# Lithium-Ion Rechargeable Batteries on Mars Rovers

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## ABSTRACT

NASA's Mars Rovers, Spirit and Opportunity, have been roving on the surface of Mars, capturing impressive images of its terrain and analyzing the drillings from Martian rocks, to answer the ever-puzzling questions of life beyond Earth and origin of our planets. These rovers are being enabled by an advanced rechargeable battery system, lithium-ion, for the first time on a space mission of this scale, for keeping the rover electronics warm, and for supporting nighttime experimentation and communications. These rover Li-ion batteries are characterized by their unique low temperature capability, in addition to the usual advantages associated with Li-ion chemistry in terms of mass, volume and energy efficiency. To enable a rapid insertion of this advanced Li-ion chemistry into flight missions, we have performed several performance assessment studies on several prototype cells over the last few years. These tests mainly focused primarily on the long-term performance characteristics, such as cycling and storage, as described in our companion paper. In addition, various tests have been performed on MER cells and engineering and proto-flight batteries, under conditions relevant to these missions. For example, we have examined the performance of the cells in: a) an inverted orientation, as during integration and launch, and b) conditions of low rate discharge, between 3.0-2.5 V to support the mission clock. Likewise, we have determined the impedance of the proto-flight Rover battery assembly unit in detail, with a view to assess whether a current-limiting resistor would be unduly stressed, in the event of a shorting induced by a failed pyro. In this paper, we will describe these studies in detail, as well as the performance of Li-ion batteries in Spirit and Opportunity rovers, during cruise and on Mars.

## INTRODUCTION

NASA's Mars Rovers, Spirit and Opportunity constitute two of the most successful space exploration missions. These two robotic missions were aimed at examining the presence of water and, thus, any evidence of life, and at understanding the geological conditions on Mars. Since their exciting landing on Mars in beginning of this year, these rovers have successfully completed the primary phase of the missions, and are about to complete the first extended phases, with about 180 sols and 160 of Martian sols completed thus far. Several astounding scientific contributions have already been made by both these rovers, including detection of past water at the both the landing sites, located at two ends of the planet, Mars.

The energy source on the rovers is comprised of deployable solar arrays with triple-junction GaInP/GaAs/Ge cells. For augmenting this power source and to support nighttime experiments, rechargeable lithium-ion batteries are being used, unlike the primary Li-$SOCl_2$ batteries on Sojourner rover in the Mars Pathfinder mission. The lithium-ion rechargeable battery system provided several unique characteristics, which enabled both the Spirit and Opportunity rovers. Specifically, the battery system could provide adequate power and energy for the missions, within the constraints of mass and volume, due to its high specific energy and energy density.[1] Furthermore, the Li-ion battery, containing a JPL-developed low temperature electrolyte, could operate well at sub-zero temperatures, down to –30°C, thus making the thermal management considerably easier. These batteries were located in the Aerogel insulated Warm Electronics Box. Using a combination of resistive heaters on external motors/cameras and internal components, radioisotope heating units (RHUs) and a thermal switch activated-loop heat pipe heat rejection system, the rover batteries are being maintained between –20°C to +30°C.

From the mission perspective, the rover lithium-ion batteries were designed to provide: 1) 24-36 V in all phases, 2) 200 Wh during launch, 3) about 160 Wh during cruise for supporting Trajectory Control Maneuvers (TCM), and about 283 Wh for surface operations, for about 300 cycles over 90 sols for the primary mission. In addition, the rover batteries were designed to provide energy to fire simultaneously three pyros (each with a load of 7 A) with an interval of at least 100 ms. To meet the above requirements, both the Sprit and Opportunity rovers have two parallel lithium-ion batteries, each with eight 10 Ah cells in series. The batteries were fabricated by Yardney Technical products, using the same chemistry that was developed earlier for MSP01 Lander missions,[1-3] and specifically containing the first generation low temperature Li-ion battery electrolyte, i.e., 1 M $LiPF_6$ dissolved in equi-proportion ternary mixture of ethylene carbonate, dimethyl carbonate and diethyl carbonate.[4] In addition to good low temperature performance, this chemistry showed excellent calendar and cycle life, much more than desired by the rover missions, and also a wide operating temperature range of –30 to +40°C.[5]

This paper describes the design and development of lithium-ion batteries on the Mars Exploration rovers. A brief discussion is also provided on the impedance characteristics of these batteries, which turned out to be rather crucial in establishing the fidelity of the pyro circuits on the spacecraft. Furthermore, the performance characteristics of these batteries on both Spirit and Opportunity, during cruise and on the surface of Mars, are described here. Finally projections have been made on the longevity of these batteries, and hence of these missions, beyond the on-going extended phase.

**MER Rover Li-ion Batteries**

The rover battery assembly unit is comprised of two parallel Li ion batteries, each containing eight prismatic 10 Ah Li-ion cells. These cells were specifically designed for the MER program, based on the envelope available. The battery housings were designed and fabricated at JPL. Each battery had an independent battery control board (BCB) to control the battery charge and discharge to within the allowable limits of 3.0 to 4.1 V. The cell balancing on charge was accomplished via individual cell bypass through 120 ohms resistor. The power subsystem as well as the battery assembly unit was so designed that the loss of one battery or the other will not impact the rest of the S/C. This was partly ensured by a divider plate between the two batteries that would provide the required pre-load on the battery, even in the event a failure from the other battery.

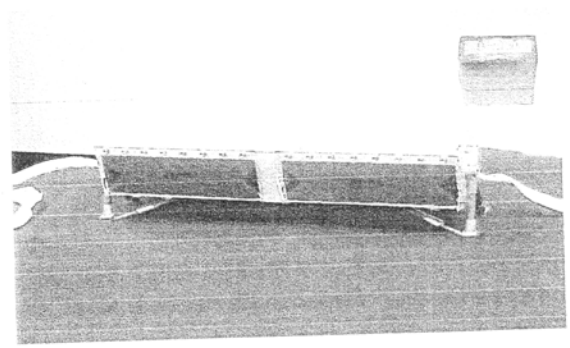

Fig. 1 Li-ion rechargeable battery Assembly unit on MER, Spirit and Opportunity

**Orientation Sensitivity of Li-Ion Cells**

One critical requirement in the design of the rover batteries was to assess the effect of cell orientation, if any, on the performance and durability of Li-ion cells. This was necessitated by the fact that the battery would be in the inverted, or upside down, orientation, either during launch or during the entire surface operations on Mars. Even though the rover cells are nearly starved of electrolyte, i.e., there is no free electrolyte that would flow onto the terminals inside; there wasn't much data in this regard.

In an initial screening test, we cycled a 7 Ah Yardney Li–ion cell through 100% DOD at room temperature, in the inverted orientation, which surprisingly showed a cell failure after about 630 cycles.

A destructive physical analysis of the cell could not lead any detectable failures within the cell. Nevertheless, it was decided that the preferred choice for the battery would be to keep the cell in the inverted mode during launch and in the upright orientation for the surface operations. In addition, we implemented another set of tests, in an accelerated fashion, to examine the effects of cell orientation on performance, i.e., two cells were cycled through 100% DOD at 25°C and 40°C, and two cells were placed on float at 4.10 V, at 25°C and 55°C. Under all these conditions, there are data available in the normal upright orientation, for comparison.

As shown in Fig. 2, the cycling characteristics of a Yardney Li-Ion cell at 40°C in the inverted mode is compared with the performance in the upright mode. As may be seen from the figure, there is virtually no difference in the performance in either orientation over about 1,000 cycles, even at 40°C. Similar tests performed for float-charge at 4.1 V at 25° and 55°C, in the upright and normal orientations, are illustrated in Fig.3. As may be seen from the figure, there is no adverse effect of keeping the cells in the upside-down orientation at 4.1 V at 25°C for over a period of 300 days. However, in a similar test performed at 55°C, the cell showed signs of failure after 115 days. In particular, the self-discharge increased significantly, as evident from an increased compensatory charge in float, as well as determined from separate charge-discharge measurements late in life.

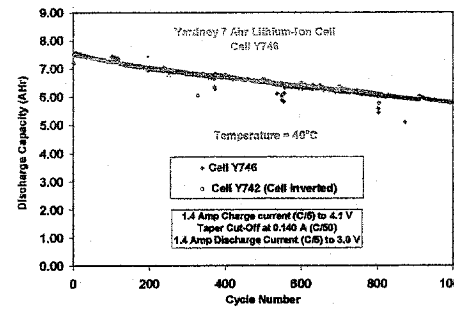

Fig.2: Cycling of Yardney Li-ion cells at 100% DoD at 25°C and 40°C in the upright and inverted orientations.

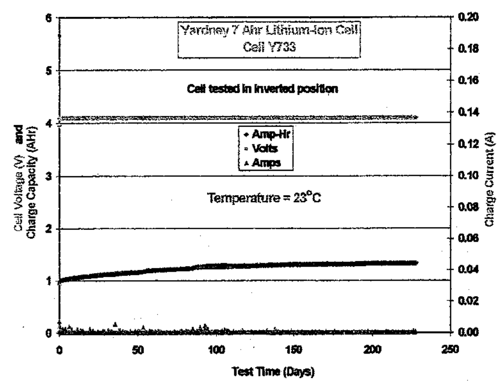

Fig. 3: Float-charging of Li-ion cells at 4.1 V at 25°C in the upright and inverted orientations.

It is thus clear from these studies that it is possible to have some adverse effects of operating Li-ion cells in the upside orientation, especially at high temperatures or over extended periods of operations. However, for the durations and temperatures expected on the MER missions, it is unlikely that this would be a factor, as also confirmed by the successful operation of these batteries descried below.

**Impedance of Rover Li-ion Batteries**

During the Assembly, Launch, and Testing Operations (ATLO) of the MER missions, especially towards the final phases on the launch pad, one of the pyros in series with the battery failed closed, which led to significantly high current to flow through the chassis and ground, thus blowing a 5 A fuse situated in between. This led to the power bus on the spacecraft, MER A, being floating, as opposed to the desired "grounded" condition. In addition, it was realized that there is a finite possibility for the current-limiting (12 A-15 A) resistor in series with the above squib and the rover battery assembly unit to be thermally stressed, if higher currents were passed through this. For an assessment of the fidelity of the pyro circuit, and hence the spacecraft, it was essential to make an analysis of the maximum current that would flow in the pyro circuit. In other words, it was critical to estimate the rover battery impedance under the prevailing conditions. Interestingly, a higher value for the battery impedance (at –16°C) was desirable (about 400 mOhms) from this standpoint. The battery impedance value was, thus, in the critical path of whether to proceed with the planned launch or not. Thus, a series of measurements were performed to make a determination on this characteristic, as discussed below.

The impedance of a cell or battery can be measured either by DC current interrupt methods or by ac Impedance. The latter method, which involves measurement of the impedance over a range of frequencies, has the advantage of separating the Ohmic, kinetic and diffusion resistances, with appropriate equivalent circuit analysis. However, it also requires extensive instrumentation, such a potentiostat, frequency response analyzer, etc., which are difficult to extend to multi-cell batteries. The former method, on the other hand, gives a composite and effective value of impedance, which is rather easy to implement and interpret. We have mostly adopted the DC current interrupt method for understanding the cell/battery impedance as a function of temperature, state-of -charge, and storage.

The DC impedance of the rover mission-simulation or engineering battery displayed values of 123 mOhms, 251 mOhms and 606 mOhms, with a sampling current of 5A for 60 second duration, at 20, 0, and -20°C, respectively. When the sampling current was increased to 30 A for a short-duration of 50 mS, the impedance values were found to decrease to 104 mOhms and 133 mOhms at 0 and –10°C, respectively. The latter data were, however, uncertain, due to slow acquisition by the Maccor battery system. It appears that the Maccor battery system typically averages over eight data points, at such rapid acquisition of one point each 10 mS. Despite this uncertainty, there is a clear trend that the impedance decreases with the sampling current, as also evident from a systematic set of measurements performed later on (Fig. 4). As may be seen from the figure, the impedance drops continuously from a high value of over 900 mOhms at 250 mA to about 500 mOhms at 5 A. Such a strong dependence of the rover battery impedance on the sampling current is rather surprising, especially at low temperatures, where the ohmic component is expectedly a dominant portion. Also, it was intriguing to estimate what the battery impedance would be at 12-15 A, which could be the currents in the pyro circuit, in the event of a pyro short. Furthermore, the above decrease in the impedance may not be attributed to any thermal effects, since a longer pulse of 60 seconds gave the similar values as above.

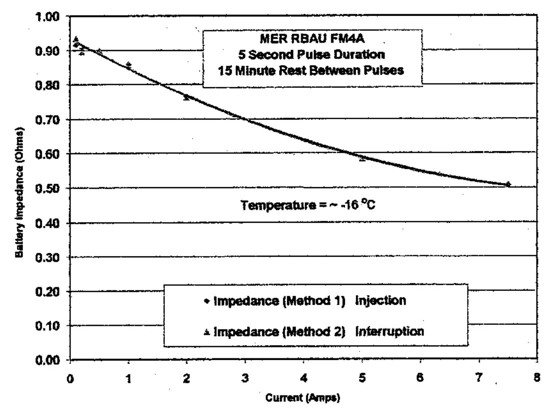


Fig. 4: The variation of impedance from DC current interrupt, with the sampling current at –16°C.

The above decrease in the impedance with increasing DC current is understandable, if the kinetic resistance is a dominant portion of the battery impedance. On recasting the data in Fig. 4, a Tafel-type plot is generated, which shows linearity between the voltage and the logarithm of current (Fig. 5).

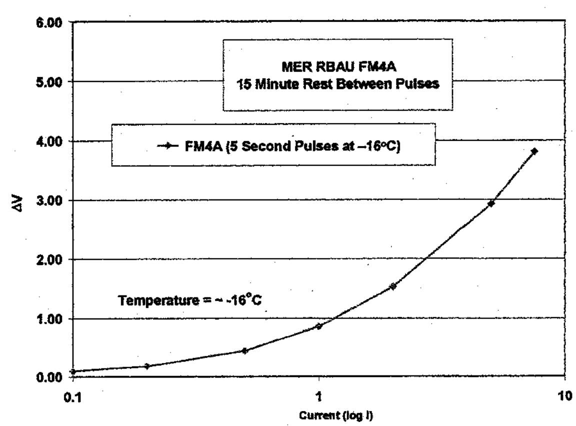


Fig. 5: Variation of the rover battery polarization with discharge current (Tafel plot)

The above plot is slightly distorted from ideal Tafel polarization curve, with contribution from ohmic polarization at low currents and from the diffusional impedances at high currents. The latter portion is further exacerbated from the impedance measurements carried out with different pulse widths (Table-1). With longer pulses, the diffusional gradient sets in and, thus, the diffusional impedance as well as the battery impedance continues to increase.

From an electrochemical perspective, the overall electrode impedance is composed of Ohmic, kinetic and mass transfer polarizations. Among these, the Ohmic polarization is independent of the magnitude and duration of the current pulse. The kinetic polarization, as well as the mass transfer polarization, on the other hand, are strong functions of the magnitude and duration of the current pulse, respectively, and are expressed by the usual electrochemical rate equation, also called the Butler-Volmer equation,

Table 1: Rover battery impedance as a function of pulse width

| Current (A) | Pulse Time | $\Delta V$ | Impedance (mOhms) |
|---|---|---|---|
| 12 | 30 | 1.9672 | 164 |
| 12 | 50 | 2.154 | 180 |
| 12 | 75 | 2.4415 | 203 |
| 12 | 100 | 2.5812 | 215 |
| 12 | 125 | 2.7003 | 225 |
| 12 | 150 | 2.8614 | 238 |
| 12 | 1000 | 4.6601 | 388 |
| 12 | 5000 | 5.1642 | 430 |

$$\frac{i}{i_o} = \left(\frac{C_o}{C^*_O}\right)\left[\exp\left(\frac{\alpha nF}{RT}\right)(E - E_{equi}) - \left(\frac{C_R}{C^*_R}\right)\exp\left(\frac{(1-\alpha)nF}{RT}\right)(E - E_{ref})\right]$$

The above equation is reduced to a simple Tafel equation at high overpotentials values, where the reverse reaction can be ignored.

$$\eta = a + b\log(i)$$

This, upon differentiation, gives:

$$\frac{\partial \eta}{\partial i} = \frac{b}{i}$$

The above equation implies that the kinetic impedance decreases with an increase in the (pulsing) current, as also observed experimentally in this case. The mass transfer impedance, on the other hand increases with either current or with duration (Table1), which is represented by the pre-exponential terms in the rate equation, i.e., the ratio of interfacial and bulk concentration or the diffusion gradients. To conclude, the impedance, measured from DC current pulse measurements, is a function of pulse characteristics and is to be measured under condition pertaining to the application.

Finally, the impedance of rover batteries was measured at 5 A, 11 A and 17 A, using an oscilloscope for rapid data acquisition. Fig. 6 shows such an oscilloscopic trace of the rover battery. The rover battery impedances thus measured were 260 mOhms, 263 mOhms, and 287 Ohms, at 5, 11, and 17 A, respectively. Even though these values are lower than estimated initially, they were perceived to be high enough, especially from the fact that the spacecraft temperatures would be a couple of degrees lower, close to –18°C, and the impedances would be proportionately higher. Accordingly, it was determined to be acceptable risk to proceed with the launch. Interestingly, the fuse did blow on both Spirit and Opportunity, thus making both spacecraft operate with 'floating power bus'.

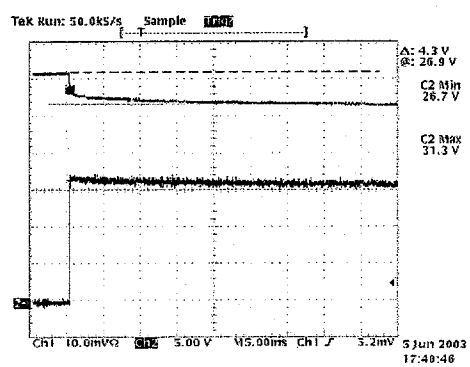


Fig. 6: Oscilloscopic repose of battery voltage to a current pulse for impedance measurements.

## In-Flight Performance of Li-ion Batteries

As mentioned before, the Li-ion batteries on the MER were designed to support the launch, the trajectory control maneuvers during cruise, and the surface operations, later on Mars. During cruise, the batteries were held as low a state-of-charge as possible, and at a temperature decreasing from +15 to –10°C. The rover batteries were charged using dedicated battery control boards that controlled battery charge and discharge voltages. These battery control boards were designed and fabricated in-house and were based on bypass circuits through 120 ohms resistors across each cell, for preventing cell overcharge. The bypass would kick in if the cell voltage was within 30 mV from the command charge voltage, which has four preset values of 3.85, 3.95, 4.15 and 4.2 V. Likewise, the bypass would stop if the cell voltage is lower than the command voltage by a margin of at least 70 mV. Fig. 7 shows the behavior of the first Li-ion battery on the Spirit, during launch and cruise.

As may be seen from the figure, the battery was discharged about 25% depth of discharge per battery. After launch, the battery assembly unit was charged fully and was kept at the state of charge for about a month. During this time, we were busy with the launching of the second rover, Opportunity. Subsequently, the state of charge battery assembly unit brought down to 80% and kept around that value for period of over five months. During this float charge on cruise, the cell divergence increased beyond 150 mV, which led to cell bypassing and cell rebalancing. There were five to six times that the battery assembly unit was subjected to such cell balancing. Again, about a month before landing, the battery assembly unit was charged fully to keep it available for the Entry, Descent, and Landing (EDL) Operations, if required, and for immediate surface operations. The behavior of the second battery is shown in Fig. 8. As may be seen from the figure, the second battery behaved much like the first battery, in terms of battery and cell voltages and cell divergence. Also, the behavior of the rover batteries on the second rover, Opportunity is similar to these batteries.

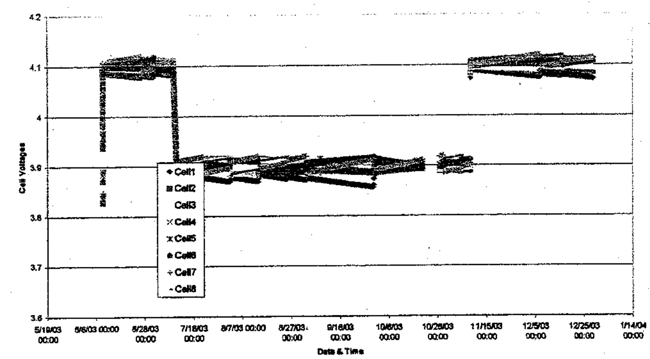


Fig. 7: Behavior of a Li-ion battery on the Spirit during launch and cruise.

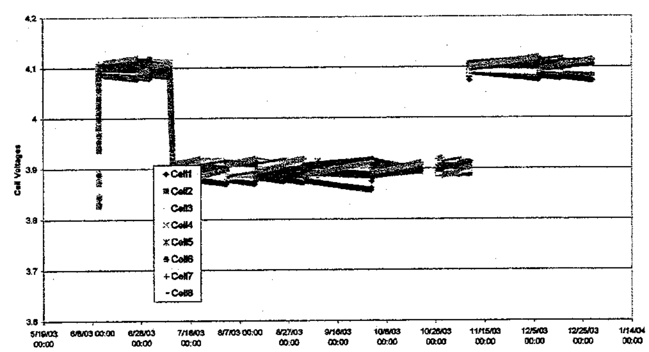


Fig. 8: Behavior of the second Li-ion battery on Spirit during launch and cruise.

## Performance on Mars Surface

The rovers, Spirit and Opportunity, have successfully completed the primary mission of 90 Martian sols, and are currently in the extended phase of the missions. Specifically, Spirit has thus far completed about 180 sols and Opportunity is about 20 sols behind. The lithium-ion batteries have been performing quite well and providing impressive support to the mission. Fig. 9 A and 9B sum up the performance of the battery assembly units on Spirit and Opportunity. The battery end-of-discharge-voltages (or minimum voltages) are all above 28 .5 V, which approximates to a state of charge of 50%.

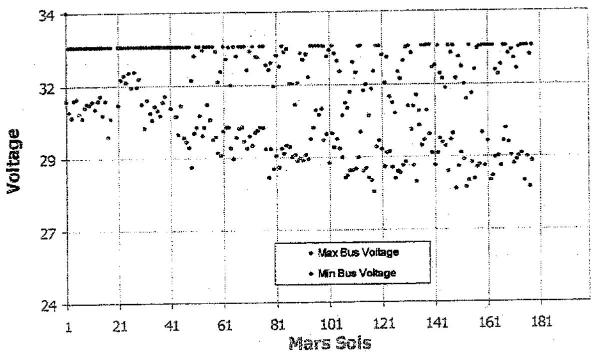


Fig. 9A: Minimum and maximum voltages of Li-ion battery on Spirit during surface operations

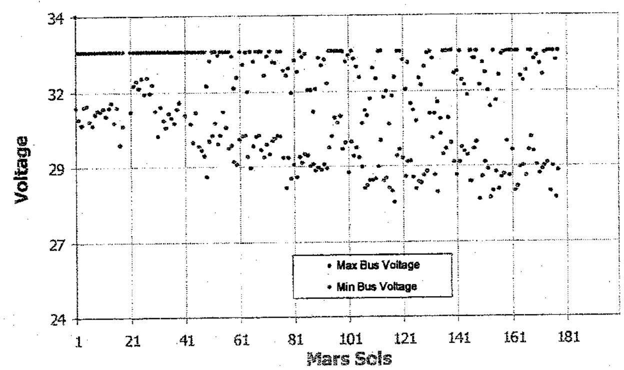


Fig. 9B: Minimum and maximum voltages of Li-ion battery on Opportunity during surface operations

Typical end of discharges are around 3.6 V. The batteries on Spirit experienced a fairly deep discharge around 20the sol, due to a flash memory problem. Nevertheless, the batteries removed subsequently and have been performing well. Fig. 10 shows the charge and discharge capacities of these batteries both on Spirit and Opportunity. The batteries on Opportunity have been experiencing deeper discharges, compared to those on Spirit, due to additional heater load, which could not be turned off.

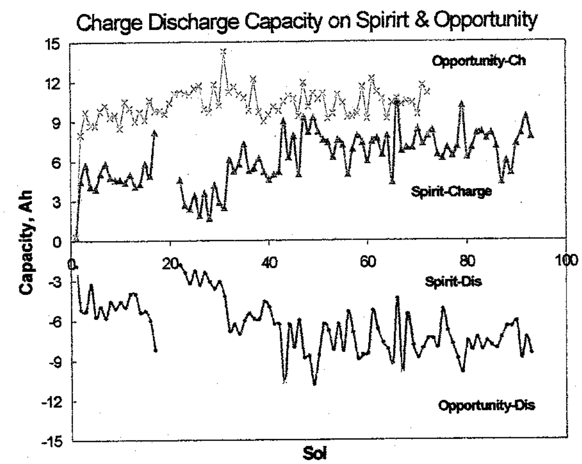


Fig. 10: Charge and discharge capacities of Li-ion batteries on Spirit and Opportunity rovers

Based on ground mission simulation testing, the variation in the battery impedance and capacity as function of temperature, before and after 90 sol simulations, are depicted in Fig. 11 and 12, respectively. As may be seen from the figure, and similar performance tests described in our companion paper, these Mars rover can be expected to operate a couple of years, subject to the longevity of solar array.

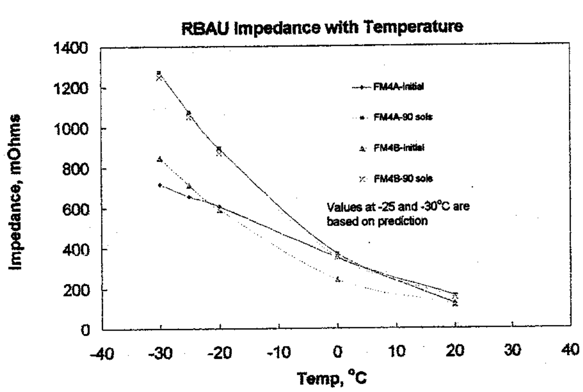


Fig. 11 Li-Ion battery impedance from ground tests

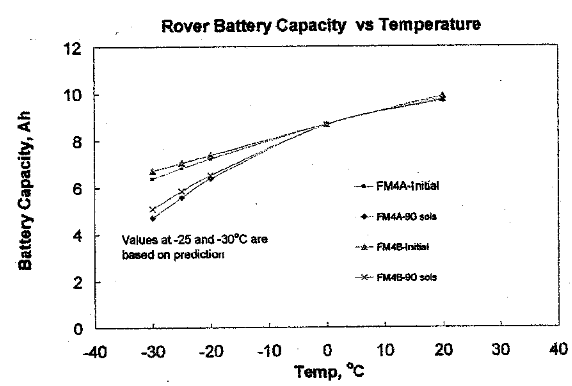


Fig. 12 Li-Ion battery impedance from ground tests

## Conclusions

Li-ion batteries provided the heart beat for the Mars Exploration Rovers. Prompted by the constraints on mass and volume, the high specific energies combined with good low temperature performance of lithium-ion batteries, resulted in enhancing the capabilities of these missions significantly, compared to the conventional aqueous rechargeable batteries. These batteries have thus far shown very little performance degradation, and may very well extend the rover missions from months to years. Finally, there will be several future missions that can be equally benefited by Li-ion battery technology.


## Acknowledgements

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