Single Cell Thermal Runaway Initiation (SCTRI)

Test – (Propagation)

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Single Cell Thermal Runaway Initiation (SCTRI) Test

RESS SCTRI Test Procedure and Test Report

1. PURPOSE

The automotive application of electric propulsion in Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Electric Vehicles (EV) relies on application of Rechargeable Energy Storage Systems (RESS) commonly referred to as batteries. The automotive application and use of a RESS, such as a Lithium-ion (Li-ion) based battery system, poses certain potential risks to vehicle operators and occupants. These potential risks are different than those associated with internal combustion engine equipped vehicles. Among the potential risks is thermal runaway of the cell(s) or battery pack(s) which in some cases may result in a combination of potentially toxic effluent venting, fire, and/or explosion.

Thermal runaway reactions can occur with cells or batteries of any chemistry, including lead acid and nickel metal hydride batteries. Although rare, thermal runaway reactions do occur in the field, even with batteries produced by the most experienced and conscientious cell and battery manufacturers, and even with batteries that meet applicable standards and routinely pass a variety of abuse tests. Some field thermal runaway failures can be ascribed to abuse of the batteries, some to identifiable manufacturing failures, and some failures remain unexplained. Thermal runaway reactions with Li-ion cells are of particular concern since cells with this chemistry have a higher energy density than the more familiar automotive battery chemistry types (lead acid or nickel metal hydride), usually contain a flammable electrolyte, and are used to make higher capacity battery packs (RESS) than previously achieved with lead acid or nickel metal hydride chemistries. Nonetheless, thermal runaway in cells of any chemistry can pose an appreciable hazard. For example batteries that contain a non-flammable electrolyte such as the aqueous based sulfuric acid electrolyte contained in lead acid batteries can emit hydrogen or acid gas upon failure.

Previous experience with cells and batteries of a variety of chemistries has shown that many of the thermal runaway reactions that occur in the field begin with a flaw in a single cell. Since these cell flaws are rare, varied, and difficult to detect, it is impossible to prove with testing that any particular cell design is impervious to failure. Thermal runaway of a single cell can pose an appreciable hazard on its own. However, the extent of the resulting hazard is strongly dependent upon the likelihood that the thermal runaway reaction propagates to adjacent cells, or compromises other battery or vehicle systems to create or increase a hazard, such as the emission of toxic or flammable vent gases into the vehicle cabin. Although single cell testing can provide some insight into the potential hazards associated with cell thermal runaway, full scale testing is required to properly assess the interaction of all RESS components, including mitigating RESS architecture and enclosure features that can limit thermal runaway propagation or control effluent venting.

Going forward, one can assume that as battery chemistries and designs evolve, the potential causes of thermal runaway reactions may change, and the resulting hazards may also change. Thus, the purpose of a Single Cell Thermal Runaway Initiation (SCTRI) testing standard is not to determine the likelihood that a single cell will undergo a thermal runaway reaction due to any particular cause. Experience with the consumer electronics, automotive, and aerospace industry has demonstrated that single cell thermal runaway reactions are always possible, even if probabilities are low. Rather, the purpose of SCTRI testing is to assume that a single cell within a RESS will undergo a thermal runaway reaction due to an unspecified cause, and to then determine whether that reaction will pose a significant hazard to the vehicle's occupant or the surrounding environment. Note that SCTRI testing will not penalize cells with a lower probability of undergoing a thermal runaway reaction. If a cell type is less susceptible to thermal runaway, then the cells surrounding an initiating cell that is forced into thermal runaway will be less susceptible to propagation of thermal runaway.

2. SCOPE

This test procedure is applicable to all RESS-equipped HEV, PHEV and EV vehicles. Specific guidance has been provided for application of the procedures to Li-ion based RESS systems as Li-ion cell chemistry is the dominant chemistry in RESS at the time of this writing, however, the approach provided could be applied to a range of other cell chemistries.
The test procedure described is composed of three parts:

a. Selecting an appropriate single cell thermal runaway initiating methodology,
b. Verifying the thermal runaway initiation methodology in coupon or module level tests; and
c. Full scale; in-vehicle testing to assess whether a single cell thermal runaway within a RESS will pose a significant hazard to the vehicle's occupant or the surrounding environment.

Ultimately, judgment of vehicle safety should be based on full scale vehicle testing results. Procedures for developing and verifying a single cell thermal runaway initiation method are provided to facilitate full scale testing. Single cell initiation testing and coupon or module verification testing are only required to ensure that at full scale testing, an appropriate method is used to initiate single cell runaway. If the testing agency can provide justification for an initiation method and verify that thermal runaway was successfully initiated in full-scale testing, then single cell and verification testing may be omitted.

3. REFERENCES

3.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of the publication shall apply.

3.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA) www.sae.org

SAE J1715 Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) Terminology,

3.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this document.

3.2.1 Electrochemical Society Publications

Available from the Electrochemical Society, 65 South Main Street, Building D, Pennington, NJ 08534-2839, Tel: 609-737-1902, http://ma.ecsdl.org/content/MA2010-03/1/762.full.pdf

"Li-ion Cells Internal Short Circuit Testing", Maleki, H., Wang, H., Zhang, W. and Lara-Curzio, The 15th International Meeting on Lithium Batteries IMLB (2010).

3.2.2 IEC Publications

Available from the International Electrochemical Commission, 446 Main Street 16th Floor, Worcester, MA 01608, Tel: +1 508 755 5663, www.iec.ch

CEI/IEC 61960 Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for portable applications.

CEI/IEC 62133 Secondary cells and batteries containing alkaline or other non-acid electrolytes – Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications.

3.2.3 IEEE Publications

Available from IEEE Standards Activities, 445 Hoes Lane, Piscataway, NJ 08854-4141, Tel: +1 732 562 5527, www.standards.ieee.org.

IEEE 1725 Standard for Rechargeable Batteries for Cellular Telephones

IEEE 1625 Standard for Rechargeable Batteries for Multi-Cell Mobile Computing Devices

3.2.4 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA) www.sae.org

SAE J2464	Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing
SAE J2929	Electric and Hybrid Vehicle Propulsion System Safety Standard – Lithium-based Rechargeable Cells

3.2.5 NFPA Publications

Available from the National Fire Protection Association (NFPA), 1 Batterymarch Park, Quincy, MA 02169-7471 Tel: +1 617 770-3000, www.nfpa.org

"Lithium-Ion Batteries Hazard and Use Assessment," Mikolajczak, C.J., et al. July 2011.

References included in 1.

SFPE Handbook of Fire Protection Engineering, 2008 Edition, "Chapter 2-6 Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat", Purser, David A.

3.2.6 NREL Publications

Available from http://www.nrel.gov/docs/fy13osti/54404.pdf

D. H. Doughty, "Technical Report: Vehicle Battery Safety Roadmap Guidance", Subcontract Report NREL/SR-5400-54404, Oct. 2012, p. 24.

References included in 1.

"Numerical and Experimental Investigation of Internal Short Circuits in a Li-ion Cell," Keyser, M., Kim, G.H., Pesaran, A., Long, D., Ireland, J., Jung, Y.S., Lee, K.J., Smith, K., Santhanagopalan, S., Darcy, E. NREL/PR-5400-50917

http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/50917.pdf

3.2.7 United Nations Publications

Available from UN Economic Commission for Europe, Information Service, Palais des Nations, CH-1211 Geneva 10, Switzerland, Tel: +41-0-22-917-44-44, www.unece.org.

Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, 5th Revised Edition, 2011. ST/SG/AC.10/11/Rev54

3.2.8 Underwriter's Laboratories Publications

Available from Underwriters Laboratories Inc. (UL), 333 Pfingsten Road, Northbrook, IL 60062-2096, Tel: +1-847-664-3480, www.ul.com.

1. UL 1642 Standard for Lithium Batteries
2. UL 1973 Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
3. UL 2054 Household and Commercial Batteries
4. UL 2271 Batteries for Use in Light Electric Vehicle (LEV) Applications
5. UL 2580 Batteries for Use in Electric Vehicles
6. "Safety Issues for Lithium-Ion Batteries" http://www.ul.com/global/documents/newscience/whitepapers/firesafety/FS_Safety%20Issues%20for%20Lithium-Ion%20Batteries_10-12.pdf
7. "UN Transportation Tests and UL Lithium Battery Program" www.prba.org/wp-content/uploads/UL_Presentation.ppt

3.2.9 United States Department of Transportation-

Code of Federal Regulations 49 CFR Part 173.185 "Lithium cells and batteries"

4. Definitions

Except as noted below, all definitions are in accordance with SAE J1715

Ah

Ampere-hour: a measure of battery capacity.

Battery

A device comprising one or more individual electrochemical cells connected in series and/or in parallel or modules packaged together with associated protection electronics and mechanical enclosure

Battery Cell (Cell)

The basic electrochemical unit of a battery, containing an anode and cathode, electrolyte, and typically separator. A cell is a self-contained energy storage and conversion device whose function is to deliver electrical energy to an external circuit. Energy is stored within the cell as chemical energy.

Battery Management System / Unit (BMS / BMU)

Electronic components that monitor and/or control battery functions such as charge and discharge operations.

Battery Module

A group of interconnected cells in a single mechanical and electrical unit that is a subassembly of a full Battery

Brick or Block

One or more battery cells connected in parallel. The voltage of a brick or block is the same as an individual cell. Bricks or blocks are commonly connected in series to create a higher voltage battery. Bricks or blocks are sometimes referred to as voltage series elements.

Electrical Isolation:

The electrical resistance between the vehicle high-voltage system and any vehicle conductive structure. Internal electrical isolation is measured inside automatic disconnects (if present) and external electrical isolation is measured outside automatic disconnects (if present).

Emergency Response Guide (ERG)

A document describing the hazards that may be encountered during an emergency response operation involving an “article”. OSHA has defined “article” as a manufactured item other than a fluid or particle; (i) which is formed to a specific shape or design during manufacture; (ii) which has end use function(s) dependent in whole or in part upon its shape or design during end use; and (iii) which under normal conditions of use does not release more than very small quantities (e.g. minute or trace amounts) of a hazardous chemical, and does not pose a physical hazard or health risk to employees.

EV: Electric Vehicle

An automobile type vehicle, powered by an electric motor that draws energy solely from a rechargeable energy storage device.

Explosion

Very fast release of energy sufficient to cause pressure waves and/or projectiles that may cause considerable structural and/or bodily damage.

Fire

The emission of flames from a battery (approximately more than 1s). Sparks are not flames.

HEV: Hybrid Electric Vehicle (HEV)

An automobile type vehicle, powered by powered by an electric motor that draws energy from two or more energy storage systems, one of which is a rechargeable energy storage device.

Initiating Cell

The cell intentionally driven into thermal runaway by use of a thermal runaway initiating method.

Lower Flammability Limit (LFL) or Lower Explosive Limit (LEL)

The minimum fuel concentration required to allow flame propagation. LFL and LEL are very similar and are often used interchangeably.

Lithium-Ion (Li-ion)

The term lithium-ion or Li-ion refers to an entire family of battery chemistries where the negative electrode (anode) and positive electrode (cathode) materials serve as a host for the lithium ion (Li^+). Lithium ions move from the anode to the cathode during discharge and are intercalated into (inserted into voids in the crystallographic structure of) or otherwise react with the cathode. The ions reverse direction during charging and are intercalated into the anode material.

Material Safety Data Sheet (MSDS)

A document that contains information on the potential hazards (health, fire, reactivity and environmental) of a chemical product.

PHEV: Plug-in Hybrid Electric Vehicle

A hybrid vehicle with the ability to store and use off-board electrical energy in a rechargeable energy storage device. A range extended EV is a type of PHEV.

Personal Protective Equipment (PPE)

Clothing, helmets, goggles, or other garments or equipment designed to protect the wearer's body from injury.

Rechargeable Energy Storage System (RESS)

The RESS is a completely functional energy storage system consisting of a battery pack(s), necessary ancillary subsystems for physical support and enclosure, thermal management and control, and electronic systems control.

Spontaneous (unprovoked) thermal runaway

When a cell in a battery pack undergoes a thermal runaway reaction in the field and there is no evidence of applied thermal, mechanical, or electrical abuse, it is often described as a "spontaneous" or "unprovoked" thermal runaway reaction. Although this terminology is not strictly accurate – the failure occurs due to a flaw within the cell, typically one that has developed over time to a point of inducing failure it is in common use, and is used in this manner within this document.

State of Charge (SOC)

The discharge capacity in ampere-hours of a battery expressed as a percent of the battery ampere-hour capacity.

Thermal Runaway

Thermal runaway refers to rapid self-heating of a battery cell derived from the exothermic chemical reaction of the highly oxidizing positive electrode and the highly reducing negative electrode. It can occur with batteries of almost any chemistry. In a thermal runaway reaction, a cell rapidly releases its stored energy. At the end of a thermal runaway reaction, no electrical energy will be stored within the cell. Note that a measurement of 0V at cell terminals alone is not evidence of thermal runaway. The cell may also have vented electrolyte, undergone a variety of irreversible chemical reactions, or have melted or burned components or activated internal protection mechanisms. Figure 22 provides an example of temperature and voltage traces obtained from a lithium-ion cell driven into thermal runaway. The thermal runaway reaction is co-incident with a sharp increase in temperature and drop in cell voltage.

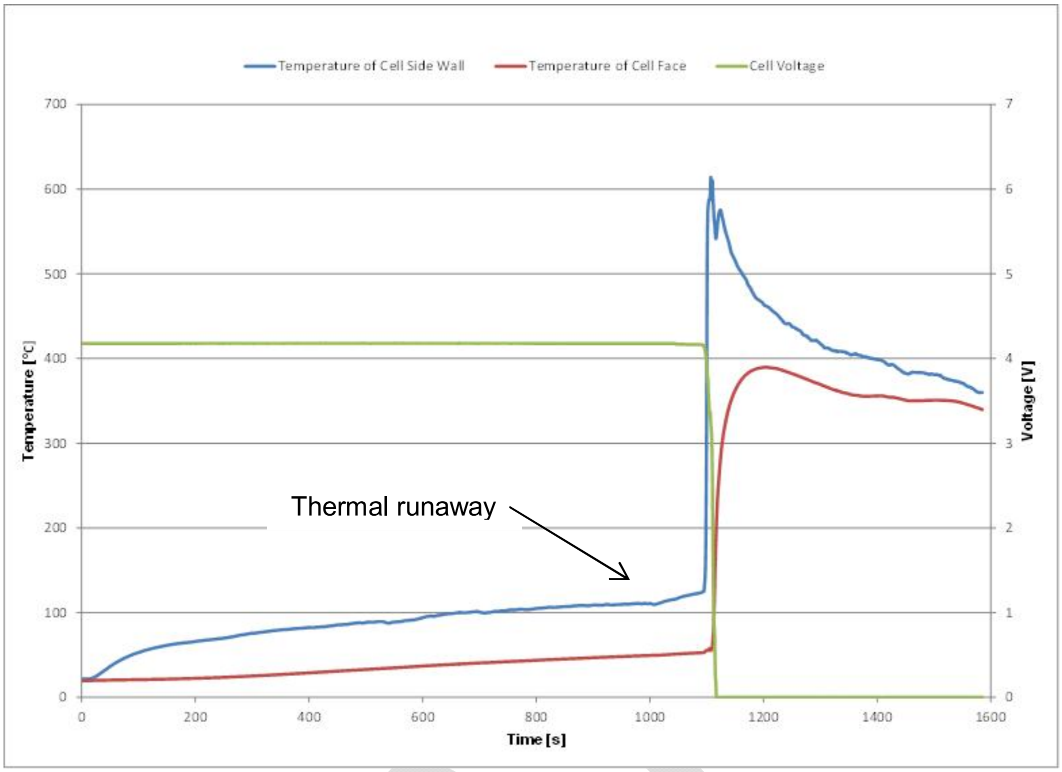

Figure 22 - An example of temperature and voltage traces of a Li-ion cell undergoing a thermal runaway reaction: note the rapid increase in temperature.

<u>Thermal runaway initiating device</u>

A testing instrument or device designed to induce single cell thermal runaway

<u>Venting</u>

The release of excessive internal pressure from a RESS cell, module, or battery pack in a manner intended by design to preclude rupture or explosion.

5. GENERAL TEST REQUIREMENTS

5.1 General Precautions

5.1.1 Conducting thermal runaway testing on any cell chemistry is potentially hazardous. Under thermal runaway conditions a cell or battery can emit flammable or toxic vapors, can become very hot, can ignite, can eject corrosive or toxic liquids, or can undergo an energetic disassembly.

5.1.1.1 Prior to conducting thermal runaway testing, the individuals conducting testing should become familiar with the contents of a battery or cell and the related potential hazards, and assemble appropriate personal protective equipment (PPE). A Material Safety Data Sheet (MSDS) or Emergency Response Guide (ERG) may provide relevant information.

5.1.1.2 Testing should be conducted in a well-ventilated environment with provisions to mitigate smoke, flammable vapors, or toxic vapors. Should an air scrubbing system be used, the system filters should be selected to be appropriate to the specific cell chemistry. System filters should be protected from ignition if emitted gas could be heated, if flammable, or if spark emission is to be expected. If testing will be conducted in open air, the testing agency should secure necessary burn permits.

5.1.1.3 If emission of flammable gases is possible, the testing facility should be prepared to mitigate the hazards of an un-intentional ignition. Potential methods of mitigation include flammable gas monitoring, capability to remotely activate appropriate fire suppression systems, high volume vapor dilution systems, and sparker systems.

5.1.1.4 Personnel conducting testing should be equipped with appropriate PPE such as a respirator with appropriate cartridges or Self-Contained Breathing Apparatus (SCBA), eye protection (safety glasses, googles, or face shield), chemical resistant gloves, high voltage resistant gloves, high temperature resistant gloves, and flame or chemical resistant clothing (e.g. Nomex coveralls, turn-out gear, etc.). The testing agency should make a determination regarding appropriate PPE prior to beginning of testing.

5.1.1.5 Personnel conducting testing should be separated from contact with ejected liquids or debris. This may include use of testing chamber, a testing enclosure, or designation of a minimum safe distance to the test article.

5.1.1.6 Personnel should be aware that test components can achieve high temperatures and can pose a burn hazard.

5.1.2 Working with a RESS to harvest components, to prepare it for SCTRI testing, or to examine it after testing is potentially hazardous.

5.1.2.1 Systems are heavy and must be removed and remounted in vehicles multiple times. Removal after testing may pose additional difficulties.

5.1.2.2 Opening a battery pack can expose personnel to high voltages and arc flash hazards.

5.1.2.3 Charging single cells or modules within a RESS can pose electrical hazards.

5.1.2.4 Charging a modified RESS prior to PPR testing may pose hazards. The testing agency should ensure that maximum charging voltage and current limits are not exceeded for each series element.

5.1.3 When performing a SCTRI test on a battery pack installed in a vehicle, the testing agency should be prepared for the vehicle to completely burn.

5.1.3.1 Various vehicle systems besides the RESS can be a source of hazard including: fuel systems (such as tanks, pumps, and fuel lines), hydraulic systems, various liquid reservoirs, airbags, pneumatic cylinders, magnesium components, and inflated tires. The testing agency may choose to mitigate the various hazards by removing various vehicle subsystems prior to testing. However, in such an instance, the testing agency will need to determine if removal of any given subsystem will materially affect test outcome.

5.1.3.2 A vehicle fire can produce a significant quantity of smoke. Should an air scrubbing system be used, the system filters should be selected to be appropriate for vehicle burn testing and the specific cell chemistry implemented in the RESS. System filters should be protected from ignition If testing will be conducted in open air, the testing agency should secure necessary burn permits.

5.1.4 Thermal runaway initiation can fail, or be delayed due to test variability. Propagation from cell to cell during a test can also be delayed, and long latency periods are common in SCTRI testing. It is often difficult for test personnel to visually determine whether a test article is safe to approach once a test has begun. The testing agency should ensure that there is appropriate monitoring of test articles, or a sufficient delay time requirement to allow testing personnel to make a determination regarding when it is appropriate to approach a test article after a test has begun. Monitoring can be accomplished with sensors such as thermocouples, thermal imaging cameras, voltage sensors, gas sensors, and flammable gas detectors.

5.1.5 After testing has concluded, test articles will be damaged and may pose a hazard during test cleanup. For example, cells may be swollen, heat damaged, or burned; conductors may have damaged insulation, enclosures may have been compromised, coolant systems may be leaking. The testing agency should develop a plan for handling and disposing of damaged test articles.

5.2 Test Specific Precautions

See Section 5.1

5.3 Safety Requirements

The testing agency must develop a test specific safety plan for each vehicle SCTRI test, including a list of required PPE for personnel. This safety plan should be based upon information provided by the manufacturer regarding RESS chemistry, and pack architecture as well as precautions typically associated with burn tests and high voltage systems. See discussion in Sections 5.1 and 5.2

5.4 Test Facility/ Equipment Requirements

5.4.1 Facility requirements for full scale in-vehicle testing.

5.4.1.1 The facility must be capable of, and permitted for, conducting a full vehicle burn.

5.4.1.2 The facility must have a thermal chamber or temperature controlled area for pre-test thermal soaking of the vehicle prior to burn testing to a temperature of 25±2°C.

5.4.1.3 The facility must have equipment to move and rotate a non-operational vehicle, including moving a vehicle in and out of the thermal chamber.

5.4.1.4 The facility must have equipment to safely remove a battery pack from the vehicle before and after testing. The battery pack will likely be damaged after testing.

5.4.1.5 The facility must have the ability to safely open the battery pack before and after testing to allow examination and charge or discharge of energized components.

5.4.1.6 The facility must have the ability to discharge/neutralize damaged cells, modules, or a full battery pack. The RESS manufacturer must specify a method to discharge/neutralize for the full scope of different potential states; for example, a salt bath methodology for cells that do not have an easily available electrical connection.

5.4.1.7 The facility must be capable of disposing of or recycling damaged or burned RESS or other byproducts of testing in compliance with environmental regulations.

5.4.2 Equipment requirements for full scale vehicle testing.

5.4.2.1 Personal Protective Equipment such as respirators, safety glasses, and high voltage gloves. See discussion 5.3 above.

5.4.2.2 Thermal runaway initiation equipment such as a film heater and a power supply appropriate for a heater method of cell thermal runaway initiation, as well as appropriate pass-throughs for electrical leads.

5.4.2.3 Sensors and Data Acquisition Equipment:

Thermocouple DAQ (recommend channel-to-channel isolation) capable of a data collection rate of at least 1 Hz
Thermocouple wire (recommend K-type with fiberglass insulation)
Thermocouple bead welder (optional – pre-made K-type thermocouples can be purchased)
Stopwatch with accuracy of ±1 second
Smoke detector with a photoelectric sensor (opacity based detection)
Gas sensor (optional)
Handheld Voltage and Isolation Resistance Meter
Hipot Tester (optional)
Video cameras (3 minimum)

5.4.3 Should single cell testing be required to select a cell thermal runaway initiation methodology prior to full scale in-vehicle testing, the facility requirements for conducting single cell testing are:

5.4.3.1 The facility must have a thermal chamber for pre-test thermal soaking of cells prior to burn testing to a temperature of 20±10°C

5.4.3.2 The facility must be capable of burning individual cells. This may require a flame resistant fume or vent hood, and the capability of handling and exhausting flammable gases.

5.4.3.3 The facility must be capable of safely discharging damaged cells, and disposing of or recycling burned cells in compliance with environmental regulations.

5.4.4 Should single cell testing be required to select a cell thermal runaway initiation methodology prior to full scale in-vehicle testing, the equipment requirements for conducting single cell testing are:

5.4.4.1 Personal Protective Equipment such as respirators, safety glasses, and chemical resistant gloves. See discussion 5.3 above.

5.4.4.2 The thermal runaway initiation device.

5.4.4.3 A voltage measurement and data logging system with an accuracy of at least 0.5% of cell maximum voltage, and a data collection rate of at least 10 Hz. For example for Li-ion single cell testing, a National Instruments NI 9205 ±10V data acquisition module was used. This has an accuracy of ± 6.22 mV (0.15% of 4.2V)

5.4.4.4 A temperature measurement and data logging system capable of reading Type K thermocouples and a data collection rate of at least 1 Hz. For example for Li-ion cell testing, a National Instruments NI 9213 data acquisition module was used.

5.4.4.5 Type K thermocouples (minimum of 2)

5.4.4.6 A stopwatch or similar timekeeping instrument with an accuracy of ±1 second.

5.4.5 Should coupon or module level verification testing be required to verify a cell thermal runaway initiation methodology prior to full scale in-vehicle testing, the facility requirements for conducting this testing are:

5.4.5.1 The facility must have a thermal chamber or other device for pre-test thermal soaking of coupons or modules prior to burn testing to a temperature of 20±10°C

5.4.5.2 The facility must be capable of burning multiple cells in coupon or module configurations. This may require a flame resistant fume or vent hood, and the capability of handling and exhausting flammable gases.

5.4.5.3 The facility must be capable of safely discharging damaged cells, coupons, and modules, and disposing of or recycling burned components in compliance with environmental regulations.

5.4.6 Should coupon or module level testing be required to select a verify a cell thermal runaway initiation methodology prior to full scale in-vehicle testing, the equipment requirements for conducting this testing are:

5.4.6.1 Personal Protective Equipment such as respirators, safety glasses, and chemical resistant gloves. See discussion 5.3 above.

5.4.6.2 The thermal runaway initiation device.

5.4.6.3 A temperature measurement and data logging system capable of reading Type K thermocouples and a data collection rate of at least 1 Hz. For example for Li-ion cell testing, a National Instruments NI 9213 data acquisition module was used.

5.4.6.4 Type K thermocouples (minimum of 2).

5.4.6.5 A stopwatch or similar timekeeping instrument with an accuracy of ±1 second.

5.5 Test Equipment Calibration

A written calibration procedure shall be provided which includes as a minimum the following information for all measurement and test equipment:

1. Type of equipment, manufacturer, model number, etc.
2. Measurement range
3. Accuracy
4. Calibration interval
5. Type of standard used to calibrate the equipment (calibration traceability of the standard must be evident)

6. TEST PROCEDURE

6.1 Test Type

6.1.1 Single Cell Thermal Runaway Initiation (SCTRI) Testing is a destructive full scale in-vehicle test where a single cell within the RESS is driven into thermal runaway. The resulting effects on surrounding cells, the vehicle cabin, and the vehicle surroundings are monitored to determine whether that reaction will pose a significant hazard to the vehicle's occupant or the surrounding environment.

6.1.2 In preparation for full-scale in-vehicle testing, destructive testing of individual cells, and coupons, or modules may be required to define and validate an appropriate device to induce a thermal runway reaction of a single cell within the RESS.

6.2 Device Under Test

6.2.1 The device under test (DUT) will be a full vehicle with an RESS that has been modified to intentionally drive a single cell into thermal runaway and instrumented to measure the result of the thermal runaway reaction.

6.2.2 Prior to full scale testing, single cell and coupon or module level testing may be required to determine an appropriate methodology for driving a single cell into thermal runaway and selecting an appropriate location within the RESS.

6.2.2.1 Single cells may be harvested from a second RESS unit, or may be provided separately by the RESS manufacturer or vehicle OEM.

6.2.2.2 Coupons may be constructed from components harvested from a second RESS unit, or may be provided separately by the RESS manufacturer or vehicle OEM.

6.2.2.3 Modules may be harvested from a RESS unit, or may be provided separately by the RESS manufacturer or vehicle OEM.

6.3 Test Guidelines

6.3.1 Testing will require one vehicle with its RESS. The vehicle and RESS should be new: less than one year old, with less than five charge / discharge cycles applied to the RESS. The RESS may be provided by the Manufacturer or vehicle OEM with the necessary modifications for conducting SCTRI testing. If the testing agency must modify the RESS for testing, then additional RESS components may be required, for example enclosure components (See Section 8.3.1.4 for an example).

6.3.2 Testing may require cells or modules. These can be provided by the RESS Manufacturer or the vehicle OEM. Alternatively they can be harvested from a second RESS.

6.4 Test Parameters

Full Scale Vehicle SCTRI test parameters are

RESS Cell Beginning Test Temperature	25 ± 5 °C
Beginning Pack Preconditioning state	Cells less than 1 year old Cells accumulated less than 5 electrical cycles
Beginning SOC of RESS	99% to 100% of the maximum normal operating SOC
Beginning energy of vehicle	Fully charged RESS; full fuel tank (HEV, PHEV)[10]

6.4.1 Single cell test parameters are:

Cell Temperature	20 ± 10°C
Cell State of Charge (SOC)	95% - 100%

6.4.2 Verification (coupon or module level) test parameters are:

Cell Temperature	20 ± 10°C
Initiating Cell State of Charge (SOC)	95% - 100%
Neighboring Cell SOC	Various, depending upon test configuration

6.5 DUT Pre Conditioning

6.5.1 All cells, modules, and RESS used for testing should be as new and uncycled as practical: they should be less than one year old and have accumulated less than 5 charge discharge cycles prior to testing. See Section 7.5 for discussion.

6.5.2 Full vehicle and RESS conditioning occurs during preparation for testing. The temperature pre-conditioning requirements are described in Section 6.6.5.

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[10] See Section 0

6.5.3 For single cell testing, the cell should be at a temperature of 20 ± 10°C prior to test initiation.

6.5.4 For coupon or module level verification testing the device under test should be at a temperature of 20 ± 10°C prior to test initiation.

6.6 Test Methodology

6.6.1 Single Cell Thermal Runaway Initiation Method Selection Process

A single cell thermal runaway initiation method must be selected.

6.6.1.1 The test agency shall select a method appropriate to the specific device under test and provide reasoning as to the selection. The test agency shall provide evidence of physical tests at the single cell level to demonstrate efficacy of the selected method: that it will induce a thermal runaway reaction. See additional discussion in Section 7.1

6.6.1.2 The selected initiation method shall force only one cell into thermal runaway. Any subsequent cell thermal runaway reactions shall be the result of propagation from the initiating cell, not caused directly by the initiation method. See additional discussion in Sections 7 and 8.

6.6.1.3 The initiation method should best represent the behavior expected from a spontaneous field failure of a single battery cell, such as failure due to an internal short circuit. For example, the selected initiation method should avoid blocking normal exhaust gas flow or adding new and significantly different exhaust paths. It should avoid preheating neighbor cells beyond what would be expected from initiator heating due to a single-cell field failure. It should avoid compromising the electrical isolation of the cell to any surroundings, or affecting the thermal boundary conditions around the initiator cell due to addition of conductive or insulating materials that are not typically present in the RESS. Further discussion of relevant test factors can be found in Section 7.2. Examples of analysis of the efficacy of various thermal runaway initiation methods can be found in Section 8.1.

6.6.1.4 Single cell thermal runaway may be initiated with a variety of methods, and no single method is appropriate for all cell chemistries and form factors. The testing agency may need to trial multiple methods to find one method that will reliably induce cell thermal runaway. Section 8.1 provides examples of thermal runaway inducing methods that are effective for some cell designs. Section 7.3 provides discussion of additional thermal runaway inducing methods.

6.6.2 Coupon or Module Thermal Runaway Initiation Method Verification Testing

A single cell thermal runaway initiation method may need to be verified through coupon or module level testing.

6.6.2.1 The testing agency shall determine whether coupon or module level testing is required. The test agency shall provide justification for the decision if coupon or module level testing is not completed.

6.6.2.2 Coupon or module level testing may be required if the testing agency suspects that the method of thermal runaway initiation could have a significant impact on the testing process in the full RESS configuration

6.6.2.3 Section 8.2 provides examples of coupon and module level verification testing, and describes the reasons for testing.

6.6.3 RESS Preparation Procedure

Broadly, preparation of the RESS for full scale testing will include: documentation and characterization of RESS in the as-received state, installation and documentation of any hardware required to initiate thermal runaway in a single cell, installation and documentation of monitoring sensors, charging of the battery pack to the maximum allowable state of charge, and closing of the battery pack.

6.6.3.1 The battery pack must be charged for testing to the maximum allowable state of charge. This can be accomplished either before or after battery pack opening and other preparation activities occur. The testing agency should determine when charging should occur based on pack architecture, hazards associated with working with a fully charged vs discharged battery pack, and estimated pack self-discharge between the time of preparation and the time of testing. A drop of 1% of capacity due to self-discharge of the battery before the test is accomplished is acceptable.

6.6.3.2 It may be most convenient to charge the battery pack with an approved vehicle system as it is installed in a vehicle, and then remove the battery pack to further prepare it for SCTRI testing prior to re-installing it in a vehicle. However, in some instances, the testing agency may choose to charge the battery pack after other preparation activities occur.

6.6.3.3 Once charging has occurred, and also immediately prior to closing the battery pack, record the voltage of the battery pack, the highest-voltage series element and its location, and the lowest-voltage series element and its location.

6.6.3.4 The RESS shall be photographed in its as-received state. Any anomalies to the pack enclosure shall be noted.

6.6.3.5 If the battery pack must be opened to install any experimental equipment, it shall be photographed after opening and prior to the installation of any experimental equipment.

6.6.3.6 If the battery pack must be opened to install any experimental equipment, an internal electrical isolation measurement should be performed prior to the installation of any experimental equipment. It is most convenient to obtain an isolation measurement while the RESS is installed in a vehicle. This will require the cooperation of the vehicle manufacturer. If a vehicle based measurement is not possible, then battery terminals inside the contactors must be accessed, likely by removing the pack cover. Isolation should then be measured between the battery negative terminal and the battery enclosure using an isolation resistance meter. A testing agency may also choose to conduct a Dielectric Withstand Test using a

6.6.3.7 Hipot tester.

6.6.3.8 A location shall be selected for thermal runaway initiation. The location should be the most likely to result in thermal runaway propagation per the test agency’s engineering judgment or results of previous testing. For example, the initiation location may be at a cell that is completely surrounded by neighboring cells, or at a cell that is furthest from active cooling systems. The testing agency shall report the reasons for their selection of initiation location, which can include evidence of physical tests.

6.6.3.9 The single cell thermal runaway initiation device shall be installed at the location identified. Multiple thermal runaway initiation devices may be installed within a single battery pack to allow for more convenient test repetition should the first initiation device fail to operate. High-temperature insulation for any electrical leads to the initiating device should be used to avoid compromising the isolation of the battery pack from the enclosure/vehicle due to the presence of these experimental equipment. Similarly, high-temperature pass-throughs should be used to avoid compromising any battery pack seals due to the presence of experimental equipment.

6.6.3.10 Any electrical leads required to activate the thermal runaway initiation device should be sufficiently long to allow test personnel to activate and deactivate the device from a safe distance from the vehicle, assuming that thermal runaway propagation occurs during testing.

6.6.3.11 Instrumentation shall be installed to inform the extent or rate of thermal runaway propagation, and to determine if a test has been completed. At a minimum, one sensor should be installed in the battery near the initiation location to confirm the first cell thermal runaway and two additional sensors should be installed on adjacent cells to determine if propagation is occurring to adjacent cells. High-temperature insulation for any electrical leads to sensors should be used to avoid compromising the isolation of the battery pack from the enclosure/vehicle due to the presence of these experimental equipment. Similarly, high-temperature pass-throughs should be used to avoid compromising any battery pack seals due to the presence of experimental equipment. Any connectors to sensors should be sufficiently long to allow a data acquisition system to be located sufficiently far from a vehicle undergoing a complete burn to remain intact.

6.6.3.12 A connection that allows both positive and negative battery terminals to be electrically accessible from outside the pack for purposes of measuring pack voltage and internal electrical isolation may be installed. This connection should have adequate insulation to avoid affecting isolation measurements. If the vehicle can provide a measurement of pack voltage or SOC and internal isolation once an instrumented RESS is installed in the vehicle, an additional connection is not required.

6.6.3.13 All modifications to within the RESS shall be documented with photographs and appropriate notes: the location of the thermal runaway initiation hardware and all sensors shall be recorded.

6.6.3.14 The RESS shall be closed according to the manufacturer's specifications. Replacing a cover may require additional materials such as sealants or gaskets. The exterior of the RESS shall be photographed. Isolation measurements as per Section 6.6.3.6 may be made after pack closing to ensure that installed instrumentation and any necessary modifications have not significantly degraded the electrical isolation of the RESS. If application of instrumentation has significantly diminished battery pack isolation, the instrumentation setup should be reviewed, and the cause of the loss of isolation should be found and if possible, eliminated.

6.6.4 Vehicle Preparation Procedure

6.6.4.1 The vehicle shall be photographed in its as-received condition. Any anomalies should be noted.

6.6.4.2 The Vehicle RESS shall be removed from the vehicle and prepared for testing as in Section 6.6.3.

6.6.4.3 Vehicle components that represent an additional hazard during testing such as airbags, pneumatic cylinders, inflated tires, and tanks of flammable liquids may be removed from the vehicle or otherwise disabled if the testing agency can determine their presence or actuation is unlikely to significantly affect the outcome of the test. Components immediately adjacent to the RESS that could be affected by heat or gas emission from the RESS should remain in place on the vehicle. Removal of any components should be documented with notes and photographs.

6.6.4.4 A standard opacity-based smoke alarm shall be installed at the center of the vehicle dashboard. Additional gas sensors or gas sampling equipment may be installed in the vehicle cabin at the discretion of the testing agency. Location of all sensors shall be documented.

6.6.4.5 At least one temperature sensor shall be installed within the vehicle cabin. This sensor shall be at the approximate location of a driver's head. Additional temperature sensors may be installed, for example at locations within the cabin adjacent to the RESS. Location of all sensors shall be documented.

6.6.4.6 The vehicle cabin shall be physically isolated during testing: doors and windows shall be closed and sealed (with provision for experimental equipment leads to exit the vehicle cabin). The vehicle cabin heating, ventilation and air conditioning (HVAC) system shall not be operational.

6.6.4.7 The instrumented RESS shall be re-installed in the test vehicle.

6.6.4.8 Battery pack voltage or SOC shall be measured and recorded.

6.6.4.9 An internal electrical isolation measurement should be performed. Isolation should be measured between the battery negative terminal and the battery enclosure. Isolation values should be compared to "as-received" values. If application of instrumentation has significantly diminished battery pack isolation, the instrumentation setup should be reviewed, and the cause of the loss of isolation should be found and if possible, eliminated.

6.6.4.10 The vehicle as prepared for testing shall be photographed.

6.6.5 Vehicle Preconditioning Procedure

The vehicle and RESS as instrumented for testing can be brought to test temperatures by placing the vehicle with installed RESS into a temperature control chamber held at 25±2°C. The vehicle should be held in the chamber for sufficient time to equalize to test temperature, at least 12 hours. Thermal runaway initiation should begin within 30 minutes of removal of the vehicle from thermal conditioning. The RESS temperature at the beginning of thermal runaway initiation shall be 25±5°C as measured by sensors installed within the RESS (Section 6.6.3).

6.6.6 Vehicle SCTRI Test Procedure

6.6.6.1 The vehicle shall be placed in a location suitable for SCTRI testing (see Section 5.4).

6.6.6.2 A minimum of three video cameras shall be located around the vehicle to record emission of smoke from the vehicle, any sounds associated with cell thermal runaway, and activation of the vehicle interior smoke detector.

6.6.6.3 Cameras should be located at a sufficiently safe distance from the vehicle to allow test personnel to approach them and change recording media (tapes) if necessary during testing, assuming that thermal runaway propagation occurs.

6.6.6.4 Temperature measurement logging devices should be configured to collect at least one measurement per second.

6.6.6.5 Any connectors to sensors should be sufficiently long to allow a data acquisition system to be located sufficiently far from a vehicle undergoing a complete burn to remain intact. Data acquisition equipment may be protected from heat using shielding or insulation.

6.6.6.6 All sensors should be connected to data logging systems, and checked to ensure proper reading and configuration.

6.6.6.7 The initiation of temperature logging and video recording should be synchronized: for example all systems should be started within 30 seconds of each other. At least five stable temperature measurements should be recorded per temperature logging channel prior to proceeding with thermal runaway initiation.

6.6.6.8 The single cell thermal runaway initiating device shall be activated and the test monitored closely for any indication that thermal runaway has occurred (sound, smoke, temperature measurements). Once the occurrence of a single cell thermal runaway has been confirmed, the thermal runaway initiating device shall be de-energized.

The testing agency shall have determined an expected time to thermal runaway during module or coupon testing (Section 8.1). If there is no indication of single cell thermal runaway within twice the expected time, then the testing agency should proceed to energize an alternative thermal runaway initiating device, if one has been installed.

If thermal runaway initiation fails to occur and no alternative initiating devices have been installed (or have all failed to induce thermal runaway), the testing agency shall abort the test and determine the cause of the experimental failure. This may involve removing the RESS and opening it. Personnel working with the battery pack should be aware that a cell within the RESS may have been damaged and could be susceptible to thermal runaway during system examination. They should conduct the examination in an appropriate location using appropriate tools and PPE.

If thermal runaway initiation is not achieved, the testing agency must select an alternative method for initiation and repeat coupon or module level testing to verify its efficacy. Then full scale testing can be repeated.

6.6.6.9 A stopwatch or other timekeeping device shall be used to measure the time from initial cell thermal runaway to any secondary cell thermal runaway reactions, activation of the in-cabin smoke detector, and the appearance of flames. If flames appear, no effort will be made by test personnel to suppress flaming combustion.

6.6.6.10 Testing is complete when:

a. Either all temperature readings on cells within the RESS are below 60°C and have been decreasing for at least 30 minutes,
b. If, thermocouple readings are not available, then after a confirmed single cell thermal runaway initiation reaction has occurred, no visible follow-up reaction has occurred after 8 hours or,
c. If a fire has occurred, 30 minutes after the RESS and vehicle have been consumed. Suppression equipment may then be used to suppress lingering flames or cool hot spots.

6.6.6.11 The vehicle shall be photographed after the completion of testing.

6.6.6.12 If the SCTRI test did not cause propagation to adjacent cells, the tested vehicle and RESS can be used as a test article for testing the effects of pollution on RESS internal isolation (proposed standard is currently under development).

6.7 Measured Data

6.7.1 Full Scale Vehicle SCTRI test reports should include the following information:

a. Details of the initiation method, including justification of the criteria in Section 7.2
b. Location of the initiation method, including justification for the selected location.
c. Locations of all installed sensors.
d. Evidence that instrumentation has not significantly affected RESS internal isolation.
e. Voltage of the pack prior to test beginning
f. Video of the test from several angles, at least three.
g. Time that the first thermal runaway occurred.
h. Evidence that the first runaway occurred, visually, audibly, or thermally.
i. Times of any subsequent runaways, vehicle events, ignition, smoke alarm activation. Use t=0 as the time when the initiating device was activated.
j. Temperature data and gas sensor data if measured.
k. Photographs of the battery pack after testing has completed.

6.7.2 Single cell initiation method testing reports should contain the following information:

a. A voltage trace of the cell showing drop of voltage at the point of the thermal runaway reaction.
b. Two cell surface temperatures up to the point of the thermal runaway reaction.
c. Time required from the start of the test to achieve thermal runaway.
d. Video recording of the entire test.
e. Photograph of the cell after testing.
f. An estimate of the amount of energy supplied to the cell by the initiation method, and a comparison to total cell energy.
g. An analysis of the test initiation method with regards to suitability for use in full scale RESS testing.

6.7.3 Initiation method verification (coupon or module level) testing reports should contain the following information:

a. A description of the cell thermal runaway initiation method used.
b. Time required from the start of the test to achieve thermal runaway, and the method used to determine that thermal runaway had occurred.
c. Temperature data from which can be extracted the average neighbor cell change in temperature at the point that the initiating cell entered thermal runaway and the neighbor cell maximum temperature.
d. Video recording of the entire test.
e. Photograph of the cell after testing.
f. An estimate of the amount of energy supplied to the cell by the initiation method, and a comparison to total brick energy.
g. An analysis of the test initiation method with regards to suitability for use in full scale RESS testing.

6.8 Inspection Method

6.8.1 If the SCTRI test did not cause propagation to adjacent cells, the tested vehicle and RESS can be used as a test article for testing the effects of pollution on RESS internal isolation (proposed standard is currently under development).

6.8.2 After testing is complete the RESS should be separated from the vehicle.

6.8.3 The RESS should be opened and visually examined to confirm cell thermal runaway reactions and to determine how to best dispose of the battery pack.

6.9 Post-Test Requirements

6.9.1 After full vehicle SCTRI testing, the vehicle and RESS should be disposed of or recycled in accordance with environmental regulations.

6.9.2 Destructive discharge of portions of the RESS may be required to allow safe disposal. The testing agency should refer to manufacturer specified destructive discharge instructions.

6.10 Acceptance Criteria

The purpose of SCTRI testing is to assume that a single cell within a RESS will undergo a thermal runaway reaction due to an unspecified cause, and to then determine whether that reaction will pose a significant hazard to the vehicle's occupant or the surrounding environment. Acceptance criteria are thus divided into two categories: hazard to the occupant, and hazard to the surrounding environment

6.10.1 Cabin Tenability Requirements

The cabin must remain tenable for sufficient time to allow safe egress of vehicle occupants after they have perceived that a serious failure has occurred with the battery pack, or for 1 hour after initiation of a single cell thermal runaway that does not produce a condition that provides significant warning properties to occupants. See Section 7.10 for further discussion.

6.10.1.1 The cabin temperature must remain tenable, assuming vehicle windows are closed, and HVAC system is not operating.

6.10.1.2 The cabin air must remain free of significant inhalation hazards, assuming vehicle windows are closed and the vehicle HVAC system is not operating.

6.10.2 Hazards to the Surrounding Environment

The vehicle must not pose an ignition or mechanical hazard to the surrounding environment

6.10.2.1 The vehicle should not ignite as a result of SCTRI testing.

6.10.2.2 Vent gases emitted by the vehicle as a result of SCTRI testing should not ignite.

6.10.2.3 There should be no explosion as a result of SCTRI testing.

7. TEST PROCEDURE RATIONALE

7.1 Mechanisms of Thermal Runaway Reactions in Lithium Ion Cells and Subsequent Propagation

Thermal runaway refers to rapid self-heating of a battery cell derived from the exothermic chemical reaction of the highly oxidizing positive electrode and the highly reducing negative electrode. In a thermal runaway reaction, a cell rapidly releases its stored energy. A thermal runaway reaction will occur if the thermal stability limits of the cell chemistry are exceeded: if the rate of heat generation within the cell exceeds the rate of heat loss. This can occur within a small local area of the cell and then propagate through the bulk of the cell (typical of a cell internal short circuit failure), or it can occur throughout the bulk of the cell (typical of external heat exposure). For any cell chemistry or design, there will be a variety of mechanisms that can cause the cell to exceed its thermal stability limits. For Li-ion cell chemistries specifically, thermal runaway reactions can be caused by thermal abuse, mechanical abuse, electrical abuse, poor cell electrochemical design, and internal cell faults associated with cell manufacturing defects.

For the purposes of assessing safety of a practical RESS system for an automotive application, the causes of thermal runaway reactions can be grouped into two categories: causes of thermal runaway that are likely to induce thermal runaway in multiple cells almost simultaneously, and causes of thermal runaway reactions that are likely to directly induce thermal runaway in only a single cell.

Causes of simultaneous multiple cell thermal runaway reactions in RESS systems tend to be extreme events such as energetic collisions that can induce mechanical damage to multiple cells within a battery pack, bulk heat exposure such as from an adjacent fire, and severe overcharge of multiple cells caused by failure of pack protection electronics and/or charging systems. There are a number of vehicle and battery pack standards that address events that may be likely to cause multiple cell thermal runaway reactions such as vehicle crash tests described in the Federally Mandated Vehicle Safety Standards (FMVSS) and battery abuse tests described in standards developed by organizations such as the Society of Automotive Engineers (SAE), Underwriters Laboratories (UL), the United Nations (UN), US DOT, the Institute of Electrical and Electronics Engineering (IEEE), Japanese Industrial Standards (JIS), and the IEC.

Causes of single cell thermal runaway reactions in RESS systems can be much more subtle than those events causing simultaneous multiple cell thermal runaway. They can include development of cell internal short circuits due to highly localized heating, highly localized mechanical damage, or latent manufacturing defects that become active as a cell ages. From a typical consumer's perspective, these faults can seem to occur "without warning", or "spontaneously"; they can appear "unprovoked". Although not truly spontaneous (some latent fault is the cause of failure), single cell thermal runaway failures can occur as single point failures – no external abuse condition is required for one of these failures to occur. Thus, spontaneous or unprovoked single cell failures should be expected and mitigated in RESS designs.

Once a cell has experienced thermal runaway, it will be hot and will transfer heat to its surroundings, including adjacent cells through conductive, convective, and radiative heating modes. Depending upon a number of factors including cell chemistry, cell state of charge, cell geometry, and module or battery pack architecture, a single cell may be able to transfer sufficient heat to an adjacent cell to cause that neighbor to exceed its thermal stability limits and also undergo a thermal runaway reaction. In this way, cell thermal runaway reactions can propagate throughout an entire battery pack. Although thermal runaway of a single cell can pose an appreciable hazard on its own, the extent of the resulting hazard is strongly dependent upon the likelihood that the thermal runaway reaction propagates to adjacent cells, or compromises other battery or vehicle systems to create a hazard.

A number of lithium-ion battery standards and industry best practices address and limit single cell susceptibility to a wide range of thermal runaway causes. However, these standards and best practices have not been able to eliminate all plausible causes of "spontaneous" single cell thermal runaway reactions, which are rare, varied, and difficult to detect. Looking forward, as cell designs and chemistries continue to evolve, it is likely that new cell designs will be susceptible to different mechanisms of thermal runaway initiation, and it will take some time for standards and industry best practices to mitigate the new mechanisms of failure. Thus, the purpose of Single Cell Thermal Runaway Initiation (SCTRI) testing is not to determine the likelihood that a single cell will undergo a thermal runaway reaction due to any particular cause or load case. The purpose of SCTRI testing is to assume that a single cell within a RESS will undergo a thermal runaway reaction due to an unspecified cause, and to then determine whether that reaction will pose a significant hazard to the vehicle's occupant or the surrounding environment.

The only standards at the time of this writing to address hazards associated with single cell thermal runaway within a RESS are propagation resistance tests found in SAE J2464 "Electric and Hybrid Vehicle Propulsion Battery System Safety Standard - Lithium-based rechargeable cells", UL 2580 "Standard for Batteries for Use in Electric Vehicles" which references SAE J2464, and UL 1973 "Batteries for Use in Light Electric Rail (LER)".

SAE J2464 states:

> *4.4.5 Passive Propagation Resistance Test (Module or Pack Level)*
>
> *This test evaluates the ability of a DUT to withstand a single cell thermal runaway event so that a thermal runaway event does not propagate to adjacent cells. It is recommended that the DUT manufacturer first perform these tests at the module level.*

> *4.4.5.1 Test Description*
>
> *The DUT is charged to 100% SOC. All external circuits, cooling systems, or other devices are turned off or disconnected. If liquid cooling is used, the liquid may remain in the DUT without circulation. The DUT is heated until the cells stabilize at 55°C or the maximum operating temperature, whichever is greater. One cell within the DUT at a locations described below is uniformly heated in-situ to a temperature of 400°C (or until the cell enters thermal runaway) in less than 5 min (for example, using resistive heating or thermal conductive heat transfer using an external heat source). The method used to create a thermal runaway in one cell will be described and documented in the report. After one of the above conditions is met, the heater is turned off and DUT is observed for 1 h. Other methods to initiate thermal runaway in one cell are allowed. This above procedure shall be repeated with cells in different locations that represent various thermal environments/relationships within the pack. The following heated cell locations are suggested for a DUT resembling a rectangular prism (See Figure 4 Below):*
>
> *1) The geometric corner of the Module or Pack.*
>
> *2) At the midpoint of an edge.*
>
> *3) At the center of one face.*
>
> *4) The interior of the Module or Pack 1/4 the distance from the center of a face (B) to the opposite face.*
>
> *5) The interior of the Module or Pack 1/4 the distance from the center of a face (C) to the opposite face.*

SAE 2464 does not provide specific methods for assessing the effect of either a single cell thermal runaway reaction or a propagating reaction on the vehicle occupant or surrounding environment. The intent of the test method is to determine if thermal runaway propagation will occur. This standard does not explore the interaction of the RESS with the vehicle.

UL 1973 states:

> *37.1 The electric energy storage system shall be designed to prevent a single cell failure within the system from cascading into a fire and explosion of the DUT. This test is applicable to lithium ion technologies.*
>
> *37.2 The fully charged electric energy storage system (MOSOC per 6.1) is to be subjected to the internal fire test which consists of heating one internal cell that is centrally located within the DUT until thermal runaway or otherwise forcing the failure of a cell through any means necessary and determining whether or not that failure remains safely controlled within the DUT. Once the thermal runaway is initiated, the mechanism used to create thermal runaway is shut off or stopped and the DUT is subjected to a 1-h observation period.*

> *Exception No. 1: Testing on a cell that is other than centrally located within the DUT may additionally be conducted if it is not clear which is the worst case scenario. The location of the failed cell is to be documented for each test.*

The UL standard considers the effects of a thermal runaway reactions on vehicle or surroundings, but only considers the hazards of fire or explosion. The UL standard does not consider the hazards associated with vent gas toxicity.

The Single Cell Thermal Runaway Initiation (SCTRI) test procedure goes beyond SAE J2464 and UL 1973, by providing a framework for evaluating and verifying possible thermal runaway initiation methods, by providing a more detailed full scale test methodology with examples depicting how tests can be conducted, and by providing a method for evaluating the interaction of a RESS with a vehicle in terms of cabin tenability as well as hazards to surroundings.

7.2 Evaluation of Single Cell Initiation Methods for Li-Ion cells.

Single cell thermal runaway initiation methods for application to Passive Propagation Resistance (SCTRI) testing should be designed to mimic expected cell spontaneous field failures. For Li-ion cells, an initiation method should mimic a cell internal short circuit (one of the most common causes of lithium ion cell thermal runaway reactions in the field). A number of organizations have proposed methods for mimicking Li-ion internal short circuit failure modes, however, not all of the proposed methods can be readily adapted for testing within a full battery pack, and not all methods are effective for all types of cell geometries. It is important to note that if a cell does not undergo a thermal runaway reaction with a particular method of initiation this is not evidence that the cell cannot undergo thermal runaway, or that the cell does not pose a spontaneous thermal runaway risk.

For purposes of SCTRI testing, the performance of an initiation method should be evaluated on the basis of the following factors:

- Initiating device effect on neighboring cells: for example, does the initiating device cause direct heating of or damage to neighboring cells. If an initiating device causes pre-heating of neighboring cells, this might be observed in an extended time to thermal runaway of the initiating cell (low “efficiency” of the initiating method).

- Comparison of the energy added to the system by the initiating method to the total energy in the cell, brick, or RESS. If an initiating method is adding significant energy to the system, rather than to the initiating cell, the low “efficiency” of the method may be observed as an extended time to thermal runaway of the initiating cell. Note that addition of energy to the system is not un-representative of spontaneous cell field failures. In many instances, field failures occur during charging of a cell, at which time a charging system may add substantial energy to the system. In addition, with many pack architectures, cells connected in parallel to a faulting cell can provide substantial energy to heat the faulting cell to thermal runaway (Figure 23).

- Effect on SOC of the initiator cell: for example, does the initiator method cause cell overcharge, and thus elevate the cell SOC beyond what would be expected in the field, and produce an uncharacteristically energetic thermal runaway reaction.

- Effect of the initiation method on gas flow path(s) from the initiator cell: for example, nail penetration can create a gas flow path in an area unrelated to the cell normal venting path. This could positively or negatively affect the test outcome.

- Effect of the initiation method on mechanical boundary conditions; for example, can the initiating device be mounted within a RESS without significantly compromising the RESS enclosure.

- Effect of the initiation method on thermal boundary conditions such as the air spaces between adjacent cell or objects, heat conduction to other cells or structures in the battery module/pack, the conductivity of the materials, and the radiation heat flow paths.

- Effect of the initiation method on electrical boundary conditions such as the number of cells that are connected in parallel, the energy of these cells, and whether or not they can continue to resistively heat the initiating cell after thermal runaway has occurred.

- Whether the initiation method requires that cells be modified or that non-production cells be used.

- Applicability of the method to module and pack configurations; and

- Reliability of the method to initiate thermal runaway.

Each initiation method will have its own strengths and weaknesses with regard to the listed factors, and with regard to each specific cell chemistry and cell, module, and pack form factor. For example, mechanically induced short circuiting by nail penetration or crush typically results in minimal additional energy added to the system. It can also provide a fast time to thermal runaway. However, mechanical initiation mechanisms often introduce non-representative gas exhaust paths. They can also be experimentally difficult to implement in a full RESS enclosure that will be mounted on a vehicle, without compromising the RESS enclosure itself.

The testing agency must make a judgment regarding the relative importance of various factors to overall test intent. The testing agency may find it useful to try a few different possible initiation methods and comparing results before settling on a final test method. Section 8.1 describes evaluation of a few, experimentally convenient and low cost initiation methods for Li-ion cells of different styles. An initiation method may be used that is not mentioned in Section 8.1 as long as it can be demonstrated to be appropriate given the factors and considerations mentioned previously.

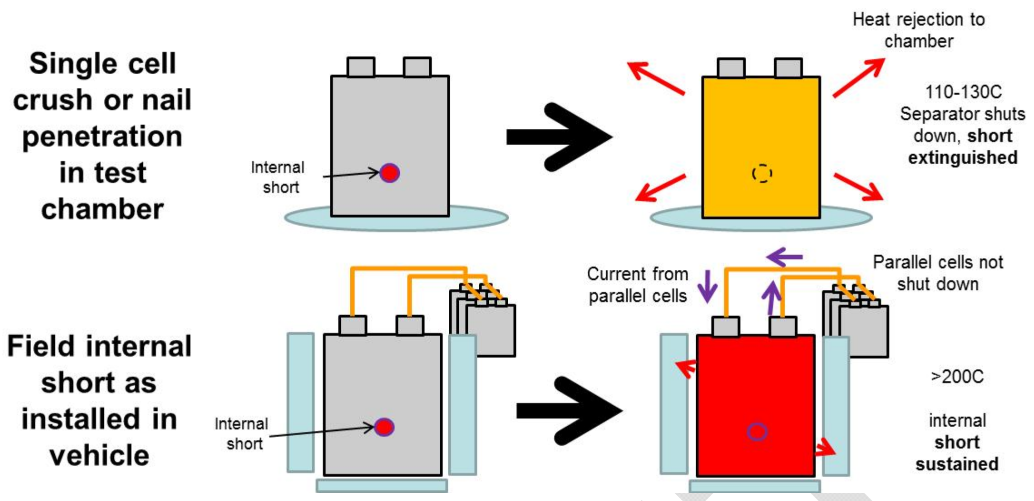

Figure 23 - An example of a cell thermal runaway initiation method that may not cause thermal runaway of a single unconnected cell, but may cause thermal runaway when that cell is connected in parallel to other cells.

7.3 Examples of Thermal Runaway Initiation Methods that can be applied to Li-ion cells

7.3.1 Thermal Initiation Methods. The most direct way to exceed the thermal stability limit of a lithium-ion cell is to subject it to external heating. Perhaps the most common, and experimentally convenient method for initiating single cell thermal runaway in a li-ion battery pack is to apply an externally powered heater to an individual cell (conductive heating). Other thermal initiation methods include: laser heating, radiant heating, applying external chemical heat sources to cells (thermite). Internal heating methods have also been explored: micro-heaters can be inserted directly into electrodes. With all of these methods, the testing agency needs to remain particularly aware of the potential for heating adjacent cells, not just the initiating cell during activation.

7.3.2 Mechanical Initiation Methods. Mechanical methods for simulating Li-ion cell internal faults have been used and researched extensively. These include nail penetration tests, blunt object crush tests, and pinch tests. For example, Underwriters Laboratories has proposed a blunt nail crush test. Oak Ridge National Laboratory (ORNL) has investigated pinch testing.

Mechanical methods of initiation typically result in minimal additional energy added to the system. They can also provide a fast time to thermal runaway. However, mechanical initiation mechanisms can introduce non-representative gas exhaust paths, they can alter the shape of the cell boundary which can affect heat transfer to neighboring cells, and they can alter thermal boundary conditions. They can also be experimentally difficult to implement in a full RESS enclosure that will be mounted on a vehicle, without compromising the RESS enclosure itself.

7.3.3 Electrical Initiation Methods. In the past, cell overcharge was considered a convenient method for inducing a single cell thermal runaway reaction. However, this method has become increasingly difficult to apply: many cylindrical cells incorporate effective charge interrupt devices (CIDs) that prevent cell overcharge and polymer cells tend to swell until electrodes are sufficiently separated to prevent further charging. Cell overcharge can also produce an uncharacteristically energetic reaction in the initiating cell that can damage surrounding cells in a non-representative manner. Other electrical initiation methods have been used to initiate thermal runaway in cells. For example Patent US8421469 B2 describes a “Method and apparatus for electrically cycling a battery cell to simulate an internal short.” These methods tend to be highly cell design dependent and can take considerable effort to develop.

7.3.4 Introduction of Electrode Defects. A number of researchers have developed methods to introduce defects into a cell electrode and then activate the defects to induce cell thermal runaway. For example, The National Renewable Energy Laboratory (NREL) has run tests where they have inserted a wax device in between the electrode layers of a pouch cell. This wax device will melt away once heated and start an internal short circuit. These methods generally require implementation of specially built cells, and thus the cooperation of the cell manufacturer. In addition, transport of cells specifically modified to allow triggering of thermal runaway reactions poses challenges with regard to transportation safety. Finally, these cells need to be safely charged and installed in a fully charged battery pack, which can be difficult with some pack architectures.

7.4 Vehicles and RESS Test Temperature

7.4.1 A RESS temperature of 25 °C at the start of thermal runaway initiation has been selected for SCTRI testing for two reasons

7.4.1.1 25 °C describes most likely conditions for a RESS in a vehicle not in use or with low charge or discharge rates. Many vehicle charge rates are low produce minimal heating during extended charge periods, for example, more than three hours.

7.4.1.2 25 °C is experimentally convenient. Testing is most likely to be conducted in an out-door environment with variable ambient temperatures. After exiting a conditioning chamber, a vehicle must be sited and data logging equipment connected. During that setup time, vehicle temperature is likely to drift toward the ambient temperature. 25 °C is a moderate temperature, and ambient is likely to be relatively close to 25 °C compared to 55 °C as specified for module level tests in SAE J2464.

7.4.2 Depending upon the heat transfer properties of various materials and ambient temperatures, vehicle temperatures may quickly become non-uniform. The RESS is likely to have a sealed enclosure and significant mass, such that it is likely to maintain a target temperature during test setup. Thus the temperature of the RESS and not the vehicle is specified for start of testing.

7.5 Electrical Preconditioning of Cells, Modules, and RESS

The test procedure specifies that cells, modules, and RESS used for testing be as new and uncycled as practical: being less than one year old and having accumulated less than five charge discharge cycles. Typically, cell capacity decreases with calendar aging and cell cycling; therefore a new test article should contain the maximum stored energy. Although cell aging may increase the likelihood of a spontaneous thermal runaway reaction, the likelihood of a spontaneous runaway reaction is not being studied and there is no evidence that properly cycled cells will have reduced SCTRI performance.

7.6 100% SOC Requirement

SCTRI testing is to be conducted on fully energized RESS (all cells at 100% SOC). This condition was selected because most spontaneous thermal runaway field failures occur when cells are fully charged. An internal short circuit in a lithium-ion cell is most likely to develop at a fully charged condition, and is most likely to heat a fully charged cell to thermal runaway. Furthermore lithium-ion cell field failure experience indicates that most thermal runaway failures occur when cells are fully charged. Neighbor cells are most susceptible to thermal runaway propagation when in a fully charged (100% SOC) condition.

7.7 Thermocouple Instrumentation

The test procedure requires only limited temperature measurements during testing: specifically to confirm that thermal runaway of the initiating cell has occurred and to monitor air cabin temperatures. Based on testing examples described in Section 8 it is evident that although temperature measurements are useful for understanding thermal propagation from a research perspective, these measurements are not necessary to determine whether a single cell thermal runaway reaction will result in a hazard to vehicle occupants or the surrounding environment. Nonetheless, the testing agency may wish to collect a far greater number of temperature measurements than the minimum required. Examples in Section 8 can provide guidance regarding the utility of measurements taken at various locations within a RESS and the vehicle.

7.8 Gas Sampling

The test procedure suggests conducting in-cabin gas sampling, but does not require this. Based on testing examples described in Section 8 it is evident that for lithium-ion cell thermal runaway testing, a smoke alarm mounted within the vehicle cabin will provide a good indication of whether vent gases are entering the cabin, and whether the cabin remains tenable. However, a gas sampling device can provide more detailed information, and thus a testing agency may choose to implement this type of sensor. Should a cell chemistry produce hazardous vent gases that may not cause activation of a smoke alarm, the testing agency should use a gas sampling device or alternative detector to monitor the cabin air.

7.9 Post-Test Observation

An extended observation time has not been included in the SCTRI test procedure.

Should a RESS maintain significant voltage relative to its pre-SCTRI condition, then the battery pack will have become polluted with cell vent gases, and may be used as a test article to assess the effect of pollution induced loss of internal isolation. A standard method for conducting this assessment is being developed. That method will be most effective if applied immediately after SCTRI testing.

Should thermal runaway propagation occur during testing and the RESS is completely consumed, an extended observation time is not useful.

If propagation occurs, but the RESS is not completely consumed, the RESS will likely have become substantially damaged and should be discharged prior to storage. The extent and degree of damage could be variable depending upon the location of thermal runaway initiation, and thus subjecting a single test article to extended observation is unlikely to provide more insight than visual inspection of the damaged battery pack.

7.10 Cabin Tenability Requirements

Cabin tenability will potentially depend upon exposure to smoke and other components of thermal runaway vent gases as well as cabin temperature. If appreciable quantities vent gases enter the vehicle cabin during SCTRI testing, or if the cabin becomes appreciably heated, then a careful assessment of the probable effect of the combination of these factors on cabin occupants should be conducted to determine tenability. One factor of importance is whether occupants will have received sufficient warning from visual, audible, or function cues to understand that an unsafe condition is imminent, and have sufficient time to exit the vehicle safely before tenability is threatened. Safe evacuation time should include time required to safety stop the vehicle (including time to find a safe stopping location) and assist passengers that may have limited mobility from the vehicle.

Discussion of the effect of combustion products and various hazardous gases, as well as high temperature exposure influences tenability can be found in references such as the SFPE Fire Protection Handbook. Fire protection literature can also provide guidance regarding egress times.

8. APPENDIX

8.1 Li-ion Single Cell Thermal Runaway Initiation Methods

8.1.1 Introduction

A variety of lithium-ion cell thermal runaway initiation methods were applied to lithium-ion cells of different form factors to demonstrate the initiation method selection process. Initiation methods were selected that have been known to cause thermal runaway in a reasonable amount of time, that require little to no special modification of cells, that can be conveniently applied to battery module and pack tests, that do not significantly affect the thermal, mechanical, or electrical boundary conditions of a RESS, and that require very limited capital investment or experimental development.

The tested methods were:

a. Conductive heating: cells wrapped in Nichrome wire.
b. Mechanical damage: nail penetration.
c. Conductive heating: hand-made film heater.
d. Conductive heating: off-the-shelf film heater.
e. Conductive heating: multiple off-the shelf film heaters.
f. Conductive heating: thick film resistor.

The methods were tested at a single cell level, and then, based on performance, were down-selected for coupon or module level verification testing. A final selection was made for application to full-scale vehicle testing.

The cells used for this demonstration were cells used in mass produced EVs. They were either supplied by the EV manufacturer, or harvested from production RESS: separated from their respective modules and not electrically connected to any other cells. The tested cells represent the 3 most common form factors found in electric vehicles: cylindrical cells, prismatic cells, and pouch cells.

a. Cell A: Small Cylindrical Cell. The cylindrical cells had an 18mm diameter and a 65mm height. This cell had a rated capacity of 3 Ah and a mass of 47g. This cell is shown in Figure 24.
b. Cell B: Large Hard Case Prismatic Cell. The prismatic cells were 171mm tall, not including the terminal screws, 101mm wide and 43mm deep. These cells had a rated capacity of 50 Ah and a mass of 1720g. This cell is shown in Figure 25.
c. Cell C: Large Pouch Cell. The pouch cells were 290mm long and 216mm wide. These cells had a rated capacity of 32.5 Ah and a mass of 787g. This cell is shown in Figure 26.

Figure 24 - Cell A, small cylindrical cell.

Figure 25 - Cell B, large hard case prismatic cell.

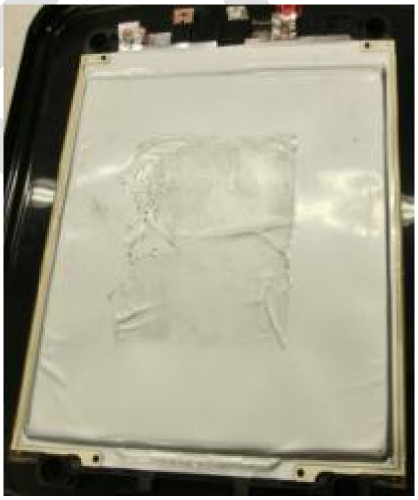

Figure 26 - Cell C, large pouch cell.

8.1.2 Test Equipment

a. Personal Protective Equipment: respirators, safety glasses, and chemical resistant gloves.
b. Vent hood.
c. Voltage measurement and data logging system: National Instruments NI 9205 ±10V data acquisition module with an accuracy of ± 6.22 mV.
d. Temperature measurement and data logging system: National Instruments NI 9213.
e. Data Translation system: MEASUREPoint DT8874.
f. Type-K Thermocouples.
g. Stop Watch with and accuracy of ±1 second.
h. Various thermal runaway initiation devices (heaters, nail penetration equipment).

8.1.3 Test Parameters

All of the tests were conducted at the following conditions.

Table 8 - Test Parameters

Test Temperature	Temperature of 20 ± 10°C
Cell State of Charge (SOC)	95% - 100%

8.1.4 General Test Methods

The following measurements were made for each test:

a. A voltage trace of the cell showing drop of voltage at the point of the thermal runaway reaction.
b. Two cell surface temperatures up to the point of the thermal runaway reaction.
c. Time required from the start of the test to achieve thermal runaway.
d. Video recording of the entire test.
e. Photograph of the cell after testing.

For each test:

a. The initiating device was installed on a cell.
b. Two thermocouples were installed on the cell.
c. Voltage measurement leads were installed on the cell.
d. The test setup was photographed.
e. The initiating device was activated, data acquisition was started, a timer was started, and a video recording was started.
f. The time when the cell visually and audibly entered thermal runaway was recorded.
g. The test was ended after thermal runaway was complete.

The time to runaway was determined by examination of temperature data and comparison with data recorded using a stopwatch. Time to runaway was defined as the time elapsed from activation of the initiating device to the point at which a significant change in slope of the measured cell temperature occurred.

For small cells, the average of the two cell temperature measurements at the moment of initiation was reported as the average cell initiation temperature. For large cells, where a significant temperature difference was observed between the two thermocouples due to large thermal gradients within the cell, the higher of the two measurements was reported as the highest temperature at initiation. The highest temperature was reported because as discussed in Section 7.1, thermal runaway can begin in a portion of a cell, and thus the cell highest temperature is most relevant. The highest temperature reached a cell at the time of initiation of cell thermal runaway is an indication of the thermal stability limit of that cell, and can be used in subsequent testing to judge whether neighbor cells have been heated excessively by an initiation method.

In many cases thermocouples became detached from cells after thermal runaway events began.[11] Examination of video recordings was used to confirm that the cells underwent thermal runaway.

The energy input that is required to initiate thermal runaway was compared to the electrical energy contained in the cell. It was also compared to the electrical energy of the parallel group of cells (as implemented in the RESS), since a short circuit in one cell can source current from any cell in parallel.

8.1.5 Cylindrical Cell Initiation Method Testing

Four thermal runaway initiation test methods were tried on small cylindrical cells: Cell A.

8.1.5.1 Conductive Heating: Cell Wrapped With Nichrome Wire. This method was selected because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and low input energy to the system. It requires no changes to the electrical systems of the cell or battery and does not affect the designed gas flow or mechanical features of the cell. This method can be applied to production cells, although perhaps not easily in an already-constructed and tightly packaged module configuration. Depending upon battery pack architecture, this method may affect some of the heat transfer characteristics of the cells and modules by altering the gaps between cells. An example of a cell wrapped in Nichrome wire is shown in Figure 27.

For this trial, 30 gauge Nichrome wire was wrapped approximately 10 times around a cell for use as a resistance heater. The wire was held against the cell using polyimide tape. The tape was also used a barrier to prevent short circuits between the wraps of wire. The resistance of the wire was measured in order to choose the voltage needed to produce 50 Watts of heating.

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[11] It is possible to apply thermocouples in a manner to obtain thermal runaway temperatures. However this generally requires more extensive setup time, and is generally unnecessary to demonstrate successful initiation thermal runaway and to determine time to initiation of thermal runaway.

Figure 27 - Cylindrical cell with Nichrome wire wrap.

8.1.5.2 Mechanical Damage: Nail Penetration. This method was selected for trial because it was not expected to add significant thermal energy to the cell. This method can provide a very short time to thermal runaway, with minimal effect on the state of charge of the initiating cell and temperatures of the neighboring cells. It requires no changes to the electrical systems of the cell or battery. It requires no special modifications to the cell and can be implemented with production cells. If the nail is used to penetrate the top cap of a cylindrical cell, where there is already a designed vent, it should have minimal impact on the gas flow from the cell during a thermal runaway reaction. Axial penetration was selected over the more common radial penetration direction because a radial penetration would alter the natural gas flow patterns of a thermal runaway event, and because radial penetration is difficult to accomplish within the RESS that will ultimately be tested. Note that nail penetration initiation methods have been found to be unreliable: the nail must cause short circuiting between active material layers in the electrode. If a short circuit develops between current collectors, the cell may not self-heat sufficiently to undergo a thermal runaway reaction.

For this trial, a 1” long steel nail with a 1/8” diameter, shown in Figure 28, was attached to an electric ram and was used to penetrate the cell. The cell was oriented vertically and penetrated axially through the center. The ram continued to press the nail into the cell until the entire nail was inserted into the cell. The nail was not removed until thermal runaway ended. Figure 29 shows a schematic diagram of the test setup.

Figure 28 - Nail used in penetration test.

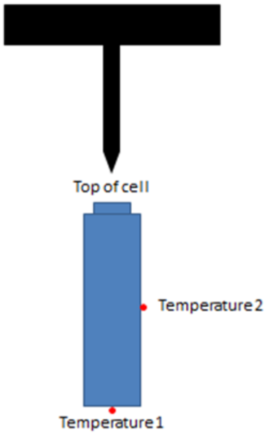

Figure 29 - Schematic diagram of nail penetration method.

8.1.5.3 Conductive Heating: Hand-Made Film Heater. This method was selected for trial because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and low input energy to the system. It is a smaller power heater than the Nichrome wrapped wire heater, but it provides a more localized heating zone and can be easier to install in a module. The hand-made film heater requires no changes to the electrical systems of the cell or battery and does not affect the designed gas flow or mechanical features of the cell: the heater is attached to the side of the cell can and will not inhibit the designed gas flow features of the cell. This method can be applied to production cells. The small-gauge wire allows the film heater to be used in many battery modules and packs without special modifications. Depending upon battery pack architecture, this method may affect some of the heat transfer characteristics of the cells and modules by altering the gaps between cells. However, because this heater is applied to a smaller area of the cell, it should provide less disruption than a Nichrome wrapped wire device, and can be oriented to minimize the disruption. An example of a hand-made film heater is shown in Figure 30.

For this trial, a film heater was made using 30 gauge Nichrome wire. The wire was wrapped in a back and forth pattern around 8 pins to form a ½” x 2” rectangular pad. The wire wraps were held together using a polyimide tape. The film heater was placed against one side of the cell and attached to it using polyimide tape. The heater was oriented such that the long side of heater was parallel to the axial direction of the cell. The cell side wall temperature measurement was made 180 degrees opposite of the heater. A diagram of this setup is shown in Figure 31 along with the location of the temperature measurements. A constant current of 1.8 A was run through the heater, resulting in approximately 30W of heating applied to the cell. The current was not increased past 1.8 A to prevent melting the Nichrome wire.

Figure 30 - Hand-made film heater.

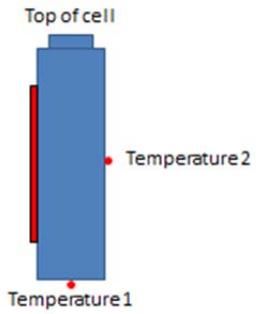

Figure 31 - Schematic of hand-made film heater.

8.1.5.4 Conductive Heating: Off-the-Shelf Film Heater. This method was selected for trial because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and low input energy to the system. It is a smaller power heater than the Nichrome wrapped wire heater, but, it provides a more localized heating zone and can be easier to install in a module. This heater provides a similar heating profile as the hand-made film heater but it is a more convenient and consistent option. The off-the shelf film heater requires no changes to the electrical systems of the cell or battery and does not affect the designed gas flow or mechanical features of the cell: the heater is attached to the side of the cell can and will not inhibit the designed gas flow features of the cell. This method can be applied to production cells. The thin nature of the heater will allow it to be used in many battery modules and packs without special modifications. Depending upon battery pack architecture, this method may affect some of the heat transfer characteristics of the cells and modules by altering the gaps between cells. However, because this heater is applied to a smaller area of the cell and is very thin, it should provide less disruption than a Nichrome wrapped wire device or a hand-made film heater, and can be oriented to minimize the disruption. An example of an off-the-shelf film heater is shown in Figure 32

For this trial, an off-the-shelf film heater was purchased from McMaster-Carr, part number 35475K283. This heater has a ½" x 2" rectangular pad and is rated to 10W/sq. in. The heater has an adhesive backing which is used to attach it to the cell. The cell side wall temperature measurements for this method are taken 180 degrees opposite of the heater. The setup of for this method is the same as for the hand-made film heater shown in Figure 31. The heater has a measured resistance of 76 ohms, thus applying 0.65 Amps will produce approximately 32W of heating. Applying a higher current will caused the heater to become open circuit from overheating.

Figure 32 - Off-the-shelf film heater.

8.1.6 Cylindrical Cell Initiation Method Results

A summary of the results for the different initiation methods attempted on the small cylindrical cells (Cell A) is shown in Table 9.

The Nichrome wrap heater method successfully initiated all the cells in three trials. The temperature and voltage traces for the Nichrome Wrap Heater trials are shown in Figure 33 through Figure 35. During the third Nichrome wire trial a more extensive setup was used to affix temperature measurement leads to better capture cell temperatures during thermal runaway reactions. However, these measurements are difficult to make accurately and are unnecessary for the purpose of this testing. From the images captured from the test videos (for example Figure 36) it is clear that the cell underwent thermal runaway. In Figure 37, a screen capture from the video recording immediately after the runaway event, the cell steel cell casing can be seen glowing bright orange. From the color of the glowing cell can wall, we can estimate that the cell wall temperatures reached at least 900° C Figure 38 shows the cells after testing. The wrapped heater method demonstrated the shortest time to thermal runaway among the heater based methods. It required no special modifications to the battery cell and showed no signs of obstructing the designed venting features. However, this method may be difficult to apply to a pre-built battery module, and the large heater area around the circumference of the cell may add significant pre-heating to the neighboring cells. This method was further investigated in verification testing (Section 8.2).

The nail penetration test only successfully initiated one of the two samples in the trial. However it produced thermal runaway almost instantly. The temperature and voltage traces for the nail penetration trials are shown below in Figure 39 and Figure 40. The second penetration trial failed to produce a thermal runaway event. In the successful trial, thermal runaway began almost immediately after the nail penetration. The cell casing color reached orange (Figure 41), indicating that a casing temperature of at least 900°C was achieved. The cells from the successful and failed nail penetration trials are shown in Figure 42 and Figure 43, respectively. After the nail from the second trial was fully inserted into the cell and it failed to go into runaway, the ram was used to try to crush the cell in an attempt to induce thermal runaway. Even with this additional deformation, the cell failed to go into runaway. This method required no additional preparation of the cell prior to the test. Due to limited reliability of this method, nail penetration was eliminated from further testing with the small cylindrical cells.

Both the hand-made and off-the-shelf thin film heaters successfully initiated all the cells in a total of five trials with similar results. The temperature and voltage traces for the hand-made film heater trials are shown in Figure 44 through Figure 46 . All trials successfully caused the cells undergo thermal runaway. One of the cells from the hand-made film heater trials is shown undergoing thermal runaway in Figure 47. Figure 48 shows the cell after testing. The temperature and voltage traces for the off-the-shelf heater trials are shown in Figure 49 and Figure 50. Both trials successfully caused the cells to undergo thermal runaway. One of the cells from the off-the shelf film heater trial is shown undergoing thermal runaway in Figure 51Figure 47. Figure 52 shows the cell after testing. These methods required a slightly longer time to achieve thermal runaway than the wrapped cell method, which can be attributed to their lower heating power. They can be easily applied to production cells and their smaller size makes them easier to attach to a cell in a battery module or pack. They did not obstruct the design venting features and their smaller, more localized heating is less likely to pre-heat the neighboring cells or influence thermal boundary conditions. These methods were further investigated in verification testing (Section 8.2).

Table 9 - Summary of single cylindrical cell initiation method results

Initiation Method	Time to Runaway [Min:Sec]	Avg Temperature at Initiation [°C]	Energy Input / Energy of Cell	Energy Input / Energy of Cells in Parallel
Nichrome #1	3:16	151	0.22	0.003
Nichrome #2	4:02	140	0.27	0.004
Nichrome #3	3:20	126	0.22	0.003
Nail Penetration #1	0:02	22	0	0
Nail Penetration #2	No Runaway	n/a	n/a	n/a
Hand-made Film Heater #1	5:50	159	0.23	0.003
Hand-made Film Heater #2	8:58	158	0.36	0.005
Hand-made Film Heater #3	5:49	167	0.23	0.003
Off the Shelf Film Heater #1	6:06	162	0.24	0.003
Off the Shelf Film Heater #2	7:34	166	0.30	0.004

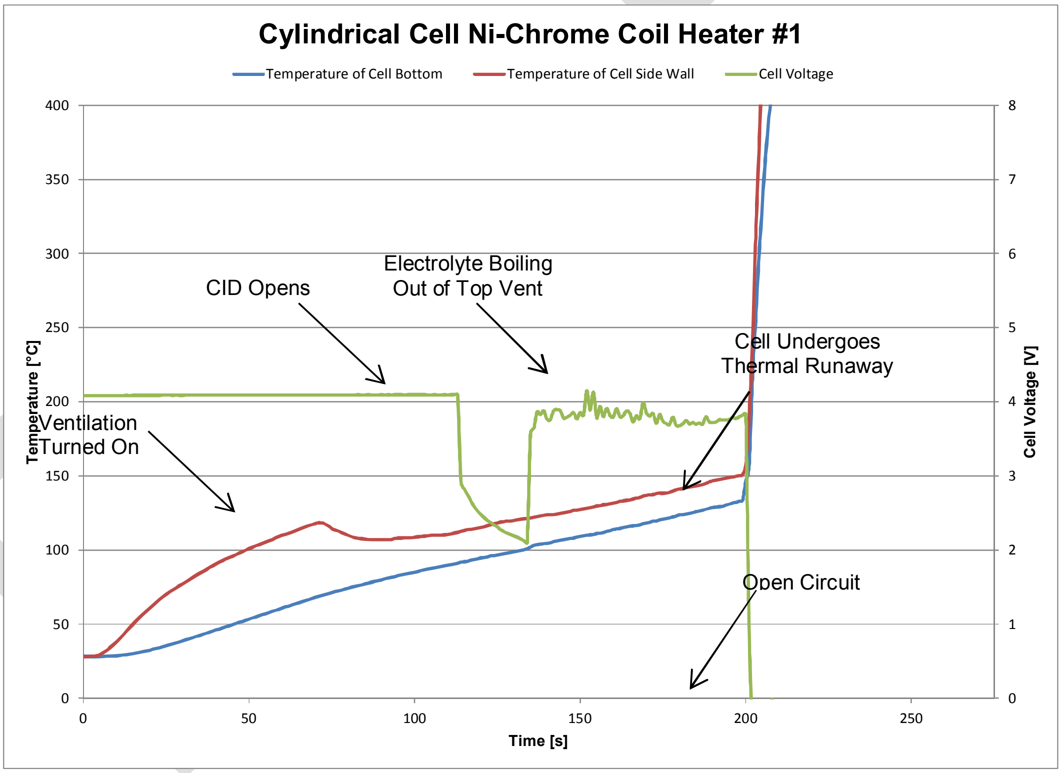

Figure 33 - Temperature and voltage traces for Nichrome Wrap Heater Trial 1.

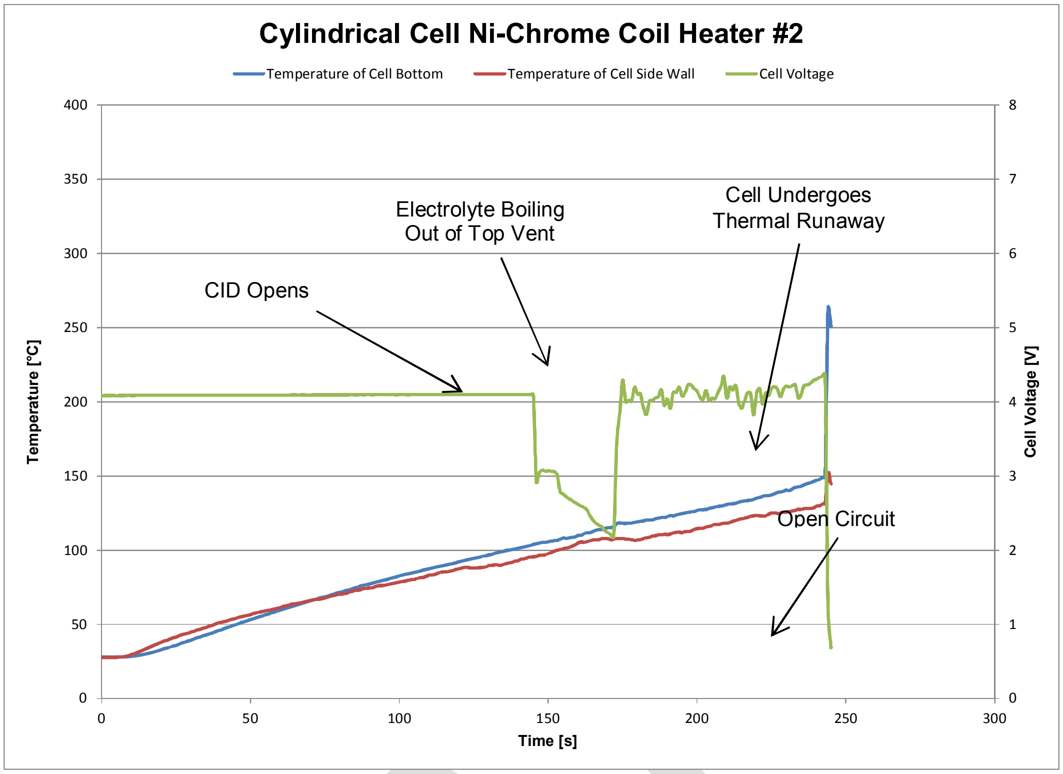

Figure 34 - Temperature and voltage traces for Nichrome Wrap Heater Trial 2.

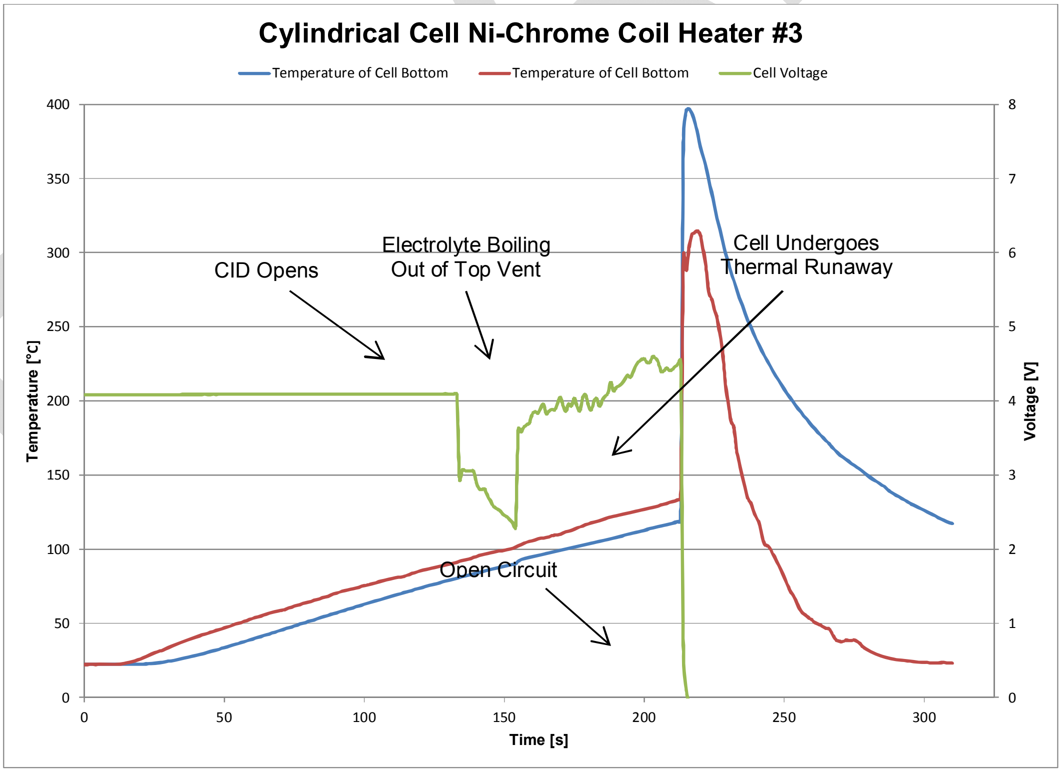

Figure 35 - Temperature and voltage traces for Nichrome Wrap Heater Trial 3.

Figure 36 - Cylindrical cell undergoing thermal runaway; Nichrome Wrap Heater method.

Figure 37 - Cylindrical Nichrome Wrap Heater cell immediately after runaway.

Figure 38 - Cells after Nichrome Wrap Heater trials.

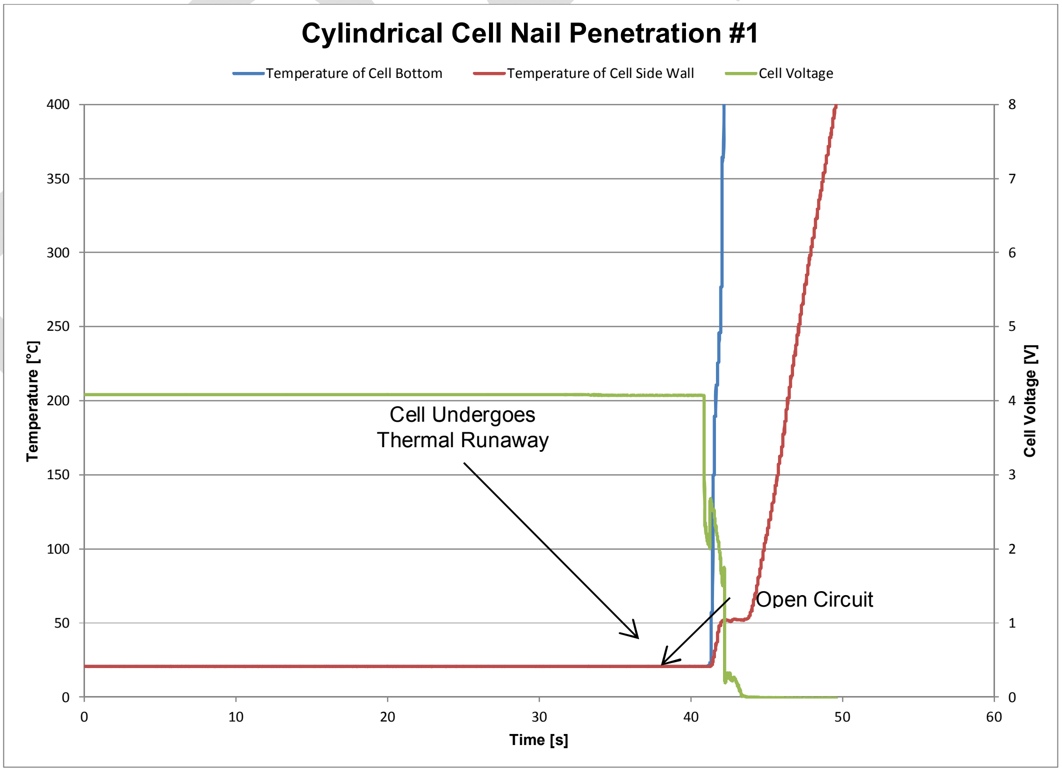

Figure 39 - Temperature and voltage traces for Nail Penetration Trial 1.

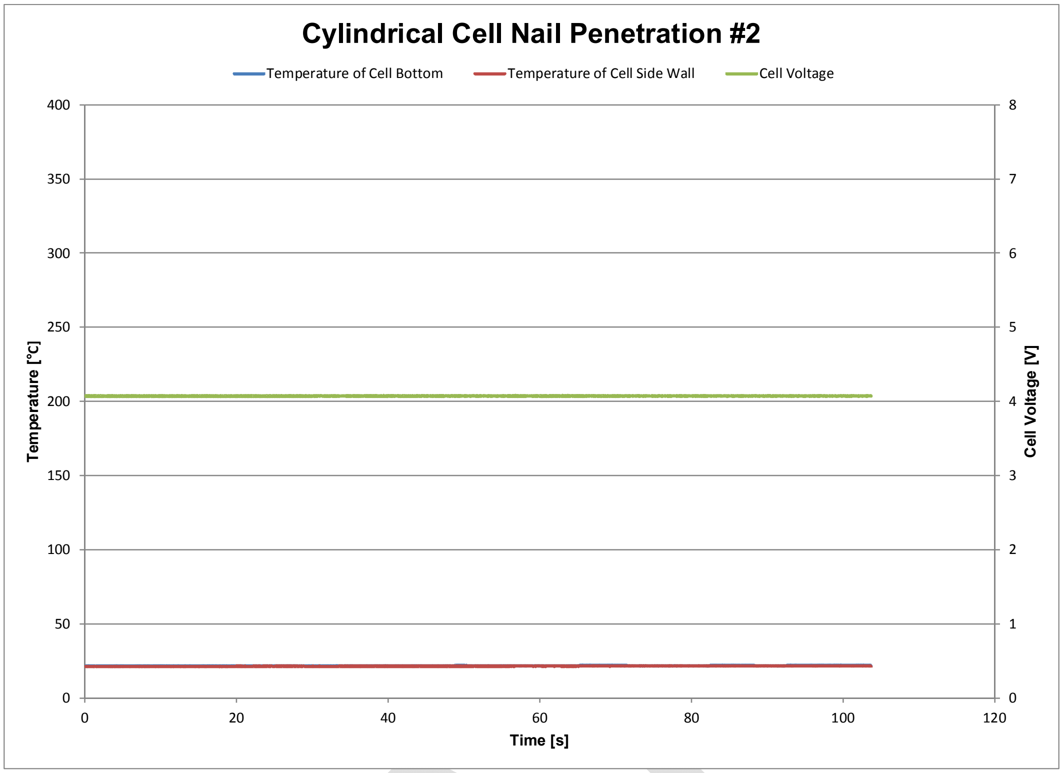

Figure 40 - Temperature and voltage traces for Nail Penetration Trial 2.

Figure 41 - Cylindrical cell immediately after nail penetration induced thermal runaway.

Figure 42 - Cylindrical cell after successful nail penetration trial.

Figure 43 - Cylindrical cell after failed nail penetration trial.

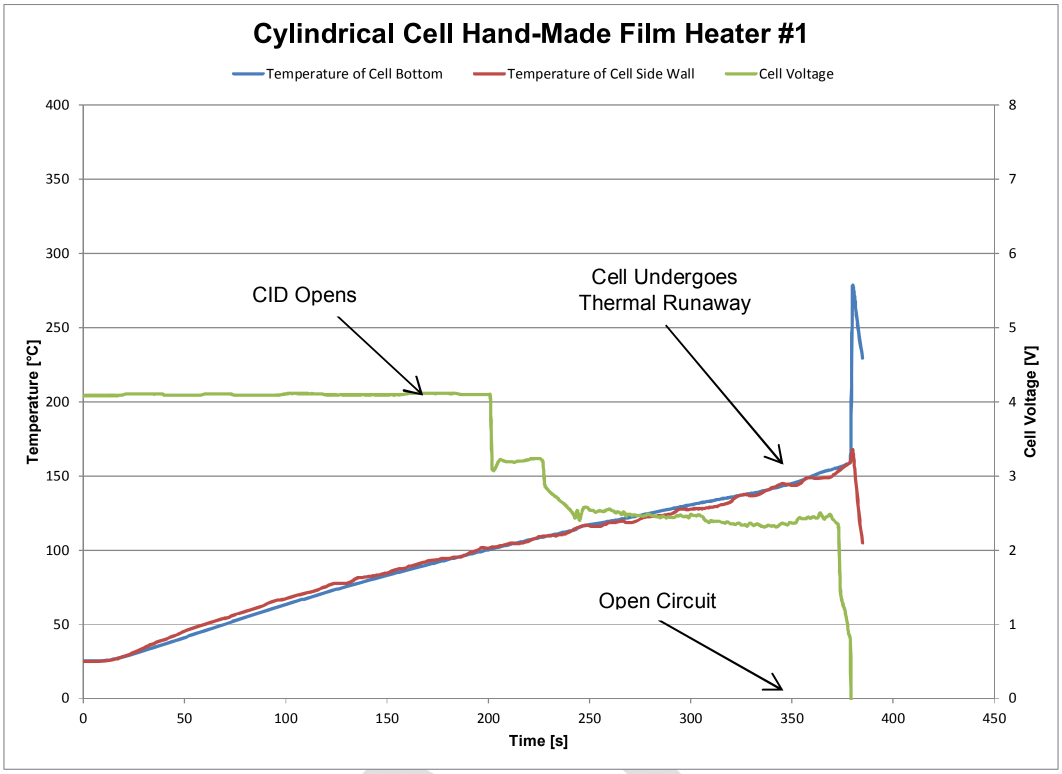

Figure 44 - Temperature and voltage traces for Hand-Made Film Heater Trial 1.

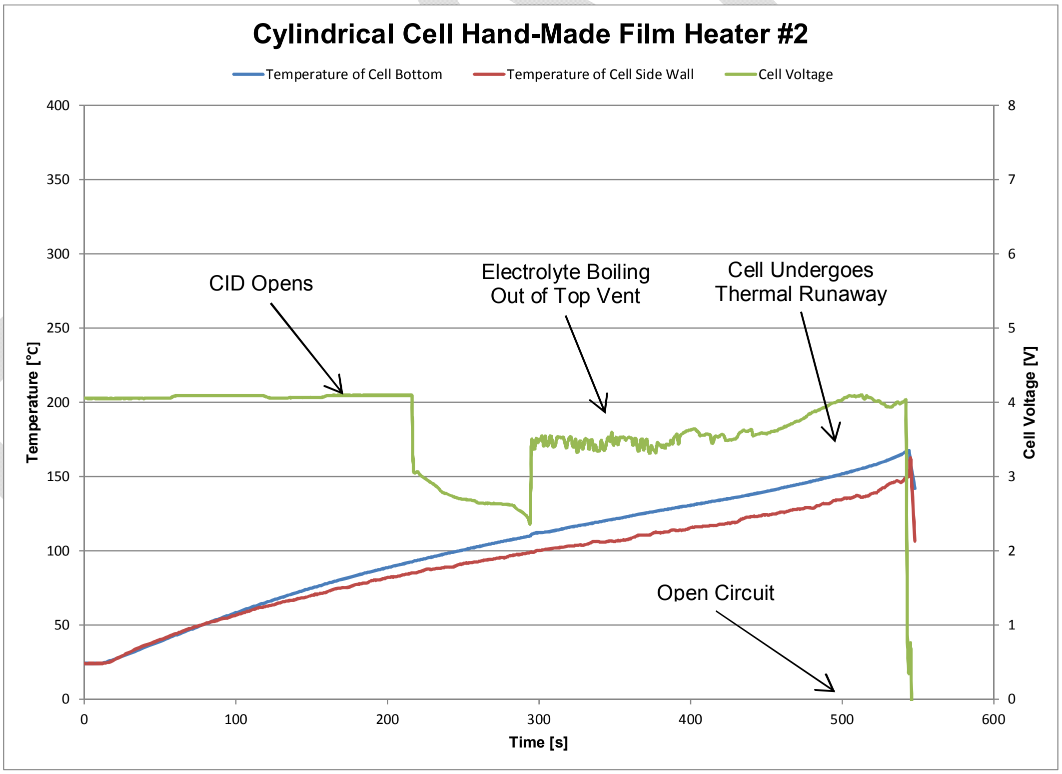

Figure 45 - Temperature and voltage traces for Hand-Made Film Heater Trial 2.

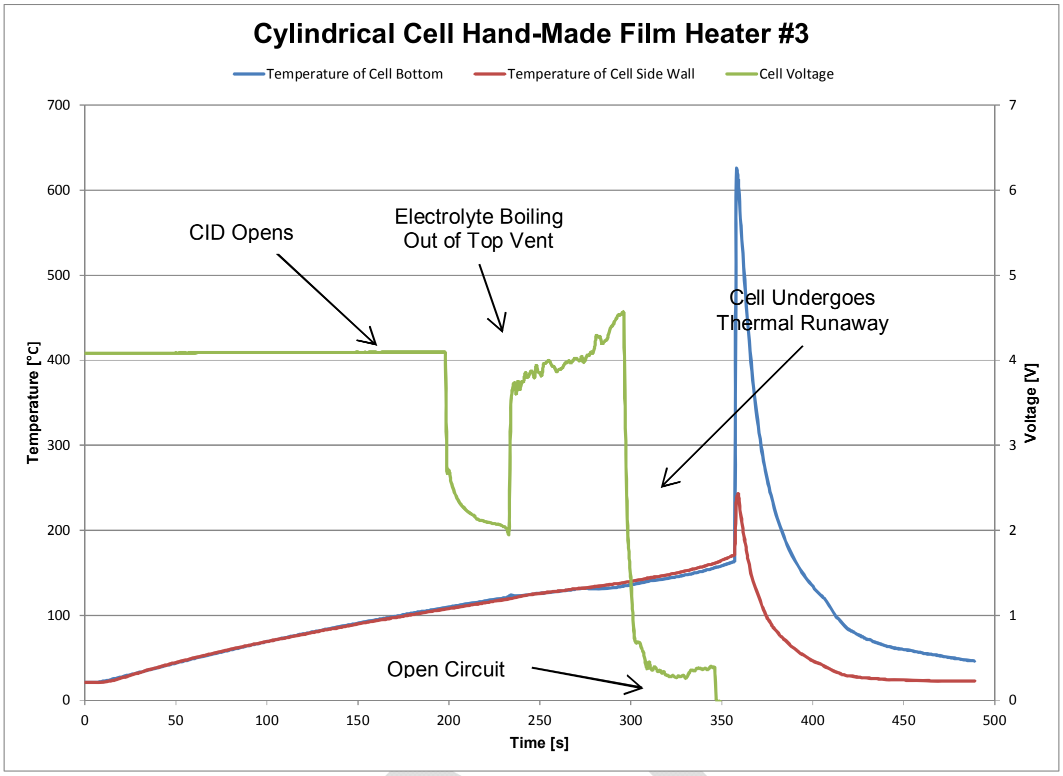

Figure 46 - Temperature and voltage traces for Hand-Made Film Heater Trial 3.

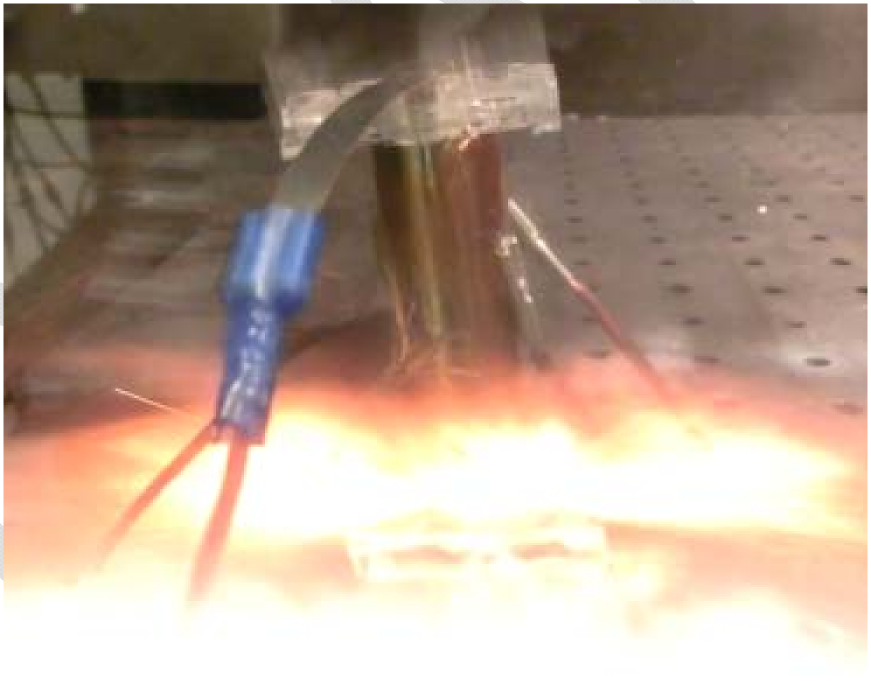

Figure 47 - Cylindrical cell undergoing thermal runaway; hand-made film heater method.

Figure 48 - Cylindrical cell after a Hand-Made Film Heater trial.

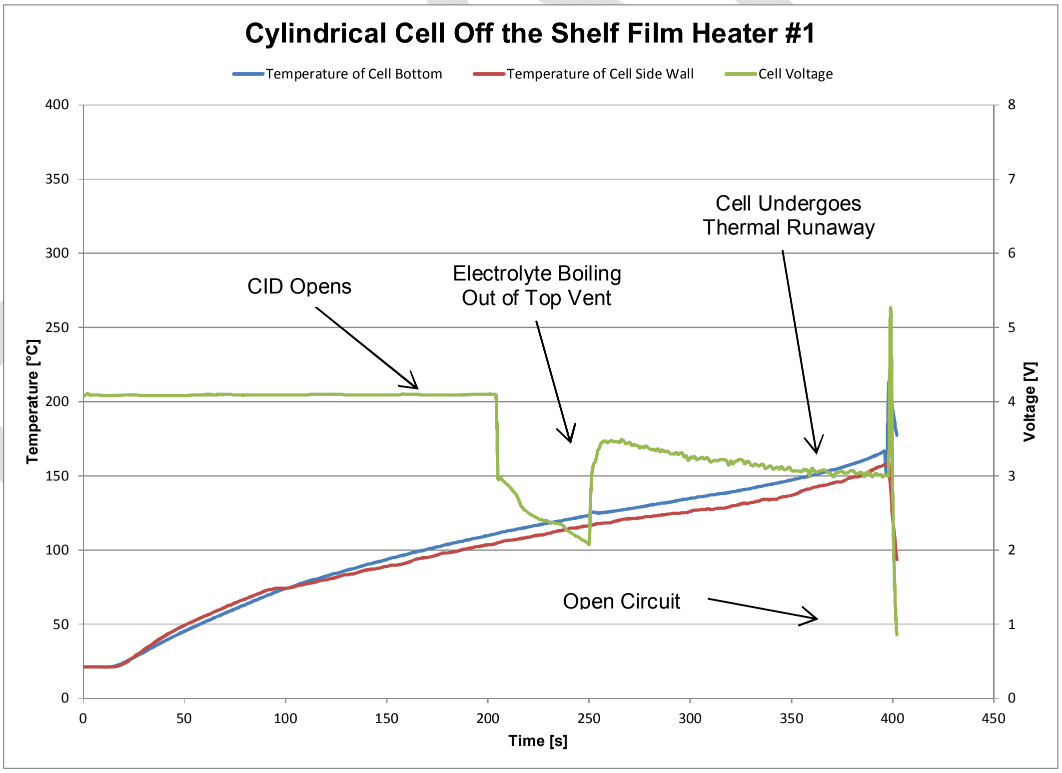

Figure 49 - Temperature and voltage traces for Off-the-Shelf Film Heater Trial 1.

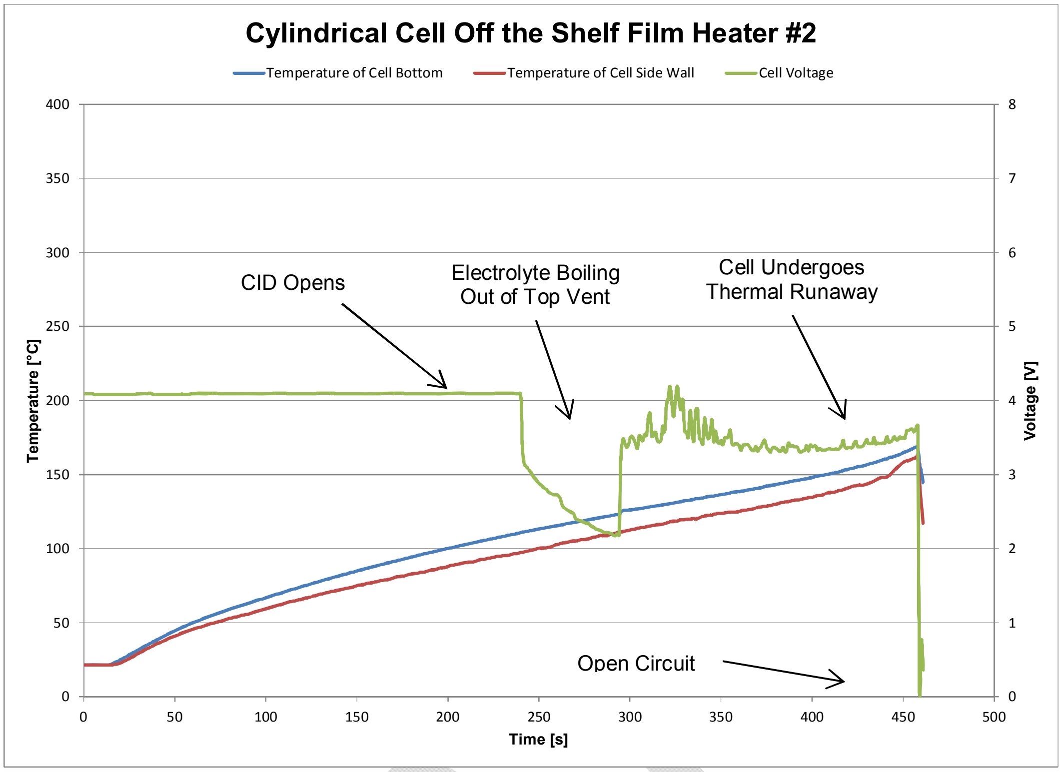

Figure 50 - Temperature and voltage traces for Off-the-Shelf Film Heater Trial 2.

Figure 51 - Cylindrical cell undergoing thermal runaway, Off-the-Shelf Heater method.

Figure 52 - Cylindrical cells after Off-the-Shelf Film Heater trials.

8.1.7 Prismatic Cell Initiation Method Testing

Four thermal runaway initiation test methods were tried on large hard case prismatic cells: Cell B.

8.1.7.1 Conductive Heating: Off-the-Shelf Film Heater. This method was selected for trial because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and overall low input energy to the system. A large heater was selected to be attached to the largest cell face in order to apply a large amount of distributed heat into the cell as quickly as possible. However, due to the large heating area, this method may add appreciable heat to neighboring cells prior to initiation. Figure 53 is a photograph of the film heater used for this trial. This method requires no changes to the electrical systems of the cell or battery. The heater is attached to the side of the cell can and does not affect the designed gas flow or mechanical features of the cell. This method can be implemented with production cells and can be easily implemented into the battery module and RESS.

For this trial, a large off-the-shelf film heater was purchased from McMaster-Carr, part number 35475K753. The heater had a 4” x 6” rectangular pad and is rated to 10W/ sq. in. The heater had an adhesive backing which is used to attach it to the large face of the cell. As connected to 120V AC, the heater was rated to 240W. The heater was applied to the largest face of the prismatic cell. One thermocouple was located on the opposite face of the cell, and second thermocouple was located on an adjacent face. A schematic diagram of the test setup is shown in Figure 54.

In the first trial, the cell was left completely exposed to the ambient air. The cell was strapped down to a large aluminum plate to secure the cell during the test and to prevent uncontrolled cell motion during thermal runaway. This setup is shown in (Figure 55). In an effort to reduce the time to thermal runaway and the total energy added to the system, for the second trial, a layer of 1/8" thick flexible ceramic insulation was wrapped around the cell to prevent the heat from escaping to the ambient air.

Figure 53 - Large off-the-shelf film heater.

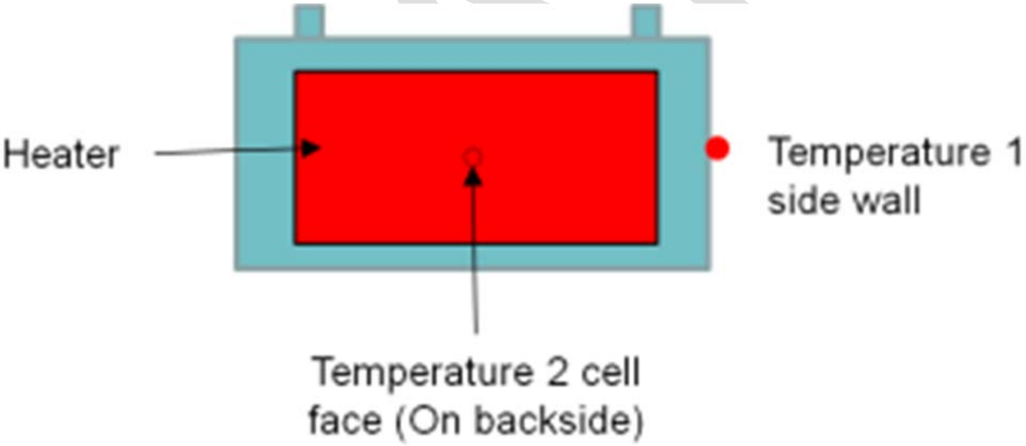

Figure 54 - Schematic of large off-the-shelf film heater setup.

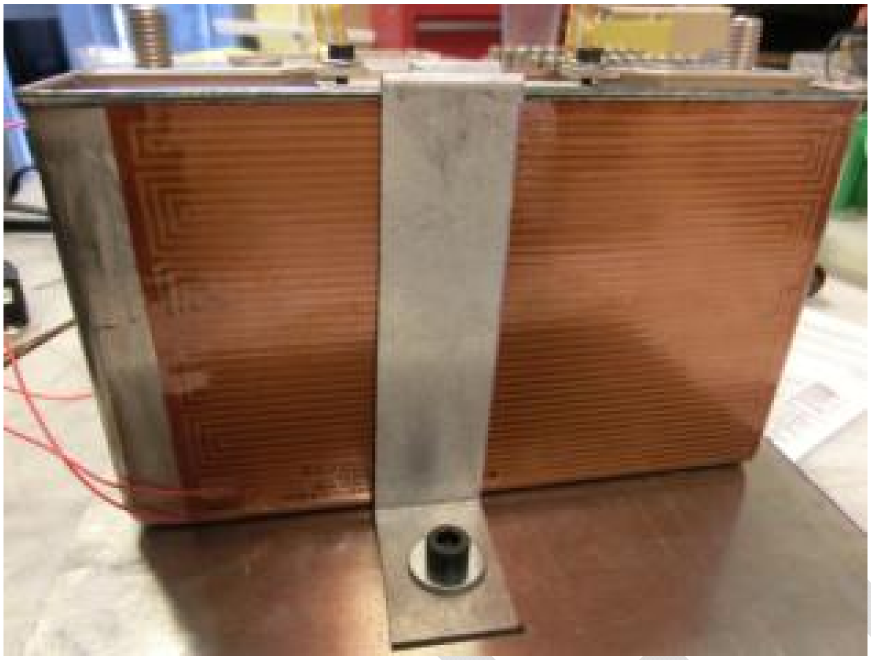

Figure 55 - Prismatic Cell Trial #1 setup

Figure 56 - Prismatic Cell Trial #2 setup

8.1.7.2 Conductive Heating: Multiple Off-the-Shelf Film Heaters. This method was selected for trial because the heaters are well thermally coupled to the cell, which should result in a short time to thermal runaway and overall low input energy to the system. Two small heaters were selected in order to try heating cell surfaces that would not be adjacent to other cells in the battery pack configuration. Thus, two heaters were applied to the smaller side walls of the cell. Insulation was added to decrease the time required to cause thermal runaway. Figure 57 is a photograph of one of the heaters used in the test attached to a cell. This method requires no changes to the electrical systems of the cell or battery. The heaters are attached to the side of the cell and do not affect the designed gas flow or mechanical features of the cell. This method can be applied to production cells and can be easily implemented into the battery module and RESS.

For this trial, two small film heaters were purchased from the McMaster-Carr with part numbers: 35475K334. The heaters had a 1" x 3" rectangular pad with a rated heat output of 10W/sq. in. With two heaters applied to the cell, the total heat input into the cell was 60W. The two heaters were attached to the narrow faces of the cell. Thermocouples were located on the large faces of the cell. A schematic diagram of the test setup is shown in Figure 58.

Figure 57 - One of the Dual Side Heater Pads

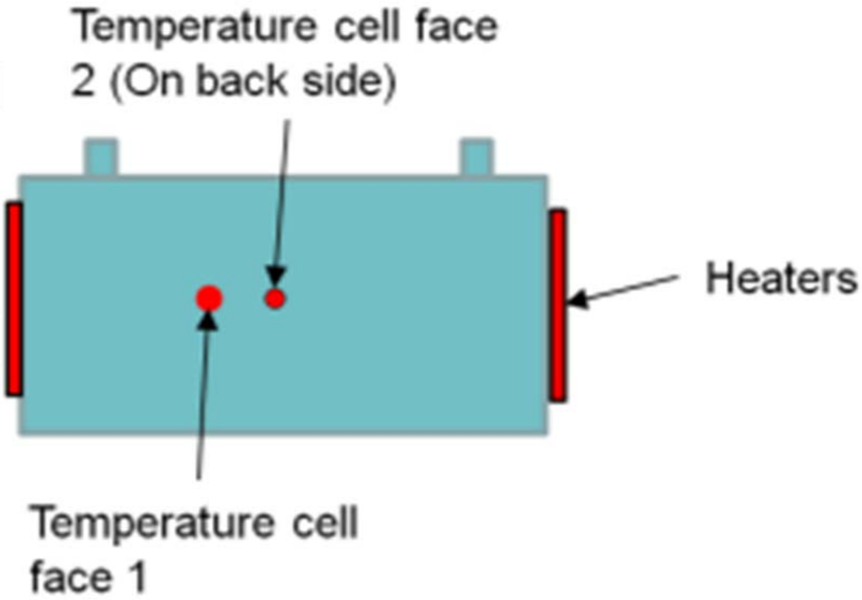

Figure 58 - Schematic of Dual Side Heater Pad setup

8.1.7.3 Mechanical Damage: Nail Penetration. This method was selected for trial because it was not expected to add significant energy to the cell. This method can provide a very short time to thermal runaway, with minimal effect on the state of charge of the initiating cell and minimal preheating of neighboring cells. It requires no changes to the electrical systems of the cell or battery. It requires no special modifications to the cell and can be done with production cells. If the nail is used to penetrate the cell vent location located in the top of the cell case (specific to the Cell B design) it will have little impact on the gas flow from the cell during a thermal runaway reaction. For the Cell B design in particular, the cell construction was examined and it was determined that the nail must penetrate the cell near the edge of the circular vent. If the nail were to penetrate along the center line of the cell it could wedge between the two internal electrode windings and fail to cause a mechanical short circuit (Figure 59). Note nail penetration initiation methods have been found to be unreliable: the nail must cause short circuiting between active material layers in the electrode. If a short circuit develops between current collectors, the cell may not self-heat sufficiently to undergo a thermal runaway reaction. In addition, this method may be difficult to implement within the physical constraints of the battery enclosure.

For the first nail penetration trial, a 1" long steel nail with a 1/8" diameter (Figure 28) was used to penetrate the top vent of the cell. The nail was attached to a mechanical drop fixture. During the first trial, the nail was allowed to remain in the cell for more than 70 minutes.

For the second nail penetration trial, a 3" long steel nail with a blunt tip was used to penetrate the top vent of the cell. A longer, blunter nail was used in an attempt to cause more internal damage to the cell.

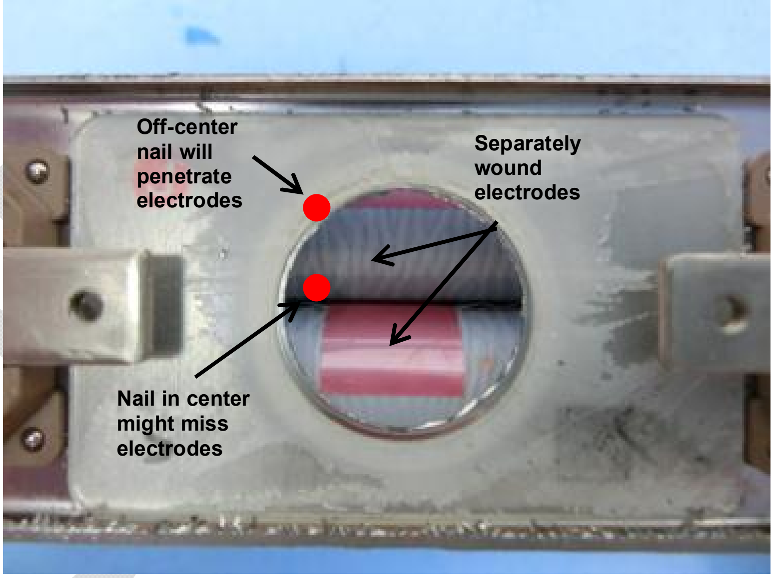

Figure 59 - Top view of prismatic cell, looking through a removed vent.

8.1.7.4 Conductive Heating: Thick Film Resistor. This method was selected for trial because it allows for a large amount of heat to be transferred very locally to the cell, at a density of approximately 150W/sq.in. A high heat flux should result in a short time to thermal runaway, little change in the cell state of charge, and little heating of the neighboring cells prior to initiation. This method will not obstruct the designed venting features of the cell. If the resistor is mounted to the cell in a manner that will allow it to detach once thermal runaway has initiated it should not obstruct the heat transfer characteristics of the cell. However, the thickness of the resistor might make installation challenging due to the tightly packaged cells in the battery pack.

For this trial, a thick film resistor (Figure 60) measuring approximately 2”x 2” x 1” was attached to the side of the cell. The resistor had a rated power of 600W and resistance of 10 ohms. Thermal joint compound was placed between the resistor base and the cell face to aid in the heat transfer from the resistor to the cell. The resistor was attached to cell using vinyl electrical tape so that once the cell entered thermal runaway the tape would melt and allow the resistor to become detached from the cell. Schematically this test is setup was identical to that of the large film heater test (Figure 54).

Figure 60 - Thick film resistor

8.1.8 Hard Case Prismatic Initiation Method Results

A summary of the results for the different initiation methods attempted on the prismatic cells is shown in Table 10. Since there was a large difference in temperature measurements between the faces of the cells due to a large internal temperature gradient within the cell, the highest of the two temperature measurements was reported.

The large film heater method successfully initiated cells in the trials with and without added insulation. Addition of a thin layer of insulation reduced the time to thermal runaway by approximately half. The temperature and voltage traces for the first trial are shown in Figure 61. Once thermal runaway began both measured cell temperatures rose quickly in unison. The temperature traces show that the cell reached a maximum temperature of 613°C. Figure 62 shows the cell emitting smoke during the thermal runaway event. Figure 63 shows the cell after thermal runaway. The temperature and voltage traces for the second trial can be seen in Figure 64. The results from this trial were very similar to the first trial, although time to thermal runaway was shorter. In this trial the highest measured temperature was 563°C and the cell cooling rate was reduced due to the presence of insulation. Figure 65 shows the cell undergoing thermal runaway. The large film heater method required no modifications to the production cell and did not obstruct the designed venting features. The large heater area could result in pre-heating effects on neighboring cells. The large heater could be easily applied to RESS level testing. Because of the effectiveness of the large film heater method and the straightforward architecture of the Manufacturer B RESS, the film heater method was selected for application to full scale vehicle testing and no further coupon or module testing was performed.

The dual side film heater method failed to produce a thermal runaway reaction in a sufficiently short amount of time. Figure 66 shows the voltage and temperature traces for this trial. Testing was aborted approximately 45 minutes after heating began. After 45 minutes, the testing agency judged that if this method were attempted in an RESS, cell heating would be further retarded due to heat loss to surrounding components. The cell experienced a maximum temperature of 72°C before the test was aborted and there were no observable changes in the cell voltage throughout the test. The cell was monitored for approximately 60 minutes after the test was aborted to ensure that a delayed thermal runaway due to heat redistribution within the cell did not occur. Once measured cell temperatures fell below 40°C it was considered unlikely that the cell would experience a delayed runaway and the monitoring was ended. As a result of a long time to thermal runaway, the dual side film heater method was eliminated from further testing with the hard case prismatic cells.

The nail penetration method was not successful in inducing a thermal runaway reaction in the hard case prismatic cells. The temperature and voltage traces for the first nail penetration trial can be seen in Figure 67. In this test, the nail was allowed to remain in the cell for more than 70 minutes, after which time, the test was aborted (the nail was removed). The cell did not undergo thermal runaway, although there was significant temperature rise (to 80° C). As the cell was heating, its voltage was decreasing (Figure 67), consistent with an internal short circuit. If the nail were allowed to remain in the cell for a much longer time it is possible that the cell could have undergone thermal runaway, however is also possible that cell SOC would have dropped sufficiently to prevent a thermal runaway reaction. Figure 68 shows the relatively small amount of localized damage from the nail penetration. The voltage and temperature traces for the second nail penetration trial can be seen in Figure 69. Application of a longer, blunter nail did result in a faster temperature rise within the cell. The cell reached 110° C within 60 minutes. However, the cell still did not undergo a thermal runaway reaction. The cell voltage dropped by approximately 0.3V over the course of this test. If the nail were allowed to remain in the cell for a much longer time it is possible that the cell could have undergone thermal runaway, however is also possible that cell SOC would have dropped sufficiently to prevent a thermal runaway reaction. Because it did not achieve thermal runaway, the nail penetration method was eliminated from further testing with the hard case prismatic cells.

The thick film resistor method was not successful in inducing a thermal runaway reaction in the hard case prismatic cell. The thick film resistor itself overheated and failed before it could cause any significant heating of the cells. Because this initiation method was not reliable it was eliminated from further testing with the hard case prismatic cells.

Table 10 - Summary of Single Prismatic Cell Initiation Method Results

Initiation Method	Time to Runaway [Min:Sec]	Highest Temperature at Initiation [°C]	Energy Input / Energy of Cell	Energy Input / Energy of Cells in Parallel
Large Side Heater Pad #1, No Surrounding Insulation	18:06	132	0.39[12]	0.39
Large Side Heater Pad #2, Insulated Cell	9:16	89	0.20	0.20
Dual Side Heater Pad, Insulated Cell	No Runaway (45:40)	(72)	0.25	0.25
Nail Penetration #1	No Runaway (70:25)	(78)	~0	~0
Nail Penetration #2	No Runaway (60:29)	(113)	~0	~0
Thick Film Resistor	No Runaway	n/a	n/a	n/a

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[12] Since one side of the heater is exposed to ambient air, the full amount energy shown may not have gone into the cell

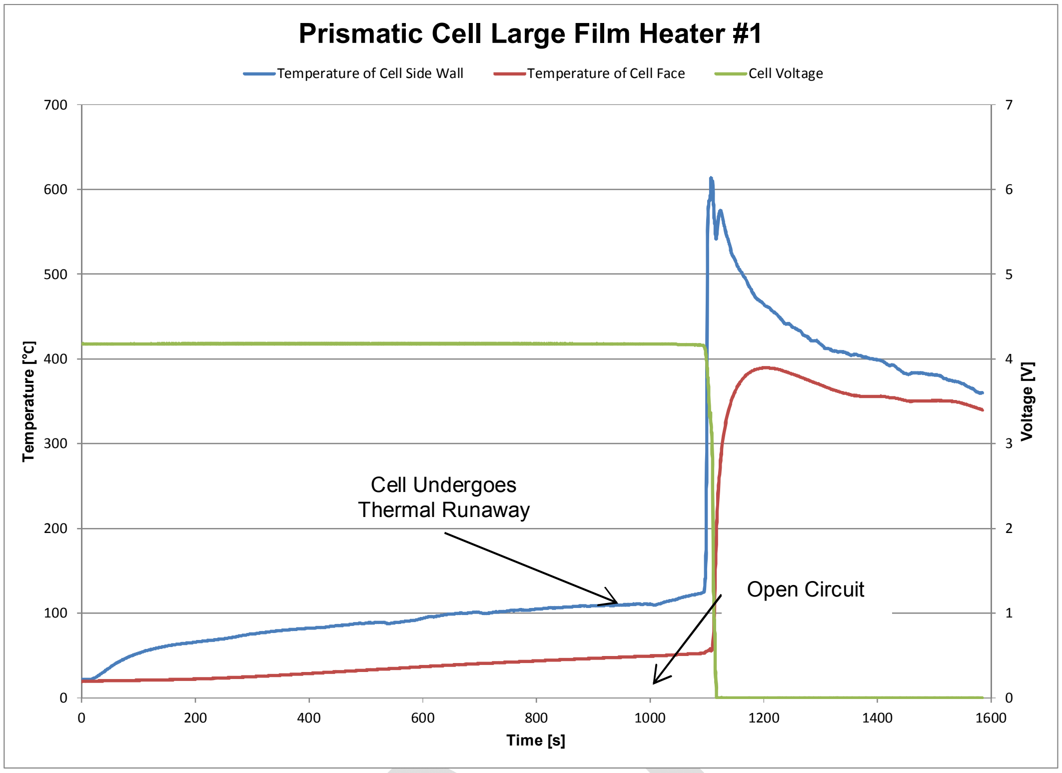

Figure 61 - Temperature and voltage traces for Large Film Heater Trial #1.

Figure 62 - Prismatic cell during thermal runaway; Large Film Heater Trial #1.

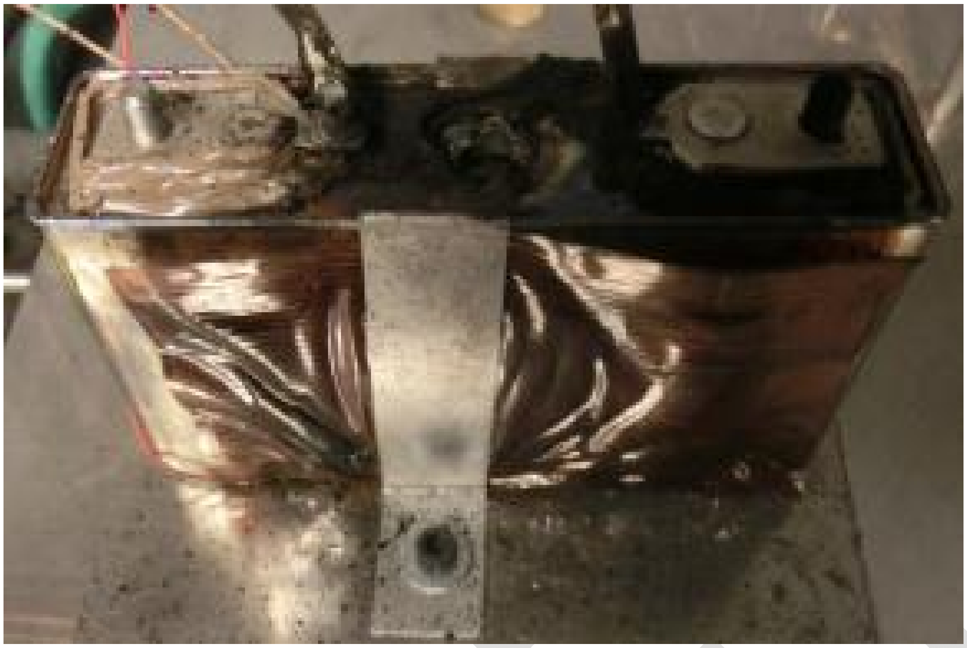

Figure 63 - Prismatic cell after thermal runaway.

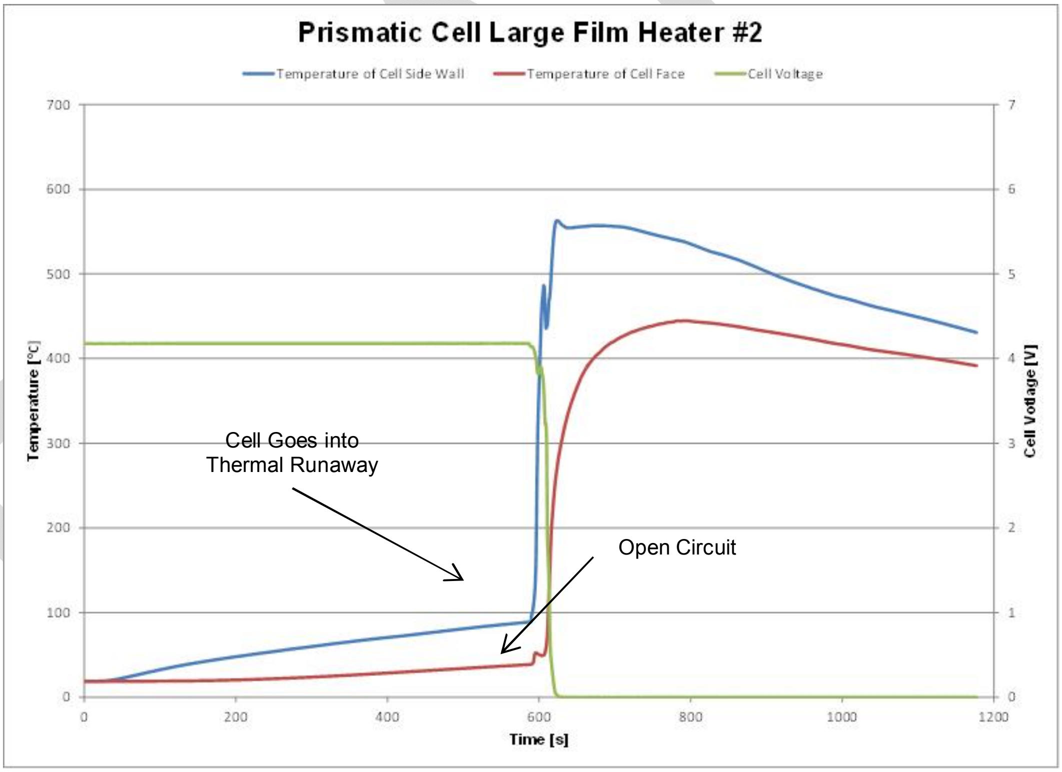

Figure 64 - Temperature and voltage traces for Large Film Heater Trial #2.

Figure 65 - Prismatic cell undergoing thermal runaway; Large Film Heater Trial #2.

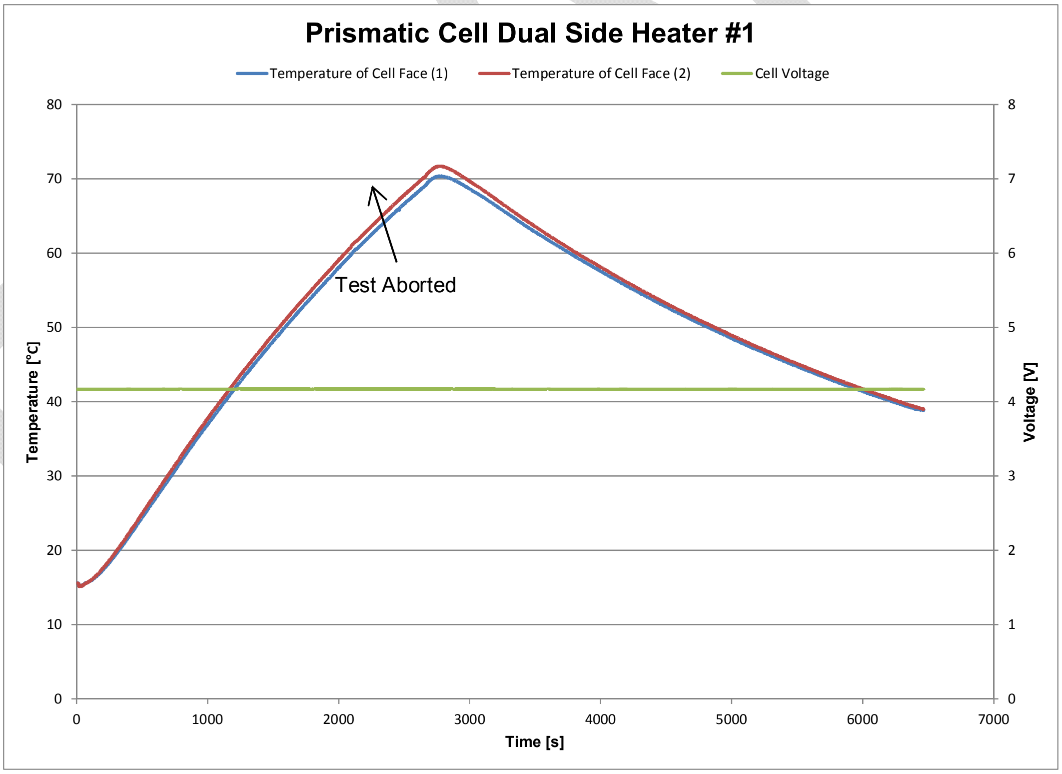

Figure 66 - Voltage and temperature traces for Dual Side Film Heater Trial #1.

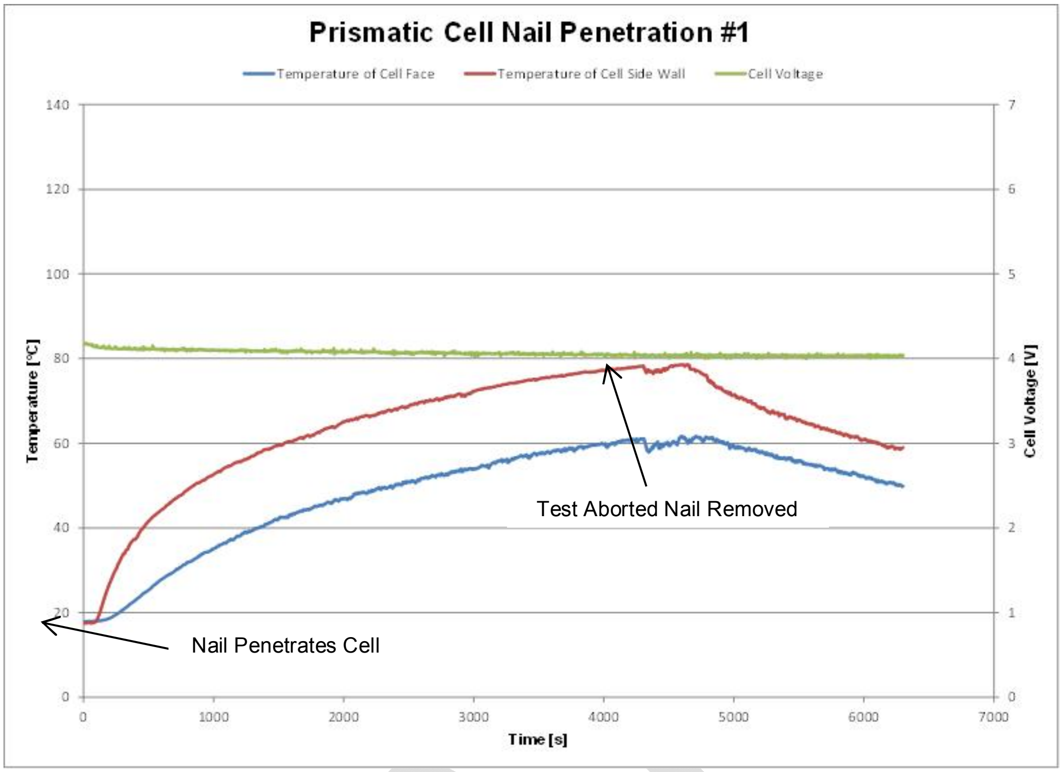

Figure 67 - Voltage and temperature traces for Nail Penetration Trail #1.

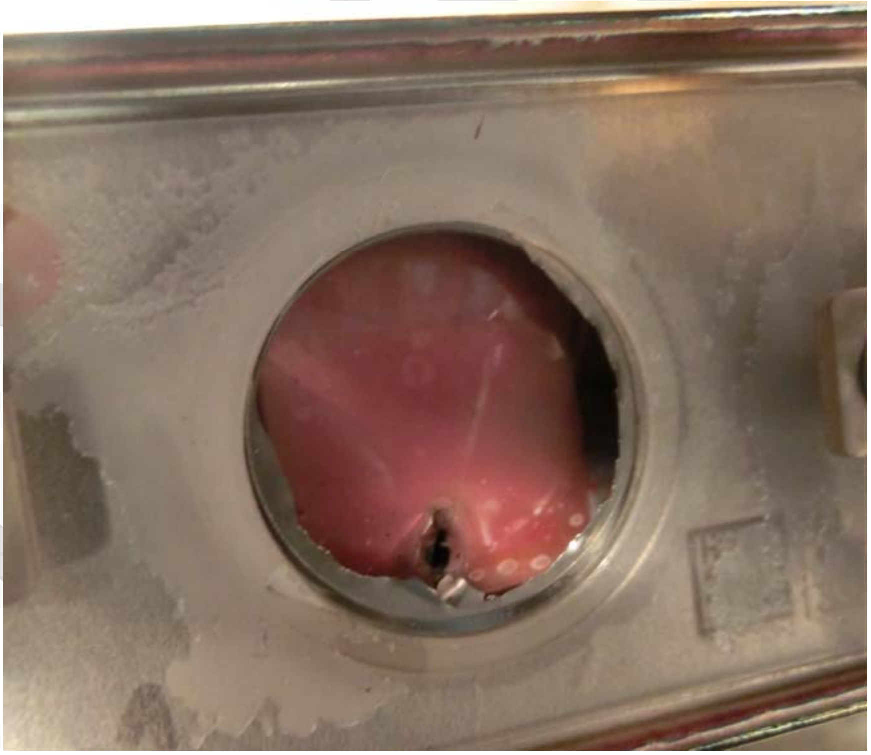

Figure 68 - Nail penetration damage.

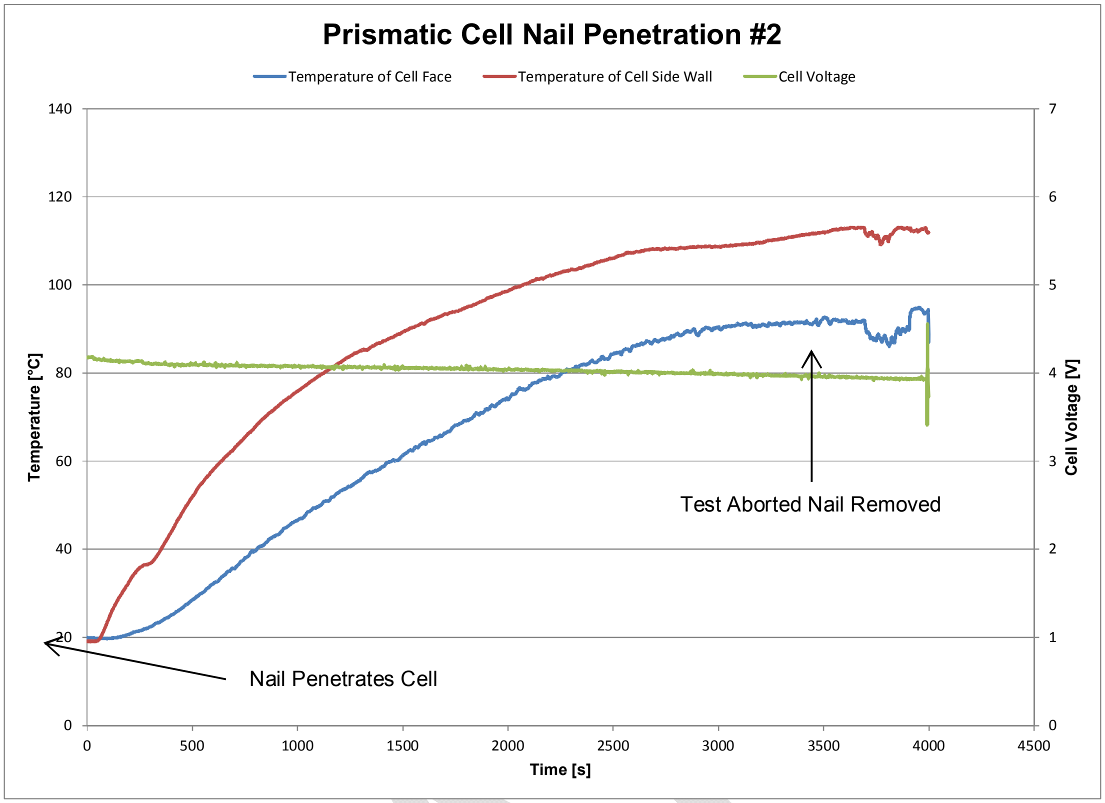

Figure 69 - Voltage and temperature traces for Nail Penetration Trial #2.

8.1.9 Pouch Cell Initiation Method Testing

8.1.9.1 Conductive Heating: Off-the-Shelf Film Heater. This method was selected for trial because the heater is well thermally coupled to the cell, which should result in a short time to thermal runaway and overall low input energy to the system. A large heater was selected in order to apply a large amount of distributed heat into the cell as quickly as possible. A large heat flux should provide a shorter time to initiate runaway. However, due to the proximity of other cell surfaces as installed in the module, initiation of a center cell may add appreciable heat to neighboring cells prior to initiation. Figure 53 shows the film heater used for this trial. This method requires no changes to the electrical systems of the cell or battery. The heater is attached to the side of the cell and does not affect the designed gas flow or mechanical features of the cell. This method can be applied to production cells and can be easily implemented into the battery module and RESS.

For this trial, a large off-the-shelf film heater was purchased from McMaster-Carr, part number 35475K753. The heater was a 4” x 6” rectangular pad rated to 10W/ sq. in. The heater had an adhesive backing which was used to attach it to the face of the cell. For this trial the heater was connected to a DC power supply and the power to the heater was ramped to ensure that a hot-spot on the heater did not cause localized melting or burn-through of the cell pouch material. Three thermocouples were installed for this trial: one directly under the heater, one on the cell beside the heater, and one on the side of the cell opposite the heater.

8.1.10 Pouch Cell Initiation Method Results

A summary of the results for the attempted initiation method attempted on the pouch cell is shown in Table 11. Since there was a large difference in temperature measurements, the highest of the three temperature measurements was reported.

The large off the shelf film heater successfully initiated a thermal runaway reaction in the pouch cell after approximately 31 minutes. The hottest temperature measured during the test was directly underneath the heater (heater temperature in Figure 70) which measured 290 °C. The thermal energy input from the heater was approximately 22% of the cell's electrical energy, and 11% of the electrical energy of a parallel group in the pack configuration. During this test, the cell was not thermally insulated; in a module configuration, more heat might be retained resulting in a shorter time to thermal runaway. Also, heater power was increased during the test; setting the heater immediately to the highest value could result in shorter time to thermal runaway.

The thermal runaway reaction of an unconstrained pouch cell appeared different than thermal runaway of a hard case cell. Prior to venting, the pouch cell swelled (Figure 71). Ultimately the increasing internal pressure and generated heat caused failure of the heat sealed seams of the pouch cell or of the pouch material itself, causing the cell to rupture and vent flammable gas. During this trial, the vented gases ignited (Figure 72). When a pouch cell is constrained within a module or RESS, it may not be able to swell, and the resulting gas flow pathways may appear different. In later module level verification testing (Section 8.2), the effect of constraining the cell was studied.

Because of the module architecture and experience with the film heater method, no additional thermal runaway initiation methodologies were tried with pouch cells.

Table 11 - Summary of Single Pouch Cell Initiation Method Results

Initiation Method	Time to Runaway [Min]	Hottest Temperature at Initiation [°C]	Energy Input / Energy of Cell	Energy Input / Energy of Cells in Parallel
Large Film Heater	31 min	290	0.22	0.11

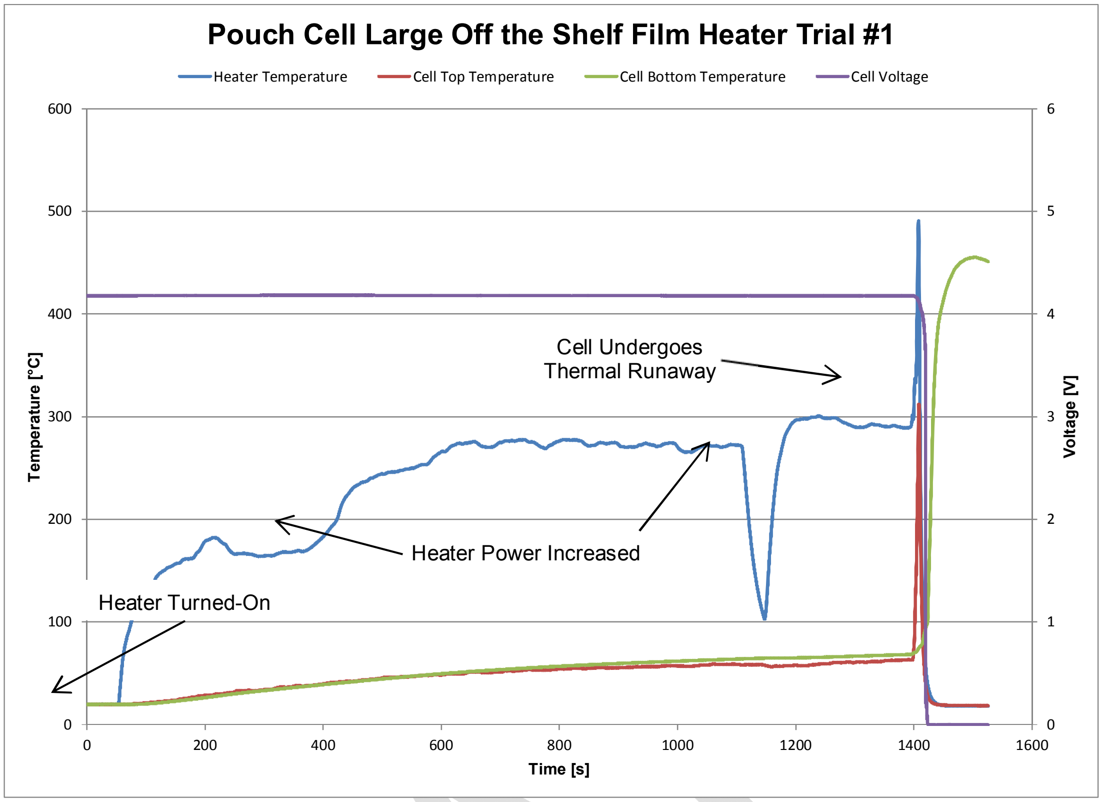

Figure 70 - Voltage and temperature traces for Pouch Cell Large Off-the-Shelf Film Heater Trial #1.

Figure 71 - Pouch cell just before thermal runaway.

Figure 72 - Ignition of thermal runaway gases from pouch cell.

8.2 Examples of Single Cell Thermal Runaway Initiation Verification Methods (Coupon or Module Level Testing)

8.2.1 Introduction

The purpose of coupon or module level initiation trials is to validate a single cell thermal runaway initiation method prior to application of that method to full vehicle and RESS testing. This testing is intended to ensure that a method of initiation identified during single cell testing will be effective in full scale RESS testing. It is intended to allow observation of the effects of interactions with neighboring cells and other battery module components on an initiation method. It is also intended to allow refinement of the initiation method prior to attempting to install an initiating device in a RESS. For example, coupon or module level testing can help determine where a specific initiation method will cause significant heating of neighboring cells, and if it is necessary to develop mitigation strategies to prevent neighbor heating such as selection of heater installation location, installation of insulation around heaters, etc.

Examples of cell thermal runaway initiation mechanism development at the single cell level were provided in Section 8.1. Building on that work, this Section provides examples of how initiation methods that appeared promising at the single cell level should be validated for testing at full scale.

Manufacturer A small cylindrical cells were tested first at the coupon level with three potential initiation devices: the wrapped Nichrome wire device, the hand-made film heater device, and the off-the shelf film heater. These methods were the most consistent during the single cell test and had the least effect on the boundary conditions of the test. This testing was focused on selecting the most representative method for inducing single cell thermal runaway. Once a device was selected, a module level test was conducted to verify device implementation.

Because of the effectiveness of the large film heater method and the straightforward architecture of the Manufacturer B RESS, the film heater method was selected for application to full scale vehicle testing and no further coupon or module testing was performed.

Manufacturer C pouch cells were tested at the module level with an off-the-shelf film heater. The goals of this testing were

a. To determine whether the selected initiation method was appropriate for cells constrained within a module.
b. To determine how the initiation method could be implemented in the module without significantly affecting gas flow pathways and boundary conditions.
c. To determine what modifications to the module enclosure would be necessary to install the heaters.
d. To determine whether modifications to the module would have significant effects on the performance of module.

8.2.2 Test Equipment

a. Personal Protective Equipment: respirators, safety glasses, and chemical resistant gloves.
b. Vent hood.
c. Temperature measurement and data logging system: National Instruments NI 9213.
d. Data Translation system: MEASUREPoint DT8874.
e. Type-K Thermocouples.
f. Stop Watch with and accuracy of ±1 second.
g. Various thermal runaway initiation devices selected based on single cell testing.

8.2.3 Test Parameters

All of the tests were conducted at the following conditions.

Table 12 - Verification (Coupon or Module Level) Test Parameters

Test Temperature	Temperature of 20 ± 10°C
Initiating Cell State of Charge (SOC)	95% - 100%
Neighboring Cell SOC	Various, depending upon test configuration

8.2.4 General Test Methods

The following measurements were made for each test:

a. Surface temperatures of neighbor cells.
b. Time required from the start of the test to achieve thermal runaway.
c. Occurrence of any secondary thermal runaway reactions.

For each test:

a. The initiating device was installed on a cell and the initiating cell was placed in a coupon configuration, or the initiating device was placed on a cell installed in a module.
b. Thermocouples were applied to neighbor cells.
c. The initiating device was activated, data acquisition was started and a timer was started.
d. The time when the initiating cell audibly underwent thermal runaway was recorded.
e. The test was continued until all neighbor cells showed evidence of cooling.

The time to runaway was best determined by the audible indication of thermal runaway.

Temperature traces of neighbor cells were examined to determine the amount of preheating of neighbor cells prior to initiation of cell thermal runaway. The average change in cell temperature from the beginning of a trial to the point of initiator cell thermal runaway was reported

Temperature traces of neighbor cells were examined to determine the maximum neighbor cell temperature after thermal runaway of the initiator cell had occurred. This temperature was reported.

8.2.5 Cylindrical Cell Verification Testing

8.2.5.1 Cylindrical Cell Verification Coupon Level Testing

A cylindrical cell coupon cluster was developed to compare possible cell thermal runaway initiation devices in a multi-cell environment based on time-to-runaway of the initiating cell, heat addition to neighbor cells, and reliability and robustness of the initiation method. The cell arrangement was based upon the layout of cells present in modules from Manufacturer A (Cells were provided by Manufacturer A). The coupon cluster consisted of 7 cells arranged in a circular pattern. The initiator cell with an attached initiating device was located in the center of the cluster, and was surrounded by 6 neighboring cells. A schematic of this coupon cluster is shown in Figure 73. The initiating cell was charged to 100% SOC.

Thermocouples were applied to 4 neighbor cells (labeled 1-4 in the schematic). Neighbor cells were charged to only 30% SOC to limit the likelihood of a thermal runaway propagation. This was an experimentally convenient method to study neighbor cell preheating by the initiator cell, without the effects of self-heating of neighbor cells. The cluster of 7 cells was then wrapped in a layer of 1/8" ceramic insulation to help simulate the largely adiabatic environment of a full module. An example cluster coupon is shown in Figure 74.

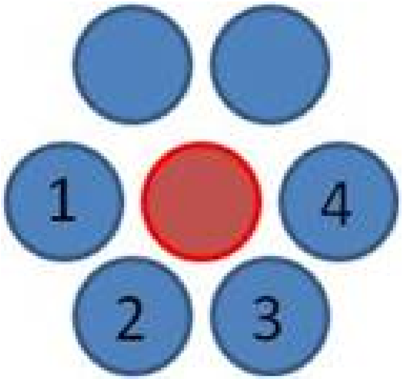

Figure 73 - Seven cell cluster module coupon.

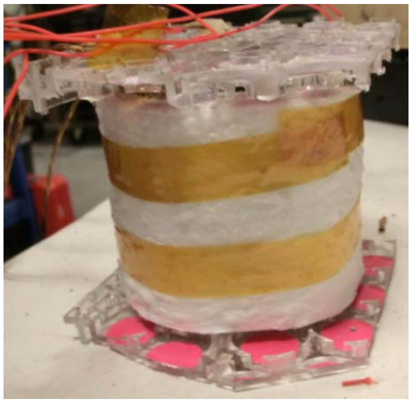

Figure 74 - Example module cluster coupon.

A summary of the test results for the module coupon cluster tests is shown below in Table 13. Reported measurements included time-to-runaway, the average change in temperature experienced by neighboring cells at the time of thermal runaway reaction of the initiating cell (amount of pre-heating), the maximum measured temperature of the neighbor cells after the initiating cell underwent a thermal runaway reaction, and the energy input to the heater as a fraction of the amount of electrical energy in the parallel group.

The first Nichrome Wrapped Wire device trial produced a time to runaway of approximately 4 minutes. The temperature traces of four neighbor cells can be seen in Figure 75. As a result of electrical interference during the heating portions of this trial data prior to the initiator cell entering thermal runaway is unavailable. Immediately after the initiator cell went into runaway and the heater was turned off the interference disappeared. Approximately 5 minutes after the initiator cell underwent a thermal runaway reaction, an additional cell (Cell 1) underwent a thermal runway reaction, and its thermocouple became detached (sudden drop in temperature in Figure 75).

The second Nichrome Wrapped Wire device trial also produced a time to runaway of approximately 4 minutes. The temperature traces of four neighbor cells can be seen in Figure 76. At the time of thermal runaway, neighbor cells were preheated by approximately 20 C. The thermal runaway event from the initiator cell caused the thermocouples to become detached from the neighboring cells: maximum neighbor cell temperatures after thermal runaway of the initiator cell occurred are not known. However, there were no visible or audible signs that any of the neighboring cells underwent a thermal runaway reaction after the initiator cell.

The first Hand-Made Film Heater device trial produced a time to runaway of approximately 7 ½ minutes. The temperature traces of four neighbor cells can be seen in Figure 77. Prior to thermal runaway, neighbor cells were preheated by approximately 29°C. The highest measured neighbor cell temperature after the initiator cell underwent thermal runway, was 93°C. None of the neighboring cells went into thermal runaway after the initiator cell.

The second Hand-Made Film Heater device trial produced a time to runaway of 6 minutes. During this time the neighbor cell temperatures increased by an average of 45°C. The maximum measured temperature achieved by a neighbor cell after the initiator cell underwent thermal runway was 168°C. None of the neighbor cells underwent a thermal runaway reaction.

The first Off-the-Shelf Film Heater device trial produced a time to runaway of approximately 6 minutes. The temperature traces of four neighbor cells can be seen in Figure 79. Prior to thermal runaway, neighbor cells were preheated by approximately 18°C. After the initiator cell underwent thermal runaway, the maximum temperature reached by a neighbor cell was 77°C. None of the neighbor cells underwent thermal runaway.

The second Off-the-Shelf Film Heater device trial also produced a time to runaway of approximately 6 minutes. The temperature traces of four neighbor cells can be seen in Figure 80. Prior to thermal runaway, neighbor cells were preheated by approximately 29°C. After the initiator cell underwent thermal runaway, the maximum temperature reached by a neighbor cell was 133°C. None of the neighbor cells underwent thermal runaway.

Based on these tests the off-the-shelf film heater device was selected for testing with Manufacturer A cells at the module level. The off-the-shelf film heater produced short times to thermal runaway and also resulted in very limited pre-heating of neighboring cells. The Nichrome wrap method produced shorter times to thermal runaway, however the instance of a secondary cell thermal runaway reaction when compared to results of other heater tests suggests that the Nichrome wrapped wire device may cause significant pre-heating of adjacent cells, may be sensitive to variations in setup, and/or alter thermal boundary conditions.

Table 13 - Summary of Cylindrical Cell Module Coupon Cluster Test

Initiation Method	**Time to Runaway [Min:Sec]**	**Average Neighbor Cell Increase in Temperature During Heating of Initiator [C]**	**Neighbor Cell Maximum Temperature [C]**	**Energy Input / Energy of Cells in Parallel**
Nichrome Wrap #1	4:22	N/A	Thermal runaway reaction occurred	0.005
Nichrome Wrap #2	3:40	20	N/A	0.004
Hand-Made Film Heater #1	7:32	29	93	0.005
Hand-Made Film Heater #2	6:12	45	168	0.004
Off the Shelf Film Heater #1	5:53	18	77	0.004
Off the Shelf Film Heater #2	6:08	29	133	0.004

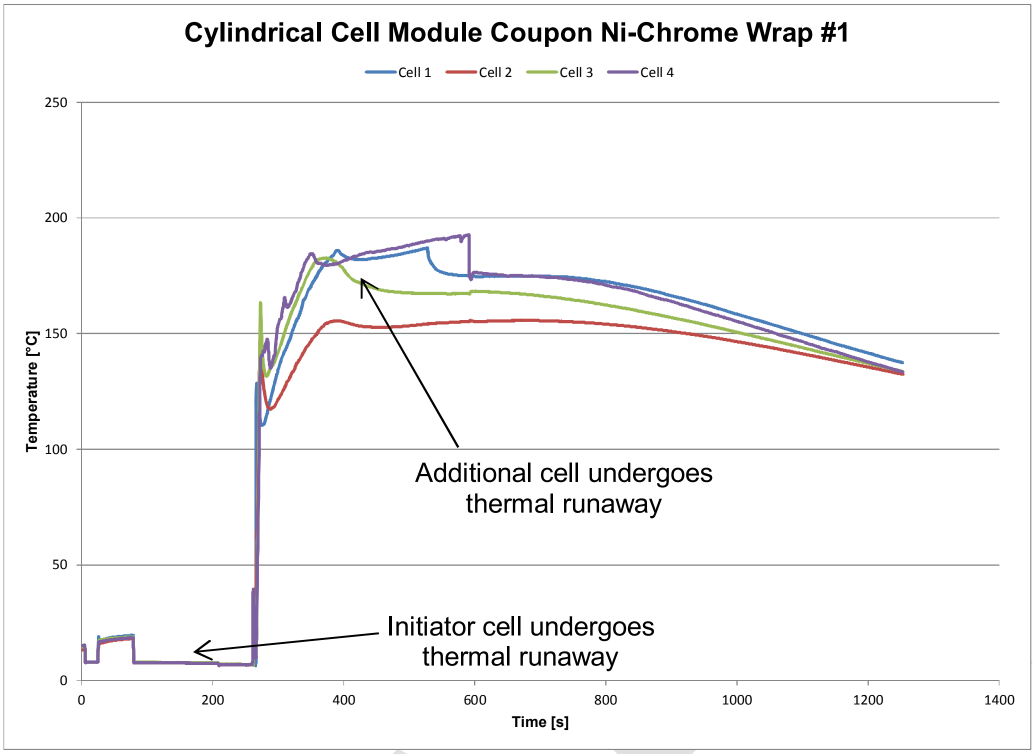

Figure 75 - Temperature traces for Nichrome Wrap Trial #1.

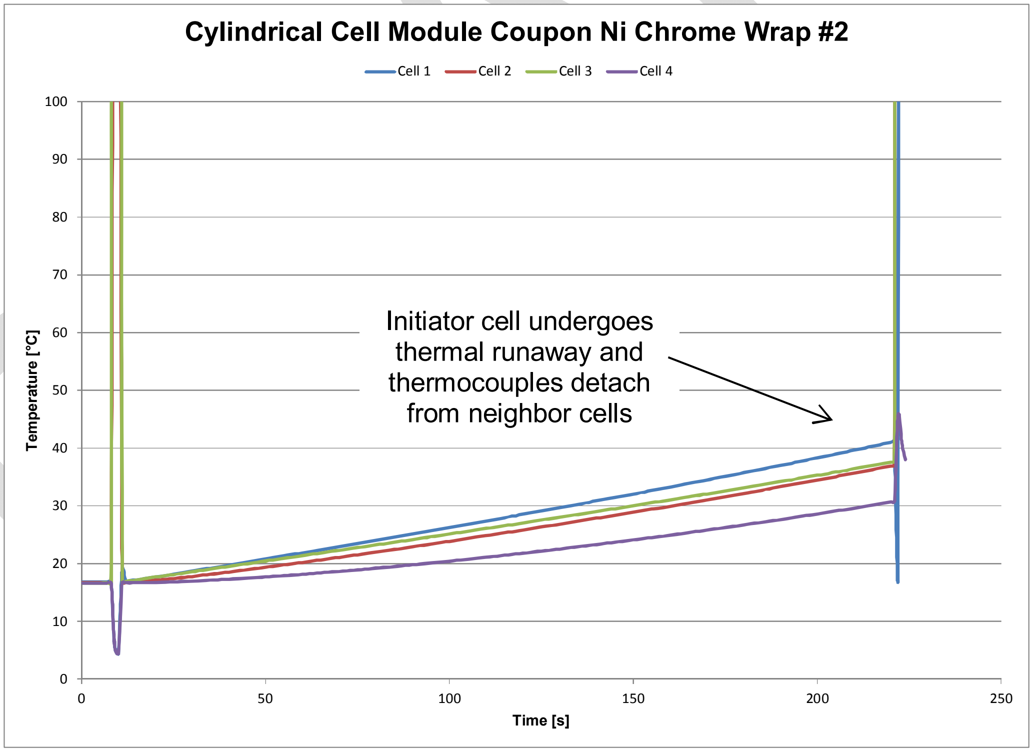

Figure 76 - Temperature traces for Nichrome Wrap Trial #2.

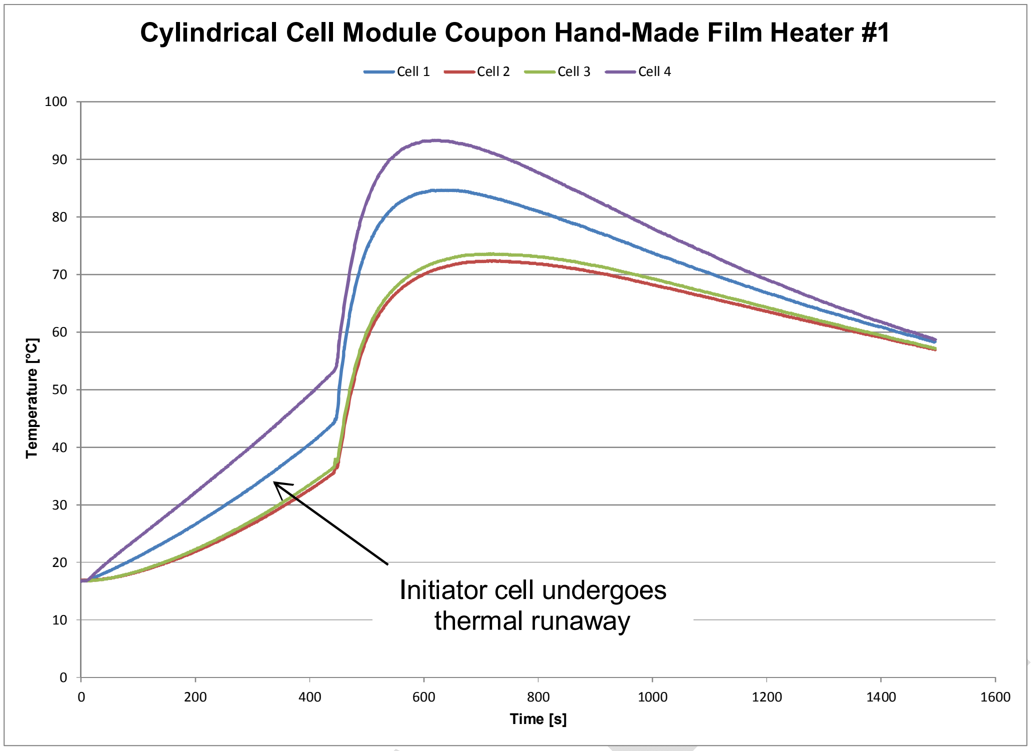

Figure 77 - Temperature traces for Hand-Made Film Heater Trial #1.

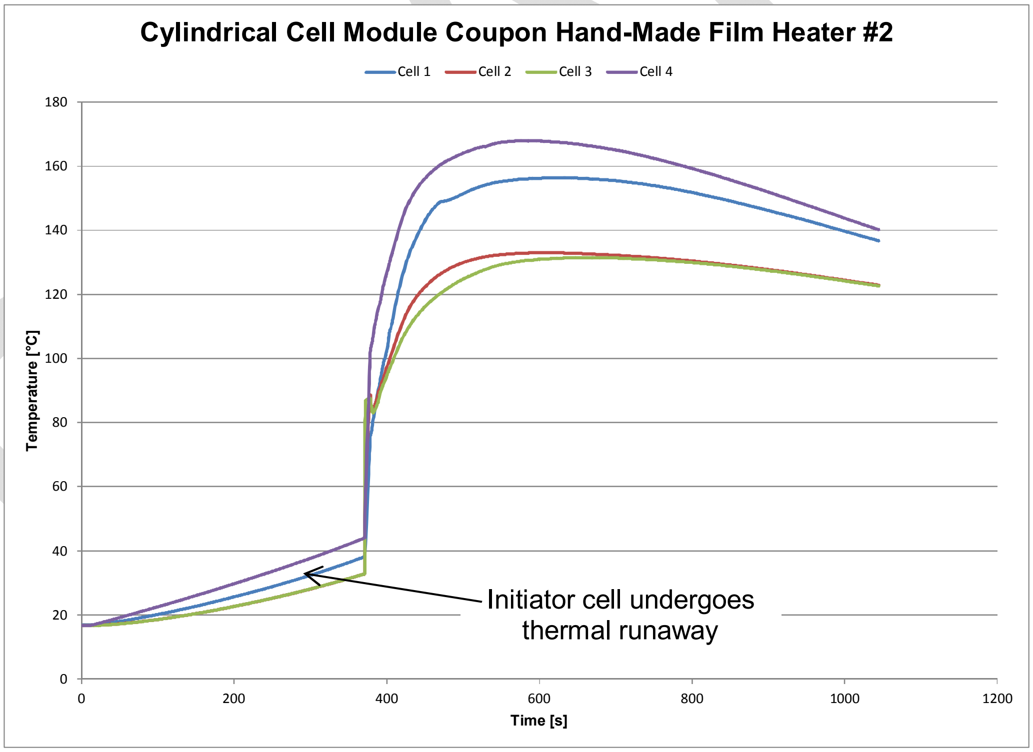

Figure 78 - Temperature traces for Hand-Made Film Heater Trial #2.

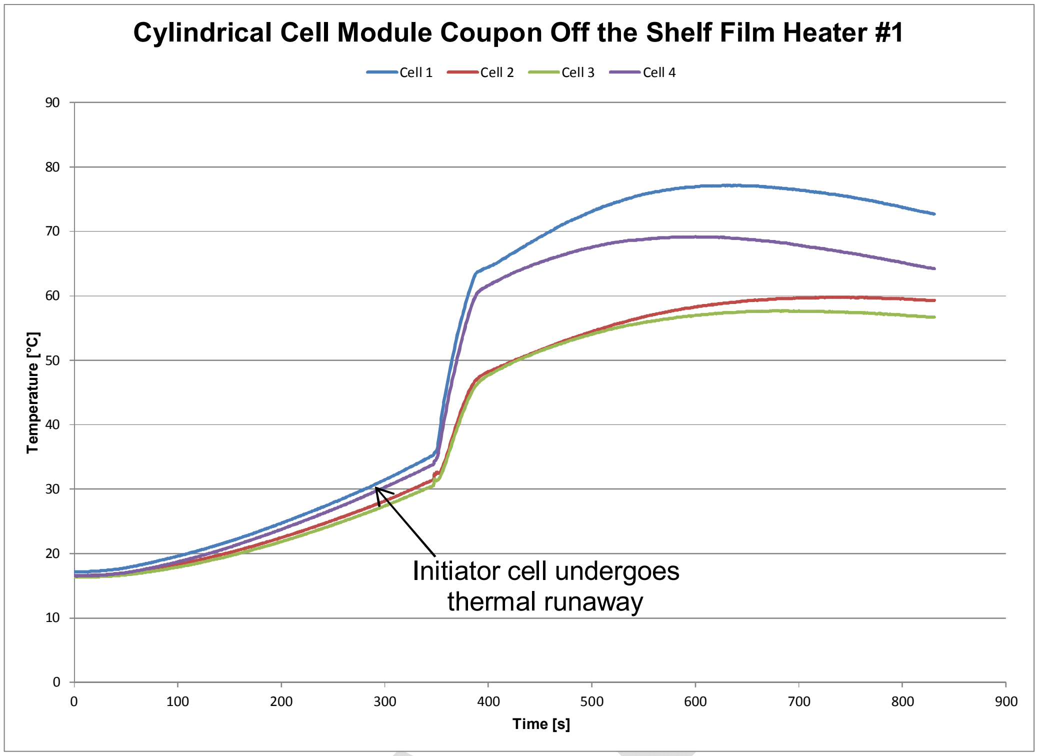

Figure 79 - Temperature traces for Off-the-Shelf Film Heater Trial #1.

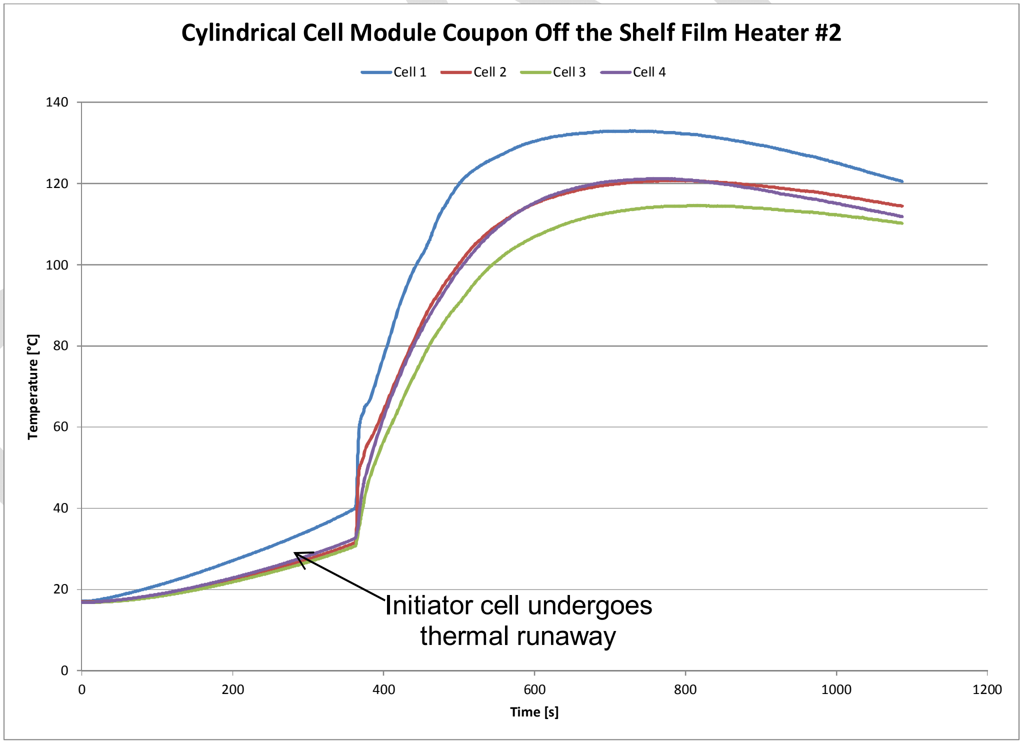

Figure 80 - Temperature traces for Off-the-Shelf Film Heater Trial #2.

8.2.5.2 Cylindrical Cell Verification Module Level Testing

Manufacturer A provided information regarding the module architecture that implements the small cylindrical cells. In particular, Manufacturer A provided information explaining which cell locations are the most thermally stressful to cells in their battery module. These locations, labeled as Cell A, B, C, & D in Figure 81 and shown in red, were selected as the thermal runaway initiation locations for module-level testing.

Initiating cells were charged to 100% SOC. Cells adjacent to initiating cells (neighbor cells), colored orange in Figure 81, were also charged to 100% SOC. Thermocouples were applied to neighbor cells. Since the purpose of this testing was to assess the effectiveness of the cell thermal runaway initiation device, and not to examine the likelihood or character of a thermal runaway propagation, the cells further removed from the initiators, colored yellow in Figure 81 were discharged. The discharged cells would provide an appropriate thermal and mechanical boundary condition for the test, but in a discharged state would not allow a thermal runaway reaction to propagate, and thus allow four initiation trials to be completed using a single module.

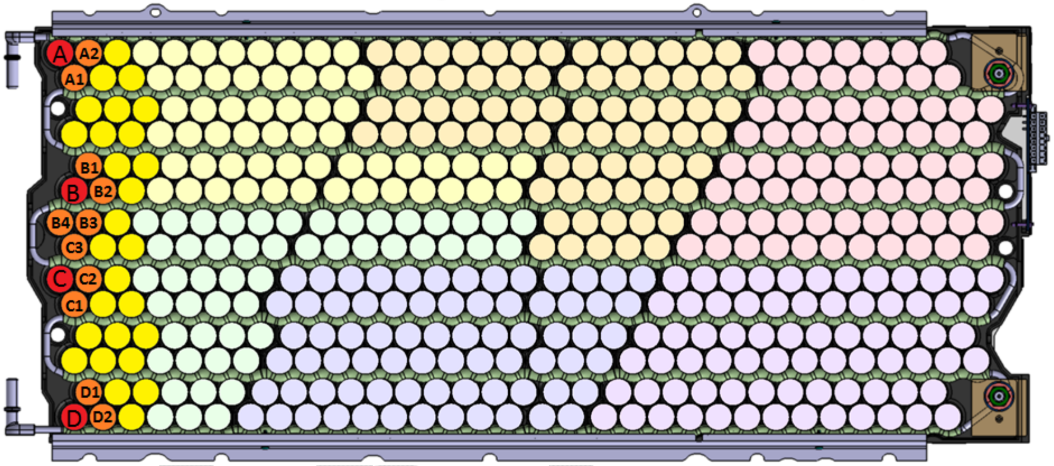

Figure 81 - Schematic of the full module SCTRI Test

Figure 82 - Thin film heater attached to cell.

For the module level test the thin film heaters were applied to the sides of the cells. Some small portions of plastic had to be trimmed to allow the heater to be fully adhered to the cell. The heater can be seen as applied to a cell within a module in Figure 82.

Because this module architecture included a coolant system, cell temperatures at the start of test could be conveniently controlled. Cells were brought to 25±2 °C prior to each initiation trial.

During module level testing, 3 out of 4 initiation trials resulted in successful initiation of a single cell thermal runaway reaction. The temperature traces for these tests is shown in Figure 83 below. The heater that was attached to the cell at Site A burned out before the cell could undergo thermal runaway (trial not shown on the temperature trace). However, trials at initiation sites C, D, and B were successful. Examining the temperature trace from left to right, test events were as follows:

- The cooling pump was running after the initiation trial at Site A failed.
- The cooling pump was turned off after cells surrounding Site C reached 25 °C, and the film heater attached to the cell at Site C was activated.
- Heating of Cell C occurred. Neighbor cells were affected by the heater: Cells C1 - C3 reached temperatures of 50- 60 °C before Cell C underwent a thermal runaway reaction. This thermal runaway reaction was marked by an audible pop and emission of smoke from the module, as well as a spike in thermocouple temperatures. Time to thermal runaway was approximately 15 minutes.
- After Cell C underwent thermal runaway, Cells C1-C3 began to heat rapidly and then began to cool down. Cell C1 reached a maximum temperature of 136 °C. None of the neighbor cells (C1-C3) underwent a thermal runaway reaction.
- After cells had cooled appreciably and no further thermal runaway reactions appeared likely, the coolant pump was turned on.
- The cooling pump was turned off after cells surrounding Site D reached 25 °C, and the film heater attached to the cell at Site D was activated.
- Heating of Cell D occurred. Neighbor cells were affected by the heater: Cell D1 reached a temperature of approximately 50 °C before Cell D underwent a thermal runaway reaction. This thermal runaway reaction was marked by an audible pop and emission of smoke from the module, as well as a spike in thermocouple temperatures. Time to thermal runaway was approximately 10 minutes.
- After Cell D underwent thermal runaway, Cells D1 and D2 began to heat rapidly and then began to cool down. Cell D1 reached a maximum temperature of 110 °C. None of the neighbor cells (D1 or D2) underwent a thermal runaway reaction.
- After cells had cooled appreciably and no further thermal runaway reactions appeared likely, the coolant pump was turned on.
- The cooling pump was turned off after cells surrounding Site B reached 25 °C, and the film heater attached to the cell at Site B was activated.

- Heating of Cell B occurred. Neighbor cells were affected by the heater: Cells B1 – B4 reached temperatures of 50- 60 °C before Cell B underwent a thermal runaway reaction. This thermal runaway reaction was marked by an audible pop and emission of smoke from the module, as well as a spike in thermocouple temperatures. Time to thermal runaway was approximately 20 minutes.

- After Cell B underwent thermal runaway, Cells B1-B4 began to heat rapidly and then began to cool down. None of the neighbor cells (B1 - B4) underwent a thermal runaway reaction. Maximum temperature of cells B1-B4 are unavailable due to electrical noise in the measurement.

- After cells had cooled appreciably and no further thermal runaway reactions appeared likely, the coolant pump was turned on.

A summary of the results of the four initiation location trials can be found in Table 14.

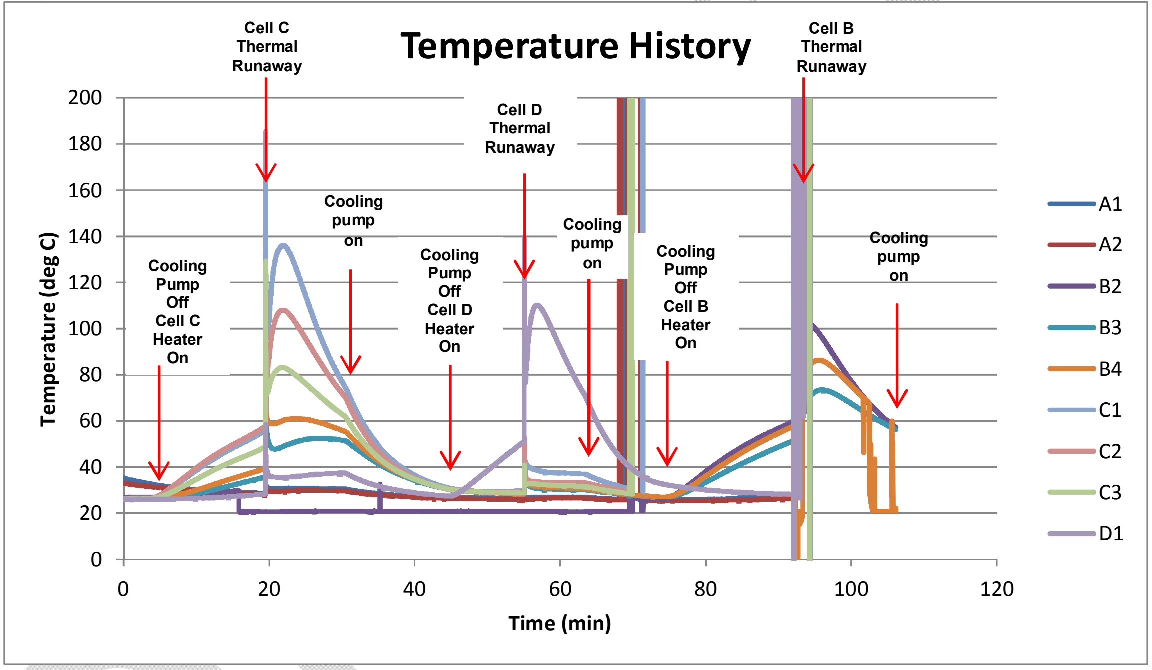

Figure 83 - Temperature Traces for the Module Level Testing – 4 trials

Table 14 - Summary of Cylindrical Cell Module Level Testing

Initiation Trial	Time to Runaway [Min]	Average Neighbor Cell Increase in Temperature During Heating of Initiator [C]	Neighbor Cell Maximum Temperature at Time of Initiator Runaway [C]	Energy Input / Energy of Cells in Parallel
Location A	Heater failure, no runaway occurred	n/a	n/a	n/a
Location B	17 min	29 C	>100 C noise in thermocouples data	0.011
Location C	16.5 min	28 C	136 C	0.011
Location D	10 min	14 C	110 C	0.007

Module level verification testing of the off-the-shelf film heater cell thermal runaway initiation method showed that this method could be applied to a module with limited modification of the module or surrounding RESS, and consistently induce a single cell thermal runaway in a module environment. This method produced times to thermal runaway of 10-20 minutes. It resulted in some heating of neighbor cells; which increased by 15-30°C during initiator heating and reached 50-60 °C before thermal runaway of the initiator cell occurred. Propagation of thermal runaway to neighbor cells did not occur. The method is subject to some experimental failure (one of four initiation attempts failed) and thus, it would be prudent to install multiple thermal runaway initiation devices within a single battery RESS as a backup should the first initiation device fail to achieve runaway.

8.2.6 Pouch Cell Verification Testing

Manufacturer C RESS architecture implemented modules composed of four Manufacturer C pouch cells stacked within a metal enclosure. Each metal enclosure (module) had exposed terminals for electrical connections. A representative pouch cell module[13] is shown in Figure 84.

Pouch cell verification testing was conducted in two stages. The initial trial was conducted on a single 4-cell module. However, thermal runaway resulted in significant swelling of a single module. Since the Manufacturer C RESS architecture constrains modules in such a way as to prevent swelling, a second trial was conducted on a constrained 3-module stack.

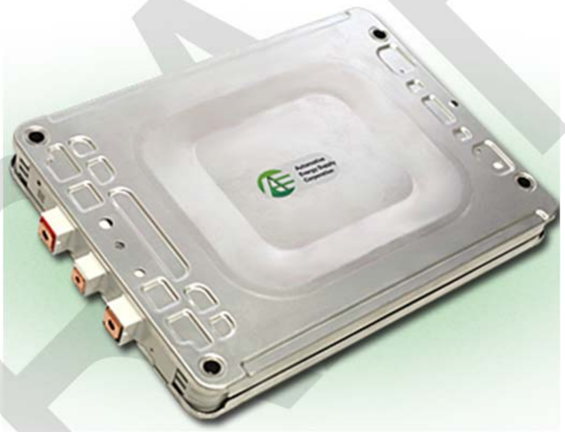

Figure 84 - Representative pouch cell module

8.2.6.1 Single Module Trial

A large off-the-shelf film heater was selected as the initiating device for Manufacturer C pouch cells. In the module configuration, the heater was installed on the outside of an edge cell between the cell and an insulator. A schematic of the Manufacturer C module is shown in Figure 85: the heater is red, the cells are yellow and insulation is blue. Thermocouples were installed between the cells and on the outside of the enclosure. All of the cells for this trial were charged to 100% SOC.

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[13] http://www.eco-aesc-lb.com/en/product/liion_ev/

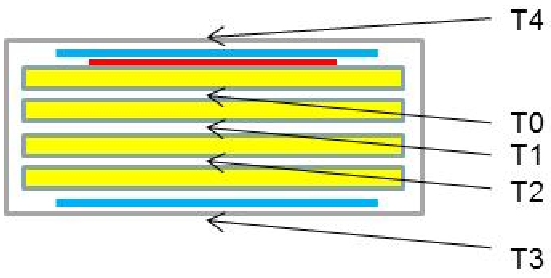

Figure 85 - Schematic of Single Module Pouch Cell Test.

The single module trial resulted in a time to runaway of approximately 7 minutes. The thermocouple traces can be seen in Figure 86. Due to the presence of insulation, the case exterior thermocouple (T4) signal lagged the audible indications of thermal runaway by approximately 30 seconds. The traces show that even though the heater was applying appreciable energy to the system (the temperature on the case exterior was rising steadily), neighboring cells remained within 5°C of initial temperatures until the first thermal runaway reaction occurred. The maximum temperature reached inside of the module enclosure was 721°C, consistent with thermal runaway reaction temperatures.

When the initiator cell underwent thermal runaway, it expanded, as seen in the single cell test, and caused deformation of the module enclosure (Figure 87). Vented gases ignited almost immediately after the first cell underwent thermal runaway. A second cell underwent thermal runaway approximately 1 ½ minutes after the initiating cell. The remaining cells underwent thermal runaway reactions with approximately 40 second delays.

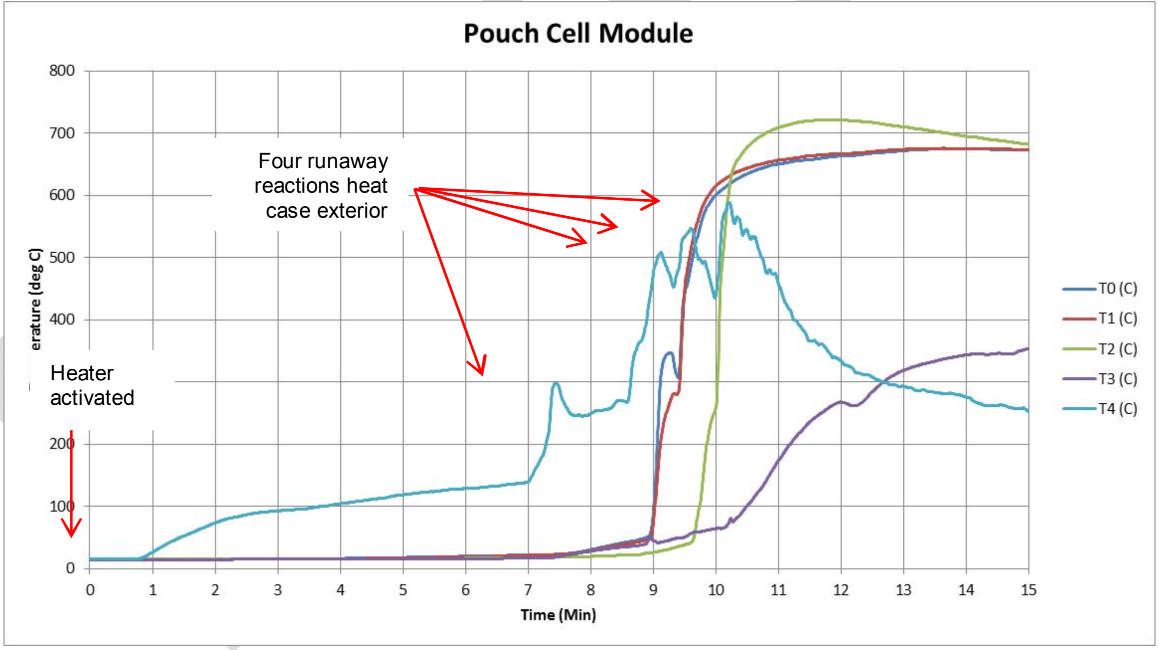

Figure 86 - Temperature traces for the Single Module Pouch Cell Trial.

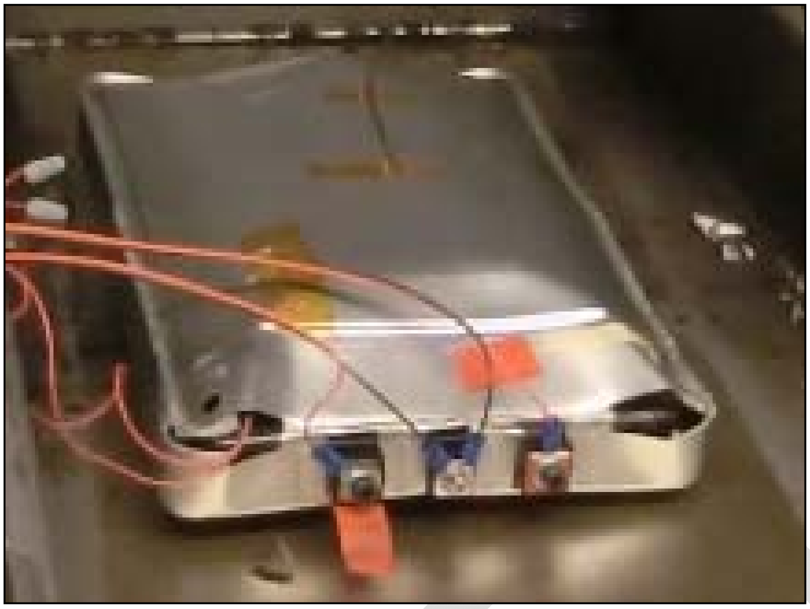

Figure 87 - Pouch cell module deformation.

8.2.6.2 Three Module Trial

The second module trial was conducted with three modules stacked on top of each other to replicate the battery pack configuration (Figure 88). The module with the installed heater was placed in the center of the stackup. The modules were held together using threaded rod inserted through the existing holes in the corners of the module. Metal bracing from the RESS unit was also installed to replicate the constraints on modules within the RESS.

Within the initiating module, all four cells were charged to 100% SOC. Adjoining cells in the adjacent modules were also charged to 100% SOC to study of propagation times between modules. The outermost cells in the stack-up were discharged. Thermocouples were placed in between each of the cells and between the module enclosures. The schematic of the test setup is shown in Figure 89: discharged cells are yellow, fully charged cells are orange, the heater is red, and the insulation is blue,

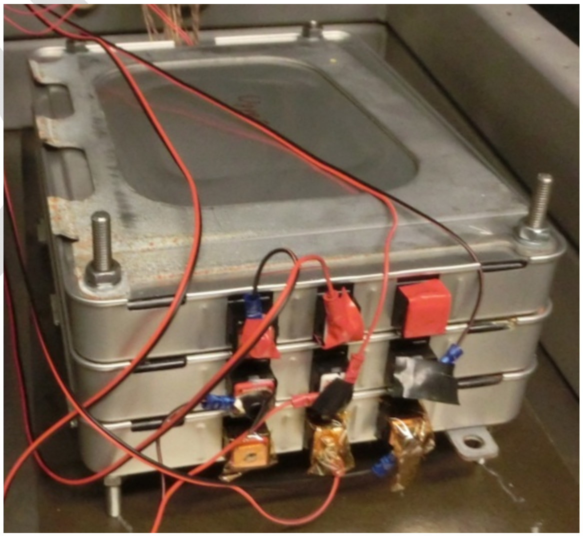

Figure 88 - Three Module Pouch Cell Test setup.

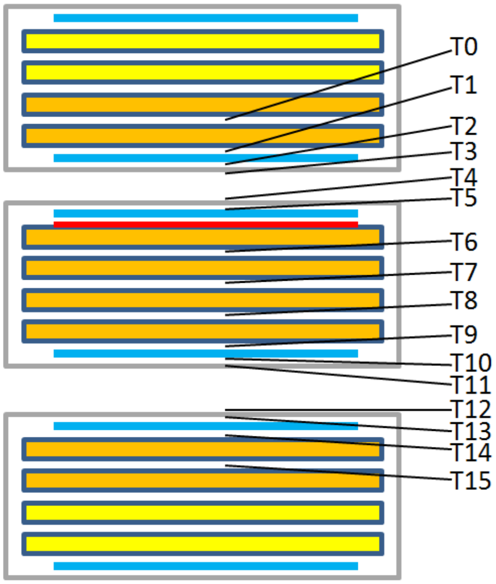

Figure 89 - Schematic of Three Module Pouch Cell Test.

The three module trial resulted in an initiator time to runaway of approximately 7½ minutes. The thermocouple traces for cells within the initiating module can be seen in Figure 90 (heating started about 1 ½ minutes after data). The neighboring cell temperatures increased by an average of 11°C prior to the initiation of the first cell. The maximum temperature reached inside of the module enclosure was 853°C, consistent with thermal runaway reaction temperatures. When the first cell went into thermal runaway and expanded, deformation of the case occurred. However, the degree of deformation was less than observed in a single module (Figure 92).

After the first cell underwent a thermal runaway reaction, adjacent cells within the same module also underwent thermal runaway, similar to the single module test. Vented gases ignited 6 minutes and 35 seconds after the first cell went into thermal runaway.

Thermal runaway propagated to the neighboring modules within approximately 10 minutes of thermal runaway initiation within the central module (Figure 91). The temperature traces show no change in slope at the time of ignition, therefore, it unlikely that the ignition of the runaway gases had significant effect on the thermal runaway of the cells in the neighboring modules.

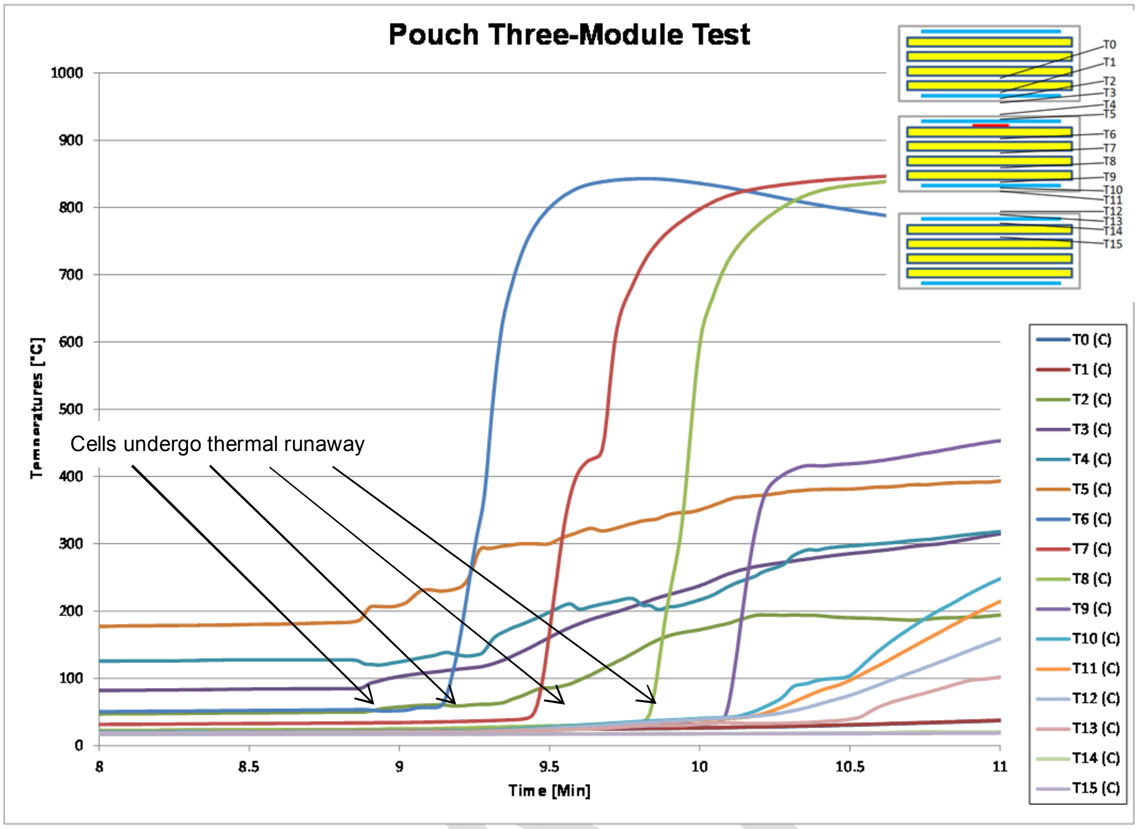

Figure 90 - Temperature traces for the center module.

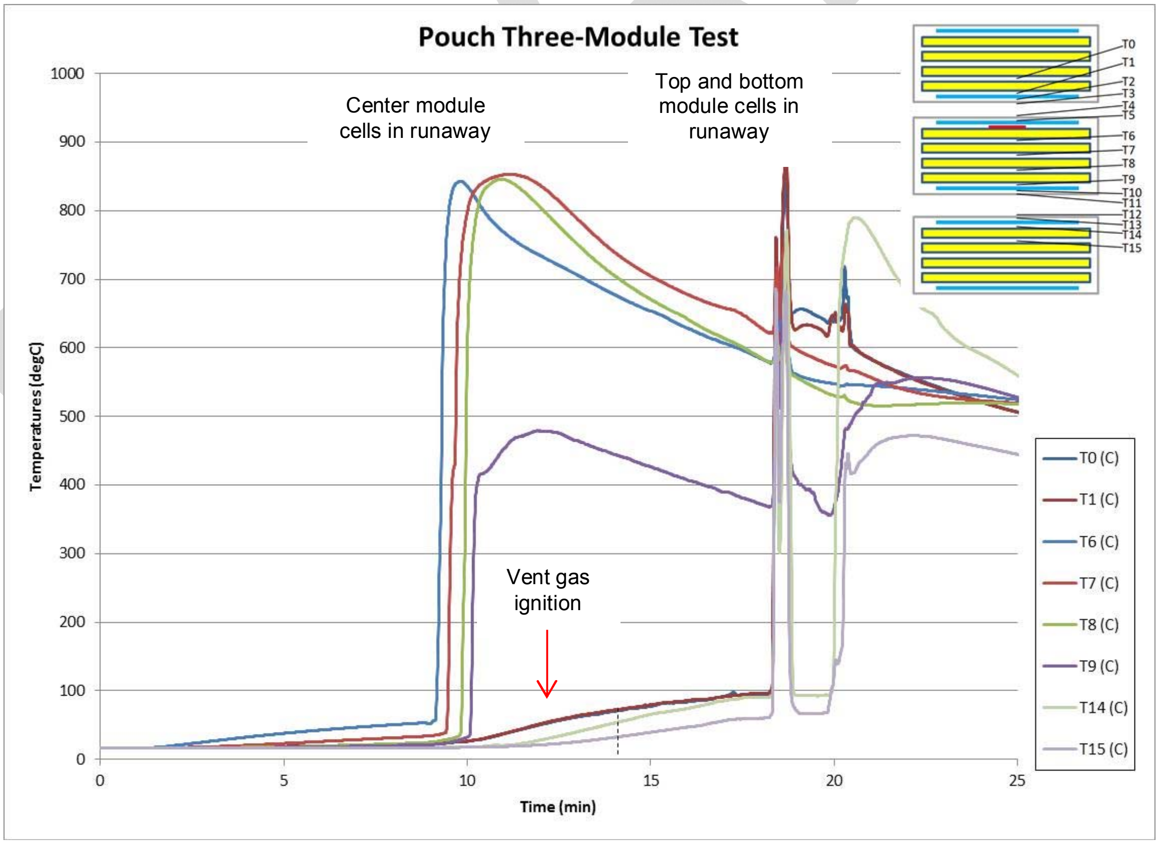

Figure 91 - Temperature traces for the neighboring modules.

Figure 92 - Deformation of pouch cell Three Module stack.

A summary of the pouch cell verification testing results is shown in Table 15. Based on the short and consistent time to thermal runaway and the small preheating effect on neighbor cells, this method this method was selected for the full scale vehicle SCTRI test

Table 15 - Summary of Manufacturer C polymer cell module level testing

Initiation Trial	Time to Runaway [Min]	Average Neighbor Cell Increase in Temperature During Heating of Initiator [C]	Neighbor Cell Maximum Temperature [C]	Energy Input / Energy of Cells in Parallel
Single Module	7 min	< 5 C	Thermal runaway occurred	0.11
3-Module Stack	7½ min	11 C	Thermal runaway occurred	0.12

8.3 Full Scale Vehicle SCTRI Testing Examples

For demonstrative purposes, full scale vehicle SCTRI tests were conducted with EVs that have implemented three types of lithium-ion cell form factors:

- Manufacturer A vehicle that includes a RESS built with small cylindrical cells;
- Manufacturer B vehicle that includes a RESS built with large, hard case prismatic cells; and
- Manufacturer C vehicle that includes a RESS built with large pouch cells.

Vehicles used for this testing had previously undergone NHTSA New Car Assessment Program (NCAP) crash testing. Although each vehicle's RESS appeared undamaged a result of previous crash testing, vehicle structures were no longer entirely representative of production vehicles. Thus, the following discussion should be used as a guide for conducting SCTRI testing, but the results of the testing may not accurately represent SCTRI performance of a non-crashed vehicle.

8.3.1 Manufacture A Vehicle: RESS Contains Small Cylindrical Cells

The RESS from Manufacturer A consisted of a large flat unit mounted to the floor of the vehicle. Within the RESS, small cylindrical cells were grouped into 14 modules. Cells within the modules were arranged in a single layer, with their long axis perpendicular to the ground (when the battery is mounted in the vehicle).

8.3.1.1 Manufacturer A SCTRI Test Specific Equipment

a. Off-the-shelf film heater: 0.5”x2” polyimide heater (McMaster-Carr Part # 35475K283).
b. Pass-throughs: Liquid-tight cord grips (McMaster-Carr Part # 6907K9).
c. Thermocouple DAQ: Data Translation MEASUREPoint DT8874.
d. Smoke Detector: First Alert P1000 Detector.
e. Gas Sensor: MultiRAE Lite Multi-Gas Detector, configured to measure oxygen, methane, carbon monoxide and % of LEL.

8.3.1.2 For this vehicle, a small film heater single cell initiation method was selected. A description of the selection process and rational for selection of this method can be found in Sections 8.1.5, and 8.1.6.

8.3.1.3 Verification testing of the selected cell initiation method was completed at both coupon and module levels. The results of this testing are described in Section 8.2.5.

8.3.1.4 Manufacturer A RESS Preparation Procedure

The RESS unit was removed from a vehicle that had undergone a frontal crash test per NCAP. Due to damage from the crash test, the vehicle’s onboard charging systems could not be used to charge the battery pack. Thus the battery pack was charged after it was removed from the vehicle. The pack was charged to 100% SOC in accordance with the manufacturer’s specifications.

The pack was opened; using chisels and pry bars to break the seal as shown in Figure 93. As a result, the battery pack covers were warped due to the removal process and new covers were obtained from the manufacturer.

Cell thermal runaway initiation location was chosen to be the most likely to result in propagation of thermal runaway and the most likely to affect cabin occupants. A module on the driver’s side near the front was chosen to target the most likely occupant position. A module was chosen that was surrounded by thinner cross members to allow for the worst-case propagation from the initiator module to a neighbor module: shorter conduction length, lower stiffness in bending if pressure or gas sealing became a factor.

Cell thermal runaway initiation location within a module was chosen based on the module architecture. A cell on the edge of the module was selected since an edge cell cannot radiate or conduct heat to multiple neighbor cells, and thus lower heat dissipation rates are expected than from a cell within the center of a module. Two cell initiation locations were chosen, one as a backup should initiation at the primary heater fail to result in a thermal runaway reaction.[14] Figure 94 shows the locations of the initiator cells within a specific module, and the location of the module within the RESS.

Figure 95 shows the heater. A minor modification was made to the plastic module case to allow the adhesive-backed heater to rest completely against the cell surface. This modification was similar to the modification made during module testing.

Thermocouples were installed at the initiating cell module and through-out the RESS interior (Figure 94). Thermocouples were installed near the initiating cell, at adjacent modules, and at the corners of the RESS. For test development and demonstrative purposes, more thermocouples were installed than would be required to conduct a SCTRI test per the procedure in Section 6.

Thermocouples were installed on module current collectors (Figure 96). While thermocouples attached directly to neighboring cells might have provided more accurate cell temperature measurements, that configuration would have been more difficult to achieve, would have been less repeatable across a variety of test labs, and would not have provided appreciably more useful information

The thermocouple beads were wrapped in polyimide tape to provide electrical insulation: while such insulation might not remain intact if a thermal runaway event occurs adjacent to the thermocouple, it will provide sufficient electrical insulation for non-propagated modules. In addition, electrically insulating thermocouple wires are important for safe test setup: if not electrically insulated, bare thermocouple ends might short circuit during setup or wire routing through grommets.

Figure 97 shows the thermocouple and heater wires as they exit the battery pack. The wires were routed along the center spine of the pack, and exited the front top cover. Thermocouple wires were routed through a liquid-tight pass-through: a nut and O-ring sealed the pass-through to the panel, and a constricting rubber sleeve sealed the wires to the pass-through.

Since contactors could not be operated by the vehicle itself (post-crash test), and access to the high-voltage chain was needed outside the enclosure to perform isolation tests, electrical leads were connected to the battery side of the contactors and run into a touch-safe connector through grommets in the enclosure. This connector (Figure 98) was subjected to further insulation and protection, and was treated with great care as it represented an always-live connection to the 350V battery pack.

The battery pack was sealed in accordance with the manufacturer's specifications (Figure 99). Since the original covers had been deformed during opening of the pack, replacement covers were obtained from the manufacturer. The pack-vehicle interface "blanket" was installed on top of the pack, with thermocouples fastened on top of that cover in order to monitor temperatures between the pack and the vehicle. The pack was filled with coolant per manufacturer specification via the fitting near the front top cover.

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[14] The module from the original pack was not suitable for initiation as the lower-range 60kWh battery purchased for the crash test did not contain the edge cells and the inner cells could not be accessed. Therefore, a module from the 85kWh battery was obtained from the manufacturer and used for this test.

Figure 93 - Opening the cylindrical pack.

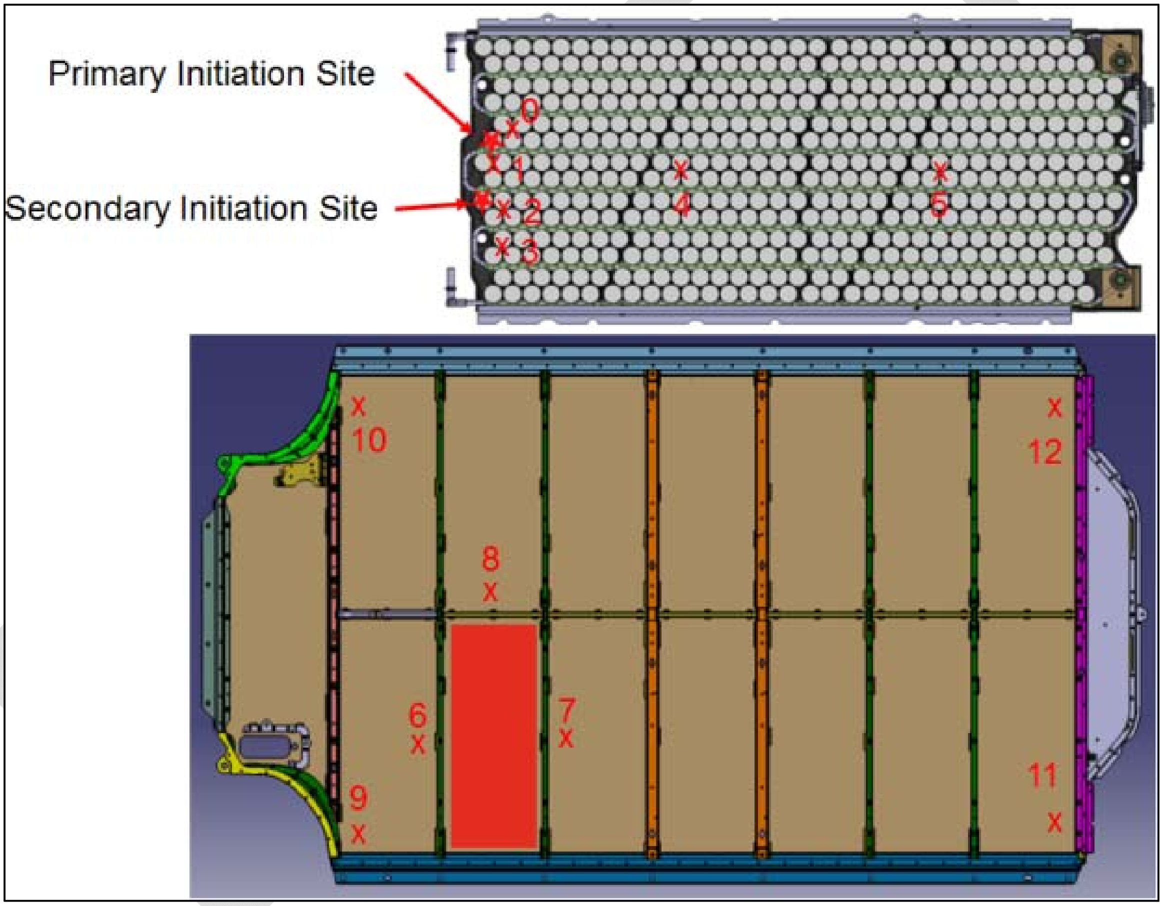

Figure 94 - Heater and thermocouple locations for the cylindrical battery pack.

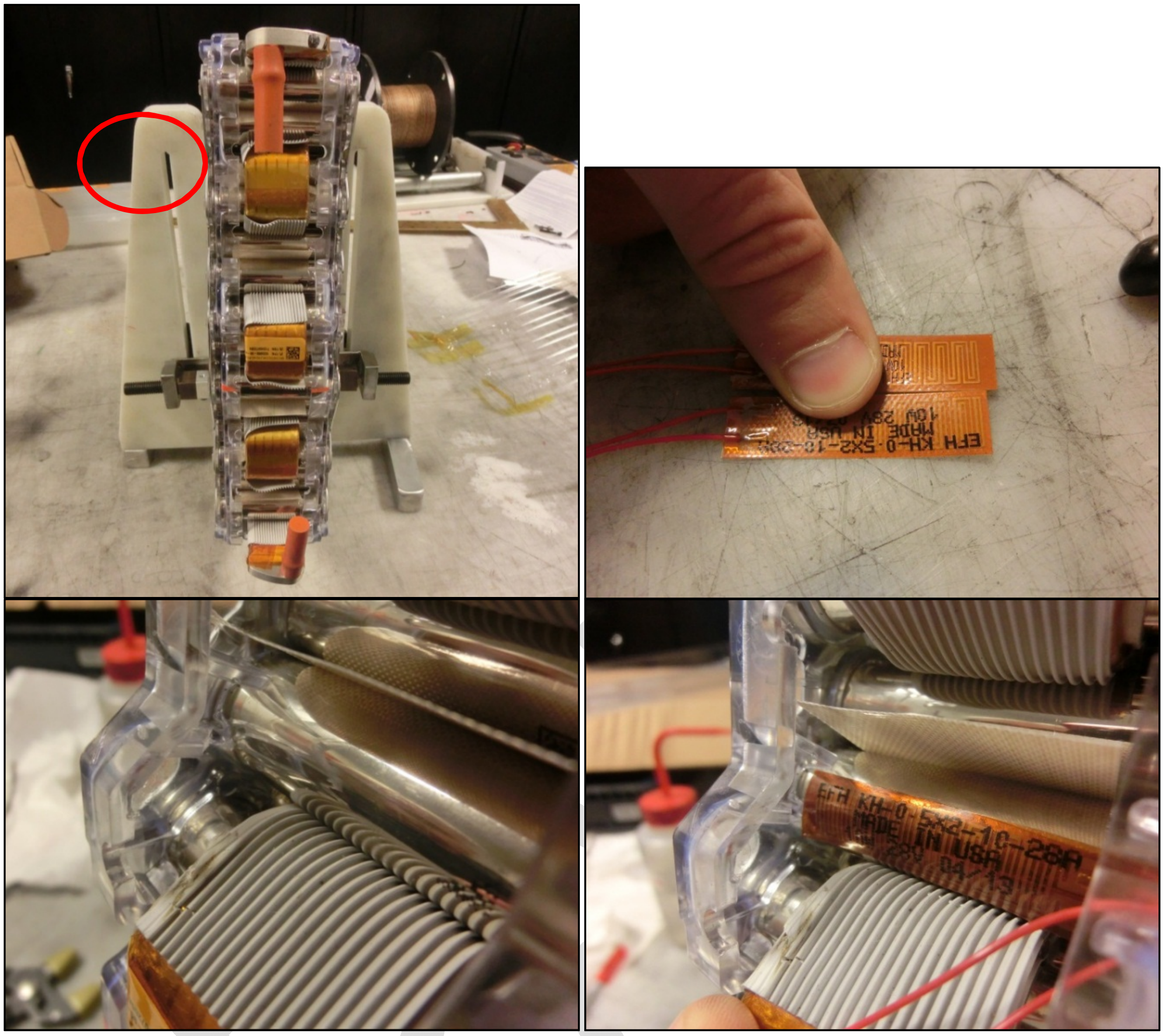

Figure 95 - Top left: the module on end. Top right: the 0.5"x2" heater, trimmed slightly to fit the module. Bottom left: a plastic rib trimmed to allow access for heater installation. Bottom right: the heater installed.

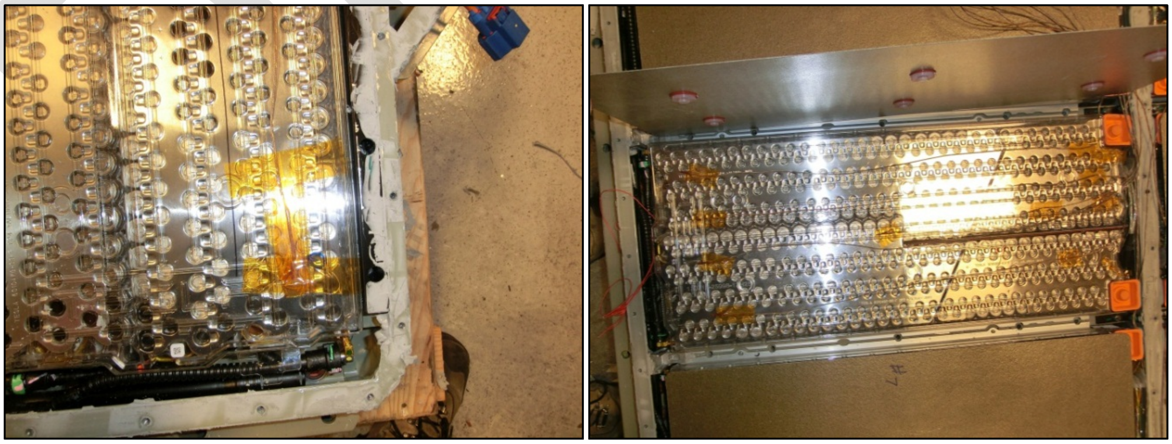

Figure 96 - Left: a thermocouple taped to the module current collector. Right: thermocouples attached to the initiator module, with the ends running towards the center of the pack.

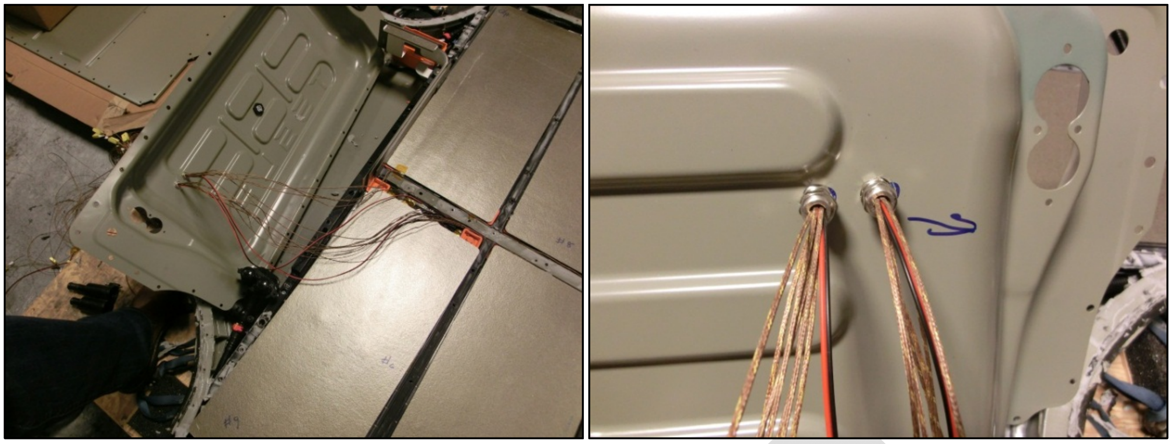

Figure 97 - The pass-through used for thermocouple and heater wires in the cylindrical battery pack.

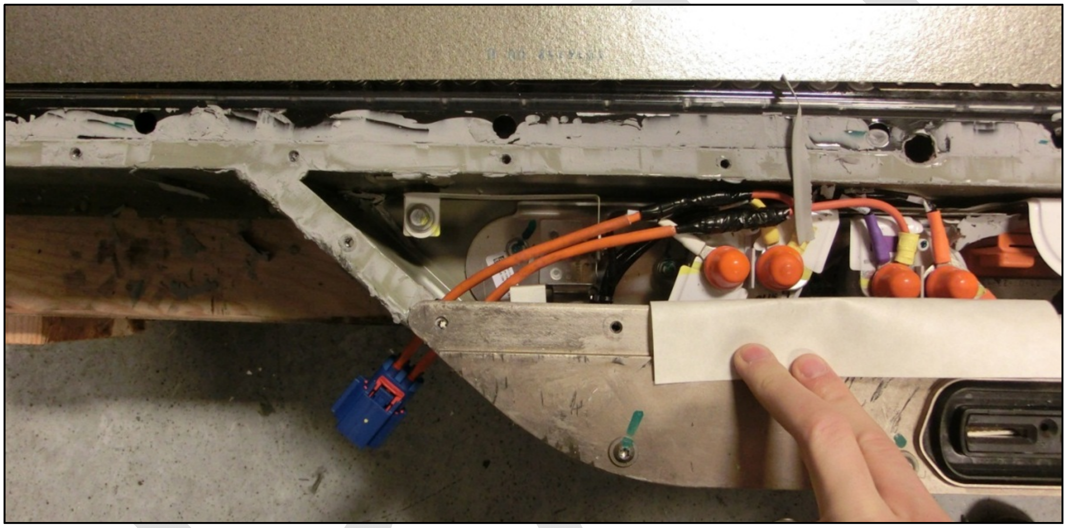

Figure 98 - The connector used for accessing the HV chain for isolation testing.

Figure 99 - The cylindrical battery pack, with sealant applied to seal the flat main cover to the front cover.

8.3.1.5 Manufacturer A Vehicle Preparation Procedure

The Manufacturer A vehicle used to demonstrate SCTRI testing is shown in Figure 100. This vehicle had previously undergone a frontal crash test per NCAP. The battery from this vehicle showed no signs of damage, other than having been opened and re-sealed following the crash-test.

The vehicle was prepared by removing unnecessary flammable material (Figure 101). Material was removed to limit the extent and intensity of any vehicle fire that might occur. However, flammable materials that might be important for understanding hazard to the occupant in the case of a propagating thermal runaway reaction were left in place. Flammables closest to the battery pack were left intact (carpets, bottom seats), as well as some materials at the top of the vehicle (portions of headliner), but many other materials were removed (dashboard and center console, seatbacks, headrests, door trim). To reduce the risk of projectiles during testing, all airbags that had not been deployed during the previous crash test were removed.

Thermocouples were installed in various remaining flammable materials: the seat cushions, on carpets, and in the headliner. They were also installed to measure air temperatures at occupant head locations. Diagrams of thermocouple locations are shown in Figure 102.

A photoelectric smoke alarm (First Alert P1000) was installed on the center of the dashboard to detect the presence of particulate inside the cabin. A probe for gas sampling was installed through the roof at the location of the driver's head.

In order to seal the cabin to allow measurement of gases that might enter the cabin from a thermal runaway reaction, windows that had been rolled down or were broken were covered with 0.010" clear plastic film.

The RESS was mounted and bolted to the underside of the vehicle. The connector to the high voltage in the RESS was carefully monitored, secured and protected.

Figure 100 - The frontal crash Manufacturer A vehicle used for the demonstration of SCTRI testing.

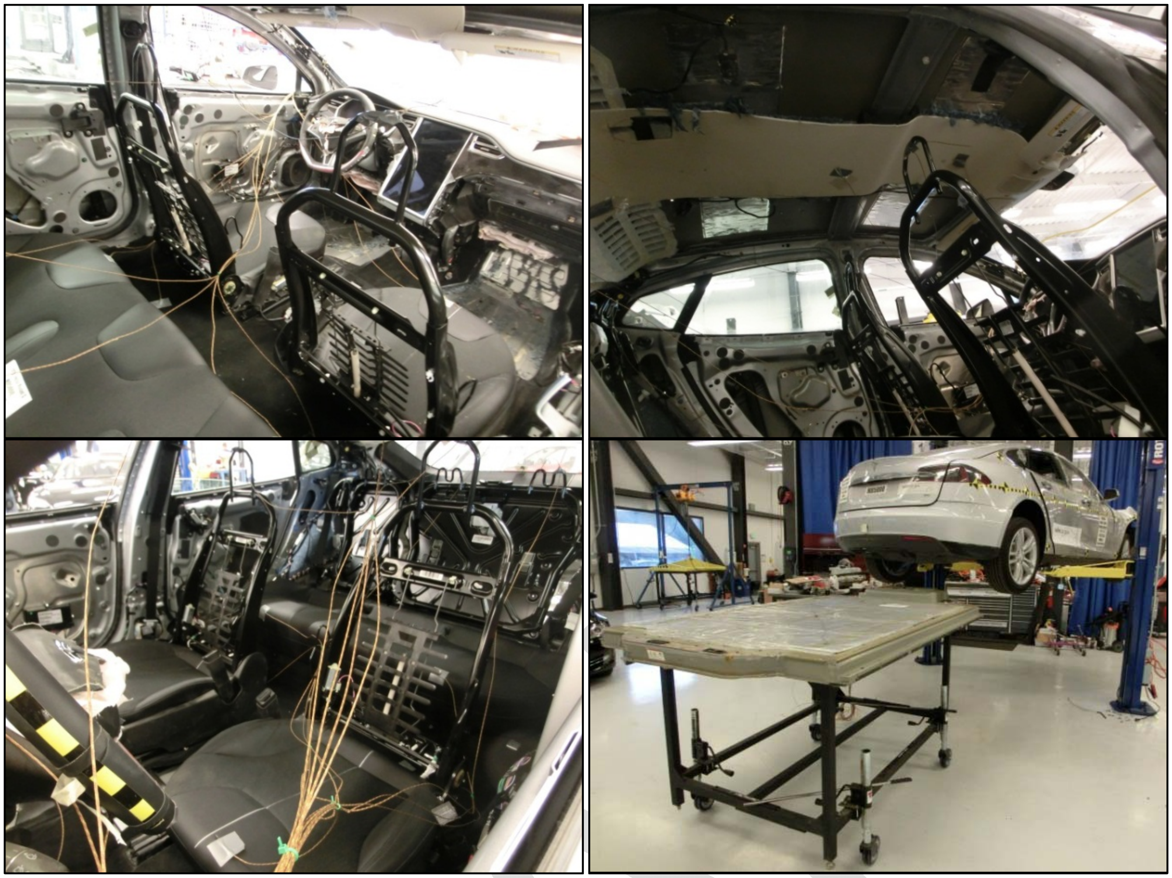

Figure 101 - Top left, top right, bottom left: flammables removed from the vehicle and thermocouples installed. Bottom right: the battery pack ready to be mounted to the vehicle.

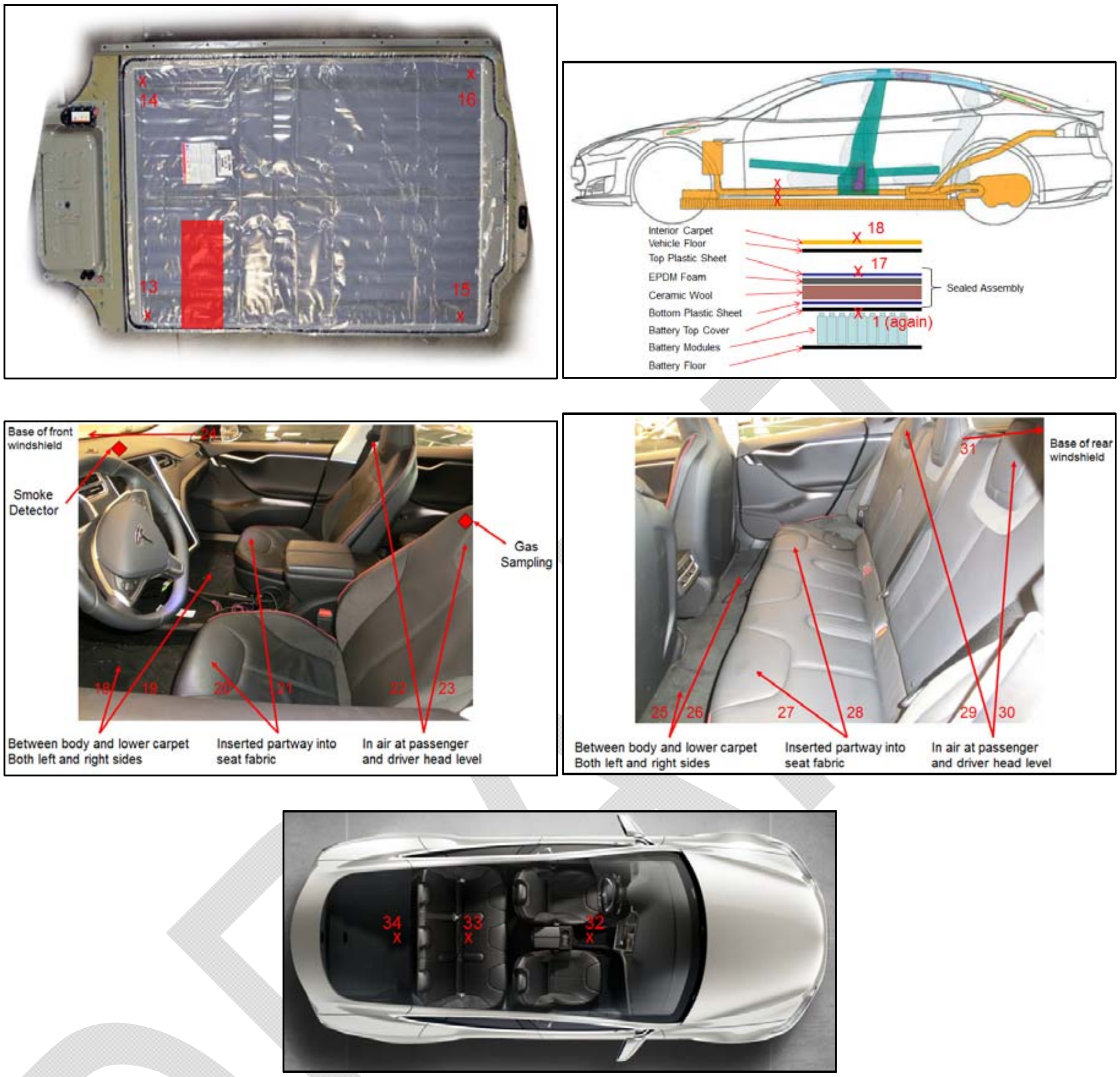

Figure 102 - Vehicle thermocouple locations for the Manufacturer A vehicle.

8.3.1.6 Manufacturer A Vehicle Preconditioning

At the test site, the vehicle was loaded into a thermal chamber to be preconditioned to 25°C. After a 12-hour soak, the pack was within 25°C±2°C. The vehicle was removed from the conditioning chamber and placed at the testing location. At the time of testing, the outdoor ambient temperature was 3°C.

8.3.1.7 Manufacturer A SCTRI Test Execution

Thermocouples and the gas sensor were connected to data logging equipment.

Battery voltage and isolation were measured with a handheld voltage and isolation meter. Dielectric Withstand Voltage was measured with a Hipot tester.

Video and data recording was started. A stopwatch was also started.

Once there was confirmation that video was being recorded and data signals were being properly logged, power was applied to the installed heater (47V, 0.6A, 28W, as determined from cell-level testing).

The vehicle was observed and audible or visible signs of a thermal runaway reaction were noted.

Once the initiating thermal runaway reaction was observed (via audible noise and a visual indication of gas escape from the pack – Figure 103), power to the heater was switched off.

Video and data were left recording until all thermocouple temperatures were decreasing and below 60°C.

Battery voltage and isolation were measured with a handheld voltage and isolation meter. Dielectric Withstand Voltage was measured with a Hipot tester. An external power supply was connected between the negative battery terminal and the enclosure and ramped up to 353V. The power supply remained connected for an hour, during which the RESS was monitored for any further thermal runaway reactions. After an hour the power supply was disconnected. Isolation and Dielectric Withstand Voltage tests were repeated.

8.3.1.8 Manufacturer A SCTRI Testing Results

The SCTRI test with Manufacturer A vehicle and RESS was conducted successfully. A summary of test results is provided in Table 16. Single cell thermal runaway initiation occurred after approximately 26 minutes, longer than required for single cell testing, likely due to interaction with the module components. A clear pop noise was heard and some grey smoke was seen exiting the battery pack near the initiator bay (Figure 103).The smoke subsided within a few seconds, and no further thermal runaway events were noticed. The smoke alarm inside the cabin did not trigger. There was no ignition of flammable gases.

Figure 104 shows the temperature measurements inside the initiation module bay as well as a plot of all the temperature measurements. At the same time the pop was heard and smoke was observed, the initiator bay temperatures momentarily jumped by 5-20°C. As expected, T0 and T1 increased the most due to their proximity to the initiator cell. Other temperatures not shown were flat throughout the test. All temperatures were steady, below 60 °C and declining after 20 minutes, after which data logging was stopped.

Gas composition measurements from inside the cabin at driver head level are shown in Figure 105. The oxygen, methane, and carbon monoxide concentration as well as the percentage of the LEL (Lower Explosive Limit) were measured. No deviation from ambient conditions (21% oxygen, no flammables) was recorded during or after the event. The smoke detector that was installed inside the cabin did not trigger. Based on the results from the gas sensor and smoke detector, it is unlikely that any run away gasses entered the passenger compartment.

Isolation resistance and Dielectric Withstand Voltage measurements before testing indicated that internal isolation of the RESS had not been significantly compromised by installation of test equipment. Isolation resistance and Dielectric Withstand Voltage were reduced after the initial cell thermal runaway, but a post-test exposure to elevated voltage did not cause any additional thermal events.

The battery pack was allowed to sit for approximately one month after conclusion of the test. No additional cells underwent a thermal runaway reaction.

Table 16 - Summary of Manufacturer A SCTRI Testing Results

Pre-test pack voltage	350 V
Pre-test Isolation – 1000V Handheld Isolation Resistance Meter	5.6 MOhm between the negative battery terminal and enclosure
Pre-test Dielectric Withstand Voltage – Hipot Tester	7.5mA current limit exceeded at 1.67kV (target was 1.7kV) a second test immediately afterward exceed the 7.5mA current limit at 1.18kV
Time to thermal runaway of initiating cell	25 minutes, 40 seconds
Energy input to heater as fraction of electrical energy in parallel group	0.01
Indication of initiation of thermal runaway	Audible sound, subsequent release of grey smoke from the battery pack
Time to cabin smoke alarm activation	Alarm did not activate
Time to second thermal runaway reaction	No additional thermal runaway reactions
Indication of second thermal runaway	No additional thermal runaway reactions
Time to flaming combustion	No ignition of combustibles
Post-test pack voltage	350 V
Post-test isolation – 1000V Handheld Isolation Resistance Meter	0 MOhm between the negative battery terminal and enclosure
Post-test Dielectric Withstand Voltage – Hipot Tester	7.5mA current limit was exceeded at 0.79kV
Isolation testing power supply maximum current	0.002A
Time to thermal runaway of additional cells	No additional thermal runaway reactions
Final isolation – 1000V Handheld Isolation Resistance Meter	0 MOhm between the negative battery terminal and enclosure
Final Dielectric Withstand Voltage – Hipot Tester	7.5mA current limit exceeded at 1.59kV

Figure 103 - Smoke escaping the battery pack as a result of thermal runaway of the initiating cell.

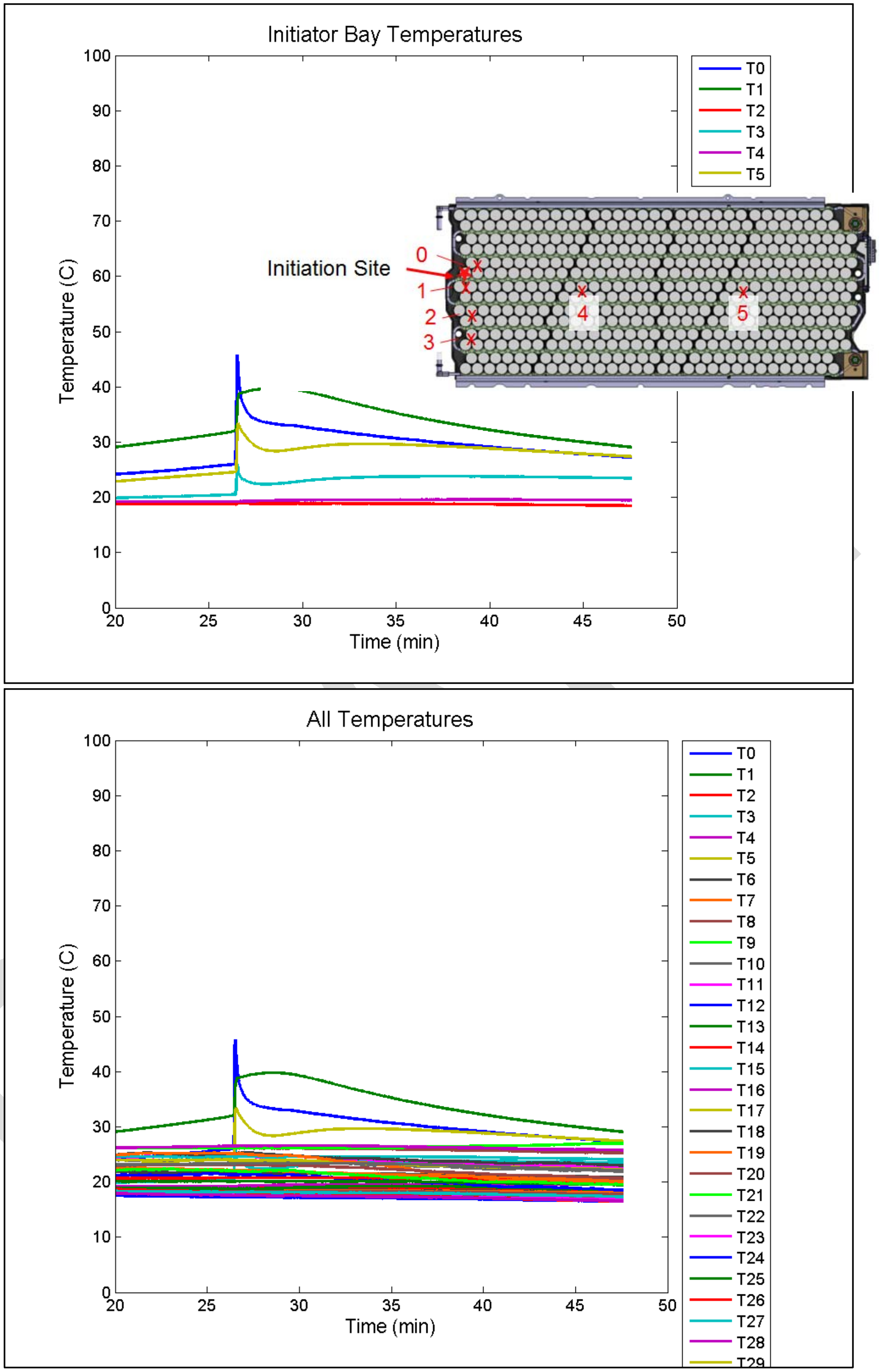

Figure 104 - Top: battery temperatures in the initiator bay. Bottom: all temperatures. Plots start at 20 minutes to crop out prior erroneous readings as thermocouple connections underwent troubleshooting.

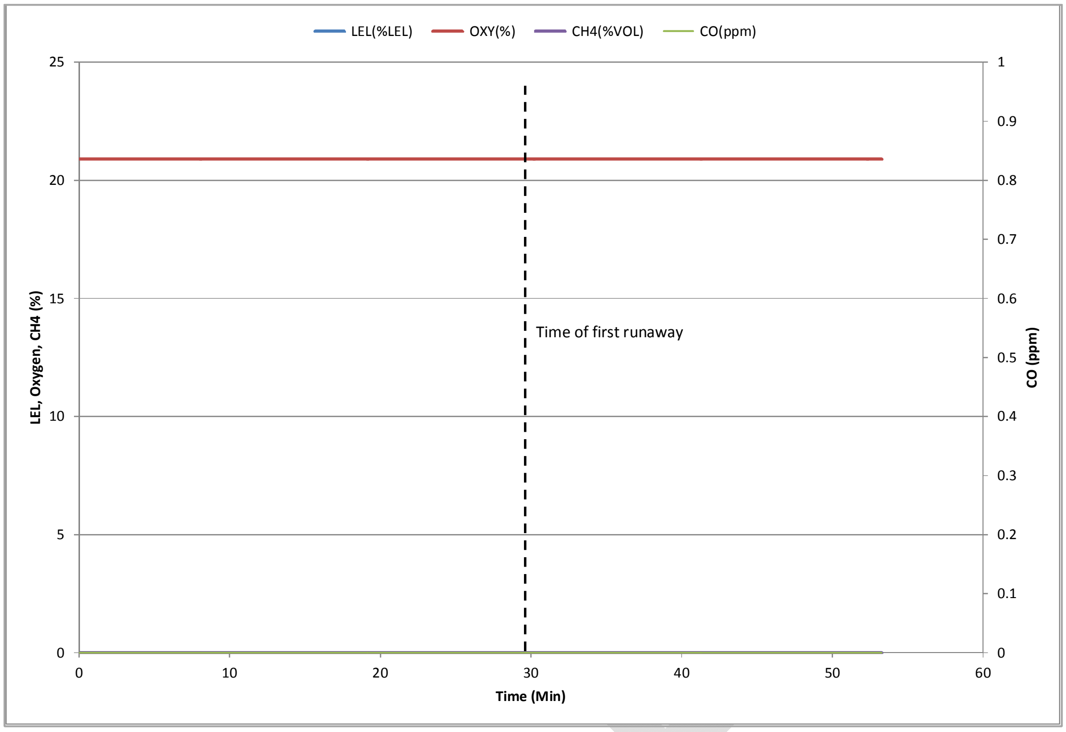

Figure 105 - Manufacturer A SCTRI testing, cabin air composition measurements.

8.3.2 Manufacture B Vehicle: RESS Contains Hard Case Prismatic Cells

The RESS from Manufacturer B consisted of a unit that was mounted to the floor of the vehicle. Within the RESS, hard case prismatic cells were arranged in “stacks” of 8 cells connected in series. Cells were arranged surrounding a central electronics area (Figure 106).

8.3.2.1 Manufacturer B SCTRI Test Specific Equipment

a. Off-the-shelf film heater: 4”x6” polyimide heater (McMaster-Carr Part # 35475K753).
b. Pass-throughs: Liquid-tight cord grips (McMaster-Carr Part # 6907K9).
c. Thermocouple DAQ: Data Translation MEASUREPoint DT8874.
d. Smoke Detector: First Alert P1000 Detector.
e. Gas Sensor: MultiRAE Lite Multi-Gas Detector, configured to measure oxygen, methane, carbon monoxide and % of LEL.

8.3.2.2 For this vehicle, a large film heater single cell initiation method was selected. A description of the selection process and rational for selection of this method can be found in Sections 8.1.7and 8.1.8.

8.3.2.3 Verification testing of the selected cell initiation method was coincident with single cell testing. The results of this testing are described in Section 8.1.8.

8.3.2.4 Manufacturer B RESS Preparation Procedure

The RESS unit was removed from a vehicle that had undergone a side impact crash test per NCAP. Due to crash test damage to the vehicle's charging system, the vehicle charging system could not be used and the battery pack was charged externally to the vehicle. Each of 8-cell stacks were removed from the battery pack, instrumented with voltage sense leads, and charged using the test lab's charger and battery management system. Cells were charged to 100% SOC per the cell manufacturer's specification.

After the cell stacks were fully charged, one of the stacks was disassembled and a single cell was removed. The yellow plastic insulation surrounding the cell was removed and a large film heater was attached to the face of the cell. The plastic insulation was replaced, and restrained using a small strip of polyimide tape (Figure 107). The cell was then re-assembled into a stack. This process was repeated with a second cell stack to prepare an alternate initiation location. Once both stacks were reassembled they were re-installed into the battery pack along with the other stacks.

Cell thermal runaway initiation location was chosen based on pack architecture. A cell on the edge of a stack was selected since an edge cell cannot radiate or conduct heat to multiple neighbor cells, and thus lower heat dissipation rates are expected than from a cell within the center of a stack. The heater was placed on the open side of the cell. If the heater was placed on the side of the cell facing the neighboring cell, it could potentially heat both cells simultaneously, causing excessive heating of a neighbor cell and /or alter the thermal boundary condition created by the neighbor cell. Edge located cells were chosen near the center electronics section of the battery pack as they were deemed more likely to propagate to the other side of the battery pack. Figure 106 shows the locations of the initiator cells (primary and auxiliary locations) for the prismatic cell battery pack.

Thermocouples were installed near the initiating cell(s), on an additional cell within the same stack, and at the corners of the RESS. Thermocouples were attached to cells by making a small incision in the plastic shrink wrap encasing the cells. and attaching the welded bead of the thermocouple to the cell with a small amount of adhesive (Figure 108). All of the thermocouple and heater wires were then routed through liquid-tight pass-throughs that had been threaded into tapped holes on the side of the battery pack (Figure 108).

The battery pack was closed and sealed. This battery pack was manufactured with a reusable seal and a bolt-on cover, so the original cover and seal were used to close the battery pack.

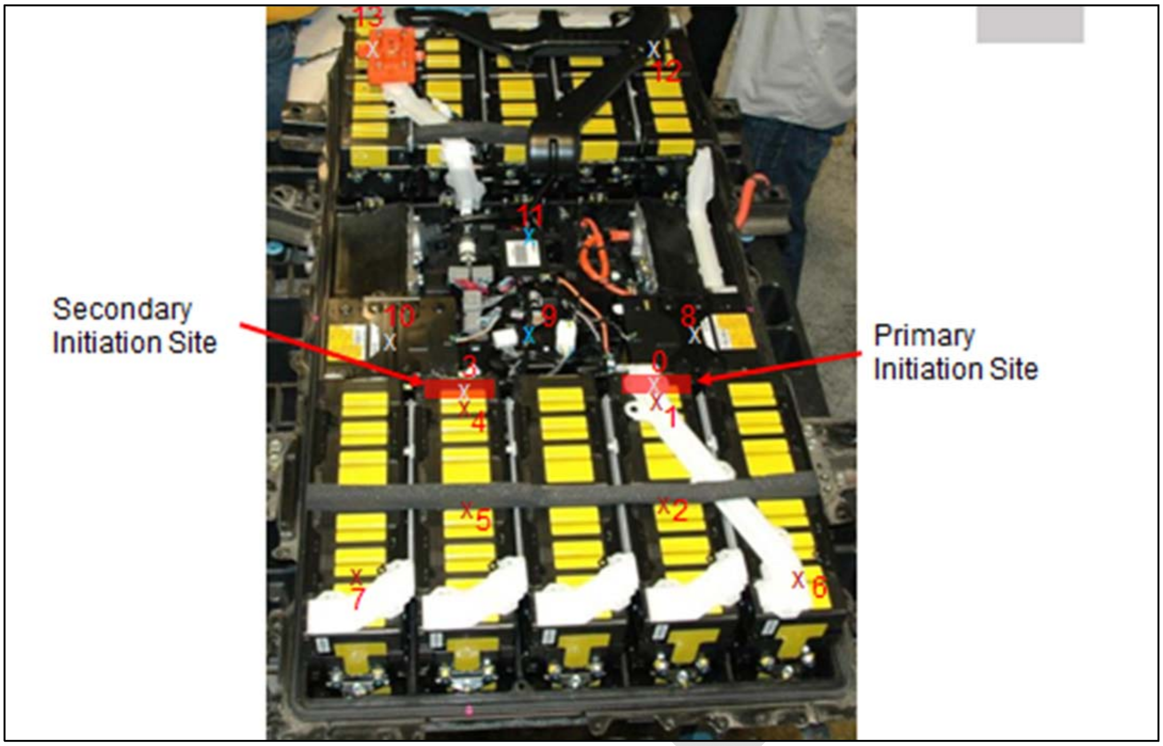

Figure 106 - Prismatic battery pack internal thermocouple and initiation locations.

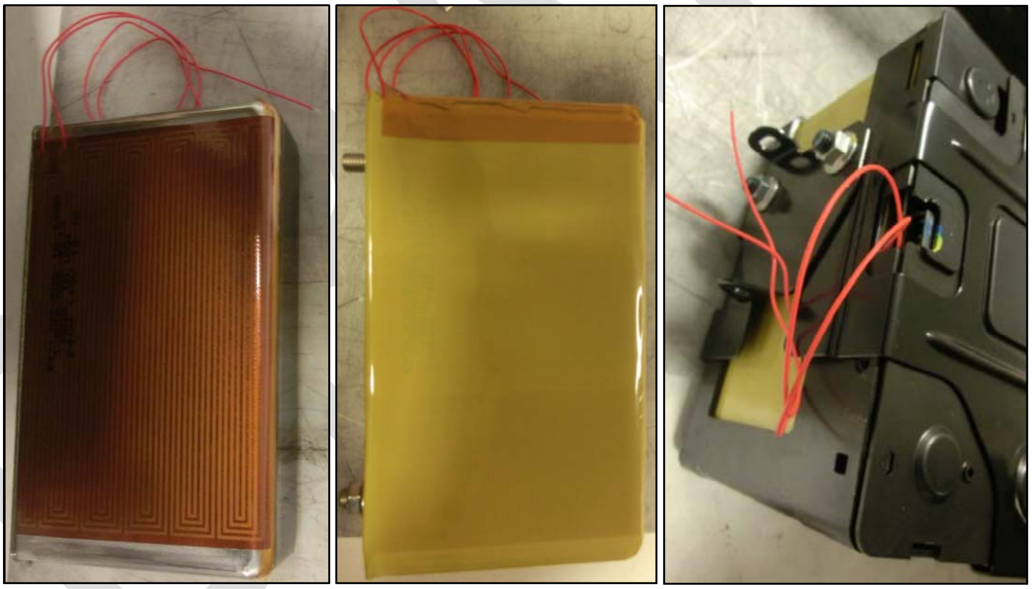

Figure 107 - Left: film heater attached to cell. Middle: plastic insulation reattached to cell. Right: cell reinstalled into stack.

Figure 108 - Left: thermocouple attached to a cell. Right: pass-throughs for thermocouples.

8.3.2.5 Manufacturer B Vehicle Preparation Procedure

The Manufacturer B vehicle used to demonstrate SCTRI testing is shown in Figure 109. This vehicle had previously undergone a side impact crash per NCAP. There was little to no damage from the side impact on the battery pack, although it had been opened and re-sealed following crash testing.

The vehicle was prepared by removing unnecessary flammable material (Figure 110). Material was removed to limit the extent and intensity of any vehicle fire that might occur. However, flammable materials that might be important for understanding hazard to the occupant in the case of a propagating thermal runaway reaction were left in place. Flammables closest to the battery pack were left intact (carpets, bottom seats), as well as some materials at the top of the vehicle (portions of headliner), but many other materials were removed (dashboard and center console, seatbacks, headrests, door trim). To reduce the risk of projectiles during testing, all airbags that had not been deployed during the previous crash test were removed.

Thermocouples were installed in various remaining flammable materials: the seat cushions, on carpets, and in the headliner. They were also installed to measure air temperatures at occupant head locations.

A photoelectric smoke alarm (First Alert P1000) was installed on the center of the dashboard to detect the presence of particulate inside the cabin. A probe for gas sampling was installed through the roof at the location of the driver’s head.

In order to seal the cabin to allow measurement of gases that might enter the cabin from a thermal runaway reaction, windows that had been rolled down or were broken were covered with 0.010” clear plastic film.

The RESS was mounted and bolted to the underside of the vehicle.

Figure 109 - Side impact Manufacturer B vehicle used for SCTRI testing

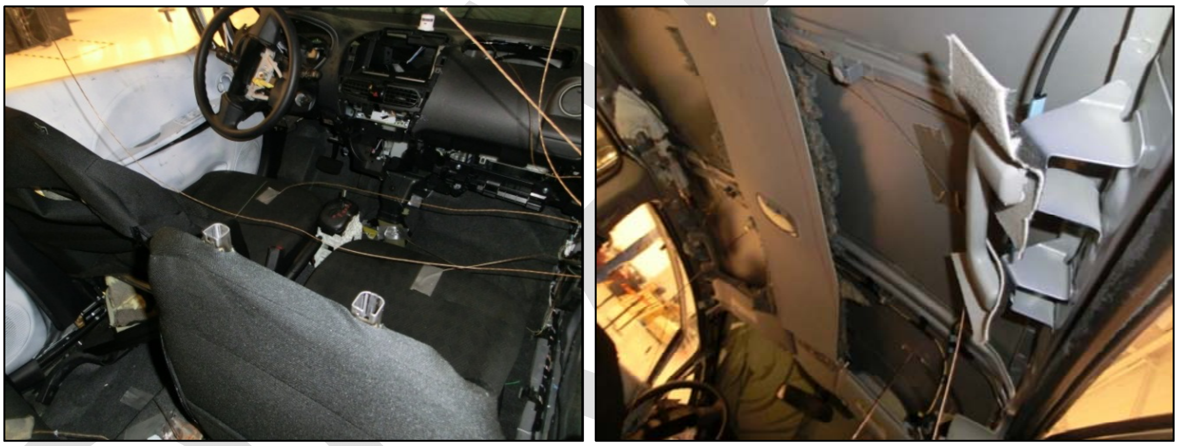

Figure 110 - Manufacture B vehicle interiors after flammables removal.

8.3.2.6 Manufacturer B Vehicle Preconditioning

At the test site, the vehicle was loaded into a thermal chamber to be preconditioned to 25°C. After a 6-hour soak, the pack was at 25±5°C. The vehicle was removed from the conditioning chamber and placed at the testing location.

8.3.2.7 Manufacturer B SCTRI Test Execution

The vehicle was set on cinderblocks and the tires were removed (for safety and flammability reasons).

Thermocouples and the gas sensor were connected to data logging equipment.

Video and data recording was started. A stopwatch was also started.

Once there was confirmation that video was being recorded and data signals were being properly logged, power was applied to the installed heater (120V, 1.9A, 228W, as determined from cell-level testing).

The vehicle was observed and audible or visible signs of a thermal runaway reaction were noted.

Once the initiating thermal runaway reaction was observed via audible noise and a visual indication of gas escape from the pack, power to the heater was switched off.

Video and data were left recording until all thermocouple temperatures were decreasing and below 60°C.

After the SCTRI test was complete, loss of isolation testing was attempted. Because the RESS had been damaged due to cell thermal runaway reactions, the driver's seat was cut away to access the service disconnect, which was removed and disassembled. A wire was soldered to the disconnect's internal busbar, and this was used instead of the negative or positive high voltage terminal for the high voltage side of isolation testing. An exposed metal portion of the vehicle near the driver's seat was used for the "enclosure" side: a bolt was removed, a ring terminal was inserted, and the bolt was re-installed.

The handheld isolation meter indicated 0.0MOhm of isolation, and the voltmeter indicated that the service disconnect busbar was approximately 120V above the vehicle potential. A Dielectric Withstand test was attempted, but the 7.5mA maximum current was achieved at 0.0kV, indicating that the loss of isolation had a very low resistance. The 1-hour power supply test was attempted, but upon making the connections, the voltage reading was slightly negative and the current value was at the saturation value: indicating that too much current was flowing even without the power supply providing additional voltage. The test was aborted to avoid over-current damage to the power supply.

8.3.2.8 Manufacturer B SCTRI Test Results

The SCTRI test with the Manufacturer B vehicle and RESS was conducted successfully. A summary of the results is provided in Table 17. Single cell thermal runaway initiation occurred after 11 minutes and 17 seconds: there was an audible popping noise followed by emission of a large amount of smoke from the underside of the vehicle (Figure 111). One minute later, the smoke alarm that was mounted on the dashboard inside the cabin was triggered. Approximately 10 minutes later the next cell underwent thermal runaway. Subsequent cells underwent thermal runaway in 4-5 minute intervals (Figure 112). A total 8 cells underwent thermal runaway during the test. The battery pack was allowed to sit for almost 3 hours after the last thermal runaway occurred as the remaining cells cooled. There was no ignition of flammable gases.

Figure 113 shows the temperature measurements inside the battery pack. After 11 minutes a large temperature spike can be seen from T0, attached to the initiator cell, indicating that the initiator cell underwent thermal runaway. Meanwhile, small temperature spikes can be seen from thermocouples on neighboring cells as the hot runaway gases pass over them. After the first cell went into runaway, temperatures at T1, attached to the neighboring cell started to climb, until that cell underwent thermal runaway. As subsequent cells, that did not have thermocouples attached to them underwent thermal runaway reactions, small temperature spikes were measured by more remotely located thermocouples.

During the events the battery cover was primarily heated above the initiation location (Figure 114). The cover exterior temperature peaked approximately 50 minutes after the initiating cell underwent thermal runaway. Inside the cabin, the rear carpet reached a peak temperature just below 40°C approximately 50 minutes after the initiating cell underwent thermal runaway (Figure 115). This was the only area in the cabin to show any significant increases in temperature.

Gas composition measurements from inside the cabin at approximately driver head level are shown in Figure 116. The oxygen, methane, and carbon monoxide concentration as well as the percentage of the LEL (Lower Explosive Limit) were measured. Almost immediately after the first cell underwent thermal runaway there was increase in the carbon monoxide concentration and %LEL. Carbon monoxide levels increased almost immediately to over 400 ppm. As a reference the Occupational Safety and Health Administration (OSHA) ceiling limit[15] for CO is 200 ppm. The carbon monoxide concentration and %LEL spikes closely follow the timing of the cell thermal runaway reactions runaways. During the time of the 7th and 8th runaway there is a noticeable drop in the oxygen concentration and an increase in the methane concentration. The %LEL, methane, and carbon monoxide reached maximums of 16%, 0.6%, and 1520 ppm, respectively. The oxygen concentration dropped from 20.9% to 20.5%. After the last cell went into runaway the levels of %LEL, methane, and carbon monoxide started to decrease.

Isolation measurement attempts after SCTRI testing showed that battery isolation to the enclosure had been severely compromised as a result of the cell thermal runaway reactions that occurred.

The battery pack was allowed to sit for approximately one month after conclusion of the test. No additional cells underwent a thermal runaway reaction.

Table 17 - Summary of Manufacturer B SCTRI Testing Results

Pre-test pack voltage	365V nominal[16]
Pre-test Isolation – 1000V Handheld Isolation Resistance Meter	Measurement not possible[9]
Pre-test Dielectric Withstand Voltage – Hipot Tester	Measurement not possible[9]
Time to thermal runaway of initiating cell	11 minutes 27 seconds
Energy input to heater as fraction of electrical energy in parallel group	0.25
Indication of initiation of thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to cabin smoke alarm activation	12 minutes 28 seconds
Time to second thermal runaway reaction	21 minutes 11 seconds
Indication of second thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to 3rd thermal runaway reaction	26 minutes 6 seconds
Indication of 3rd thermal runaway	Audible sound, subsequent release of smoke from the battery pack

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[15] The ceiling limit is the maximum concentration which a person may be exposed to at any time

[16] The Manufacturer B vehicle was non-functional and thus could not be used to charge the RESS before testing, measure voltage, or self-check isolation resistance. To charge the RESS, groups of modules were removed from the RESS and charged independently, then reassembled into the RESS: voltages of bricks were measured during charge and pack preparation. The testing agency chose not to install voltage measurement leads into the battery pack to ensure that such leads could not be a source of arcing within the RESS during the SCTRI test. Thus, once the pack was closed, there was no straightforward way to measure pack voltage, isolation resistance, or perform dielectric withstand testing.

Time to 4th thermal runaway reaction	31 minutes10 seconds
Indication of 4th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to 5th thermal runaway reaction	38 minutes 59 seconds
Indication of 5th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to 6th thermal runaway reaction	43 minutes 57 seconds
Indication of 6th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to 7th thermal runaway reaction	49 minutes 3 seconds
Indication of 7th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to 8th thermal runaway reaction	53 minutes 27 seconds
Indication of 8th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to flaming combustion	No ignition of combustibles
Post-test pack voltage	Accurate measurement was not possible due to burned string of cells
Post-test isolation – 1000V Handheld Isolation Resistance Meter	0.0 MOhm between the negative service disconnect terminal and enclosure
Post-test Dielectric Withstand Voltage – Hipot Tester	7.5mA current limit was exceeded at 0.0 kV - large loss of isolation
Isolation testing power supply maximum current	Test aborted
Time to thermal runaway of additional cells	n/a test aborted
Final isolation – 1000V Handheld Isolation Resistance Meter	n/a test aborted
Final Dielectric Withstand Voltage – Hipot Tester	n/a test aborted

Figure 111 - Left: smoke starting during first runaway. Right: peak smoke emission during the first runaway.

Figure 112 - Darkest smoke during the seventh runaway.

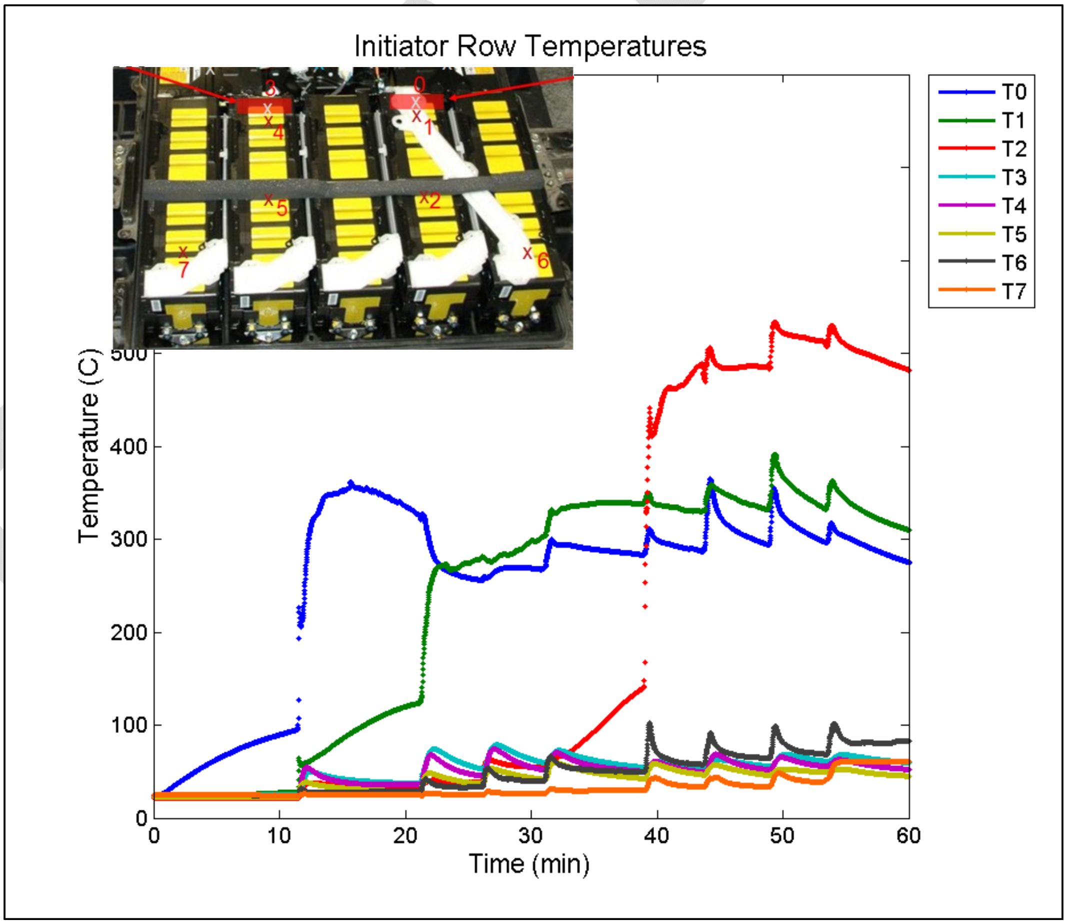

Figure 113 - Temperatures near the initiation location.

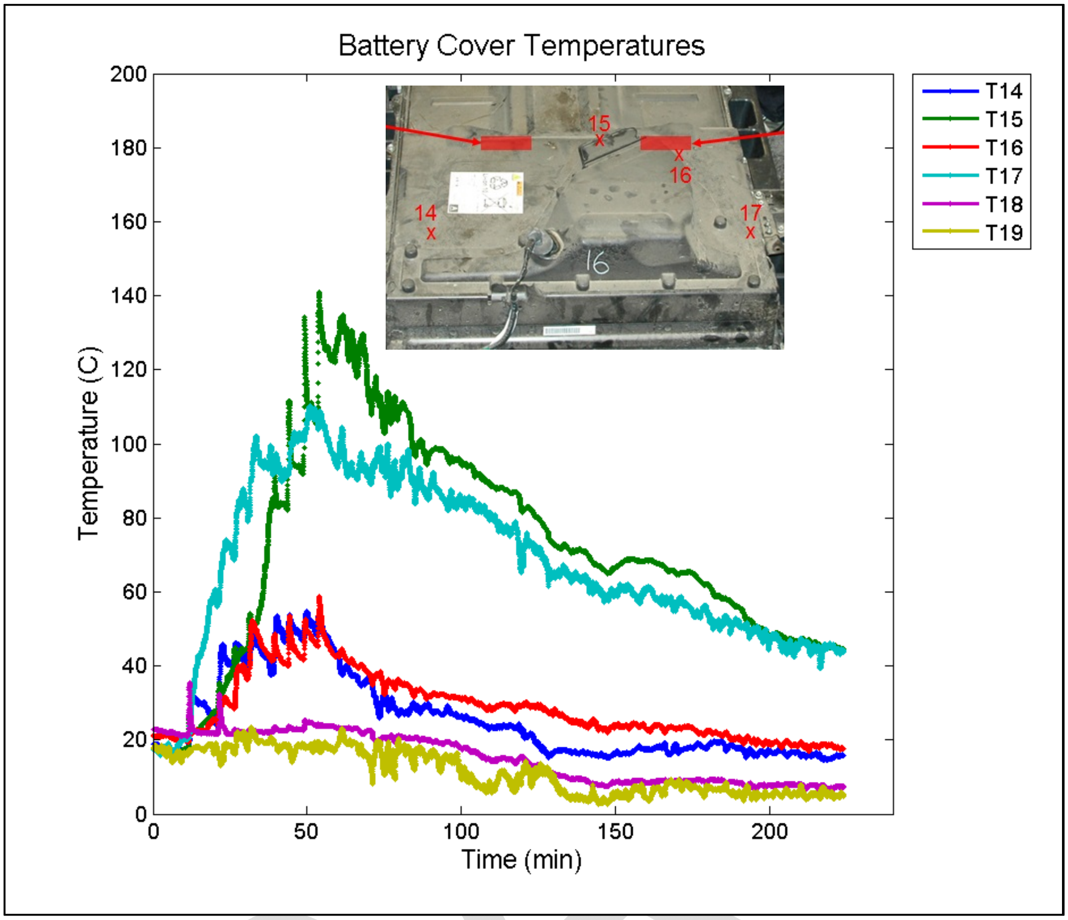

Figure 114 - Battery cover temperatures.

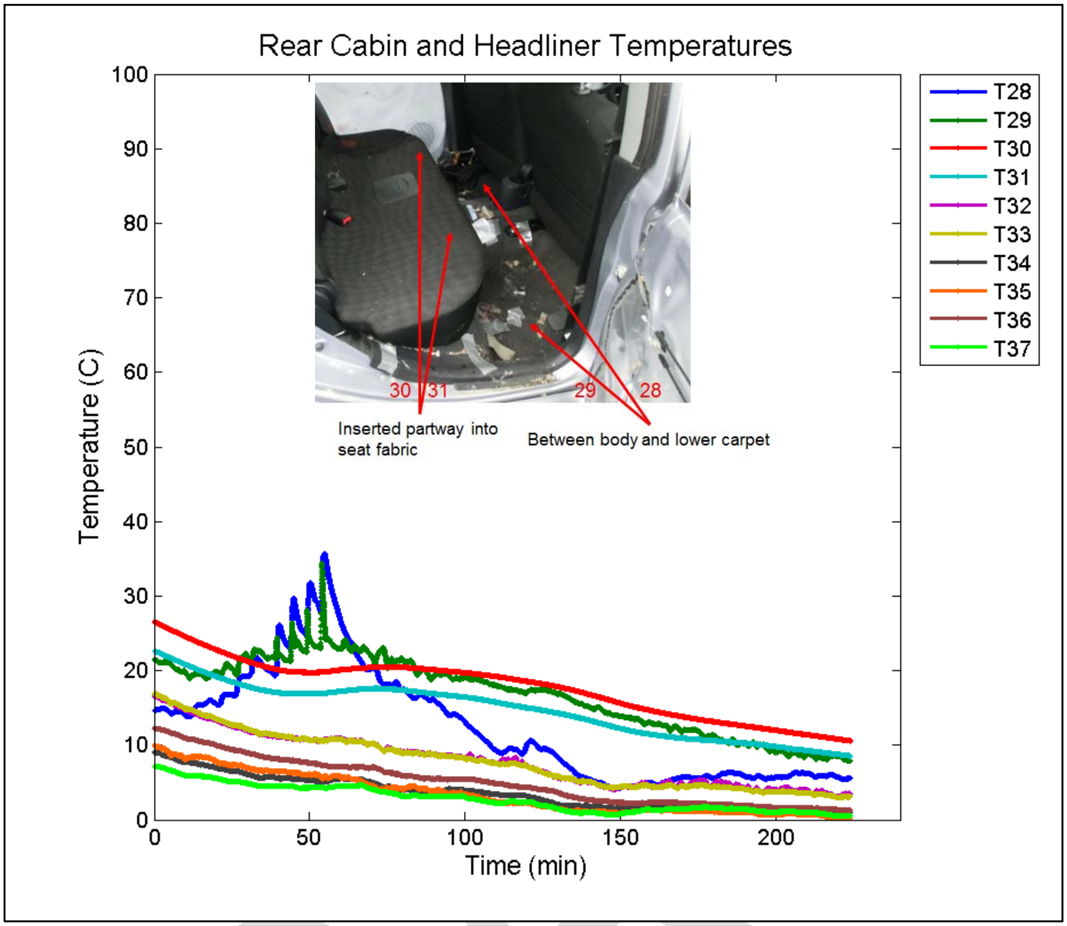

Figure 115 - Rear cabin and headliner temperatures.

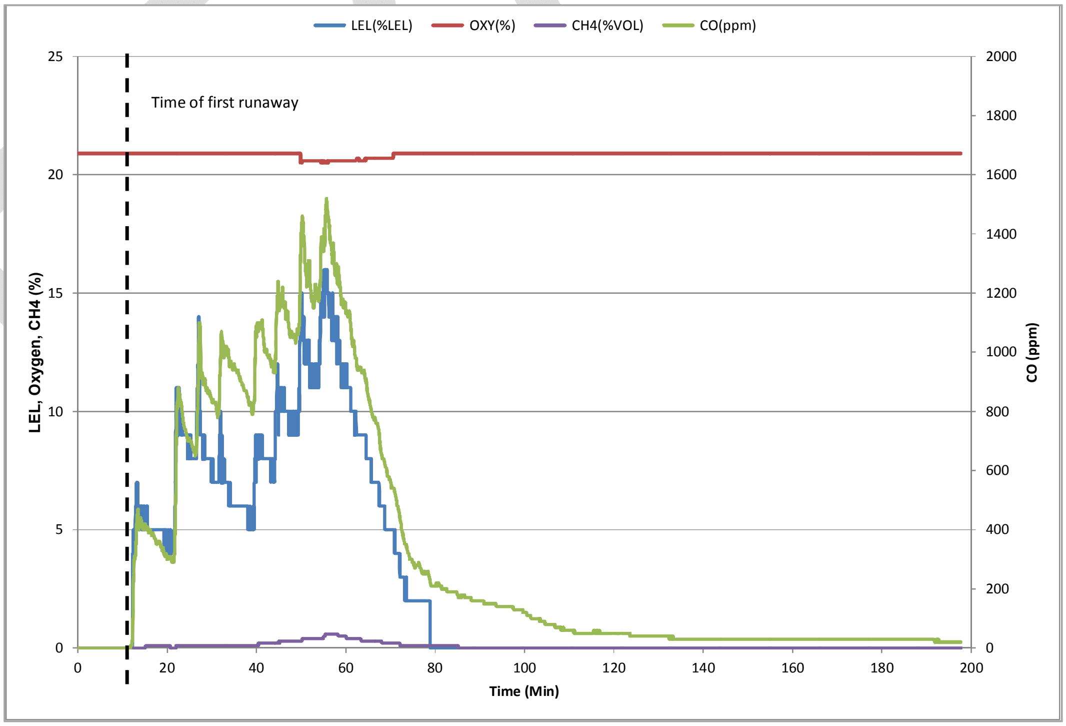

Figure 116 - Manufacturer B SCTRI testing, cabin air composition measurements.

8.3.3 Manufacturer C: RESS Contains Pouch Cells

The RESS from Manufacturer C consisted of a unit that was mounted to the floor of the vehicle. Within the RESS, pouch cells were arranged in groups of 4 within modules. The modules were arranged in various groupings throughout the pack (Figure 117).

8.3.3.1 Manufacturer C SCTRI Test Specific Equipment

a. Off-the-shelf film heater: 4”x6” polyimide heater (McMaster-Carr Part # 35475K753).
b. Pass-throughs: Liquid-tight cord grips (McMaster-Carr Part # 6907K9).
c. Thermocouple DAQ: Data Translation MEASUREPoint DT8874.
d. Smoke Detector: First Alert P1000 Detector.
e. Gas Sensor: MultiRAE Lite Multi-Gas Detector, configured to measure oxygen, methane, carbon monoxide and % of LEL.

8.3.3.2 For this vehicle, a large film heater single cell initiation method was selected. A description of the selection process and rational for selection of this method can be found in Sections 8.1.9 and 8.1.10.

8.3.3.3 Verification testing of the selected cell initiation method was completed at two coupon levels. The results of this testing are described in Section 8.2.6

8.3.3.4 Manufacturer C RESS Preparation Procedure

The RESS unit was removed from a vehicle that had undergone a frontal crash test per NCAP. Due to damage from the crash test, the vehicle’s onboard charging systems could not be used to charge the battery pack. Thus the battery pack was charged after it was removed from the vehicle. The communication protocols for the battery management system were unknown, and thus the integrated sense voltage leads could not be used to monitor full pack charging. Instead, modules were removed from the battery pack in groups. Each group of modules was instrumented with sense leads at every module terminal and charged with the test lab’s charger and battery management system. The pack was charged to 100% SOC in accordance with the cell manufacturer’s specifications.

Because of the application of a strong adhesive sealant, the battery pack was opened using pry tools and hammers. The cover suffered minor local deformations as shown in Figure 118, but these were flattened and the cover was later resealed with generous application of sealant.

The cell thermal runaway initiation location was chosen to be the most likely to result in propagation of thermal runaway. A module in the center of the rear stack was chosen as a worst-case initiation location (Figure 117), since it would be in close thermal contact with a large number of contiguous cells and offer the greatest chance for propagating across air gaps. Since the initiation method involved a large flat heater, a cell at the edge of a module was chosen for initiation. Placing the heater between cells in a module would likely heat them both and potentially initiate thermal runaway in two cells rather than one. This initiation method had been subjected to verification testing (Section 8.2.6).

Figure 119 shows the heater installation. After pack opening and selective bus bar removal, the rear stack of 24 modules was removed from the pack. Two modules were removed from this stack, and one edge of the sheet metal case was folded up for access. The 4”x6” heater pad had its adhesive backing removed, and then was slid between the cell and the insulator. The case was then folded back flat. A second module was prepared as an auxiliary initiator in case the first initiator failed to achieve thermal runaway.

Thermocouples were applied as shown in Figure 120. Each thermocouple bead was wrapped in polyimide tape to provide electrical insulation from module components and ensure that there would not be a safety hazard if bare thermocouple leads were to come into electrical contact. Each taped thermocouple bead was inserted between the center two cells of each module indicated in Figure 117. Implanting the sensors inside modules, shielded the sensors from transient heating due to the flow of hot gas from nearby thermal runaway reactions. The leads were routed out through liquid-tight pass-throughs, which had been threaded into tapped holes in the flange containing the HV connector, and sealed with an O-ring.

The pack was sealed as in Figure 121, which shows the generous application of Three Bond RTV sealant in place of the original cover adhesive, which had been peeled away during opening and was no longer tacky. A sufficient amount of Three Bond was used to fill any imperfections in the outer edge of the cover, which had been locally deformed during removal. The sealant was allowed a week to dry before testing continued.

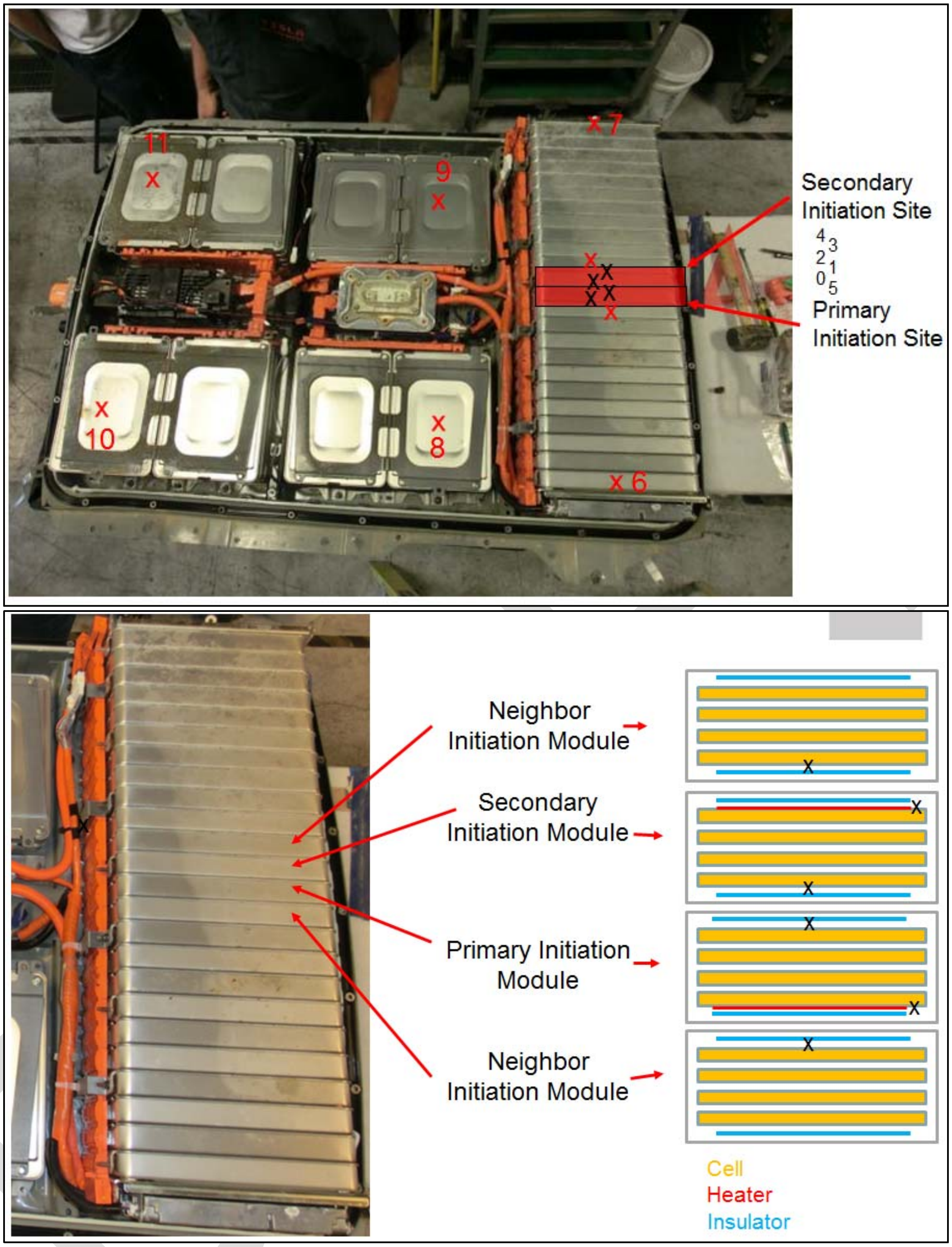

Figure 117 - The thermocouple and heater map for the pouch cell battery pack. For TCs 8-11, the top module in the stack was instrumented. Except where indicated, TCs are between the two center cells in the module.

Figure 118: The cover after removal from the battery pack.

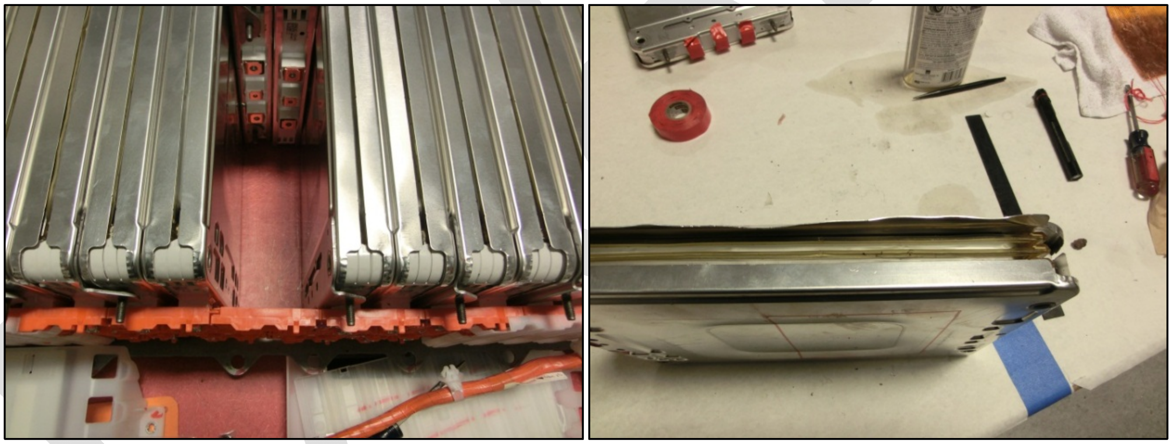

Figure 119 - Left: modules were removed from the center of the rear stack. Right: A flap of the sheet metal case was folded up for heater installation access. Red marker on the bottom case indicates the projection of the heater pad.

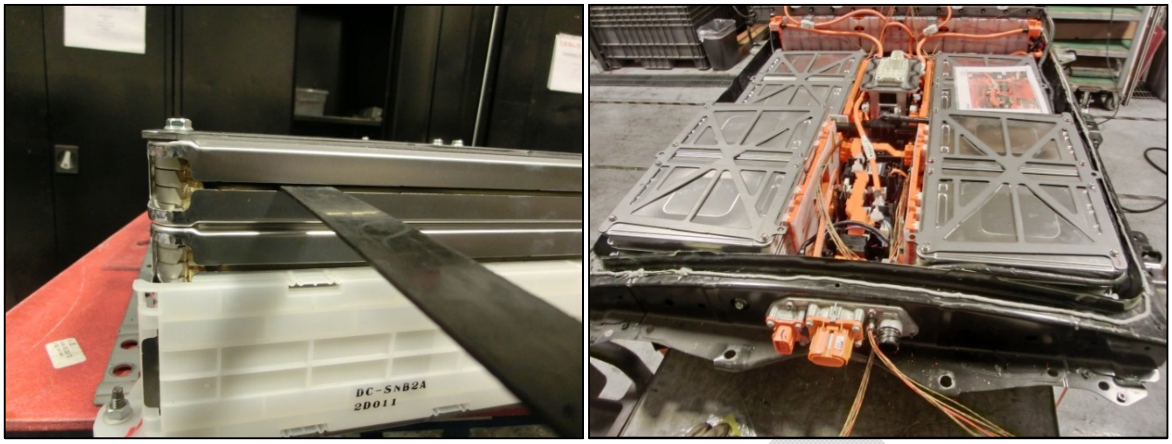

Figure 120 - Left: plastic strip used between the center two cells in a module to install a thermocouple. Right: all thermocouples routed through the pack, exiting through grommets, and the pack with a bead of sealant applied around the perimeter.

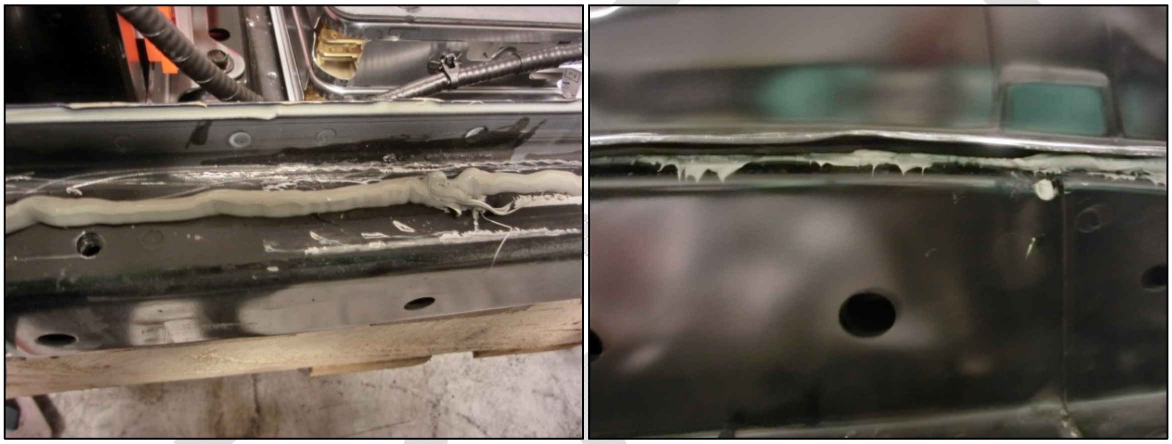

Figure 121 - Left: the generous silicone bead applied to the perimeter of the battery pack to compensate for the missing adhesive. Right: squeeze-out filling local deformations in the cover.

8.3.3.5 Manufacturer C Vehicle Preparation Procedure

The Manufacturer C vehicle used to demonstrate SCTRI testing is shown in Figure 122. This vehicle had previously undergone a frontal crash per NCAP. There was little to no damage from the impact on the battery pack, although it had been opened and re-sealed following crash testing.

The vehicle was prepared by removing unnecessary flammable material (Figure 123). Material was removed to limit the extent and intensity of any vehicle fire that might occur. However, flammable materials that might be important for understanding hazard to the occupant in the case of a propagating thermal runaway reaction were left in place. Flammables closest to the battery pack were left intact (carpets, bottom seats), as well as some materials at the top of the vehicle (portions of headliner), but many other materials were removed (dashboard and center console, seatbacks, headrests, door trim). To reduce the risk of projectiles during testing, all airbags that had not been deployed during the previous crash test were removed.

Thermocouples were installed in various remaining flammable materials: the seat cushions, on carpets, and in the headliner. They were also installed to measure air temperatures at occupant head locations.

A photoelectric smoke alarm (First Alert P1000) was installed on the center of the dashboard to detect the presence of particulate inside the cabin. A probe for gas sampling was installed through the roof at the location of the driver's head.

In order to seal the cabin to allow measurement of gases that might enter the cabin from a thermal runaway reaction, windows that had been rolled down or were broken were covered with 0.010" clear plastic film.

The RESS was mounted and bolted to the underside of the vehicle.

Figure 122 - The Manufacturer C frontal crash vehicle used for the test.

Figure 123 - The Manufacturer C vehicle, with thermocouples installed and many flammable materials removed.

8.3.3.6 Manufacturer C Vehicle Preconditioning

Once transported to the test site, the vehicle was loaded into the thermal chamber to be pre-conditioned. After a 24-hour soak, the pack had reached 35°C. The vehicle was removed from the thermal chamber and allowed to sit in the 5°C outdoor environment for 2 hours to cool to 30°C.

8.3.3.7 Manufacturer C SCTRI Test Execution

The vehicle was set on cinderblocks and the tires were removed (for safety and flammability reasons).

Thermocouples and the gas sensor were connected to data logging equipment.

Video and data recording were started. A stopwatch was also started.

Once there was confirmation that video was being recorded and data signals were being properly logged, power was applied to the installed heater (120V, 1.8A, 216W, as determined from cell-level testing).

The vehicle was observed and audible or visible signs of a thermal runaway reaction were noted.

Once the initiating thermal runaway reaction was observed (via audible noise and a visual indication of gas escape from the pack –Figure 124), power to the heater was switched off.

Video and data were left recording until the event was deemed complete, for this test when all cells were consumed and the resulting fire was subsiding.

8.3.3.8 Manufacturer C SCTRI Test Results

The SCTRI test with the Manufacturer C vehicle and RESS was conducted successfully. A summary of the results is provided inTable 18.

Single cell thermal runaway initiation occurred after 6 minutes 55 seconds of heating (Figure 124). There was an audible noise followed by emission of smoke from the underside of the vehicle. Three additional thermal runaway events occurred in the module occurred over the next 90 seconds. About 7 minutes later, a similar event (four thermal runaway reactions in rapid succession) was observed, followed by more events at increments between 2 minutes and 5 seconds, resulting in a steady smoke stream exiting the rear of the vehicle. At approximately 20 minutes, the smoke alarm within the vehicle activated. At 23 minutes, ignition of the vent gases occurred (Figure 125). Burning vent gases ignited the vehicle rear bumper. The cell runaways and vehicle fire continued, and flames were observed inside the cabin at approximately 28 minutes. The fire continued until approximately 50-55 minutes after heater initiation (Figure 126).

Temperature histories of the initiator modules are shown in Figure 127. Thermocouple T0, which was attached to the initiator cell, measured a steady rise in temperature as the nearby cell surface was heated, until approximately 7 minutes when the first cell underwent a thermal runaway reaction and the temperature rose sharply. Thermocouple T1, which was mounted on the opposite side of the initiating module, measured relatively cool temperatures until a thermal runaway reaction occurred in the neighboring cell at approximately 8 minutes. The temperature measured by thermocouples T5 mounted in a module adjacent to the initiating cell shows limited conductive heat input from the initiator module until thermal runaway occurs. After the initial thermal runaway reaction, the temperature at T5 (and also at T2), rose sharply to 300 C. Temperature measurements plateaued at this temperature for a number of minutes before thermal runaway propagated to adjacent modules. Temperature measurements at T3 indicate thermal runaway occurred within this module, before propagating to the next module: the temperature spike measured by T4 lags that of T3 by a number of minutes.

Figure 128 shows temperatures measured at further distances from the initiating cell. These temperatures remained low even after ignition of the vent gases at approximately 23 minutes, suggesting that thermal runaway was still progressing throughout the RESS. Within 40 minutes of the beginning of the test, all corners of the RESS had undergone thermal runaway. Thermocouple signals became noisy late in testing: after the vehicle had ignited and burned for a number of minutes. This was likely due to electrical noise in the DAQ.

An alternative means of summarizing the temperature data is shown in Figure 129, which shows the time each instrumented cell/module went into runaway. Time from first to last cell in the first module was approximately one minute, while the neighbor module propagated from its first to last cell in 30 seconds. As the event progressed and more surfaces became hot, the preheating of each module became more intense and evenly distributed. Thus propagation within each module was faster, and propagation from module to module also became faster.

Figure 130 through Figure 133 show the vehicle temperature measurement data. Sensors on the battery cover recorded temperature peaks directly above the initiation site within minutes of thermal runaway intitiation. Subsequent, thermal peaks followed as sections of the battery pack became heated by thermal runaway reactions. Vehicle interior temperature measurements showed that the vehicle cabin (carpets, seats, headliner, and air temperatures near occupant head levels) remained cool until ignition of vent gases occurred and flames entered the cabin at approximately 28 minutes.

Gas composition measurements from inside the cabin at approximately driver head level are shown in Figure 134. The oxygen, methane, and carbon monoxide concentrations as well as the percentage of the LEL were measured. A few minutes after the first thermal runaway reaction occurred, but before the second module underwent thermal runaway, the concentration of carbon monoxide inside the cabin start to increase. Shortly after each module underwent thermal runaway, there was a step change in cabin carbon monoxide concentration. Carbon monoxide concentrations exceeded 200 ppm at the time of vent gas ignition; approximately 3 minutes after the smoke alarm activated. For reference the Occupational Safety and Health Administration (OSHA) ceiling limit[17] for CO is 200 ppm.

No post-test isolation measurements were performed since the entire battery pack had been consumed.

Table 18 - Summary of Manufacturer C SCTRI Testing Results

Pre-test pack voltage	398 V nominal[18]
Pre-test Isolation – 1000V Handheld Isolation Resistance Meter	Measurement not possible[18]

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[17] The ceiling limit is the maximum concentration of a chemical to which a person may be exposed to at any time.

[18] The Manufacturer C vehicle was non-functional and thus could not be used to charge the RESS before testing, measure voltage, or self-check isolation resistance. To charge the RESS, groups of modules were removed from the RESS and charged independently, then reassembled into the RESS: voltages of bricks were measured during charge and pack preparation. The testing agency chose not to install voltage measurement leads into the battery pack to ensure that such leads could not be a source of arcing within the RESS during the SCTRI test. Thus, once the pack was closed, there was no straightforward way to measure pack voltage, isolation resistance, or perform dielectric withstand testing.

Pre-test Dielectric Withstand Voltage – Hipot Tester	Measurement not possible[18]
Time to thermal runaway of initiating cell	6 minutes 55 seconds
Indication of initiation of thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to cabin smoke alarm activation	20 minutes 36 seconds
Time to second thermal runaway reaction	7 minutes 5 seconds – multiple cells within initiating module
Indication of second thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to 3rd thermal runaway reaction	14 minutes 45 seconds through 16 minutes – multiple cells within a module
Indication of 3rd thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to 4th thermal runaway reaction	18 minutes 51 seconds
Indication of 4th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Time to 5th thermal runaway reaction	21 minutes 40 seconds through 23 minutes – multiple cells within a module
Indication of 5th thermal runaway	Audible sound, subsequent release of smoke from the battery pack
Additional thermal runaway reactions	Multiple thermal runaway reactions were audible after vehicle ignition – reactions continued until vehicle was consumed.
Time to flaming combustion	23 minutes
Post-test pack voltage	n/a battery was entirely consumed / burned
Post-test isolation – 1000V Handheld Isolation Resistance Meter	n/a battery was entirely consumed / burned
Post-test Dielectric Withstand Voltage – Hipot Tester	n/a battery was entirely consumed / burned
Isolation testing power supply maximum current	n/a battery was entirely consumed / burned
Time to thermal runaway of additional cells	n/a battery was entirely consumed / burned
Final isolation – 1000V Handheld Isolation Resistance Meter	n/a battery was entirely consumed / burned
Final Dielectric Withstand Voltage – Hipot Tester	n/a battery was entirely consumed / burned

Figure 124 - Top left: 7:07, beginning of first runaway. Top right: 8:16, fourth cell runaway in the first module. Bottom left: 14:47, second module begins after lull. Bottom right: 22:10, several modules into event, ignition coming soon. Between runaways, the smoke cleared and resembled the top left image.

Figure 125 - Top left: 23:41, ignition has occurred. Top right: 26:44, rear flames continue. Bottom left: 28:22, flames inside cabin. Bottom right: 30:53, many internal flames.

Figure 126 - Top left: 31:56, tallest flames. Top right: 36:04, vehicle fire concentrated in front. Bottom left: 46:03, event subsiding. Bottom right: 51:03, event nearing completion.

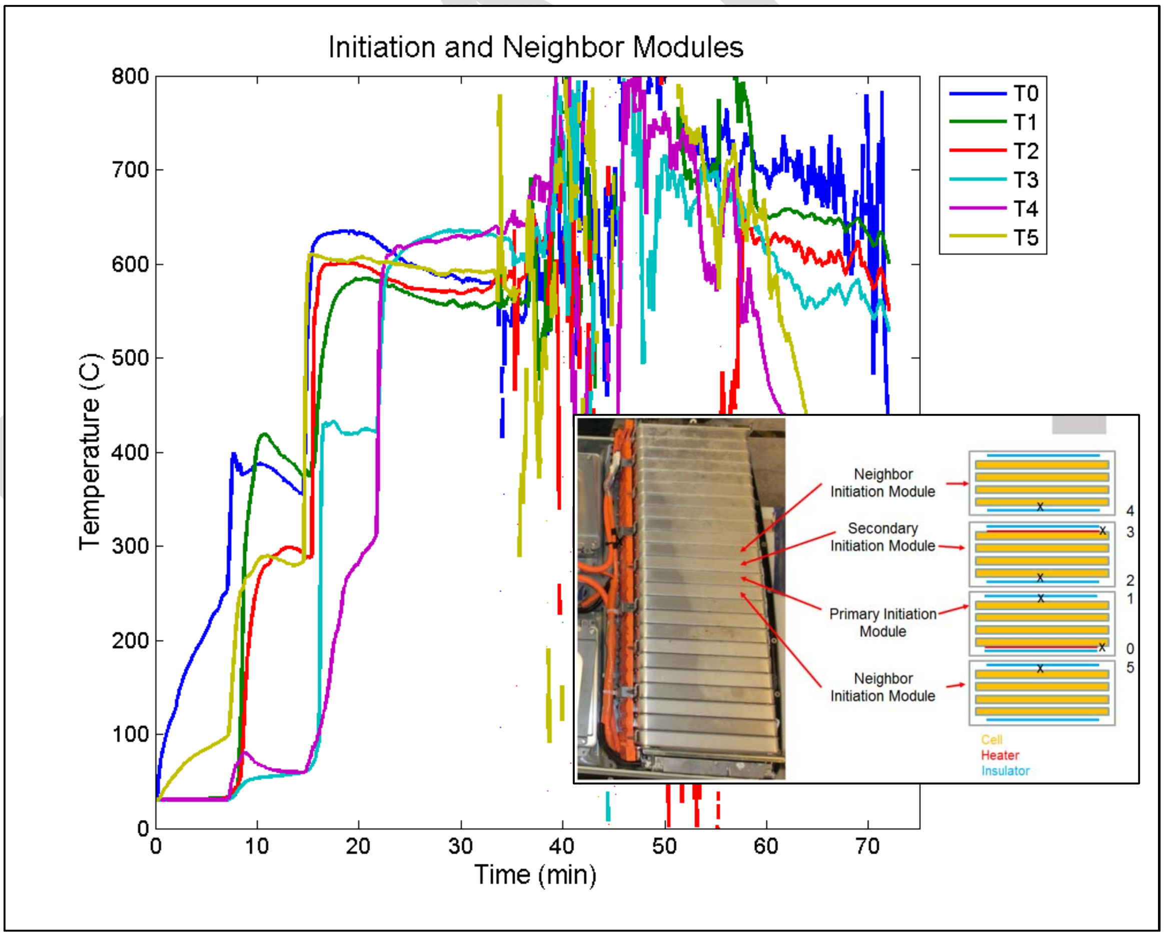

Figure 127 - Manufacturer C SCTRI test, temperatures near initiating modules.

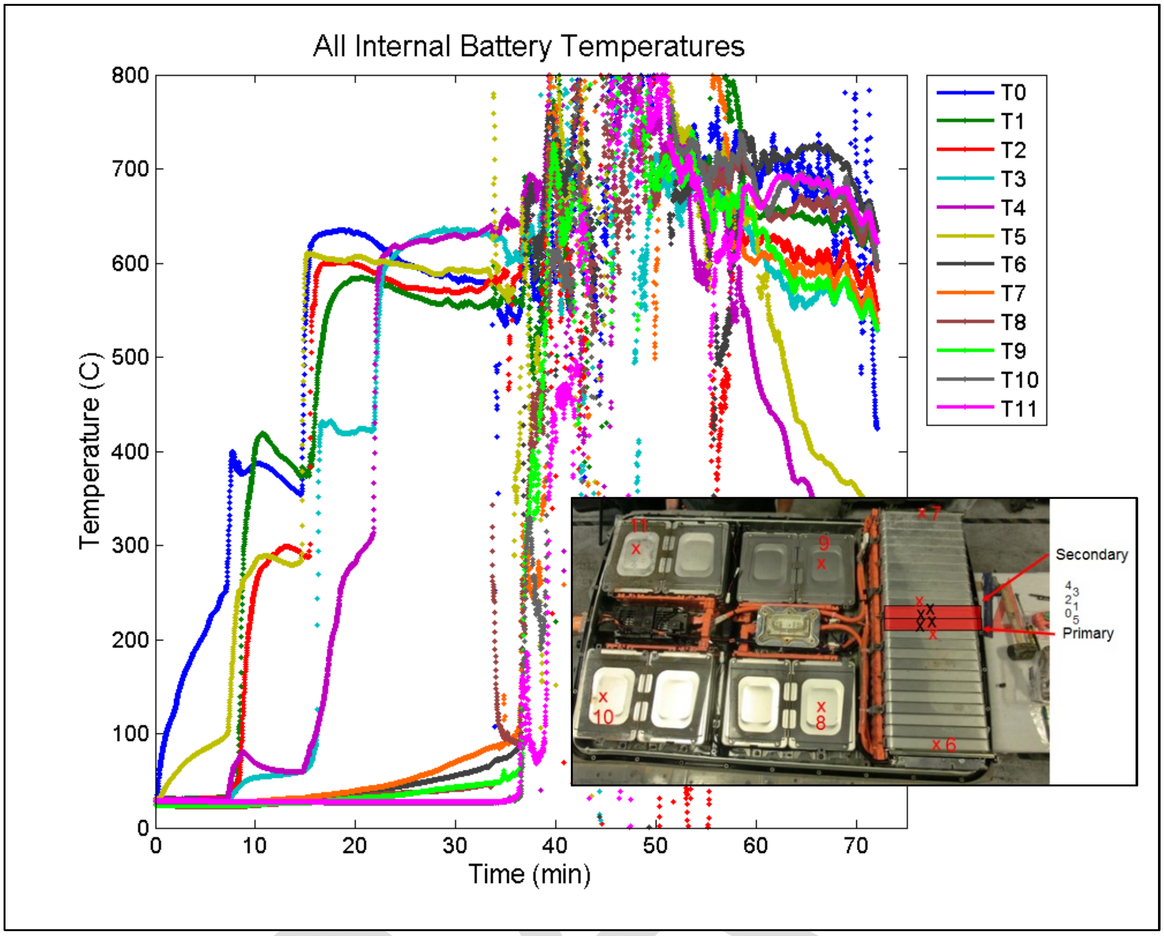

Figure 128 - Manufacturer C SCTRI test, all internal battery temperatures.

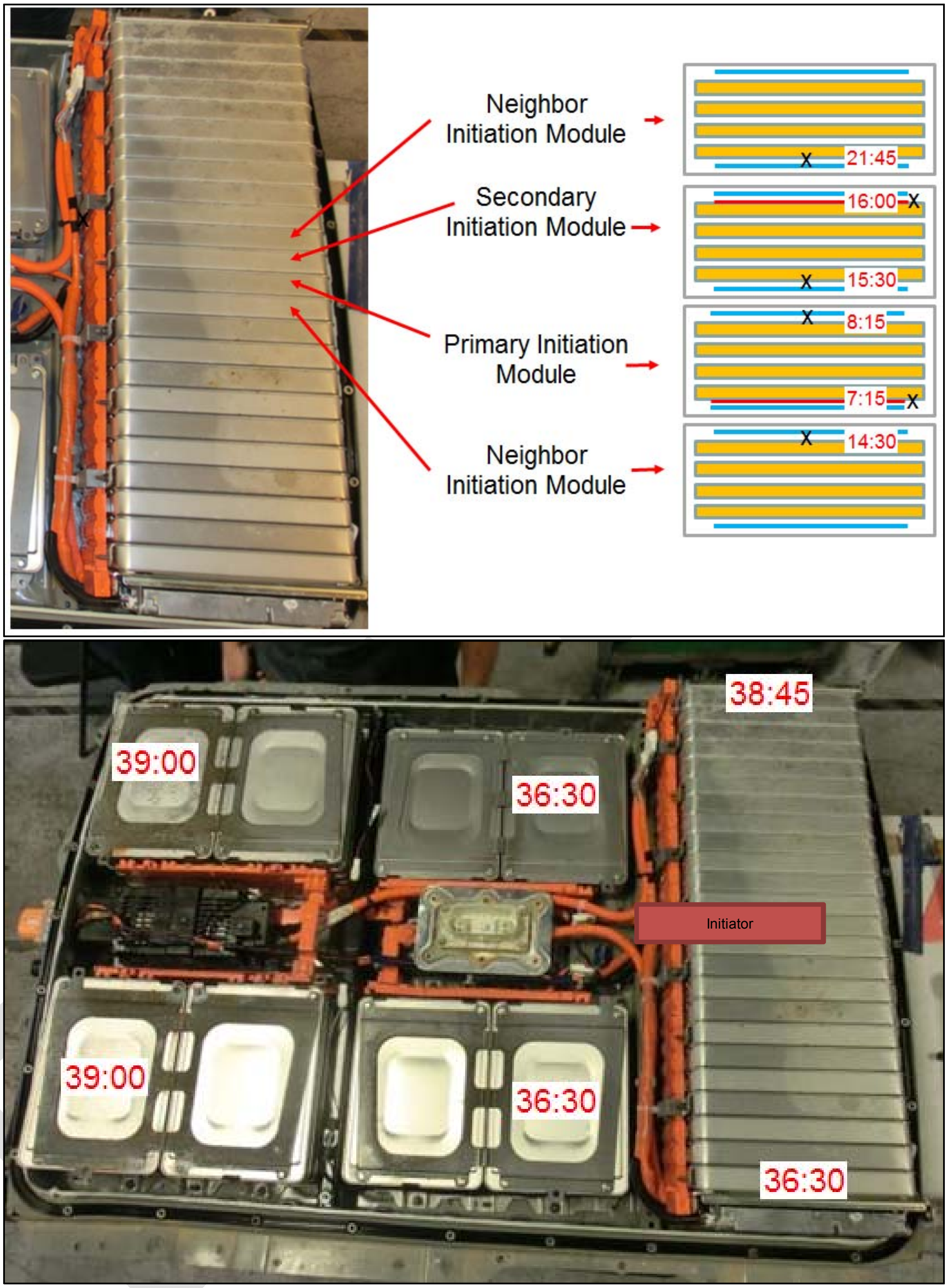

Figure 129 - Estimates of runaway time from temperature traces (mm:ss), rounded to the nearest 0:15.

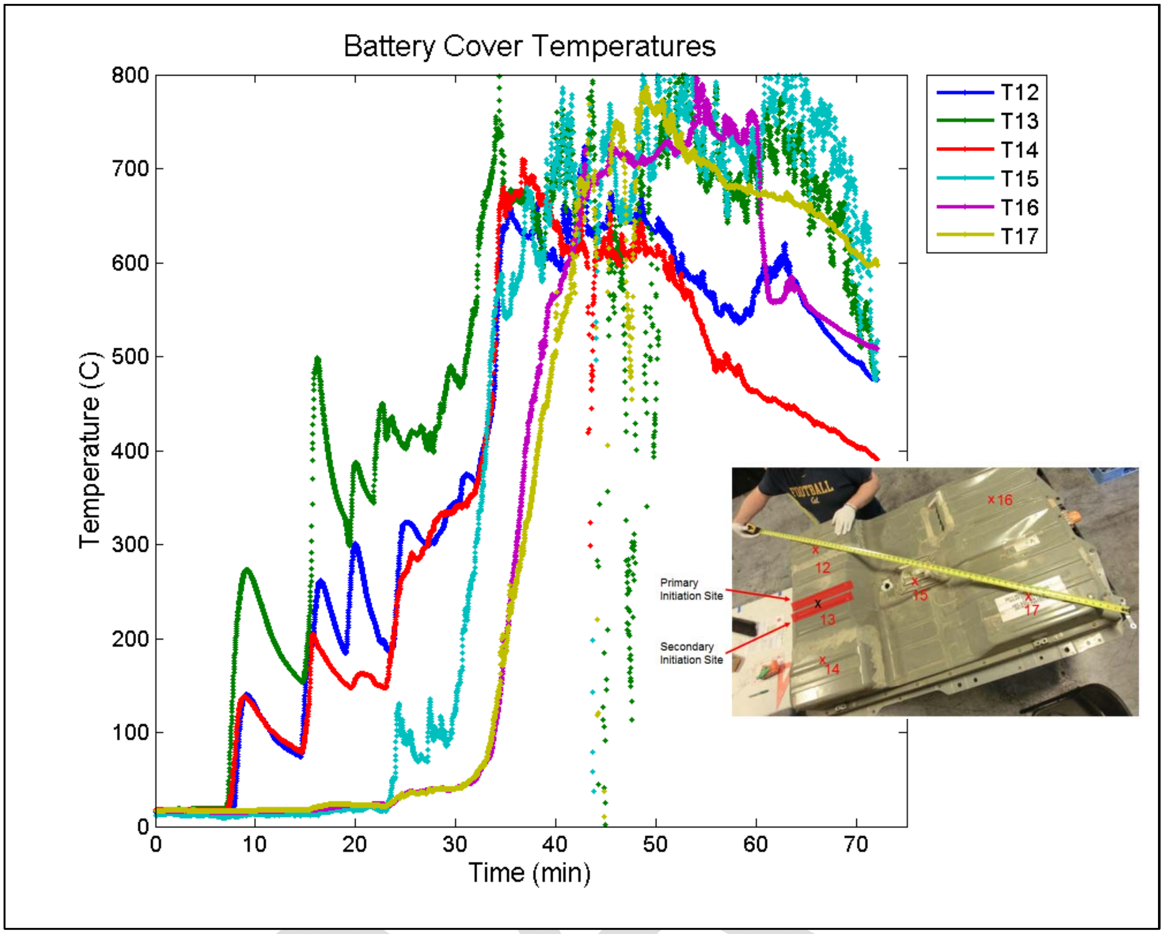

Figure 130 - Manufacturer C SCTRI test, temperatures measured on the battery cover.

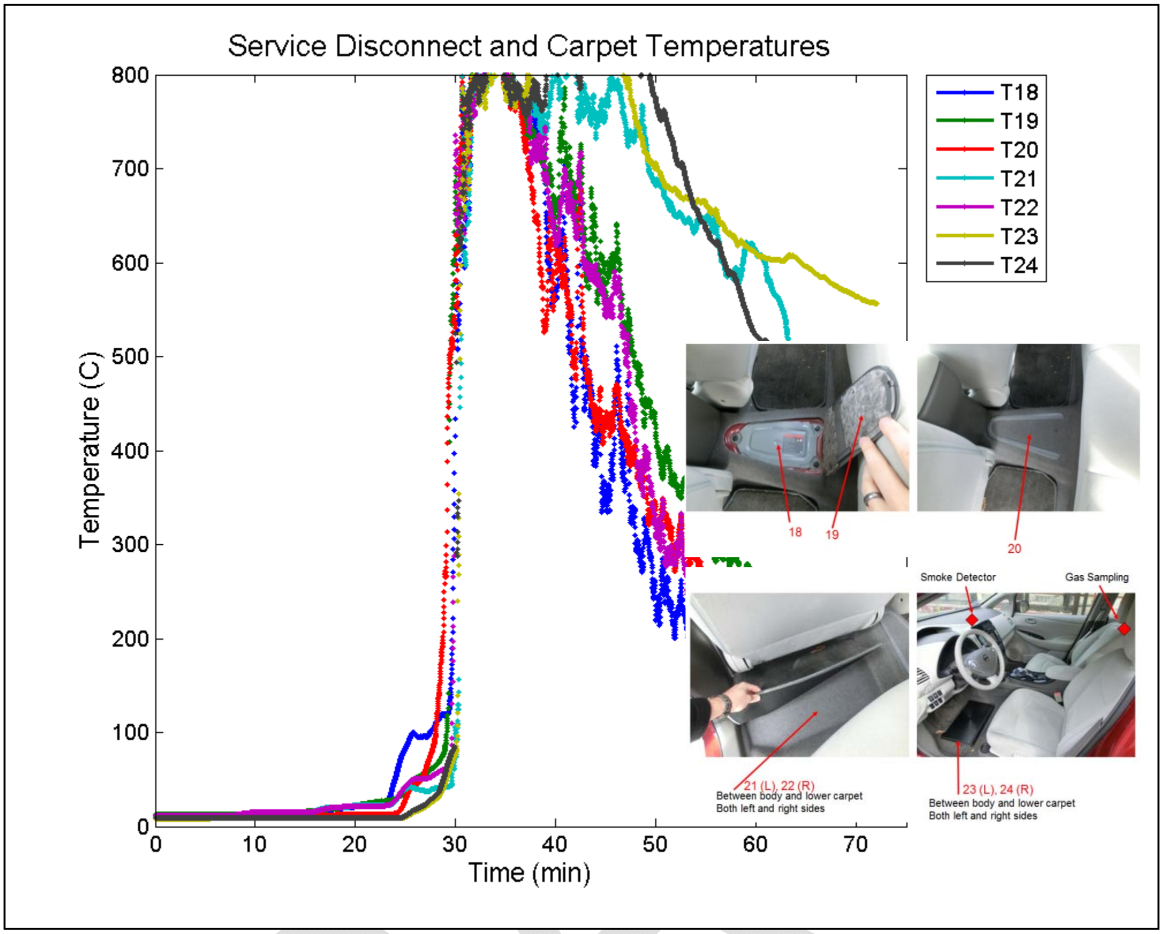

Figure 131 - Manufacturer C SCTRI test, temperatures measured at the vehicle service disconnect and at floor level.

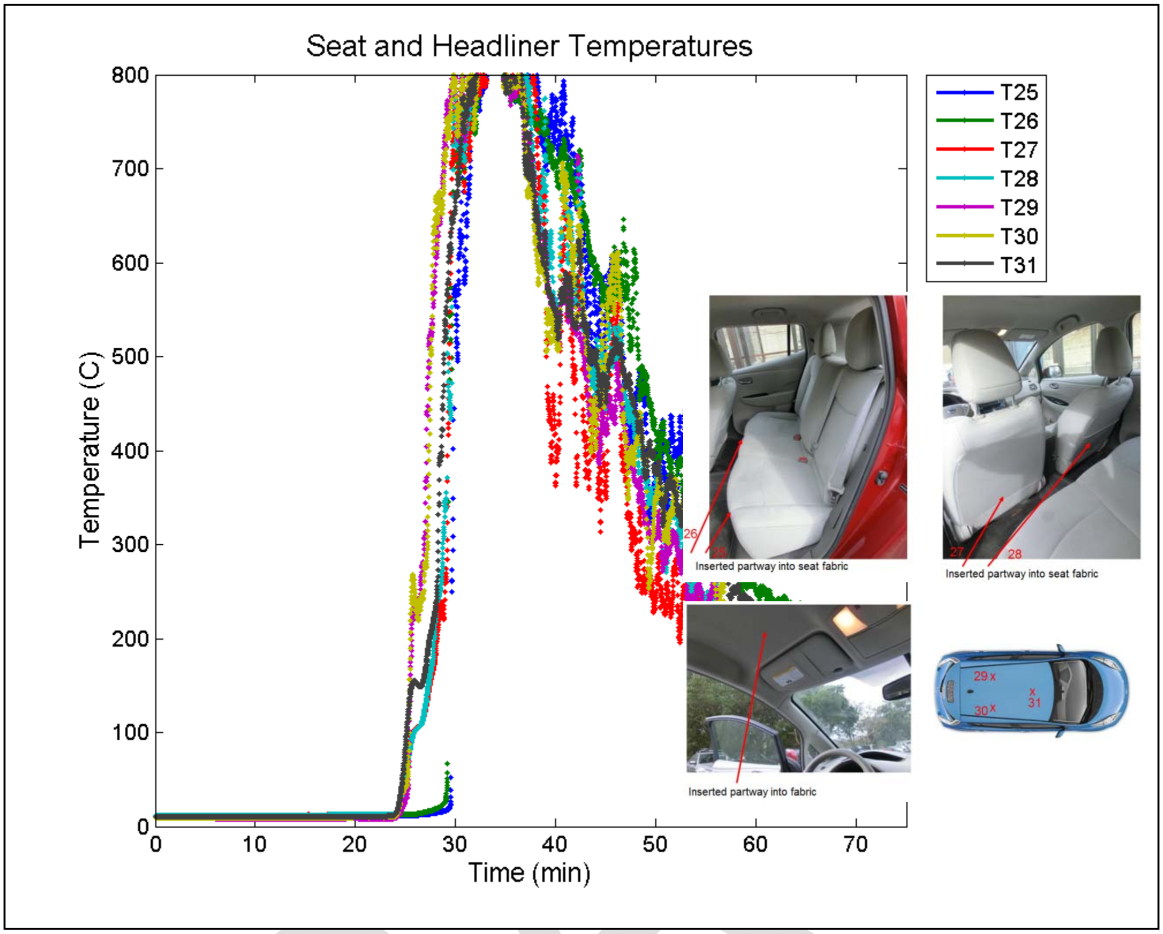

Figure 132 - Manufacturer C SCTRI test, temperatures measured at seat level and at the headliner.

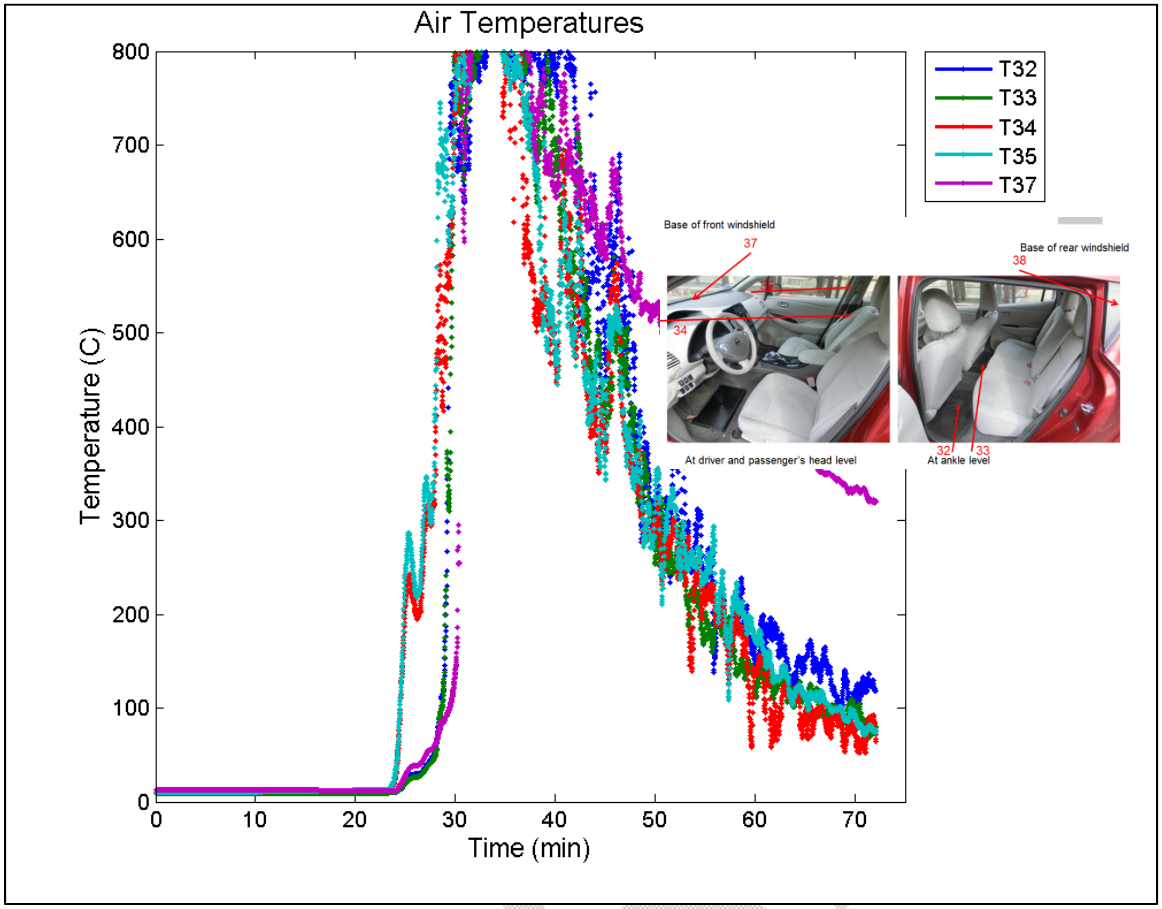

Figure 133 - Manufacturer C SCTRI test, air temperatures measured at driver head level.

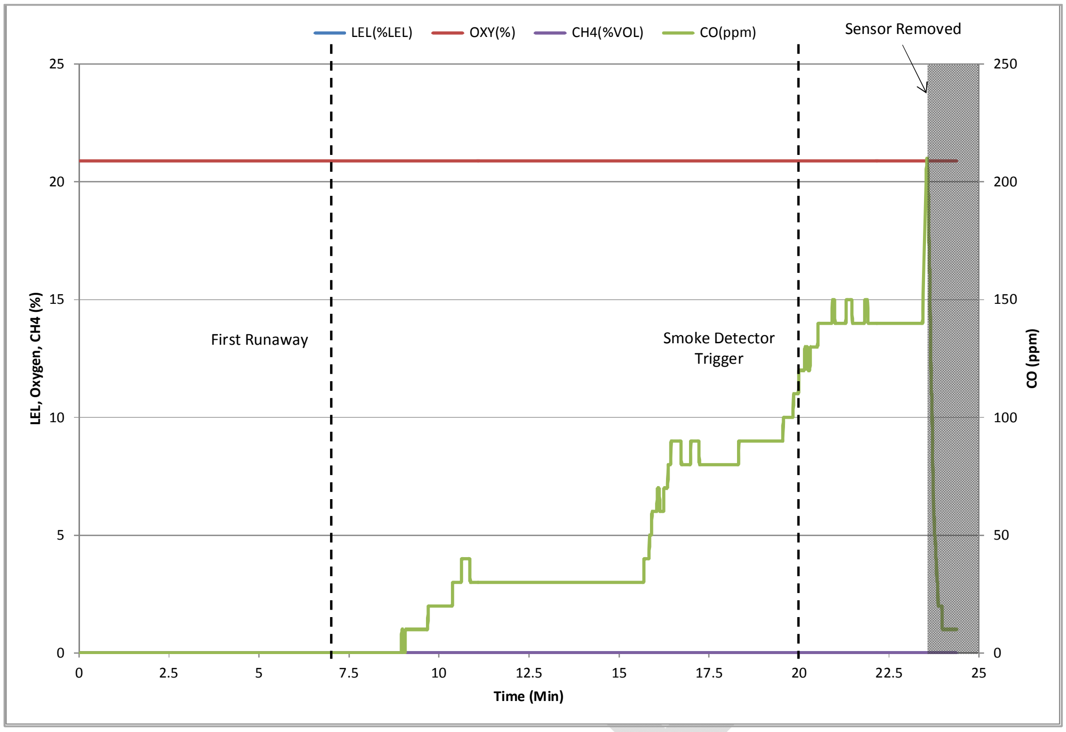

Figure 134 - Manufacturer C SCTRI Test cabin gas composition measurements; the sensor was removed once vehicle ignition occurred.

All test data is available on hard drive labeled "SAE-3257 RESS ISS Tests", folder "Section 2 – Single Cell Thermal Runaway".

[END OF DOCUMENT]