Lithium Iron Phosphate Applications in Space Power Batteries

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T/J Technologies, Inc. Ann Arbor, MI
Outline

• Characteristics of Lithium Iron Phosphate
  • Rate
  • Safety
• Cell performance
  • Low temperature
  • Cycle life
• Aerospace and defense applications
T/J Technologies

- Incorporated in 1991, based in Ann Arbor, Michigan
- Over 60 R&D Contracts Awarded (Over $26M)
- Wholly owned subsidiary of A123 Systems-2006
- National Awards/Recognitions:
  - 2005 NASA “Special Recognition” Award for “Contributions to Space”
  - Winner of two Advanced Technology Program (ATP) Grants to develop advanced energy technologies from the Department of Commerce
  - Department of Defense Nunn Perry Award
  - NASA Glenn Garrett Morgan Commercialization Award
Conventional oxide cathode compared to LFP

Oxide-based Li Ion (conventional technology)

Conventional Li-ion diffusion: large particle size = poor rate capability

A123-TJ doped nanophosphate

Dopant increases electrical conductivity eight orders of magnitude

10 micron

<0.1 micron
LFP Technology: Best Combination of Power, Safety, and Life.

<table>
<thead>
<tr>
<th>Rechargeable Battery Technology</th>
<th>Power Density /W/kg</th>
<th>Weight to Discharge @1500W /lbs</th>
<th>Safety</th>
<th>Life at 100% DOD 1C rate /cycles</th>
<th>Environmental</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFP Li-ion</td>
<td>3600</td>
<td>0.9</td>
<td>✓</td>
<td>7000</td>
<td>✓</td>
</tr>
<tr>
<td>LNCO Li-ion</td>
<td>1800</td>
<td>1.8</td>
<td>×</td>
<td>700</td>
<td>×</td>
</tr>
<tr>
<td>NiMH</td>
<td>750</td>
<td>4.4</td>
<td>✓</td>
<td>1000</td>
<td>✓</td>
</tr>
<tr>
<td>NiCd</td>
<td>600</td>
<td>5.5</td>
<td>✓</td>
<td>1000</td>
<td>×</td>
</tr>
</tbody>
</table>

Based on: Nano-structured LFP cathode active materials, low impedance cell design, and novel electrolyte.

Application: Power application at NASA, hybrid electric vehicles, power tools, military FCS…
**Power.**
>110Wh/kg
>3000W/kg

100C pulse discharge

**Safety.**
Intrinsically safe chemistry
No thermal runaway
Abuse-tolerant

**Life.**
Cycle life: >7000 @ 100% DOD
Excellent high temperature stability
Low impedance growth
## 26650 specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>2.3 Ah</td>
</tr>
<tr>
<td>Energy</td>
<td>7.6 Wh (110 Wh/kg, 220 Wh/L)</td>
</tr>
<tr>
<td>Nominal voltage</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Cylindrical cell dimensions</td>
<td>25.9 mm diameter x 65.4 mm high</td>
</tr>
<tr>
<td>Cell volume</td>
<td>34.45 cc</td>
</tr>
<tr>
<td>Cell mass (without external tabs)</td>
<td>70 grams</td>
</tr>
<tr>
<td>Impedance (1 kHz)</td>
<td>8 mΩ</td>
</tr>
<tr>
<td>Impedance (10A, 10s)</td>
<td>15 mΩ</td>
</tr>
<tr>
<td>Recommended temperature range</td>
<td>-30 °C to 60 °C</td>
</tr>
</tbody>
</table>
Conventional crimped cell packaging

- Can
- Top header
- Valve
- CID
- PTC
- Seal

Can crimped seals survive 15 years of use?

A123 double plate tubular construction

All laser welded design for long calendar life
Additional Advantages for Aerospace Applications

- Lower self discharge – the charged batteries will maintain their activation throughout longer mission delays.

- Very high charge/discharge rate – the cells can be charged to over 90% capacity in less than ten minutes.

- Improved safety – less heat and gas generation.

- Flat voltage profile – simpler voltage regulation to provide constant pulse power throughout wide range of SOC.

- LFP/LTO system also results in very long cycle life in extended deep cycle applications such as LEO satellites.
A123 26650 high power cells: High rate capability
= fast charge and discharge

100% DOD continuous discharge
1A, 6A, 10A, 30A at 25ºC
High-power pulse data on 2.3Ah 26650 cell

- From 100% SOC
- Maximum power for 10-30s pulse is achieved with 120A discharge
- Higher power can be achieved with shorter pulses

<table>
<thead>
<tr>
<th></th>
<th>100A</th>
<th>120A</th>
<th>140A</th>
<th>150A</th>
<th>200A</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power density (W/kg)</td>
<td>Power density (W/kg)</td>
<td>Power density (W/kg)</td>
<td>Power density (W/kg)</td>
<td>Power density (W/kg)</td>
</tr>
<tr>
<td>0.1 seconds</td>
<td>3449</td>
<td>3120</td>
<td>2829</td>
<td>4200</td>
<td>4990</td>
</tr>
<tr>
<td>5 seconds</td>
<td>3120</td>
<td>3100</td>
<td>2886</td>
<td>3400</td>
<td>3300</td>
</tr>
<tr>
<td>10 seconds</td>
<td>2829</td>
<td>2943</td>
<td>2771</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 seconds</td>
<td>2714</td>
<td>2957</td>
<td>2900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 seconds</td>
<td>2757</td>
<td>3014</td>
<td>2914</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Safety Comparison

**Oxide-based Li-ion (competitors)**

- Thermal runaway above 150 °C
  - Oxygen evolution
  
  \[
  \text{Li}_{0.8} \text{CoO}_2 \rightarrow 0.5 \text{LiCoO}_2 + \frac{1}{6} \text{Co}_3\text{O}_4 + \frac{1}{6} \text{O}_2
  \]

- Excess lithium can plate during overcharge

  \[
  \text{LiCoO}_2 \rightarrow \text{Li}_{1-x} \text{CoO}_2 + x\text{Li}^+ + xe^-
  \]

- Failure mode on overcharge: self-accelerating heat generation, explosion

- Higher voltage cathode (more electrolyte oxidation)

**A123-T/J Technology**

- No thermal runaway
  - No oxygen evolution

- No excess lithium in cathode
  - Overcharging will not plate Li

  \[
  \text{LiFePO}_4 \rightarrow \text{FePO}_4 + \text{Li}^+ + e^-
  \]

- Failure mode on overcharge: venting due to gas pressure

- Lower voltage cathode
  - Less electrolyte oxidation, longer life

- Excellent fast-charge capability

- Good tolerance to overdischarge

**Requires:**

- Overcharge protection
- Shutdown mechanism
# 26650 cells pass UL 1642 and UN safety tests

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Title</th>
<th>Test Description</th>
<th>Requirement</th>
<th>Results with M1 Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Short Circuit Test</td>
<td>Cell are held at 20°C and 55°C and shorted until completely discharged.</td>
<td>Case temperature does not exceed 150°C. The cells will not explode or catch fire.</td>
<td>Meets Requirement Max case $T = 90^\circ$C</td>
</tr>
<tr>
<td>11A</td>
<td>Abnormal Charging Test</td>
<td>A discharged cell is charged at 3x maximum recommended charge current for a minimum of 7 hours.</td>
<td>The cells will not explode or catch fire.</td>
<td>Meets Requirement At 60 A</td>
</tr>
<tr>
<td>11B</td>
<td>Forced-Discharge Test</td>
<td>A discharged cell is further discharged by charged cells in series.</td>
<td>The cells will not explode or catch fire.</td>
<td>Meets Requirement for 10-cell pack</td>
</tr>
<tr>
<td>12</td>
<td>Crush Test</td>
<td>Cells are crushed under 3000 pounds of force.</td>
<td>The cells will not explode or catch fire.</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>13</td>
<td>Impact Test</td>
<td>Impact with 9.1 kg mass from 61 cm.</td>
<td>The cells will not explode or catch fire.</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>14A</td>
<td>Shock Test</td>
<td>Three 125-175 g shocks in x, y, z orientations.</td>
<td>The cells will not vent, leak, explode, or catch fire.</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>15</td>
<td>Vibration test</td>
<td>10 Hz to 55 Hz to 10Hz in 135 min, in x, y, z orientations. 0.8 mm amplitude.</td>
<td>The cells will not vent, leak, explode, or catch fire.</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>18A</td>
<td>Heating Test</td>
<td>Cells are brought to 130°C at 5°/min and held for 10 min</td>
<td>The cells will not explode or catch fire.</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>18B</td>
<td>Temperature Cycling Test</td>
<td>10 repetitions of: 70°C for 4 hours, 20°C for 2 hours, -40°C for 4 hours, 20°C for 2 hours</td>
<td>The cells will not vent, leak, explode, or catch fire.</td>
<td>Meets Requirement</td>
</tr>
<tr>
<td>18C</td>
<td>Low Pressure (Altitude Simulation) Test</td>
<td>6 hours at ( \leq 0.11 ) atmospheres, 20°C</td>
<td>The cells will not vent, leak, explode, or catch fire.</td>
<td>Meets Requirement</td>
</tr>
</tbody>
</table>
A123 26650 high power cells: Good thermal stability

= no thermal runaway and explosion
Unmatched A123-T/J M1 Li-ion cell safety

Nail penetration test: the nail is pushed through the cell’s end cap.

State of the art Li-ion

Explosion!

TJ/A123 M1 Li-ion

Safe, no explosion
Low-temperature electrolytes

1. We are working with JPL, ARL and Industry leaders to develop low temperature electrolyte systems.

2. We are testing a number of formulations with freezing temperatures less than -40°C.

3. Numerous risk areas: electrochemical stability, vapor pressure, flammability (APZ additives?)
C/2 Discharge of 26650 Cells (2.3 Ah) and Lab cells (13.5 mAh) at 25, 0, -20, -30 Degree C
Significantly lower DCR of new elytes at low temps.

Low-temperature rate experiments in progress

Commercial cell elyte: pink line
RT Cycling Stability of LFP/LTO Lab Cells
## Testing A123 cells by NASA centers

<table>
<thead>
<tr>
<th>Location</th>
<th>Application</th>
<th>Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA JSC</td>
<td>Space suits</td>
<td>Dr. Eric Darcy/Judy Jeevarajan</td>
</tr>
<tr>
<td>NASA Goddard</td>
<td>LRO, Satellite and Launch Applications</td>
<td>Dr. Gopalkrishna Rao</td>
</tr>
<tr>
<td>NASA JPL</td>
<td>Hybrid devices (Fuel Cell + Battery)</td>
<td>Dr. S. R. Narayanan/Kumar Bugga</td>
</tr>
<tr>
<td>NASA GRC</td>
<td>CLV, Space suits, etc.</td>
<td>Michelle Manzo/Concha Reid</td>
</tr>
</tbody>
</table>
NASA partnership seed fund competition selection

New Lithium-ion Batteries with Enhanced Safety and Power Density for Future NASA and Aerospace Missions

- Above proposal is based on A123 cells and was selected for award by NASA HQ
- Team members include:
  - NASA GRC
  - TJ-A123 Systems
  - NASA JPL
  - Northrup Grumman
  - ABSL
Defense aerospace programs

- Launch vehicles
- Civilian aircraft
- Thermal battery – AMRAAM telemetry battery
- MEO eclipse ride-through (MDA proposal)
  - 10,000 cycles/15 yr life
- MKV (MDA proposal, confidential load profile)
- Orion/CEV thrust vector control
  - 10 kW for up to 600 sec (10C rate, 100% DOD)
  - 13 sec duration 35 kW peak (35C peak power)
  - Space qualified
Phase II Launch Vehicle Battery Pack Deliverable

**Key Battery Specs:**
- **Voltage:** 28V
- **Capacity:** 7Ah
- **Power:** 3.4kW max output pulse
- **Energy:** 189 Wh
- **Weight:** Approx 5 lbs
- **Volume:** Approx 2L
- **Operating temp:** 0°C to +60°C

**Benefits:**
- Using commercially available LFP/graphite 26650 cells or 7Ah prismatic cells
- Higher power to weight ratio than NiCd/NiMH and lead acid
- Safer than traditional lithium-ion, no fire or explosion risk
- Weight and volume savings
- Long cycle and storage life, less maintenance

Batteries will be tested at Boeing
Large-Format M1 Cells

Prototype 5 Ah M1 cells have been assembled by Lithion:

- demonstrates feasibility of adapting M1 chemistry to large-format prismatic form factor.
- Rate capability of 26650 cell is maintained up to 10C.
- Cycle life >600 cycles at 60°C
- 7 Ah cells will be produced in the next phase.
The 5Ah cell retains >98% of C/10 capacity at 10C rate.
Performance of Large-Format M1 Cells: Life

Cycle life of the 5 Ah cell is >>500 cycles at 60°C.
Summary

• A123-T/J has developed high performance, safe nanophosphate cathode materials and commercialized high power batteries.

• The batteries have demonstrated high rate capability, long cycle life, low self-discharge and excellent safety.

• 26650 cells and packs are being tested for defense aerospace applications.

• Large format cells are under development.