Thermal Runaway Initiation and Propagation – xEV Cell, Module and Pack Testing

Steven Recoskie

Research Council Officer

Energy, Mining and Environment – Ottawa

613-998-9786

Co-authors : NRC : Dean D. MacNeil, Oltion Kodra, Giulio Torlone, Ryan Kroeker, Joel Perron; Transport Canada : Ghislain Lalime, Kyle Hendershot

September 25-27th, 2017 **EVS 14 - GTR** **Ottawa, ON, Canada**

Introduction and background

- Several events could potentially initiate cell failure within rechargeable electrical energy storage systems (REESS):

    1. Cell defect (internal short circuit)
    2. Control system failure (overcharge)
    3. External force (mechanical abuse or applied heat)

- There are many existing types of mechanical, electrical and thermal abuse tests to assess lithium ion battery safety performance (e.g. nail penetration, slow external heating).

- However, these methods suffer from disadvantages that introduce significant bias or uncertainty in initiating cell failure and/or in the propagation dynamics observed.

Objectives (Review)

1. **Thermal Runaway Initiation** - Develop a safety test method that embodies the characteristics of an ideal compliance test:
   - Representative of a realistic abuse event
   - Minimally invasive to the REESS design (minimal addition of foreign **holes, material** or **energy**)
   - Reliable and repeatable
   - Adaptable to all cell and pack designs
2. **Propagation** - Assuming a single cell within a REESS undergoes a thermal runaway reaction due to an unspecified cause, determine if and how this failure propagates to adjacent cells and if it poses a significant hazard to the vehicle's occupant or the surrounding environment.

Methods (Review)

- After thorough review and experimentation using existing methods, an internal short circuit (SC) that leads to thermal runaway (TR) has been identified as a realistic abusive scenario that may inevitably occur within a REESS.
- The main difference between a similar resistance external and internal SC is that during an internal SC all current passes through a small area on the cell, creating a localized hot spot.
- For a compliance test, this needs to be initiated externally.
- The proposed thermal runaway initiation mechanism (TRIM) presented here, consists of applying a high powered heat pulse to small area on the cell’s external surface matching the time scale of a SC event.

Methods (Review)

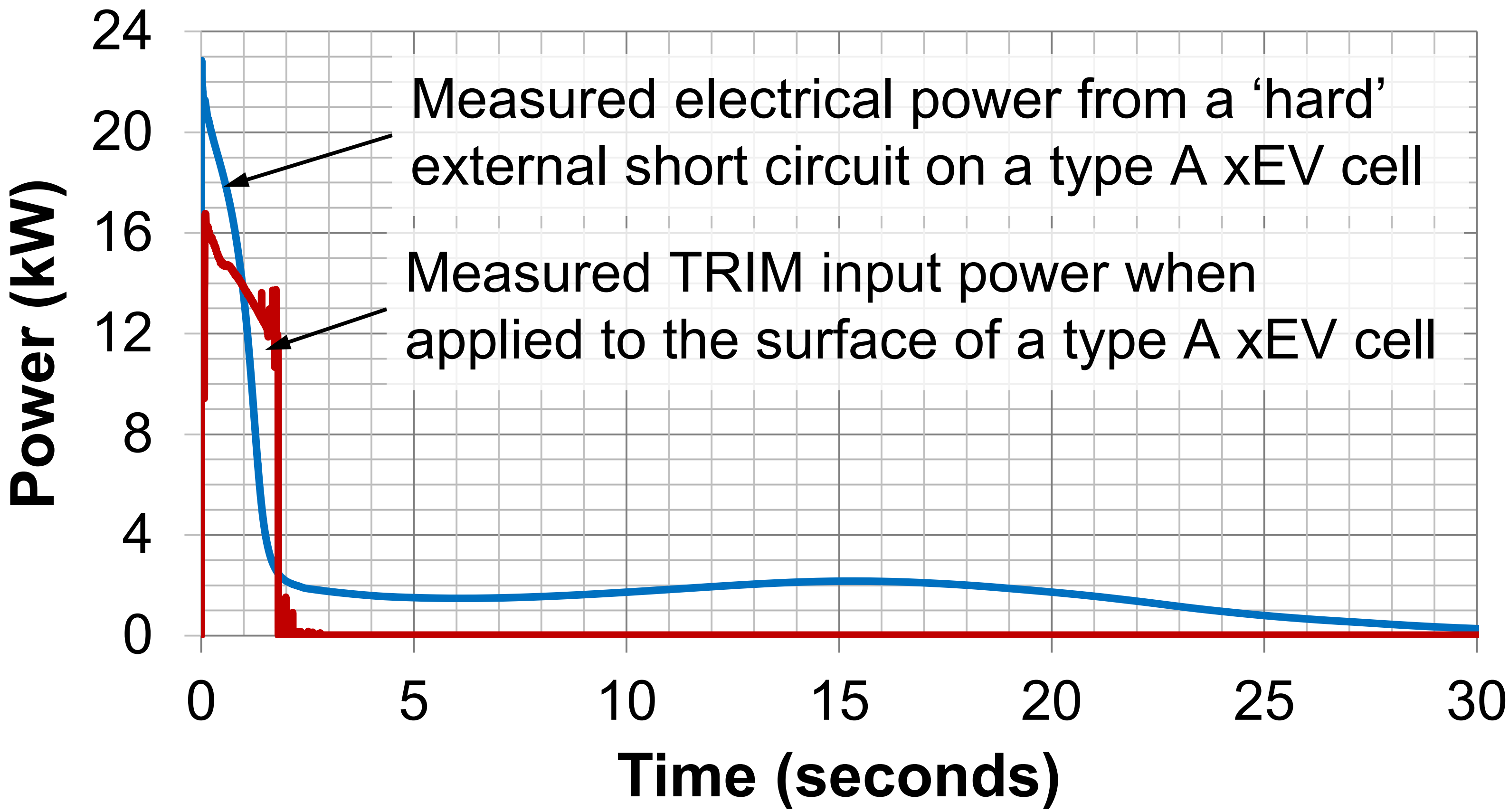


Figure 1. Comparison of TRIM input power applied to a type A xEV cell to the measured power during a 2.2mΩ external short circuit on an identical cell.

Setup – Module Testing (Review)

- Modules were constructed using extracted cells from EV packs that were representative of the Canadian EV fleet and use different cell types and formats.
- The modules were assembled in the same configuration and orientation as they were extracted.
- The rated capacity of each module was between 2.2 and 2.5 kWh.
- The TRIM was installed within the module in a strategic location that would permit the investigation of thermal propagation within the module without removing or deforming existing OEM components.

Setup – Module Testing (Review)

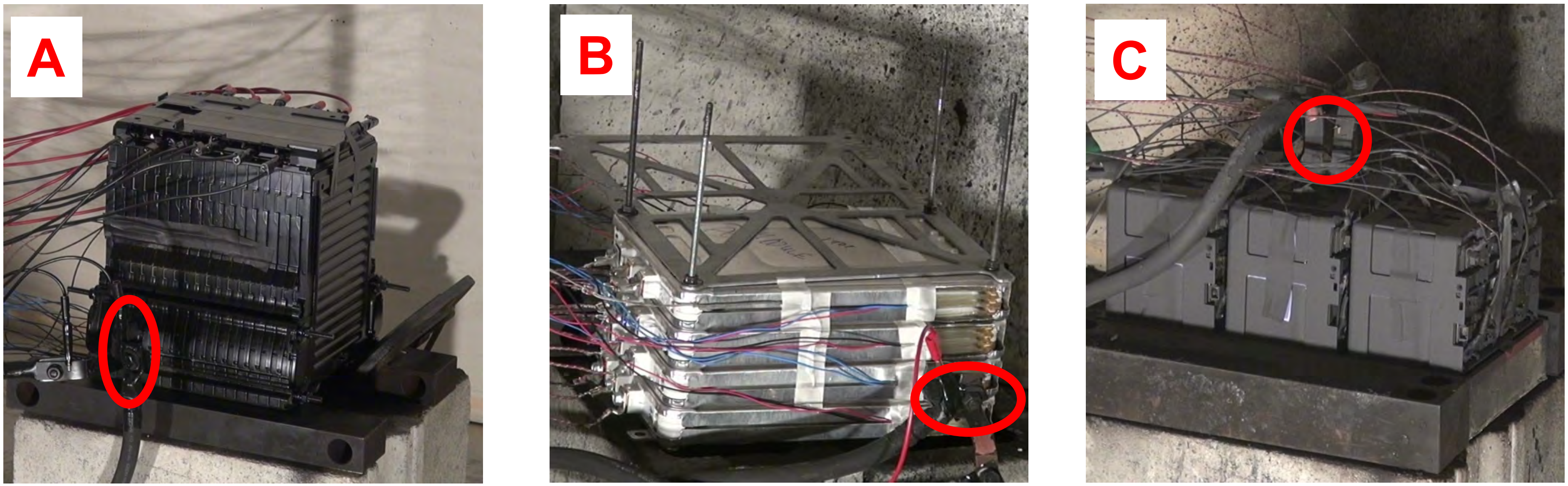


Figure 2. Three extracted xEV battery modules under test (types A, B and C). The location of the failure initiation device is circled in red.

Setup – Module Testing (Review)

Figure 3. View of module type A taken 10 seconds after failure initiation.

Results – Module Testing (Review)

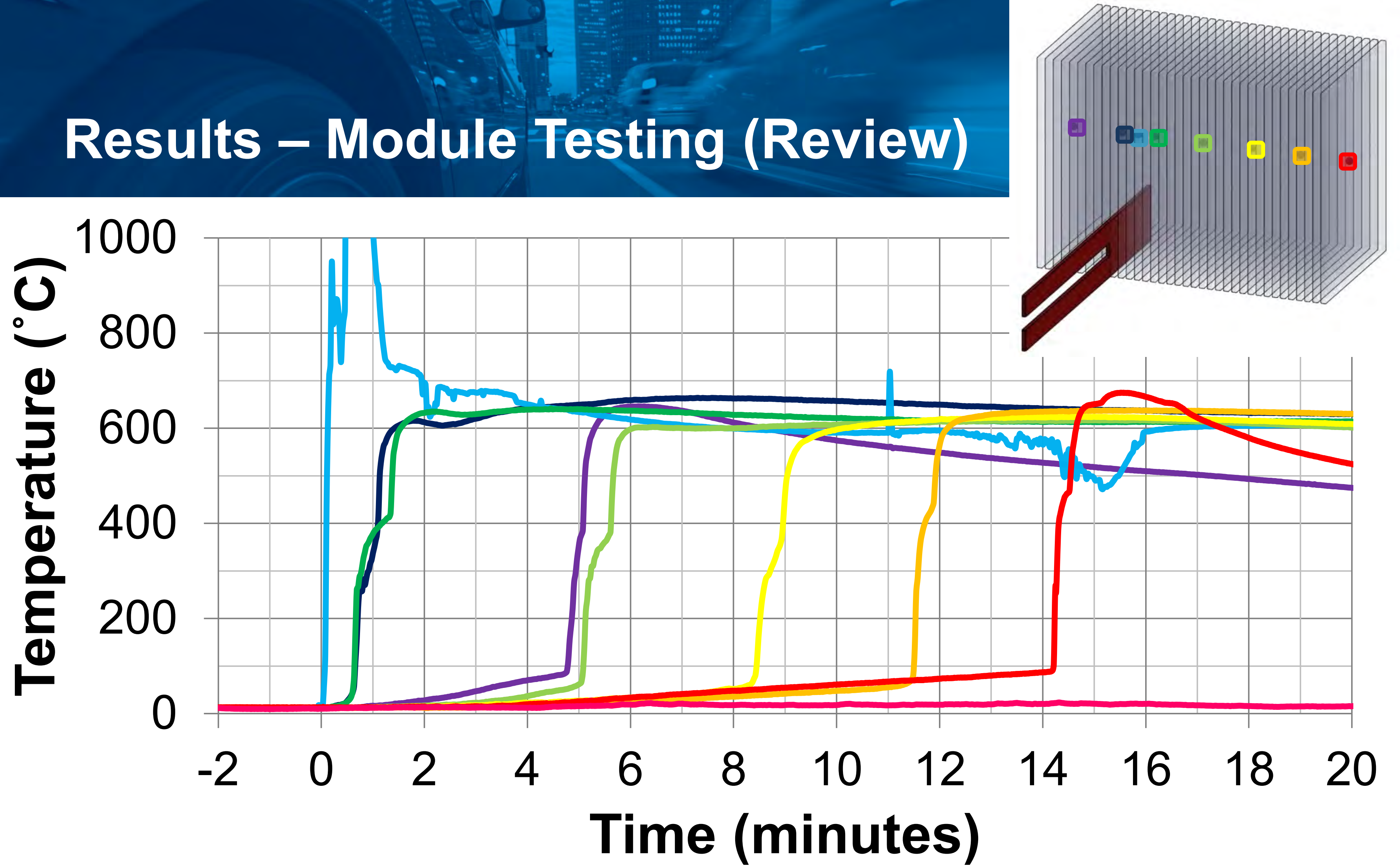


Figure 4. Temperature-time series showing cascading failures of individual cells throughout the module type A.

NRC·CNRC

Results – Module Testing (Review)

- Both the temperature evolution and the thermal runaway propagation time interval varied greatly between each module design.
- TRIM initiated TR consistently (similar time, temperature and applied energy) with **no observable temperature increase in the adjacent cells**.
- Generally, failures propagated more rapidly between cell in close proximity and in good thermal contact but, the propagation dynamics were also found to be dependent on:
    - Cell construction (case material, geometry/format, chemistry, capacity, internal safety mechanisms),
    - Thermal runaway reaction dynamics (gas venting velocity/direction, ignition of gases, mass transfer),
    - Module construction (cell spacing, surrounding components),
    - Pack construction (thermal mass, thermal management, vapor containment, safety mechanisms), and
    - External influences (ambient temperature, operational mode)

Latest method development

Newest TRIM design (provisional patent submitted 09/09/17)

Key Parameters	Value
Thickness (mm)	1.0
Active Surface Area (cm^2)	5.6
Mass (g)	3.9
Peak Applied Power (W)	2000
Heat Flux (W/m^2)	$> 1 \times 10^6$
Applied Energy compared to Type A cell capacity (%)	< 10

Formable to any cell (18650 shown)

Temperature feedback for optimized TR and element failure prevention

Method advantages

- **Representative of a realistic abusive event**: The input power function for the element matches well to the power measured from a “hard” SC on the same cell. The same device can also be used to simulate a wide range of SC or TR conditions (short resistance, applied power and area, etc.) or optimized to initiate TR in any cell type.

- **Minimally invasive**: The only foreign object introduced is the heating element and the only modifications are two small (6mm) holes for it’s connection. The element is small and thin (1mm) which allows insertion between existing clearances. Applied energy is no more than 10% of the cell’s rated capacity.

- **Reliable and Repeatable**: Tested 24 times on various cell geometries (pouch/prismatic/cylindrical) and ambient operating temperatures (0°C to 25°C).

- **Adaptable:** Has been effective on 5 different xEV battery types (pouch, prismatic and 18650) and installed in various locations. New temperature feedback control prevents premature failure of the TRIM device (can be safely “dry heated”).

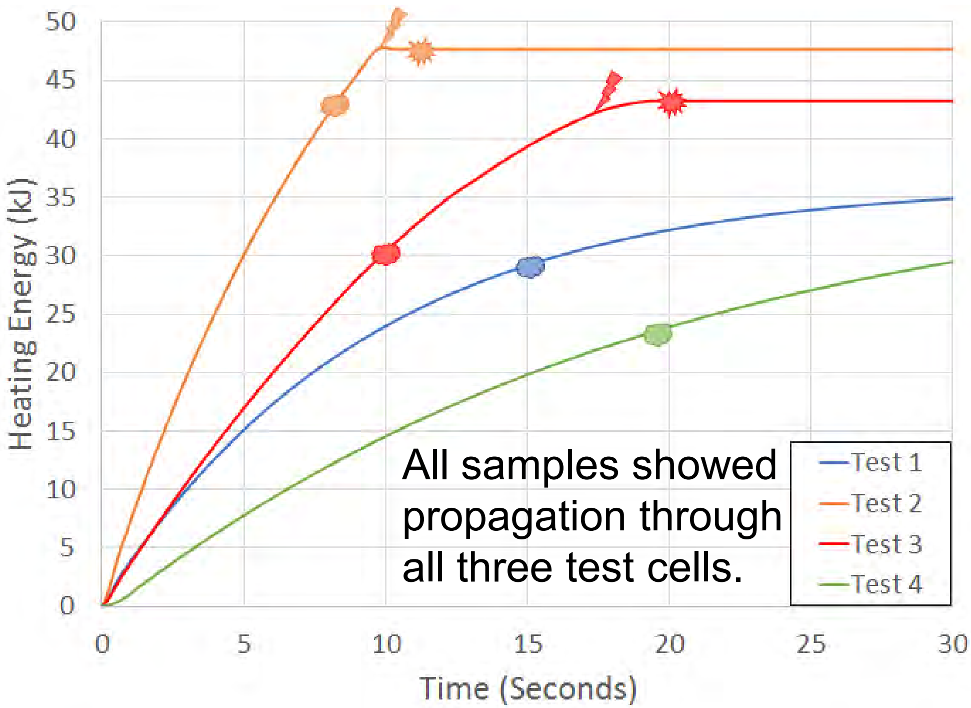
Current Challenges and Research Directions

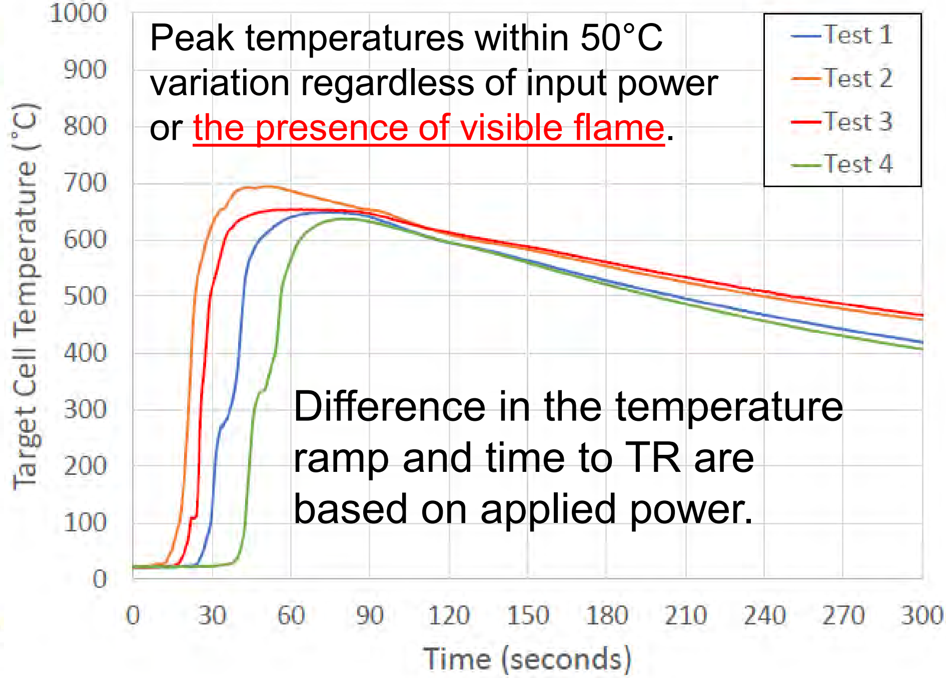
Research key parameters for Thermal Propagation within EV cells then proceed to large scale testing. Refinement performed through the use of a standard 1S3P (45Ah) EV submodule test set up.

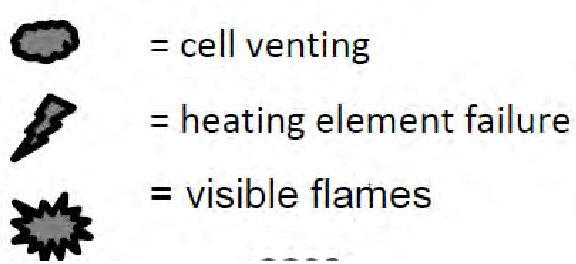
Main Discussion Points:

1. Ignition of venting gases or no ignition
2. Realistic power/temperature profile or optimized TR initiation

1. Ignition of venting gases







Test #	Peak Power	Time	First vent	Fire?	Last vent
1	X kW	Y sec	15 sec	NO	89 sec
2	2X kW	Y sec	8 sec	YES (11 sec)	80 sec
3	X kW	2Y sec	10 sec	YES (20 sec)	73 sec
4	0.5X kW	2Y sec	19 sec	NO	74 sec

1. Ignition of venting gases

Ignition of venting gases or no ignition

NO IGNITION

IGNITION

Movie of tests showing ignition and no ignition

1. Ignition of venting gases

Discussion Topics

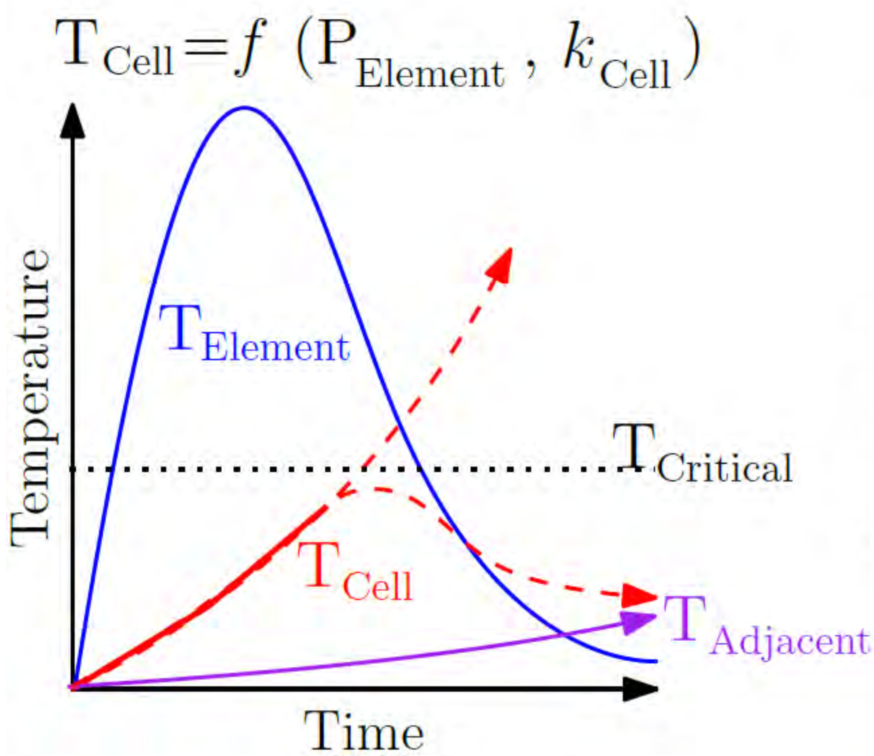
- Is ignition of venting gases a necessity for a thermal propagation test or not?

- Considering the potential of spark sources in close proximity in-situ, should ignition be caused intentionally during the test? Spark igniter?

- What is worst for the occupants and surrounding environment? Fire or Smoke

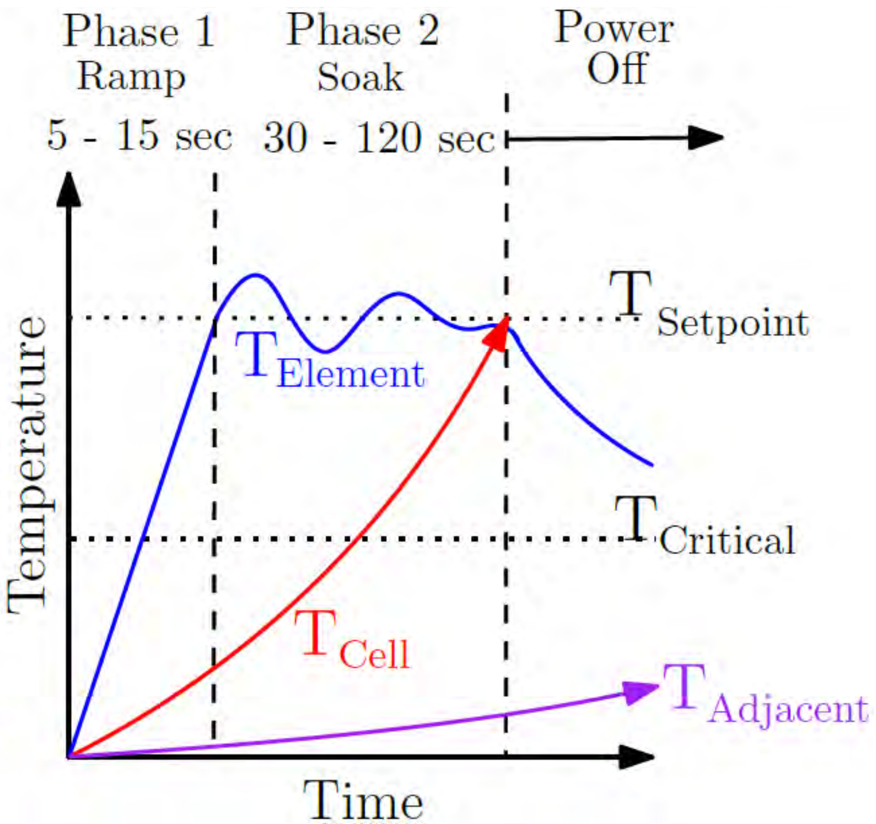
2. Realistic power/temperature profile or optimized thermal runaway initiation

A. Reproduce a “Realistic” event



Requires $P_{Element}$ input function defined by SC or TR cell data for each and every EV cell type.

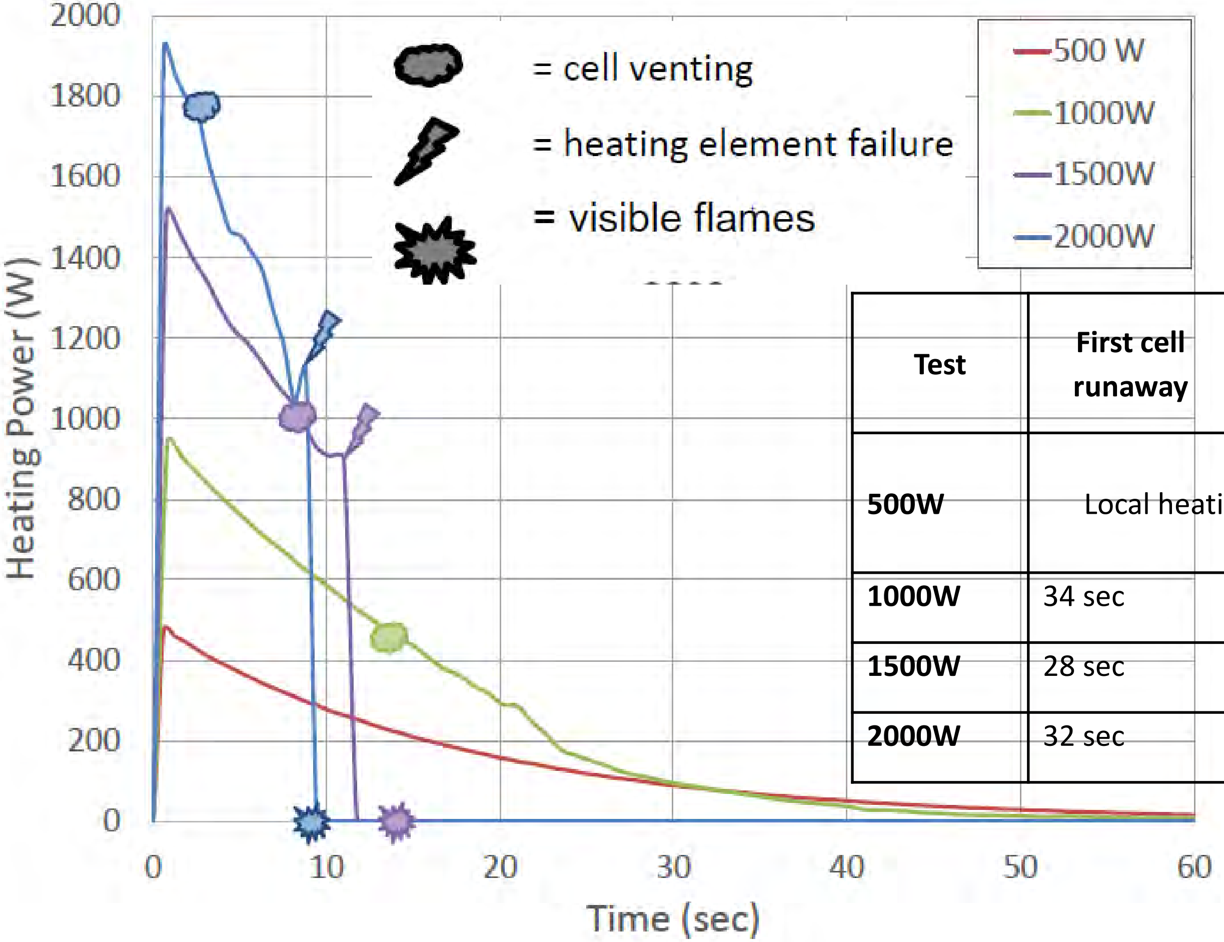
B. Optimized for Runaway



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

2. Realistic power/temperature profile or optimized thermal runaway initiation

A. "Realistic" event – Determining power requirement for TR and fire

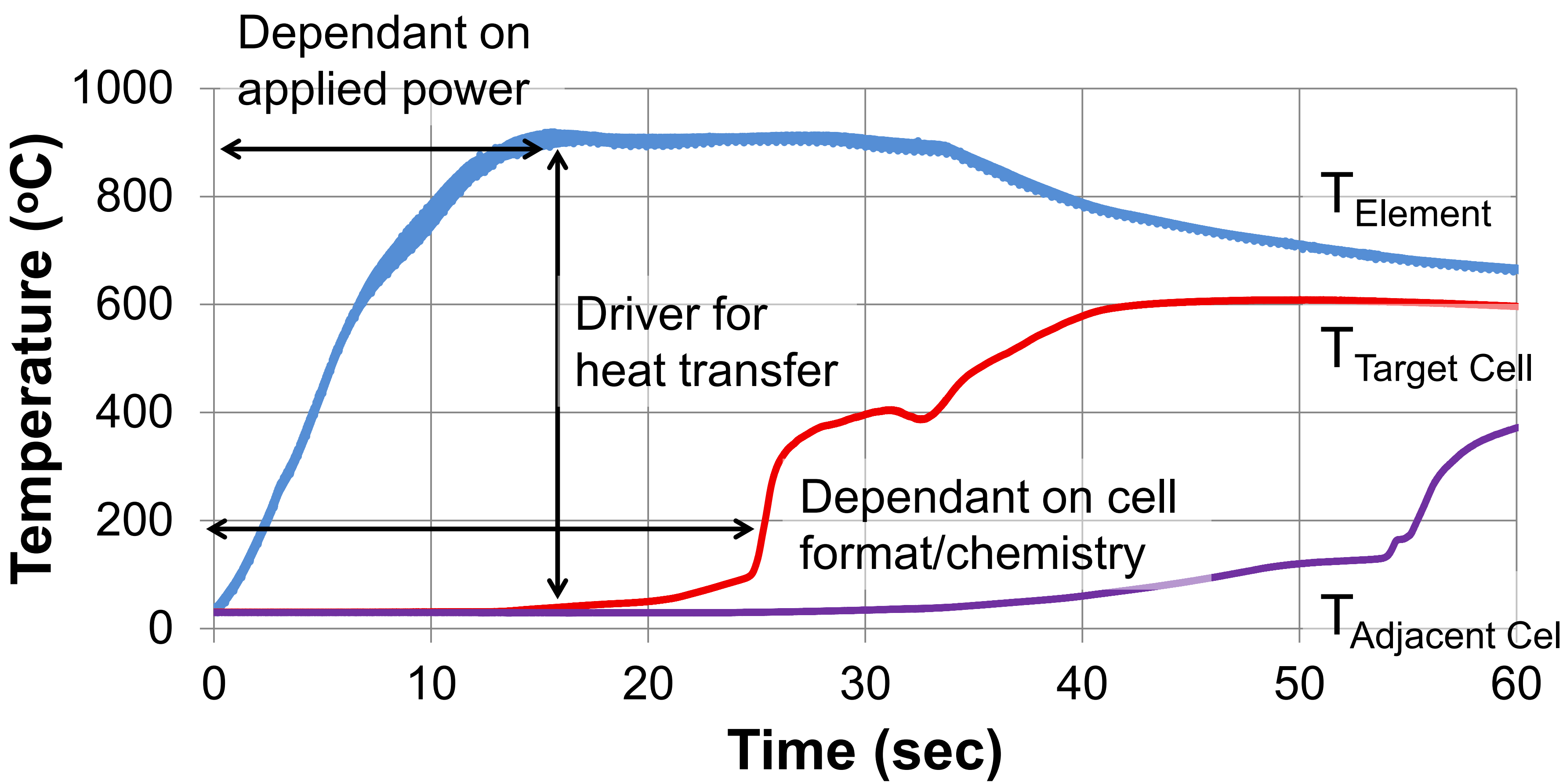


Total applied energy to heater for all tests is **<10%** of one cell's stored energy

Test	First cell runaway	Time to peak cell temp	Fire?	Last cell runaway
500W	Local heating only, no thermal runaway, no propagation			
1000W	34 sec	80 sec	NO	110 sec
1500W	28 sec	83 sec	YES (14 sec)	76 sec
2000W	32 sec	80 sec	YES (9 sec)	80 sec

2. Realistic power/temperature profile or optimized thermal runaway initiation

B. Optimized for Runaway



NRC·CNRC

Discussion Topics

- What are we trying to simulate?

1. Are we trying to match the thermal response to simulate a specific event? Which one? This will change frequently based on chemistry, cell choice, manufacturing. – **Realistic**

2. Are we trying to initiate a thermal runaway in the target cell regardless of type or format, to assess propagation response? Does this bypass the cell level safety? – **Reliable / Repeatable**

- How is repeatability defined? The TR initiation of the first cell, or the propagation results?

Other Discussion Topics

Other test considerations:

- Containment

  How is propagation affected by environment around cell? Is the pack fully sealed (starved or displaced O_2)? What about other system level propagation containment devices and the burning of surrounding materials?

- Pass/Fail for Thermal Propagation

  Is fire required? What about smoke effects? What about test method initiation criteria (total energy delivered, ambient temperature, test surface area, etc…).

Our Proposed Method

Preliminary results indicate initiation of various target cells (pouch, prismatic, 18650) is repeatable and controllable, but propagation is dependent on many external forces.

Other Discussion Topics

Other test considerations:

- Ambient temperatures and the effects of preheating
- Cell formats/geometries/sizes
- Pack thermal management (e.g. liquid cooling)
- Implementation challenges at vehicle level

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!

Canada

NRC·CNRC

Any Questions or Comments

Transport Canada Transports Canada