Thin Film Users Group: Alternative Energy Symposium

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JM Energy’s Lithium Ion Capacitor: The Hybrid Energy Storage Advantage
Outline

1. Introduction to: JSR Corp, JSR Micro Inc, JM Energy.
2. Lithium Ion Capacitor: Concept, Features, Assembly, Applications.
4. Safety.
5. LIC Packs and Modules
6. Reliability.
7. Improvement Plans
8. Summary.
JSR Corp, Overview

- JSR Corp, was founded in 1957, HQ in Tokyo, Japan
- Annual revenues of over $4.2 billion.
- 5,122 employees
- Major Facilities:
  - Japan: Yokkaichi, Yamanashi, Kyushu, Tsukuba, Chiba and Kashima
  - US: Sunnyvale, CA
  - Europe: Leuven, Belgium
- Major Subsidiary Companies:
  - JM Energy, dedicated to the development and production of Lithium Ion Capacitors.
  - JSR Micro Inc, the US division of JSR Corp.
    - Distributor for JM Energy and all JSR Corp products.
  - JSR Micro NV, the European division of JSR Corp.
JM Energy’s Yamanashi HQ plant.
- Construction completed in October 2008; production started in January 2009
- Investment: $18.9 million

Production Capacity.
- January 2009 300K cells/year
- 2009 600K cells/year
- 2010 1.2 million cells/year
- 2011 2.4 million cells/year
Highly reliable, safe, high power, and high energy density capacitor
About 4 times higher energy density than conventional EDLC,
More than 2 times higher power density than conventional secondary batteries.
The Lithium Ion Capacitor is a Hybrid Device

Key technology: Pre-doping of Li to the carbon anode
Hybrid construction summary:

- The activated carbon cathode is a capacitor cathode.
  - In a Lithium Ion Battery thermal runaway occurs at the cathode when the Li spinel decomposes and reacts with the electrolyte.
- Since LIC has an activated carbon cathode, thermal runaway will not occur.
- The Li-doped carbon anode is a battery anode, undergoing Li doping during charge and de-doping during discharge.
- The electrolyte contains a Li salt and is a battery electrolyte.

Hybrid construction creates a capacitor which yields the best performance features of batteries and capacitors.
LIC vs. EDLC: Capacitance Comparison

**EDLC**

- Output

**Lithium Ion Capacitor**

- Output

\[
\frac{1}{C_{\text{cell}}} = \frac{1}{C^-} + \frac{1}{C^+}
\]

\[
C^- = C^+ = C
\]

\[
C_{\text{cell}} = \frac{1}{2}C
\]

LIC’s Capacitance is twice as high

\[
C^- \gg C^+
\]

\[
C_{\text{cell}} = C^+
\]
LIC vs. EDLC: Charge-Discharge Cycles

- For EDLC the anode and cathode potentials change symmetrically and the maximum cell voltage is 2.5 to 2.7v.
- For LIC the anode’s potential stays almost constant due to the lithium doping and the maximum cell voltage is 3.8v.
Hybrid Performance Advantages

- **Battery-Like Advantages**
  - High Energy Density
    - 14-15 Wh/kg
  - High Voltage
    - 3.8v to 2.2v discharge range
    - When connected in series, 1/3 fewer LIC cells are needed compared to a conventional EDLC supercapacitor
  - Low Self-Discharge Rate
    - Will hold 95% of its charge after 3 months

- **Capacitor-Like Advantages**
  - Safety: No Thermal Runaway
    - Since the cathode does not contain Li spinel, thermal runaway cannot occur
  - High Power Density
    - >1000 W/kg
  - Can be charged/discharged quickly.
  - High Reliability
    - Estimated life is 1 million charge/discharge cycles
  - Wide Temperature Range
    - -20°C to 70°C
Assembly of Laminated LIC Cell

Stacking of electrode & separator

- anode
- separator
- cathode

Al-laminated package

- Li-metal
- Cu
- electrode unit
- Al

Electrolyte

Li$^+$ pre-doping
Schematic figure of Li pre-doping

Cathode porous current collector

Li foil

Separator

Anode porous current collector

Li\(^+\) Pre-dope start after electrolyte is impregnated
Features of JM Energy’s-LIC

- Environmentally friendly materials: C, Al, Cu, Li
- High performance
  - High energy density
  - High Voltage
- Key technology:
  - Lithium pre-doping
  - Electrode/cell design
- Mass-producible
  - (Conventional mass production technology is applicable)
- Highly reliable
  - (Less degradation of positive electrode)
  - Less self discharge
  - Long life
LIC Applications

Energy generation & storage
- Wind Turbine
- Solar Cells
- LED Display

Transportation
- Trains/Trams
- Cars
- Buses/Trucks
- Airplanes

UPS
- Voltage sag compensation
- Bridge power

Medical Equipment
- CT, MRI, etc.

Industrial Machines
- Forklift
- Power shovel
- Cranes
- AGV
Highly reliable, safe, high power, and high energy density capacitor
About 4 times higher energy density than conventional EDLC,
More than 2 times higher power density than conventional secondary batteries.

LIC Performance Overview
## Advantage of LIC against EDLC

<table>
<thead>
<tr>
<th></th>
<th>JM Energy - LIC</th>
<th>EDLC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacitance (F)</strong></td>
<td>2 0 0 0</td>
<td>2 0 0 0</td>
</tr>
<tr>
<td><strong>Volume (mL)</strong></td>
<td>1 2 4</td>
<td>3 7 3</td>
</tr>
<tr>
<td><strong>Weight (g)</strong></td>
<td>2 0 8</td>
<td>4 0 0</td>
</tr>
<tr>
<td><strong>Internal resistance (mΩ)</strong></td>
<td>1 . 4</td>
<td>0 . 4</td>
</tr>
<tr>
<td><strong>Max operation voltage (V)</strong></td>
<td>3 . 8</td>
<td>2 . 7</td>
</tr>
<tr>
<td><strong>Volume Energy density (Wh/L)</strong></td>
<td>2 5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Weight Energy density (Wh/kg)</strong></td>
<td>1 4</td>
<td>4 . 5</td>
</tr>
</tbody>
</table>
## LIC Cell Performance (1000F, 2000F)

<table>
<thead>
<tr>
<th>Measurement Items</th>
<th>Unit</th>
<th>1000F Standard</th>
<th>2000F Standard</th>
<th>2000F Low-resistance</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temp. Range</td>
<td>°C</td>
<td>20 ~ + 70</td>
<td>20 ~ + 70</td>
<td>20 ~ + 70</td>
<td></td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>V</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>Initial Properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>F</td>
<td>1100±100</td>
<td>2200±200</td>
<td>2200±200</td>
<td>10CA, C.C. Discharge at 25°C</td>
</tr>
<tr>
<td>DC-IR</td>
<td>mohm</td>
<td>4.5±0.6</td>
<td>2.3±0.3</td>
<td>1.4±0.3</td>
<td></td>
</tr>
<tr>
<td>ESR</td>
<td>mohm</td>
<td>2.8±0.6</td>
<td>1.4±0.3</td>
<td>1.0±0.3</td>
<td></td>
</tr>
<tr>
<td>Energy Density (weight)</td>
<td>Wh/kg</td>
<td>12</td>
<td>14</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Energy Density (Volume)</td>
<td>Wh/L</td>
<td>21</td>
<td>25</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>Temp. Dependence</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>F</td>
<td>850±150</td>
<td>1700±300</td>
<td>1700±300</td>
<td>10CA, C.C. Discharge</td>
</tr>
<tr>
<td>DC-IR</td>
<td>mohm</td>
<td>46±6</td>
<td>23±3</td>
<td>19±3</td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>F</td>
<td>1150±150</td>
<td>2300±200</td>
<td>2300±200</td>
<td></td>
</tr>
<tr>
<td>DC-IR</td>
<td>mohm</td>
<td>2.4±0.8</td>
<td>1.4±0.3</td>
<td>0.8±0.3</td>
<td></td>
</tr>
<tr>
<td>High Temp. Load Life</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>F</td>
<td>1000±150</td>
<td>2000±300</td>
<td>2000±300</td>
<td></td>
</tr>
<tr>
<td>DC-IR</td>
<td>mohm</td>
<td>5.0±0.8</td>
<td>2.6±0.4</td>
<td>1.6±0.4</td>
<td></td>
</tr>
<tr>
<td>Cycle Test Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>F</td>
<td>1000±150</td>
<td>2000±300</td>
<td>2000±300</td>
<td></td>
</tr>
<tr>
<td>DC-IR</td>
<td>mohm</td>
<td>5.0±0.8</td>
<td>2.6±0.4</td>
<td>1.6±0.4</td>
<td></td>
</tr>
<tr>
<td>Self Discharge Voltage Drop</td>
<td>%</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>24h at 25°C</td>
</tr>
<tr>
<td></td>
<td>&lt;5%</td>
<td>&lt;5%</td>
<td>&lt;5%</td>
<td>&lt;5%</td>
<td>3 Month at 25°C</td>
</tr>
<tr>
<td>Cell Dimension</td>
<td>mm</td>
<td>138×106×5</td>
<td>138×106×9</td>
<td>138×106×11</td>
<td>Active Size</td>
</tr>
<tr>
<td>Cell Weight</td>
<td>g</td>
<td>113±4</td>
<td>208±4</td>
<td>270±6</td>
<td></td>
</tr>
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</table>
### LIC Cell Performance (350F, 500F)

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>350F</th>
<th>500F</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operating Temperature</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>C</td>
<td>-20° ~ 70°</td>
<td>-20° ~ 70°</td>
<td></td>
</tr>
<tr>
<td><strong>Rated Voltage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>V</td>
<td>3.8V</td>
<td>3.8V</td>
<td>10CA constant current discharge at 25°C</td>
</tr>
<tr>
<td>Minimum</td>
<td>V</td>
<td>2.2V</td>
<td>2.2V</td>
<td></td>
</tr>
<tr>
<td><strong>Initial Property</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>F</td>
<td>370F</td>
<td>550F</td>
<td>10CA constant current discharge at 25°C</td>
</tr>
<tr>
<td>ESR</td>
<td>mΩ</td>
<td>5.6</td>
<td>3.9</td>
<td>1kHz</td>
</tr>
<tr>
<td>DC-IR</td>
<td>mΩ</td>
<td>10.4</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Energy Density by Weight</td>
<td>Wh/kg</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Energy Density by Volume</td>
<td>Wh/L</td>
<td>26</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>-20°</td>
<td>%</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>from 25°</td>
<td></td>
<td></td>
<td></td>
<td>10CA constant current discharge</td>
</tr>
<tr>
<td>70°</td>
<td>%</td>
<td>105</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>from 25°</td>
<td></td>
<td></td>
<td></td>
<td>10CA constant current discharge</td>
</tr>
<tr>
<td><strong>Heat Resistance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>from Initial</td>
<td>%</td>
<td>90</td>
<td>90</td>
<td>3.8V, 70°C, 100 h</td>
</tr>
<tr>
<td><strong>Cycle Test Performance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>from Initial</td>
<td>%</td>
<td>90</td>
<td>90</td>
<td>100CA constant current discharge 25°C, 100K Cycles</td>
</tr>
<tr>
<td><strong>Self Discharge</strong></td>
<td>ΔVoltage</td>
<td>%</td>
<td>&lt;5</td>
<td>&lt;5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3 months at 25°C</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>Convex</td>
<td>mm</td>
<td>52×66×6.5</td>
<td>52×66×9.0</td>
</tr>
</tbody>
</table>
Cell Dimensions (2000F, 1000F)

Cell thickness: 2000F Low Resistance 10.5 ± 1.0mm
2000F Standard 8.5 ± 1.0mm
1000F Standard 5.0 ± 1.0mm
Cell Dimensions (350F, 500F)

Positive

Negative

Microwave seal

350F Standard \( t = 6.0 \text{ mm} \)

500F Standard \( t = 9.0 \text{ mm} \)
Ragone Plots (Weight), 2000F

Test Condition:
Charge: CCCV 50A to 3.8V for 15min
Discharge: CC 10, 50, 75, 100, 125, 150, 200A to 2.2V
Ambient Temperature: 25°C
Ragone Plots (Volume), 2000F

Test Condition:
Charge: CCCV 50A to 3.8V for 15min
Discharge: CC 10, 50, 75, 100, 125, 150, 200A to 2.2V
Ambient Temperature: 25°C

Power Density [W/L]

Energy Density [Wh/L]
Discharge Curve (2000F, Standard Type)

【Test Condition】
Charge: CCCV 50A to 3.8V (CV: 15min)
Discharge CC 10 ~ 200A to 2.2V
Ambient Temperature::25℃
Temperature Dependence (2000F)

Discharge: CC 10A, 3.8-2.2V

Retention: 76% vs. R.T
Cycle Test Performance (2000F, Standard Type)

- > 90% after 100,000 cycles
- < 115% after 100,000 cycles

**Cycle condition**:
- Charge: CC, 100A
- Discharge: CC, 100A
- Ambient Temperature: 25°C
Self Discharge Performance, (2000F, Standard type)

> 95% retention after 3 months
Thermal Runaway Model of Li-ion Battery

Composition of Electrodes

<table>
<thead>
<tr>
<th>Negative Electrode</th>
<th>Positive Electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Material</td>
<td>LiCoO₂, LiMn₂O₄, etc</td>
</tr>
</tbody>
</table>

Thermal runaway cannot be stopped once decomposition of the lithium spinel in the cathode occurs.
No thermal chain reaction occurs, since the positive electrode does not contain any lithium spinel.
Safety Test of LIC Cells

**Over Charge test**

**Over Discharge test**

**Heat test**

**Nail test**
## Summary of Safety Test

<table>
<thead>
<tr>
<th>Items</th>
<th>Test Methods</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over Charge Test</td>
<td>Charge up to 250% of rated capacitance with 1A constant current</td>
<td>pass</td>
</tr>
<tr>
<td>Over Discharge Test</td>
<td>Discharge to 0V with 1A constant current</td>
<td>pass</td>
</tr>
<tr>
<td>Heat Test</td>
<td>Heat by $5^\circ$C/min and kept at $130^\circ$C×1h</td>
<td>pass</td>
</tr>
<tr>
<td>Nail Test</td>
<td>Vertical penetration by a nail of 2.5mm $\Phi$ through the center of the cell</td>
<td>pass</td>
</tr>
</tbody>
</table>
Equivalent Lithium Content

- Due to its low lithium content, LIC is not subject to the Class 9 transportation regulations.

- The equivalent lithium ion content of the 2000F cell is less than 0.30 grams.

- The equivalent lithium content is calculated in grams by multiplying the capacity in ampere hours by 0.3
  - The capacity of the 2200F cell is 0.980Ah.
  - $0.980 \times 0.3 = 0.294$
LIC Pack and Module Advantages

- Due to their higher energy density and voltage, LIC’s provide a smaller, lighter power supply.
- The number of cells is reduced by 33%.
- The weight of the cells is reduced by 66%.
- The volume of the cells is reduced by 78%.

- The low self-discharge rate also provides faster start-up.
  - At room temperature, the cells will retain more than 95% of their charge for 3 months.
Welded Packs of LICs

- Multiple cell packs:
  - The lead terminal of the LIC cell is combined together in series by ultrasonic welding to get high voltage as a pack.
  - Standard pack sizes are 4, 7 or 12 cells in series; 15.2v, 26.6v or 45.6v.
Prototype Modules (4 cells, 7 cells)

7 cells: 290x190x100 mm (26.6V)

4 cells: 290x190x80 mm (15.2V)
10 and 12 Cell Modules

1000F×10 cells
(Commercial Module)

2000F×12 cells
(Test Module)
Inside a 12 Cell Prototype
Examples of Open LIC Modules

1000F×4 cells
(Open module, with no control circuit)

1000F×12 cells
(Open module, with no control circuit)
Estimated Life at 30°C (1100F, Capacitance)

**Capacitance Change**

![Graph showing Capacitance Change]

- **Sift Factor:** 0.25
- \(10^{0.25} = 1.7783\)

<table>
<thead>
<tr>
<th>Ret. of Cap.</th>
<th>70°C [h]</th>
<th>60°C [h]</th>
<th>30°C [h]</th>
<th>30°C [Year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C(90%)</td>
<td>1184</td>
<td>2106</td>
<td>11841</td>
<td>1.4</td>
</tr>
<tr>
<td>C(85%)</td>
<td>3172</td>
<td>5642</td>
<td>31725</td>
<td>3.6</td>
</tr>
<tr>
<td>C(80%)</td>
<td>9023</td>
<td>16045</td>
<td>90229</td>
<td>10.3</td>
</tr>
<tr>
<td>C(78.2%)</td>
<td>13358</td>
<td>23754</td>
<td>133581</td>
<td>15.2</td>
</tr>
<tr>
<td>C(75%)</td>
<td>27454</td>
<td>48820</td>
<td>274536</td>
<td>31.3</td>
</tr>
</tbody>
</table>

**Log (t) [h]**

- 60°C
- 70°C
- Data sifted
Estimated Life at 30°C (1100F, DC-IR)

DC-IR Change

Sift Factor: 0.425
\[10^{0.425} = 2.661\]

<table>
<thead>
<tr>
<th>DC-IR Change</th>
<th>70°C [h]</th>
<th>60°C [h]</th>
<th>30°C [h]</th>
<th>30°C [Year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R((+10%))</td>
<td>1219</td>
<td>3244</td>
<td>61097</td>
<td>7.0</td>
</tr>
<tr>
<td>R((+15%))</td>
<td>2110</td>
<td>5615</td>
<td>105768</td>
<td>12.1</td>
</tr>
<tr>
<td>R((+17.1%))</td>
<td>2639</td>
<td>7021</td>
<td>132246</td>
<td>15.1</td>
</tr>
<tr>
<td>R((+20%))</td>
<td>3569</td>
<td>9496</td>
<td>178874</td>
<td>20.4</td>
</tr>
</tbody>
</table>
Performance Improvement Plans

1. Improvement of Internal Resistance (within 1 year)
   Target: less than 1mΩ at Room temp.
   less than 5 times at -20°C compared to R. T.

2. Improvement of Energy Density (within 1-2 year)
   Target: First step; 20wh/kg (within 1 year)
   Second step; 30h/kg (within 2 year)

Summary

- Lithium Ion Capacitor is a hybrid energy storage device.
  - It combines the best features of batteries and capacitors.
- LIC’s energy density is 4 times greater than a conventional EDLC and its maximum voltage is 3.8 volts.
- LIC is a safe, reliable and has a very low self-discharge rate.
- Due to its higher energy and compact size it provides a smaller, lighter power supply.
- Higher performance and capacity products are being developed.