Performance Testing of Yardney Li-ion Cells and Batteries in Support of Future NASA Missions

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Outline

- Introduction
- Performance Testing for Mars Exploration Missions
  - Testing of MSP’01 Design Cells (25 Ah nameplate)
  - Testing of MER Design Cells (8 Ah nameplate)
  - LEO-type Cycling
  - Planetary Surface Operation Simulation
- Performance Testing for Future Outer Planets Missions
- Development of Advanced Chemistries
  - Wide Operating Temperature Range Systems
  - High Specific Energy Systems
- Conclusions
Demonstration of Life Characteristics for Past, Present and Future NASA Missions

- Performance testing of Li-ion cells and batteries has been performed for a number of NASA missions at JPL to demonstrate that the technology possesses the requisite life characteristics to meet all mission objectives.

- Due to the infancy of the technology and a limited data base, the earlier missions generally had shorter mission life requirements and had more emphasis upon performing life characterization testing.
  - 2001 MSP’01(1999) – 90 Sols and 2 year wet life
  - 2009 MSL Mission (2007) – 360 Sols and 3.5 year wet life
  - 2011 JUNO Mission (2011) – 7 year wet life (mostly cruise period)
  - Future Missions to the Outer Planets (i.e., Europa Orbiter)

- The adoption of Yardney Li-ion batteries for the MSL mission has been due to the heritage that has been established in previous missions (i.e., MSP’01 Lander, 2003 MER Rover, and 2007 Mars Phoenix Lander), and the corresponding data base that exists as a result of these missions.
Mission requirement was to deliver ~ 90 sols of operation on Mars (~ 2 year life)

- Battery fully space qualified prior to mission cancellation
- Ability to withstand launch environments.
- Demonstrated 10 month cruise storage capability (at cell level)
- Demonstrated Mars surface operational capability (at cell level)
  - Met EDL Performance Requirements
  - 50 A Pulse operations at 0°C.
  - > 300 simulated Sol operational capability at -20 to 40°C (testing continuing)
- Currently testing ATLO 8-cell ‘01 Lander battery according to ‘07 mission profile
Objectives
* Demonstrate the viability of using Lithium-Ion cell technology for future Lander missions.

Accomplishments:
* Subjected Yardney MSP’01 design lithium-ion cells to cruise storage period, EDL profile, and surface mission cycling profile.
* Cells retained > 95% of the original capacity after being stored for 11 months on the buss at 10°C and 70% SOC.
* Cells capable of withstanding EDL pulse profile with little polarization with > 3.4Vobserved per cell throughout profile.
* Cells successfully cycled for more than 1200 sols (after storage and EDL profile) according to Mars surface temperature profile.
* Minimal performance degradation observed with cells to-date.
* Goal is to demonstrate capability of completing > 1000 cycles.
* Further optimization of operating conditions can be performed to extend life characteristics.
Yardney Li-Ion Mars Battery Heritage

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

Mars Surface Operation Mission Simulation Test (MSP01 Profile)

- Subjected to cruise storage for 11 months prior to surface simulation (~ 5 years ago)
- Surface Operation Tested both under MSP 01 Lander as well as MSL profiles.
- Meets calendar life (wet life) needs of MSL
MSP’01 battery has completed 26,500 cycles at 40% DOD, with the discharge voltages in excess of 26 V (over five years of operation).

Test data above represent LEO-type cycling, consisting of 1.5 hour cycles at constant ambient temperature (charge voltage = 30.40V).
The battery required cell balancing only every 7,000 - 10,000 cycles during the course of cycling. The cells have been balanced 3 times since the initiation of the testing (i.e., the cells were manually resistively discharged to set voltage).
A number of tests have been performed on individual cells to determine the influence of temperature and depth of discharge on cycle life performance.

As expected, improved life is obtained when lower temperatures and lower depth of discharge is used.
Lithium-ion technology was used for ‘03 MER Rovers
Currently testing prototype cells to support mission

Rover Battery 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
Lithion 10 Ah Li-Ion Batteries for Mars Exploration Rover (MER)

Summary of Capacity and Energy of FM4B Measurements Prior to and After Cruise + 1010 Sols of Surface Operation

- Discharge capacity and energy determined with charging battery at room temperature
  - 100 % DOD Cycling (C/10 Charge to 32.40V, C/5 Discharge to 24.0V)
MER 8 Ah Rover Lithium-Ion Battery (FM4B)
Characterization After Cruise Period + 1010 Sols (Mission Simulation Battery)
Observed Capacity Loss After Completing Cruise + 1010 Sols

Approx. 14% capacity loss observed at 20°C since initiation of testing (> 5.00 years).

Capacity fade observed to be more dramatic at low temperature.
~ 39% Capacity fade observed at -20°C as a result of completing cruise period and 1010 sols under mission simulation conditions (24 V cut-off, C/5 Rate).

Values represent low temperature charging.
Lithion 10 Ah Li-Ion Batteries for Mars Exploration Rover (MER)
Current-Interrupt Impedance Measurements of FM4A
Impedance Measurements After Cruise + 1010 Sols of Surface Operation

Battery impedance at room temperature has roughly doubled since initiation of testing.
Lithion 10 Ah Li-Ion Batteries for Mars Exploration Rover (MER)

Current-Interrupt Impedance Measurements of FM4A

Impedance Measurements After Cruise + 1010 Sols of Surface Operation

- Somewhat slightly higher impedance rise was observed at 0°C.
Yardney Lithium-Ion Cells for Aerospace Applications

100% DOD Cycle Life Performance

Temp = 23°C

![Graph showing 100% DOD Cycle Life Performance at 23°C]

- Comparable cycle life performance obtained with a range of cell sizes fabricated by Lithion, Inc. (from 5 to 25 Ahr).

- Stable performance displayed when continuous cycling is performed at -20°C (lower capacity fade rate compared to room temperature).

Temp = -20°C

![Graph showing 100% DOD Cycle Life Performance at -20°C]

- Comparable cycle life performance obtained with a range of cell sizes fabricated by Lithion, Inc. (from 5 to 25 Ahr).

- Stable performance displayed when continuous cycling is performed at -20°C (lower capacity fade rate compared to room temperature).
In contrast to partial depth of discharge cycling, the impedance growth is much more dramatic when cycling full DOD (i.e., 3.0 to 4.10V).
2009 Mars Science Laboratory (MSL)

- **Launch:** Fall 2009
- **Science Goals:** To assess habitability: whether Mars ever was an environment able to support microbial life.
  - The biggest, most advanced suite of instruments ever sent to the martian surface.
  - Analyze dozens of samples scooped from the soil and cored from rocks in the onboard laboratory to detect chemical building blocks of life (e.g., forms of carbon) on Mars.
- **Landing:** Parachute assisted and power descent, lowered on tether like sky crane.
- **Programmatic Goals:**
  To demonstrate the:
  - Ability to land a very large, heavy rover to the surface of Mars (future Mars Sample Return)
  - Ability to land more precisely in a 20-kilometer (12.4-mile) landing circle
  - Long-range mobility (5-20 kilometers or about 3 to 12 miles)

**Battery Details**

- Two 8-cell batteries in parallel (8S2P).
- 30 V, 40 Ah (MER Chemistry)
- Qualification Temperature range: -30 to +40°C.
- **Life:** About 4 years
- **Cycle life:** ~ 2000 at partial DOD.
Lithium-Ion Cell/Battery Development
Performance Requirements for 2009 MSL Mission

- Operation for more than 40 months after launch and a calendar life of > 4 years.
- Consist of two Li-ion rechargeable batteries, each with a nameplate capacity rating of 20 Ah for redundancy.

Surface Operation Capability:
- Provide 670 cycles of up to 310 Wh at 0-30°C, with a 22 A max capability to 25V.
- Provide 670 cycles of up to 295 Wh at -20 to +30°C, with a 10 A max to 25V.
- Provide 670 cycles of up to 555 Wh at 0 to +30°C, with a 22 A max to 25V (only once per Martian sol).
- Possess capability of meeting the performance requirements with an average battery temperature of +15°C and an absolute maximum of +30°C on the surface of Mars.

Launch Capability:
- Provide capability of providing 920 Wh during launch at a battery temperature between 20 to +30°C with a 22 A maximum discharge current.

EDL Capability:
- Provide capability of supporting a 21 A load for 18 mSec (each battery).
- Support sequential (grouped) pyro events as close together as 120 mSec.
Yardney Li-ion 20 Ah Li-Ion Performance Testing
Discharge Rate Characterization at Different Temperatures

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Yardney Li-ion 20 Ah Li-Ion Performance Testing

Discharge Rate Characterization at 20°C

Discharge Capacity (Ah)

Discharge Energy (Wh/Kg)

- Discharge Rate = C/20 (1.00 A)
- Discharge Rate = C/10 (2.00 A)
- Discharge Rate = C/5 (4.00 A)
- Discharge Rate = C/2 (10.00 A)
- Discharge Rate = 0.75C (15.00 A)
- Discharge Rate = 1.00C (20.00 A)
Yardney Li-ion 20 Ah Li-Ion Performance Testing
Discharge Rate Characterization at -20°C

Discharge Capacity (Ah)  Discharge Energy (Wh/Kg)

Mars Science Laboratory (MSL) 20 Ahr Li-Ion Cell
MCMB - LiNi1/3Co1/3O2 Cell
ATLO Lot Cell

Discharge Rate = C/20 (1.00 A)
Discharge Rate = C/10 (2.00 A)
Discharge Rate = C/5 (4.00 A)
Discharge Rate = C/2 (10.00 A)
Discharge Rate = 0.75C (15.00 A)
Discharge Rate = 1.00C (20.00 A)
Yardney Li-ion 20 Ah Li-Ion Performance Testing
Charge Rate Characterization at +20°C

![Graph showing cell voltage and current over time]

**Mars Science Laboratory (MSL) 20 Ahr Li-Ion Cell**
MCMB - LiNi0.5C0.25O2 Cell
ATLO Lot Cell

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<td>MCMB - LiNi0.5C0.25O2 Cell</td>
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<tr>
<td>ATLO Lot Cell</td>
</tr>
</tbody>
</table>

**Table: Cell MSL-115**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Charge Rate</th>
<th>Discharge Current</th>
<th>Charge Capacity (Ah)</th>
<th>Charge Time (Hours)</th>
<th>Percent C/10 Capacity</th>
<th>Percent C/10 Capacity at 20°C</th>
<th>Charge Watt. Hrs (Wh)</th>
<th>Discharge Watt.Hrs (Wh)</th>
<th>Watt Hour Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C</td>
<td>0.05C</td>
<td>1.000</td>
<td>25.737</td>
<td>25.8159</td>
<td>100.00</td>
<td>100.00</td>
<td>94.0588</td>
<td>91.2645</td>
<td>97.03</td>
</tr>
<tr>
<td></td>
<td>0.10C</td>
<td>2.000</td>
<td>25.3177</td>
<td>12.8806</td>
<td>98.37</td>
<td>98.37</td>
<td>92.7204</td>
<td>91.2691</td>
<td>98.43</td>
</tr>
<tr>
<td></td>
<td>0.20C</td>
<td>4.000</td>
<td>25.1393</td>
<td>6.6795</td>
<td>97.68</td>
<td>97.68</td>
<td>92.4562</td>
<td>91.3611</td>
<td>98.82</td>
</tr>
<tr>
<td></td>
<td>0.50C</td>
<td>10.000</td>
<td>25.0397</td>
<td>3.1654</td>
<td>97.29</td>
<td>97.29</td>
<td>93.0827</td>
<td>91.3927</td>
<td>98.18</td>
</tr>
<tr>
<td></td>
<td>0.75C</td>
<td>15.000</td>
<td>24.9592</td>
<td>2.3275</td>
<td>96.98</td>
<td>96.98</td>
<td>93.4732</td>
<td>91.1826</td>
<td>97.55</td>
</tr>
<tr>
<td></td>
<td>1.00C</td>
<td>20.000</td>
<td>24.9395</td>
<td>1.9474</td>
<td>96.90</td>
<td>96.90</td>
<td>94.0112</td>
<td>91.1418</td>
<td>96.95</td>
</tr>
</tbody>
</table>
Yardney Li-ion 20 Ah Li-Ion Performance Testing
Charge Rate Characterization at + 20°C

Charge Capacity (Ah)

1.0C Rate Charge

Charge Capacity (Ah) and Cell Voltage (V)

Mars Science Laboratory (MSL) 20 Ahr Li-Ion Cell
MCMB - LiNi0.8Co0.2O2 Cell
ATLO Lot Cell

Charge Rate = 0.05C (1.00 A)
Charge Rate = 0.10C (2.00 A)
Charge Rate = 0.20C (4.00 A)
Charge Rate = 0.50C (10.00 A)
Charge Rate = 0.75C (15.00 A)
Charge Rate = 1.00C (20.00 A)

Chamber Temperature = 20°C

20.0 Amp Charge Current (1.0 C) to 4.16 V
0.400 Amp taper current cut-off (C/50)
C/10 Discharge Rate (2.00 A) to 2.50 V

Charge Current (A)

Cell MSL115
Cells were capable of being charged at high rates at low temperatures, without any evidence of lithium plating observed.
Battery Requirements

- Voltage: 24-32
- Capacity: 6-8 Ah
- Cycle Life: < 400
- Calendar Life: 6-8 Years
- Sp. Energy: > 100 Wh/kg
- Energy Density: >240 Wh/l

Technology Challenges

- Long Calendar Life
- Radiation Tolerance

➢ Demonstrated Li-ion resilience to radiation
A number of cells stored on the bus at 50% SOC at different temperatures.

- Cells cycled at both 23 and 0°C every 3 months to determine reversible capacity.
- Less than 10% capacity loss observed with cells if stored at temperatures of 10°C or less.

Tests on-going for further validation of projections.
Current interrupt impedance measurements performed every three months (starting in 2005)
- Initial value taken from similar 7 Ah cell measured under identical conditions
- Modest increase in impedance observed and less dramatic at mid-SOC
- Good cell to cell reproducibility
Performance Testing of Aerospace Quality Prototype Li-Ion Cells

Performance of Ester-Based Electrolytes at Low Temperatures

• Obtained a number of high power 7 Ah cells fabricated by Yardney Technical Products containing JPL developed Low temperature electrolytes:

  1.0 M LiPF_6 EC+EMC+MP (20:60:20 v/v %)
  1.0 M LiPF_6 EC+EMC+EP (20:60:20 v/v %)
  1.0 M LiPF_6 EC+EMC+EB (20:60:20 v/v %)
  1.0 M LiPF_6 EC+EMC (20:80 v/v %)
  1.0 M LiPF_6 EC+DEC+DMC+EMC (1:1:1:3 v/v %)
  1.0 M LiPF_6 EC+DEC+DMC (1:1:1 v/ %) (Baseline - 2003 MER Rover Electrolyte)

Test Plan

• Performed a number of performance evaluation tests
  • Conditioning cycling performed at 20°, 0°, and -20° C (with impedance)
  • Discharge Rate Characterization at Various Temperatures
    ▪ Wide temperature range (-80 to 20°C)
    ▪ Wide range of discharge rates (C rate to C/400 rate)
    ▪ Comparison of electrolyte types
  • Pulse Discharge Characterization at Various Temperatures
  • Current-Interrupt Impedance Measurements
Ester co-solvents greatly improve the performance at these very low temperatures (-60°C).

Discharge capacity (Ah) and discharge energy (Wh/Kg) at -40°C, using a C/2 rate discharge (3.50 A), of prototype 7 Ah lithium-ion cells containing electrolytes consisting of 1.0M LiPF$_6$ EC+EMC+X (20:60:20 v/v %) (where X = MP, EP, and EB), as well as cells with baseline all carbonate-based electrolytes.
Discharge capacity (Ah) and discharge energy (Wh/Kg) at -40°C, using a C rate discharge (7 A), of prototype 7 Ah lithium-ion cells containing electrolytes consisting of 1.0M LiPF₆ EC+EMC+X (20:60:20 v/v %) (where X = MP, EP, and EB), as well as cells with baseline all carbonate-based electrolytes.
The methyl propionate-based electrolyte was observed to result in cells with high specific energy at -40°C, with over 75 Wh/kg being delivered at a C/5 rate.
Yardney 7 Ah Prismatic Li-Ion Cells
Characterization of Cells Containing Advanced Electrolytes
100 % DOD Cycle Life Testing at Room Temperature
Discharge Capacity (Ah) at 20°C

Cells containing ester-based electrolyte also display good cycle life characteristics, being comparable to the all carbonated based systems at room temperature.
Cells containing the “next generation” electrode chemistry display higher specific energy (~ 140 Wh/kg). Values anticipated to be much higher in larger capacity cell (> 25 Ah size).
SUMMARY and CONCLUSIONS

• **Performance testing of large capacity Li-ion cells have been demonstrated to have excellent life characteristics**
  – 25 Ah battery has completed over 26,500 cycles under 40% DOD LEO test.
  – 25 Ah battery has completed over 500 cycles under Mars surface operation profile.
  – MSP’01 cells have completed 1,600 cycles under Mars surface operation profile.
  – Ground testing MER RBAU has completed > 1,100 sols with < 15% loss in capacity.
  – Cells have been stored for over 7 years with > 10% loss in capacity.
  – MSP’01 cells have completed 1,600 cycles under Mars surface operation profile.

• **Prototype cells for MSL has been demonstrated to have good performance characteristics.**
  – Good discharge rate capability is observed over a wide range of temperature.
  – Good charge rate capability observed, even at low temperatures.

• **Demonstrated improved performance with advanced chemistries**
  – Improved low temperature performance is observed with cells containing electrolytes possessing ester co-solvents.
  – High energy designs appear to be very promising, displaying comparable cycle life characteristics compared to the baseline materials.
Acknowledgments

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA) for the 2009 Mars Science Laboratory Project, 2003 Mars Exploration Rover Project, and the NASA-Exploration Systems Mission Directorate (ESRT).