Initial working document by Secretary

Model Regulation with respect to thermal propagation of REESS for electric power train

Remark: The text below was prepared by the interim secretary, acknowledging tremendous contribution by some of industry experts, to facilitate the discussion at the ad-hoc Special Interest Group on model regulation regarding the safety of electric vehicles with a focus on a thermal propagation test method.

The contents are, in principle, the compilation of the available materials which seemed to have received certain level of consent at the former informal working group on EVS-GTR. As the SIG activity is focusing on the regulation applied under type approval scheme, the structure has been transformed to the UNR100 format.

In this document, the texts in blue are current texts of UN-R100 which would be related to thermal propagation requirements and the texts in orange are based on the the outcomes from former EVS-GTR IWG, where the modifications are marked in bold for new or strikethrough for deleted characters.

The intent of this model regulation is to enhance the requirements of thermal propagation prescribed in the Global Technical Regulation No. 20 (ECE/TRANS/180/Add.20) with the view to implement robust and practicable certification procedure.

The numbering of paragraph in this document corresponds to those of 03 series of amendments to UN Regulation No.100. Technical aspects of this model regulation may be adopted also for other national regulations based on Global Technical Regulation No.20.

1. Scope

1.1. Part I: Safety requirements with respect to the electric power train of road vehicles of categories M and N[1], with a maximum design speed exceeding 25 km/h, equipped with electric power train, excluding vehicles permanently connected to the grid.

Part I of this regulation does not cover**;**

(a) Post-crash safety requirements of road vehicles.

(b) High voltage components and systems which are not galvanically connected to the high voltage bus of the electric power train.

1.2. Part II: Safety requirements with respect to the Rechargeable Electrical Energy Storage System (REESS), of road vehicles of categories M and N equipped with electric power train, excluding vehicles permanently connected to the grid.

Part II of this Regulation does not apply to a battery whose primary use is to supply power for starting the engine and/or lighting and/or other vehicle auxiliaries' systems..

2. Definitions

For the purpose of this Regulation the following definitions apply:

2.1. "*Active driving possible mode*" means the vehicle mode when application of pressure to the accelerator pedal (or activation of an equivalent control) or release of the brake system will cause the electric power train to move the vehicle.

2.2. "*Aqueous electrolyte*" means an electrolyte based on water solvent for the compounds (e.g. acids, bases) providing conducting ions after its dissociation.

2.3. "*Automatic disconnect*" means a device that when triggered, conductively separates the electric energy sources from the rest of the high voltage circuit of the electric power train.

2.4. "*Breakout harness*" means connector wires that are connected for testing purposes to the REESS on the traction side of the automatic disconnect

2.5. "*Cell*" means a single encased electrochemical unit containing one positive and one negative terminals, which exhibits a voltage differential across its two terminals and used as rechargeable electrical energy storage device.

2.6 "*Conductive connection*" means the connection using connectors to an external power supply when the Rechargeable Electrical Energy Storage System (REESS) is charged.

2.7. "*Connector*" means the device that provides mechanical connection and disconnection of high voltage electrical conductors to a suitable mating component including its housing

2.8. "*Coupling system for charging the Rechargeable Electrical Energy Storage System (REESS)*" means the electrical circuit used for charging the REESS from an external electric power supply including the vehicle inlet.

2.9. "*C Rate*" *of* "*n C*" is defined as the constant current of the Tested-DeviceTested-Device, which takes 1/n hours to charge or discharge the Tested-

[1] As defined in the Consolidated Resolution on the Construction of Vehicles (R.E.3.), document ECE/TRANS/WP.29/78/Rev.6, para. 2 https://unece.org/transport/standards/transport/vehicle-regulations-wp29/resolutions

DeviceTested-Device between 0 per cent of the state of charge and 100 per cent of the state of charge.

2.10. "*Direct contact*" means the contact of persons with high voltage live parts.

2.11. "*Electric energy conversion system*" means a system (e.g. fuel cell) that generates and provides electric energy for electric propulsion.

2.12. "*Electric power train*" means the electrical circuit which includes the traction motor(s), and may include the REESS, the electric energy conversion system, the electronic converters, the associated wiring harness and connectors, and the coupling system for charging the REESS.

2.13. "*Electrical chassis*" means a set made of conductive parts electrically linked together, whose potential is taken as reference.

2.14. "*Electrical circuit*" means an assembly of connected live parts which is designed to be electrically energized in normal operation.

2.15. "*Electrical protection barrier*" means the part that provides protection against direct contact with the high voltage live parts.

2.16. "*Electrolyte leakage*" means the escape of electrolyte from the REESS in the form of liquid

2.17. "*Electronic converter*" means a device capable of controlling and/or converting electric power for electric propulsion.

2.18. "*Enclosure*" means the part enclosing the internal units and providing protection against any direct contact.

2.19. "*Explosion*" means the sudden release of energy sufficient to cause pressure waves and/or projectiles that may cause structural and/or physical damage to the surrounding of the Tested-Device.

2.20. "*Exposed conductive part*" means the conductive part which can be touched under the provisions of the protection degree IPXXB, and which is not normally energized, but which can become electrically energized under isolation failure conditions. This includes parts under a cover that can be removed without using tools.

2.21. "*External electric power supply*" means an alternating current (AC) or direct current (DC) electric power supply outside of the vehicle.

2.22. "*Fire*" means the emission of flames from a Tested-Device. Sparks and arcing shall not be considered as flames.

2.23. "*Flammable electrolyte*" means an electrolyte that contains substances classified as Class 3 "flammable liquid" under "UN Recommendations on the Transport of Dangerous Goods – Model Regulations (Revision 17 from June 2011), Volume I, Chapter 2.3"[2]

2.24. "*High Voltage*" means the classification of an electric component or circuit, if its working voltage is > 60 V and ≤ 1500 V DC or > 30 V and ≤ 1000 V AC root mean square (rms).

2.25. "*High voltage bus*" means the electrical circuit, including the coupling system for charging the REESS that operates on high voltage. In case of electrical circuits, that are galvanically connected to each other and fulfilling the voltage condition specified in paragraph 2.42., only the components or parts of the electric circuit that operate on high voltage are classified as a high voltage bus.

2.26. "*Indirect contact*" means the contact of persons with exposed conductive parts.

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[2] www.unece.org/trans/danger/publi/unrec/rev17/17files_e.html

2.27. "*Live parts*" means the conductive part(s) intended to be electrically energized under normal operating conditions.

2.28. "*Luggage compartment*" means the space in the vehicle for luggage accommodation, bounded by the roof, hood, floor, side walls, as well as by the barrier and enclosure provided for protecting the occupants from direct contact with high voltage live parts, being separated from the passenger compartment by the front bulkhead or the rear bulk head.

2.29. "*Manufacturer*" means the person or body who is responsible to the approval authority for all aspects of the approval process and for ensuring conformity of production. It is not essential that the person or body is directly involved in all stages of the construction of the vehicle or component which is the subject of the approval process.

2.30. "*Non-aqueous electrolyte*" means an electrolyte not based on water as the solvent.

2.31. "*Normal operating conditions*" includes operating modes and conditions that can reasonably be encountered during typical operation of the vehicle including driving at legally posted speeds, parking and standing in traffic, as well as, charging using chargers that are compatible with the specific charging ports installed on the vehicle. It does not include conditions where the vehicle is damaged, either by a crash, road debris or vandalization, subjected to fire or water submersion, or in a state where service and or maintenance is needed or being performed.

2.32. "*On-board isolation resistance monitoring system*" means the device which monitors the isolation resistance between the high voltage buses and the electrical chassis.

2.33. "*Open type traction battery*" means a liquid type battery requiring refilling with water and generating hydrogen gas released to the atmosphere.

2.34. "*Passenger compartment*" means the space for occupant accommodation, bounded by the roof, floor, side walls, doors, window glass, front bulkhead and rear bulkhead, or rear gate, as well as by the barriers and enclosures provided for protecting the occupants from direct contact with live parts.

2.35. "*Protection degree IPXXB*" means protection from contact with high voltage live parts provided by either an electrical protection barrier or an enclosure and tested using a Jointed Test Finger (IPXXB) as described in Annex 3.

2.36. "*Protection degree IPXXD*" means protection from contact with high voltage live parts provided by either an electrical protection barrier or an enclosure and tested using a Test Wire (IPXXD) as described in Annex 3.

2.37. "*Rechargeable Electrical Energy Storage System (REESS)*" means the rechargeable energy storage system that provides electric energy for electrical propulsion.

A battery whose primary use is to supply power for starting the engine and/or lighting and/or other vehicle auxiliaries' systems is not considered as a REESS.

The REESS may include the necessary systems for physical support, thermal management, electronic controls and casing

2.38. "*REESS subsystem*" means any assembly of REESS components which stores energy. A REESS subsystem may or may not include the entire management system of the REESS.

2.39. "*Rupture*" means opening(s) through the casing of any functional cell assembly created or enlarged by an event, large enough for a 12 mm diameter test finger (IPXXB) to penetrate and make contact with live parts (see Annex 3).

2.40. "*Service disconnect*" means the device for deactivation of the electrical circuit when conducting checks and services of the REESS, fuel cell stack, etc.

2.41. "*Solid insulator*" means the insulating coating of wiring harnesses provided in order to cover and prevent the high voltage live parts from any direct contact

2.42. "*Specific voltage condition*" means the condition that the maximum voltage of a galvanically connected electrical circuit between a DC live part and any other live part (DC or AC) is ≤ 30 V AC (rms) and ≤ 60 V DC.

Note 1: When a DC live part of such an electrical circuit is connected to chassis and the specific voltage condition applies, the maximum voltage between any live part and the electrical chassis is ≤ 30 V AC (rms) and ≤ 60 V DC

Note 2: For pulsating DC voltages (alternating voltages without change of polarity) the DC threshold shall be applied.

2.43. "*State of Charge (SOC)*" means the available electrical charge in a Tested-Device expressed as a percentage of its rated capacity.

2.44. "*Tested-Device*" means either complete REESS or REESS subsystem that is subjected to the tests prescribed by this Regulation.

2.45. "*Thermal event*" means the condition when the temperature within the REESS is significantly higher (as defined by the manufacturer) than the maximum operating temperature.

2.46. "*Thermal runaway*" means an uncontrolled increase of cell temperature caused by exothermic reactions inside the cell.

2.47. "*Thermal propagation*" means the sequential occurrence of thermal runaway within a REESS triggered by thermal runaway of a cell in that REESS.

2.48. "*Type of REESS*" means systems which do not differ significantly in such essential aspects as:

(a) The manufacturer's trade name or mark;

(b) The chemistry, capacity and physical dimensions of its cells;

(c) The number of cells, the mode of connection of the cells and the physical support of the cells;

(d) The construction, materials and physical dimensions of the casing and

(e) The necessary ancillary devices for physical support, thermal management and electronic control.

2.49. "*Vehicle connector*" means the device which is inserted into the vehicle inlet to supply electric energy to the vehicle from an external electric power supply.

2.50. "*Vehicle inlet*" means the device on the externally chargeable vehicle into which the vehicle connector is inserted for the purpose of transferring electric energy from an external electric power supply.

2.51. "*Vehicle type*" means vehicles which do not differ in such essential aspects as:

(a) Installation of the electric power train and the galvanically connected high voltage bus;

(b) Nature and type of electric power train and the galvanically connected high voltage components.

2.52. "*Venting*" means the release of excessive internal pressure from cell or REESS subsystem or REESS in a manner intended by design to preclude rupture or explosion."

2.53. "*Working voltage*" means the highest value of an electrical circuit voltage root-mean-square (rms), specified by the manufacturer, which may occur between any conductive parts in open circuit conditions or under normal operating condition. If the electrical circuit is divided by galvanic isolation, the working voltage is defined for each divided circuit, respectively.

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5. Part I: Requirements of a vehicle with regard to specific requirements for the electric power train

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5.2. Rechargeable Electrical Energy Storage System (REESS)

5.2.1. For a vehicle with a REESS, the requirement of either paragraph 5.2.1.1. or paragraph 5.2.1.2. shall be satisfied.

5.2.1.1. For a REESS which has been type approved in accordance with Part II of this series of Amendments to this Regulation, it shall be installed in accordance with the instructions provided by the manufacturer of the REESS, and in conformity with the description provided in Annex 1, Appendix 2 to this Regulation.

5.2.1.2. The REESS including related vehicle components, systems and structure as applicable, shall comply with the respective requirements of paragraph 6. of this Regulation.

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5.2.3. Warning in the event of failure in REESS

The vehicle shall provide a warning to the driver when the vehicle is in active driving possible mode in the event specified in paragraphs 6.13. to 6.15.

In case of optical warning, the tell-tale shall, when illuminated, be sufficiently bright to be visible to the driver under both daylight and night-time driving conditions, when the driver has adapted to the ambient roadway light conditions.

This tell-tale shall be activated as a check of lamp function either when the propulsion system is turned to the "On" position, or when the propulsion system is in a position between "On" and "Start" that is designated by the manufacturer as a check position. This requirement does not apply to the tell-tale or text shown in a common space.

6. Part II: Requirements of a Rechargeable Electrical Energy Storage System (REESS) with regard to its safety

6.1. General

The procedures prescribed in Annex 9 of this Regulation shall be applied.

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6.12. Management of gases emitted from REESS

6.12.1. Under vehicle operation including the operation with a failure, the vehicle occupants shall not be exposed to any hazardous environment caused by emissions from REESS.

6.12.2. Open-type traction batteries shall meet the requirements of paragraph 5.4. of this Regulation with regard to hydrogen emissions.

6.12.3. For REESS other than open-type traction battery, the requirement of paragraph 6.12.1. is deemed to be satisfied, if all applicable requirements of the following tests are met: paragraph 6.2. (vibration), paragraph 6.3. (thermal shock and cycling), paragraph 6.6. (external short circuit protection), paragraph 6.7.

(overcharge protection), paragraph 6.8. (over-discharge protection), paragraph 6.9. (over-temperature protection) and paragraph 6.10. (overcurrent protection).

6.13. Warning in the event of operational failure of vehicle controls that manage REESS safe operation.

The REESS or vehicle system shall provide a signal to activate the warning specified in paragraph 5.2.3. in the event of operational failure of the vehicle controls (e.g. input and output signals to the management system of REESS, sensors within REESS, etc.) that manage the safe operation of the REESS. REESS or vehicle manufacturer shall make available, at the request of the Technical Service with its necessity, the following documentation explaining safety performance of the system level or subsystem level of the vehicle:

6.13.1. A system diagram that identifies all the vehicle controls that manage REESS operations. The diagram must identify what components are used to generate a warning due to operational failure of vehicle controls to conduct one or more basic operations.

6.13.2. A written explanation describing the basic operation of the vehicle controls that manage REESS operation. The explanation must identify the components of the vehicle control system, provide description of their functions and capability to manage the REESS, and provide a logic diagram and description of conditions that would lead to triggering of the warning.

6.14. Warning in the case of a thermal event within the REESS.

The REESS or vehicle system shall provide a signal to activate the warning specified in paragraph 5.2.3. in the case of a thermal event in the REESS (as specified by the manufacturer). REESS or vehicle manufacturer shall make available, at the request of the Technical Service with its necessity, the following documentation explaining safety performance of the system level or subsystem level of the vehicle:

6.14.1. The parameters and associated threshold levels that are used to indicate a thermal event (e.g. temperature, temperature rise rate, SOC level, voltage drop, electrical current, etc.) to trigger the warning.

6.14.2. A system diagram and written explanation describing the sensors and operation of the vehicle controls to manage the REESS in the event of a thermal event.

6.15. Thermal propagation.

For a REESS containing flammable electrolyte, the vehicle occupants shall not be exposed to any hazardous environment caused by thermal propagation which is triggered by an internal short circuit leading to a single cell thermal runaway. To ensure this, the requirements of paragraphs 6.15.1. and 6.15.2. shall be satisfied **in accordance with the verification procedure described in paragraph 5.4.12.4**.[3]

6.15.1. The REESS or vehicle system shall provide a signal to activate the advance warning indication **in the event of a thermal propagation which is triggered by an internal short circuit leading to a single cell thermal runaway:**

(a) To allow egress prior to the presence of a hazardous situation inside the passenger compartment; or

(b) 5 minutes prior to the presence of a hazardous situation inside the passenger compartment.

~~in the vehicle to allow egress or 5 minutes prior to the presence of a hazardous situation inside the passenger compartment caused by thermal propagation~~

[3] The manufacturer will be accountable for the verity and integrity of documentation submitted, and assume full responsibility for the safety of occupants against adverse effects arising from thermal propagation caused by internal short circuit.

~~which is triggered by an internal short circuit leading to a single cell thermal runaway such as fire, explosion or smoke.~~ This requirement is deemed to be satisfied if the thermal propagation does not lead to a hazardous situation for the vehicle occupants **or if the single cell thermal runaway does not lead to thermal propagation in the REESS**. ~~REESS or vehicle manufacturer shall make available, at the request of the Technical Service with its necessity, the following documentation explaining safety performance of the system level or sub-system level of the vehicle:~~

6.15.1.1. **REESS or vehicle manufacturer shall make available the following documentation:**

6.15.1.**1.**1. The parameters (for example, temperature, voltage or electrical current) which trigger the warning indication.

6.15.1.**1.**2. Description of the warning system.

6.15.2. The REESS or vehicle system shall have functions or characteristics in the cell**,** ~~or~~ REESS **or vehicle** intended to protect vehicle occupants (as described in paragraph 6.15.) in conditions caused by thermal propagation which is triggered by an internal short circuit leading to a single cell thermal runaway. ~~REESS or vehicle manufacturers shall make available, at the request of the Technical Service with its necessity, the following documentation explaining safety performance of the system level or sub-system level of the vehicle:~~

6.15.3. **Thermal propagation verification process**

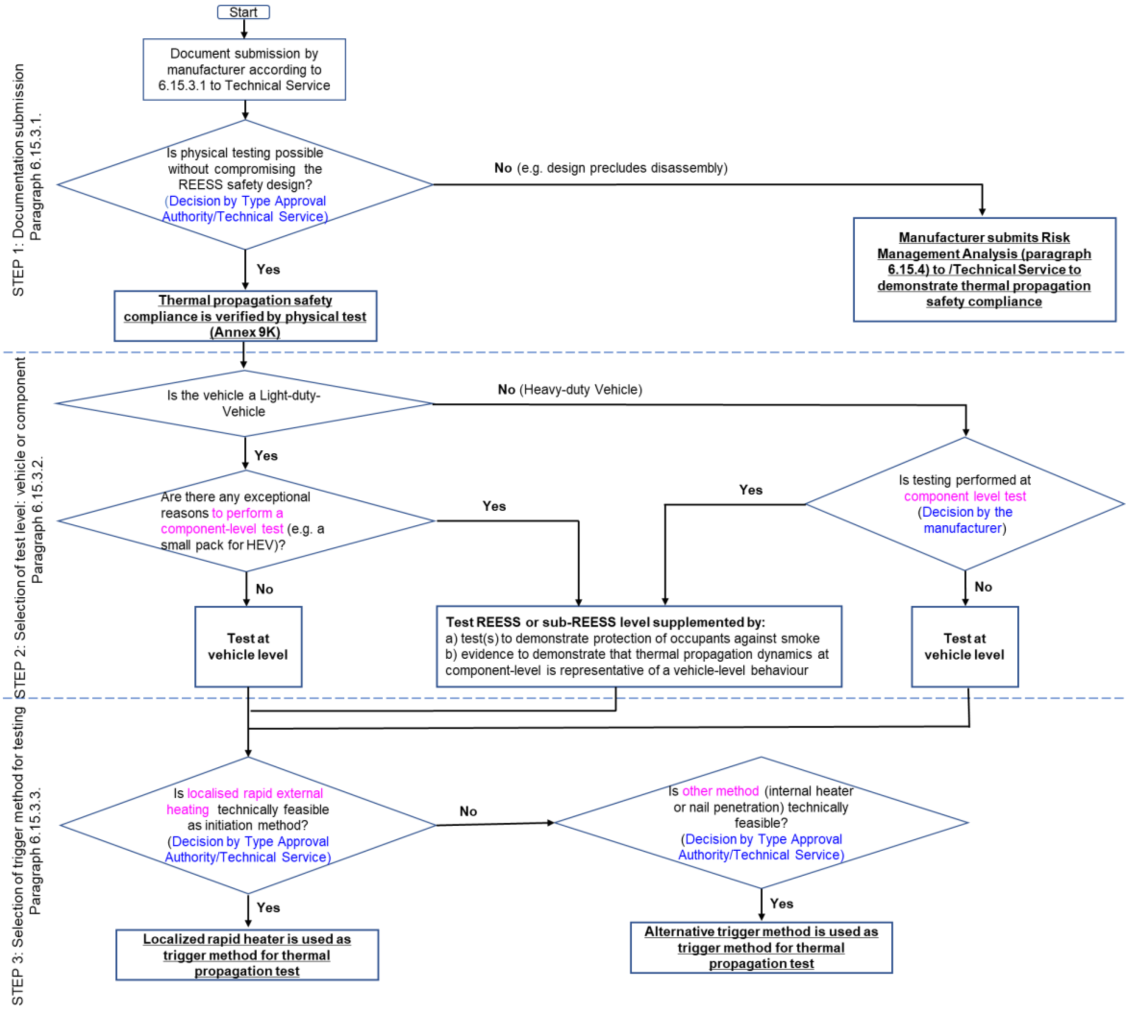
Recognizing that there are different REESS and vehicle designs on the market, and to ensure the technical neutrality of this requirement, the thermal propagation verification process follows a multi-step approach described in the flowchart in Figure 3.

Conformance with thermal propagation safety is either demonstrated by physical testing (as described in Annex 9K) or, when it is deemed that physical testing is not plausible, e.g. because REESS design precludes disassembly, by a systematic risk management analysis method (paragraph 6.15.4.). The steps in the thermal propagation safety verification process are described in paragraphs 6.15.3.1, 6.15.3.2 and 6.15.3.3.

The Type Approval Authority and the Technical Services shall determine if physical testing is possible without compromising the safety functionality and design of the vehicle/REESS, which can result in unrepresentative safety behaviour of the vehicle/REESS, based on documentation provided by the vehicle/REESS manufacturer.

Figure 3

Flow-chart for the verification of thermal propagation safety compliance



6.15.3.1. Step 1: Documentation submission requirements for the assessment of testing feasibility

The manufacturer shall provide technical documentation to enable the Type Approval Authority and Technical Services to judge if physical testing is feasible and to inform about instrumentation needed of the Tested-Device as well as the vehicle, if applicable, for testing.

(a) A system diagram of all relevant physical systems and components;

(b) A diagram showing the functional operation of the relevant systems and components, identifying all risk mitigation functions or characteristics;

(c) For each identified risk mitigation function of characteristic implemented, the physical system or component which implements the function shall be identified and the operating strategy described; and

(d) If applicable, recommendations on how to prepare and instrument the Tested-Device and the vehicle.

Relevant systems and components are those which contribute to protection of vehicle occupants from hazardous effects caused by thermal propagation triggered by a single cell thermal runaway.

If the Type Approval Authority and Technical Services judges that physical testing is not feasible based on the technical information provided by the manufacturer, Risk management analysis according to paragraph 6.15.4. shall be performed.

6.15.3.2. Step 2: Selection of test level

For light duty vehicles, vehicle testing is preferred. Component based test can only be selected if there are extraordinary circumstances that makes vehicle testing inappropriate. The appropriate test level is determined by the Type Approval Authority and Technical Services.

For heavy duty vehicles, the manufacturer determines if testing shall be performed on vehicle or component level.

Thermal propagation testing on component level shall be supplemented by:

(a) Additional test(s) to demonstrate that vehicle occupants are protected against emissions from the REESS; or

(b) Evidence to demonstrate that thermal propagation dynamics at component-level is representative of a vehicle-level behaviour.

The placement of the REESS in relation to the passenger compartment and its effect on the risk of occupant exposure to the emissions shall be considered.

6.15.3.3. Step 3: Selection of trigger method

Physical testing shall be performed when deemed possible by the Type Approval Authority and Technical Services.

Localized fast external heater is the preferred trigger method for physical testing of thermal propagation safety performance. Alternative methods: localized internal heater or nail penetration, may be used if the localized fast heater trigger method is deemed inappropriate for the REESS design by the Type Approval Authority and Technical Services.

Test method descriptions for the respective trigger methods are found in paragraphs 6.4.1, 6.4.2 and 6.4.3.

6.15.3.4 Acceptance criteria for physical thermal propagation test

During the test there shall be no evidence of:

(a) Fire

(b) Explosion

(c) Hazardous conditions inside the passenger compartment during egress or 5 minutes after the activation of the warning indication

The evidence of hazardous condition inside the occupant compartment shall be verified by visual inspection without disassembling any part of the Tested-Device or the vehicle.

6.15.4. Risk management analysis method

The manufacturer shall perform and document a risk assessment and risk reduction analysis for all operational modes (e.g. active drive possible, parking and external charging modes). The risk analysis shall be holistic and follow a systematic work process, taking on a top-down approach from vehicle to battery system and/or subsystem level(s), including both hardware and software aspects, (see for example ISO 6469-1:2019/AMD 2022 and ISO 26262 or equivalent standards for additional guidance). The work product shall be comprehensive and transparent documentation explaining the safety performance of the vehicle systems in conditions

caused by thermal propagation which is triggered by an internal short circuit leading to a single cell thermal runaway.

The manufacturer shall make available, at the request of the regulatory or testing entity as applicable with its necessity, a high-level report including essential data and a summary of important information from the risk assessment and the risk reduction activities. The report structure shall comprise a four-part structure with the elements described in paragraphs 6.15.4.1., 6.15.4.2., 6.15.4.3. and 6.15.4.4. below.

6.15.4.1. System analysis

The system analysis includes:

(a) A system diagram of all relevant physical systems and components;

(b) Description of systems/components relevant to single-cell thermal runaway and thermal propagation due to internal short circuit and their interoperability. Relevant systems and components are those which contribute to protection of vehicle occupants from hazardous effects caused by thermal propagation triggered by a single cell thermal runaway include but are not limited to REESS, sensors, thermal management system, battery management system, etc.;

(c) Description of advanced warning indication and operating logic; and

(d) Functional analyses identifying the conditions leading to single cell thermal runaway, i.e. internal short circuit of the cell, and allocating them to the corresponding components or functional units or subsystems;

6.15.4.2. Risk identification and mitigation

A risk reduction analysis using appropriate industry standard methodology (for guidance, see for example, IEC 61508, MIL-STD 882E, ISO 26262, AIAG & VDA FMEA Handbook, fault analysis as in SAE J2929, or similar), which documents the risk to vehicle occupants caused by thermal propagation triggered by an internal short circuit leading to a single cell thermal runaway and documents the reduction of risk resulting from implementation of the identified risk mitigation functions or characteristics. The severity of the thermal event and the risk of propagation to adjacent cells in the battery pack shall be determined.

The risk identification and mitigation analysis shall include:

(a) Risk mitigation by design;

(b) Risk mitigation by manufacturing control; and

(c) Risk mitigation by other means;

The risk analysis shall also include information about and justify any assumptions made on system performance characteristics and properties, model behaviour or relative relevance and likelihood of specified risk scenarios.

The risk assessment is limited to the operational design domain of the REESS.

6.15.4.3. Risk mitigation effectiveness – validation & verification

The effectiveness of each of the risk reduction measure shall be analysed and evaluated. Effectiveness may be analysed by testing, analysis, simulation, models, reference to scientific papers, field data and/or other appropriate methods, either singly or in combination. Effectiveness assessments shall fulfil the requirements of paragraphs 6.15.4.1. and 6.15.4.2., as appropriate.

6.15.4.3.1. Tests and verification methods

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. Recognized industry standard tests, for example ISO, IEC, SAE or equivalent, should be used when available and appropriate for the testing purposes. In the absence of appropriate industry standard methods and tests, the manufacturer shall design test methods and verification techniques that are feasible to verify component and/or system performance as required to verify and validate the effectiveness of the risk mitigation strategy. 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, as well as the rationale for why the method is appropriate.

6.15.4.3.2. 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. Major uncertainty factors shall be identified and quantified as far as possible.

Data can comprise of technical specifications and verifying test reports from suppliers and/or manufacturers, mathematical simulations from theoretical or empirical system models, scientific reports and publications, as wells as field 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. The sources of externally derived data shall be identified.

A completeness check shall be conducted so as to ensure that all relevant information and data needed for the interpretation are available and complete.

A sensitivity check shall be conducted to evaluate the reliability of the final results and the conclusions by determining how they are affected by uncertainties in the data, allocation methods or assumptions made about the REESS.

6.15.4.4. Conclusions

(a) The concluding part of the report shall comprise a brief summary of the major results of the risk reduction analysis and a statement that the requirements in paragraphs 6.15.1. and 6.15.2. are satisfied, including: The methods used are scientifically and technically valid for the scope of the risk reduction analysis;

(b) The data used are appropriate and reasonable in relation to the intention of the risk reduction analysis;

(c) The interpretations are relevant and reflect the assumptions made and the limitations identified for the study;

This part may be in the form of an internal or external critical review report, if the manufacturer has such a process in place.

6.15.5. REESS/Vehicle family for verification of thermal propagation

REESS/vehicles having the same characteristics with respect to their evaluation on the criteria below may be grouped into REESS/vehicle families for the purpose of compliance verification of the thermal propagation protection.

6.15.5.1. REESS family criteria

REESSs that are substantially similar with respect to the following elements may consist of the same REESS family:

(a) The chemistry, capacity and physical dimensions of its cells;

(b) REESS design influencing the thermal propagation protection;

(c) Battery Management System (BMS) (with regards to thermal propagation protection);

(d) Operation strategy of all components influencing the thermal propagation protection;

(e) Venting strategy

At the request of the manufacturer, with appropriate technical justification, and, with the approval of the technical service, if applicable, the manufacturer may deviate from the above criteria for families.

6.15.5.2. Vehicle family criteria for vehicles of categories M_1 and N_1

Vehicles that are substantially similar with respect to the following elements may consist of the same family:

(a) REESS mounting method and position;

(b) REESS mechanical protection, such as REESS casing and/or chassis structures around the REESS

(c) REESS venting strategy;

(d) REESS clearance with vehicle body and floor;

(e) REESS family

At the request of the manufacturer, with appropriate technical justification, and, with the approval of the technical service, if applicable, the manufacturer may deviate from the above criteria for families.

6.15.5.3. Vehicle family criteria or vehicles of categories M_2, M_3, N_2 and N_3

"Vehicle family" means a category of power-driven vehicles which do not differ in such essential respects, in so far as they have an adverse effect on the result of the thermal propagation test prescribed in this Regulation:

(a) REESS location in a truck, regardless of application fall broadly into the following;

(i) Under body: outside and/or inside frame rails, left or right hand side

(ii) Under cab

(iii) Behind cab

(iv) Any combination of the above

or

(b) REESS location in a bus, regardless of application fall broadly into the following;

(i) Under floor

(ii) On roof

(iii) "Engine" compartment

(iv) Any combination of the above

At the request of the manufacturer, with appropriate technical justification, and, with the approval of the technical service, if applicable, the manufacturer may deviate from the above criteria for families.

6.15.2.1. A risk reduction analysis using appropriate industry standard methodology (for example, IEC 61508, MIL-STD 882E, ISO 26262, AIAG DFMEA, fault analysis as in SAE J2929, or similar), which documents the risk to vehicle occupants caused by thermal propagation which is triggered by an internal short circuit leading to a single cell thermal runaway and documents the reduction of risk resulting from implementation of the identified risk mitigation functions or characteristics.

6.15.2.2. A system diagram of all relevant physical systems and components. Relevant systems and components are those which contribute to protection of vehicle occupants from hazardous effects caused by thermal propagation triggered by a single cell thermal runaway.

6.15.2.3. A diagram showing the functional operation of the relevant systems and components, identifying all risk mitigation functions or characteristics.

6.15.2.4. For each identified risk mitigation function or characteristic:

6.15.2.4.1. A description of its operation strategy;

6.15.2.4.2. Identification of the physical system or component which implements the function;

6.15.2.4.3. One or more of the following engineering documents relevant to the manufacturers design which demonstrates the effectiveness of the risk mitigation function:

(a) Tests performed including procedure used and conditions and resulting data;

(b) Analysis or validated simulation methodology and resulting data.

Annex 9

REESS test procedures

Annex 9 - Appendix 1

Procedure for conducting a standard cycle

A standard cycle shall start with a standard discharge followed by a standard charge. The standard cycle shall be conducted at an ambient temperature of 20 ± 10 °C.

Standard discharge:

Discharge rate:	The discharge procedure including termination criteria shall be defined by the manufacturer. If not specified, then it shall be a discharge with 1C current for a complete REESS and REESS subsystems.
Discharge limit (end voltage):	Specified by the manufacturer

For a complete vehicle, discharge procedure using a dynamometer shall be defined by the manufacturer. Discharge termination will be according to vehicle controls.

Rest period after discharge:	Minimum 15 min

Standard charge:

The charge procedure shall be defined by the manufacturer. If not specified, then it shall be a charge with C/3 current. Charging is continued until normally terminated. Charge termination shall be according to paragraph 2. of Annex 9, Appendix 2 for REESS or REESS subsystem.

For a complete vehicle that can be charged by an external source, charge procedure using an external electric power supply shall be defined by the manufacturer. For a complete vehicle that can be charged by on-board energy sources, a charge procedure using a dynamometer shall be defined by the manufacturer. Charge termination will be according to vehicle controls.

Annex 9 – Appendix 2

Procedure for SOC adjustment

1. The adjustment of SOC shall be conducted at an ambient temperature of 20 ± 10 °C for vehicle-based tests and 22 ± 5 °C for component-based tests.

2. The SOC of the Tested-Device shall be adjusted according to one of the following procedures as applicable. Where different charging procedures are possible, the REESS shall be charged using the procedure which yields the highest SOC:

   (a) For a vehicle with a REESS designed to be externally charged, the REESS shall be charged to the highest SOC in accordance with the procedure specified by the manufacturer for normal operation until the charging process is normally terminated;

   (b) For a vehicle with a REESS designed to be charged only by an energy source on the vehicle, the REESS shall be charged to the highest SOC which is achievable with normal operation of the vehicle. The manufacturer shall advise on the vehicle operation mode to achieve this SOC;

   (c) In case that the REESS or REESS subsystem is used as the Tested-Device, the Tested-Device shall be charged to the highest SOC in accordance with the procedure specified by the manufacturer for normal use operation until the charging process is normally terminated. Procedures specified by the manufacturer for manufacturing, service or maintenance may be considered as appropriate if they achieve an equivalent SOC as for that under normal operating conditions. In case the Tested-Device does not control SOC by itself, the SOC shall be charged to not less than 95 per cent of the maximum normal operating SOC defined by the manufacturer for the specific configuration of the Tested-Device.

3. When the vehicle or REESS subsystem is tested, the SOC shall be no less than 95 per cent of the SOC according to paragraphs 1. and 2. above for REESS designed to be externally charged and shall be no less than 90 per cent of SOC according to paragraphs 1. and 2. above for REESS designed to be charged only by an energy source on the vehicle. The SOC will be confirmed by a method provided by the manufacturer.

Annex 9K

Thermal propagation test

1. Purpose

The purpose of the thermal propagation test is to ensure the occupant safety in a vehicle in case an internal short circuit leading to a single-cell thermal runaway occurs in the battery system.

2. Installations

This test shall be conducted at the vehicle level or using the complete REESS or REESS subsystem(s). The appropriate test level is determined by the Type Approval Authority and Technical Services based on the outcome of the thermal propagation verification process described in paragraph 6.15.3.

3. General test conditions

The following conditions shall apply to the test

3.1. Environmental conditions

(a) At the beginning of the test, the REESS temperature shall be maintained between 18 °C to maximum permissible operating temperature, defined by the manufacturer;

(b) The test shall be conducted either indoors or outdoors. 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 Tested-Device 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 funneling affects during test execution;

(c) The test shall be carried out at a relative humidity of 10% to 90%.

3.2. Tested-Device

(a) Required modifications shall be kept to a minimum compared to the original un-modified Tested-Device. Any manipulation of REESS components, such as mechanical and thermal barriers, cooling plates/channels, electrical connections, and cell to cell spacing shall be documented and rationalized as to why such changes do not result in significant change to performance. The original sealing capability of the REESS shall not be compromised through instrumentation and any venting shall be through pre-existing seals. All components and features that are required for the functioning of the Tested-Device and safety related features e.g. cell connecting busbars, tab welding, BMS software shall be according to their production specification;

(b) At the beginning of the test, the state of charge (SOC) shall be adjusted according to the procedure defined in Annex 9- Appendix 1 to this Regulation;

(c) At the beginning of and, as long as possible, during the test, all necessary function of the Tested-Device shall be operational. The Tested-Device shall be representative of the REESS when installed in a vehicle that is “on” and set in "parked" mode. The defined thermal management/safety strategy and the battery management

system used within the REESS shall be fully operational. The coolant flow could be null or active depending on the BMS. The native cooling strategy (if installed), BMS and any other battery control systems, which are necessary for the test, shall be operational for as long as possible during the test.

3.3. Initiation cell

In the field, a single cell thermal runaway may occur in any cell location within the REESS. For the test, the initiation cell selection shall consider the number of adjacent cells, cell packaging, and the distance between cells in proximity to the potential initiation cell as well as the practicality of initiation.

Any cell that meets the requirements of paragraphs 3.1 and 3.2 above can be selected as the target cell.

3.3.1. Installation of test equipment shall not compromise the functionality of the REESS. The installation shall minimize modification to thermal insulators and structure and shall not:

(a) Disable or modify the thermal management system;

(b) Disable or affect the functionality of the BMS;

(c) Change pack gas flow and permeability, both internal and exit paths.

3.3.2. A cell shall be selected that represents severe conditions for generating a potentially hazardous condition in case of a thermal runaway:

(a) A high level of heat transfer to at least one adjacent cell (e.g. thinnest spacers/gaps/barriers or vent direction towards an adjacent cell);

(b) Subject to (a), few heat sinks and non-productive thermal pathways (e.g. edge cell with few adjacent cells and/or with large adjacent air space);

(c) Other criteria known be the manufacturer to reflect a condition/location which may have greater potential to lead to a hazardous condition.

4. Recorded data and measurements

4.1. The following information shall be recorded during the test and during the observation period. All data measurement systems shall be referenced to the same starting time.

(a) Identification of the test method, including the trigger method, and a description of the test set-up;

(b) Test conditions (e.g. environmental conditions, SOC, and other pre-conditioning parameters);

(c) Temperature of the initiation cell;

(d) Voltage of the initiation cell during the thermal runaway triggering procedure;

(e) Temperature of one adjacent cell (if possible);

(f) Independent voltage measurement of the Tested-Device as a function of time and, if possible, include the BMS pack voltage for comparison;

(g) Video and audio recording, including indication of a time stamp of any observable system state change during the test (e,g, initiation cell thermal runaway/venting, thermal propagation to adjacent cell(s), smoke, fire/flame, explosion, etc);

(h) Condition of the Tested-Device and/or vehicle at the end of the test, supported by video or photographs (before and after test);

(i) If possible, surface temperature of an adjacent module, if applicable, to observe propagation between modules;

(j) If the test is performed on vehicle level, the time stamp of warning indications or alarms to occupants.

5 Detection of thermal runaway

5.1. Main Criteria

Thermal runaway can be detected by the following conditions (The energy density of a cell is calculated according to IEC 62660-1:2018, clause 7.6.3.1):

5.1.1. 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:

(a) temperature rise $dT/dt > 1$ K/s and temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer; or

(b) temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer with a rapid and distinct voltage drop; or

(c) temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer with venting gas or smoke release and at least one of supplementary criteria listed in paragraph 5.2. below; or

(d) temperature rise $dT/dt > 1$ K/s and venting gas or smoke release and rapid and distinct voltage drop.

5.1.2. 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:

(a) temperature rise $dT/dt > 15$ K/s and temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer; or

(b) temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer with a rapid and distinct voltage drop; or

(c) temperature exceeding the thermal runaway onset temperature determined by the cell manufacturer and at least one of the supplementary criteria below; or

(d) temperature rise $dT/dt > 15$ K/s with venting gas or smoke release and a rapid and distinct voltage drop.

5.2. Supplementary criteria

The following indicators can be considered as supportive evidence of the occurrence of thermal runaway due to the test trigger method:

(a) $dP/dT \geq 0.01$ bar/s of the measured pressure in the battery pack for at least 1 s;

(b) Occurrence of ejected solid material outside of the battery pack;

(c) Failure of the BMS or signal faults (if the BMS is still active). Logged faults in the BMS shall be analysed.

5.3. (Placeholder) Criteria for determining no thermal runaway

In the case a cell within the REESS cannot be brought to thermal runaway, either because the cell chemistry is intrinsically safe or the REESS design effectively prevents single-cell thermal runaway to occur, the thermal propagation test shall be considered valid provided that the two consecutive tests using at least two alternative cell trigger methods in section 6.4 has failed to initiate thermal runaway in the initiation cell.

4. Trigger methods to initiate thermal runaway

The appropriate trigger method to initiate thermal runaway in the initiation cell is determined by the Type Approval Authority and Technical Services based on the outcome of the thermal propagation verification process described in paragraph 6.15.3.

The initiation method shall not affect the adjacent cell(s) such that they exceed the extremities of their operating or storage specifications (whichever is the more extreme) for the cell. Appropriate methods may be used to isolate the adjacent cell(s), provided that the REESS original functionality is not impeded.

Localized fast external heater (Annex 9K, Appendix 1) is the preferred trigger method. If this method is not suitable, optional trigger methods that can be selected are:

(a) Internal localized heater (Annex 9K, Appendix 2);

(b) Nail penetration (Annex 9K, Appendix 3).

Pre-testing procedures, for example to identify appropriate thermal runaway initiation trigger parameters for the Tested-Device, are not part of the homologation process and may be provided by the manufacturer upon request and subject to availability.

Annex 9K – Appendix 1

Thermal runaway initiation method with localized fast external heater

1. Preparation of Tested-Device

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

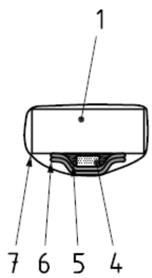
1.2. The chosen heating element shall be set to avoid contact to any REESS assembly surface except for the initiation cell. Intimate thermal contact between the heating element and the initiation cell surface is important for the successful application of this method. Thermal contact between the heating element and initiation 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).

1.3. A sample of potential heater application methods are shown in Figure 1 and the applied method is dependent on the REESS or REESS subsystem design. Maintain a contact pressure for the heating element on the initiation cell during the test to ensure contact and optimal heat transfer, see Figure 1.

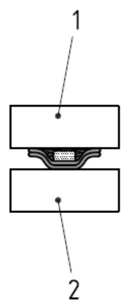
Figure 1

Methods to apply pressure on the heating element to maintain heating element contact to initiation cell throughout the test for different cell types.

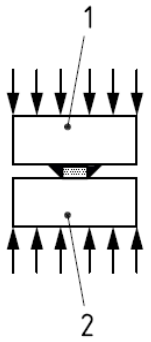
(a) REESS with large spacing between cells



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



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



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

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

2. Heater element selection guide

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

2.2. 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 1.

Table 1
Heater device selection guide: Target parameters

Parameter	*Value*	*Rationale*
Heater device material	Nickel-chrome with an isolating barrier or another suitable resistive heating material	Achieve high temperatures and prevent element failures. Isolating materials may include alumina, ceramic, or fiberglass.
Thickness	<5 mm	Minimize effect of heater on REESS. Some REESS 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 initiation cell	Concentrate heat to the smallest feasible area on the cell surface. Largest cell surface should be used, if possible
Heating rate	15 °C/s	Similar to heating rates observed within thermal runaway conditions.[a]

Maximum temperature	100 °C larger than the chosen setpoint temperature	Heater shall maintain integrity at the chosen operating temperature and take into account temperature deviations from heater element to thermocouple.[b]
Control method	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 types to avoid 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.		

3. Test procedure for vehicle level test

The general conditions in Annex 9K, paragraph 3. shall be satisfied when the method is implemented at the vehicle level.

(a) Instrument the REESS as outlined above and connect all cooling/communication and high voltage lines and reinstall REESS into vehicle.

(b) Connect to CAN-bus or other vehicle monitoring system to collect data about battery management system.

(c) Install video camera inside vehicle cabin to record video (dashboard/information screen) and audio (warnings) from vehicle during test if applicable.

(d) Perform multi-gas measurement according to “Recorded data and measurements” paragraph if applicable.

(e) Turn vehicle “on” and set it in the “parked” mode.

(f) Verify there are no warning indications related to REESS or powertrain failure before proceeding.

(g) Begin recording temperature and battery management system data.

(h) Begin sending power to the heating element.

(i) Open relay to heater after:

(i) a predetermined maximum heating period, or

(ii) a total energy input to the heater that is > 20 % of initiation cell energy, or

(iii) earlier, based on thermal runaway detection criteria in the initiation cell given in Annex 9K, paragraph 5.

(j) Discontinue the heating when the thermal runaway of the initiation cell is confirmed by fulfilment of one of the main criteria in Annex 9K, paragraph 5.1.

4. (Placeholder) Test procedure for REESS or REESS subsystem test

Annex 9K – Appendix 2

Thermal runaway initiation method with internal heater

This test method is similar with the external heating method except it 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.

1. Trigger method description

The heater is a resistor made of a tungsten flat spiral (Figure 3). 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:

(a) thickness of heating filament: see Figure 1,

(b) resistance: (200 ± 5) mΩ,

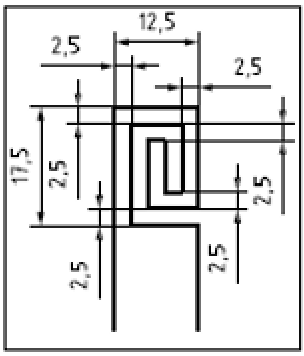
(c) heating power: from 50 watts to 200 watts between 10 s and 120 s to the cell,

(d) 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.

The 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.

Figure 1
Example of an internal heater flat spiral of tungsten



(mm)

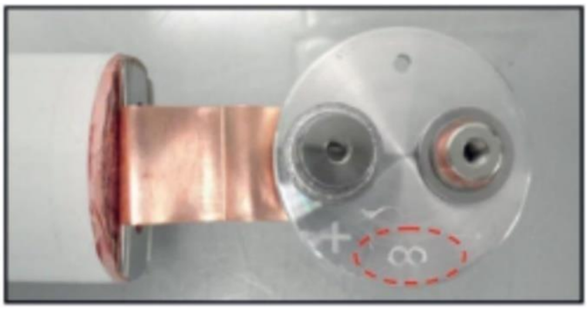
NOTE: The wire diameter is usually 0.1 mm to 0.3 mm

2. Initiation cell 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.

2.1. 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 4).

Figure 2
Example of specific holes in cover for heater connection

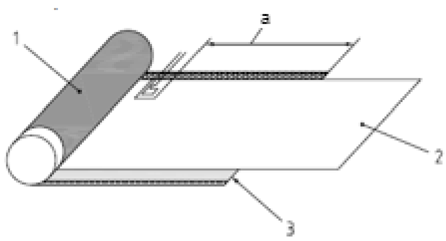


2.2. Step 2: Unroll the separators and the electrodes to insert the heater.

2.3. Step 3: Locate the heater on the last wrap of electrode (Figure 4). The heater should be placed between the outermost negative and positive electrodes for the cell, if possible (see Figures 3, 4 and 5). The location should be determined between the manufacturer and Technical Services.

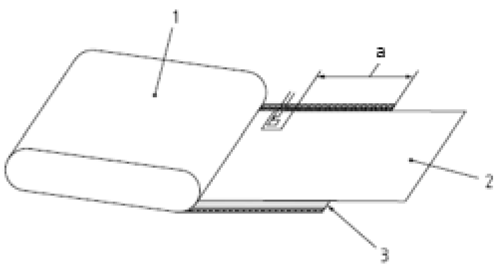
Avoid unrolling a larger part of the jelly roll, since this can lead to damage of the jelly roll. Use an outer stack in case of stacked layers.

Figure 3
Example of heater location inside the cylindrical cell.



Key
1 positive electrode
2 separator
3 negative electrode
a 180mm from end of positive electrode and 15mm from end of negative electrode, tolerance ±5 mm.

Figure 4
Example of heater location inside the prismatic cell.



Key
1 positive electrode
2 separator
3 negative electrode
a 180mm from end of positive electrode and 15mm from end of negative electrode, tolerance ±5 mm.

Figure 5
Example of heater located on the last lap of negative electrode

Figure 6
Example of jelly roll equipped with heater

2.4. Step 4: Wind the jelly roll with the heater (see Figure 6).

Figure 6
Example of jelly roll equipped with heater

2.5. 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 7). Assemble the lithium-ion cell according to standard manufacturing processes (e.g. electrolyte filling, cover welding).

All wires used in the REESS or REESS 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.

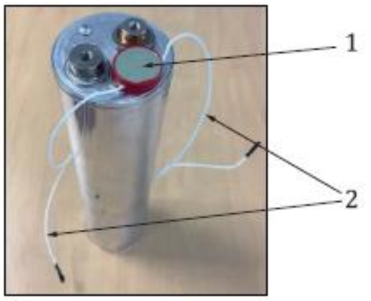
Selection of resin is critical as the strength of seal shall be greater than any installed vent of the cell. Furthermore, it should be ensured that no electrolyte or gases can leak out through the space between the wire strand and the wire insulator.

After cell cover welding, obtain the final sealing of the cell by adding a resin (e.g. epoxy glue). 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. After it is completely dry, carry out a helium test to check the sealing before filling the cell with electrolyte (see Figure 8).

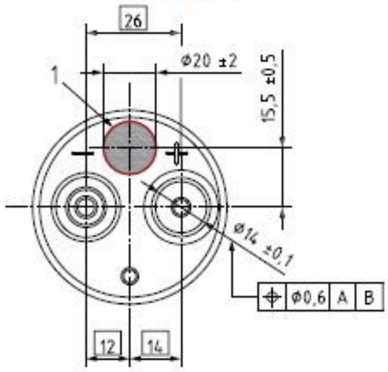
When the helium test is successful, the cell is ready to be filled and formed.

Figure 7

Example of finished cell with heater.



a) picture



b) illustration

Key

1 resin for sealing of the heater supply

2 supply wires of the heater

Figure 8

Example of cell before filling with electrolyte.

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

If the modified cell is integrated into a REESS subsystem, without connecting wires (temperature sensor and internal power supply), some module modification may be necessary. Create a hole with sufficient diameter on the REESS or REESS 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 Tested-Device. Connect all wires of the heater, thermocouples and voltage sensors to the outside of the REESS or REESS subsystem though a hole in the REESS casing and seal the holes with heat-resistant resin.

For a vehicle level test, mount the REESS on the vehicle, according to manufacturer's specifications.

4. Internal heater test procedure

The test procedure consists of the following steps:

(a) checking and connecting the heater;

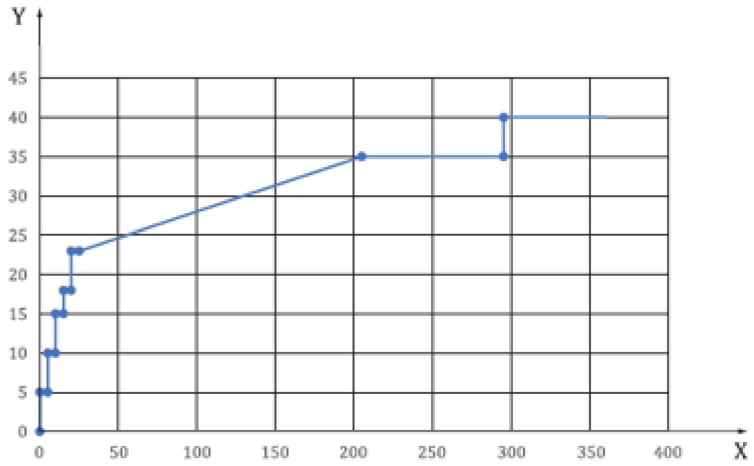
(b) checking heater resistance;

(c) applying the heater current profile specified in Table 1 and Figure 9 until thermal runaway;

(d) discontinue the heating sequence when thermal runaway when the thermal runaway of the initiation cell is confirmed by fulfilment of one of the main criteria in paragraph 6.3.5.1

(e) continue the measurements until the cell temperature decreases to 60 °C.

Figure 9
Current profile for heater



Key
X time (s)
Y current (A)

Table 1
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

Annex 9K – Appendix 3

Thermal runaway initiation method with nail penetration trigger

(Placeholder)