Temperature Adjustable Thermal Management System with Thermal Runaway Protection for Li-ion Packs

Mark Hartmann - CTO
• Cell Chemistry and Energetics - High power/energy but poor stability. Lower power/energy but good stability.

ref: BatteryUniversity.com
Thermal Event Energies

- Thermal Event Energy Data ranges for different Li-ion Chemistries
  - All data based on 18650 Cylindrical cells at 100% SOC

<table>
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<tr>
<th>Chemistry</th>
<th>Tmax</th>
<th>Heat of Reaction, ΔH in Joules</th>
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<tbody>
<tr>
<td>LFP</td>
<td>243-330 °C</td>
<td>1000-7300</td>
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<tr>
<td>NMC</td>
<td>665-731 °C</td>
<td>14,900 – 24,900</td>
</tr>
<tr>
<td>LCO</td>
<td>654-709 °C</td>
<td>17,900-20,600</td>
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<tr>
<td>NCA</td>
<td>-</td>
<td>31,100</td>
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Ref: Experimental Analysis of Thermal Runaway in 18650 Cylindrical Li-Ion Cells Using an Accelerating Rate Calorimeter, Lei, et. al, *Batteries* June 2017, vol. 3, issue 2, 14
Experimental Thermal Runaway Data

- Nail Penetration at 100% SOC
Various technologies and solutions that work in specific cases.

<table>
<thead>
<tr>
<th></th>
<th>Paraffin PCM</th>
<th>Graphite</th>
<th>Air</th>
<th>Combination 1</th>
<th>Optimized Combination 2</th>
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<tr>
<td>Thermal Mass</td>
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<td>Thermal Conductivity</td>
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<tr>
<td>Hi Pack Energy Density &amp; Connectivity (s/p)</td>
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<td>Fail</td>
<td>PASS</td>
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<tr>
<td></td>
<td>High thermal mass/ latent heat but poor FR</td>
<td>High conductivity but no thermal mass</td>
<td>Poor conduct., no thermal mass, no FR</td>
<td>Poor thermal mass</td>
<td>Optimized thermal mass and other properties</td>
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</table>
Nail Penetration- Thermal Runaway Protections

21700 NCA cells, 5S2P

<table>
<thead>
<tr>
<th>Transition Temperature (degree C)</th>
<th>Dim. Between Cells (mm)</th>
<th>Test Condition</th>
<th>Behavior of Trigger Cell (Burning Cell)</th>
<th>Behavior of Adjacent Cell</th>
<th>Judgement</th>
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<tr>
<td></td>
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<td>Environmental Temperature (degree C)</td>
<td>Cell Charging Condition</td>
<td>Peak Temperature (degree C)</td>
<td>Burned or not</td>
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<tr>
<td>40-45</td>
<td>1.5</td>
<td>55</td>
<td>Full</td>
<td>658</td>
<td>Burned</td>
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<td></td>
<td>55</td>
<td>Full</td>
<td>592.8</td>
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<td></td>
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<td>20</td>
<td>Full</td>
<td>709.4</td>
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<td>45</td>
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</table>

Test Sample: 5S2P Battery Pack
Pack Design Variables

NO one-size-fits-all

Matrix
Design & Properties

- Operating Environment
- Thermal Curves
- Charge / Discharge
- Pack Enclosure

- EC+
- Pack energy
- Series/parallel

- Therm. Management Benefit
- Latent Heat Content
- Fire Retardant Properties
- Thermal Conduct.
Two Benefits of Outlast Battery Matrix

Temperature/Safety Relationship

- Higher Trans. T Range
- Lower Trans. T Range

No Temperature Management

Safety

NO SAFETY

Temperature Management

Confidential to Outlast Technologies LLC
LHS® Solutions

- Thermal Runaway Protection
- Cell Surface Thermal Control
- Homogenous Pack Temperatures
- Temp. Management leads to Increased Cell Life
- Improved Fast Charging Properties
- Passive Thermal Management
- Electrically Insulative
- Allows for Cell Expansion/Contraction
- Shape Stable
- Less Complexity, Economical and generally lower weight than metal or ceramic.
LHS Products for Battery, Electronic and Industrial Applications

LHS materials are provided in a number of different formats from compounded product to finished components:

- **E-mobility**
  - Electric car
  - Electric scooter

- **Industrial & Electronics**
  - Industrial vehicle
  - Drone
  - Lighting fixture
Products

• Fill and Flow material (F&F, F&F FR)
• Matrix sheets
  – Same material as molded cylindrical cell matrix
  – Provide thermal management and inhibit propagation for pouch and prismatic cell systems
LHS Matrix for Battery Packs

- Various large scale customers and pack
Thermal Propagation Testing

- 700 Wh series connected pack - PASS
LHS Matrix - Pack Temperature Homogenous Temperatures

- A 10-15°C reduction in battery temp. Batteries stay below 55°C
- Better homogeneity for battery temperatures.
- Less complex C/D electronics required (BMS)
LHS® Battery Thermal History Comparison

Battery exposed to less thermal history, ~97°C·min/cycle in this experiment.
Thermal Cycling and Reliability

**Testing Program:**
- A control cell and a LHS® covered cell were tested on Arbin BT Battery System (UR18650RX).
- The cells rest for 1 minute before charging at 1.95A till voltage reaches 4.2V, then trickle charges until current drops to 0.25A.
- Cells rest for 10 seconds before discharging at 20A until voltage of 2.5V is achieved.
- The cells rest for 5 minutes before looping back to the charge cycle. This repeats for 1000+ cycles.
- **Control cell degraded and died after 700-800 cycles. Similar batteries in LHS® products continued for >1000 cycles.**
  - No loss of LHS® properties, no damage or matrix change.

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**Graphs:**
- **Cell Surface Temperature - 20A Discharge Testing Compilation**
- **Discharge Capacity Retention**

**21-40% improvement in discharge capacity retention**
Results of 6-cell en bloc
- NCR cells (high energy) show generally higher temperatures than UR cells (high power)
Concluding Remarks

- Understanding the pack variables, one can adjust the product transition temperatures and latent heat storage capacity to provide:
  - Prevent Li-ion cell thermal propagation and runaway.
  - Effectively reduce li-ion battery temperatures and improve battery life.
  - Provide homogenous temperatures across packs.

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Outlast Technologies LLC
831 Pine Ridge Road, Golden, CO 80403

OutlastLHS.com
Competitive Technologies
<table>
<thead>
<tr>
<th>Benefits &amp; Comparison</th>
<th>LHS® Battery Matrix</th>
<th>PCM/Graphite</th>
<th>Ceramic</th>
<th>Metal/Graphite Heat Sink</th>
<th>Air</th>
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Benefits and Comparison

• Carbon or Metal Heat Sinks
  • Electrical cond., weight, thermal cond. (pro/con)., rigid, $, etc.

• Ceramics
  • Weight, thermal cond. (pro/con)., rigid, $-$$$, etc.

• Active cooling systems
  • $$, complexity, homogenous cell touch, weight, propagation resistance?

• Intumescent FR systems
  • $, smother fire, no temp. management, lose pack, design to contain, etc.
<table>
<thead>
<tr>
<th>Benefits</th>
<th>Battery Matrix</th>
<th>Battery Sheet</th>
<th>LHS FR, Fill &amp; Flow</th>
<th>LHS Fill &amp; Flow</th>
<th>Battery Sleeve / Elastomer</th>
<th>Encapsulant &amp; Potting Compound</th>
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