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Thermal Runaway Initiation and Propagation requires consideration of system-level influences

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June 11-13th, 2019 **EVS 18 - GTR** **Tokyo, Japan**

National Research Council Canada Conseil national de recherches Canada

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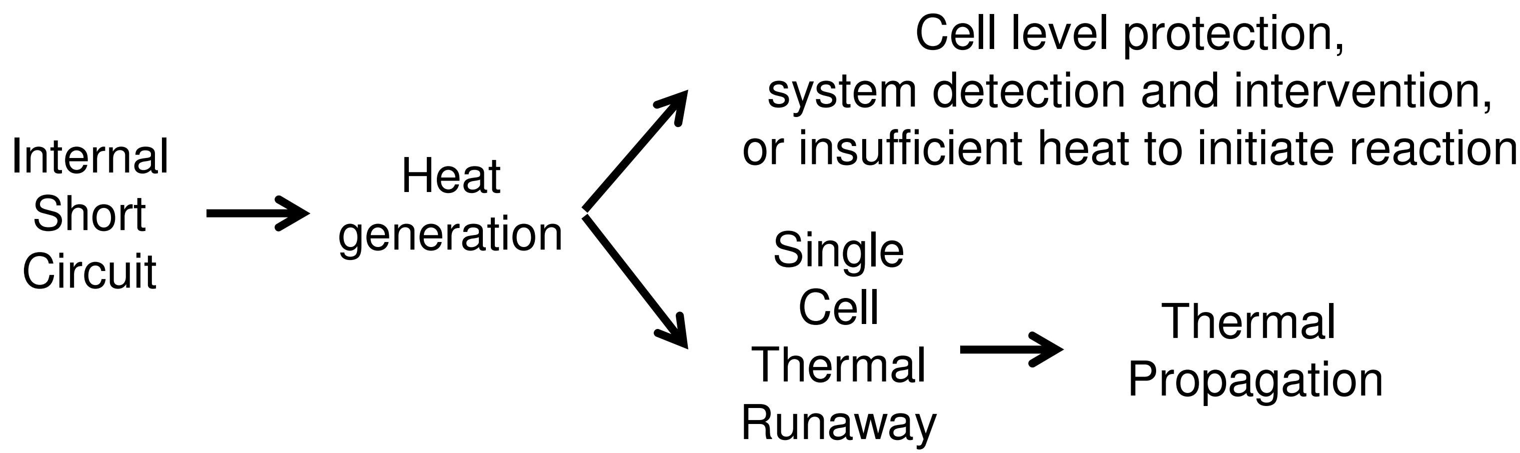
Thermal propagation requirement in current GTR draft (Review)

"5.4.12: Thermal Propagation: For the vehicles equipped with a REESS containing flammable electrolyte, the vehicle occupants shall not be exposed to any hazardous environment **caused by thermal propagation which is triggered by an internal short circuit leading to a single cell thermal runaway**…"



As stated in 5.4.12: we should consider the second case, unless first case is ubiquitous and soundly proven for a given design based on field history, documentation or prequalification test (as suggested in C3).

Current Research Test Program

Researching key parameters pertinent to thermal propagation within EVs.

In this meeting presentation:

1. The importance of active thermal management during thermal propagation testing

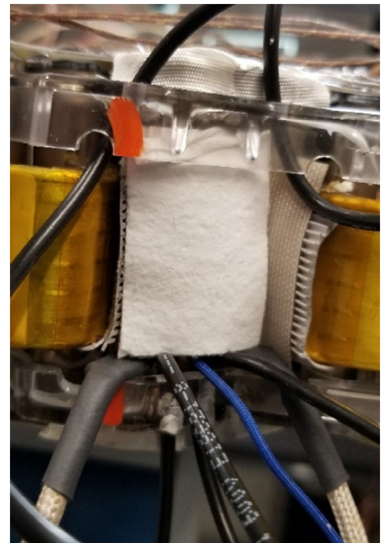
Update: Direct comparison experiments of modules consisting of cylindrical 18650 cells, tested one without and one with liquid cooling.

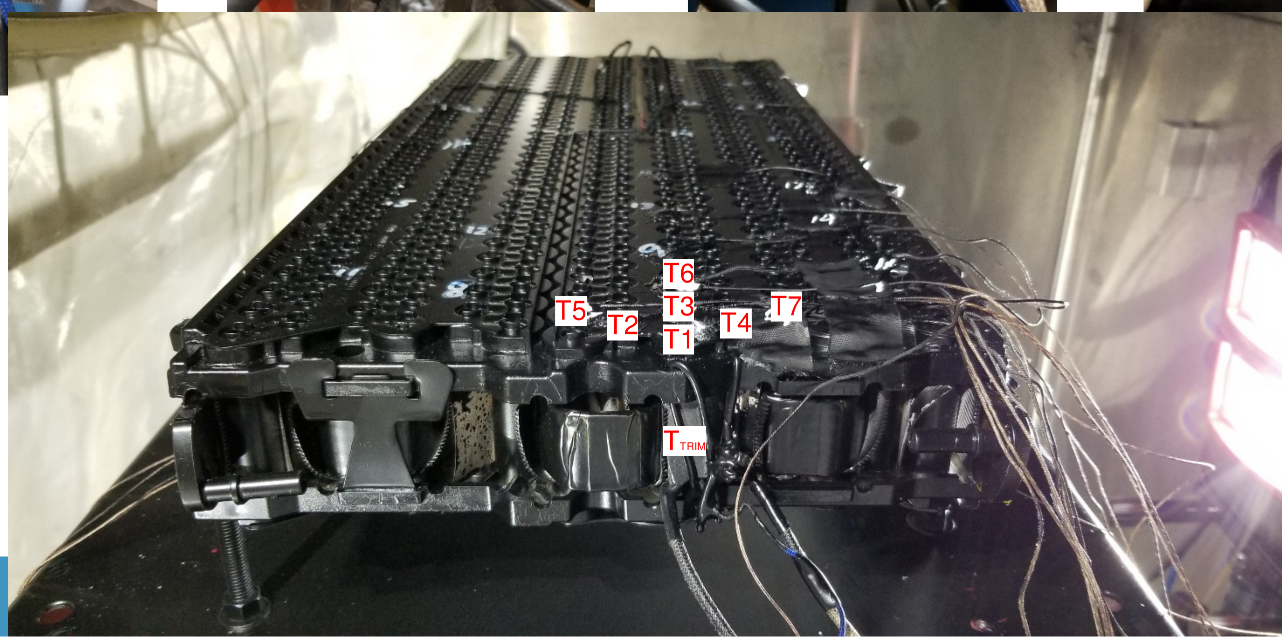
2. The importance of considering the entire system response

Update: Vehicle-level test results

1. Importance of active thermal management

Test Setup

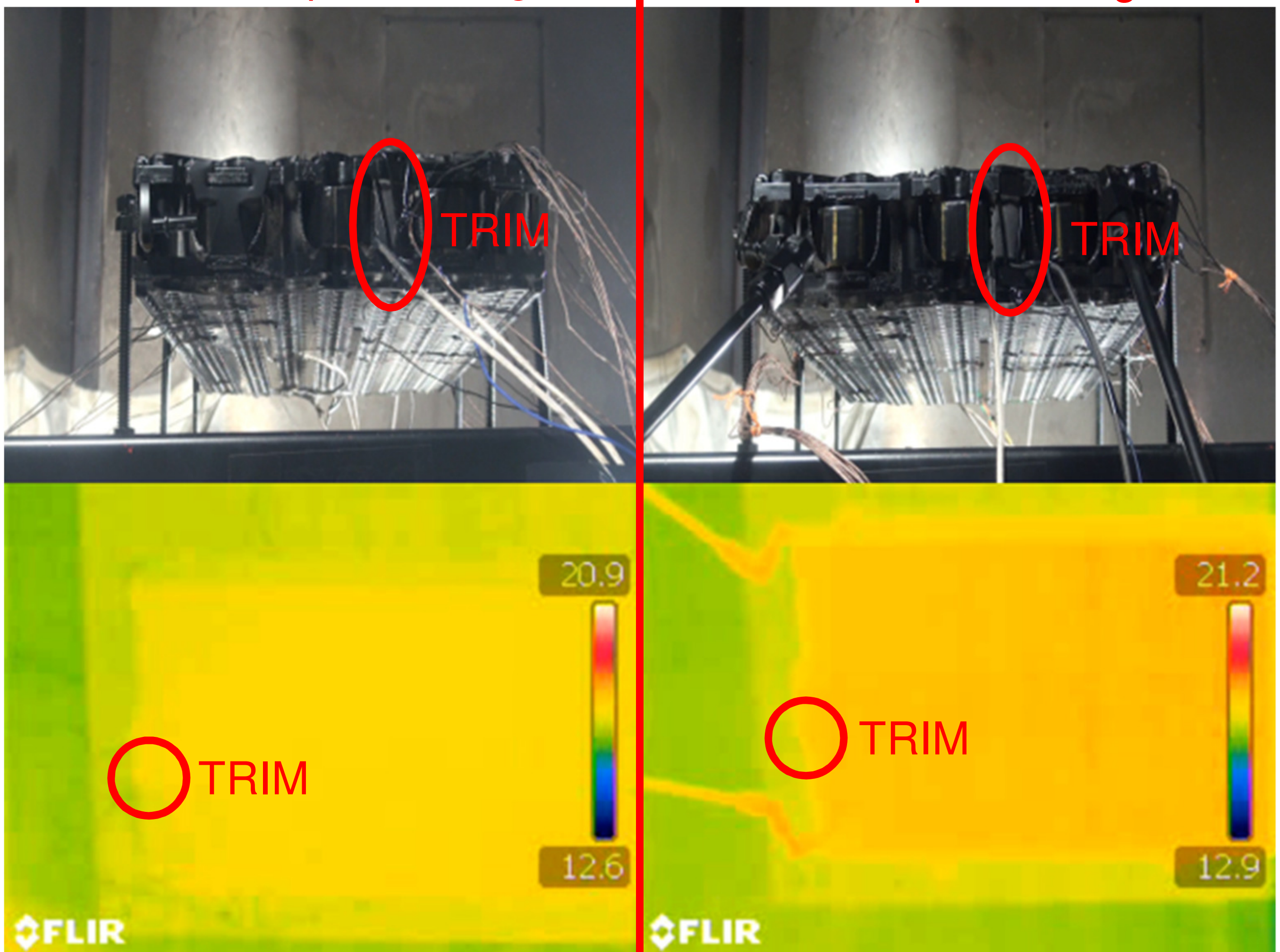




1. Importance of active thermal management

Test video

Without liquid cooling | With liquid cooling



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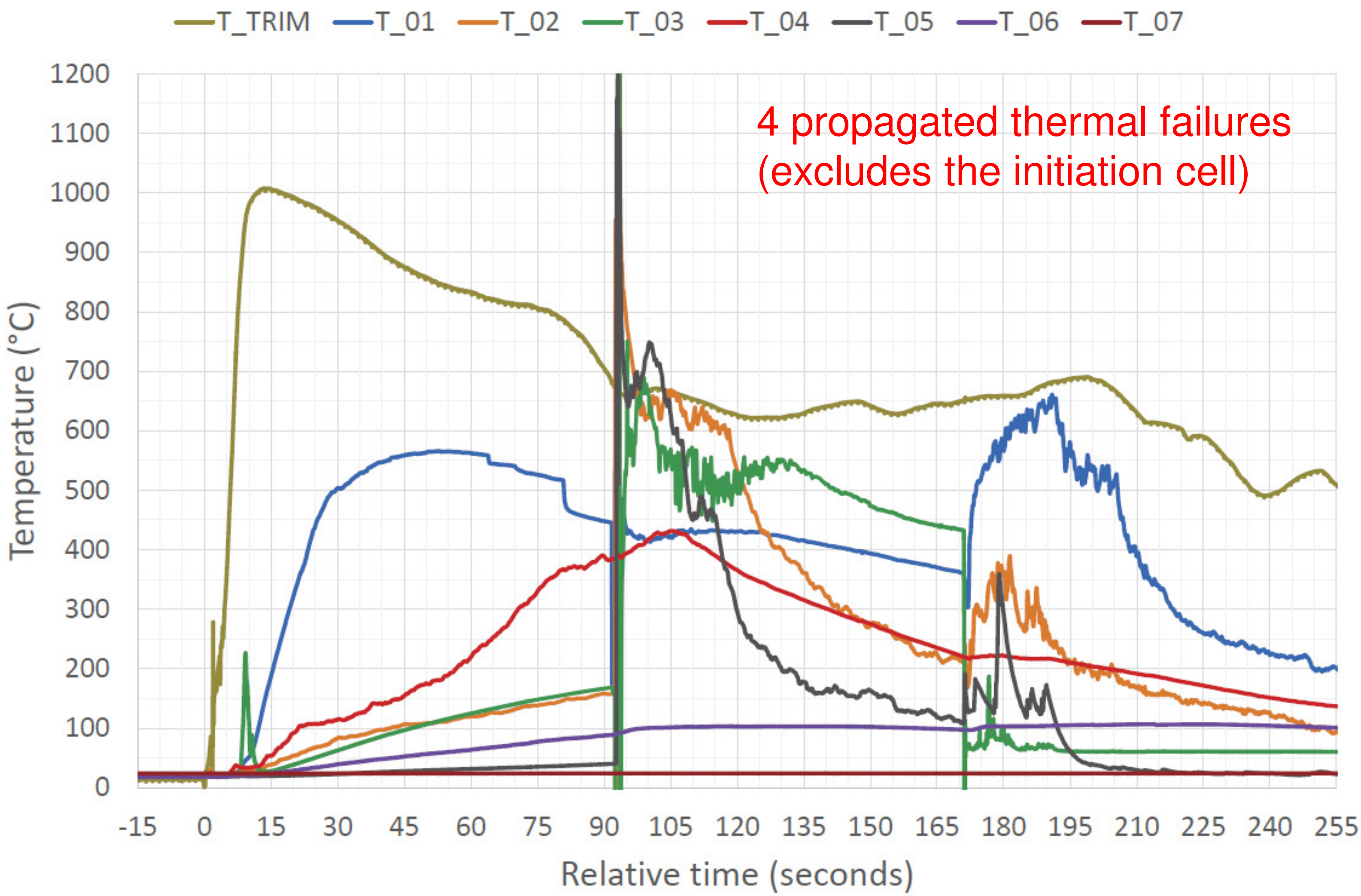
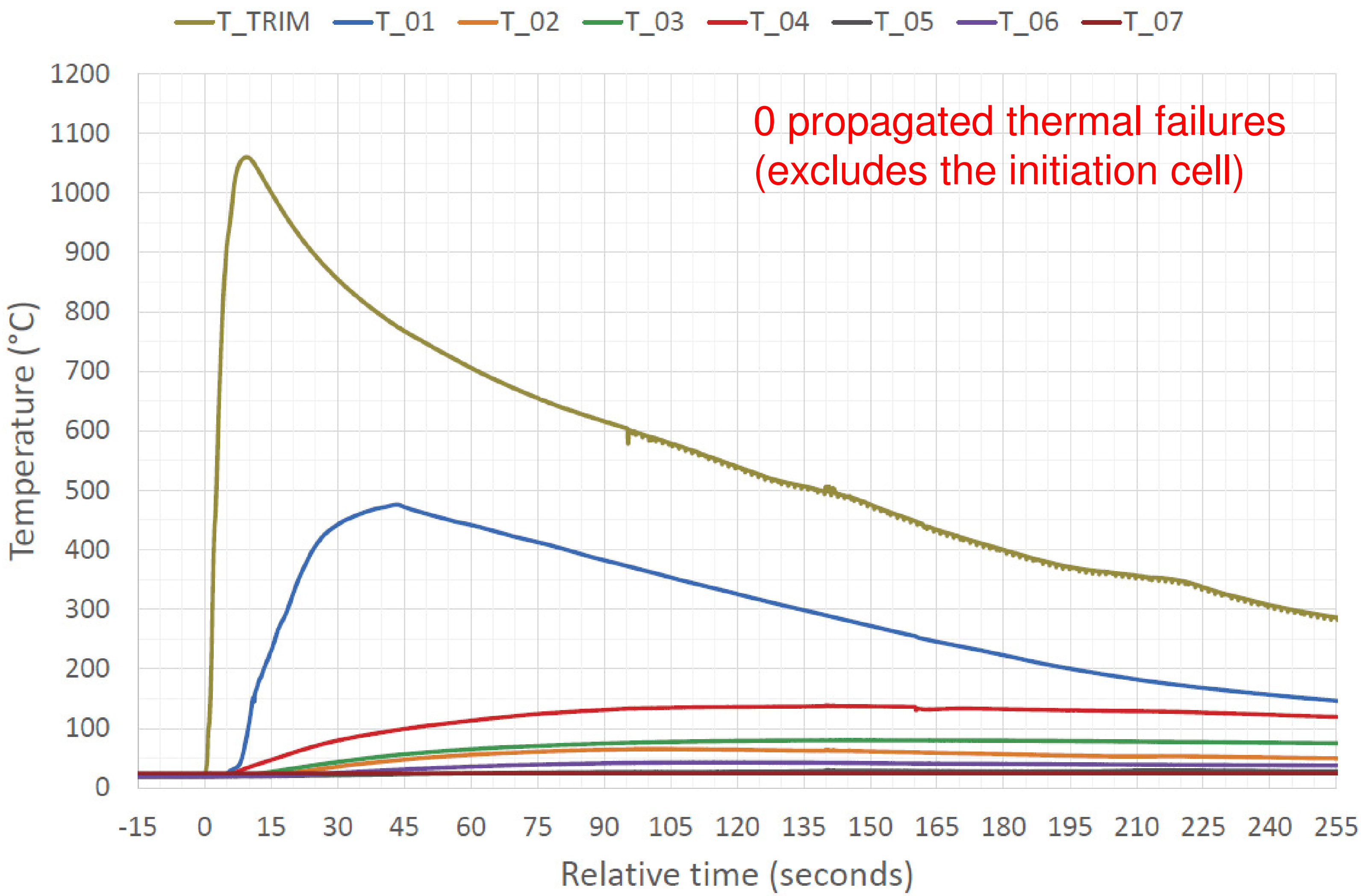
1. Importance of active thermal management

Results – Temperatures WITHOUT cooling



1. Importance of active thermal management

Results – Temperatures WITH cooling



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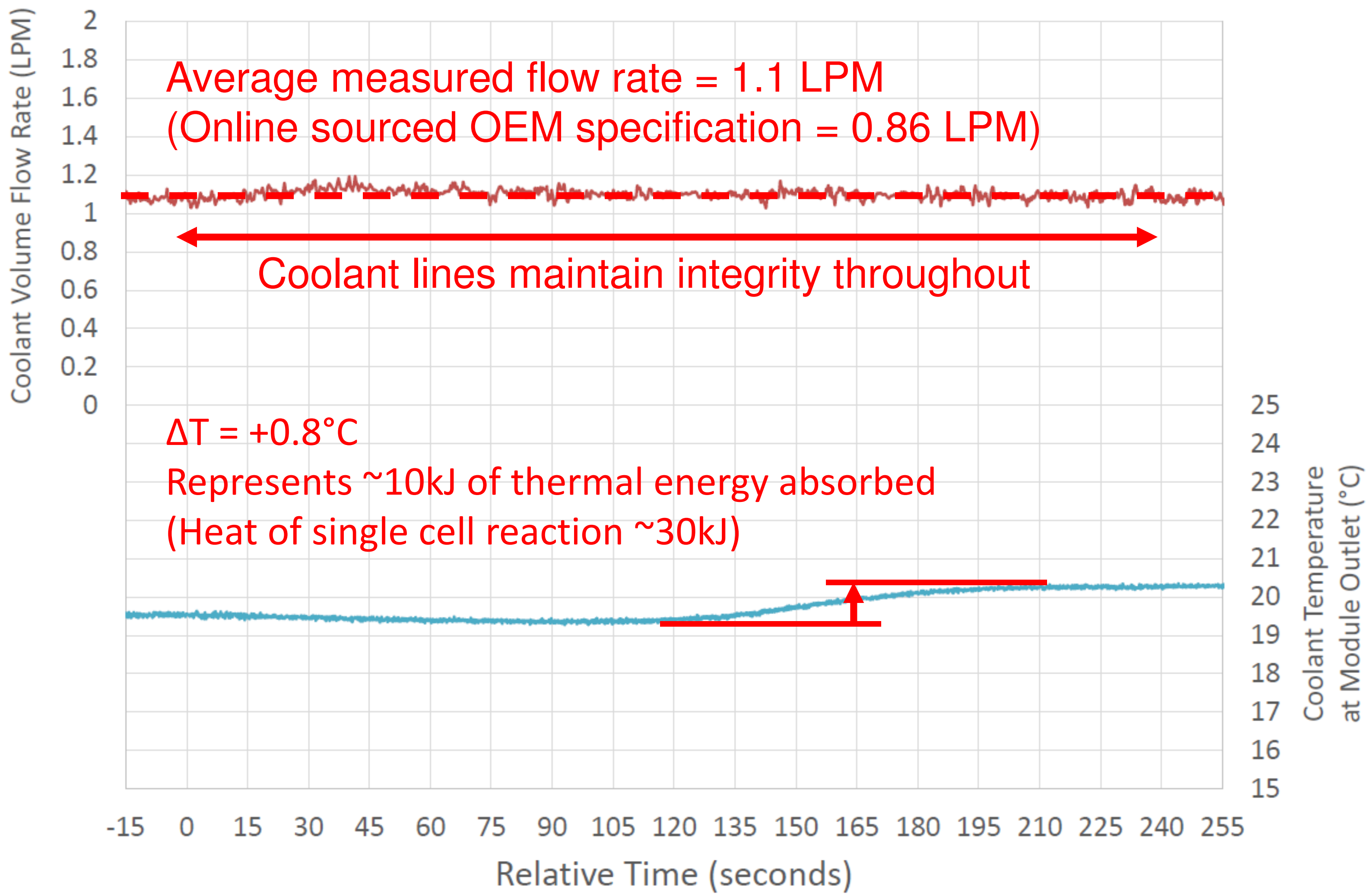
Results – Coolant flow rate and temperature



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1. Importance of active thermal management

Findings

- Active thermal management can play a significant role in the extent of thermal propagation and cannot be ignored
- No measureable change in voltage in either experiment
  - Module design has 74 cells in parallel
  - Cell voltage cannot be the primary indicator of thermal runaways
- Note: Module level test with no containment
  - Adjacent thermal barriers and thermal mass are not present
  - Thermal energy discharged from vents is lost from the system (this energy may contribute to TP during pack/vehicle-level)

2. Importance of vehicle-level response

Review of previous pack-level tests

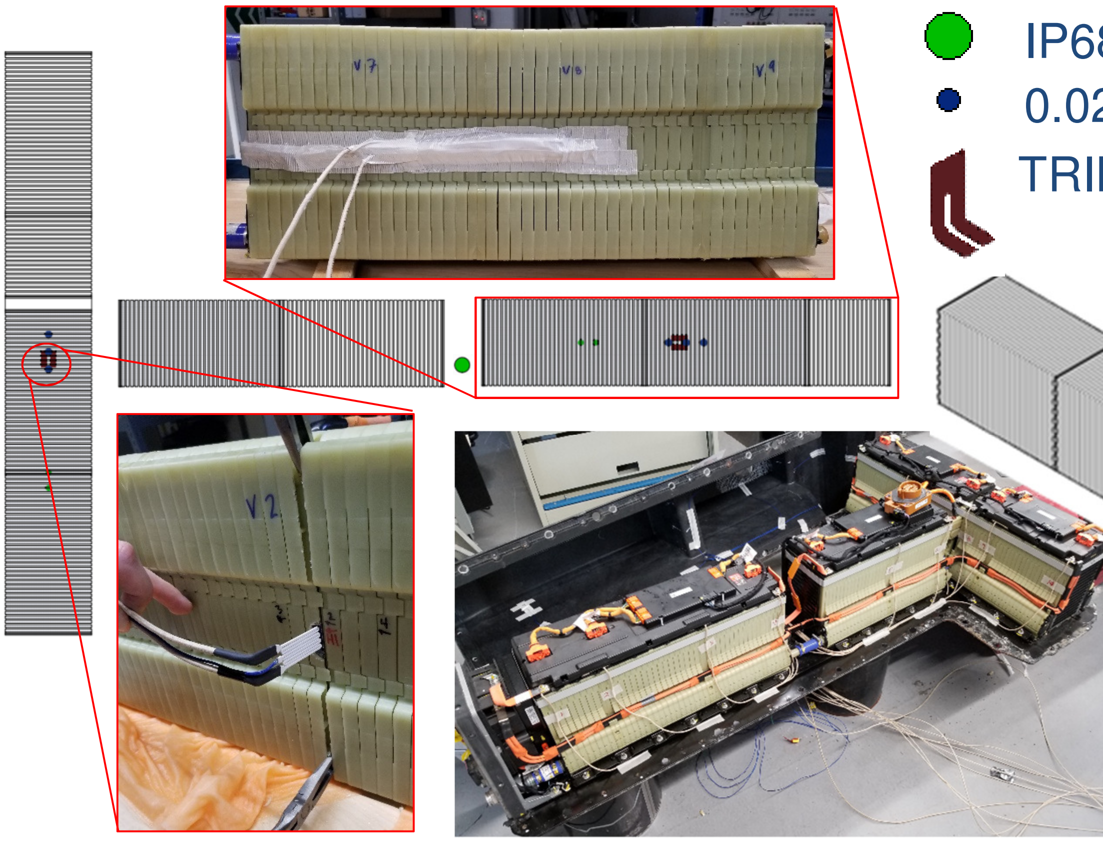
Conditions	2016 Test	2018 Test
TRIM version	1 [13kJ applied]	3 [7.1kJ applied]
Manipulation to pack seal integrity	High	Low
Thermal management	**Inactive**	**Active** (replica to vehicle)
Ambient temperature	6˚C	23˚C

Key results	2016 Test	2018 Test
No. of cell failures	198 [68.8% of pack]	10 [3.5% of pack]
Time to first vent	7 sec	7 sec
Fire occurrence	Yes	No (not visible)
Smoke occurrence	Yes	Yes
End of visible gas production	166 min	5 min

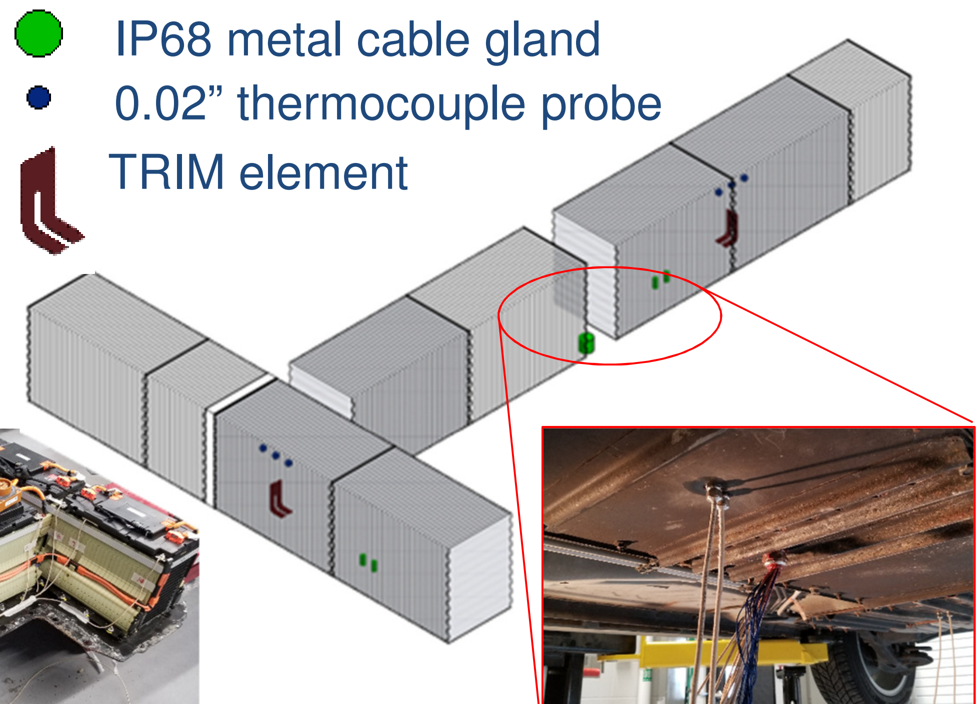
2. Importance of vehicle-level response

Pack instrumentation

Bottom view



Isometric view



2 TRIM elements
9 module voltages,
20 thermocouples

No leaks during pressure test of coolant lines

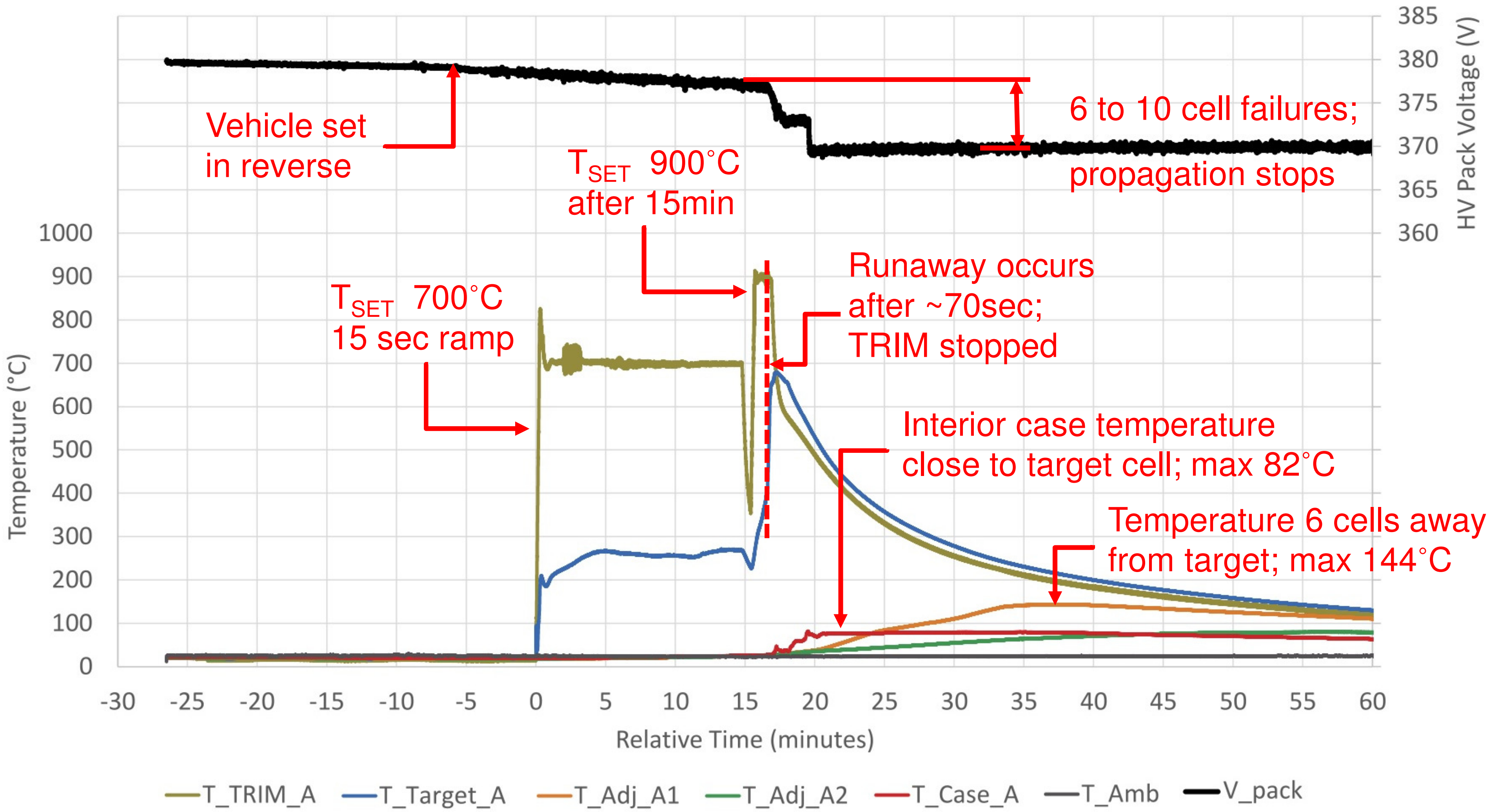
2. Importance of vehicle-level response

Test setup

Test video

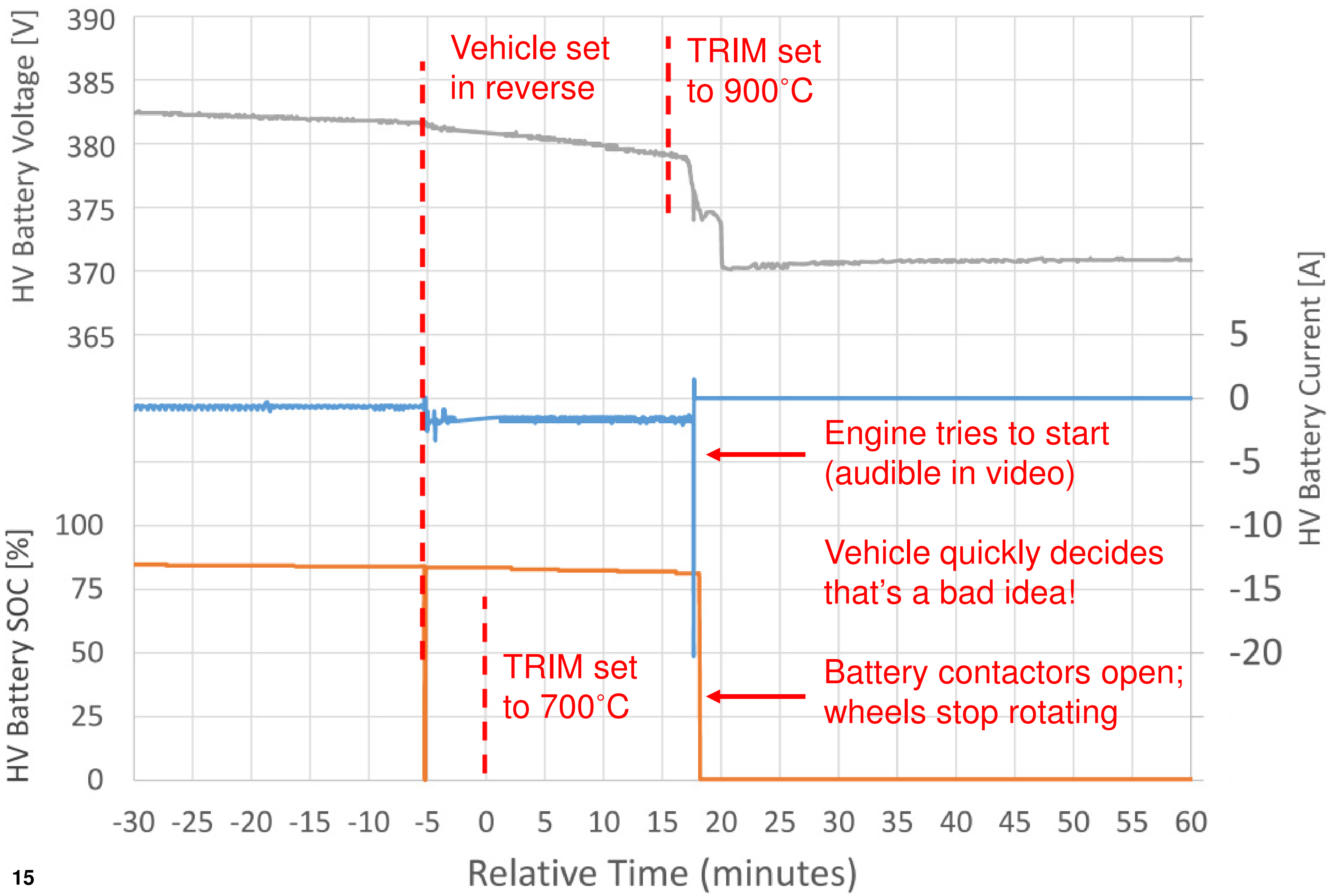
2. Importance of vehicle-level response

Results 1 – Voltages and temperatures



2. Importance of vehicle-level response

Results 2 – OBDII data log using FleetCarma C2



2. Importance of vehicle-level response

Test observations 1

- The reason TR did not occur during 700°C setpoint is still unknown:
  - Never before seen in 15 NRC tests of this cell type
  - A second measurement of the cell's surface temperature (~5cm away from TRIM) recorded >260C (steady state) for 10 minutes before setpoint was changed to 900˚C .
  - Possible contributing factors: Thermal management response, SOC @ 82%
  - Requires further analysis and pack disassembly.

- Thermal management system appeared to have responded reactively during TRIM operation and during the TR event.
  - Temperature measurements of cells far removed from the targeted location dropped by ~1C over 20 minutes.
  - Cell temperatures were below the ambient temperature at the time of the TR event.
  - Coolant reservoir was empty after the test = coolant lines within the pack had failed at some point during the test.

2. Importance of vehicle-level response

Test observations 2

- The TR event was detected by the BMS and it responded.
  - HV battery contactors were opened and drive mode became disabled within one minute.
  - A “service high voltage” message was present on the display.

- Several sources of gathered test data still requires processing and interpretation:
  - Thermal video, gas sampling, BMS data including coolant temperatures/pressures.

- Small amounts of visible gas escape the underside of the pack, however, there has been no indication of any risks* to potential occupants or bystanders. Egress would not have been required in this case.

  *such as visible flame, high temperatures outside the REESS, or hazardous gas quantities above preset alarm thresholds inside the cabin

2. Importance of vehicle-level response

Test comparison

Conditions	2016 Pack Test	2018 Pack Test	2019 Vehicle Test
TRIM version	1 [13kJ applied]	3 [7.1kJ applied]	4 [205kJ at 700˚C (103%)] [25kJ at 900˚C (13%)]
Manipulation to pack seal	High	Low	Low
Thermal management	**Inactive**	**Active** (NRC replica)	**Active (Reactive?)** (OEM original)
SOC and operational state	100% and under no load	100% and under no load	82% and reverse drive mode engaged
Key results	**2016 Pack Test**	**2018 Pack Test**	**2019 Vehicle Test**
No. of cell failures	198 [68.8% of pack]	10 [3.5% of pack]	Between 6 - 10 [To be determined]
Time to first vent	7 sec	7 sec	N/A at 700˚C 70 sec at 900˚C
Fire occurrence	Yes	No (not visible)	No (not visible)
Smoke occurrence	Yes	Yes	Yes
End of visible gas production	166 min	5 min	8 min

2. Importance of vehicle-level response

Findings

Compared to the pack-level test, we found the vehicle-level was:

1. In many ways, <u>easier</u> to execute:
   - No requirement for custom external cooling system or custom pack mounts
   - Less internal instruments required due to BMS / OBD / onboard display monitoring

2. Most representative of in-situ conditions:
   - Full system response - no components need to be disabled or replicated that affect safety performance
   - Permits direct evaluation of pass / fail criteria - no equivalency required.

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

Conclusions and future topics

- The rapid, localized heating approach:
  - Has been adapted to 8 different xEV REESS designs (to date),
  - Has been demonstrated at the cell, module, pack and vehicle level, and
  - Does not require disabling of components that have been shown here to significantly influence safety performance during comparative thermal propagation experiments.
- Despite forced TR in the target cell, there was no indication of any risks to occupants/bystanders during the vehicle test.
  - Although only one data point, this provides evidence that single cells do not need to always reside in the "safe zone" for the system to be considered safe overall, and that
  - xEV designs that safely mitigate single cell failure propagation are not only feasible; they exist today!
- **Special thanks to the OEM that contributed valuable time, experience and technical support for the vehicle test!**
- We are considering another (different) vehicle-level test and would greatly appreciate other OEMs to collaborate.

Acknowledgements

The authors gratefully acknowledge financial support for this project from Transport Canada through its Motor Vehicle Standards - Research and Development Branch, ecoTechnologies for Vehicles Program and the National Research Council through its Vehicle Propulsion Technologies Program.

Thank you for your kind attention!

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Any Questions or Comments

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