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Performance Characteristics of Lithium-Ion Cells for NASA's Mars 2001 Lander Application

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ABSTRACT

NASA requires lightweight rechargeable batteries for future missions to Mars and the outer planets that are capable of operating over a wide range of temperatures, with high specific energy and energy densities. Due to the attractive performance characteristics, lithium-ion batteries have been identified as the battery chemistry of choice for a number of future applications, including Mars rovers and landers. The Mars 2001 Lander (Mars Surveyor Program MSP 01) will be among one of the first missions which will utilize lithium-ion technology. This application will require two lithium-ion batteries, each being 28 V (eight cells), 25 Ah and 8 kg. In addition to the requirement of being able to supply at least 200 cycles and 90 days of operation upon the surface of Mars, the battery must be capable of operation (both charge and discharge) at temperatures as low as –20°C. To assess the viability of lithium-ion cells for these applications, a number of performance characterization tests have been performed, including: assessing the room temperature cycle life, low temperature cycle life (-20°C), rate capability as a function of temperature, pulse capability, self-discharge and storage characteristics, as well as, mission profile capability. This paper will describe the Mars 2001 Lander mission battery requirements and will contain results of the cell testing conducted to-date in support of the mission.

aerospace batteries

INTRODUCTION

NASA is planning several missions in the near future to continue the exploration of the Mars, including some of the latter missions being aimed at retrieving Martian samples back to the Earth. Various missions, such as Landers, Rovers, Mars Ascent Vehicles (MAV) and Orbiters are thus being planned and will be supported by different advanced technologies. One advanced technology in the area of power sources is the lithium ion battery, which form the baseline for the upcoming MSP 2001 Lander. The MSP 2001 Lander is scheduled for launch in April 2001, and is expected to land in Jan. 2002. The descent imaging camera will provide images of the Martian landing site for geological analyses and will aid in the planning of initial operations and traverses for the MSP 2001 Rover. The Rover will be similar to the Sojourner that successfully accompanied the Mars Pathfinder and will be powered by primary Li-$SOCl_2$ for nighttime operations and will augment the solar array. In addition, the MSP 2001 Lander will consist of a platform for instruments and technology experiments designed to provide key insights to possible human missions in the later years. Prominent among these technologies are 1) in-situ demonstration of the rocket propellant production, using gases in the Martian atmosphere, 2) Mossbauer spectrometer and thermal emission spectrometer for characterizing the Martial soil properties, and 3) radiation monitor for detecting the surface radiation environment.

POWER SUBSYSTEM FOR MSP 01 LANDER

The main power source for the MSP 2001 Lander consists of a 300 W Ga-As solar cell array. The auxiliary power source augmenting the solar array for the nighttime operations is a Li ion rechargeable battery. There are two lithium ion batteries, one for redundancy, each of 28 V (eight cells), 25 Ah (name plate capacity) and 8 Kg. An important feature of the battery is its ability to operate (both charge and discharge) at continuous rate of C/5 at low temperatures down to -20°C, with a minimum BOL capacity of 25 Ah. The typical discharge drains will be C/5 to a maximum of 50% DOD. A single battery can mostly fulfil the needs of the entire mission; the second battery may thus be viewed as back up. However, with both the batteries being connected in parallel (with a diode protection), the actual depths of discharge could be even lower than 50%. Each of the batteries have an independent charge-control unit, with individual cell bypass features for charge control. The maximum charge current will be around 5 A (C/5). The batteries need to provide pulses of about 60 A at 10°C during EDL. In case that the Li ion batteries are unable to meet this criterion, a thermal battery (Li-FeS_2) is being used as in the case of Mars Pathfinder. Finally, the battery must survive a pre-discharge storage duration nearly 2 years (approximately 1 year pre-cruise storage and one year cruise period) at 10°C-30°C.

NASA/DoD JOINT EFFORT FOR Li ION BATTERIES

There is a considerable commonality in the needs of NASA and the Air Force for advanced rechargeable lithium ion batteries, especially for LEO/GEO satellites. Accordingly, a NASA/DoD Inter-agency consortium was recently initiated with the main intent of developing domestic capability to manufacture lithium-ion cells and batteries with smart chargers for both NASA and Airforce needs. Under this program, multiple manufacturers are being supported to provide the desired technological developments. As a part of this program, various lithium ion cells, in both prismatic and cylindrical configuration, and with capacities ranging from 4 to 40 Ah, are being evaluated at JPL under generic performance conditions as well as those relevant to Mars Surveyor Program 2001 Lander and 2003 Sample Return Athena Rover. In this paper, we report some of our recent observations on the behavior of Lander cells (20-40Ah) from these on-going tests. Similar tests carried out on smaller cells (4-7Ah) for MSP 2003 Sample Return Athena Rover are being communicated in our companion paper.[1]

Li ION CELL/BATTERY EVALUATION

In order to assess the viability of using lithium-ion technology for the Mars 2001 Lander, a test plan was formulated by Lockheed-Martin and JPL which reflected the need for data relating to the low temperature capability of SOA cells, as well as, their capacity retention characteristics. The test plan generally consists of determining: (i) the room cycle life performance (25°C), (ii) low temperature cycle life performance (-20°C) (iii) discharge and charge rate capability at different temperatures (-20, 0, 25, and 40°C), (iv) pulse capability at different temperatures and different state-of-charge (SOC), and the (v) optimum storage condition to ensure minimal loss of performance. These tests are aimed at establishing the baseline performance data and validating lithium ion technology for the the Mars 2001 Lander (Table 1). In addition to these core series of tests, a number of miscellaneous tests were also conducted to aid in the understanding of the thermal characteristics, temperature-compensated voltage charging, effect of charge methodology, as well as, safety and failure modes. Mission specific tests include cycling at partial depths of discharge and at alternating high and low temperatures, as well as, accelerated and real-time cruise and mission simulation tests.

In order protect the proprietary nature of their results, all cell data reported in this paper are presented anonymously and comparisons between vendor performance are not made. In most cases, each topic of discussion includes a mixture of data not associated with any one particular vendor or cell design.

Some preliminary results of lithium-ion cell testing at JPL for both Rover and Lander applications has been presented earlier.[2,3,4]

Li Ion Cell Testing for the Mars 2001 Lander

Physical, Formation and EIS (impedance)

Generic performance

- Cycling at RT
- Cycling at LT
- Charge rate vs. T
- Discharge rate vs. T
- Storage Behavior

Mission specific

- Cruise conditions
- Cycling @ low DOD
- Pyro -pulses
- Cycling at different temperature
- Mission simulation

Miscellaneous

- V/T Charge
- Thermal characteristics
- EIS vs. Cycling

Table 1: Schematic table illustrating the various tests being undertaken to assess the viability of lithium-ion cells for Mars Lander applications.

CELL TESTING RESULTS

Cells from different sources, ranging in capacity from 20-40 Ah were tested according to the various tests described above. After a preliminary incoming inspection, five conditioning cycles were conducted on all incoming cells under the voltage limits specified by the manufacturer.

ROOM TEMPERATURE CYCLE LIFE PERFORMANCE

After determining the nominal capacity from initial formation cycles (5 cycles), cells from a number of vendors were placed on 100% DOD cycle life tests at room temperature. These tests consist of charging the cells under conditions of constant current (C/5) to a potential of 4.1 and allowed to taper to a C/50 cut-off (or a 3 hour time limit) and then discharged at a C/5 rate to a 3.0V cut-off.

For the Mars Lander application, which requires a minimum cycle life of ~ 200 cycles, the life performance typically displayed by the cells under evaluation are more than adequate. As illustrated in Fig. 3, the large capacity lithium-ion cells currently being tested display comparable results in terms of the cycle life performance, yielding over 80% of the original capacity after 200 cycles.

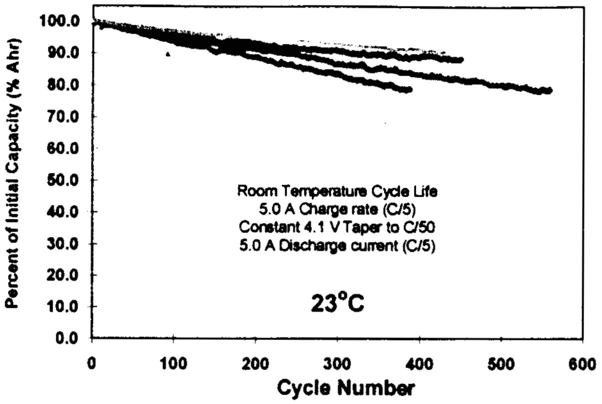

Fig. 1. Room temperature cycle life performance of various large capacity lithium-ion cells, expressed in terms of the percent of initial capacity delivered.

LOW TEMPERATURE CYCLE LIFE PERFORMANCE

In addition to being able to be cycled successfully at room temperature, the cells must be operational at–20°C over a minimum of 200 days. In order to address these requirements, cells from each vendor were cycled continuously at low temperature (-20°C). Although the operation of the battery on Mars is projected to involve charging under conditions of moderate temperatures (0-30°C), it was deemed necessary to assess the worst case scenario in which the battery was both charged and discharged at –20°C continuously. Thus, cycling tests were performed at –20°C in an environmental chamber under conditions of convective cooling to minimize the effects of self-heating. Significant improvements in cell performance at low temperature can be envisioned at the battery level, due to higher heat generation and retention, and with the implementation of insulating structures.

In the early stages of the program, a number of the cells evaluated displayed limited low temperature capabilities. However, due primarily to improvements in electrolyte formulations[5,6,7], much better low temperature performance has been demonstrated with a number of systems and cell types. As illustrated in Fig.4, when the cells from a number of vendors were cycled at –20°C (charge rate=C/5 and discharge rate = C/5) greater than 60% of the initial room temperature capacity was delivered over 200 cycles in most cases.

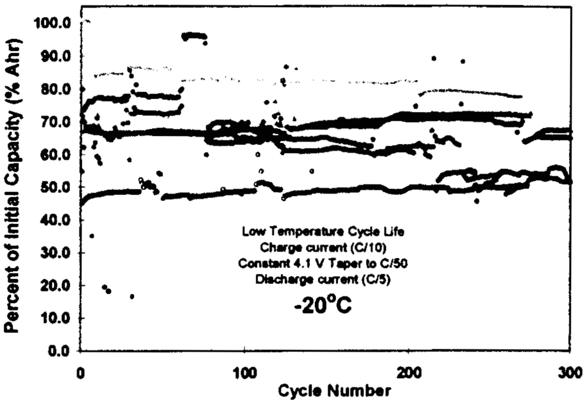

Fig. 2. Low temperature cycle life performance of various large capacity lithium-ion cells, expressed in terms of the percent of initial room temperature capacity delivered.

CYCLING AT VARIOUS TEMPERATURES

In addition to evaluating the cells at room and low temperature, it was also necessary to evaluate the cycle life performance of the cells at high temperature (40°C). As shown in figure 3, the cycle life performance for a group of cells is compared at different temperatures illustrating that high temperatures are more detrimental to the cell life over prolonged cycling. However, generally good cycling performance was observed over a wide temperature (-20 to 40°C) in a number of cases when the test are held constant at the specified temperature.

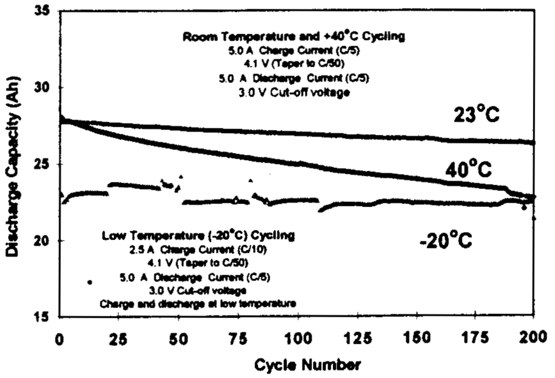

Fig. 3. Cycle life performance of 25 Ah cells at different temperatures. (C/5 or C/10 charge to 4.1V-C/5 discharge to 3.0V).

However, in the course of the investigating the overall cell performance it was observed that in most cases the low temperature performance characteristics display a sensitivity to variable temperature cycling. In some cases, the low temperature performance capabilities have decreased as a result of exposure and/or cycling at higher temperatures (> 20°C). This is presumably ascribed to increasing cell resistance, which is accelerated at higher temperature. These effects are magnified at low temperature and prohibit effective operation at moderate rates.

In order to assess this issue, we have conducted tests in which the cells are cycled intermittently between the two temperature extremes (-20°C and 40°C) in an attempt to assess the impact of high temperature cycling upon the low temperature performance. As shown in Fig. 4, the impact of cycling a cell intermittently at 40°C (20 cycles) results in a dramatic decrease in amount of capacity being able to be delivered at low temperature. As illustrated, only negligible capacity was realized after 170 cycles when cycled at low temperature (-20°C).

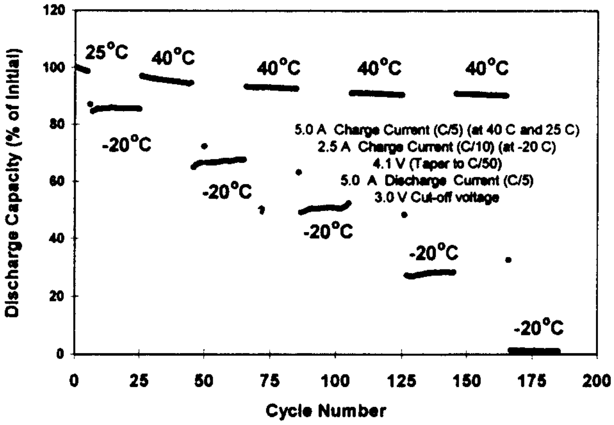

Fig. 4. Variable temperature cycling of a large capacity Li-ion cell.

As shown if Fig. 5, the observed watt-hour efficiency values decreased incrementally after each exposure to high temperature. This results suggests that the cell impedance is increasing more significantly at high temperature, resulting in more heat generation at low temperatures due to increased resistivity. However, more recent cell chemistries and designs, appear to display less sensitivity to variable temperature cycling.

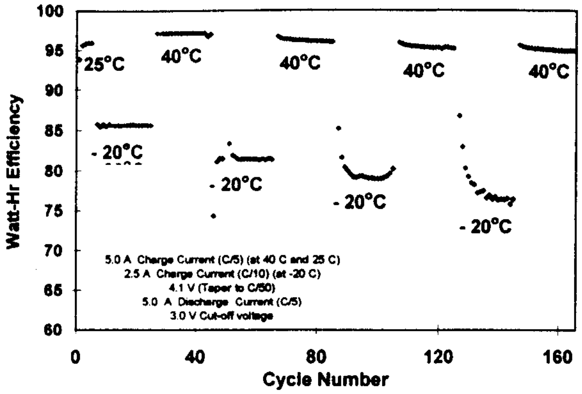

Fig. 5. Effect of variable temperature cycling upon the watt-hour efficiency of a large capacity Li-ion cell.

DISCHARGE PERFORMANCE AT DIFFERENT TEMPERATURES

In order to fully characterize the dependence of the discharge capacity with temperature, the cells were cycled using a number of different rates (C/10, C/5, C.3.3 and C/2) at different temperatures (-20, 0, 25, and 40°C). In many cases, excellent rate capability was observed over a wide range of temperatures with little polarization and capacity decline observed upon going to moderate rates (i.e., C/3.3-C/2), as illustrated in Fig. 6.

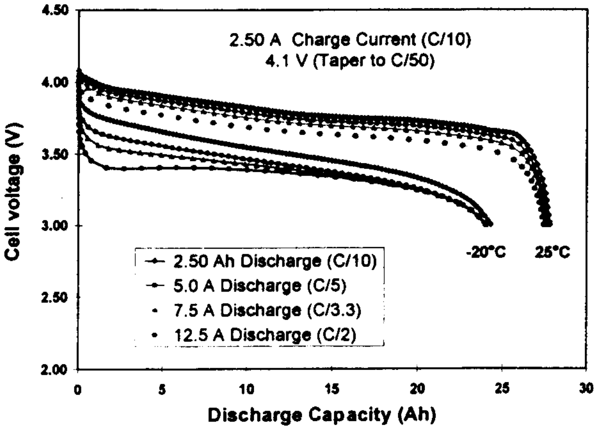

Fig. 6. Discharge rate capability of a typical 25 Ah cell at different temperatures (-20 and 40°C).

As shown in Fig. 7, one cell chemistry was capable of delivering >80 % of the room temperature capacity at –20°C when rates as high as C/2 are used.

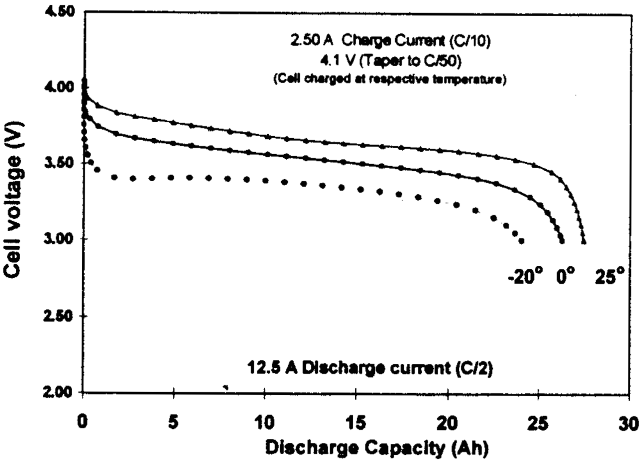

Fig. 7. Discharge capacity of a large Li-ion cell at different temperatures (C/2 discharge).

In the course of investigating the discharge rate capability as a function of temperature, the watt-hour efficiency at different discharge rates and temperatures was observed, as shown in Fig. 8 (expressed in terms of Δ watt-hour). In this particular example, it can be concluded that rougly a three-fold increase in heat generation occurs at –20°C in contrast to ambient temperatures.

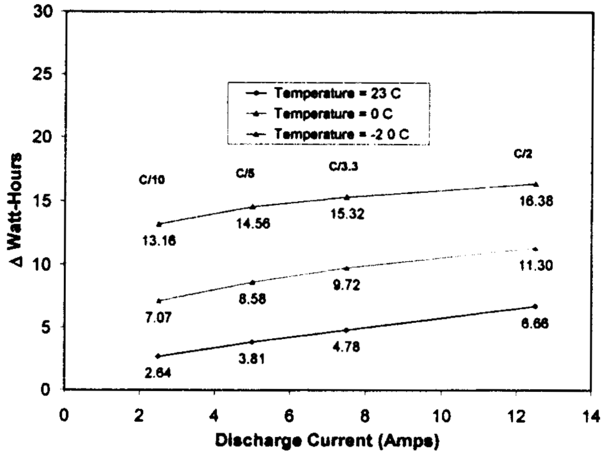

Fig. 8. Effect of temperature and discharge rate upon□watt-hour inefficiency.

CHARGE CHARACTERISTICS AT DIFFERENT TEMPERATURES

In the same manner in which the discharge capacity as a function of temperature was evaluated, the charge characteristics were assessed at different rates and temperatures. At room temperature, the cells generally displayed good charge acceptance characteristics over the range of rates investigated (C/2). In addition to investigating the rate capabilbity, the charge characteristics were also studied during the course of 100% DOD cycling. As shown in Fig. 9, if the charge profiles are compared at various cycles during a typical room temperature life cycling test it is evident that it takes longer to charge the cell and the peak potential (4.1V) is reached earlier in the charge step.

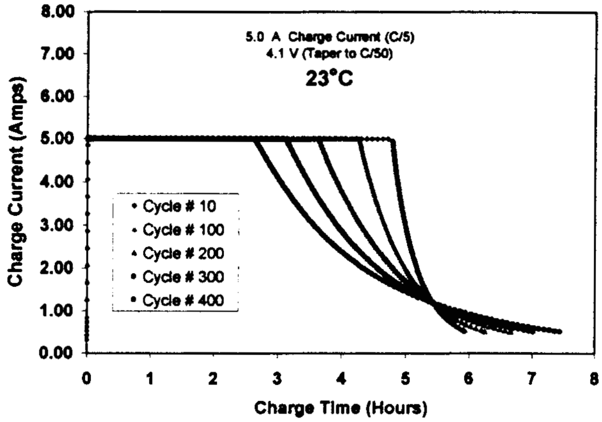

Fig. 9. Charge characteristics of a lithium-ion cell subjected to room temperature life cycling test (C/5 charge current to C/50 taper cut-off).

When the cells were evaluated at lower temperatures (-20°C), lower capacities were obtained even at the lower rates (C/10). It was also generally observed that the cells required larger charge times and were not capable of sustaining high charge currents for any significant period. In addition, although two different cells can accept comparable capacity at low temperature (-20oC), the charge profile observed can be significantly different, as shown in Fig. 10.

In most cases, the cell chemistries tested were typically charged using 4.1V as the preferred charge voltage. However, in order of understanding the impact upon performance, some cells were continuously cycled at higher voltages, such as 4.2 V. As illustrated in Fig. 11, the cells can successfully cycle when charge potential is set higher, however, it is evident that the capacity fade is more significant at the higher voltages, being roughly three time greater than that of the standard charge methodology of constant potential 4.1V charging.

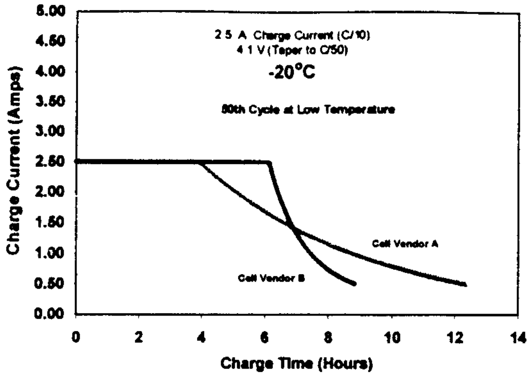

Fig. 10. Charge characteristics of lithium-ion cells at low temperature (–20°C).

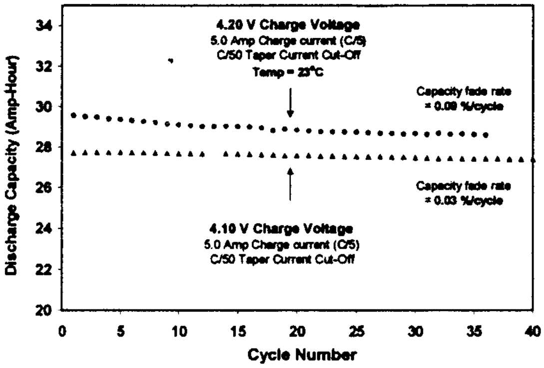

Fig. 11. Effect of charge voltage upon cycling characteristics of lithium-ion cells (C/5 charge current to C/50 taper cut-off).

STORAGE CHARACTERISTICS

For many applications, including the Mars 2001 Lander, the cells/battery must be capable of operation after a prolonged storage period. In the case of the Mars 2001 Lander, the battery must be operational after an 11-month cruise period while the spacecraft is in transit to Mars. Thus, it is crucial to understand general capacity retention characteristics inherent to lithium-ion technology, as well as, more specifically the manner in which individual cell chemistries and cell designs behave under particular conditions. The issue of capacity retention is complicated further by the fact it is difficult to obtain real-time data due to the long duration of many tests envisioned. To offset this difficulty, various means have been employed to generate meaningful data in a short period of time. For example, to address the need of the Mars Lander program, we have implemented routine capacity retention tests, which consist of storing the cells for two months under different conditions. In order to represent the extremes projected for the cruise storage period, two different temperatures were selected (0 and 40°C) and two different states-of-charge (50 and 100%) were utilized. For these initial tests, the cells were (I) first cycled (5-10 cycles) prior to storage (ii) stored at the selected temperature and state-of-charge (iii) discharged to 3.0V to determine the residual capacity and (iv) then cycled a number of times (5-10 cycles) to determine the extent of permanent capacity loss of the cells (if any) as a result of the storage period. Early tests demonstrated that the best performance, assessed in terms of least amount of permanent capacity loss observed (or alternatively expressed as reversible capacity) was obtained under conditions of low temperature (i.e., 0°C) and low states of charge (i.e., 50% SOC). In contrast, significant permanent capacity loss was obtained when some of the cells were stored at high temperatures (40°C) and high state-of-charge (100%), being as high as 10% loss in capacity after a two month period, as shown in Fig, 12.

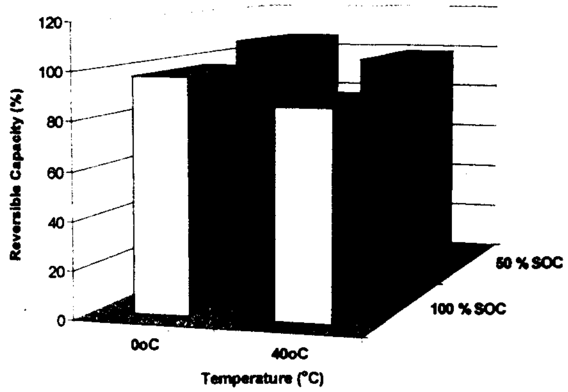

Fig. 12. Reversible capacity delivered by cells after a two-month storage period.

However, this behavior does not appear to be a universal characteristic of lithium-ion technology, and has been observed to vary with cell chemistry and cell design. For example, more recent tests performed on newer generation cells have yielded excellent performance with negligible permanent capacity loss observed after the two-month storage period as illustrated in Fig. 13.

Storage Temp (°C)	State of Charge	Capacity Loss (Ahr)	Permanent Capacity Loss (%)
0	50%	12.03 Ahr	1.6 %
0	100%	6.10 Ahr	2.9 %
40	50%	14.00 Ahr	0.6 %
40	100%	2.37 Ahr	2.0 %

Fig. 13. Reversible capacity delivered by cells after a two-month storage period.

CONCLUSIONS

A number of electrical characterization tests have been performed to evaluate the viability of using lithium-ion technology for the Mars 2001 Lander. A number of cells have been received from a number of vendor sources consisting of various cell types and designs for consideration. Results obtained from the characterization tests indicate that the cycle life requirement of these near-term missions is easily met (room temperature conditions) regardless of cell type or cell chemistry. The requirement of successful operation down to temperatures as low -20°C is much more challenging and more variation in performance between cell types is generally observed. However, very promising results have been obtained in terms of the low temperature cycle life and rate capability with a number of cells at –20°C, demonstrating that operation at these temperatures is indeed feasible. In fact, in some cases more than 80% of the room temperature capacity can be delivered at –20°C using a C/5 discharge rate. One issue of concern is related to the effect of high temperature exposure upon the low temperature performance. Studies are on-going in an attempt to systematically characterize this effect and the impact of cell chemistry and design upon this behavior. In addition to the low temperature performance, other issues of concern related to up-coming Lander mission include the capacity retention characteristics (or shelf life) of lithium-ion cells. Recent results, however, demonstrate that there is little permanent capacity loss over short periods of time (two months) over a range of temperatures (0 to 40°C) and states-of-charge (50-100% SOC).

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