Design and Performance of the MER (Mars Exploration Rovers) Solar Arrays

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ABSTRACT

The Mars Exploration Rovers (MER) program posed a significant engineering and technology challenge. Now that the Rovers have operated beyond their original design life of three months by nearly a factor of four it is clear that the challenge was met and far exceeded. A key to the success of MER has been the enhanced power provided by the cruise and Rover solar arrays. Benefiting from a nearly 50% improvement in cell efficiency compared to the single junction GaAs cells used on Pathfinder, the MER designs were subject to many constraints both in design and in operation. These constraints included limited available panel area, changing illumination levels and temperatures, and variable shadowing, atmospheric conditions and dust accumulation for the rovers. This paper will discuss those constraints and their impact on the design. In addition, flight data will be provided to assess the performance achieved during the mission.

INTRODUCTION

Following the failure of Mars Climate Orbiter and Mars Polar Lander in December, 1999, and the subsequent failure investigations, a decision for the 2003 launch of the two MER spacecraft (and their Rovers) was made later than optimal. Although some time was gained by basing the design on the successful Pathfinder mission, requirements differed enough so that the resulting array designs shared some (cruise array) or nothing (Rovers) with the earlier design. Array requirements were dictated by spacecraft power requirements and the operational environments. The major requirements and constraints are discussed below for the cruise and rover arrays.

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The cruise array substrate design was basically that of the Pathfinder design. A large annular fixed array assembled from four equal size quadrants was attached to aluminum struts on the rear side. The cruise array would provide power following launch to charge up the batteries and operate the spacecraft (S/C) during the cruise from Earth to Mars. Since the S/C was spin stabilized and pointed primarily towards the Earth for communication, a maximum array sun off pointing of 40 degrees was required.

Due to the cruise array configuration, with the inner portions situated over propellant tanks and the entry module, thereby blocking the radiative view factor to space, cell temperatures would vary across the array predominantly radially, with the highest temperatures nearest the center. Superimposed on this was the gradual temperature decrease as the S/C traversed from the orbit of Earth to the orbit of Mars (~1.5AU). The impact of reduced intensity and temperature as the S/C traversed to Mars impacted the array performance by a change in cell current and voltage. Additionally, at Earth it was necessary to allow for any possible unfavorable orientation following launch prior to achieving full attitude control. The result of these requirements meant that an allowable maximum temperature of 90C might be achieved at 1 AU falling to -20C at Mars.

In order to take advantage of improvements in cell technology, the MER solar cells differed considerably from the Pathfinder GaAs cells (8cm^2 of ~18% efficiency) to the Spectrolab, large area (~27.4cm^2), ~27.5% efficiency triple junction solar cells.

Connectors are located on the rear surface of the substrate in locations previously used for Pathfinder so as to avoid harness redesign. Wire routing was limited to specific areas with pass-throughs under the substrate support struts in positions also defined by Pathfinder.

Rover Arrays

The Rover arrays were to differ in most features from the Pathfinder rover array. The later was a small fixed panel with an array of GaAs solar cells. The MER array design was modified well into the array design and fabrication phase in order to maximize power output. The final substrate configuration consisted of one fixed panel and five deployable panels, with two of the latter requiring secondary deployments. Rover structures such as the Pancam Mast Assembly (PMA), the High-Gain Antenna (HGA) and the

Low-Gain Antenna (LGA) would create relatively large shadows which could have a virtually unlimited range of orientations and shadow patterns depending on time of Martian day, season, ground surface inclination and Rover orientation. In this situation the power analysis was done on a "best estimate" basis by mathematical means and by subjecting a scale model to various illumination orientations.

An additional factor such as Mars atmospheric conditions also impacts output, with estimates made based on atmospheric models developed from the Mars Pathfinder mission. The dusty atmosphere would impact overall solar intensity at the Rovers' positions and also the conversion efficiency of the solar cells. As part of JPL's efforts to characterize the solar cell performance at Mars, it was determined that production triple junction solar cells, in which separate junctions respond to different portions of the spectrum, would not be optimized to the Mars spectrum. For Mars, the dusty atmosphere reduces the short wavelength portion of the incident solar spectrum thereby reducing the current generated in the current limiting top cell. This leads to a direct reduction in cell efficiency by up to 10%, depending on atmospheric dust loading and solar zenith angle, when compared to the efficiency outside the atmosphere. Due to these considerations JPL developed a range of performance for Rover operation.

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The cruise array was required to provide power for the transit from Earth to Mars. The power requirement was on the order of 300 watts. To handle the Earth and Mars intensity and temperature requirements efficiently, two different series string lengths were used. For near Earth operation, a string length of 19 cells was used. For near Mars string lengths of 16 cells in series were optimum. A requirement on the shunt radiator maximum current capability meant that the entire array would be configured as a set of circuits which would be switched in as required. One array quadrant was left continuously on the bus. This quadrant had 17 strings of 19 cell series strings (323 cells total). A second panel was composed of 9 strings of 19 cells and 10 strings of 16 cells (331 cells total). The remaining two panels consisted of 16 series circuits, 20 on one (320 cells) and 21 (336 cells) on the other. The total number of cells was 1310. The quadrant with strings of only 19 cells in series also had an Isc and a Voc cell for reference data. Each quadrant also had one temperature sensor. In order to provide some mapping of the temperature distribution, the sensors were placed at differing locations with respect to the spacecraft center. One sensor was placed near the perimeter of a panel, one near the inside and the remaining two approximately midway between inboard and outboard positions.

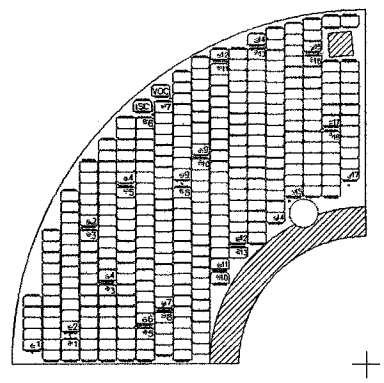

Fig. 1. Cruise panel #1 configuration.

The total "electrical" add-on mass (cells, covers, wiring, connectors, diodes and boards, and temperature sensors, etc.) was 7.4 and 7.3KG for each four panel Cruise array.

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The MER Rover arrays were considerably more complicated than the cruise arrays. The former had the advantage of a substrate design that was well defined early in the program. The rover panels, in contrast were in design, well into the array fabrication process leaving approximately twelve months from the contract start with Spectrolab until hardware delivery. The Rover array consisted of six (6) panels, one fixed and five (5) deployable.

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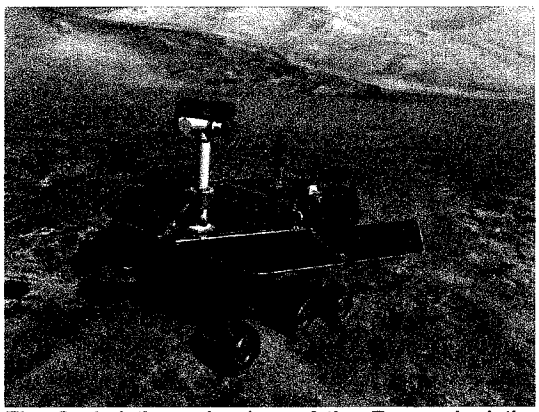

Fig. 2. Artist's early view of the Rover depicting approximate solar array panel configuration

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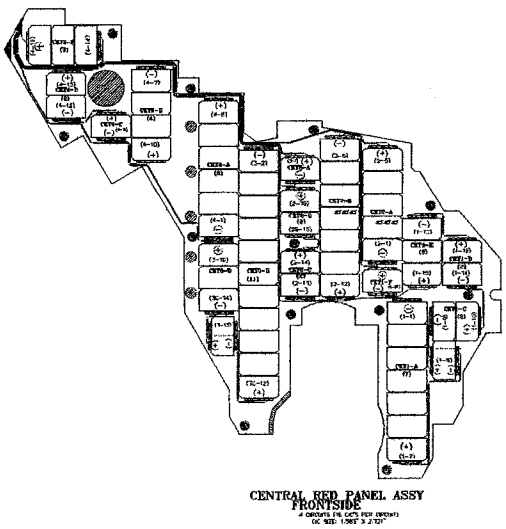

Fig. 3. Rover array RED panel

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As mentioned in a previous section, analysis of anticipated power output contained many variables which would not be identified until actual landing on Mars (atmospheric conditions) and others which would vary depending on each Rover's instantaneous orientation. Clearly, the data of the actual Rover panel performances on Mars were highly anticipated, not only to observe changes due to dust accumulation, but also for the initial performances.

ARRAY PERFORMANCE

With nearly one year's operation at Mars, the MER Rovers have exceeded their original design life of three months and clearly have performed up to and beyond expectations. Some highlights of the array performances are discussed below.

Cruise Arrays

Although not the "glamorous" solar array for the MER mission, the Cruise Array performance allowed the successful Rover missions to happen. The environmental performance factors (intensity, temperature, etc.) are typical of those for most missions and can be predicted with high confidence. However, since it is not always possible to obtain accurate array performance data, the results from MER will be useful in verifying assumptions and for designing future interplanetary solar arrays. Figure 4 shows the array temperatures during and following launch for MER-A (Spirit) As expected, there is a low and a high reading for thermocouples located far from and close to the S/C center, with two intermediate for thermocouples located approximately midway out on the panels. The high temperature is slightly below 80C, which in turn is 10C below the "worst case" design estimate.

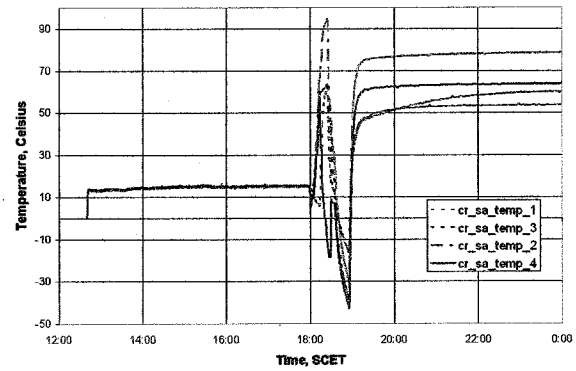

Fig. 4. MER-A cruise array launch temperatures.

The solar array current for the same period are shown in figure 5.

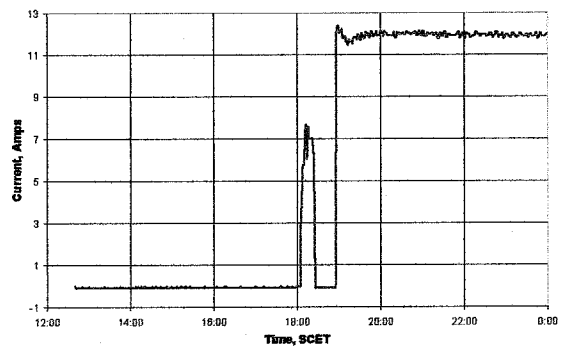

Fig. 5. MER-A cruise array current.

Results for MER-B (Opportunity) BOL array current are slightly lower due to a greater sun off-pointing angle for MER-B than MER-A. The MER-A angle was approximately 30 degrees and MER-B, ~45 degrees. The MER-B solar array current was approximately 10A compared to MER-A at ~12A.

MER-A and MER-B temperatures at EOL (end of life - at Mars), were comparable with an average panel temperature measurement of approximately -5C. In both cases the sun pointing angle is approximately 40 degrees.

MER-A array current is shown in figure 6 for the same period. The array generated current is seen to be comparable to the beginning of mission values.

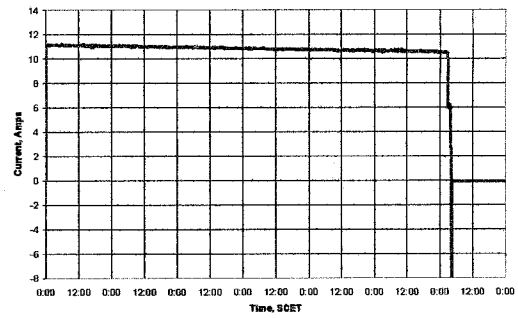

Fig. 6. MER-A cruise array current at EOL.

Rover Arrays

It would be an understatement to say that the Rover array performances on Mars were highly anticipated. With the large number of performance impacting variables, the uncertainty in actual output was considered to be large. The arrays were designed with sufficient power to absorb the expected loss due to dust accumulation that was observed on Pathfinder and consequently should handle the initial power needs. However, any initial shortfall would eventually lead to mission termination at worst or mission reprogramming at best.

The initial array current turned out to agree well with predictions. This is shown in figure 7. The predicted array current is corrected for the measured atmospheric tau values (a measure of the opacity of the atmosphere). For both Spirit and Opportunity, the tau value at landing was at the high end of the anticipated range (~0.9) and has decreased throughout the mission to values of ~0.3 (Spirit) and 0.45 (Opportunity) indicating that the atmosphere is less dusty at present than at initial landing. During the first week, the array temperatures varied from approximately -95C at night and 25C at "noon".

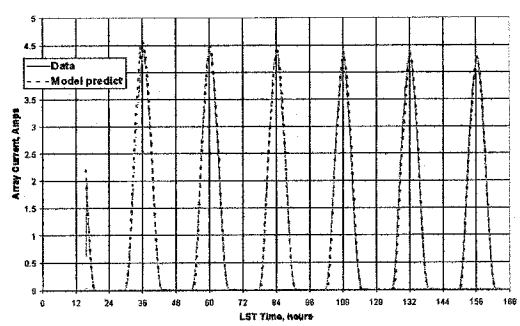

Fig. 7. Spirit solar array current for initial seven days (actual vs. predicted).

During this time, Spirit remained essentially in a fixed position while JPL engineers carefully planned the initial move onto the Martian

surface. The gradual array current decrease is attributable to dust accumulation although at Sol (a Martian day) four, the Rover experienced a slight change in orientation, decreasing the sun angle by an additional 10 degrees.

A more complete review of Spirit's performance can be seen in figure 8, which plots the array total daily solar energy (watt-hrs.) and current from Sol one through Sol 323. The lowest values correspond to the Martian winter season, the most difficult part of the Martian year for photovoltaic energy generation. For much of this time Spirit was maintained with a Northward tilt to allow charging of the batteries in order to survive the low night-time temperatures.

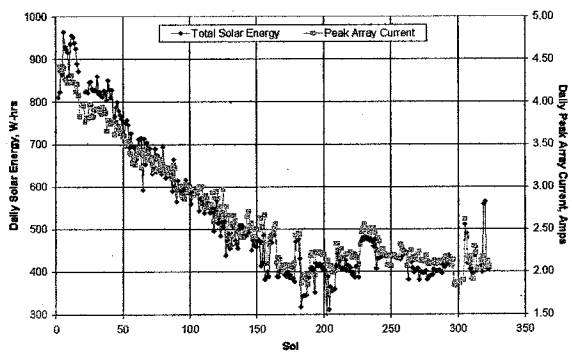

Fig. 8. Spirit array performance through Sol 323

The calculated loss due to dust accumulation is shown below in figure 9. The leveling of the loss is clear in this and would suggest that dust accumulation reaches a balance with dust loss, rather than continue to decrease solar array output.

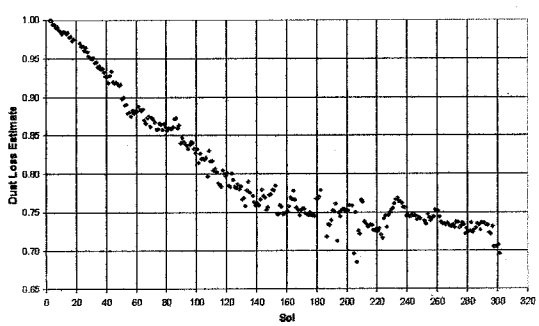

Fig. 9. Calculated loss due to dust for Spirit array.

Whereas much of the performance of the Rover arrays was met with somewhat of a sense of relief in that the assumptions and engineering analyses were well founded, the big surprise was the performance of Opportunity. As shown in figure 10, it is obvious that the array power has returned almost to its initial value. The initial dust loss was similar to Spirit with a 20% dust induced array current loss over the first ~120 Sols. However, after continuing to show increased loss due to dust, at Sol 190, Opportunity suddenly showed an improvement of about 3%. This was followed by another sudden improvement of 5% at Sol 219 and another 4% at Sol 270, resulting a calculated loss in power due to dust of only 11% at Sol 303. This suggests that dust was removed from Opportunity in a series of distinct actions. Speculation is that possible wind removal, enhanced by the tilted configuration of the array was instrumental in this. Whatever the reason, this is evidence that the adherence of dust to the solar arrays is weak.

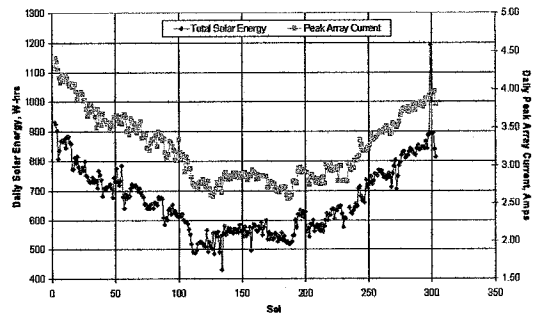

Fig. 10. Opportunity array performance through Sol 303

CONCLUSIONS

The performance of the Mars Rovers have met and exceeded expectations. A key to this has been the performance of the solar arrays. As they continue to operate well beyond their design life they provide valuable information on the operation of solar arrays on the Martian surface. Both Opportunity and Spirit results show strong evidence of a saturation in the loss due to dust of about 30% and the unexpected recovery of most of Opportunity's initial performance suggests that the dust does not adhere to the solar arrays and is capable of being removed. This can have an enabling impact on many studies of future Mars surface.

ACKNOWLEDGEMENT

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration. The authors wish to thank the numerous individuals at Spectrolab and JPL, for their dedication in designing, fabricating, and testing the MER solar arrays.

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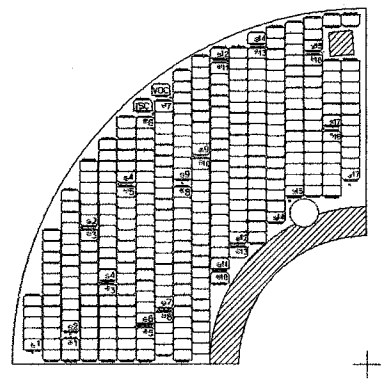

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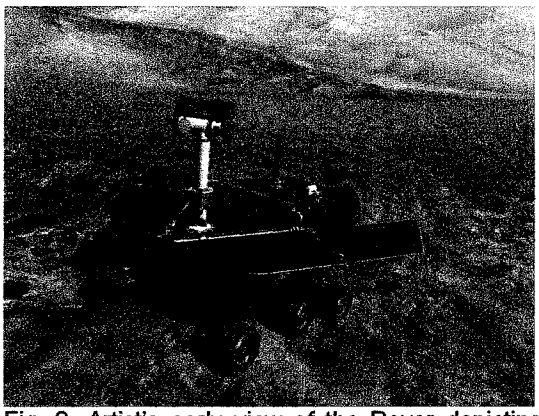

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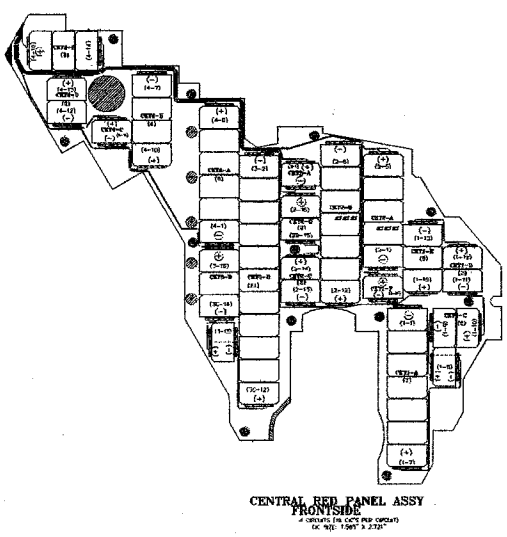

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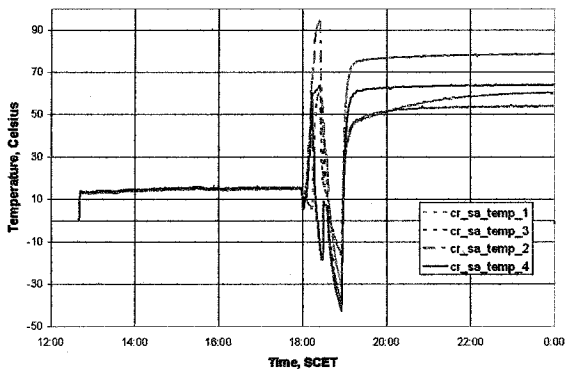

Fig. 4. MER-A cruise array launch temperatures.

The solar array current for the same period are shown in figure 5.

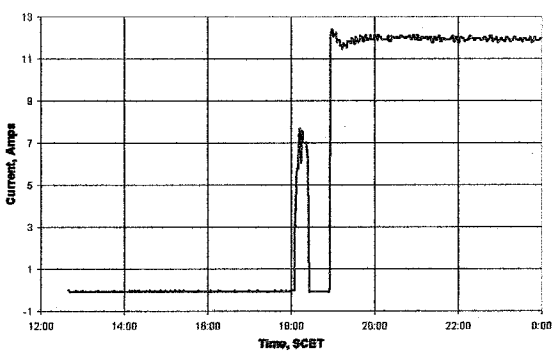

Fig. 5. MER-A cruise array current.

Results for MER-B (Opportunity) BOL array current are slightly lower due to a greater sun off-pointing angle for MER-B than MER-A. The MER-A angle was approximately 30 degrees and MER-B, ~45 degrees. The MER-B solar array current was approximately 10A compared to MER-A at ~12A.

MER-A and MER-B temperatures at EOL (end of life - at Mars), were comparable with an average panel temperature measurement of approximately -5C. In both cases the sun pointing angle is approximately 40 degrees.

MER-A array current is shown in figure 6 for the same period. The array generated current is seen to be comparable to the beginning of mission values.

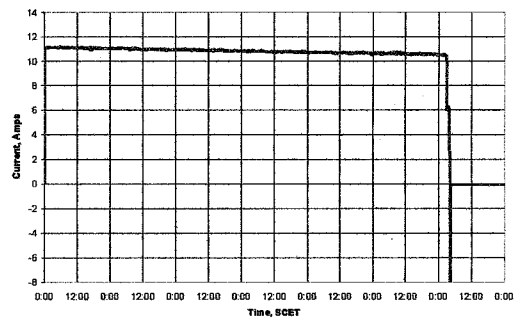

Fig. 6. MER-A cruise array current at EOL.

Rover Arrays

It would be an understatement to say that the Rover array performances on Mars were highly anticipated. With the large number of performance impacting variables, the uncertainty in actual output was considered to be large. The arrays were designed with sufficient power to absorb the expected loss due to dust accumulation that was observed on Pathfinder and consequently should handle the initial power needs. However, any initial shortfall would eventually lead to mission termination at worst or mission reprogramming at best.

The initial array current turned out to agree well with predictions. This is shown in figure 7. The predicted array current is corrected for the measured atmospheric tau values (a measure of the opacity of the atmosphere). For both Spirit and Opportunity, the tau value at landing was at the high end of the anticipated range (~0.9) and has decreased throughout the mission to values of ~0.3 (Spirit) and 0.45 (Opportunity) indicating that the atmosphere is less dusty at present than at initial landing. During the first week, the array temperatures varied from approximately -95C at night and 25C at "noon".

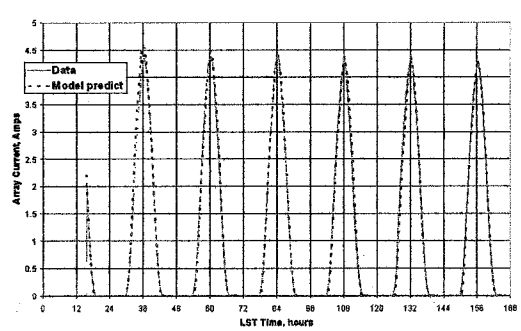

Fig. 7. Spirit solar array current for initial seven days (actual vs. predicted).

During this time, Spirit remained essentially in a fixed position while JPL engineers carefully planned the initial move onto the Martian

surface. The gradual array current decrease is attributable to dust accumulation although at Sol (a Martian day) four, the Rover experienced a slight change in orientation, decreasing the sun angle by an additional 10 degrees.

A more complete review of Spirit's performance can be seen in figure 8, which plots the array total daily solar energy (watt-hrs.) and current from Sol one through Sol 323. The lowest values correspond to the Martian winter season, the most difficult part of the Martian year for photovoltaic energy generation. For much of this time Spirit was maintained with a Northward tilt to allow charging of the batteries in order to survive the low night-time temperatures.

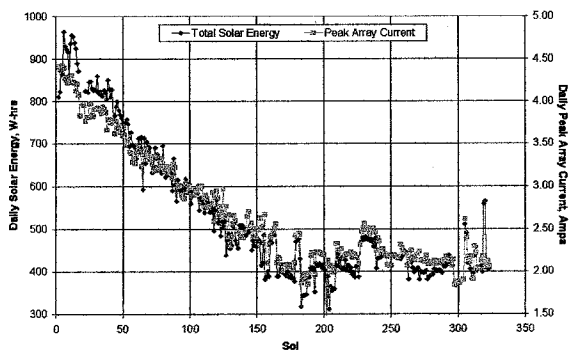

Fig. 8. Spirit array performance through Sol 323

The calculated loss due to dust accumulation is shown below in figure 9. The leveling of the loss is clear in this and would suggest that dust accumulation reaches a balance with dust loss, rather than continue to decrease solar array output.

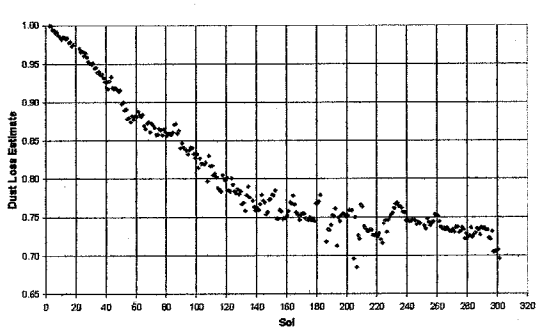

Fig. 9. Calculated loss due to dust for Spirit array.

Whereas much of the performance of the Rover arrays was met with somewhat of a sense of relief in that the assumptions and engineering analyses were well founded, the big surprise was the performance of Opportunity. As shown in figure 10, it is obvious that the array power has returned almost to its initial value. The initial dust loss was similar to Spirit with a 20% dust induced array current loss over the first ~120 Sols. However, after continuing to show increased loss due to dust, at Sol 190, Opportunity suddenly showed an improvement of about 3%. This was followed by another sudden improvement of 5% at Sol 219 and another 4% at Sol 270, resulting a calculated loss in power due to dust of only 11% at Sol 303. This suggests that dust was removed from Opportunity in a series of distinct actions. Speculation is that possible wind removal, enhanced by the tilted configuration of the array was instrumental in this. Whatever the reason, this is evidence that the adherence of dust to the solar arrays is weak.

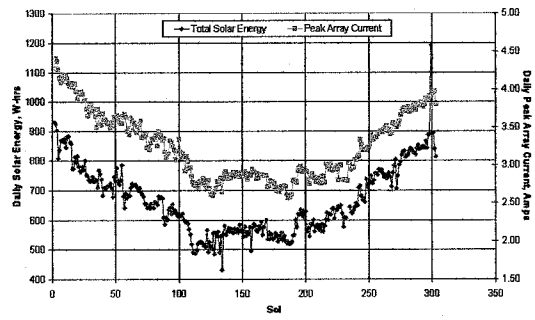

Fig. 10. Opportunity array performance through Sol 303

CONCLUSIONS

The performance of the Mars Rovers have met and exceeded expectations. A key to this has been the performance of the solar arrays. As they continue to operate well beyond their design life they provide valuable information on the operation of solar arrays on the Martian surface. Both Opportunity and Spirit results show strong evidence of a saturation in the loss due to dust of about 30% and the unexpected recovery of most of Opportunity's initial performance suggests that the dust does not adhere to the solar arrays and is capable of being removed. This can have an enabling impact on many studies of future Mars surface.

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