Design Guidelines for Safe, High Performing Li-ion Batteries with 18650 cells

By

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Outline

• Introduction
• Applications and Motivation
• 5 Battery Design Guidelines
• Trading thermal isolation vs heat dissipation
  – Full thermal isolation
  – Drawing heat from cell bottoms
  – Full can length interstitial heat sink approach
• Risk of side wall breaches during thermal runaway
• Insights from cell calorimetry combined with X-ray videography
• Summary
NASA-Johnson Space Center (JSC), Houston, TX

• Human spaceflight projects are led by JSC
  – ISS
  – Orion Exploration Vehicle
  – Commercial Crew

• Astronaut selection & training
Orion Multi-Purpose Crew Vehicle
-- 4-man crew
-- Beyond Low Earth Orbit

Command Module Battery System
• 132V, 4 kWh x 4
• \( \frac{3}{4} \) C discharge rate
ISS Commercial Cargo/Crew Vehicles

- SpaceX Dragon Module and Falcon 9 launch vehicle
  - 28V, 26 kWh of Li-ion batteries for Dragon
  - 28V, 3 kWh of Li-ion batteries for Falcon
- Boeing CT-100 Starliner
  - 28V, 58 kWh of Li-ion batteries for command module
  - 28V, < 1 kWh of Li-ion batteries for service module
- Sierra Nevada Dreamchaser
  - 28V, 46 kWh of Li-ion batteries
  - 140V, 9 kWh of Li-ion batteries
Some of NASA’s Future Battery Applications

- **Robonaut 2**
  - To enhance and reduce frequency of manned spacewalks
  - High energy density and high specific energy battery needed
  - 90V, 4 kWh, 7 hour mission

- **Mars Rover Vehicle**
  - Terrestrial demonstration vehicle needing high voltage, power battery
  - 400V, 4 kWh, 1 hour mission

- **Valkyrie, RoboSimian**
  - Terrestrial dangerous operations robot
  - 90V, 2 kWh, 1 hour mission

- **X-57 Electric Plane**
  - All electric aircraft demonstrating distributed electric propulsion
  - 525V, 50 kWh, 1 hour mission
High Power/Energy 18650 Cell Designs

- Specific Energy Range 259-276 Wh/kg
- Energy Density Range 704-735 Wh/L

<table>
<thead>
<tr>
<th>C/10 at RT</th>
<th>Panasonic NCR GA</th>
<th>Samsung 3.5E</th>
<th>Sony VC7</th>
<th>LG MJ1</th>
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<td>Discharge Capacity (Ah)</td>
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<td>276</td>
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<td>266</td>
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<td>Energy Density (Wh/L)</td>
<td>704</td>
<td>733</td>
<td>735</td>
<td>720</td>
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</table>

Panasonic NCR18650GA

Sony US18650VC7

LG INR18650 MJ1

Samsung INR18650-35E

Sony US18650VC7
C/10 Capacity Performance Comparison

Voltage vs Capacity at 350 mA constant current
Comparison of 4 high energy/power cell designs
After 350mA charge to 4.2V to 70mA taper
Room temperature
Cell Voltage vs Capacity (Ah) for cell design comparison at C-rate
Charge at 350mA to 4.2V with 70mA taper termination
Discharge at 3.4A to 2.5V with 350mA with 1s pulse at 50% SoC
Ambient temperature and pressure

<table>
<thead>
<tr>
<th>Cell Model</th>
<th>LG MJ1</th>
<th>LG M36-BV</th>
<th>PAN GA</th>
<th>PAN B</th>
<th>SAM 35E</th>
<th>SONY VC7</th>
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<tr>
<td>Discharge Energy</td>
<td>Wh</td>
<td>11.53</td>
<td>11.43</td>
<td>11.29</td>
<td>10.92</td>
<td>11.80</td>
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<td>Weight</td>
<td>g</td>
<td>46.903</td>
<td>47.608</td>
<td>47.008</td>
<td>45.801</td>
<td>47.883</td>
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<td>Specific Energy</td>
<td>Wh/kg</td>
<td>245.8</td>
<td>240.2</td>
<td>240.3</td>
<td>238.5</td>
<td>246.5</td>
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</table>
Cell Can Wall Cross Sections

NCR18650B COTS design averages 127 μm
ICR18650-26F (2.6Ah Samsung) averages 160 μm
ICR18650J (2.4Ah Moli) averages 208 μm

Thin can wall with >660 Wh/L ➔ high propensity to side wall ruptures/breaching
Other factors include high reaction kinetics and high header crimp burst pressure
Axial View – Header of NCR18650B Cell

Double crimp header design

Can crimp
Gasket seal
Internal crimp
Internal seal

Spin groove

0.005” (125 micron)
Can wall thickness

Scored burst disc
CID mechanism

Header button
Button vent

PTC annulus switch
Insulator

Note the double crimped header design

Burst Pressure of Crimped Header ~1000psia (68 atm)

3 of 30 cells experienced side wall ruptures during oven heating to TR
LG INR18650 MJ1 - Axial View - Header - Cell

- Can crimp
- Gasket seal
- Spin groove
- Thinning of can wall
- Header button
- Button vent
- Scored burst disc
- (+) tag
- No Mandrel
- Can wall thickness 0.0085" (165 microns)

0 of 30 cells experienced side wall ruptures during oven TR tests

Note the single crimped header design with burst pressure ~800 psia (~54 atm)
5 Battery Design Guidelines for Reducing Hazard Severity from a Single Cell TR

- **Reduce risk of cell can side wall breaches**
  - Without structural support most high energy density (>660 Wh/L) designs are very likely to experience side wall breaching during TR
  - Battery should minimize constrictions on cell TR pressure relief

- **Provide adequate cell spacing and heat rejection**
  - Direct contact between cells nearly assures propagation
  - Spacing required is inversely proportional to effectiveness of heat dissipation path

- **Individually fuse parallel cells**
  - TR cell becomes an external short to adjacent parallel cells and heats them up

- **Protect the adjacent cells from the hot TR cell ejecta (solids, liquids, and gases)**
  - TR ejecta is electrically conductive and can cause circulating currents

- **Prevent flames and sparks from exiting the battery enclosure**
  - Provide tortuous path for the TR ejecta before hitting battery vent ports equipped flame arresting screens

Source: NASA NESC Task Report TI-14-00942 “Assessment of ISS/EVA Lithium-ion Battery TR Severity Reduction Measures” May 2017
Jeevarajan\textsuperscript{1} showed that without any heat dissipation path except through electrical parallel connections, adjacent cells get damaged (shorted) with even 4 mm spacing.

\textsuperscript{1} Jeevarajan et al. NASA Aerospace Battery Workshop, Nov 2014
X-57 Battery Design Fails PPR Testing in 2016

- 320-cell module catastrophically fails during single cell PPR testing
  - Multiple cells propagated TR nearly simultaneously
  - DPA revealed numerous cell can side wall ruptures

- Design not following guidelines 1 and 2
  - Doesn’t protect against sidewall rupture
    - Nomex paper (yellow) is weaved in between cell can walls
    - Cell secured at their ends with G10 capture plates maybe held too tightly
  - Doesn’t provide sufficient heat dissipation between cells
    - Cell heat is dissipated through Ni bussing
    - Ni is a poor thermal conductor

- Battery redesign and retest will require trigger cells with ISC device
Achieving Passive TR Propagation Resistant Designs

Pass/fail Criteria

• No TR propagation resulting from the TR of any single cell location at worst case temperature and pressure conditions

• Demonstration required by test
  – Minimum of 3 tests if adjacent cells cycle nominally after the test
  – Minimum of 6 tests if in any one test the adjacent cells are damaged
    • CID opens, cell vents, or leakage
    • Charge retention (soft short)

Source: NASA NESC Task Report TI-14-00942 “Assessment of ISS/EVA Lithium-ion Battery TR Severity Reduction Measures” May 2017
Orion Battery 14-cell Block

18650 CELL

18650 CELL

304 Stainless Steel Sleeve – 9 mil wall thickness

LOWER HEAT-SINK CAPTURE PLATE 6061-T651 ALUM

Draw cell heat generation through cell bottom

Orion 14P-8S Superbrick

UPPER CAPTURE PLATE G10 FR4 FIBERGLASS COMP

MACOR VENT TUBES

SYNTACTIC FOAM LINER

6061-T651 ALUM
Isolating vs Providing a heat path

- If you thermally isolate cells (air)
  - Adjacent cell $\Delta T$ rise 80-100°C
  - *Limited to cell designs with little risk of side wall ruptures*
  - Achieves 160-170 Wh/kg
- Orion - Partially conductive (Draw heat from cell bottom)
  - Conduct heat to divider plate
  - Adjacent cell $\Delta T$ rise 60-70°C and shorter exposure
  - 14P-8S superbrick with SS sleeves achieves 150-160 Wh/kg
Safer, Higher Performing Battery Design

Compliance with the 5 rules

• Minimize side wall ruptures
  • Al interstitial heat sink
• No direct cell-cell contact
  • 0.5mm cell spacing, mica paper sleeves on each cell
• Individually fusing cell in parallel
  • 12A fusible link
• Protecting adjacent cells from TR ejecta
  • Ceramic bushing lining cell vent opening in G10 capture plate
• Include flame arresting vent ports
  • Tortious path with flame arresting screens
  • Battery vent ports lined with steel screens

Features

• 65 High Specific Energy Cell Design 3.4Ah (13P-5S)
• 37Ah and 686 Wh at BOL (in 16-20.5V window)
• Cell design likely to side wall rupture, but supported
LLB2 Heat Sinks

No corner cells - Every cell has at least 3 adjacent cells

0.5mm cell spacing, Al 6061T6
• 13P-5S Configuration with 3.4 Ah LG cell design yielding 37 Ah at 3.8 A mission rate.
• Aluminum interstitial heat sink, 0.5 mm spacing between cells
• Mica sleeves around shrink wrap, 2 FT
• The G10 capture plate houses the + and - ends of the cells and prevents the Ni bussing from shorting to the heat sinks.
• The ceramic Macor bushing acts as a chimney to direct ejecta outwards and protect the G10/FR4 capture plate.
Cell Brick Assembly > 180 Wh/kg

- With 12.41 Wh/cell, cell brick assembly achieves 191 Wh/kg
  - Assuming 12.41Wh per cell
- Design has 1.4 parasitic mass factor
  - Cell mass x 1.4 = Brick mass

<table>
<thead>
<tr>
<th>Mass Categories</th>
<th>g</th>
<th>%</th>
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<tbody>
<tr>
<td>3.4Ah 18650 Cells</td>
<td>3012.75</td>
<td>71.3%</td>
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<tr>
<td>Heat sinks</td>
<td>824.95</td>
<td>19.5%</td>
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<tr>
<td>Mica sleeves</td>
<td>182.31</td>
<td>4.3%</td>
</tr>
<tr>
<td>Capture plates</td>
<td>115.81</td>
<td>2.7%</td>
</tr>
<tr>
<td>Ceramic bushings</td>
<td>60.15</td>
<td>1.4%</td>
</tr>
<tr>
<td>Ni-201 bussing</td>
<td>29.71</td>
<td>0.7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4225.7</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Mass Distribution
Attempts to Drive TR with Cell Bottom Heater Fails

Cell bottom surface heater

Can’t get trigger cell > 100°C after > 1hr and 3 attempts

Al heat sink

Bottom of Cell Heater Test with Al Heat Sink

Heater fails at 48W

TCs 1-7

TC 8
Metallic Interstitial Heat Sink is Effective

- Cell can isolated with mica paper sleeves and very small air gap
- Heat sink spreads heat more quickly through multiple layers than through mica and onto cells
- Heat from trigger cell is quickly dispersed and shared among more cells
NREL/NASA Cell Internal Short Circuit Device

Active anode to cathode collector short

- Wax formulation used melts ~57°C
- US Patent # 9,142,829 issued in 2015
- 2010 Inventors:
  - Matthew Keyser, Dirk Long, and Ahmad Pesaran at NREL
  - Eric Darcy at NASA

Thin (10-20 μm) wax layer is spin coated on Al foil pad

Wax formulation used melts ~57°C

ISC Device in 2.4Ah cell design
Placed 6 winds into the jellyroll

Top to Bottom:
1. Copper Pad
2. Battery Separator with Copper Puck
3. Wax – Phase Change Material
4. Aluminum Pad

Graphic credits: NREL

Runner-up NASA Invention of 2017

2016 Award Winner
Open air test with cell charged to 4.2V and with TCs welded to cell side wall (2) and bottom (1)
Heater power ~42W for 180s. Onset of TR (OTR) occurs 180s after power on and coincides with trigger bank OCV dip. Adjacent cell1 has $\Delta T = 58.9^\circ C$ to max of $92.0^\circ C$, while adjacent cells 2 & 3 have $\Delta T = 48^\circ C$ to max of $76.0^\circ C$.
No TR Propagation, Only Smoke Exits Battery

Mesh 40 & 30 steel screens arrest flames and sparks

However, trigger cell was only 2.4Ah cell
Test with 3.5Ah ISC Device Trigger Cell

Adjacent cell temperatures TC1, TC2, and TC3 peak at $133^\circ C$, $117^\circ C$, and $117^\circ C$ in 77-87s from onset temperatures of $39^\circ C$, $37^\circ C$, and $38^\circ C$ for $\Delta T = 94^\circ C$, $77^\circ C$, and $78^\circ C$, respectively.

OCV dips $\Delta V = 158$ mV corresponding to 57A in-rush current

ISC device in 3rd wind of JR in 3.5Ah Cell
No TR Propagation – Only Clean Smoke Exits Gore Vent

3.5Ah cell with ISC device trigger location

Flame arresting steel screens

Gore fabric Vent design

3.5Ah cell with ISC device in 3rd JR wind

Battery bottom edge seal fails and relieves internal pressure at ~11.4 psig (0.77 bar)
3.5 Ah Trigger Cell Experienced a Side Wall Breach

Trigger cell was a struggle to extract from heat sink. The mica insulation was severely damaged adjacent to rupture

<table>
<thead>
<tr>
<th>Cell</th>
<th>OCV (V)</th>
<th>Mass (g)</th>
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<tr>
<td>Trigger</td>
<td>0</td>
<td>17.161</td>
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<tr>
<td>1</td>
<td>3.474</td>
<td>46.801</td>
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<tr>
<td>2</td>
<td>0.336</td>
<td>46.691</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>46.671</td>
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3.5Ah Cell #21 with ISC Device Video

Time (s) = 1.6575

Image and video courtesy of D. Finegan, University College of London
3.5Ah Cell #21 with ISC Device

- JR ejected
- Top edge of crimp shows reflow steel
- Side wall breach in neck of crimp is clocked with ISC device
- Smaller breach in can wall is slightly off the ISC device clocking and above it
Side-wall Breach of MJ1 Cell
ISC device 3 winds in

Side-wall breach

Hotspot clocked with ISC device followed by side-wall breach (SWB)

First capture of side wall breach using high speed X-ray imaging. Bulging around the point of initiation occurs and the propagation front makes early contact with the cell casing. The direction of flow shifts towards the widening SWB.
Adjacent cell max temperatures < 83°C
Post-Test Photos – Trigger Cell

Post-Test Mass: 25.3g

Bottom breach

Spin groove is stretched
Findings from 2\textsuperscript{nd} Test with 3.5Ah ISC Trigger Cell

- ISC device in 3.5Ah 18650 cell triggered in 127 seconds with bottom heater at 32W average
  - Very similar initiation time (1\textsuperscript{st} run was in 119s)
  - Very similar biasing of adjacent cells (34-35\degree C) at onset of TR (1\textsuperscript{st} run at 37-39\degree C)

- No propagation of TR
  - Despite bottom breach of trigger cell, which damaged the G10/FR4 negative capture plate
  - Reusing the same heat sinks from the first test – undamaged after both tests

- Max adjacent cell temperatures < 83\degree C
  - Adjacent cell temperature rise was 46-47\degree C, significantly lower than 1\textsuperscript{st} run (77-94\degree C)
  - Bottom breach yields a much less severe impact than side wall breach
Three trigger cell locations
LG 3.3Ah with thicker can walls (250 microns) and ISC device in bottom of JR
Thermocouples welded to bottom of adjacent cells.
Comparing the 2 Interstitial Heat Sink Options

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<th>Mass Categories</th>
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<th>Mass Categories</th>
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<td></td>
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<td>Vaporizing Interstitial</td>
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<tr>
<td>LG MJ1 cells</td>
<td>3013</td>
<td>71.30%</td>
<td>LG MJ1 cells</td>
<td>3013</td>
<td>84.81%</td>
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<tr>
<td>Heat sinks</td>
<td>825</td>
<td>19.50%</td>
<td>Heat sinks</td>
<td>334.1</td>
<td>9.40%</td>
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<td>Mica sleeves</td>
<td>182.3</td>
<td>4.30%</td>
<td>Mica sleeves</td>
<td>0</td>
<td>0.00%</td>
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<td>Capture plates</td>
<td>115.8</td>
<td>2.70%</td>
<td>Capture plates</td>
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<td>3.26%</td>
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<td>Ceramic bushings</td>
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<td>Ni-201 bussing</td>
<td>29.71</td>
<td>0.70%</td>
<td>Ni-201 bussing</td>
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<td>0.84%</td>
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<tr>
<td>Total</td>
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<td>Total</td>
<td>3553</td>
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<tr>
<td>Parasitic mass factor</td>
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<td>Parasitic mass factor</td>
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<td>Brick Specific Energy</td>
<td>191</td>
<td>Wh/kg</td>
<td>Brick Specific Energy</td>
<td>227</td>
<td>Wh/kg</td>
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KULR Vaporizing Heat Sink enables
- 19% improvement in Wh/kg
- 1.5 lbs mass savings per spacesuit battery (or 16%)
- For the X-57 battery (55 kWh) this would save > 101 lbs
Video snapshots of all 3 trigger tests

- Max $\Delta T$ on adjacent cell 40-63°C, a bit higher than with Al heat sink brick test
  - However in Al brick test 2.4Ah trigger cell vs 3.3Ah for vaporizing brick test
- All adjacent cells cycled nominally post test
Vaporizing Thermal Runaway Shields - Blow Torch Test

• Design
  • Highly conductive carbon fiber wick
  • Soft, thin, & compliant polyethylene enclosure & seal
  • 2mm thickness
  • Much lighter than solid Al
• Tests
  • No blow through failures after multiple direct flame impingement 10-sec blow torch exposures
  • Plastic melts, water leaks out, but wet carbon fiber layer stays intact
  • Merits testing with cells likely to side wall rupture
LG 18650 3.35Ah - Axial View - Header - Cell

- Header button
- Button vent
- Can crimp
- Gasket seal
- Spin groove
- Scored burst disc
- (+) tag
- Thinning of can wall
- Can wall thickness 0.009” (220 microns)
- Can wall thickness 0.010” (250 microns)
- No Mandrel

Note the single crimped header design with burst pressure ~800 psia (~54 atm)
LG 3.35Ah Cell Design with Bottom Vent

3.35Ah cell design, a bit more power capable than 3.5Ah design

<table>
<thead>
<tr>
<th></th>
<th>3.5Ah vs 3.5Ah</th>
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<tr>
<td>Diameter</td>
<td>max. 18.65</td>
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<tr>
<td>Height</td>
<td>max. 65.3</td>
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<tr>
<td>Wall thickness</td>
<td>0.15</td>
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<tr>
<td>Mass</td>
<td>47.0 g</td>
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<tr>
<td>Capacity</td>
<td>3.5Ah</td>
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<tr>
<td>Energy</td>
<td>12.7 Wh</td>
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<tr>
<td>Voltage</td>
<td>2.6~4.2</td>
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<tr>
<td>Max current</td>
<td>10A</td>
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<tr>
<td>AC Resistance</td>
<td>30</td>
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</table>
LG 3.35Ah with Bottom Vent (BV)

Bottom vent disk separates completely
Heat Distribution Calorimeter

Characterising the difference between failure types
Highlight risks associated with the spread of heat sources when cells rupture and compare to when they remain intact

Heat Distribution Calorimeter
- Measure heat output from single cylindrical cells
- **Decouple heat generated within the cylindrical casing and heat generated by ejected material**
- X-ray transparent for in-situ high-speed X-ray imaging
- Scalable to fit any cylindrical cell design
- Ambidextrous design for bottom vent cells

Bore Chamber
- Slows down and extracts heat from escaping flames and gas

Ejecta Mating
- Captures ejected solids such as the electrode assembly
- Thermally isolated from the cell chamber

Cell Chamber
- Contains the cylindrical cell
- Includes heating system for thermally induces failure
Higher energy density cells released more heat

- 3.5Ah MJ1 cells generated 22% more heat than 3.35Ah cells that have 3% more capacity

The distribution of heat released from ejected material and from the cylindrical body of the cell was measured

- A combination of 3.35Ah cells with bottom vents (BV) and without bottom vents (NBV) were tested

Calorimetry experiments have been conducted at the NASA JSC Energy Systems Test Area (ESTA) and at the European Synchrotron Radiation Facility (ESRF) and Diamond Light Source (DSL):
- 38 sets of data processed for successful tests processed to date
- 27 runs at the ESRF and 62 very recently performed with the new calorimeter at the DSL

### Key Findings

- Higher energy density cells released more heat
- 3.5Ah MJ1 cells generated 22% more heat than 3.35Ah cells that have 3% more capacity
- The distribution of heat released from ejected material and from the cylindrical body of the cell was measured
- A combination of 3.35Ah cells with bottom vents (BV) and without bottom vents (NBV) were tested

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>LG 18650-MJ1</th>
<th>3.35 Ah LG 18650</th>
<th>Samsung 18650-30Q</th>
<th>Molicel 18650-J</th>
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<tbody>
<tr>
<td>Capacity at 100% SOC</td>
<td>Ah</td>
<td>3.43</td>
<td>3.35</td>
<td>3.0</td>
<td>2.3</td>
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<td>Nominal Voltage</td>
<td>V</td>
<td>3.67</td>
<td>3.7</td>
<td>3.6</td>
<td>3.78</td>
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<td>Stored Electrochemical Energy</td>
<td>kJ</td>
<td>45.3</td>
<td>44.6</td>
<td>38.9</td>
<td>31.3</td>
</tr>
<tr>
<td>Cell Mass</td>
<td>g</td>
<td>47</td>
<td>47</td>
<td>48</td>
<td>47</td>
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<tr>
<td>Special Features Tested</td>
<td>-</td>
<td>-</td>
<td>BV / ISC / TCW</td>
<td>-</td>
<td>Separator</td>
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<tr>
<td>Number of Successful Tests</td>
<td>-</td>
<td>9</td>
<td>22</td>
<td>3</td>
<td>5</td>
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<td>Test Facility</td>
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<td>ESTA</td>
<td>ESRF</td>
<td>ESTA</td>
<td>ESRF</td>
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</table>

*BV: Bottom Vent Cells
NBV: Non-Bottom Vent Cells
ISC: Internal Short Circuit Device
TCW: Thin Can Wall
S1 & S2: Two proprietary separators

Credit: Will Walker (NASA)
Comparison between the heat distribution of cells with and without bottom vents

Key Findings

- **Bottom vent cells produce around 12% less heat than non-bottom vent cells.**
  - May be due to bottom-vent cells ejecting less material and thermal runaway reactions being oxygen limited.

- A higher proportion of heat is generated within the cylindrical casing in cells with bottom vents.
  - This may be due to a decreased risk of the cell bursting and ejecting the electrode assembly.

- A higher proportion of heat is generated from ejected material in cells without bottom vents.

- For both cells, over 60% of the heat generated during thermal runaway stems from ejected material.

![Graph showing energy release for different cell capacities](image-url)
Test Plan - Cell ISC Device Implantations

- Objective #1 is to determine the safety merits of bottom vents vs thicker can walls
  - LG Initial design (Group 1)
    - No bottom vent
    - 220 μm (0.009”) side wall
  - LG-BV (Groups 2-5)
    - Bottom vent
    - 220 μm (0.009”) side wall
  - LG-TC (Groups 6-9)
    - No bottom vent
    - 250 μm (0.010”) side wall
    - Adds 777mg vs the initial design

- Objective #2 is to determine the side wall rupture sensitivity to the location of the ISC device
  - 3 winds into middle of JR
  - 6 winds into middle of JR
  - 6 winds into top of JR
  - 6 winds into bottom of JR
High-speed X-ray Imaging

- Oct 2017: Experiment at The European Synchrotron (ESRF), France.
- 29 x 18650 cells with ISC devices placed at different locations were brought to thermal runaway
- Cell design features varied; with two different wall thicknesses and w/ or w/o bottom vents
- Simultaneous high-speed X-ray imaging and single cell calorimetry

Aim:
- To link internal phenomenon with external risks and uncover conditions that lead to worst-case failure scenarios
- Clarify the merits of bottom vents and thicker casing walls
Bottom Vents: Determining Merits

No Bottom Vent (NBV)

Key findings
- Base-plate domes outwards as the gases and debris deflect and take a U-turn through the vacant core of the electrode assembly
- The inner winds of the electrode assembly shear and eject

Bottom Vent (BV)

Key findings
- Gases and debris does not take a U-turn. The residence time of reacting material is therefore less.
- The thermal mass of the base plate is reduced which may increase the risk of breach due to deflecting material
- The electrode assembly shifts towards the base-vent rather than the top-vent
Bottom Vent vs No Bottom Vent (only 3.35Ah Cells)

- Inside Calorimeter
  - Bottom vent cells retain 54% of their mass post TR
  - While cells without BV retain only 40%
- Outside Calorimeter with circumferential heater
  - Bottom vent cells retain 50% of their mass post TR
  - While cells without BV retain only 42%
- Counting all tests
  - BV cells retain 52% vs 41% of their pre-test mass
  - Similar results inside or outside calorimeter
  - Pictures of cell can walls, occurrence of side wall ruptures, and post test mass all suggest BV feature produces less violent TR events

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<th>Calorimeter Runs</th>
<th>3.35Ah w BV</th>
<th>3.35Ah w/o BV</th>
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<td>Average (g)</td>
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% of pre-test mass

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Bottom Vent, Thicker Can Wall Results

- 3.5Ah LG cell design with thin can wall (165 micron) and ISC device in 3 winds into JR
  - yields > 80% chance to SWB
  - Count = 36
  - Excellent worst case trigger cell for battery testing because clocking of SWB is predictable
- 3.35Ah LG cell design with thicker 220 micron can wall and bottom vent
  - 1 of 31 or 3% chance of SWB
  - Risk is not eliminated
- 3.35Ah LG cell design with thickest 250 micron can wall but no bottom vent
  - 4 of 18 or 22% chance of SWB
  - Higher risk than with bottom vent
- Post test masses are higher for BV cells, TR appear less violent
  - 50% vs 42% of pre test mass
Summary Conclusions

Heat output
- 3.5Ah MJ1 cells produce the most heat (1.72 kJ/kJ stored) whereas 3.35Ah cells produce 1.44 kJ/kJ stored.
- > 70% of the heat output is from ejected material in the 2 cell designs cells.
- Cells that undergo bottom breach, on average, produce less heat.

Rupture/Breaching of 18650 cell enclosure
- Side wall, spin groove, bottom, and top cap breaching is melt-through thermal breach, not a pressure induced rupture
- 18650 cells extend by 2-3 mm during header rupture. Allowances need to be made for this extension to avoid unwanted pressure build-up and side-wall breaches.

Merits of bottom vent
- Bottom vent reduces residence time of reacting species.
- The bottom vent leads to less ejected material due to decreased flow rate, and less overall heat generation but more heat generated within the casing of the cell. This suggests that the reactions are oxygen starved.

Safe, High Performing Battery Design Guidelines
- Must address risk of side wall breaches: bottom vent, thicker can wall, & protect vulnerable spin groove area
- Provide adequate heat dissipation: conductive interstitial heat sinks along cylindrical wall (also protect against side wall breaches) are best
- Fuse parallel cells to electrically isolate internally shorted cells
- Allow hot ejected materials to disperse their energy quickly while protecting the adjacent cells
- Equip battery vent port with flame arresting features