vehicle test as the boundary conditions vary.

Any modifications to the RESS enclosure shall provide the same (or better) sealing capability that the original unmodified RESS.

6.7.7.3.3 Vehicle testing

Conducting this test while the vehicle is "on" and a trigger method which does not affect the vehicle system, permits the validation of all systems towards a single cell thermal runaway event. The test may also be performed with the vehicle in "off" mode to investigate what occurs in that mode. Other vehicle modes such as driving, parked, charging may be explored with this method to determine the variability in vehicle response with operating mode. The critical warnings for tests run at a vehicle level are warnings associated to the RESS system, other vehicle warnings (if they appear) are not the focus of this test.

6.7.8 Triggering of the DUT through nail penetration

6.7.8.1 Introduction and method specification

This test describes the nail penetration of a target cell in a DUT to observe the potential for thermal propagation. The position of the target cell shall be at the most vulnerable position in the RESS or RESS subsystem. The aim of the nail penetration is to bring the target cell into a thermal runaway to release its electrical and chemical energy.

To achieve this result, it is necessary to have knowledge about the dependency between the penetration parameter and the behaviour of the cell with respect to the thermal environment and mechanical compression of the cell. If this knowledge from previous cell tests is not available, it is recommended to carry out preliminary tests at cell level with the thermal and mechanical boundary conditions corresponding to the pack conditions. The result and the parameters shall be documented. The aim is to find a set of parameters with which a short circuit is triggered between the electrodes and which, above a threshold, provides enough heat for self-reinforcing heat generation leading to a thermal runaway of the cell. Starting point for finding this parameter set shall be the range of the given values in Table 14.

6.7.8.2 Test description

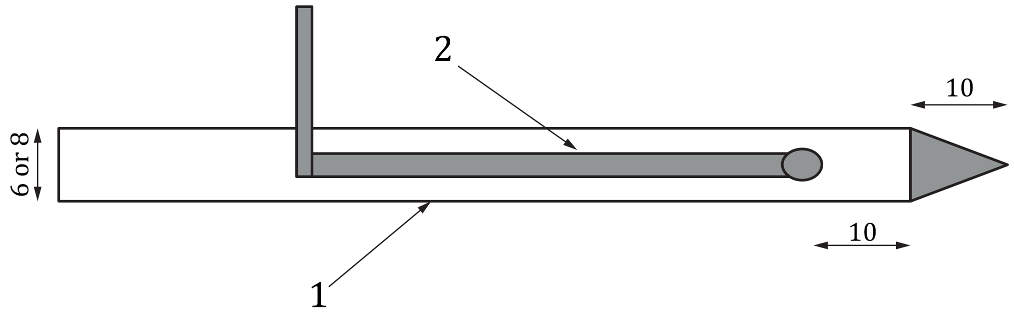
6.7.8.2.1 Trigger method description

Penetration shall be carried out using a solid steel or ceramic nail or hollow test rod with parameters as given in Table 14.

A hollow rod supports monitoring of the temperature profile within the target cell by an integrated temperature sensor during the TP test. The cables of the temperature sensor are rooted out through a drilled hole in the upper end of the shaft rod for clamping the test rod into the nailing machine, see Figure 17.

During the test, high temperatures are expected between the thermo couple and nail. Hence, use high temperature resistant material for the insulation of the thermal couple cable.

Dimensions in millimetres



Key

1 nail

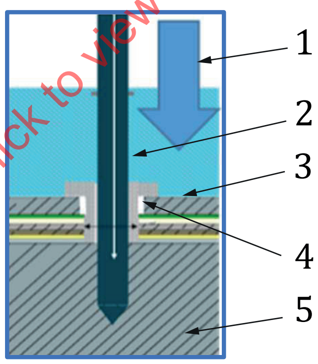
2 thermo couple

NOTE A screw thread at the lower end of the hollow rod allows usage of different nail tips with the desired geometry.

Figure 17 — Example of nail with integrated temperature sensor

6.7.8.2.2 DUT preparation

If the REES is enclosed in a housing, a sealed feed through shall be installed which enables the nail to be inserted into a cell inside the RESS. This non-conductive sleeve ensures a potential-free passage of the nail through the battery housing and provides a seal that prevents hot venting gas to leak out through the nail hole, see Figure 18. The sleeve also serves to guide the nail.



Key

1 feed direction

2 nail

3 RESS housing

4 non-conductive sleeve to ensure a leak tightness and galvanic separation

5 cell/cellblock

Figure 18 — – Example for test set-up

NOTE 1 Certain ceramics are non-conductive sleeve materials.

NOTE 2 Knowledge of the inner design of the RESS supports the placement of the sealed feedthrough correctly.

The DUT preparation consists of the following steps:

1) manufacture a test RESS with a provision for nail passage, respectively drill a hole into the battery housing;

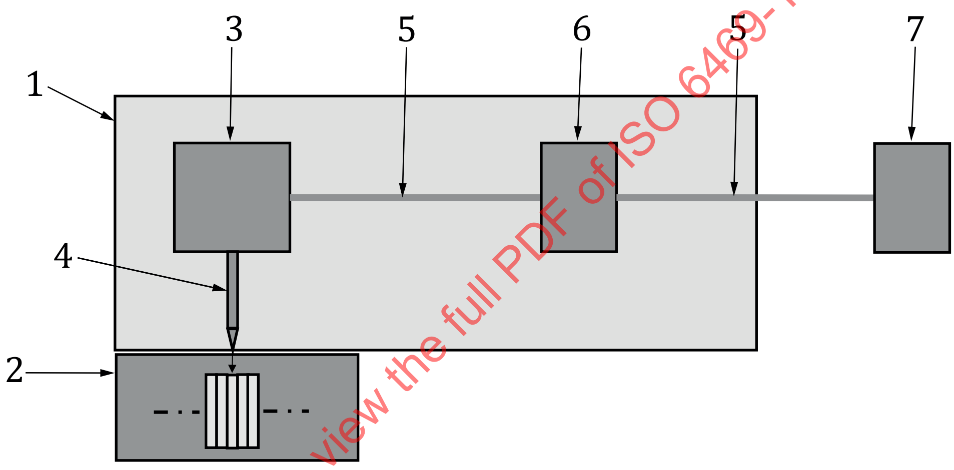
2) mount the non-conductive sleeve into the hole;

3) place the nail in the non-conductive sleeve and attach the nailing machine on the RESS housing;

4) seal the nailing machine to the RESS housing with high temperature resistant silicone.

6.7.8.2.3 Test methodology

The nailing apparatus inserts the nail into a cell inside the DUT. The nail is the trigger for the thermal runaway by initiating a cell internal short circuit. The nail feed can alternatively take place via an electrical actuator, hydraulic cylinder or pneumatic cylinder. Figure 19 provides a schematic structure of a pneumatic nail device.

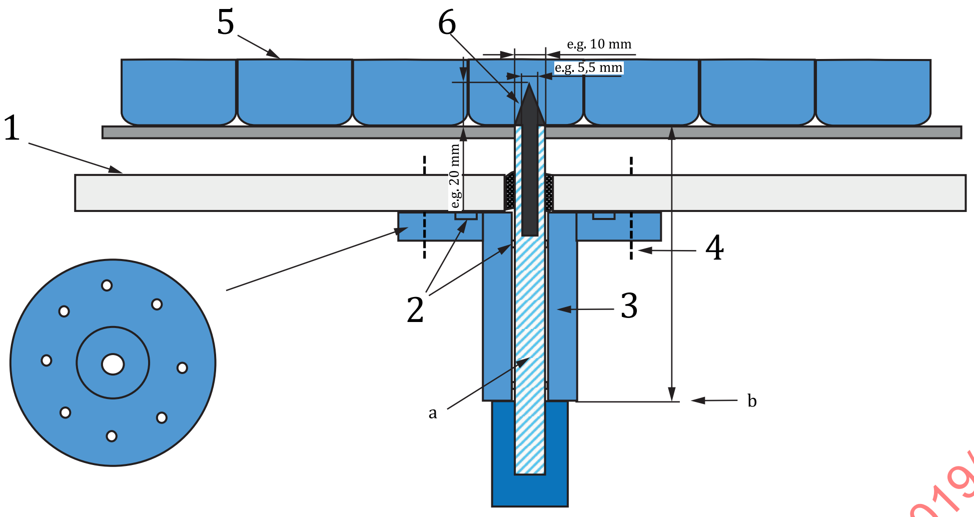


Key

1 nail device
2 RESS
3 pneumatic cylinder
4 nail
5 compressed air connection
6 control unit
7 compressed air supply

Figure 19 — Example for test apparatus

The nailing apparatus used to penetrate the target cell in the RESS shall be such that the nail stays thermally and electrically isolated during penetration, see Figure 20.



Key

1 storage housing
2 gas tight seals
3 guide sleeve
4 screw
5 cell
6 nail
[a] Heat and electrically insulating holder for the nail.
[b] The position of the stop defines the nail penetration depth.

Figure 20 — Example of test setup

NOTE 1 Isolation limits the heat dissipation via the nail and ensures that no additional current path is created between the interior of the penetrated cell and a common ground.

Penetration shall be done by using a nail as described above. The orientation of penetration shall be perpendicular to the largest cell surface area for pouch and prismatic cells. For cylindrical cells the orientation of the penetration shall be perpendicular to the jelly roll.

The x and y-position, perpendicular to the penetration direction of the nail, shall be selectable and fixable, in order to assure the intended location of penetration with respect to the DUT and the trigger-cell. The penetration position on the DUT shall be representative of worst-case heat dissipation from the cell.

The penetration velocity shall be selectable within the planned range by an appropriate control of the z-drive. The z-position shall be limited to the intended penetration depth. This can be achieved by an adjustable mechanical stop or an appropriate drive control. After reaching the intended penetration depth, the nail shall be held in its z-position and remain there until it is deliberately removed after the test has been completed.

The test parameters in Table 14 shall apply.

Table 14 — Test parameters

Parameter	Values	Advices and explanations
Nail diameter	3 mm to 10 mm	Diameter of solid nails: 3 mm. Hole diameter for hollow test rods with integrated temperature sensor: 6 mm to 8 mm. Diameter influences the TR initiation and TR reaction of triggered cell.
Shape of nail tip	conical tip flat bladed tip cross tip	To ensure that the penetration of the test rod leads to an internal short circuit, different shapes of the tip are possible. Conical tips are advantages if the penetration is perpendicular to the electrode plates. Whereas flat bladed or cross tips are advantages if the penetration is parallel to the electrode plates and blades are perpendicular to electrode plates. At least one blade of the flat bladed tip or cross tip shall be perpendicular to the electrode plates.
Rate of penetration	0,01 mm/s to 80 mm/s	The rate of penetration influences on the TR initiation and TR reaction of the triggered cell.
Penetration depth	The nail shall be stopped when thermal runaway is achieved or when reaching the target penetration depth. Target penetration shall be: 1. cells with J/R's: 50 % of the thickness of one J/R. 2. cells with stacked electrodes: a) perpendicular: 50 % of the sub stack thickness if the stack is subdivided or 50 % of the total thickness if the stack is not subdivided. b) in plane: 15 mm measured from the cell housing surface.	The penetration depth influences on the TR initiation and TR reaction of the triggered cell.
SOC of DUT	≥ 95 % of the operating window of the RESS	

NOTE 2 To get valuable results, a higher number of DUT per test is useful. RESS as DUT can be used to improve expressiveness.

6.7.8.2.4 Test procedure

The thermal propagation test consists of the following steps:

1) prepare and precondition the DUT;
2) check DUT and the state of the signals;
3) place the DUT in test bench;
4) start data acquisition and CAN-measurement;
5) set DUT in active driving possible mode (connectors in closed state);
6) start nail moving according to the manual of the operating nail device;
7) observe the DUT described in 6.7.5.2.

6.7.8.2.5 Data collection and recording specific to the method

Data should be collected as presented in 6.7.5.

6.7.8.2.6 Method specific test conditions

When thermal runaway of the target cell occurs or the pre-defined penetration depth is reached, stop the nail immediately and let it stay in its final position in the cell. The DUT shall be observed for the observation period described in 6.7.5.2.

The penetration shall not affect cells adjacent-to the target cell, i.e. the nail shall not penetrate or dent adjacent cells. The test is finished after the system does not show any thermal activity.

NOTE Heat dissipation through the nail is negligible in relation to the heat released during thermal runaway reaction of the cell.

Clause 7

Add a Clause 7 as follows:

7 Guideline for demonstration of thermal propagation risk mitigation

7.1 General

7.1.1 Purpose

Safety is one of the key elements of automotive development. With the trend of increasing technological complexity, software content and mechatronic implementation, there are increasing risks from systematic failures and random hardware failures. A lithium-ion based RESS for propulsion of electrically propelled road vehicles is an example of a complex technological system which implements electrical, electronic, software as well as electrochemical components.

This methodology demonstrates thermal propagation safety performance and risk mitigation for a lithium-ion RESS used for electric vehicle propulsion. The objective is to identify and evaluate the risk of thermal propagation within a RESS/RESS subsystem due to thermal runaway caused by internal short circuit of a single cell and to demonstrate that appropriate and reasonable measures have been taken to eliminate hazards when possible and to mitigate harm for persons at risk.

A systematic work process is applied, which comprises a defined sequence of steps that shall be performed and documented in a comprehensive and transparent manner to develop a safety case for thermal propagation of the RESS.

7.1.2 Methodology

System safety is achieved through a number of safety measures, which are implemented in a variety of technologies and applied at the various levels of the development process.

This systematic approach involves applying a structured methodology of risk assessment and hazard analysis, allocating the root causes and effects to appropriate components and/or functional units in the RESS and defining the required safety performance characteristics of the system. Iterative looping between the product development steps and the performance verification steps will ensure that the identified risks are addressed, and counter acted by appropriate mitigating measures at different levels in the system.

Figure 21 shows the steps involved in developing the safety case for thermal propagation of the RESS. The manufacturer shall document product robustness in the event of an internal cell failure based on knowledge of cell and RESS behaviour to such an event in the vehicle application. Risk mitigation is achieved by appropriate product design and manufacturing controls.

A quality system shall be in place for the whole RESS development process.

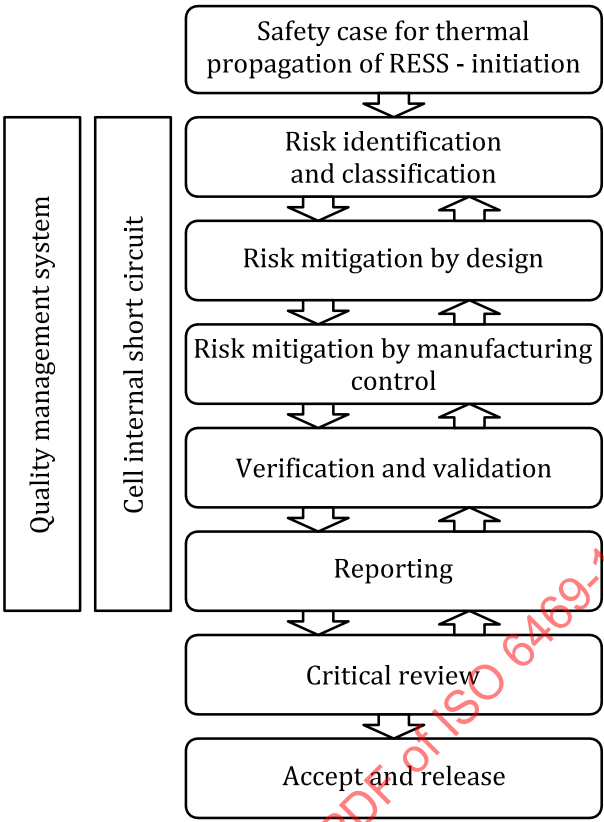


Figure 21 — Developing the safety case for thermal propagation of the RESS

The safety case for thermal propagation of the RESS does not include faults in cell and RESS electronics since these belong to the scope of the ISO 26262 series. The results of the safety case from the ISO 26262 series regarding the BMS can feed into the safety case for thermal propagation of the RESS, when appropriate, to demonstrate RESS level safety against effects of thermal propagation.

7.2 Contents of safety case for thermal propagation of the RESS

7.2.1 Description of the lithium-ion RESS

A system diagram of all relevant physical systems and components of the RESS shall be provided, including information about the cell type and electrical configuration, cell chemistry, electrical capacity, voltage, current limits during charging and discharging and thermal limits of the components, e.g. cells, that are critical for thermal propagation safety.

7.2.2 Operational description of functional units

A diagram showing the functional operation of relevant systems and components and their inter-relationships shall be provided.

An explanation shall be included regarding which functions and unit processes are included in the thermal propagation safety demonstration and to which level of detail they are studied.

The RESS and functional units included in the assessment can be related to the limits of the expected energy and/or material transport paths, for example, the paths vented gases will take, based on the system design and component layout. These boundary conditions shall be explained and justified.

7.2.3 Allocation procedure

The study shall identify conditions that may result in internal short circuit and thermal runaway of a single cell and allocate them to appropriate components or functional units within the system. The associated preventive and/or mitigating functions and/or actions adopted by the RESS and/or vehicle to manage thermal propagation should also be identified.

7.2.4 Data sources and quality requirements

The data set shall evaluate performance of the components and functional units that have been identified in the allocation process. The relevance and appropriateness of the data shall be described and justified.

Data may comprise of technical specifications and verifying test reports from suppliers, mathematical simulations from theoretical or empirical system models, scientific reports and publications, field data and laboratory tests. Measured data are preferred with respect to calculated and estimated data as long as measured data are technically obtainable.

Major uncertainty factors should be identified and quantified as far as possible.

The data quality requirements should address the following:

a) precision: measurement of the variability of the data values;

b) completeness;

c) representativeness: qualitative assessment of the degree to which the data set reflects the true performance of the system;

d) consistency: qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis;

e) reproducibility: qualitative assessment of the extent to which information about the methodology and data values would allow an independent practitioner to reproduce the results;

f) sources of the data, if derived externally, and an assessment of the uncertainty of the information.

7.2.5 Assumptions

Any assumptions made about system performance characteristics and properties, model behaviour or relative relevance and likelihood of specified risk scenarios shall be documented and justified.

7.2.6 Limitations of analysis

The analysis is limited to the operational design domain.

7.3 Risk identification and classification

7.3.1 General

The objective is to identify all known risks related to failure of a cell, i.e. internal short circuit, that can result in thermal runaway by applying a systematic risk assessment method, as described in 7.3.3. The severity of the thermal event and the risk of propagation to adjacent cells in the RESS shall be determined.

7.3.2 Methodology

The first step in this process is to identify the hazard and determine the likelihood and severity of the occurrence; this constitutes the risk.

7.3.3 Hazard analysis and risk assessment methodology

An appropriate recognized industry standard method or equivalent, shall be used to identify and evaluate risks and hazards levels for the case of failure of a single cell for the process of producing the risk assessment inventory.

NOTE Known methodology standards for risk assessment are Failure Mode and Effect Analysis (FMEA) and Failure Modes, Effects and Criticality Analysis (FMECA), IEC 60812, SAE J1739, MIL-STD-1629A, AIAG FMEA-4 Guidelines, Root Cause Analysis (RCA) and IEC 62740.

7.3.4 Documentation

Documentation of the risk assessment process shall be in accordance with the requirements and templates stipulated by the chosen standard method.

7.4 Risk mitigation by design

The risk assessment process shall include appropriate mitigating measures to manage the identified risks. For each identified risk mitigation function or characteristic, its operating strategy shall be described and the physical system or component implementing the function identified.

NOTE Examples of risk mitigation by design:

a) preventive function of the BMS: detection function in place which identifies a cell at risk of developing ISC and gives service indication to the driver;

b) mitigating function of the BMS: ISC detection system in place which allows an early warning to the driver to enable safe operation and evacuation of vehicle.

The description should include information about hardware and software components that are activated, and the system parameters used for detection.

Technical specifications for safety devices and circuitry, sensors and measurement systems shall be provided.

7.5 Risk mitigation by manufacturing control

Manufacturing of cells and cell assemblies into RESS subsystems and the RESS shall have the following key elements in place:

a) a quality management system (QMS) implemented to an established standard;

   NOTE ISO 9001 and IATF 16949 are examples of quality management system standards.

b) a quality plan to:

   1) limit contaminant levels (H_2O, dust, oils, etc.) and cross contamination;

   2) use protocols to prevent damage (mechanical, electrical, thermal) during manufacturing, transportation and handling;

   3) use training to ensure the effectiveness of the protocols;

c) a product development function that has the skill, knowledge, tools, and resources necessary for the product.

7.6 Verification and validation

7.6.1 General

Test and verification methods used for unit testing, implementation, testing and validation shall be documented, clearly identifying which safety functionalities are addressed with the respective methods.

7.6.2 Verification and validation data

At times, indirect data measurement or indirect methods may be the only way to obtain data. When indirect data is used for performance verification, the relationship with the measured and the desired performance characteristics should be explained and justified.

In the absence of suitable industry standard methods and tests, the manufacturer will need to design test methods and verification techniques that are feasible to verify component and/or system performance as required by the safety case for thermal propagation of the RESS. Any such methods used shall be explicitly documented, including an explanation of what property, capability or attribute that is tested and the suitability of the method to generate the data required.

7.6.3 Collecting data

Information about the type of measurements and sampling rates shall be included.

If data are collected from public sources, the sources shall be referenced. Information about the data quality should be recorded.

7.6.4 Calculating data

All calculation procedures shall be explicitly documented, and the assumptions made shall be clearly stated and explained. The same calculation principles should be consistently applied throughout the study.

If data are generated from mathematical modelling, the type of model, main model equations, input data, system boundaries, assumptions and model verification details should be described. Commercial modelling software used shall be identified.

7.6.5 Validation of data

A check on data validity shall be conducted to confirm that the data quality requirements are fulfilled.

7.6.6 Consolidation of verification and validation data

All relevant results available shall be gathered and consolidated to verify consistency of the results from different data sources and to establish the reliability of the results obtained.

7.6.7 Completeness check

The objective of the completeness check is to ensure that all relevant information and data needed for the interpretation are available and complete. If any relevant information is missing or incomplete, the necessity of such information for developing the safety case of thermal propagation shall be considered.

7.6.8 Sensitivity check

The objective of the sensitivity check is to evaluate the reliability of the results and the conclusions by determining how they are affected by uncertainties in the data, allocation methods or assumptions made about the RESS. The level of detail required in the sensitivity check depends mainly on the findings in the risk assessment process and the impact of coupled causes and effects.

7.6.9 Consistency check

The objective of the consistency check is to verify that the system boundaries and allocation procedures are applied consistently throughout the study. Furthermore, assumptions and results derived from different data sources and methods are analysed to verify that they are consistent with each other and that there are no conflicting results.

7.7 Reporting and safety case for thermal propagation of the RESS

The primary purpose of the safety case for thermal propagation of the RESS is to provide information required to demonstrate that an acceptable risk mitigation level is achieved. This is done by showing that the hazards associated with an internal cell failure are assessed, appropriate limits and conditions are defined and that reasonable and practicable safety measures are identified and put in place. As such it should present information at a high-level and reference detail in other project documentation. Any referenced documentation should be uniquely identified and traceable.

Annex F comprises examples of template checklists for documentation of risk reduction measures on cell, RESS subsystem, RESS, and vehicle levels.

The safety case for thermal propagation of the RESS should be subject to review and update during the development process.

The claims in a safety case for thermal propagation of the RESS should be supported by robust arguments and evidence. The evidence may be based on:

— scientific law;

— application of relevant codes and standards;

— calculation analysis;

— direct evidence from testing and operational experience;

— prior research.

The format of the report and the level of detail in the report should be appropriate for the intentions of the safety case for thermal propagation of the RESS, and comprehensive to the users of the report.

The results and conclusions shall be reported without bias. The results, data, methods, assumptions, and limitations shall be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and potential of inherent trade-offs of the system evaluation.

7.7.1 Additional requirements for a third-party report

Information shall be provided about the professionals who have constituted the practitioners' team, their technical expertise and role.

Information shall be provided about the date of the report.

A statement that the safety case of thermal propagation of the RESS is conducted according to the requirements of this document shall be provided.

A dossier shall be prepared containing certified copies of testing certificates and technical specifications referenced in the report.

7.8 Critical review

7.8.1 General

In order to ensure the effectiveness of the risk mitigation measures, a critical review process is required so that it facilitates the:

— evaluation of the implementation process required for the risk mitigation activities;

— evaluation of the effectiveness of the risk mitigation measures.

The critical review process shall ensure that:

— the methods used for the development of the safety case of thermal propagation of the RESS are conformant with this document;

— the methods used for the development of the safety case of thermal propagation of the RESS are scientifically and technically valid;

— the data used are appropriate and reasonable in relation to the intention of the study;

— the interpretations are relevant for the scope of the study;

— the interpretations reflect the assumptions made and the limitations identified for the study;

— the report is transparent and consistent.

7.8.2 Critical review by internal or external expert

A critical review may be carried out by an internal or external expert. The expert performing the review shall be independent and not part of the practitioner team who has performed the study. The review statement, comments of the practitioner team and any response to recommendations made by the reviewer shall be included in the report.

An example template for a third-party review statement is shown in Annex G.