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 Ahr 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

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<td>HIGH VOLTAGE BATTERIES (270 V)</td>
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<td>HIGH VOLTAGE BATTERIES (100V)</td>
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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°C to 40°C)

Approach:
Store cells for > 10 months to simulate cruise period
Test cells under EDL profile at 0°C
Cycle cells under varying temperature profile
  - 12 Hour charge period (-20 to 40°C)
  - 12 Hour discharge period (40 to -20°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 10ºC (70% SOC)

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Yardney 25 Ahr Lithium-Ion Cell

Cell Y018

5.0 Amp Discharge Current (C/5)
3.0 Volt Cut-off

Capacity Prior To Storage = 33.804 Ahr
Capacity After Storage = 32.964 Ahr
Reversible Capacity = 97.5 %
Capacity Loss = 2.5 %

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<th>Storage After 20 Days</th>
<th>Storage After 11 Months</th>
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<tr>
<td>Last Discharge Prior to Storage (Ahr)</td>
<td>1st Discharge After Storage (Ahr) 23ºC</td>
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<tr>
<td>Y018</td>
<td>33.804</td>
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<tr>
<td>Y031</td>
<td>33.962</td>
</tr>
<tr>
<td>Y043</td>
<td>34.153</td>
</tr>
<tr>
<td>Y054</td>
<td>33.727</td>
</tr>
</tbody>
</table>
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
Lithium Ion Technology Demonstration for Future Smart Lander Missions

Lander Surface Operation Mission Simulation Performance Test

2001 MSP01 Surveyor Lander Design Cells (Yardney)

- 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)

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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 9.00" x 60°
- 3.63" x 14.60"
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
**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

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

Discharge Capacity (AHr)

Cell Voltage Dispersion (ΔV)
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at 20°C

After Cell Balancing – 32.8 V Charge

Yardney MSP01 8-Cell Lander Battery

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

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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 (Ah)

Cell Dispersion During Storage (ΔV)
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

Cell Voltage (V)

Battery Voltage (V)

Time Hours

Charge Current = 5 A (C/5 Rate)
Charge Voltage = 32.40 V (4.05V 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

24.73 Ahr Charge Capacity

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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.

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

After Cell Balancing

- 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)
Yardney MSP01 8-Cell Lander Battery

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

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

- **After Cell Balancing**
  - Tighter 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 4.00 V/cell)

**Graph**

- **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

**Temperature** = 20°C
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

Prior
28.900 Ahr

After
29.085 Ahr

0.6 % Capacity Loss

- Capacity after storage (32.0 V Charge)
- Capacity prior to storage (32.0 V Charge)

Very little capacity loss observed due to the cruise storage period

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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

Much higher capacities observed after cell balancing.

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

21.732 Ahr
27.975 Ahr

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

Mars Surface Operation Mission Simulation Test (MSP01 Profile)

1st Full Charge (32.4 V Charge) – Cell Dispersion Characteristics

\[ \Delta V = 0.179V \]

\[ 4.146V \] (Cell # 1)

\[ 3.967V \] (Cell # 6)

\[ \Delta V = 0.118V \]

Battery Voltage = 32.400 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
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)

- Battery Voltage: 27.588 V
- Cell #1 Voltage: 3.429 V
- Cell #5 Voltage: 3.479 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

ΔV = 0.050 V
(End of Discharge)
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
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)

\[ \Delta V = 0.117 \text{ V} \]  
(Initially)

\[ \Delta V = 0.138 \text{ V} \]  
(Cycle 28)

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
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

- 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

Rover Battery intended to support launch, cruise anomalies, and Mars surface operations

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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

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

- 20°C
- 20°C (Room Temperature Charge)
- 20°C (Low Temperature Charge)
23°C

Charge Current = 0.80 A (C/10 Rate)
Charge Voltage = 32.40 V (4.05V per cell)
Discharge Current = 1.6 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

- 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)
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
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

* Mission currently being re-planned and requirements likely to change.

- Lander battery should be capable of supporting launch, cruise, and Mars surface operations over range of temperature (-40 to +40°C).
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
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 LiPF₆ EC+DEC+DMC+EMC (1:1:1:3)

Cell Voltage (V)

Discharge Energy (Watt-Hr/Kg)

A ▲ Temperature = 25 C
B ■ Temperature = 0 C
C ▲ Temperature = -10 C
D ▲ Temperature = -20 C
E ▲ Temperature = -30 C
F ▲ Temperature = -40 C
G ▲ Temperature = -50 C
H ▲ Temperature = -60 C

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)
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

- 60
-50
-40
-30
-20
-10
 0
 10
 20
 30
 40
 50
 60

Time (Hours)

Cell Voltage (V)

Aux # 1
Aux # 2
Volts

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

Legend:
△ 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)
SAFT DD-Size Lithium-Ion Cells for Mars Rover Applications
Performance with Improved Anode Material and JPL Electrolyte

Discharge Rate Capability at –70°C

- Improved low temperature electrolytes have translated into increased mission capability.
- Introduces possibility of powering survival mode of lander or rover to very low temperatures.

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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 +40ºC demonstrated
  – Improved electrolytes result in improved mission capability
  – Very low temperature capability may be beneficial to power survival mode
Acknowledgments

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