Lithium-ion Battery Demonstration for the 2007 NASA Desert Research and Technology Studies (Desert RATS) Program

The NASA Glenn Research Center (GRC) Electrochemistry Branch designed and produced five lithium-ion battery packs for demonstration in a portable life support system (PLSS) on spacesuit simulators. The experimental batteries incorporated advanced, NASA-developed electrolytes and included internal protection against over-current, over-discharge and over-temperature. The 500-gram batteries were designed to deliver a constant power of 38 watts over 103 minutes of discharge time (130 Wh/kg). Battery design details are described and field and laboratory test results are summarized.
Li-ion Battery Demonstration for the 2007 NASA Desert Research and Technology Studies Program

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Huntsville, AL
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Battery Demonstration Overview

DEMONSTRATION OBJECTIVE:

• Demonstrate performance of a lithium-ion battery with ETDP-developed NASA electrolyte.
• Support field trials with the Desert Research and Technology Studies (D-RATS) EVA cryopac
• Complement field test data with laboratory testing under controlled-environment conditions.

2007 HIGH-LEVEL SCHEDULE:

• Fabrication/qualification testing - May → late-August
• Internal GRC Concepts and Safety Review – July 17
• JSC Readiness Review – August 8
• “Dry Run” at JSC – August 13-17
• Final Safety & Readiness Review – August 21
• Desert RATS field demonstrations – September 10-14

Develop/build 5 working prototypes in 4 months
D-RATS Cryopac Power System

Power System for the MarkIII/I-suit D-RATS Cryopac

• Block Diagram

Sources

Hardline power supply

Battery and mount

Power box.

13 to 16.8 VDC

Bat. on/off

Pump on/off

DC/DC converter

Adjustable DC/DC converter

Ultra Capacitors

12 VDC

~ 8 VDC

Loads

Cryopac data system

2Watt

Audio DSP

5Watt

Pump

11-24Watt

Commercial (3.8 Ah) Li-ion Battery

Cooling pump

Required battery output:

22 to 38 W

13 to 16.8 V

2.5 hour run time at 22 W
2006 D-RATS Commercial Battery

Endura “E-50S” Lithium-Ion 14.4V/3.8Ah
- commercial Li-ion video-camera battery
- ~2 hour run time in D-RATS Cryopac
- Quick, easy swap out with commercial V-mount plate
- Dimensions: 86mm (W) x 142mm (L) x 33mm (D).
- Weight: 520g (1.16 lbs.)
- 105 Wh/kg
2007 NASA D-RATS Battery

Experimental NASA-Electrolyte Li-Ion 14.4V/4.5Ah
- four Quallion 4.5 Ah CERDEC pouch cells
- IDX adapter compatible with existing mount
- Dimensions: 76mm (W) x 150mm (L) x 39mm (D).
- Weight: 500g
- 130 Wh/kg

Physically interchangeable with Endura battery
Battery Pouch Cell

VENDOR: Quallion, LLC, Sylmar, CA

The Quallion prismatic pouch cell (part no. QL4500A) was developed for U.S. Army CERDEC under the “Ultra Safe High Energy Density Rechargeable Soldier Battery” Program (Contract No. W15P7T-05-C-P212) to address needs for soldier systems and equipment applications:

- Alternative cathode material with optimized particle size / enhanced safety
- Optimized CERDEC cell fabrication processes
- 200 Wh/kg

4.5 Ah CELL CHEMISTRY:

Positive Electrode: LiNiCoMnO₂

Negative Electrode: Graphite

Electrolytes:

- Quallion Standard (baseline): LiPF₆ in EC/DEC/EMC (all carbonate)
- NASA JPL-2: LiPF₆ in EC/DEC/DMC/EMC (all carbonate)
- NASA JPL-5: LiPF₆ in EC/EMC/MP (methyl propionate co-solvent)

Tight Ah capacity distribution from Quallion acceptance tests on all delivered battery cells

The NASA electrolytes were developed by JPL under the current NASA Exploration Technology Development Program (ETDP) for optimized low-temperature performance:

- Electrolyte blends formulated / purified at JPL
- Previously incorporated in other prototype industrial cell designs
Assembly Concept for Desert RATS Battery

• 4-cell package prepared by Quallion
• modified IDX adapter
• printed circuit board
  • over-discharge control
  • fuse
  • thermal fuse
• aluminum cover
• cells immobilized with heat transfer agents
IDX Adapter with PC Board

- Printed circuit includes fuse, thermal fuse and over-discharge protection
- Wide traces carry current from battery terminals to adapter power pins
- Negative current trace serves as current-measuring shunt
Over-Discharge Protection Circuit

- Comparator monitors battery voltage
- Protection circuit turns relay off at <12V
- Requires external reset
# Safety Considerations

<table>
<thead>
<tr>
<th>Condition</th>
<th>Precautions</th>
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</thead>
<tbody>
<tr>
<td><strong>over charge</strong></td>
<td>• voltage monitor &lt;br&gt;• temperature monitor &lt;br&gt;• individual cell voltage control &lt;br&gt;• manual supervision &amp; procedures</td>
</tr>
<tr>
<td><strong>over discharge (cell reversal)</strong></td>
<td>• limited mission time (2 hr.) &lt;br&gt;• battery shutdown (&lt;12 V) &lt;br&gt;• monitored cell balance, before and after every use</td>
</tr>
<tr>
<td><strong>over-load (short-circuit)</strong></td>
<td>• fuse (4 amp) &lt;br&gt;• battery shutdown (&lt;12 V) &lt;br&gt;• shielded connectors</td>
</tr>
<tr>
<td><strong>over temperature</strong></td>
<td>• thermal fuse (70°C) &lt;br&gt;• battery shutdown (&lt;12 V) &lt;br&gt;• charge temperature monitor</td>
</tr>
<tr>
<td><strong>misconnection</strong></td>
<td>• keyed V-mount adapter &lt;br&gt;• keyed connectors</td>
</tr>
</tbody>
</table>

**mechanical abuse**<br>• safety spotters <br>• encapsulated components
**NASA Electrolyte/Quallion Pouch Cell Abuse Testing**

Crush test caused short-circuit and fire in one cell with NASA JPL-2 electrolyte

Significant loss of open-circuit voltage (OCV) in two other crush tests, but no incident

<table>
<thead>
<tr>
<th>Cell ID</th>
<th>Initial IR (mohm)</th>
<th>Initial OCV (V)</th>
<th>Initial Weight (g)</th>
<th>Initial Capacity (Ah)</th>
<th>Pre-Test IR (mohm)</th>
<th>Pre-Test OCV (V)</th>
<th>Pre-Test Weight (g)</th>
<th>Safety Test</th>
<th>Post-Test IR (mohm)</th>
<th>Post-Test OCV (V)</th>
<th>Post-Test Weight (g)</th>
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<tr>
<td>JPL2-26</td>
<td>6.47</td>
<td>3.40</td>
<td>80.58</td>
<td>4.58</td>
<td>6.35</td>
<td>4.18</td>
<td>80.57</td>
<td>Nail</td>
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<td>6.23</td>
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<td>4.18</td>
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<td>5.59</td>
<td>4.03</td>
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<td>79.50</td>
<td>Crush</td>
<td>57</td>
<td>15.21</td>
<td>4.03</td>
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</table>

**Crush Test**

- JPL2-29 before
- JPL2-29 after crush

**Post-Test**

- max temp. (°C)
- IR (mohm)
- OCV (V)
- Weight (g)

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www.nasa.gov
Battery Assembly

- Heat transfer agent
- 4-cell stack
- PC board
- Components soldered together
- Adapter
- Data & cell voltage taps
- Status LEDs
Maximum Power Pre-Ship Test

- 38 W constant power (worst-case test)
- 4.36 Ah / 1.6 hours
- shutdown circuit activates at 12.0 V
- final mid-stack temperature: 37°C

Expected capacity with acceptable temperature increase
Maximum Power Pre-Ship Test

Battery cell-voltage range under discharge (max – min)

- 10 mV range
- 200 mV at end of discharge

Diagram showing cell voltage range (mV) versus capacity (Ah) for different battery types after battery assembly, discharge at maximum power.
Data Loggers

Pace Scientific XR440

• Battery volts, current & ambient temperature
• 158 grams

Omega OM-CP-TC4000

• Cell core temperature & ambient temperature
• 27 grams
Objectives

• confirm fit & function with Cryopac
• test over-discharge circuit
• field trial with data loggers

Results

• three successful suit trials
• expected battery run-time & capacity
• over-discharge circuit activates at <12V
  • false activation at start-up in one trial
• EMI issues with data loggers

Day-2 trial at JSC “rock-pile”
Field Trial at Cinder Lake – September 2007

Day 1 - Mark III Suit Run

- 1.9 hour run time
- 3.7 Ah delivered

Results:

- three successful suit trials
- shielding reduced logger noise
- a fourth trial was abandoned when safety-circuit interfered with start-up (EMI?)
Laboratory Testing

Battery constant-power test

Results at –30°C, 12V limit:
• 40% of room temperature capacity
• ~20% improvement with JPL-5 electrolyte
• commercial battery does not function at –30°C
Cell constant-power test

**Preliminary results**

- capacity improvement with JPL-5 at -35°C
- voltage recovery by self-heating benefits JPL-2 and baseline electrolyte cells
- -40°C temperature-limit under these conditions

**testing at other load-profiles is under way**
Laboratory Testing - JPL

constant current test

C/2 Discharge Rate (2.00 A)

Temperature = - 40°C

Cell Voltage (V)

Percent of Room Temperature Capacity (%)

- Cell QX018 - Baseline Electrolyte
- Cell QX220 - Electrolyte Type = JPL-2
- Cell QX222 - Electrolyte Type = JPL-2
- Cell QX523 - Electrolyte Type = JPL-5
- Cell QX524 - Electrolyte Type = JPL-5
- Cell QX530 - Electrolyte Type = JPL-5

1.50 Amp Charge current to 4.1 V
Taper Cut-Off at 0.040 A (~ C/100)
Cells charged at RT prior to LT discharge

data courtesy of Marshall Smart, JPL
Conclusions & Future Work

• Successful battery demonstration in six field-trials
  • expected battery capacity, temperature in limits
  • need to understand safety-circuit issues on start-up (EMI?)
  • logger data quality needs to be improved

• Good low-temperature function with all three electrolytes

• Some advantage with JPL-5 in constant-power testing
  • working to understand differences between JPL and GRC screening (load type, thermal environment etc.)
Acknowledgement

Chris Moore, NASA Headquarters
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Judy Jeevarajan, JSC
Paul Beach, Quallion
Vince Visco, Quallion
Backup Slides
Battery cell-balance at low temperature

cell temperature gradient induces early separation of cell voltages at low temperature
Cell energy at reduced temperature

2.25 A (C/2) charge to 4.2V, taper to C/10
all charging at 23°C
Dry Run Field-Trial Results

Day 4: Mark III suit indoor trial
• 1.4-hour EVA time
• continue discharge after EVA to test over-discharge protection circuit
• 2.6-hour total run time to safety circuit shutdown

Battery Voltage

![Graph showing battery voltage over time with EVA ends and safety circuit shutdown markers.]

Unshielded loggers are sensitive to EMI.
Battery cell voltage balance at low temperature

• trend in cell voltage correlates with position
• cell #1 benefits from greater self-heating
Battery Charging Elements

• power supply limits current/voltage (redundant fuse in monitor)
• battery housed in fire-proof enclosure
• keyed connections between equipment items make misconnection impossible
• charge monitor serves as redundant limiter for cell voltage control
• operator’s record to monitor cell balance
Quallion Pouch Cell Abuse Testing Results

Quallion has performed extensive safety and abuse tests on this pouch cell design.

Per Quallion, no explosion, smoke or fire, indicating a thermal runaway situation, was observed during such tests.

- Fully-charged cell / heated to 150°C and voltage drop to 3V after ~3 hours
- Fully-charged cell / voltage drop and temperature rise recorded (test mimics an internal short-circuit event)
- Fully-charged cell / heated to 150°C and voltage drop to 3V after ~3 hours
- Fully-charged 7-cell stacks of Quallion pouch cells and LiCoO$_2$ pouch cells after bullet shot test
Battery Charge Monitor

- Five controllers monitor individual cell voltages and battery temperature
- Charge current supplied by 18 volt / 3 amp dc power supply
- Current to battery is interrupted if any monitored value falls out of range
- Requires operator action to reset
- Battery discharge uses 8 ohm 50 W resistor

Protects battery if fault develops in the charge voltage control
Individual-Cell Charge-Voltage Control

• Automatically shunts current to limit upper cut-off voltage of individual cells

• Developed by Rob Button/GRC for Li-ion cell testing at Crane, Indiana

• Over 20 units have been operating successfully at Crane for over three years
Cell Balance

voltage range under worst-case drain test

Maximum Power Test

cell voltage-range (mV)

hours

0 0.5 1 1.5 2

1000 100 10 1

Quall C1 4.469
Quall C2 4.459
Quall C3 4.468
Quall C4 4.474
JPL2-5 4.507
JPL2-7 4.467
JPL2-11 4.496
JPL5-10 4.529
JPL5-3 4.504
JPL5-8 4.496
JPL5-9 4.505
avg 4.488
min 4.459
max 4.529
range 0.070
range/avg 2%
c. of var. 0.50%
PLSS Battery Loads

- Cryopac data system
  - Custom electronics supplied by Oceaneering.
  - 8-24 VDC input (internal 5 VDC regulator).
  - 2 Watts maximum total.
- Audio DSP
  - Custom electronics supplied by Kennedy Space Center.
  - Power box regulator 83% efficient: Power One P/N DFA6U12S12.
  - 12 VDC input (internal 5 VDC regulator).
  - 5 Watts maximum total.
- Pump
  - Greylor PQ-12 [http://www.greylor.com/]
  - Power box regulator 79% efficient: Power One P/N DFA20E12S12.
  - 11 Watts nominal, 24 Watts maximum.
  - Voltage is varied to achieve desired flow rate.
  - Pump must continue to run during all cryogenic operations.

<table>
<thead>
<tr>
<th>Load elements (2 pump cases)</th>
<th>battery voltage</th>
<th>12 V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>net</td>
<td>gross</td>
</tr>
<tr>
<td></td>
<td>Watts</td>
<td>eff.</td>
</tr>
<tr>
<td>data system</td>
<td>2</td>
<td>100%</td>
</tr>
<tr>
<td>Audio DSP</td>
<td>5</td>
<td>83%</td>
</tr>
<tr>
<td>Pump nominal</td>
<td>11</td>
<td>79%</td>
</tr>
<tr>
<td>total</td>
<td>18</td>
<td>total 21.948</td>
</tr>
</tbody>
</table>

expected battery current:
1.83 amp. nominal
3.20 amp. maximum
Current-carrying Capacities

cell maximum: 9 A (vendor limit)
maximum current to loads: 3.2 A
fuse rating: 4 A, 7A limit measured in laboratory
relay capacity (both poles): 4 A, switched
thermal fuse: 15 A