The European Commission's science and knowledge service

Joint Research Centre

Progress on thermal propagation testing

Andreas Podias, Akos Kriston, Andreas Pfrang, Vanesa Ruiz

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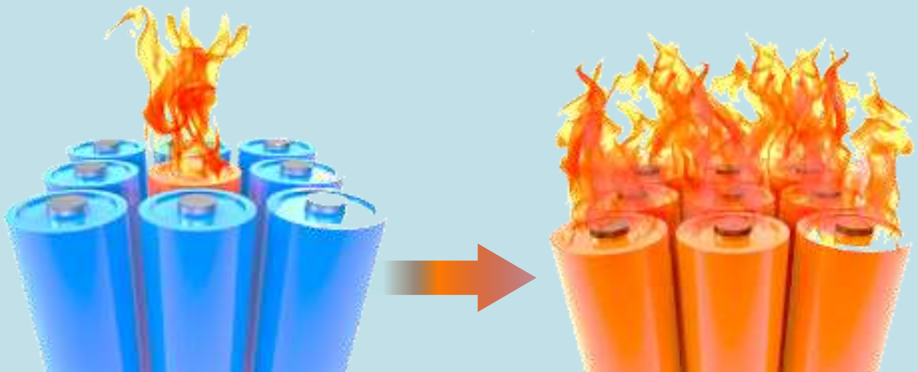

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Outline

- **JRC experimental TP activity**
- Short stack tests update
- Module tests update
- Conclusions and outlook

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 orientation
- 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)

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

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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Outline

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- **Short stack tests update**
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Short stack test matrix: completed

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**

One 2-cell stack test was carried out with two layers of the HKO DEFENSOR-Flex® ML 17 material with a separation distance of ca. 8 mm.

* One of these four penetration tests was repeated due to experimental issues.

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Testing matrix 5 cell stack tests

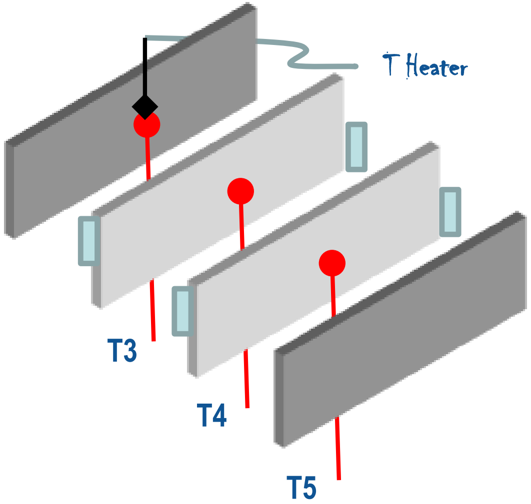
Initiation Method	Insulation material	
	None	HKO Defensor-Flex® ML (multilayer) 17
TRIM	6	6
Ceramic nail	2	2
Total	8	8

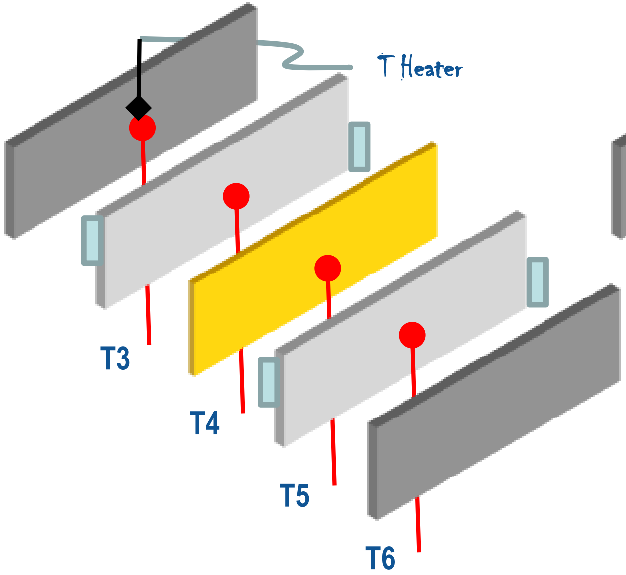
Different orientation of the stack, i.e.:

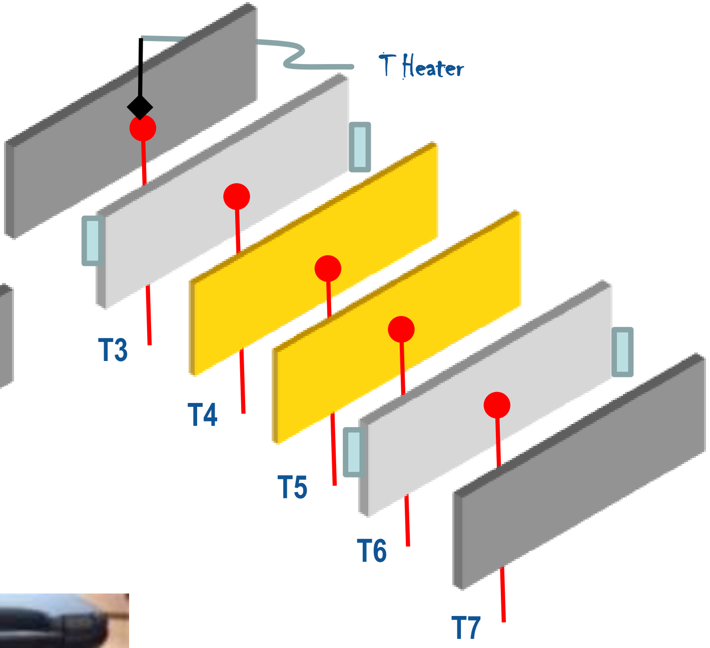
- cells standing up-right and
- cells lying flat on largest surface

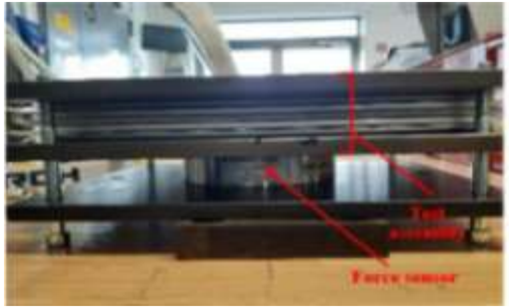
was also assessed for TRIM (with/without ML 17)

Evaluation of 2-cell short stack tests / external rapid heating: impact of thermal insulation material









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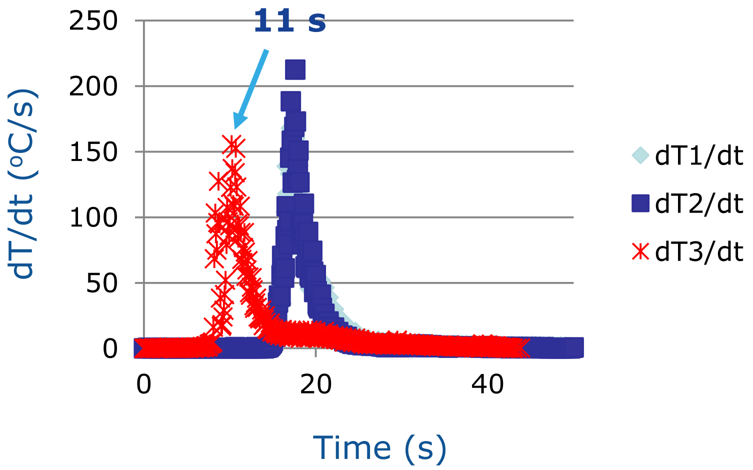
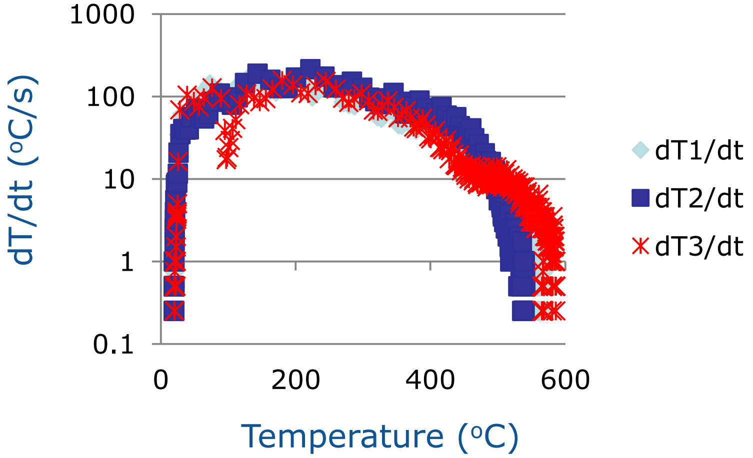
Evaluation of 2-cell short stack tests / external rapid heating: input parameters and findings' overview

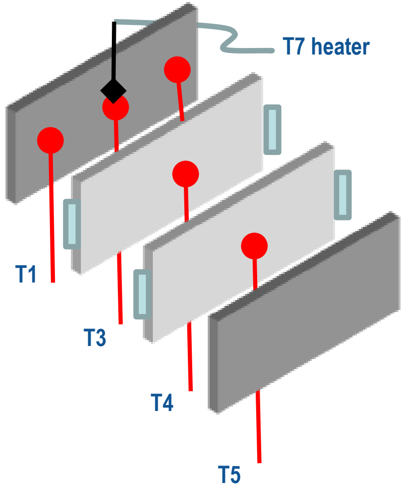
TRIM 2-cell stack experiments (50 °C/s ; T set=600 °C)			Max. Temperature (°C)							Cell-to-cell TP time (s)
Insulation	Injected Energy (Wh)	Inj. Energy / Cell Energy content (%)	T max. Heater	T3	T4	T5	T6	T7	T Ambient	Defined by the voltage drop < 2V
No	**0.99**	**0.86**	**712.70**	585.90	885.20	565.59			16.90	**24**
ML17	**1.55**	**1.34**	**653.20**	515.00	773.54	856.29	448.39		25.20	**110**
(2x) ML17	**1.45**	**1.25**	**703.90**	511.20	746.79	548.59	278.20	91.09	21.10	**No TP**

- Delay of propagation by addition of multi-layer material
- No cell-to-cell propagation in a 2-cell stack test with two layers of HKO's Defensor-Flex® ML 17 with a separation distance of ca. 8 mm

Evaluation of 2-cell short stack tests / external rapid heating







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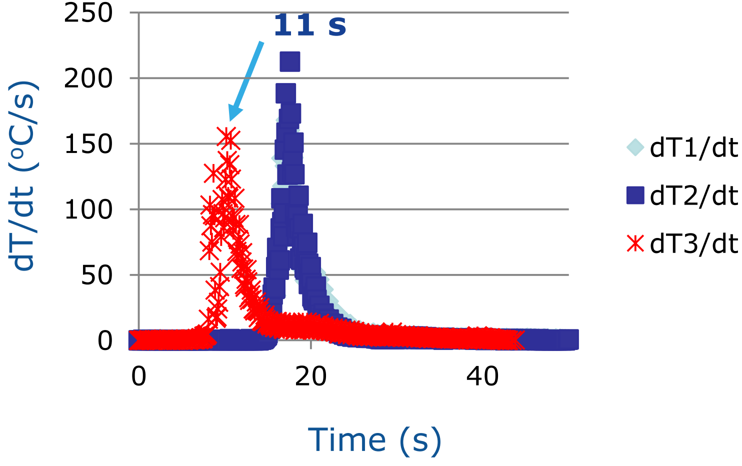
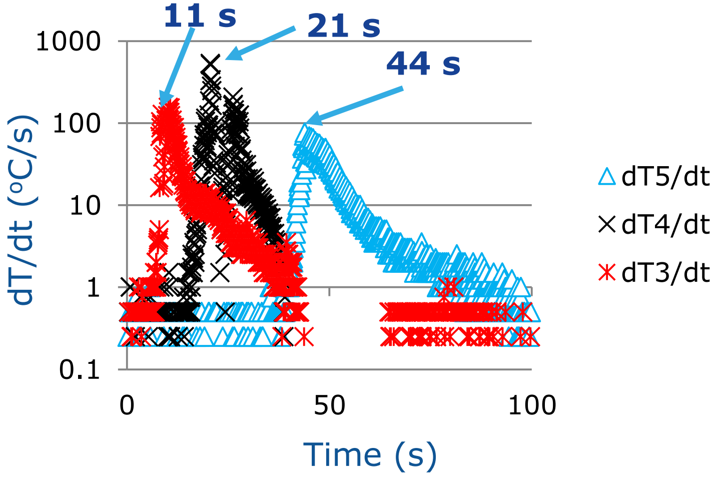
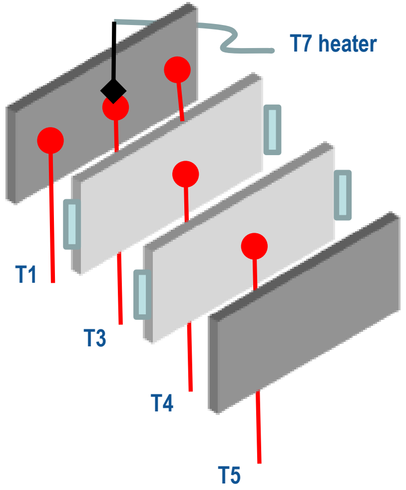
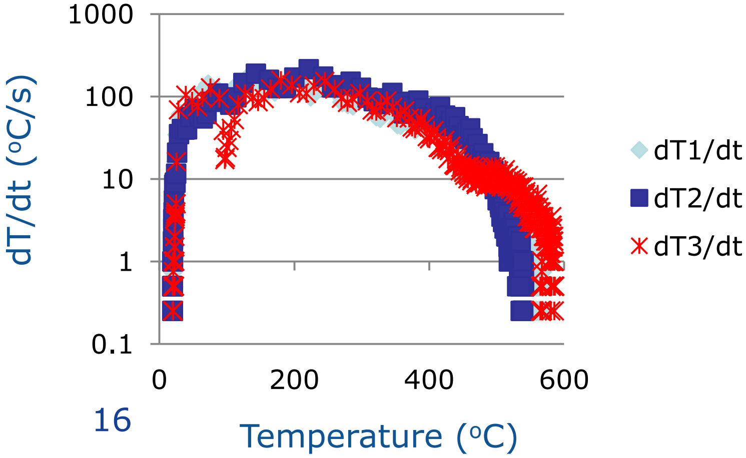
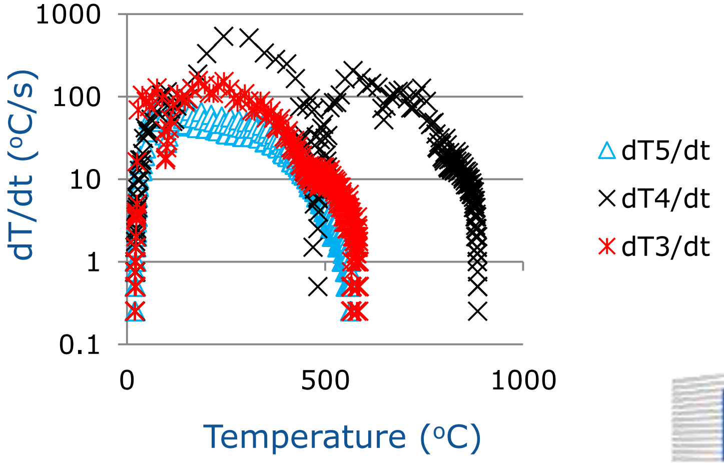
Evaluation of 2-cell short stack tests / external rapid heating







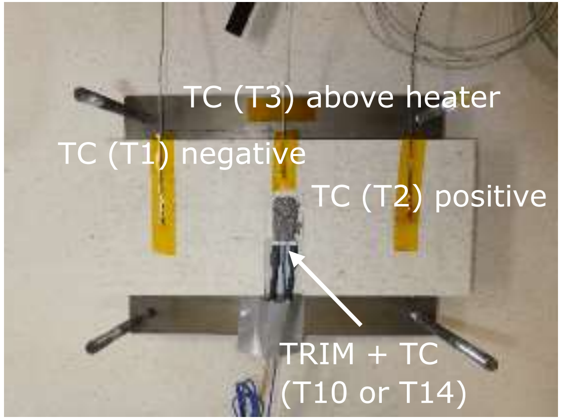


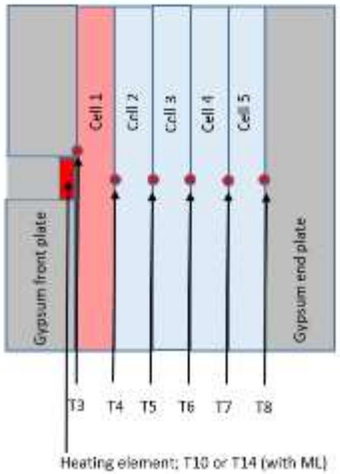


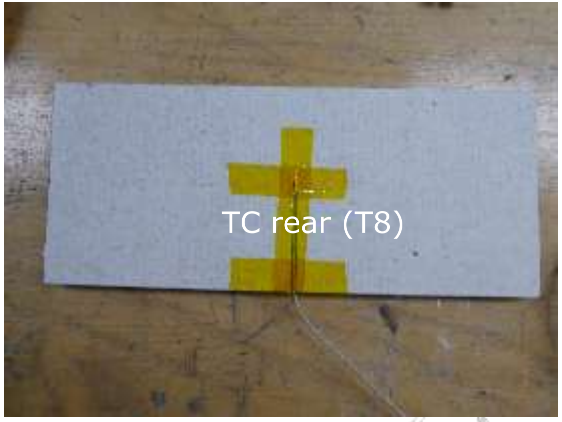
Evaluation of short stack tests

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

Target temperature	Temperature increase rate	SoC
600°C	50°C/s	100%







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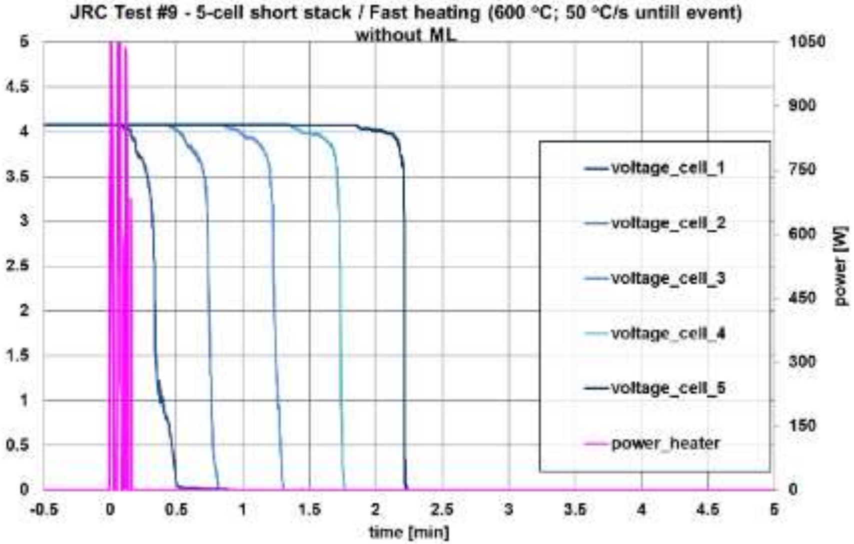
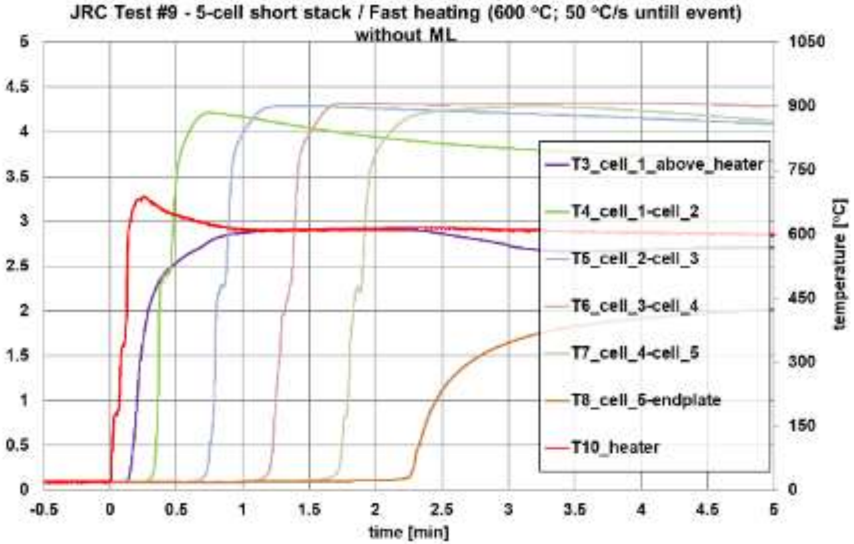
Evaluation of short stack tests

External rapid heating





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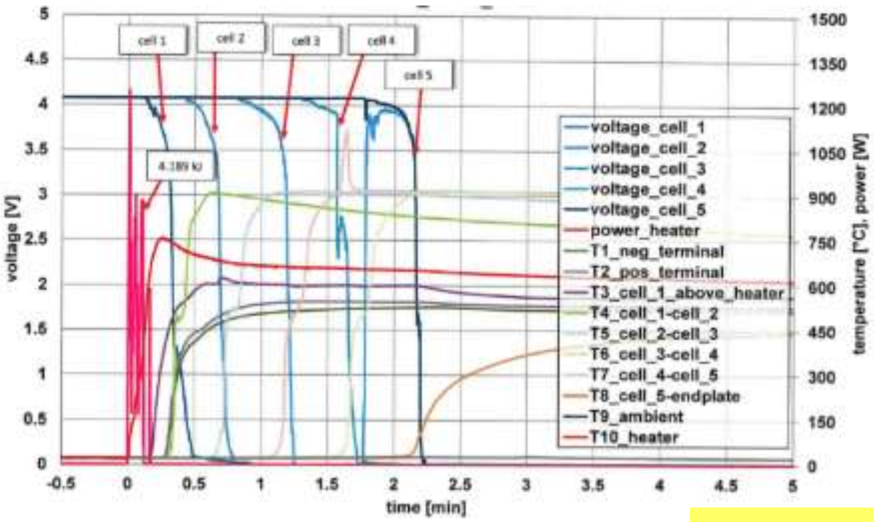
Evaluation of short stack tests

External rapid heating

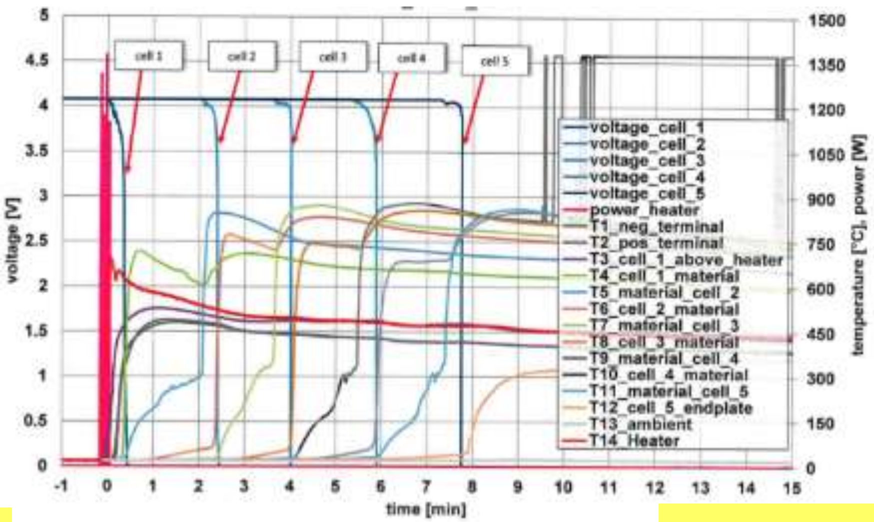
5-cell short stack/rapid heating (600 ºC; 50 ºC/s until event)

Without ML



5 minutes

With ML



15 minutes

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5-cell stack / Input parameters and findings' overview

Average Heating Power (W)	Heating Duration (s)	Heating Energy (Wh)	T max. Heater (°C)	Orientation	Insulation	Cell-to-cell TP time-defined by Voltage drop < 2V				Total TP time (s)	T max. Cell surface (°C)	Fire duration (s)	Mass loss (%)
						1→2 (s)	2→3 (s)	3→4 (s)	4→5 (s)				
506	12.5	**1.77**	**695**	cells standing up-right	ML17	122	97	112	112	**443**	**870**	**No fire**	**35.18**
509	11.8	**1.67**	**720**			94	77	46	95	**312**	**890**	**360**	**36.17**
1582	3.6	**1.63**	**754**			103	105	109	72	**389**	**912**	**231 (long delay; not continuous)**	**35.29**
558	7.4	**1.16**	**754**		No	22	30	27	31	**110**	**912**	**156**	**36.19**
417	9.7	**1.15**	**688**			25	29	30	29	**113**	**907**	**167**	**35.44**
312	12	**1.05**	**703**			22	29	25	35	**111**	**901**	**135**	**35.97**
419	10.1	**1.2**	**675**	cells lying flat	ML17	94	96	107	92	**389**	**884**	**241 (long delay; not continuous)**	**35.10**
480	12.4	**1.66**	**724**			90	88	95	82	**355**	**917**	**324 (long delay)**	**34.82**
437	11.4	**1.40**	**729**			132	97	89	98	**416**	**878**	**367 (delay)**	**36.28**
414	9.8	**1.12**	**724**		No	22	28	31	29	**110**	**917**	**139**	**35.52**
466	8.5	**1.11**	**729**			28	28	29	27	**112**	**878**	**167**	**35.98**
712	4.7	**0.94**	**706**			22	29	29	32	**112**	**910**	**127 (small delay)**	**36.10**

Evaluation of short stack tests

Main findings / external rapid heating

- Minimal energy input (0.8% - 1.5% of cell’s energy density) was needed to initiate TR
- Propagation times
  - Rather consistent for identical conditions (orientation, separation)
  - Delay of propagation by addition of multi-layer material
- Mass loss seem not influenced by the initiation method
- Mass loss seem not influenced by orientation and separation in rapid heating
- Occurrence of fire when **no separation** was present rather consistent for both orientations
- Occurrence of fire when separation was present not continuous – No occurrence fire in one test (cells were standing up-right)

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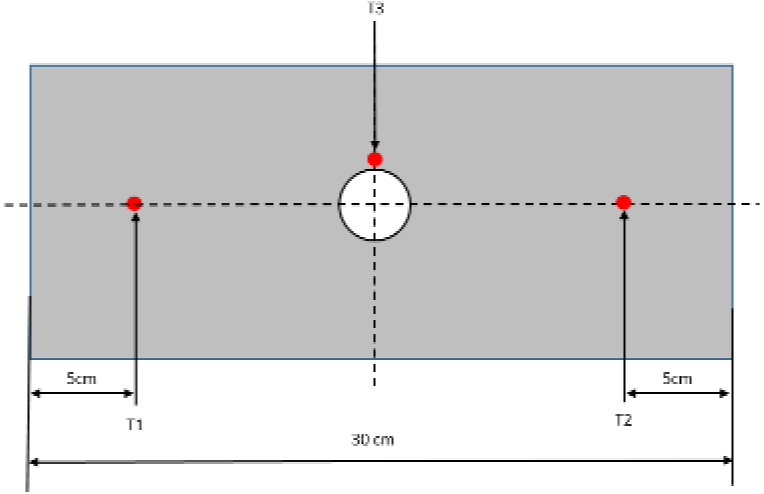
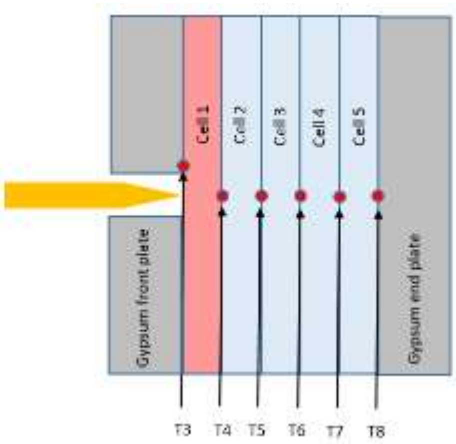
Evaluation of short stack tests

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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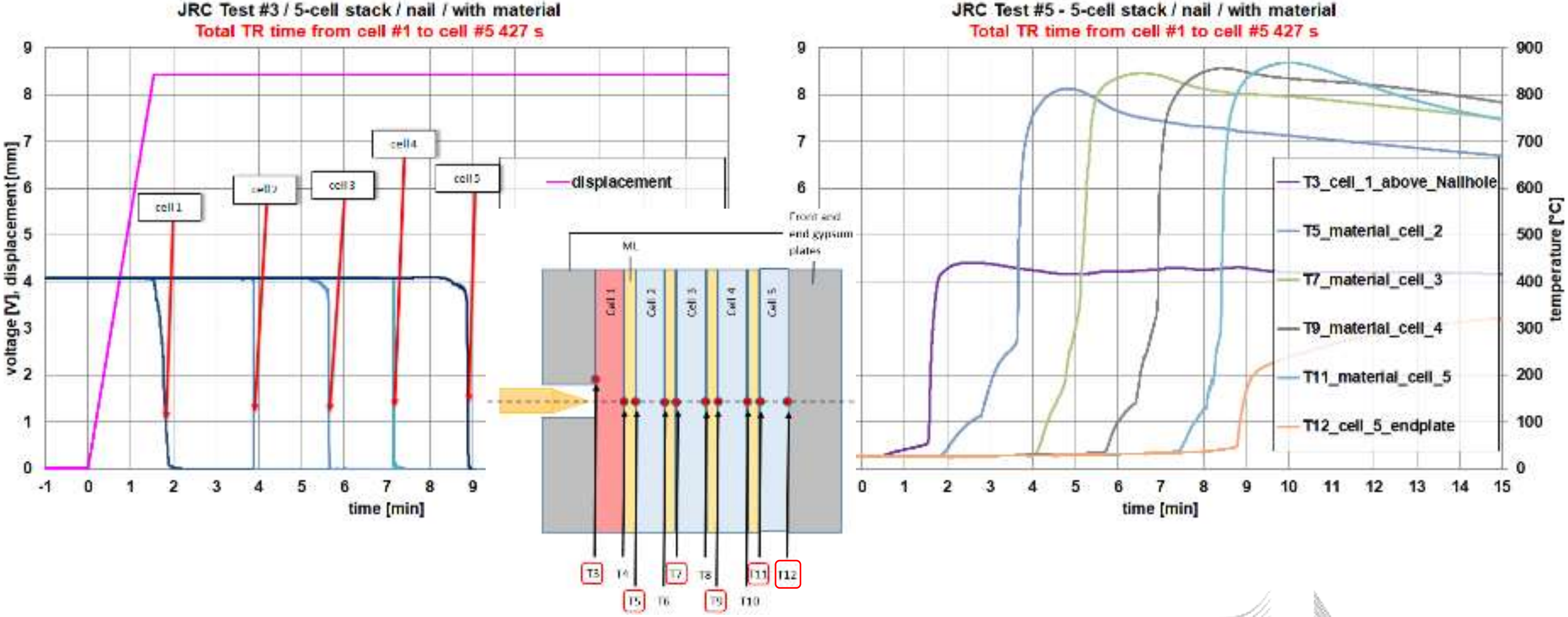
Evaluation of short stack tests

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



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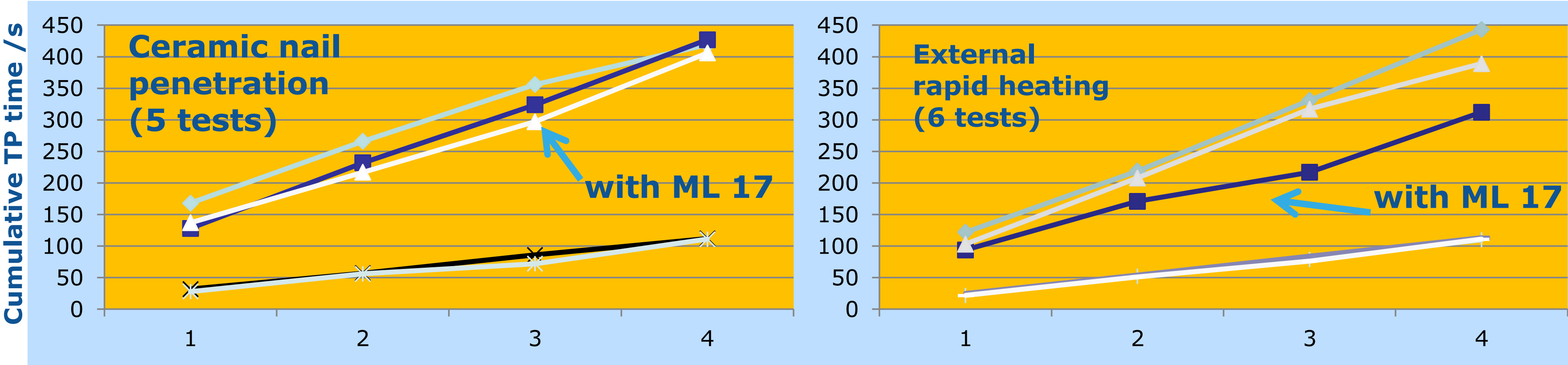
5-cell short stack evaluation
Penetration *vs.* Rapid heating; cells standing up-right
Influence of separation (thermal barrier Defensor-Flex® ML 17)



→ Progression of TP seems to be repeatable for both cases

→ ML 17 slowed down TP (by a factor of about 4) for either of the initiation methods

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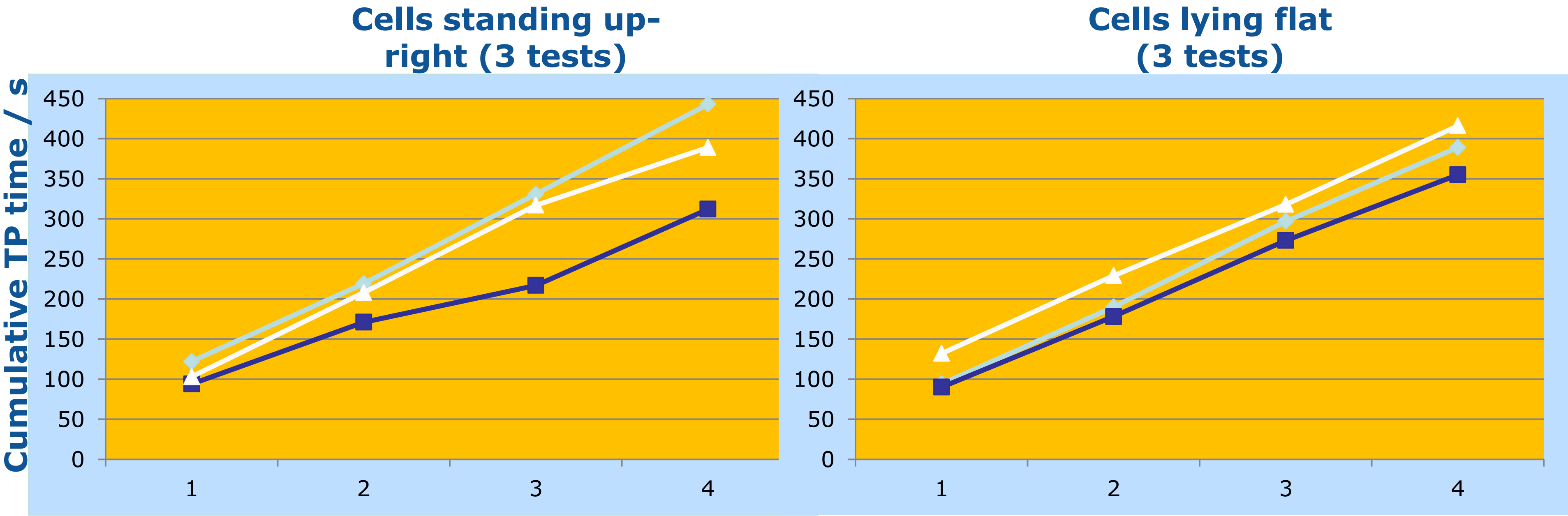
5-cell short stack evaluation: External rapid heating
Cells' orientation influence (with ML 17)



→ Progression of TP seems to be repeatable and not influenced by the cells' orientation

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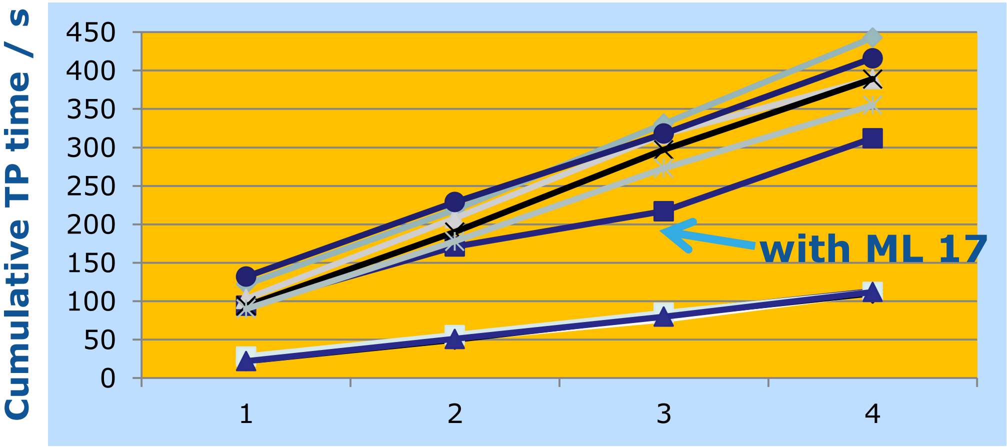
5-cell short stack evaluation: rapid heating
Both orientations in the picture (12 tests)
Influence of separation (thermal barrier Defensor-Flex® ML 17)



→ Progression of TP seems to be repeatable

→ ML 17 slowed down TP (by a factor of about 4) for either of the orientations

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Evaluation of short stack tests

Main findings (1/2)

- Initiation by rapid heating and ceramic nail penetration both trigger TR - no significant difference was found between their effects
- External rapid heating method is easy to use and stable – localised, with minimal energy input (0.8% - 1.5% of cell's energy density) was needed to initiate TR
- Voltage drop is an indicator/evidence of TR occurrence
- Propagation times
  - Rather consistent for identical conditions (orientation, separation)
  - Delay of propagation by addition of multi-layer material
  - No cell-to-cell propagation in a 2-cell stack test with two layers of HKO's Defensor-Flex® ML 17 with a separation distance of ca. 8 mm

Evaluation of short stack tests

Main findings (2/2)

- Mass loss seem not influenced by the initiation method
- Mass loss seem not influenced by orientation and separation in rapid heating
- Occurrence of fire when **no separation** was present rather consistent for both orientations
- Occurrence of fire when separation was present not continuous – No occurrence fire in one test (cells were standing up-right)

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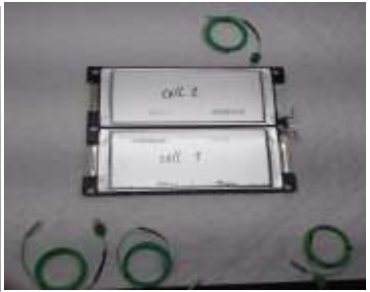
Outline

- JRC experimental TP activity
- Short stack tests update
- **Module tests update**
- Conclusions and outlook

Evaluation of module tests

External rapid heating (TRIM) // preparations
10s2p (ca. 3 kWh) module



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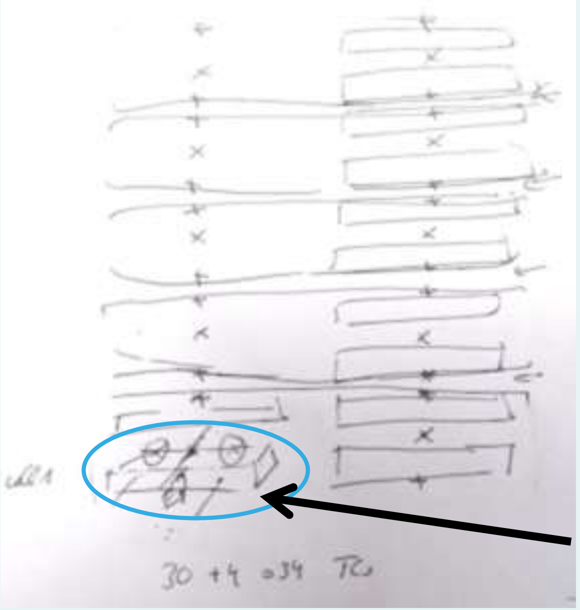
Evaluation of module tests - External rapid heating method

Test conditions, parameters and manipulations

Number and location of TCs



Initiation Cell 1

34 TCs in total, 30 of which be located in the centre of each cell surface (note, however, that the centre of the bottom surface of the initiation cell is covered by the heater). The initiation cell was equipped with 2 additional TCs at the front and back surface.

See hereafter…

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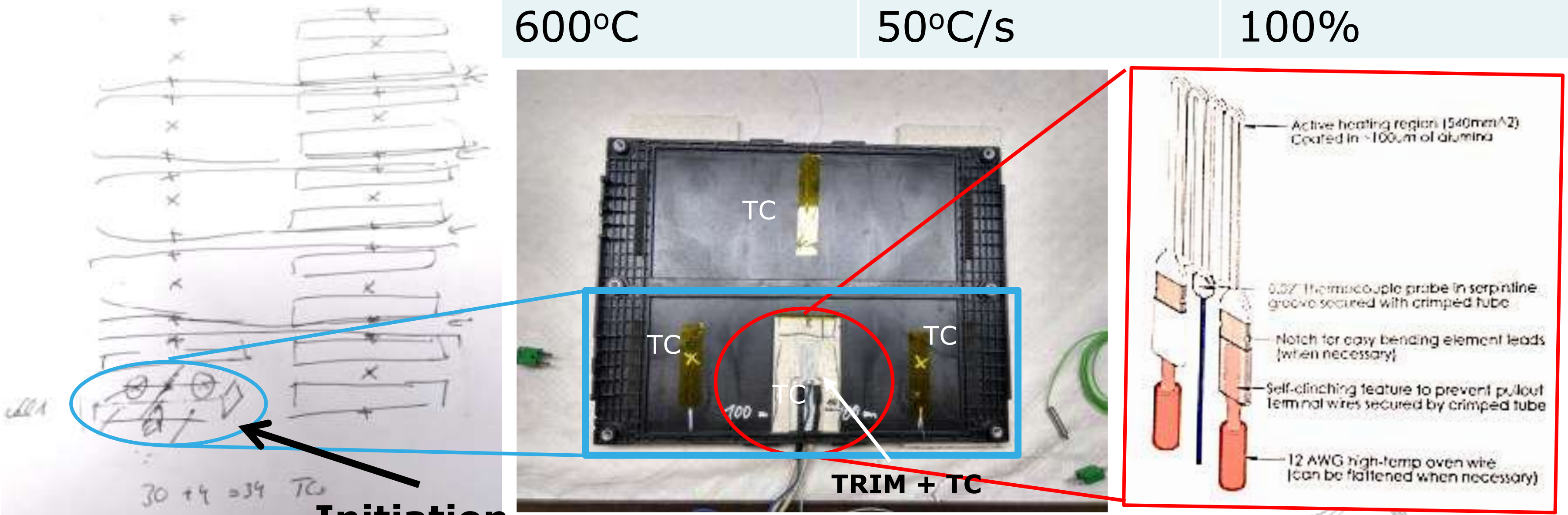
Evaluation of module tests

External, rapid heating test conditions and location of initiation cell and TCs

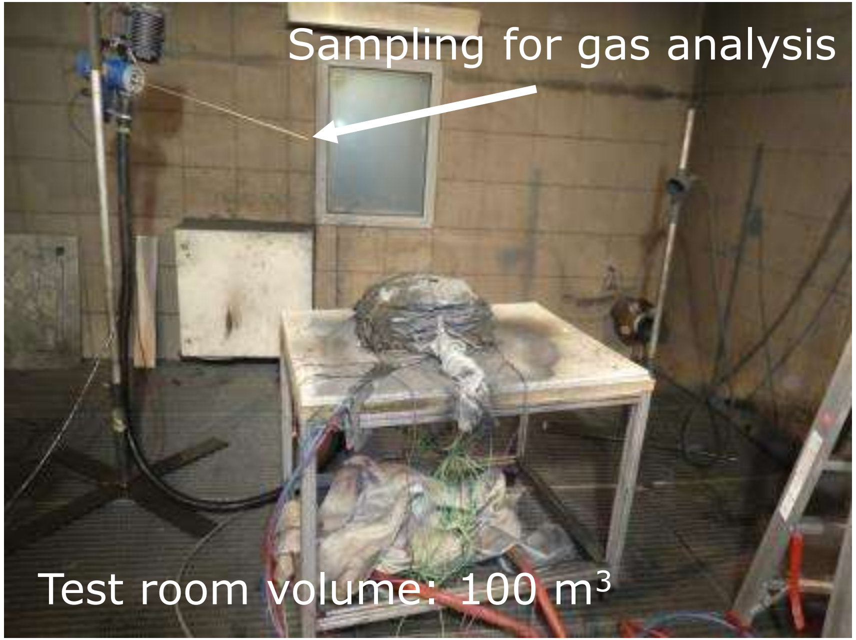
Target temperature	Temperature increase rate	SoC
600°C	50°C/s	100%



Initiation Cell 1

Module level tests

pre TP



post TP

Evaluation of module tests - External rapid heating method

Test conditions and input test parameters				Main findings		
Average Heating Power (W)	**Heating Duration (s)**	**Heating Energy (Wh)**	**T max. Heater (°C)**	**Total TP time (s)**	**T max. Cell surface (°C)**	**Fire duration (s)**
475	12.2	1.62	690	505	970	1620
336	14.3	1.34	655	603	907	> 800

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Module test / External rapid heating: Gas analysis (online FTIR 1/4)

Group of Substance	Substance	Formula	Reference*	Average	Maximum	Unit
				Concentration		
	Vapor water	H2O	wet	2,12	5,03	Vol-%
Carbon Oxides	Carbon dioxide	CO2	dry	1,91	5,39	Vol-%
	Carbon monoxide	CO	dry	530,78	1501,9	ppm
Short Hydrocarbons	Methane	CH4	dry	37,47	156,8	ppm
	Acetylene	C2H2	dry	18,81	54,9	ppm
	Ethylene	C2H4	dry	49,30	358,8	ppm
	Ethane	C2H6	dry	4,18	43,4	ppm
	Propylene	C3H6	dry	3,06	19,8	ppm
	Propane	C3H8	dry	1,12	26,1	ppm
	1,3-Butadiene	C4H6	dry	3,39	38,3	ppm
	n-butane	C4H10	dry	1,32	37,3	ppm
	n-heptane	C7H16	dry	1,82	12,4	ppm
	Hexadecane	C16H34	dry	0,43	2,0	ppm
	Benzene	C6H6	dry	15,20	51,6	ppm
	Toluene	C7H8	dry	2,54	15,1	ppm
	Xylene-o	C8H10	dry	12,81	36,2	ppm
	Xylene-m	C8H10	dry	0,05	6,9	ppm
	Xylene-p	C8H10	dry	0,60	19,7	ppm
	Styrene	C8H8	dry	27,37	126,7	ppm

*Total gas volume with/without humidity

Gas composition was quantified with two complementary methods: Fourier transform infrared spectroscopy (FTIR) and Gas Chromatography

Test room volume: 100 m^3

Delay time of sampling system: 25 s

Sampling rate: 7 samples/min

Module test / External rapid heating: Gas analysis (online FTIR 2/4)

Group of Substance	Substance	Formula	Reference*	Average	Maximum	Unit
				Concentration		
Alcohols	Methanole	CH3OH	dry	9,23	124,7	ppm
	Ethanole	C2H5OH	dry	12,32	115,8	ppm
	Phenole	C6H5OH	dry	13,70	70,8	ppm
Aldehydes / Ketones	Formaldehyde	HCHO	dry	6,41	17,1	ppm
	Acetaldehyde	H3C2HO	dry	1,91	63,5	ppm
	Propionaldehyde	H5C3HO	dry	0,33	13,7	ppm
	Benzaldehyde	H5C7HO	dry	1,12	2,7	ppm
	Acrolein	H4C3O	dry	2,67	7,4	ppm
	Acetone	H6C3O	dry	10,97	28,5	ppm
Acid gases	Hydrogen flouride	HF	dry	29,7	220,6	ppm
	Hydrogen chloride	HCl	dry	1,6	9,4	ppm
	Hydrogen cyanide	HCN	dry	2,4	8,2	ppm
	Formic acid	CHO2H	dry	0,8	5,4	ppm
	Acetic acid	C2H3O2H	dry	1,3	11,3	ppm
	Ethylacetate	C4H7O2H	dry	0,3	22,7	ppm

*Total gas volume with/without humidity

Module test / External rapid heating: Gas analysis (online FTIR 3/4)

Group of Substance	Substance	Formula	Reference*	Average	Maximum	Unit
				Concentration		
Carbonates	Vinylene carbonate	C3H2O3	dry	0,7	5,1	ppm
	Ethylene carbonate	C3H4O3	dry	10,5	103,4	ppm
	Dimethyl carbonate	C3H6O3	dry	0,4	7,8	ppm
	Propylene carbonate	C4H6O3	dry	0,1	0,4	ppm
	Ethyl methyl carbonate	C4H8O3	dry	29,5	367,8	ppm
	Diethyl carbonate	C5H10O3	dry	13,2	140,7	ppm
Fluor gases	Carbonyl flouride	COF2	dry	0,3	2,0	ppm
	Fluoroform	CHF3	dry	0,0	0,3	ppm
	Tetrafluormethane	CF4	dry	5,0	85,6	ppm
	Difluoroethane	C2H4F2	dry	0,3	3,2	ppm
			dry			
Phosphor gases	Phosphine	PH3	dry	14,5	39,8	ppm
	Dimethyl phosphite	C2H7O3P	dry	1,0	21,5	ppm
	Triethyl phosphate	C6H15O4P	dry	0,1	2,0	ppm
	Sum TOC (Propane-eq.)		dry	371,7	1232,0	ppm

*Total gas volume with/without humidity

Many Toxic / Flammable substances were present/detected!

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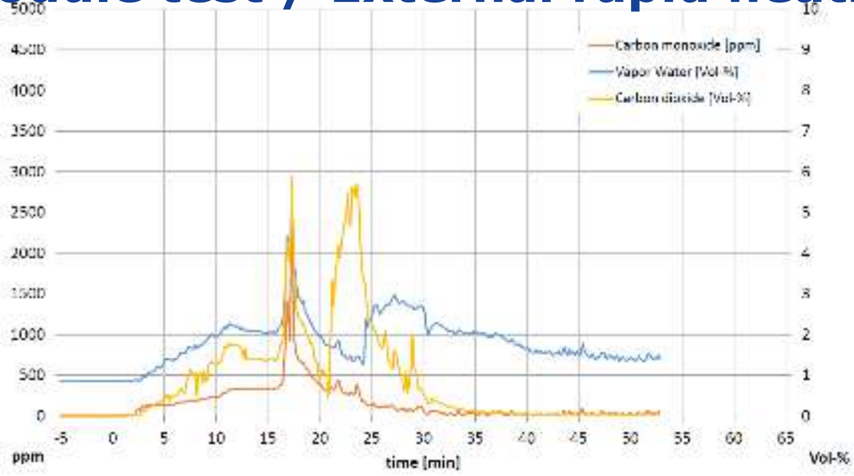
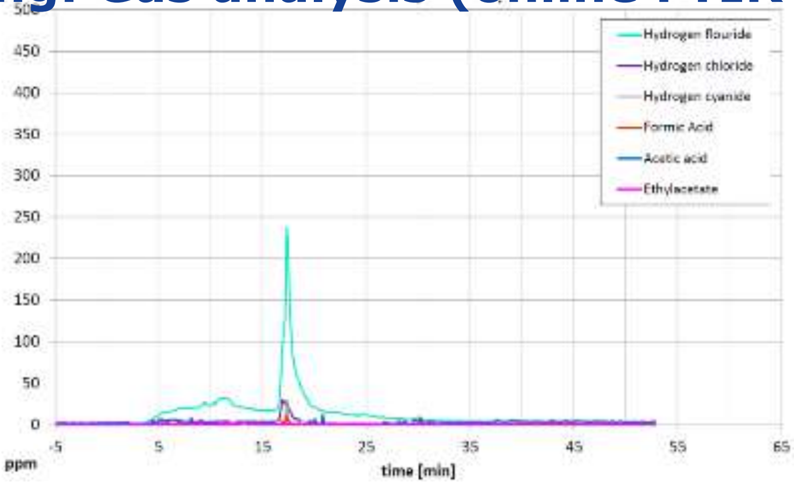
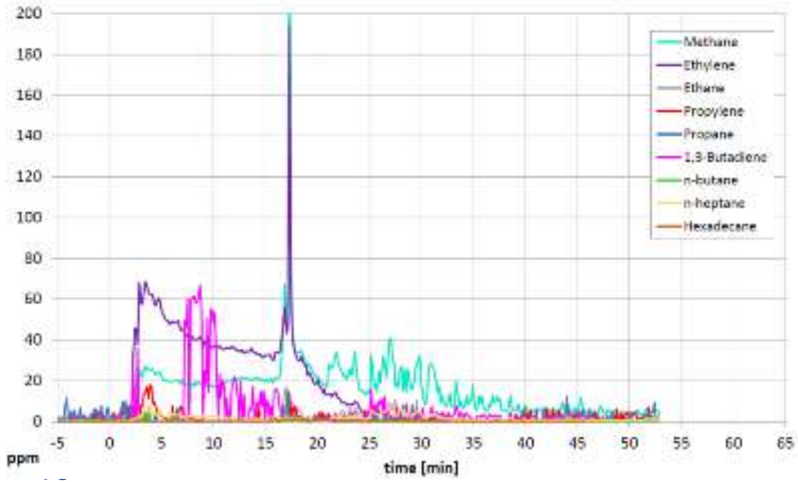
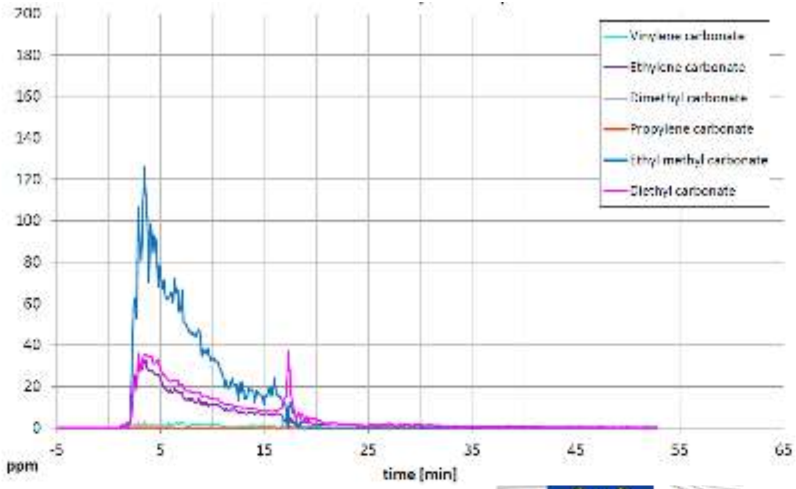
Module test / External rapid heating: Gas analysis (online FTIR 4/4)









Evaluation of module tests - External rapid heating method (2 tests)

Main findings (1/2)

- Minimal manipulation (some manipulation is needed, though)
- Initiation by rapid heating triggers TR
- Minimal energy input (1.2%, 1.4% of cell's energy density) was needed to initiate TR

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Evaluation of module tests - External rapid heating method

Main findings (2/2)

- Propagation times comparable but difficult to measure by voltage drop

(Voltage drop might be influenced by burning isolation of the sense wires)

- Occurrence of fire - Yes, both tests
- Emission of smoke – Yes, both tests

(also black smoke, making the fire not visible in one test out of two)

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Outline

- JRC experimental TP activity
- Short stack tests update
- Module tests update
- **Conclusions and outlook**

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Conclusions and outlook

- External rapid heating is a good candidate initiation method that worked reliably, in a repeatable way in our experience at cell-, short stack- and module-level tests

- External rapid heating will be investigated further on pack- and vehicle-level

- Contribution by European OEMs to the test campaign preparation is acknowledged

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For provision of HKO Defensor-Flex® ML 17
ulrich.stude@saint-gobain.com, carsten.stoeckmann@saint-gobain.com, steffen.mielke@saint-gobain.com

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

360º 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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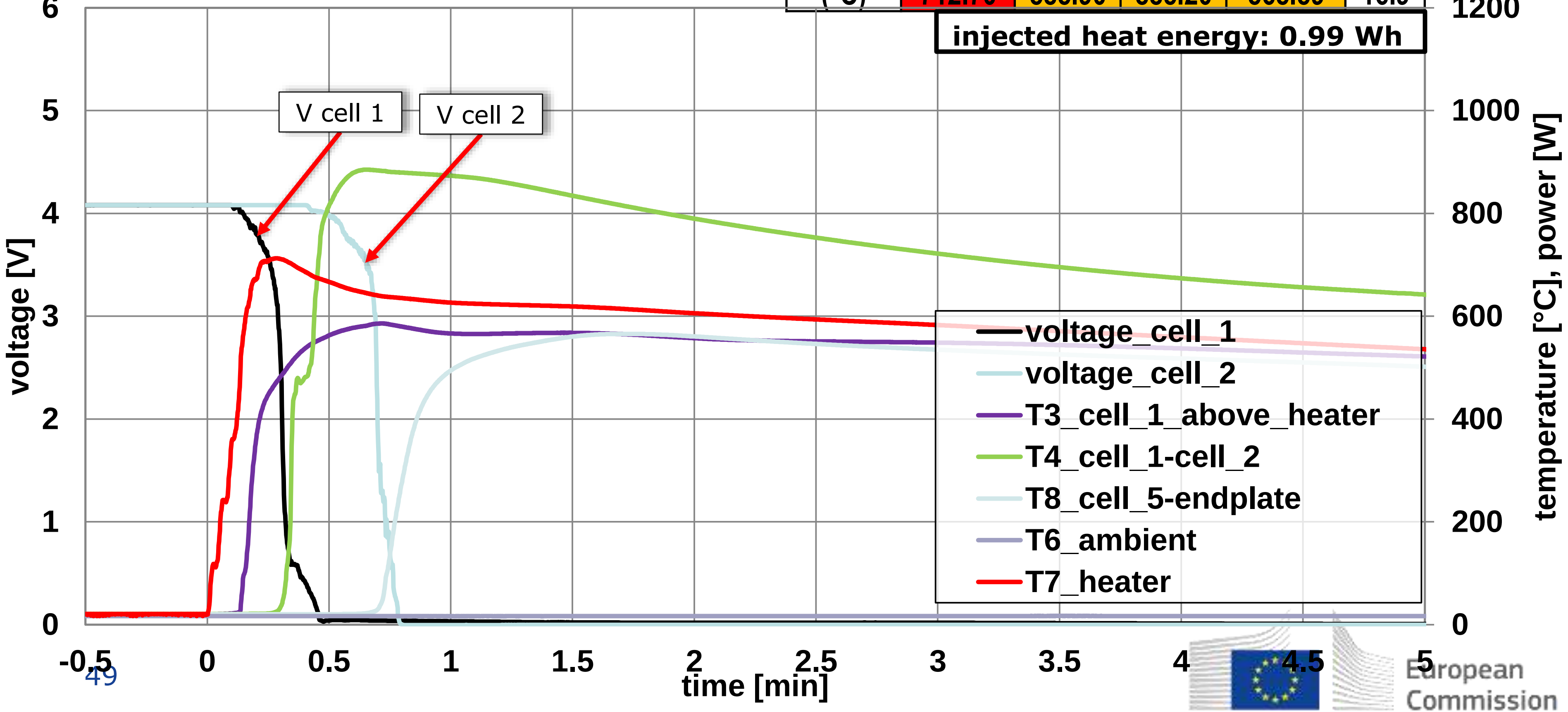
Back-up slides

Evaluation of 2-cell short stack tests / external rapid heating / no ML 17

Max. T (°C)	T7	T3	T4	T5	T6
	712.70	585.90	885.20	565.59	16.9

injected heat energy: 0.99 Wh



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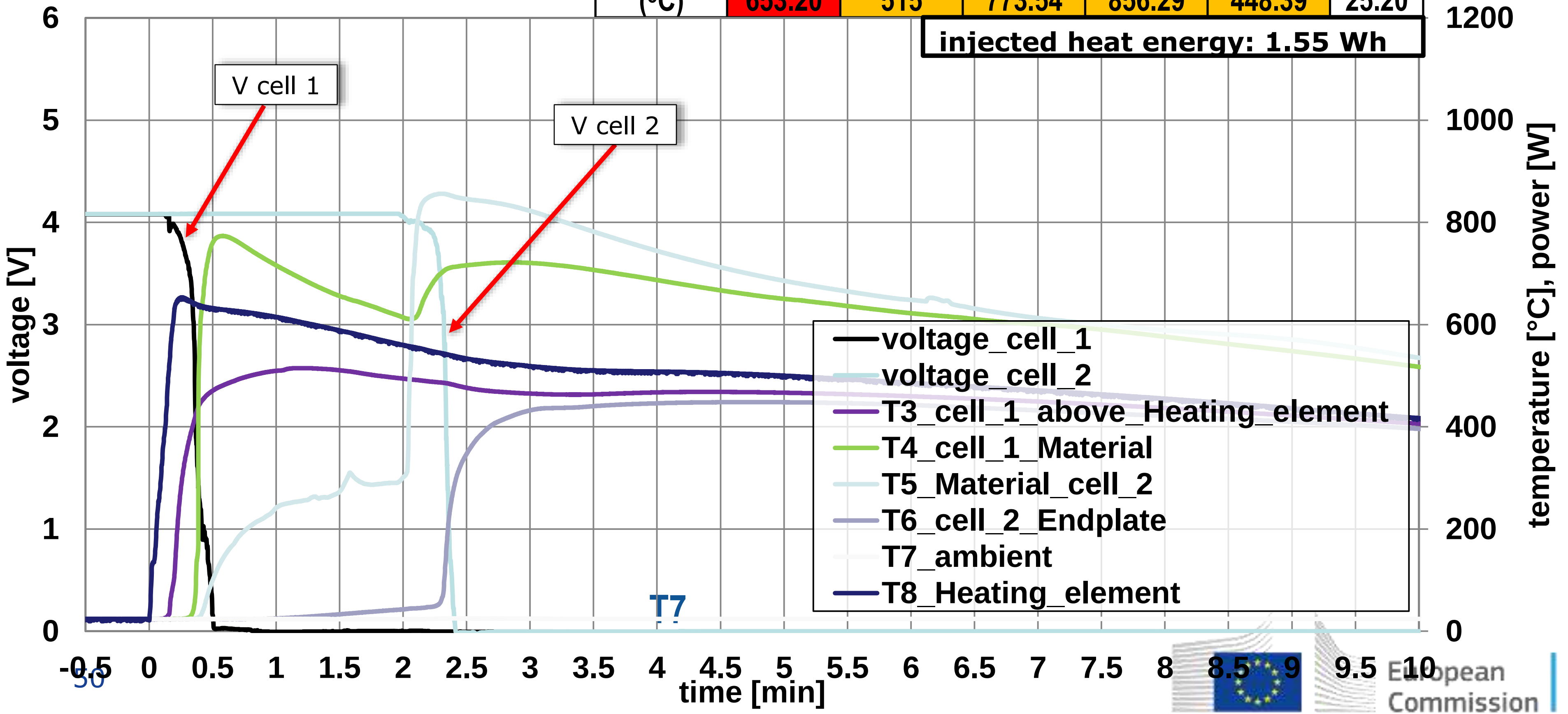
Evaluation of 2-cell short stack tests / external rapid heating / with ML 17

Max. T (°C)	T8	T3	T4	T5	T6	T7
	653.20	515	773.54	856.29	448.39	25.20



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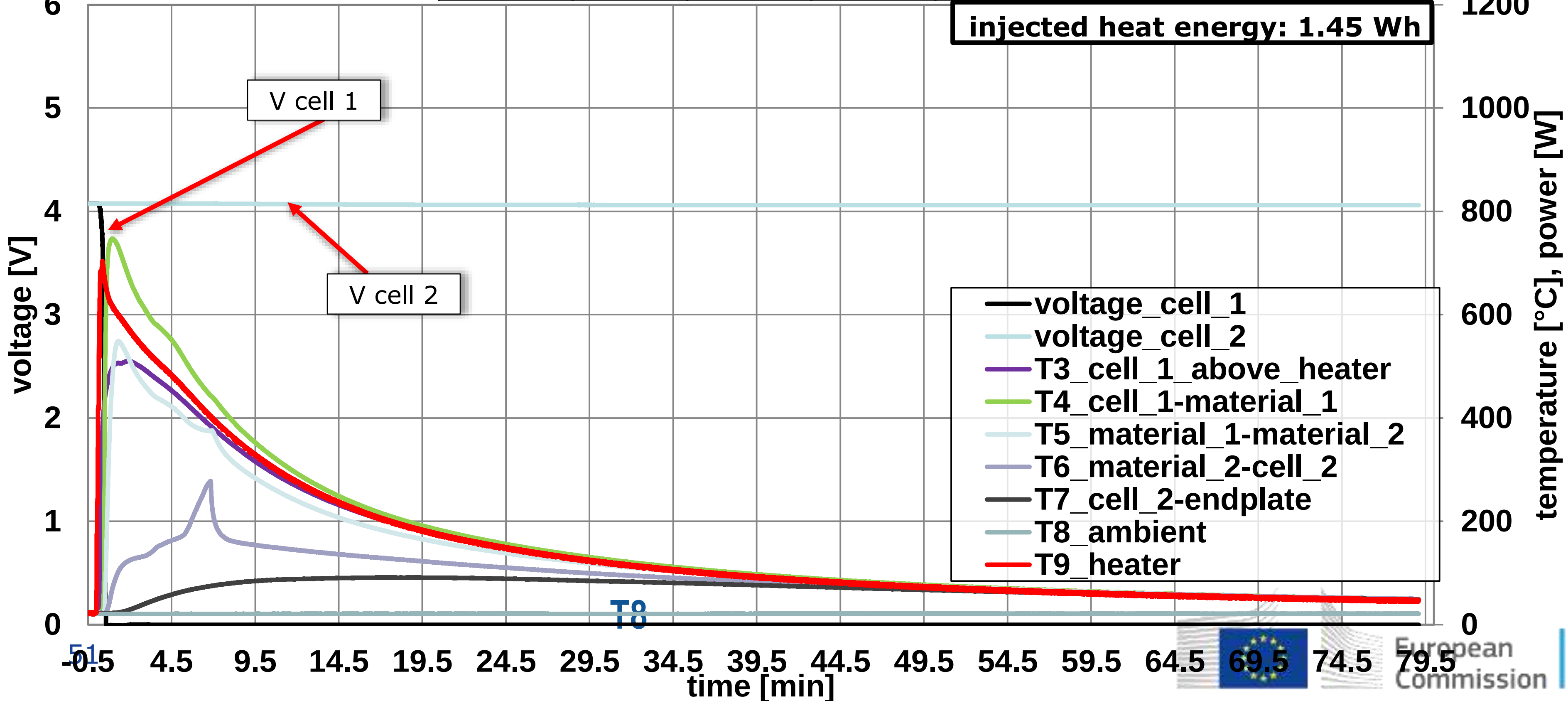
Evaluation of 2-cell short stack tests / external rapid heating / with 2x ML 17

Max. T (°C)	T9	T3	T4	T5	T6	T7	T8
	703.90	511.20	746.79	548.59	278.20	91.09	21.1



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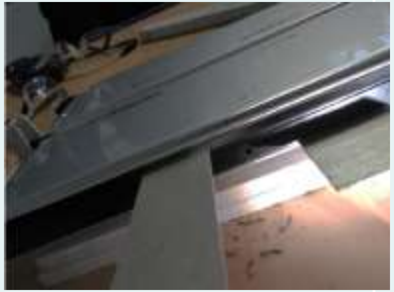
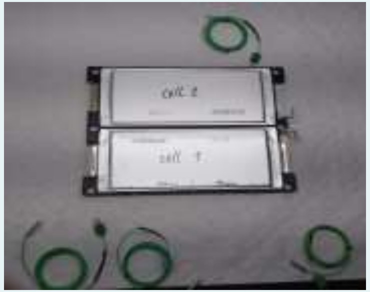
Evaluation of module tests - External rapid heating method

Test conditions, parameters and manipulations	
Cells’ orientation	Original orientation in the car (i.e. cells lying flat on largest surface).
Location of heater for triggering	An end, bottom cell was triggered.
	A hole was created into the plastic bottom cover and replaced with a gypsum plate (GP) of the same size to accommodate heater and one thermocouple (TC)-the GP is glued to the bottom plastic cover using Förch PU power adhesive plus and tape.
Number and location of TCs	34 TCs in total, 30 of which be located in the centre of each cell surface (note, however, that the centre of the bottom surface of the initiation cell is covered by the heater). The initiation cell was equipped with 2 additional TCs at the front and bac

Evaluation of module tests - External rapid heating method

Test conditions, parameters and manipulations

			
Groves were cut into the sides of the Al covers (see photo). Then a TC was inserted and glue (Förch PU power adhesive plus) was used to fix the TC.	Holes were drilled into the sides of the plastic holders to insert a TC between two cells (for drilling cells were pushed aside using thin plates, see photo).	The same glue is used to fix the TC and to close the hole (see photo 4-cell block with four installed TCs).	Finally also two TCs are glued to the top plastic cover.

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Evaluation of module tests - External rapid heating method

Test conditions, parameters and manipulations			
			
A fuse box on one side of the module was removed to allow disassembly of the module and instrumentation. The fuse box was remounted.	It was decided to also remount the two side end plate (EPs) (one of which covers the fuse box). The sense cables that are attached underneath those EPs were led through existing holes in the EPs.	Torque for screws holding module together - a torque of 8 Nm for closing the screws on the module under test (this was carried out with a mechanical torque key).	Module ready for test.