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# *Review of the Canadian EV-Safety Thermal Propagation Principles*


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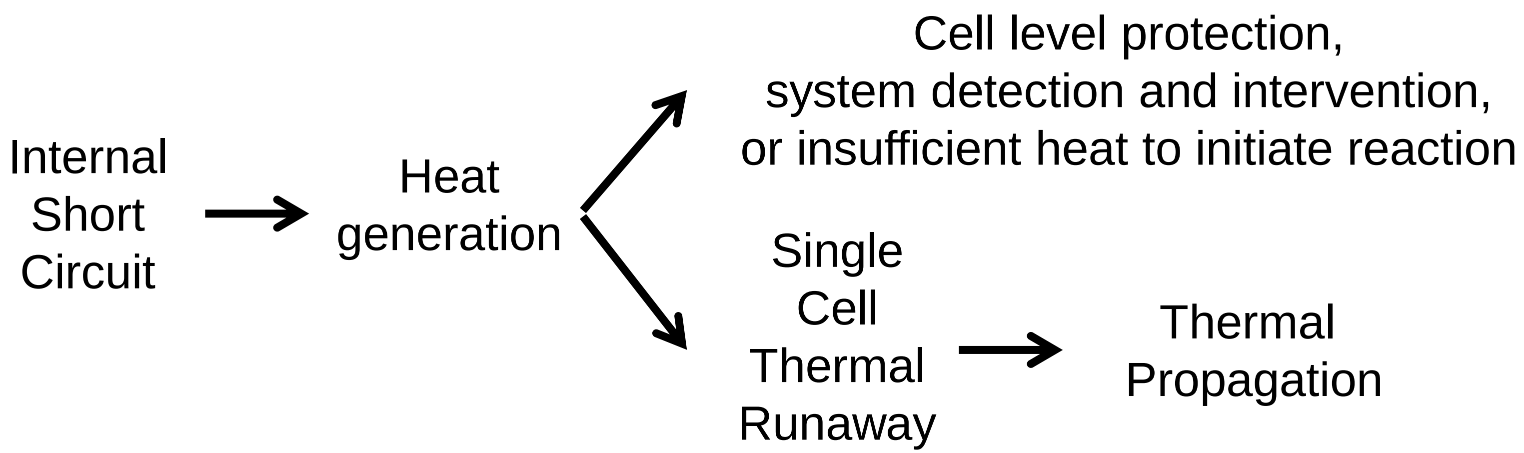
# Outline

- Review
- Discussion on lingering questions
  - What are we simulating:
    ISC or locally initiated TR triggered by unspecified cause
  - Our approach
  - How to define boundary and set conditions for TRIM
  - Test implementation
- Upcoming Test Program
- Conclusion

# 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**…"

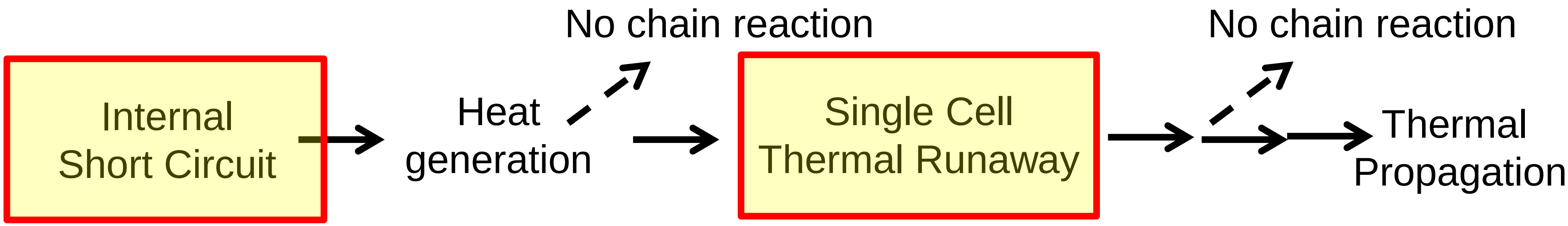



As stated in 5.4.12: we should consider the second case, unless first case is ubiquitous and soundly proven for a given design based on field history, documentation or prequalification test (as suggested in C3).

# Introduction and Background

- In the field, latent defects are very difficult to detect, but they have led to significant safety events in numerous industries.
- It has been documented that these latent defects, from experienced and reputable manufacturers, are estimated to occur at 0.1 to 1 ppm probability (well beyond 6 $\sigma$).
- These defects can not be effectively removed at the manufacturing or pack assembly stage by rigorous screening.
- So how can a manufacturer guarantee that it can be detected before initiating side reactions? Especially if one is not monitoring these changes quickly enough and with enough precision for **all cells** in the battery pack.
- There is no question; industry is working on solutions, but will they be sufficient? Will these rigorous solutions be applied unilaterally across all the various industry suppliers?

# What should be simulated? (Review)

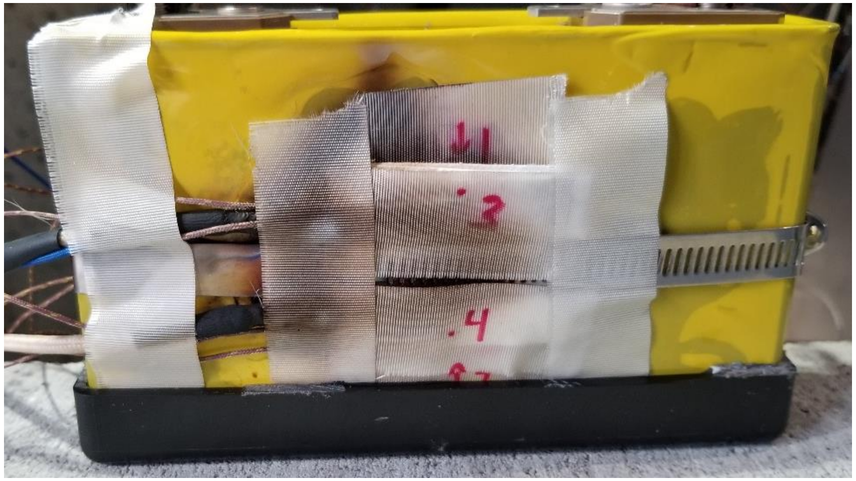



- Difficult to define heat generation time/energy (dependent on SC, materials, cell construction, etc.)
- There’s no mechanism to conclusively identify OR ability to measure these internal properties from field data, especially after a thermal event.
- Can be theorized and numerically modelled, but no validation data exist
- Even internal short circuit devices have chosen characteristics that require validation (contacting surfaces, surface area, resistance, etc.).

- It is easier to characterize and reproduce a TR response for a given cell type than ISC.
- One option: Heat generation time/energy of TR can be characterized by adiabatic ARC tests on single cells.
- Does not require the definition of SC and covers any single-cell failure mode.

# Internal short circuit caused by localized heating

- TRIM tests performed on 50Ah prismatic EV cells charged to 33% SOC**
- Result: ISC (voltage drop) and no thermal runaway.
- Could low SOC tests be used to determine ISC conditions?



**** Important note:** We do NOT recommend regulatory testing at 33% SOC as this does not represent the worst-case scenario.
TRIM tests with the same temperature ramp and soak schedule resulted in TR for the same cell type when charged to 100% SOC. It is possible that the thermal conditions to cause an ISC by external heating are higher than the thermal stability temperature of the active materials, in some cell types.

# How to implement ISC Test in a regulatory environment?

- Any ISC test (internally or externally activated) requires ISC data to emulate. External short circuit data from individual cells could be used, but is this realistic of a true internal short?
- Can we choose what is a realistic reproduction of an internal short circuit? Need to define the Contact areas, Resistances and Power **for every cell.**
- Results from literature, **using engineered cells**, show numerous types of short circuits and only some result in thermal runaway.

# How to implement ISC Test in a regulatory environment?

- It is widely accepted that ISC can occur and that TR due to ISC is a potential outcome (inherent of the current LIB technology and observed in other industries using LIBs of similar type).

## Our Proposed Method

- In our opinion, the battery pack/vehicle design should mitigate the worst-case scenario of an ISC:
  - The generation of a local hot spot that provides sufficient heat to initiate the self-propagating exothermic decomposition of active material leading to a thermal runaway within a single cell.

(Exceptions could be possible if it can be proven that this worst-case scenario cannot exist for a given design or technology.)

# OUR APPROACH

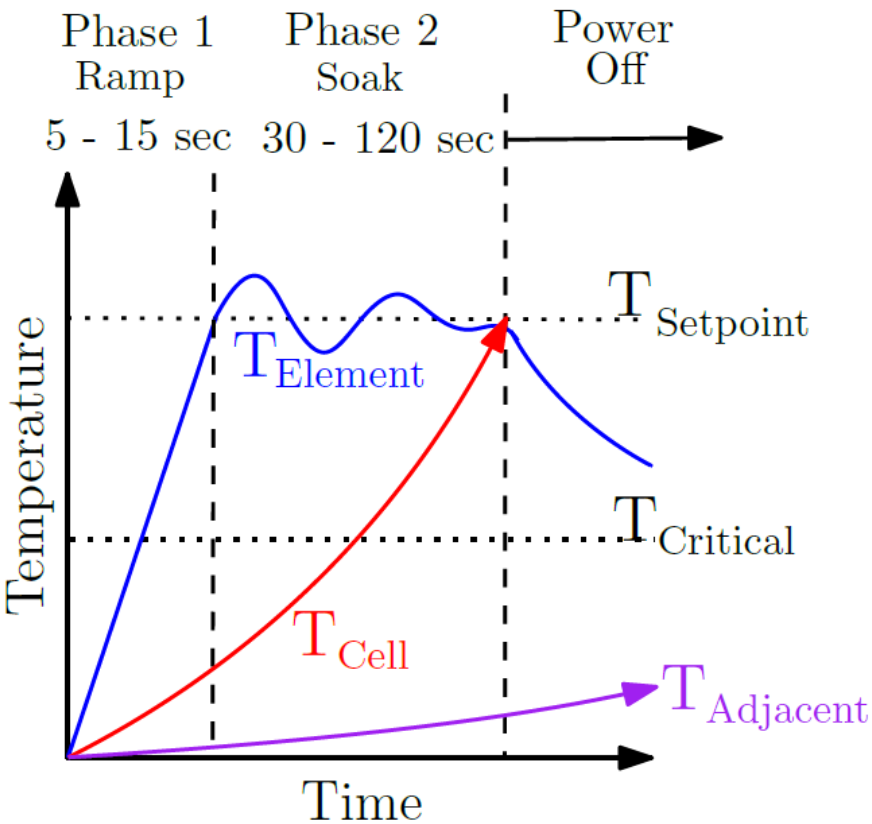
- Thus, we need to design a test to determine the response of the pack/vehicle towards thermal runaway initiated from a **localized thermal event with unspecified root cause**.

- 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.

- Our full-scale testing has shown that single cell thermal runaway and even some extent of thermal propagation can be tolerable without creating a hazardous environment for occupants/bystanders.

# OUR APPROACH - Visual Implementation

**Optimized for Runaway**

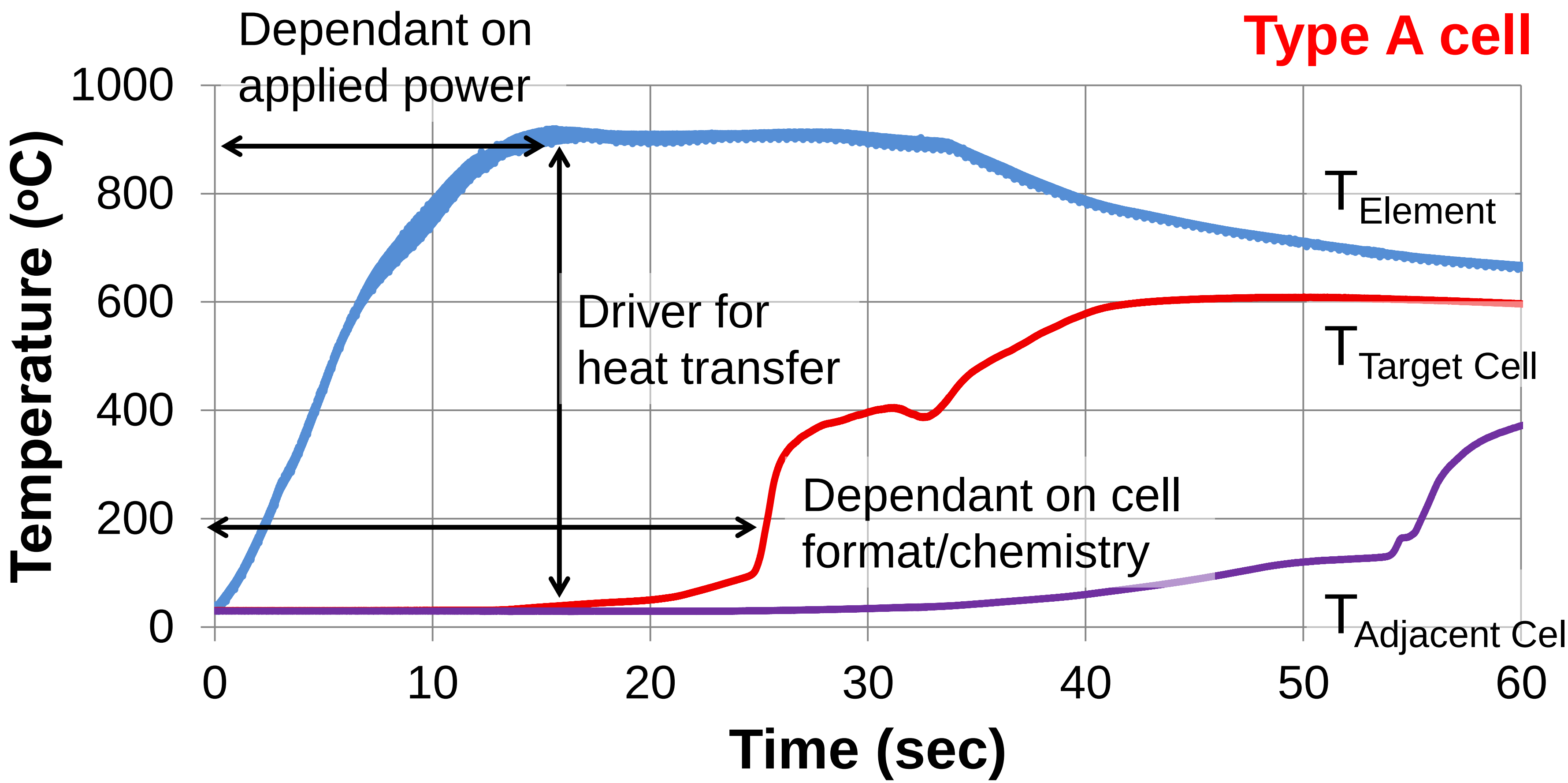



Requires $T_{Setpoint}$ and Ramp/Soak time definitions within test method.

$T_{setpoint}$ – dependent on cell chemistry and construction but X° above the thermal stability of the battery materials

Ramp/Soak – dependent on thermal conductivity of chosen cell design/chemistry. Could be a value for pouch/prismatic/cylindrical

# Defining boundary conditions



# Defining boundary conditions

- This is a question of heat transfer. How can you get sufficient heat **INTO** a cell, to initiate internal self-propagating exothermic reactions (or ISC, if possible), from the outside without significantly affecting the neighboring environment?

- We have begun a modelling activity in hand with validation from experimental results.
  - There are many things to consider: casing material, electrode material, cell size, neighboring environment, internal construction etc..

# Heat transfer during external heating explained:

Example: CT scan of swelling due to internal gas

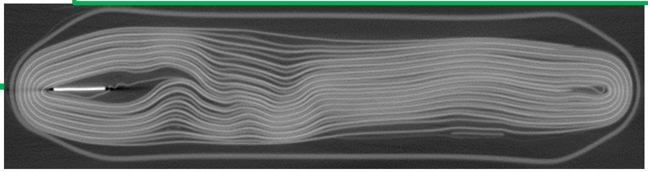


*Photo source: DfR Solutions*

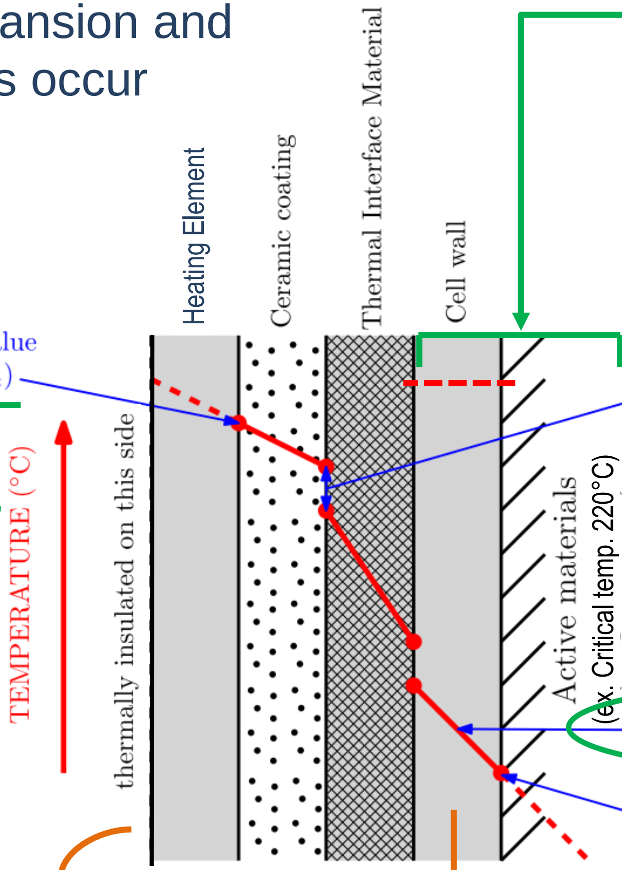
Simplified 1D heat transfer **before** physical expansion and exothermic reactions occur

Other observed barriers to heat transfer during tests:
- Non-uniform electrode windings
- Extra separator layers
- Internal gas generation
- Element delamination due to physical expansion or improper installation

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.




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)

Note: Thicknesses shown are not to scale

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

# Conditions for external heating

- Heating ramp rate:
  - Should be maximized to reduce inefficient heating
  - Equipment limitation (element design / power and overshoot control)
  - ≥20°C/sec suggested as reasonable to achieve and realistic of ISC / TR

- Example setpoints which “force TR” from TRIM V4 (5.4 $cm^2$) experience:

| Cell format | Setpoint | % Surface area | Heating power / mass |
|---|---|---|---|
| Cylindrical | 350°C | 10 to 15% | $10^4$ W/kg |
| Pouch | 500°C | 1 to 2 % | $10^3$ W/kg |
| Prismatic with 0.016” SS case wall | 700°C | 1 to 5 % | $10^2$ W/kg |
| Prismatic with 0.032” AL case wall | 500°C<br>larger area? | 1 to 5 % | $10^2$ W/kg |

- Although adjusting set points is logistically convenient, having 2 or 3 different heating element sizes would be optimal considering the variation cell format properties.

# Checks and balances

- Thermally stable chemistries require more thermal energy to force thermal runaway.
- This concern could be managed by:
  1. Setting additional conditions that stop the test before TR:
     - Evidence of a statistically significant voltage drop, sustained self-discharge, CID or vent activation (other failure modes that would prevent further heat generation due to an ISC)
     - Applied heater energy should not exceed “X”% (ex. 30%)** of the cell’s rated discharge capacity
  2. Setting heating profile that is realistic for the target chemistry
     - Setpoint should not exceed peak TR temperature based on cell level characterization**

**(plus an adjustment factor for losses due to cell wall type)

# Test implementation

- Ideally, one single method could be applied to all vehicle designs to reduce the challenge of finding equivalency.
- Since TR conditions will be different for each cell type, the test method should be allowed to be tailored based on the cell properties (ex. capacity, format, chemistry). These adjustments can be established through single-cell characterization.
- Test methods must consider how they could be implemented at the vehicle level and significant modifications to BMS, REESS seal integrity, or thermal management system **should not be permitted**.

# Test implementation

- We have shown previously how active thermal management can play a significant role in the extent of thermal propagation and cannot be ignored within test designs
- We have shown how, in some module/pack designs, there can be no measureable change in voltage during a single cell thermal runaway, thus voltage drop should not be used as the sole/primary indicator of a cell failure
- We found the vehicle-level was easier to execute (no custom cooling/mounts/instrumentation) and most representative of actual field conditions.

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

# Example summary of test method suitability

| | Rapid localized heating (ex. TRIM) | Other methods? |
|---|---|---|
| Cell formats:<br>Cylindrical, pouch, prismatic cells | ✓ | |
| Lithium-ion chemistries used in EVs:<br>NMC, NCA, LFP | ✓ | PLEASE COMPLETE |
| Cells with internal safety devices:<br>CID, PTC | ✓ | |
| Module level | ✓ | |
| Pack level | ✓ | |
| Vehicle level | ✓ | |
| Pack seal integrity after method installation is equivalent to original design | ✓ | |
| Method installation and operation is undetectable by BMS | ✓ | |
| Does not disable primary thermal management system functionality | ✓ | |

| LEGEND | |
|---|---|
| Demonstrated | ✓ |
| Unknown | ? |
| Not suitable | ✗ |



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# Future Topics and test Program

- Comparison of TRIM heater with another high heat flux heater
- Vehicle Level test Program (Spring 2020):
  - 2014 Tesla Model S and
  - 2019 Nissan Leaf
  - OEM help/experience is encouraged
- Refining set-point temperature and dwell times via thermal modelling
- We are working within ISO to create a standard test for thermal propagation using rapid external heating (generic).

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***Thank you for your kind attention!***

Any Questions or Comments

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