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Thermal runaway criteria
GTR-EVS
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Joint Research Centre

Introduction

- Test campaign on 66 Li ion cells on Thermal Runaway (TR) by JRC/ZSW
- Different initiation methods
  - Nail penetration: steel, ceramic
  - Heating: conventional heating, rapid heating
  - Inductive heating
- 5 different types of cells
  - prismatic, pouch, cylindrical
  - 3.1 Ah – 94 Ah
- Look at TR from different angles
  - GTR-20 criteria
  - Location of thermocouple on the cell
- Presented at earlier meetings

Initiation method	Automotive battery type					
Cell type	21700 4.8 Ah	Prismatic 94 Ah	Pouch 39 Ah	Pouch 40 Ah	18650 3.1 Ah	Total
Resistive heating (RH)	3	4	4	4	-	15
Nail penetration	4	3	4	4	-	15
Ceramic nail penetration	4	4	3	4	-	15
Rapid heating	4	4	4	3	-	15
Inductive heating	-	1	2	-	3	6
Total	15	15+1	15+2	15	3	60+6

2

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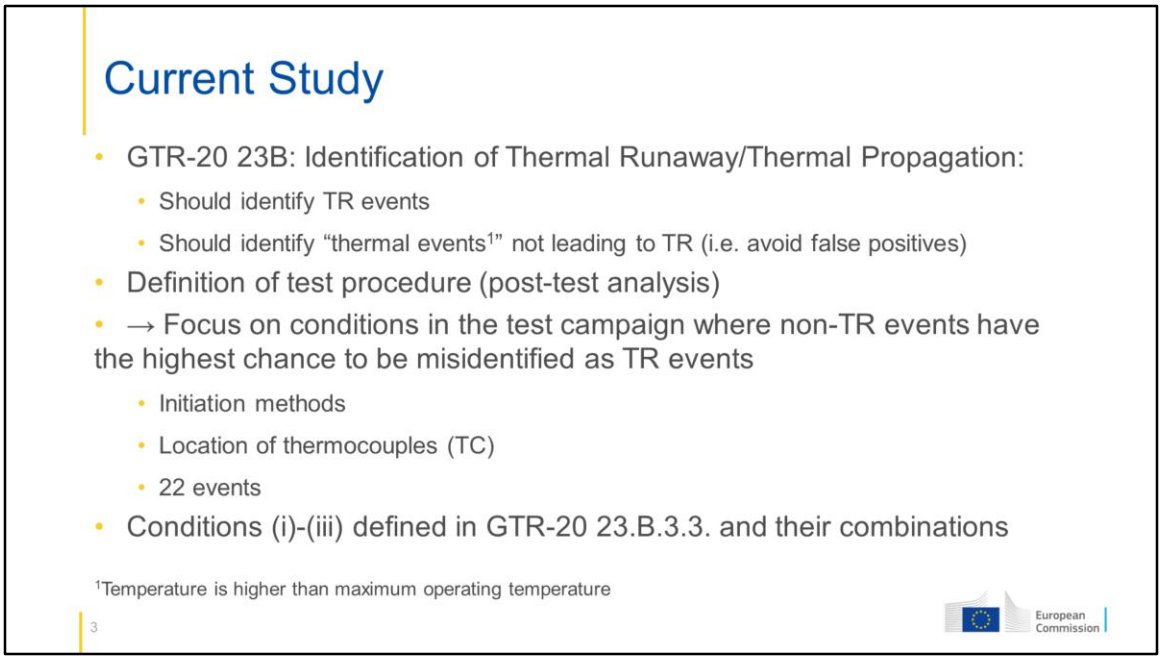
The JRC has carried out a test campaign on 66 cells used in the EV market. Aim of this test campaign is to analyse a number of parameters wrt. their impact on the initiation and detection of TR events: type of cell, initiation method, location of the thermocouples on the cell, thresholds for the GTR-20 conditions, data processing (dT/dt) etc.

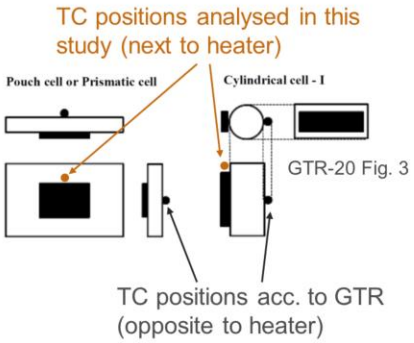


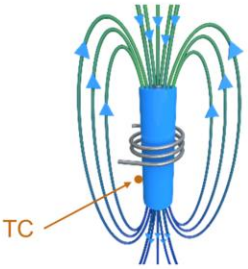
GTR-20, section 23B.3.3. provides criteria that should allow to identify TR events from the measured cell voltage and temperature. For these criteria to be fit for purpose they need to identify with great certainty TR events but also avoid false positives, i.e. avoid signalling simple "thermal events" as TR events although no actual TR occurred. The study focusses on the definition of a post-test procedure. The implications of the results for other applications (such as controlling something during a test or triggering an alarm signal for the occupants of a car) may be very different.
To asses the criteria that are currently in GRT-20, we had a closer look at those experimental conditions from the study that were most likely to lead to false positives, i.e. those with quick heating and those where the temperature was measured close to the heating source.
We have also started looking at the criteria defined in the GTR-20 and especially the filtering applied to the temperature channels for the determination of dT/dt.

Experimental Setup

- Fast initiation methods: rapid heating, induction
- Thermocouple (TC) close to heat source

rapid heating





inductive heating

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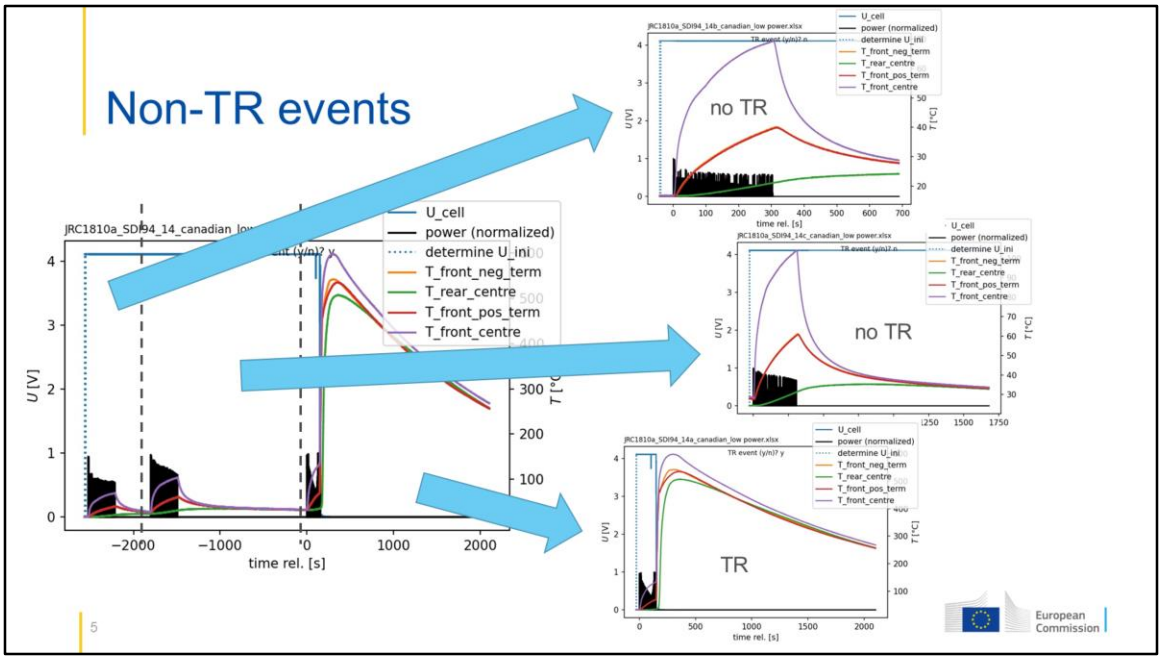
4

The two selected quick heating methods:
- “rapid heating”: (the configuration shown was developed by the NRC of Canada), in contrast to the configuration in GTR-20, the thermocouples where placed next to the heat source (and not on the opposite side of the cell).
- “inductive heating”: The TC was located between the inductive coil and the lower term of the cell.

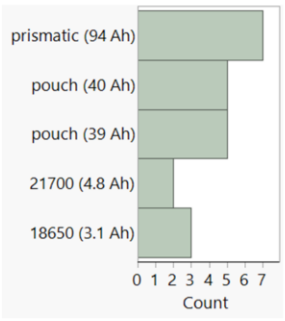


Some tests needed several starts to go into thermal runaway. These test records were split in several parts (vertical dashed lines) and the thermal events not resulting in thermal runaways were considered as independent tests. (It is acknowledged that that is not the same as starting a test with a fresh battery, e.g. inner temperature might be different.)

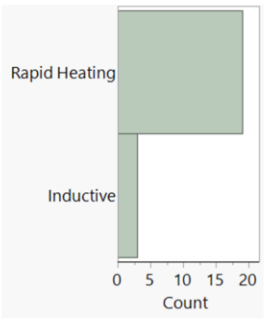
The graphs provide overviews of the test (segments).

- The blue curve is the cell voltage (the 2 vertical dashed lines indicate the interval in which the initial cell voltage is determined)
- The black lines show then heating pulse. (It is normalized by the maximum power)
- The coloured lines are the different temperature signals. The one considered here is T_front_centre. Since that thermocouple was close to the heat source, it shows the highest temperature.

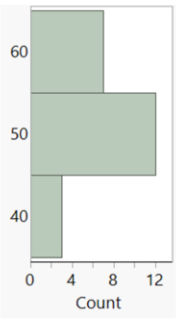
Summary test conditions



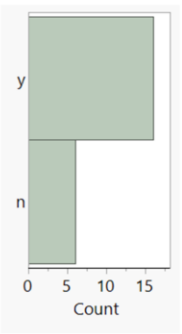
Cell



Heating Method



$T_{max\ op}$



Thermal Runaway

6

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Distribution of the main parameters in the tests discussed here. All inductively heated tests were carried out on 21700 cells. In total there where 6 non-TR events (extracted from “failed TR initiations”, see slide 5) and 16 TR events.
$T_{max\ op}$ is the maximum operating temperature specified for the cell.

TR Detection criteria in GTR-20

23B.3.3. Detection of thermal runaway.

Thermal runaway can be detected by the following conditions:

(i) The measured voltage of the initiation cell drops;

(ii) The measured temperature exceeds [the maximum operating temperature defined by the manufacturer];

(iii) $dT/dt \geq$ [1 K/s] of the measured temperature.

Thermal runaway when:

(a) Both (i) and (iii) are detected; or

(b) Both (ii) and (iii) are detected.

7

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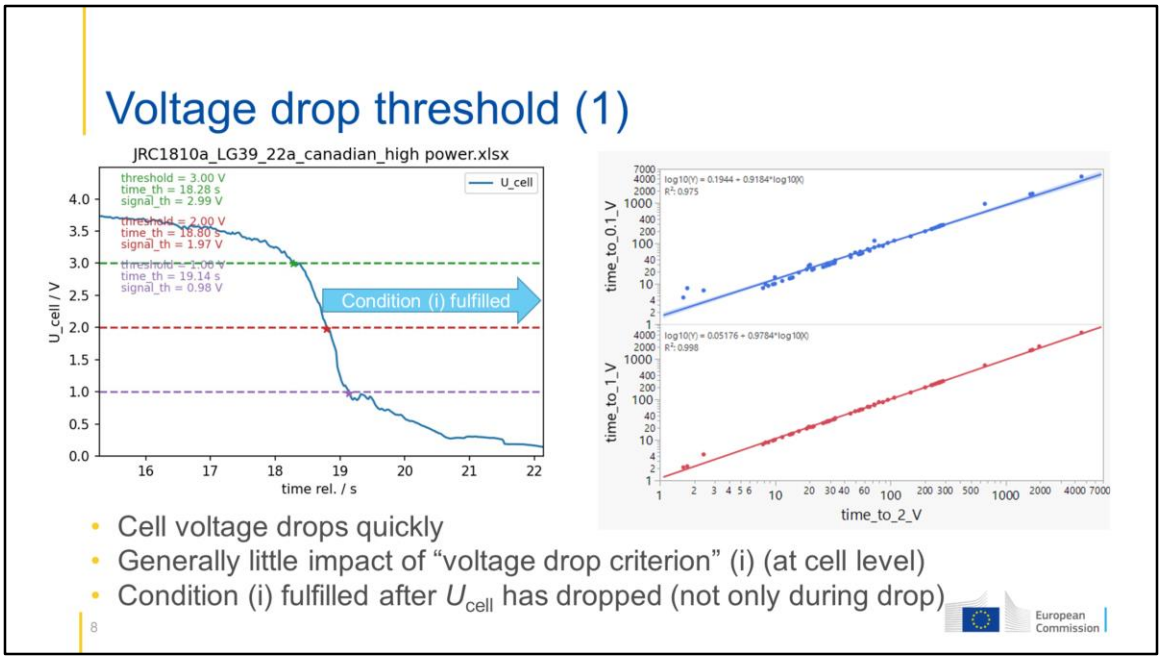
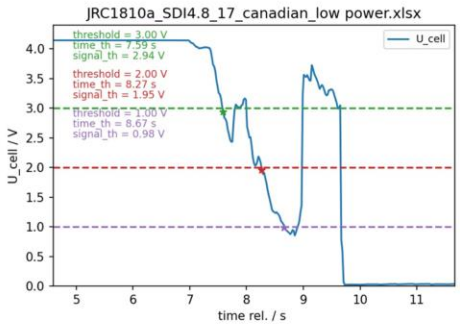
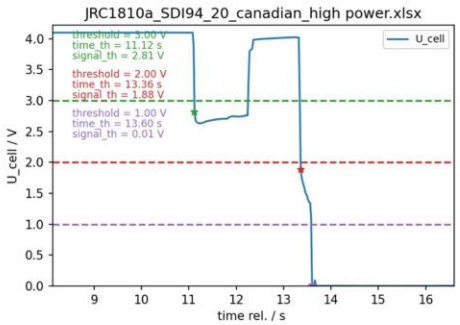
The data were analysed using the detection criteria in 23B.3.3. of GTR-20.
Criteria (i) and (iii) need further specification (see following slides).



Left: Cell voltage generally drops quite quickly (dashed lines show 3 V, 2 V and 1 V thresholds) The thresholds are reached in quick succession.
Right: Plot of the time when the cell voltage drops to 0.1 V and 1 V vs. the time to reach 2 V for all tests from the full campaign where these voltage levels are reached (~ 64 tests, depending on the threshold). The times when the different thresholds are reached are strongly correlated (and very close to each other). So the actual value of the threshold for the cell voltage does not matter too much in general.

Voltage drop threshold (2)





- In some cases U_{cell} (partly) recovers for a limited time.
- In all observed cases (so far) recovery was only temporary and a TR event followed.

9

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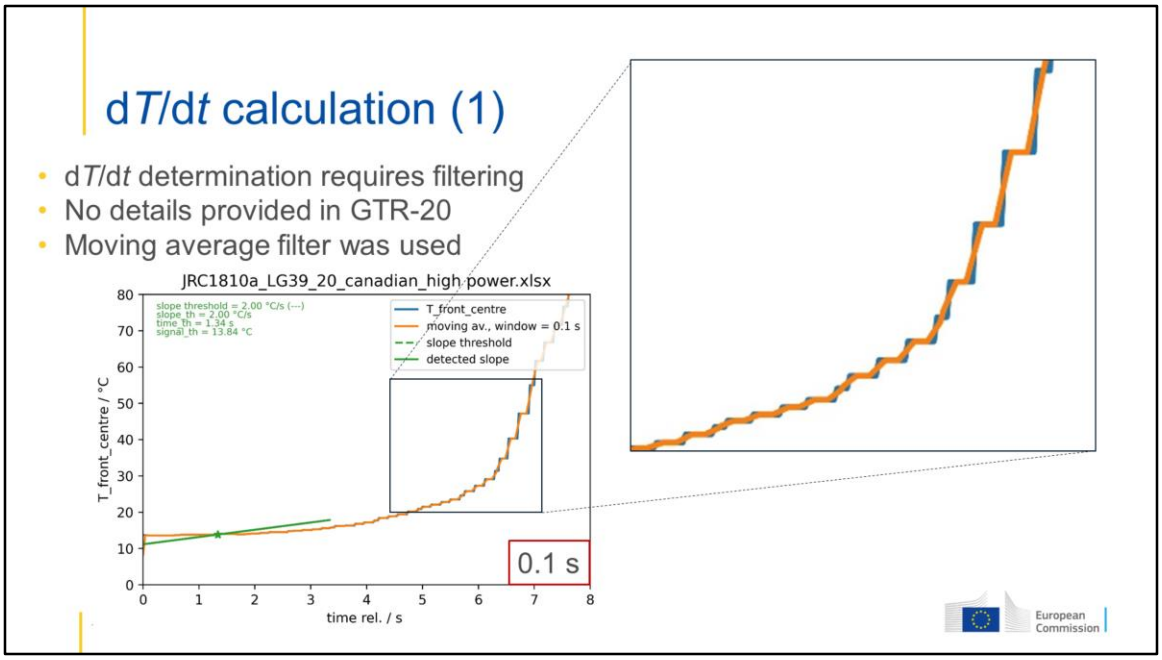
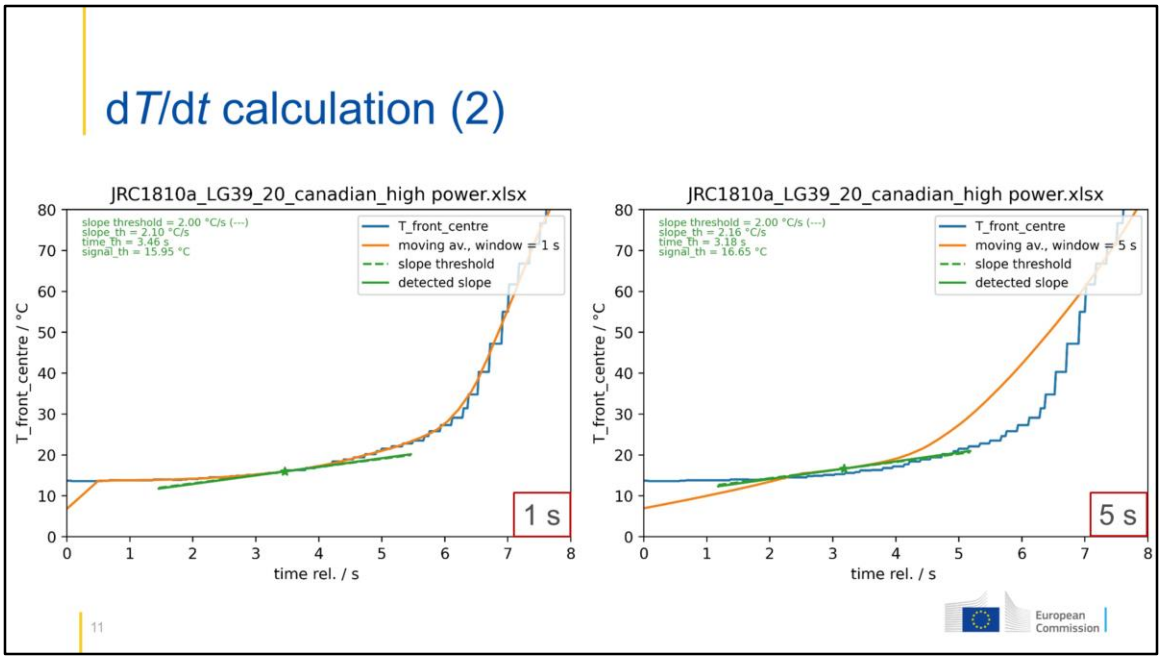
In some cases, however, it was observed that the cell voltage can “recover” to some extend. In all cases where this recovery was observed so far, a TR event followed. However, it needs to be checked if this recovery also can happen in cases that do not lead to TR events.



slope threshold: threshold set for d*T*/d*t* (here 2 °C/s)
slope_th: slope actually detected
time_th: moment at which slope_th is reached
signal_th: measured temperature at time time_th

The signal was filtered with a moving average filter with a 0.1 s time window. The filtered function still has a “step function” character, leading to a “non-physical” temperature slope as indicated by the green line which is the calculated slope at the moment where the d*T*/d*t* for the first time is above the threshold, but it’s clearly not the tangent to the temperature curve; the the time window is too small.



These are plots with 1 s (left) and 5 s (right) time windows.
In the case of the 5 s time window the green line is the tangent of the filtered (orange) curve, however, the filtered curve (orange) does not follow the measured (blue) temperature signal; the time window is too big.
The left curve with a 1 s time window in contrast meets both conditions: the green curve is the tangent of the orange curve (so the filtered curve is smooth enough to yield a reasonable derivative) and the time window is small enough so that the filtered curve closely follows the measured temperature signal.

Criteria in this study

(i) "*Voltage drop of the initiating cell*"

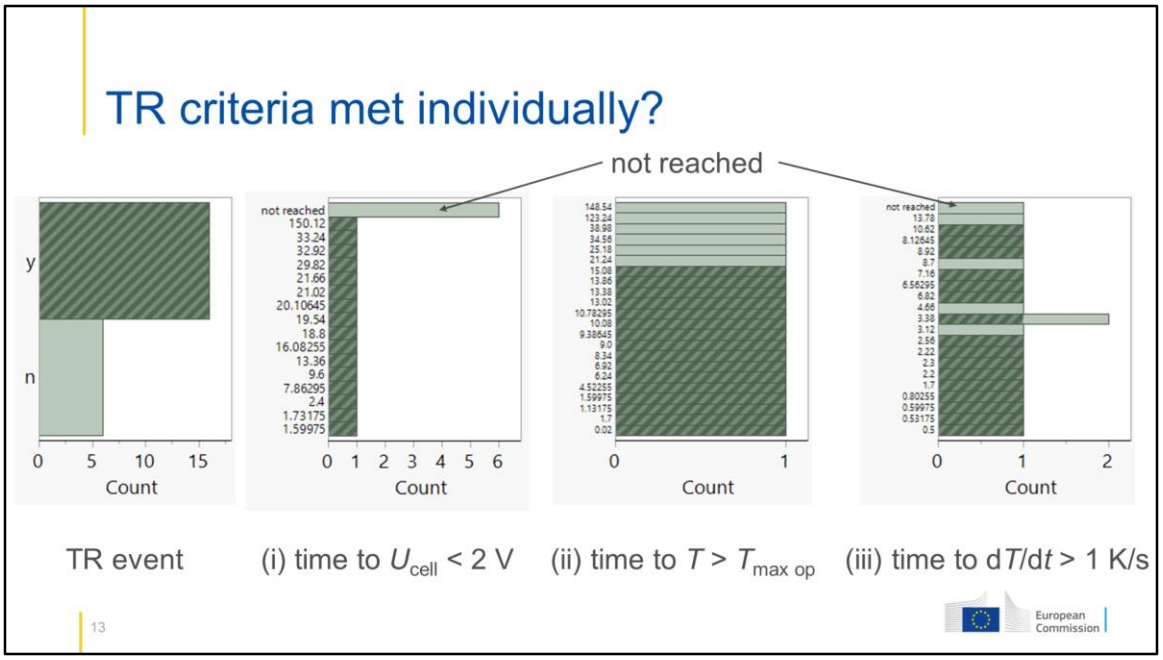
- Cell voltage U_{cell} < 2 V (not specified in GTR)

(ii) T exceeds $T_{max\ op}$ as specified by manufacturer

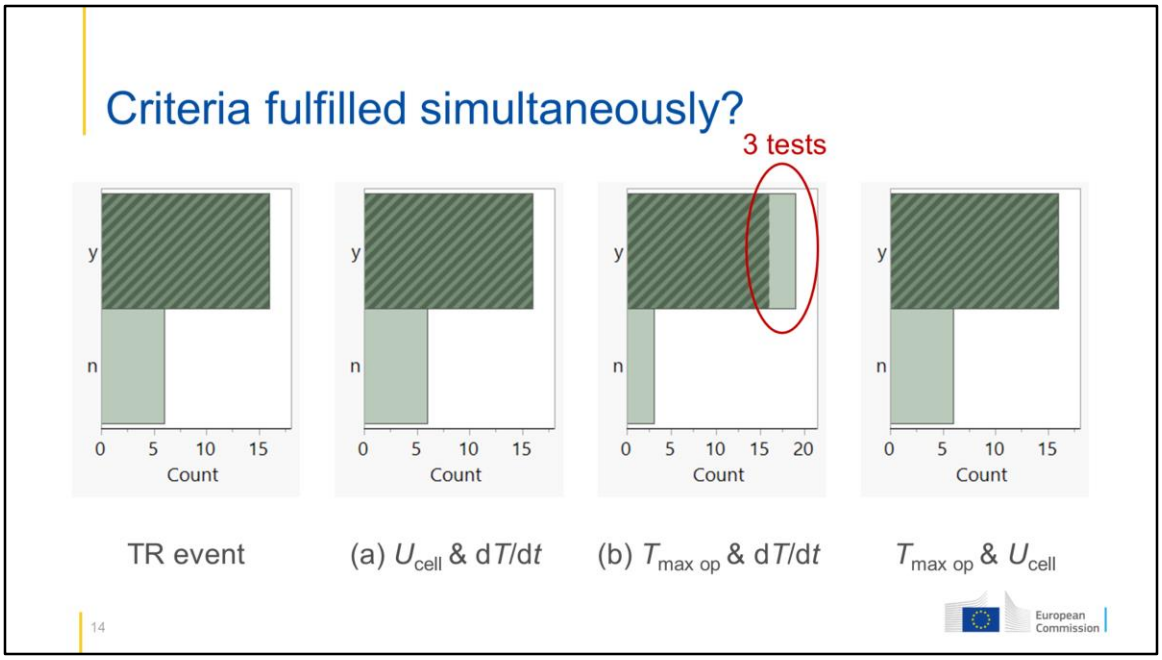
(iii) dT/dt > 1 °C/s

- Moving average filter with 1 s window (not specified in GTR)
- Met simultaneously
  - (a) with criterion (i) "*voltage of the initiation cell drops*": if U_{cell} < 2 V (i.e. not only if U_{cell} drops while dT/dt > 1 °C/s)
  - (b) with criterion (ii) if $T > T_{max\ op}$

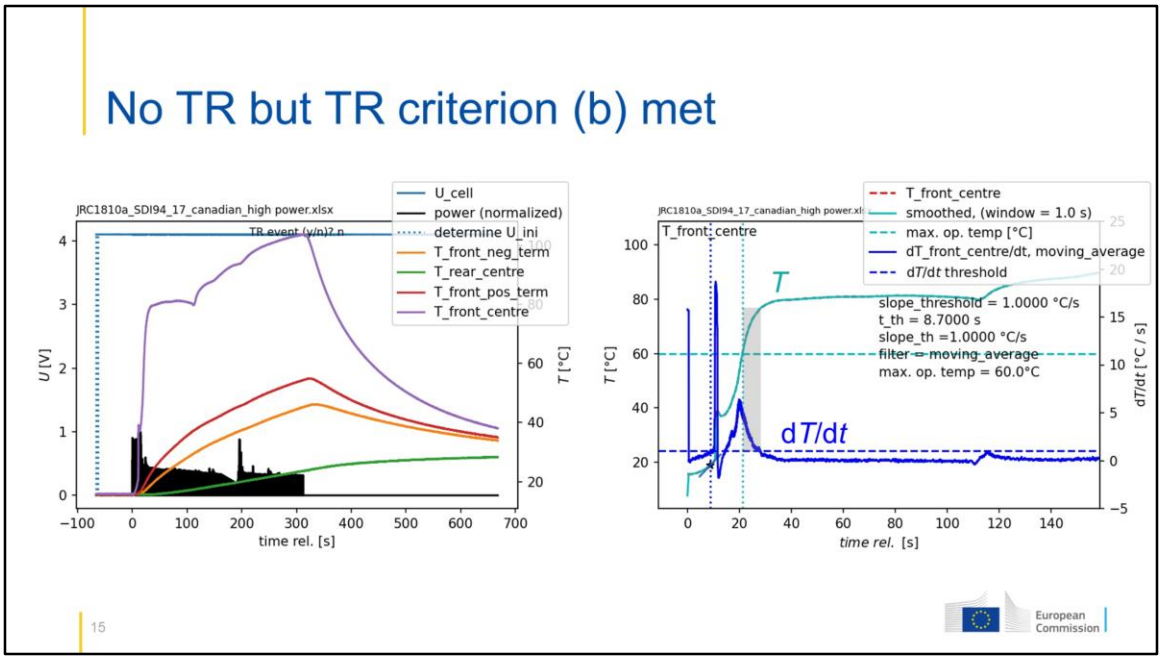
These are the criteria applied in the current study. The text in blue highlights the specifications used here that are not specified in the GTR-20.



Overview of which tests meet which of the GTR-20 criteria individually. The hatched areas represent the same tests (the TR events) in all plots.
The actual times when the criteria are met are not further considered here since they depend on the details of the test configuration (like heating power).
Note that:
(i) all TR events but no non-TR events met the cell voltage criterion
(ii) all cells (including the non-TR cases) were heated above the maximum operation temperature (but the TR cases get there faster).
(iii) the dT/dt criterion was fulfilled by all TR cases and all but one non-TR case.



Check if the criteria are reached simultaneously. The last combination $T_{max\ op}$ & U_{cell} is not included in the GTR-20.
3 tests meet the TR criterion (b) specified in the GTR but are not TR-events. These tests are presented in the next slides.

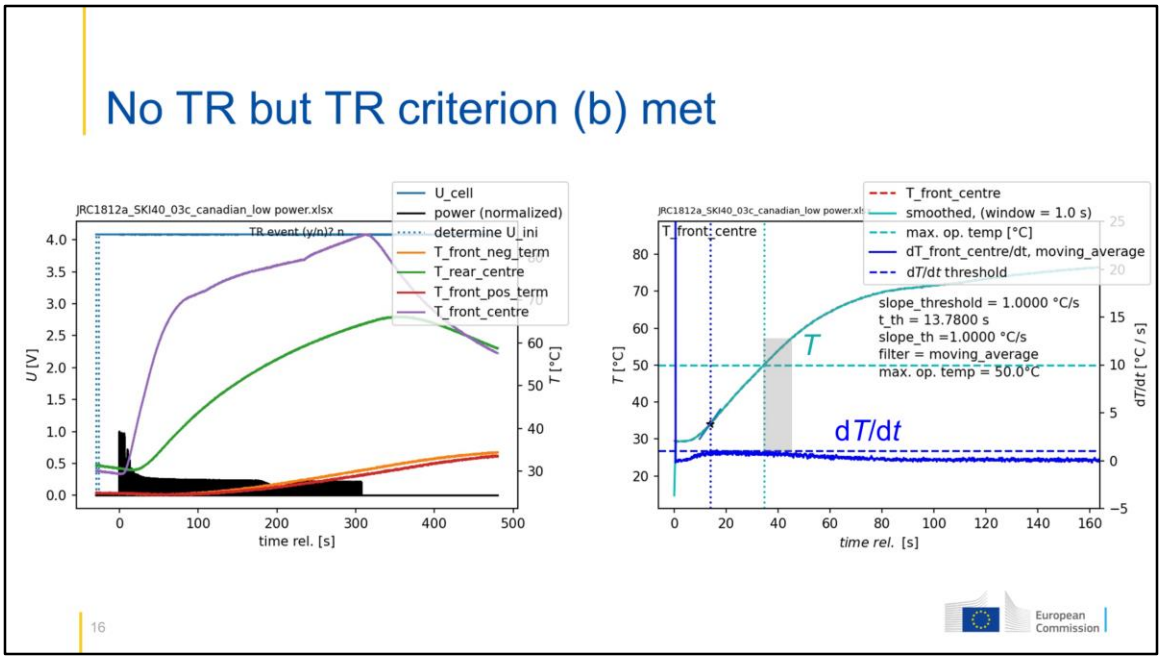


The left graph provides an overview of the test.

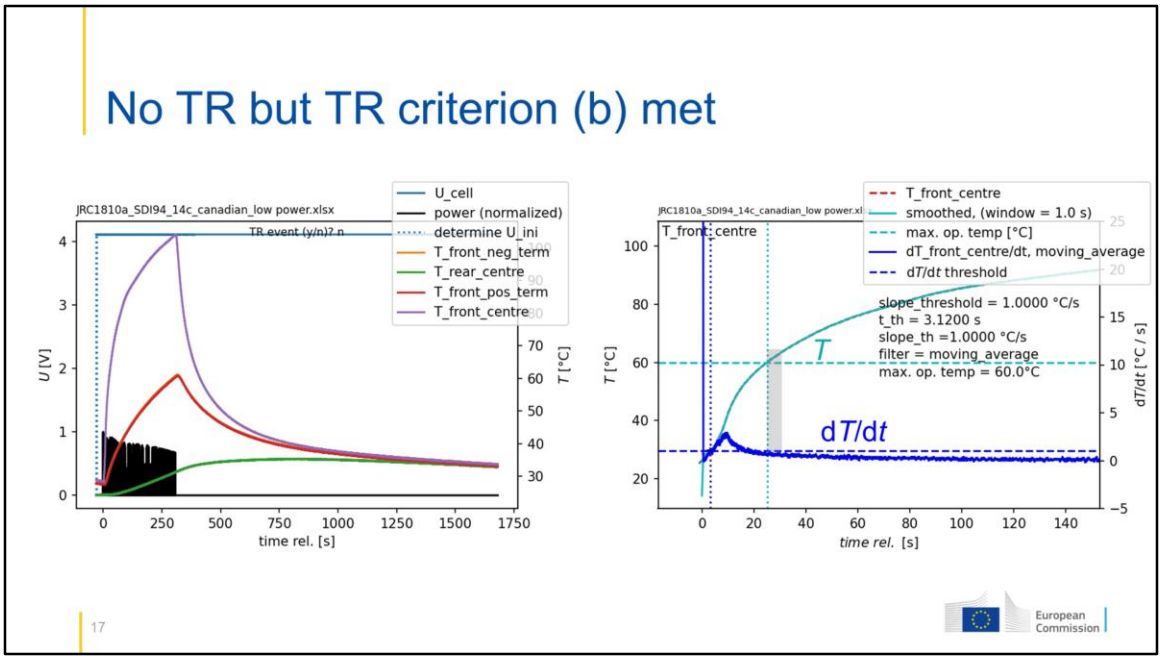
- The blue curve is the cell voltage (the 2 vertical dashed lines (very close to each other) at the very left of the plot indicate the interval in which the initial cell voltage is determined)
- The black lines show then heating pulse. (It is normalized by the maximum power)
- The coloured lines are the different temperature signals. The one considered here is *T*_front_centre. Since that thermocouple was close to the heat source, it shows the highest temperature.

The right graph allows monitoring the TR criteria (i) and (iii) over time. The light blue is the temperature signal *T* and the dark blue is d*T*/d*t*. In each case the horizontal long dashed line indicated the threshold l (max. operating temperature for *T* and 1 K/s for d*T*/d*t*).

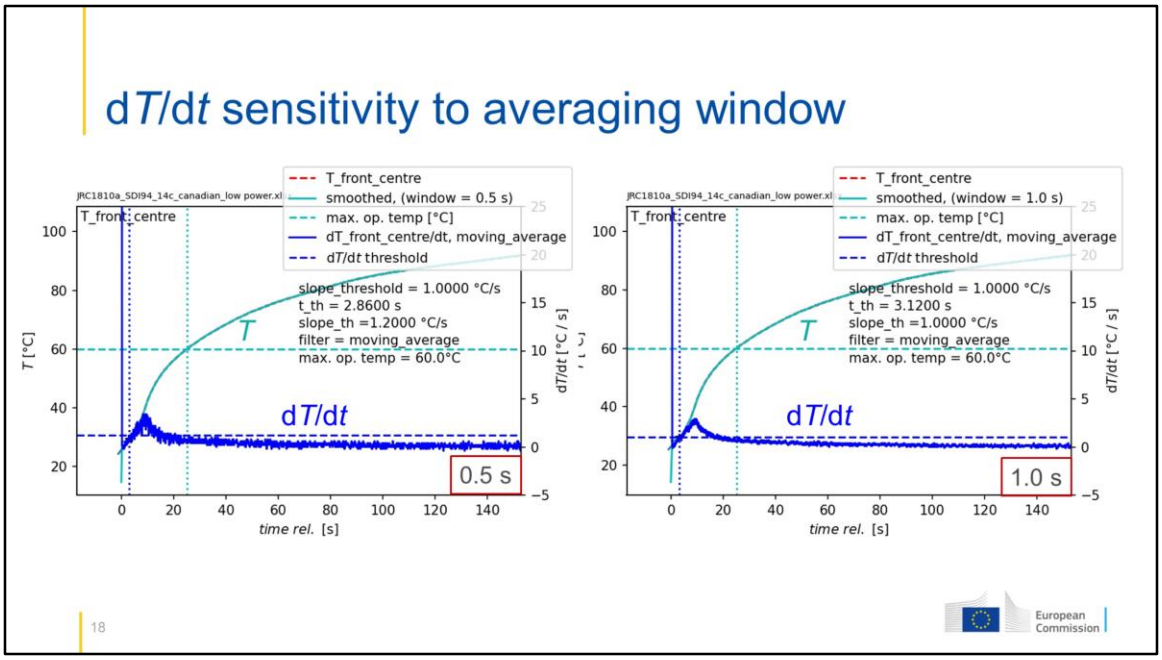
The grey rectangle indicates the area where both criteria a met simultaneously.



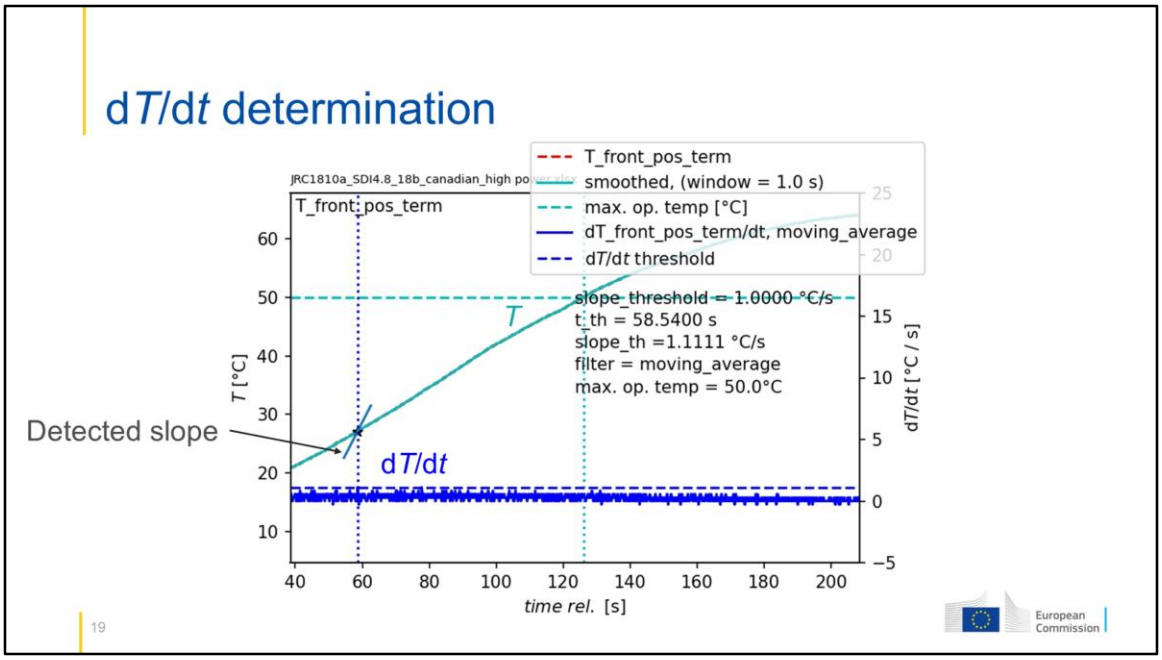
For description see previous slide.
The d*T*/d*t* criterion (iii) is met only for short moments after the measured temperature reaches the maximum operating temperature. This is strongly influenced by the filtering.



For description see pre-previous slide.
The d*T*/d*t* criterion (iii) is met only for short moments after the measured temperature reaches the maximum operating temperature. This is strongly influenced by the filtering.



Impact of the width of the window used in the moving average filter (left 0.5 s, right 1.0 s) on the noise of the d*T*/d*t* curve.



Because of the noise on the d*T*/d*t* signal, the detected slope is significantly exceeds the average slope at that moment.

Conclusions

- GTR criteria for identifying TR have been assessed on 16 TR and 6 non-TR events.
- All TR events met both GTR criteria.
- JRC work has shown that GTR EVS criteria need clarification:
  - Criterion (b) ($T_{max\ op}$ & dT/dt) is shown not to be always robust.
    At cell level 3 non-TR events were identified as TR when criterion (b) was used.
  - Condition (i) – specification on voltage drop – needs to be defined.
    At cell level voltage condition (i) was found to be relatively independent from threshold value.
  - dT/dt condition (iii) was demonstrated to be sensitive to filter parameters (e.g. time averaging window), some specifications should be introduced.
- Implications depend on use case (test, alarm)

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Outlook

Evaluation of the remaining JRC tests is ongoing:

- At cell level with rapid heating initiation - analysis of temperature signals recorded by thermocouples at other locations;
- At cell level with other initiation methods;
- At short stack and module level with rapid heating initiation method

→ Assessment/Development of criteria for Thermal Runaway and Thermal Propagation.

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