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

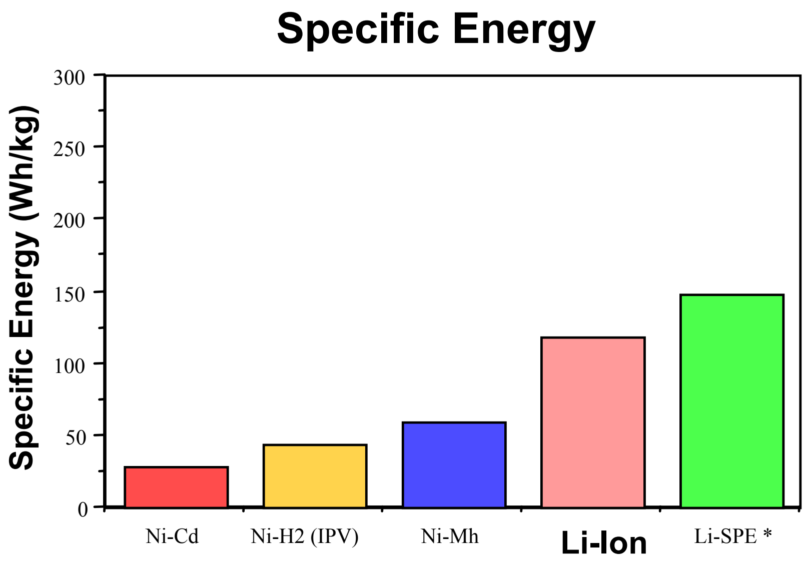
- Assess viability of using lithium-ion technology for future NASA applications, with emphasis upon Mars landers and rovers which will operate on the planetary surface.

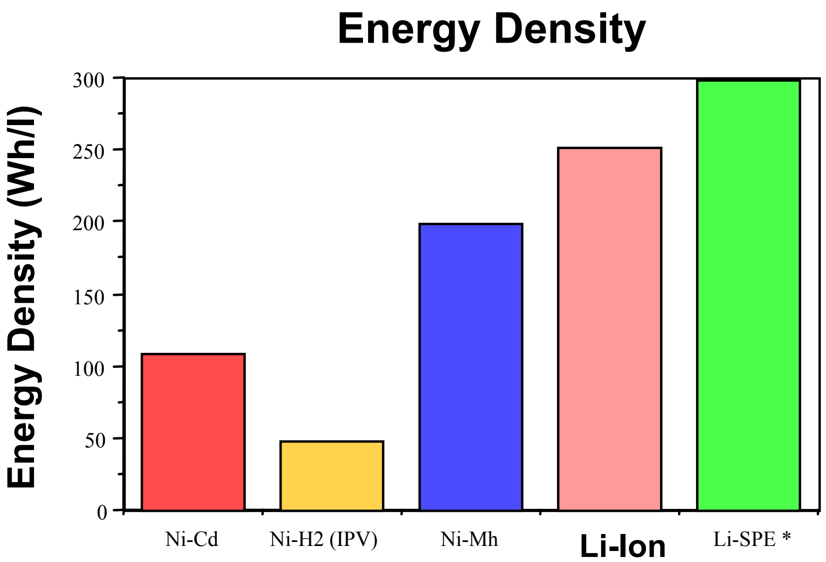
- Support the JPL 2003 Mars Exploration Rover program to assist in the delivery and testing of a 8 AHr Lithium-Ion battery (Lithion/Yardney) which will power the rover.

- 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-H_2 BATTERY MASS
  - 200-230 kg MASS SAVINGS FOR 8-10 kW GEO PAYLOADS
- REDUCED POWER SYSTEM VOLUME
  - 25 % OF Ni-Cd/Ni-H_2 BATTERY VOLUME
  - SIMPLER POWER SYSTEM INTEGRATION
- LOWER LAUNCH COSTS
  - REDUCED POWER SYSTEM WEIGHT
  - REDUCED SOLAR ARRAY SIZE
- ENHANCE SMALL SPACECRAFT MISSIONS

Technology Challenges/Drivers

MISSION	TECHNOLOGY DRIVER
LANDER/ROVER	LOW TEMP. OPERATION HIGH RATE PULSE CAPABILITY
GEO S/C	TEN-TWENTY YEAR OPERT. LIFE LARGE CAPACITY CELLS (50-200 Ah)
LEO/PLANTERARY S/C	LONG CYCLE LIFE (30,000) MED. CAPACITY CELLS (50 Ah)
AIRCRAFT	LOW TEMP OPERATION HIGH VOLTAGE BATTERIES (270 V)
UAV	LARGE CAPACITY CELLS (200 Ah) HIGH VOLTAGE BATTERIES (100V)

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

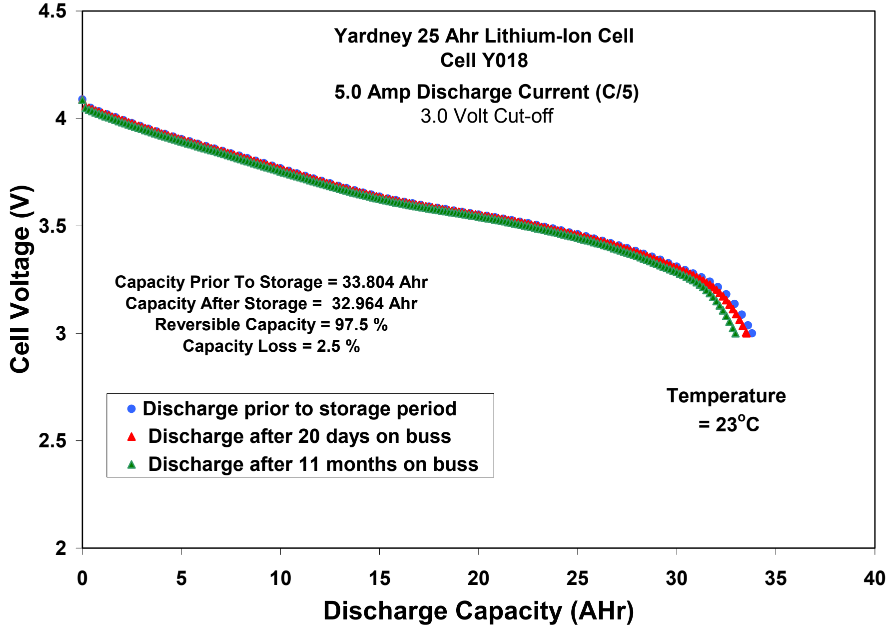
Possible Evaluation Criteria**:**

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

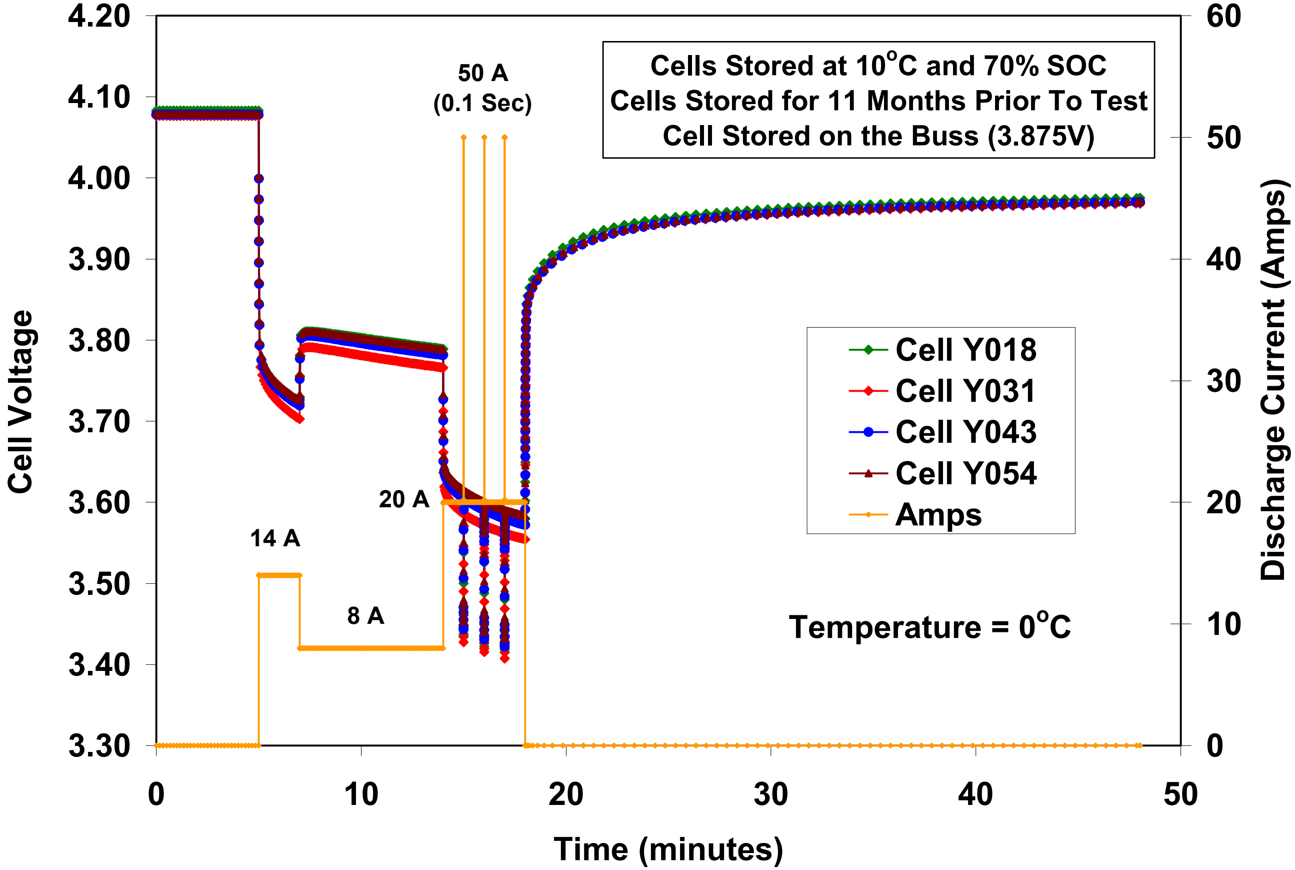
Cells Stored on the Buss at 10°C (70% SOC)



	Last Discharge Prior to Storage (Ahr)	Storage After 20 Days: 1st Discharge After Storage (Ahr) 23°C	Storage After 20 Days: 2nd Discharge After Storage (Ahr) 23°C	Storage After 20 Days: % of Initial Capacity (Reversible Capacity)	Storage After 20 Days: Permanent Capacity Loss (%)	Storage After 11 Months: 1st Discharge After Storage (Ahr) 23°C	Storage After 11 Months: 2nd Discharge After Storage (Ahr) 23°C	Storage After 11 Months: % of Initial Capacity (Reversible Capacity)	Storage After 11 Months: Permanent Capacity Loss (%)
Y018	33.804	26.034	33.523	99.169	0.831	25.6252	32.9636	97.515	2.485
Y031	33.962	25.959	33.534	98.738	1.262	29.059	32.266	95.006	4.994
Y043	34.153	25.445	32.788	96.005	3.995	25.639	32.999	96.622	3.378
Y054	33.727	25.922	33.460	99.210	0.790	25.478	32.917	97.599	2.401

Yardney 25 Ah Lithium-Ion Cells for Mars Lander Applications

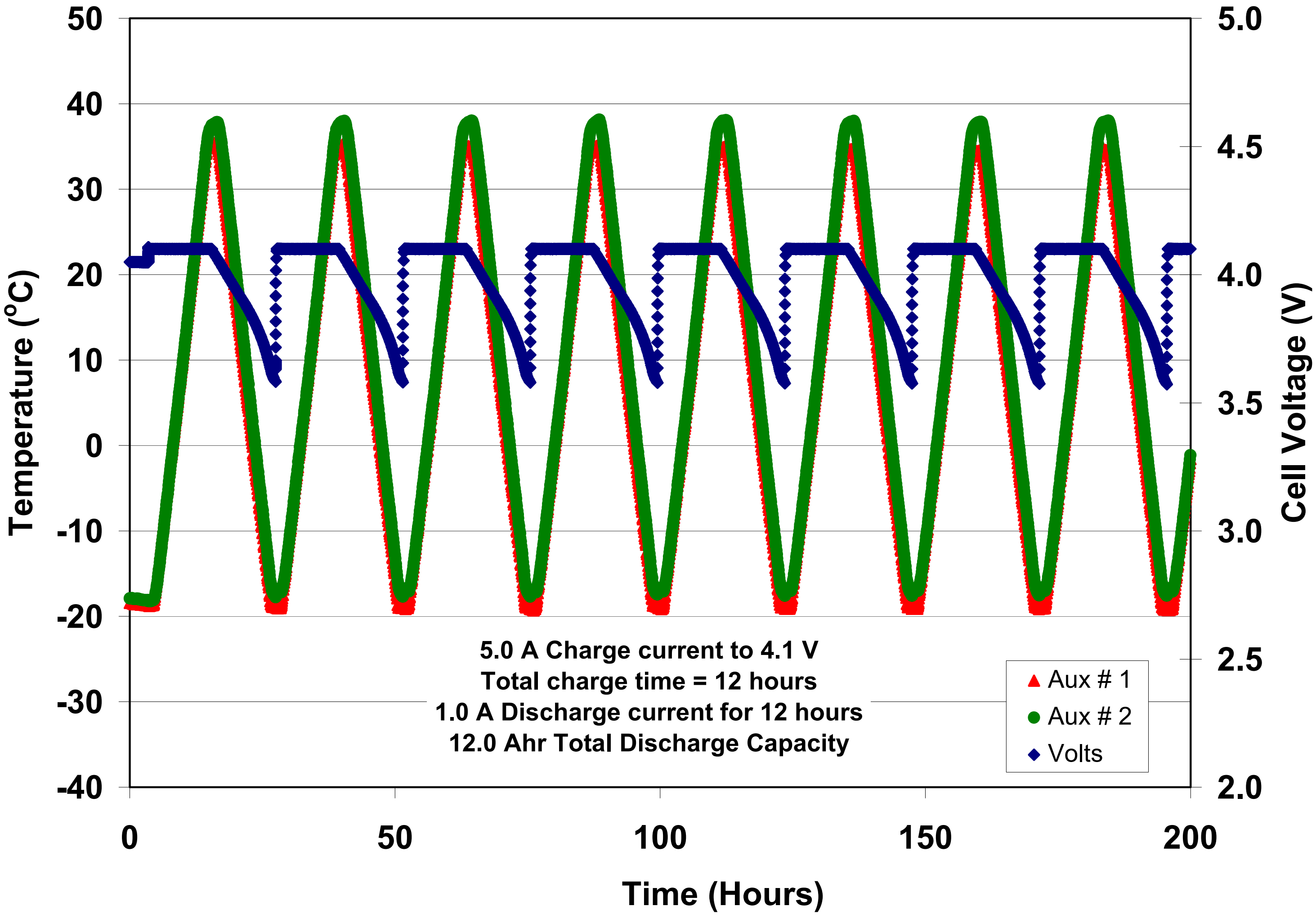
EDL Discharge Profile Simulation of MSP01 Design Cells



- 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

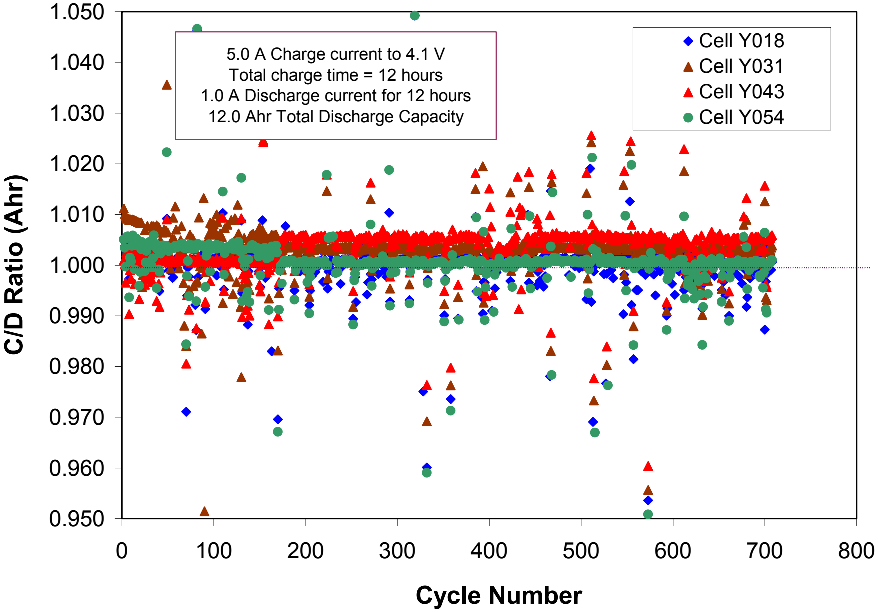
Mission Simulation Cycling (Temperature Range = - 20 to +40^oC)



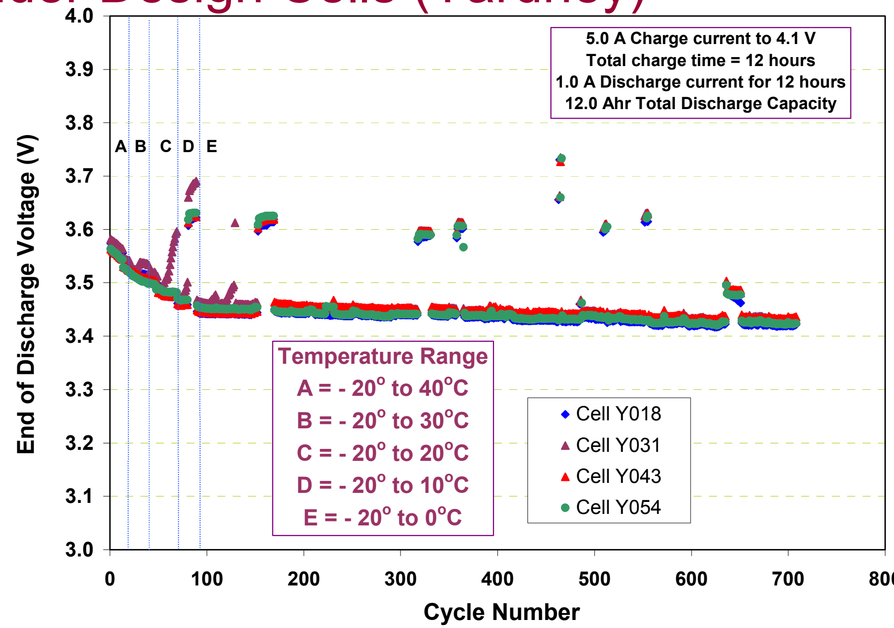
Lithium Ion Technology Demonstration for Future Smart Lander Missions

Lander Surface Operation Mission Simulation Performance Test

2001 MSP01 Surveyor Lander Design Cells (Yardney)



Charge-Discharge Ratio (AHr)



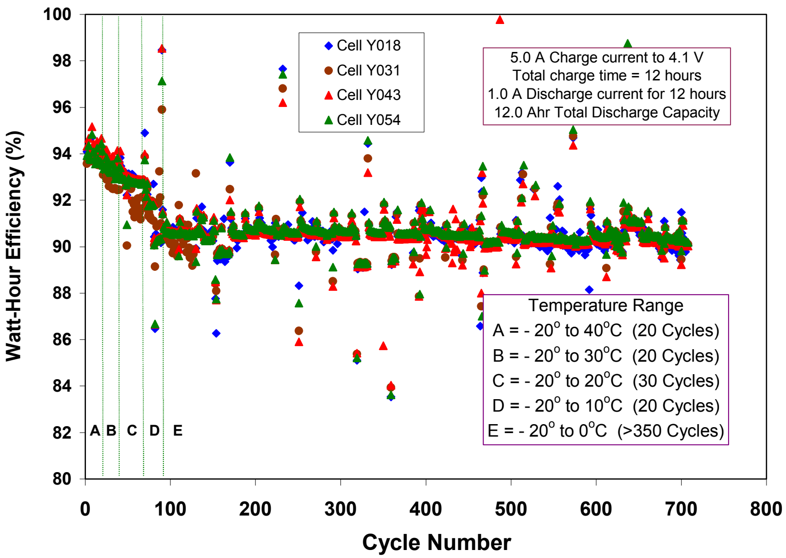
End of Discharge Voltage (EODV)

- **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)**

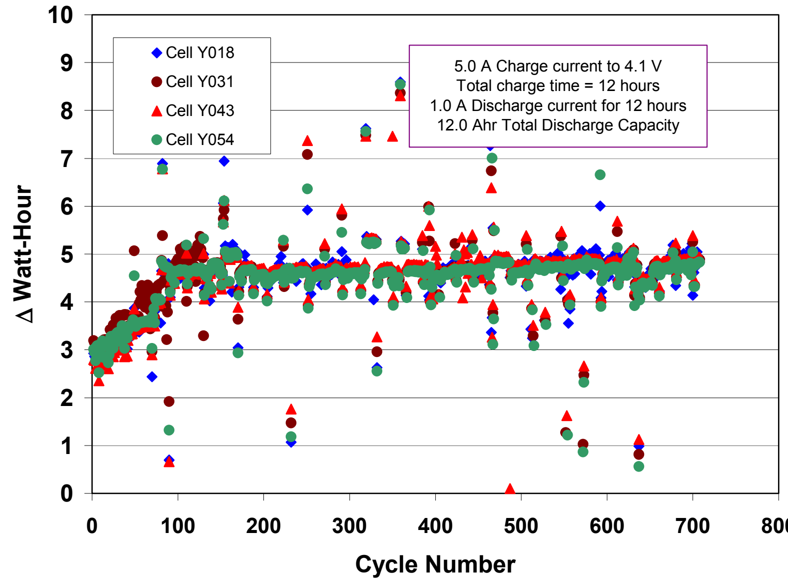
Lithium Ion Technology Demonstration for Future Smart Lander Missions

Lander Surface Operation Mission Simulation Performance Test

2001 MSP01 Surveyor Lander Design Cells (Yardney)



Watt-Hour Efficiency



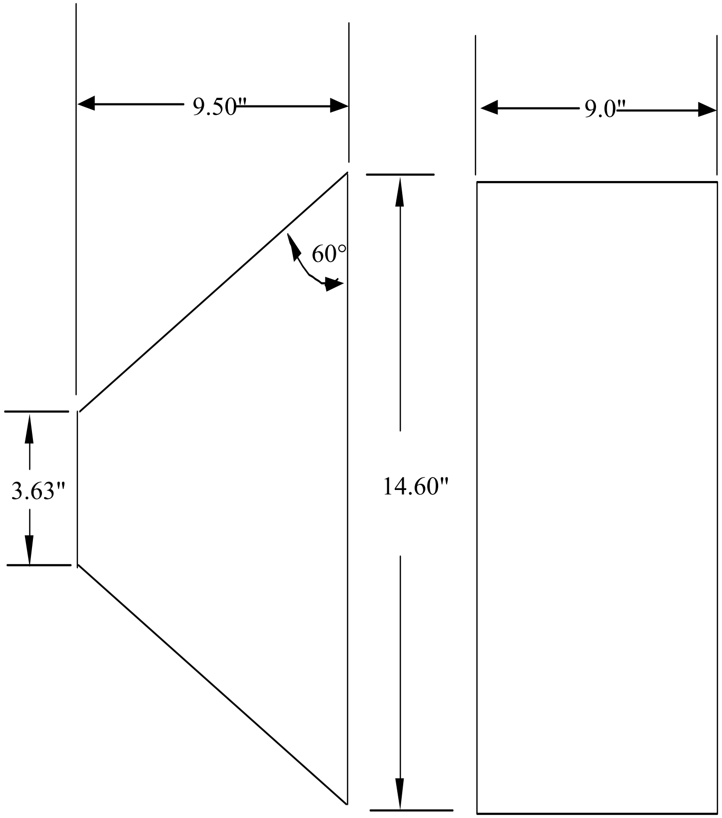
Δ Watt-Hour

- 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



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^{o}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 inividual 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 20ºC (determination of storage impact)
- Charge battery using C/5 discharge rate to 32.8 V
- Soak battery for 24 hours at 0ºC
- 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

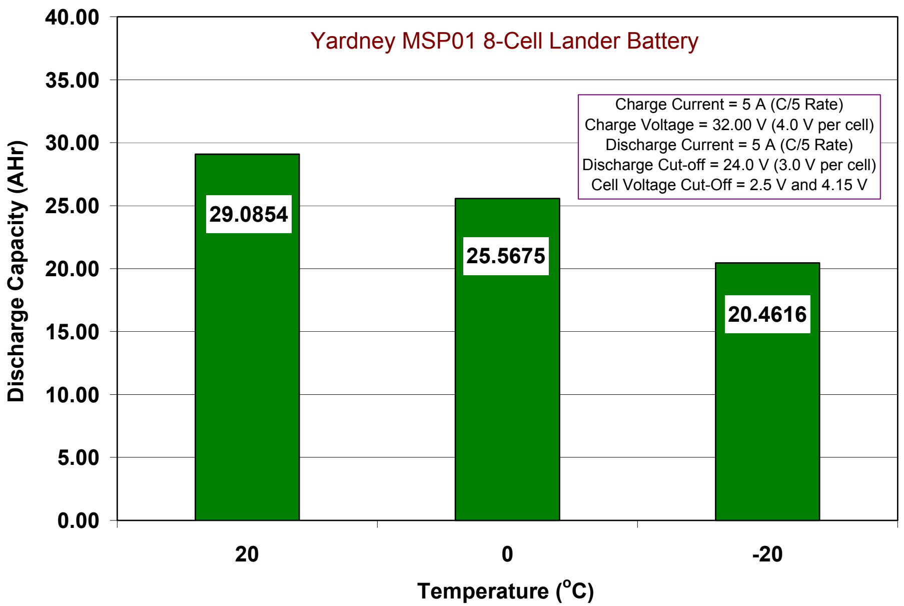
8.0 Post Mission Characterization

- More detailed pulse characterization
- More detailed rate characterization as a function of temperature

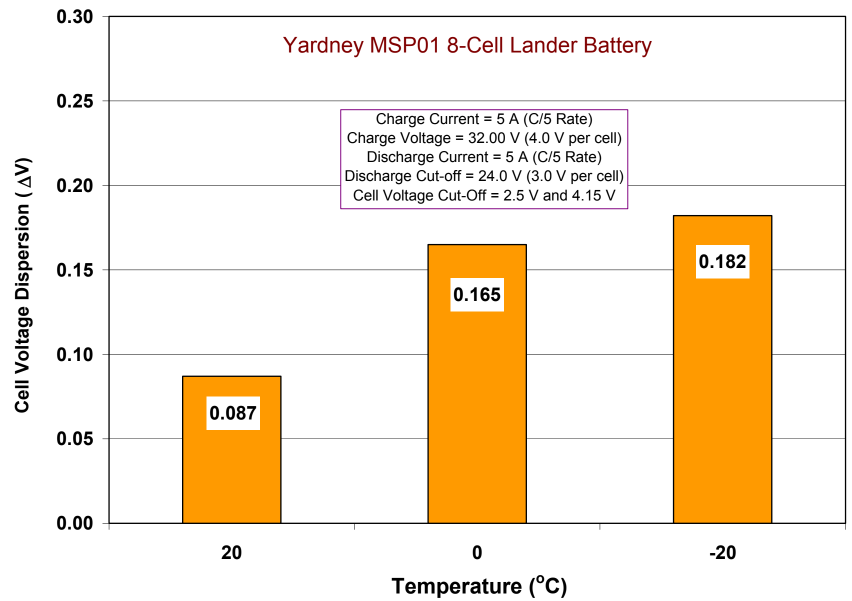
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at Different Temperatures

32.0 V Charge - Discharge Capacity (AHr) at Various Temperatures



Discharge Capacity (AHr)



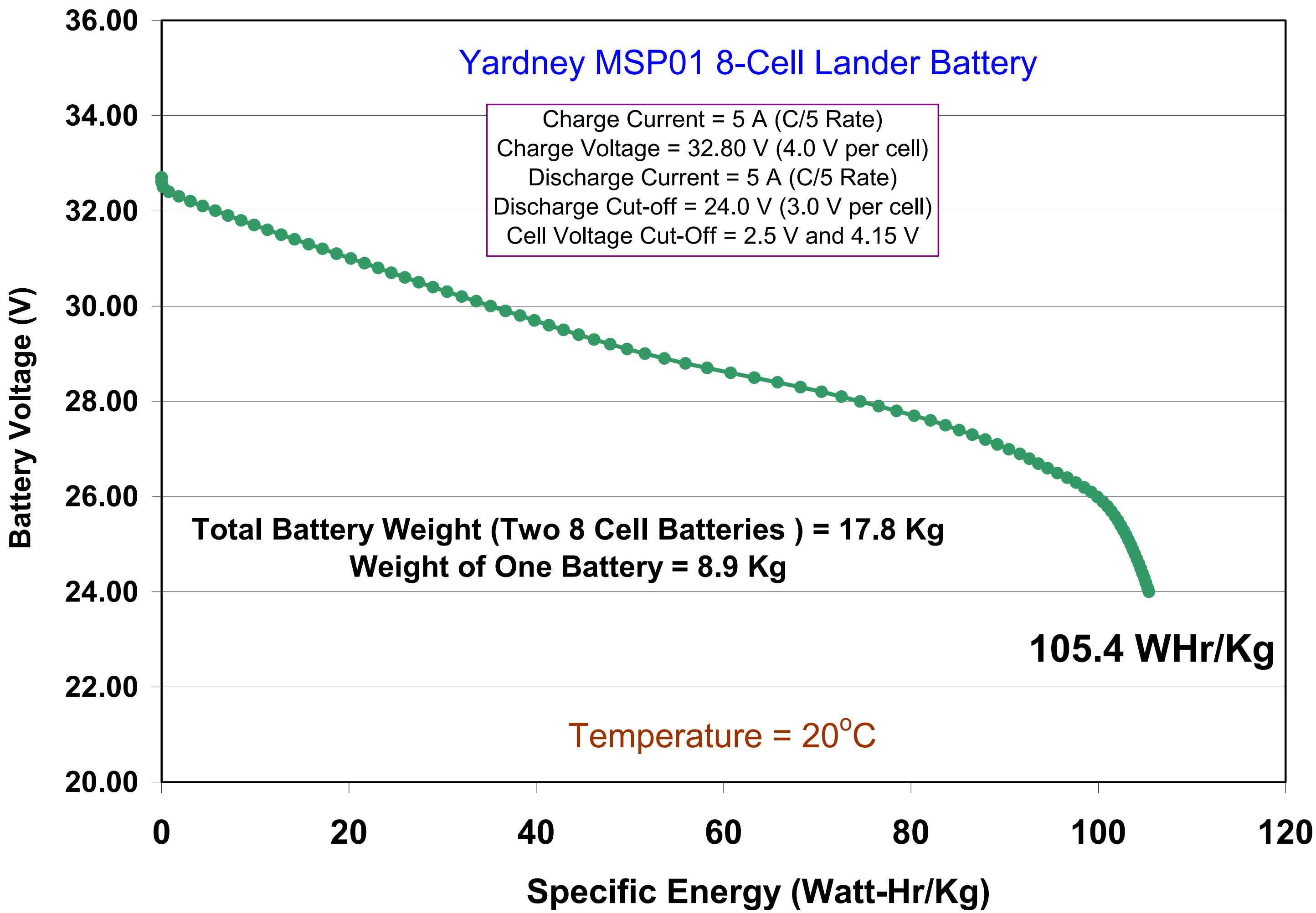
Cell Voltage Dispersion (ΔV)

- 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

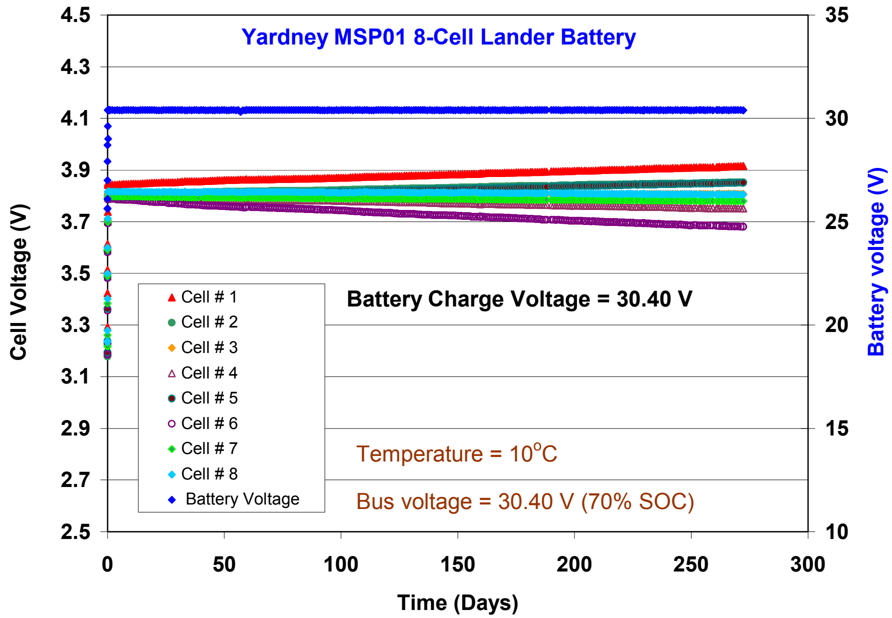
After Cell Balancing – 32.8 V Charge

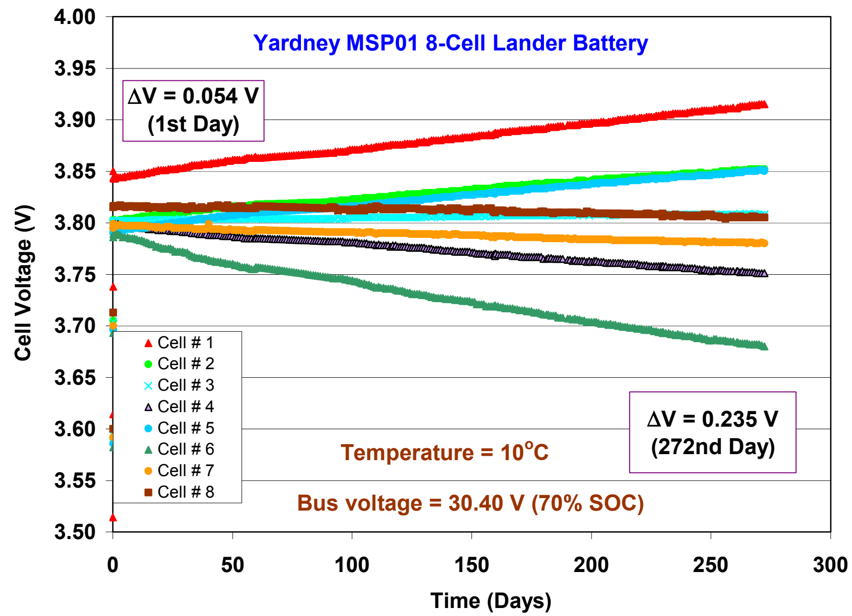


Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Cruise Storage Simulation (Bus Voltage = 30.40 V at 10°C)

Battery and Cell Voltages During Storage (~ 9 months)



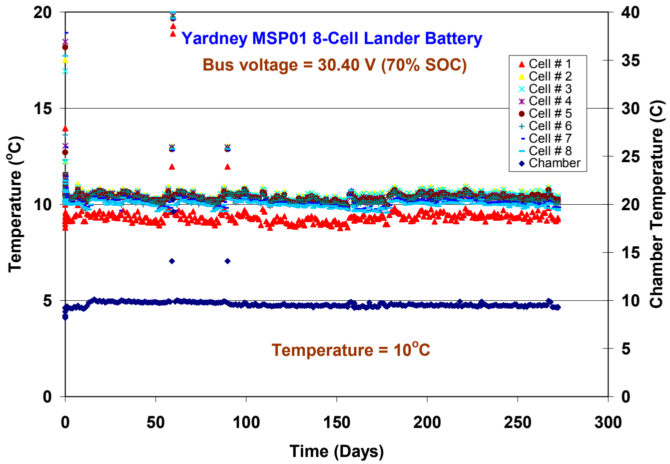


- Cells balanced prior to storage test
- Cell dispersion potential issue depending upon charge methodology

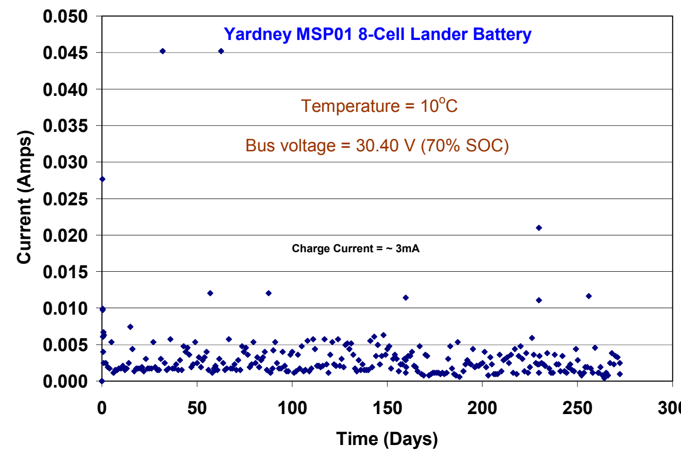
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Cruise Storage Simulation (Bus Voltage = 30.40 V at 10°C)

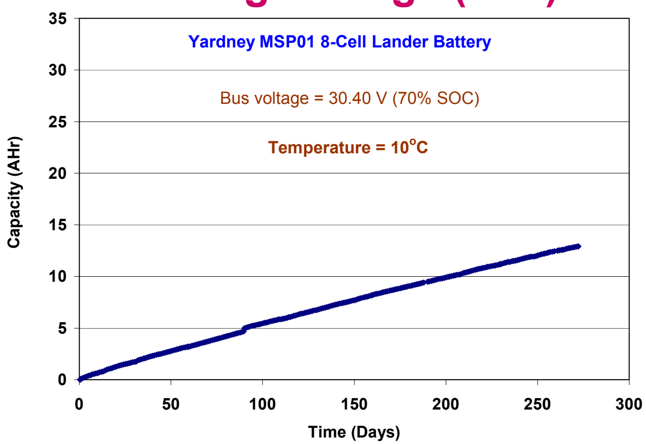
Cell and Chamber Temperatures (°C)



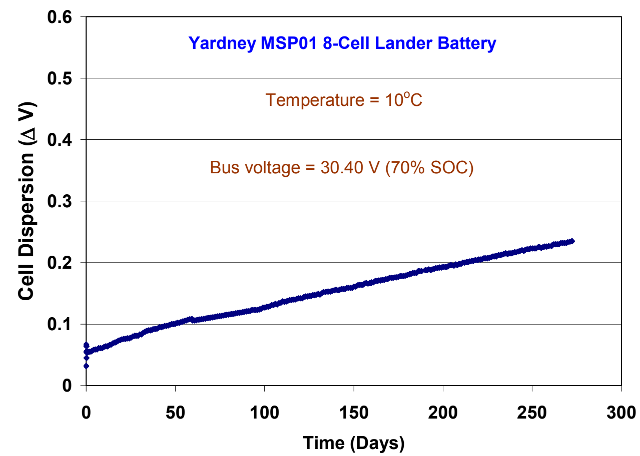
Charge current (A)



Cumulative Charge Capacity During Storage (AHr)



Cell Dispersion During Storage (ΔV)

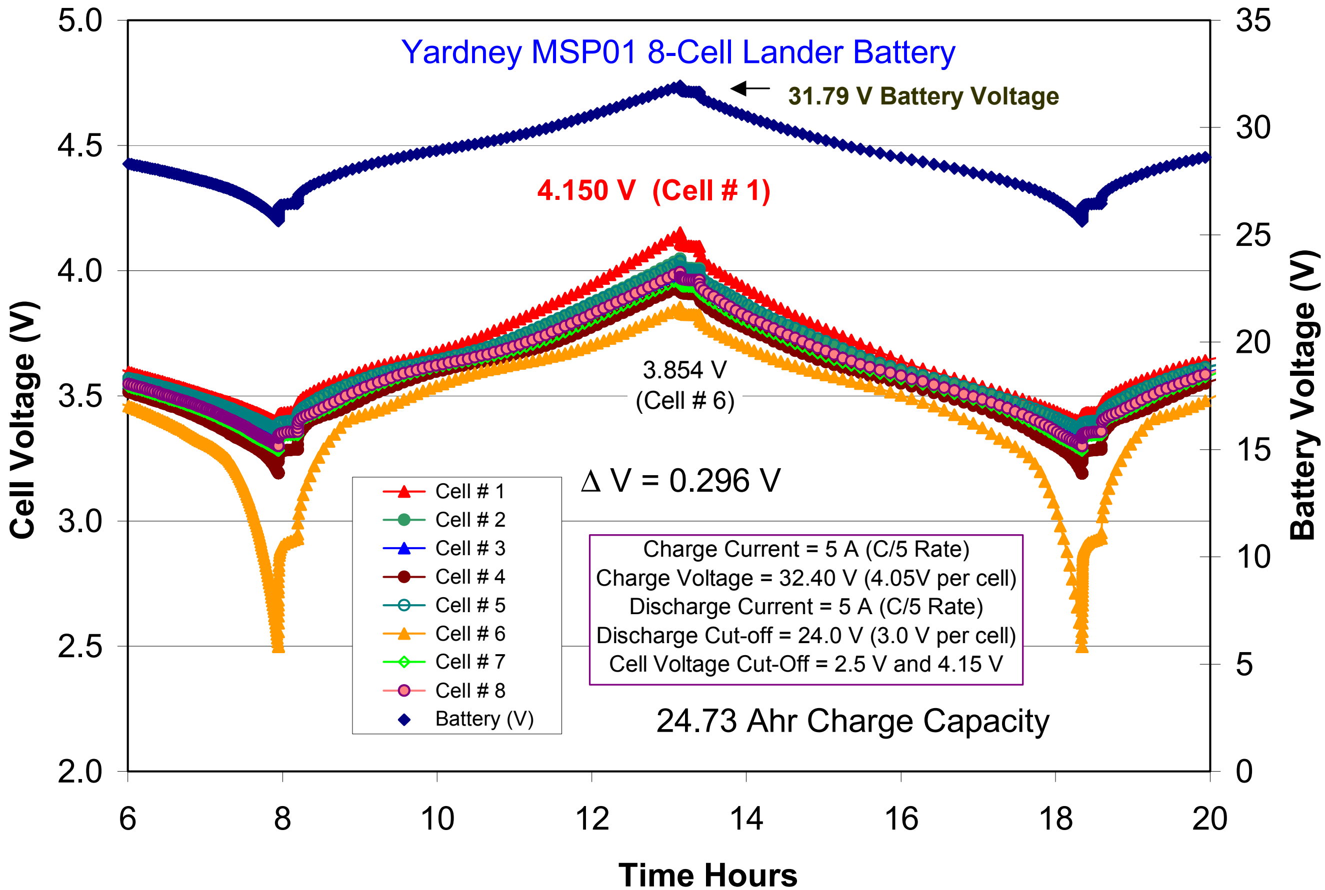


Electrochemical Technologies Group

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



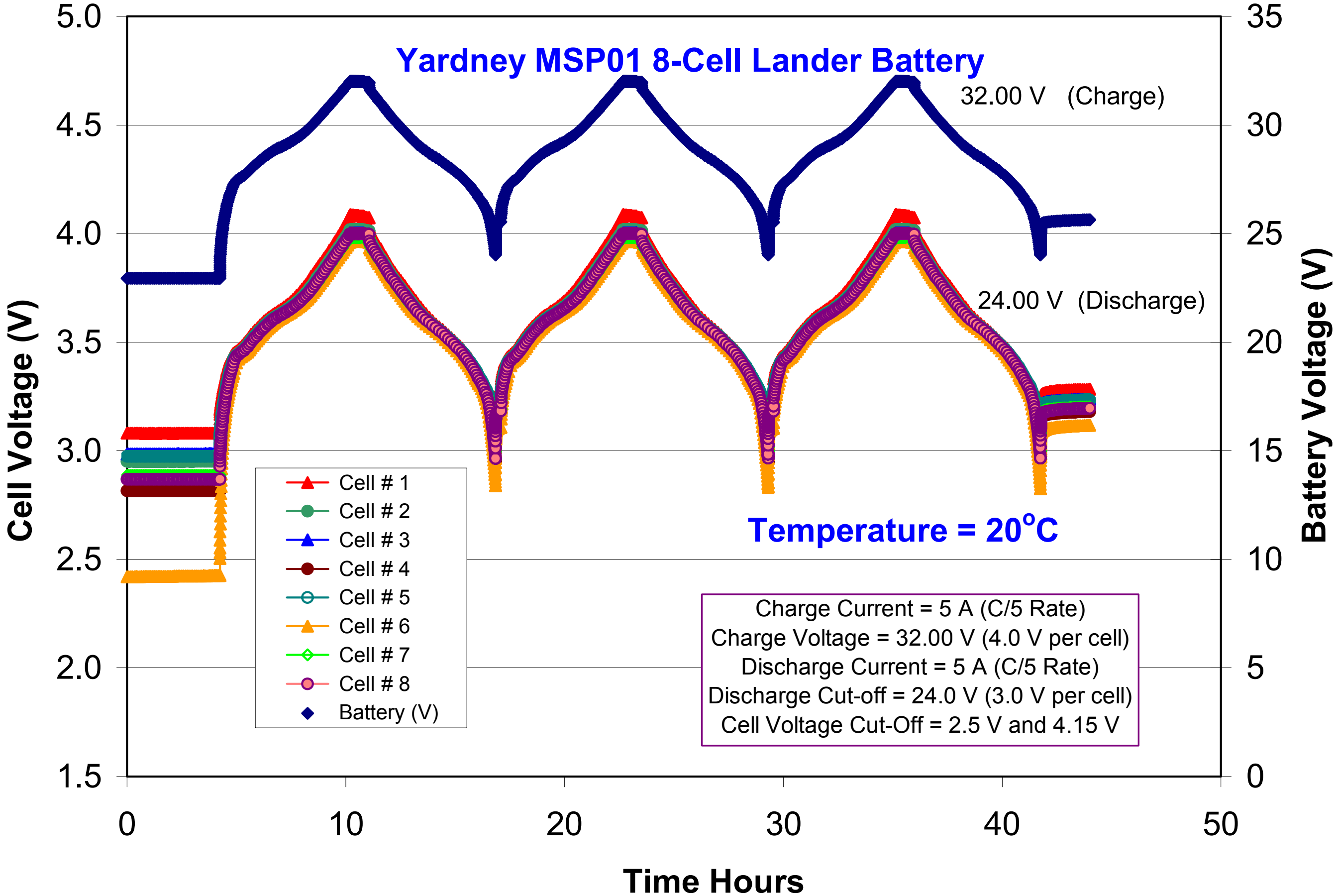
- Due to cell imbalance, battery was not fully charged after storage (24.73 AHr)
- Cell #1 terminated charge prior to reaching 32.40 V battery charge voltage

Electrochemical Technologies Group

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

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

After Cell Balancing

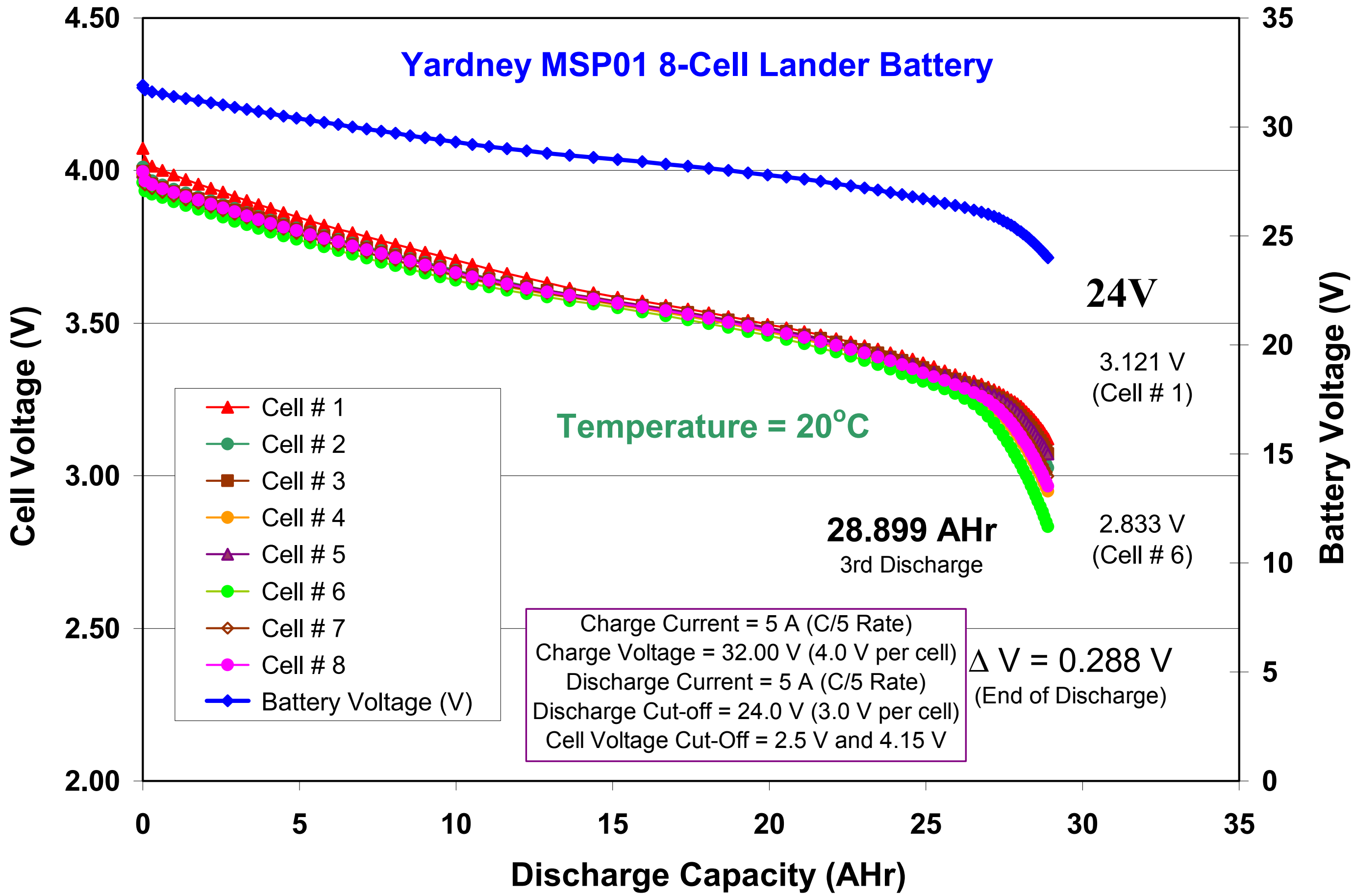


- After cell balancing cell dispersion characteristics were improved.

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

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

After Cell Balancing

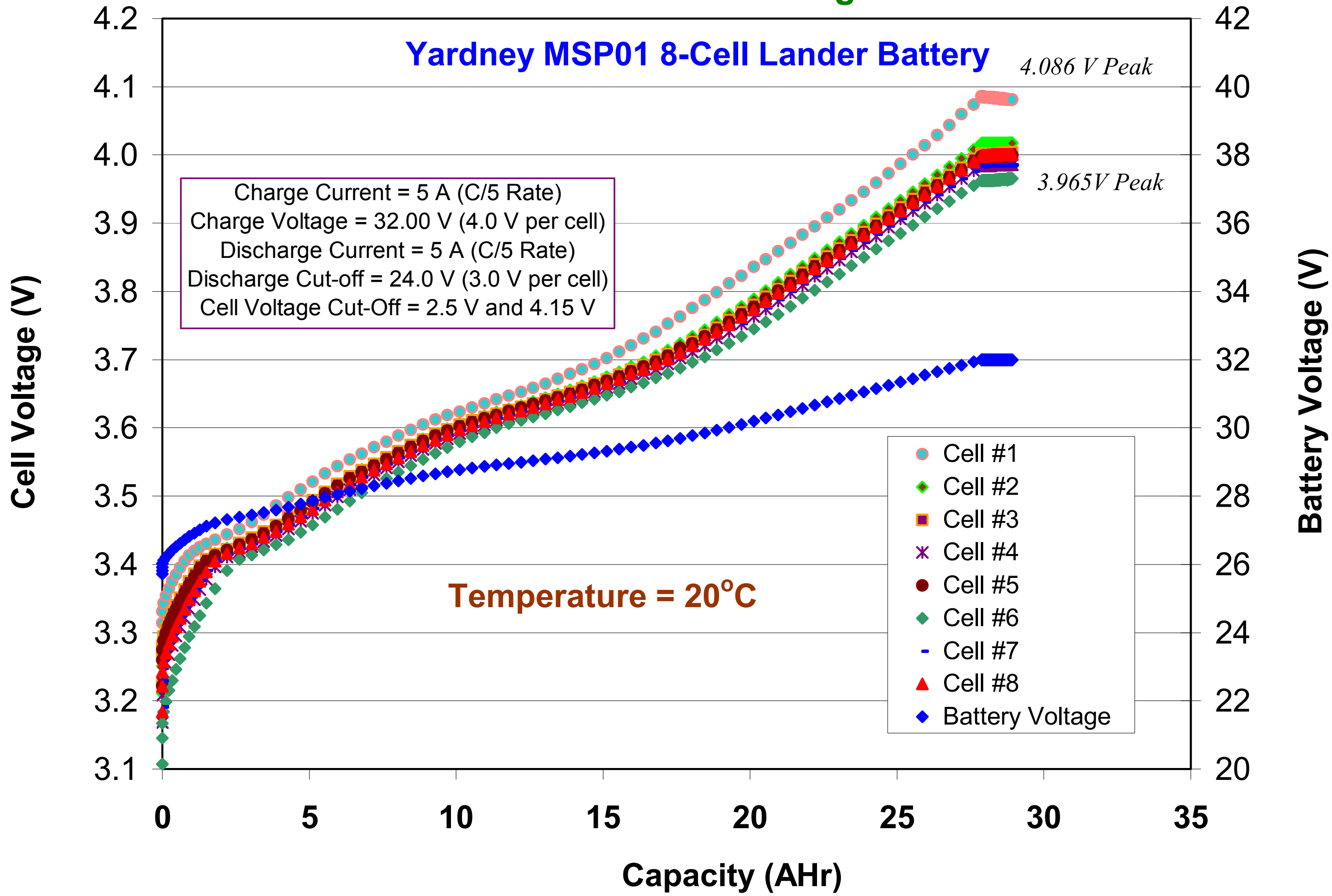


- After cell balancing, battery was able to be cycled effectively between prescribed voltage limits (24V – 32V)
- 28.90 Ahr delivered at 20°C (32.0 V Charge or 4.00V/cell)

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

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

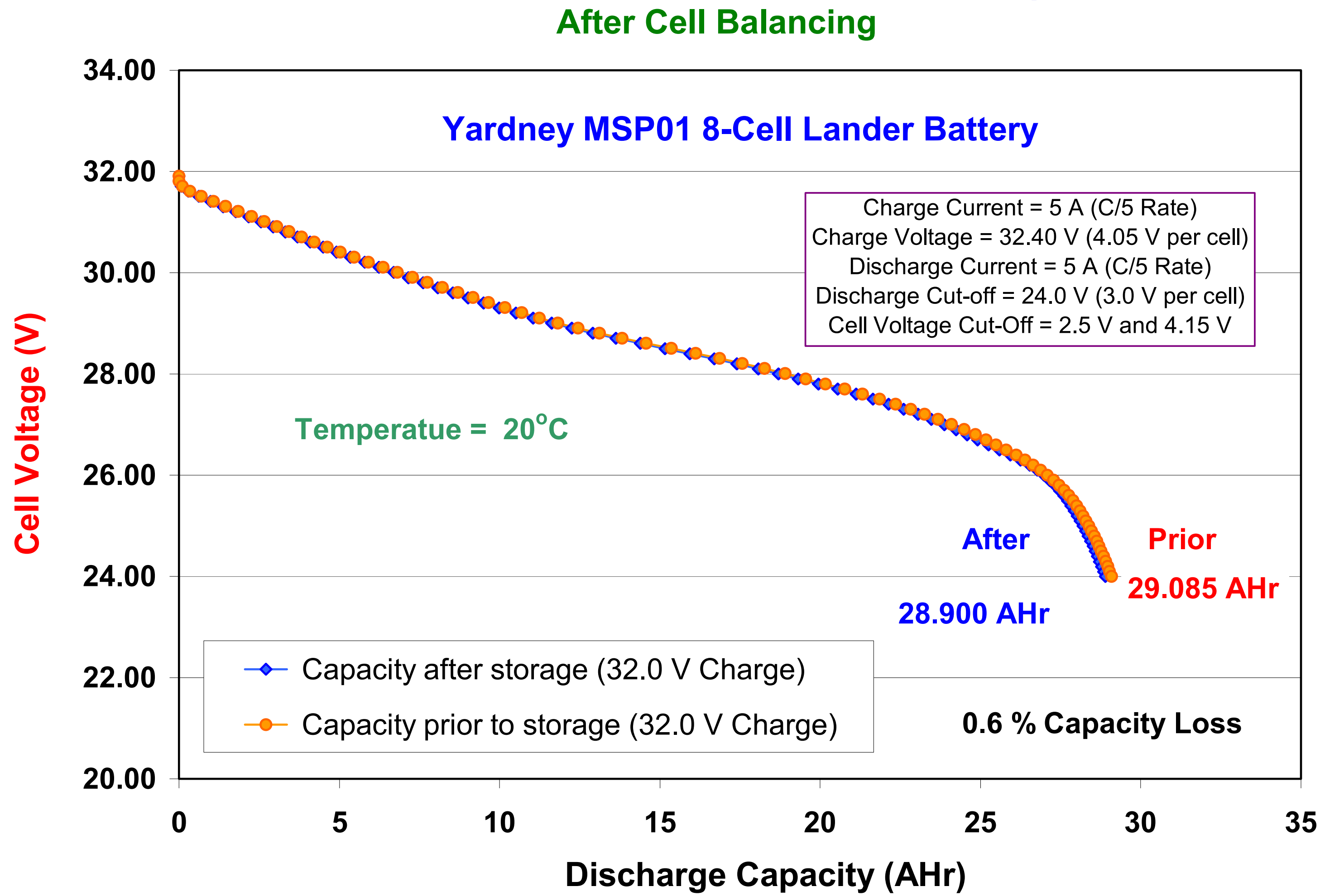
After Cell Balancing



- 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)

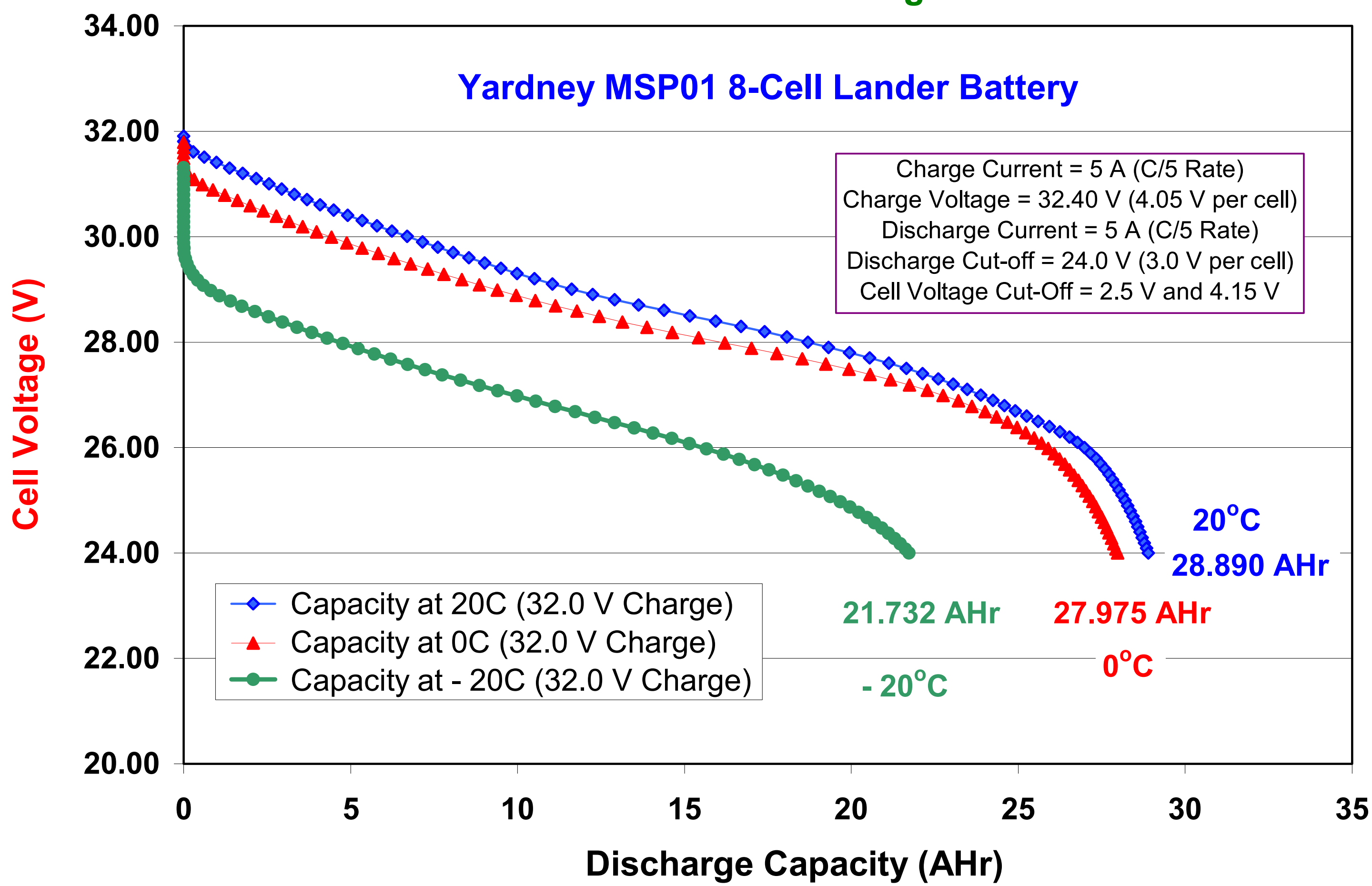


- Very little capacity loss observed due to the cruise storage period

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

Performance Characterization After Cruise (32.00 V Charge)

After Cell Balancing

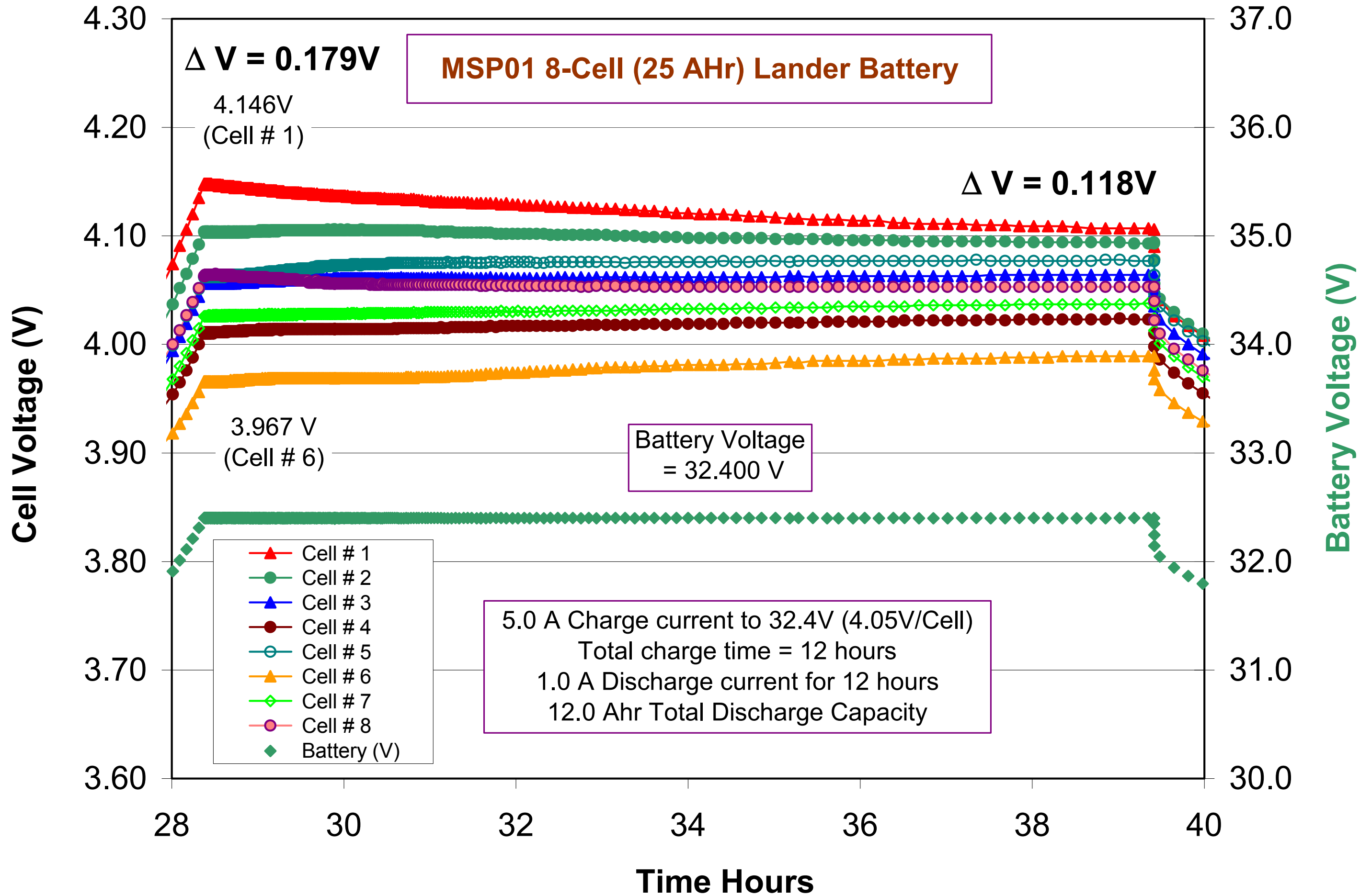


- Much higher capacities observed after cell balancing.

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

Mars Surface Operation Mission Simulation Test (MSP01 Profile)

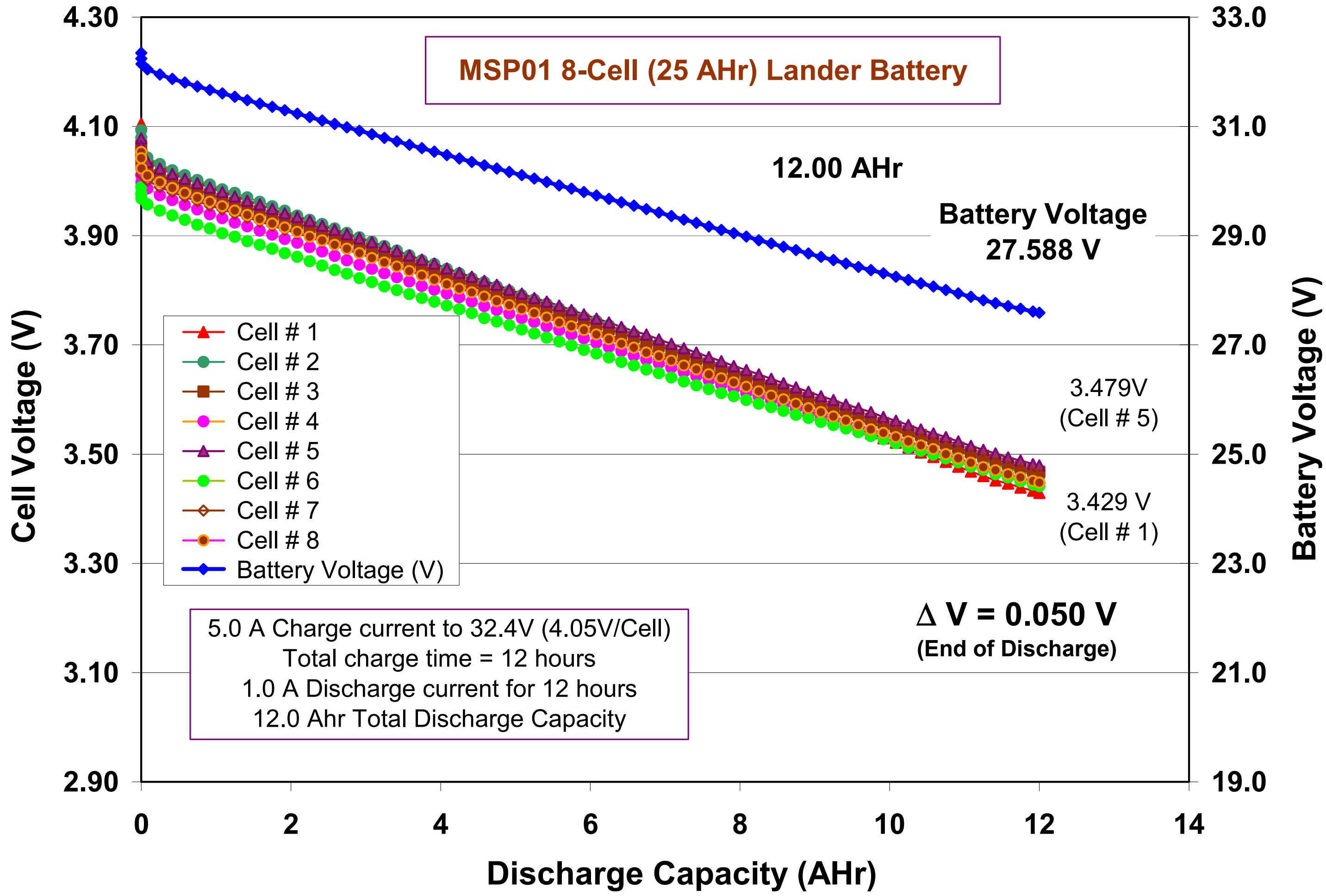
1st Full Charge (32.4 V Charge) – Cell Dispersion Characteristics



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

Mars Surface Operation Mission Simulation Test (MSP01 Profile)

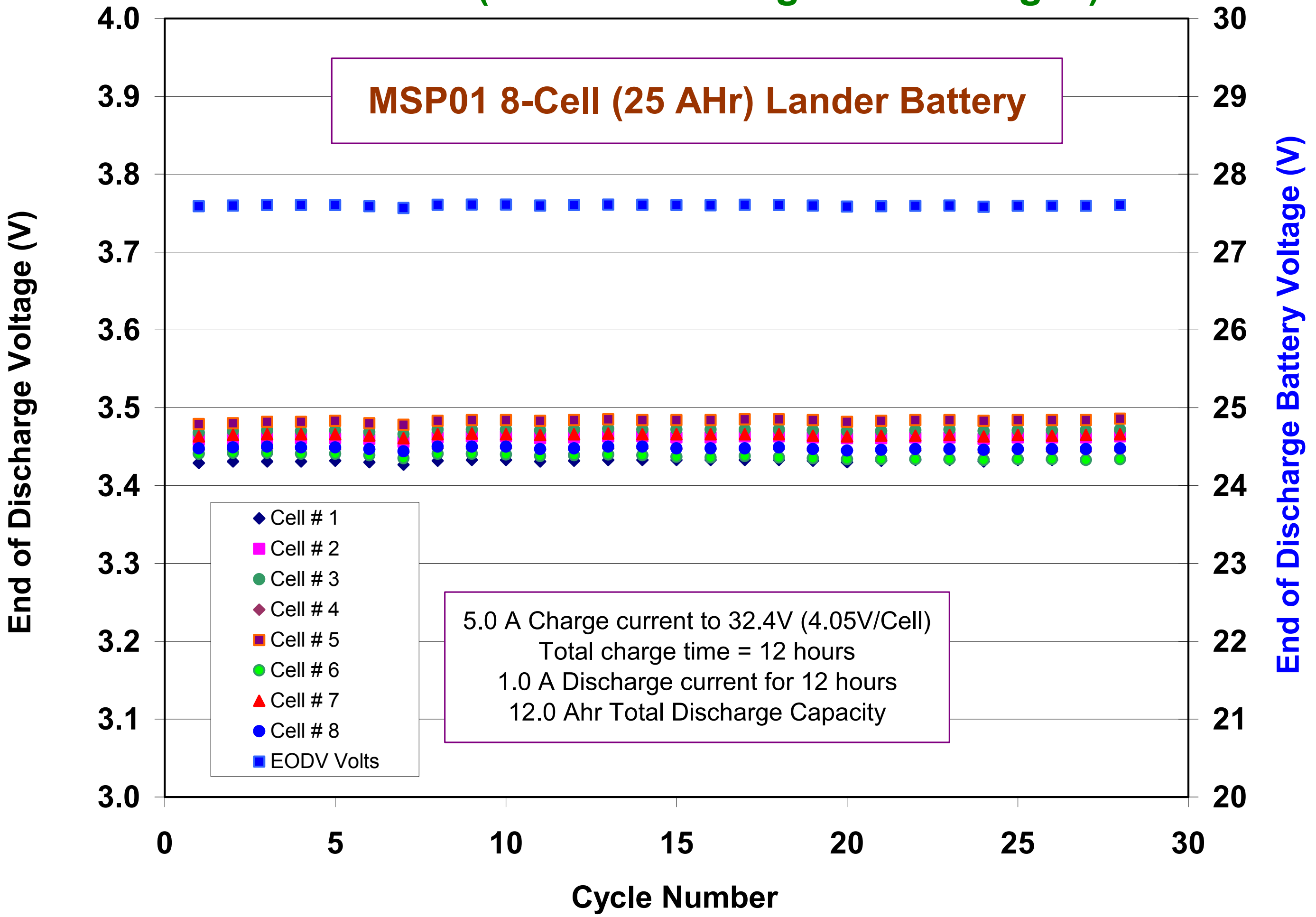
Typical Discharge (12 AHr – C/25 Rate)



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

Initial Characterization/Conditioning at Different Temperatures

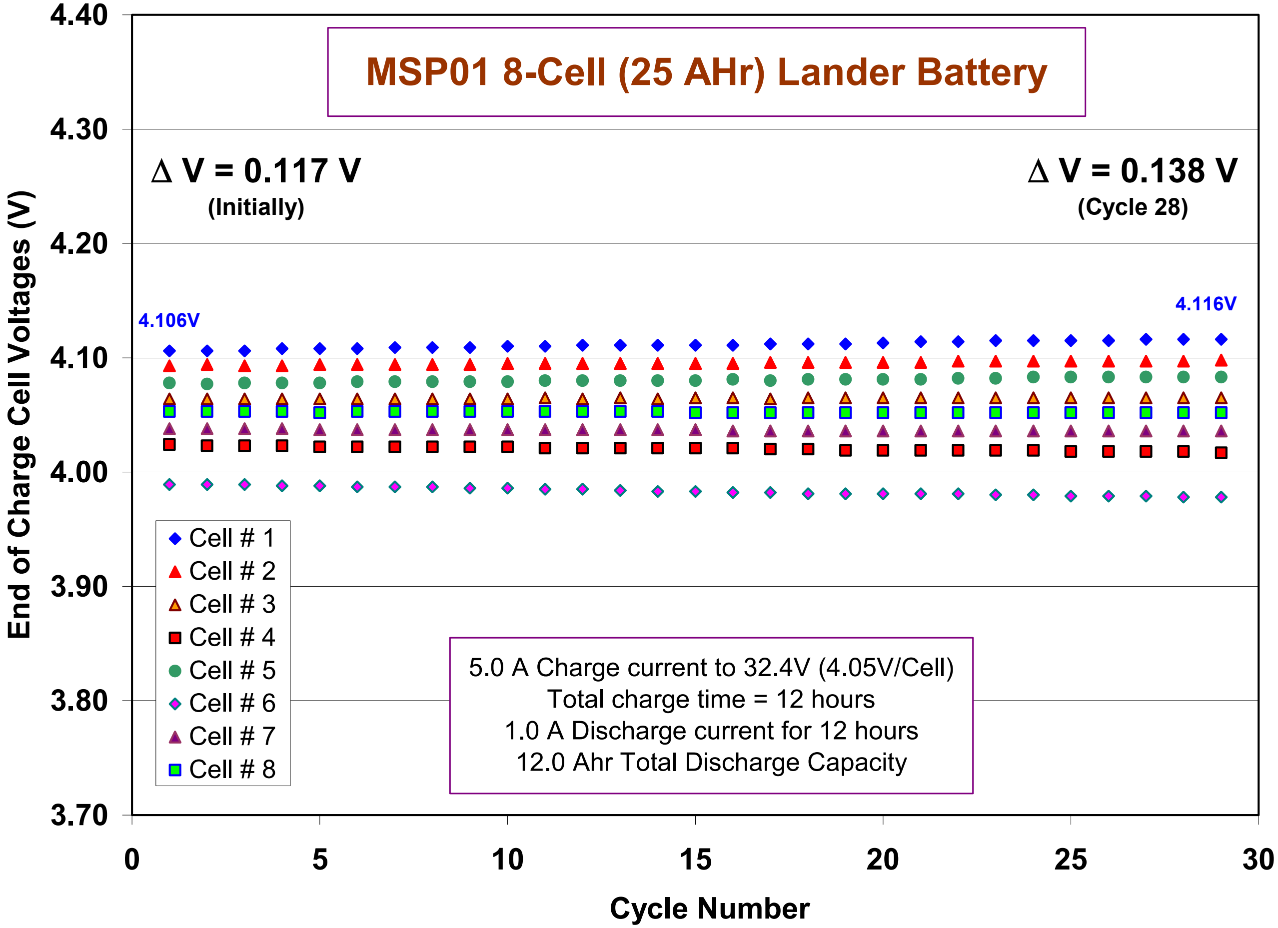
First 28 Sols (End of Discharge Cell Voltages)



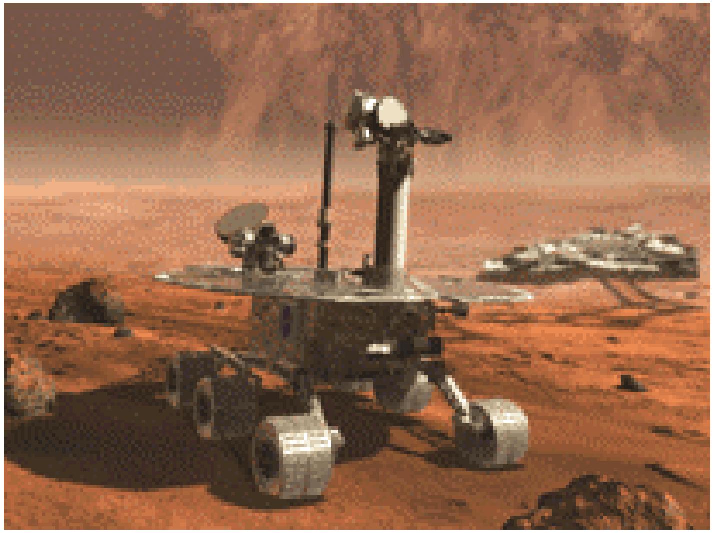
Yardney MSP01 25 Ah Lithium-Ion Battery for Mars Lander Applications

Initial Characterization/Conditioning at Different Temperatures

First 28 Sols (End of Charge Cell Voltages)



2003 MARS Exploration Rover Secondary Battery



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

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.

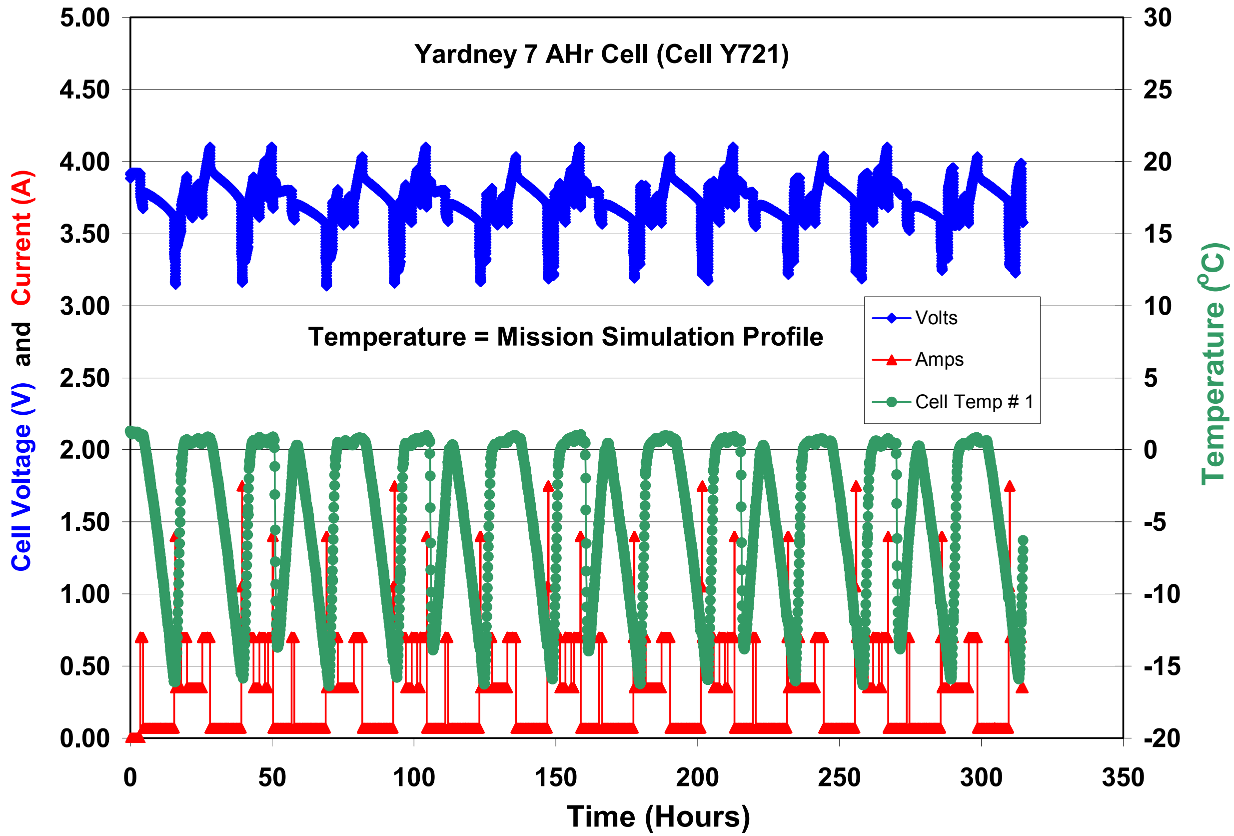
Mission Requirements

- Voltage : 32-24 V
- Capacity: 16 Ah (BOL) at RT and 10 Ah at –20^{o}C (BOL)
- Load : C/2 max at RT; Typical C/5
- Temperature : Charge at 0-25^{o}C and discharge >-20^{o}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

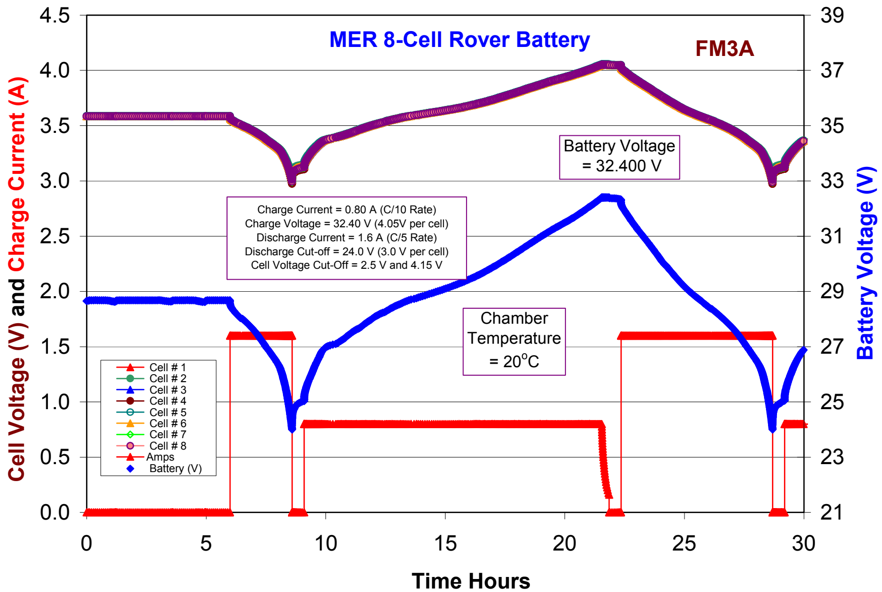
Mission Simulation Temperature Profile



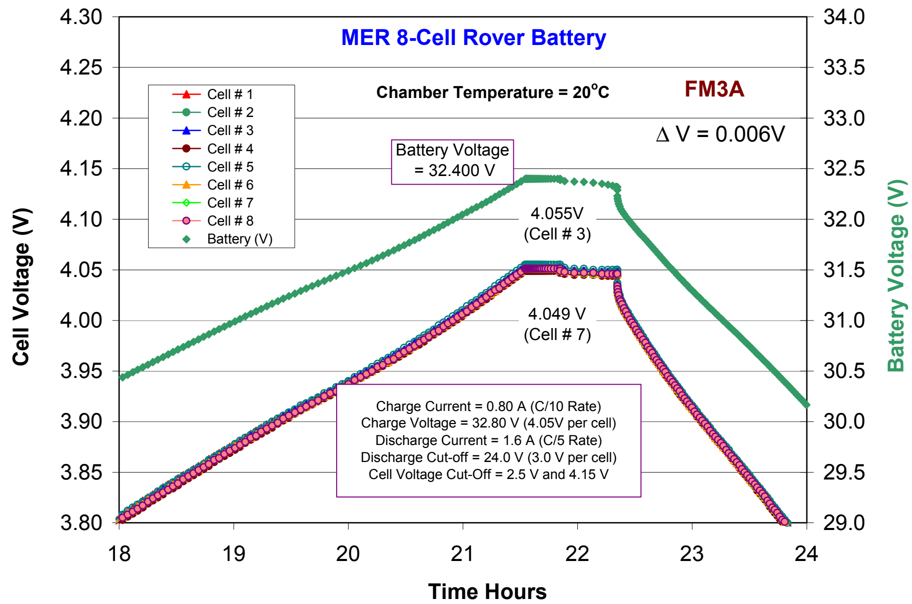
- Environmental temperature range = 0 to –20^{o}C
- Battery will be charged by solar array during the daytime (~ 0^{o}C charge)
- Data represents first 8 sols of operation on the surface of Mars

MER 10 Ah Rover Lithium-Ion Battery (FM3A)
Initial Characterization/Conditioning at 20°C

Battery/Cell Voltage and Current

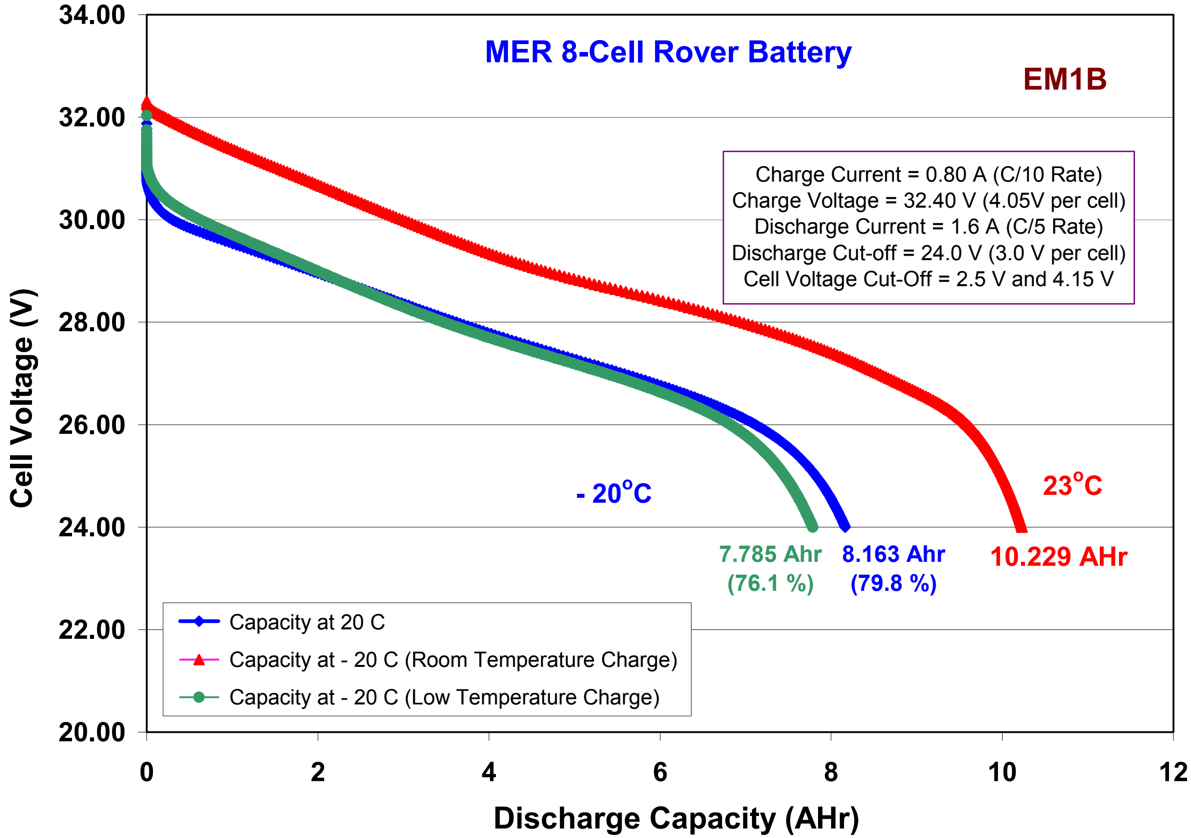


Cell Dispersion During Charge



- 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)

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

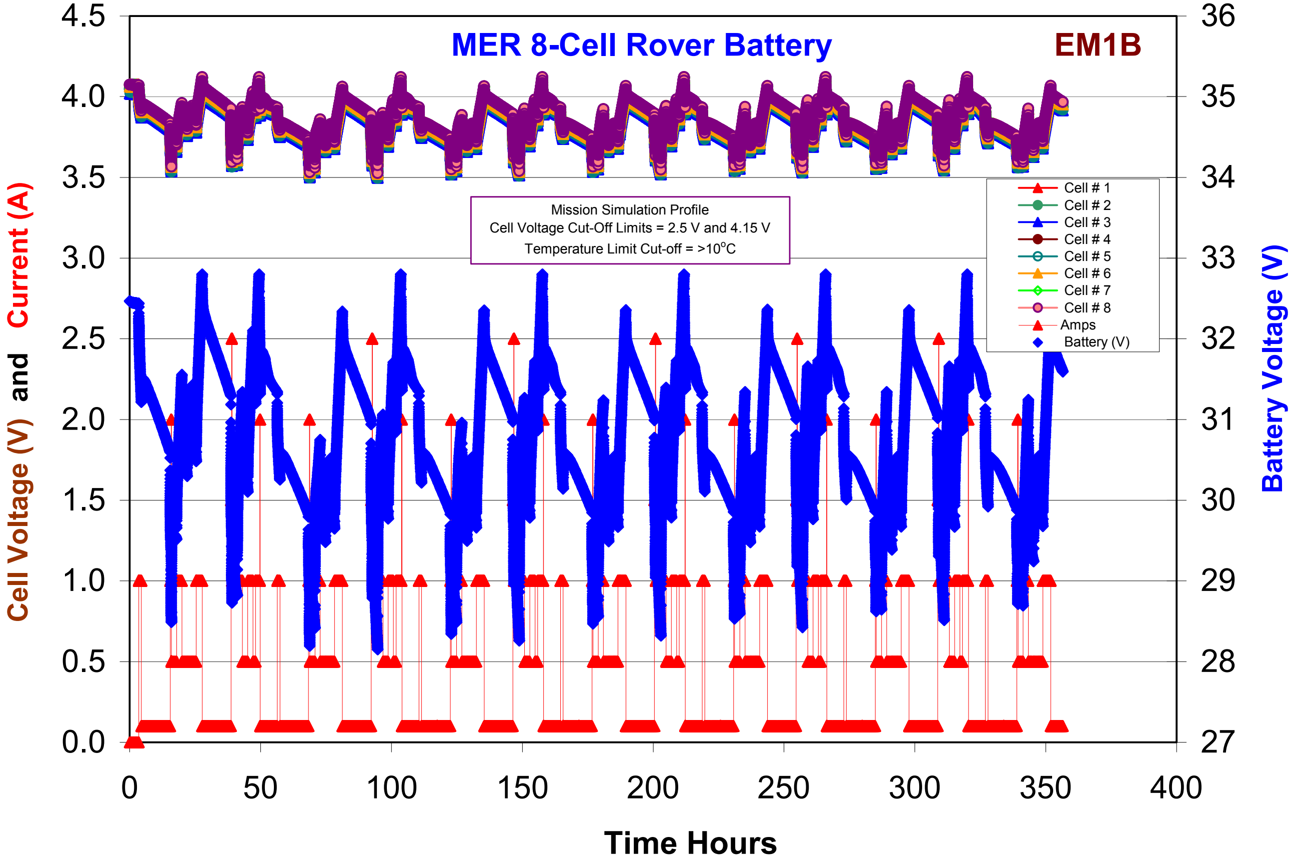


- **Good low temperature performance observed at the battery level**
- **Over 75% of the room temperature capacity delivered at –20°C (C/5 rate)**

MER 8 Ah Rover Lithium-Ion Battery (EM1B)

Mission Simulation Testing

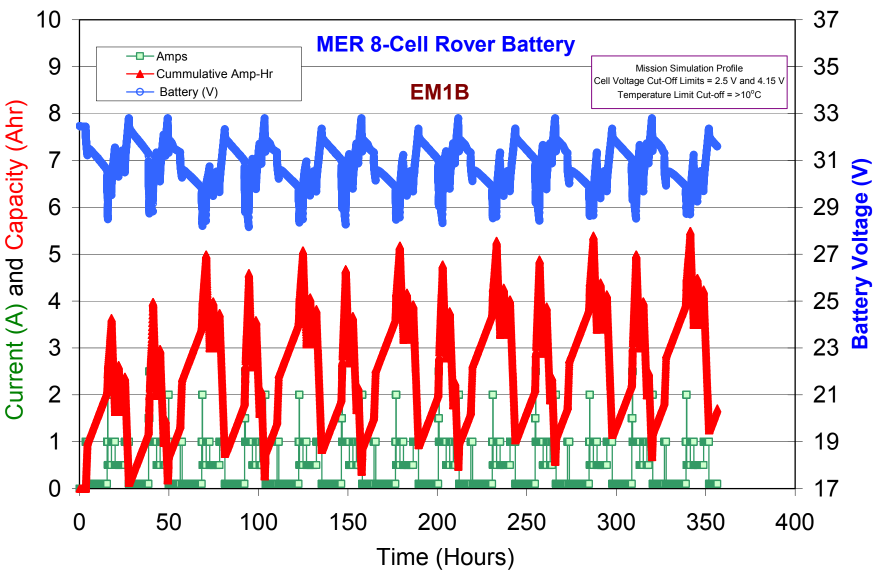
SOLS 1- 10



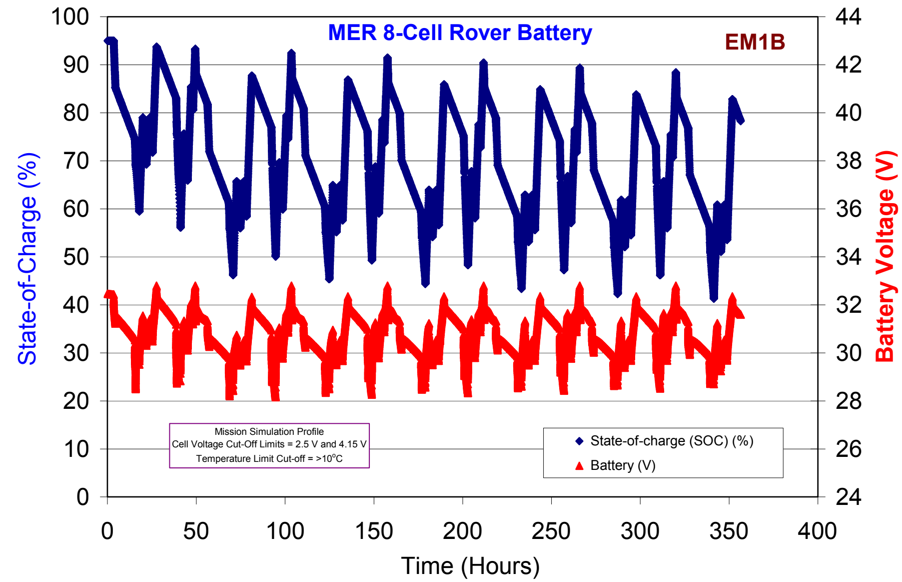
- Mission simulation performed without the benefit of battery charge control electronics
- Performance superior to that obtained at cell-level (due to fresher cells and thermal effects)

MER 8 Ah Rover Lithium-Ion Battery (EM1B)
Mission Simulation Testing
SOL 1-12 (Capacity)

SOL 1-12 (Capacity)

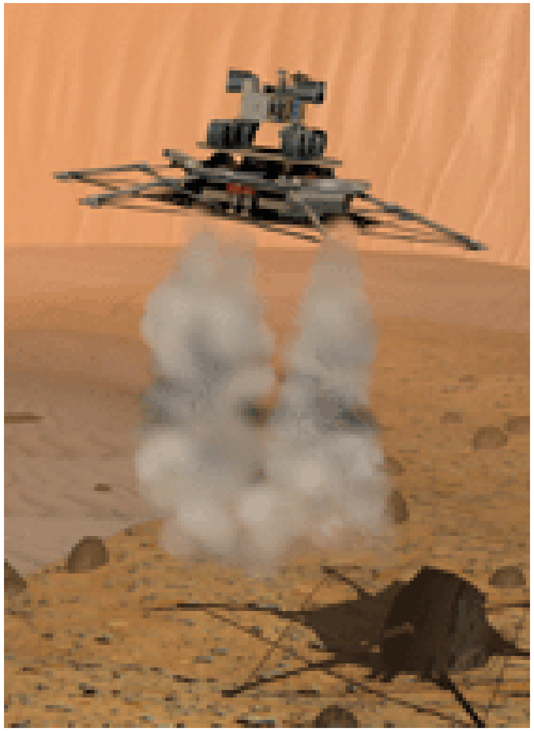


Battery State-of-Charge (SOC) (%)



- 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

Future Missions: 2009 Smart Lander Secondary Battery



• Lander battery should be capable of supporting launch, cruise, and Mars surface operations over range of temperature (-40 to +40°C).

Battery Description *

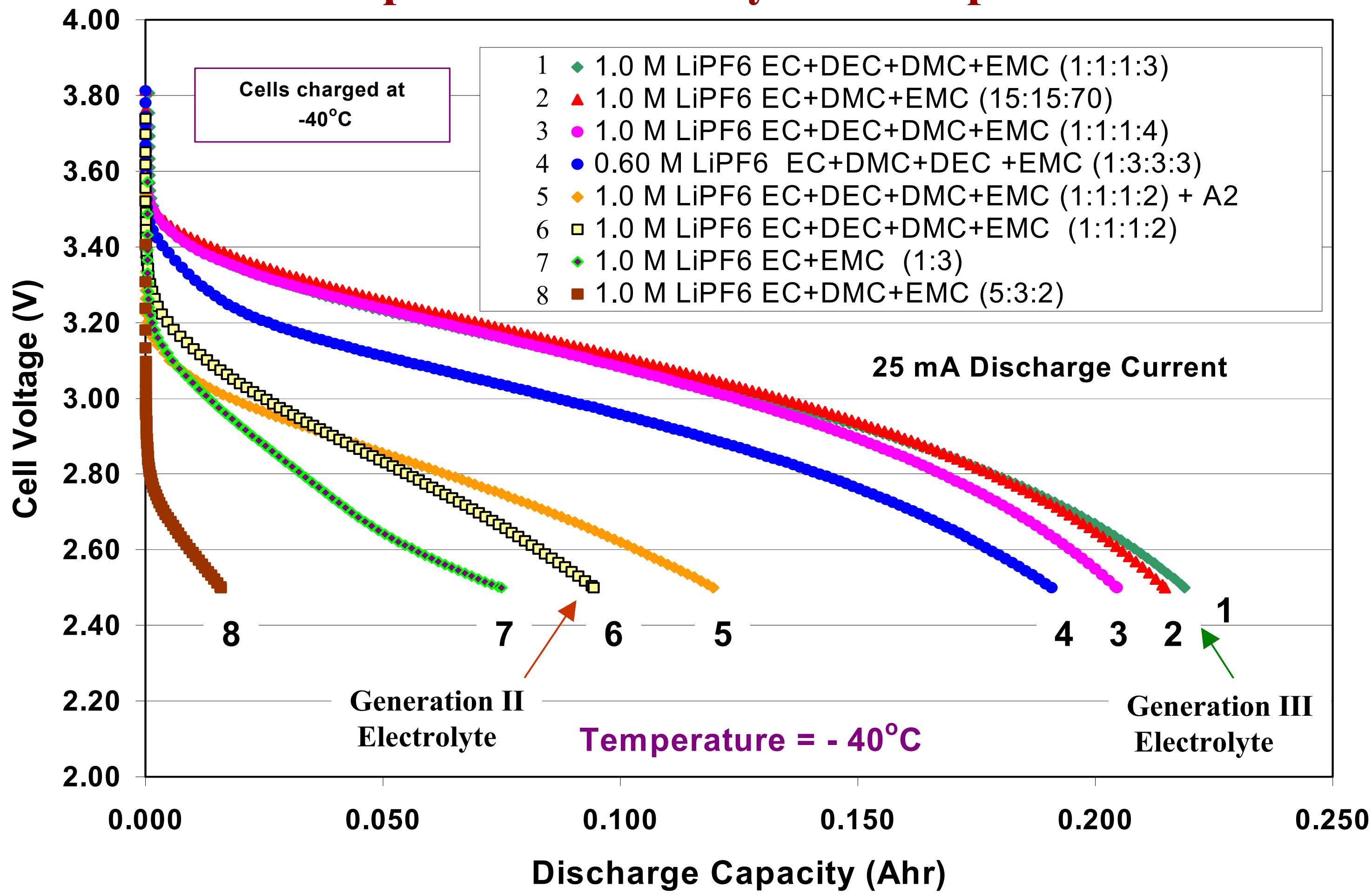
- Rechargeable system: Lithium-ion
- High specific energy > 100 Wh/kg
- Configuration: TBD
- Capacity: 30-60 AHr
- Vendor : TBD

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.

Future Missions: 2007 Smart Lander Secondary Battery
Low Temperature Electrolyte Development at JPL

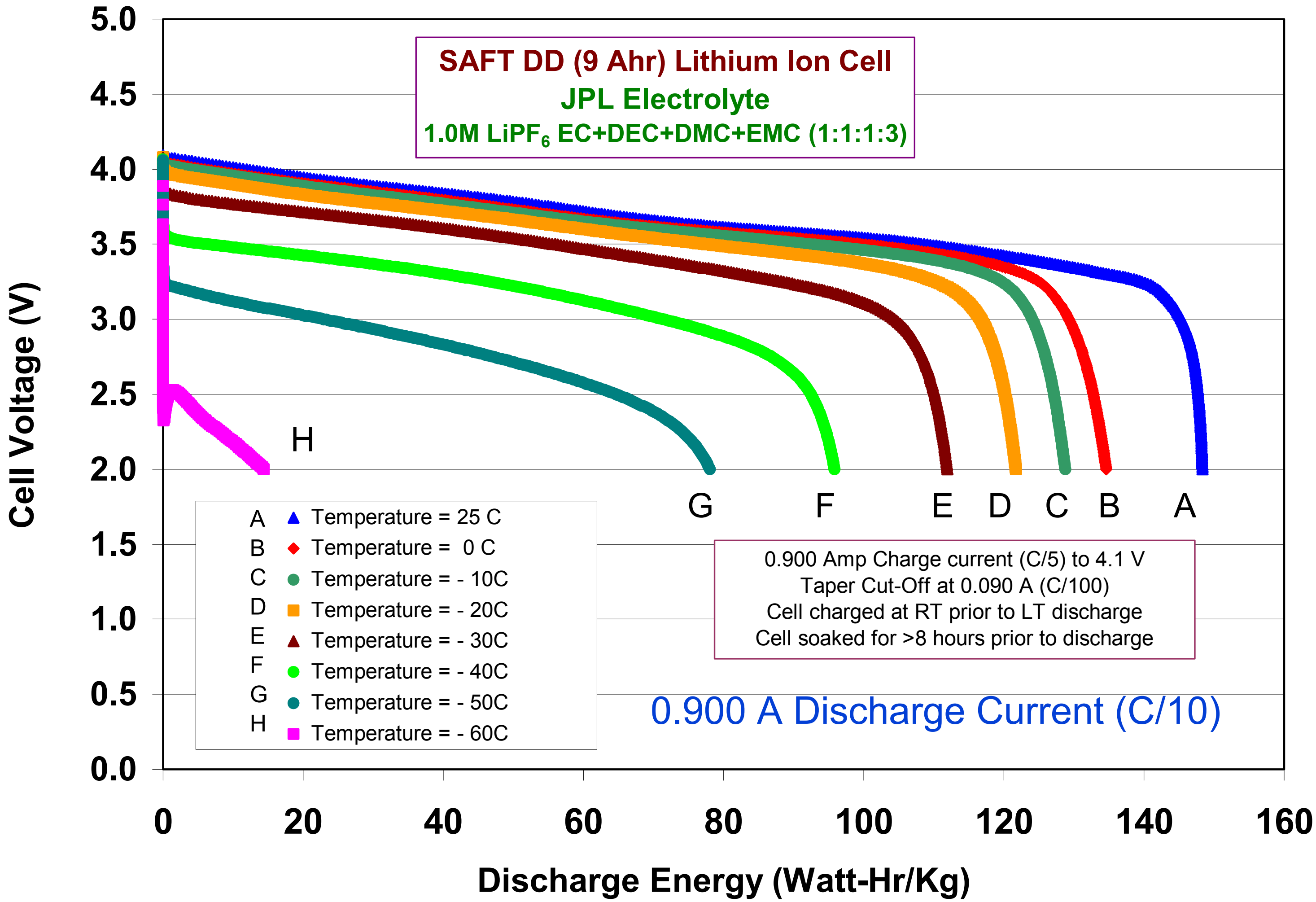


- Identified a number of improved low temperature electrolytes enabling –40°C operation
- Smart et al., ***11th International Meeting on Lithium Batteries (IMLB)***, June 28, 2002, Monterey, CA

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

Cell Performance at Low Temperatures: JPL Electrolyte

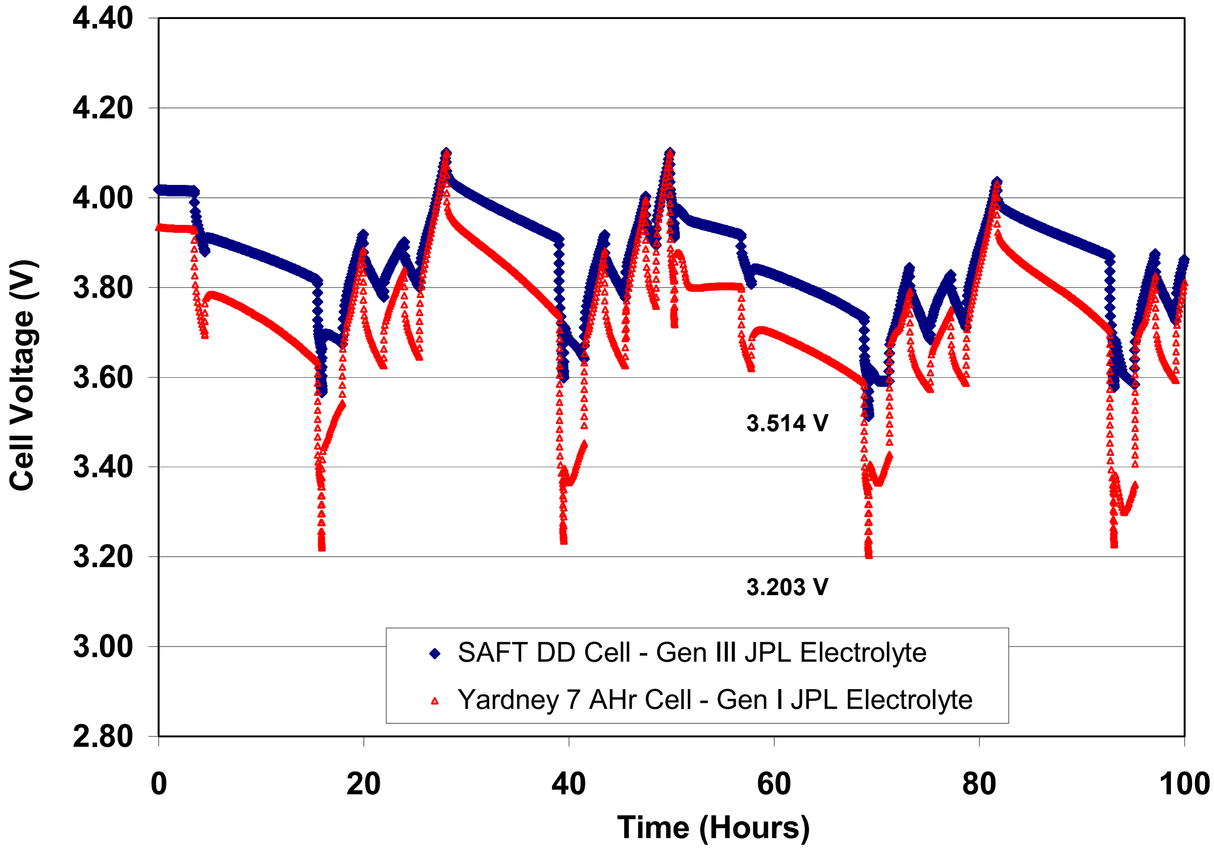
Discharge Energy (Watt-Hr/Kg) – C/10 Rate (0.90 A)



Lithium-Ion Cells for Future Mars Applications

Mission Simulation of Mars Surface Operations

2003 MER Mission Simulation Temperature Profile

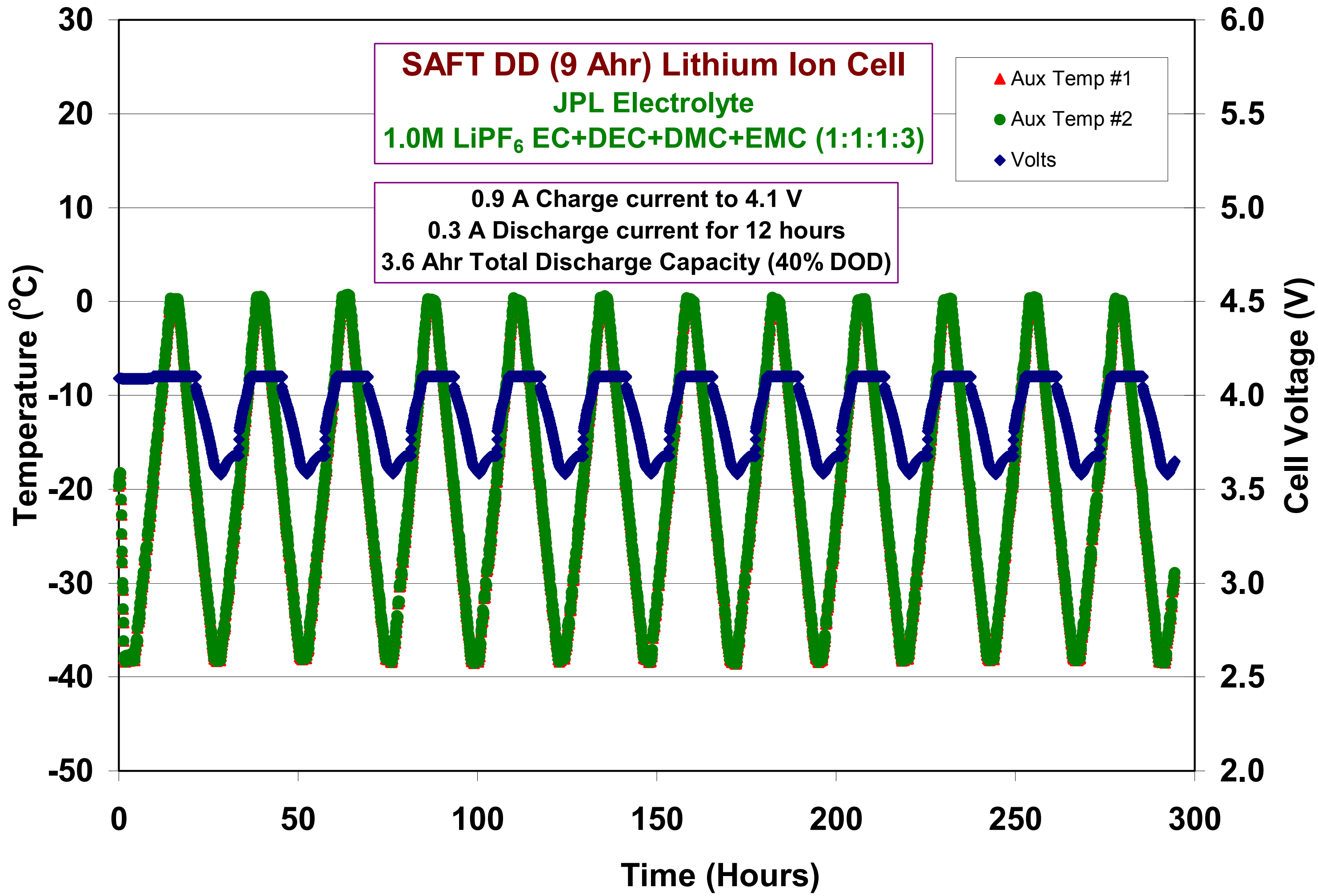


- Improved low temperature electrolytes have translated into increased mission capability.
  - Cells charged at 0°C to 4.05 V (no taper) prior to test

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

Mars Mission Surface Operation Simulation Cycling

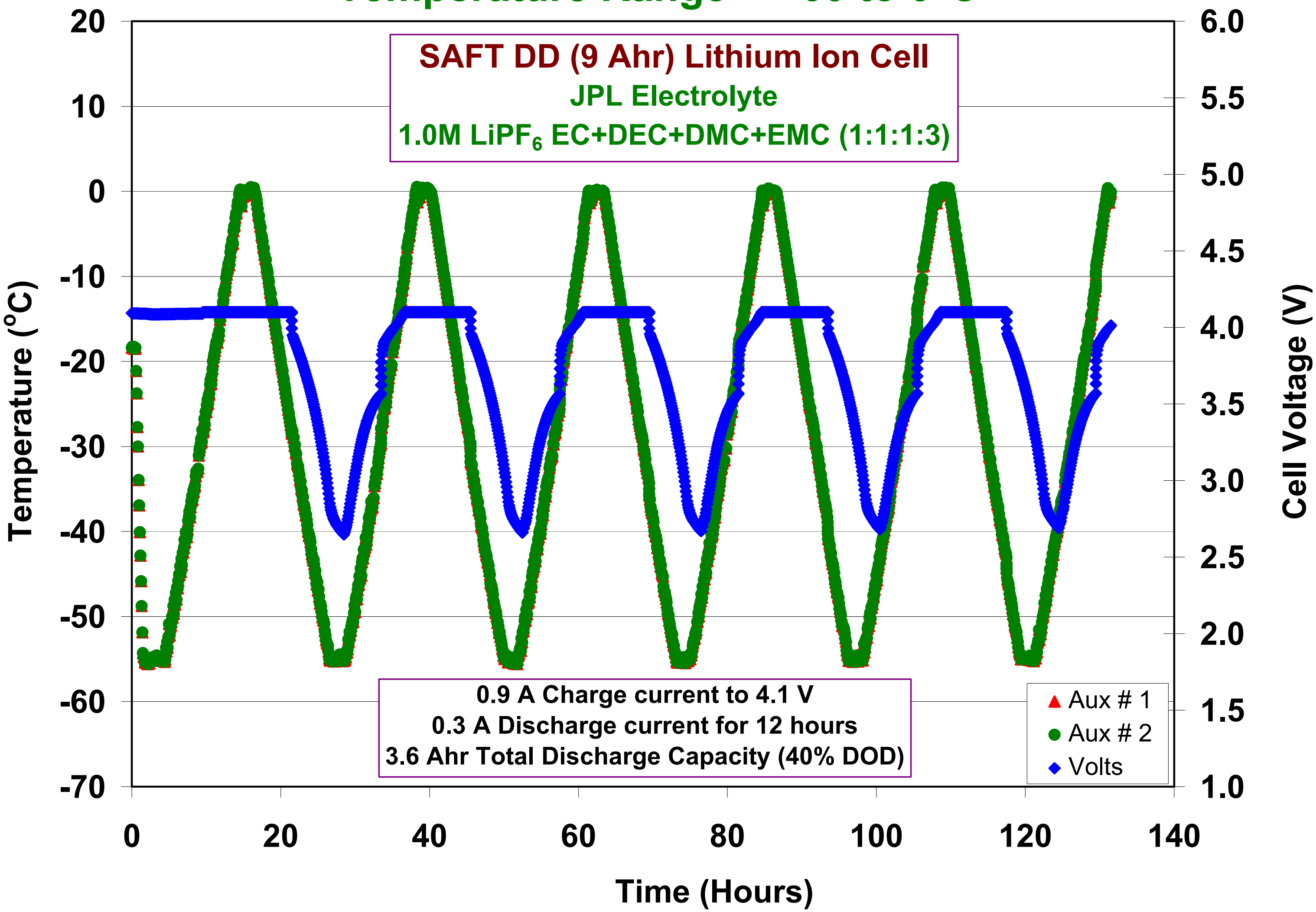
Temperature Range = - 40 to 0°C



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

Mars Mission Surface Operation Simulation Cycling

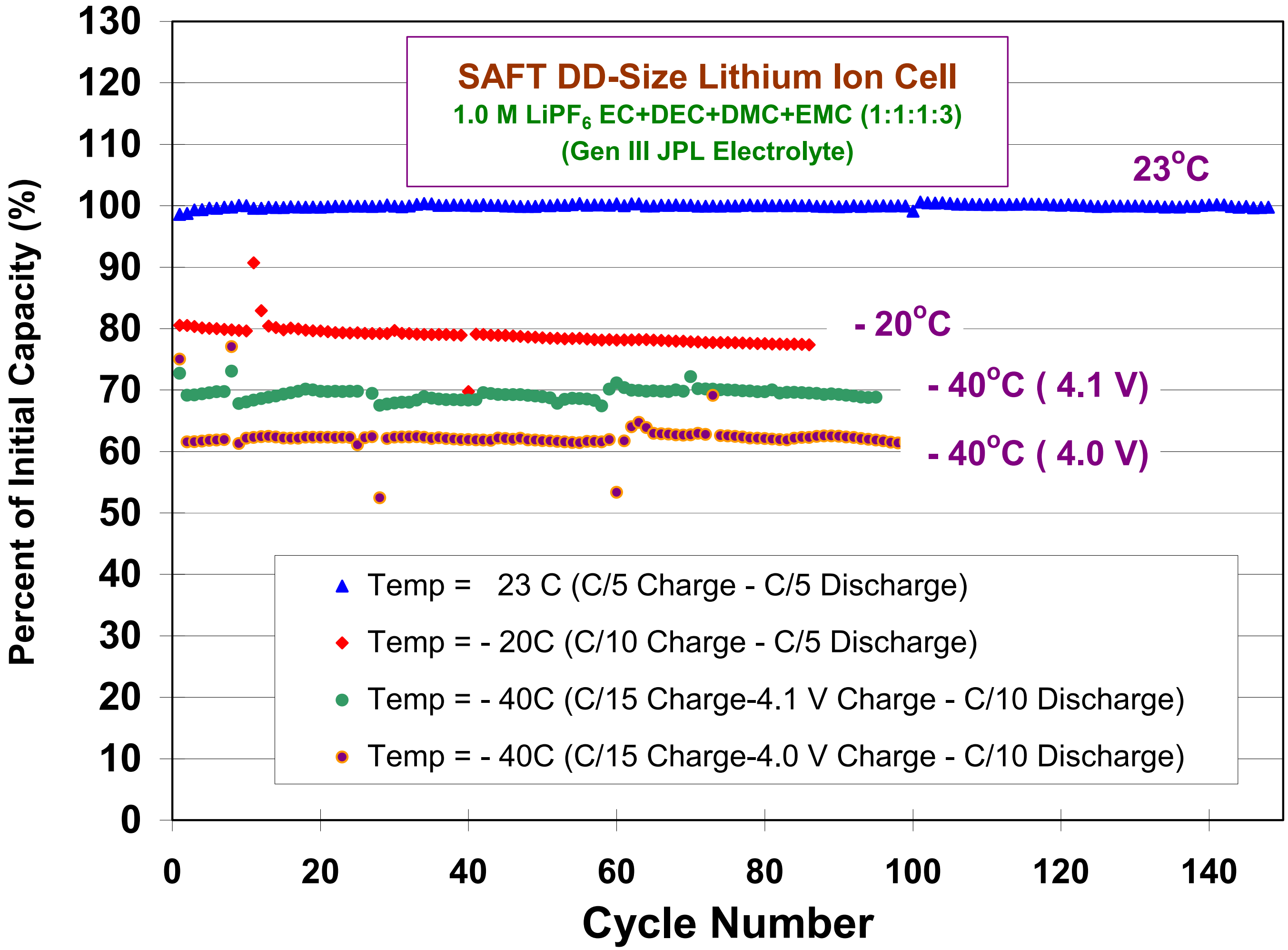
Temperature Range = - 60 to 0^{o}C



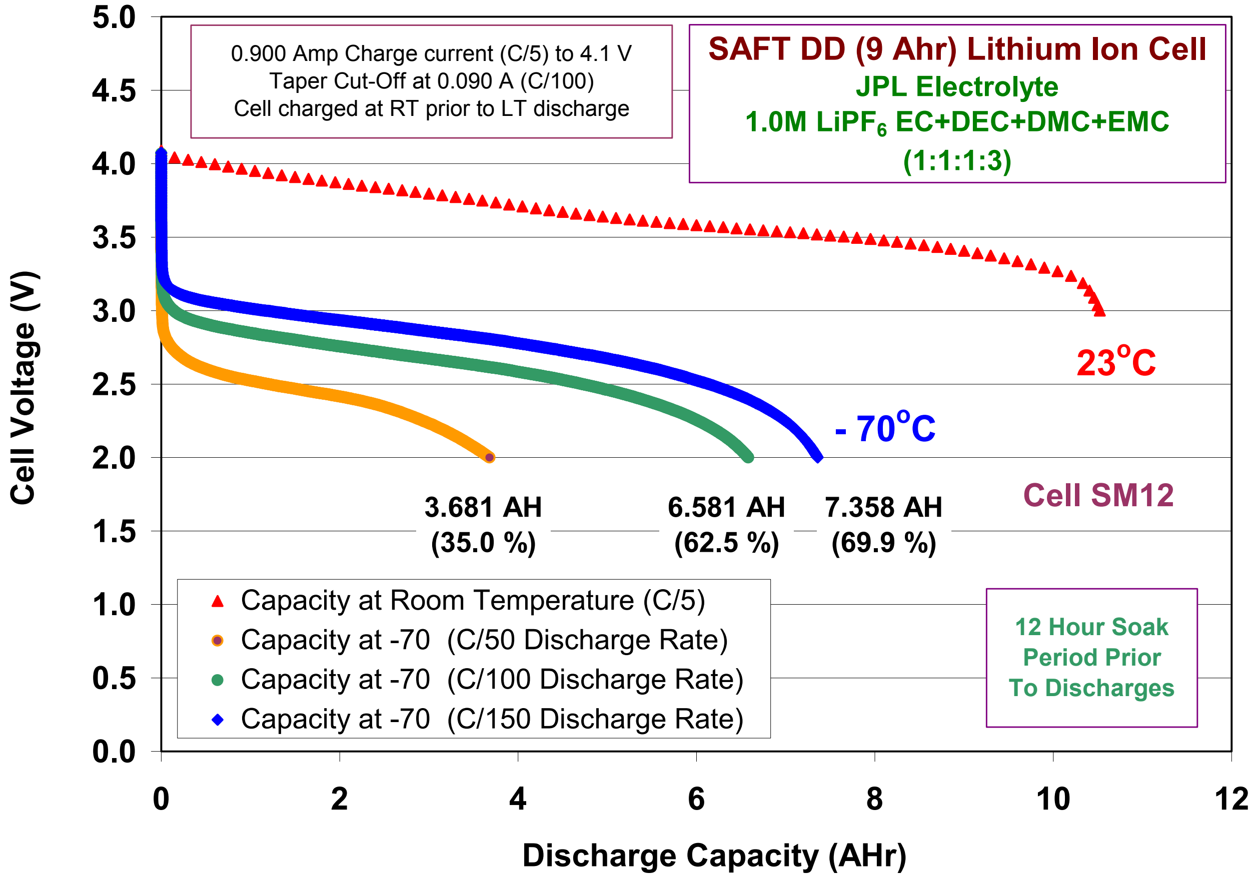
SAFT DD-Size Lithium-Ion Cells for Mars Rover Applications

Performance with Improved Anode Material and JPL Electrolyte

Cycle Life Performance at Different Temperatures



SAFT DD-Size Lithium-Ion 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.**

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 tem)*
  - *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^{o}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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