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
  - 2003 MER Mission (2001) – 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.**

JPL Li-Ion Battery Testing Program

MSP'01 Lander Battery Testing

- 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

Lithium-Ion Cell/Battery Development

Demonstration of MSP01 Li-Ion Cell Technology

Mission Simulation Profiles

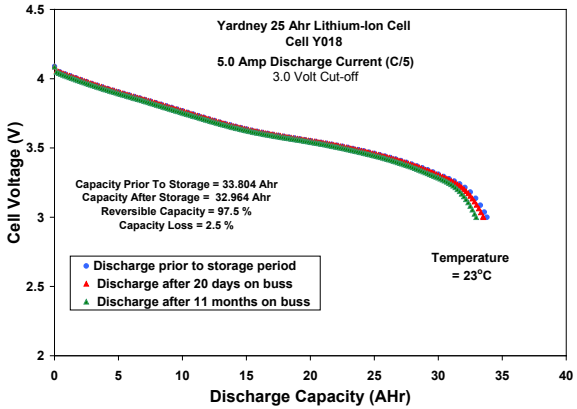
Objectives

* Demonstrate the viability of using Lithium-Ion cell technology for future Lander missions.

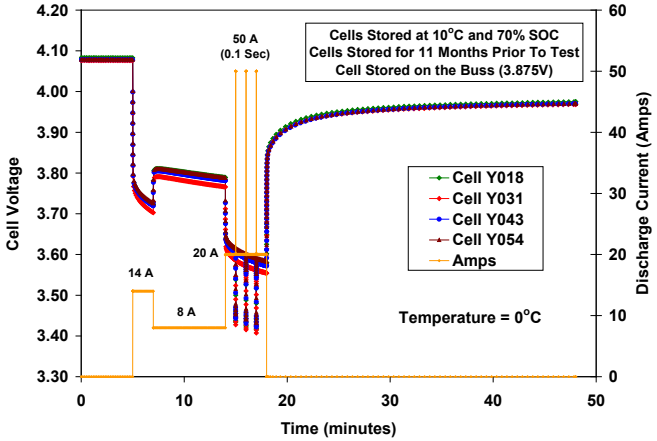
Accomplishments:

* 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.**

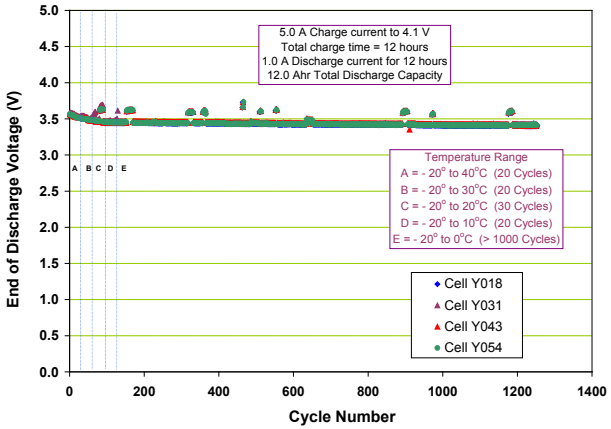
Simulation of Cruise Period: Minimal Capacity Loss Observed (< 5% Loss)



Entry, Descent and Landing Profile: All Cells > 3.4 V During Pulse Profile



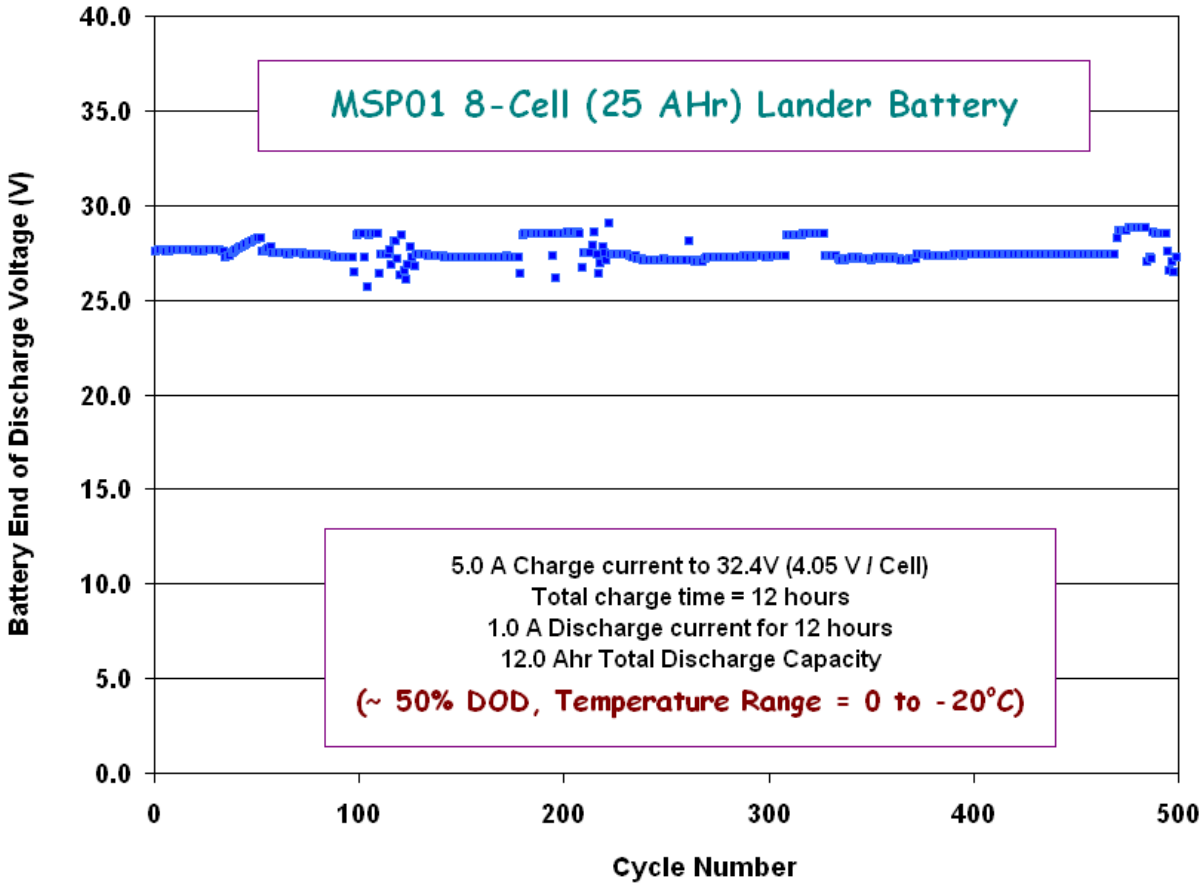
Mars Surface Mission Simulation Cycling Profile: Over 1200 Sols Demonstrated (~ 50% DOD)



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)

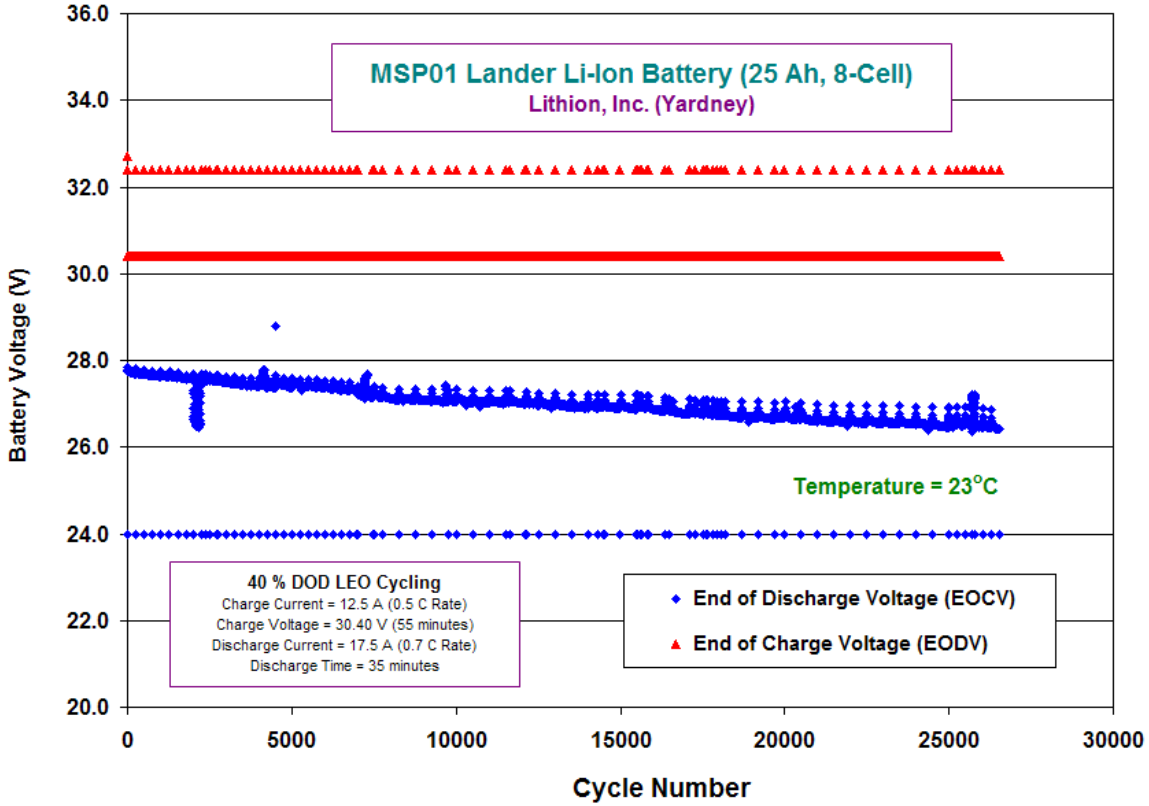


- Subjected to cruise storage for 11 months prior to surface simulation (~ 5 years ago)
- Surface Operation Tested both under MSP 01 Lander as well as MSL profiles.
- Meets calendar life (wet life) needs of MSL

Yardney Li-Ion Mars Battery Heritage

Yardney MSP01 25 Ah Li-Ion Battery at 40 % DOD cycling at 23°C

End-of-Charge (EOC) Voltage and End-of-Discharge (EOD) Voltage

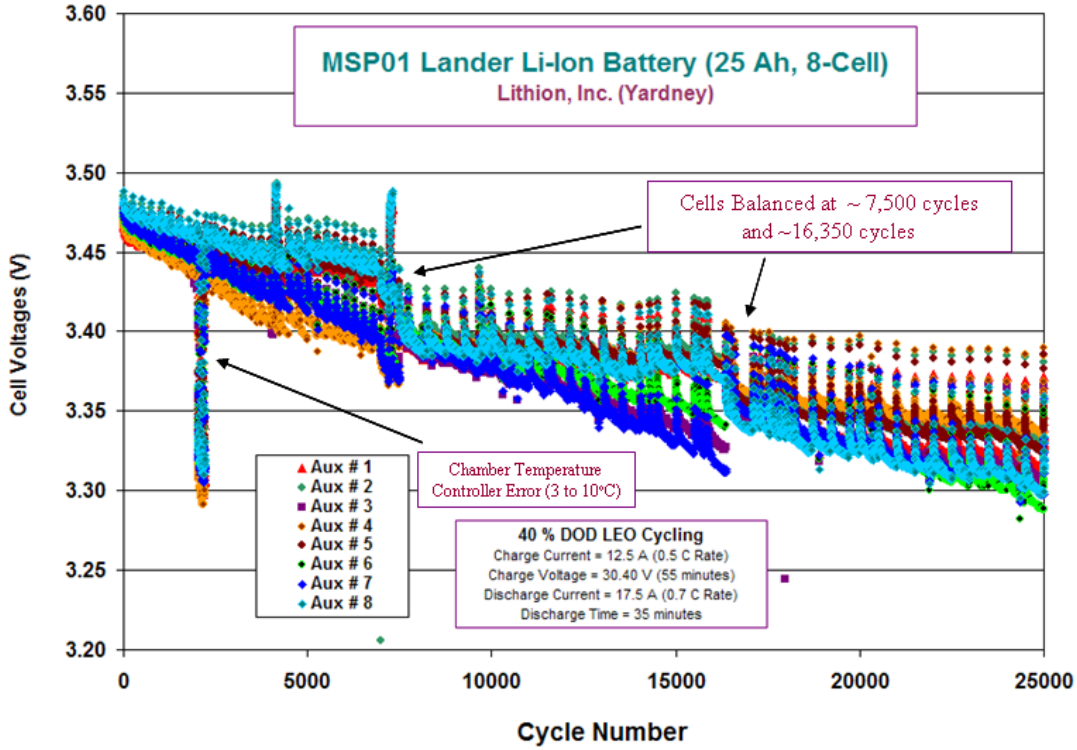


- MSP'01 battery has completed 26,500 cycles at 40% DOD, with the discharge voltages in excess of 26 V (over five years of operation).
- Test data above represent LEO-type cycling, consisting of 1.5 hour cycles at constant ambient temperature (charge voltage = 30.40V).

Yardney Li-Ion Mars Battery Heritage

Yardney MSP01 25 Ah Li-Ion Battery at 40 % DOD cycling at 23°C

Individual Cell End-of-Discharge (EOD) Voltages

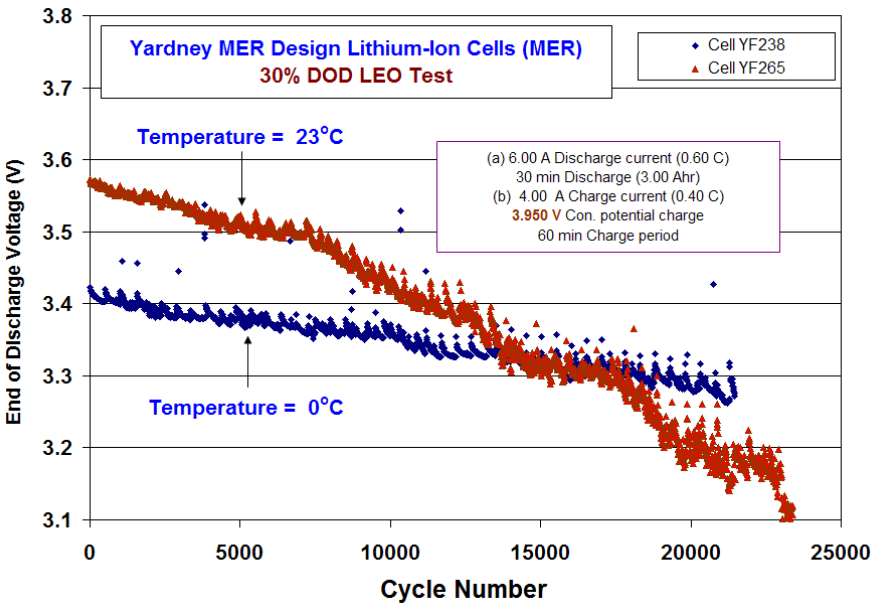


- The battery required cell balancing only every 7,000 – 10,000 cycles during the course of cycling.
- The cells have been balanced 3 times since the initiation of the testing (i.e., the cells were manually resistively discharged to set voltage)

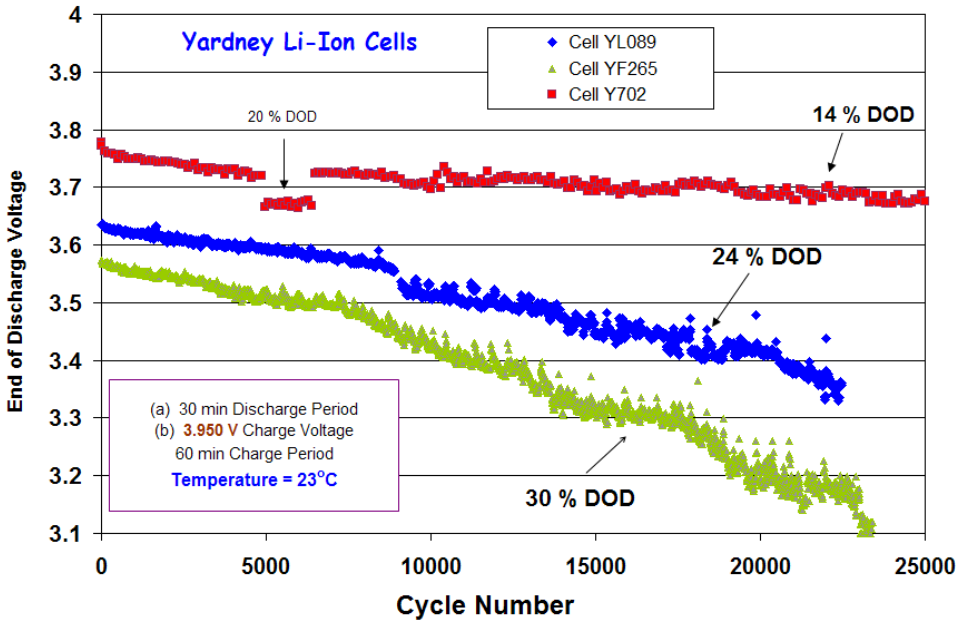
Yardney Lithium-Ion Cells for Orbiter Applications

30% DOD LEO-type Cycle Life Performance

Effect of Temperature



Effect of DOD



- 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.

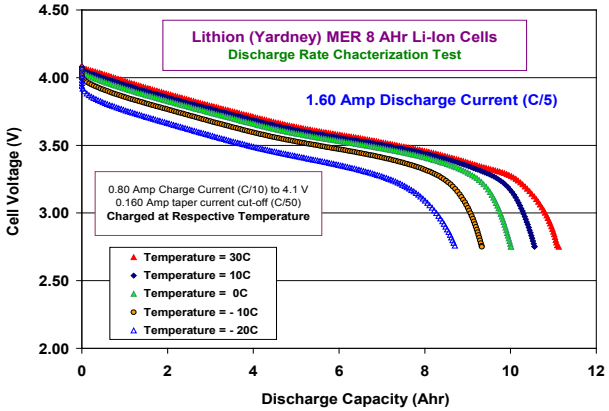
Mars Exploration Rover- Rover Batteries

- Lithium-ion technology was used for '03 MER Rovers
- Currently testing prototype cells to support mission

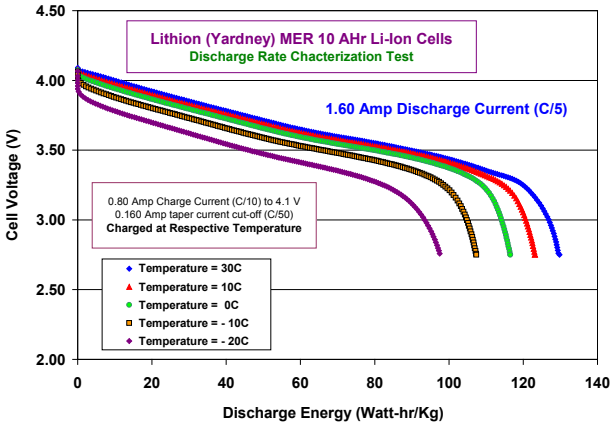
Rover Battery Requirements

- 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

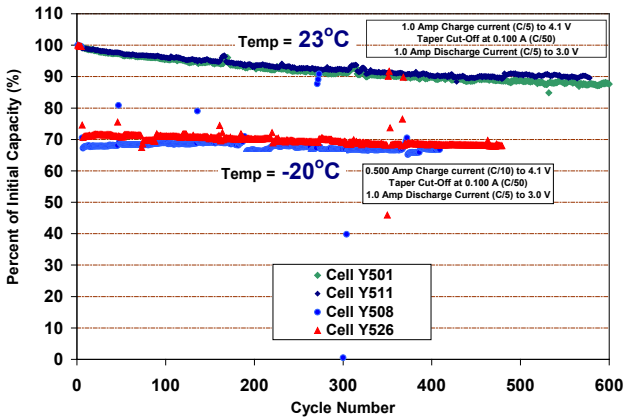
Discharge Capacity (Ah)



Discharge Energy (Wh/kg)



100% DOD Cycling at 23 and -20°C



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

	Temperature = 20°C				Temperature = 0°C				Temperature = - 20°C				Temperature = - 30°C			
RBAU 4B	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)	Discharge Capacity (Ah)	Capacity (% of Capacity After Cruise)	Discharge Energy (Wh)	Energy (% of Energy After Cruise)	Discharge Capacity (Ah)	Capacity (% of Initial)	Discharge Energy (Wh)	Energy (% of Initial)	Discharge Capacity (Ah)	Capacity (% of Capacity After 180 Sols)	Discharge Energy (Wh)	Energy (% of Energy After 180 Sols)
Performance Prior to Cruise	10.0478	100.00	289.64	100.00					7.8641	100.00	215.92	100.00				
Performance After Cruise	9.5981	95.52	276.83	95.58	8.8455	100.00	252.34	100.00	7.5391	95.87	206.71	95.73				
After Completing 90 Sols	9.7419	96.96	280.06	96.69	8.9914	101.65	254.81	100.98	7.2951	92.77	198.61	91.98				
After Completing 180 Sols	9.6111	95.65	275.84	95.24	8.8965	100.58	251.61	99.71	7.0627	89.81	191.65	88.76	5.7586	100.00	150.25	100.00
After Completing 270 Sols	9.5430	94.98	273.38	94.38	8.7993	99.48	248.27	98.39	6.9291	88.11	187.93	87.04	5.4196	94.11	140.35	93.41
After Completing 360 Sols	9.4479	94.03	270.31	93.32	8.6321	97.59	242.81	96.22	6.7099	85.32	181.14	83.89	5.3636	93.14	139.31	92.72
After Completing 450 Sols	9.3381	92.94	266.62	92.05	8.4794	95.86	237.76	94.22	6.4720	82.30	174.29	80.72	5.1948	90.21	134.63	89.60
After Completing 540 Sols	9.2171	91.73	263.21	90.87	8.3252	94.12	232.76	92.24	6.2211	79.11	166.64	77.18	4.8452	84.14	124.74	83.02
After Completing 640 Sols	9.0285	89.86	256.89	88.69	7.9919	90.35	223.08	88.40	6.0836	77.36	162.99	75.48	4.7373	82.27	122.22	81.35
After Completing 730 Sols	8.8536	88.12	252.11	87.04	7.8583	88.84	219.03	86.80	5.8950	74.96	157.53	72.96	4.4223	76.80	113.62	75.62
After Completing 820 Sols	8.9544	89.12	254.37	87.82	8.1079	91.66	226.21	89.64	5.8176	73.98	155.04	71.80	4.4054	76.50	112.82	75.09
After Completing 920 Sols	8.7119	86.70	247.50	85.45	7.6635	86.64	213.12	84.46	5.7638	73.29	154.14	71.38	4.4170	76.70	113.43	75.49
After Completing 1010 Sols	8.6784	86.37	245.72	84.84	7.4624	84.36	206.84	81.97	5.2628	66.92	138.64	64.21	3.5077	60.91	88.65	59.00

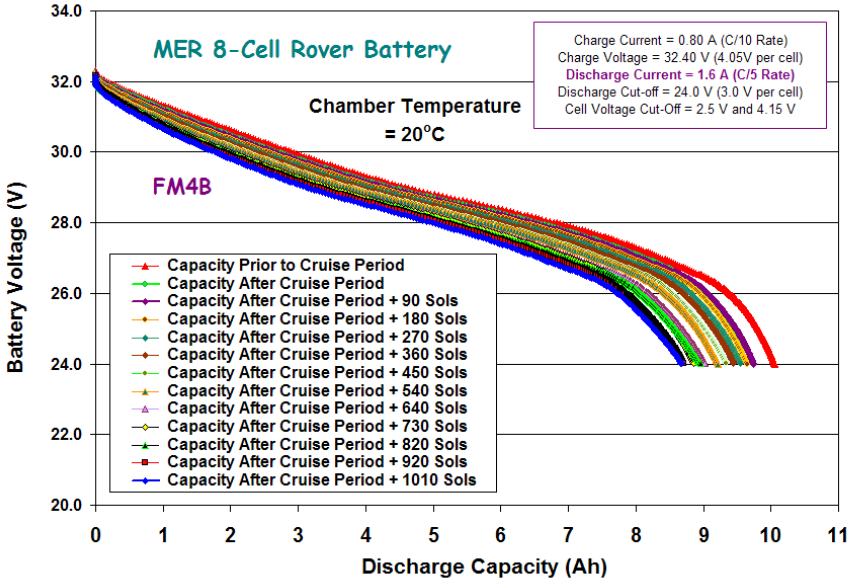
- **Discharge capacity and energy determined with charging battery at room temperature**
  - **100 % DOD Cycling (C/10 Charge to 32.40V, C/5 Discharge to 24.0V)**

MER 8 Ah Rover Lithium-Ion Battery (FM4B)

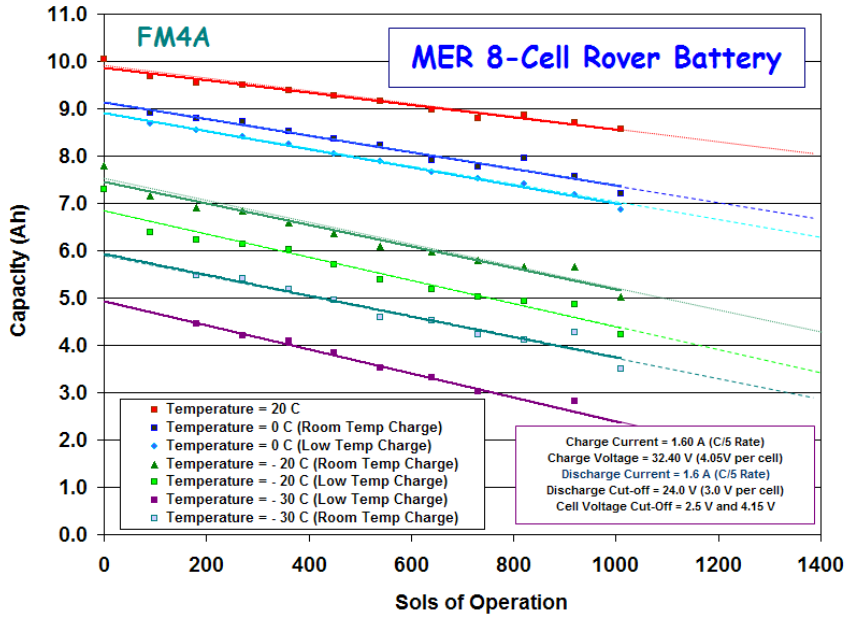
Characterization After Cruise Period + 1010 Sols (Mission Simulation Battery)

Observed Capacity Loss After Completing Cruise + 1010 Sols

Capacity Determination at 20°C



Capacity Fade Trends

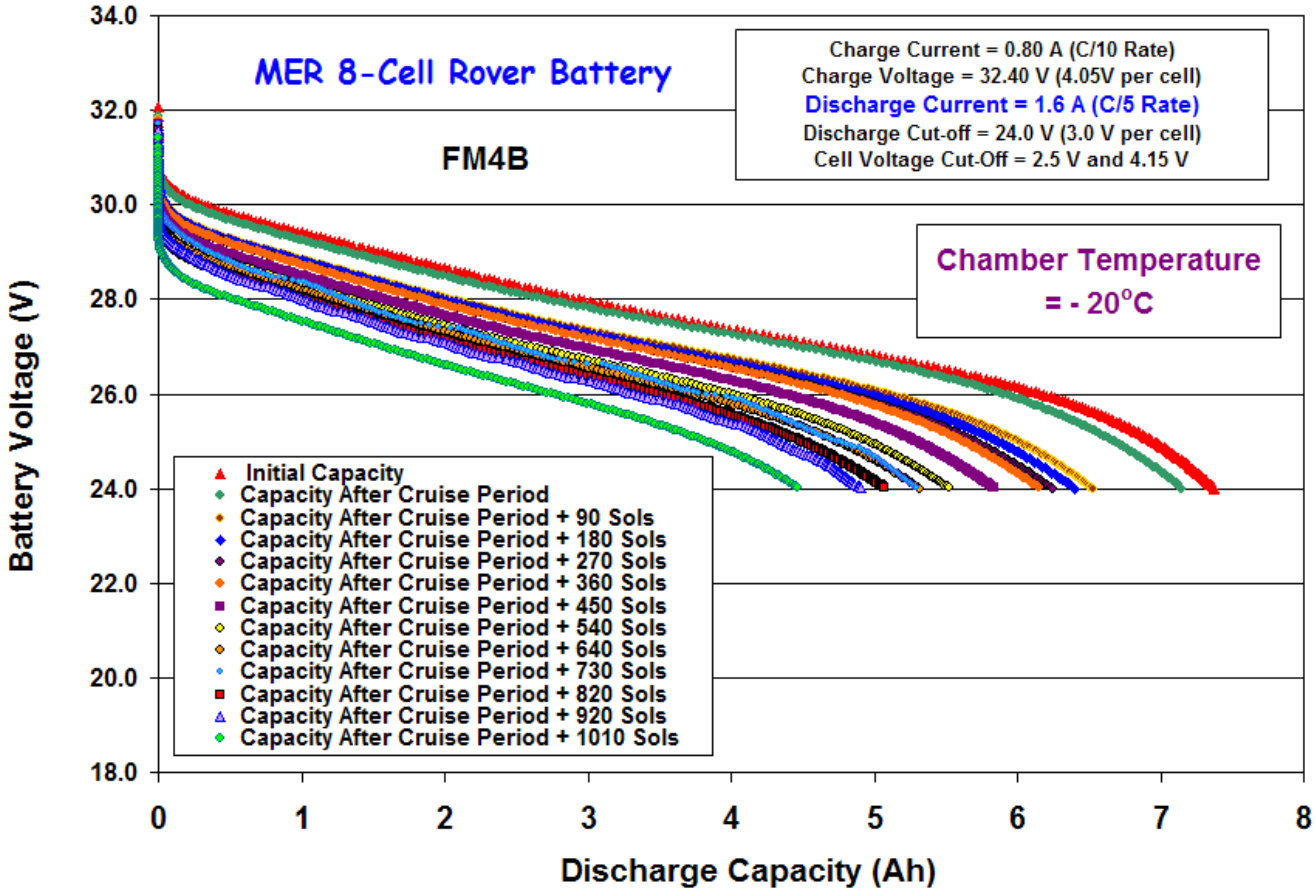


- **Approx. 14% capacity loss observed at 20°C since initiation of testing (> 5.00 years).**
- **Capacity fade observed to be more dramatic at low temperature**

MER 8 Ah Rover Lithium-Ion Battery (FM4B)

Characterization After Cruise Period + 1010 Sols

Performance at - 20°C

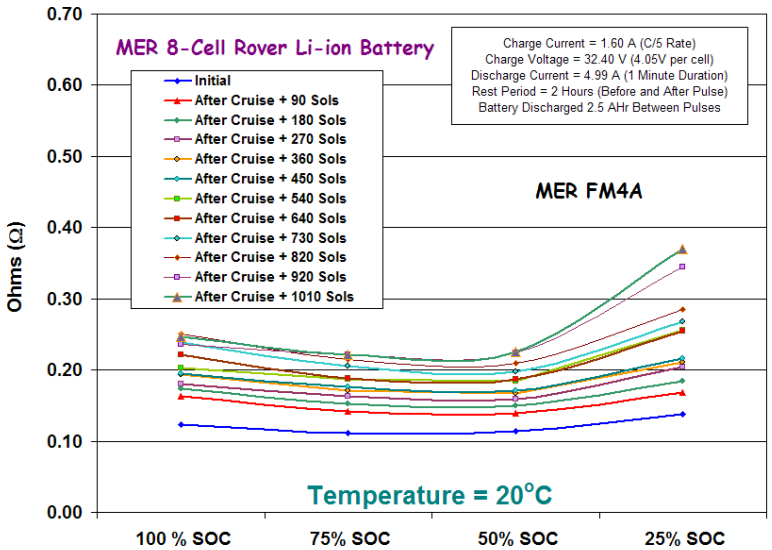


- ~ 39 % Capacity fade observed at - 20°C as a result of completing cruise period and 1010 sols under mission simulation conditions (24 V cut-off, C/5 Rate).
- Values represent low temperature charging

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



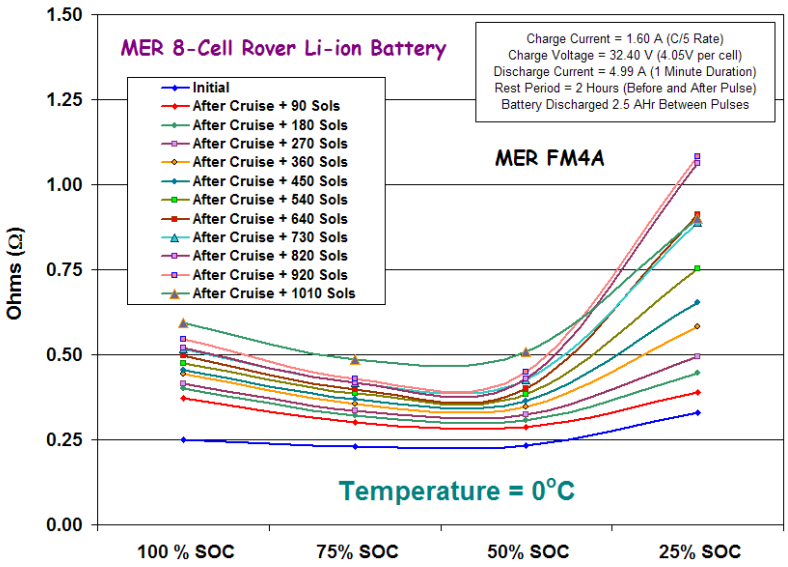
Condition	100 % SOC (Ohms)	75% SOC (Ohms)	50% SOC (Ohms)	25% SOC (Ohms)
Initial	0.1234	0.1113	0.1147	0.1379
After Cruise + 90 Sols	0.1638	0.1416	0.1388	0.1687
After Cruise + 180 Sols	0.1741	0.1530	0.1495	0.1841
After Cruise + 270 Sols	0.1805	0.1629	0.1599	0.2040
After Cruise + 360 Sols	0.1941	0.1719	0.1678	0.2109
After Cruise + 450 Sols	0.1953	0.1763	0.1719	0.2169
After Cruise + 540 Sols	0.2033	0.1874	0.1845	0.2561
After Cruise + 640 Sols	0.2218	0.1881	0.1878	0.2549
After Cruise + 730 Sols	0.2386	0.2060	0.1978	0.2690
After Cruise + 820 Sols	0.2500	0.2148	0.2094	0.2856
After Cruise + 920 Sols	0.2363	0.2215	0.2236	0.3447
After Cruise + 1010 Sols	0.2464	0.2215	0.2248	0.3699

- **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



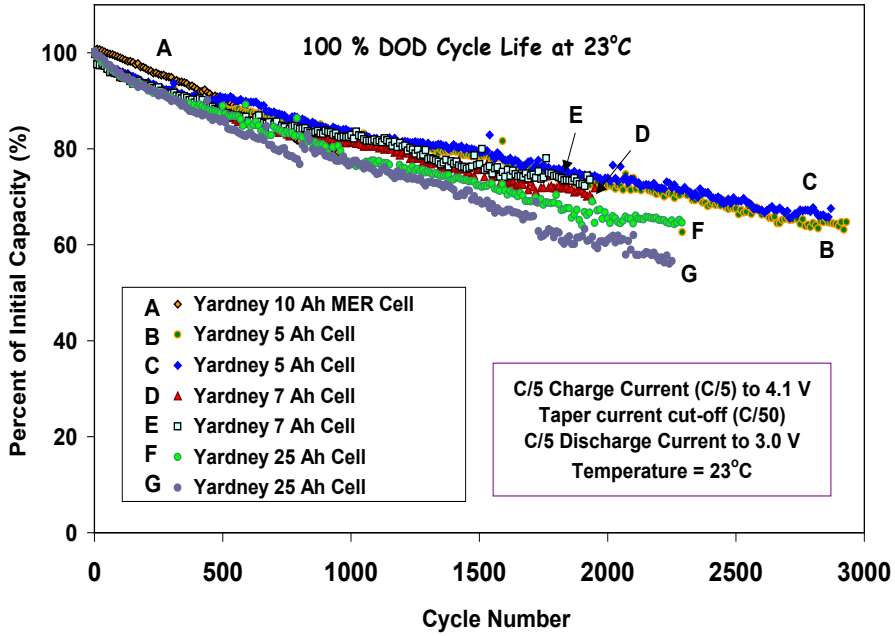
Condition	100 % SOC (Ohms)	75% SOC (Ohms)	50% SOC (Ohms)	25% SOC (Ohms)
Initial	0.2512	0.2314	0.2330	0.3300
After Cruise + 90 Sols	0.3723	0.3004	0.2872	0.3904
After Cruise + 180 Sols	0.4008	0.3203	0.3074	0.4461
After Cruise + 270 Sols	0.4151	0.3342	0.3241	0.4939
After Cruise + 360 Sols	0.4433	0.3548	0.3470	0.5833
After Cruise + 450 Sols	0.4536	0.3692	0.3625	0.6522
After Cruise + 540 Sols	0.4739	0.3875	0.3826	0.7542
After Cruise + 640 Sols	0.4970	0.3983	0.4014	0.9113
After Cruise + 730 Sols	0.5157	0.4188	0.4252	0.8896
After Cruise + 820 Sols	0.5209	0.4180	0.4281	1.0621
After Cruise + 920 Sols	0.5455	0.4297	0.4494	1.0832
After Cruise + 1010 Sols	0.5925	0.4860	0.5092	0.8994

- **Somewhat slightly higher impedance rise was observed at 0°C .**

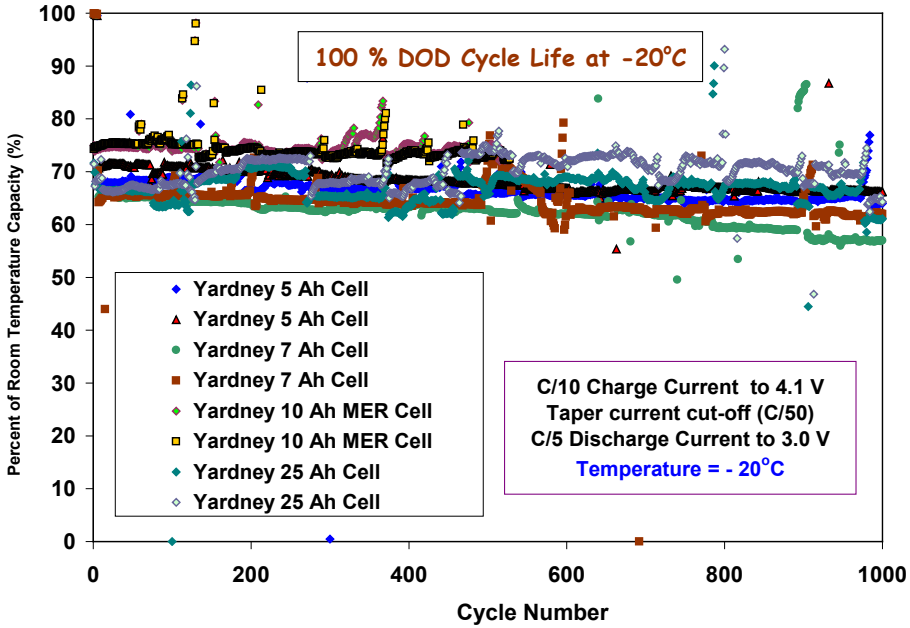
Yardney Lithium-Ion Cells for Aerospace Applications

100% DOD Cycle Life Performance

Temp = 23°C



Temp = - 20°C

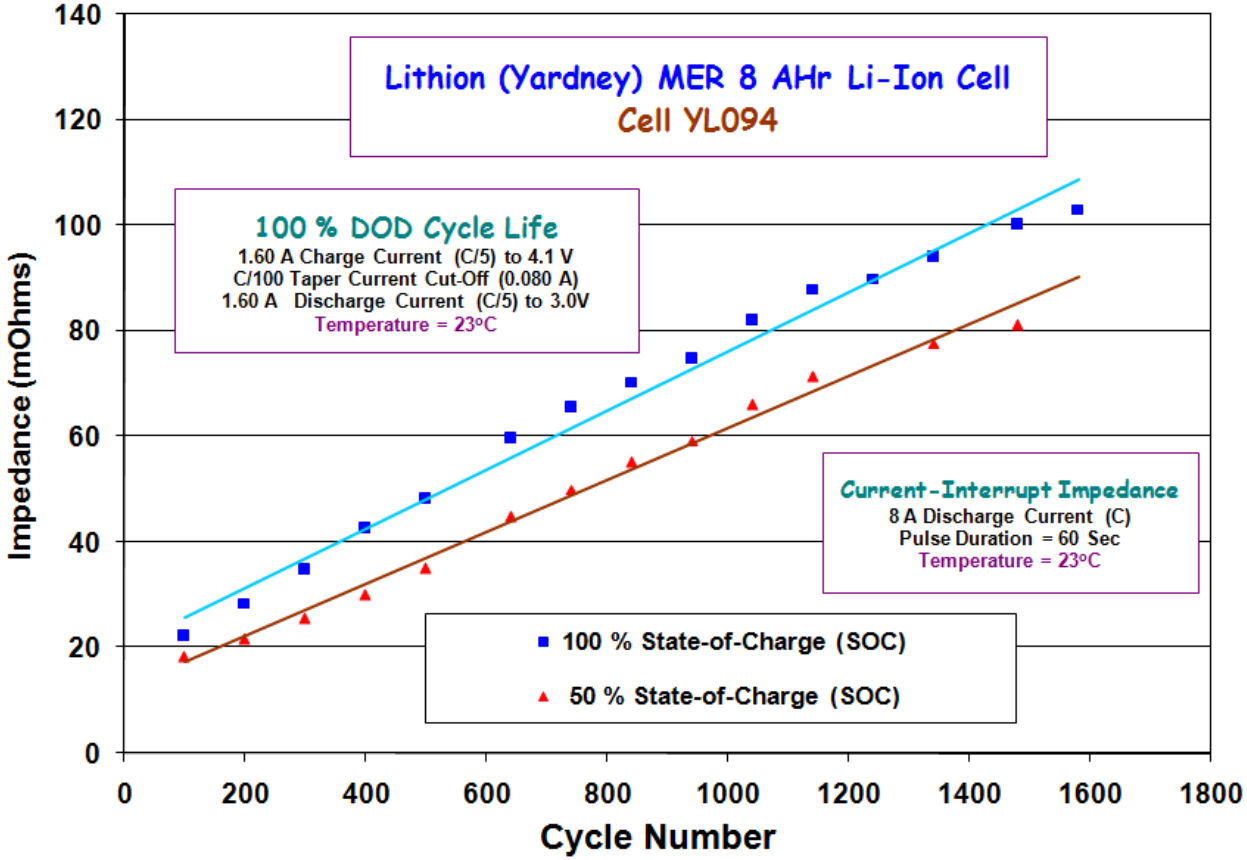


- Comparable cycle life performance obtained with a range of cell sizes fabricated by Lithion, Inc. (from 5 to 25 Ahr).
- Stable performance displayed when continuous cycling is performed at – 20°C (lower capacity fade rate compared to room temperature).

Yardney Lithium-Ion Cells for Aerospace Applications

100% DOD Cycle Life Performance

Impedance Characteristics at 23°C



- 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 for 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.**

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.

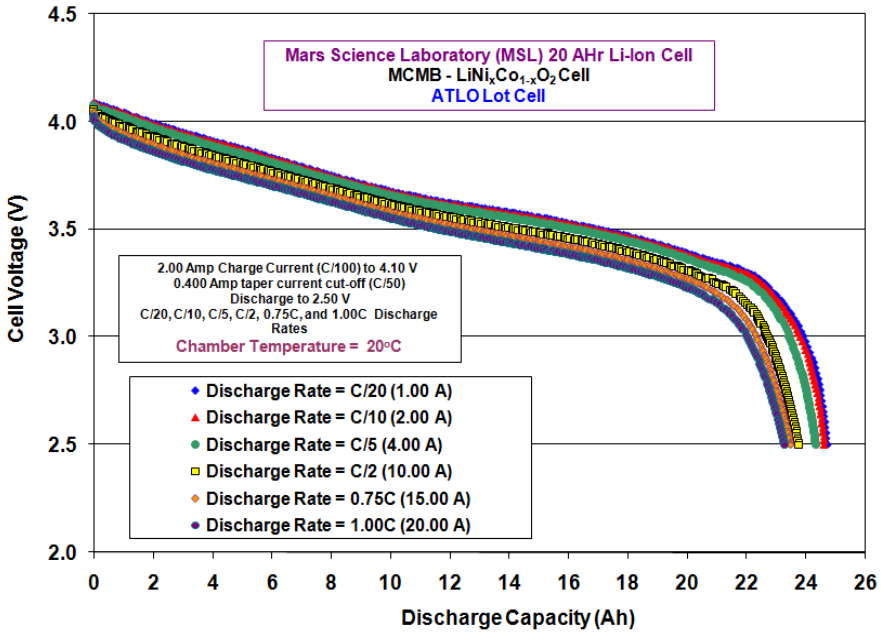
Yardney Li-ion 20 Ah Li-Ion Performance Testing

Discharge Rate Characterization at Different Temperatures

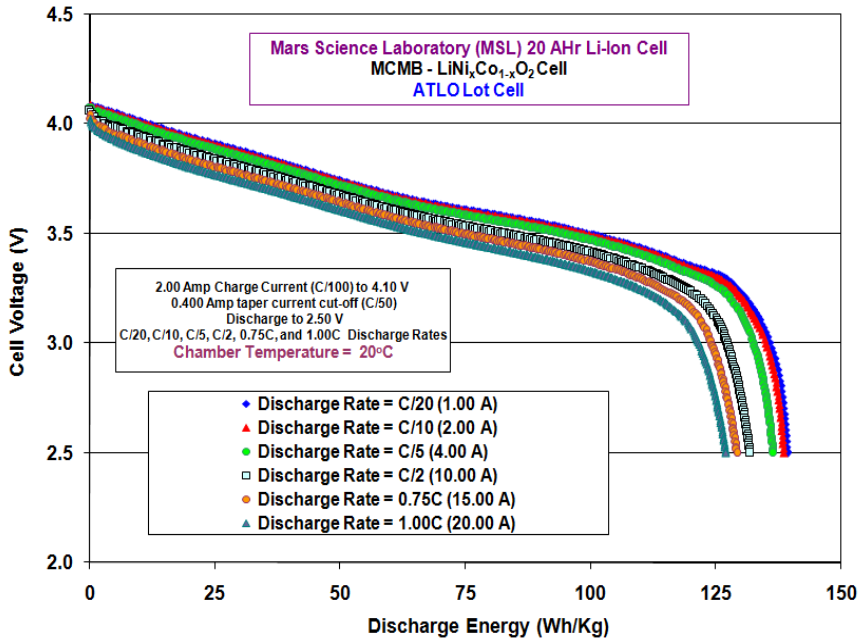
			Cell # 010					Cell # 113				
Temperature	Discharge Rate	Discharge Current (A)	Discharge Capacity (Ah)	Percent C/10 Capacity	Percent C/10 Capacity at 20°C	Discharge Watt-Hr (Wh)	Discharge Energy (Wh/Kg)	Discharge Capacity (Ah)	Percent C/10 Capacity	Percent C/10 Capacity at 20°C	Discharge Watt-Hr (Wh)	Discharge Energy (Wh/Kg)
20°C	C/20	1.000	24.7003	100.00	100.00	89.1935	139.28	25.0873	100.00	100.00	90.6149	141.36
	C/10	2.000	24.6093	99.63	99.63	88.7008	138.51	24.9849	99.59	99.59	90.0956	140.55
	C/5	4.000	24.3341	98.52	98.52	87.3878	136.46	24.7080	98.49	98.49	88.7990	138.53
	C/2	10.000	23.7537	96.17	96.17	84.4158	131.82	24.1382	96.22	96.22	85.9336	134.06
	0.75C	3.225	23.4793	95.06	95.06	82.7387	129.20	23.8555	95.09	95.09	84.2589	131.45
	1.00C	4.300	23.2750	94.23	94.23	81.3205	126.98	23.6899	94.43	94.43	83.0328	129.54
10°C	C/20	1.000	24.3141	100.00	98.44	87.7090	136.96	24.6892	100.00	98.41	89.0928	138.99
	C/10	2.000	23.8798	98.21	96.68	86.0135	134.31	24.2313	98.15	96.59	87.3329	136.24
	C/5	4.000	23.2971	95.82	94.32	83.5970	130.54	23.6257	95.69	94.17	84.8591	132.39
	C/2	10.000	22.5870	92.90	91.44	79.9476	124.84	22.9023	92.76	91.29	81.2267	126.72
	0.75C	3.225	22.3475	91.91	90.47	78.2195	122.14	22.6797	91.86	90.40	79.5977	124.18
	1.00C	4.300	22.2126	91.36	89.93	76.9139	120.10	22.5743	91.43	89.98	78.4381	122.37
0°C	C/20	1.000	23.0073	100.00	93.15	83.1018	129.77	23.3295	100.00	92.99	84.3115	131.53
	C/10	2.000	22.4005	97.36	90.69	80.7054	126.02	22.7010	97.31	90.49	81.8601	127.71
	C/5	4.000	21.8319	94.89	88.39	78.1083	121.97	22.1086	94.77	88.13	79.2018	123.56
	C/2	10.000	21.2802	92.49	86.15	74.5409	116.40	21.5295	92.28	85.82	75.5819	117.91
	0.75C	3.225	21.1294	91.84	85.54	72.9047	113.84	21.3850	91.67	85.24	73.9950	115.44
	1.00C	4.300	21.0598	91.54	85.26	71.6948	111.95	21.3434	91.49	85.08	72.9092	113.74
- 10°C	C/20	1.000	21.3987	100.00	86.63	77.1502	120.47	21.6610	100.00	86.34	78.1600	121.93
	C/10	2.000	20.8543	97.46	84.43	74.6717	116.60	21.1105	97.46	84.15	75.6692	118.05
	C/5	4.000	20.4227	95.44	82.68	72.1180	112.61	20.6463	95.32	82.30	72.9907	113.87
	C/2	10.000	20.0277	93.59	81.08	68.5560	107.05	20.2360	93.42	80.66	69.3613	108.21
	0.75C	3.225	19.9422	93.19	80.74	67.0060	104.63	20.1558	93.05	80.34	67.8604	105.87
	1.00C	4.300	19.9163	93.07	80.63	65.7291	102.64	20.1330	92.95	80.25	66.8040	104.22
- 20°C	C/20	1.000	19.6363	100.00	79.50	70.0193	109.34	19.8682	100.00	79.20	70.9076	110.62
	C/10	2.000	19.2146	97.85	77.79	67.4832	105.38	19.4212	97.75	77.41	68.2710	106.51
	C/5	4.000	18.8235	95.86	76.21	64.5680	100.82	19.0256	95.76	75.84	65.3134	101.89
	C/2	10.000	18.5031	94.23	74.91	60.9530	95.18	18.6773	94.01	74.45	61.5949	96.09
	0.75C	3.225	18.4461	93.94	74.68	59.5334	92.96	18.6315	93.78	74.27	60.2377	93.97
	1.00C	4.300	18.3440	93.42	74.27	58.1755	90.84	18.5532	93.38	73.95	59.0083	92.06
- 30°C	C/20	1.000	17.3274	100.00	70.15	59.9788	93.66	17.4505	100.00	69.56	60.4010	94.23
	C/10	2.000	16.8023	96.97	68.02	56.6529	88.46	16.8650	96.64	67.22	56.8208	88.64
	C/5	4.000	16.3935	94.61	66.37	53.5326	83.59	16.4056	94.01	65.39	53.4654	83.41
	C/2	10.000	16.0214	92.46	64.86	49.9939	78.07	15.9493	91.40	63.58	49.6822	77.51
	0.75C	3.225	15.8621	91.54	64.22	48.3059	75.43	15.7351	90.17	62.72	47.9337	74.78
	1.00C	4.300	15.6782	90.48	63.47	46.5247	72.65	15.4545	88.56	61.60	45.9966	71.76

Yardney Li-ion 20 Ah Li-Ion Performance Testing
Discharge Rate Characterization at 20°C

Discharge Capacity (Ah)

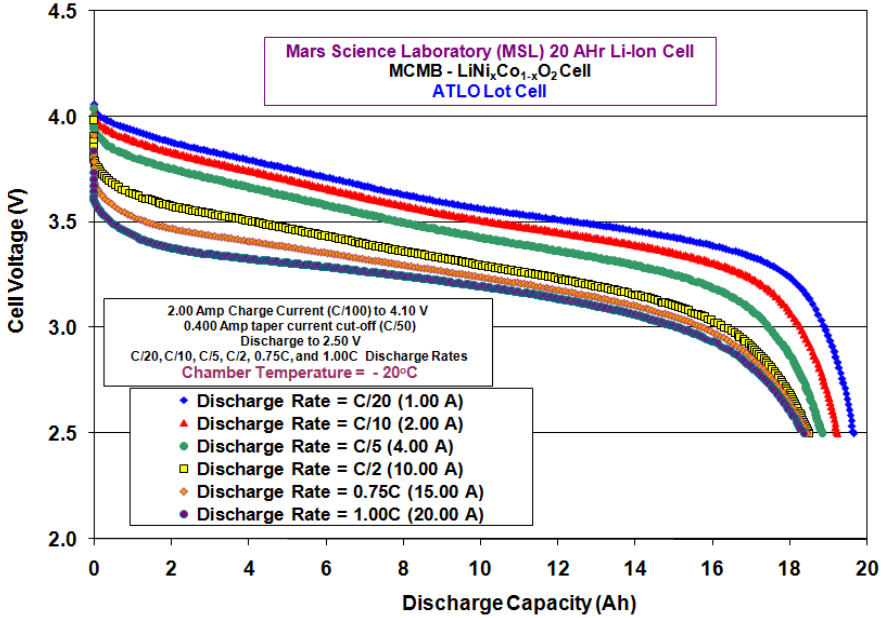


Discharge Energy (Wh/Kg)

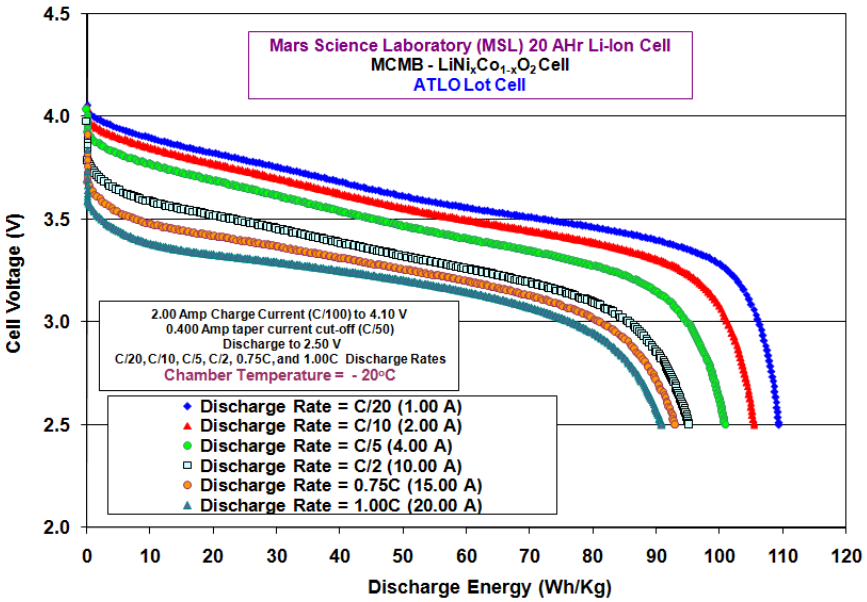


Yardney Li-ion 20 Ah Li-Ion Performance Testing
Discharge Rate Characterization at - 20°C

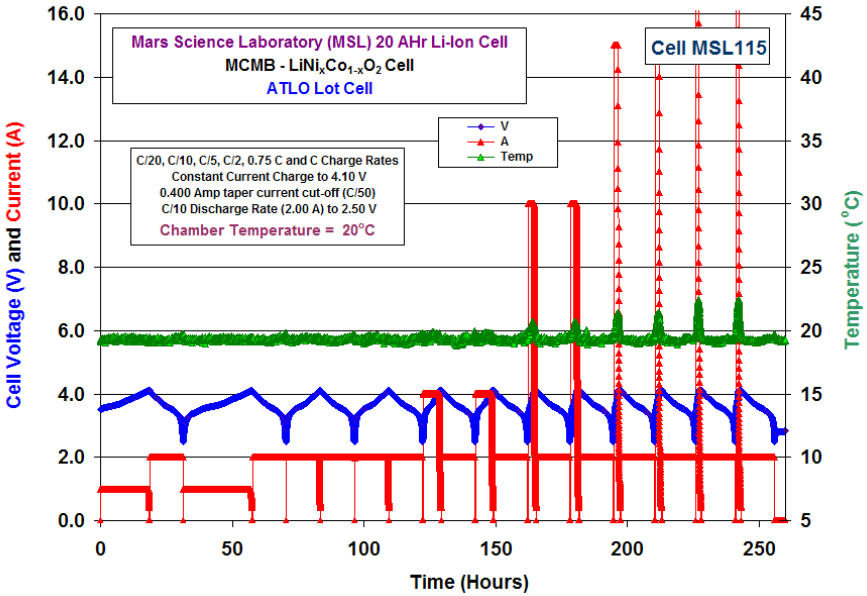
Discharge Capacity (Ah)



Discharge Energy (Wh/Kg)



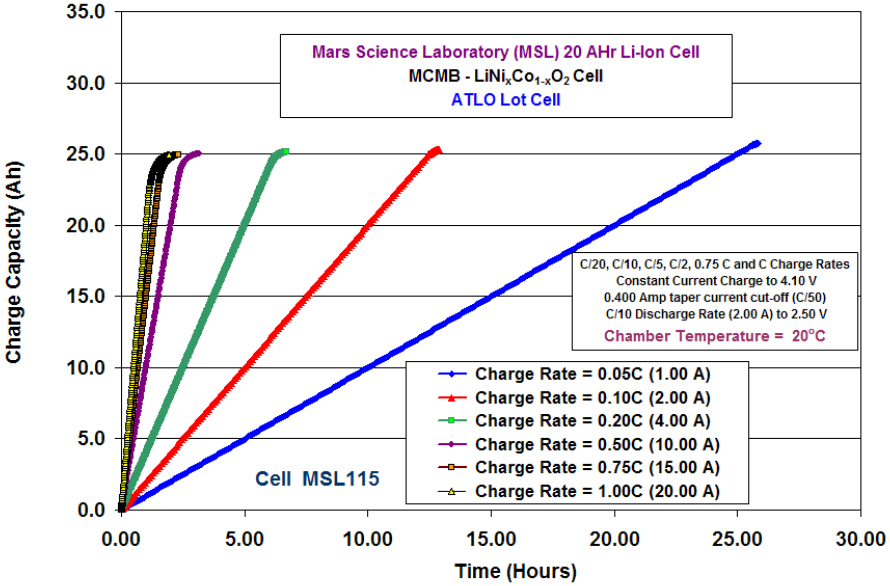
Yardney Li-ion 20 Ah Li-Ion Performance Testing
Charge Rate Characterization at + 20°C



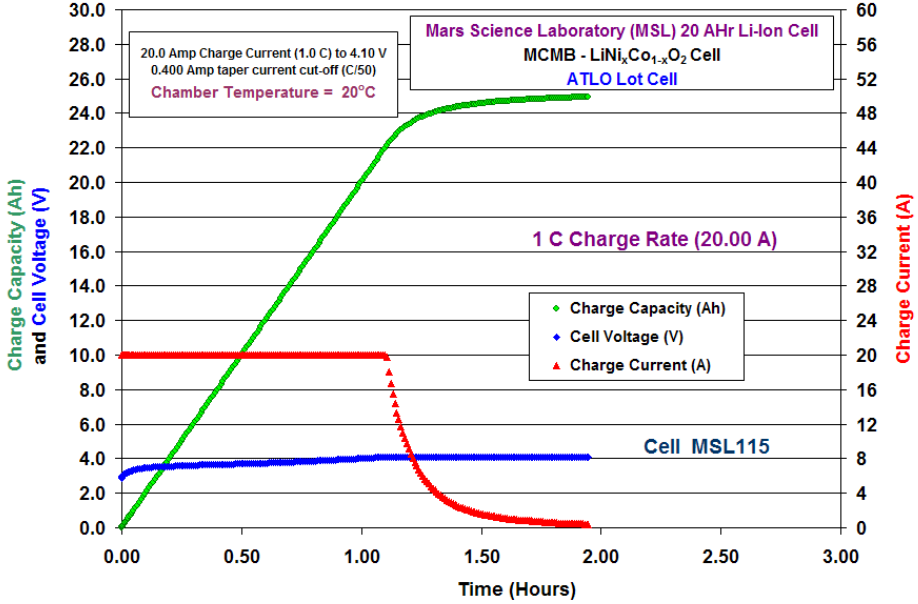
			Cell MSL-115						
Temperature	Charge Rate	Discharge Current (A)	Charge Capacity (Ah)	Charge Time (Hours)	Percent C/10 Capacity	Percent C/10 Capacity at 20°C	Charge Watt-Hr (Wh)	Discharge Watt-Hr (Wh)	Watt Hour Efficiency (%)
20°C	0.05C	1.000	25.7371	25.8159	100.00	100.00	94.0588	91.2645	97.03
	0.10C	2.000	25.3177	12.8806	98.37	98.37	92.7204	91.2691	98.43
	0.20C	4.000	25.1393	6.6795	97.68	97.68	92.4562	91.3611	98.82
	0.50C	10.000	25.0397	3.1654	97.29	97.29	93.0827	91.3927	98.18
	0.75C	15.000	24.9592	2.3275	96.98	96.98	93.4732	91.1826	97.55
	1.00C	20.000	24.9395	1.9474	96.90	96.90	94.0112	91.1418	96.95

Yardney Li-ion 20 Ah Li-Ion Performance Testing
Charge Rate Characterization at + 20°C

Charge Capacity (Ah)



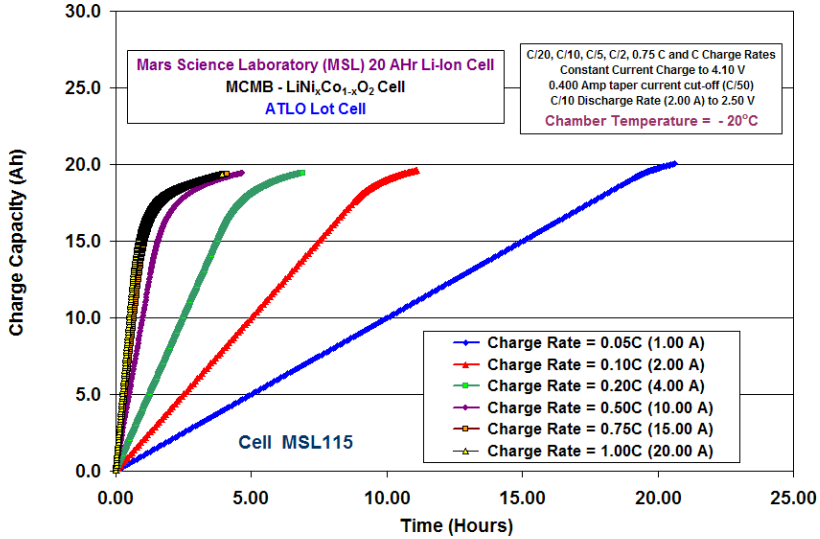
1.0C Rate Charge



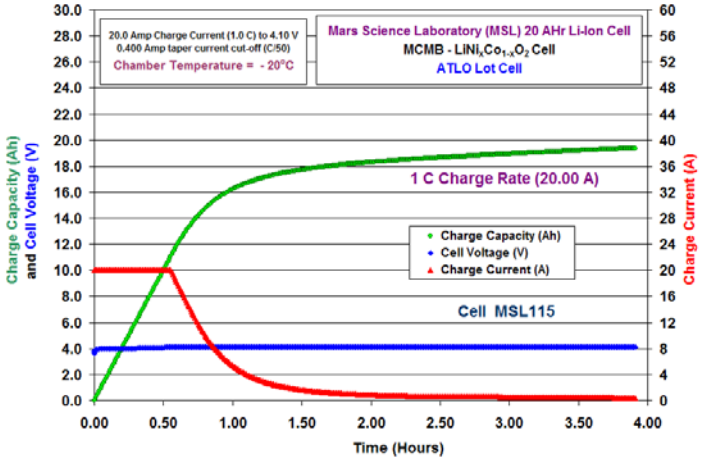
Yardney Li-ion 20 Ah Li-Ion Performance Testing

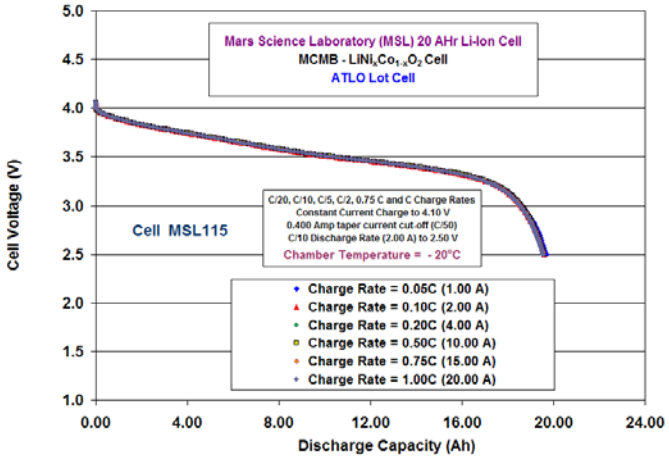
Charge Rate Characterization at - 20°C

Charge Capacity (Ah)



1.0C Rate Charge





- Cells were capable of being charged at high rates at low temperatures, without any evidence of lithium plating observed.

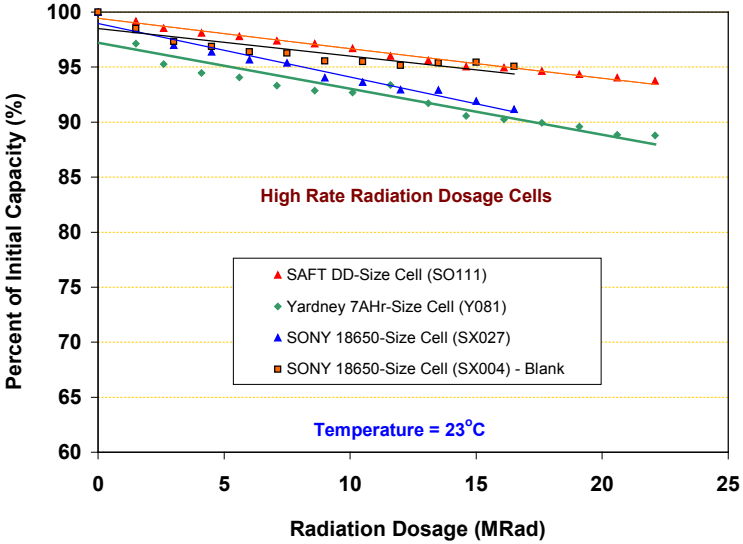
Future Outer Planets Missions

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



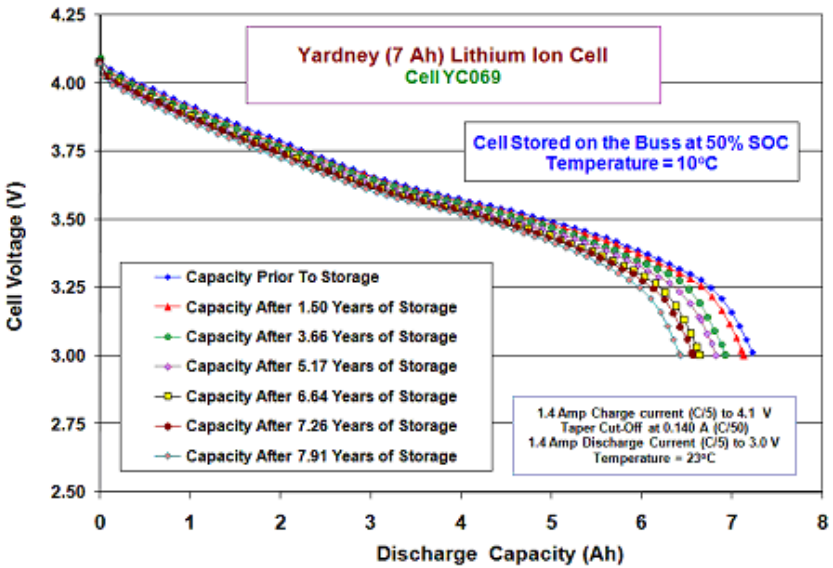
➢ Demonstrated Li-ion resilience to radiation

Lithium-Ion Cells for Future Outer Planets Program Applications

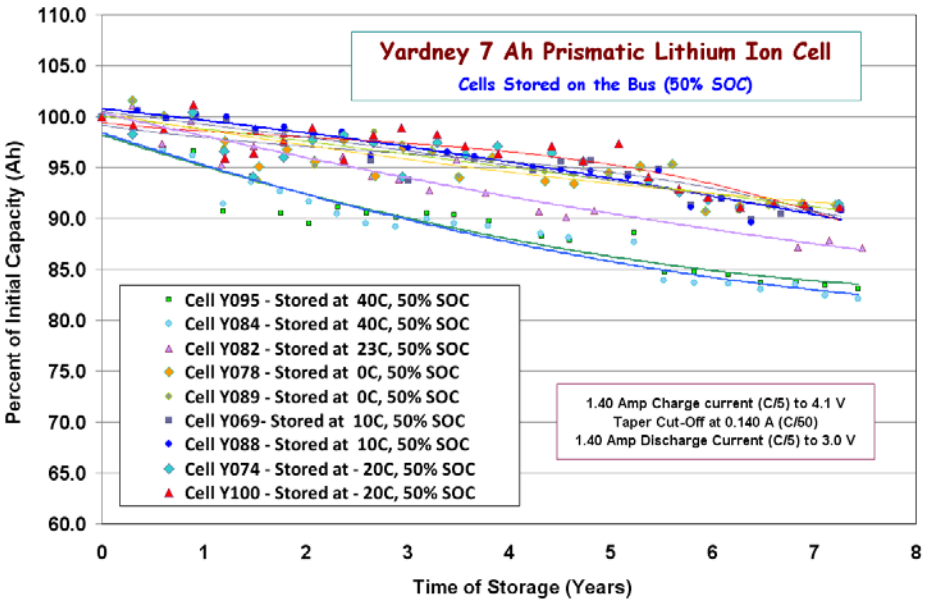
Storage Characteristics of SAFT and Yardney Li-Ion Cells

Cells Stored at Various Temperatures at 50% SOC (Float Charged)

Saft 9 Ah Cells Stored at 10°C



Yardney 7 Ah Cells Stored at Various Temps

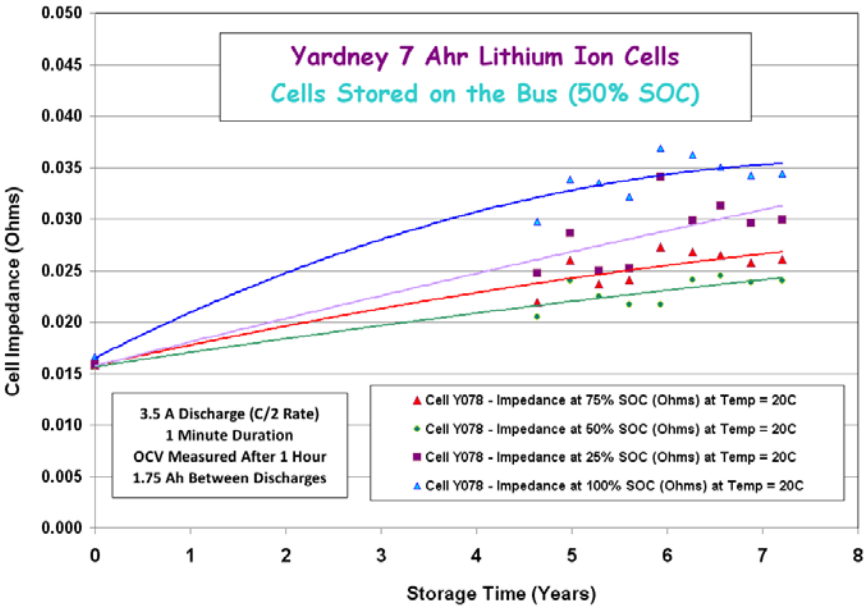


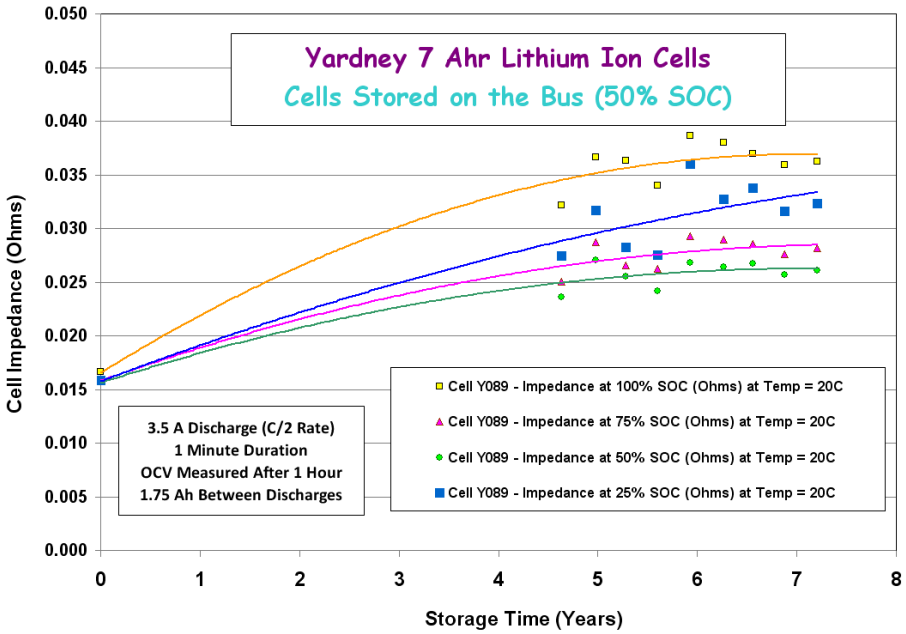
- A number of cells stored on the bus at 50% SOC at different temperatures.
- Cells cycled at both 23 and 0°C every 3 months to determine reversible capacity.
- Less than 10% capacity loss observed with cells if stored at temperatures of 10°C or less.
- Tests on-going for further validation of projections.

Yardney 7 Ah Lithium-Ion Cells

Long Term Storage Characteristics

Summary of Impedance Growth (Cell YC078)





- 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

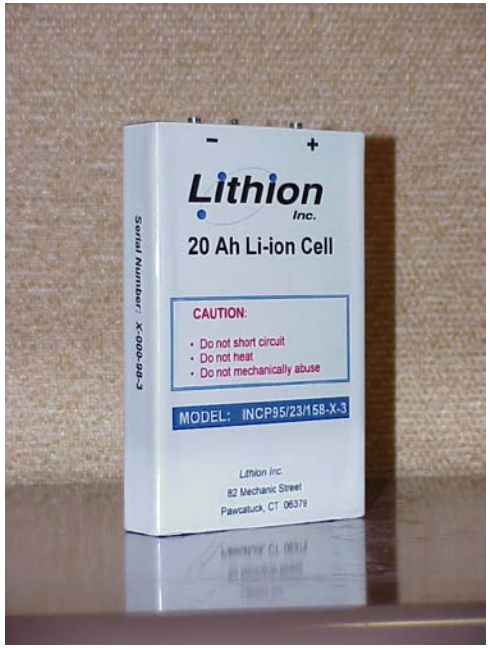
Performance of Ester-Based Electrolytes at Low Temperatures

- **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

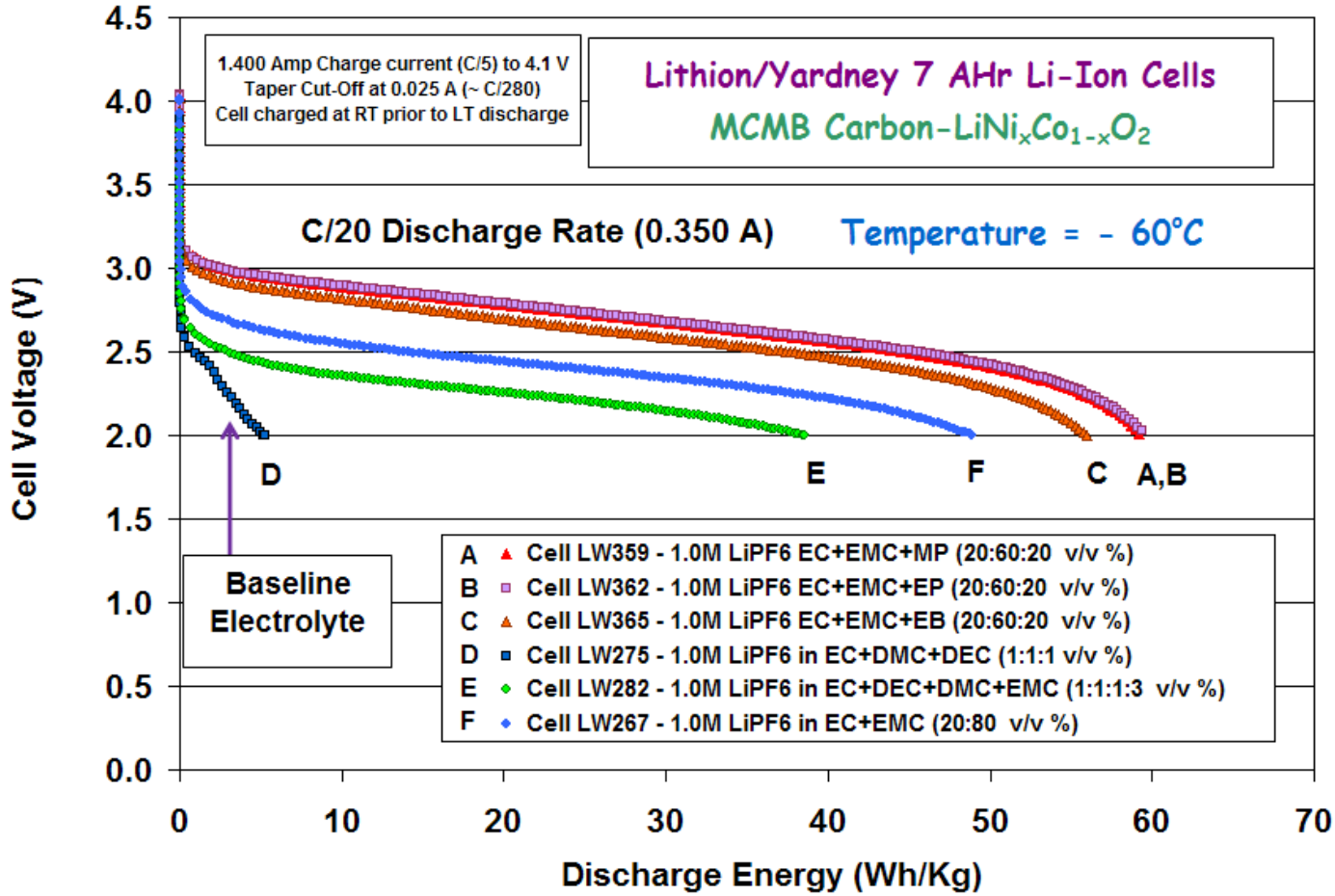
- Performed a number of performance evaluation tests
  - *Conditioning cycling performed at 20°, 0°, and -20°C (with impedance)*
  - *Discharge Rate Characterization at Various Temperatures*
    - *Wide temperature range (-80 to 20°C)*
    - *Wide range of discharge rates (C rate to C/400 rate)*
    - *Comparison of electrolyte types*
  - *Pulse Discharge Characterization at Various Temperatures*
  - *Current-Interrupt Impedance Measurements*

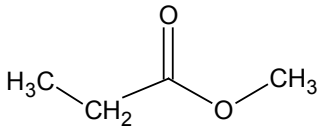


Prototype Lithium-Ion Cells for ESMD Applications

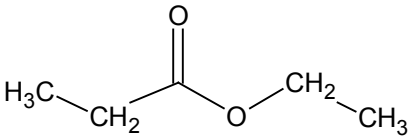
Assessment of All-Carbonate-Based Low Temperature Electrolytes

Discharge Energy at -60°C (C/20 Rate)

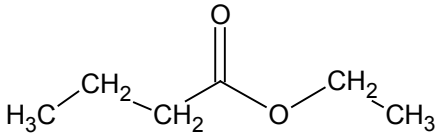




Methyl propionate



Ethyl propionate



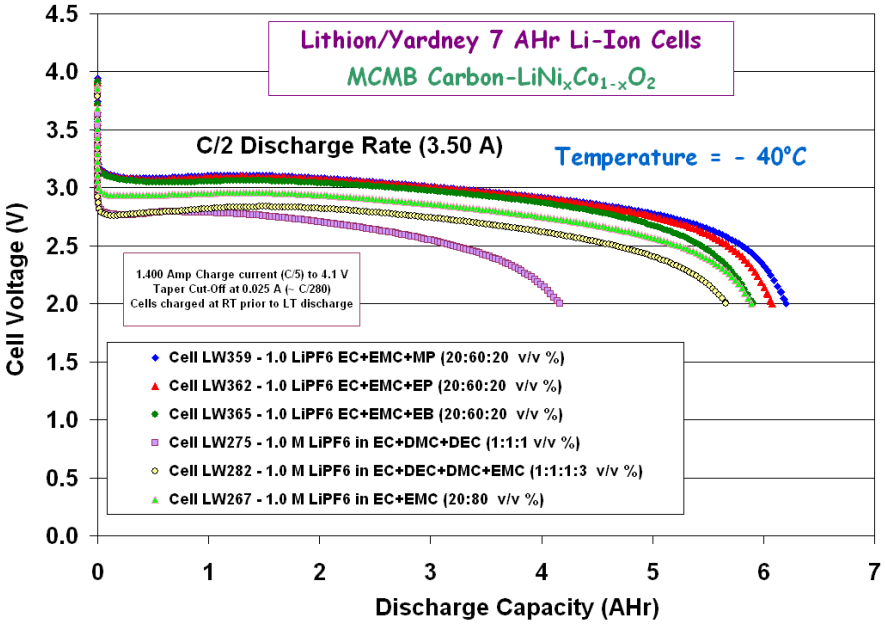
Ethyl butyrate

- Ester co-solvents greatly improve the performance at these very low temperatures (-60°C).
- M.C. Smart, and B.V. Ratnakumar, L.D. Whitcanack, K.A. Smith, S. Santee, R. Gitzendanner, V. Yevoli, "Li-Ion Electrolytes Containing Ester Co-Solvents for Wide Operating Temperature Range", ECS Trans. 11, (29) 99 (2008).

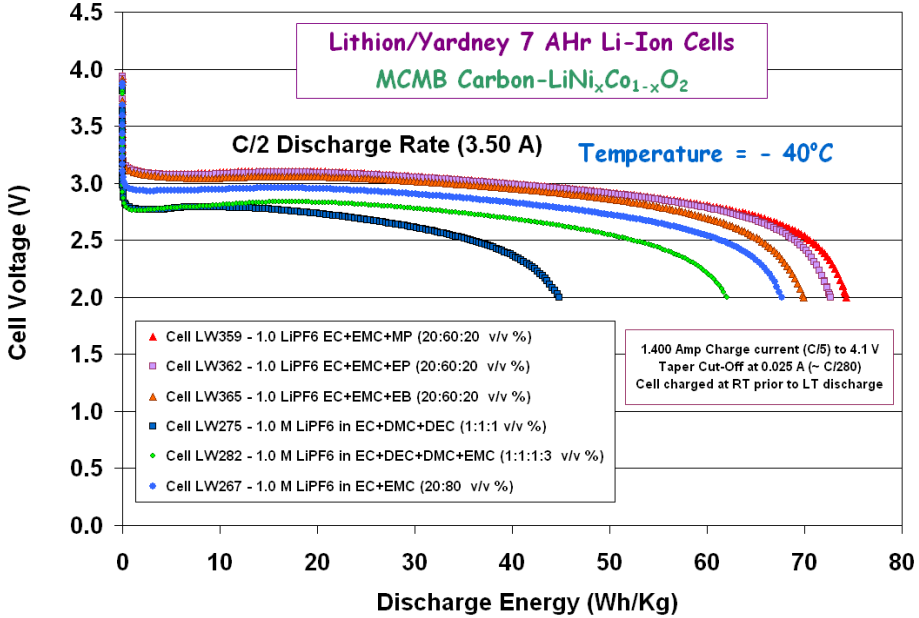
Yardney 7 Ah Prototype Cells with Advanced Electrolytes

Low Temperature Discharge Performance at -40°C (C/2 Rate)

Discharge Capacity (Ah)



Discharge Energy (Wh/Kg)

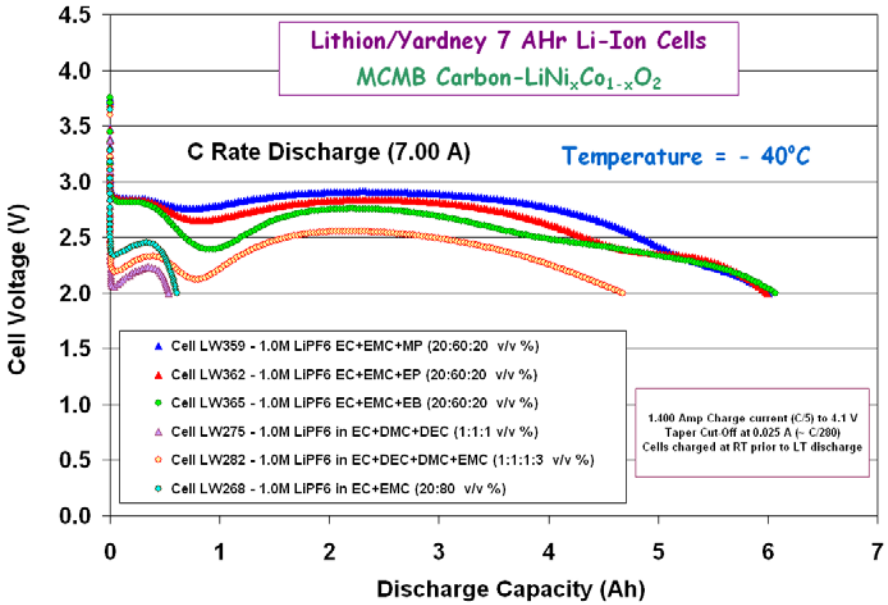


Discharge capacity (Ah) and discharge energy (Wh/Kg) at -40°C, using a C/2 rate discharge (3.50 A), of prototype 7 Ah lithium-ion cells containing electrolytes consisting of 1.0M $LiPF_6$ EC+EMC+X (20:60:20 v/v %) (where X = MP, EP, and EB), as well as cells with baseline all carbonate-based electrolytes.

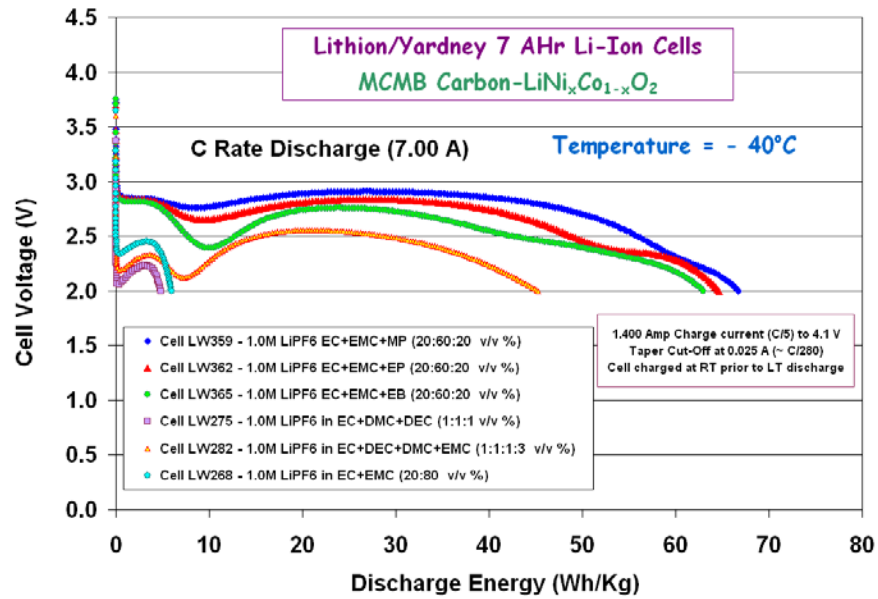
Yardney 7 Ah Prototype Cells with Advanced Electrolytes

Low Temperature Discharge Performance at -40°C (C Rate)

Discharge Capacity (Ah)



Discharge Energy (Wh/Kg)

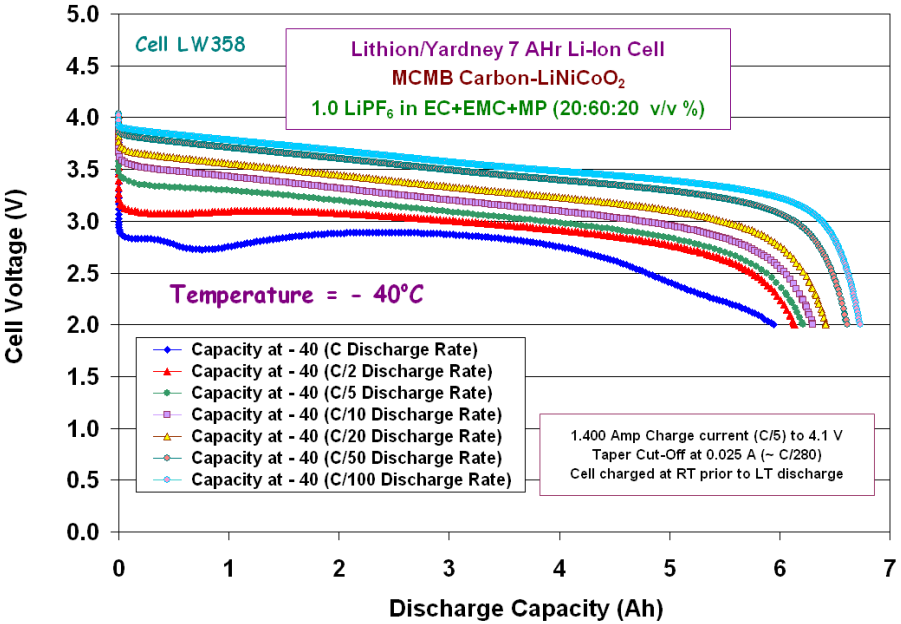


Discharge capacity (Ah) and discharge energy (Wh/Kg) at -40°C, using a C rate discharge (7 A), of prototype 7 Ah lithium-ion cells containing electrolytes consisting of 1.0M $LiPF_6$ EC+EMC+X (20:60:20 v/v %) (where X = MP, EP, and EB), as well as cells with baseline all carbonate-based electrolytes.

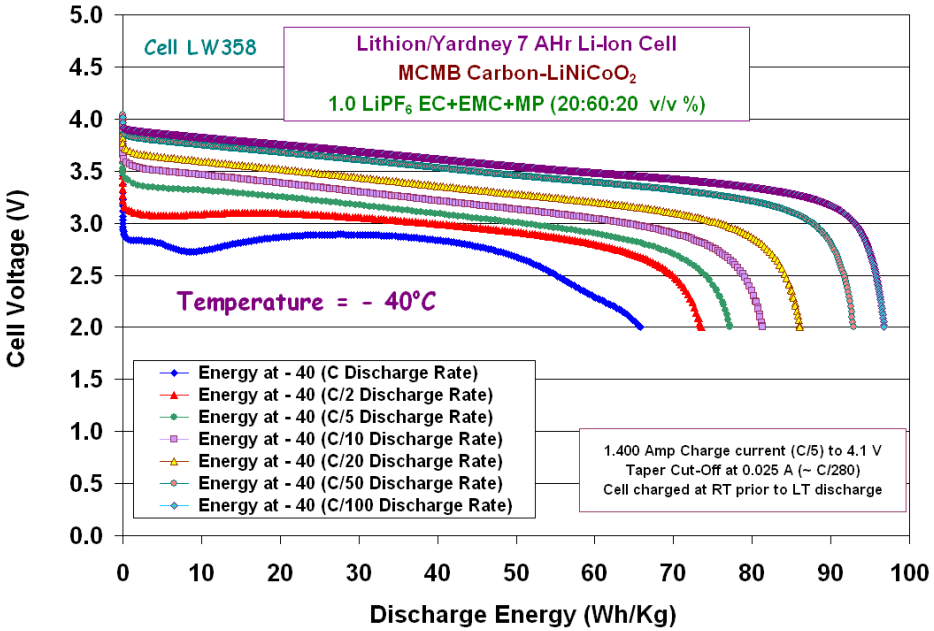
Yardney 7 Ah Prototype Cells with Advanced Electrolytes

Low Temperature Discharge Performance of Prototype Cells

Discharge Capacity (Ah)



Discharge Energy (Wh/Kg)



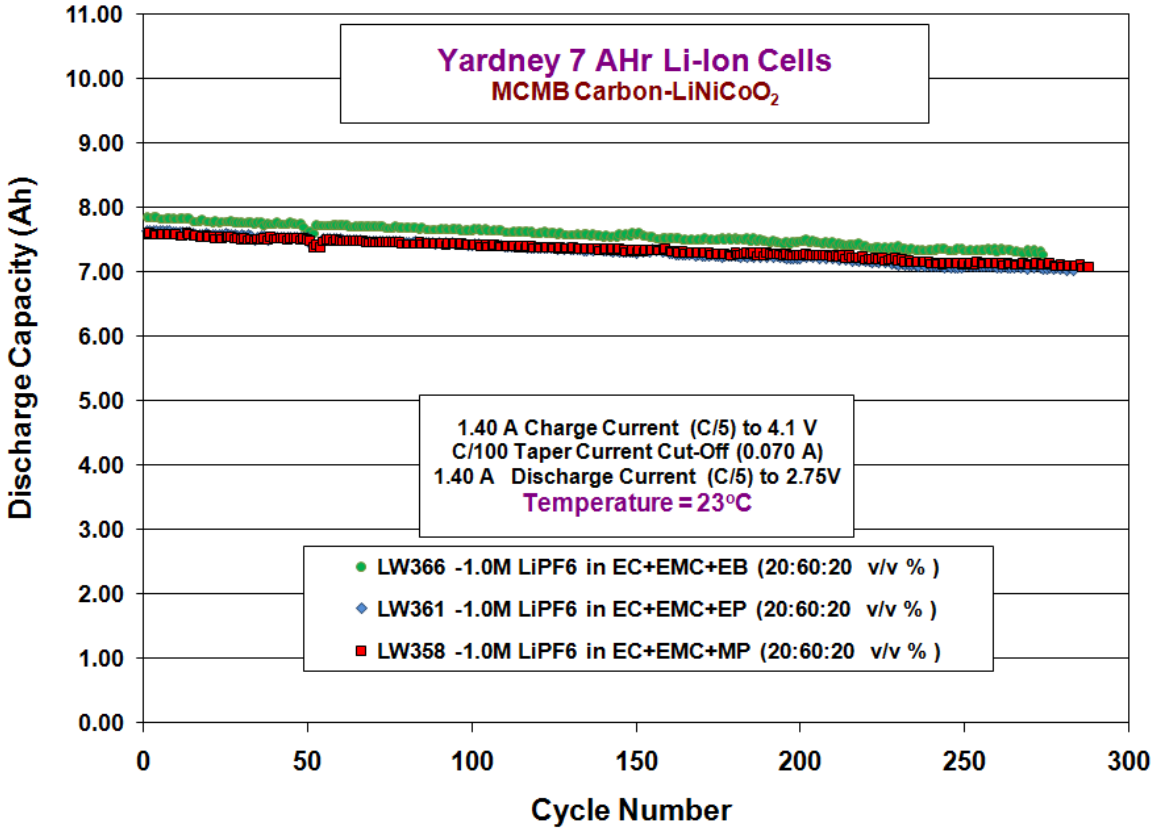
- The methyl propionate-based electrolyte was observed to result in cells with high specific energy at –40°C, with over 75 Wh/kg being delivered at a C/5 rate.

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



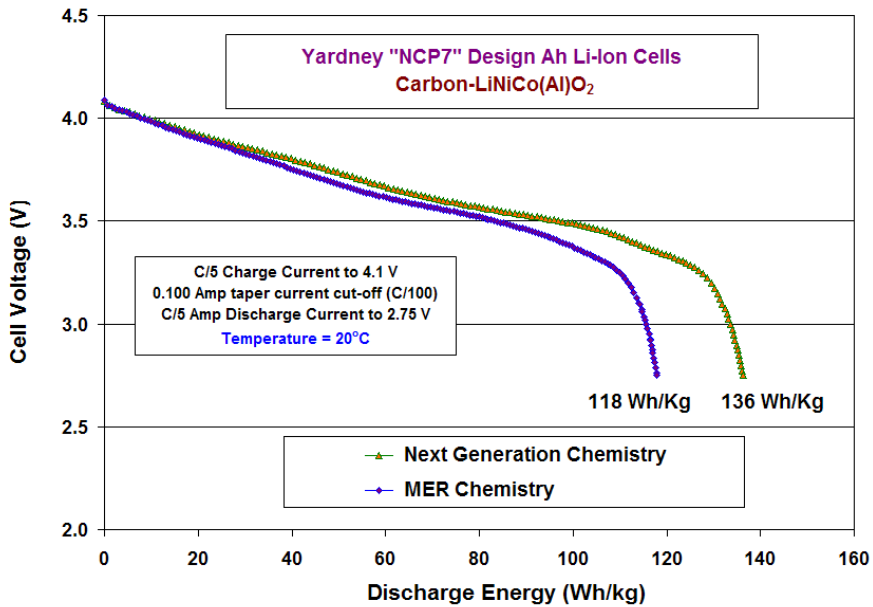
Cells containing ester-based electrolyte also display good cycle life characteristics, being comparable to the all carbonated based systems at room temperature.

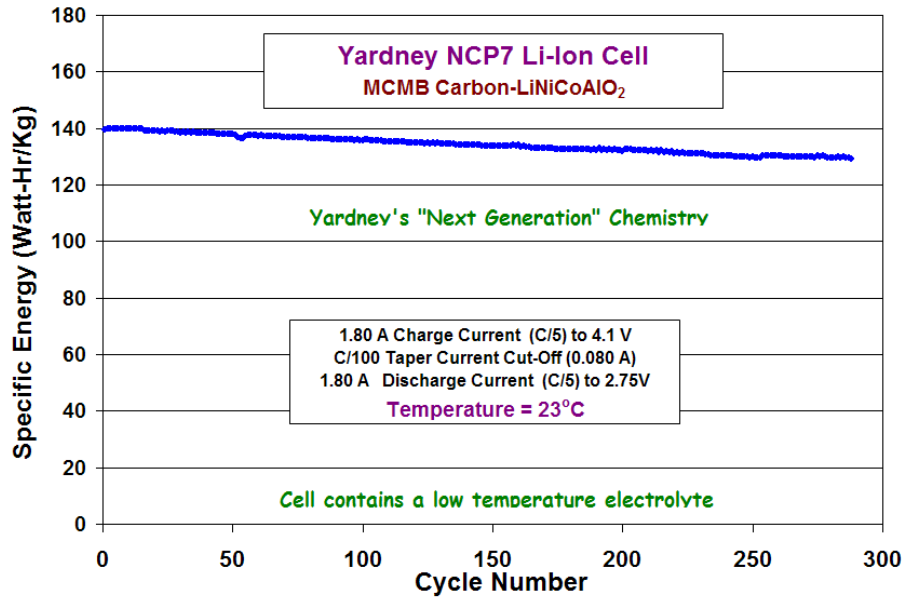
Yardney 7 Ah Prismatic Li-Ion Cells

Characterization of Cells Containing Advanced Chemistries

100 % DOD Cycle Life Testing at Room Temperature

Discharge Energy (Wh/Kg) at 23°C





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).