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**

### Specific Energy

![Specific Energy Graph]

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

### Energy Density

![Energy Density Graph]

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

### 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>
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<th>TECHNOLOGY DRIVER</th>
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<td>HIGH RATE PULSE CAPABILITY</td>
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<td>GEO S/C</td>
<td>TEN-TWENTY YEAR OPER. LIFE</td>
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<td>LARGE CAPACITY CELLS (50-200 Ah)</td>
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<td>LEO/PLANETARY S/C</td>
<td>LONG CYCLE LIFE (30,000)</td>
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<td>AIRCRAFT</td>
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<td>UAV</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 10°C (70% SOC)

Discharge Capacity (AHr) vs. Cell Voltage (V)

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 %

Storage After 20 Days | Storage After 11 Months

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<th>Last Discharge</th>
<th>1st Discharge</th>
<th>2nd Discharge</th>
<th>% of Initial</th>
<th>Permanent</th>
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<td>After Storage (Ahr) 23°C</td>
<td>After Storage (Ahr) 23°C</td>
<td>Capacity (Reversible Capacity)</td>
<td>Capacity Loss (%)</td>
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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)
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.

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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.
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)
Test Plan for the MSP01 Lithium-Ion Battery:
2009 Lander Mission Simulation Testing Plan

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
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

Yardney MSP01 8-Cell Lander Battery

Temperature = 20°C

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

Specific Energy (Watt-Hr/Kg)

Temperature = 20°C

Specific Energy (Watt-Hr/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)
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.

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

Temperature = 20°C

Discharge Capacity (Ahr)

Cell Voltage (V)

Battery Voltage (V)

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

End of Discharge

ΔV = 0.288 V

28.899 Ahr delivered at 20°C (32.0 V Charge or 4.00V/cell)
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 4.00V/cell)
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

Temperatue = 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
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications
Performance Characterization After Cruise (32.00 V Charge)

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

- 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)

Much higher capacities observed after cell balancing.

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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

ΔV = 0.179V

MSP01 8-Cell (25 Ahr) Lander Battery

ΔV = 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

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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
- **Discharge Capacity**: 12.00 AHr
- **Cell Voltage**: 3.429 V (Cell #1), 3.479 V (Cell #5)

**End of Discharge**: 0.050 V

**Total Charge Time**: 12 hours

**Charge Current**: 5.0 A

**Discharge Current**: 1.0 A

**Total Discharge Capacity**: 12.0 Ahr

**MSP01 8-Cell (25 AHr) Lander Battery**
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)

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)

**Battery/Cell Voltage and Current**

**Cell Dispersion During Charge**

**MER 8-Cell Rover Battery**
Chamber Temperature = 20°C
Charge Current = 0.80 A (C/10 Rate)
Charge Voltage = 32.80 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

Battery Voltage = 32.400 V

**FM3A**
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 –20ºC (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

* 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.

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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 LiPF₆ 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)

Percent of Initial Capacity (%) vs Cycle Number

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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 +40°C demonstrated
  - Improved electrolytes result in improved mission capability
  - Very low temperature capability may be beneficial to power survival mode
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