Passive Fire Protection for Lithium Battery Shipments & Extinguishment of Lithium Battery Thermal Runaway

Presented to:  Triennial Meeting
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Date:  12-04-2013
Background

• Lithium batteries have been the cause of fires in small personal electronic devices and larger “bulk” quantities and continue to grow in popularity and use.
  – Small-scale incidents
    • Approximately 64 cargo/baggage incidents have been recorded by the FAA since 1991. \[3\]
  – Incidents involving large quantities of cells
    • A battery fire caused an accident in Dubai in 2010. \[2\]
    • An aircraft fire involving lithium batteries occurred in 2006. \[1\]
    • Numerous lithium-ion car fires have occurred.
  – Properly extinguishing lithium battery fires involves ensuring that cell-to-cell propagation of thermal runaway is prevented; Thermal runaway of a single cell lasts for only a short time and wouldn’t be as much of a hazard if propagation was prevented.
Introduction (packaging)

- Batteries are shipped in various configurations.
  - Lithium-ion and lithium-metal cells are generally shipped either adjacent to each other without any separation or with a divider material such as cardboard or foam.
  - Lithium-ion-polymer batteries are generally placed individually in a molded plastic carton.
Objective (packaging)

- The objective of the packaging study was to determine an effective packaging configuration to prevent the propagation of thermal runaway of 18650-sized batteries.
  - Vary state-of-charge of the cells. (based on 2600 mah capacity)
  - Vary divider materials.
    - Cardboard
    - Cardboard treated with fire-retardant spray
    - Aramid
    - ABS plastic
    - Aluminum
  - Water packet above the cells.
Setup (packaging)

- Tests were performed in battery boxes with a 16 cell capacity and a thermocouple on each cell.

- One of the 16 cells was replaced with a cartridge heater which was used to initiate thermal-runaway in the adjacent cells.

- Tests were conducted within a 64 ft³ chamber with a constant ambient air temperature.
Test Procedures (packaging)

- Data collection began and the heater was powered on.
- When the first cell began thermal runaway the heater was powered off.
- Data collection continued until all cells propagated or Temperature decreased enough to signal that propagation would no longer occur.
## Tests Performed (packaging)

<table>
<thead>
<tr>
<th>State of Charge</th>
<th>Cardboard Separators (as shipped)</th>
<th>Aluminum Separators</th>
<th>Fire Retardant Cardboard</th>
<th>Water Pack Above the Cells</th>
<th>Acrylic</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
</tr>
<tr>
<td>40%</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
</tr>
<tr>
<td>50%</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
</tr>
<tr>
<td>60%</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
</tr>
<tr>
<td>70%</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
</tr>
<tr>
<td>80%</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
</tr>
<tr>
<td>90%</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
</tr>
<tr>
<td>100%</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
<td>x2</td>
</tr>
</tbody>
</table>
Data Processing (packaging)

- Tests were quantified in two ways:
  - Tests were quantified by the average of the peak temperatures.
  - Tests were quantified by the amount of time required for complete propagation.

- Other qualitative results were observed.
Results (packaging): temperature

- The average maximum temperature of the cells increased as state-of-charge increased.
- Insulating materials decreased the temperatures.
Results (packaging): propagation time

- The time required for the entire package to burn increased as state-of-charge decreased.
- Insulating divider materials increased the propagation time of the package.
Other Results (packaging)

- The packet of water above the cells prevented propagation.

- Explosions of the cells stopped propagation.

- Packages with the treated cardboard remained intact with cells at 50% SOC
Summary (packaging)

- The temperature of the cells *increases* with higher states of charge.
- The temperature of the cells *decreases* with insulative materials (Propagation slows down so cells have more time to cool).
- The time required for a package to burn *decreases* as state-of-charge increases.
- The time required for a package to burn *increases* with more insulative materials.
Introduction (Extinguishment)

• Battery Fire Extinguishment
  – Previous tests at the FAA showed that water was effective at stopping thermal-runaway of a lithium battery.
  – Battery companies suggest a variety of extinguishing agents such as dry chem., CO2, Foam, Lith-X, Powdered graphite and Water
Objective

• The objective of the extinguishment study was to determine the effectiveness of fire extinguishing agents in preventing thermal-runaway propagation.
  – Cooling effectiveness with a hot-plate: Water, AF-31, AF-21, Aqueous A-B-D Agent, Novec 1230, Purple-K, Halotron, Halon 1211, Fe-36, FM-200
  – Handheld extinguishing agents on a lithium battery fire: Water, AF-31, AF-21, Aqueous A-B-D Agent, Novec 1230, Purple-K, Halotron, Halon 1211, Fe-36, FM-200
Setup (extinguishment)

• Hotplate Tests: Extinguishing agents were applied to a hotplate from 8 inches above the plate and temperature drop was recorded.

• Lithium Battery Tests: 5 cells (Li-ion and Li-Metal) and a cartridge heater were aligned, thermal runaway was initiated and the effectiveness of each agent was recorded.
## Tests Performed (extinguishment)

<table>
<thead>
<tr>
<th></th>
<th>Hot Plate</th>
<th>Lithium-ion</th>
<th>Lithium-metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (No Agent)</td>
<td>X4</td>
<td>X4</td>
<td>X7</td>
</tr>
<tr>
<td>Water</td>
<td>X14</td>
<td>X3</td>
<td>X1</td>
</tr>
<tr>
<td>Aqueous A-B-D</td>
<td>X5</td>
<td>X3</td>
<td>X1</td>
</tr>
<tr>
<td>AF-21</td>
<td>X2</td>
<td>X3</td>
<td>X1</td>
</tr>
<tr>
<td>AF-31</td>
<td>X4</td>
<td>X2</td>
<td>X1</td>
</tr>
<tr>
<td>Novec 1230</td>
<td>X6</td>
<td>X3</td>
<td>X1</td>
</tr>
<tr>
<td>Halon 1211</td>
<td>X4</td>
<td>X2</td>
<td>X1</td>
</tr>
<tr>
<td>FM-200</td>
<td>X2</td>
<td>X2</td>
<td>X2</td>
</tr>
<tr>
<td>Halotron I</td>
<td>X3</td>
<td>X2</td>
<td>X2</td>
</tr>
<tr>
<td>FE-36</td>
<td>X2</td>
<td>X1</td>
<td>X2</td>
</tr>
<tr>
<td>Purple-K</td>
<td>X1</td>
<td>X2</td>
<td>X1</td>
</tr>
<tr>
<td>CO2</td>
<td></td>
<td></td>
<td>X2</td>
</tr>
</tbody>
</table>

Various volumes of each agent were tested.
• Aqueous extinguishing agents cooled the plate more than the non-aqueous agents.
## Results (hotplate tests)

<table>
<thead>
<tr>
<th>Agent</th>
<th>Application to Hotplate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>Aqueous A-B-D Agent</td>
<td></td>
</tr>
<tr>
<td>Novec 1230</td>
<td></td>
</tr>
<tr>
<td>Halon 1211</td>
<td></td>
</tr>
<tr>
<td>FM-200</td>
<td></td>
</tr>
<tr>
<td>Halotron I</td>
<td></td>
</tr>
<tr>
<td>FE-36</td>
<td></td>
</tr>
<tr>
<td>Purple-K</td>
<td></td>
</tr>
<tr>
<td>AF-31 25% (aqueous)</td>
<td></td>
</tr>
<tr>
<td>AF-21 (aqueous)</td>
<td></td>
</tr>
</tbody>
</table>

Application of each agent to the hotplate
Results (extinguishment)

• Streaming Tests
  – Lithium-ion cells failed to propagate with aqueous streaming agents.
  – Lithium-ion cells continued to propagate with non-aqueous streaming agents.
  – Lithium-metal cells failed to propagate with aqueous and non-aqueous streaming agents. (Note: propagation continued with one test of purple-k, one of Halotron I and one of FE-36)
Results (extinguishment)

- The lithium-metal cells generally showed one of four behaviors during thermal runaway.

1) Vent holes were in alternate locations.
2) Cell vented through pre-existing vent holes at the positive terminal.
3) Internal components were partially ejected.
4) Internal components were fully ejected.

Shown in order of most common to least common
Summary (extinguishment)

• Aqueous agents cooled the hotplate more than non-aqueous agents.
• Aqueous agents were more effective at stopping propagation in lithium-ion and lithium-metal cells.
Future Tests

• Perform cardboard (as shipped) tests with another Lithium-ion chemistry
• Perform packaging tests with lithium-metal cells.
• Vary the packaging separation distance between each cell.
• Once conditions that prevent cell propagation are determined they may be verified with a full box test.
Questions or Suggestions?

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Citations