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Joint Research Centre

# Progress on thermal propagation testing

*Andreas Podias, Akos Kriston, Andreas Pfrang, Vanesa Ruiz, Adriano Antonelli, Lois Brett*

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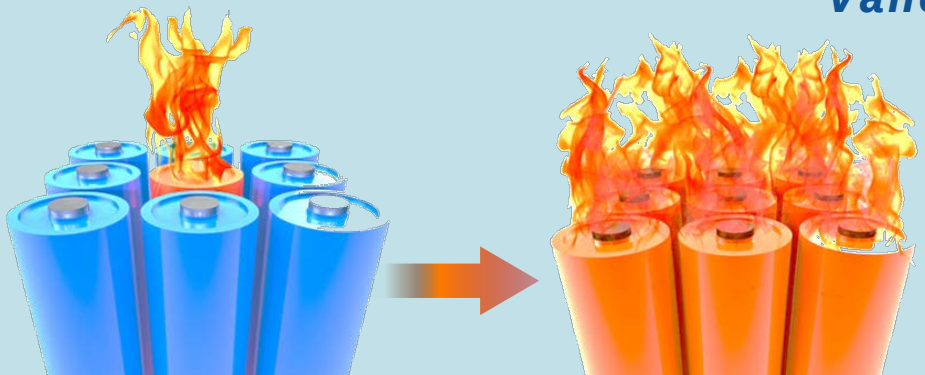

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# Outline

- **JRC experimental TP activity**
- Initiation tests: update on inductive heating
- First results from short stack tests
- Next steps: further evaluation and module tests

# JRC experimental TP activity

## Cell & material

Comparison of initiation techniques

- Trigger energy/ energy release
- Repeatability
  + ARC, DSC

## Short stack

Analyse influential factors on the outcome

- Temperature, SOC…
- Cell configuration
- Spark source

## Module

Evaluate repeatability, reproducibility

- Check proposed test descriptions (also with testing bodies)
- Round robin tests
- Define pass/fail criteria

## Pack, Vehicle

Verification and finalization of method

- Round robin tests
- Practical aspects
- Define robust evaluation methods (e.g. gas analysis)

Narrow down init. methods

Refine test description

Select equivalent test(s)

# JRC experimental TP activity

## Cell & material

Comparison of initiation techniques

- Trigger energy/ energy release
- Repeatability
  + ARC, DSC

## Short stack

Analyse influential factors on the outcome

- Temperature, SOC…
- Cell ~~configuration~~ orientation
- ~~Spark source~~
- Cell separation

## Module

Evaluate repeatability, reproducibility

- Check proposed test descriptions (also with testing bodies)
- Round robin tests
- Define pass/fail criteria

## Pack, Vehicle

Verification and finalization of method

- Round robin tests
- Practical aspects
- Define robust evaluation methods (e.g. gas analysis)

Narrow down init. methods

Refine test description

Select equivalent test(s)

# Recap of previous findings

- Literature review and JRC workshop showed that the currently proposed description of TR initiation techniques in the GTR might not be fully suitable for TP assessment
- Simulation of thermal runaway showed that the resistance ($R_{ext}/R_{int}$) ratio and the surface-to-volume ratio have the highest impact on thermal runaway probability
- Initiation test campaign showed that TRIM method works reliably on different cell types (also nail penetration worked ok, but it was sensitive to boundary conditions)

# Evaluation of methods: if triggering TR is the purpose

| Initiation method | Indicators | | | | | |
|---|---|---|---|---|---|---|
| | Influence of parameters | Energy insert | Locality | Readiness | Manipulation | Scores |
| **Heating** | Low | High | No | Yes | High | 2 |
| **Steel nail** | High | Low | Yes | Yes | High | 3 |
| **Ceramic nail** | High | Low | Yes | Yes | High | 3 |
| **TRIM method** | Low | Low | Yes | Yes | Low | 5 |
| **Inductive heating** | Low | Low | Yes | No | TBC | 3 |

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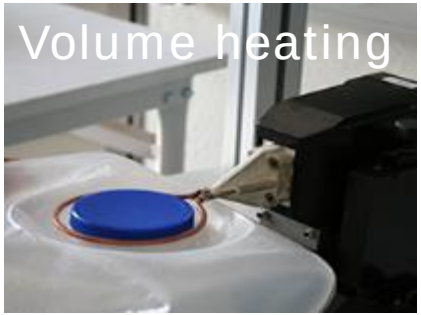
# Alternative initiation method: Inductive heating

## Why?






## How?

Alternating electromagnetic field generate local current (eddy current) which in turn generate heat in any closed loop conductors, e.g. Al, Cu, graphite, NMC

- Does not require direct contact: less manipulation may be needed
- Coil geometry is not limited in shape and size

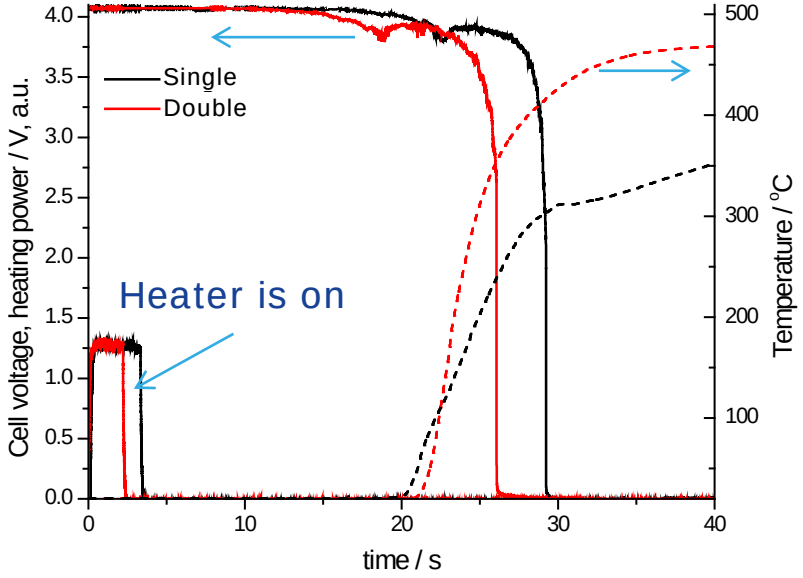
# Pouch cell tests

Initiation

Single coil #4

Double (Helmholtz) coil #5

Initiation ➡ ISC Development ➡ TR



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# Preliminary results on single cells

*The current device was not optimized for short ‘on’ time, therefore the heating energy is just a rough approximation.

| Cell | Power, heating time* | Results |
|---|---|---|
| #1, 18650 3.1 Ah | 1.2 kW for 2 s: ca. 6.5% of cell’s energy, single coil around the cell | TR with fire, $T_{max}$=830°C. TR happened during heating. The case opened near the coil. |
| #2, 18650 3.1 Ah | 1.2 kW for 1 s, ca. 3.3% of cell’s energy, single coil around the cell | TR with fire, $T_{max}$=734°C. TR happened during heating. The case also opened near the coil. |
| #3, 18650 3.1 Ah | 1 kW for 0.5 s, ca. 1.5% of cell’s energy, single coil around the cell | TR with fire, $T_{max}$=741°C. TR happened several seconds after the heater was switched off. The pouch opened near the coil. |
| #4, Pouch, 39 Ah | 1.2 kW for 2 s, ca. 0.41% of cell’s energy. The coil is placed parallel to the surface at the middle of the cell | TR with fire, $T_{max}$=ca. 400°C The pouch opened near the coil. |
| #5, Pouch, 39 Ah | 1.2 kW for 1 s, ca. 0.2% of cell’s energy. The cell was placed between the coil. | TR without fire, $T_{max}$=420°C The cell ruptured at the side but not under the coil. |
| #6, Prismatic, hard Al case, 96 Ah | 2.4 kW for 3 s, ca. 0.78% of cell’s energy | TR with fire, $T_{max}$=550°C. The case opened near the coil. |

- Locally damage the cell
- Works fast
- Needs small amount of energy

Video 18650, #3

# Updated results on single cells

Inductive heating conditions were reproduced (cell replaced by stainless steel screw) and current/voltage and heating duration were measured.

| Cell | Nominal power, heating time | Estimated power, heating time | Estimated inserted energy / electrical energy content |
|---|---|---|---|
| #1, 18650 3.1 Ah | 1.2 kW for 2 s | max. 1.2 kW for ca. **3.1 s** | ca. 6.9 % |
| #2, 18650 3.1 Ah | 1.2 kW for 1 s | max. 1.2 kW for **2.2 s** | ca. 3.1 % |
| #3, 18650 3.1 Ah | 1 kW for 0.5 s | max. 1 kW for **1.6 s** | ca. 0.9 % |
| #4, Pouch, 39 Ah | 1.2 kW for 2 s | max. 1.2 kW for **3.1 s** | ca. 0.5 % |
| #5, Pouch, 39 Ah | 1.2 kW for 1 s | max. 1.2 kW for **2.2 s** | ca. 0.25 % |
| #6, Prismatic, hard Al case, 96 Ah | 2.4 kW for 3 s | max. 2.4 kW for **4.2 s** | ca. 0.7 % |

A. Kriston, A. Antonelli, A. Kersys, S. Ripplinger, S. Holmstrom, S. Trischler; H. Döring, A. Pfrang, Initiation of thermal runaway in Lithium-ion cells by inductive heating, submitted to Journal of Power Sources

# Conclusion remains valid

- Inductive heating tests showed, that minimal energy input (~1%) was needed to initiate TR. Local initiation is sufficient to trigger TR

# Outline

- JRC experimental TP activity
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- **First results from short stack tests**
- **Next steps: further evaluation and module tests**

# Draft short stack test matrix

| Initiation method | Automotive 39 Ah pouch cells / stacks / modules | | | |
|---|---|---|---|---|
| **Test type** | Cell initiation | Short stack | Module | Total |
| **Heating?** | | ? | | |
| **Ceramic nail** | | | | |
| **TRIM method** | | | | |
| **Total** | **5** | **16** | **2** | **23** |

# Short stack test matrix

| Initiation method | Automotive 40 Ah pouch cells / stacks / modules | | | |
|---|---|---|---|---|
| **Test type** | 2 cell stack | 5 cell stack | Module | Total |
| **Ceramic nail** | - | 4 | - | 4 |
| **TRIM method** | 3 | 12 | 2 | 17 |
| **Total** | **3** | **16** | **2** | **21** |

# Short stack test matrix: progress

| Initiation method | Automotive 40 Ah pouch cells / stacks / modules | | | |
|---|---|---|---|---|
| **Test type** | 2 cell stack | 5 cell stack | Module | Total |
| **Ceramic nail** | - | 4 | - | 4 |
| **TRIM method** | 3 | 12 | 2 | 17 |
| **Total** | **3** | **16** | **2** | **21** |

Executed

To be executed

# Initiation test campaign: severity

| Test | Low severity | High severity | Comment |
|---|---|---|---|
| Steel nail | Stop nail at a certain voltage drop (mV) | Penetrate until event | Every cell has different voltage drop |
| Ceramic nail | | | |
| Heating | 1 heater | 2 heaters | The heating power per heater kept constant. Increasing the energy intake |
| TRIM | Lowest possible e.g. 250 °C for pouch | 600 °C until event | Varying soaking temperature and time |

# Testing matrix 5 cell stack tests

| Initiation Method | Insulation material | |
|---|---|---|
| | None | HKO Defensor-Flex® ML (multilayer) 17 |
| TRIM | 6 | 6 |
| Ceramic nail | 2 | 2 |
| Total | 8 | 8 |

Compression of ML17 from 5 mm to 4 mm thickness by applying 1 kN (further compression possible with larger force)

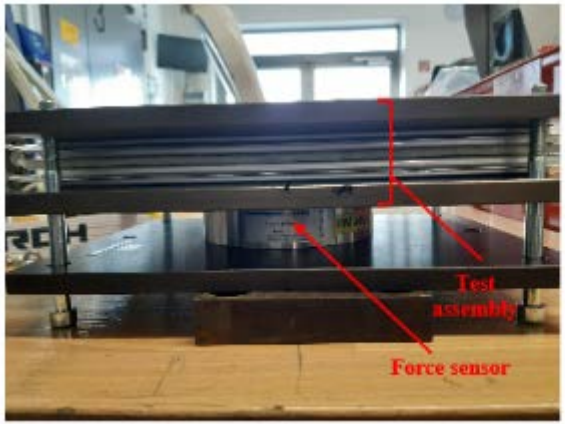
Different orientation of the stack (vertical or horizontal cells) will also be assessed for TRIM

# Evaluation of short stack tests

Preparatory steps – same compression force (1 kN) for all tests

Ceramic nail penetration // Fast heating (TRIM)

2-cell short stacks // 5-cell short stacks




(A)

(B)



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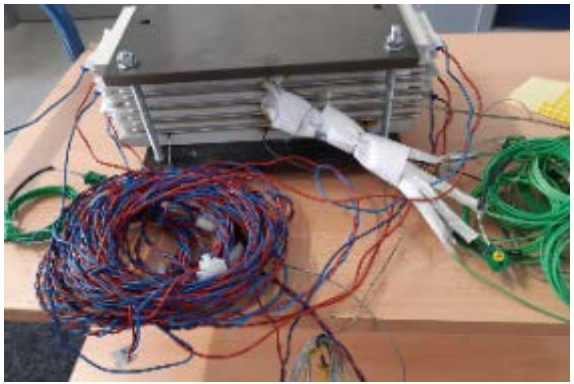
# Evaluation of short stack tests

## Ceramic nail penetration tests // 5-cell stack

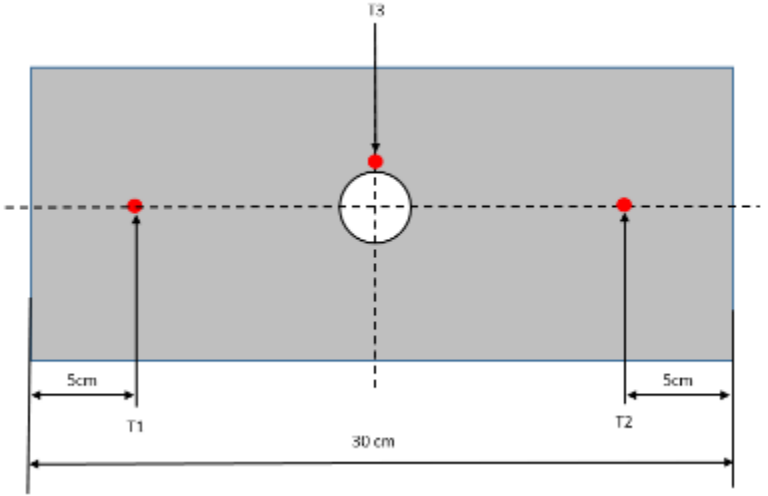
| Graphite / Ni rich NMC pouch cells | | |
|---|---|---|
| Capacity | Specific energy at C/3 | Volumetric energy density at C/3 |
| 40 Ah | 150 Wh/kg | 230 Wh/l |

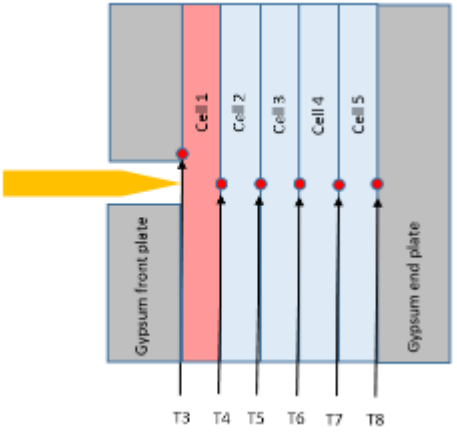


# Evaluation of short stack tests

## Ceramic nail penetration test conditions and location of thermocouples // 5-cell stack without ML

| Nail diameter | Circular cone tip angle | Penetration Velocity | SoC |
|---|---|---|---|
| 3mm | 30º | 0.1 mm/s | 100% |



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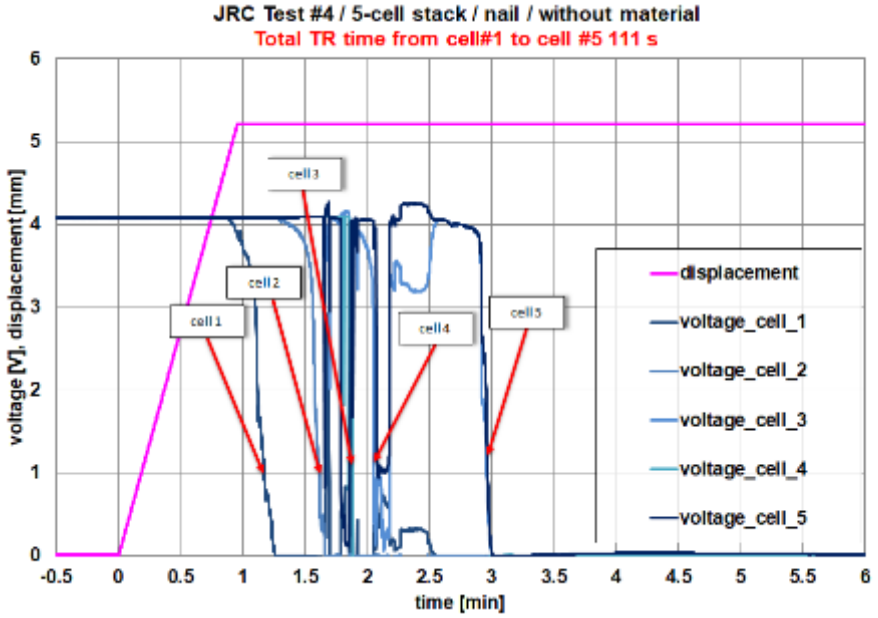
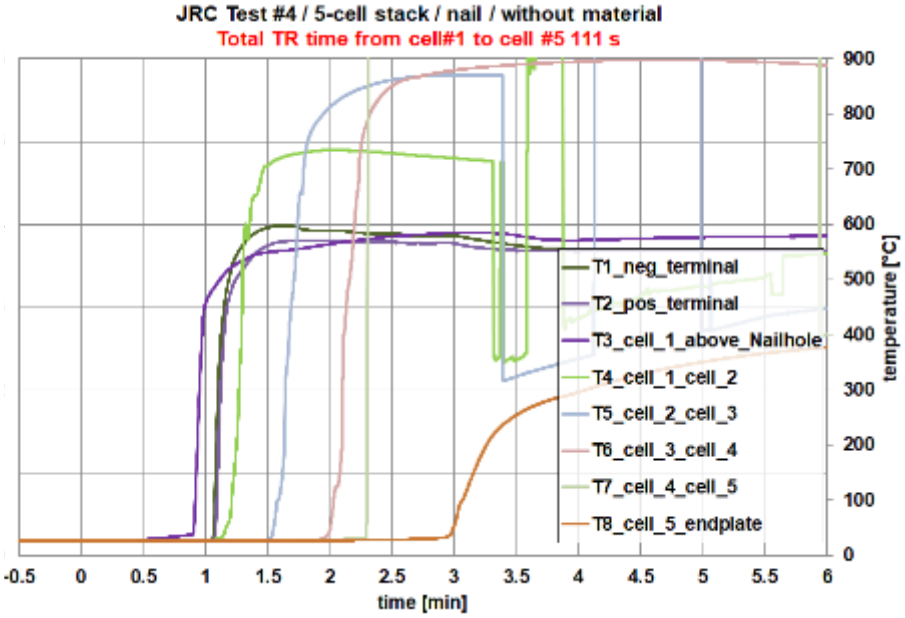
# Evaluation of short stack tests

## Ceramic nail penetration tests // 5-cell stack without ML



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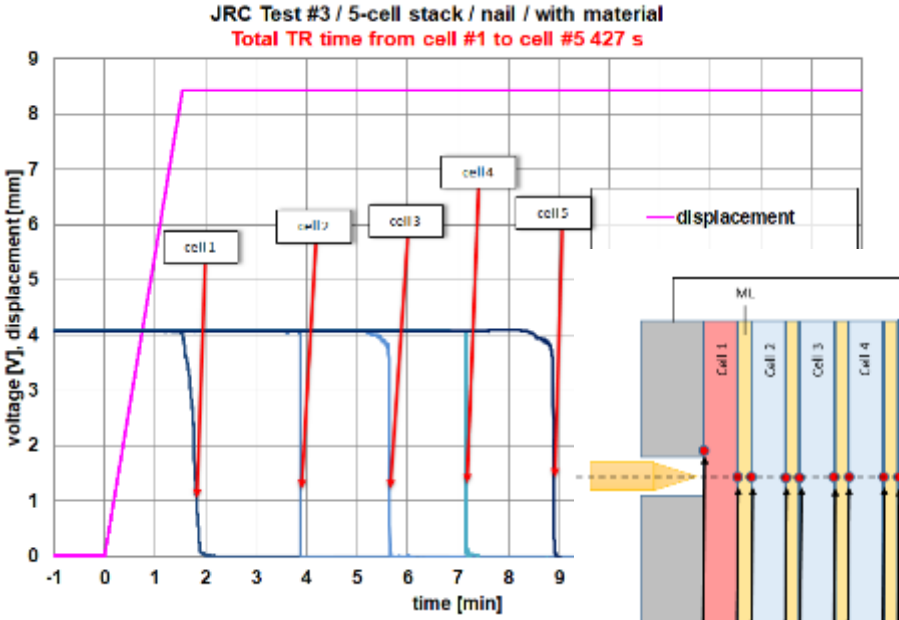
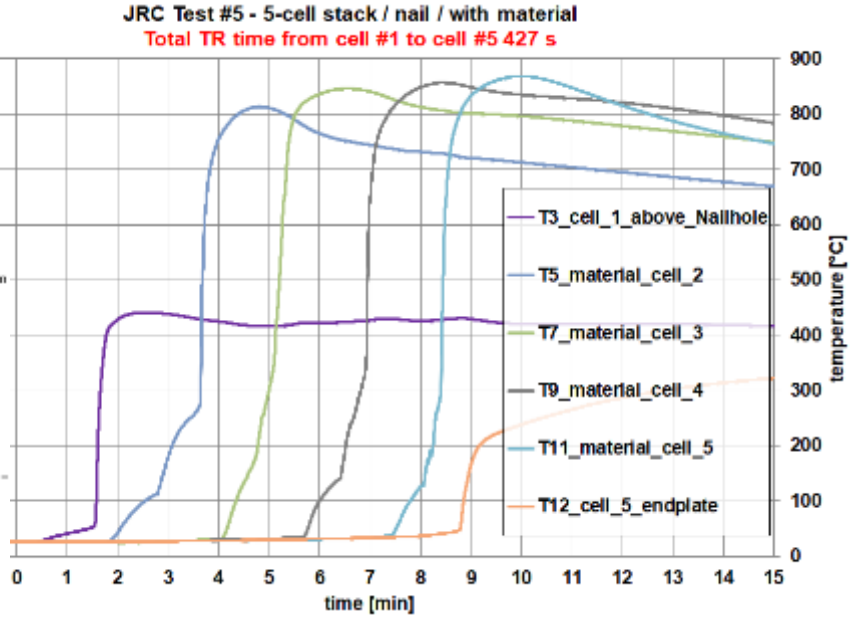
# Evaluation of short stack tests

## Ceramic nail penetration tests // 5-cell stack with ML









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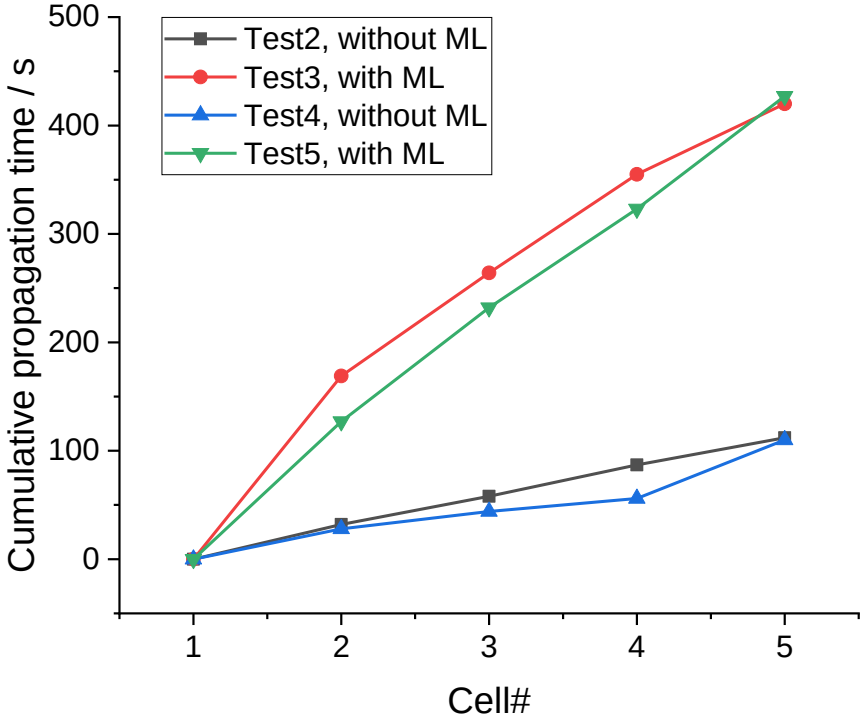
# Evaluation of short stack tests (preliminary)

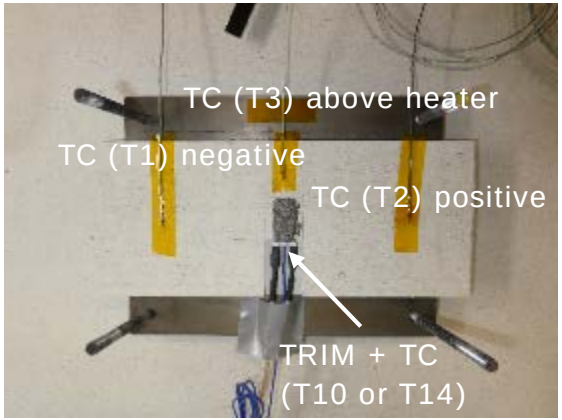


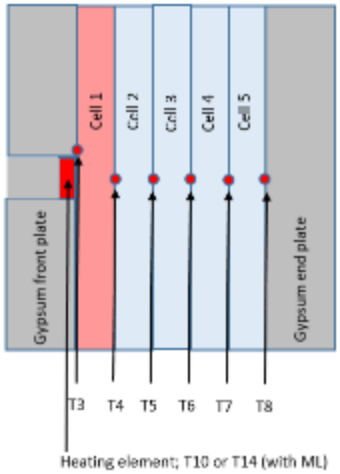

- Progression of TP seems to be predictable for both cases
- ML slowed down TP (by a factor of about 4)

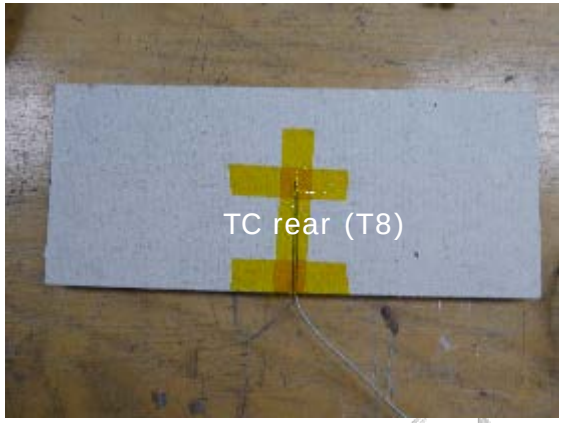
# Evaluation of short stack tests

## Fast heating (TRIM) test conditions and location of thermocouples // 5-cell stack without ML

| Target temperature | Temperature increase rate | SoC |
|---|---|---|
| 600ºC | 50ºC/s | 100% |



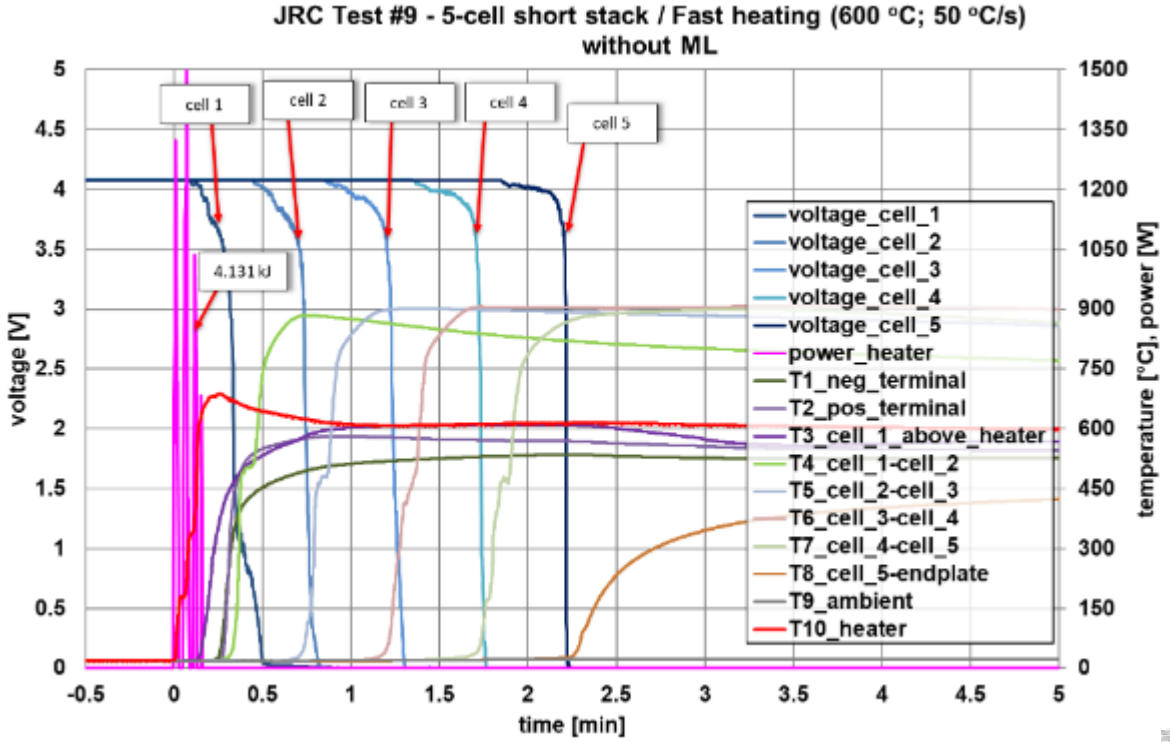



# Evaluation of short stack tests

## Fast heating (TRIM) // 5-cell stack // preparations

# Evaluation of short stack tests
# Fast heating (TRIM)



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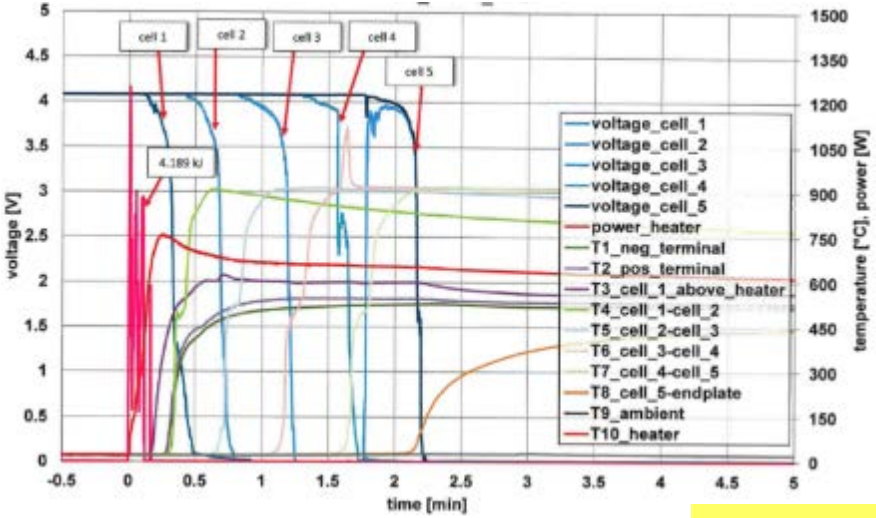
# Evaluation of short stack tests

## Fast heating (TRIM)

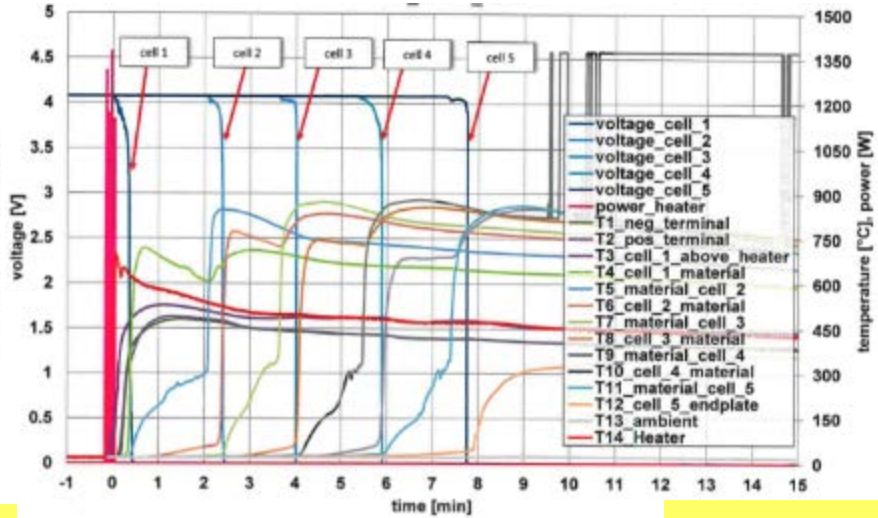
**5-cell short stack / Fast heating (600oC; 50oC/s until event)**

**Without ML**




5 minutes

**With ML**




15 minutes



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# Evaluation of short stack tests

Still on-going

# Evaluation of short stack tests

## Preliminary findings

- Initiation by TRIM and ceramic nail penetration works ok
  - **Criterion for stopping initiation (‘until event’) to be evaluated further**
- Propagation times
  - **Rather consistent for identical conditions**
  - **Delay of propagation by addition of multi-layer material**
  - **Statistical analysis will be performed**
- Time/criteria for defining/determining thermal runaway to be investigated further

# Further steps

- Improve understanding of the different failure mechanisms caused by different methods (e.g. local and global effects)
- Further complementary experimental work at material level (e.g. thermal analysis) and at cell level (ARC)
- Evaluation of stack/module-level TP testing campaign

**Further collaboration with Canada on TRIM method**

- Proceed with pack and vehicle level tests

*Regular discussions with other parties are appreciated*

# Acknowledgement *BATTEST group*

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ulrich.stude@saint-gobain.com,
carsten.stoeckmann@saint-gobain.com,
steffen.mielke@hko.de



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# Relevant references

V. Ruiz, A. Pfrang, JRC exploratory research: Safer Li-ion batteries by preventing thermal propagation, Workshop report, ISBN 978-92-79-96399-5, Publications Office of the European Union, https://ec.europa.eu/jrc/en/publication/jrc-exploratory-research-safer-li-ion-batteries-preventing-thermal-propagation

OPEN ACCESS

A. Kriston, A. Antonelli, A. Kersys, S. Ripplinger, S. Holmstrom, S. Trischler; H. Döring, A. Pfrang, Initiation of thermal runaway in Lithium-ion cells by inductive heating, submitted to Journal of Power Sources

OPEN ACCESS

A. Kriston, I. Adanouj, V. Ruiz, A. Pfrang, Quantification and simulation of thermal decomposition reactions of Li-ion battery materials by simultaneous thermal analysis coupled with gas analysis, Journal of Power Sources 435 (2019), 226774

Project website https://ec.europa.eu/jrc/en/research-facility/battery-energy-storage-testing-safe-electric-transport

360° view of the battery testing laboratory at JRC https://visitors-centre.jrc.ec.europa.eu/virtual-tour/batterytesting/en/

Movie about battery testing at JRC https://www.youtube.com/watch?v=6u2Gjiudcas

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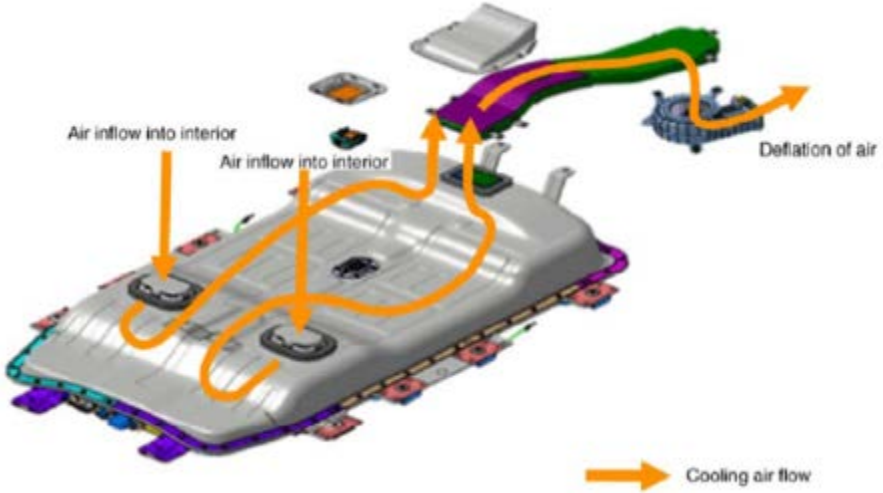
# Back up slides




# Ni-rich NMC/graphite 40Ah pouch cells

# Evaluation of short stack tests

## Ceramic nail penetration tests // 5-cell stack with ML

(A) t=100 s - cell #1 in TR; first instance of white smoke appearance (nail penetrates from the right hand side)

(B) t=105 s - cell #1 in TR; just after grey smoke and sparks appeared

(C) t=113 s - cell #1 in TR; start of fire

t = 0 s corresponds to start of nail motion (nail might not touch at start)