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Thermal runaway initiation of hard-cased lithium-ion cells without inducing sidewall rupture

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Background

- Single cell thermal failures may inevitably occur
  = Need for passive propagation resistance in battery pack design
- Ejected material during TR can account for over 60% of heat released[1]
- Many incumbent thermal runaway (TR) trigger methods are known to cause sidewall ruptures (SWR) which significantly alter thermal energy release patterns.
- Dedicated pressure relief vents are common features in cylindrical and hard-cased prismatic cells and SWR may be an "unnatural" failure mode
- Battery pack designers may choose to control release through vent channels[2]
  = SWR during TR initiation should be avoided to remain technology neutral

1. Darcy, E. Darst, J. Walker, W. Finegan, D. Shearing, P. Design Guidelines for Safe, High Performing Li-ion Batteries with 18650 cells. *JRC Exploratory Research Workshop*. Petten, Netherlands. March 8, 2018
2. Rengaswamy Srinivasan *et al* 2020 *J. Electrochem. Soc.* **167** 020559

Thermal Runaway Trigger Methods

- A commonly considered potential cell failure scenario:
  An internal short circuit (caused by manufacturing defect, dendrite growth, etc.) occurs, which creates a localized hot spot inside the cell, which causes a single cell thermal runaway

- Conventional trigger methods (both internal and external to the cell) may cause a SWR in the target cell since this outcome is not managed by the trigger method

- Localized rapid external heating with a thermostatic feedback loop can be designed to avoid both premature element failures and SWR

Localized Rapid Heating

- Apply high power heat pulses (heating rate target of 20-50°C/sec) to a small area (<20%) on the cell's external surface.

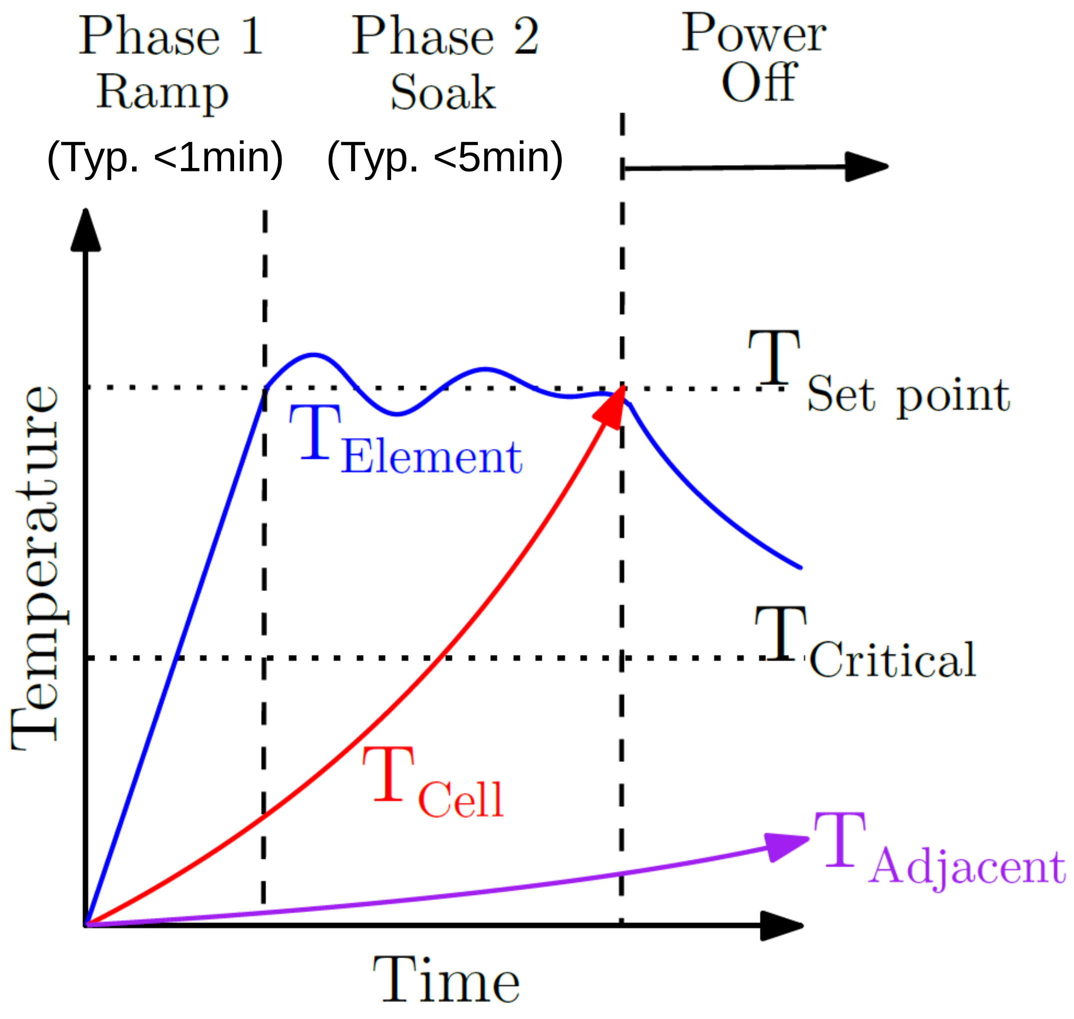
- Goal = provide sufficient heat to rapidly initiate self-propagating exothermic decomposition reactions of active material, leading to TR.

- Developed as a TR test methodology used to evaluate safety at the **system level** and being adopted within ISO 6469-1:AM1 and potentially UNECE Global Technical Regulation on Electric Vehicle Safety

- **Critical** that initiation method does not add significant energy, affect neighboring cells, or alter pack/system safety strategies, since this would bias the test result.

- Method has been demonstrated on various cell chemistries (NMC/NCA/LFP), on various cell formats (cylindrical/pouch/prismatic), at various scales (cell/module/component/fully operational system), and by various agencies in Canada, US, European Union, Japan, China, Korea, etc.)

Localized Rapid Heating Profile Visualization



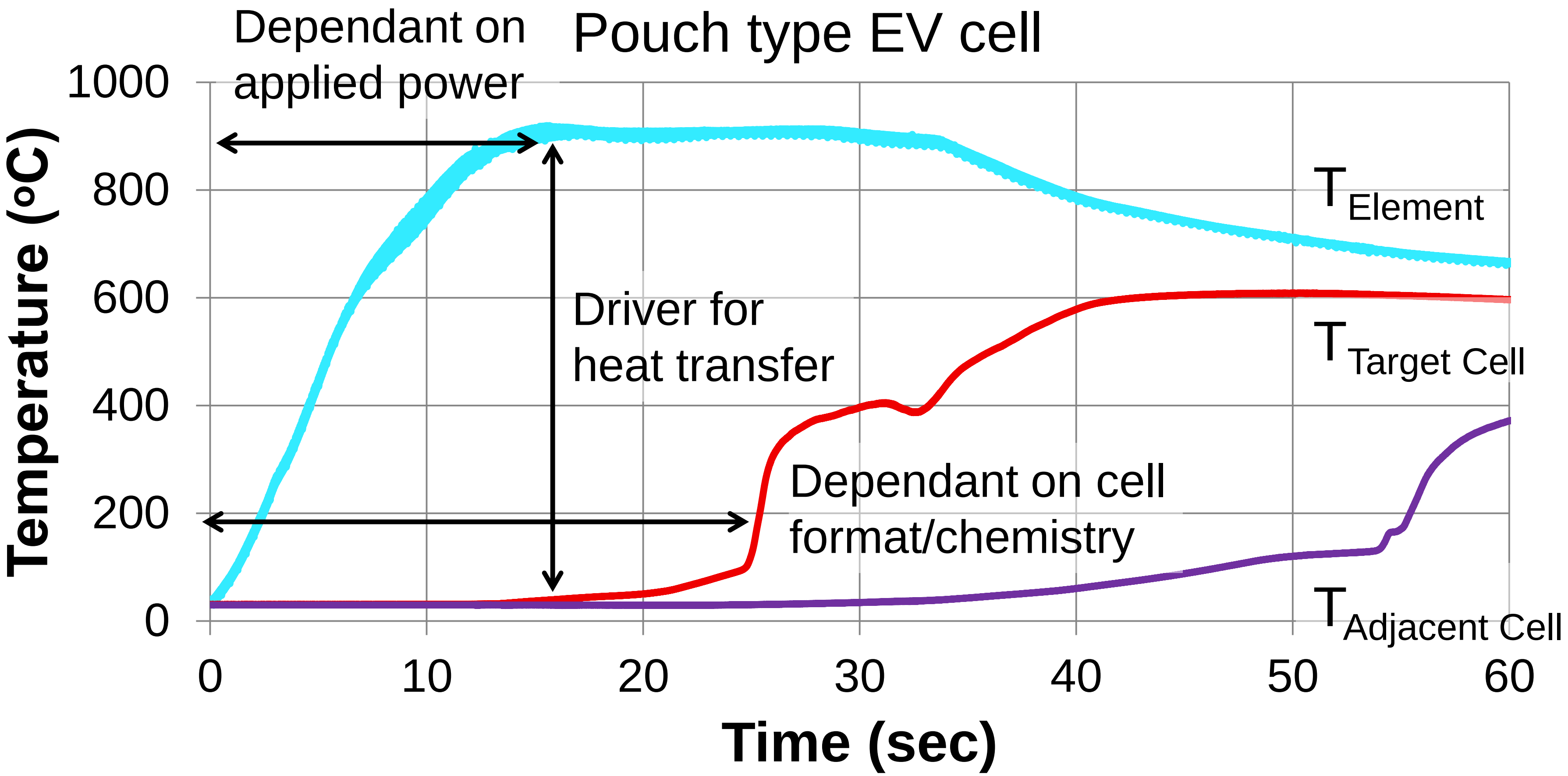
- **Requires $T_{Setpoint}$ and Ramp/Soak time value which are defined by cell type and chemistry.**
- **Conventional external heating uses constant input power, however, heat transferred to the cell depends on the thermal contact conditions and the element's temperature (not constant).**

$$q = -k\nabla T$$

- **Feedback control can be optimized to initiate a TR with minimum applied energy while avoiding undesirable outcomes**

NOTE: Please refer to ISO 6469-1:AM1 for more detailed procedural information. Currently in last stage of commenting and projected to be finalized by 04 / 2022 (available for purchase)

Example of Localized Rapid Heating



$T_{Element} \neq T_{Target\ Cell}$ …heat transfer to cell is time dependant

NRC heating elements

Version	Target Application	Image	Active heating area	Thickness of element	Thickness of connections	Retained features	Other features
V4	General use		16mm x 35mm (5.6 cm^2)	1.2mm	2.5mm	Ceramic coated Embedded temperature feedback	
V4B	Cylindrical cells		10mm x 42mm (4.2 cm^2)	0.7mm	0.7mm		Pre-curving of elements for cylindrical cells is not required
V5	Prismatic cells		39mm x 55mm (21.5 cm^2)	0.7mm	0.7mm	Low voltage DC operation	Designed to tolerate SWR, if it occurs Larger heating area supports diffusion losses

"Apparatus and Method for initiating Thermal Runaway in a Battery" with application date of January 18, 2018. PCT/CA2018/050055

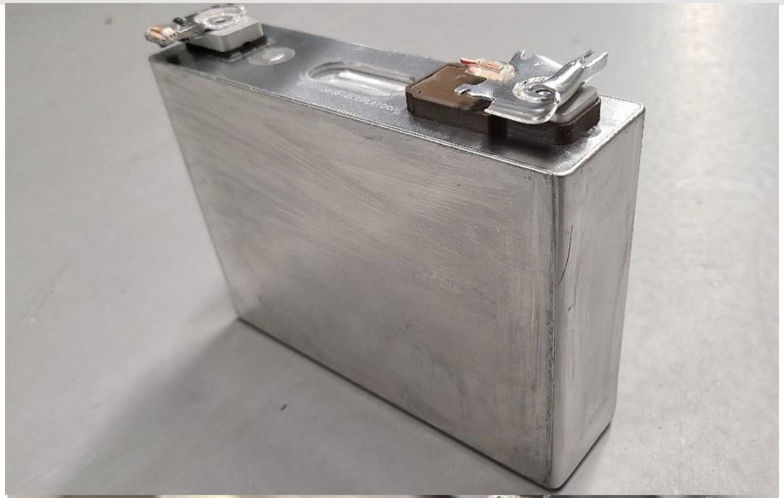
NOTE: other commercial heating elements (non-NRC) are suitable for localized rapid heating

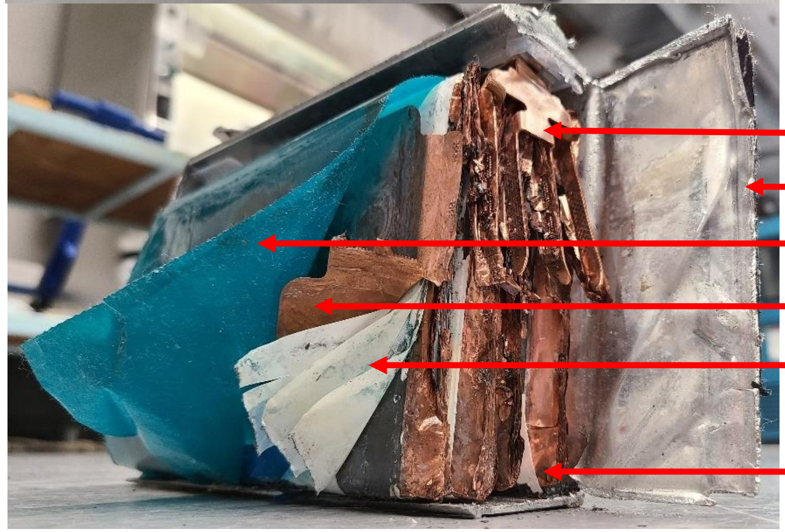
Experimental Testing Objectives

1. **Initiate TR in large prismatic cells consistently and reliably without element failures**

2. **Initiate TR in large prismatic cells without inducing a sidewall rupture (SWR)**

Target cell description





60Ah – NMC-based lithium ion cell (2014)
Aluminum hard-cased prismatic cell

Internal structure determined by disassembly or internal scan to select suitable heating locations (<u>Highly recommended</u>)

4 internal electrode rolls
Interior welded tabs (~16mm gap between rolls and side wall)
1.6mm thick outer wall
blue wrapper around electrode rolls
uncoated copper sheet
extra layers of separator

These are thermal barriers when heating the largest face

Small contact area between rolls and bottom wall

<u>Each side has a different thermal resistance</u>

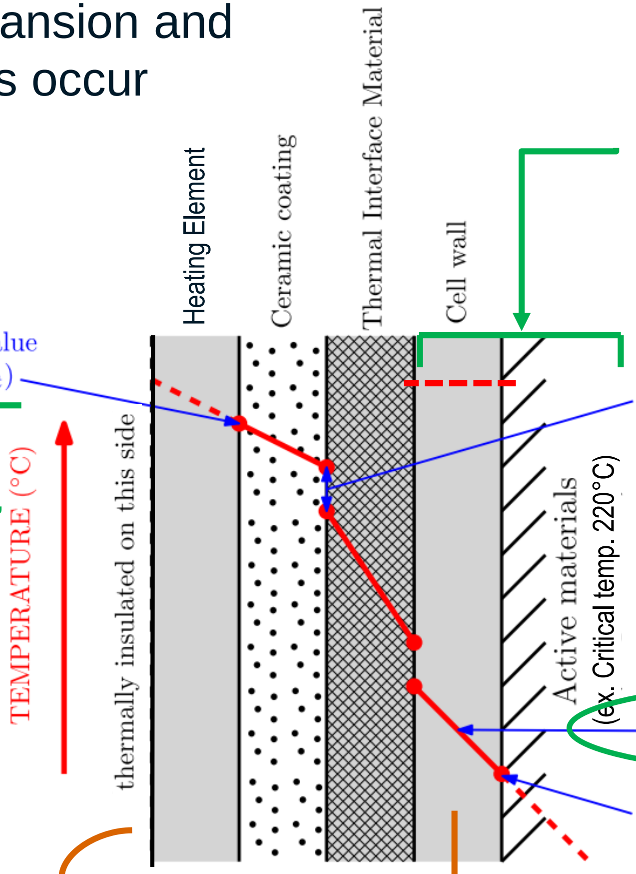
Thermal challenges during rapid heating

Simplified 1D heat transfer **before** physical expansion and exothermic reactions occur

At steady state, This temperature value is constant ($T_{setpoint}$)

Maximum setpoint temperature is limited below cell wall failure temperature, to avoid "unnatural" side wall ruptures.

Minimum setpoint temperature is greater than thermal stability of active materials, and adjusted to account for all sources of heat transfer barriers/losses.



Note: Thicknesses shown are not to scale

Other observed barriers to heat transfer during tests:
- Gaps between electrode windings and cell wall
- Extra separator layers
- Internal gas generation
- Element delamination due to physical expansion or improper installation

Contact resistance
f(Applied pressure, Surface roughness, ...)

During rapid heating, the cell's construction is the **rate limiting step to effective heat transfer** for a given element area and temperature setpoint

Thermal resistance
f(Materials conductivity and thickness)

This temperature value increases over time

Heat losses away from target cell (ex. through insulation)

Heat losses due to thermal diffusion / capacitance (includes active thermal management)

Example: CT scan showing swelling due to internal gas

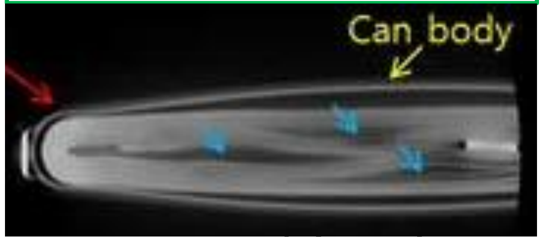
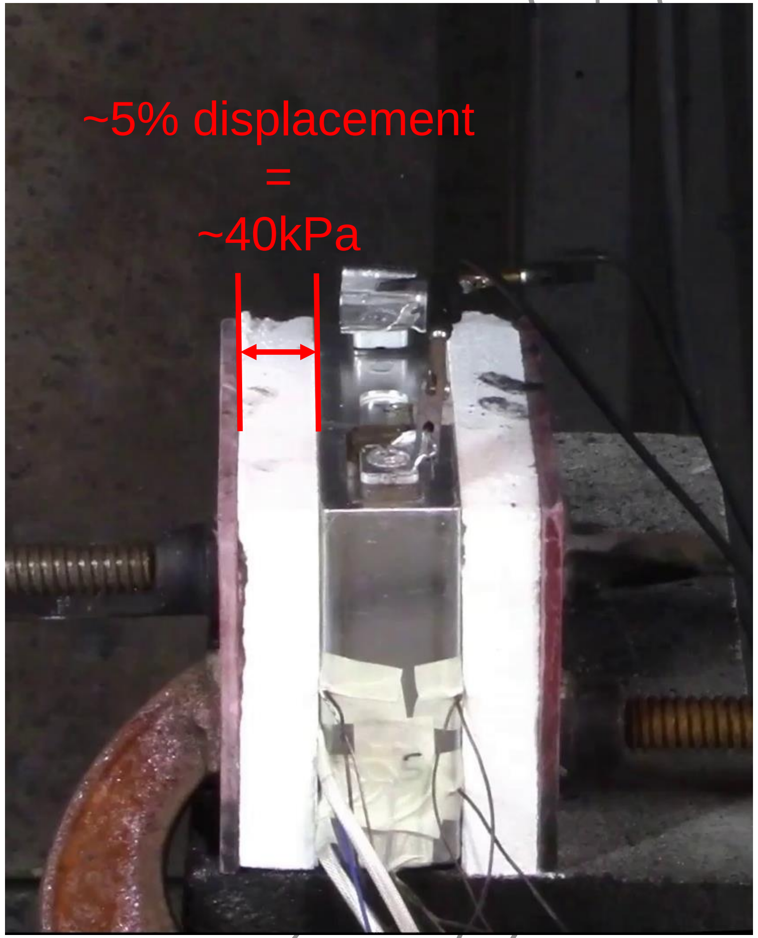
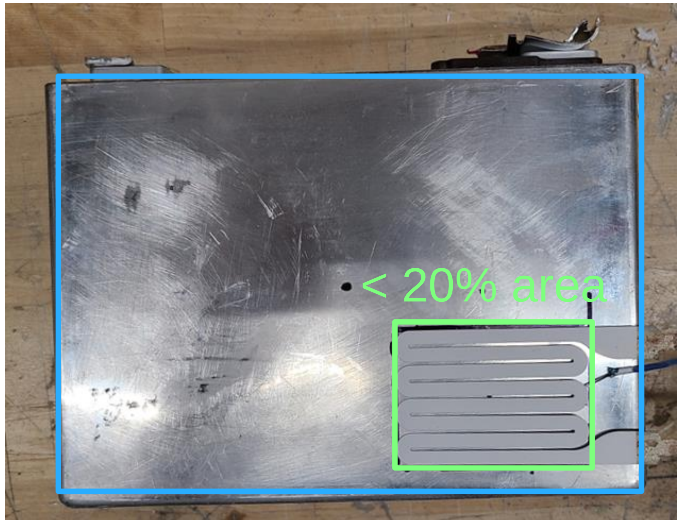


Image source: Lee, SH., Ko, IH. Failure Analysis of Swelling in Prismatic Lithium-Ion Batteries During Their Cycle Life After Long-Term Storage. *J Fail. Anal. and Preven.* **18,** 554–561 (2018). https://doi.org/10.1007/s11668-018-0440-6

Test setup

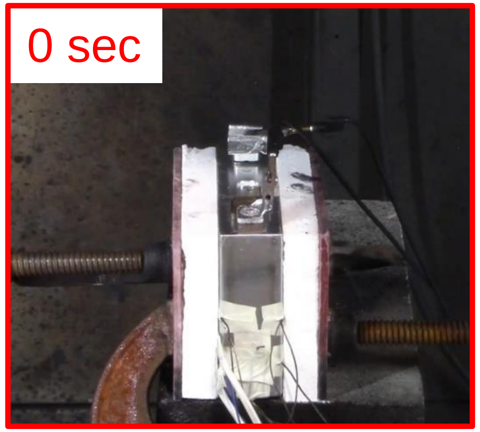
- Cell surface cleaned of films and residue
- Cell charged to 4.2V (100% SOC)
- Nickel-based heat transfer paste (2.6 W/mK) used as element thermal interface material
- Contact pressure estimated based on compressive strain of rigid ceramic insulation; maintained with clamps

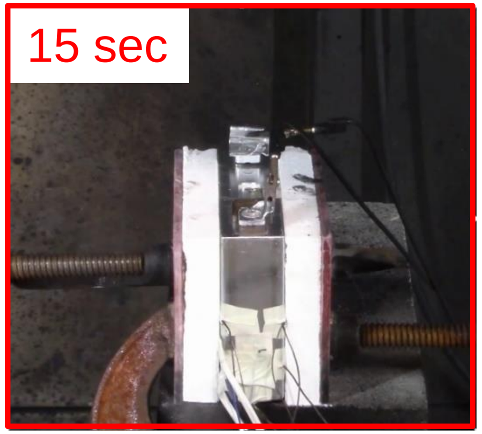


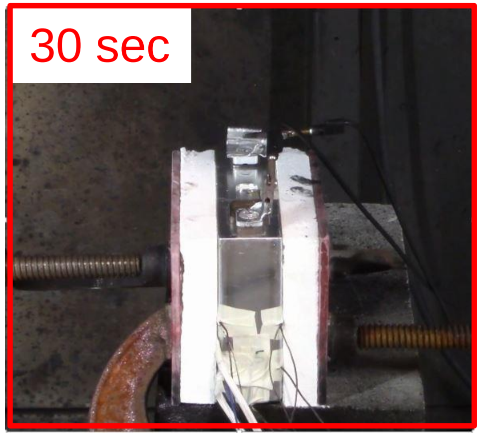


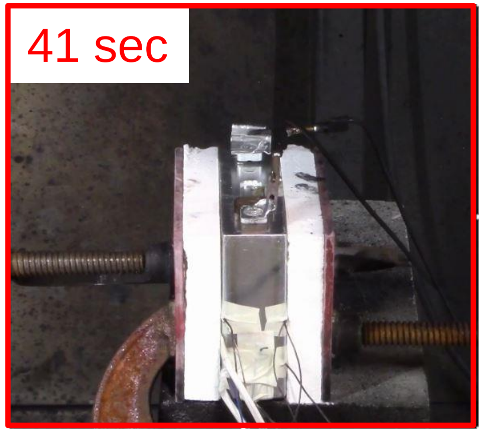
Test video (#3)

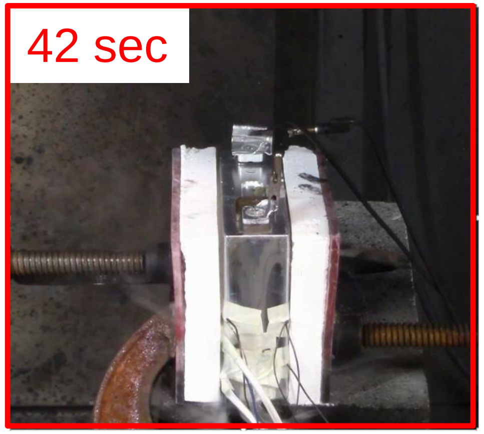
Video shown during presentation

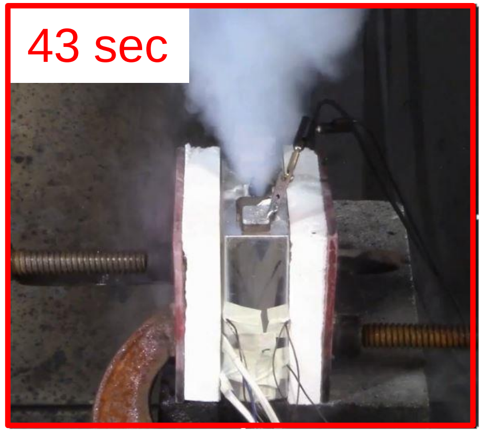




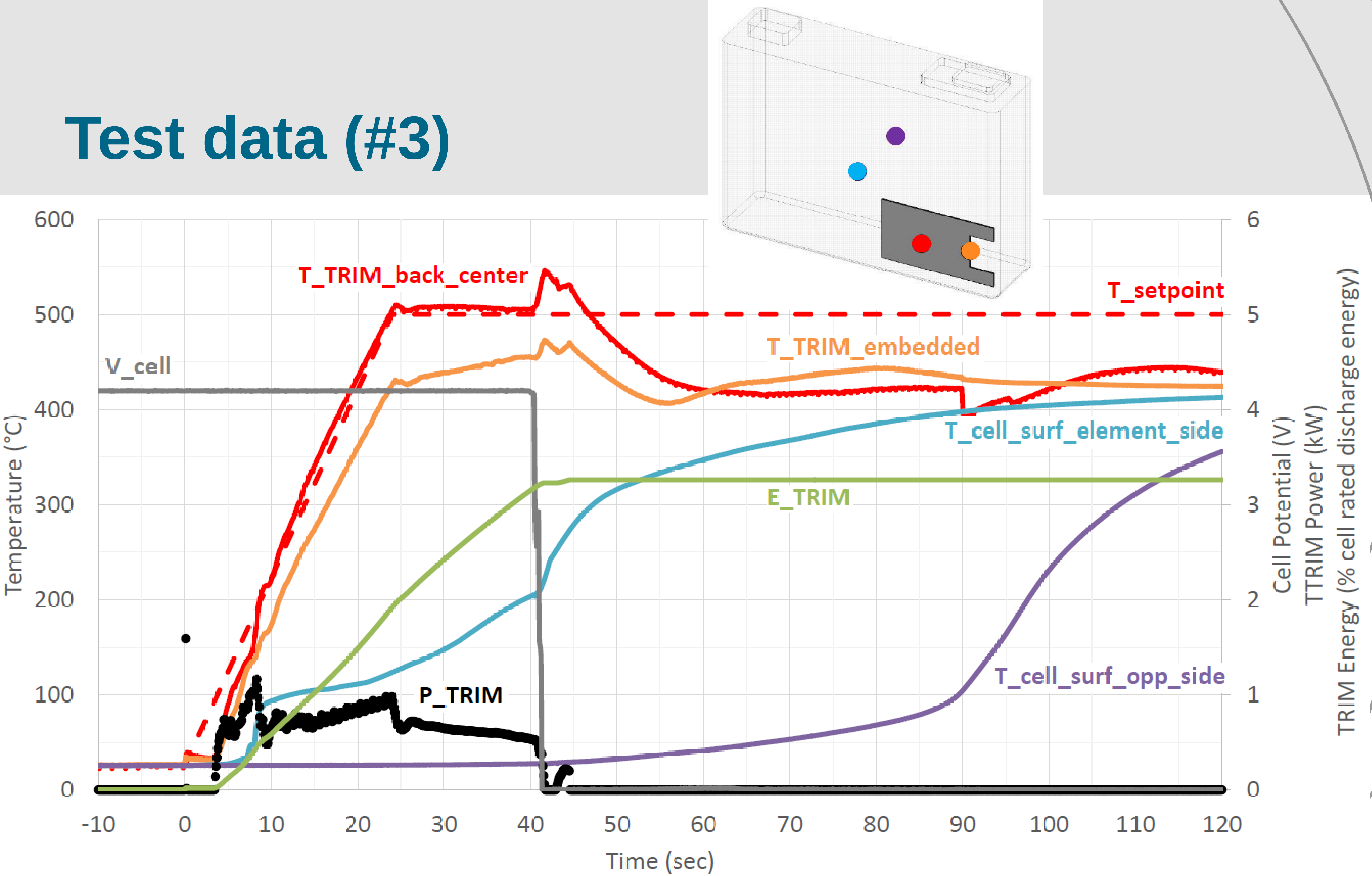






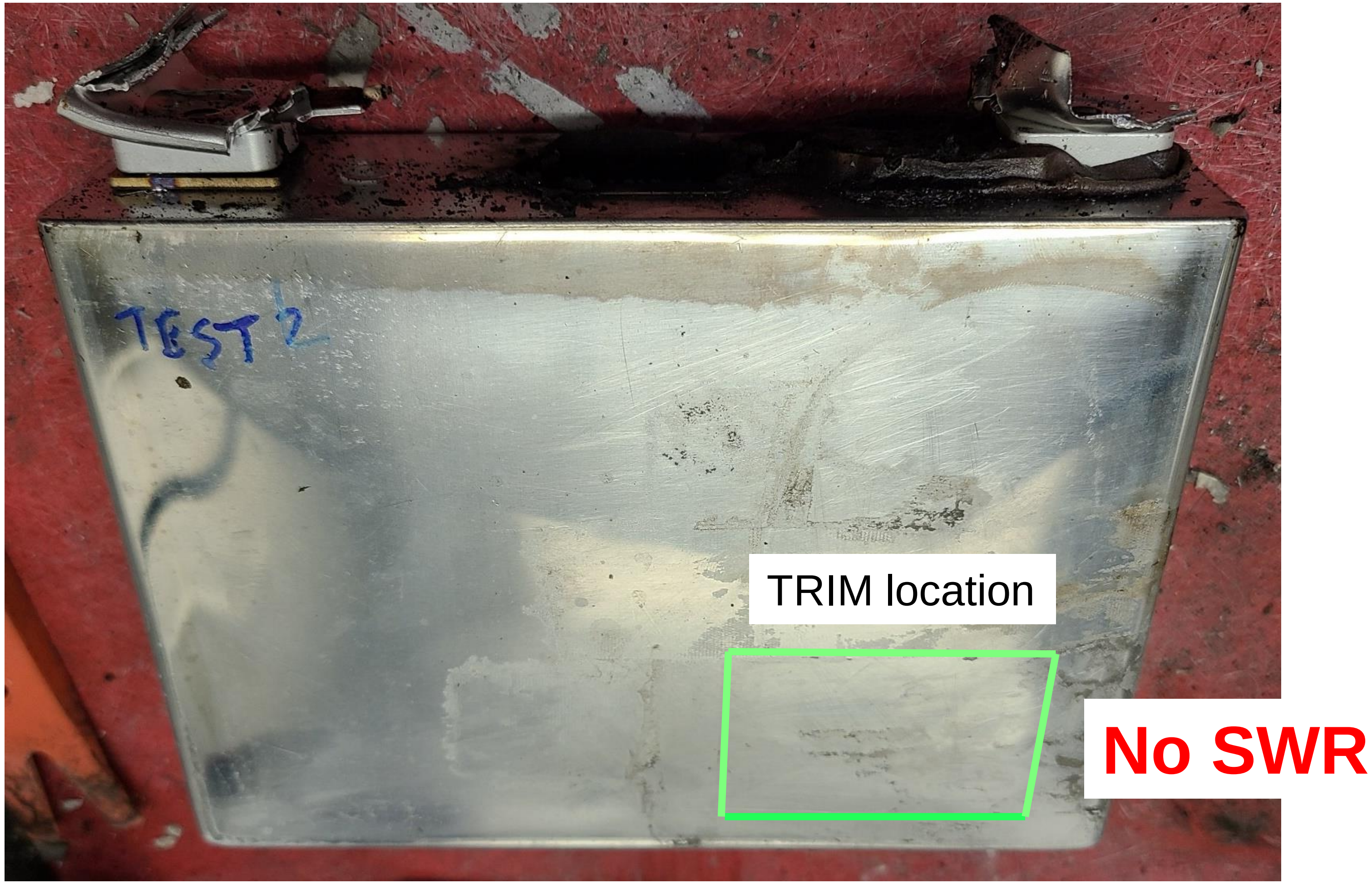


Test data (#3)



T_TRIM_back_center
T_setpoint
T_TRIM_embedded
V_cell
T_cell_surf_element_side
E_TRIM
P_TRIM
T_cell_surf_opp_side
Temperature (°C)
Time (sec)
Cell Potential (V)
TTRIM Power (kW)
TRIM Energy (% cell rated discharge energy)
600
500
400
300
200
100
0
6
5
4
3
2
1
0
-10
0
10
20
30
40
50
60
70
80
90
100
110
120

Post-test photo (#3)



Summary of test results

	Test Description			Outcomes			Key Metrics							
Test #	Target face on cell	Temperature Feedback Location	Ramp/soak at back center location	TR	SWR	Pressure relief vent opened	Time to TR (sec)	Average applied power (W)	Average applied heat flux[a] (W/cm^2)	Energy applied to TR (%)	Peak element temperature (°C)	Peak cell surface temperature (°C)	Mass Loss (%)
1	Largest face	Not used (constant power)	40°C/sec ramp, 900°C peak	YES	YES	NO	15	1464	68	4.2%	900	437	27%
2		Embedded near element edge	34°C/sec ramp, 800°C peak	YES	YES	NO	19	1057	49	3.4%	800	434	27%
3		Back center of element	20°C/sec ramp, 500°C soak	YES	NO	YES	42	654	30	3.3%	540	456	29%
4				YES	NO	YES	55	611	28	3.7%	540	467	30%
5				YES	NO	YES	75	556	26	5.3%	515	446	29%
6[b]				YES	NO	YES	650	216	10	17%	530	543	32%

Notes:

a. Calculation assumes negligible heat losses. For reference, conventional film heaters are typically rated for 1.5 W/cm^2

b. Poor element contact pressure caused by reused ceramic insulation sheets; estimated to be less than 3kPa. All other tests equal or greater than 30kPa

Key findings (1 of 2)

- **TR initiation was achieved in all tests**
- **Heating elements survived all tests and were still operational after tests**
  (however not advised to reuse due to cured paste)
- **Peak cell surface temperatures and cell mass losses were similar for wide range of settings / install qualities, however:**
- ***how* energy is released may influence the system level, since it is highly directional**
- **Melting point of aluminum is 660°C but internal gas pressure and thermal weakening cause cell wall to fail closer to 580°C.**
  Important to measure (or at least account for) the hottest point on the heating element

Key findings (2 of 2)

- **Achieving higher applied* heat flux is always better in terms of reduced time to TR and reduced input energy, which are the primary advantages of rapid heating over conventional slow heating methods**
  (* Remember: Input power is provided based on **need** to maintain temperature schedule; input power is not constant)

- **Applied heat flux is a function of:**

  1. **Element thermal contact conditions**
     (surface prep, element back pressure, heat transfer paste material and thickness, etc.)

  2. **Cell internal structure under heating element site**
     (cell wall material, distance to electrodes, additional non-active layers, thermal resistance, etc.)

- **#1 can be controlled, but #2 cannot** (control over heating site selection only)

Conclusions

- **Reliable and repeatable initiation of TR in hard-cased prismatic cells by rapid external heating is possible through thoughtful experiment design**
- **If the goal is to avoid SWR, then cells with a high thermal resistance and dedicated pressure relief vents (ex. hard-cased prismatic cells) are more sensitive than other cell formats (ex. pouch) to the heating element installation quality and temperature schedule selection.**
- **For these cells, on the large face, 30 W/cm2 is maximum effective heat flux to avoid risks of SWR. Below 10 W/cm2 - longer activation times and increased energy input (undesirable; may lead to pre-TR venting).**
- **Using this methodology, a similar range of settings can be determined for each cell type and format to avoid SWR**

Thank you for your kind attention!

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