Characterization of Commercial Li-ion Cells in Pouch Format

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April 2014
The 2014 Space Power Workshop
Background

- Commercial off-the-shelf (COTS) li-ion cells are frequently subjected to a standard set of tests to determine their performance and safety in order to add them to a database that allows users at NASA, specifically at Johnson Space Center, to choose cell designs for different applications.

- In recent years, Li-ion polymer cells in pouch format are used increasingly in portable equipment applications and are commonly being referred to as lithium polymer cells, although these cells are not of the true polymer types.

- Several Li-ion polymer or pouch cells have been tested at NASA-JSC in the past 15 years. Cells of this type have developed from being low rate (Ultralife, 1998) to medium rates (Valence, Samsung, Kokam, etc. ~2005) and then on to high energy and high rates (~2010-).

- Testing of these li-ion polymer cells have shown that long term storage as well as vacuum exposures cause swelling of the pouch; there is also a variance in their safety characteristics under off-nominal conditions.

- Recent test programs at NASA-JSC have focused on testing the li-ion polymer cells for their safety as well as their performance under different rates and temperatures, and in addition to this, under vacuum and reduced pressure conditions.

- 100% of flight batteries including button cells undergo vacuum leak checks before they are flown for NASA space applications. The lack of pouch li-ion cells to vacuum conditions may require a change in test methods for batteries that use this cell design. Use of reduced pressure has been an option.

- Hence this test program was started to determine the tolerance of these cells to vacuum as well as reduced pressure environments.

- The most recent tests included cells of the following types:
  - SKC 15 Ah (high-rate capability)
  - Tenergy 6 Ah (medium rate medium energy density)
  - Altairnano 13 Ah (nanotitanate anode with high rate capabiliy)
  - Wanma 5 Ah (medium rate medium energy density)
  - iPad Battery ~4.0 Ah
  - GMB 3.9 Ah
  - Kokam 5.0 Ah
Tests Under Various Low Pressure Environments
SKC 15 Ah Li-ion Cell with Continuous Cycling Under Ambient and Vacuum Environments

Cells show loss in capacity when cycled under vacuum conditions.

Vacuum: 30 cycles
C/2 Charge and Discharge

Unrestrained
6.5%

Restrained
29%

4.2 to 3.0 V
(Ch: 1.5 A EOC current)

Ch: C/2
Disch: C/2
500 cycles
3.6% loss

3.2%

8.9%
SKC 15 Ah Li-ion Cell with Cycling Under Low Pressure and Vacuum Environments

Under restraints, the performance of the cells at reduced pressure and vacuum remains similar. The performance for both without cell restraints is very poor.
SKC Li-ion Cell Performance After Charge Under Vacuum and Storage at Ambient Pressure

One charge under vacuum; storage at full charge at ambient pressure for 20 days

20 Day storage period

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SKC Li-ion Cell Performance After Cycling Under Reduced Pressure and Storage at Ambient

One cycle under reduced pressure; storage at full charge at ambient pressure for 20 days

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Tenergy 6 Ah Li-ion Cell with Continuous Cycling Under Vacuum Environments

C/2 charge and discharge Vacuum; 30 cycles

Charge: C/2
Disch: C/2
Ambient Pressure

2.2 % cap loss

63 %
83 %
78 %

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Tenergy Li-ion Cell Performance After Charge Under Vacuum and Storage at Ambient Pressure

Restrained

One charge under vacuum; storage at full charge at ambient pressure for 20 days

Unrestrained

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Tenergy Li-ion Cell Performance Under a Combination of Reduced Pressure Cycling and Ambient Pressure Storage

Restrained

Unrestrained

Tenergy Li-ion Cell Performance Under a Combination of Vacuum Environment Cycling and Ambient Pressure Storage

Restrained

Unrestrained
Altairnano 13 Ah Continuous Cycling in Vacuum Conditions

Burst Pressure: 23 to 31 psi

Higher capacities observed with restrained than with unrestrained cells

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Altairnano 13 Ah Li-ion Cell Tests

Nameplate Capacity: 13 Ah
Average Capacity at C/2: 14.3 Ah

Ch/Disch: 13 A/60 A

Ch/Disch: 13 A
Wanma Performance Tests

Ch:C/2
D: 1C

4.85 Ah Cycle 2
4.1 Ah Cycle 250

15.5% loss
Wanma 5 Ah Li-ion Cell with Continuous Cycling Under Vacuum Environments

- **Restrained**
  - Wanma 5 Ah Li-ion Cell with Continuous Cycling Under Vacuum Environments
    - W002
      - First Ambient Discharge: 16.7%
      - First 0.1 PSI Vacuum Discharge: 11.5%
      - Final 0.1 PSI Vacuum Discharge: 8.3%

- **Unrestrained**
  - W003
    - First Ambient Discharge: 92%
    - First 0.1 PSI Vacuum Discharge: 42%

  - W004
    - First Ambient Discharge: 73%
    - First 0.1 PSI Vacuum Discharge: 48%
    - Final 0.1 PSI Vacuum Discharge: 43%
Wanma Li-ion Pouch Cell Charge under Vacuum With Storage under Ambient Pressure

Restrained

1% 15.9%

Unrestrained

33.5% 1.4%
Wanma 5 Ah Li-ion Cell with Cycling Under Low Pressure or Vacuum Environments and Storage at Ambient

Vacuum exposure reduces performance tremendously Compared to low pressure environments  J. Jeevarajan, Ph.D. / NASA-JSC
iPad Li-ion Pouch Cells Under Vacuum and Reduced Pressure Conditions

Vacuum exposure for 6 hours at 0.1 psi
1.94 Ah retained after vac exposure;
original capacity was 2.66 Ah (27% capacity loss);
No swelling was observed post-vacuum.

Low Pressure exposure for 6 hours at 9 +/- 0.5 psi.
1.91 Ah retained after low pressure exposure;
original capacity was 2.95 Ah (35% capacity loss);
No swelling was observed post-vacuum.
Kokam 5 Ah pouch Li-ion cells under Vacuum and Reduced Pressure Environments

First cycle

Discharge Capacity = 4.689 Ah

KOKAM Discharge Capacity at Ambient Pressure
0.5C Discharge Current

Time (h:mm:ss)
Voltage (V)

KOKAM Discharge Capacity at 8 PSI
0.5C Discharge Current

Time (h:mm:ss)
Voltage (V)

1st Cycle Discharge Capacity = 4.625 Ah
25th Cycle Discharge Capacity = 4.633 Ah

KOKAM Discharge Capacity at 0.1 PSI
0.5C Discharge Current (sample 1)

Time (h:mm:ss)
Voltage (V)

1st Cycle Discharge Capacity = 4.040 Ah
25th Cycle Discharge Capacity = 3.946 Ah

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GMB 4.0 Ah Li-ion Pouch Cells under Ambient, Reduced Pressure and Vacuum Environments

GMB Test B1 Discharge Capacity at Ambient Pressure
0.5C Discharge Current

Voltage (V)

Time (h:mm:ss)

0:00:00 0:30:00 1:00:00 1:30:00 2:00:00

Discharge Capacity = 3.925 Ah

GMB Test B1 Discharge Capacity at 0.1 PSI
0.5C Discharge Current

1st Cycle Discharge Capacity = 3.495 Ah
25th Cycle Discharge Capacity = 3.107 Ah

GMB Test B1 Discharge Capacity after 8 PSI
0.5C Discharge Current

1st Cycle Discharge Capacity = 3.809 Ah
25th Cycle Discharge Capacity = 3.817 Ah

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Safety Characterization
SKC 15 Ah Cell Safety Tests

**Overcharge Test**

(15 A; 12 V limit; max 6 hours)

**External Short Test**

<table>
<thead>
<tr>
<th>Cell ID</th>
<th>Pre OCV (V)</th>
<th>OCV at Peak Current (V)</th>
<th>Post OCV (V)</th>
<th>Load Value (mΩ)</th>
<th>Peak Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>204</td>
<td>4.165</td>
<td>≈2.03</td>
<td>1.353</td>
<td>3.60</td>
<td>482.00</td>
</tr>
<tr>
<td>301</td>
<td>4.148</td>
<td>≈2.49</td>
<td>4.083</td>
<td>1.76</td>
<td>1,410.10</td>
</tr>
<tr>
<td>302</td>
<td>4.151</td>
<td>≈2.37</td>
<td>1.733</td>
<td>1.76</td>
<td>1,393.30</td>
</tr>
<tr>
<td>309</td>
<td>4.137</td>
<td>≈2.77</td>
<td>0.658</td>
<td>1.60</td>
<td>1,395.80</td>
</tr>
<tr>
<td>313</td>
<td>4.161</td>
<td>≈2.96</td>
<td>2.853</td>
<td>1.60</td>
<td>1,404.10</td>
</tr>
</tbody>
</table>

Cell swelling
SKC 15 Ah Li-ion - Simulated Internal Short Test

With Restraints

Without Restraints

SKC 15 Ah Li-ion - Heat to Vent Test

Venting and thermal runaway above 175 deg C
Tenergy 6.0 Ah Li-ion Prismatic Pouch Cell Overcharge Test

1 C current; fresh cell

Both cells vented violently

1 C current; Cell had undergone 300 cycles

0.5C current overcharge produced same results
Overcharge Test of Tenergy 6.0 Ah Li-ion Cell

0.2 C current; fresh cell

No thermal runaway was observed in both cases

0.2C current; Cell had undergone 300 cycles
External Short Test on Tenergy Li-ion 6.0 Ah Prismatic Pouch Cell

<table>
<thead>
<tr>
<th>Test Temp (°C)</th>
<th>Sample Condition</th>
<th>Sample #</th>
<th>Sample ID</th>
<th>Resistance (mOhm)</th>
<th>Initial OCV (V)</th>
<th>Initial ACR (mOhm)</th>
<th>Maximum Temp (°C)</th>
<th>Maximum Current (A)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Fresh Chg</td>
<td>1</td>
<td>11</td>
<td>30</td>
<td>4.1284</td>
<td>20.4</td>
<td>28.9</td>
<td>62.0</td>
<td>Cathode tab burned off</td>
</tr>
<tr>
<td>20</td>
<td>Fresh Chg</td>
<td>2</td>
<td>8</td>
<td>30</td>
<td>4.1327</td>
<td>20.4</td>
<td>27.2</td>
<td>63.0</td>
<td>Cathode tab burned off</td>
</tr>
<tr>
<td>20</td>
<td>Fresh Chg</td>
<td>3</td>
<td>9</td>
<td>30</td>
<td>4.1325</td>
<td>20.3</td>
<td>29.7</td>
<td>65.0</td>
<td>Cathode tab burned off</td>
</tr>
<tr>
<td>20</td>
<td>Fresh Chg</td>
<td>3-Cell</td>
<td>25,26,27</td>
<td>27</td>
<td>12.431</td>
<td>63.2</td>
<td>27.2</td>
<td>113.0</td>
<td>Cathode tab burned off</td>
</tr>
</tbody>
</table>

Cathode Tabs from all three cells burned off and became disconnected.
Simulated Internal Short Test on Tenergy Li-ion 6.0 Ah Prismatic Pouch Cell

<table>
<thead>
<tr>
<th>Test Temp ('C)</th>
<th>Sample Condition</th>
<th>Sample #</th>
<th>Maximum Temp ('C)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Fresh Chg</td>
<td>1</td>
<td>172.6</td>
<td>Fire</td>
</tr>
<tr>
<td>20</td>
<td>Fresh Chg</td>
<td>2</td>
<td>309.8</td>
<td>Fire</td>
</tr>
</tbody>
</table>

Burst Pressure Test for Tenergy Li-ion 6.0 Ah Prismatic Pouch Cell

<table>
<thead>
<tr>
<th>Test Temp ('C)</th>
<th>Sample Condition</th>
<th>Sample #</th>
<th>Sample ID</th>
<th>Max Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Fresh Chg</td>
<td>1</td>
<td>40</td>
<td>662</td>
</tr>
<tr>
<td>20</td>
<td>Fresh Chg</td>
<td>2</td>
<td>5</td>
<td>617</td>
</tr>
</tbody>
</table>

Heat-to-Vent Test for Tenergy Li-ion 6.0 Ah Prismatic Pouch Cell

<table>
<thead>
<tr>
<th>Test Temp ('C)</th>
<th>Sample Condition</th>
<th>Sample #</th>
<th>Maximum Temp ('C)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Fresh</td>
<td>1</td>
<td>189.8</td>
<td>Fire</td>
</tr>
<tr>
<td>20</td>
<td>Fresh</td>
<td>2</td>
<td>192.0</td>
<td>Fire</td>
</tr>
</tbody>
</table>
Altairnano Safety Tests

Altair B1c Overcharge, Cell 4

**Single Cell**

- TC1
- TC2
- Cell Voltage

Time (2 sec intervals)

Cell Voltage

Altair B1c Overcharge at 11 A

8SString

Time (5 second intervals)

8SString

Temperature C

Time (5 second intervals)

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Overcharge Test on Wanma Li-ion Pouch Cell

All 3 samples vented violently with fire and thermal runaway

Violent venting observed for 0.5 C overcharge at single Cell level

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Wanma 5 Ah Li-ion Pouch Cell – External Short Test

No venting or thermal Runaway was observed
iPad Li-ion Pouch Cell Battery
iPad Battery Level Overcharge and Overdischarge
iPad Cell Overcharge Test

Max Temp 76 deg C

Cells did not show any swelling under overdischarge or external short conditions
Analysis of Pouch Materials from the Different Manufacturers

Wanma
- Outside: Nylon 6 & with a possible Acrylic adhesive
- Inside: Polypropylene

Tenergy
- Outside: Nylon 6
- Inside: Polypropylene

SKC 15 Ah
- Outside: Nylon 6
- Inside: Polypropylene

Altair nano 11 Ah
- Outside: Polyethylene terephthalate & Nylon 6
- Inside: Polypropylene
Analysis of Pouch Materials from the Different Manufacturers

iPad
Polypropylene
Inner layer
Nylon-6
Black outer layer

Kokam
Polypropylene
Inner layer
Nylon-6
Outer layers

GMB
Polypropylene
Inner layer
Nylon-6
Outer layer
Summary

- The li-ion pouch design cells exhibit similar behavior under off-nominal conditions as those in metal cans that do not have the internal safety devices.
  - Safety should be well characterized before batteries are designed.
- Some of the li-ion pouch cell designs studied in this program reacted most violently to overcharge conditions at the medium rates but were tolerant to overcharge at very low rates.
- Some pouch cell designs have higher tolerance to vacuum exposures than some others.
  - A comparison of the pouch material itself does not show a correlation between this tolerance and the number of layers or composition of the pouch indicating that this is a property of the electrode stack design inside the pouch.
- Reduced pressure (8 to 10 psi) test environments show that the extent of capacity degradation under reduced pressure environments is much less than that observed under vacuum conditions.
- Lithium-ion Pouch format cells are not necessarily true polymer cells
Acknowledgment

Test Team Members:

**NASA-JSC**: Bruce Duffield, Henry Bravo, Michael Andrews, Olga Vyshtykailo, Mike Salinas

PC Test Engineering: Dr. Chung, James Park and Kwang Jung

Mobile Power Solutions: Dr. Andy Tipton and team

Space Information Labs: Jim Hammond and team