Can Cell to Cell Thermal Runaway Propagation be Prevented in a Li-ion Battery Module?

Judith Jeevarajan, Ph.D.
NASA- JSC
Carlos Lopez
TAMU/ NASA Fellowship Summer Intern
Josephat Orieukwu
ESCG/NASA-JSC

September 2014
New requirement in NASA-Battery Safety Requirements document: JSC 20793 Rev C

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.

NASA has traditionally addressed the threat of thermal runaway incidents in its battery deployments through comprehensive prevention protocols. This prevention-centered approach has included extensive screening for manufacturing defects, as well as robust battery management controls that prevent abuse-induced runaway even in the face of multiple system failures. This focused strategy has made the likelihood of occurrence of such an event highly improbable.

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.

In addition to prevention protocols, programs developing battery designs with catastrophic failure modes should take the steps necessary to assess the severity of a possible thermal runaway event. Programs should assess whether there are reasonable design changes that could appreciably affect the severity of the outcome.

Evaluation should include environmental effects to surrounding hardware (i.e., temperature, pressure, shock), contamination effects due to any expelled contaminates, and venting propulsive effects when venting overboard.
# Cell Specifications

<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</td>
<td>4.3 V</td>
<td>4.2 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 mA</td>
<td>50 mA</td>
<td>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</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>Temperature</td>
<td>Discharge</td>
<td>-20 to 60 °C</td>
<td>-20 to 60 °C</td>
<td>-40 to 70 °C</td>
</tr>
<tr>
<td>Vent Location</td>
<td>Header</td>
<td>Header</td>
<td>2 on flat side</td>
<td></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 carried out inside an abuse test chamber
- A 5 minute N₂ purge was carried out before start of test and after test.

Omega KHLV-202/40-P

9/15/2014
J. Jeevarajan, Ph.D. NASA/JSC
<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, 4 mm</td>
<td>Intuplas</td>
</tr>
</tbody>
</table>
Tests

• Preliminary Runs
  – BP 5300 and LG B4cell tests with 2mm (air) spacing; Series configuration; 100% SOC

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

• Radiant Barrier - BP
  – Folded radiant barrier sample; 100% and 50% SOC; 4P

• Intuplas – LG and BP
  – 2 mm; 100% SOC; 9P (Fork)
BP5300 2mm Air Space at 100% SOC (9S config.)

- Complete Thermal runaway of cell 5
- Propagation to cell 2 (in vent path), and cell 8 (adjacent to heater)
- Contents ejected from cell 5 and 7
- Heater power 20W (1A at 20V)
- Spacers (in left picture below) removed before test
LG B4 4mm Cell-to-Cell Space at 100% SOC 9S config.

- Thermal runaway observed in trigger cell 5
- No propagation
- All other voltages held at 4.19V
LG B4 4mm Space at 100% SOC (9S config.)

Post-OCVs (4.2 V pre)

Cell 6

Cell 5

Temperature (°C)

Time (s)

Voltage/Current (V/A)

#1 4.16
#2 4.16
#3 4.17
#4 4.16
#5 0.0
#6 4.16
#7 4.17
#8 4.16
#9 4.16

Temp 1
Temp 2
Temp 3
Temp 4
Temp 5
Temp 6
Temp 7
Temp 8
Temp 9
Ambient
Heater Current
Voltage 1
Voltage 2
Voltage 3
Voltage 4
Voltage 5
Voltage 6
Voltage 7
Voltage 8
Voltage 9

9/15/2014
J. Jeevarajan, Ph.D. NASA/JSC
Cell-to-Cell Space LG C2 Cell Tests

- 1, 2, and 4 mm spacing between cells
- LG 18650 C2 (2.8 Ah) in 9P configuration
LG C2 – 1mm Space 9P Fork Config.

100% SOC

- 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

8.8mm diagonal

1mm horizontal

J. Jeevarajan, Ph.D. NASA/JSC
LG C2 – 1mm Air Space 9P Fork Config. 100% SOC

20W Heater on Cell 5

Post-OCVs (4.3 V pre)

- #1: 4.27
- #2: 0
- #3: 4.27
- #4: 0.637
- #5: 0
- #6: 2.086
- #7: 4.27
- #8: 0.429
- #9: 4.26

Cell 5

Cell 2

Cell 8

Time (s)

Bank Voltage/Heater Current (V/A)

Temperature (°C)

Bank Voltage
LG C2 – 1mm Air Space 9P Serpentine (S-type) 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
- Elevated adjacent cell temperatures (120-150 °C)
LG C2 – 1mm Air Space 9P Serpentine (S-type) Config.

100% SOC

Post-Test OCV: all 0 V

Cell 5

Adjacent Cells

20W Heater on Cell 5
Complete thermal runaway of cell 5
Thermocouple wire melted from venting
Voltage/capacity drain observed from adjacent cells 2, 6, and 8
No crimp opening or extrusion of electrode roll
Elevated adjacent cell temperatures (100 °C)
LG C2 – 2mm Air Space 9P Serpentine (S-type) Config. 100% SOC

- 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)
LG C2 – 4mm Air Space 9P Fork Config. 100 % SOC

- Complete thermal runaway of cell 5
- No propagation
- Capacity/Voltage drain observed on adjacent cells 2 and 8
- No crimp opening or extrusion of electrode roll
Radiant Barrier

- To mitigate radiation heat transfer and protect against direct flame from side vents in BP cells
- Per Boeing donor
  - Outer layers are quartz cloth,
  - There are 5 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 config.)

- Can ruptured and contents ejected from triggered cell
- No propagation

Post-OCVs (4.2 V pre)

- #4: 4.18V
- #3: 4.18V
- #1: 4.18V
- #2: 0V
BP5300 at 100% SOC with Radiant Barrier (4P config.)

- Can ruptured and contents ejected from triggered cell
- No propagation

Post-OCVs (4.2 V pre)

#4: 4.18V
#3: 4.18V
#1: 4.18V
#2: 0V
BP5300 at 50% SOC with Radiant Barrier (4P config.)

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

Pre-test:
- Restraint Clip

Post-test:
- Gap in barrier w/ melting of restraint clip

Post-OCVs (4.2 V pre):
- #4: 0.28 V
- #3: 1.5 V
- #1: 0 V
- #2: 0 V

Jeevarajan, Ph.D. NASA/JSC
Intumescent Material

• Intuplas
  – Nanocomposite consisting of thermoplastic carrier and 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 and off-gas test
(Courtesy: Mike Fowler)
Intuplas Modules

3 each of 2 mm, 4mm spacing for BP and 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 2mm 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

Cell 2
Cell 9
Cell 5

Time (s)
0 1000 2000 3000 4000 5000 6000 7000 8000 9000

Temperature (°C)
0 500 1000 1500 2000 2500

Module Voltage (V)
2 3
BP5300 at 100% SOC with 2mm Intuplas (9P config.)

Positive Terminals

Negative Terminals (Top of Module during test)

All cells held 4.17V
Except cell 5

Temperature (°C)

Module Voltage (V)

Time (s)
SKC LFP 14.7 Ah 14P Module 2-100 % SOC

50 W Heater  Cell positive terminals

7 deg C / min. Heating rate
SKC LFP 14.7 Ah 14P Module 2-100 % SOC

50W Heater
Power on Cell 8

Temperature (°C)

Module Voltage (V)

Time (s)

Cell 8

4 3 2 1

TC-2 TC-3 TC-4

9 8 7 6 5

TC-5 TC-6 TC-7

14 13 12 11 10

TCB

Cell 8

Cell 13

Cell 9

Cell 3

Cell 7

Cell 8

Cell 11

Cell 2

Cell 14

Chamber Temp

Mod Voltage

9/15/2014

J. Jeevarajan, Ph.D. NASA/JSC

PROPULSION & POWER DIVISION
Thermal Propagation Analysis
(Calculations by Carlos Lopez)

- Convection negligible in space
- Conduction dominates at \( T < 500 \, ^\circ\text{C} \)
- Radiation exponentially increases with temperature
- Increasing spacing significantly decreases heat transfer
- Fire due to electrolyte venting in the presence of high temperatures can cause significant propagation.

\[
Q_{\text{cond}} = kA \frac{T_1 - T_2}{\Delta x}
\]

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

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

\[
C = 1 + \Delta x / r
\]

<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>

\( T_1 = 500\, ^\circ\text{C} \quad \varepsilon_1 = 0.9 \)
\( T_2 = 100\, ^\circ\text{C} \quad \varepsilon_2 = 0.9 \)

Radiation view factor, \( F_{12} \)
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 and 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 may provide a benefit in reducing cell to cell damage propagation.
Acknowledgment

- NASA-JSC Test Area Team
- Pyrophobic Systems Team
- Bruce Drolen – Boeing Seattle
Test Chamber Setup

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