Validation of Lithium-Ion Cell Technology for 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., cruise period), operate in an inverted position, and support high currents (e.g., firing pyro events). In order to determine the viability of Lithium-ion technology to meet these stringent requirements, a comprehensive test program was implemented aimed at demonstrating the performance capability of prototype cells fabricated by Lithion, Inc. (Yardney Technical Products, Inc.). The testing performed includes, determining the (a) room temperature cycle life, (b) low temperature cycle life (-20°C), (c) rate capability as a function of temperature, (d) pulse capability as a function of temperature, (e) self-discharge and storage characteristics mission profile capability, (f) cycle life under mission simulation conditions, (g) impedance characteristics, (h) impact of cell orientation, and (i) performance in 8-cell engineering batteries. As will be discussed, the Lithium-ion prototype cells and batteries were demonstrated to meet, as well as, exceed the requirements defined by the mission.

I. Introduction

In 2003, the Jet Propulsion Laboratory launched two spacecraft (one on June 10 and the other on July 7), each containing a robotic rover, to explore the planet Mars in support of the 2003 Mars Exploration Rover (MER) mission.[1] After traveling over 300 million miles, 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 objective of the rover missions is to determine if water may have once been present on the planet and to assess the possibility that past environmental conditions could have sustained life. 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 prelanding mission success being determined 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 roves have successfully completed the primary phase of their respective missions, leading NASA/JPL to extend the mission. As of July 29, 2004, the rover Spirit had completed over 200 sols, whereas, Opportunity had successfully operated for over 180 sols, thus, both far exceeding the primary mission requirement.

In order to power the rovers during the exploration of the Mars surface, deployable solar arrays with triple-junction GaInP/GaAs/Ge cells have been employed in conjunction with rechargeable lithium-ion batteries. In addition to providing power for mobility and communications, the power source enables the operation of a number of instruments, including a panoramic camera, two remote sensing instruments (a mini-thermal emission spectrometer and a mid-IR point spectrometer), and a number of in-*situ* pay-load elements (a Mossbauer spectrometer, an alpha-particle X-ray spectrometer, a microscopic imager, and a rock-abrasion tool). The role of the

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rechargeable lithium-ion batteries specifically 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 and correct any possible anomalies occurring during the cruise period to Mars. [2]

Rechargeable lithium-ion batteries were selected for incorporation into the rover design in light of their high specific energy, good low temperature performance, low self-discharge, and high coulombic and energy efficiency. Due to the importance of limiting the mass and volume of the energy storage device, 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 dictated that the rechargeable lithium-ion battery meet a number of requirements, 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°C), 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°C).

To meet these requirements, lithium-ion batteries were developed by Lithion, Inc. (Yardney technical Products, Inc.), the Jet Propulsion Laboratory, USAF-WPAFB, and NASA-GRC under the 2003 MER project and a NASA-DoD consortium to develop aerospace quality lithium-ion cells/batteries.[3,4] The chemistry employed for the 2003 MER batteries was originally developed and demonstrated for the 2001 Mars Surveyor Program (MSP'01) lander battery, and consist of mesocarbon microbeads (MCMB) anodes, $LiNi_xCo_{1-x}O_2$ cathode materials, and a low temperature electrolyte developed at JPL. [5, 6, 7, 8] 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).

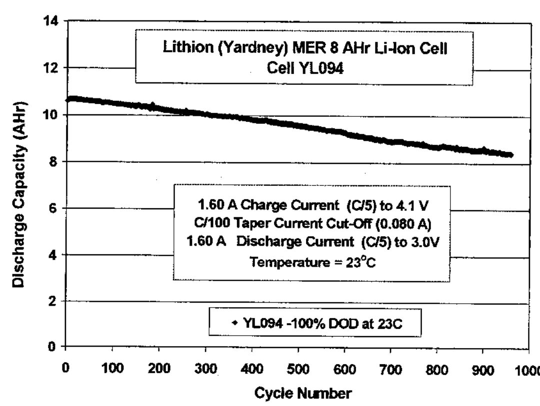
II. Prototype Cell and Battery Performance Testing

In order to determine the viability of using lithium-ion technology, and more specifically Lithion, Inc. prototype cells and batteries, for the 2003 MER mission described, a number of standard and mission specific performance evaluation tests were implemented on cells and batteries received. The testing performed includes, determining the (a) room temperature cycle life, (b) low temperature cycle life (-20°C), (c) rate capability as a function of temperature, (d) pulse capability as a function of temperature, (e) self-discharge and storage characteristics, (f) cycle life under mission simulation conditions, (g) impedance characteristics, (h) impact of cell orientation, and (i) performance in 8-cell engineering batteries. Given that a large data-base had been generated on previously obtained lithium-ion prototypes of similar chemistry (ranging from prismatic 5 Ah to 33 Ah cell sizes) from Lithion, Inc., much of this data contributed to establishing the viability of the technology to support the mission in addition to the performance testing performed on the MER cell design.

A. Cycle Life Performance

As mentioned previously, the requirements of the MER mission dictate that the lithium-ion battery successfully operate for at least 90 sols on the surface of Mars, or at least 270 cycles under conditions of 50% depth-of-discharge (DOD) at 0°C, after completing a lengthy cruise period. In order to assess the capability of the technology to meet these requirements, a number of cells were placed on 100% DOD cycle life testing at various temperatures, including at 40, 23, and –20°C. As shown in Fig. 1, a 10 Ah MER design prototype cell ("flight-like" cell design) displays excellent cycle when subjected to a 100% DOD cycle life test (cycled between 3.0 Vdc and 4.1 Vdc using C/5 charge and discharge rates) at 23°C, with over 900 cycles demonstrated to-date while still retaining over 80% of the original capacity. When this performance is compared to that displayed by other cell sizes possessing the same chemistry, as shown in Fig. 2, it is apparent that

Figure 1. Cycle life performance (100% DOD) of Lithion 10 Ah prototype lithium-ion cells at 23°C.



similar trends are displayed with over 2,000 deep discharge cycles being demonstrated, in some cases One aspect that is notable with these results it that with varying the cell size there is not a dramatic change in the performance trend, illustrating that scaling issues do not significantly affect the cycle life aspects, especially through 1500 cycles. In addition, the data illustrates that the chemistry exceeds the life requirements of the MER mission by a large margin.

Figure 2. Cycle life performance (100% DOD) of prototype lithium-ion cells of varying capacity at 23°C.

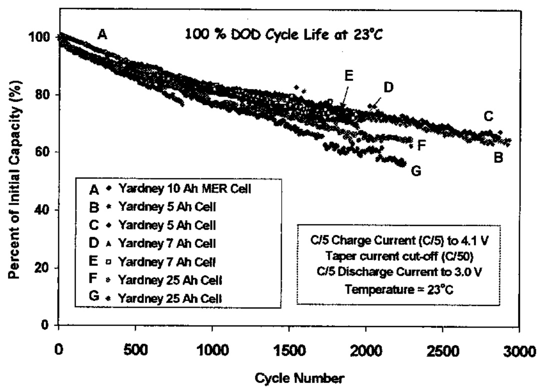
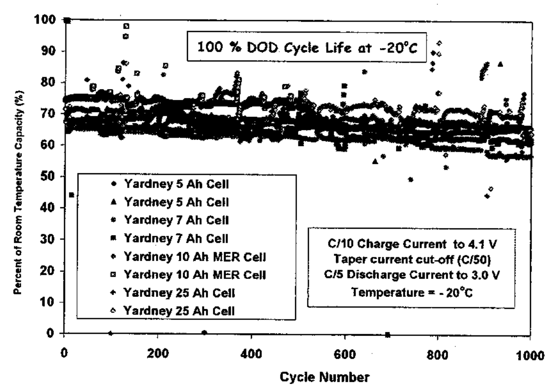


Figure 3. Cycle life performance (100% DOD) of prototype lithium-ion cells of varying capacity at - 20°C.



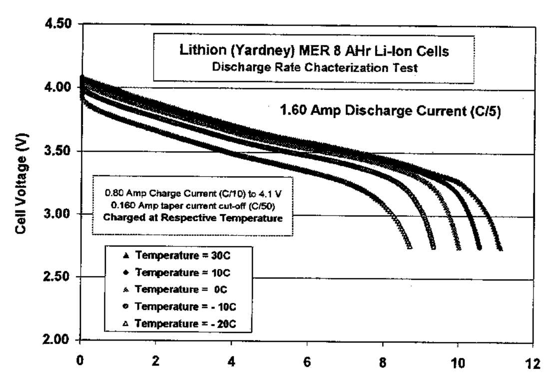
In addition to evaluating the cycle life performance at ambient temperatures, full depth-of-discharge cycling (100% DOD) tests were performed at low temperature (e.g., -20°C). As illustrated in Fig. 3, all of the prototype cells evaluated displayed comparable performance when the cells were continuously cycled at –20°C, displaying ~ 70% of the room temperature performance. These tests were performed utilizing a C/10 charge rate and a C/5 discharge rate and cycled between 4.1 Vdc and 3.0 Vdc. Although higher charge rates have been demonstrated on these prototypes at low temperature, lower charge currents are generally preferred to avoid any deleterious effects due to the phenomena of lithium plating occurring on the anode. [9, 10] As illustrated, very stable performance is observed when the cells are cycled at –20°C, generally displaying lower capacity fade rates than observed at ambient temperatures.

Due to concerns of the effects of the battery orientation during cruise (since the battery experiences weightlessness and is "up-side down"), additional tests were performed in which cells were tested in an inverted mode. As discussed in our companion paper[3], the orientation was not observed to affect the ability of the cells/batteries to successfully meet the mission requirement. In addition to 100% DOD cycle life testing, considered to be the most rigorous and demanding life test, other cycle life testing was performed utilizing lower depth-of-discharge and/or lower charge voltages (i.e., 15-40% DOD under low-earth-orbit, LEO, testing regimes). As expected, higher cycle life performance was obtained using lower DOD under these conditions (i.e., over 20,000 cycles demonstrated using 30% DOD at 0°C).

B. Cell Discharge Performance and Rate Capability as a Function of Temperature

Since the performance requirements for the mission dictated that efficient operation be realized over a wide temperature range, a significant emphasis was placed upon evaluating the discharge capacity over a number of different rates (C, C/2, C/3, C/5, and C/10) and temperatures (-30, -20, 0, 23, and 40°C). When the discharge capacity was compared using a C/5 discharge rate over the range of temperatures, as shown in Fig. 4, good performance was observed with over 82% of the room temperature capacity being delivered at –20°C. It

Figure 4. Discharge capacity of a Lithion, Inc. 10 Ahr lithium-ion cell at a C/5 discharge rate and at different temperatures.



is significant to note that in these comparisons, the low temperature discharge performance was obtained following a charge at low temperature. When the data is expressed in terms of the specific energy delivered by the cell as a function of temperature, as shown in Fig. 5, over 97 Wh/kg was delivered at –20°C and over 123 Wh/kg was observed at 23°C. As shown in Fig. 6, good discharge performance was obtained over the temperature range of interest (-20 to 30°C), with reasonable performance still being delivered at high rates (C rate discharge, based on a 8 Ah nameplate capacity) at –20°C. In addition to performance discharge characterization tests in which the cells were charged at the respective temperature of interest, a number of tests were performed in which the cell was charged at ambient temperatures and discharged at low temperatures. As expected, increased capacity was obtained in all cases.

To meet the mission requirements, the cells must also display the ability to be efficiently charged at low temperatures, corresponding to the early morning conditions on Mars. Thus, a number of charge characterization performance tests were performed to assess the viability of charging over a wide range of temperatures, including the ability to charge over a reasonable length of time without displaying any deleterious effects, such as lithium plating. As shown in Fig. 7, nearly full cell capacity could be obtained in less than 5 hours at –20°C (full capacity being defined as the amount of capacity obtained at the respective temperature using low rate), using a C/2 in-rush current. It is significant to note that no apparent evidence of lithium plating was observed under these conditions of high rate charge, as ascertained by the absence of any aberrations in the voltage profile of the subsequent discharge profile. If lithium plating is pronounced, one would expect initially a higher voltage plateau in the subsequent discharge curve due to the lower overpotential associated with the lithium stripping reaction compared with the normal de-lithiation process of the carbon anode.

C. Pulse Capability as a Function of Temperature

Although Li-SO_2 batteries were designed to support the Entry, Descent, and Landing (EDL) operations once the spacecraft approached the surface of Mars, there was interest to determine the viability of using the lithium-ion cell technology to support such activities. Thus, a number of tests were performed at the cell level to determine the pulse capability as a function of temperature, as well as, as a function of state-of-charge. The testing consisted of applying 42 high current pulses (21 to 30A, corresponding to ~2C to 3C rate, respectively) in rapid succession, each being 50 msec in duration. It was anticipated that the temperature of these events would occur at 0°C, however, the performance was evaluated over a range of temperatures. As shown in Fig. 8, good performance was obtained when applying 30 A pulses (considered

Figure 5. Discharge energy of a Lithion, Inc. 10 Ah lithium-ion cell at a C/5 discharge rate and at different temperatures.

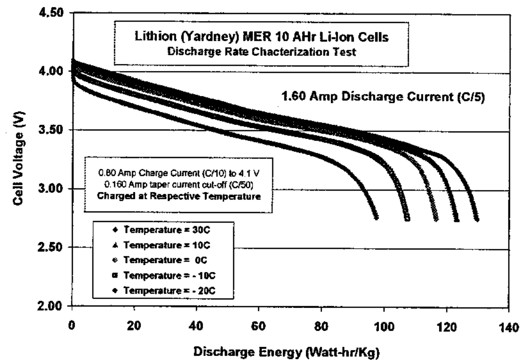


Figure 6. Discharge capacity energy of a Lithion, Inc. 10 Ah lithium-ion cell over a range of temperatures (-20 to 30°C), using different rates (C to C/10 rates).

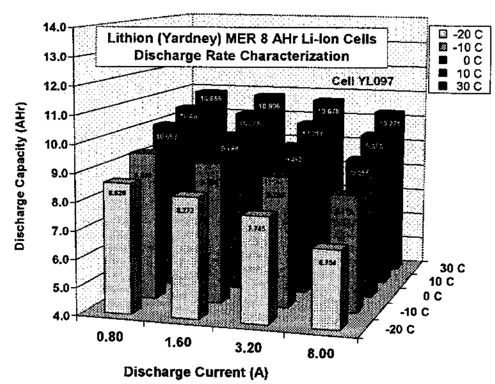
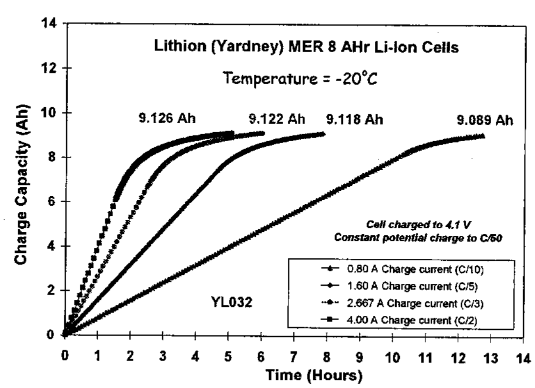
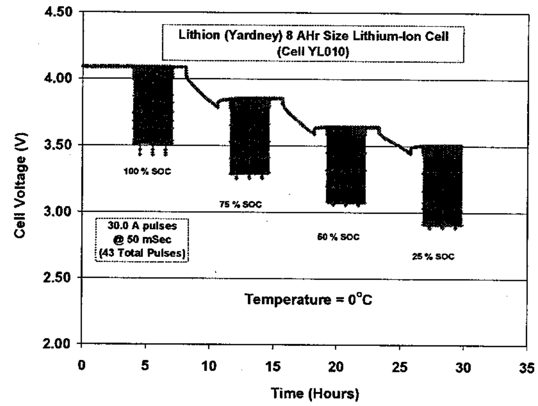


Figure 7. Charge characteristics of a Lithion, Inc. 10 Ahr lithium-ion cell at -20, using a range of rates (C/2 to C/10 rates).



to a worst-case scenario) at 0°C, with the cell voltage not dipping below 3.0V when the cell is in 100, 75, or 50% SOC. As expected, the end of discharge voltage is lowest at low states of charge, however, prior to entry into the Mars atmosphere it was planned to fully charge the battery (which, indeed, was the case).

Figure 8. Entry-Descent-and-Landing testing of a MER design 10 Ahr lithium ion cell.

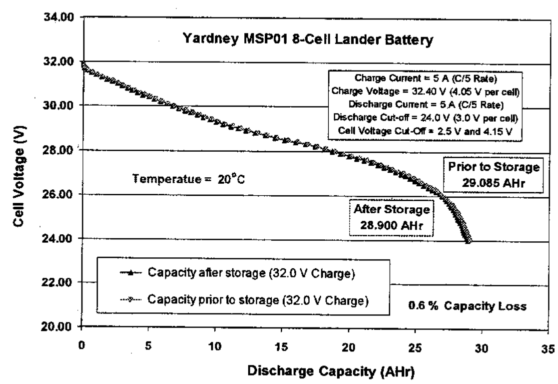


D. Self Discharge and Storage Characteristics

A critical aspect of the MER mission is that the battery be capable of providing the desired performance characteristics after the long cruise period (> 7 months). In the case of the MSP'01 mission (which was originally scheduled to launch in April 2001, however, was cancelled by NASA due to programmatic issues), the cruise period was even longer, consisting of 10-11 months. As a result of this requirement, a number of tests were performed aimed at determining the effect of storage temperature and cell state-of-charge upon the irreversible capacity loss. Initial tests were focused upon evaluating the performance of cells subjected to open circuit storage. From these tests, it was determined that lower state-of-charge (i.e., 50% SOC) and lower storage temperatures (i.e., 0°C) are preferred to minimize the permanent capacity loss (less than 4% of the initial capacity was lost after storage for one year under these conditions). However, it was shown that the impact upon the low temperature capability is more dramatic, primarily due to increased impedance during the storage period.

Recent efforts have focused upon evaluating the viability of storing the cells connected to the bus for the duration of the storage period, which is preferred in terms of spacecraft design. In support of the MSP'01 mission, a number of large capacity cells (25 Ah) were stored for ~ 11 months (at 10°C) connected to the bus to simulate the potential cruise conditions and kept at ~ 70% SOC by float charging them at 3.875V. After the storage period, excellent reversible capacity was obtained, with less than 5% permanent capacity loss observed in all cases. When a test was performed under similar conditions on the "flight-like" MSP'01 8-cell battery, even better results were obtained with less than 1 percent loss in permanent capacity being observed, as illustrated in Fig. 9.

Figure 9. Capacity of a MSP'01 25 Ah 8-cell lithium-ion battery before and after completing an 11 month storage period at 10°C.



E. Cycle Life Under Mission Simulation Conditions

In support of the MER mission, specific tests were performed to simulate how the battery would perform once the rover was fully operational on the surface of Mars. Thus, tests were implemented at the cell and battery level in which the temperature was varied to simulate the fluctuations of a typical Martian sol . Although is gets extremely cold on the surface of Mars at night (approaching as low as –120°C), the battery is exposed to much warmer temperatures due to the presence of heaters and its location in the "Warm Electronics Box". The test was devised to operate between a range of 0° and –20°C for the preliminary cycling based on initial predictions. However, unexpectedly the battery temperatures observed on both Spirit and Opportunity have actually been warmer than anticipated. As shown in Figs. 10 and 11, stable performance was obtained when mission simulation tests were performed on 7 Ah and 10 Ah lithium-ion prototype cells, respectively. As illustrated, the load profile is somewhat complex reflecting the support of various activities and instruments, while interacting with the solar arrays. As shown, the cells were capable of supporting the load profile without dipping below the minimum voltage limit, even during high current discharge transmission events (Fig. 11). Prior to the actual mission operation on Mars, over 600

Figure 10. Mars surface operation mission simulation testing of Lithion, Inc. 7 Ah prototype cells.

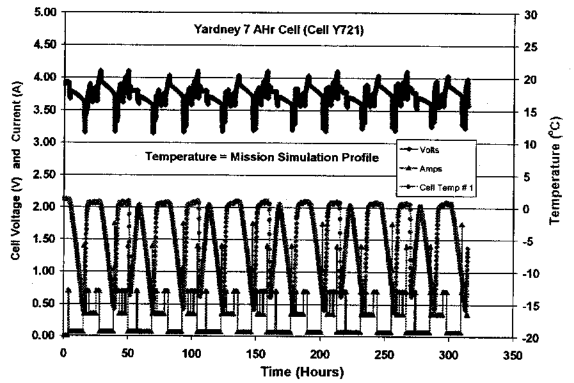
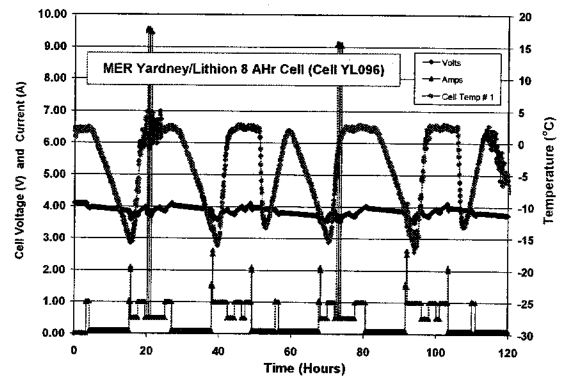


Figure 11. Mars surface operation mission simulation testing of Lithion, Inc. 10 Ah prototype cells (MER design).



hours of continuous operation had been demonstrated on a "flight-like" cell, corresponding to over 25 sols of operation, with little change in voltage profile. Similar to the MSP'01 surface operation profile, the MER profile as discussed corresponds to ~ 50 % depth-of-discharge (DOD). It should be mentioned that excellent data has been obtained on the MSP'01 design prototype cells under a similar type of mission simulation test, and over 1200 cycles have been delivered to date, corresponding to over three years of continuous operation on the surface of Mars. These results suggest that the technology can support the mission well beyond the mission requirements (90 sols), as indeed has been demonstrated by Spirit and Opportunity, and that the long-term operation of the rovers may be limited by other factors (e.g., solar array health).

F. Performance of 8-Cell Engineering Batteries (RBAUS)

In support of the mission needs, Lithion, Inc. and JPL have developed a Li-ion Rover Battery Assembly Unit (RBAU) which consists of two 10 Ah batteries (8 Ah nameplate capacity) which are wired separately. For each battery, an independent battery control board (BCB) was utilized to control the battery charge and discharge parameters and implement a cell balancing methodology on charge by individual cell bypassing through resistors. During the course of the battery development, a number of engineering batteries were fabricated, one of which was dedicated to long-term ground mission simulation testing to provide data in support of real-time mission operation activites involving Spirit and Opportunity. This battery has been subjected to conditions similar to that experienced by the actual flight batteries, including: 1) undergoing the launch sequence, 2) being subjected to a lengthy cruise period, and 3) operating under a surface operation mission simulation profile. In addition to these tests, a number of 100 % DOD capacity checks were performed at a number of temperatures (20, 0, and –20°C) to determine the battery health at different stages of life. Furthermore, current-interrupt impedance measurements were also periodically performed at different temperatures and states-of-charge to determine the rate at which the battery impedance increases. One significant difference between the ground testing of the RBAU described, compared with the operation of the batteries on the two rovers on Mars, is that there is no active cell balancing methodology implemented. In some respects, this aspect is preferred due to the fact that we can obtain additional information regarding the extent to which the cell dispersion characteristics increase with cycling and/or storage. However, this fact necessitated the balancing of the the cells periodically (performed by resistively discharging the cells to a set voltage) to maintain proper battery operation.

After performing initial characterization tests and subjecting the RBAU to the prescribed cruise period (stored on the bus at 30.40V at 10°C, corresponding to 70% SOC), the batteries were tested according to the aforementioned surface operation mission simulation test. As illustrated in Fig. 12, stable performance has been obtained for over 150 sols with little degradation being observed in the operating battery voltage. Initially this test was implemented over a temperature range of 0 to –20°C, however, upon determining that the actual batteries on the two rovers on the surface of Mars were experiencing much warmer temperatures, the range was modified to 5 to 23°C to more clearly reflect mission performance. In general, the performance obtained at the battery level was observed to be superior to that observed at the cell level, especially at low temperatures, most likely due to beneficial thermal aspects.

After completing 90 sols of operation (actual test time exceeded 90 sols due to diagnostic current-interrupt impedance characterization tests performed during this time), a number of diagnostic test were implemented to determine battery health. As shown in Fig. 13, when the capacity of the batteries were compared before and after being subjected to the cruise period and 90 sols of operation, excellent performance was obtained with less than 4% permanent capacity loss being observed. As in the case of the data generated at the cell level, the capacity loss was somewhat more pronounced when compared at low temperature (i.e., at –20°C), being attributable primarily to increased battery impedance. These results are especially encouraging when attempting to assess the battery health on the two rovers and the viability of providing support to an extended mission. Additional performance characterization tests will be performed after the RBAU has completed 180 sols of operation to assist in future battery health predictions.

In order to more fully predict battery health, current-interrupt impedance measurements were performed periodically, as previously mentioned. As illustrated in Fig. 15, when the individual cell impedance values generated at 0°C before cruise, after cruise, and after completing 90 sols, the cell impedances were observed to rise 30-40%. These measurements were performed with the battery in a near full state-of-charge, however, minor variations in the individual cell SOCs were apparent due to cell dispersion effects. Given that it is well established that the cell impedance varies as a function of state-of-charge, effort was taken to compare values obtained with the cells in similar SOC for each measurement. As expected the cell/battery impedance increases with decreasing temperature, and the impedance at low temperature was observed to increase more dramatically with cycling compared with the impedance seen at ambient temperatures. It should also be noted that the value derived for the cell battery impedance is highly dependent upon the discharge current magnitude and duration (as fully described in our companion paper)[3], thus, all comparisons were made using a similar testing regimes. Current activities are focused upon further characterizing the trends in capacity loss and impedance growth with the intent of providing inputs to enable the refinement of performance models that are used in mission operation.

Figure 12. Mission simulation surface operation profile performed on a MER Rover 8-cell lithium-ion battery (mission sim. engineering battery)..

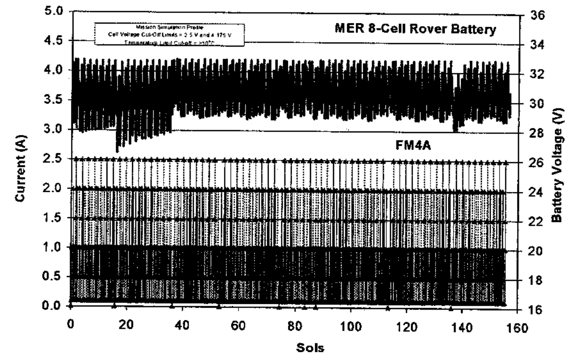


Figure 13. Capacity of a MER Rover 8-cell lithium-ion battery before and after completing a 7 month period and 90 sols (mission sim. engineering battery).

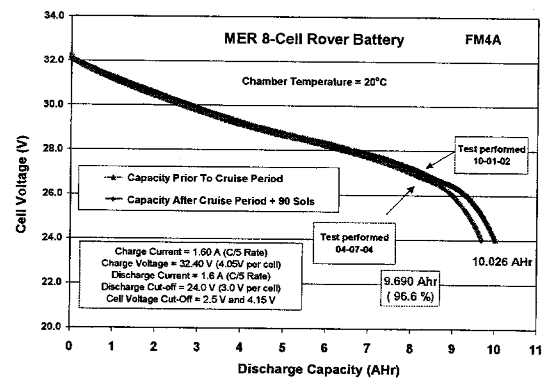
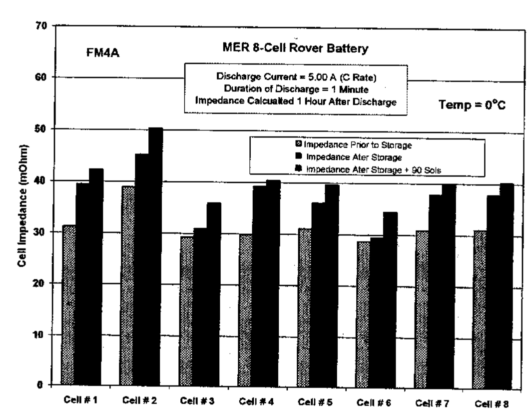


Figure 14. Individual cell impedance values obtained from a MER Rover 8-cell lithium-ion battery as a function of life (mission sim. engineering battery).



III. Conclusion

In order to determine the viability of Lithium-ion technology to meet these stringent requirements, a comprehensive test program was implemented aimed at demonstrating the performance capability of prototype cells fabricated by Lithion, Inc. (Yardney Technical Products, Inc.). The testing performed includes, determining the (a) room temperature cycle life, (b) low temperature cycle life (-20°C), (c) rate capability as a function of temperature, (d) pulse capability as a function of temperature, (e) self-discharge and storage characteristics mission profile capability, (f) cycle life under mission simulation conditions, (g) impedance characteristics, (h) impact of cell orientation, and (i) performance in 8-cell engineering batteries. In addition to generating performance data on the 2003 MER design cell in support of the mission (10 Ah prismatic cell, 8 Ah nameplate capacity), relevant data has also been obtained with previously developed prototypes consisting of the same chemistry, including 5 Ah, 7 Ah, and 33 Ah (MSP'01 Lander cells, 25 Ah nameplate). These tests have demonstrated that the technology meets or exceeds all mission requirements, including: 1) displaying excellent cycle life characteristics, far exceeding the requirement of 90 sols of operation, 2) displaying a wide operating temperature range for both charge and discharge (-30 to +30°C), 3) exhibiting good storage characteristics with little permanent capacity loss, and 4) good pulse capability. Based on data generated from the ground testing of an engineering battery RBAU, as well as data obtained from the testing of prototype cells, current projections indicate that the batteries on Spirit and Opportunity can support an extended mission well beyond 200 sols. Due to seasonal changes in temperature and solar intensity, the coming winter months are more demanding on battery and solar array performance, however, with proper management the rovers have the potential to work well into the future.

Acknowledgments

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