Performance Testing of Lithion 8-Cell, 25 AHr Lithium-Ion Batteries for Future Aerospace Applications

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ABSTRACT

Under the Mars Surveyor Program (MSP 01), lithium-ion batteries were developed by Lithion, Inc. (Yardney Technical Products, Inc.), each being 28 V, 25 Ah, 8-cells, and 9 kg and fully qualified prior to mission cancellation. In addition to the requirement of being able to supply at least 90 cycles on the surface of Mars, the battery was demonstrated of being capable of operation (both charge and discharge) over a large temperature range (–20°C to +40°C), with tolerance to non-operational excursions to –30°C and 50°C. After 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 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 AHr 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 (30% DOD), while periodically checking the battery impedance and full capacity (100% DOD). Prior to initiating these tests, a number of characterization tests were performed to determine general performance attributes and battery health. In addition to presenting battery data, results obtained with individual cells will also be presented to further describe the capabilities of the technology to meet future applications.

INTRODUCTION

NASA has a sustained interest in obtaining batteries that have the potential to further enhance mission capability. Batteries that display higher gravimetric and volumetric energy densities, longer cycle life, wider operating temperature range, and better rate capability can all translate into increased payload and spacecraft capability. In many cases, advanced battery technologies can be mission enabling, rather than just enhancing, and may facilitate increased scientific capabilities of the mission, such as with the planetary exploration of Mars.

The first major NASA mission to adopt lithium-ion technology was the 2001 Mars Surveyor Program (MSP01), in which the advanced battery technology was developed for the Mars Lander (this mission was originally scheduled to launch in April 2001, however, it was cancelled by NASA due to programmatic issues). The surface Lander spacecraft for this mission, fabricated by Lockheed-Martin Astronautics in collaboration with JPL, required two Lithium-ion batteries, each being 28 V (eight cells), 25 Ah and 9 kg (18 kg total).[1] In addition to the requirement of being able to supply at least 90 cycles on the surface of Mars after a one year storage and cruise time, the battery was expected to be capable of operation (both charge and discharge) over a wide temperature range (–20°C to +40°C), with tolerance to non-operational excursions to –30°C and 50°C. These requirements are much more demanding than those encountered with the previous Mars Pathfinder mission which utilized Ag-Zn technology.[2] In contrast, the Mars pathfinder battery was only expected to operate between 0 to 30°C and deliver 30 cycles on the surface of Mars. Although the Surveyor mission was cancelled by NASA prior to launch, the Lander battery was fully developed (by Lithion/Yardney Technical Prod., Pawcatuck, CT) and flight qualified prior to the program closure.[3,4] The lithium-ion cell chemistry adopted by Lithion, Inc. to meet the projected mission requirements consisted of mesocarbon microbeads (MCMB) carbon anodes, $LiNi_xCo_{1-x}O_2$ cathode materials, and a low temperature electrolyte (1.0 M $LiPF_6$ EC+DMC+DEC (1:1:1)) developed at JPL.[5,6]

In addition to these two missions, NASA (JPL and GRC) is considering the use of lithium-ion batteries for a number of other up-coming missions, including the Mars 2009 Smart Lander ($Ni\text{-}H_2$ batteries are currently baselined) and future Mars planetary orbiters. Initial projections for the Mars 2009 Smart Lander necessitated the use of a high energy density battery, which could operate effectively at very low temperatures (down to –40°C) and provide long life (> 3 years of operation on the surface of Mars). However, recent developments at NASA/JPL which involve the incorporation of radioisotope thermoelectric generators (RTG's), in lieu of solar arrays, have shifted the focus of the battery requirements from enabling a wide temperature range of operation to enabling longer life (> 5 years on the surface of Mars). In addition to future Mars Landers and Rovers, there is interest in using lithium-ion technology for planetary orbiter applications. The high specific energy of lithium-ion technology makes it especially attractive, however, the long life characteristics needed for such applications have not been effectively demonstrated to-date.

After the mission cancellation, there were a total of five batteries that were available for distribution and testing (3 flight batteries and 2 ATLO [protoflight] batteries). In order to assess the capabilities of the technology, a multi-institutional team was assembled to implement a test plan that would demonstrate the performance capabilities of the batteries to meet future NASA applications. The three "flight" batteries were communally designated for LEO testing (currently being tested at JPL, NASA-GRC, and AFRL/PRPB) and the remaining two batteries were allocated for mission simulation testing (a Mars Lander simulation test being performed at JPL and a GEO application test being performed at NRL). It must be noted that much of the cell and battery technology (and hardware) development effort was made possible, in part, by the participation of a NASA-Air Force consortium formed in 1998 to establish domestic capability to manufacture lithium-ion cells and batteries in the US.[7]

MSP01 LANDER Li ION BATTERY REQUIREMENTS

As stated, one of the five batteries fabricated was specifically designated to determine if the technology could meet the MSP01 mission requirements originally projected. The program dictated that a number of performance requirements must be met by the 28 volt, 25.0 Amp-hour batteries to successfully complete the planned mission. One important feature of the battery is its requirement to operate (both charge and discharge) at continuous rate of C/5 over a wide range of temperatures (-20° to +40°C) once the Lander has successfully landed on the surface of Mars. The battery should be capable of providing a minimum EOL capacity of 25 Ah. The typical discharge drains will be C/5 to a maximum of 50% DOD. However, with both the batteries being connected in parallel (with a diode protection), the actual depths of discharge could be even milder than 50%. The maximum charge current was projected to be approximately 5 A (C/5). In addition to operating efficiently on the surface of Mars, the batteries should be able to withstand the entry, descent, and landing (EDL) pulses (50A or 2C) at 0°C for short duration (< 100 msec). Prior to satisfying both of these requirements, the battery must survive a ground/cruise storage duration of nearly 2 years (6 months to one year pre-cruise storage) and an ~ one year cruise period at 0° to 30°C.

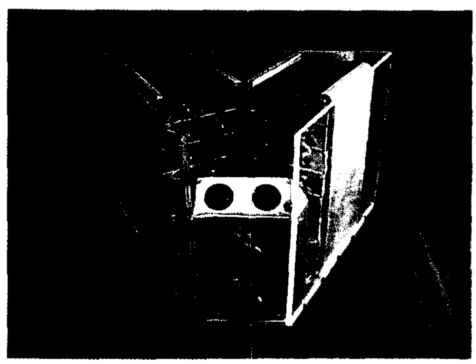

Fig.1. MSP'01Lander lithium-Ion battery (2 8-cell batteries) fabricated by Lithion, Inc. (Pawcatuck, CT)

CELL TESTING RESULTS IN SUPPORT OF FUTURE MARS LANDERS

In addition to testing the protoflight 8-cell battery articles, a number of cell level tests were implemented to demonstrate the capability to meet the mission requirements, as well as, to demonstrate the overall performance characteristics. According to the projected MSP01 mission plans, the battery should be capable of providing a minimum of 90 cycles once the spacecraft has reached the surface of Mars. Due to the fluctuating temperatures on the surface of Mars during a typical day (sol period) and during a season, the battery was required to cycle efficiently over a wide temperature range (-20 to +40°C). In addition, successful operation must be demonstrated after being subjected to an extended cruise period (~ 11 months) and an additional storage period from the date of manufacturing to the time of launch. In order to assess the viability to meet these requirements, a number of general performance tests were implemented to establish a comprehensive data base to enable predictive performance trends. For example, the life characteristics were assessed by initiating deep discharge cycling (100 % DOD) at various temperatures (cycled between 3.0 Vdc and 4.1 Vdc). As illustrated in Fig. 2, 20 Ahr prototype cells have been cycled successfully over 2300 cycles at both ambient temperatures as well as at –20°C (charged and discharged at low temperature).

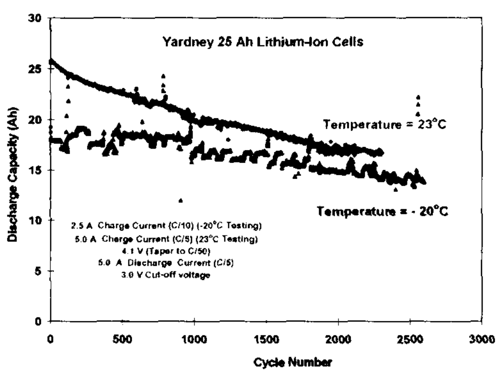

Fig. 2. Cycle life performance (100% DOD) of Lithion 20 Ahr prototype lithium-ion cells at 25 and –20°C.

Once the spacecraft has landed on the surface of Mars, the battery was expected to cycle for a minimum of 90 sols, with the desire of successfully completing at least 200 cycles. According to the current estimates of the Martian surface temperature profile, and the corresponding temperature swings that will be experienced within the Lander thermal enclosure, the battery will be expected to operate over a large range of temperatures (Δ60°C). In order to simulate the battery operation over the course of the entire mission, a number of temperature ranges were investigated which correlate to the projected battery environment as the Martian season begins to change. These ranges are characterized by the widest temperature swings experienced in the beginning of the mission, and less severe, but colder temperature ranges later in the mission. The electrical profile during this cycling consists of charging the cells with a constant current (C/5 rate) to 4.1V for a total charge time of 12 hrs, and a relatively mild discharge current (1 Amp or C/25 rate) for a total of 12 hrs, corresponding to 12 Ahr of capacity (~40% DOD). Under the adopted test regime, the beginning of the charge period occurs when the battery experiences the coldest temperatures, whereas, the beginning of the discharge period commences when the highest temperatures are experienced. Thus, these conditions represent a worst-case scenario, due to the fact that the charge period under a typical mission simulation cycle would occur at warmer temperatures.

Due to the fact that a fixed amount of capacity is discharged each cycle (12 Ahr), the performance characteristics of the mission simulation cycling is most adequately expressed in terms of the end-of-discharge voltage. The end of life for the cells subjected to this test has been designated as being when the cells drop below 3.0 V upon discharge. As illustrated in Fig. 3, when prototype 20 Ahr cells were cycled under these conditions, successful completion of over 900 cycles has been observed with little performance degradation. These cells had previously been subjected to a 12-month OCV storage and EDL pulsing prior to the mission simulation testing.[8] Thus, the observed cell performance is especially relevant, since the cell histories prior to the mission simulation profile testing reflect similar conditions to that expected to be experienced by the actual Lander battery. As shown, after 900 cycles the operating cell voltages are still above 3.4 V and display little fade, which suggests that the performance target of three years of continuous operation on the surface of Mars can easily be met.

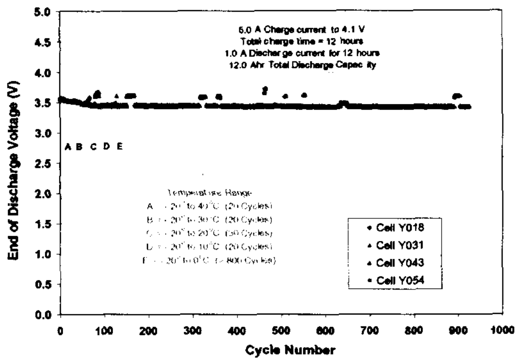

Fig.3. Mission simulation cycling of Yardney prototype MSP01 lithium-ion cells.

MSP'01 MISSION SIMULATION 8-CELL BATTERY TESTING RESULTS

Prior to the discontinuation of the mission, Yardney successfully space-qualified the battery design which was observed to meet all specified requirements, including shock, vibration and landing load, thermal vacuum, capacity, and abuse requirements. When the battery was charged to 32.8V (tested without charge control methodology developed at LMA) and discharged to 24V, over 32 AHr was delivered, corresponding to 932 WHr or ~ 105 WHr/kg. Good cell dispersion characteristics were generally observed given periodic cell balancing (cells resistively discharged), suggesting minimal reliance upon charge control methodologies implemented. When the battery was evaluated at –20°C, similar trends were obtained to that observed at the cell level, with ~ 75% of the room temperature capacity being delivered.

After initial characterization, the 8-cell Lander battery was subjected to an 11-month storage period under constant applied voltage (corresponding to ~ 70% SOC) at a temperature of 10°C to simulate the cruise period to Mars. Increased cell dispersion was observed as a result of the storage period and necessitated cell balancing protocols (e.g., resistively discharging each cell to 2.5V) to obtain full capacity. The wider cell voltage dispersion had the greatest impact upon the low temperature performance, due to the fact that the cell voltage cut-off limits were triggered prematurely (4.15V on charge and 2.5V on discharge) leading to incomplete charging/ discharging of the battery. This behavior is more pronounced at low temperatures due to the higher cell impedances, and is not of great concern given proper cell charge control methods. After cell balancing, the battery was observed to deliver nearly the full initial capacity (> 99%), displaying very similar trends to that obtained at the cell level, delivering over 29 Ah at 20°C with charging to 32.0V (corresponding to 4.0V per cell). Higher battery capacities can be obtained by using higher charge voltages (i.e., 32.4 Ahr was obtained initially using a 32.8V charge), however, lower charge voltages were more frequently used for characterization cycling to prolong the life characteristics of the battery.

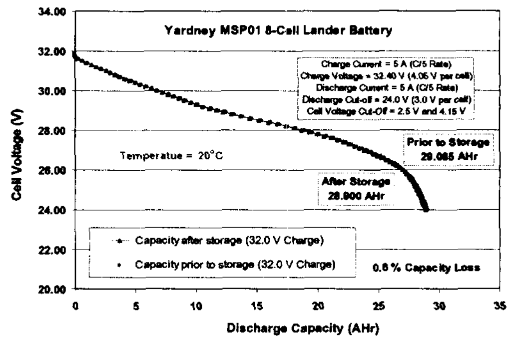

Fig. 4. Discharge capacity prior to and following an 11-month cruise period (stored on buss at 70% SOC).

In addition to determining the impact of the storage period upon the room temperature performance, we also performed capacity characterization cycles at 0° and –20°C. As shown in Fig. 5, good performance was obtained over the temperature range evaluated with > 75% of the ambient temperature capacity being delivered at –20°C using a C/5 discharge rate. Again, higher capacities are expected over the range of temperatures if higher charge voltages are used (up to 32.8V, or 4.1V per cell) and/or lower discharge voltages are used (20V, or 2.5V per cell).

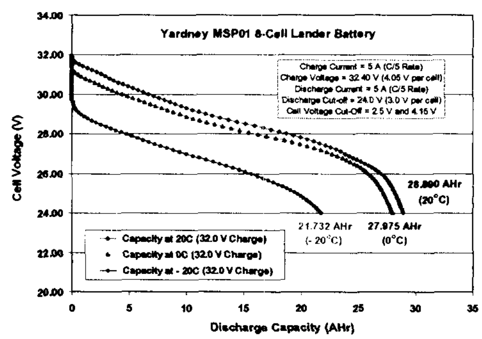

Fig.5. Discharge capacity of the MSP01 8-cell Lander battery at different temperatures (32.0V charge).

After completing the post-storage characterization, a Mars surface operation mission simulation profile was adopted similar to that expected by the MSP'01 mission. As mentioned previously, each cycle consists of a 12 hour charge period (C/5 charge rate to 32.0V) and a 12 hour discharge period (C/25 rate) to coincide with a typical Martian sol, as shown in Fig. 6, where the results are displayed for the first sol.

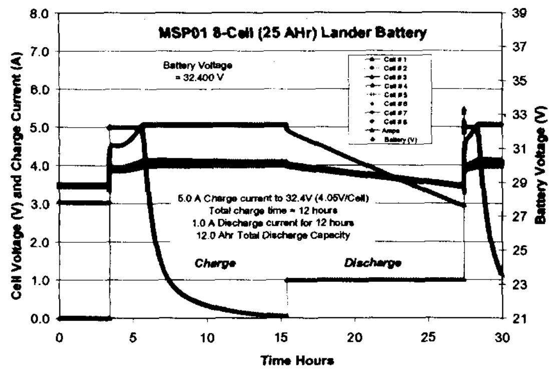

Fig. 6. MSP'01 surface operation mission simulation testing of the MSP01 8-cell Lander battery (Sol 1).

In contrast to the method in which the cell level testing was performed, the battery testing was performed over an initial temperature range of –20° to 0°C with the charging period being performed at the coldest temperatures. To date, over 70 cycles have been performed under the MSP'01 load profile, representing over two months of operation on the surface of Mars with little performance degradation observed, as illustrated in Fig. 7. The actual testing time (and wet life) is longer due to periodic chamber failures and the implementation of the MSL mission simulation profile (discussed below) consisting of ~ 4 cycles. As shown in Fig. 7, the end-of-discharge voltages are observed to rise at ~ cycle 35, which has been attributed due to lack of synchronicity between the environmental test chamber program and the Maccor testing schedule resulting in the charge period (and end of discharge) occurring at warmer temperatures. This behavior illustrates that the test represent a worse-case scenario and that improved performance is expected under actual conditions (where a significant portion of the charge period occurs at the warmer temperatures). Given that the MSP'01 mission requirement was to provide 90 sols of operation (after an 11 month cruise storage), it is highly likely that the battery will successfully meet these goals with minimal performance degradation. The current intent is to continuously cycle the battery and complete >1000 sols of operation to demonstrate the viability of the technology to support prolonged missions on the surface of Mars.

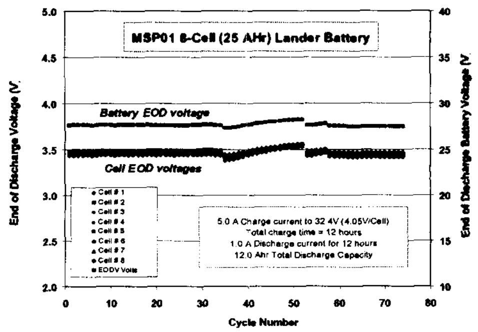

Fig. 7. MSP'01 surface operation mission simulation testing of the MSP01 8-cell Lander battery (Sol 1).

MSL'09 MISSION SIMULATION 8-CELL BATTERY TESTING RESULTS

As mentioned previously, the MSP'01 lander testing was temporarily suspended in order to perform a brief mission simulation test in support of the Mars Science Laboratory (MSL) currently being planned at JPL. Although initial projections of the mission involved a solar powered Lander vehicle requiring excellent low temperature performance (-40 to +30°C), more recent projections have focused on a nuclear powered Lander which would provide much milder temperatures ranges for the battery, assumed to be similar to that envisioned for the MSP'01 mission. The primary function of the battery in the MSL'09 mission is to augment the RTG during peak power events (i.e., communication) and as a load leveling device. As shown in Fig. 8., the battery was successfully cycled using the projected MSL'09 load profile over a temperature range of -20 to +10°C (maximum charge/discharge current = ~ 4 A with average ~ 1-2A). Work is underway to demonstrate the viability of lithium-ion technology to meet the challenging life performance requirements of the MSL09 mission at the cell level (goal is to demonstrate 3-5 years of operation).

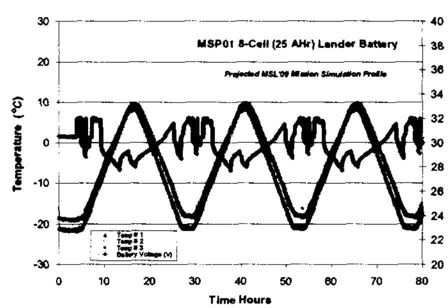

Fig. 8. MSL'09 surface operation mission simulation. testing of the MSP01 8-cell Lander battery (Sols 1-3).

LOW-EARTH-ORBIT (LEO) 8-CELL BATTERY TESTING RESULTS

In addition to future planetary Landers and Rovers, lithium-ion technology is being considered for future orbiter applications which generally possess much more demanding life cycling requirements, such as 15,000 to 40,000 cycles and/or a 10-20 year calendar life. For most of these applications, however, the cycling required typically corresponds to a shallow depth of discharge (<50% DOD). In collaboration with the other institutions mentioned, a LEO cycling test consisting of 40% DOD at 23°C using a 30.4V charge (55 min. charge period and 35 min. discharge period) was implemented on the second battery (a "flight" battery) currently being tested at JPL. These conditions were selected such that a direct comparison can be made with the test data being generated at the other institutions with the intent of understanding the effect of particular testing variables (i.e, charge voltage and temperature). In addition to implementing the LEO test described, 100% DOD capacity checks are being performed periodically (every 250 cycles) at different temperatures (at 23°, and at 0° and –20° every 1000 cycles) as well as, performing current-interrupt impedance measurements. As shown in Fig. 9, excellent performance was observed during the initial characterization cycling, with 33.0 Ahr being delivered at 20°C using a 32.8V charge. In addition, the cell dispersion observed in this battery was much less than that seen with the protoflight battery being using for the Mars Lander testing previously described, reflecting the fact that fewer acceptance tests were performed on the flight article and the cell selection process was more rigorous during assembly. The good behavior observed is also significant due to the fact that these results were obtained ~ 2.5 years after the initial cell activation and battery fabrication.

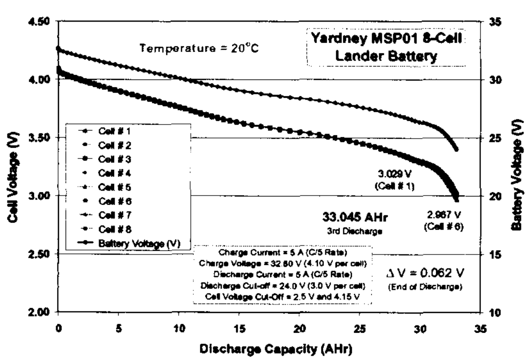

Fig. 9. Discharge capacity obtained on the flight battery using a C/5 discharge and 32.8V charge.

In order to determine the effect of cycling upon cell impedance characteristics, current-interruption impedance testing was performed and the corresponding impedance was calculated for the battery, as well as, the individual cells. As shown in Fig. 10, the test consists of applying 25A pulses of 10 second duration at various states-of-charge (100, 80, 60, 40 and 20% SOC, based on the nameplate 25 Ah capacity). After each pulse sequence, the battery was allowed to stand 2 hours in an open circuit condition to establish steady-state conditions. The impedance calculations were performed with the voltages recorded after 1 hour, although little change was observed in the cell and battery voltages after 15 minutes. It is anticipated, however, that late in cell/battery life, especially at low temperatures, the steady-state voltages will take longer to be established due to increased impedance as a result of electrode passivation.

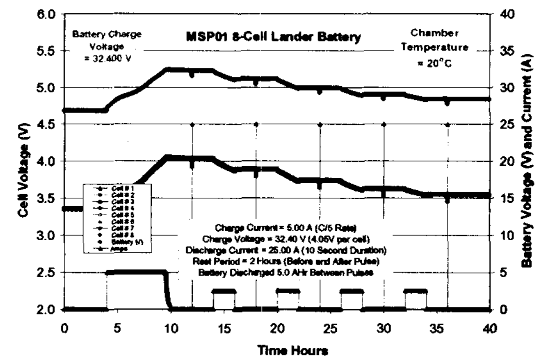

Fig. 10. Test methodology of the current-interrupt impedance measurements performed on the battery.

As shown in Fig. 11, the average cell impedance was within a 3.0 - 3.5 mOhms range from full SOC to 20% SOC at 20°C, corresponding to 25-30 mOhms for the entire battery. However, at very low state-of-charge (20%) the cell/battery impedance is markedly higher, which is believed to be due to the changing electronic conductivity of the electrodes as a function of SOC (i.e., the conductivity of the anode becomes much lower as the level of lithiation decreases). Similar measurements have been performed at 0° and –20°C and higher impedance was observed, as expected, corresponding to ~ 70 mOhms and ~ 200 mOhms being calculated for the battery, respectively. These measurements will be repeated throughout the life of the battery to determine the effect of cycling upon cell performance.

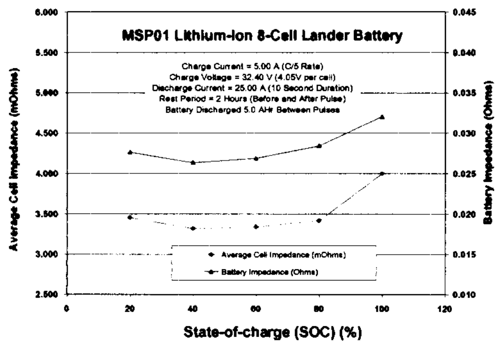

Fig. 11. Calculated battery and average cell impedance values as a function of SOC at 20°C.

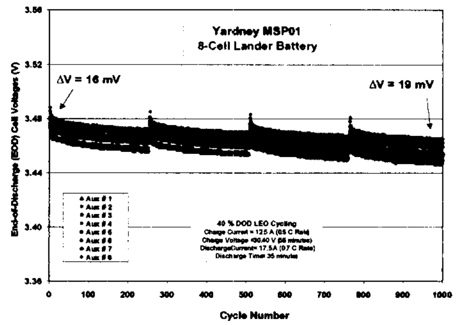

Fig. 13. End-of-discharge (EOD) cell voltages during a 40% LEO test performed on the 8-cell lithium-ion flight battery at 23°C (30.4V charge voltage).

Since the actual LEO testing was recently started, only 1000 cycles have been demonstrated to-date. However, very stable performance has been observed thus far, with little change in the end-of-discharge voltage, as illustrated in Fig. 12, with approximately 140 mV decline seen after 1000 cycles (or 15-20 mV per cell). In addition, minimal increase in the cell dispersion characteristics was observed over the first 100 cycles, as shown in Fig. 13, corresponding to only a 3 mV increase. This is especially significant in that the cell dispersion behavior will dictate if and when cell balancing is necessary (no individual charge control is utilized in the current testing). In order to obtain the longest cycle life possible from the battery, the charge voltage will be incrementally increased later in life once the end-of-discharge voltage dips below 22.0V for any specified charge voltage.

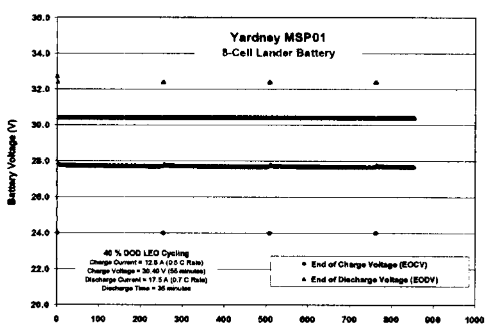

Fig. 12. End of battery charge and discharge voltages during 40% DOD LEO cycling (30.V charge).

As shown in Fig. 14, the 100% DOD capacity was determined for the battery after every ~ 250 cycles completed under the 40% LEO regime. As illustrated, excellent capacity retention has been observed thus far, with over 98% of the initial capacity being observed after 1000 cycles. Ultimately, the intention of the current testing is to demonstrate ~ 30,000 cycles and 5 years of continuous operation. In addition, as mentioned previously, the goal of the testing is also to determine the effect of temperature and charge methodology upon performance by comparing the results obtained with the other battery being tested in parallel at the different institutions.

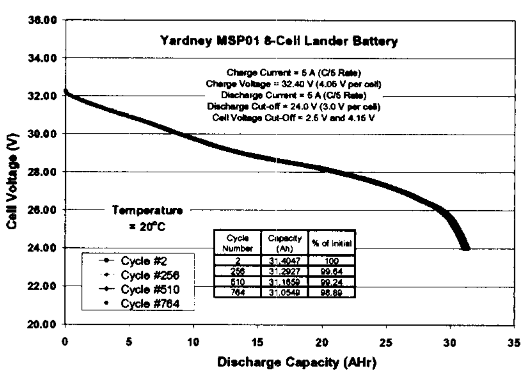

Fig. 14. 100% DOD capacity determination (32.8V charge and 24.0V discharge cut-off using C/5 rates) during 40% LEO testing.

Conclusions

As a result of the MSP'01 program, a number of flight quality, 8-cell, lithium ion batteries were fabricated by Lithion, Inc. and delivered to NASA in support of the mission. However, due to the mission cancellation, the batteries became available for general performance testing. In order to obtain relevant data for future aerospace applications, a multi-institutional collaboration was established to test the batteries most effectively. As a result, JPL is in the process of performing Mars mission simulation performance testing on one of the batteries, while performing a 40% DOD LEO test on the other battery. The performance observed to-date from the first battery indicates that the battery can effectively support the performance requirements originally projected by the MSP'01 mission and is capable of supporting a 90 day mission on the surface of Mars after a long storage period (11 months). In addition, it was demonstrated that the technology can support the projected load profile for the Mars Smart Lander mission, which is currently being formulated. Current efforts are targeted on demonstrating the life characteristics of the battery and the ability to support a long mission on the surface of Mars (3-5 years of operation). In addition to assessing the technology to meet future Mars mission applications, a LEO test has been initiated on the second Lander battery currently being tested at JPL. Although only 1000 cycles has been demonstrated to-date on the battery, very stable performance has been obtained thus far. Ultimately, the goal of this testing is to determine the viability of the technology to support long life orbiter applications, replacing the commonly used aqueous battery technologies (i.e., Ni-H_2).

Acknowledgements

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