THERMAL PROPAGATION TEST EXPERIENCE

November 2016
OICA Submission to EVS-GTR Task Force 5
Agenda

• Objective & key messages
• Thermal propagation testing
  • Initiation methods
  • Repeatability
  • Propagation behavior
  • DUT modifications
• Additional Discussion Topics
  • Engineering standard compared to regulatory requirement
  • Current practice of one OEM
Objective

• Share vehicle manufacturer thermal runaway and thermal propagation test experience, illustrating that the currently proposed thermal propagation test method is not sufficiently mature for regulation
Key Messages

- Proposed initiation methods are not equivalent and are not repeatable
- Performance criteria are inconsistent and largely unrelated to propagation behavior
- Necessary DUT modifications are extensive and affect test outcomes
- Wide variation in allowable test parameters creates opportunity for manufacturers to select most advantageous conditions which may not reflect intended purpose of test
- Continues to be very limited evidence suggesting that this issue is a significant field concern for automobiles
Extent of Recent Test Experience – One OEM

- 126 tests conducted over past 18 months
  - Single cell (no enclosure): 63
  - 4-cell “module” (enclosure and no enclosure): 53
  - Simulated pack (enclosure): 10

- 4 Cell types
  - Two energy cells (26-60 A-hr): 46 tests
  - Two power cells (5-7 A-hr): 80 tests

- 4 Initiation Methods
  - Heating: 79 tests
    - Constant temperature increase rate (5 rates)
    - Constant power (2 rates)
  - Overcharge: 24 tests
    - Varying constant rates (C/3 to 3C)
  - Nail penetration: 21 tests
    - Varying speeds and nail sizes
  - Other potential methods: 2 tests
Thermal Propagation Testing
Initiation methods Part 1

Key message: Proposed initiation methods are not equivalent

[Expanded detail on information shared in EVSTF-08-64e.pdf]
Initiation Method Comparison
Heating vs Overcharge

• **DUT**
  - Non-production “modules”
    - **Identical** except for presence of heater
    - Four pouch cells
    - No enclosure

• **Test Methods**
  - **Heating**
    - 0.5degC/s
    - One side of end cell
  - **Overcharge**
    - 3C Rate
    - No voltage limit

Initiation methods are not equivalent
Overcharge Test Set-up

Heating Test Set-up
Thermal runaway initiated
Thermal propagation occurred

“Front” indicates side facing initiating end of module
“Back” indicates side facing non-initiating end of module
Thermal runaway initiated
No thermal propagation

“Front” indicates side facing initiating end of module
“Back” indicates side facing non-initiating end of module
Heat vs. Overcharge | t_C1_Back_Cen | Test D048 vs. Test D050
Heat vs. Overcharge | t_C2_Front_Cen | Test D048 vs. Test D050
Thermal Propagation Testing
Initiation methods Part 2

Key message: Proposed initiation methods are not repeatable

[New information not previously shared.]
Cell Heating Test Repeatability

• Test article:
  • 4-cell stack, face to face
  • 6.8 Ahr pouch cell

• Initiation method:
  • Block heater – 2.75degC/sec
Out of 6 tests run the same way:
2 propagate, 4 do not.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Cells in Thermal Runaway</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>1</td>
</tr>
<tr>
<td>002</td>
<td>1</td>
</tr>
<tr>
<td>003</td>
<td>2</td>
</tr>
<tr>
<td>004</td>
<td>1</td>
</tr>
<tr>
<td>008</td>
<td>1</td>
</tr>
<tr>
<td>010</td>
<td>3</td>
</tr>
</tbody>
</table>
Key message: Wide variation in allowable test parameters creates opportunity for manufacturers to select most advantageous conditions which may not reflect intended purpose of test

[New information not previously shared.]
Single cell overcharge
Charge rate variation

Variation in test parameters allows manufacturers to select advantageous conditions.
Single cell overcharge summary:

<table>
<thead>
<tr>
<th>Test #</th>
<th>Rate</th>
<th>Charge time (seconds)</th>
<th>Thermal runaway?</th>
<th>Approx. %SOC (based on charge time and rate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F26</td>
<td>C/3</td>
<td>11028</td>
<td>No</td>
<td>202%</td>
</tr>
<tr>
<td>F27</td>
<td>1C</td>
<td>3646</td>
<td>No</td>
<td>201%</td>
</tr>
<tr>
<td>F29</td>
<td>2C</td>
<td>1519</td>
<td>Yes</td>
<td>184%</td>
</tr>
<tr>
<td>F28</td>
<td>3C</td>
<td>920</td>
<td>Yes</td>
<td>177%</td>
</tr>
</tbody>
</table>

Significant outcome variation within allowable range.
Single cell overcharge

Dotted line indicates test that did not go into thermal runaway
Thermal Propagation Testing
Propagation behavior

Key message: Performance criteria are inconsistent and largely unrelated to propagation behavior

[Expanded detail on information shared in EVSTF-09-40-TF5-19.pdf]
Large Scale DUT Tested within bounds of Draft Regulation

• Test article:
  • Non-production battery pack configuration
  • Pouch cell in a 2p28s arrangement
  • Voltage: ~116 V
  • Nominal capacity: ~52 A-hr (2 x 26 A-hr cells in parallel)

• Initiation method:
  • Block heater – 1.6 kW, constant power
  • Overcharge – 1 C rate (less than 1 hour)

• Initiation Cell Location (see following page)
  • End of pack
  • Mid pack
Initiation Cell Locations

End of Pack
Initiation Cell Location

Mid Pack
Initiation Cell Location
Results Summary

Heating

- Flame visible for approx. 1 second
- Visible smoke

Overcharge

- Visible smoke
- Flame visible for >160 seconds
- Visible smoke

Inconsistent results
## Results Summary

<table>
<thead>
<tr>
<th></th>
<th>D76 Heating – End</th>
<th>D77 Overcharge – End</th>
<th>D78 Heating – Mid</th>
<th>D79 Overcharge - Mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Results</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time to all cells vent (approx. secs)</td>
<td>2550</td>
<td>2750</td>
<td>1950</td>
<td>1700</td>
</tr>
<tr>
<td>Cell groups vented* @ 300 seconds (# cells)</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Cell groups vented* @ 600 seconds (# cells)</td>
<td>8</td>
<td>7</td>
<td>12</td>
<td>&gt;13</td>
</tr>
<tr>
<td>Cell groups vented* @ 900 seconds (# cells)</td>
<td>12</td>
<td>10</td>
<td>14</td>
<td>Unknown</td>
</tr>
<tr>
<td>Cell groups vented* @ 1200 seconds (# cells)</td>
<td>15</td>
<td>14</td>
<td>16</td>
<td>Unknown</td>
</tr>
<tr>
<td>Cell groups vented* @ 1500 seconds (# cells)</td>
<td>16</td>
<td>16</td>
<td>19</td>
<td>Unknown</td>
</tr>
<tr>
<td>Order of voltage loss</td>
<td>Sequential (C1 to C28)</td>
<td>Sequential (C1 to C28)</td>
<td>C9, C10, C11, C12, C13, C8, C14, C7, C15, C6, C16, C5, C4, C3, C1, C17, C18, C19, C20, C21, C22, C23, C24, C25, C28, C26, C27</td>
<td>C9, C8, C10, C7, C11, C6, C5, C12, C4, C3...cannot be distinguished.</td>
</tr>
</tbody>
</table>

*Voltage loss of the cell group is assumed indicative of cell venting

Results unrelated to intended assessment
Example of influence of test set-up on results
D78 Mid pack, Heater

Insulating plate to prevent heater from initiating 2 cells.

Initial propagation direction (4 cells)

Results influenced by test method
Cell heated (w/ 1.6kW) for approx. 1134 sec

v_C2 unavailable due to data acquisition anomaly
Overcharge time (@ 1C) = approx. 3230 sec

Data acquisition anomaly in v_C1 causes apparent oscillation of voltage. Real voltage does not oscillate. V_C1 not shown on graph.
Cell heated (w/ 1.6kW) for approx. 967 sec
Thermal Propagation Testing

DUT Modifications

Key message: Necessary DUT modifications are extensive and affect test outcomes

[Information shared in EVSTF-09-40-TF5-19.pdf]
Remove cover for modification

Pack cover removed
Heating – mid-pack:
Remove bus bars
Heating – mid-pack:
Cell sensing circuit removed
Heating – mid-pack: Preparation to cut through cell connection board

Cell connection board must be cut to insert heater
Heating – mid-pack:
Cut through cell connection board

Cell connection board cut
Heating – mid-pack & end-pack: Remove cell constraint fasteners

1) Compress stack with clamps
2) Remove top “strap”
3) Remove fasteners

Cell stack unconstrained to allow heater insertion on end or mid pack.
Heating – mid-pack: Insertion of heater

Separate cell stack, remove holding frame, insert heater

Separate cell stack

Remove holding frame to fit heater

Insert heater
Heating – mid-pack & end-pack:
Modification/fabrication of parts required

- Longer fasteners required (both heater positions)
- Larger “strap” required (both heater positions)
All packs:
Thermocouple fixed to target cell

Cell stack must be expanded to include thermocouple
Overcharge – mid-pack & end-pack
Install Charging Wires to Initiation Cell

Charge wires

Install terminals for wire connection

Note: Voltage measurement wires for data collection.
(Not required part of test)
Overcharge – mid-pack & end-pack
Remove parallel cell from electrical circuit

Cell tab severed to disconnect target cell from parallel configured cell pair (a single cell tab is disconnected).
Conclusions
Conclusions

- Thermal propagation behavior depends on METHOD of initiating thermal runaway in a single cell
- Proposed allowable test method variation enable conditions which BOTH generate and do not generate thermal runaway in a single cell
- Thermal propagation appears UNCORRELATED to proposed test pass-fail criteria
- Proposed test methodology results in INCONSISTENT results
- SIGNIFICANT modification of DUT will likely be required and may affect test outcome
- Proposed thermal propagation test method is not sufficiently mature for regulation
Additional Points for Discussion

• Engineering standard compared to regulatory requirement
• How one OEM addresses thermal propagation risk
Engineering Standard vs Regulatory Requirement
## Comparing Engineering Standards and Regulations

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Engineering Standard</th>
<th>Regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose</td>
<td>Assist manufacturer in development of product and/or communication with suppliers</td>
<td>Assure public safety</td>
</tr>
<tr>
<td>Usage Requirement</td>
<td>Optional at manufacturer discretion</td>
<td>Mandatory</td>
</tr>
<tr>
<td>Procedure Robustness</td>
<td>Sufficient to suit manufacturer’s needs</td>
<td>Repeatable and reproducible</td>
</tr>
<tr>
<td>DUT (including modification)</td>
<td>As determined by manufacturer</td>
<td>Must represent product as used by customer</td>
</tr>
<tr>
<td>Required technical merit</td>
<td>May be included in standard even if evidence supporting it is limited</td>
<td>Needs to be effective at assuring a product which complies is safe</td>
</tr>
<tr>
<td>Degree of detail</td>
<td>Can be vague/non-specific [manufacturer discretion]</td>
<td>Must be highly specific so minimize mis-interpretation</td>
</tr>
<tr>
<td>Acceptance criteria</td>
<td>Likely not part of standard; at manufacturer’s discretion</td>
<td>Must be specified unambiguously</td>
</tr>
</tbody>
</table>

*A test suitable for an engineering standard IS NOT necessarily appropriate for regulation.*
Current Practice of One OEM
Application to thermal propagation Mitigation

Safety designs at all levels contribute to total system safety

- Stable chemistry selected
- Cell performance evaluated
- Propagation potential assessed
- System / vehicle effects evaluated
Cell performance evaluated

• Cell abuse tests have been used to assess performance to various simulated failure modes

• Selected methods simulate, to some degree, failure mode of interest
  • External short circuit
    + Simulates high current event through current collectors
    - Current density low at electrodes
  • Nail penetration
    + Electrode to electrode shorting possible
    - More distributed heating than internal short
  • Crush
    + Electrode to electrode shorting possible
    - Robust mechanical design may prevent internal short
Cell test results example

- Maximum cell temperature
- Nail Penetration
- External Short Circuit
- Crush
Propagation potential assessed

• Of the three tests considered, the highest thermal energy was released in the test with maximum peak temperature since all cell tests were conducted in similar environments.

• Reproduce similar thermal energy event while cell in module
  • Observe for event propagation
    • Number of cells
  • Observe for type of thermal outcome
    • Benign temperature increase
    • Venting
    • Fire
Thermal propagation assessment method

*Test method example only. The illustrated test is NOT applicable for other REESS designs. Each module/pack design requires a unique test configuration or method. Such a method is not possible for ALL REESS designs.*
Thermal propagation assessment example
System / vehicle effects evaluated

• Does amount of vent gas exceed allowable levels?

• Was fire / flame observed?

• Other system level effects noted?