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Mars Solar Power

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NASA missions to Mars, both robotic and human, rely on solar arrays for the primary power system. Mars presents a number of challenges for solar power system operation, including a dusty atmosphere which modifies the spectrum and intensity of the incident solar illumination as a function of time of day, degradation of the array performance by dust deposition, and low temperature operation. The environmental challenges to Mars solar array operation will be discussed and test results of solar cell technology operating under Mars conditions will be presented, along with modeling of solar cell performance under Mars conditions. The design implications for advanced solar arrays for future Mars missions is discussed, and an example case, a Martian polar rover, are analyzed.

Nomenclature

AM0	Air Mass Zero (space sunlight at Earth orbit)
Isc	Short circuit current
τ	tau (optical depth)
Voc	Open Circuit Voltage

I. Introduction

NASA missions to Mars, both current robotic missions and projected human missions rely on solar arrays for the primary power system. Mars presents a number of challenges for solar power system operation, including a dusty atmosphere which modifies the spectrum and intensity of the incident solar illumination as a function of time of day, degradation of the array performance by dust deposition, and low temperature operation. The environmental challenges to Mars solar array operation will be discussed, along with modeling of solar cell performance under Mars conditions. The design implications for advanced solar arrays for future Mars missions, both robotic and human, will be discussed.

II. Photovoltaics on Mars

A. Solar arrays in the Martian environment

Operating photovoltaic arrays on the surface of Mars represents a significantly different problem from operation of arrays on either the Earth's surface or in orbit. For many proposed Mars missions, the performance of the solar arrays presents the main operational constraint on the allowed latitude of the landing site, on the amount of power available for science operations, and on how long during each day the scientific instruments can operate.

Figure 1 shows an example of a high efficiency solar cells used on Mars, the Mars Exploration Rover solar array.

The environmental conditions on the surface of Mars are quite different from the orbital environment in which space solar arrays normally operate [1]. Differences of the Martian surface from operating conditions of Earth orbit which will affect the performance of the solar cells in the array are:

- lower solar intensity due to greater distance of Mars from the sun
- suspended atmospheric dust, which modifies the solar spectrum and reduces intensity [2-5]
- low operating temperatures
- deposition of dust on the arrays [6]

The suspended atmospheric dust consists of both a long-term part, which is constantly in the atmosphere of Mars, and also dust storms, which temporarily add a large loading of dust into the atmosphere. Dust storms can be local storms, of a few days, regional storms, covering a larger area, or "global" storms, which spread from the southern hemisphere during the southern hemisphere summer and can last for several months. In addition, localized "dust devils" can pick up dust from the surface in a tornado-like column.

At the surface of Mars, the atmosphere provides the equivalent of roughly 20 gram/cm^2 of shielding from radiation, and thus radiation exposure is not a significant source of degradation.

The redder spectrum of Mars and the low operating temperature tend to favor lower bandgap solar cell technologies. Constraints due to shock and g-loading of the landing are also a factor, as well as flexure of the arrays due to wind. This will favor more robust cell substrate materials. The requirement for small array sizes for roving vehicles, on the other hand, drives the solar cell technology toward high-efficiency solar cell designs, since only a limited amount of array area is available. GaInP/GaAs/Ge triple-junction cells were the technology chosen for the two Mars Exploration Rovers (fig. 1), which landed on Mars in January 2004. (The British Mars lander, Beagle-2, also chose triple-junction cells for the solar arrays, although the mission did not land successfully on Mars).

Dust deposition on the solar arrays was measured on the Pathfinder mission to degrade the performance at a rate of 0.28% per sol during the initial 30 sols of the mission [6]. Longer measurements on the MER mission are continuing, but initial data [7] indicates that the long-term degradation rate is about half this value.

Additional environmental effects which may affect the array materials and structure include:

- wind loading
- peroxide components of the soil
- low atmospheric pressure
- electrostatic charging [8,9] and possible Paschen discharge [10]

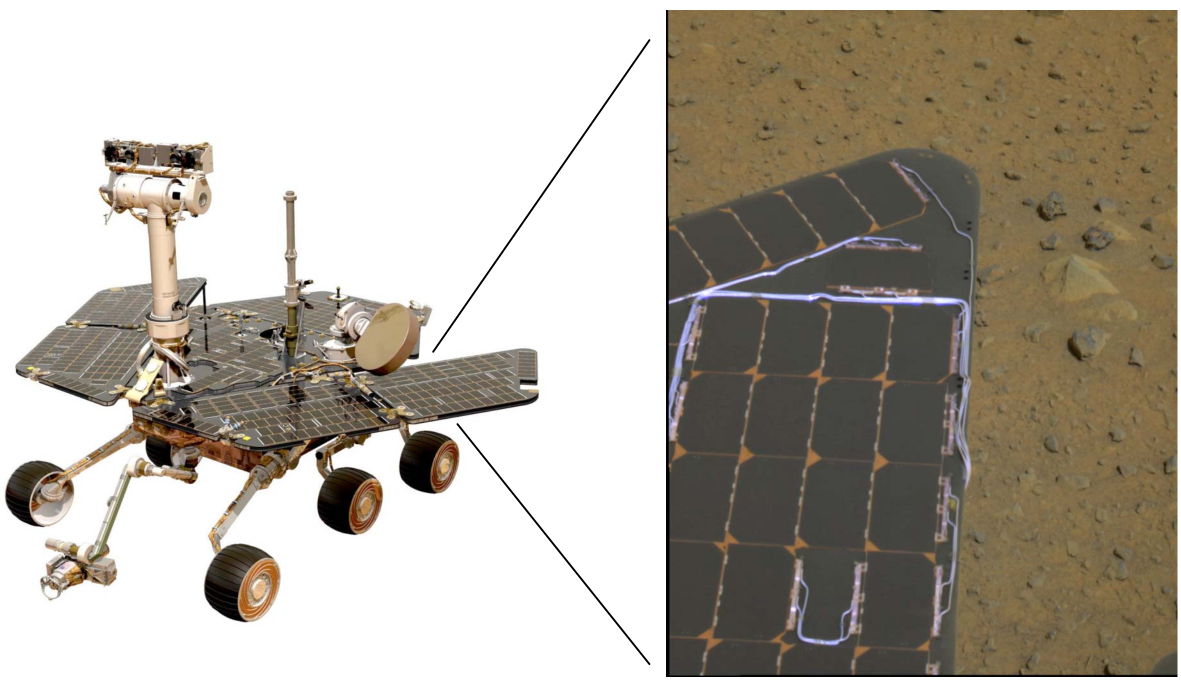


Figure 1.—Solar Array of the Mars Exploration Rover on Mars.

B. Atmospheric effects on solar energy

The solar energy on the Martian surface depends on the amount of dust in the atmosphere. Figures 2 and 3 show modeled results of the calculated total solar flux on a horizontal surface at the MER-1 Gusev Crater landing site for two different dust conditions, a low dust opacity (optical depth $\tau = 0.5$) and a high dust opacity ($\tau = 0.95$). The graph shows both the direct and scattered components of the illumination. In the high-dust case, the direct illumination is reduced, while the scattered component is increased. (The actual atmospheric conditions at the MER landing sites showed a high optical depth, measured at about 0.9, at the landing, and the optical depth decreased during the mission to as low as 0.2).

Since the sky of Mars scatters light, the sunlight comes from a range of angles, rather than in a straight line from the sun. During a relatively clear day, the indirect (scattered) component is relatively low (*e.g.,* 30% of the total sunlight is indirect for optical depth 0.4.) When the optical depth is high, however, the majority of the total sunlight reaching the surface can be indirect.

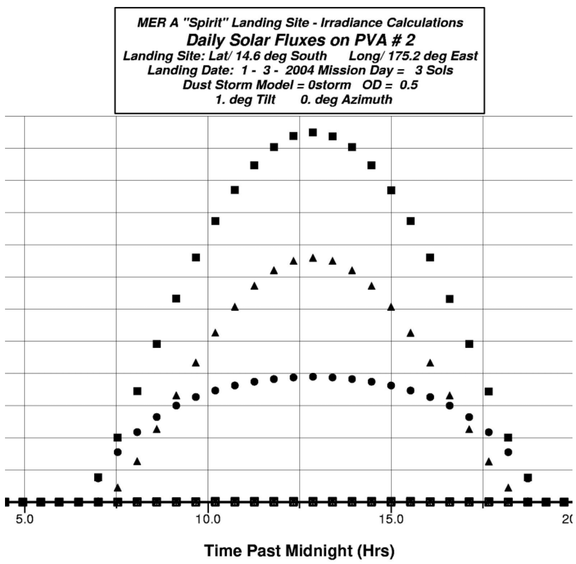


Figure 2.—The Diurnal Profile of Solar Energy on a Horizontal Surface on Mars (Low Dust Case, $\tau = 0.5$), Showing The Direct (Circles), Scattered (Triangles), and Total Isolation During the Course of a Martian Sol.

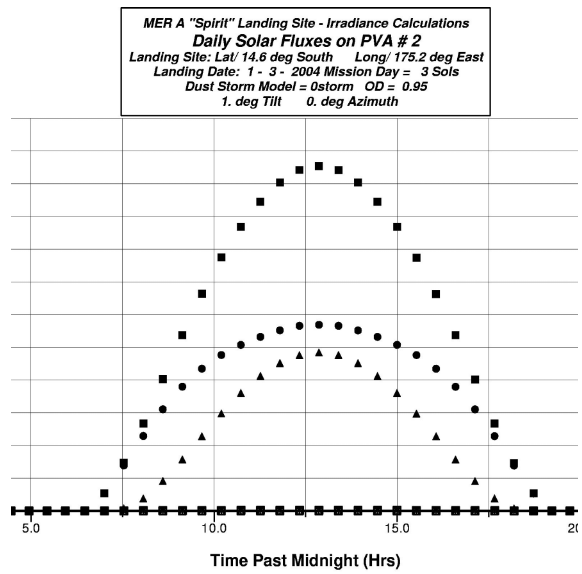


Figure 3.—The Diurnal Profile of Solar Energy on a Horizontal Surface on Mars (High Dust Case, $\tau = 0.95$).

As well as the intensity, the spectrum is significantly altered by the atmospheric dust. Figure 4 shows an example calculation, for the case of an optical depth $\tau = 1$, and zenith angle 0° (noon), similar to the conditions at the MER rover sites near the landing day. This can be compared directly with the quantum efficiency of the solar array.

In addition, atmospheric dust settles on the solar array [6], both changing the spectrum and also reducing the performance as the mission duration increases.

C. Cell Measurements

Following the successful use of solar power on the Mars Pathfinder mission, in which both the lander and the rover used GaAs solar cells for primary power, the Mars Exploration Rovers, “Spirit” and “Opportunity,” demonstrated the first use of triple-junction GaInP/GaAs/Ge solar cells on the surface of Mars.

The photovoltaic cell performance depends on the spectrum, intensity, and temperature of the arrays. For the triple-junction solar cells used on the MER solar arrays, the short-circuit current is limited by the top sub-cell of the three-cell stack. Figures 5 shows the quantum efficiency of the top GaInP solar cell used in the MER solar arrays, showing that it is primarily responding to the visible and blue spectral range, with a long-wavelength cut-off of about 650 nm (0.65 micrometers). This can be compared to the effect of dust on the transmissivity of the atmosphere, showing that the GaInP cell response is in the spectral region most affected by atmospheric dust.

Figures 6 and 7 show the effect of temperature on the cell performance, showing measurements made at both 1 AU (Earth distance) and Mars intensity under simulated AM0 solar spectrum.

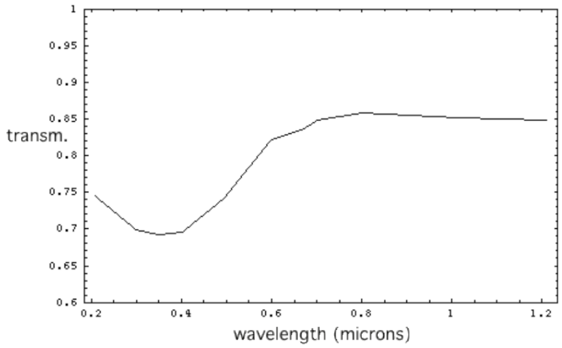


Figure 4.—Example Spectrum of Solar Energy as a Function of Wavelength on Mar, Modeled for the Case of Noon, Optical Depth τ = 1).

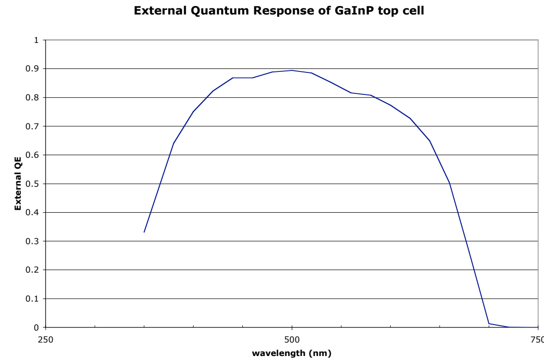


Figure 5.—Measured External Quantum Efficiency of the Top Sub-Cell of the MER Rover Solar Array.

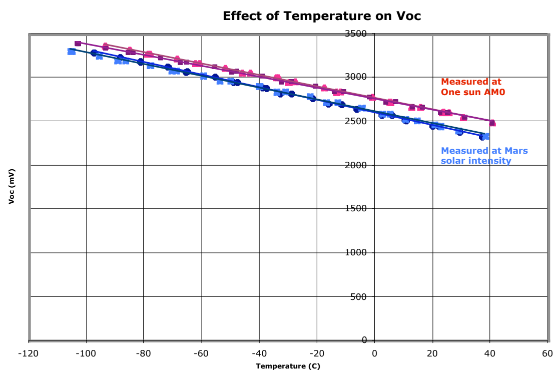


Figure 6.—Effect of Temperature on Cell Open Circuit Voltage at AM0 Earth Solar Intensity (Top Curves) and Mars Solar Intensity (Bottom).

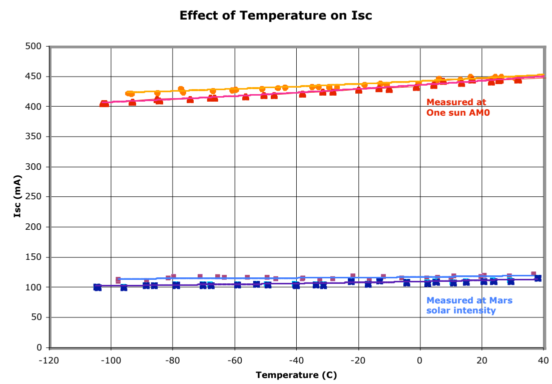


Figure 7.—Effect of Temperature on Cell Short-Circuit Current at AM0 Earth Solar Intensity (Top) and Mars Solar Intensity (Bottom).

III. Polar Rover Solar Array Case Study

A. Background, Requirements and Design Approach

Polar lander missions [11,12] have been of interest to studies in Mars climate history (polar ice cap stratigraphy) and exobiology (search for microorganisms in the soil permafrost, water-ice boundary). However, these landers are limited to a single locality in which to conduct scientific operations. A rover, on the other hand, offers the advantages of extended range and selective targeting of scientifically interesting surface features.

In this current work, the authors have assessed design and performance attributes of a polar rover solar array in support of a 90-sol, Mars Scout mission for the 2007 launch opportunity [12]. The chosen landing site is at 82° North latitude, 20° East longitude and the landing date is September 26, 2008. For this mission, a representative atmospheric opacity, or optical depth, value of 0.5 is chosen.

The rover power requirement is 150-watts (W) of continuous power for 90-sols (a sol is a Martian day equal to 24.66 Earth hours). Since the Sun remains close to the local horizon for polar missions, a vertical solar orientation was chosen with a single, azimuthal Sun-tracking gimbal. A vertical array has the additional benefit of minimizing the collection of airborne dust that settles out of the atmosphere and deposits on surfaces. For a rover vertical solar array, the dust obscuration rate was assumed to be much smaller than that for a horizontal array. A degradation rate of 0.028% per sol was used for the study.

For aeroentry, the rover must be placed within a compact, heat resistance shell, and the solar array panels must be stowed on the rover top deck. Shortly after rover landing, fan-folded panels are deployed using an extendable mast, or pantograph, to form a planar solar array. The solar array size is a design variable iteratively determined to satisfy the rover power requirement.

To minimize array area and mass, high efficiency, triple-junction $GaInP_2$/GaAs/Ge photovoltaic cells were chosen. These cells have demonstrated excellent performance under cold, blue-deficient illumination operating conditions in the laboratory as well as on the surface of Mars. Deployment, night time and peaking power is provided by a low-temperature, 20 amp-hr, lithium ion secondary battery. Power is distributed to rover loads using a 28-VDC, unregulated bus.

Several array designs were considered. A low-mass, open-weave, flexible solar array panel substrate [13] was one option. This design used a one meter wide vertically-deployable array, with the length variable to produce the required power. Another design was a three-panel folding rigid array. As shown in figure 8 (right), the three-panel array is designed to fold around the rover during the cruise and landing, forming three sides of a tetrahedron, and then deploy to a near-vertical array.

The solar performance and sizing were determined using the NASA Glenn developed code “MSEPS” [14]. This code calculates the hourly performance of solar power systems throughout a generally defined Mars surface mission. MSEPS also implements a Mars surface insolation model[9,10] that includes atmospheric optical depth, solar zenith angle, and local surface albedo dependencies.

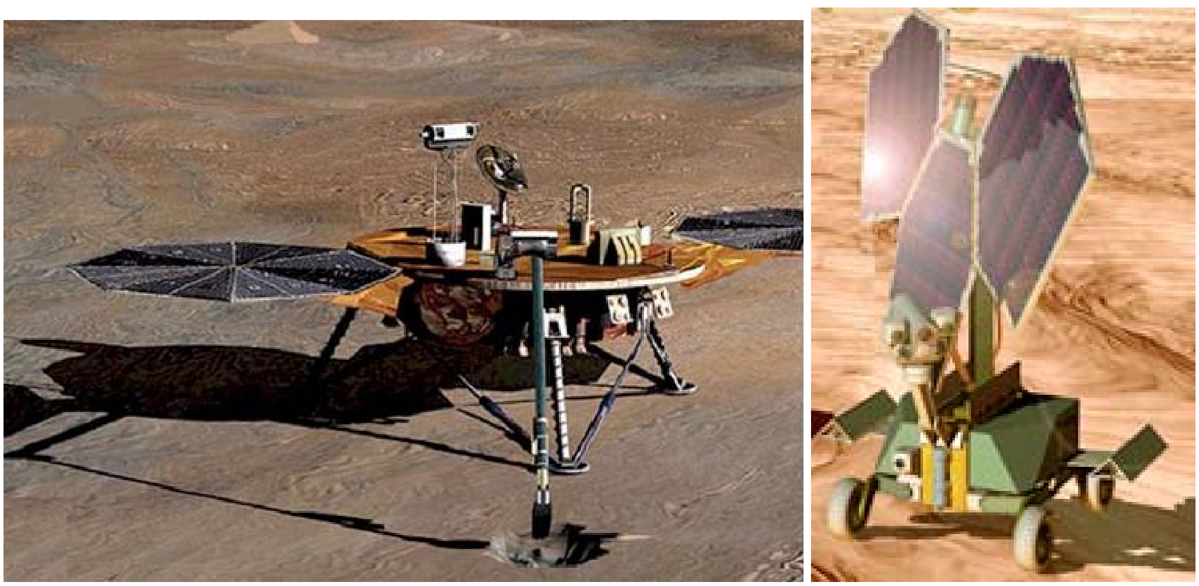


Figure 8.—Solar Arrays for Mars Polar Missions. Left: Phoenix Lander Concept, Scheduled for Launch in 2007, Shown With Two Fixed-Angle Horizontally-Mounted Solar Arrays. Right: The "Long Day's Drive" Rover, a Proposed Scout Mission, Featured a Nearly-Vertical Three-Panel Solar Array that Tracks the Sun Near the Horizon on a Vertical Axis [12].

D. Results

This polar mission results in very low levels of local solar insolation as shown in figure 9. Even though the exoatmospheric insolation increases through the mission (Mars is moving toward the Sun), the surface insolation falls since the local solar zenith increases (Sun is closer to local horizon) and greater attenuation of sunlight occurs.

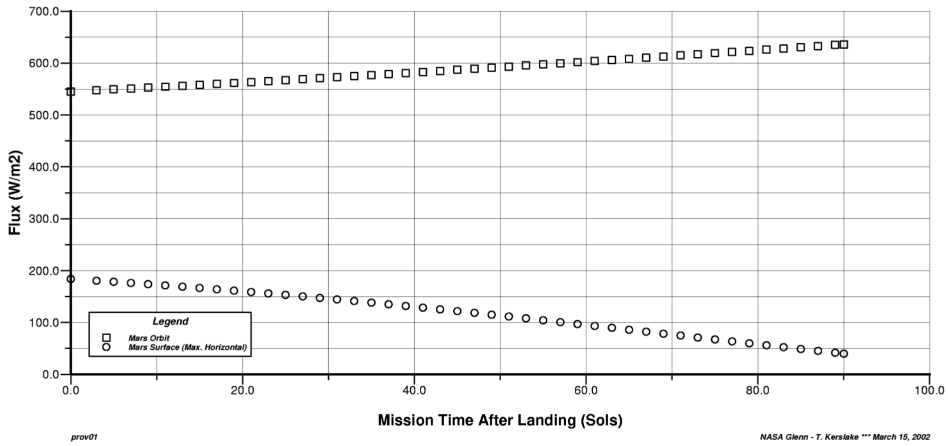


Figure 9.—Mars Polar Scout Mission Study, Solar Insolation. Landing Site: 82.0° North, 20.0° East. Landing Date September 26, 2009; Dust Storm Model: No Storms.

The mission day and night times are shown in figure 10. The rover enjoys 52-sols of continuous sunlight, but by the end of the mission on sol-90, experiences nearly equal day and night periods. Throughout the mission, the solar array photovoltaic cells operate between a peak day time temperature of -15 °C and a nighttime low temperature of -127 °C.

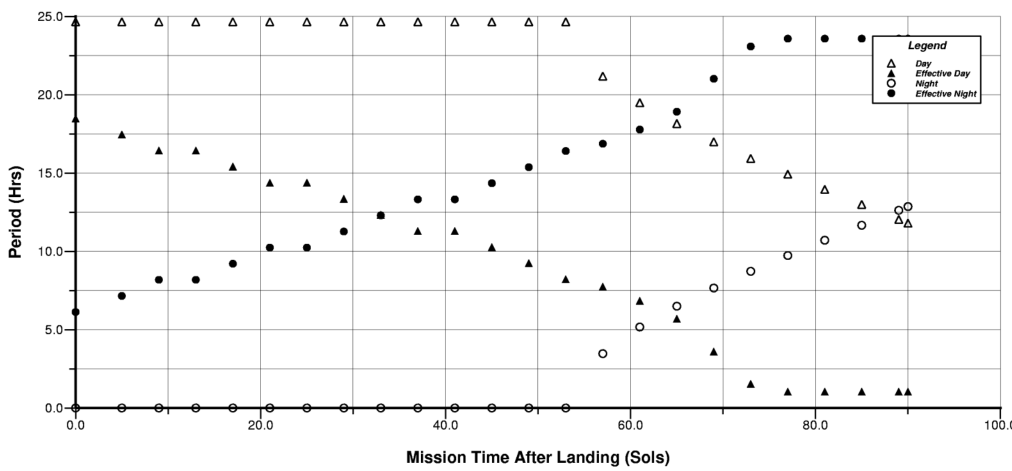


Figure 10.—Mars Polar Scout Mission Study, Mission Day and Night Periods for Landing Site 82 North, 20 East.

The initial set of mission assumptions led to low solar insolation values and long nighttime periods that conspire to produce an unreasonably large (>100-kg) solar power system which is unacceptable for this class of rover mission. Therefore, alternative mission assumptions must be investigated.

To preserve the optimum launch and landing dates, one could consider a shorter mission of 30-sols. This mission takes advantage of the available period of full sunlight days and results in a reasonable power system design including: a 1-m wide by 8-m tall solar array with 19.4-kg mass and a complete power system mass of 28.8-kg. As shown in figure 11 for mission sol 3, the daily solar zenith decreases to a minimum of 64° (at 90°, the Sun is on the horizon) resulting in a 26° solar off-pointing angle for the azimuthally tracked, vertical array. The daily array power and available rover "user" load power profiles are shown in figure 12. A 6-hour battery recharge period was selected and executed around local noon when excess solar power is available.

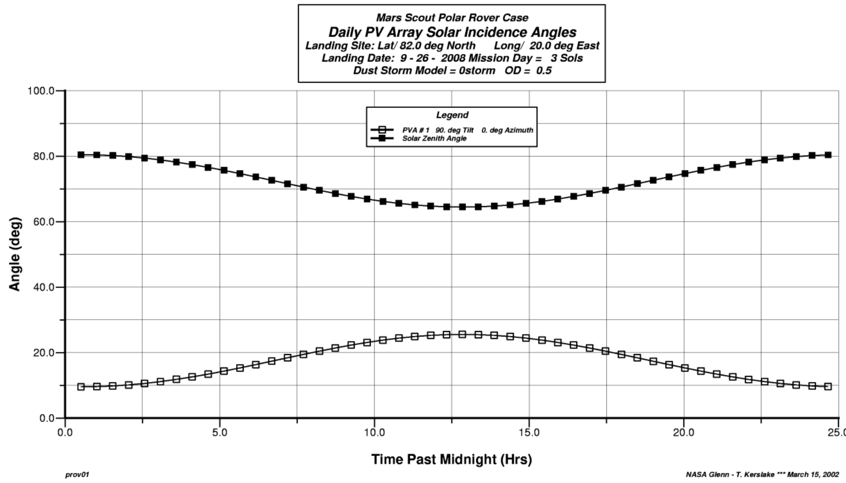


Figure 11.—Mars Polar Scout Mission Study, Solar Incidence Angles for Sol 3.

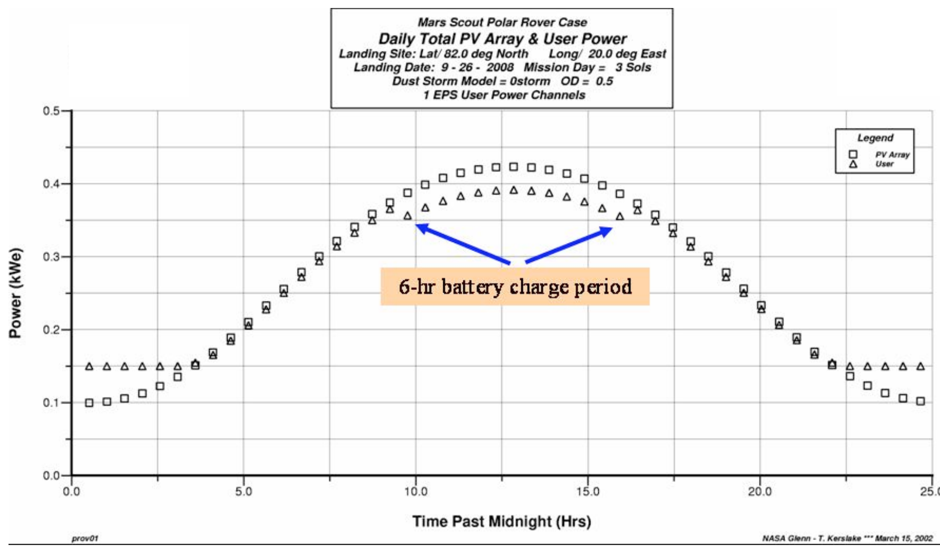


Figure 12.—Mars Polar Scout Mission Study, Daily Power Profile for Sol 3 (optical depth $\tau = 0.5$).

Another alternative mission approach would be to restrict rover daily driving to those periods when more than 150-W of solar array power is available. Adopting this approach extends mission operations of the rover (with the same power system design as in the 30-sol case) to 50-sols. The penalty is that the daily rover drive time available decreases from 24.66-hr per sol to 19 hr per sol, at the mission start, and to 9 hr per sol, at the mission end (50-sols). However, based on observed operations of the Mars Exploration Rovers, this drive time restriction may not be too penalizing. This is true since a large amount of rover stationary time is required to operate the science instruments and collect data from local surface samples.

The last alternative mission scenario would be to launch 2-months earlier, land on July 26, 2008 and enjoy more favorable, Mars polar surface solar insolation conditions. Adopting this approach, the full 90-sol mission is achievable with the baseline, 1-m by 8-m, 19.4-kg solar array. The penalty of this approach is the non-optimum launch window which will require increased launch delta-V and/or greater aeroentry energy dissipation requirements.

Since the exact atmospheric optical depth at the landing site is not known a priori, an optical depth parametric study can be useful for designing a Mars surface solar array. The impact of optical depth on solar power system design is summarized in table 1. When the optical depth is increased from 0.5 to 1.5, the array height and mass nearly triples to 22.5-m and 54.9-kg, respectively. These values are likely unreasonable from the design standpoint of array structure aero-bending moments and the operating standpoint of rover tipping moments on uneven terrain and under wind loading.

Table 1.—Solar Array Design Summary.

Array Configuration	Optical Depth	Array Dimensions (m)	Array Mass (kg)	Power System Mass (kg)
Unifacial		1.0 x 8.0	19.4	28.8
Bifacial	0.5	1.0 x 5.5	20.8	30.2
Unifacial		1.0 x 18.0	44.0	53.4
Bifacial	1.0	1.0 x 10.7	38.3	47.7
Unifacial		1.0 x 22.5	54.9	64.3
Bifacial	1.5	1.0 x 11.9	43.0	52.5

To ameliorate these issues, one could consider a "bifacial" solar array configuration instead of the baseline "unifacial" configuration. In the bifacial configuration, the solar array panel substrate would be populated with solar cells on both sides. The solar array panel areal mass roughly doubles, but the backside solar cells would contribute power from diffuse sunlight and surface albedo. Thus, the required solar array area and attendant structural support mass would decrease.

The design results of the bifacial solar array study are also shown in table 1. Under clear sky conditions with an optical depth of 0.5, a modest 30% reduction in array area is achieved with a 7% solar array mass increase penalty. For more opaque sky conditions, such as during a local dust storm with optical depth of 1.5, the relative amount of diffuse sunlight increases greatly. Thus, the area of the bifacial solar array is only half that of the unifacial solar array and offers an overall savings in array mass of 22%. In addition, the reduction in array height reduces the array base structure aerobending moment by a factor of ~2, for 0.5 optical depth, and a factor of ~4.5, for a 1.5 optical depth.

IV. Human Mission Studies

In addition to the robotic missions, solar arrays may be used for human missions to Mars. For example, a large deployable solar array could be the primary power source for an "In-situ resource utilization" plant, which converts the carbon dioxide atmosphere of Mars into rocket propellant. Figure 13 shows a visualization of one design for an array for a human mission. This uses the "tent" array structure, previously proposed for lunar base PV applications [15] which has several advantages:

1. Structural efficiency
2. East-west "tent" orientation allows higher power in morning and afternoon; flatter power profile
3. Inherent dust mitigation; dust does not adhere to tilted surface as well as to flat surface

Analysis of power systems for human missions to Mars is similar in principle to analysis for robotic probes; however, a human mission to Mars is likely to have much higher power levels than robotic missions. The higher power level makes high voltages desirable in order to minimize resistive losses. At the 7-9 mbar atmospheric pressure of Mars, voltages over roughly 250-350 Volts results in a Paschen breakdown of the atmosphere, and electrostatic discharge [10]. This will have to be taken care of in a design.

Preliminary analysis of one typical human mission power system showed that the preferred hardware technologies would be multijunction crystalline photovoltaics combined with lithium ion battery technology. Given the current technological choices, this offers the lowest solar electric power system mass and the smallest solar array size. Thin-film solar array option, although lower mass, have a larger deployed area due to lower conversion efficiency. Large area array stowage and deployment challenges are exacerbated.

Development of several technologies will be key to use of photovoltaic technology for human missions:

Power system

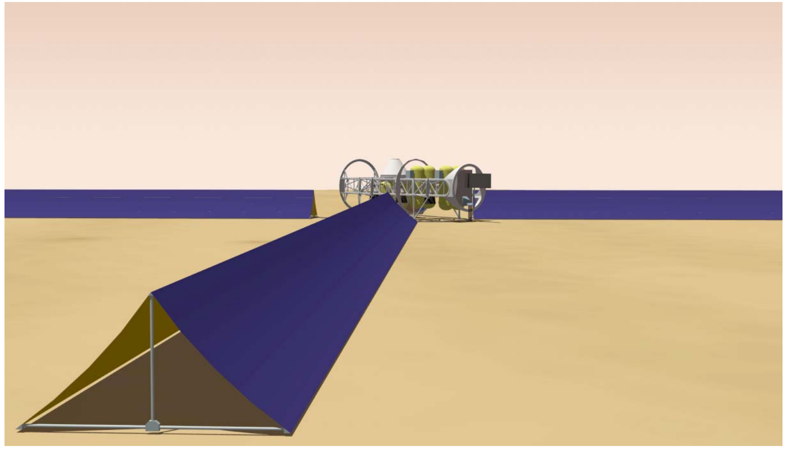
- High conversion efficiency photovoltaics
- Solar cell dust abatement (and integrated solar cell plus dust abatement technologies) [16,17]
- Low-temperature electrolyte, high W-hr/kg Lithium ion cells (50 to 100 A-hr class)

Engineering Development

- Large-array solar array stowage, deployment, structures
- High voltage power electronics (converters, switchgear, fault protection, intelligent control)
- Managing solar array triboelectric charging and Paschen discharge

Precursor Demonstrations

- Solar cell dust characterization and dust abatement
- Solar array triboelectric charging and Paschen discharge measurement



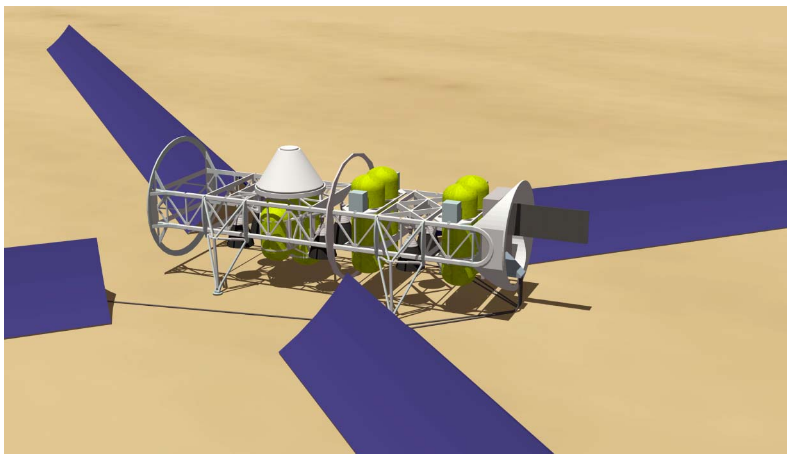


Figure 13.—Two Views of a Design of a Mars Solar Array for an ISRU Plant to Manufacture Propellant for a Human Mission, Using Four "Tent" Array Structures.

V. Concluding Remarks

We summarized the challenges represented by the surface of Mars to solar array operation, and presented a preliminary solar array design for a notional rover undertaking a 90-sol Mars polar surface mission in the 2008 timeframe. A reasonable solar array design solution was presented and discussed in the context of rigorous Martian polar surface environmental factors including: atmospheric dust, wind, cold temperatures and low intensity sunlight. For this mission, a “bifacial” solar array configuration, with solar cells populating both sides of the planar solar array, appears to offer attractive benefits in terms of area, mass and structural reductions.

References

[1.] G. Landis, "Solar Cell Selection for Mars," *IEEE Aerospace and Electronic Systems Magazine, Vol. 15,* No. 1, pp. 7-21 (January 2000). Presented at the 2nd World Conference on Photovoltaic Energy Conversion, Vol. III, Vienna, Austria, July 1998, pp. 3695-3698.

[2.] R. Haberle, C.P. McKay, O. Gwynne, D. Atkinson, G. Landis, R. Zurek, J. Pollack and J. Appelbaum, "Atmospheric Effects on the Utility of Solar Power on Mars," *Resources of Near Earth Space,* pp. 799-818. U. Arizona Press Space Science Series (1993).

[3.] J. Appelbaum, G. Landis and I. Sherman, "Solar Energy on Mars: Stationary Photovoltaic Array," *Journal of Propulsion and Power, Vol. 11* No. 3, pp. 554-561 (1995).

[4.] J. Appelbaum and G. Landis, "PV Arrays for Martian Surface Power," *Acta Astronautica, Vol. 30*, pp. 127-142 (1993); paper IAF-92-0591, 43rd IAF Congress (1992).

[5.] J. Appelbaum, G. Landis and I. Sherman, "Sunlight on Mars: Update 1991," *Solar Energy, Vol. 50* No. 1, pp. 35-51 (1993).

[6.] G. Landis and P. Jenkins, "Measurement of the Settling Rate of Atmospheric Dust on Mars by the MAE Instrument on Mars Pathfinder," *J. Geophysical Research, Vol. 105,* No. E1, pp. 1855-1857 (January 25, 2000).

[7.] R. Arvidson *et al.,* "Initial Localization and Physical Properties Experiments Conducted with the Mars Exploration Rover Mission at Gusev Crater," *Science, Vol. 305,* No. 5685, 793, August 6, 2004.

[8.] *Electrical and Chemical Interactions at Mars Workshop, Volume 1--Final Report,* NASA CP-10093, pp. 18 (1992).

[9.] D.D. Sentman, "Electrostatic Fields in a Dusty Martian Environment," *Sand and Dust on Mars,* NASA CP-10074, pp. 53 (1991).

[10.] R.N. Leach, "Effect of Pressure on Electrostatic Processes on Mars," *Sand and Dust on Mars,* NASA CP-10074*,* pp. 36 (1991).

[11.] G. Landis, "Polar Options for a First Mars Expedition," paper MAR-98-082; *Proc. of the Founding Convention of the Mars Society, Vol. 3,* Univelt Publishing, San Diego, 835-842 (1999). Presented at the Founding Convention of the Mars Society, August 13-16, 1998, Boulder, CO.

[12.] M.H. Sims and C.P. McKay, "LONG DAY'S DRIVE: an alternative paradigm for Martian Robotic Exploration," paper No. 8053, *Third Mars Polar Science Conference,* Alberta, Canada, October 13-17, 2003.

[13.] P.A. Jones, *et al.*, "A High Specific Power Solar Array For Low To Mid-Power Spacecraft," *Proceedings of the 12th Space Photovoltaic Research and Technology Conference (SPRAT 12)*, May 1992, pp. 177-187.

[14.] T.W. Kerslake, and L.L. Kohout, "Solar Electric Power System Analyses for Mars Surface Missions," paper SAE-1999-01-2482, *34th Intersociety Energy Conversion Engineering Conference,* SAE 99-01-2482, Vancouver, British Columbia, Canada, August 1-5, 1999. (see also NASA/TM-1999-209288).

[15.] G. Landis, S. Bailey, D. Brinker and D. Flood, "Photovoltaic Power for a Lunar Base," *Acta Astronautica,* Vol. 22, pp. 197-203 (1990). Paper IAF-89-254.

[16.] G. Landis, "Mars Dust Removal Technology," *J. Propulsion and Power,* Vol. 14, No. 1, pp. 126-128, January 1998.

[17.] G. Landis and P. Jenkins, "Dust Mitigation for Mars Solar Arrays," *Proceedings of the 29th IEEE Photovoltaic Specialist's Conference,* New Orleans, LA, May 19-24, 2002, pp. 812-815.

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NASA missions to Mars, both robotic and human, rely on solar arrays for the primary power system. Mars presents a number of challenges for solar power system operation, including a dusty atmosphere which modifies the spectrum and intensity of the incident solar illumination as a function of time of day, degradation of the array performance by dust deposition, and low temperature operation. The environmental challenges to Mars solar array operation will be discussed and test results of solar cell technology operating under Mars conditions will be presented, along with modeling of solar cell performance under Mars conditions. The design implications for advanced solar arrays for future Mars missions is discussed, and an example case, a Martian polar rover, are analyzed.

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