Rapid Heating Test Methodology for Thermal Runaway System Level Testing

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April, 2023 UN IWG on Hazard based classification of lithium batteries

About National Research Council

Canada's Research and Technology Organization (RTO)

- Canada's national research laboratories (Est. 1916)
- 3,700 employees
- 14 Research Centres across Canada

Three key roles:

Business innovation
Federal policy mandates
Advancing knowledge

Background

NRC actively supporting Transport Canada to provide expert input and research into global technical regulations (GTR) for electric vehicles.

Early focus was on the risks to vehicle occupants of EVs compared to ICE vehicles when exposed to an external fire.

Result: Minimal risk with EVs compared to ICE, since the large thermal mass of the battery provided sufficient egress time before any battery thermal activity was detected.

Current Focus – Thermal Runaway

What is the potential of a lithium-ion single cell thermal runaway to propagate to adjacent cells inside a battery pack.

From: Hyundai Kona Electric Explodes, Blows Hole In Garage: Cause Unknown (insideevs.com)

From: GM Tells Some Chevy Bolt Owners to Park 50 Feet Away From Others on Fire Risk - Bloomberg

Background - Battery Regulations and Standards

System level Thermal Runaway (TR) and Thermal Propagation (TP) test methods are a significant gap within automotive regulations/standards for EVs.

Most cell level battery standards (UL, IEC, SAE etc..) have established criteria and test methods for evaluating TR/TP.

Within automotive regulations, any potential test methodology must be based on potential field events and should be based on a complete system level testing approach (at least in North America).

Not evident if existing cell level testing methodologies can be adopted for a potential single cell thermal runaway within an EV battery for an automotive regulation.

Traditional Approaches to TR Initiation

Mechanical (Nail, Crush, Screw) - common, questionable reproducibility, minimal energy introduction, rapid, difficult to implement in full pack/vehicle, alters significantly cell/module boundary conditions

Electrical (Overcharge, Short Circuit) - common, good reproducibility, difficult to implement across all cell designs (CID, swelling - internal safety mechanisms), potential to add significant energy to cell

Cell Defect Introduction - not common, unknown reproducibility, require specialty built cells making implementation impractical and a safety hazard

Cell Heating – most common, good reproducibility, many potential approaches, long activation and heat up of adjacent cells

Our Goal – System level testing is our Motivation!

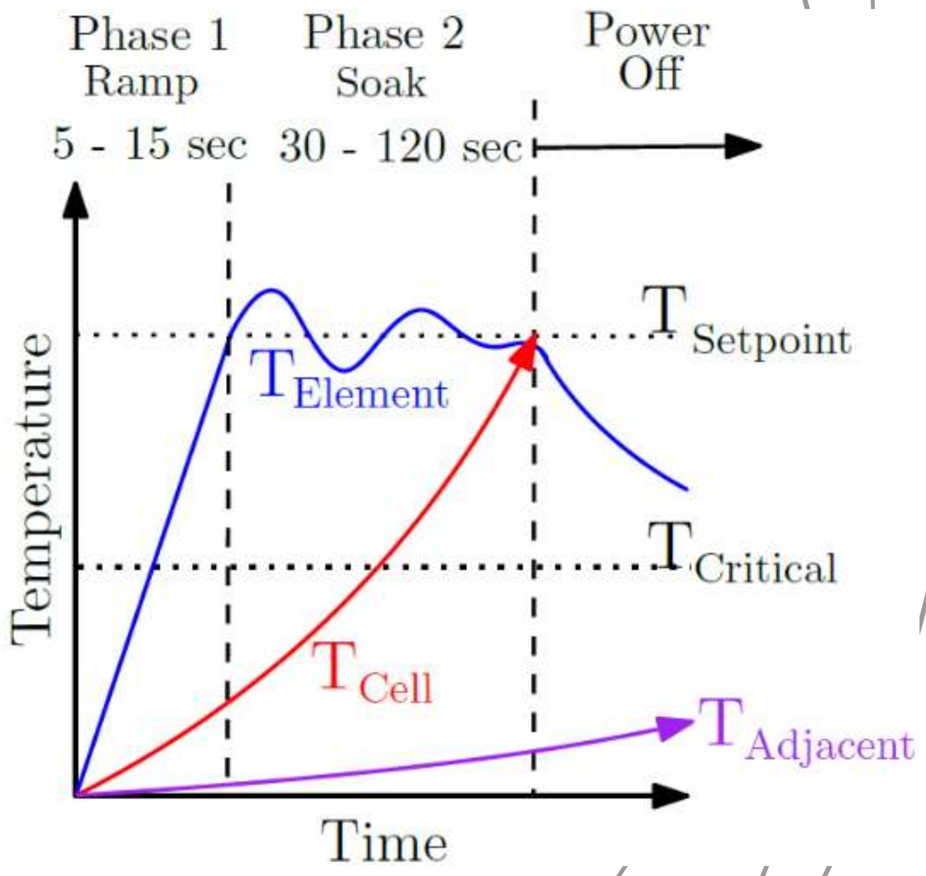
To ensure that the most safety critical end result of a single cell thermal event (thermal runaway) is tested and regulated, we focused on triggering thermal runaway within a single cell from an external heat source.

It is critical that this testing occurs without biasing any pack or vehicle level safety system, any neighboring cells and without the addition of significant energy to the system. This includes not affecting any cooling features, structural members or other containment bodies found within the battery pack or vehicle.

NRC Approach to Thermal Runaway/ Propagation

Localized Rapid External Heating - apply high power heat pulses (targeted heating rate of 20-50°C/sec) to a small area (<20%) on the cell's external surface via thermostatic controlled temperature feedback loop.

Goal - provide sufficient heat to rapidly initiate self-propagating exothermic decomposition reactions of active material inside the cell, leading to the thermal runaway of a **single cell**.



Requires $T_{Setpoint}$ and Ramp/Soak time values, which are defined by cell type and chemistry.

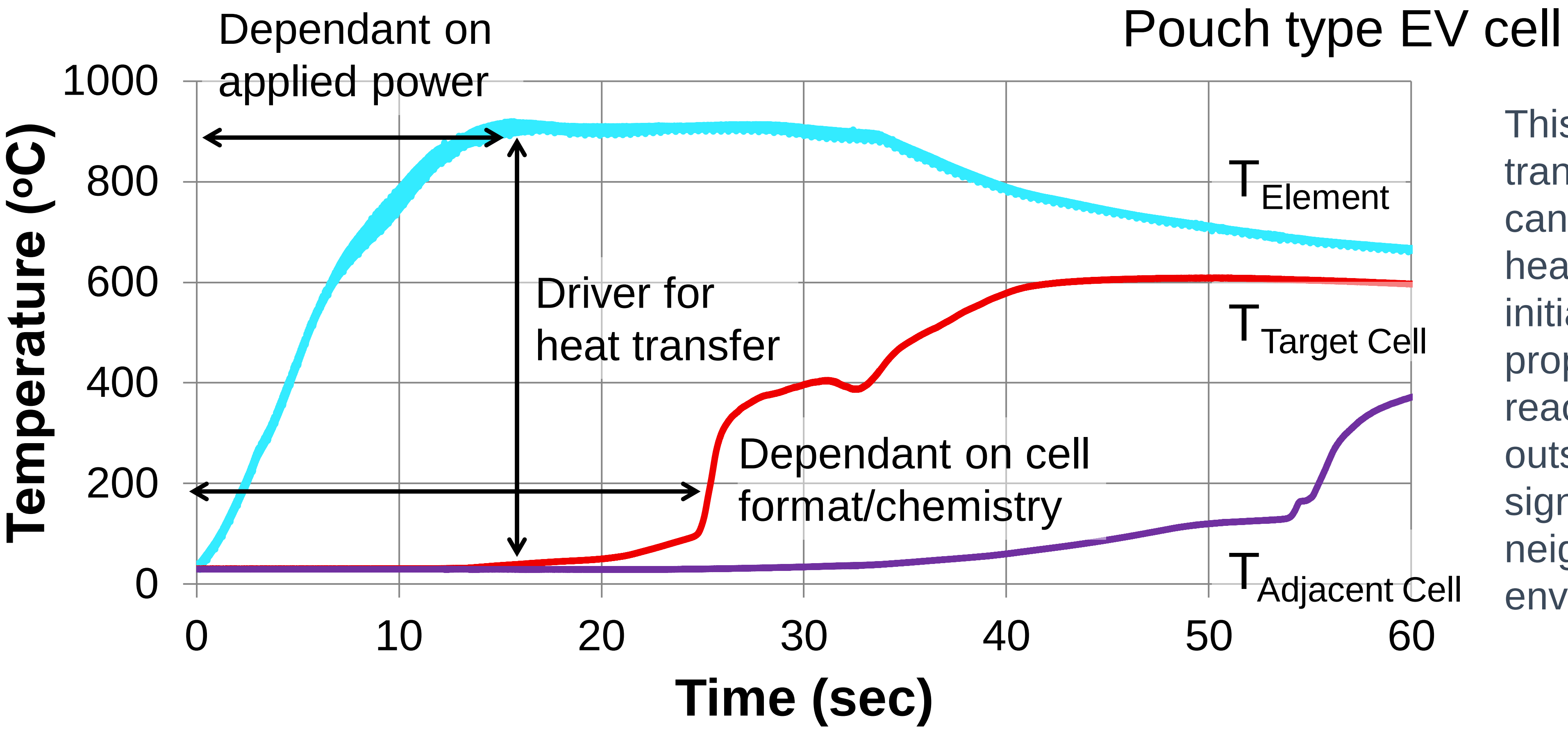
Localized Rapid Heating – Current Status

- Developed as a TR test methodology used to evaluate safety at the **system** level and is adopted within ISO 6469-1: Amd1 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.

Example of Localized Rapid Heating



This is essentially a heat transfer question. How can you get sufficient heat INTO a cell, to initiate internal self-propagating exothermic reactions, from the outside without significantly affecting the neighboring environment?

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

NRC heating elements

NOTE: other commercial heating elements (non-NRC) are suitable for localized rapid heating, but we were bound to what was possible for SYSTEM level testing

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 Low voltage DC operation	
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		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

Heater Selection Guide – System Testing

Table 12 — 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 alumina, ceramic, or fiberglass.
Thickness [mm]	<5	Minimize introduction of foreign objects, some RESS 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 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 RESS 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 chosen heater.

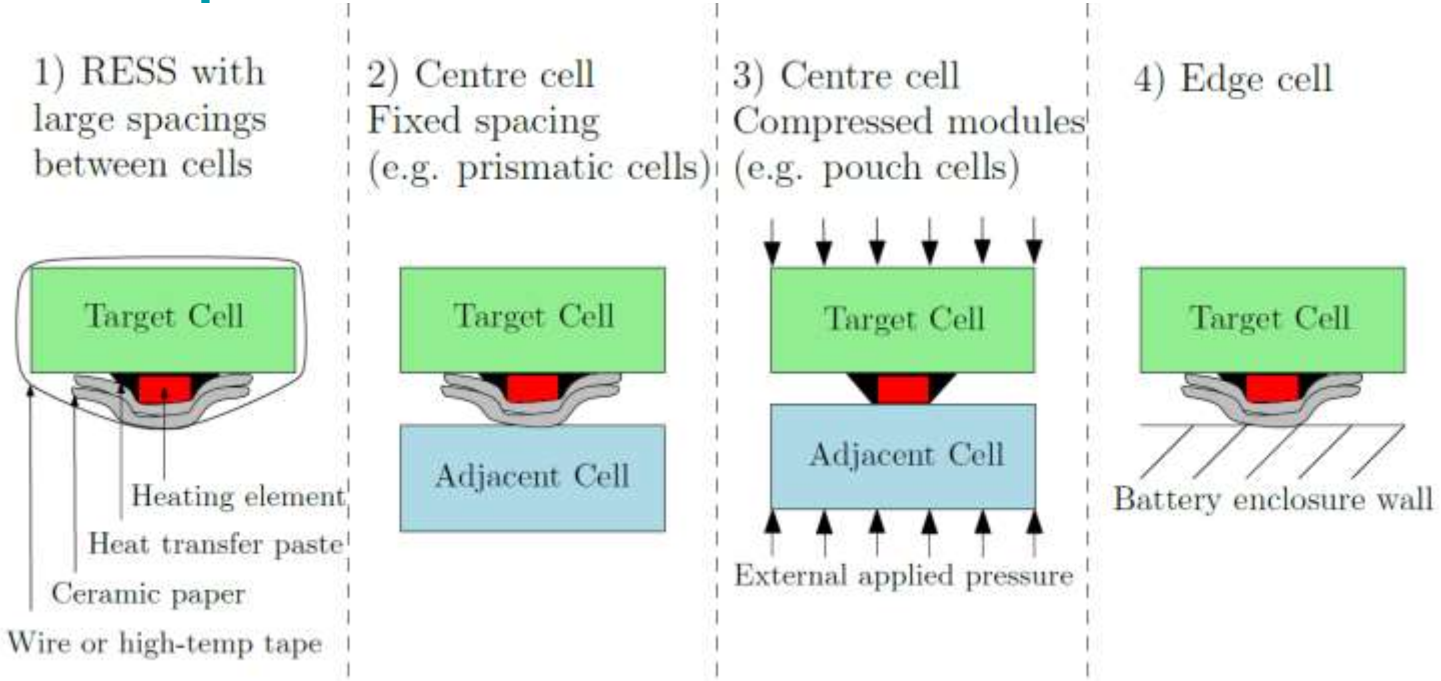
[b] This temperature may need adjustment for other chemistries and potentially other cell construction techniques (cell sidewall ruptures).

[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.

Installation considerations

- Installation method depends on testing goals
  (ex. target cell selection, perceived invasiveness of modifications)

- NRC follows an opportunistic approach to target cell selection and installation options:



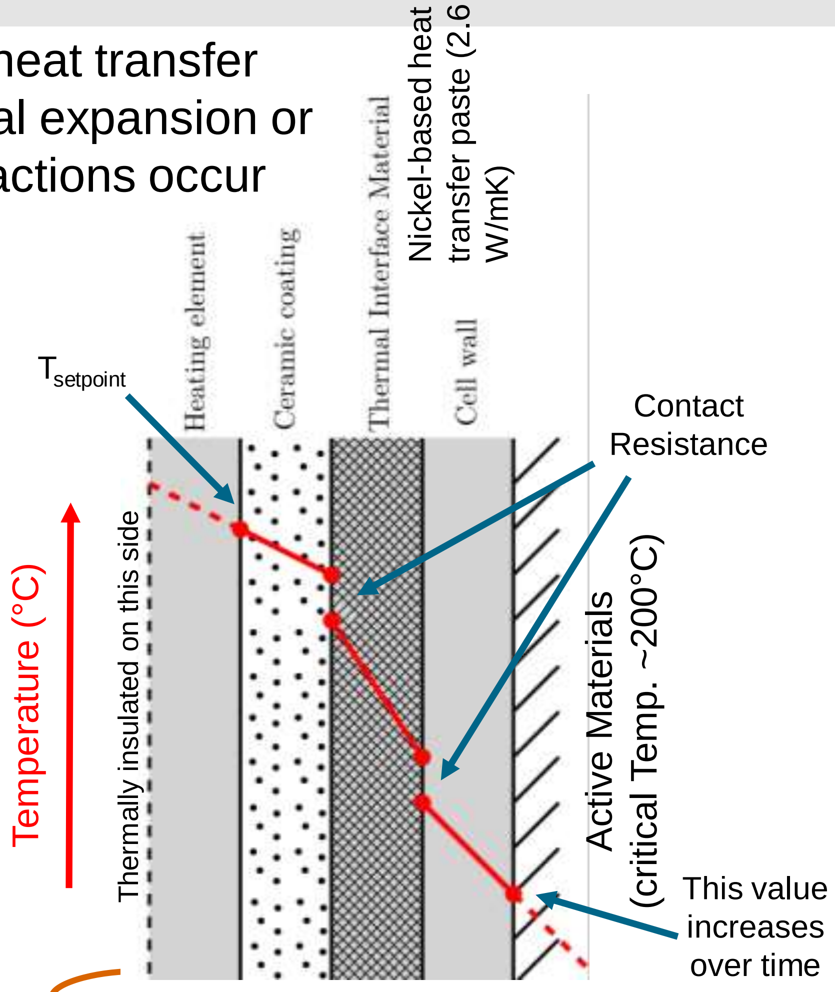
CELL LEVEL TESTING VALIDATION

Thermal Transfer Challenges for ANY External Heating Method to Trigger TR

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

Maximum $T_{setpoint}$ is limited to below cell wall failure T, to avoid side wall ruptures.

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



Heat losses away from target cell

Note: Thicknesses shown are not to scale

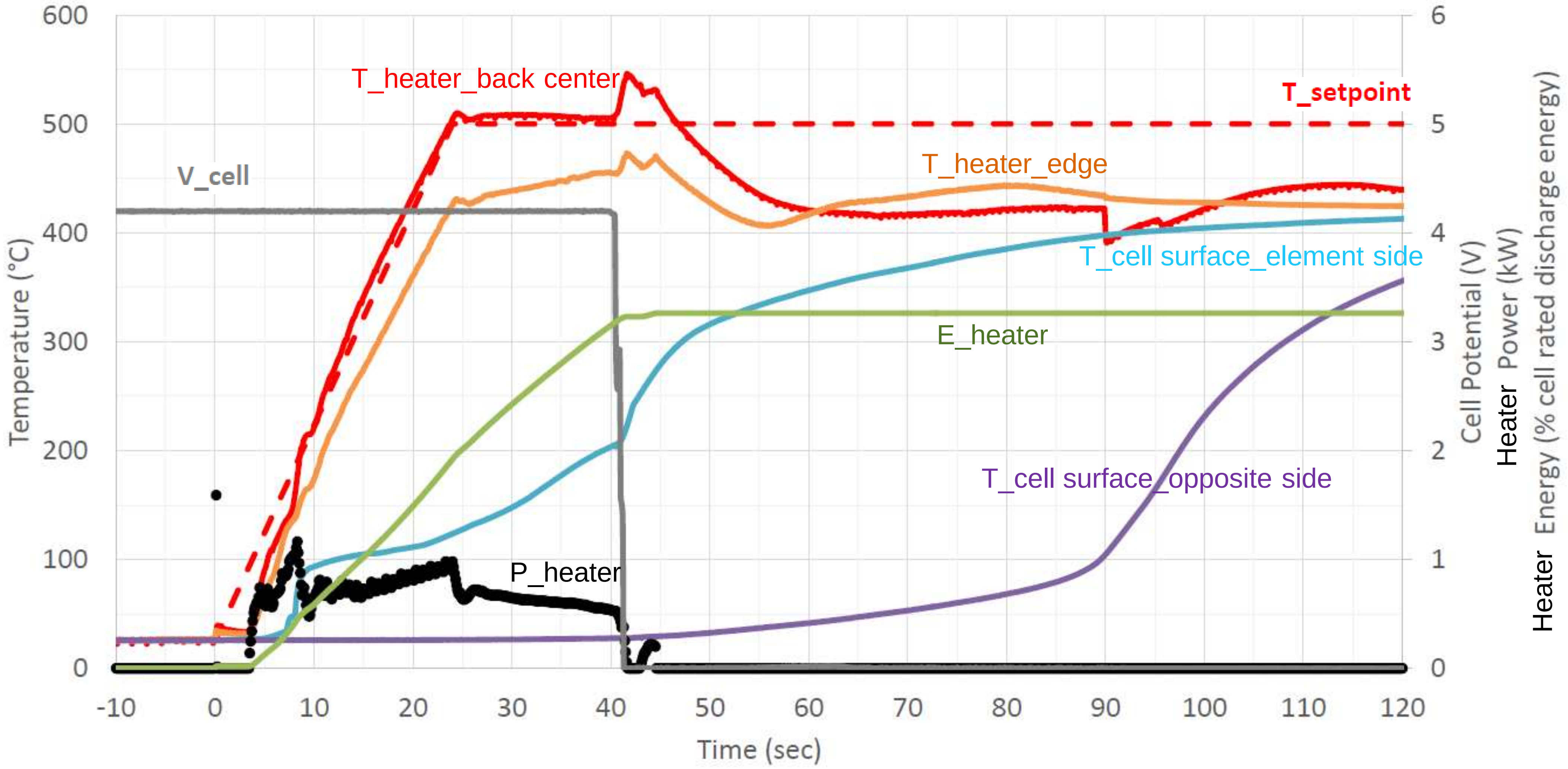
Heat losses due to thermal diffusion (includes active thermal management)

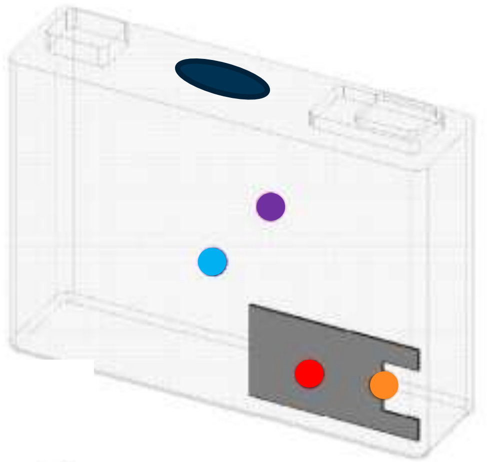
During rapid heating, the cell's construction is the **rate limiting step to effective heat transfer**

Aluminum Prismatic EV Cell

4 internal electrode rolls
Interior welded tabs
1.6mm thick outer can wall
insulator around electrode rolls
uncoated copper sheet
extra layers of separator
Contact area between rolls and bottom wall

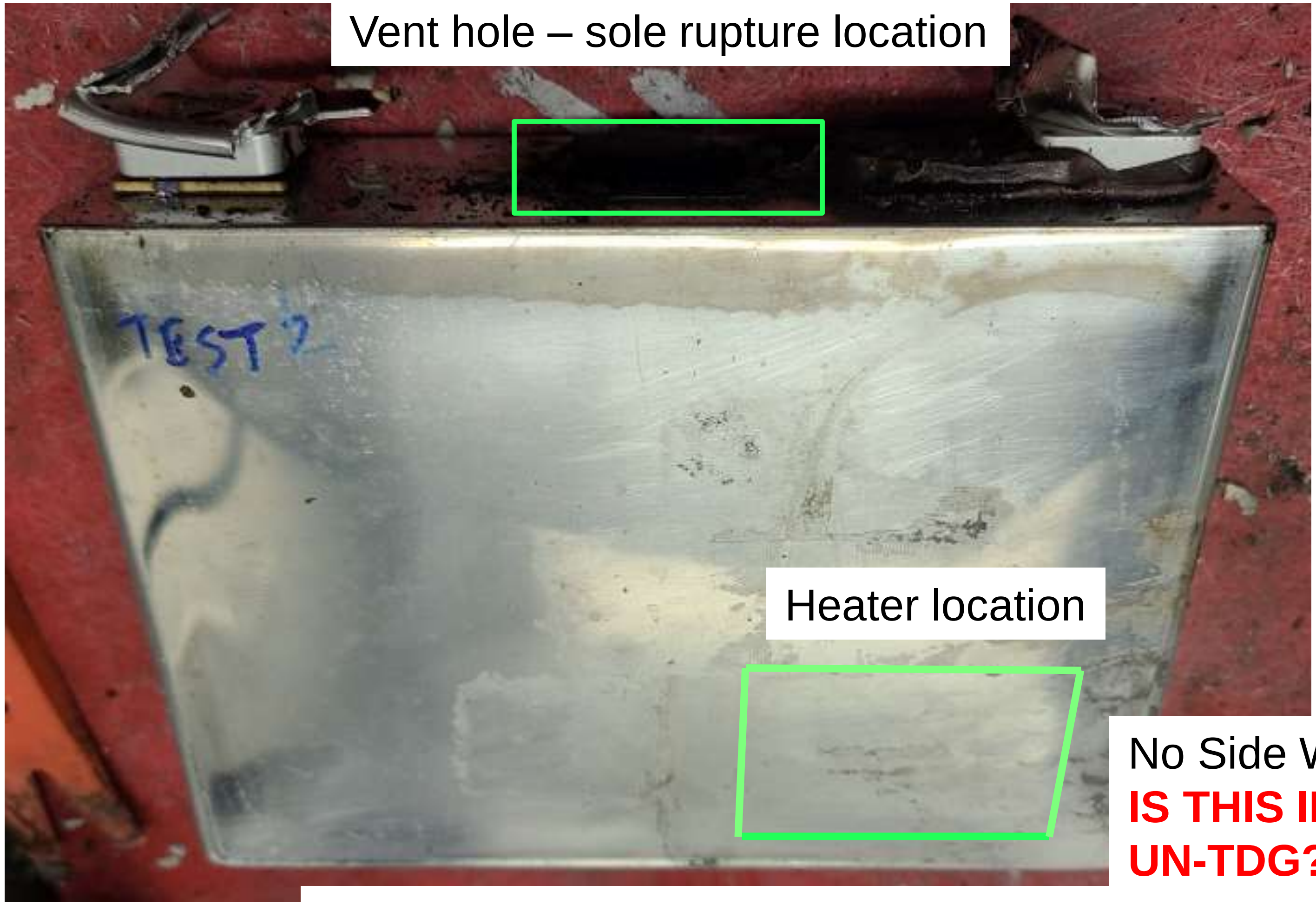
Sample Data - Large Prismatic EV Cell





3.2% of cell's energy added to the heater

Post-test Visual Evidence



Heating elements survived all tests and were still operational after tests
(however not advised to reuse due to cured paste)

how energy is released may influence the system level, since it is highly directional.

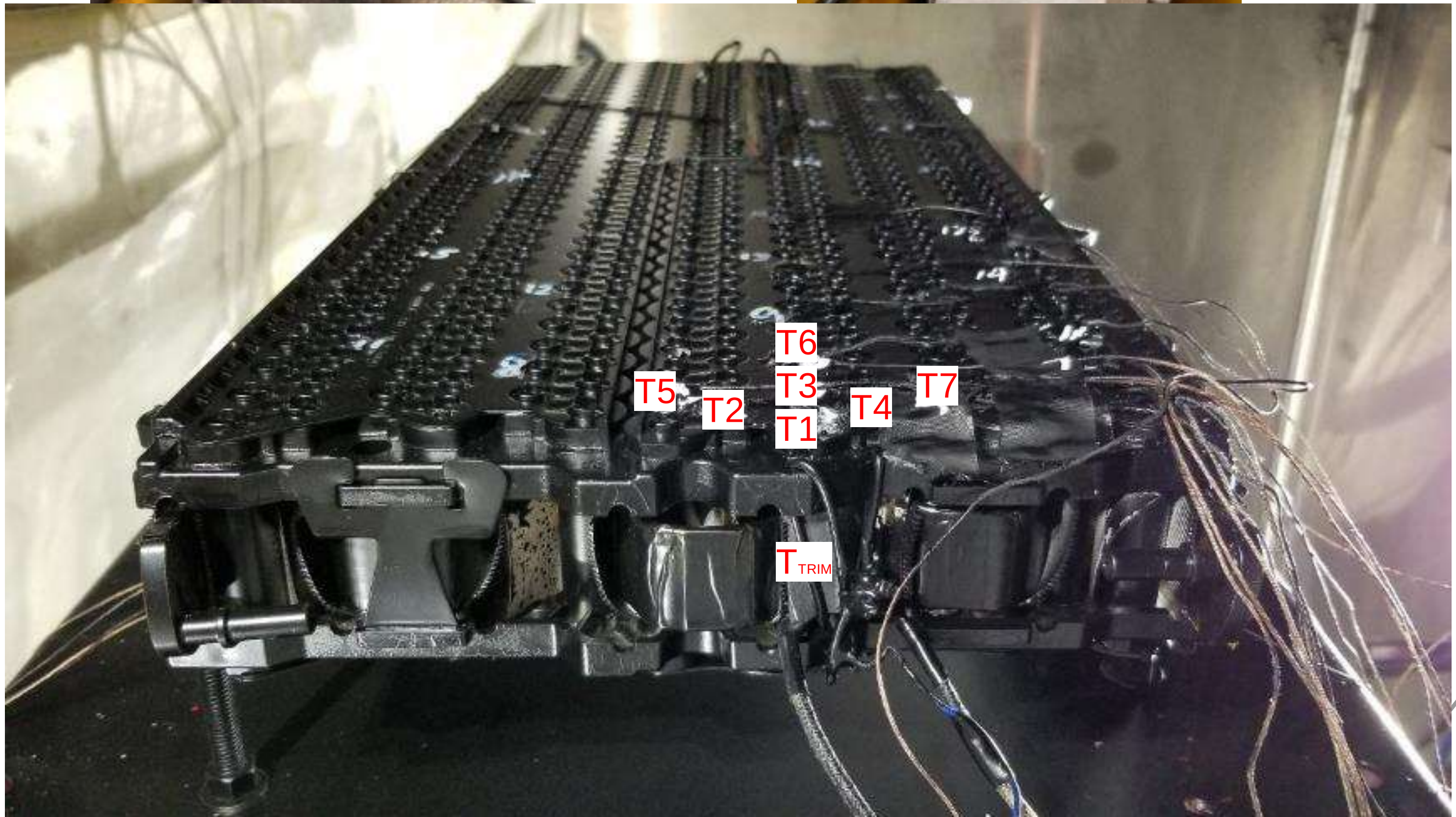
No Side Wall Rupture (SWR),
IS THIS IMPORTANT TO UN-TDG?

Is a SWR within cells, with dedicated pressure relief vents, an acceptable outcome for a TR test methodology?

WORKING TOWARDS SYSTEM LEVEL TESTING

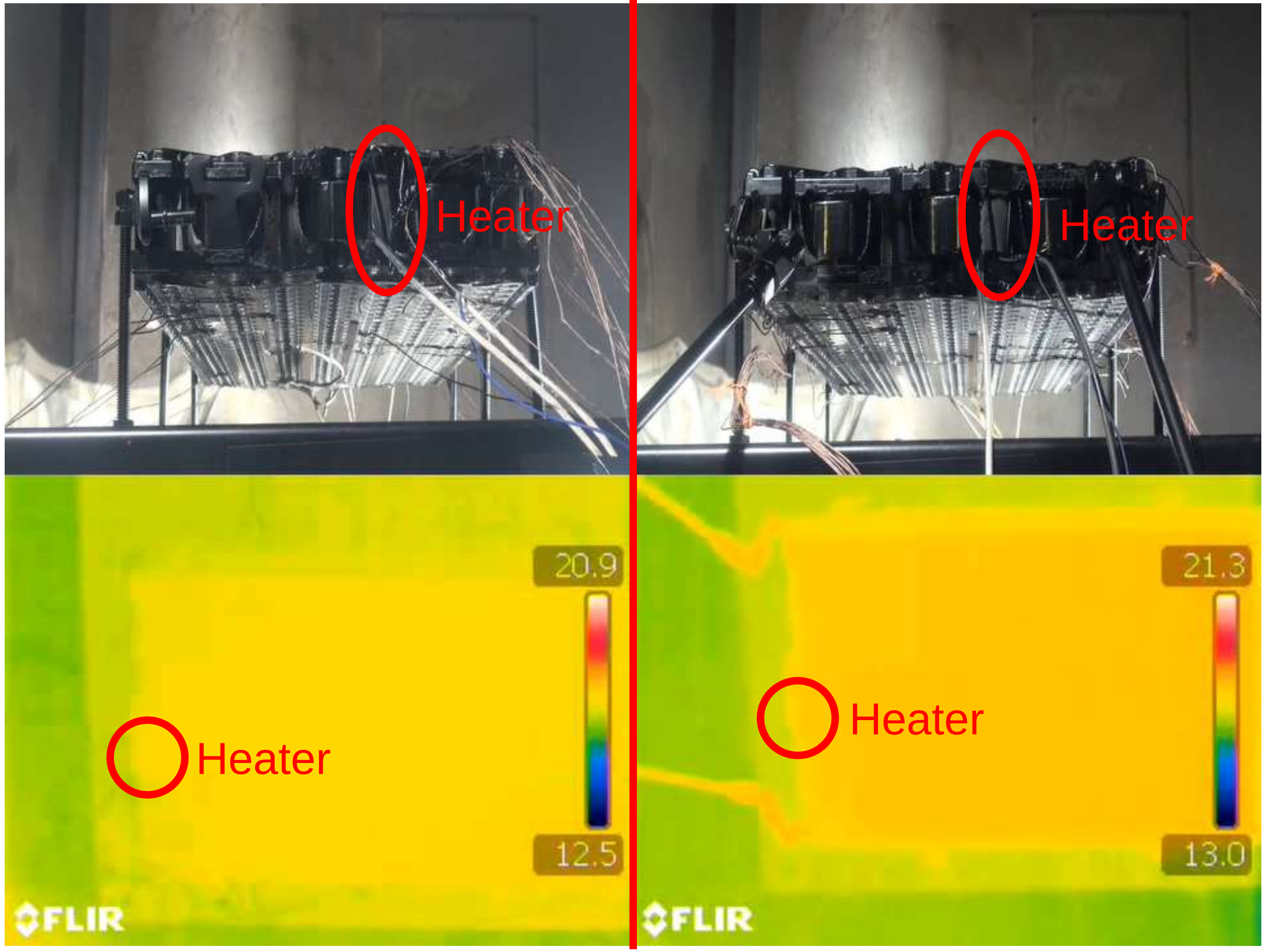
EV Module Testing

18650 Installation in a Liquid Cooled EV Module

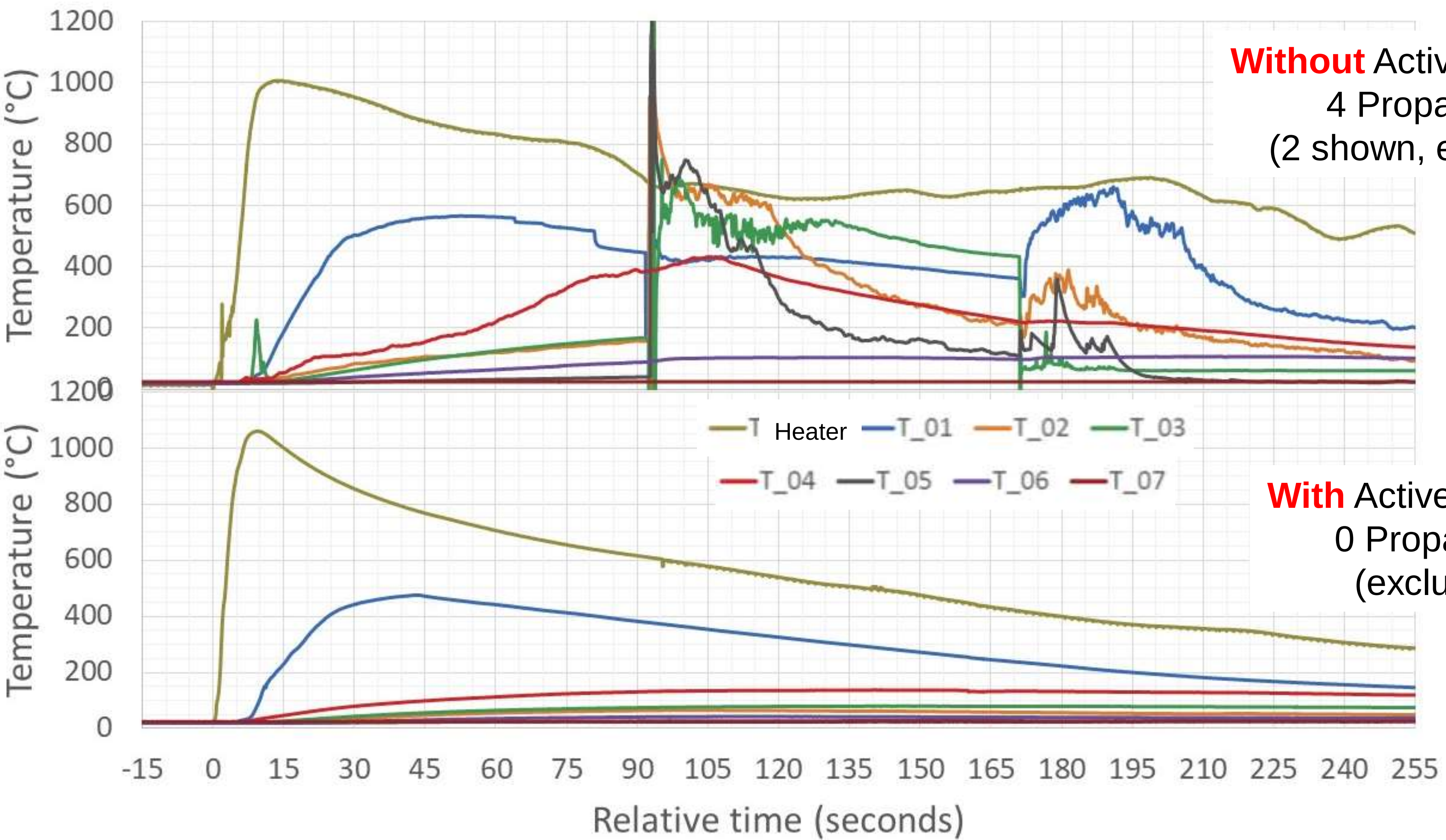


Test Video

Without liquid cooling | With liquid cooling



Module Thermal Runaway Testing



Without Active Thermal Management
4 Propagated TR Failures
(2 shown, excludes initiation cell)

With Active Thermal Management
0 Propagated TR Failures
(excludes initiation cell)

APPLICATION AT THE FULL SYSTEM LEVEL

Full Vehicle Level Testing

Vehicle Testing Introduction

Can proposed method be used on a fully operational vehicle?

Ensure the heater can be installed in such a way it is invisible to the full system;
Ensure the vehicle can turn on and ideally operated within a driving mode.

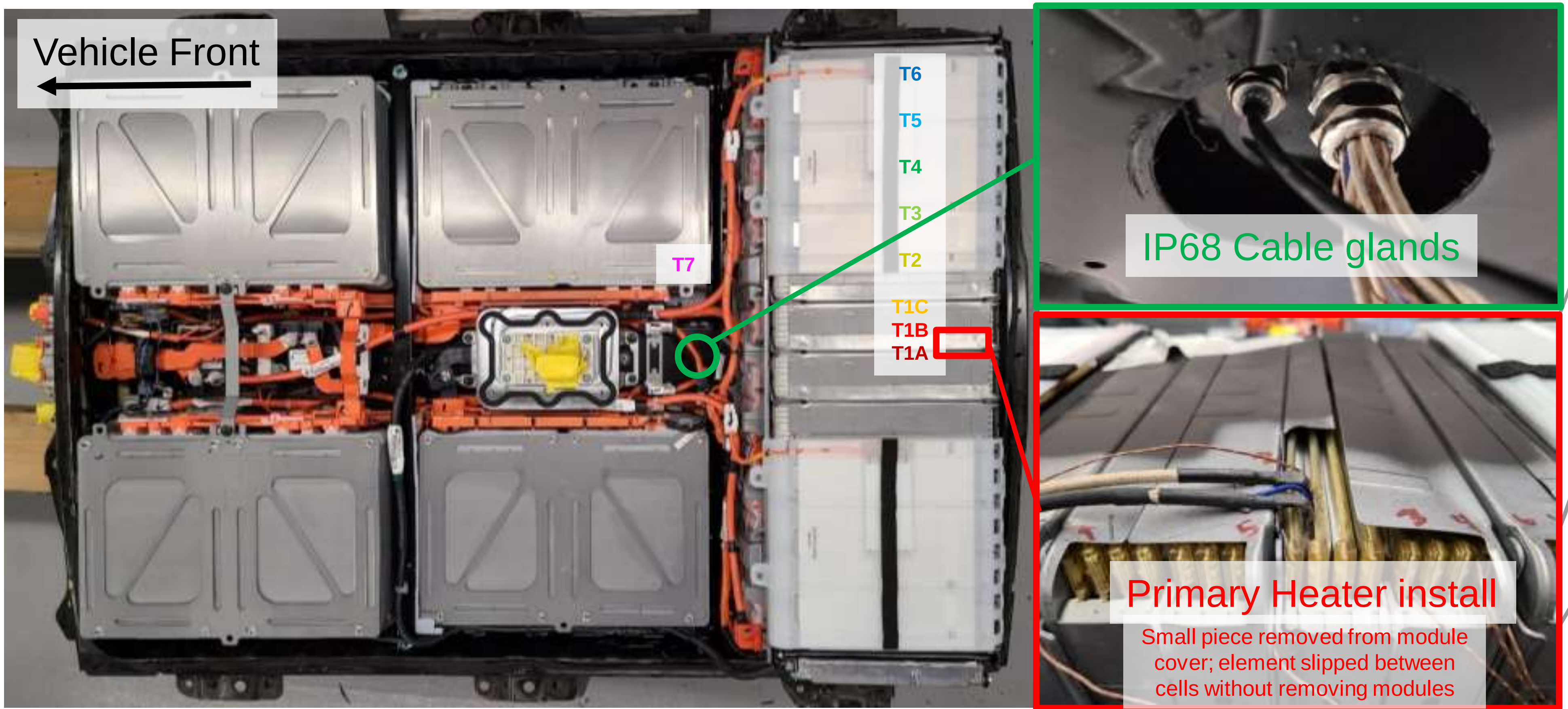
Recall – Module tests have NO containment!

Missing thermal barriers/mass, loss of discharged thermal energy from the system and easy access to oxygen to sustain any fire.

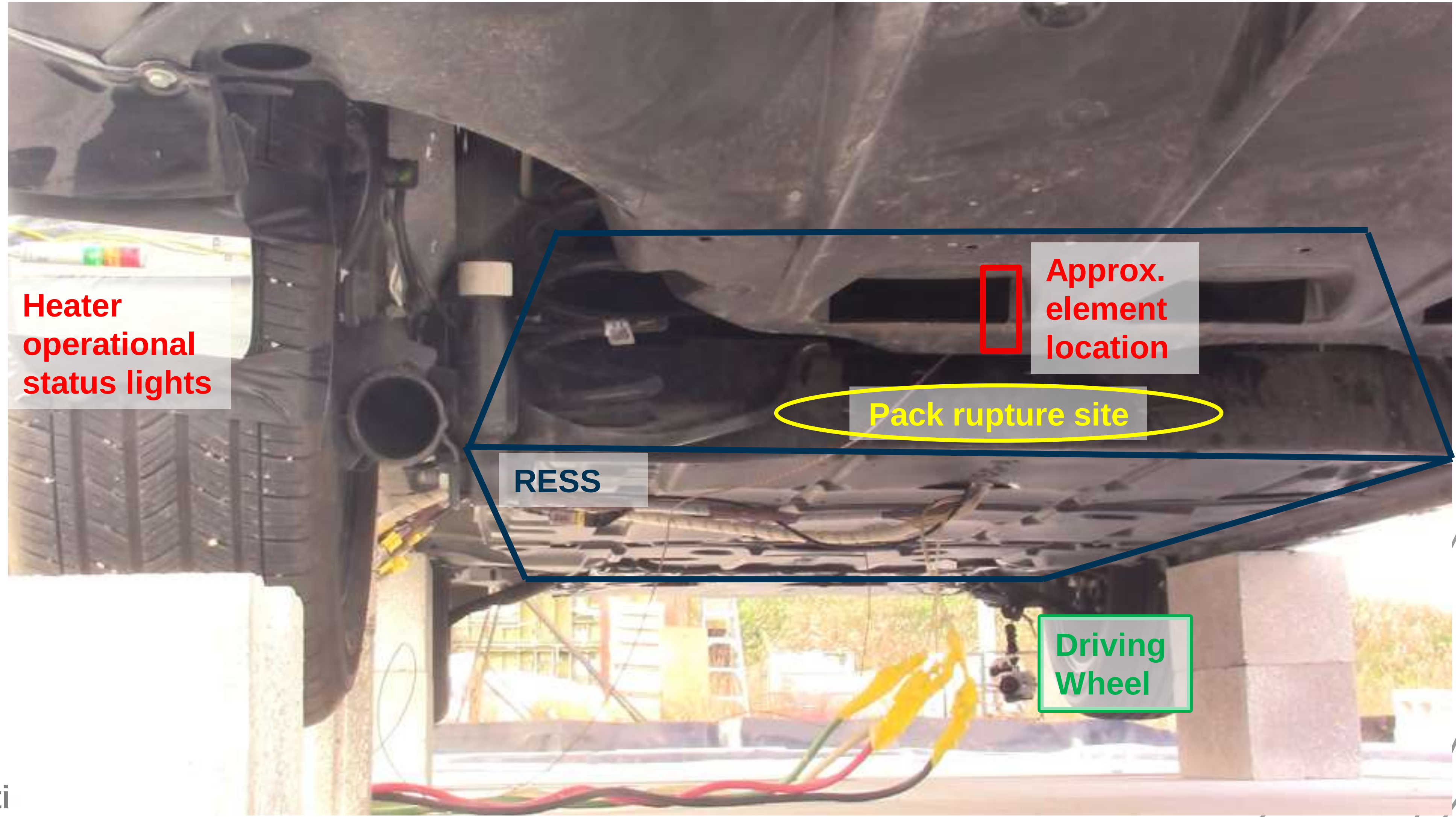
Vehicle Testing Pack Instrumentation

Extraction / heater install / reseal / reinstallation following OEM service manual

No vehicle error codes present after reinstallation



Vehicle Testing Test Video



Vehicle Testing Event Log

00:00 - Heating starts

00:11 - Initial TR occurs

00:12 - RESS enclosure ruptures at seal between top/bottom halves

00:15 - Heating stops

00:18 - Several visual dash warnings to stop were provided, vehicle propulsion was slowly reduced to stop

00:40 - Gas emissions intensify

12:20 - External fire begins from rupture site

13:20 - Hazardous environment is present within the cabin (based on multigas meter)

14:00 – External fire suppression applied (water)

Findings

System-level tests are, in many ways, easier to execute:

- No requirement for custom external cooling system;
- Less instrumentation required due to BMS / OBD / onboard display monitoring.

AND, most representative of in-situ conditions:

- Full system response - no component needs to be disabled or replicated that may affect safety performance;
- Permits direct evaluation of pass / fail criteria - no equivalency req.

To be technology neutral, the full system level response must be considered during thermal propagation testing

Conclusion

Introduced a robust Rapid Heating testing methodology for triggering thermal runaway – Demonstrated at cell, module and most importantly a fully operational vehicle level.

Methodology can be applied on cylindrical, pouch and prismatic cells, systems with or without cooling and can trigger TR on cylindrical/prismatic cells without inducing a side wall rupture.

Methodology is a useful tool for investigating and validating the impacts of a potential TR event within a variety of designs and systems with minimal invasiveness to OEM safety and design strategies.

Key Methodology take away for cell level testing

- 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)

Future - 1

UN Global Technical Regulations for EV Safety

NRC developed methodology is being evaluated by other countries to determine suitability as a regulatory test method. At this stage no other viable option exist from other contracting parties.

ISO 6469-1 AMD 1 – Safety management of thermal propagation for EVs

Rapid heating test methodology is one of three test methods within this standard for TR evaluation in EVs and it is published.

Other Standards

Rapid Heating test methodology is a valuable tool for triggering thermal runaway in fully operational systems. We are working (and will work) with various standard/regulatory bodies and test agencies to develop acceptance of the methodology for use in full system testing.

Future - 2

Other Areas

The methodology can be applied at various stages of development, which will permit investigation of thermal propagation dynamics, effectiveness of mitigation strategies, gas/heat released from TR/TP and many other parameters.

Interested?

The Rapid Heating Methodology is currently being evaluated by multiple organizations (OEMs, test labs, RTOs) worldwide. NRC is seeking active collaboration on advancing the methodology from industry for both testing/validation and manufacturing of the heater; as well as inclusion into other potential standards for system evaluation.

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THANK YOU and Please contact me if you desire more information

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