National Highway Traffic Safety Administration

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Status Update on NHTSA's Lithium-ion based Rechargeable Energy Storage System Safety Research Programs

November 2014

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NHTSA Vehicle Safety Research

This presentation will include:

- Status updates on the existing NHTSA research projects on Li-ion RESS
  - There have been no project completions since the last GTR update
- ***DRAFT*** copies of some test procedures and lab reports (5 Selected)
- Follow-on test plan for validation and performance data in the areas:
  - System Level Safety Controls
  - Thermal Performance
  - Diagnostics within an inoperable RESS
  - Stranded Energy
  - Vehicle Immersion

  - Proposed 2015 projects and 2016 + projects scopes

Background (From May 2014 Presentation)

Updates

Test Procedure Development

- Pack Level Crush
- Overcharge
- Broad Range Impedance Short Circuit
- BMS Performance – DC Level 3 Fast Charge
- Vehicle Immersion
- Single Cell Thermal Runaway Initiation
- Thermal Containment
- Fire Exposure
- Vibration with Shock and Thermal Cycle
- Comprehensive Vehicle System Test
- Isolation Stress

Safety Assessment Methods and Tools

- Diagnostic Tool Set
- Stranded Energy

Test Procedures Development: <u>System Level Safety Controls</u>

1) BMS Performance – DC Level 3 Fast Charge

2) Sequential Vehicle System Test

Low temperature, failed heating system simulation – look for appropriate limiting of charge and discharge behavior

High temperature, failed cooling system simulation – look for appropriate limiting of charge and discharge behavior

Ability to withstand or protect from **Overdischarge**

Ability to withstand or protect from **Over-current Overcharge**

Ability to withstand or protect from **Over-voltage Overcharge**

Ability to withstand an **External Short Circuit**

Test Procedures Development: System Level Safety Controls

BMS Performance – DC Level 3 Fast Charge

Goal: Test methods to evaluate RESS BMS response to failure modes and boundary condition limits during a DC Level 3 Fast Charge

Safety Metric: Evaluate the BMS safety response to charging system conditions

Approach:

1. Failure Mode Identification and Evaluation
   - Developed a Block Diagram of BMS interaction with vehicle functions and prepared a comprehensive list of Failure Modes
   - Use DFMEA experience gained from prior analysis of commercial battery pack
   - Developed concept for “Breakout Box” interface between charger and vehicle.
2. Validate and Demonstrate (Full Vehicle Test 5/12/14 – 6/27/14)

Test Procedures Development: System Level Safety Controls

BMS Performance – DC Level 3 Fast Charge

Ground Fault Test
Chassis Ground Offset Test
DC Bus Short Test
DC Bus Held High Test
System Overvoltage Test (12V Board)
12V System Under voltage Test
12V System Disturbance Test
12V System EMI/EMC Test
Vehicle Movement Test
Vehicle Crash or Bump Test

Charge Operation Disturbance Test
Charge Connector Control Signal Disturbance Test
Charge Connector Field Ground Connection Disturbance
Charge Connector HV Connection Disturbance
Visual Inspection of Charge Port
Cooling Heating System
BMS Internal Fault Detection
Overcharge Test

Test Procedures Development: System Level Safety Controls

BMS Performance – DC Level 3 Fast Charge

Ground Fault Test
Chassis Ground Offset Test
DC Bus Short Test
DC Bus Held High Test
System Overvoltage Test (12V Board)
12V System Under voltage Test
12V System Disturbance Test
12V System EMI/EMC Test
Vehicle Movement Test
Vehicle Crash or Bump Test
(Theoretic fail – G.M.)

Charge Operation Disturbance Test
Charge Connector Control Signal
Disturbance Test
Charge Connector Field Ground Connection
Disturbance
Charge Connector HV Connection
Disturbance
Visual Inspection of Charge Port
Cooling Heating System
BMS Internal Fault Detection
Overcharge Test

Test Procedures Development: <u>**System Level Safety Controls**</u>

Sequential Vehicle System Test

- **Low temperature**, failed heating system simulation – look for appropriate limiting of charge and discharge behavior
- **High temperature**, failed cooling system simulation – look for appropriate limiting of charge and discharge behavior
- Ability to withstand or protect from **Overdischarge**
- Ability to withstand or protect from **Over-current Overcharge**
- Ability to withstand or protect from **Over-voltage Overcharge**
- Ability to withstand an **External Short Circuit**

This test sequence was developed as a portion of a larger scope effort by the Subject Matter Expert *"Vehicle Sequential Testing after 5000 Mile Preconditioning".* NHTSA accepts the effort that the SME put into the "preconditioning" portion of the project, however, the functional attributes of the control performance must be compliant across the entire life cycle of the RESS. Therefore, we will be including these components in a greater comprehensive test sequence of minimal control performance independent of "pre-conditioning".

Test Procedures Development: <u>System Level Safety Controls</u>

<u>Proposed</u> NHTSA Next phase (2015) Research Projects in this area:

BMS Performance – DC Level 3 Fast Charge

Validate with data this procedure (BMW i3), then add to this work to make a complete charging system performance sequence

- Unresolved items will include: non- SAE J1772 systems (CHAdeMO, Tesla)

Sequential Vehicle System Test

Validate with data, expand and/or modify these procedures on several (TBD) vehicles which exist in the national laboratory fleet.

Test Procedures Development: <u>Thermal Performance</u>

Single Cell Thermal Runaway Initiation (SCTRI)

Goal: Test method to evaluate the effect of a single cell runaway in a RESS.

Safety Metric: Measure and compare thermal data and toxic gases in the DUT and cabin with respect to time.

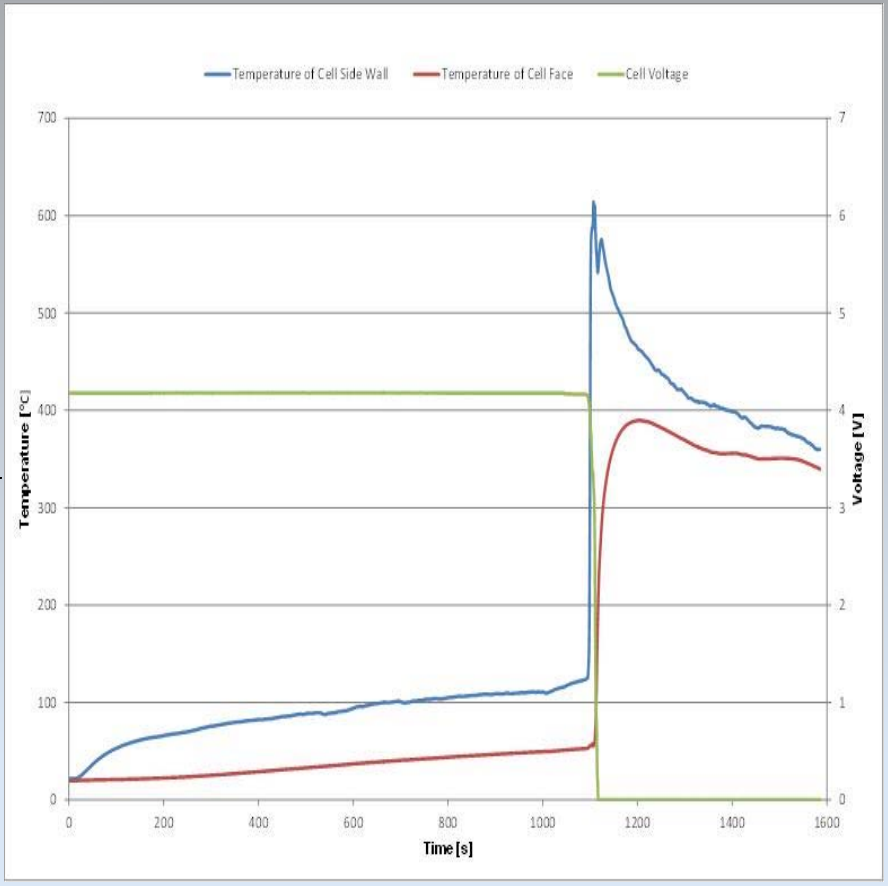
Approach:
The test procedure described is composed of three parts:

1. Selecting an appropriate single cell thermal runaway initiating methodology
2. A single cell thermal runaway initiation method may need to be verified through coupon or module level testing
3. 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.

Test Procedures Development: Thermal Performance (SCTRI)

Description provided of a cell thermal runaway reaction:

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 1 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.



Test Procedures Development: <u>Thermal Performance</u> (SCTRI)

A cell thermal runaway initiation method should be evaluated based on a set of criteria:

- Initiating device effect on neighboring cells: for example, does the <u>initiating device</u> cause direct heating of or damage to neighboring cells.
- Comparison of the energy added to the system by the initiating method to the total energy in the cell, brick, or RESS
- 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.
- 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.

Test Procedures Development: Thermal Performance (SCTRI)

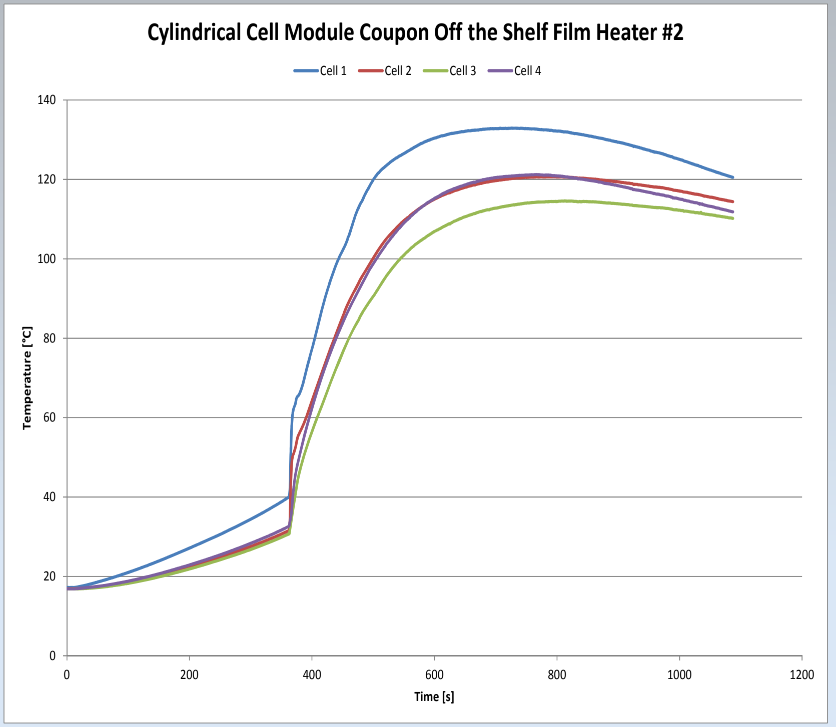
A variety of thermal runaway methods were demonstrated and evaluated on small cylindrical cells, large hard case prismatic cells, large soft-pack polymer cells

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

Test Procedures Development: Thermal Performance (SCTRI)

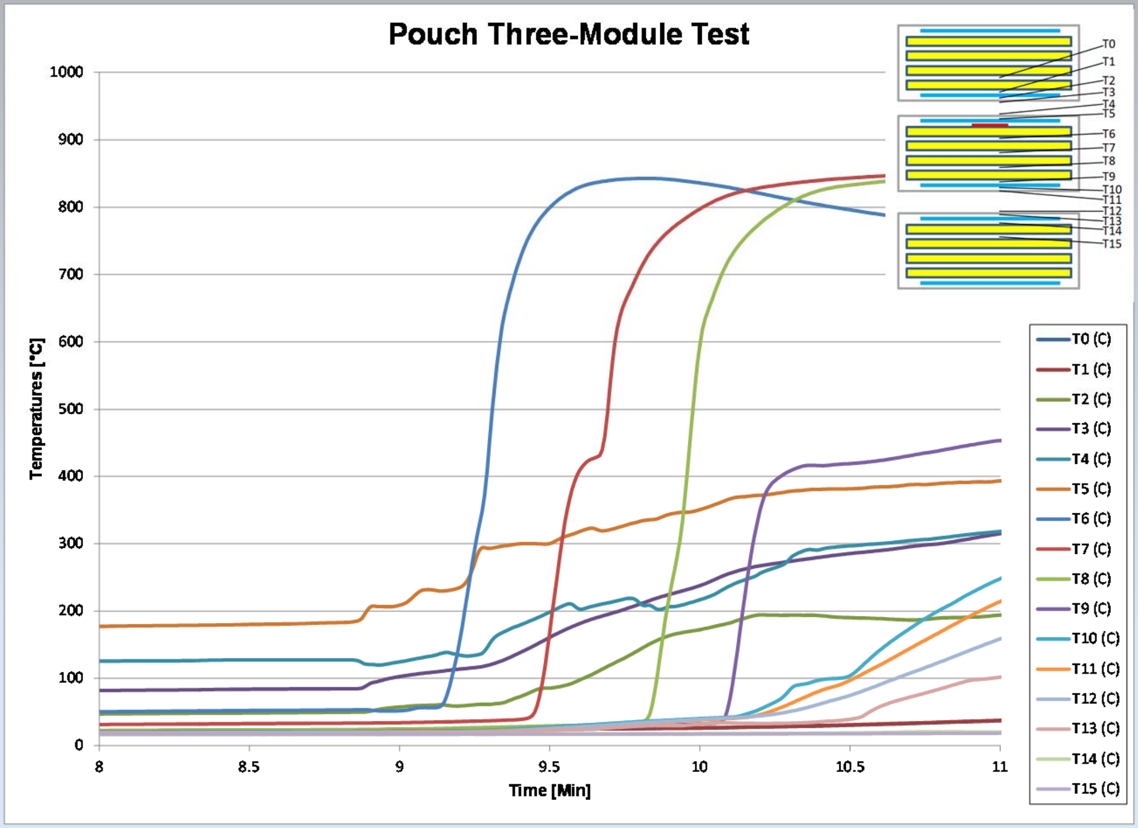
Coupon level validation demonstrated: to ensure that initiation method does not significantly affect surrounding cells

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



Test Procedures Development: Thermal Performance (SCTRI)

Demonstrated a method for module level validation

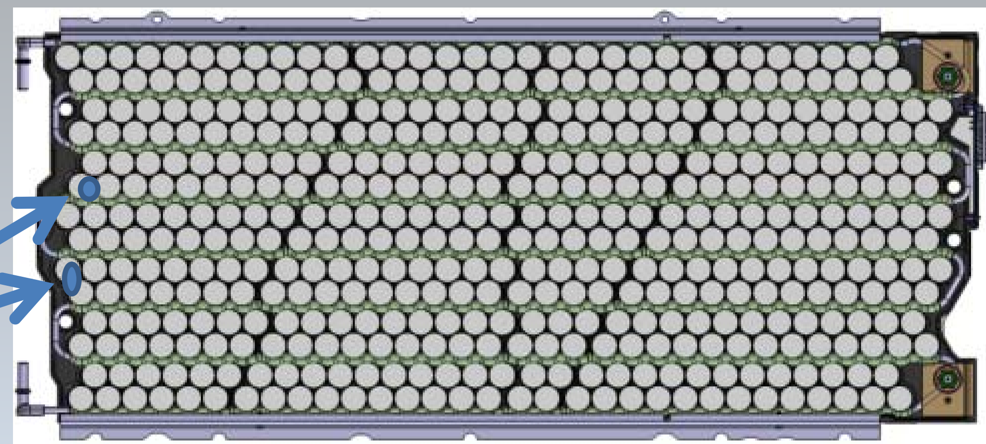


Test Procedures Development: Thermal Performance (SCTRI)

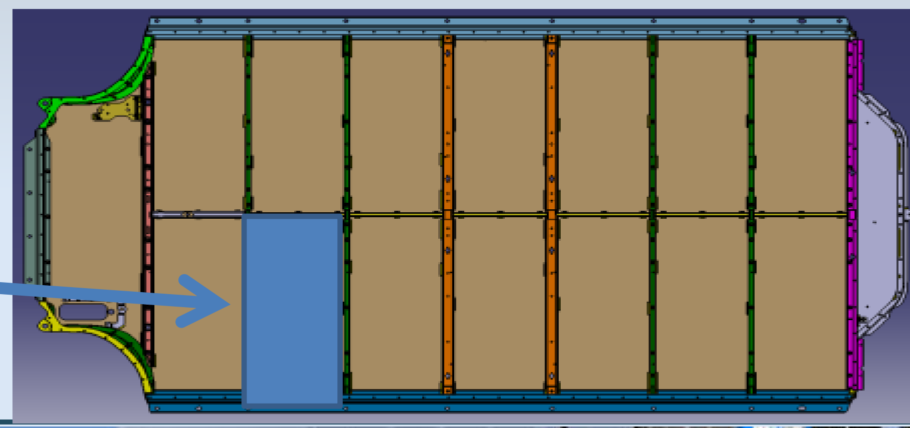
Manufacturer A Full Vehicle Test

Initiation Points

Cell Locations



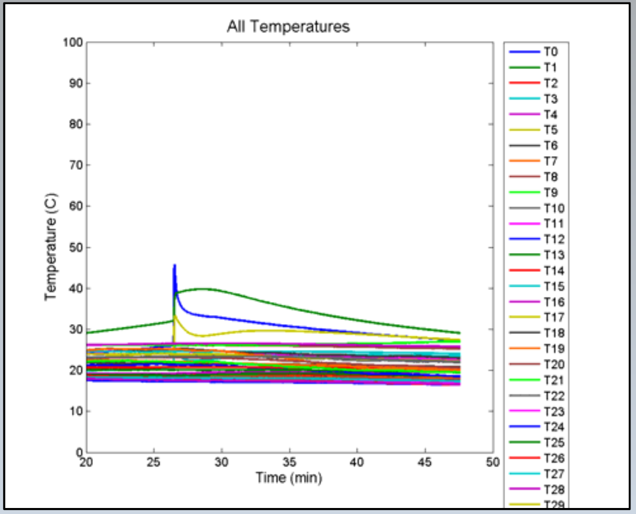
Module Location

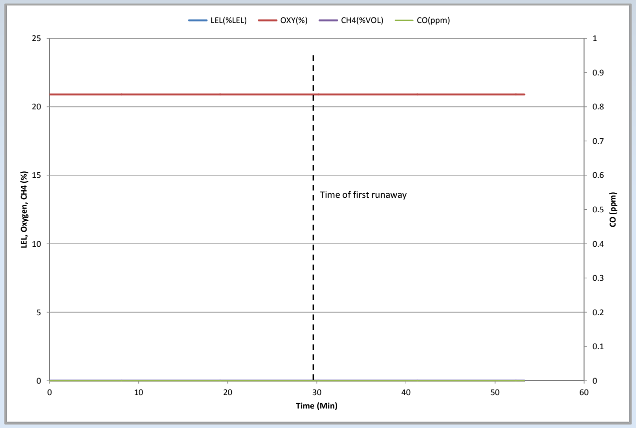


Test Procedures Development: Thermal Performance (SCTRI)

Manufacturer A Full Vehicle Test

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





Test Procedures Development: Thermal Performance (SCTRI)

Manufacturer B Full Vehicle Test

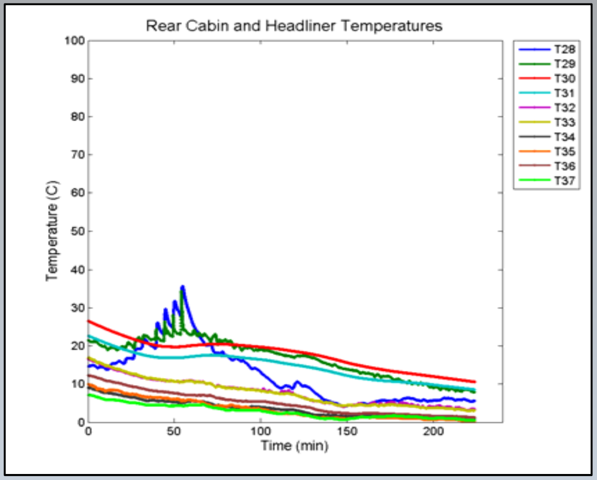
Large Side Heater
240 W

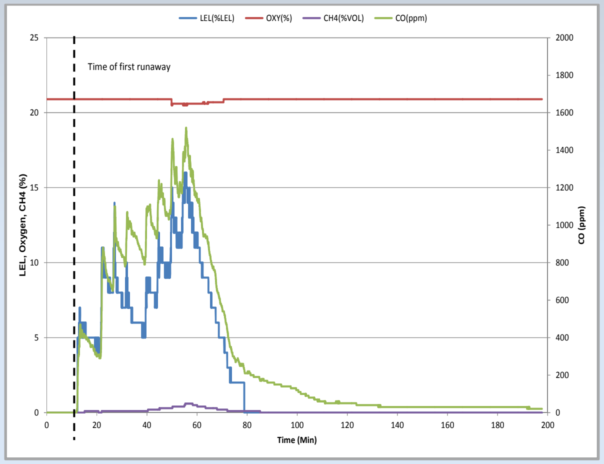
Initiation Points

Test Procedures Development: Thermal Performance (SCTRI)

Manufacturer B Full Vehicle Test

Pre-test pack voltage	365V nominal[1]
Pre-test Isolation – 1000V Handheld Isolation Resistance Meter	Measurement not possible[1]
Pre-test Dielectric Withstand Voltage – Hipot Tester	Measurement not possible[1]
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
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





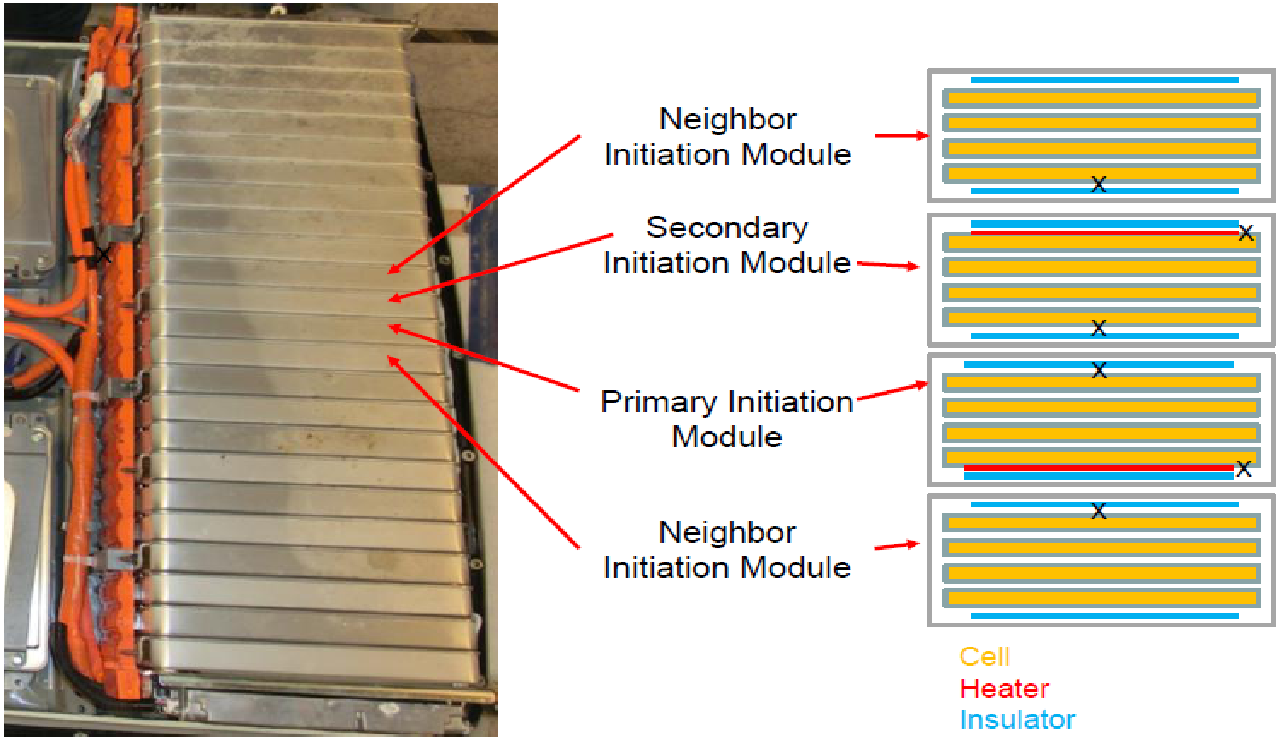
Test Procedures Development: Thermal Performance (SCTRI)

Manufacturer C Full Vehicle Test

Test Procedures Development: Thermal Performance (SCTRI)

Manufacturer C Full Vehicle Test

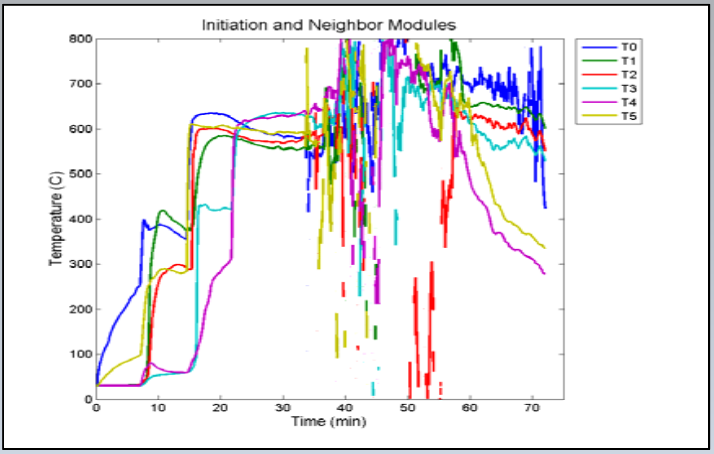
Close up of Initiation Modules

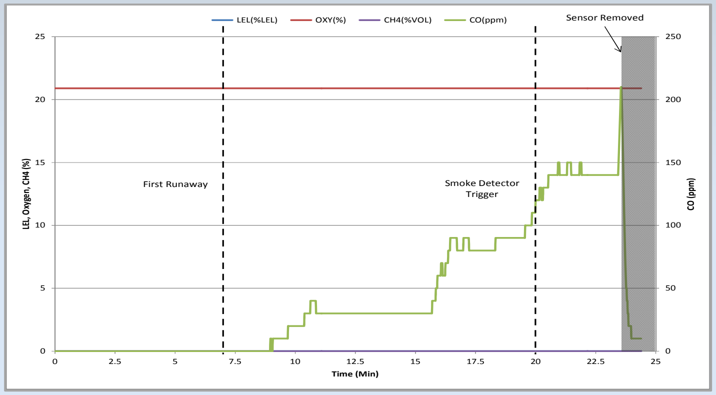


Test Procedures Development: Thermal Performance (SCTRI)

Manufacturer C Full Vehicle Test

Pre-test pack voltage	398 V nominal[1]
Pre-test Isolation – 1000V Handheld Isolation Resistance Meter	Measurement not possible[1]
Pre-test Dielectric Withstand Voltage – Hipot Tester	Measurement not possible[1]
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





Test Procedures Development: Thermal Performance (SCTRI)

Status:

A variety of single cell thermal runaway initiation methods were demonstrated for a variety of cell form factors

Validation of initiation method using coupons and modules was demonstrated

Full scale vehicle testing was demonstrated using 3 types of RESS: Dec. 16, 2013. Testing produced a range of vehicle responses.

Test procedure and report delivered in April 2014.

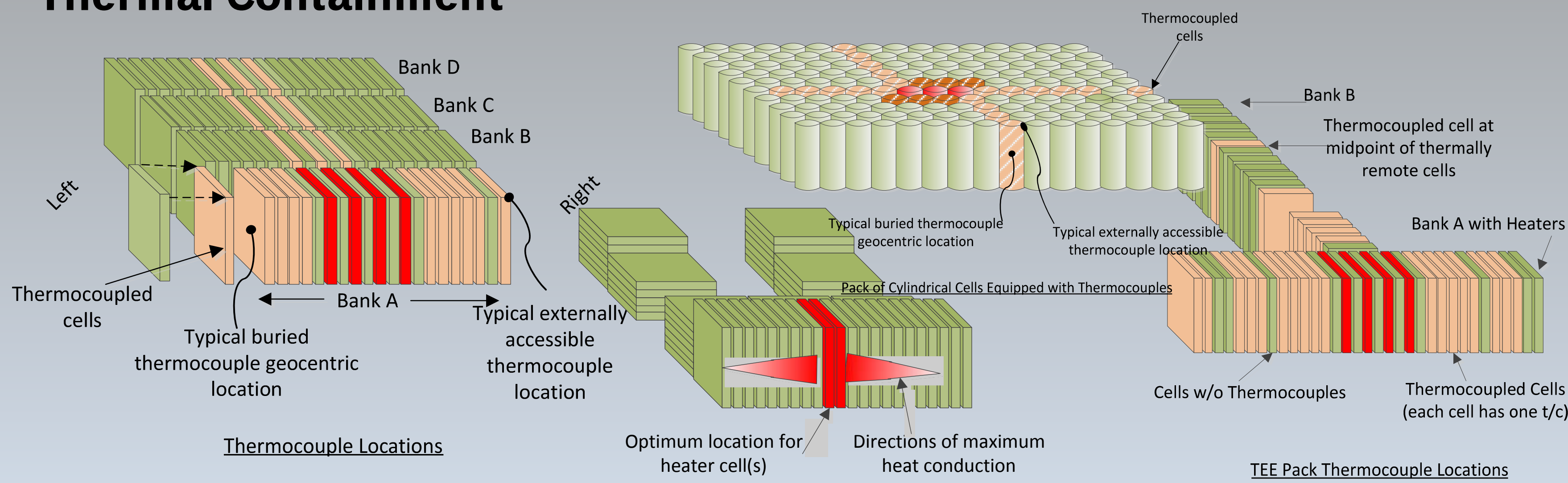
Next Steps:

Update test procedure incorporating feedback.

Test wider range of vehicles with SCTRI Procedure: testing of PHEVs and other xEVs should be done.

Test Procedures Development: Thermal Performance

Thermal Containment



Goal: Test method to evaluate the effect of an internal battery fire involving forced thermal runaway of many cells as might be observed from a substantial abuse condition.

Approach: Trigger pack thermal runaway by multiple heater assemblies (5) installed into the battery pack Trigger cell should reach 400°C within 5 minutes

Test Procedures Development: <u>Thermal Performance</u>

<u>Proposed</u> NHTSA Next phase (2015) Research Projects in this area:

SCTRI

Validate with data this procedure with 3-4 additional vehicles.
Validate the "Isolation Stress" procedure during this process.

Thermal Containment

Redevelop a suitable test based upon SCTRI techniques in "multiple cells" or adapt a rapid heat source (thermite) to avoid thermal ramp-up of adjoining cells.

Test Procedures Development:

Vehicle Immersion Test (Conductive Fluid Contaminants)

Goal: Test methods at the vehicle level (full system operational) for evaluating the effect of immersion in salt water

Though still viewed as an essential test requirement due to field observations, this test procedure will require further boundary parameter definitions though an empirical DOE before further validation. In question are appropriate salinity levels, temperature and duration.

- 2/12 vehicles tested experienced thermal activity – test failure
  - Vehicle 1 – (3.5% NaCl at 2 hrs immersion) loss of HV isolation across the contactors leading to complete consumption
  - Vehicle 2 – (1.75 NaCl at 1 hour) thermal activity on monitoring board

Further research proposed in 2016 FY

Safety Assessment Methods and Tools

Safety Assessment – Diagnostic Tool Set

Goal:

Develop a diagnostic tool set to identify battery state-of-health and stability characteristics that commonly assess the safety a RESS DUT after a test, abuse condition, or during normal use.

Approach:

The body of this work is cell to module to pack progressive and will be in part a derivative of cell level Complex Impedance Spectroscopic Properties leveraging the scientific experience and expertise of Sandia National Labs. This project will also adopt Idaho National Labs developed “rapid impedance spectra measurement techniques” that can be adapted to a BMS monitoring board.

Partners:

Sandia N.L., Idaho N.L., National Research Canada, Argonne N.L. (Stranded Energy)

Safety Assessment Methods and Tools

Stranded Energy Diagnostics and Liberation

Goal:

This project seeks to define and demonstrate a common strategy for diagnostics of an inoperable and potentially damaged RESS that is physically or electronically isolated within its enclosure, and describe the architectural requirements to assist in liberation of the energy when necessary.

The scope of the project defines:

This project is intended to inform and bridge gaps in technology and standards that may exist in areas of safe handling of the RESS devices and exposure to people within the entire community from a "cradle to grave" perspective.

Partner:

Argonne National Laboratories – Project completion November 26, 2014

Proposed: Stakeholders Workshop on this topic March/May 2015 – Argonne N.L.

Questions and Discussions