An Update on the Performance of Li-Ion Rechargeable Batteries on Mars Rovers

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ABSTRACT

NASA's Mars Rovers, Spirit and Opportunity have been exploring the surface of Mars for the last thirty months, far exceeding the primary mission life of three months, performing astounding geological studies to examine the habitability of Mars. Such an extended mission life may be attributed to impressive performances of several subsystems, including power subsystem components, i.e., solar array and batteries. The novelty and challenge for this mission in terms of energy storage is the use of lithium-ion batteries, for the first time in a major NASA mission, for keeping the rover electronics warm, and supporting nighttime experimentation and communications. The use of Li-ion batteries has considerably enhanced or even enabled these rovers, by providing greater mass and volume allocations for the payload and wider range of operating temperatures for the power subsystem and thus reduced thermal management. After about 800 days of exploration, there is only marginal change in the end-of discharge (EOD) voltages of the batteries or in their capacities, as estimated from in-flight voltage data and corroborated by ground testing of prototype batteries. Enabled by such impressive durability from the Li-ion batteries, both from a cycling and calendar life stand point, these rovers are poised to extend their exploration well beyond 1000 sols, though other components have started showing signs of decay. In this paper, we will update the performance characteristics of these batteries on both Spirit and Opportunity.

INTRODUCTION

NASA's Mars Rovers, Spirit and Opportunity constitute two of the most successful robotic space exploration missions in the recent past. The detailed science objectives of these two 'robotic geologists' were aimed at a) Searching for and characterize a diversity of rocks and soils that hold clues to past water activity, b) Investigating landing sites which have a high probability of containing physical and/or chemical evidence of the action of liquid water, c) Determining the distribution and composition of minerals, rocks, and soils, which will have a bearing on our understanding of its (Mars's) origin.[1] d) Characterizing mineral assemblages and textures in the geologic context, e) Identifying and quantifying iron-bearing minerals indicating aqueous processes, and f) Extracting clues from geologic investigation related to liquid water to assess whether past environments were conducive for life. The programmatic objectives include a) Demonstrating long-range traverse capabilities by mobile science platforms, b) Demonstrating complex science operations with two mobile laboratories and c) Validating the standards, protocols, and capabilities of the orbiting Mars communications infrastructure. Some of the significant milestones accomplished by these twin rovers in their three-year existence include:

1) The MER-A rover, *Spirit*, was launched on June 10, 2003 and MER-B, *Opportunity*, on July 7, 2003. *Spirit* landed in 95km-wide Gusev crater on January 4, 2004, which was created by an asteroid or comet impact early in Mars' history. Its twin rover *Opportunity* landed in the Meridiani Planum on the opposite side of Mars from *Spirit*, on January 25, 2004. In the week following *Spirit*'s landing, NASA's website recorded 1.7 billion hits and 34.6 terabytes of data transferred, eclipsing records set by previous NASA missions.

2) On January 21, the Deep Space Network lost contact with the *Spirit* rover, which was believed to have been caused by an error in the rover's Flash memory subsystem. The problem was corrected by reformatting *Spirit's* flash memory and upgrading the software with a patch to avoid memory overload; *Opportunity* was also upgraded with the same patch as a precaution. *Spirit* was returned to full

scientific operations by 5 February, after missing just about ten days of science and no ill effects on the batteries. To date, this was the most serious anomaly in the mission.

3) On March 23, new compelling evidence emerged from the Rovers in the search for hints of past liquid water on the Martian surface. Pictures and data sent by Opportunity revealed a stratification pattern and cross bedding within the rocks in the outcrop inside a crater in Meridiani Planum, suggesting a history of flowing water in the region. The irregular distribution of chlorine and bromine also suggests that the rover sat in a place that once had been the shoreline of a salty sea, now evaporated.

4) On September 22, 2004, NASA announced that it was extending the mission life of the rovers for another 6 months. *Opportunity* was to leave Endurance crater, visit its discarded heat shield, and then proceed to Victoria crater. *Spirit* was to attempt to climb to the top of the Columbia Hills.

5) On April 6, 2005, with the two rovers still functioning well, NASA announced an additional 18 month extension of the mission to September 2006. *Opportunity* was to visit the "Etched Terrain" and *Spirit* was to climb a rocky slope toward the top of Husband Hill.

6) On August 21, 2005, *Spirit* summitted "Husband Hill" after 581 sols and a drive of 4.81 kilometers (2.99 mi). Fig. 1 shows Spirit's "postcard" view from the summit of Husband Hill: a windswept plateau strewn with rocks, small exposures of outcrop, and sand dunes. This approximate true-color composite spans about 90 degrees and consists of 18 frames captured by the rover's panoramic camera.

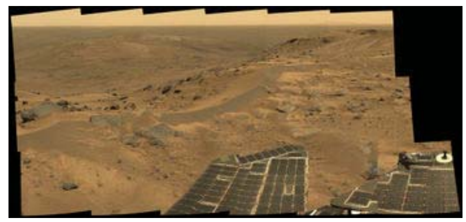


Fig. 1 One of Spirit's many wonders from Mars

7) *Spirit* celebrated its one Martian year anniversary (669 sols or 687 Earth days) on November 20, 2005. *Opportunity* celebrated its anniversary on December 12. Both rovers have lasted over seven times their original life expectancy.

8) On February 7, 2006, *Spirit* reached the semicircular rock formation known as Home Plate. It is a layered rock outcrop that puzzles, yet excites scientists. It is thought that Home Plate's rocks are explosive volcanic deposits, yet other possibilities exist, including impact deposits or wind/water borne sediment.

9) On March 13, 2006, *Spirit's* front right wheel ceased working while moving itself to a slope to maximize sunshine during the coming Martian winter. It continues the attempt, driving backwards and dragging the inoperative wheel. The motors that rotate Spirit's wheels have revolved more than 13 million times, far more than called for in the rovers' design. Spirit has already lost the use of its rock abrasion tool because the teeth have become too worn to grind the surface off any more rocks. Its wire-bristle brush, though, can still remove loose coatings to give imaging instruments a clearer view of rock specimens.

To summarize, after about thirty six months in space, over 800 sols on the Martian surface and over 6 km of roving distance, the rovers are still capable of performing ‘full’ mission operations, with the power system components looking robust and healthy as ever. In this paper, we will provide a detailed update on the performance of the lithium-ion batteries.

Power Subsystem

The power source 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 was about 1000 Wh per sol. Over the course of 800 cycles and thirty months 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 partly restoring their energy levels. The energy storage system on these rovers is comprised of lithium-ion rechargeable batteries, used for the first time in such planetary exploration missions of NASA.[2-5] The use of Li-ion batteries enhanced or even enabled the rovers significantly, compared to the state of practice rechargeable batteries, by 1) reducing the mass and volume by factors of 4 and 6, respectively and thus allowing greater mass and volume for the pay load, and 2) considerably simplifying the thermal management by virtue of its wide range of operating temperatures. The latter characteristic is inherently borne out of use of non-aqueous electrolytes for Li-ion batteries, which have been further improved for enhanced low temperature performance, through the development of several advanced materials and basic electrochemical studies at JPL in the last decade. Thus, the electrolyte developed for MSP01 lander and MER could operate well at sub-zero temperatures, down to –30^{o}C, as well as ambient temperatures (30^{o}C), while several subsequent electrolyte formulations showed good performance at further lower temperatures.

MER Li-Ion cell

The Li-ion cell used for the MER batteries is prismatic in shape with a name plate capacity of 8Ah and actual capacity of ~ 10 Ah, developed and fabricated by Yardney Technical Products (Lithion), Pawcatuck, CT (Fig.2). The cells contained MCMB graphite coated over copper as anode and lithiated nickel cobalt oxide coated over aluminum as the cathode. The electrolyte employed was the first-generation low temperature electrolyte developed at JPL, which contains 1 M $LiPF_6$ dissolved in equi-proportion ternary mixture of ethylene carbonate, dimethyl carbonate and diethyl carbonate. This chemistry showed impressive performance characteristics for Lander/Rover applications, including excellent calendar and cycle life, much more than required by the rover missions, and also a wide operating temperature range of –30 to +40^{o}C.[7] Cells and batteries containing this electrolyte have shown impressive performance in Mars lander simulation tests in our laboratory.[8,9] as well as planetary orbital or Low Earth satellite applications.[10]

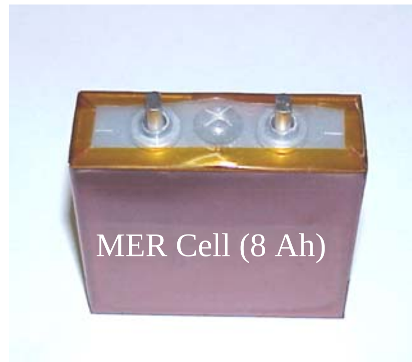


Fig. 2 : Advanced Li-ion cell for MER. With improved low temperature capability.

MER Li-Ion Battery

The role of the lithium-ion batteries is four-fold. They were designed to provide about 200 Wh during launch, about 160 Wh during cruise for supporting anomalies during Trajectory Control Maneuvers (TCM), about 280 Wh for surface operations, and to provide energy to fire three simultaneous pyros, (each with a load of 7 A), multiple times during the Entry-Descent and Landing (EDL) sequence. Finally, there was a need for redundancy, i.e., the minimum energy needs of the mission to be met even with the loss of one battery. To meet the above requirements, the rovers have two parallel lithium-ion batteries housed in rectangular box, with each battery containing eight cells in series. The battery housings were designed and fabricated at JPL. A notable feature of the battery housing was to ensure that adequate preload was maintained on each battery, even in the event of one battery failure, to ensure redundancy. The batteries were equipped with Radioisotope heater Units (RHUs) as well as warm-up and survival heaters to ensure that the lowest operating temperature is $\geq$ -20^{o}C. Likewise adequate radiators were facilitated along with heat loop pipes to limit the battery's operating temperature to 30^{o}C. However, the prototype batteries were qualified over a wider temperatures, i.e., -30 to +40oC, as well through set of anticipated environments in the spacecraft, i.e., random vibration, pyroshock, landing load and thermal vacuum cycling.

Fig. 3 : Rover Battery Assembly Unit (RBAU) containing two Li-ion batteries in parallel (28 V, 20 Ah) for MER

In order ensure that the Li-ion cells in the batteries didn't encountering any electrical abuse, i.e., overcharge beyond 4.1 v/cell or overdischarge below 2.5 V/cell, the battery are equipped with dedicated Battery control Board (BEC). These BCBs were designed and fabricated at JPL to monitor and control individual cell voltages in each of the batteries. The later is achieved during overcharge by discharging cells with high voltage though shunt and thus allow the other cells to catch up. In other words, the cell balancing during charge was accomplished via individual cell bypass through a 120 ohms resistor. Four different charge voltages, i.e., 3.85, 3.95, 4.15, and 4.20V were available to command (thus termed as command voltage, V_{com}) from ground to allow the battery to be charged to ~

50%, 80%, 100% and a little over 100% (in the latter parts of the mission, if needed) respectively. Charging of the cells is permitted only if the cell voltages are at least 150 mV lower than the command voltage and will be stopped when the voltage of any cell exceeds the command voltage or when all the cells get into the bypass mode. Meanwhile, the cell bypass starts when the cell voltage approaches within 30 mV of V_{com}, and ends when the cell voltage drops below 70 mV of the V_{com}. Likewise, the discharge of a cell is permitted only if its voltage is higher than 3.4 V and ended if the voltage drops below 2.9 V. This scheme of charge/discharge control of the lithium-ion batteries worked quite successfully, both on ground and on the spacecraft, in avoiding overcharge and overdischarge, while providing reasonable cell balance, as evident in the performance data provided below. It may be mentioned that the loads have been shred equally between the two batteries of these RBAUs even after three years of operation, which attest to the quality of the cells and batteries as well as to the robustness of the charge control scheme adopted here.

BOL Performance of MER Batteries

The *BOL* performance of the batteries used in Spirit and Opportunity rovers was determined prior to integrating the batteries into the spacecraft. The discharge characteristics of the two batteries on Spirit were measured at nominal discharge current of C/5 at both room temperature and -20^{o}C, using a Maccor Battery System, i.e., without the benefit of cell balancing possible with the BCB. The batteries A and B on the Spirit showed initial capacities of 10.037 and 10.046 Ah at 20^{o}C, respectively. The corresponding capacities at -20^{o}C and C/5 are 7.49 and 7.52 Ah, respectively. The maximum cell divergence in the Battery A, at -20^{o}C, is 14 mV at the end of charge, while at the end of discharge the divergence increased to 31 mV. The corresponding values for the Battery B are 19 and 95 mV, respectively. Similar tests performed on the batteries A and B of the Opportunity rover showed capacities of 10.042 and 10.047 Ah at 25^{o}C, respectively. Their corresponding capacities at -20^{o}C are 7.464 and 7.562 Ah, respectively (Fig. 4). The voltage differential between strongest and the weakest cell is 41 mV during charge and 141 mV during discharge at-20^{o}C in the case of Battery A. Battery B showed divergence of 28 mV and 85 mV during charge and discharge at -20^{o}C, respectively. Both the batteries in each of the RBAUs showed good performance characteristics, combined with low cell divergence, even at low temperatures. This was made possible largely due to the care exercised in cell fabrication as well as in cell matching. Various performance characteristics, such as capacities at different temperatures, self discharge rate and impedance, with appropriate weightings were taken into account, for selecting cells for the batteries, from a batch of cells, almost twice the required number.

Launch and Cruise

Several battery parameters were followed via telemetry during the mission. These include individual battery voltages (two per rover), individual cell voltages (eight per battery and sixteen per rover), rover battery current (one per battery and two per rover) and four battery temperatures (four per rover). The four temperature probes (PRTs) are located on two end cells, one on the middle cell and on the battery casing.

Both the batteries on each rover were fully charged before launch. During launch, both the batteries shared the loads of ~ 200 Wh equally at ambient temperature, thus discharging to ~ 40%. Following launch, the batteries were subsequently charged fully to 32.8 V or 100%, which was later adjusted to ~ 80% to support cruise anomalies, such as trajectory control maneuvers (TCMs). In addition to being at low state of charge, the batteries were held at a low temperature as well during cruise, with the battery temperature decreasing from an initial value of 15^{o}C to a final value of –10^{o}C during cruise, with the objective of minimizing the permanent loss in the battery capacity during on-buss storage in cruise.[8] Due to the engineering personnel being busy with the launching of Opportunity, the batteries on the Spirit were allowed to stay at 100% state of charge for a longer duration (3-4 weeks) than desired. The cruise anomaly corrections would require about 160 Wh, which would have been a challenge for single battery to support, especially in the latter parts of cruise when temperatures were at -10^{o}C. However, the rovers didn't experience any such cruise anomaly in their 7-month cruise to Mars, such that the services from rover batteries were not solicited during cruise. However, in this storage on bus, the individual cell voltages showed divergence beyond 140 mV, which triggered their balance through by-pass. Such a sequence of cell divergence, followed by cell balance through by-pass shunts happened about 6-8 times. Later, about a month before landing on Mars, the batteries were charged back to full state of charge, for the Entry Descent and Landing (EDL) Operations, if required, and for immediate surface operations.

Performance on Mars

The rovers, Spirit and Opportunity have successfully completed one Martian year of exploration and have thus about 863 and 841 sols, respectively to their credit. The lithium-ion batteries have been performing quite well and providing impressive support to the mission. Fig. 6A and 6B sum up the performance of the battery assembly units on Spirit and Opportunity.

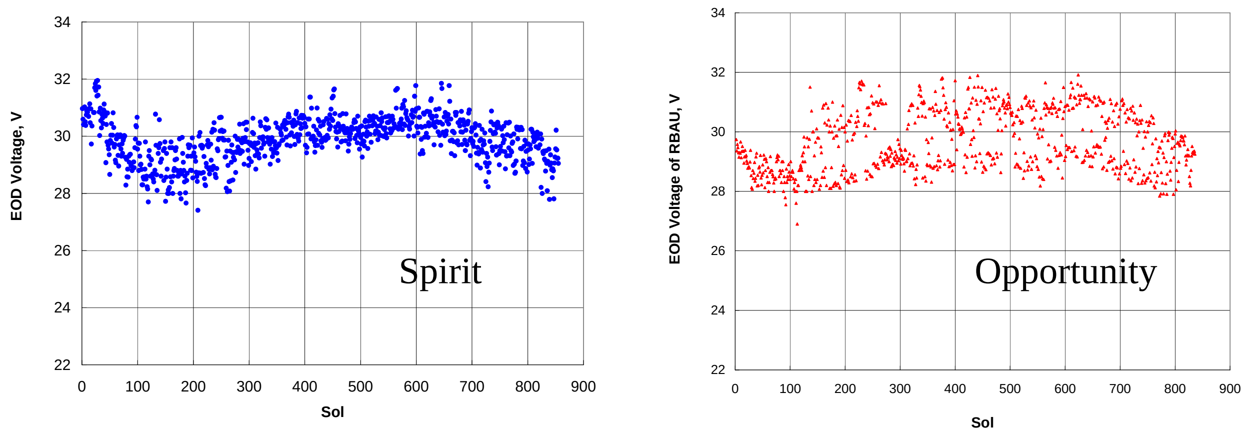


Fig. 4: Summary of RBAU performance on Spirit and Opportunity during 30 months on Mars.

There is some variation in the science experiments performed on each day. As well there are changes in the battery temperatures, due to seasonal change on Mars. Yet, the minimum RBAU voltages or the battery end of discharge voltages on both Spirit and opportunity are above 28 V, which provides a good margin of over 400 mV even after three years of operation in space. 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, as also illustrated in Fig. 6, which shows the individual battery voltages and currents in each of the batteries, for example on Spirit on sols 820-826.

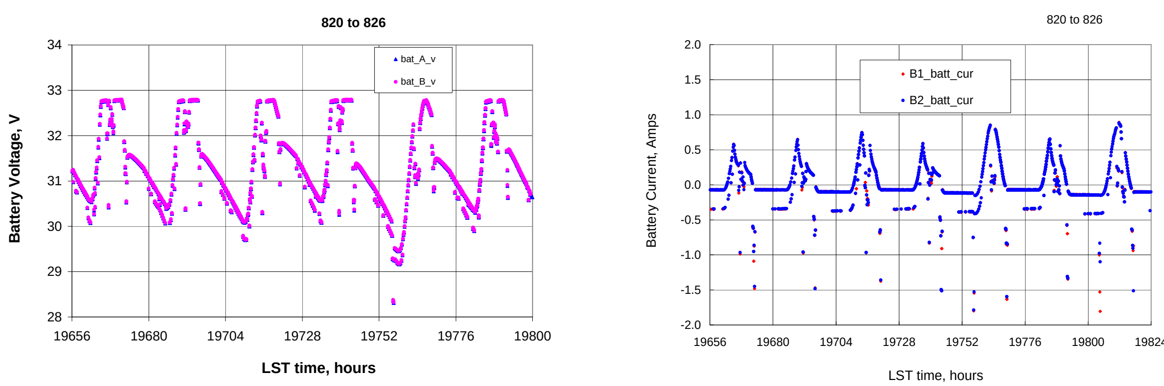


Fig. 5 Individual battery voltages and current from sol 820-826 on the Spirit

As may be seen from the figure, the discharge and charge currents are fairly moderate, which combined with a moderate depth of discharge, and sub-ambient temperatures would extend the life of the batteries. Fig.6 shows the maximum and minimum values of the state of charge as well as capacity available for use.

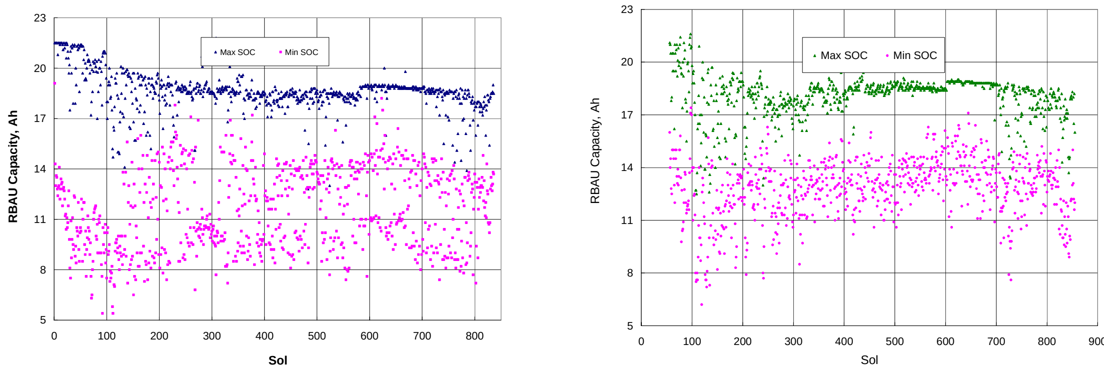


Fig. 6: Estimated capacities of the RBAUs on Spirit and Opportunity on Mars, after 30 months.

The available capacity, estimated from an engineering model is little more than 10 Ah i.e., the depth of discharge is a little less than 50%. This low 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. Our laboratory tests revealed cycle life in excess of 3000 cycles at depth of discharge ≤50%. The lower EOD voltages as well as deeper depth of discharge observed on Opportunity may be attributed to one of its heaters losing control and being locked in the 'on' position.

Cell Voltages

Apart from the batteries in the RBAUs matching well in terms of their load share, the cells within a battery showed good balance in terms of their voltages. Fig. 7 shows the typical individual cell voltages in the two batteries of Spirit and Opportunity, respectively, after three years of operation in space.

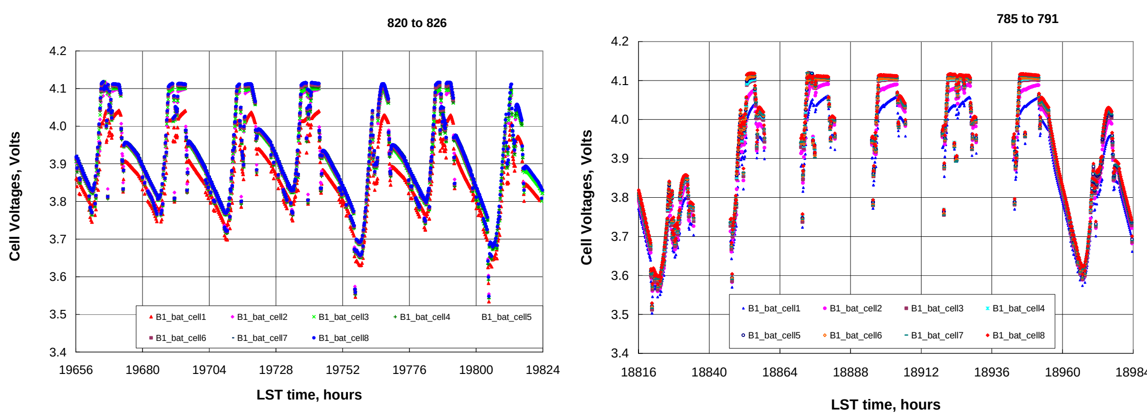


Fig.7: Individual cell voltages in one of the two batteries on the Spirit and Opportunity.

As may be seen from the figures, the cell divergence is low even towards the end of the mission, less than 100 mV during charge or discharge. This may attributed to the adequacy of the cell balancing, even though it is partial by-pass through shunt in this case.

Battery Temperatures

Fig. 8 shows the maximum and minimum daily temperatures over 500 Mars sols for the Spirit and opportunity rovers. The batteries on the Spirit have experienced a continuous decrease in the minimum temperatures to ~ -18°C till sol 200 followed by an increase back to the initial values of 10°C. This is consistent with the seasonal pattern on Mars. The Opportunity rover, on the other hand, has higher temperatures of 5-10°C and the trend is not as smooth as with the Spirit. This may be related to heater problem mentioned above.

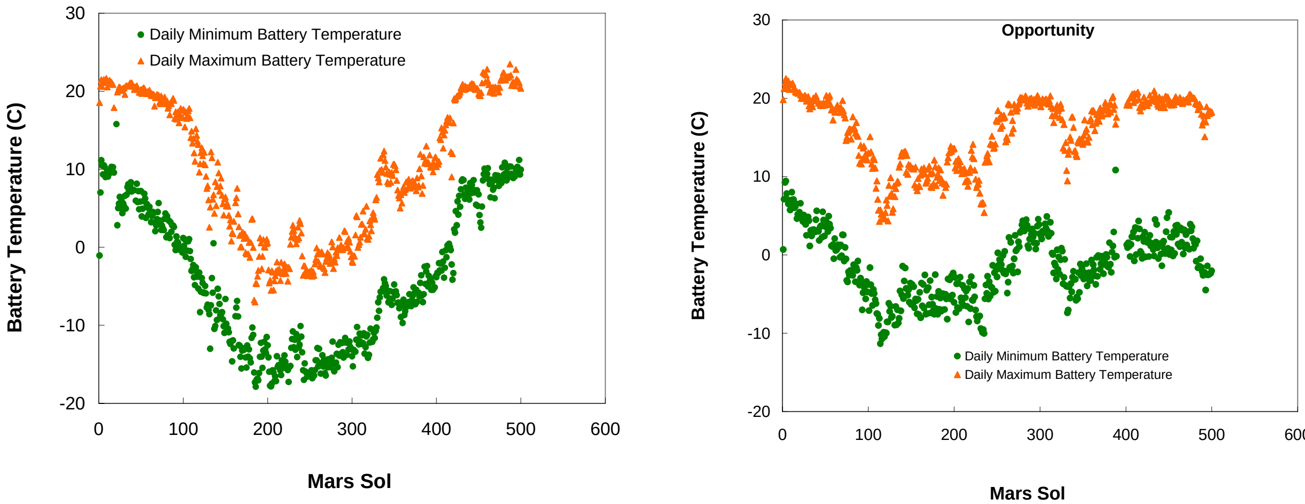
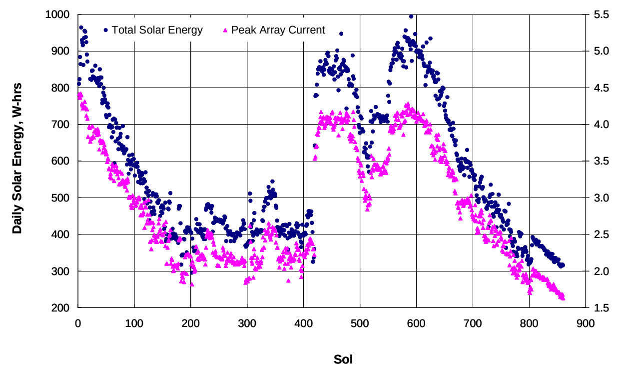


Fig. 8: Temperature of the RBAus on Spirit and Opportunity

The rovers are heading into a colder temperature regime once again in a few months, due to the on-set of winter on Mars. This may affect the overall energy generated by the solar array and to some extent, the energy storage capability of the batteries.

PROJECTION ON MISSION LIFE

After over 830 cycles into the Mars exploration, 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 expectations. The solar array, for example, lost power in between due to dust accumulation on the panel during mid-course. Fortunately, subsequent winds cleaned up the solar array. As a result, the solar array recovered to large extent, currently displaying daily energy values of ~ 700 Wh, with peak currents of over 3 A around sol 500, followed by a decrease in both during the on-set of winter (Fig. 8). 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 (see our companion paper[9]) estimate the capacity loss in the MER batteries is about 10% thus far. 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 three years or beyond.



Fig, 9. Solar array performance on the Spirit after three years in space

CONCLUSIONS

Li-ion battery technology, infused into the Mars Exploration Rovers for the first time, demonstrated its advantages over the conventional aerospace rechargeable battery in terms of mass, volume and operating temperature range. The Li-ion batteries have thus considerably enhanced the capabilities of these missions. After about four years following fabrication, three years of operation in space, thirty months on the surface of mars and about 830 cycles of charge-discharge, the Rover batteries are continuing to display impressive performance and durability, with little change in the end-of discharge voltages. Based on the ground tests on the mission simulation batteries, and from the engineering models, it is clear that almost 85-90% of the initial capacities are still being retained in all the four batteries. Since mission needs are only moderate in terms of depth of discharge and charge/discharge rates, it may be expected that the batteries will be healthy for a couple years more, if the spacecraft funding is retained. However, it may be optimistic that the mission will be extended beyond another year, due to the signs of wear on the rover components. Nevertheless, the Mars Exploration rovers have provided excellent platform for Li-ion batteries to demonstrate their long-term use in future Mars and lunar surface missions, i.e., Phoenix Lander in 2007 and Mars Science Laboratory (MSL) in 2009.

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