Thermal Runaway Initiation and Propagation – Review and Potential Test Procedure

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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 this failure propagates to adjacent cells and if it poses a significant hazard to the vehicle's occupant or the surrounding environment.

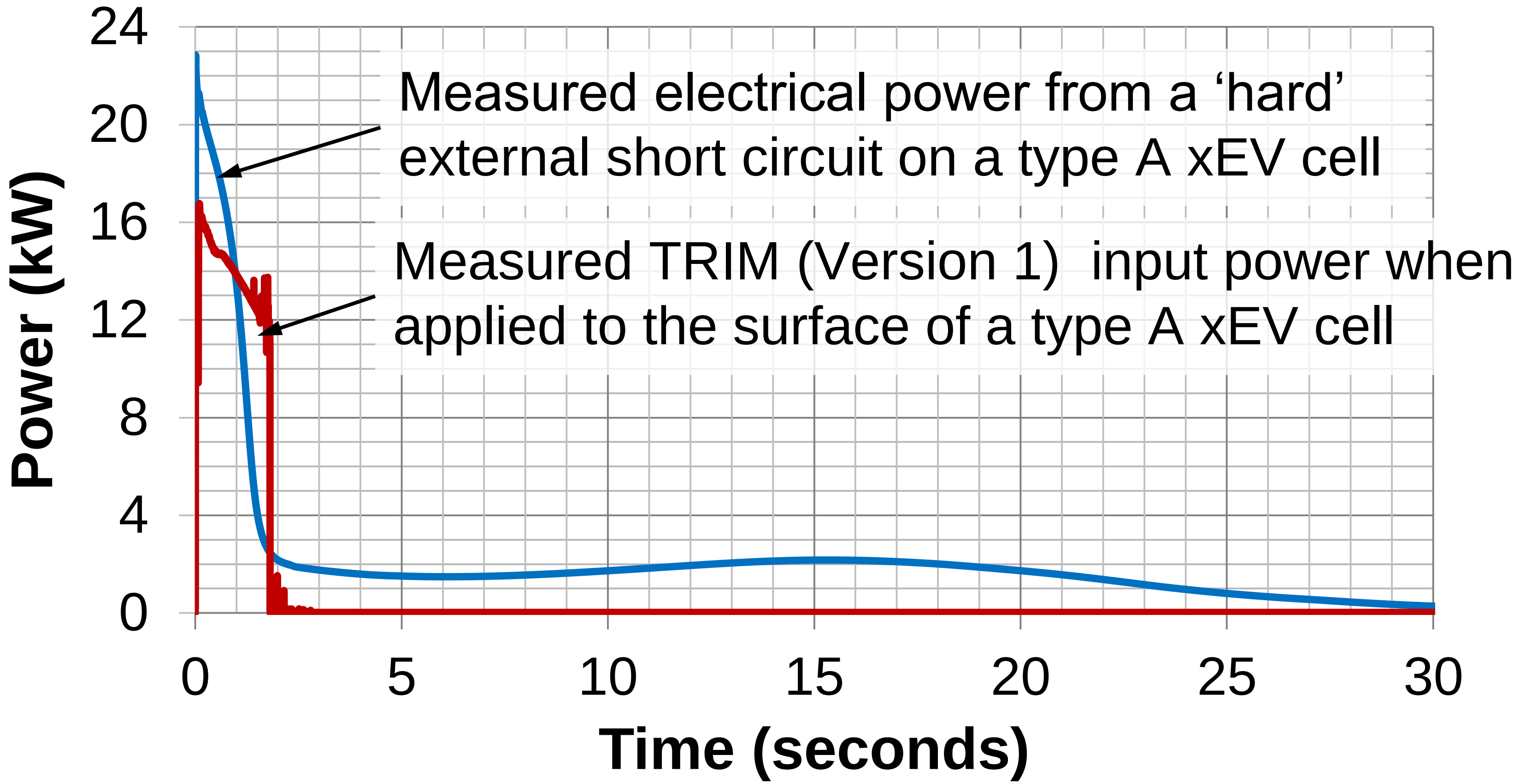
Methods (Review)

- For a robust comprehensive compliance test, thermal runaway needs to be initiated externally.

- 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.

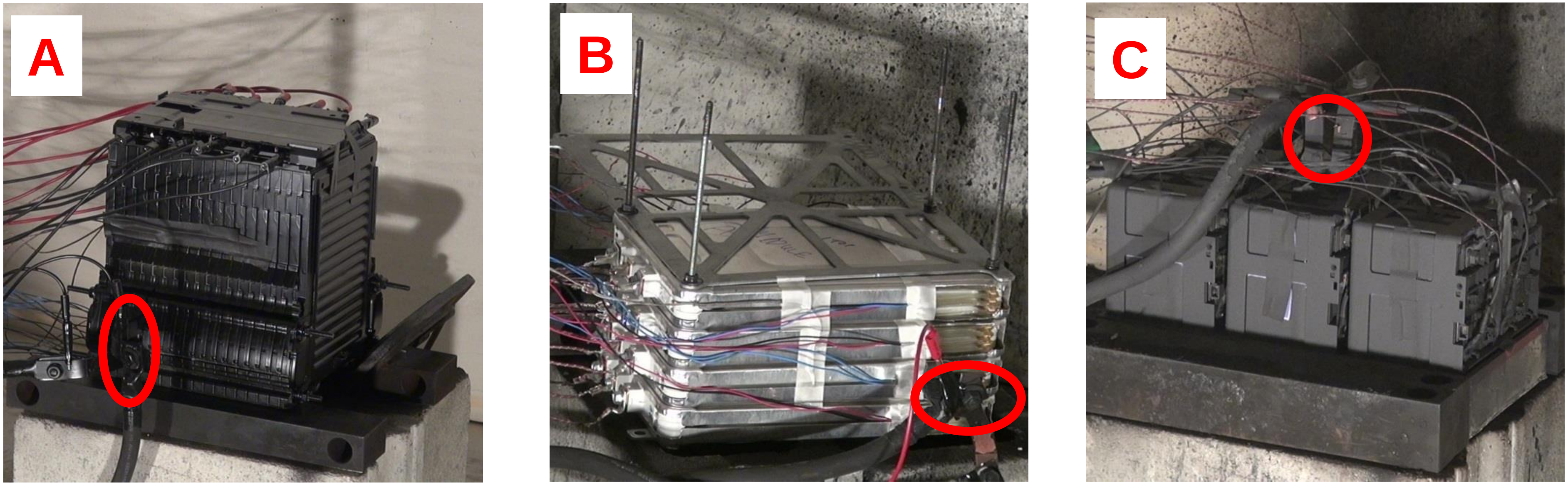
- The proposed Thermal Runaway Initiation Mechanism (TRIM), consists of applying a high powered heat pulse to small area on the cell's external surface. We can match the power/energy/time scale of a "hard" external SC event of an EV cell (but could mimic other resistances or thermal profiles and could be optimized for each cell design).

Methods (Review)



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.

Module Testing (Review)



Three extracted xEV battery modules under test (types A, B and C).

The location of the thermal runaway initiation device is circled in red.

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**

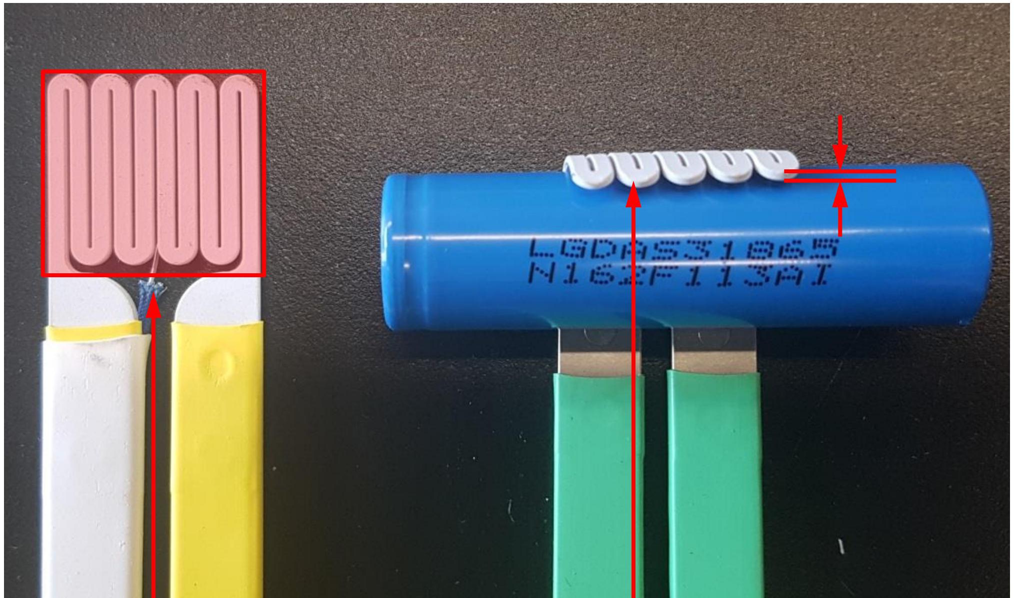
Results – Module Testing (Review)

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 (Review)

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)	> 1×10^6
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 (Review)

- **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 30 times on various cell geometries (pouch/prismatic/cylindrical) and ambient operating temperatures (0°C to 25°C).
- **Adaptable:** Has been effective on 6 different xEV battery types (pouch, prismatic and 18650) and installed in various locations.

Current Challenges and Research Directions

Research key parameters for Thermal Propagation within EV cells then proceed to large scale testing.

Main unresolved discussion points from previous meeting:

1. Ignition of venting gases or no ignition

Update: Research is being conducted to study flammability limits of TR venting gases

Current Challenges and Research Directions

Main unresolved discussion points from previous meeting:

2. Realistic power/temperature profile or optimized TR initiation

Update: Focus on developing a better understand of the latter case, “scenario independent”. Tests were conducted with new V3 elements with temperature feedback control, to establish temperature offsets and limits, and to verify whether less input power is required to initiate a runaway than the “scenario specific”/realistic power case.

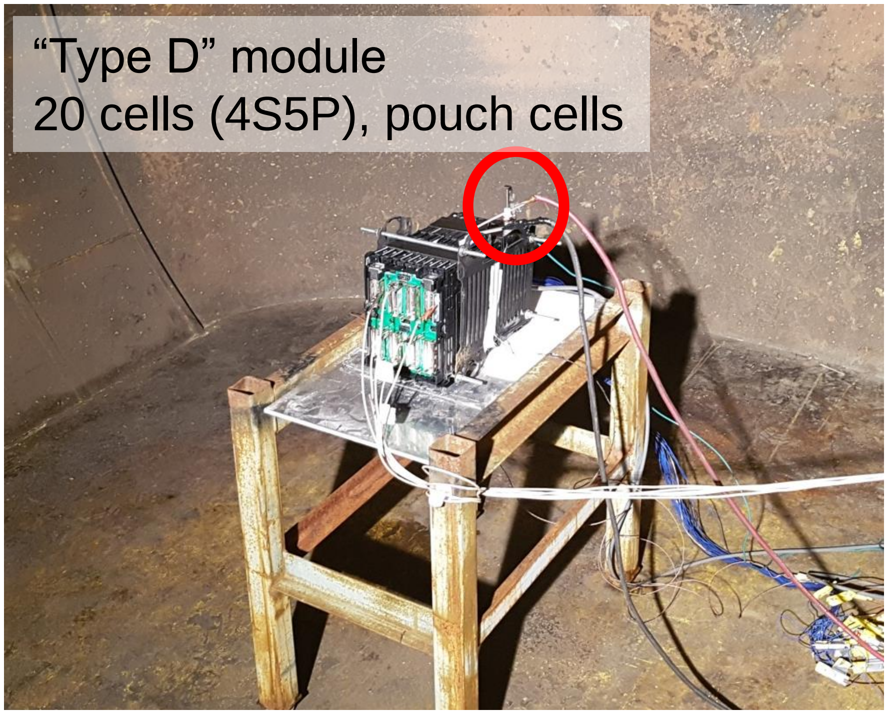
1. Ignition of Venting Gases

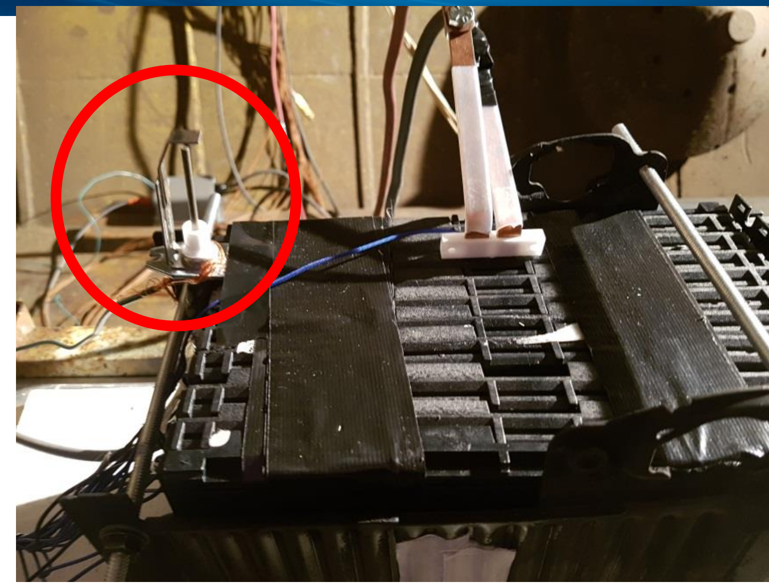
- Previous work has shown that many times ignition of vented gases does not occur and that the ignition is a “random” event.
- Ignition was also not required to induce propagation of thermal runaway within a battery pack.
- Many proposed methods do not have the ability to control for ignition conditions (whether desirable or undesirable).
- Is ignition of vented gases a required outcome of the test?

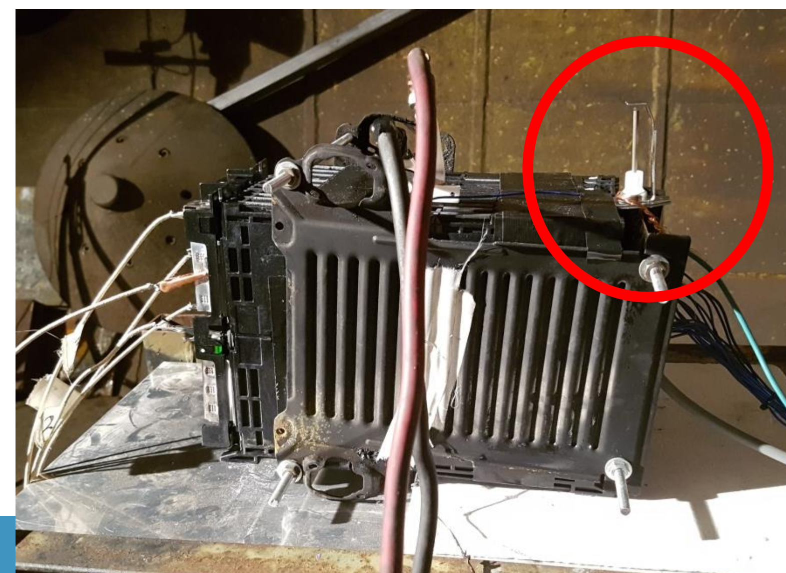
- Our studies using the proposed TRIM method would consistently show ignition only after the failure of the heating element creating a local spark. This was not acceptable, thus…

1. Ignition of Venting Gases

Spark Ignitor

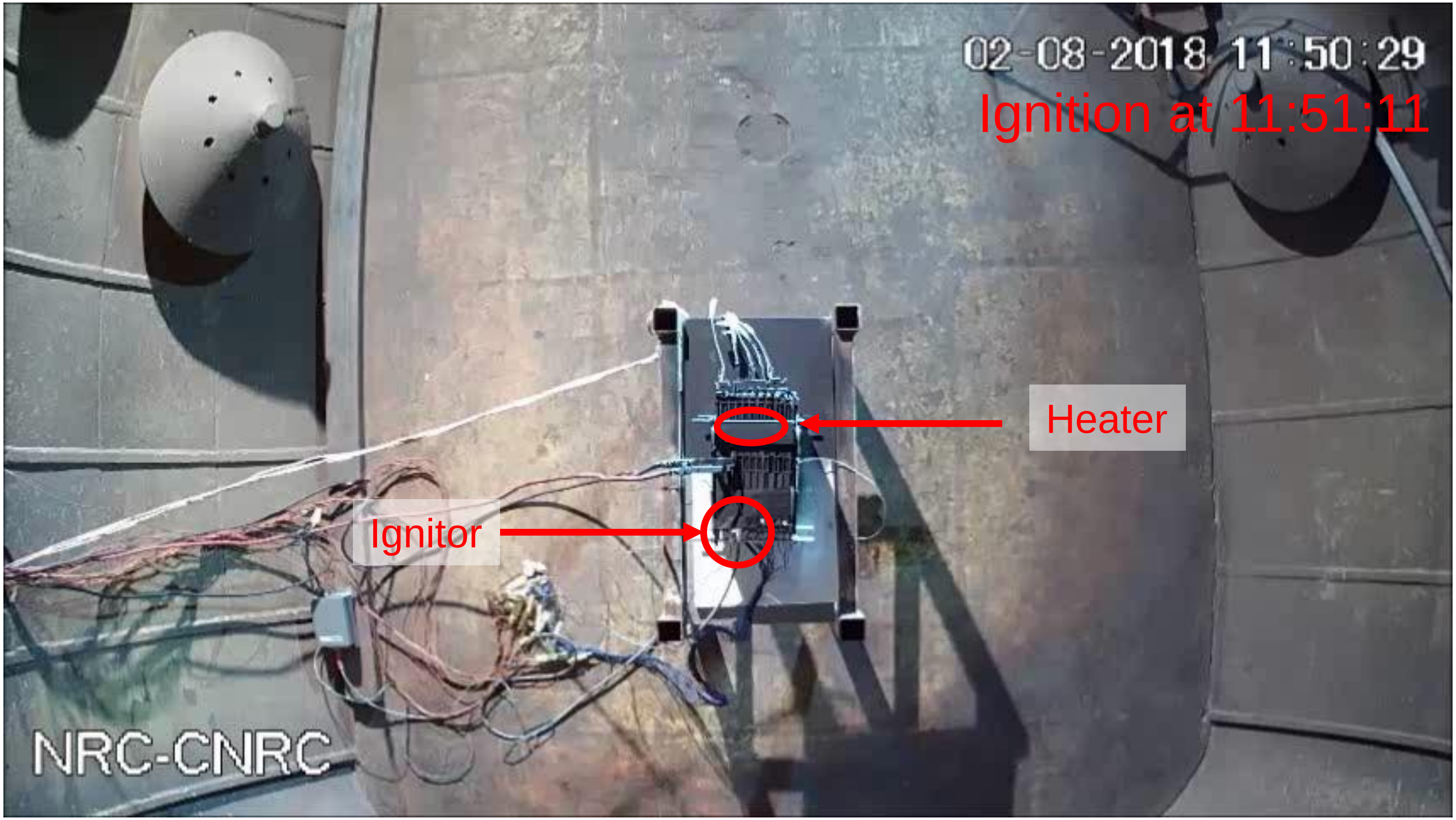




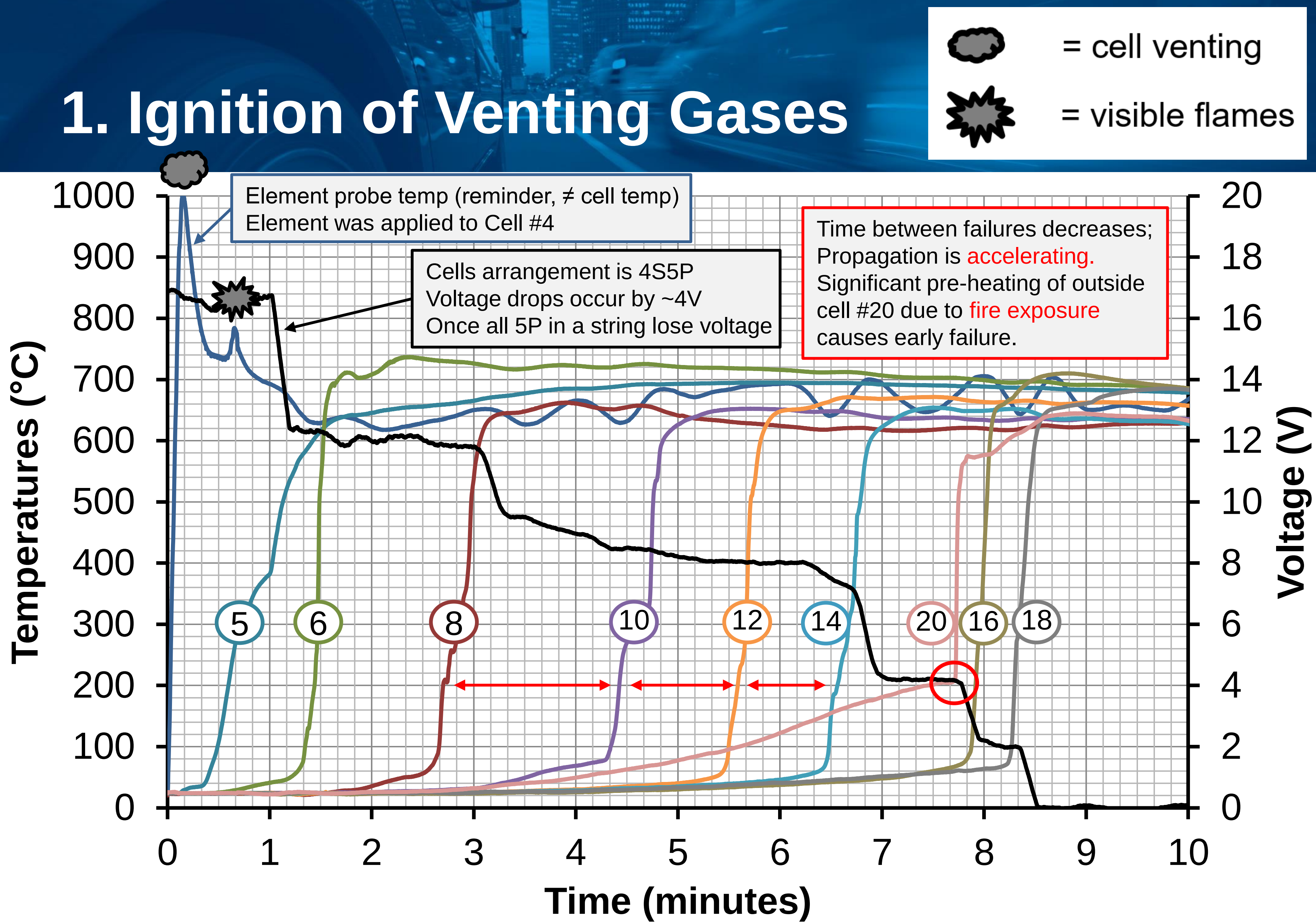


Ignitor characteristics
15kV, 4.2mm spark gap,
duty cycle of 100ms every 1 second,
run continuously throughout experiment

1. Ignition of Venting Gases



1. Ignition of Venting Gases



1. Ignition of Venting Gases

Discussion Topics

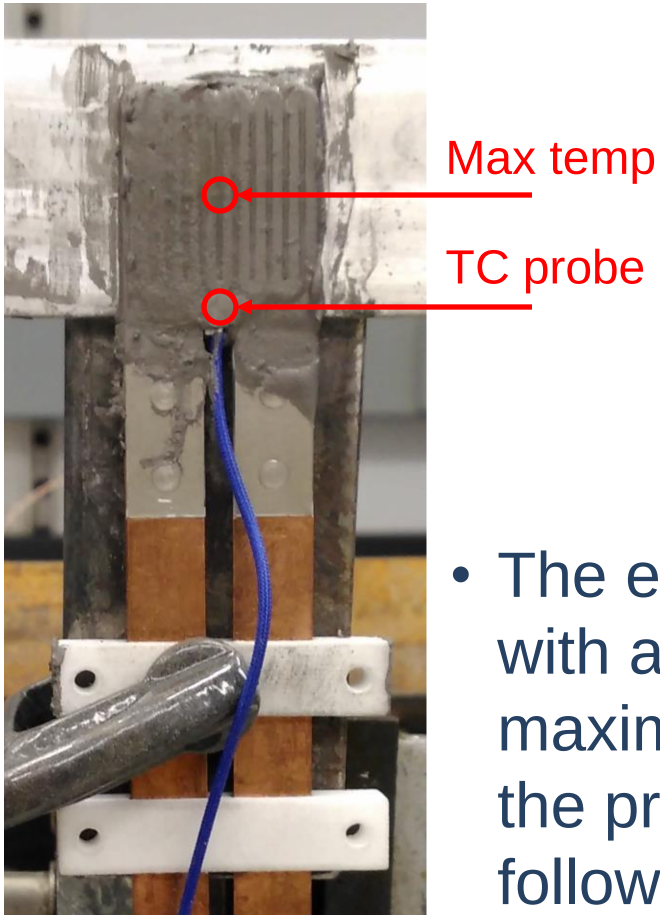
- TR temperatures and TP rates are increased with the presence of fire. Is ignition of venting gases a necessity for a thermal propagation test or not?

- Considering the potential of spark sources in close proximity in-situ, should an ignition source be present during the test? How will other methods deal with ignition?

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

2. Optimized thermal runaway initiation - Method qualification

2A. Element temperature calibration

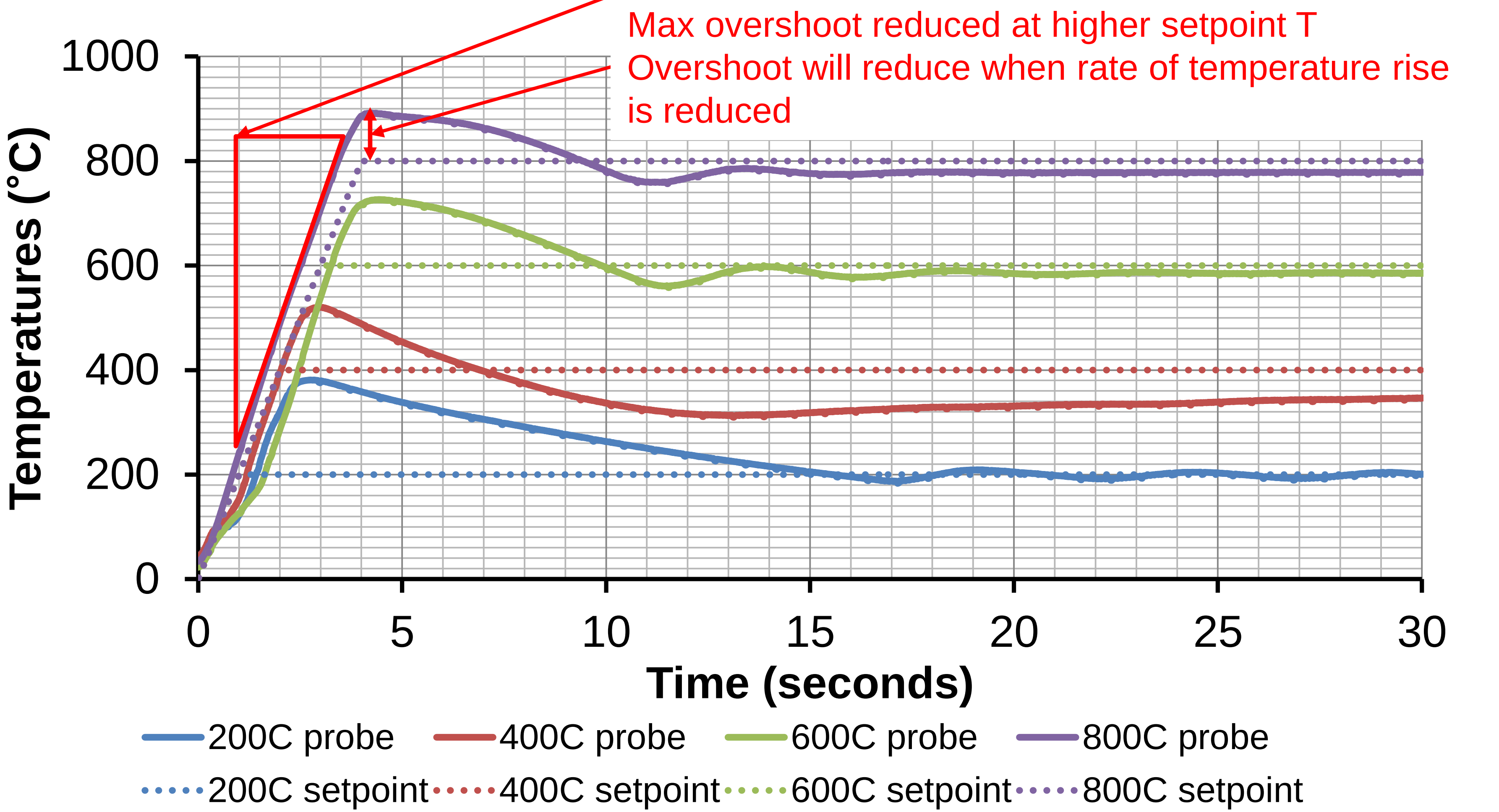


- V3 heating element was secured to an aluminium heat sink.
- Heat transfer paste is used to provide uniform and high thermal conductivity
- The exposed element face was recorded with an IR camera as power applied. The maximum temperature was 35% higher than the probe temperature, on average, but follows a predictable function of temperature and input power.

2A. Method qualification

Element temperature calibration

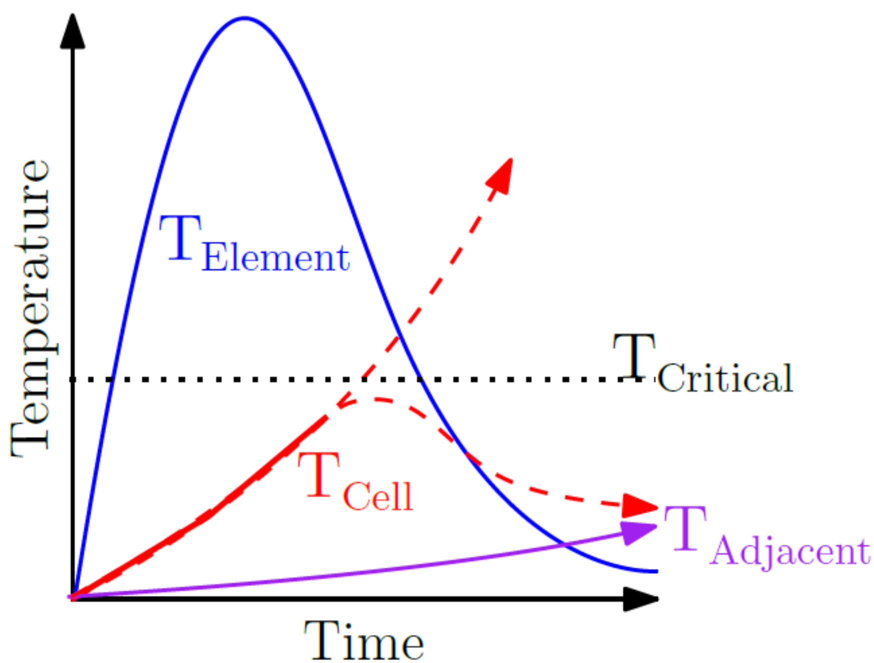
Maximum obtainable temperature rise: 200˚C/sec



2B. Realistic power/temperature profile or optimized thermal runaway initiation (Review)

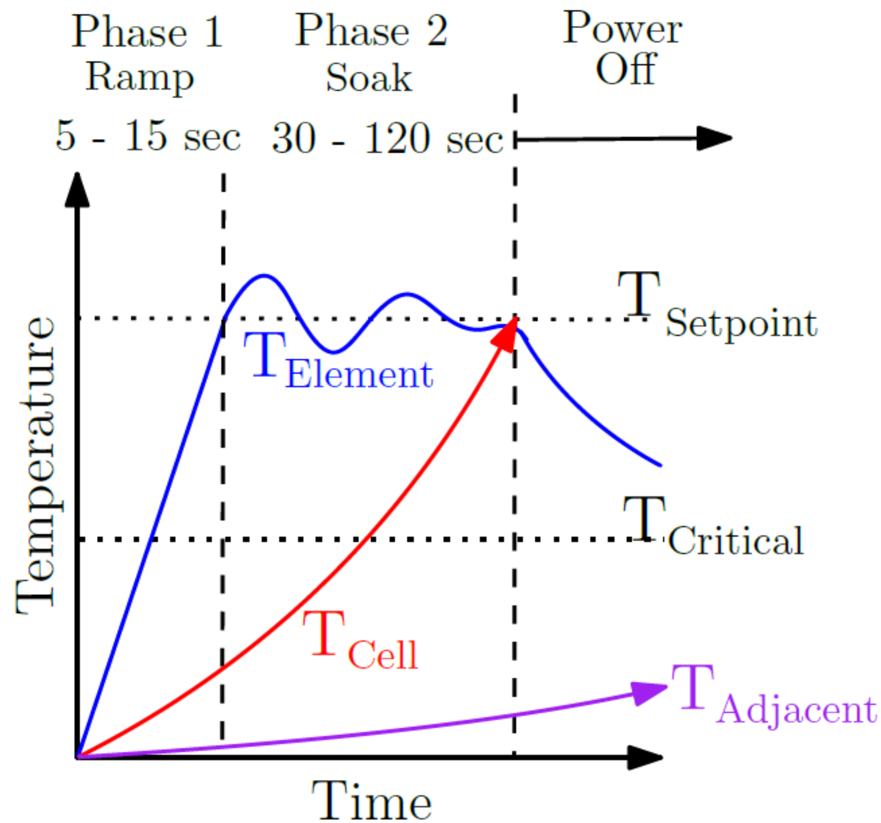
A. Reproduce a “Realistic” event

$$T_{Cell} = f\left(P_{Element}, k_{Cell}\right)$$



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.

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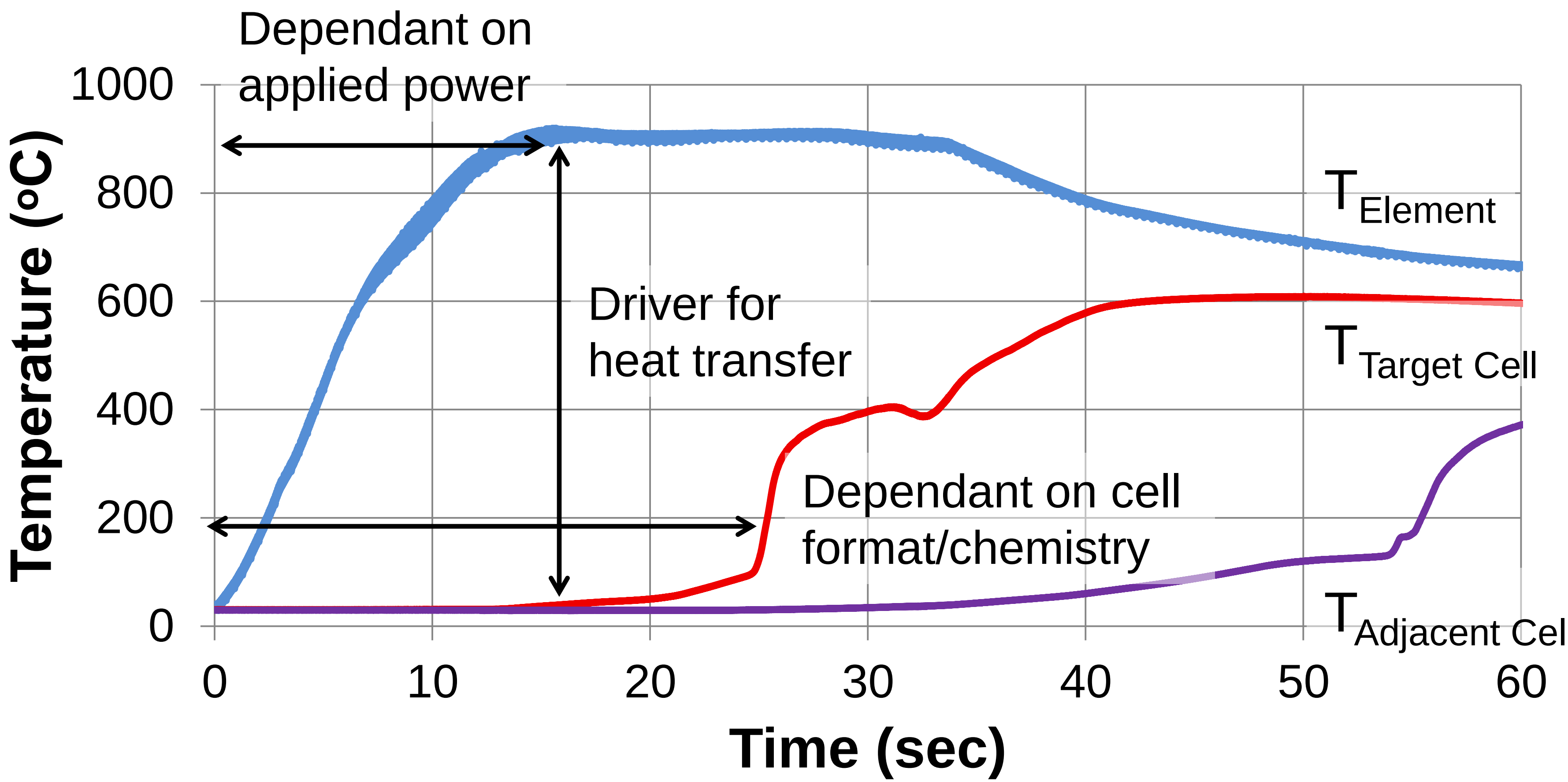
2B. Concepts of external heating

Type A cell

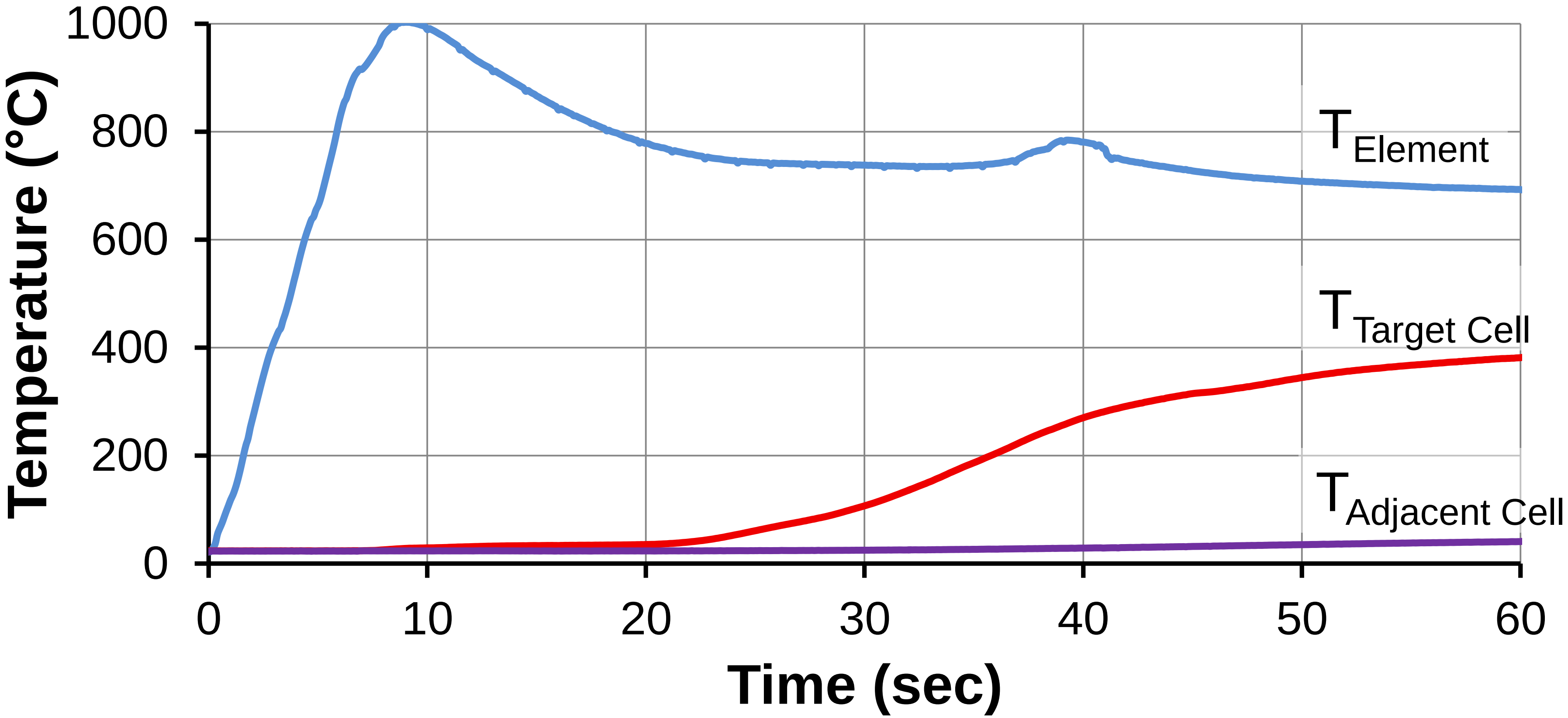


$T_{Element} \neq T_{Target\ Cell}$ …heat transfer to cell is time dependant

2B. Concepts of external heating cont.

Temperature feedback control method was used for ignition test presented on slide 14, this shows an expanded time scale:

Type D cell



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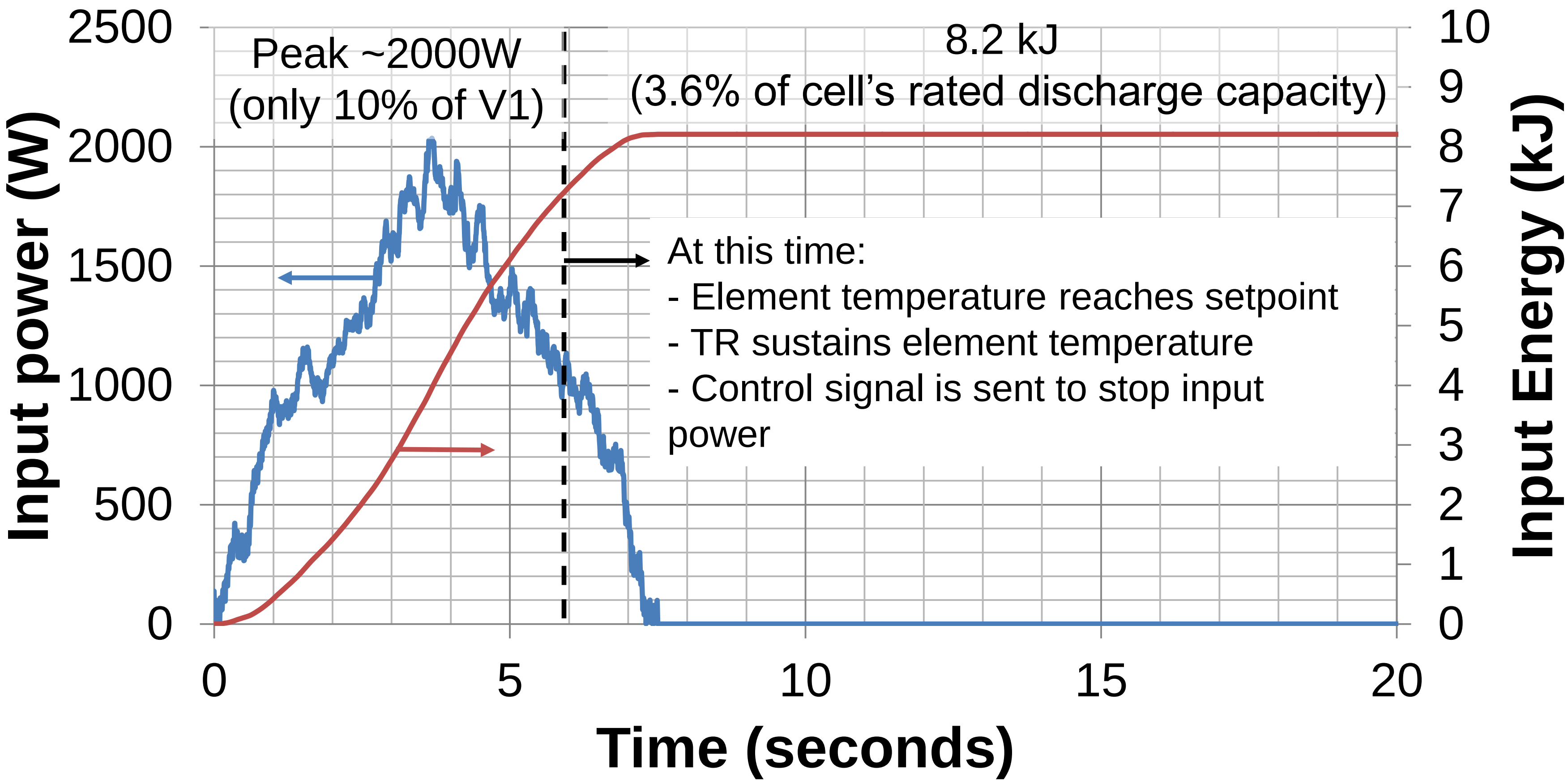
2B. Input power and energy

One advantage of optimized runaway method is minimal added energy; even less than the realistic event scenario:



2B. Comparison of cell types using method 2B

Another major advantage is the adaptability to different cell types/formats. Please refer to slide 19 for terminology.

Cell type	No. of tests to date using method 2B*	Phase 1 (Ramp) Time (s)	Phase 2 (Soak) Time (s)	Runaway initiated?	Total energy applied (kJ)	% of cell's rated discharge capacity (%)
A	1	11	15	Yes	11.8	5.2
B	1	7	8	Yes	9.5	1.9
C	3 **	7	150	Yes	55.0	7.3
D	1	9	20	Yes	8.2	3.6

* Setpoint of 800C, soak until runaway in target cell

** The average value is shown for all tests

- Similar ramp times for all tests (a function of heat transfer conditions)
- Pouch cell types A, B and D have comparable soak time and energy
- Prismatic cell type C requires far more time and energy, as anticipated, due to the cell's thick can wall

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

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 – OUR CURRENT FOCUS**

- 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…).

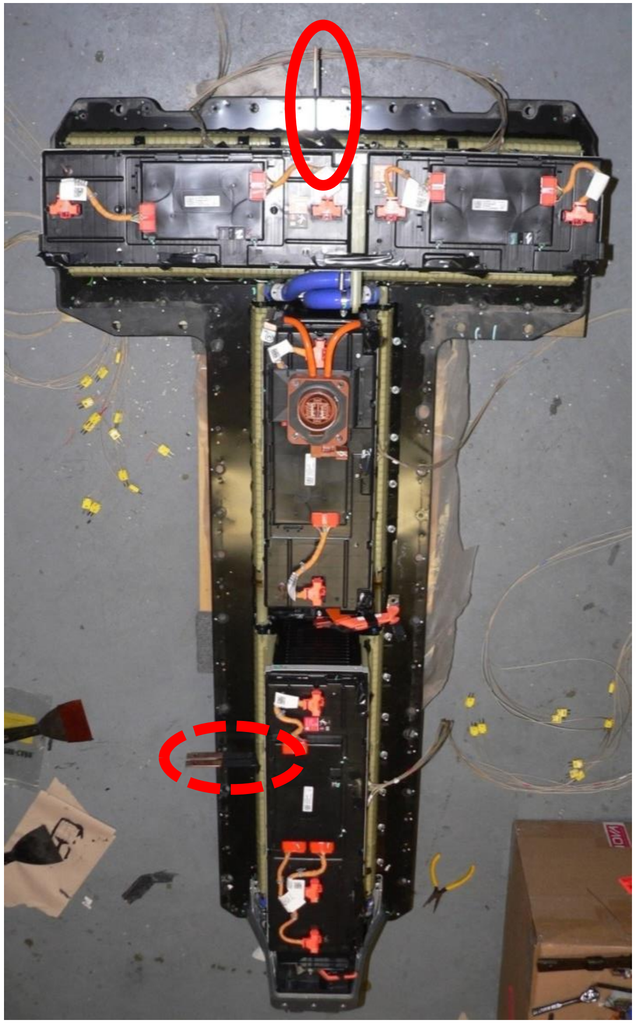
Our Proposed Method

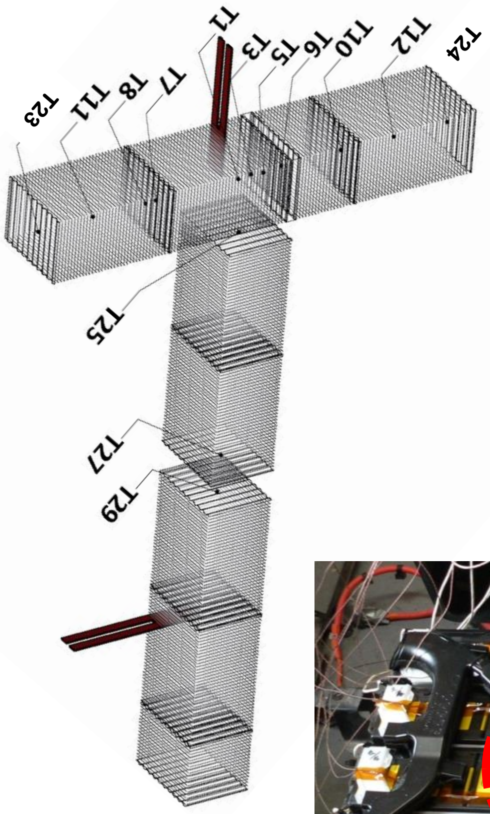
Preliminary results indicate initiation of various target cells (pouch, prismatic, 18650) is repeatable and controllable, but propagation is dependent on many external forces.

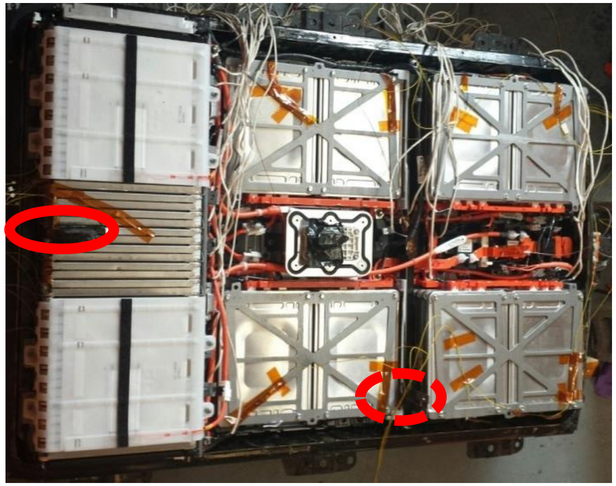
Key test conditions – Rapid heating

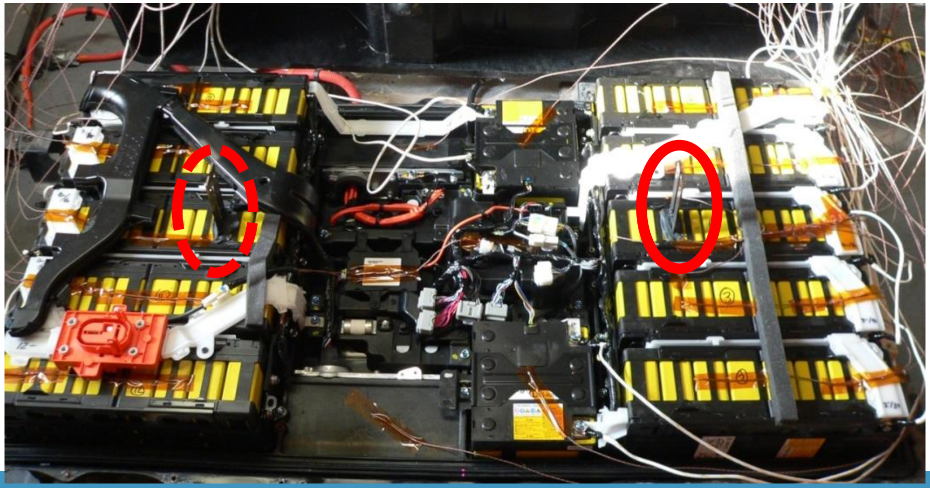
		Ideal Condition	NRC Current Conditions	Reasoning
Heater	Material	Any with non-conductive surface	NiChrome with non-conductive coating	Standard material with high temperature stability
	Thickness (mm)	< 5	1	To minimize additional foreign volume
	Area (cm^2)	< 25	5.6	To concentrate heat to a small area of the cell
Heating Rate (˚C/sec)		> 50	Up to 200	To minimize unproductive heat transfer and adjacent cell preheating
Maximum heater temperature (˚C)		~700˚C	Selectable 700-1200˚C, depending on method	700˚C represents a typical TR temperature. Dependent on realistic vs optimized objective.
Heat Flux (W/cm^2)		$> 1 \times 10^3$	$> 1 \times 10^6$	To ensure concentrated localized heat
Ratio of total input energy to cell energy (%)		< 20	< 10, typically < 5	Minimize the addition of additional energy to the system
Total heating duration (seconds)		< 180	< 180, typically < 60	Dependent on realistic vs optimized objective and cell choice
Acceptable neighboring cell temperature rise (˚C)		<10	0	This creates result bias and is unwanted
Target cell location		Multiple positions (3)	Least invasive position & highest research value	Single cell TR can occur anywhere, Worst-case scenario is not obvious
Pack modifications		None	Holes for TRIM wires Disconnect coolant lines	Ideally, the pack thermal management system would be active during test
Ambient temperature (˚C)		Max. operating temperature	22˚C +/-5˚C, but dependent on test location	Higher ambient temperatures will be worst-case scenario
Test instrumentation		BMS response and/or the voltage/temperature of target cell (minimum)	Temperature and voltage of every cell or module (for research purposes)	Using BMS response only would be minimally invasive, but external voltage/temperature of target cell required for validation. NRC adds many external sensors for research studies.

Examples









NRC research test methodology (abridged)

No	Test preparation - Step description	Comments
1	Charge REESS to 100% SOC in the vehicle and soak at room temperature for 24h	
2	Remove REESS from vehicle	Remove service disconnect
3	Cap REESS liquid cooling lines, if present	Ideally, thermal management system would be operational
4	Remove top cover of REESS	
5	Select module and target cell for heater insertion	Thus, far it has been chosen based on installation accessibility and data research value, usually ¼ way through one module.
6	If insertion between cells: Loosen module pressure to insert heater, install with heat transfer paste, retighten to original pressure. If external cell surface mount: Secure using heat transfer paste and bends in heater electrodes/wires to provide strain relief	Not all pack designs allow for heater insertion, external cell surface mount is sometimes necessary.
7	If a venting gas ignition source is desirable, mount ignitor within 100mm of TRIM location (where space permits).	
8	Instrument pack with voltage sense wires and thermocouples. Create holes in top cover, only as necessary and away from target location, and install sealed wire pass through connection into case to route all wires through (including TRIM and ignitor wires) while maintaining pack's original gas permeability.	Every cell for module level tests; and every module (based on pack design) for pack level plus additional near the target cell and outside casing.
9	Return top cover of REESS and seal with high-temperature silicone epoxy	
10	Connect sensor wires to data acquisition system and verify operation. Confirm REESS SOC. Ensure master switch to TRIM is open.	

NRC research test methodology (abridged)

No	Test execution - Step description		Comments
1	Configure and prepare the TRIM system depending on realistic vs optimized objective:		
	Realistic event: a. Open circuit relay b. Adjust TRIM circuit series resistance to achieve desired energy release time constant (ex. 30 seconds to 95% energy depletion) c. Connect energy source and charge to predetermined energy value based on desired peak power output (ex. 2000W)	Optimized TR: a. Open circuit relay b. Connect fixed voltage power supply and temperature regulating controller c. Connect temperature feedback thermocouple to the controller d. Configure controller for desired temperature set point, and ramp and soak times (ex. 800°C, 20sec, 180sec)	
	Connect TRIM voltage and current sense wires to data acquisition system.		
2	Begin recording temperature and voltage data (≥10Hz sampling rate recommended)		
3	Begin spark ignitor, if installed (15kV, 4.2mm spark gap, duty cycle of 100ms every 1 second, run continuously)		
4	Final checks: ensure doors are closed, exhaust is active, PPE is available, personnel are removed		
5	Close electronic relay (remotely activated) to begin the release of energy to the TRIM		
6	Observe data		
7	Open relay after energy source voltage or current drop below 1V or 1A, respectively (ex. for >95% energy depletion).	Open relay after a predetermined maximum heating period (ex. 180 sec), or earlier, based on TR detection in the target cell*.	* TR detection is currently defined as having >200C and >10C/sec, surface temperature of the target cell, measured on the opposite face or far removed from the TRIM installation.
8	If a TR reaction occurs: - Monitor and observe until the maximum temperature of all temperature measurements, drops below 60C, then continue recording for an additional 60 minutes. Stop spark ignitor, if installed. If a TR reaction does not occur: - Monitor and observe for a minimum of 60 minutes. Stop spark ignitor, if installed.		
9	Carefully remove REESS and resistively discharge remaining cells/modules that show a voltage.		
10	Perform teardown analysis, place in secure storage or dispose REESS appropriately		

White Paper Discussion

- Comments submitted and uploaded to UN site
- Main points:
  - Narrow objective, Intent should be to focus on limiting thermal runaway regardless of cause of initiation.
  - Non-automotive events should be used as evidence of potential issues. Other industries use “high quality” cells and designs.
  - Battery/pack design should be able to mitigate any single cell thermal runaway scenario.
  - The battery pack is a fuel source and it may be impractical to prevent propagation entirely (design restrictive). Ultimately, the vehicle's ability to detect the issue, alert the driver, and attempt to contain or at least delay the event should be considered as the minimum requirement.

White Paper Discussion

- The merit of initiation methods need to be discussed before evaluation criteria can be discussed.
- Pass/fail criteria should be determined by what the group deems to be the appropriate “minimum” level of safety associated with thermal runaway of a single cell.
- It's likely that no one method exists with no manipulation (added material, energy or access holes). Minimizing manipulation may be the only course of action feasible.
- Higher temperatures increase reactivity. Highest possible (realistic) ambient temperature would represent worst-case scenario.

Acknowledgements

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Thank you for your kind attention!

Any Questions or Comments

Canada
NRC-CNRC

Transport Canada   Transports Canada