Can Cell-to-Cell Thermal Runaway Propagation in Li-ion Modules Be Prevented?

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Background

Lithium-ion batteries have a very high energy density but have catastrophic consequences such as fire and thermal runaway associated with them— as observed by the incidents in the commercial electronics and aerospace industry.

New requirement in NASA-Battery Safety Requirements document: JSC 20793 RevC

5.1.5.1 Requirements – Thermal Runaway Propagation

a. For battery designs greater than a 80-Wh energy employing high specific energy cells (greater than 80 watt-hours/kg, for example, lithium-ion chemistries) with catastrophic failure modes, the battery shall be evaluated to ascertain the severity of a worst-case single-cell thermal runaway event and the propensity of the design to demonstrate cell-to-cell propagation in the intended application and environment.

b. The evaluation shall include all necessary analysis and test to quantify the severity (consequence) of the event in the intended application and environment as well as to identify design modifications to the battery or the system that could appreciably reduce that severity.
<table>
<thead>
<tr>
<th>Spec.</th>
<th>Cond.</th>
<th>LG18650B4</th>
<th>LG18650C2</th>
<th>BP 5300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>Nominal</td>
<td>2.6 Ah</td>
<td>2.8 Ah</td>
<td>5.3 Ah</td>
</tr>
<tr>
<td>Voltage</td>
<td>Nominal</td>
<td>3.7</td>
<td>3.72 V</td>
<td>3.65 V</td>
</tr>
<tr>
<td>Std. Charge</td>
<td>CC/CV</td>
<td>0.5C</td>
<td>0.5C</td>
<td>0.7C</td>
</tr>
<tr>
<td></td>
<td>Cut off</td>
<td>4.2 V 50 mA</td>
<td>4.3 V 50 mA</td>
<td>4.2 V 50 mA</td>
</tr>
<tr>
<td>Std. Discharge</td>
<td>CC</td>
<td>0.2C</td>
<td>0.2C</td>
<td>0.2C</td>
</tr>
<tr>
<td></td>
<td>Cut off</td>
<td>2.75 V</td>
<td>3.0 V</td>
<td>2.75 V</td>
</tr>
<tr>
<td>Weight</td>
<td>Max</td>
<td>48.0 g</td>
<td>53.0 g</td>
<td>93.5 g</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>Charge</td>
<td>0 to 45 °C</td>
<td>0 to 45 °C</td>
<td>-20 to 60 °C</td>
</tr>
<tr>
<td></td>
<td>Discharge</td>
<td>-20 to 60 °C</td>
<td>-20 to 60 °C</td>
<td>-40 to 70 °C</td>
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<tr>
<td>Vent Location</td>
<td></td>
<td>Header</td>
<td>Header</td>
<td>2 on flat side</td>
</tr>
</tbody>
</table>
Thermal Runaway Trigger Method

- 2-inch square Kapton heater elements (40W)
- Pressure sensitive adhesive (PSA) on backside
- 20W (20V @ 1A) heater power applied
- 3-5 °C/min desired heating rate
- All tests were performed inside an abuse test chamber
- 5-min N₂ purge was performed before start of test & after test

Omega KHLV-202/40-P
### Test Matrix

<table>
<thead>
<tr>
<th>Test #</th>
<th>Cell Type</th>
<th>Configuration</th>
<th>SOC</th>
<th>Cell Arrangement</th>
<th>Intercell space Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BP5300</td>
<td>9S</td>
<td>100%</td>
<td>3x3, 2mm</td>
<td>Air</td>
</tr>
<tr>
<td>2</td>
<td>LGB4</td>
<td>9S</td>
<td>100%</td>
<td>3x3, 2mm</td>
<td>Air</td>
</tr>
<tr>
<td>3</td>
<td>LGB4</td>
<td>9S</td>
<td>100%</td>
<td>3x3, 4mm</td>
<td>Air</td>
</tr>
<tr>
<td>4</td>
<td>BP5300</td>
<td>4S</td>
<td>100%</td>
<td>2x2,</td>
<td>Radiant Barrier</td>
</tr>
<tr>
<td>5</td>
<td>LGC2</td>
<td>9P, Fork-tabs</td>
<td>100%</td>
<td>3x3, 4mm</td>
<td>Air</td>
</tr>
<tr>
<td>6</td>
<td>LGC2</td>
<td>9P, Fork-tabs</td>
<td>100%</td>
<td>3x3, 2mm</td>
<td>Air</td>
</tr>
<tr>
<td>7</td>
<td>BP5300</td>
<td>4P, Fork-tabs</td>
<td>100%</td>
<td>2x2,</td>
<td>Radiant Barrier</td>
</tr>
<tr>
<td>8</td>
<td>BP5300</td>
<td>9P, Fork-tabs</td>
<td>50%</td>
<td>2x2,</td>
<td>Radiant Barrier</td>
</tr>
<tr>
<td>9</td>
<td>LGC2</td>
<td>9P, Fork-tabs</td>
<td>100%</td>
<td>3x3, 1mm</td>
<td>Air</td>
</tr>
<tr>
<td>10</td>
<td>LGC2</td>
<td>9P, Serpentine (S) tabs</td>
<td>100%</td>
<td>3x3, 1mm</td>
<td>Air</td>
</tr>
<tr>
<td>11</td>
<td>LGC2</td>
<td>9P, S-tabs</td>
<td>100%</td>
<td>3x3, 2mm</td>
<td>Air</td>
</tr>
<tr>
<td>12</td>
<td>BP5300</td>
<td>4P, S-tabs</td>
<td>50%</td>
<td>2x2,</td>
<td>Radiant Barrier</td>
</tr>
<tr>
<td>13</td>
<td>LFP/SKC</td>
<td>14P, (2.2 Ah) Fork Tabs (10A fuse)</td>
<td>100%</td>
<td>5X5X4</td>
<td>Air</td>
</tr>
<tr>
<td>14</td>
<td>LFP/SKC</td>
<td>14P, (2.0 Ah) Fork tabs (10A fuse)</td>
<td>100%</td>
<td>5X5X4</td>
<td>Air</td>
</tr>
<tr>
<td>15</td>
<td>BP5300</td>
<td>9P</td>
<td>100%</td>
<td>3x3, 2mm</td>
<td>Intuplas</td>
</tr>
<tr>
<td>16</td>
<td>LGC2</td>
<td>9P</td>
<td>100%</td>
<td>3X3, 2mm</td>
<td>Intuplas</td>
</tr>
<tr>
<td>17-20</td>
<td>BP/LG</td>
<td>9P</td>
<td>100% &amp; 50%</td>
<td>3X3, 4mm</td>
<td>Intuplas</td>
</tr>
</tbody>
</table>
Preliminary Runs:
- BP 5300 & LG B4 cell tests with 2-mm (air) spacing; series configuration; 100% SOC

Cell-to-cell Spacing – LG C2 cells:
- 1-, 2-, & 4-mm spacing; 100% SOC; 9P (Fork & Serpentine)

Radiant Barrier – BP cells:
- Folded radiant barrier sample; 100% & 50% SOC; 4P

Intuplas – LG C2 & BP cells:
- 2-, -4 mm; 100% SOC; 9P (Fork)
Cell-to-Cell Space LG C2 Cell Tests

- 1-, 2-, & 4-mm spacing between cells
- LG 18650 C2 (2.8 Ah) in 9P configuration
- Propagation to adjacent cells
- No propagation to diagonal cells
- Voltage/capacity drain observed
- No crimp opening or extrusion of electrode roll
- Elevated adjacent cell temperatures (120 °C)

Fork Pattern

8.8-mm diagonal
1-mm horizontal
LG C2 – 1-mm Space 9P Fork Config. 100% SOC

Post-OCVs (4.3 V pre)

20W Heater on Cell 5

<table>
<thead>
<tr>
<th>Cell</th>
<th>Temp (°C)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4.27</td>
<td>0.637</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0.429</td>
</tr>
<tr>
<td>3</td>
<td>4.27</td>
<td>2.086</td>
</tr>
<tr>
<td>9</td>
<td>4.26</td>
<td>0.429</td>
</tr>
</tbody>
</table>

Cell 2, Cell 5, Cell 8

Graph showing temperature and current over time for each cell under various conditions.
LG C2 – 1-mm Space 9P Serpentine Config. 100% SOC

- Significant damage to adjacent cells
- No propagation to all diagonal cells
- Post-test OCVs all 0 V
- No extrusion of electrode roll
- Adjacent cell temperatures were elevated (120-150 °C)
LG C2 – 1-mm Space 9P Serpentine Config. 100% SOC

Post-Test OCV: all 0 V

Cell 5

Adjacent Cells

20W Heater on Cell 5

Temperature (°C)

Bank Voltage/Heater Current (V/A)

Time (s)
LG C2 – 2-mm Space 9P Configurations
100% SOC

**9P Fork**
- Complete thermal runaway of cell 5
- Thermocouple wire melted from venting
- Observed voltage/capacity drain from adjacent cells 2, 6, & 8
- No crimp opening or extrusion of electrode roll
- Elevated adjacent cell temperatures (100 °C)

**9P Serpentine**
- Complete TR of cell 5
- Some damage to cell 4
- Post-test OCVs all 0V
- No extrusion of electrode roll
- Elevated adjacent cell temperatures (100 °C)

**Pre-Test**
- Images of 9P Fork and 9P Serpentine configurations

**Post-Test**
- Images of 9P Fork and 9P Serpentine configurations
LG C2 – 4-mm Space 9P Fork Config. 100% SOC

- Complete thermal runaway of cell 5
- No propagation
- Capacity/voltage drain observed on adjacent cells 2 & 8
- No crimp opening or extrusion of electrode roll
BP5300 2-mm Space at 100% SOC (9S Config.)

- Complete thermal runaway of cell 5
- Propagation to cell 2 (in vent path), & cell 8 (adjacent to heater)
- Contents ejected from cells 5 & 7
- Heater power 20W (1A at 20V)
- Spacers (in left picture below) removed before test
Radiant Barrier

- To mitigate radiation heat transfer & protect against direct flame from side vents in BP cells
- Radiant barrier description per Boeing donor:
  - Outer layers are quartz cloth
  - Five nickel foil layers inside with Linoweave (open mesh quartz cloth) separator layers between the nickel foil layers
BP5300 at 100% SOC with Radiant Barrier (4S and 4P Config.)

- Identical Results
- Can ruptured & contents ejected from triggered cell
- No propagation
BP5300 at 50% SOC with Radiant Barrier (4P Config.)

- No expulsion of contents
- Fire started through vent opening & spread to adjacent cell
- Heat transferred from cell 2 to cell 1
- Cells 3 & 4 displayed capacity/voltage drain

Post-test

Gap in barrier w/melting of restraint clip

Pre-test

Restraint Clip

<table>
<thead>
<tr>
<th>Post-OCVs (4.2 V pre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#4: 0.28V</td>
</tr>
<tr>
<td>#3: 1.5V</td>
</tr>
<tr>
<td>#1: 0V</td>
</tr>
<tr>
<td>#2: 0V</td>
</tr>
</tbody>
</table>
Intumescent Material

Intuplas:
- Nanocomposite consisting of thermoplastic carrier & inorganic intumescent activator
- Activates at 200 °C to form a dense, insulating ash
- 2-hour fire rating with ASTM E119
- Manufactured by Pyrophobic Systems Ltd.

WSTF Testing:
- Flame propagation
- Off-gassed products
- Tested to NASA-STD-6001
- Material passed flame propagation & off-gas test

(Courtesy: Mike Fowler)
Intuplas Modules

Three each of 2-mm, 4-mm spacing for BP & LG cells designs

<table>
<thead>
<tr>
<th>QTY</th>
<th>Form Factor</th>
<th>Layout</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>BP5300</td>
<td>3x3</td>
<td>2mm</td>
</tr>
<tr>
<td>3</td>
<td>BP5300</td>
<td>3x3</td>
<td>4mm</td>
</tr>
<tr>
<td>3</td>
<td>18650</td>
<td>3x3</td>
<td>2mm</td>
</tr>
<tr>
<td>3</td>
<td>18650</td>
<td>3x3</td>
<td>4mm</td>
</tr>
</tbody>
</table>
LG C2 at 100% SOC with 2-mm Intuplas (9P Config.)

All cells vented

- Cell 1
- Cell 2
- Cell 3
- Cell 4
- Cell 5 (Heater)
- Cell 6
- Cell 7
- Cell 8
- Cell 9
- Chamber Temp
- Module Voltage

Pre-test

Post-test

LG C2
BP5300 at 100% SOC with 2-mm Intuplas (9P Config.)

All cells held 4.17V Except cell 5
SKC LFP 14.7 Ah 14P Module 2
100% SOC

LFP: Lithium Iron Phosphate

50 W heater
Cell positive terminals

7 deg. C/min. heating rate
SKC LFP 14.7 Ah 14P Module 2
100% SOC
Convection negligible in space

- Conduction dominates at $T < 500 \, ^{\circ}C$
- Radiation exponentially increases with temperature
- Increasing spacing significantly decreases heat transfer
- Fire because of electrolyte venting in the presence of high temperatures can cause significant propagation

\[
Q_{\text{cond}} = kA \frac{T_1 - T_2}{\Delta x}
\]
\[
Q_{\text{rad}} = \frac{\sigma(T_1^4 - T_2^4)}{\varepsilon_1 A_1} + \frac{1}{F_{12}} + \frac{1}{\varepsilon_2 A_2}
\]

\[
F_{12} = \frac{1}{2\pi} \left\{ \pi + \sqrt{c^2 - 2^2} - c - 2 \cos^{-1}\left[\frac{2}{c}\right] \right\}
\]

\[
c = 1 + \frac{\Delta x}{r}
\]

(Calculations by Carlos Lopez)

<table>
<thead>
<tr>
<th>Spacing</th>
<th>Rate of Heat Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta x$ (mm)</td>
<td>$Q_{\text{rad}}$ (W)</td>
</tr>
<tr>
<td>1</td>
<td>5.69</td>
</tr>
<tr>
<td>2</td>
<td>5.34</td>
</tr>
<tr>
<td>4</td>
<td>4.77</td>
</tr>
</tbody>
</table>

$T_1 = 500^\circ C$, $\varepsilon_1 = 0.9$

$T_2 = 100^\circ C$, $\varepsilon_2 = 0.9$

$\Delta x$ is the spacing, $F_{12}$ is the radiation view factor.
Summary

- **Increasing cell spacing decreased adjacent cell damage**
- Electrically connected adjacent cells drained more than physically adjacent cells
- **Radiant barrier prevents propagation when fully installed between BP cells**
- **BP cells vent rapidly & expel contents at 100% SOC:**
  - Slower vent with flame/smoke at 50%
  - Thermal runaway event typically occurs at 160 °C
- **LG cells vent, but do not expel contents:**
  - Thermal runaway event typically occurs at 200 °C
- **SKC LFP modules did not propagate; fuses on negative terminal of cell (away from cell vents) may benefit in reducing cell-to-cell damage propagation**
Future Work

- Optimize materials and designs that will completely eliminate the cell-to-cell propagation
- Look at design solutions that may extinguish a fire in the battery
- Develop inherent cell safety through chemical modifications to cell components
Acknowledgments

- NASA-JSC Test Area Team
- Pyrophobic Systems Team
- Bruce Drolen – Boeing Seattle
Backup Slides
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP</td>
<td>Boston Power</td>
</tr>
<tr>
<td>LFP</td>
<td>Lithium iron phosphate</td>
</tr>
<tr>
<td>mm</td>
<td>millimeter</td>
</tr>
<tr>
<td>OCV</td>
<td>Open Circuit Voltage</td>
</tr>
<tr>
<td>P</td>
<td>Cells in parallel (bank)</td>
</tr>
<tr>
<td>S</td>
<td>Cells in series (String)</td>
</tr>
<tr>
<td>SOC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>V</td>
<td>Voltage</td>
</tr>
<tr>
<td>W</td>
<td>Watts</td>
</tr>
<tr>
<td>WSTF</td>
<td>White Sands Test Facility</td>
</tr>
</tbody>
</table>
Test Chamber Setup

- Buckeye pressure vessel
- Nitrogen pre- and post-purge
- Data acquisition:
  - K-type thermocouples
  - Voltage sense
  - Dual video feeds
  - 1 sample/sec.
- Heater voltage & current