Working Towards Protection Guidance for Warehouse Storage Li-ion Batteries

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Experimental Knowledge Timeline

- **Reduced-commodity evaluation**
  - Sprinklered fire test

- **2.6 Ah**
  - Phase 2, 2012
  - Cylindrical
  - Polymer
  - Power tool packs

- **20 Ah**
  - Phase 3, 2015
  - Polymer

- **20 Ah**
  - Phase 3, 2016
  - Polymer
Li-Ion Battery Characterization
Package Description

- Cardboard box: 17”x13.5”x6.5”
- Total weight: 27 lb. (including cells)
- Contents:
  - 20 battery cells
  - White polystyrene crates
  - Polyethylene bubble wraps
Battery Cell Description

Lithium-Ion Pouch Cell

- Dimension: 9”x6”x0.3”
- Weight: 1.1 lb
- Capacity: 20 Ah
- Voltage: 3.3 volts
Electrical Characterization

- Stacked Electrode Design
- Cell Chemistry: Lithium Iron Phosphate (LiFePO$_4$)
- As-Received SOC: 49.4%
- Electrolyte Mass: 0.083 lb
### Battery Package Mass Summary

**Content per One Package**

<table>
<thead>
<tr>
<th>Description</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Battery Cells (including Electrolyte)</td>
<td>21.7 lb</td>
</tr>
<tr>
<td>10 White Battery Crates</td>
<td>3.9 lb</td>
</tr>
<tr>
<td>Cardboard</td>
<td>1.4 lb</td>
</tr>
<tr>
<td>Parking Material</td>
<td>0.04 lb</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>1.7 lb</td>
</tr>
<tr>
<td><strong>Total Weight</strong></td>
<td><strong>27.0 lb</strong></td>
</tr>
</tbody>
</table>

**Pie Chart:**
- Twenty (20) Battery Cells including Electrolyte, 80.5%
- Ten (10) White Battery Crates, 14.3%
- Cardboard Box, 5.0%
- Packing Material (Bubble Wrap), 0.1%
Task 1
Completed: July, 2015
REDUCED-COMMODITY TEST
Reduced-Commodity Test: Design

- Storage height: 15 ft
- Protection: none  
  - Freeburn
- Commodity:  
  - 4 full pallet loads
  - 4,480 batteries
- Ignition  
  - Propane, 45 kW
Reduced-Commodity Test

30 s  
60 s  
90 s  
120 s
Hazard Comparison

Convective HRR (kW) vs Time (s)

- CUP Commodity
- Class 2 Commodity
Hazard Comparison

Convective HRR (kW)

Time (s)

CUP Commodity

Class 2 Commodity

Cylindrical, 2.6 Ah

Prismatic Pouch, 2.6 Ah
Hazard Comparison

- CUP Commodity
- Prismatic Pouch, 20 Ah
- Battery Pack, 2.6 Ah (x 10)
- Class 2 Commodity

Convective HRR (kW) vs. Time (s)
Hazard Comparison

Convective HRR (kW)

Time (s)

- CUP Commodity
- Prismatic Pouch, 20 Ah
- Battery Pack, 2.6 Ah (x 10)
- Class 2 Commodity
- Cylindrical, 2.6 Ah
- Prismatic Pouch, 2.6 Ah
- Prismatic Pouch, 20 Ah
Comparison to Previous Testing

- Similar fire development
  - Initial growth dominated by cartons
  - Fire size and growth rate similar at sprinkler operation

- Time of significant battery Involvement
  - Large-format: 90 - 120 s
  - Small-format: 300 s

- Higher hazard than small format Li-ion cells
Potential Application of Results

- Sprinkler protection option established
  - Applied to all cells with a hazard ≤ cell used in sprinklered test
  - Cell hazard evaluated in reduced-commodity test
Task 2
Scheduled: April, 2016
LARGE-SCALE TEST
Large-Scale Test: Schematics

Large-scale test conducted with a standard external ignition
Large-Scale Test: Design

- Storage height: 15 ft (4.6 m)
- Ceiling height: 40 ft (12.2 m)
- Sprinkler: K22.4 gpm/psi^{1/2} (320 lpm/bar^{1/2})
  - Response: quick-response, 165\(^\circ\)F (74\(^\circ\)C)
  - Density: 1.3 gpm/ft^{1/2} (53 mm/min)
  - Spacing: 10 × 10 ft (3 x 3 m)
  - Ignition: Offset, under-1 sprinkler
- Commodity: 24 pallet loads (~27k batteries)
Existing vs. Typical

- Smaller main array
  - Reduced damage area
  - Minimize target jump
- CUP target commodity
  - No fire within carton
  - Requires early extinguishment
- Increased protection
Task 3
Completed: September 2015

INTERNAL IGNITION TEST
Battery-to-Battery Spread

How does thermal run away spread from battery to battery?

1) Combustion of chemical energy
   – Battery rupture releases flammable electrolyte
   – Burning electrolyte produces heat Results in Fire

2) Release of electrochemical energy
   – Electrical energy is converted to heat
   – Heat transferred to adjacent batteries Results in Heat
Combustion of Chemical Energy

- How much air is needed?
- Electrolyte
  - Air-to-fuel ratio: 7:1
  - Mass per battery: 34 g

<table>
<thead>
<tr>
<th>Required Air Per Battery</th>
<th>Available Air Per Carton</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 m³</td>
<td>0.01 m³</td>
</tr>
</tbody>
</table>

- Not enough air to burn ONE battery
- Fire must burn outside carton
Electrochemical Heat

- Film heaters: 650°F
- Battery at middle level
- Battery rupture @ 5 min
- 2 hour test duration
- Three batteries ruptured

Propagation did not occur
Task 3
In progress: 2015/2016

SUPPRESSION TESTS
What if batteries do become involved?

Suppression tests

- Internal ignition
- Pilot flame outside carton
- Water Application Apparatus
  - Water applied when batteries are involved in fire

- Allows for water application at a later stage of battery involvement than large-scale test
Ignition Scenarios

Aisle Ignition

- Ignition Carton

Flue Ignition

- Internal ignition within central carton

6in.
Aisle Ignition Scenario

- Required external pilot ignition
- Center pallet load collapsed
- Fire extinguished
  - Water application delayed 70s
- 30% of batteries damaged
Summary

- Large-format Li-ion batteries represent higher hazard than small-format batteries
  - Thus, large-scale results with large-format batteries can be applied to small-format batteries
- Large-scale fire test scheduled for April, 2016
  - External ignition should be used for large-scale test
- Suppression test suggest sprinkler water can extinguish a developed battery fire
- Conclusion to be finalized at completion of project
Acknowledgements

- Property Insurance Research Group
- Fire Protection Research Foundation


Cartons as received (no repack)
Pallet loads require restacking (42 in. × 42 in.)
Current Battery Hazard Knowledge

- Use and Hazard Assessment (Phase 1)
- Reduced-commodity test (Phase 2)
  - 2.6 Ah cells (cylindrical, polymer, packs) and standard cartoned commodities
  - Comparison of hazard up to 1st sprinkler operation
  - Cylindrical and polymer cells similar
  - Power packs equivalent to CUP
    ➢ Applicable to cartoned warehouse storage

- No protection options directly from battery tests
### QR Sprinkler, 10 ft (3 m) Clearance

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Link Operation Time (s)</th>
<th>$Q_{be}$ (kW)</th>
<th>Fire Growth Rate (kW/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-ion, 20 Ah Prismatic Pouch</td>
<td>37</td>
<td>335</td>
<td>33</td>
</tr>
<tr>
<td>Li-ion, 2.6 Ah small-format</td>
<td>43</td>
<td>270</td>
<td>20</td>
</tr>
<tr>
<td>Class 2</td>
<td>59</td>
<td>209</td>
<td>15</td>
</tr>
<tr>
<td>CUP</td>
<td>43</td>
<td>232</td>
<td>16</td>
</tr>
</tbody>
</table>

- **Sprinkler: $RTI = 50 \text{ ft}^{1/2} \text{s}^{1/2}$, 165°F** $(28 \text{ m}^{1/2} \text{s}^{1/2}), (74^\circ\text{C})$