Performance Testing of Lithion Li-ion Cells and Batteries in Support of JPL's 2003 Mars Exploration Rover Mission

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In early 2004, JPL successfully landed two Rovers, named Spirit and Opportunity, on the surface of Mars after traveling > 300 million miles over a 6-7 month period. In order to operate for extended duration on the surface of Mars, both Rovers are equipped with rechargeable Lithium-ion batteries, which were designed to aid in the launch, correct anomalies during cruise, and support surface operations in conjunction with a triple-junction deployable solar arrays. The requirements of the Lithium-ion battery include the ability to provide power at least 90 sols on the surface of Mars, operate over a wide temperature range (–20°C to +40°C), withstand long storage periods (e.g., including pre-launch and cruise period), operate in an inverted position, and support high currents (e.g., firing pyro events). In order to determine the viability of meeting these requirements, ground testing was performed on a Rover Battery Assembly Unit (RBAU), consisting of two 8-cell 8 Ah lithium-ion batteries connected in parallel. The RBAU upon which the performance testing was performed is nearly identical to the batteries incorporated into the two Rovers currently on Mars. The primary focus of this paper is to communicate the latest results regarding Mars surface operation mission simulation testing, as well as, the corresponding performance capacity loss and impedance characteristics as a function of temperature and life. As will be discussed, the lithium-ion batteries (fabricated by Yardney Technical Products, Inc.) have been demonstrated to far exceed the requirements defined by the mission, being able to support the operation of the rovers for over three years, and are projected to support an even further extended mission.

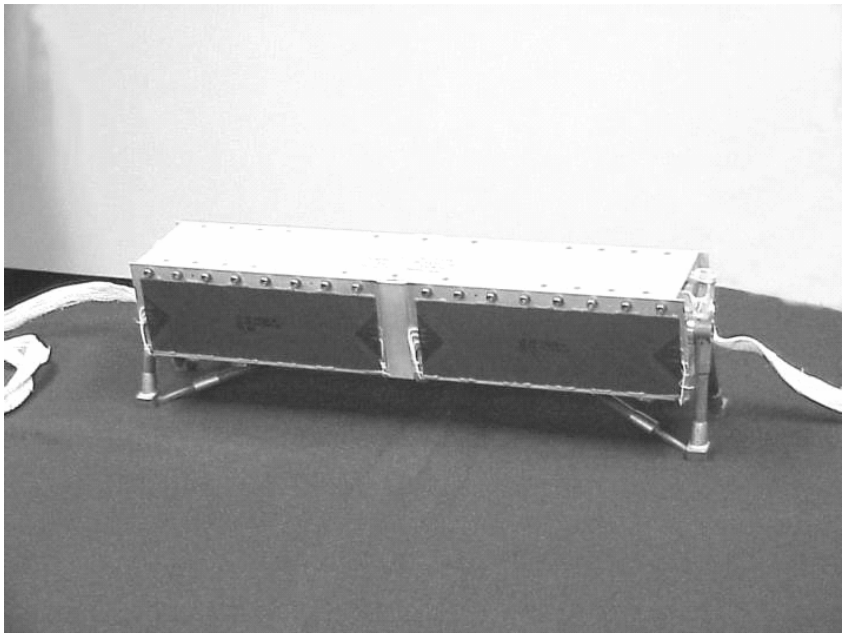
I. Introduction

During the summer of 2003, the Jet Propulsion Laboratory launched two robotic rovers, equipped with a number of instruments, to explore the planet Mars in support of the Mars Exploration Rover (MER) mission.[2] The first spacecraft, carrying the first rover named "Spirit", landed successfully in Gusev crater on January 4, 2004, using an airbag landing system similar to that developed for the Mars Pathfinder mission. The second spacecraft, carrying the second rover named "Opportunity", also landed successfully 21 days later on the Meridiani Planum on Mars. The primary objectives of the mission were to determine if water may have once been present and if any form of life could have existed on the planet. 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 twice. As of May 31, 2007, the rover Spirit has completed 1206 sols of operation and has traveled over 7,120 meters (~ 4.42 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 7, 2007, the rover Opportunity has successfully operated for 1199 sols, and has traveled over 11,108 meters (~ 6.9 miles) since landing. Thus, both rovers have exceeded the primary mission requirement (90 sols of operation on the surface of Mars) by over 13 times to-date.

The excellent life displayed by both of the rovers on the surface of Mars can, in part, be attributed to the fact that the deployable solar arrays still continue to generate high power levels, due to periodic wind storms which remove dust which may block out light, and the rechargeable lithium-ion batteries continue to perform well with little loss in performances. The power source of the rover enables a number of operations, including providing power for: a) mobility, b) communications, c) a number of remote sensing instruments, d) and a number of in-*situ* pay-load elements. Specifically, the role of the 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 during the later phases of the missions, 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. [3] The main purpose of this paper is to provide an up-date upon our efforts to assess their health and life characteristics by performing ground testing in support of the mission.

The factors that lead the to the selection of rechargeable lithium-ion batteries for the MER rovers, 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. The MER mission required that the rechargeable lithium-ion battery meet a number of operational conditions, including: 1) an operating voltage of 24-36V, 2) providing sufficient energy during launch (e.g., 220 Wh), 3) supporting any fault induced attitude excursion during the cruise period (e.g., 160 Wh), 4) providing sufficient energy for surface operations (at least 283 Wh/sol at 0^oC), 5) providing sufficient cycle life (for at least 270 cycles at 50% DOD and/or 90 sols of operation), and 6) the ability to support multiple pulses of 30 A for 50mS, both at ambient and at low temperatures. In addition, the battery should display operational capability, both charge and discharge, over a wide temperature range (e.g., -20° to $+30^oC$), throughout the length of the mission.

Figure 1. Lithium-ion RBAU fabricated by Lithion, Inc. (Yardney Technical Products.



The lithium-ion batteries used for the 2003 MER project were fabricated by Yardney Technical Products, Inc., and the technology was 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). Each rover was equipped with a Rover Battery Assembly Unit (RBAU), shown in Fig. 1, which consists of two 8-cell, 10 Ah batteries connected in parallel. The RBAU was designed such that each battery would be cycled to typically 40-50% depth-of-discharge each sol, or in the event one battery failed to operate the other battery could support the primary mission needs. During the course of the project, Yardney Technical Products, Inc. fabricated and delivered seven RBAUs to JPL (two flight, one flight spare, one ATLO, and three engineering units). The results described below involve the electrical performance testing that was performed on an engineering RBAU, which was dedicated to mission simulation ground testing.

II. Performance Testing of Rover Battery Assembly Units

In our previous papers[10,11], a detailed discussion of the acceptance testing performed on each 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. Thus, only a brief description of these tests, and the corresponding results, will be mentioned. 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 cells and an engineering RBAU were tested according to profiles consisting of high current pulses (up to 30A) over 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 device 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 (10 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, 0, -20, and -30oC), the results of which are described below.

A. Surface Operation Mission Simulation Testing

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°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°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. As shown in Fig. 2, 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° to + 16.6 ^{o}C).

Figure 1. Battery voltage and temperature for surface operation over sols 1-350

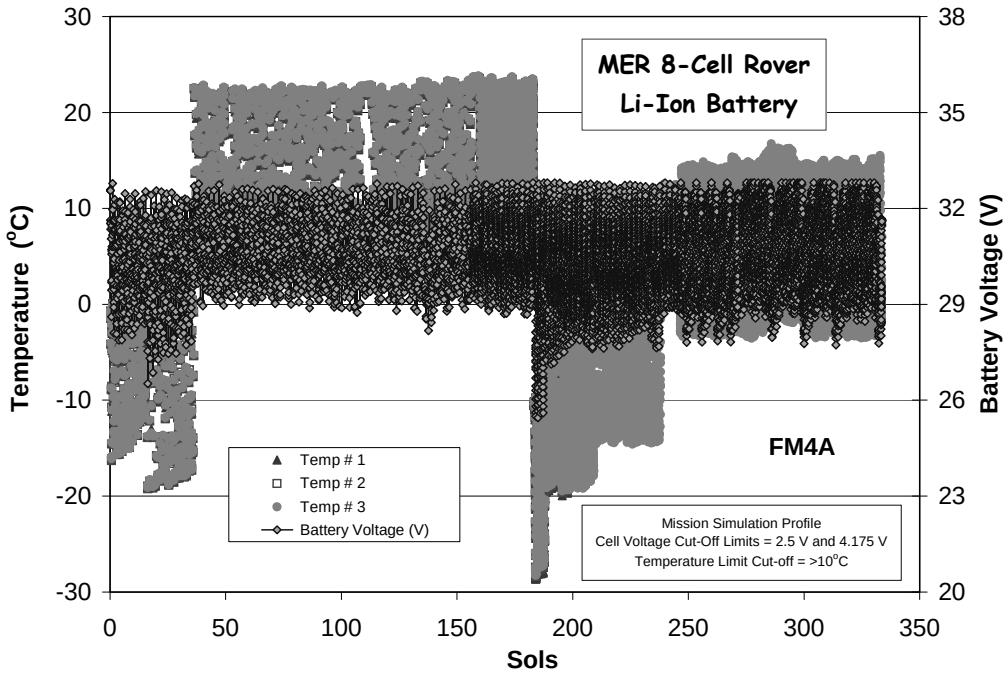
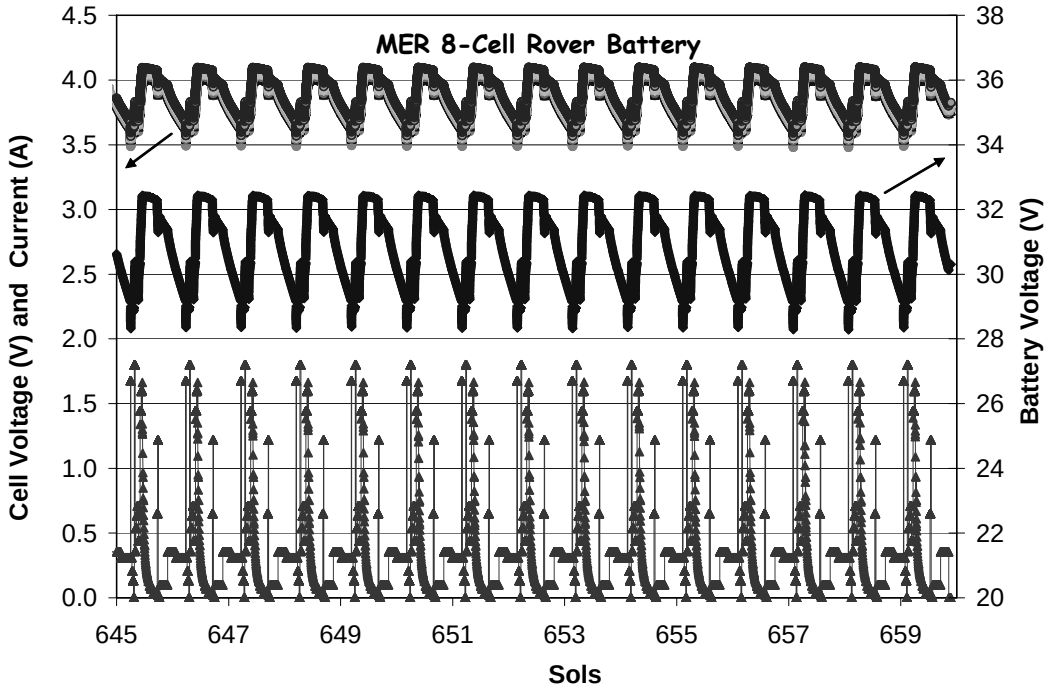


Figure 2. Surface operation profile for Sols 645-660.



In addition to modifying the temperature range during the implementation of the surface operation testing, the load profile was revised after completing 180 sols to more closely resemble the actual conditions experienced on the rovers, based upon mission telemetry data. This revised profile, as illustrated in Fig. 3 in which the performance for sols 645-660 is displayed, consists of comparable charge/discharge rates and DOD to the previous load profiles. .

B. Capacity Determination during Surface Operation Testing

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 < 25 mV dispersion) so as to obtain full capacity and optimal performance, as well as to closely mirror the conditions experienced on the two rovers. In summary, excellent performance has been obtained thus far, which is encouraging to the project and factors into the decisions to extend the mission further. As shown in Table 1, one of the batteries (FM4A) still exhibits 87.6 % of the initial capacity after completing the cruise period and 730 sols of surface operation simulation. As shown in Table 2, the other battery under test (FM4B) shows very complementary data with 88.1 % 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 and 2 at the lower temperatures (i.e., 0°, -20°, and -30^oC), represent conditions in which the batteries are charged at room temperature prior to low temperature discharge. In contrast, the discharge capacities and energies displayed at the lower temperatures in Tables 3 and 4 represent conditions in which the batteries are charged at the respective temperatures. 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^oC of one of the batteries (FM4B) using a room temperature charge was 5.895 Ah after 730 Sols (see Table 2), whereas, only 5.296 Ah was obtained at -20^oC when the battery was charged at low temperatures (see Table 4).

Table 1. Capacity loss at different temperatures of a MER design 10 Ahr lithium ion battery (FM4A) subjected to mission surface operation simulation. Discharge capacities obtained at low temperatures were obtained using a room temperature charge (20^oC).

	Temperature = 20^oC				Temperature = 0^oC				Temperature = -20^oC				Temperature = -30^oC			
RBAU 4A	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	10.0391	100.00	289.12	100.00					7.8060	100.00	213.68	100.00				
Performance After Cruise	9.5032	94.66	281.55	97.38	8.8765	100.00	252.41	100.00	7.4968	96.04	205.17	96.02				
After Completing 90 Sols	9.6904	96.53	278.33	96.27	8.9135	100.42	252.15	99.90	7.1536	91.64	194.11	90.84				
After Completing 180 Sols	9.5375	95.00	273.45	94.58	8.7983	99.12	248.37	98.40	6.9090	88.51	186.78	87.41	5.4703	100.00	142.00	100.00
After Completing 270 Sols	9.4922	94.55	271.59	93.94	8.7191	98.23	262.52	104.00	6.8308	87.51	184.68	86.43	5.4162	99.01	139.77	98.43
After Completing 360 Sols	9.3906	93.54	268.39	92.83	8.5315	96.11	239.61	94.93	6.5951	84.49	177.44	83.04	5.1798	94.69	134.02	94.39
After Completing 450 Sols	9.2763	92.40	264.55	91.50	8.3649	94.24	234.12	92.76	6.3553	81.42	170.50	79.79	4.9593	90.66	128.00	90.14
After Completing 540 Sols	9.1671	91.31	261.49	90.45	8.2307	92.72	229.61	90.97	6.0894	78.01	162.49	76.04	4.5978	84.05	117.86	83.00
After Completing 640 Sols	8.9787	89.44	255.09	88.23	7.9004	89.00	220.05	87.18	5.9855	76.68	159.78	74.78	4.5329	82.86	116.56	82.09
After Completing 730 Sols	8.7969	87.63	250.11	86.51	7.7648	87.48	215.94	85.55	5.8061	74.38	154.53	72.32	4.2301	77.33	108.34	76.30

Table 2. 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

Table 3. Capacity loss at different temperatures of a MER design 10 Ahr lithium ion battery (FM4A) subjected to mission surface operation simulation. Discharge capacities obtained at low temperatures were obtained with charging at the respective temperatures.

	Temperature = 20°C				Temperature = 0°C				Temperature = - 20°C				Temperature = - 30°C			
RBAU 4A	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	10.0391	100.00	289.12	100.00					7.2880	100.00	200.08	100.00				
Performance After Cruise	9.5032	94.66	281.55	97.38	8.6925	100.00	247.44	100.00	7.0828	97.18	194.19	97.06				
After Completing 90 Sols	9.6904	96.53	278.33	96.27	8.6710	99.75	245.53	99.23	6.3802	87.54	172.75	86.34				
After Completing 180 Sols	9.5375	95.00	273.45	94.58	8.5546	98.41	241.90	97.76	6.2376	85.59	168.83	84.38	4.4458	100.00	114.87	100.00
After Completing 270 Sols	9.4922	94.55	271.59	93.94	8.4128	96.78	236.89	95.74	6.1251	84.04	165.58	82.76	4.2083	94.66	108.75	94.67
After Completing 360 Sols	9.3906	93.54	268.39	92.83	8.2540	94.95	231.99	93.76	6.0251	82.67	162.94	81.44	4.0917	92.03	105.67	92.00
After Completing 450 Sols	9.2763	92.40	264.55	91.50	8.0488	92.60	225.54	91.15	5.6985	78.19	153.29	76.62	3.8388	86.35	98.85	86.06
After Completing 540 Sols	9.1671	91.31	261.49	90.45	7.8970	90.85	220.78	89.23	5.3950	74.03	144.44	72.19	3.5341	79.49	90.54	78.82
After Completing 640 Sols	8.9787	89.44	255.09	88.23	7.6571	88.09	213.91	86.45	5.1927	71.25	138.74	69.34	3.3232	74.75	84.79	73.82
After Completing 730 Sols	8.7969	87.63	250.11	86.51	7.5146	86.45	209.79	84.78	5.0323	69.05	134.53	67.24	3.0269	68.09	77.07	67.10

Table 4. 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 with charging at the respective temperatures.

	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					7.3779	100.00	203.31	100.00				
Performance After Cruise	9.5981	95.52	276.83	95.58	8.6645	100.00	247.44	100.00	7.1498	96.91	196.42	96.61				
After Completing 90 Sols	9.7419	96.96	280.06	96.69	8.7608	101.11	248.49	100.43	6.5265	88.46	177.43	87.27				
After Completing 180 Sols	9.6111	95.65	275.84	95.24	8.6552	99.89	245.04	99.03	6.4023	86.78	173.92	85.55	4.5967	100.00	119.45	100.00
After Completing 270 Sols	9.5430	94.98	273.38	94.38	8.4838	97.91	239.37	96.74	6.2447	84.64	169.33	83.29	4.3602	94.86	112.95	94.56
After Completing 360 Sols	9.4479	94.03	270.31	93.32	8.3218	96.04	234.29	94.68	6.1480	83.33	166.83	82.06	4.2995	93.53	111.56	93.40
After Completing 450 Sols	9.3381	92.94	266.62	92.05	8.1412	93.96	228.55	92.37	5.8411	79.17	157.71	77.57	4.0827	88.82	105.64	88.44
After Completing 540 Sols	9.2171	91.73	263.21	90.87	7.9716	92.00	223.35	90.27	5.5213	74.84	148.44	73.02	3.7797	82.23	97.31	81.47
After Completing 640 Sols	9.0285	89.86	256.89	88.69	7.7359	89.28	216.57	87.53	5.3169	72.07	142.57	70.13	3.5372	76.95	90.68	75.92
After Completing 730 Sols	8.8536	88.12	252.11	87.04	7.5936	87.64	212.57	85.91	5.2964	71.79	142.53	70.10	3.2430	70.55	82.93	69.43

When the discharge curves of the 100% DOD capacity tests are compared, which are performed approximately every 90 sols, as shown in Fig. 4, 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 they is a leaving off in the performance degradation. As expected, the capacity decline and polarization effects are more pronounced at low temperature, as illustrated in Fig. 5, in which the discharge cpacity 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. 6, after completing 730 sols of the surface operation load profile, the batteries are still capable of supporting operation over a wide temperature range (+30° to -30°C). As illustrated, nearly half 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 4.5 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 that the 730 cycles represented by the surface operation test. When the capacity loss is compared for the two batteries at room temperature, as illustrated in Fig. 7, good reproducibility of the data is observed with ~ 88% of the original capacity being retained after testing. With the intent of trying to predict the performance capabilities into the future, the capacity degradation trends were projected to 1200 sols, as illustrated in Fig. 8. As evident from the figure, the batteries can clearly support the mission well into the future over a wide temperature range (-20 to +30o), provided the depth-of-discharge (DOD) remains moderate (40-50 % DOD).

Figure 4. Discharge capacity (100 % DOD) at 20°C as a function of surface operation life.

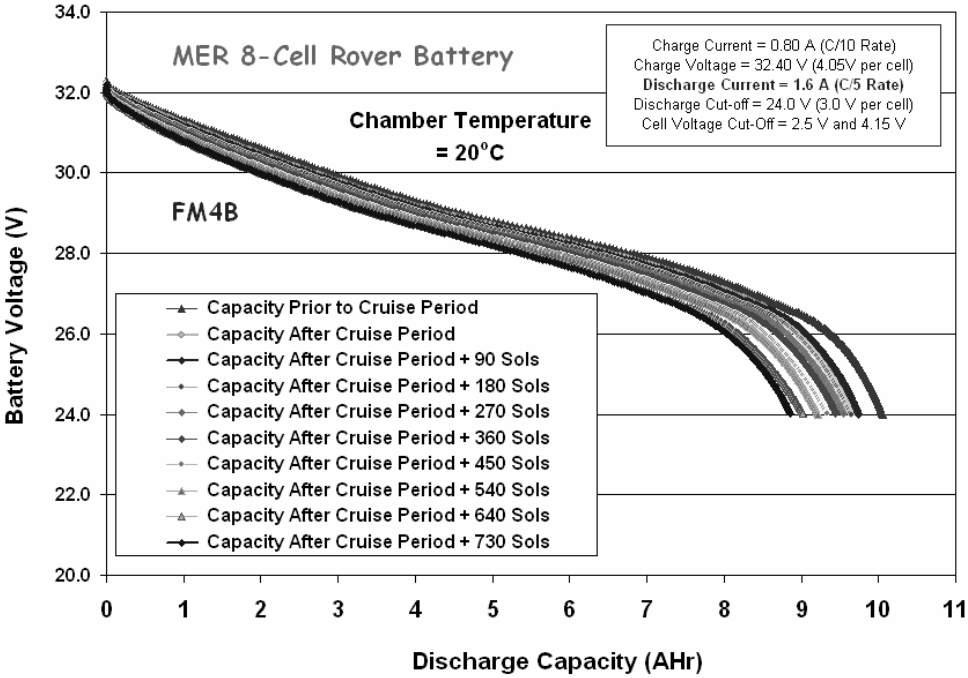


Figure 5. Discharge capacity at - 20°C as a function of surface operation life.

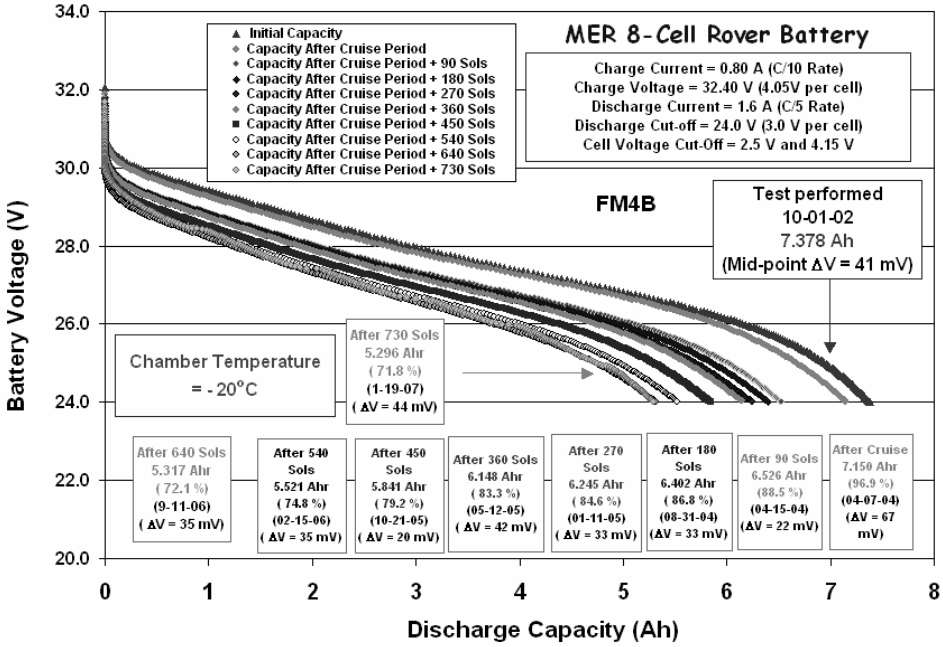


Figure 6. Discharge capacity at different temperatures after completing 730 sols of surface operation. Battery was charged at room temperature prior to low temperature discharge.

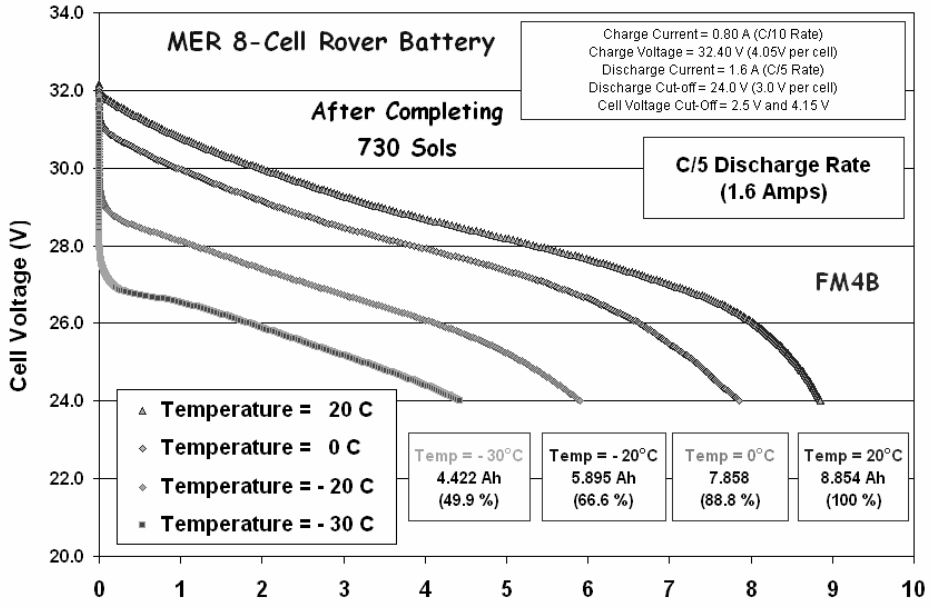


Figure 7. Percent of initial capacity observed with both FM4A and FM4B of the mission simulation battery.

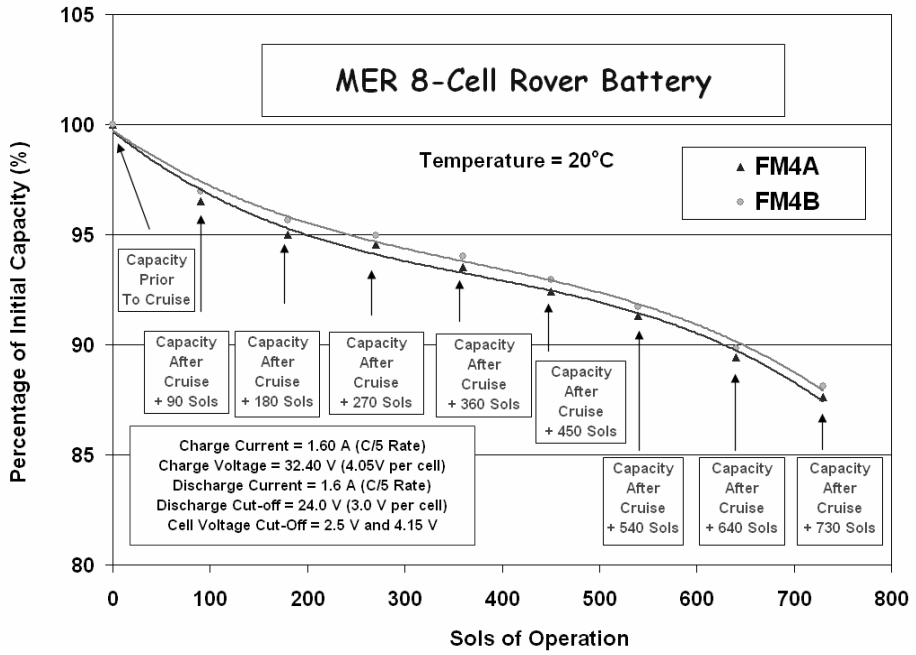
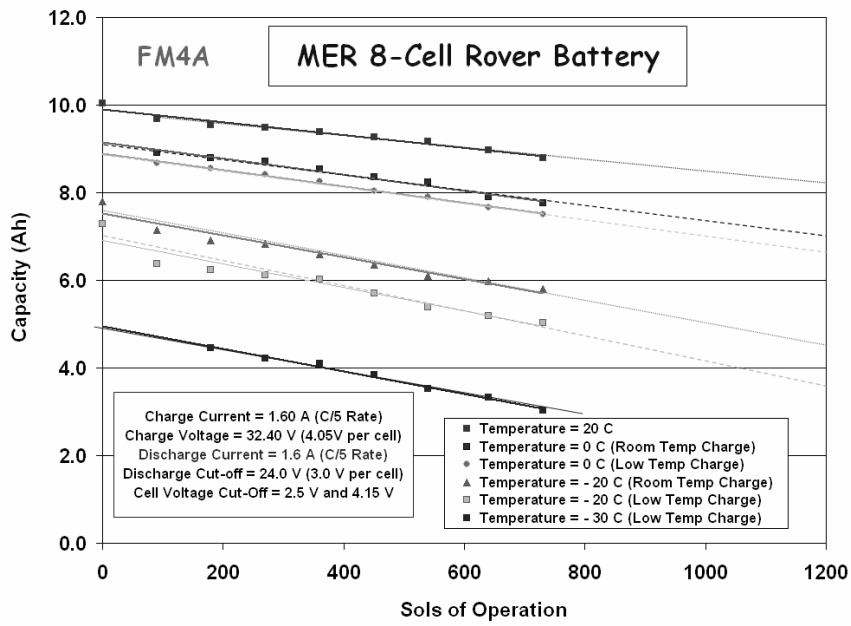


Figure 8. Projected capacity loss of FM4A over a range of temperatures (-20 to +20°C).



C. Impedance Determination during Surface Operation Testing

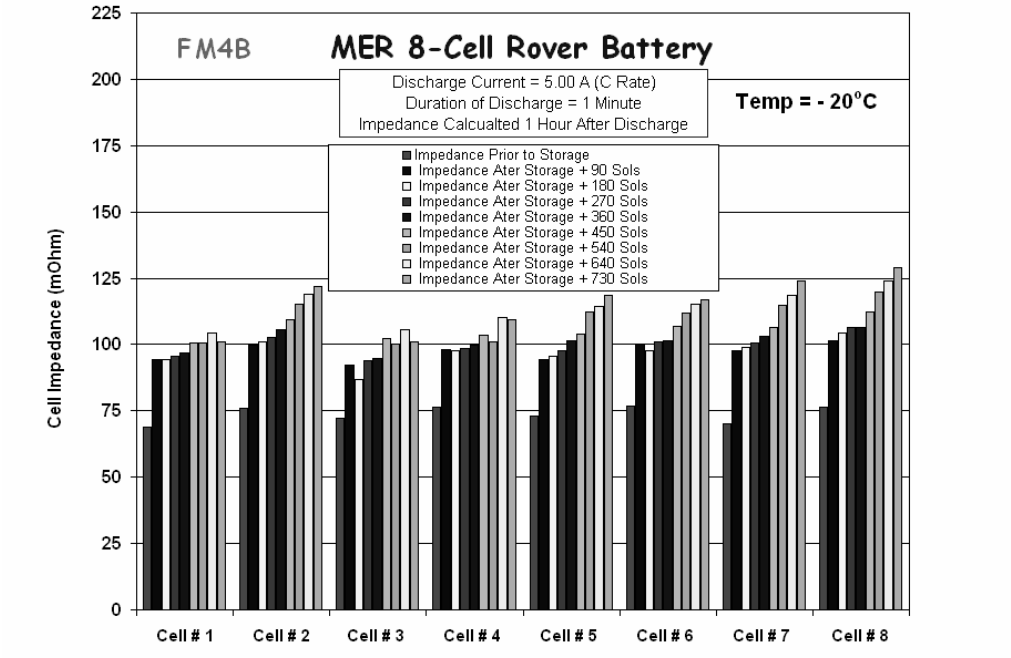
In addition to assessing the capacity losses as a function of life, the impedance of the batteries and the cells has been determined by performing current-interrupt testing. As mentioned previously, it is important to consistently impose identical pulsing conditions to make meaningful conclusions. Due to the fact that it is difficult to determine the precise SOC and state of health of the batteries on Mars, an enhanced understanding of the impact that capacity loss and impedance growth have upon the polarization behavior is of great benefit. For this reason, we have been systematically performing impedance measurements at various states-of-charge and temperatures throughout the life of the batteries. As shown in Table 5, the impedance of the battery steadily increases as a function of cycle life, being more dramatic at lower temperatures. As illustrated, after completing 730 sols of the surface operation profile and the ~ 7 month cruise period, the batteries displayed a 90-94% increase in the impedance measured (at ~ 100% SOC). Although an incomplete data set was performed immediately after the cruise period, it appears as though the greatest increase in impedance was sustained in the first 90 sols of operation. The impedance for individual cells has also been calculated from the data generated from the current-interrupt impedance measurements, as illustrated in Fig. 8, in which the performance at -20°C is illustrated. From the data, it appears as though the impedance growth is more dramatic for certain cells, perhaps suggesting either that the thermal environments differ during the course of cycling or there are minor difference introduced during the cell fabrication process. However, caution should be taken in interpreting the impedance data, due to the sensitivity of cell SOC and minor differences in temperature upon the impedance characteristics.

Table 5. Impedance measurements as a function of cycle life.

FM4A	Performance Prior to Cruise	Performance After Cruise and Completing 90 Sols		Performance After Cruise and Completing 180 Sols		Performance After Cruise and Completing 270 Sols		Performance After Cruise and Completing 360 Sols		Performance After Cruise and Completing 450 Sols		Performance After Cruise and Completing 540 Sols		Performance After Cruise and Completing 640 Sols		Performance After Cruise and Completing 730 Sols	
Temperature (°C)	Battery Impedance (mOhms)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)
20°C	123.3	163.8	32.79	174.3	41.32	180.5	46.34	194.1	57.39	195.2	58.28	203.3	64.82	221.8	79.83	238.6	93.45
0°C*	251.3	372.3	48.16	400.8	59.50	415.1	65.18	443.3	76.39	453.6	80.48	473.9	88.56	497.0	97.76	515.7	105.21
- 20°C*	607.0	895.4	47.51	949.8	56.48	949.7	56.46	971.8	60.11	1019.3	67.92	1046.7	72.44	1071.6	76.55	1100.6	81.33
- 30°C*				1401.9		1434.2		1440.9		1461.0		1514.5		1570.9		1591.5	

FM4B	Performance Prior to Cruise	Performance After Cruise and Completing 90 Sols		Performance After Cruise and Completing 180 Sols		Performance After Cruise and Completing 270 Sols		Performance After Cruise and Completing 360 Sols		Performance After Cruise and Completing 450 Sols		Performance After Cruise and Completing 540 Sols		Performance After Cruise and Completing 640 Sols		Performance After Cruise and Completing 730 Sols	
Temperature (°C)	Battery Impedance (mOhms)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)	Battery Impedance (mOhms)	Impedance (% of Initial)
20°C	118.2	155.1	31.26	164.6	39.30	172.8	46.24	183.0	54.87	184.2	55.90	191.4	62.01	208.7	76.60	224.7	90.17
0°C*	241.7	354.8	46.81	379.7	57.08	396.6	64.09	421.6	74.44	430.6	78.14	450.1	86.24	473.4	95.85	490.5	102.93
- 20°C*	589.9	871.3	47.69	922.8	56.42	925.9	56.96	938.2	59.04	988.8	67.62	1014.7	72.02	1040.2	76.33	1066.1	80.72
- 30°C*				1372.4		1408.2		1406.0		1426.7		1479.4		1537.3		1544.3	

Figure 8. Impedance characteristics of individual cells of FM4B at -20°C, as a function of cycle life.



III. Conclusion

To support the on-going MER project, mission simulation ground testing on a Li-ion RBAU has been performed at JPL. To-date, over 730 sols of surface operation testing has been performed, accompanied by extensive capacity and impedance characterization periodically. Thus far, both batteries in the engineering RBAU have retained ~ 88% of the original capacity at ambient temperature. Projections suggest that the batteries can support the mission well into the future (> 1200 sols), while still being capable of operating over a wide temperature range.

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