The Effect of Thermal Management Material on Thermal Runaway Propagation

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Lithium-Ion Battery Fires
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- Lithium ion battery fires serious threat
  - Hoverboards
  - Galaxy Note 7
- Safety concern for aerospace companies
  - Dreamliner grounded due to battery fire
  - Jet propulsion laboratory prototype robot destroyed by 98 cell explosion
- Must engineer lithium ion packs assuming one cell will short
  - Boeing with the best BMS and fusing still had a failed cell cause a catastrophic fire
Thermal Runaway, Cell Level

- Thermal runaway: Cell chemistry reacts rapidly generating heat
- Accelerating Rate Calorimetry
  - See what temperature cell enters TR
  - Depends on cell and state of charge
  - 90°C to 120°C

![Graph](image-url)  
**Threshold: 100°C**
Thermal Runaway Propagation: Heat transfer

Success Criteria: Adjacent cell temperature $T_c < 100^\circ C$

- **Q**: Cell heat generation from TR
  - Cell energy
  - Parallel welds
  - Combustion

- Conduction to adjacent cells
  - Pack material thermal diffusivity
  - Cladding thickness
  - Contact resistance

- Convection to surroundings

- Thermal diffusivity a function of temperature in phase change materials

$$T_c \approx D = \frac{k}{\rho C_p(T)}$$
Research Overview

- Evaluate what cell packaging materials can prevent the propagation of thermal runaway in a small pack of 18650 style cells.
  - Air
  - Graphite
  - Wax
  - Graphite and Wax (PCC)
- Evaluate the importance of battery configuration and weld strength on thermal runaway propagation
- Nail penetration test
### Battery Pack Materials Evaluated

- **Phase Change Composite (PCC)**
  - 20 wt.% graphite
  - 80 wt.% wax
  - Wax micro-encapsulated
  - Melts at 55°C
  - \(\frac{1}{2}\) Latent heat of ice

- Graphite only (90% porous)
- Wax (100%)
- Air
## Different Material Properties

<table>
<thead>
<tr>
<th></th>
<th>Air</th>
<th>Graphite Only</th>
<th>Wax Only</th>
<th>PCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity (W/m-K)</td>
<td>0.024</td>
<td>13.77 (in-plane)</td>
<td>0.15</td>
<td>17.21 (in-plane)</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1.23</td>
<td>200</td>
<td>775</td>
<td>935</td>
</tr>
<tr>
<td>Specific Heat (J/kg-K)</td>
<td>1005</td>
<td>725</td>
<td>2384</td>
<td>1837</td>
</tr>
<tr>
<td>Latent Heat (J/g)</td>
<td>N/A</td>
<td>N/A</td>
<td>211</td>
<td>153</td>
</tr>
<tr>
<td>Diffusivity (mm²/s)</td>
<td>19.42</td>
<td>94.96</td>
<td>0.08</td>
<td>10.02</td>
</tr>
</tbody>
</table>
## Battery Pack Specifications

<table>
<thead>
<tr>
<th>Pack specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification</td>
<td></td>
</tr>
<tr>
<td>Configuration</td>
<td>10s4p</td>
</tr>
<tr>
<td>Energy (Wh)</td>
<td>413</td>
</tr>
<tr>
<td>Voltage, nominal (V)</td>
<td>36.2</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>2.75</td>
</tr>
<tr>
<td>Specific Energy (Wh kg(^{-1}))</td>
<td>150</td>
</tr>
<tr>
<td>Dimensions (cm)</td>
<td>32 x 9 x 13</td>
</tr>
<tr>
<td>Casing</td>
<td>Aluminum &amp; plastic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification</td>
<td></td>
</tr>
<tr>
<td>Form Factor</td>
<td>18650</td>
</tr>
<tr>
<td>Capacity, nominal (Ah)</td>
<td>2.85</td>
</tr>
<tr>
<td>Voltage, nominal (V)</td>
<td>3.62</td>
</tr>
<tr>
<td>Specific Energy (Wh kg(^{-1}))</td>
<td>224</td>
</tr>
<tr>
<td>Energy Density (Wh L(^{-1}))</td>
<td>603</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Graphite anode, NCA cathode</td>
</tr>
</tbody>
</table>
Pack Build Procedure

- 6 welds on trigger cell (normally 4)
- Hole drilled in casing for nail penetration
Air Pack TRP Video

- https://youtu.be/vmUpbou8VtA
TRP occurred slowly due to air low thermal conductivity and low ability to store heat.
Graphite Only: Thermal Runaway Propagation

- TRP occurred quickly due to high thermal conductivity and low ability to store heat.
Wax Only: Thermal Runaway Propagation

- TRP occurred quickly due to liquid wax flow and wax combustion
Phase Change Composite (PCC): Avoided Thermal Runaway Propagation

- TRP was prevented due to phase change absorbing thermal runaway energy
Comparison Between Packs

<table>
<thead>
<tr>
<th>Pack Material</th>
<th>Thermal Runaway Propagation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>Fail</td>
</tr>
<tr>
<td>Graphite</td>
<td>Fail</td>
</tr>
<tr>
<td>Wax</td>
<td>Fail</td>
</tr>
<tr>
<td>PCC</td>
<td>Pass</td>
</tr>
</tbody>
</table>

Graph:
- Time to neighbor cell peak temp.
- Peak Temperature
- Time to Neighbor Cell Peak Temperature (s) vs Neighbor Cell Peak Temperature (°C)

- Air (blue circle)
- Graphite (orange circle)
- Wax (purple circle)
- PCC (black circle)
Autopsy

No Thermal Runaway Propagation

Thermal Runaway Propagation

*Pack was sprayed with water after second cell propagated in packs that propagated
Nickel separation during cell venting

Nickel Cladding can separate from venting cell isolating electrical energy available for thermal runway propagation

Not 100% reliable separation. Cells can vent outside of side casing
Ongoing Research with PCC

<table>
<thead>
<tr>
<th>Cell Energy</th>
<th>Pack Configuration</th>
<th>Thermal Runaway Propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9 Ah</td>
<td>10s4p</td>
<td>Pass</td>
</tr>
<tr>
<td>3.2 Ah</td>
<td>10s4p</td>
<td>Pass</td>
</tr>
<tr>
<td>3.5 Ah</td>
<td>10s4p</td>
<td>Fail</td>
</tr>
<tr>
<td>3.5 Ah</td>
<td>10s0p</td>
<td>Pass</td>
</tr>
</tbody>
</table>
Conclusions and Future Work

- PCC (graphite and wax) reliably prevented TRP in 2.9 Ah, 10s4p packs

- Packs need to be engineered for TRP on a case by case basis
  - Cell energy (2.9, 3.2, 3.5 Ah…)
  - Material thermal properties
  - Parallel configuration and cladding separation

- Future tests will investigate different cell energies and graphite densities for AllCell Battery Products: http://www.allcelltech.com/
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