Performance Testing of Yardney Li-ion Cells and Batteries in Support of JPL's 2009 Mars Science Laboratory Mission

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In 2009, JPL is planning to launch an unmanned rover mission to the planet Mars. This mission, referred to as the Mars Science Laboratory (MSL), will involve the use of a rover that is much larger than the previously developed Spirit and Opportunity Rovers for the 2003 Mars Exploration Rover (MER) mission, that are currently still in operation on the surface of the planet after more than three years. Part of the reason that the MER rovers have operated so successfully, far exceeding the required mission duration of 90 sols, is that they possess robust Li-ion batteries, manufactured by Yardney Technical Products, which have demonstrated excellent life characteristics. Given the excellent performance characteristics displayed, similar lithium-ion batteries have been projected to successfully meet the mission requirements of the up-coming MSL mission. Although comparable in many facets, such as being required to operate over a wide temperature range (-20^o to 40^{o}C), the MSL mission has more demanding performance requirements compared to the MER mission, including much longer mission duration (~ 687 sols vs. 90 sols), higher power capability, and the need to withstand higher temperature excursions. In addition, due to the larger rover size, the MSL mission necessitates the use of a much larger battery to meet the energy, life, and power requirements. In order to determine the viability of meeting these requirements, a number of performance verification tests were performed on 10 Ah Yardney lithium-ion cells (MER design) under MSL-relevant conditions, including mission surface operation simulation testing. In addition, the performance of on-going ground life testing of 10 Ah MER cells and 8-cell batteries will be discussed in the context of capacity loss and impedance growth predictions.

I. Introduction

The next planetary exploration mission to Mars involving a robotic rover is the 2009 Mars Science Laboratory (MSL) mission, which is planned to launch in the Fall of 2009. The MSL rover will be much larger than the MER rovers, Spirit and Opportunity, being twice as long and over three times as heavy. The primary objective of the MSL mission will be to collect Martian soil samples and rock cores and to analyze them for organic compounds, the presence of which may be indicative that the planet is, or has been, capable of supporting microbial life. Unlike previous Mars planetary missions, MSL will the first to employ precision landing techniques, which enables the spacecraft to fly to the desired location above the surface of Mars prior to landing, which will involve the use of a parachute, retro rockets, and a tether. Once on the surface of Mars, the rover will utilize a suite of instruments to attempt to detect proteins, amino acids, and/or other organic compounds that are essential to life.

In order to carry out these science experiments, the MSL rover will utilize a radioisotope power system to generate the needed electricity, similar to other previously flown NASA spacecraft to Mars, such as the Viking landers in 1976. In addition to providing electricity, radioisotope systems can serve as heaters to maintain the desired temperatures in extreme environments, such as on the 1997 Mars Pathfinder Sojourner rover and the 2003 MER rovers (which both have RHUs). In the case of MSL, the "multi-mission" radioisotope thermoelectric generator (or MMRTG) will enable long life for the rover, since it will not be hindered by the fluctuating power levels that could occur with solar arrays. Thus, in contrast to the MER mission which was designed to operate for 90 sols (or 90 Martian days), the MSL mission is being designed to operate a minimum of a full Martian year, or 687 Earth days, with the anticipation that it will likely continue to operate longer. In addition to this long life, the

Rover should be able to demonstrate long range mobility on the surface, being capable of traversing anywhere between 5 to 20 kilometers during it's lifetime in search of desirable samples. [1]

A critical component in the power system is a rechargeable Li-ion battery, which will serve a number of functions throughout the mission, including: (a) providing power during the launch phase of the mission, (b) assist the thermal batteries during the entry, descent, and landing (EDL) phase of the mission, and (c) support the power loads on the Martian surface that exceed the output of the MMRTG. More specifically, the rechargeable battery must meet a number of mission requirements for the mission to be successful, including: (1) possess the ability to be stored 6-12 months prior use on the spacecraft, (b) being capable of providing 920 Wh with a voltage greater than 25 V and a maximum discharge current of 22A during the Launch phase, (c) possess the ability to withstand the cruise phase of the mission (9 month duration) while the battery is maintained at 50-70% state-of-charge (SOC) over a temperature range of -20 to +40^{o}C, (d) being capable of serving as a back-up power during "turn to entry" maneuvers during the cruise phase, which consists of supporting 30 A pulses while the battery is in full SOC, (e) being capable of supporting the EDL power loads (i.e., 25 A short duration pulses), and (e) be capable of augmenting the RTG during the surface operations for at least 670 sols. With regard to the surface operation, the battery must be capable of: (i) being charged and discharged over a wide temperature range (-20^{o}C to +30^{o}C), (ii) operate for over 2,000 cycles, in which the depth-of-discharge (DOD) shall not exceed 45%, and (iii) the operating voltage shall not dip below 25V. In contrast to the MER mission, the temperature that the battery will be exposed to throughout the mission will be somewhat milder for the MSL rover, with an anticipated average temperature of +15^{o}C. However, the battery should be capable of operating over a much wider range of temperatures, namely over a range of -20^{o} to +30^{o}C. In order to avoid conditions which potentially could degrade the life of the battery and/or operating conditions which would be difficult to meet throughout the duration of the mission life, the cycling requirements of the battery was further elaborated upon to include the following conditions: (a) provide 670 cycles of up to 310 Wh between a temperature range of 0 to 30^{o}C, while not exceeding a 22A maximum current, (b) provide 670 cycles of up to 295 Wh between a temperature range of -20^{o} to 30^{o}C, while not exceeding a 10A maximum current, and (c) provide 670 cycles of up to 555 Wh between a temperature range of 0^{o} to 30^{o}C, while not exceeding a 22A maximum current. Furthermore, there shall not be more than three cycles per sol and there shall not be more than one 555 Wh cycles per sol. Lastly, the overall wet life of the battery shall be a minimum of 40 months.

To meet these requirements, Yardney Technical Products is currently fabricating a Rover Battery Assembly Unit (RBAU) which consists of two 8-cell strings of 20 Ah (nameplate capacity) Li-ion cells connected in parallel. Yardney Technical Products successfully fabricated the RBAUs for the MER rovers Sprit and Opportunity, which both landed on the surface of Mars in January of 2004. The two rovers were each designed to operate over a primary mission life of 90 sols (one sol, or Martian solar day, has a mean period of ~ 24 hours and 39 minutes), with mission success being determined, in part, to be at least 600m being traversed by at least one of the rovers on the surface of Mars. To-date, both of the Mars rovers have successfully completed the primary phase of their respective missions, leading NASA/JPL to extend the mission a number of times. As of June 11, 2008, the rover Spirit has completed 1579 sols of operation and has traveled over 7,528 meters (~ 4.7 miles). Unfortunately, one of Spirit's six wheels no longer rotates, thus it leaves a deep track as it drags through the soil. However, the process of dragging has lead to an exciting discovery; that there is exceptionally high silica content in the Martian soil, as determined by the alpha particle X-ray spectrometer, which is indicative of water at some point in the Martian past. As of June 10, 2008, the rover Opportunity has successfully operated for 1557 sols, and has traveled over 11,691 meters (~ 7.3 miles) since landing. Thus, both rovers have exceeded the primary mission requirement (90 sols of operation on the surface of Mars) by over 17 times to-date. The role of the MER rechargeable lithium-ion batteries is to augment the primary power source, the triple-junction solar arrays, and to provide power for nighttime operations. In addition to supporting the surface operations, the lithium-ion batteries were also required to assist during the initial launch period, allow time to correct any possible anomalies occurring during the cruise period to Mars, and support EDL pyros. [2,3]

Given the fact that the Li-ion batteries have displayed excellent life characteristics on the two MER rovers, the same chemistry has been selected for the MSL mission to take advantage of their heritage. This technology was originally developed under a NASA-DoD consortium (including Yardney, the Jet Propulsion Laboratory, USAF-WPAFB, and NASA-GRC) established to develop aerospace quality lithium-ion cells/batteries.[4,5] The chemistry employed for the 2003 MER batteries was originally developed and demonstrated for the 2001 Mars Surveyor Program (MSP'01) lander battery, and consists of mesocarbon microbeads (MCMB) anodes, $LiNi_xCo_{1-x}O_2$ cathode materials, a low temperature electrolyte developed at JPL, encased in a hermetically sealed prismatic stainless steel can. [6,7,8,9] Although using similar chemistries, the MER mission necessitated the design of a smaller cell size (10 Ah, with an 8 Ah nameplate capacity) in contrast to the larger MSP'01 cell design (~ 33 Ah actual and 25 Ah nameplate capacity). Ths MSL mission will require a cell size that falls in between that of the MSP'01 design and the MER design, (i.e., a ~ 24 Ah cell is needed, with a 20 Ah nameplate capacity). In addition, it should also be noted that this same chemistry has been adopted by the Phoenix Polar Lander, in the format of the previously developed MSP'01 battery, which recently successfully landed on Mars. In general, the attractive features of Li-ion batteries for use in planetary exploration missions include: (a) their high specific energy, (b) capability to operate over a wide temperature range, especially at low temperature, (c) low self-discharge rate, (d) high coulombic efficiency and (e) high energy efficiency. Due to mass and volume limitations on the spacecraft, lithium-ion technology is especially attractive when compared with other battery chemistries, such as Ni-Cd, Ni-H_2, and Ag-Zn.

In the present paper, we would like to briefly describe the performance testing that has been performed at JPL on cells and batteries manufactured by Yardney Technical Products in support of previous missions, including MSP'01 and MER , that has led to the performance projections for the MSL mission. In addition, performance testing specifically targeted at MSL mission requirements and performed on MER-based test articles will be discussed. Lastly, preliminary results involving the testing of the cells specifically designed for the MSL mission will be discussed.

II. Performance Testing of MSP'01 8-Cell Batteries and Cells

Since the adoption of Li-ion technology for many NASA missions was benefited by the performance test data base initiated during the development of the 2001 MSP'01 battery, a brief discussion of the results will be provided. Although the MSP'01 mission was eventually cancelled for programmatic reasons, prior to cancellation the battery was fully space qualified. In addition, a number of performance tests were enacted at JPL, Yardney, and Lockheed-Martin to establish the viability of the technology for the mission, including generic charge and discharge characterization testing, 100% DOD cycle life testing, and mission specific simulation testing (i.e., EDL testing and surface operation testing). For example, as illustrated in Fig. 1, prototype 20 Ah cells were cycled under a mission simulation condition which consisted of charging the cells with a constant current (C/5 rate) to 4.1V for a total charge time of 12 hrs, and using a relatively mild discharge current (1 Amp or C/25 rate) for a total of 12 hrs, corresponding to 12 Ah of capacity (~40% DOD). Under these conditions, successful completion of over 1,500 cycles was observed with little performance degradation, representing over four years of testing. These cells had previously been subjected to a 12-month OCV storage and EDL pulsing prior to the mission simulation testing.[8]

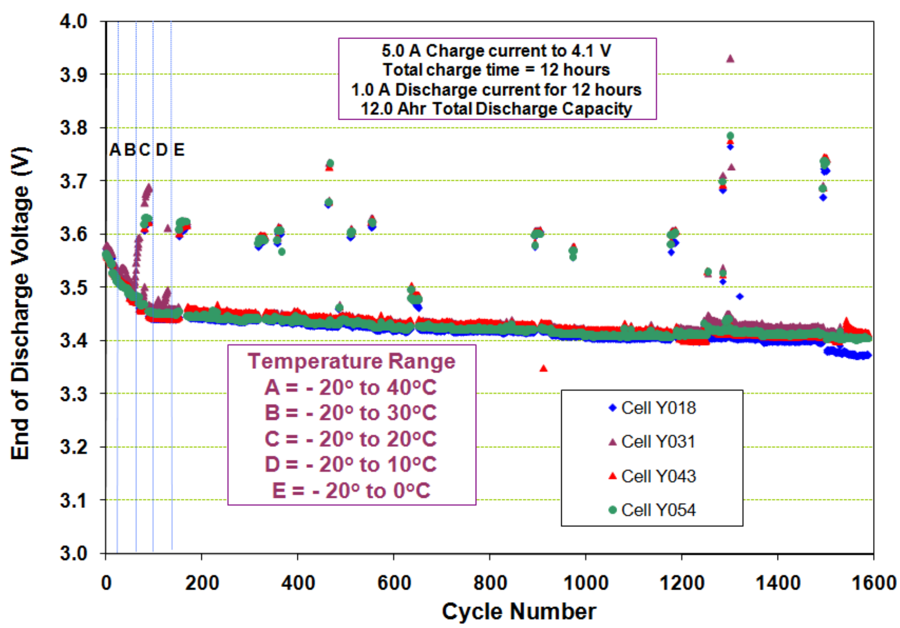

Figure 1. End of discharge voltages of MSP'01 design cells (25 Ah nameplate capacity) subjected to ~ 40% DOD Mars surface operation simulation testing.

After the mission cancellation, the batteries delivered to JPL were subjected to generic performance tests to demonstrate the applicability of the technology to meet future NASA aerospace applications. One of the two batteries currently being tested at JPL is undergoing testing according to anticipated performance requirements of future Mars Lander and Rover applications. The primary goal of this activity is to determine the performance capability to power surface operation on the planet Mars for a prolonged period (> 3 years) after being subjected to a long cruise period. The second 25 Ah battery is currently being tested to determine the viability of using lithium-ion technology for future planetary orbiter applications. The test implemented consists of cycling the battery continuously under LEO conditions (40% DOD), while periodically checking the battery impedance and full capacity (100% DOD). As shown in Fig. 2, over 22,000 cycles have been demonstrated with excellent performance as illustrated by the slowly decaying end of discharge voltage. After completing 22,000 cycles under these conditions (over 4 years of operation) the battery was still capable of delivering 27.377 Ah (or 87.17 % of the initial capacity, 31.405 Ah). Although not directly relevant to MSL, this data illustrates the life characteristics of the batteries are excellent under these conditions.

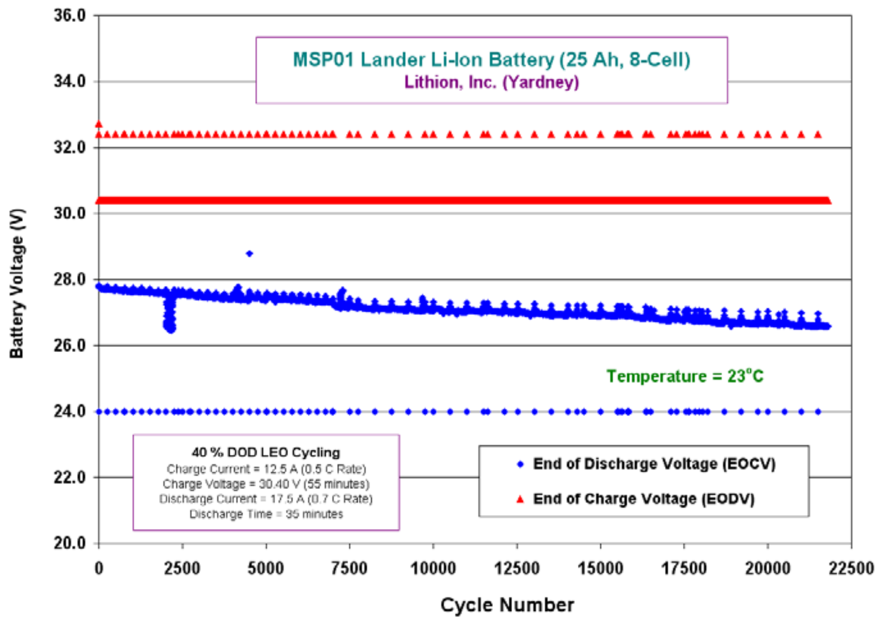

Figure 2. Battery End of battery charge and discharge voltages during 40% DOD LEO cycling (30.40V charge).

III. Performance Testing of MER Rover Battery Assembly Units and Cells

In our previous papers[10,11,12], a detailed discussion of the acceptance testing performed on each MER RBAU was provided, as well as, the testing performed on engineering modules involving the simulation of the launch requirements, cruise environment, and entry, descent and landing (EDL) load profiles. In summary, the acceptance testing of the RBAUs involved performing capacity determination tests at two different temperatures (20 and -20°C), performing open circuit stand tests to determine the self-discharge behavior (72 hours), and performing current-interrupt impedance measurements of the batteries at different states-of-charge (SOC). To determine the ability to meet the launch requirements and any possible trajectory maneuvers during the cruise period, engineering RBAUs were subjected to load profiles consisting of moderate rates (~ C/2 charge and discharge rates) over range of temperatures (0 to 25°C), and demonstrated to provide the required energy to support these operations. To determine the capability to support the EDL operations, both MER cells and an engineering RBAU were tested according to profiles consisting of high current pulses (up to 30A) over a range of temperatures (0 to 30°C) and states-of-charge (SOC).

One of the main objectives of performing ground testing was to provide meaningful input regarding battery health and operating characteristics throughout the mission, thus, there was a concerted attempt to devise a test plan which closely mirrors the conditions anticipated by the two flight batteries of Spirit and Opportunity. With this in mind, after completing some of the initial characterization testing described, one of the RBAUs was dedicated as a mission simulation battery. This battery was subjected to: 1) preliminary acceptance testing, (2) determining the capacity at different temperatures, (3) performing current interrupt impedance measurements, (4) performing cruise period storage simulation testing (7 months on the bus at ~ 70% SOC), and (5) performing surface operation mission simulation testing. To assist in the assessment of the health, periodically the capacity determination and impedance characterization testing was performed over a range of temperatures (20^o, 0^o, -20^o, and -30^{o}C), the results of which are described below. This data was especially helpful in the design phase of the MSL mission.

A. Surface Operation Mission Simulation Testing of MER RBAUs

After completing the initial characterization tests described above, the mission simulation battery was subjected to a 7-month storage period to mimic the conditions that the battery would experience on the way to Mars. This test consisted of storing the battery at ~ 70% SOC on the bus, corresponding to 30.40 V, at 10^{o}C. The battery SOC was selected to minimize the capacity loss and impedance growth, while still providing enough energy in reserve to allow for any maneuvers during cruise. Once this test was completed and post-cruise characterization had been performed, the RBAU was tested according to a surface operation profile, similar to that expected of the Mars rovers. This initial profile consisted of cycling the batteries over a temperature range of -20 to 0^{o}C, using moderate rates (< C/4 charge and discharge rates, based on actual capacity) and a depth of discharge (DOD) of ~ 45% (representing one cycle per Martian sol, or 24.65 hours). Although the DOD implemented has remained pretty consistent (40-50% DOD) over the course of testing, the temperature range has been changed a number of times to address the need for information of how the battery will respond to the different seasons on Mars, as well as, to accurately mimic the capacity loss and impedance growth under these different conditions. Thus, the batteries were initially subjected to a lower range of temperatures (sols 1-45) and then exposed to warmer temperatures (sols 45-180), followed by much lower temperatures to simulate the onset of winter. Currently, the battery is being exposed to a temperature range which represents an average of what the two batteries on Mars are experiencing (-2^o to + 16.6 ^{o}C).

B. Capacity Determination during Surface Operation Testing of MER RBAUs

To determine the performance degradation characteristics as a function of cycling, 100% DOD capacity measurements were performed at different temperatures every 90 sols to aid in estimates of the permanent capacity loss experienced by the batteries on Spirit and Opportunity. Prior to performing the measurements, the cells within the batteries were balanced (to < 50 mV dispersion) so as to obtain full capacity and optimal performance, as well as to closely mirror the conditions experienced on the two rovers. Excellent performance has been obtained thus far, which has been encouraging to the MER project and has factored into the decisions to extend the mission further, as well as providing a benchmark for the performance to be expected for the MSL mission. As shown in Table 1, one of the batteries (FM4B) still exhibits 86.7 % of the initial capacity after completing the cruise period and 920 sols of surface operation simulation. In addition, the other battery under test (FM4A) shows very complementary data with 86.6% of the original capacity being displayed, emphasizing the good reproducibility of the data between the two batteries. The discharge capacities and energies tabulated in Tables 1 at the lower temperatures (i.e., 0^o, -20^o, and -30^{o}C), represent conditions in which the batteries are charged at room temperature prior to low temperature discharge. As expected, somewhat lower values are observed when charging at lower temperatures, due to the poorer charge acceptance characteristics. For example, the discharge capacity obtained at -20^{o}C of one of the batteries (FM4B) using a room temperature charge was 5.764 Ah after 920 Sols, whereas, only 4.906 Ah was obtained at -20^{o}C when the battery was charged at low temperatures.

Table 1. Capacity loss at different temperatures of a MER design 10 Ahr lithium ion battery (FM4B) subjected to mission surface operation simulation. Discharge capacities obtained at low temperatures were obtained using a room temperature charge (20°C).

	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

When the discharge curves of the 100% DOD capacity tests are compared, which are performed approximately every 90 sols, as shown in Fig. 3, the voltage profile displays little change. As illustrated by the figure, the greatest decline in capacity and polarization appears to have occurred as a result of the cruise period and first ninety sols of operation, after which there is a leveling off in the performance degradation. As expected, the capacity decline and polarization effects are more pronounced at low temperature, as illustrated in Fig. 4, in which the discharge capacity is shown as a function of cycle life at -20°C. It should be noted that the capacity values, and the corresponding discharge curves, illustrated in the figure were obtained with a low temperature charge. In contrast to the room temperature data, the performance observed at -20°C appears to suggest that the cruise had a less dramatic effect upon the low temperature performance, whereas the impact of the first 90 sols had a much more prominent impact. It should also be mentioned that all capacity determination testing (at all temperatures) was performed using a 32.40V charge voltage, with the intent of preserving consistency throughout the testing. Thus, higher capacity will be certainly obtained using higher charge voltages (i.e., 32.80V), however, the trends in performance should be comparable.

As shown in Fig. 5, after completing 920 sols of the surface operation load profile, the batteries are still capable of supporting operation over a wide temperature range (+20° to -30°C). As illustrated, ~ 40% of the room temperature discharge capacity can be delivered at -30°C, when the battery is charged at room temperature. The fact that the low temperature performance is preserved to such an extent is significant, given that the RBAU has been on test for over 5 years under a range of conditions. Furthermore, since capacity and impedance characterization has been performed every ~ 90 sols, the batteries have been subjected to more exercise than the 920 cycles represented by the surface operation test. With the intent of trying to predict the performance capabilities into the future, the capacity degradation trends were projected to 1200 sols, as illustrated. As evident from the figure, the batteries can clearly support the mission well beyond 1,200 sols over a wide temperature range (-20° to +30°C), provided the depth-of-discharge (DOD) remains moderate (40-50 % DOD). Of course, this is also supported by the fact that the MER rovers have demonstrated over 1,500 sols of operation, to date.

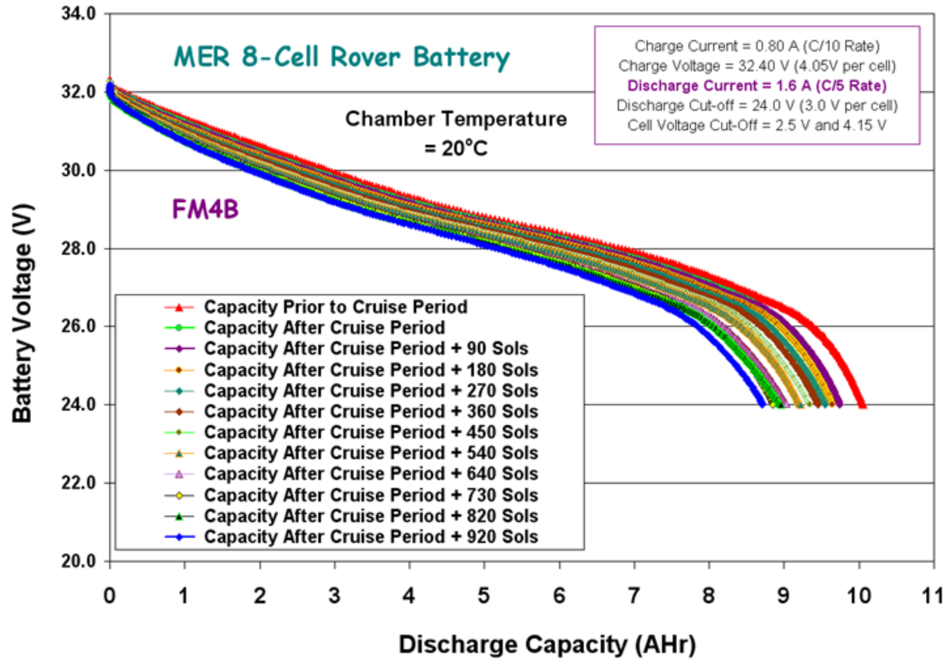

Figure 3. Discharge capacity (100 % DOD) at 20°C as a function of surface operation life.

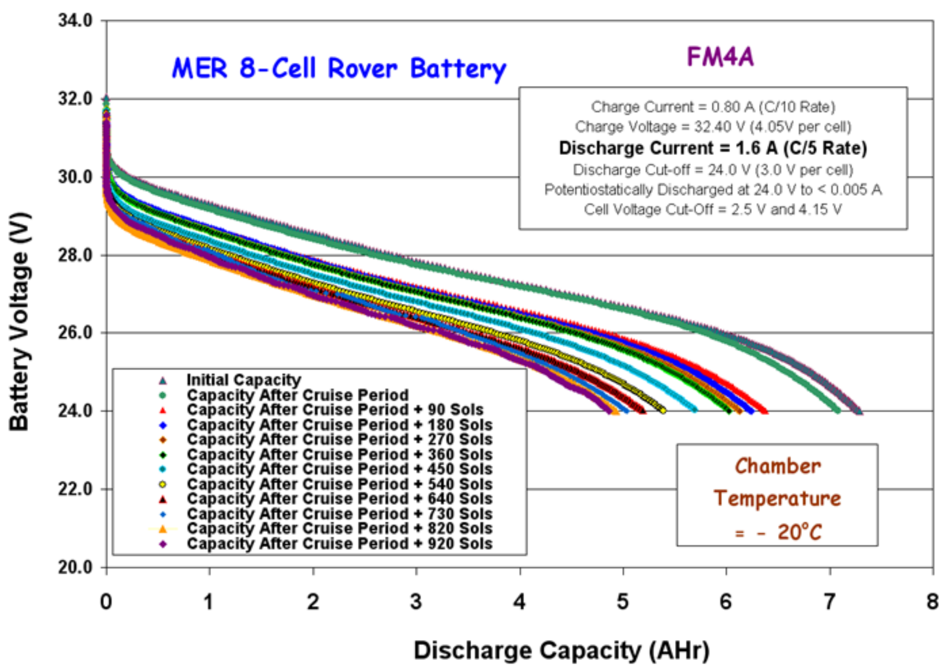

Figure 4. Discharge capacity at - 20°C as a function of surface operation life.

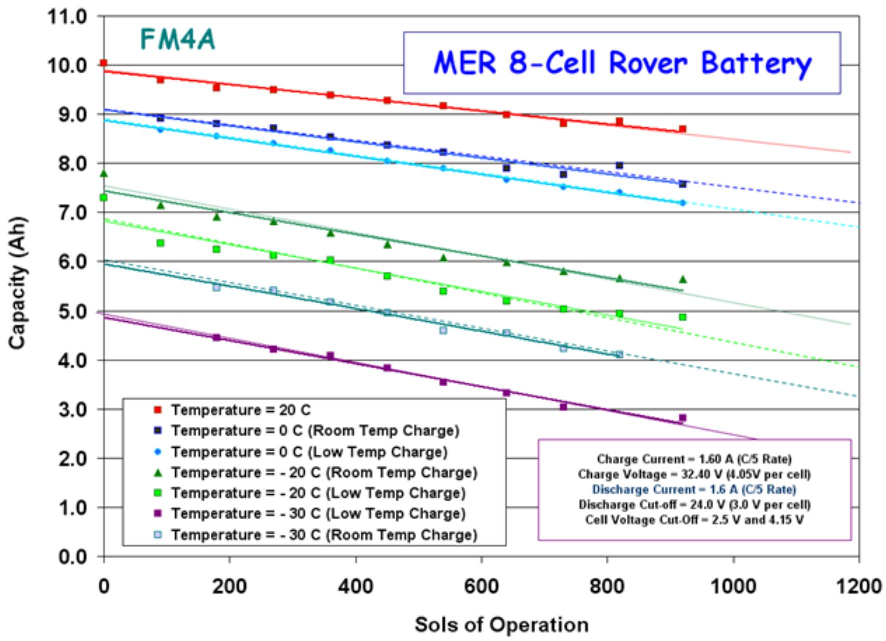

Figure 5. Discharge capacity at different temperatures after completing 920 sols of surface operation. Battery was charged at room temperature prior to low temperature discharge.

IV. Performance Testing of MER Cells for the MSL Mission

Although these results accumulated for the MER program are certainly encouraging with respect to the performance target of providing > 670 sols of operation for the MSL mission, there are significant differences between the two missions, with the latter possessing more challenging requirements, such as: (1) much warmer temperatures predicted during the cruise phase of the mission, (2) increased power needs on the surface (i.e., higher discharge currents anticipated), and (3) the need to maintain a higher operating voltage during surface operation (25.2 V vs. 24.0V). For this reason, a number of performance tests have been performed on cells of similar chemistry to that of the MSL-design cells (e.g., MER heritage cells) to attempt to quantify the performance degradation associated with the conditions anticipated for MSL, including (a) the capacity loss and impedance growth brought about by being subjected to warm temperatures during cruise and (b) the power and capacity loss as a function of time (number of sols completed) and depth of discharge. To supplement these preliminary results, a comprehensive test program will be initiated on the MSL-design cells in the near future.

A. Impedance Determination during Surface Operation Testing

Prior to finalizing the mission battery requirements, a number of tests were initiated on MER-design cells to determine the effect of the DOD upon the life characteristics of the cells when subjected to variable temperature surface operation testing. A number of surface operation load profiles were devised based upon initial projections involving sols where strenuous driving of the rover would occur, involving deeper DOD and higher current, coupled with sols in which there were more moderate power needs. In addition, a number of scenarios were tested in which the DOD was systematically varied (i.e., 40, 60, and 80% DOD) while keeping the temperature profile constant (-3 to +30^{o}C). An example of the surface load profile is illustrated in Fig. 6, in which a 60% DOD load profile is displayed where there are alternating low current sols coupled with high current sols. It should be noted that these initial surface operation projections were based on utilizing a battery with lower capacity for the mission compared to the current design of two 20 Ah batteries in parallel. Furthermore, the average temperature of the battery during the surface operation is expected to be lower than originally anticipated. Thus, it should be emphasized that the results obtained on these preliminary tests overestimate the capacity degradation, average DOD, as well as the power demands. Furthermore, the tests were performed on cells which were in storage for over two and half years prior to testing.

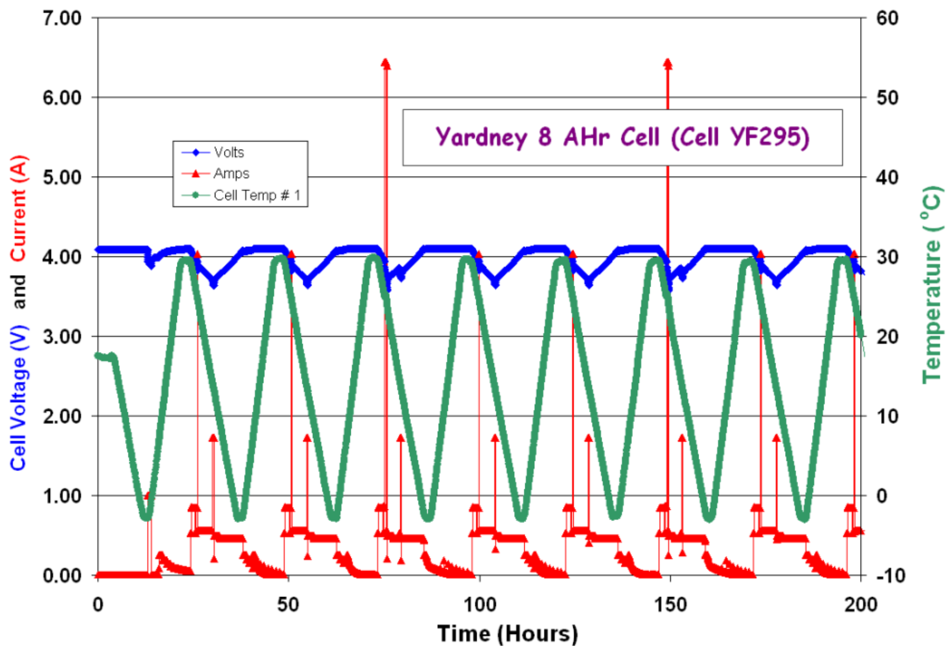

Figure 6. MSL surface operation load profile (~60% DOD) implemented on a MER-design cell over a temperature range of -3° to +30°C.

After completing increments of 90 sols of operation under the testing regime described above, the cells were characterized to determine their capacity and impedance at different temperatures (20, 0, and -20°C). As shown in Fig. 7, the capacity decline was more pronounced in the case of the cell which was cycled using the more aggressive DOD (80%), as expected, being especially pronounced at the lower temperature. Similar trends were observed with regard to the impedance growth, as determined from DC current-interrupt impedance measurements performed as a function of state of charge. These measurements were helpful in assessing the power loss as a function of cycle life and the voltage drop associated with this impedance growth. For example, the voltage drop characteristics of a cell at 0°C being subjected to a ~ 0.4C discharge rate as a function of life (number of sols completed with a ~ 60% DOD surface profile) is illustrated in Fig. 8. As expected, these power losses are even more dramatic at lower temperatures and if the cells are subjected to surface profiles with more aggressive DODs. These preliminary results support the conclusion that life characteristics of the preliminary design involving a smaller battery were limited by the power capability, especially at lower temperatures, which is exacerbated if high DOD is necessitated by the mission. These results, in part, led to the adoption of a larger battery for the mission, which has the benefit of lowering the power demands on the battery, decreasing the average DOD (so that it shall not exceed 45%), and providing a larger thermal mass, which helps to moderate the battery temperature. In the near future, MSL-design cells will be subjected to a revised surface operation profile to enable us to quantify the capacity fade and impedance growth over the duration of the mission. In summary, we anticipate that the newly designed batteries will successfully meet the capacity and power needs of the mission for > 670 sols, with margin to spare.

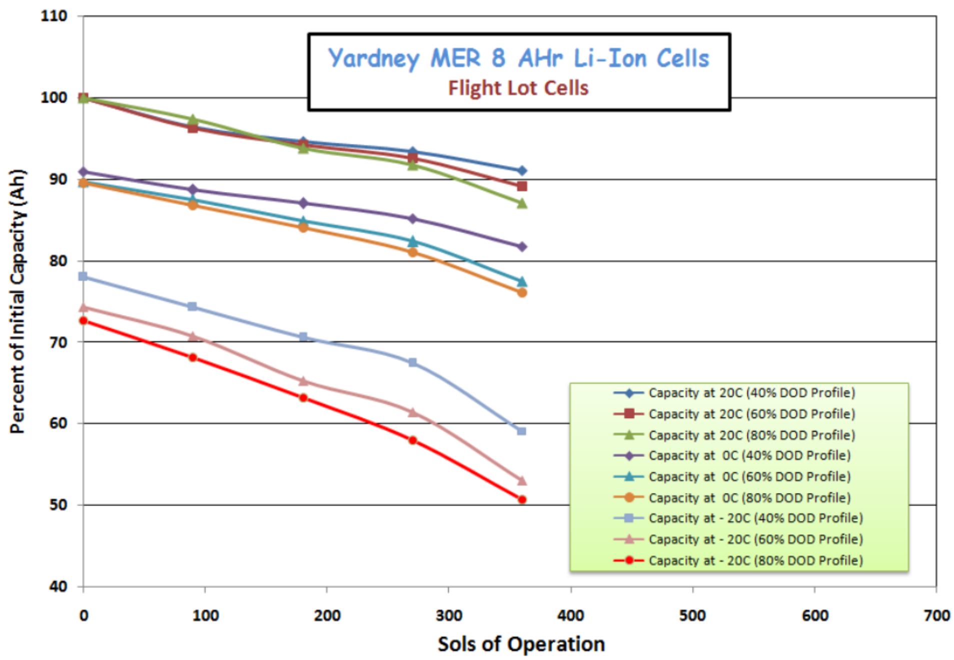

Figure 7. Discharge capacity at different temperatures after completing 360 sols of MSL surface operation where the average DOD was varied.

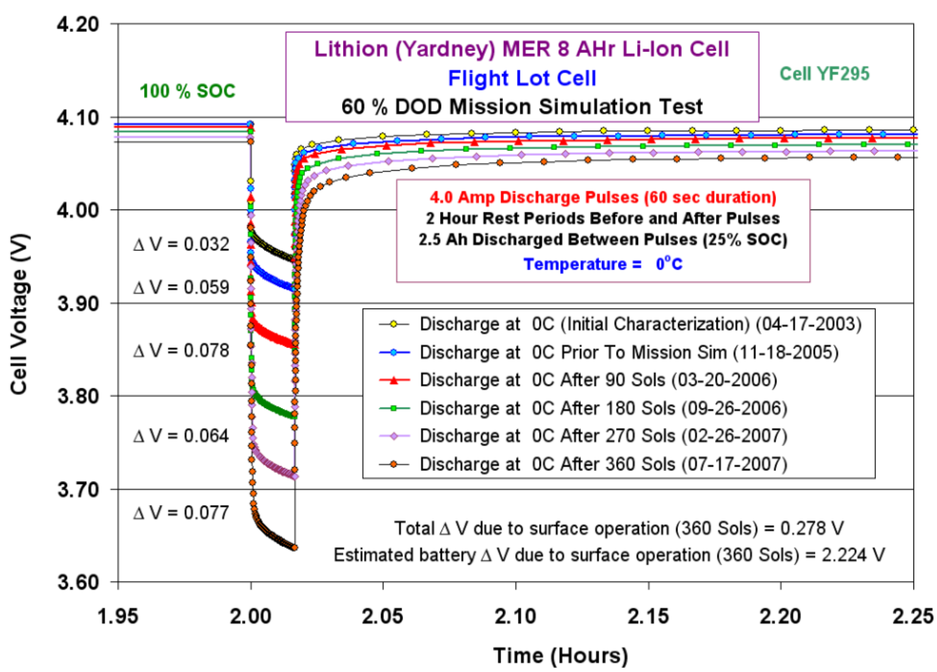

Figure 8. Voltage drop characteristics of a cell at $0^{o}C$ before and after being subjected to surface operation mission simulation (~ 60% DOD profile).

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References

[1] For details describing the MSL mission, see: http://www.jpl.nasa.gov/

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