Updated draft regulatory text for the Thermal ~~Runaway~~ Propagation test

Global Technical Regulation on Electric Vehicle Safety Phase 2

I Statement of technical rationale and justification

C. Technical background

3. Thermal propagation

Thermal ~~runaway~~ propagation

In order to ensure the overall safety of vehicles equipped with a REESS containing flammable electrolyte, the vehicle occupants should not be exposed to the hazardous environment resulting from ~~either a~~ thermal ~~runaway or thermal runaway~~ propagation triggered by a single cell thermal runaway due to an internal short circuit.

Thermal ~~runaway~~ propagation test shall be conducted to verify that the hazard of the thermal ~~runaway~~ propagation is prevented or eliminated by design.

Initiation method

The [main] initiation method for triggering thermal runaway during the thermal ~~runaway~~ propagation test is localised rapid external heating.

The ~~trigger~~ initiation method applies a high-powered heat pulse, locally, to the external surface of one - ~~initiation~~ target - battery cell within the REESS via an external heater with minimal increase in temperature of the adjacent 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 REESS.

If the heating element is inserted between two cells, sufficient thermal insulation or barriers shall be added to thermally insulate the cell adjacent to the ~~initiation~~target cell. Such thermal insulation or barriers shall not impede ~~natural~~ REESS functionality, such as cooling.

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 XX.[1]

Table XX — 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

[1] Table XX 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) may require variations to the target parameters.

		alumina, ceramic, or fiberglass
Thickness [mm]	<5	Minimize introduction of foreign objects, 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 target ~~initiation~~ 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 REESS 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 <u>surface of the </u>chosen heater.

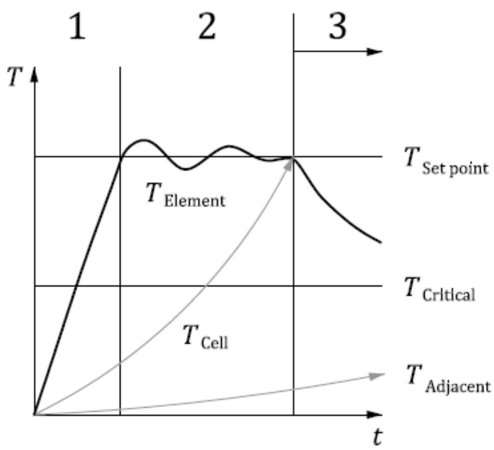
[b] This temperature may need adjustment for other chemistries and potentially other cell construction techniques (cell sidewall ruptures).

[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.

<u>Test methodology</u>

The heating methodology shall follow the following temperature/time profile shown in Figure YYY.

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



Key to Figure YYY

1	Phase1 ramp

2	Phase 2 soak
3	Power off

A temperature controller (i.e. thermostat) should be utilized to track the temperature/time profile as shown in Figure YYY 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 XXX 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 XXX). The effect of the heat generated by the heating element on the adjacent cells or chosen REESS architecture shall be minimized and shall be lower than the maximum operating temperature of the REESS or REESS 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 XXX – Typical heater parameters for implementation of localised rapid external heating methodology

Parameter	**Pouch cell**	**Cylindrical cell 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 ~~initiation~~ 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 ~~initiation~~target cells' maximum rated energy.			Heating until thermal runaway is achieved within 5 min. In 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 XX.

[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.

Test application and necessary modifications

Subsystem level testing

The use of this test method relies on quickly and effectively heating up a single cell into thermal runaway within a REESS and REESS 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, soak time) for the specific cell used in the chosen REESS design, which vary (from those shown in Tables XX and XXX) upon change of cell chemistry and cell size/construction. A subsystem test also refines the ~~trigger~~ initiation method placement within the chosen REESS cells. Modifications required for subsystem level testing should mimic those found in the REESS to obtain an accurate test result relative to that obtained at a REESS test level. Any subsystem level testing should follow the guidelines presented in the “Test procedure” section for the thermal ~~runaway~~ propagation test for cell selection and modifications such that they may be implemented during subsequent vehicle level test. It is important that any subsystem level test replicate the configuration, orientation, thermal conditions of the potential future vehicle level test.

Vehicle testing

Conducting this test while the vehicle is “on” in the “parked” mode “(i.e. in the vehicle with the main switch “on”, shift on “P”, energy supply disconnected, and the REESS with power line connected, cooling system operational and BMS energised) and an ~~trigger~~ initiation method which does not affect the vehicle system, permits the validation of all systems towards a single cell thermal runaway event. The critical warnings for tests run at a vehicle level are warnings associated to the REESS system, other vehicle warnings (if they appear) are not the focus of this test.

~~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 XXXX can be used for guidance to report the test outcome.~~

~~Table XXXX — Possible test outcomes~~

~~Scenario~~	~~Description~~	~~Effect~~
~~0~~	~~Target cell was not triggered to thermal runaway.~~	
~~1~~	~~Target cell thermal runaway was successfully initiated.~~	~~There is no thermal event of target cell. System controls and mitigations have stabilized the cell.~~
~~2~~	~~Target cell thermal runaway was successfully initiated.~~	~~Thermal runaway occurs in target cell, but there is no propagation to adjacent cells.~~
~~3~~	~~Target cell thermal runaway was successfully initiated. 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. 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.~~
~~5~~	~~Target cell thermal runaway was successfully initiated. 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.~~

II Text of regulation

5. Performance requirements

For the vehicles equipped with a REESS containing flammable electrolyte, the vehicle occupants shall not be exposed to any hazardous environment caused by thermal ~~runaway~~ propagation which is triggered by an internal short circuit leading to a single cell thermal runaway.

To ensure this, the vehicle shall provide an advance warning indication to allow egress or 5 minutes prior to the presence of a hazardous situation inside the passenger compartment caused ~~either~~ by thermal ~~runaway or thermal runaway~~ propagation, 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 ~~runway and/or its~~ propagation does not lead to a hazardous situation for the vehicle occupants. This warning shall have characteristics in accordance with paragraph 5.3.3.2.

6. Test procedures

Purpose

The purpose of the thermal ~~runaway~~ propagation test is to ensure the occupant safety in a vehicle if thermal runaway occurs in the battery system.

Installations

This test shall be conducted at the vehicle level[2], whereby the response of the vehicle level detection and/or safety system (warning symbols, alarms), tenability of the vehicle cabin ~~and effect on surrounding environment~~ could be evaluated.

Procedures

General test conditions

Environmental conditions

The following conditions shall apply to the test:

(a) At the beginning of the test, ~~T~~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 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.

(c) The test shall be carried out at a relative humidity of 10% to 90% and an atmospheric pressure of 86kPa to 106kPa.

DUT conditions

(a) Required modifications shall be kept minimum compared to the original un-modified DUT. Any manipulation of REESS components, such as thermal barriers, cooling plates/channels, electrical connections, and cell to cell spacing shall be kept at a minimum and be reported. The original sealing capability of the REESS shall not be compromised through instrumentation. For minimum modifications, all cell connecting busbars, tab welding, safety relevant

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[2] JRC research has shown that thermal ~~runaway~~ propagation can occur at higher rate in a REESS installed in a vehicle compared to a REESS level test. See presentation EVS25-E1TP-0500 [EC]JRC's thermal runaway propagation test campaign at.pdf.

components, BMS software should be maintained and un-compromised within the DUT according to their delivery stage.

(b) At the beginning of the test, the state of charge (SOC) shall be adjusted according to paragraph 6.2.1.2;

(c) At the beginning of and for as long as possible during the test, all test devices shall be operational; Defined cooling/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), battery control unit (BCU) and any other battery control systems, which are necessary for the test, shall be operational for as long as possible during the test.

~~Initiation~~Target cell

The ~~initiation~~ target cell shall be chosen among those with a maximum number of nearest neighbours approximating the centre of the battery pack.

DUT preparation

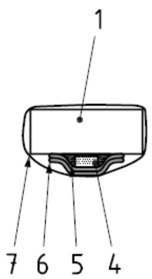
The feedthrough installation of the chosen heating element should only modify the REESS by permitting electrical and thermocouple connections to the heating element. These connections shall provide greater seal integrity than the other connectors in the REESS.

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.

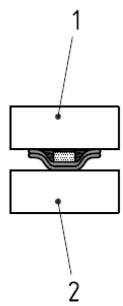
The chosen heating element shall be set to avoid contact to any REESS assembly surface except for the ~~initiation~~ target cell. Intimate thermal contact between the heating element and the target cell surface is important for the successful application of this method. Thermal contact between the heating 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 YY and the applied method is dependent on the REESS or REESS subsystem design. Maintain a contact pressure for the heating element on the ~~initiation~~target cell during the test to ensure contact and optimal heat transfer, see also Figure YY.

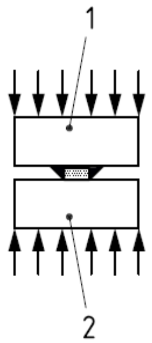
Figure YY - Methods to apply pressure on the heating element to maintain heating element contact to target cell throughout the test



a) REESS with large spacing between cells



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



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

Key to Figure YY

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

For implementation in vehicle level tests, the vehicle should be agnostic to the insertion of this ~~trigger~~ initiation method into the REESS, 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.

Recorded data and measurements

The following information shall be recorded during the test~~,~~ and 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 REESS and REESS subsystem level t~~The following information shall be recorded:

— identification of test 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;~~
— heating element temperature,
—~~initiation~~target cell temperature,
— ~~current and~~ voltage of the ~~initiation~~target cell during heating.
— 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;
— video and audio recording including indication of a time stamp of any observable system state change during test (such as defined in "Test events and outcome description" paragraph);
— condition of DUT at the end of test supported by photographs (before and after test) or video;
— attach thermocouples, not only on the ~~initiation~~target 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 REESS or REESS subsystem level.~~

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

— the time stamp of warning indications or alarms to vehicle occupants.

The following data may be provided as additional information:

— 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;

— 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 REESS or REESS subsystem level.

— 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~~ the testing entity and ~~supplier~~manufacturer. 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.

Test procedure

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

— Instrument the REESS as outlined above and connect all cooling/communication and high voltage lines and reinstall REESS 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 "Recorded data and measurements" paragraph if applicable.

— Turn vehicle "on" and set it in the "parked" mode.

— 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 ~~initiation~~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 ~~initiation~~target cell given in "Detection of thermal runaway" paragraph.

~~— 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 temperatures may be viewed through IR cameras.~~

~~— If a thermal runaway reaction does not occur:~~

~~— monitor and observe for a minimum of 2 h.~~

~~—Wait 24 h with remote monitoring of test vehicle to ensure no further thermal reactions.~~

Detection of thermal runaway

Main criteria

Thermal runaway can be detected by the following conditions:

(i) The measured voltage of the ~~initiation~~target cell drops, and the drop value exceeds 25% of the initial voltage;

(ii) The measured temperature of the ~~initiation~~target cell exceeds the maximum operating temperature defined by the manufacturer;

(iii) $dT/dt \geq 1$ °C/s of the measured temperature of the ~~initiation~~target cell for at least 3s.

Supplementary criteria

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

— dP/dt ≥ 0.01 bar/s of the measured pressure in the pack for at least 3s;
— smoke release;
— 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 ~~initiation~~target cell and whether this has resulted in thermal propagation in the REESS or REESS subsystem:
— mass loss greater than its electrolyte mass of the ~~initiation~~target cell;
— REESS or cell rupture;
— REESS 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.

Thermal runaway can be judged when:
(a) Both (i) and (iii) are detected;
(b) Both (ii) and (iii) are detected; or
(c) At least two supplementary criteria and (iii) are detected.