Li-Ion Rechargeable Batteries on Mars Exploration Rovers

B. V. Ratnakumar, M. C. Smart, L.D. Whitcanack, R. C. Ewell and S. Surampudi
Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Dr., Pasadena, CA 91109

ABSTRACT

Lithium-ion batteries have contributed significantly to the success of NASA's Mars Rovers, Spirit and Opportunity that have been exploring the surface of Mars for the last two years and performing astounding geological studies to answer the ever-puzzling questions of life beyond Earth and the origin of our planets. Combined with the triple-junction solar cells, the lithium-ion batteries have been powering the robotic rovers, and assist in keeping the rover electronics warm, and in supporting nighttime experimentation and communications. The use of Li-ion batteries has resulted in significant benefits in several categories, such as mass, volume, energy efficiency, self discharge, and above all low temperature performance. Designed initially for the primary mission needs of 300 cycles over 90 days of surface operation, the batteries have been performing admirably, over the last two years. After about 670 days of exploration and at least as many cycles, there is little change in the end-of discharge (EOD) voltages or capacities of these batteries, as estimated from the in-flight data and corroborated by ground testing. Aided by such impressive durability from the Li-ion batteries, both from cycling and calendar life stand point, these rovers are poised to extend their exploration well beyond two years. In this paper, we will describe the performance characteristics of these batteries during launch, cruise phase and on the surface of Mars thus far.

INTRODUCTION

NASA's planetary exploration consists of three different types of missions, i.e., a) orbiters for global mapping the planetary surface and atmosphere, b) probes for a localized surface atmospheric and exploration and c) rovers and landers for an extended surface exploration. The recent orbiter missions, under the Mars Exploration, included Mars Global Surveyor (1998), Mars Odyssey (2001) and the Mars Reconnaissance Orbiter (2005). Typically each of the orbiter missions lasts over five years and has thus far been supported by rechargeable nickel-hydrogen batteries. A typical probe mission was Mars Microprobe, which was piggy-backed on the unsuccessful Mars Polar Lander and was supported by a Li-$SOCl_2$ primary battery, designed specifically to withstand high impact (80,000g) as well as ultra-low surface temperatures (-80^{o}C). In the category of Mars Rovers and Landers, we had the highly successful Mars Pathfinder mission, which had a Lander and a small rover, Sojourner. Following that huge success, NASA attempted to have another Lander mission in the form of Mars Polar Lander, which encountered failure in landing, which also triggered the cancellation of subsequent Mars Surveyor Lander in 2001. Almost eight years after the Mars Pathfinder, NASA has had an even more resounding success through the on-going twin Mars Exploration Rovers, Spirit and Opportunity, launched in 2003.

From a historical perspective, the Mars Exploratron Rovers are almost ten times as big and also with more than ten-fold roving capability as the Sojourner rover in the Pathfinder mission (Fig.1). In terms of power technologies, the Mars Pathfinder Lander as well as Sojourner rover were assisted by solar arrays, which were augmented by rechargeable silver-zinc batteries and primary lithium-thionyl chloride batteries, respectively. While the cycle life of the silver-zinc batteries limited the mission of Pathfinder Lander to less than 100 cycles, the limited energy of the primary battery on the Sojourner rover restricted its mission to 90 days. The Mars Exploration Rovers, on the other hand, are being assisted by rechargeable lithium-ion batteries, for the first time in a major space mission.[1-4] Even though the batteries were intended to support the primary mission life of 300 cycles over 90 days, their performance has far exceeded these expectations. Since their exciting landing on Mars in the beginning of 2004, these rovers have successfully completed the primary phase of the mission and first extended phase, and are well into their second extended phase, with about 670-690 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 opposite sides of Mars.

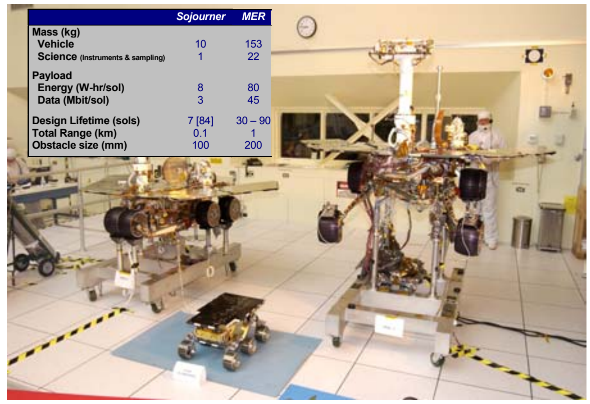

Fig.1 MER Spirit and Opportunity rovers on either of the Sojouner Rover on the Pathfinder mission

The energy conversion system on the rovers is comprised of deployable solar arrays with triple-junction GaInP/GaAs/Ge cells. The BOL (beginning of life) energy of the solar array is about 1000 Wh per sol. Over the course of 660 cycles and almost two years of operation, there have been decreases in their energy levels, partly due to Martian dust accumulation on the array. However, these arrays were partly cleaned multiple times by localized winds, thus restoring their energy levels and are currently over 500 Wh. The energy storage system on these rovers is comprised of lithium-ion rechargeable batteries, as mentioned above. The use of Li-ion batteries, in place of conventional aqueous or alkaline systems, was primarily governed by the power and energy needs for the missions, within the constraints of mass and volume. Alkaline systems would have provided either 25-20 % of the desired energies (e.g., Ni-Cd or Ni-H_2) in the available mass and volume, or a mission life of < 90 days (e.g., Ag-Zn) (Table-1). Furthermore, the MER Li-ion battery, aided by a JPL-developed low temperature electrolyte, could operate well at sub-zero temperatures, down to –30°C, as well as at ambient temperatures (25°C), which made the thermal management relatively easy, with reduced mass and size.

Table-1: factors governing the selection of Li-ion batteries for MER

System → Characteristic ↓	Nickel-Cadmium	Nickel-Hydrogen	Silver-Zinc	Lithium-Ion
Specific Energy (Wh/kg)	25	30	~100	>100
Energy Density (Wh/lit)	100	50	~150	>250
Battery Mass for 300Wh MER (kg)	33	28	11	6
Battery Volume for 300 Wh MER (Lit)	9	17	6	2.2
Cycle Life (50% DoD)	>1000	>1000	<100	>1000
Wet life (Storageability)	Excellent	Excellent	Poor	Good
Self-Discharge (per month)	15%	30%	15-20%	<5%
Low temperature Performance (-20°C)	Moderate	Moderate	Moderate	Excellent
Temperature Range, °C	-10- 30	-10- 30	-10- 30	-20 to +40
Charge Efficiency %	80%	80%	70%	~100%

These batteries were located in the aerogel-insulated Warm Electronics Box. Using a combination of resistive heaters, radioisotope heating units (RHUs) and thermal switch activated heat rejection system, the rover batteries are being controlled thermally between –20°C to +25°C. The batteries were fabricated by Yardney Technical products, or currently Lithion, located in Pawcatuck, CT, using the same chemistry that was developed earlier for MSP01 Lander missions.[5] This chemistry utilized our 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.[6] In addition to good low temperature performance, this chemistry showed excellent calendar and cycle life, much more than required by the rover missions, and also a wide operating temperature range of –30 to +40°C.[7]

Li-Ion batteries on Mars Exploration Rovers

The rover battery assembly unit was comprised of two parallel Li ion batteries, each contained 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. Such a device is critical to ensure safe operation from a lithium ion battery. Li-ion cells are rather intolerant to overcharge; Several exothermic processes, including electrolyte oxidation occurs, which lead to thermal runaway, cell venting, fire or even explosion. During overdischarge, on the other hand, the reliability is heavily compromised, due to possible dendrites from copper (anode substrate) dissolution and redeposition. The Battery Control Board designed and fabricated at JPL monitors each cell voltage and ensured that both overcharge as well as overdsicharge are avoided. During charge, there could be cell imbalance sue to different degree of self-discharge and/or degradation of the cells, The BCB compensates for this cell divergence, by facilitating cell balancing on charge via individual cell bypass through 120 ohms resistor on the weaker cells, thus allowing the stronger cells to be charged. Each battery has thus one dedicated BCB on the rovers, tofacilitate charging to four different cell/battery voltage limits and with cell balance to limit the cell divergence to 150 mV.

Fig.2 Li-Ion Rechargeable Battery Assembly Unit (RBAU) on Mars Exploration Rovers, Spirit and Opportunity

IN-FLIGHT PERFORMANCE OF LI-ION BATTERIES

Launch and Cruise

The Li-ion batteries on the MER were designed to provide about 200 Wh during launch at ambient temperatures, which corresponds to about 50% depth of discharge, if both batteries were functional and fully charged to 32.8 V. Subsequently, the battery state of charge was adjusted to ~ 80% to support cruise anomalies, which include trajectory control maneuvers. In addition to being at low state of charge, the batteries were held at a low temperature as well during cruise, with the temperature of decreasing from an initial value of 15^{o}C to a final value of –10^{o}C during cruise. These measures were recommended with the objective of minimizing the permanent loss in the battery capacity during on-buss storage in cruise.[8] The cruise anomaly corrections required about 160 Wh, which would be a challenge for single battery to support, especially at -10^{o}C. However, as illustrated below, the rovers didn't experience any such cruise anomaly, and the batteries were not discharged during cruise. Fig. 3 shows the behavior of the Li-ion batteries on the Spirit during launch and cruise. The batteries on the Opportunity rover showed similar behavior.

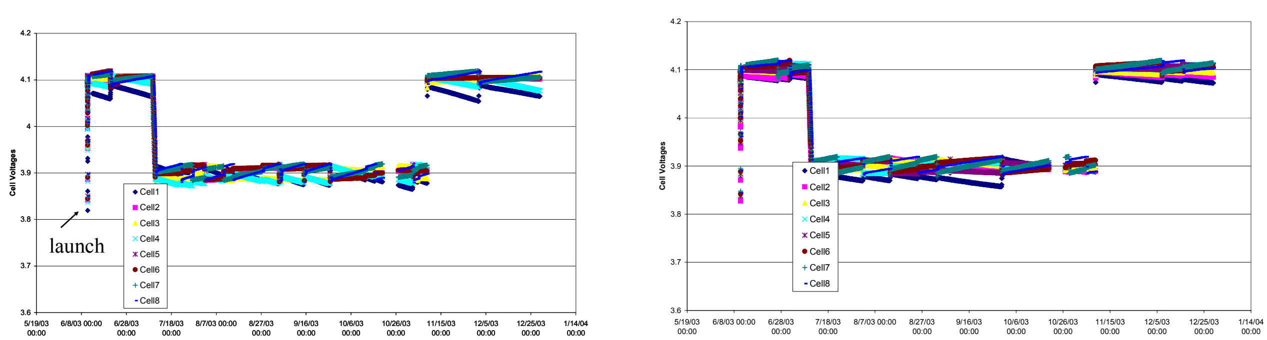

Fig. 3: Behavior of Li-ion batteries on the Spirit during launch and cruise

As may be seen from the figure, each battery was discharged to about 25% depth of discharge per battery during launch, with lowest cell voltages being 3.82 V. After launch, both the batteries were fully charged and were maintained at the state of charge for about a month, due to the mission personnel being tied up with the launching of the second rover, Opportunity. In this one-month duration, the individual cell voltages showed slight divergence a couple of times, to probably beyond 140 mV, which prompted the implementation of cell balance through by-pass. Subsequently the state of charge in both the battery assembly units was brought down to 80% and maintained over a period of four months. Once again, during these four months, the cell divergence increased beyond 150 mV, followed bypass and cell rebalance, for about 6-8 times. Later, about a month before landing on Mars, the batteries were charged back to 100% state of charge, to be ready for the Entry Descent and Landing (EDL) Operations, if required, and for immediate surface operations. The behavior of the Li-ion batteries on the second rover, Opportunity is similar to these batteries.

PERFORMANCE ON MARS SURFACE

The rovers, spirit and Opportunity have successfully completed the primary mission of 90 Martian sols and are currently in the second extended phase of the missions. Specifically, Spirit has thus far completed about 690 sols and Opportunity has about 670 sols to its credit. The lithium-ion batteries have been performing quite well and providing impressive support to the mission. Fig. 4A and 4B sum up the performance of the battery assembly units on Spirit and Opportunity.

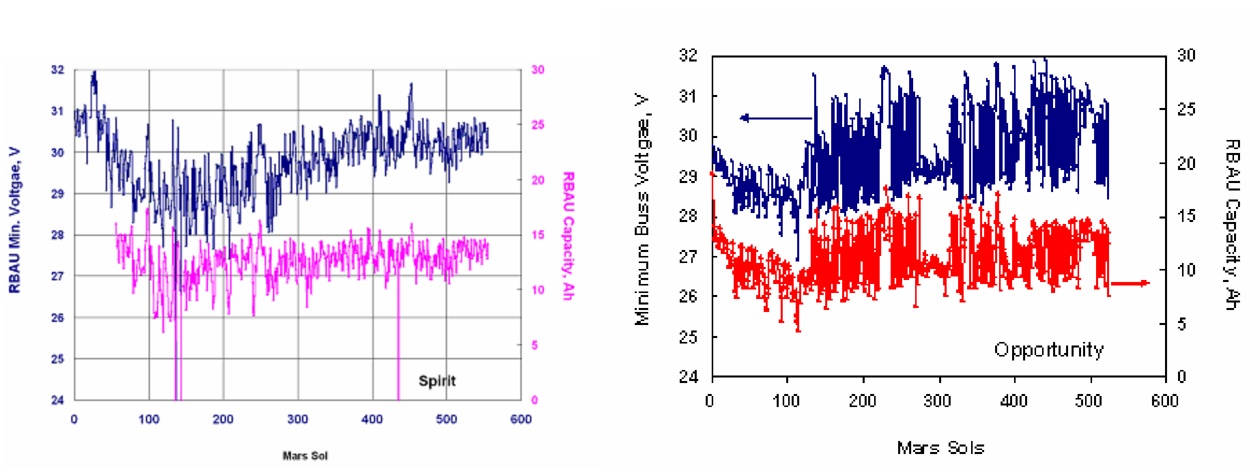

Fig. 4: Summary of RBAU performance on Spirit and Opportunity

There was a software-related anomaly around sol 20 for the Spirit, specifically the flash memory being full, when the batteries were completely discharged and were recharged only after a few days. This anomaly, however, didn't affect their subsequent performance. The minimum RBAU voltages or the battery end of discharge voltages are above 28 V. The maximum discharge (or charge) capacity is little more than 10 Ah voltage, i.e., 50% depth of discharge for the RBAU (Fig. 4). Based on the high RBAU voltage, it may be inferred that both the batteries in these RBAUs have been functioning well, sharing the load (and energy) between them, almost equally. This moderate DOD in turn will have considerable benefit on the cycle life that may be expected from these batteries, especially when the operating temperatures are low.

PROJECTION ON MISSION LIFE

After over 660 cycles into the Mars expiration, the energy conversion system as well as energy storage device, i.e., solar arrays as well as the Li-ion batteries have performed well beyond the expectations. The solar array for example lost power in between due to dust accumulation on the panel, which subsequently cleared by itself. As a result, the solar array recovered almost totally, currently displaying daily energy values of ~ 600 Wh, with peak currents of over 3 A (Fig. 5). The Li-ion rechargeable batteries, on the other hand, have healthy discharge (minimum) voltages, indicating little degradation in their capacity. The ground tests being performed on the mission simulation battery estimate the capacity loss in the MER batteries is 5-10% thus far (Fig. 6).[9] Both the solar arrays as well the batteries are therefore expected to continue providing power to the Sprit and Opportunity rovers through over 1000 sols and thus extend the Martian surface to about three years.

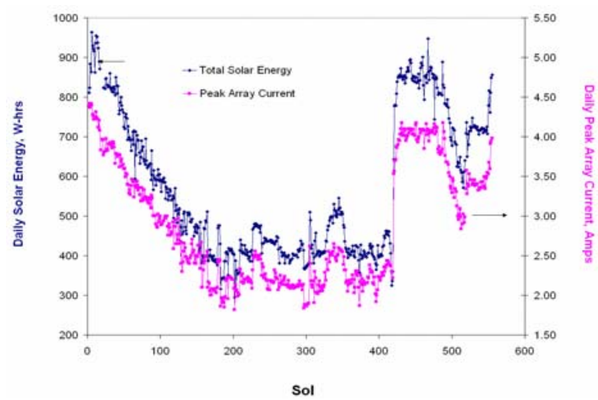

Fig. 5. Solar array power on MER

CONCLUSIONS

Li-ion batteries provided the heart beat for the Mars Exploration Rovers; It may be argued that the lithium-ion batteries have considerably enhanced or even enables the Mars Rover missions, as judged by the constraints on the battery mass and volume and the need to operate at low temperatures over a few years. After about 670 cycles and 670 days of surface exploration and about three and half years after their fabrication, these batteries have very healthy discharge characteristics. Based on the ground tests on the mission simulation batteries, it is clear that there is very little performance degradation in the rover batteries, and these batteries are well poised to extend the rover missions from an initial design life of couple of months to couple of years. Finally, the insertion of Li-ion batteries into the Mars Rover will provide much-needed flight heritage and validation to this technology, such that several future surface missions i.e., Phoenix Lander in 2007 and Mars Science Laboratory (MSL) in 2009. It is only a matter of one or two years before the insertion of Li-ion batteries for long-life missions, such as planetary orbiters and LEO/GEO satellites.

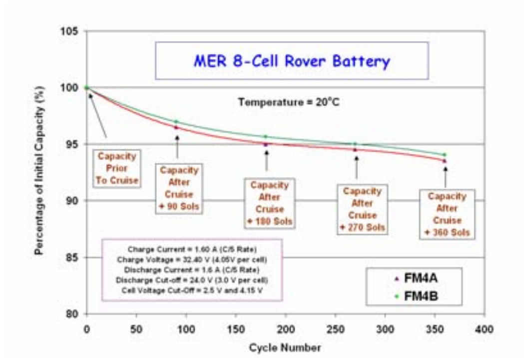

Fig. 5 Mission simulation ground testing of MER Li-Ion batteries

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