Mars Mission Surface Operation Simulation Testing of Lithium-Ion Batteries

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Outline

- Introduction and Objectives
- Mission Simulation Testing of MSP01 Lander Cells
- Mission Simulation Testing of MSP01 Lander Battery
- Mission Simulation Testing of 2003 MER Cells
- Mission Simulation Testing of 2003 MER Batteries
- Mission Simulation Testing of Next Generation Cells
- Conclusions
- Acknowledgements
Test Plan for the MSP01 Lithium-Ion Cells and Battery:
 Program Objectives

• Assess viability of using lithium-ion technology for future NASA applications, with emphasis upon Mars landers and rovers which will operate on the planetary surface.

• Support the JPL 2003 Mars Exploration Rover program to assist in the delivery and testing of a 8 A.hr Lithium-Ion battery (Lithion/Yardney) which will power the rover.

• Demonstrate applicability of using lithium-ion technology for future Mars applications.
  * Mars 09 Science Laboratory (Smart Lander)
  * Future Mars Surface Operations (General)
Lithium-Ion Cell/Battery Development
Potential NASA Benefits and Comparison to Conventional Technologies

**Benefit to NASA Missions**
- REDUCED POWER SYSTEM MASS
  - 25 % OF Ni-Cd/Ni-H₂ BATTERY MASS
  - 200-230 kg MASS SAVINGS FOR 8-10 kW GEO PAYLOADS
- REDUCED POWER SYSTEM VOLUME
  - 25 % OF Ni-Cd/Ni-H₂ BATTERY VOLUME
  - SIMPLER POWER SYSTEM INTEGRATION
- LOWER LAUNCH COSTS
  - REDUCED POWER SYSTEM WEIGHT
  - REDUCED SOLAR ARRAY SIZE
- ENHANCE SMALL SPACECRAFT MISSIONS

**Technology Challenges/Drivers**

<table>
<thead>
<tr>
<th>MISSION</th>
<th>TECHNOLOGY DRIVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>LANDER/ROVER</td>
<td>LOW TEMP. OPERATION</td>
</tr>
<tr>
<td></td>
<td>HIGH RATE PULSE CAPABILITY</td>
</tr>
<tr>
<td>GEO S/C</td>
<td>TEN-TWENTY YEAR OPER. LIFE</td>
</tr>
<tr>
<td></td>
<td>LARGE CAPACITY CELLS (50-200 Ah)</td>
</tr>
<tr>
<td>LEO/PLANTERARY S/C</td>
<td>LONG CYCLE LIFE (30,000)</td>
</tr>
<tr>
<td></td>
<td>M E D . C A P A C I T Y C E L L S (50 Ah)</td>
</tr>
<tr>
<td>AIRCRAFT</td>
<td>LOW TEMP OPERATION</td>
</tr>
<tr>
<td></td>
<td>HIGH VOLTAGE BATTERIES (270 V)</td>
</tr>
<tr>
<td>UAV</td>
<td>LARGE CAPACITY CELLS (200 Ah)</td>
</tr>
<tr>
<td></td>
<td>HIGH VOLTAGE BATTERIES (100V)</td>
</tr>
</tbody>
</table>

**Specific Energy**

**Energy Density**

Specific Energy (Wh/kg)

Energy Density (Wh/l)

Ni-Cd | Ni-H₂ (IPV) | Ni-Mh | Li-Ion | Li-SPE *

Ni-Cd | Ni-H₂ (IPV) | Ni-Mh | Li-Ion | Li-SPE *
Lithium-Ion Cells for the Mars Surveyor 2001 Lander EDL and Mission Simulation Tests

**Requirement:**
- Meet entry, descent and landing (EDL) power requirements
- Successfully cycle cells on the surface of Mars
  (temperature range of \(-20^\circ\text{C} \text{ to } 40^\circ\text{C}\))

**Approach:**
- Store cells for > 10 months to simulate cruise period
- Test cells under EDL profile at \(0^\circ\text{C}\)
- Cycle cells under varying temperature profile
  - 12 Hour charge period (-20 to 40\(^\circ\text{C}\))
  - 12 Hour discharge period (40 to -20\(^\circ\text{C}\))
  - Change temperature range to model seasons

**Possible Evaluation Criteria:**
- Discharge voltage on EDL profile (>3.0V each cell)
- End of discharge voltage on cycling test (>3.0V each cell)
- Cell variance
- Capacity fade upon cycling
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
Storage Characteristics of MSP01 Design Cells- Results of 11 Month Storage Test

Cells Stored on the Buss at 10°C (70% SOC)

<table>
<thead>
<tr>
<th></th>
<th>Storage After 20 Days</th>
<th>Storage After 11 Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Last Discharge Prior to Storage (Ahr)</td>
<td>33.804</td>
<td>33.962</td>
</tr>
<tr>
<td>1st Discharge After Storage (Ahr) 23°C</td>
<td>26.034</td>
<td>25.959</td>
</tr>
<tr>
<td>2nd Discharge After Storage (Ahr) 23°C</td>
<td>33.523</td>
<td>33.534</td>
</tr>
<tr>
<td>% of Initial Capacity (Reversible Capacity)</td>
<td>99.169</td>
<td>98.738</td>
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<tr>
<td>Permanent Capacity Loss (%)</td>
<td>0.831</td>
<td>1.262</td>
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<tr>
<td>1st Discharge After Storage (Ahr) 23°C</td>
<td>25.6252</td>
<td>29.059</td>
</tr>
<tr>
<td>2nd Discharge After Storage (Ahr) 23°C</td>
<td>32.9636</td>
<td>32.266</td>
</tr>
<tr>
<td>% of Initial Capacity (Reversible Capacity)</td>
<td>97.515</td>
<td>95.006</td>
</tr>
<tr>
<td>Permanent Capacity Loss (%)</td>
<td>2.485</td>
<td>4.994</td>
</tr>
</tbody>
</table>
Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications
EDL Discharge Profile Simulation of MSP01 Design Cells

- Cells capable of supporting EDL load profile – Including 50 A (2C) pulses
- Cells also display good uniformity after prolonged storage period
Lithium-Ion Cells for Mars Lander Applications
Mission Simulation Cycling (Temperature Range = -20 to +40°C)

- 5.0 A Charge current to 4.1 V
  Total charge time = 12 hours

- 1.0 A Discharge current for 12 hours
  12.0 Ahr Total Discharge Capacity
Minimal performance degradation observed with cells to-date.
Stable performance observed (constant C/D ratio)
Excellent reproducibility of cell performance observed:
   Only 15 mV spread among 4 cells observed for the end of discharge voltage EODV
The coldest temperature range (-20° to 0°C) appears to be the least detrimental to cell health (< 25 mV decline in EODV observed over last 500 cycles)
Cells projected to be capable of providing > 1000 cycles (EODV > 3.0V/cell)
Lithium Ion Technology Demonstration for Future Smart Lander Missions

Lander Surface Operation Mission Simulation Performance Test

2001 MSP01 Surveyor Lander Design Cells (Yardney)

Watt-Hour Efficiency

- Impedance growth appears to be minimized at the colder temperature range (-20° to 0°C)
- Cycling in the coldest temperature range (-20° to 0°C) results in minimal change to energy efficiency observed
- Long life (> 1000 cycles (EODV > 3.0V/cell)) under these conditions seems probable, providing minimal high temperature excursions.
MSP 2001 Lander Battery

- Two 25 Ah, 8-Cell Li Ion Batteries (N+1)
- Individual Cell Monitoring and control via Cell Bypass Unit (CBU) to prevent overcharge
- Individual Charge Control Unit (CCU).
- Constant Voltage Charging at - 32.8 Vdc.
- 16 Selectable V/T curves.
- Amp Hour Integration.

Battery Envelope:

- 9.50” x 9.0” x 3.63” x 14.60” x 60°
Test Plan for the MSP01 Lithium-Ion Battery:
Testing Methodology

- Test Setup
  - Ensure Electrical Isolation (Cell/battery/chamber)
  - 25 Ahr 8-cell battery (24-34.4 V)

- Charge Control
  - 25 Ahr 8-cell battery (24-34.4 V)
  - Battery voltage controlled charging
  - Constant current and constant potential charging
  - Individual cell monitoring
  - Battery protection limits
    - Individual cell voltage exceeded ( > 4.2 V)
    - Individual cell voltage exceeded ( < 2.5 V)
    - Temperature limits exceeded (> 50°C for any input)
    - Charge/discharge capacity limit (>35 Ahr)
    - Step time ( > 10 hours)
  - Battery cell balancing methodology
    (i.e., resistively discharging cells to 2.5V)
1.0 Receiving and Inspection
   • Measure battery voltage and individual cell voltages and impedance.
   • Ensure electrical isolation (Case)

2.0 Initial Electrical Performance Characterization
   • Implement cell balancing protocol: Resistively discharge each cell to 3.0 V (1 Ohm)
   • 3 cycles at 20°C
     • C/5 charge rate (5 amps) to 32.8 V (8 x 4.1 = 32.8)
     • Constant potential charge to current taper cut-off (0.50 A)
     • C/5 discharge rate to 24 V (or first cell to reach 3.0V)
     • One cycle battery will be charged to 32.0 V (4.0V / cell)
   • 3 cycles at 0°C (repeat testing as above)
   • 3 cycles at -20°C (C/10 charge rate (0.10 A taper cut-off)

3.0 Cruise Storage Test (10-12 Months)
   • Store battery on bus with a clamp voltage of 30.40 V
     (3.8 V x 8 = 30.40 V) (~70 % SOC)
   • Store battery at 10°C
   • Record individual cell voltages
Test Plan for the MSP01 Lithium-Ion Battery:
2009 Lander Mission Simulation Testing Plan

4.0 EDL Pulse Capability Test
• Discharge battery using C/5 discharge rate to 24 V
• Cycle battery 3 times at 20°C (determination of storage impact)
• Charge battery using C/5 discharge rate to 32.8 V
• Soak battery for 24 hours at 0°C
• Initiate EDL pulse profile
  • 14 Amps (2 minutes)
  • 8 Amps (7 minutes)
  • 20 Amps (4 minutes)
  • 50 Amps (30 over baseline 20) (100 mSec)
• Discharge battery using C/5 discharge rate to 24 V

5.0 Electrical Performance Characterization
• Same as section 2.0

6.0 Mission Simulation Cycling (In Progress)
• Discharge battery using C/5 discharge rate to 24 V (optional cell balancing)
• Charge battery using C/5 discharge rate to 32.8 V (4.1V per cell)
• Program chamber to run variable temperature profile (see charts)
• Charge battery using C/5 discharge rate (5 A) to 32.4 V (4.05 V per cell)
• Total charge time 12 hours (extended taper)
• Discharge battery using C/25 rate (1A) for 12 hours

7.0 Electrical Performance Characterization
• Same as section 2.0

8.0 Post Mission Characterization
• More detailed pulse characterization
• More detailed rate characterization as a function of temperature
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications
Initial Characterization/Conditioning at Different Temperatures
32.0 V Charge - Discharge Capacity (AHR) at Various Temperatures

Discharge Capacity (AHR)

- Battery capacity at different temperatures determined
- Capacity determined after cell balancing
- Greater cell voltage dispersion observed at lower temperature

Cell Voltage Dispersion (ΔV)

Charge Current = 5 A (C/5 Rate)
Charge Voltage = 32.00 V (4.0 V per cell)
Discharge Current = 5 A (C/5 Rate)
Discharge Cut-off = 24.0 V (3.0 V per cell)
Cell Voltage Cut-Off = 2.5 V and 4.15 V
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at 20°C

After Cell Balancing – 32.8 V Charge

Charge Current = 5 A (C/5 Rate)
Charge Voltage = 32.80 V (4.0 V per cell)
Discharge Current = 5 A (C/5 Rate)
Discharge Cut-off = 24.0 V (3.0 V per cell)
Cell Voltage Cut-Off = 2.5 V and 4.15 V

Total Battery Weight (Two 8 Cell Batteries) = 17.8 Kg
Weight of One Battery = 8.9 Kg

Temperature = 20°C

105.4 WHr/Kg
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications
Cruise Storage Simulation (Bus Voltage = 30.40 V at 10°C)
Battery and Cell Voltages During Storage (~ 9 months)

- Cells balanced prior to storage test
- Cell dispersion potential issue depending upon charge methodology
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications
Cruise Storage Simulation (Bus Voltage = 30.40 V at 10°C)

Cell and Chamber Temperatures (°C)

Charge current (A)

Cumulative Charge Capacity During Storage (Ahr)

Cell Dispersion During Storage (ΔV)

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Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Performance Characterization After Cruise (32.00 V at 20°C)

Cycling Characteristics After Storage (Temperature 20°C) – No Cell Balancing After Cruise

Due to cell imbalance, battery was not fully charged after storage (24.73 AHR)

Cell #1 terminated charge prior to reaching 32.40 V battery charge voltage

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Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications
Performance Characterization After Cruise (32.00 V at 20°C)

After cell balancing, cell dispersion characteristics were improved.
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Performance Characterization After Cruise (32.00 V at 20°C)

After Cell Balancing

- Charge Current = 5 A (C/5 Rate)
- Charge Voltage = 32.00 V (4.0 V per cell)
- Discharge Current = 5 A (C/5 Rate)
- Discharge Cut-off = 24.0 V (3.0 V per cell)
- Cell Voltage Cut-Off = 2.5 V and 4.15 V

After cell balancing, battery was able to be cycled effectively between prescribed voltage limits (24V – 32V)
- 28.90 Ahr delivered at 20°C (32.0 V Charge or 4.00V/cell)
Tighten cell dispersion after balancing cells (cell #1 and cell #6 still somewhat divergent)

- 28.99 Ahr charged at 20°C (32.0 V Charge or 4.00V/cell)
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Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications
Performance Characterization After Cruise (32.00 V Charge)

After Cell Balancing

Yardney MSP01 8-Cell Lander Battery

Charge Current = 5 A (C/5 Rate)
Charge Voltage = 32.40 V (4.05 V per cell)
Discharge Current = 5 A (C/5 Rate)
Discharge Cut-off = 24.0 V (3.0 V per cell)
Cell Voltage Cut-Off = 2.5 V and 4.15 V

Temperature = 20°C

Capacity after storage (32.0 V Charge) = 28.900 Ahr
Capacity prior to storage (32.0 V Charge) = 29.085 Ahr

0.6% Capacity Loss

Very little capacity loss observed due to the cruise storage period
Much higher capacities observed after cell balancing.

- Capacity at 20°C (32.0 V Charge): 21.732 Ahr
- Capacity at 0°C (32.0 V Charge): 27.975 Ahr
- Capacity at -20°C (32.0 V Charge): 28.890 Ahr

Charge Current = 5 A (C/5 Rate)
Charge Voltage = 32.40 V (4.05 V per cell)
Discharge Current = 5 A (C/5 Rate)
Discharge Cut-off = 24.0 V (3.0 V per cell)
Cell Voltage Cut-Off = 2.5 V and 4.15 V
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Mars Surface Operation Mission Simulation Test (MSP01 Profile)

1\textsuperscript{st} Full Charge (32.4 V Charge) – Cell Dispersion Characteristics

\begin{align*}
\Delta V &= 0.179V \\
&= 4.146V \\
&\quad \text{(Cell # 1)} \\
\Delta V &= 0.118V \\
&= 3.967 V \\
&\quad \text{(Cell # 6)}
\end{align*}

Battery Voltage

\begin{align*}
\text{Battery Voltage} &= 32.400 V \\
\text{Total charge} &= 12 \text{ hours} \\
\text{Total Discharge Capacity} &= 12.0 \text{ Ah}
\end{align*}
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Mars Surface Operation Mission Simulation Test (MSP01 Profile)

Typical Discharge (12 AHr – C/25 Rate)

12.00 AHr

Battery Voltage 27.588 V

Δ V = 0.050 V
(End of Discharge)

5.0 A Charge current to 32.4V (4.05V/Cell)
Total charge time = 12 hours
1.0 A Discharge current for 12 hours
12.0 Ahr Total Discharge Capacity

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Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications
Initial Characterization/Conditioning at Different Temperatures

First 28 Sols (End of Discharge Cell Voltages)

- MSP01 8-Cell (25 Ahr) Lander Battery
- 5.0 A Charge current to 32.4V (4.05V/Cell)
- Total charge time = 12 hours
- 1.0 A Discharge current for 12 hours
- 12.0 Ahr Total Discharge Capacity

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Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at Different Temperatures

First 28 Sols (End of Charge Cell Voltages)

MSP01 8-Cell (25 Ahr) Lander Battery

$\Delta V = 0.117 \text{ V}$  \hspace{1cm}  $\Delta V = 0.138 \text{ V}$

- Initially
- Cycle 28

End of Charge Cell Voltages (V)

5.0 A Charge current to 32.4V (4.05V/Cell)
Total charge time = 12 hours
1.0 A Discharge current for 12 hours
12.0 Ahr Total Discharge Capacity

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2003 MARS Exploration Rover Secondary Battery

Battery Description

- Rechargeable system: Lithium-ion
- Good low temperature performance
- Demonstrated storage capability
- High specific energy > 100 Wh/kg
- Configuration: Prismatic
- Excellent performance data base
- Two parallel strings each with 8 cells
- Vendor: Yardney Tech. Prod., Inc.

Mission Requirements

- Rover Battery intended to support launch, cruise anomalies, and Mars surface operations
- Voltage: 32-24 V
- Capacity: 16 Ah (BOL) at RT and 10 Ah at -20°C (BOL)
- Load: C/2 max at RT; Typical C/5
- Temperature: Charge at 0-25°C and discharge >-20°C
- Light weight and compact
- Long cycle life of over 300 cycles
- Long storage life of over 2 years
Yardney Lithium-Ion Cells for Mars Rover Applications

Mission Simulation of Mars Surface Operations

Mission Simulation Temperature Profile

- Environmental temperature range = 0 to –20°C
- Battery will be charged by solar array during the daytime (~ 0°C charge)
- Data represents first 8 sols of operation on the surface of Mars
MER 10 Ah Rover Lithium-Ion Battery (FM3A)
Initial Characterization/Conditioning at 20°C

Battery/Cell Voltage and Current

Cell Dispersion During Charge

- Conditioning cycles performed at various temperatures (20, 0, and –20°C) (C/10 charge-C/5 discharge)
- Minimal cell dispersion observed at the battery level (< 25 mV)

Electrochemical Technologies Group
MER 8 Ah Rover Lithium-Ion Battery (EM1B)
Initial Characterization/Conditioning Tests
Discharge Capacity at Different Temperatures

- Good low temperature performance observed at the battery level
- Over 75% of the room temperature capacity delivered at –20°C (C/5 rate)

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Mission simulation performed without the benefit of battery charge control electronics
Performance superior to that obtained at cell-level (due to fresher cells and thermal effects)
MER 8 Ah Rover Lithium-Ion Battery (EM1B)
Mission Simulation Testing
SOL 1-12 (Capacity)

SOL 1-12 (Capacity)

Battery State-of-Charge (SOC) (%)

- Cycling on the surface of Mars is projected to correspond to ~ 50 % DOD
- SOC marginally decreasing with cycling (incomplete charge)
- Trend will be off-set by integration of charge electronics

Electrochemical Technologies Group
Future Missions: 2009 Smart Lander Secondary Battery

Battery Description *

- Rechargeable system: Lithium-ion
- High specific energy > 100 Wh/kg
- Configuration: TBD
- Capacity: 30-60 Ahr
- Vendor: TBD

Mission Requirements *

- Voltage: 32-24 V
- Capacity: 30-60 Ahr
- Load: TBD
- Temperature: Charge at -20 to -25°C and discharge >- 40°C
- Light weight and compact
- Long cycle life of over 1000 cycles
- Long storage life of over 2 years

* Lander battery should be capable of supporting launch, cruise, and Mars surface operations over range of temperature (-40 to +40°C).
* Mission currently being re-planned and requirements likely to change.
Future Missions: 2007 Smart Lander Secondary Battery
Low Temperature Electrolyte Development at JPL

- Identified a number of improved low temperature electrolytes enabling –40°C operation
- Smart et al., 11th International Meeting on Lithium Batteries (IMLB), June 28, 2002, Monterey, CA

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SAFT DD-Size Lithium-Ion Cells for Mars Rover Applications

Cell Performance at Low Temperatures: JPL Electrolyte

Discharge Energy (Watt-Hr/Kg) – C/10 Rate (0.90 A)

SAFT DD (9 Ahr) Lithium Ion Cell
JPL Electrolyte
1.0M LiPF$_6$ EC+DEC+DMC+EMC (1:1:1:3)

- 0.900 Amp Charge current (C/5) to 4.1 V
- Taper Cut-Off at 0.090 A (C/100)
- Cell charged at RT prior to LT discharge
- Cell soaked for >8 hours prior to discharge

0.900 A Discharge Current (C/10)
Lithium-Ion Cells for Future Mars Applications

Mission Simulation of Mars Surface Operations

2003 MER Mission Simulation Temperature Profile

- Improved low temperature electrolytes have translated into increased mission capability.
- Cells charged at 0°C to 4.05 V (no taper) prior to test
SAFT DD-Size Lithium-Ion Cells for Mars Rover Applications
Mars Mission Surface Operation Simulation Cycling
Temperature Range = -40 to 0°C

SAFT DD (9 Ahr) Lithium Ion Cell
JPL Electrolyte
1.0M LiPF₆ EC+DEC+DMC+EMC (1:1:1:3)

0.9 A Charge current to 4.1 V
0.3 A Discharge current for 12 hours
3.6 Ahr Total Discharge Capacity (40% DOD)
SAFT DD-Size Lithium-Ion Cells for Mars Rover Applications

Mars Mission Surface Operation Simulation Cycling

Temperature Range = -60 to 0°C

SAFT DD (9 Ahr) Lithium Ion Cell
JPL Electrolyte
1.0M LiPF₆ EC+DEC+DMC+EMC (1:1:1:3)

0.9 A Charge current to 4.1 V
0.3 A Discharge current for 12 hours
3.6 Ahr Total Discharge Capacity (40% DOD)
SAFT DD-Size Lithium-Ion Cells for Mars Rover Applications
Performance with Improved Anode Material and JPL Electrolyte

Cycle Life Performance at Different Temperatures

SAFT DD-Size Lithium Ion Cell
1.0 M LiPF₆ EC+DEC+DMC+EMC (1:1:1:3)
(Gen III JPL Electrolyte)

- 23°C
- 20°C
- 40°C (4.1 V)
- 40°C (4.0 V)

Temp = 23 C (C/5 Charge - C/5 Discharge)
Temp = - 20C (C/10 Charge - C/5 Discharge)
Temp = - 40C (C/15 Charge-4.1 V Charge - C/10 Discharge)
Temp = - 40C (C/15 Charge-4.0 V Charge - C/10 Discharge)
Improved low temperature electrolytes have translated into increased mission capability.

Introduces possibility of powering survival mode of lander or rover to very low temperatures.
SUMMARY and CONCLUSIONS

• Li-Ion cells/batteries for the MSP 2001 Lander mission:
  – Demonstrated the technology readiness of Li-Ion technology (Yardney)
  – Good Discharge Rate Capability (Delivers required capacity at low temp)
  – Good Storage Characteristics (Able to meet other requirements after cruise)
  – Mission Simulation Testing (Able to support > 700 sols on surface. More than 2 Years of operation)
  – Battery fully space qualified (Yardney/LMA/JPL) prior to mission cancellation
  – Lander battery was demonstrated to support efficient Mars surface operation (MSP01 profile)

• Li-Ion cells/batteries for the 2003 MER mission:
  – Good Cycle Life Performance (Exceeds requirements at all temps)
  – Discharge Rate Capability (Delivers required capacity at low temp)
  – Mission Simulation Testing (Able to support projected surface operation load profile)

• Li-Ion cells testing for future Mars Lander applications
  – Excellent low temperature performance demonstrated in prototype cells
  – Operating temperature range of – 60 to +40°C demonstrated
  – Improved electrolytes result in improved mission capability
  – Very low temperature capability may be beneficial to power survival mode
Acknowledgments

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