The Stretched Lens Solar Array for Mars Surface Power

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[Abstract] With implementation of the ambitious U.S. space exploration policy underway, new technology to provide power on the Martian surface becomes a priority. Early missions anticipate the use of fuel cells, but the primary power system will rely heavily upon solar arrays. These arrays should have the following characteristics: high efficiency, light weight, high packaging density and be able to withstand low temperature operation in wind and dust storms. This paper will describe how the Stretched Lens Array (SLA) can effectively and reliably provide power on the Mars surface overcoming the environmental challenges.

I. Introduction

WITH implementation of the ambitious U.S. space exploration policy underway, new technology to provide power on the Martian surface becomes a priority. Early missions anticipate the use of fuel cells, but the primary power system will rely heavily upon solar arrays. These arrays should have the following characteristics: high efficiency, light weight, high packaging density and be able to withstand low temperature operation in wind and dust storms. This paper will describe how the Stretched Lens Array (SLA) can effectively and reliably provide power on the Mars surface overcoming the environmental challenges.

Dust accumulation, wind forces, operating temperatures, and other challenges to solar array operation on the surface of Mars will be discussed and the SLA's solution to each factor will be presented. An analysis of the wind loads, taking into account the average Mars surface pressure, will be done and will be recreated in a laboratory setting to do testing on the SLA. Tests will determine the durability of lens material with simulated dust along with operation and flexure of the arrays due to wind. The lens' impressive shape error tolerance toward wind and vibration will be demonstrated. Ground testing will prove the SLA's durability in high voltage operations effectively fixing the problematic issue of electrostatic discharge due to the Paschen breakdown effect. The SLA will be shown to be capable of reliable operation on the Martian surface and thus be a suitable candidate for that use.

II. SLA Background

SLA is a unique ultra-high-performance, ultra-light, cost-effective photovoltaic concentrator array using refractive concentrator technology. Unlike reflective concentrators, refractive Fresnel lens concentrators can be configured to minimize the effects of shape errors, enabling straightforward manufacture, assembly, and operation on orbit. By using a unique arch shape, these Fresnel lenses provide more than 100X larger slope error tolerance than either reflective concentrators or conventional flat Fresnel lens concentrators.[1] The first refractive concentrator array was developed and flown on the PASP-Plus mission in 1994-

Figure 1. Stretched Lens Module in Sunlight

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95, which included a number of small advanced arrays with a mini-dome lens concentrator.[2] It was quite successful. In the late 1990's, a new line-focus Fresnel lens concentrator, which is easier to make and more cost-effective than the mini-dome lens concentrator, was developed. From 1998-2001 the SCARLET® (Solar Concentrator Array using Refractive Linear Element Technology) solar array was flown on the Deep Space 1 NASA mission.[3] SCARLET used a (8.5 cm wide aperture) silicone Fresnel lens to focus sunlight at 8X concentration onto radiatively cooled triple-junction cells. The SLA is an evolved version of SCARLET, retaining the essential power-generating elements. Rigid panel and flexible-blanket version have been developed and tested. Figure 1 shows the basic concept of SLA. Figure 2 shows a 2.5 x 5 m full scale building block module of the SLA on ATK's SquareRigger platform (SLASR). This module is sized to produce 3.75 kW and weighs only about 10 kg.

For the SquareRigger SLA version, the lenses form one flexible blanket while the radiator elements, containing the photovoltaic receivers, form a second flexible blanket. Both blankets fold up into a very compact stow volume for launch, and automatically deploy on orbit. Figure 3 shows the unique deployment. The SquareRigger platform was originally developed by ABLE under funding from the Air Force Research Laboratory for use with thin-film photovoltaic blankets in space. SLASR technology offers spectacular 300-500 W/kg specific power and 80-120 kW/m^3 stowed power in the next 5-10 years. In the longer term (2020-2025), with constantly improving solar cell efficiencies and incorporation of new cells and technology materials into the lens and radiator elements, SLA's technology roadmap leads to 1,000 W/kg solar arrays.[4] Additional testing will be necessary to determine if the SquareRigger platform is robust enough to withstand the flexure caused by the Martian wind.

The SLA is unique among all solar array technologies in its portfolio of attributes, which include world-record-level solar-to-electric conversion efficiency (high W/m^2), ultra-light mass density (low kg/m^2), spectacular stowed power density (kW/m^3), highly scalable power (kW to multi-MW), high-voltage capability (kV), modularity (individual lens/cell building blocks), mass-producibility, and cost effectiveness. The SLA has a substantial inherent mass advantage over planar, one-sun multi-junction-cell solar arrays. Similarly, due to its 85% cell area and cost savings, SLA has a substantial

Figure 2. Full scale SLASR module

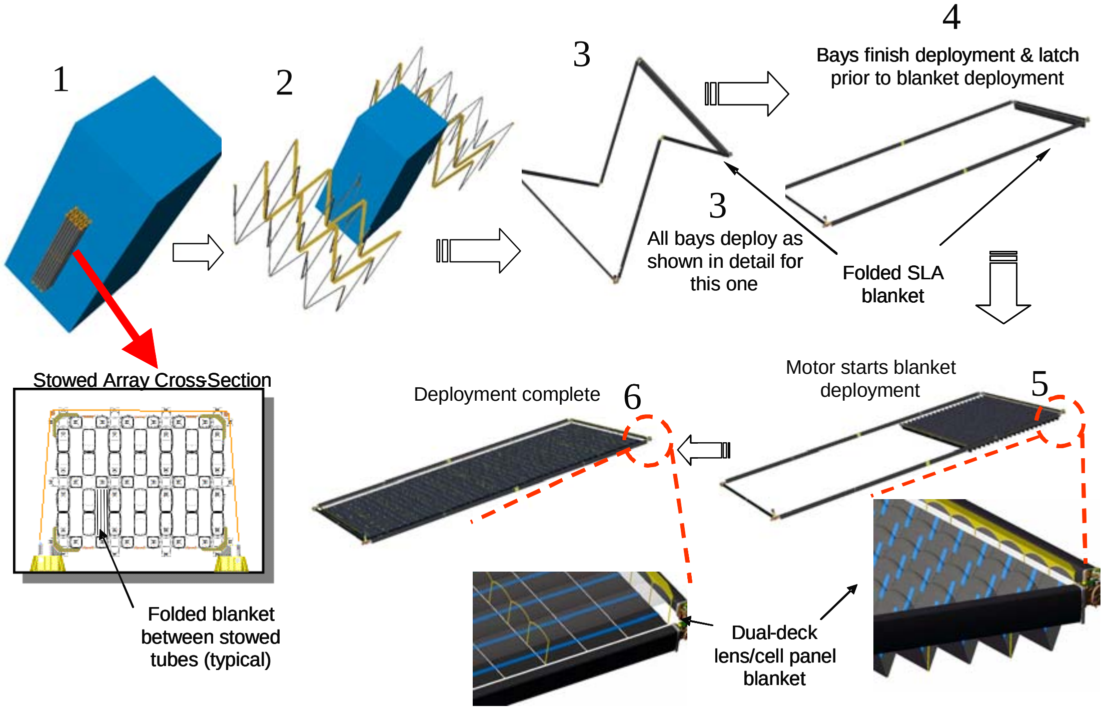

Figure 3. Deployment of the SLASR

inherent power cost advantage ($/W) over such planar multi-junction-cell arrays. SLA's small cell size also allows super-insulation and super-shielding of the solar cells to enable high-voltage operation and radiation hardness in the space environment.

III. Obstacles to Martian Power

Dust accumulation, wind forces, operating temperatures, lower solar intensity, and other challenges to solar array operation on the surface of Mars will be discussed and the SLA's solution to each factor will be presented. The SLA will be shown to be capable of reliable operation on the Martian surface.

A. Dusty Atmosphere

Previously, solar concentrator systems were not seriously considered for power on Mars because the dusty atmosphere causes low direct normal irradiance and dust accumulation on the optical surfaces cause significant power loss. Dust plays a huge factor in solar array power delivery. The amount of dust in the atmosphere dictates the amount of solar energy on the Martian surface. Dust also scatters the light causing the sunlight to come from a range of angles instead of a straight line. A comparison of the direct sunlight available to a tracking concentrator versus the total irradiance available to a fixed flat plate over a Martian day over a typical Martian year has been computed.

The solar radiation constant in Mars orbit is only 590 W/m^2, compared to 1370 W/m^2 in Earth orbit. The dusty atmosphere cuts an average 25% of the incident sunlight before reaching the surface, leaving only an average 440 W/m^2 at the Martian equatorial surface which further reduces the effectiveness of solar array power options. During a dust storm the reduction of sunlight intensity can reach 75%, further reducing the surface insolation to only 150 W/m^2.[5]

The dusty sky of Mars scatters light causing the sunlight to come from a range of angles versus a straight line from the sun. During a relatively clear day, the indirect component is relatively low, 30% for an optical depth 0.4.[7] When the optical depth is high, over 99% of the total sunlight reaching the surface can be indirect. Planar arrays can accept light from a wide range of angles but concentrators require direct light. This is one reason why is it thought concentrators will be less effective than planar technologies on the Mars surface at least during the times of highest dust concentration.

Figures 4 and 5 show a comparison of the diurnal variation of the global, direct beam, and diffuse irradiance for a horizontal surface and a two-axis tracking surface for a clear and for a dusty day at the Viking Lander 1 location.[8] This information can be used to deterimine the impact of Mars atmosphere conditions on power produced by planar and concentrator arrays as shown in Fig. 6. The short circuit current on Mars was calculated using the average current density of a ATJ cell (e.g. 17.1 $mA.cm^2$) and multiplying it by the intensity values given in the figures below for two different conditions of the Martian atmosphere. That value was then used to compute the power produced. In this calculation, it was assumed that the loss in open circuit voltage due to the increased intensity was offset by the

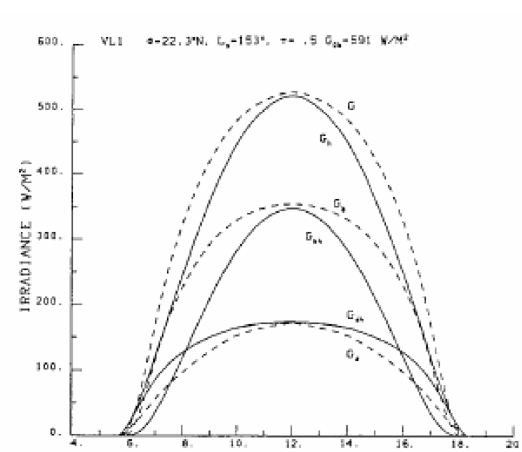

Figure 4. Global (top curve), direct beam (middle) and diffuse (bottom) insolation for a fixed horizontal surface (solid line) compared with a tracking surface (dashed line) for a relatively clear day (L,=153O at Viking Lander site VL-1.[8]

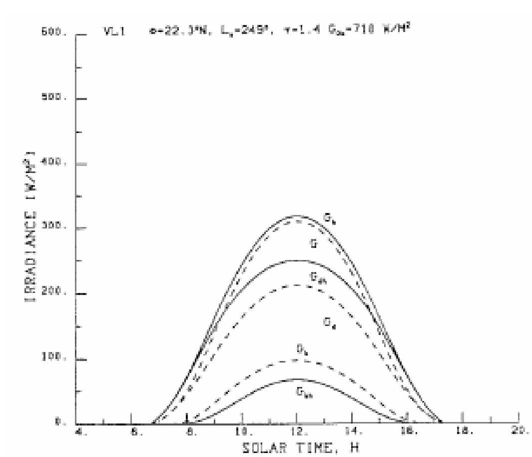

Figure 5. Global (top curve), diffuse (middle), and direct (bottom) insolation for a fixed horizontal surface (solid line) compared with a tracking surface (dashed line) for a relatively dusty day (L,=24go) at Viking Lander site VL-1.[8]

increase in open circuit voltage due to the decreased temperature. It is also important to note the the effect of the spectral shift had to be considered which caused a reduction of 10% in Isc.[9] It can be seen that due to the heavy concentration of dust in the air a planar array is much more practical on the surface of Mars because it uses both direct and diffuse light for power generation.

Another power limiting factor is the settling of dust onto the surface of the solar array. The wind causes cyclic periods of removal and redistribution of dust on the solar arrays. Horizontal flat arrays can lose power as fast as 0.5% to 1% per day due to dust accumulation.[5] While early results from the Viking Lander sites suggested it is important to elevate the array 10 to 20 cm. off the Martian surface to alleviate the majority of dust accumulation, current Phoenix Lander and rover activities show substantial dust accumulation at several feet off the ground.[6] The wind may help with some dust removal but is not always strong enough to remove the majority of dust from the surface except when a dust devil passes over the array. Some dust is still expected to adhere to the solar array due to the Van der Waals adhesive forces and possibly even electrostatic adhesion.[6] Other cleaning options consists of vibrating the tracking system to shake off the dust on the lenses along with the inherent dust mitigation of the lens being tilted. If this was insufficient the array could also be periodically rotated into a vertical orientation and vibrated to increase dust removal. It is important to note that dust devils have been helpful in cleaning off the arrays on Mars rovers Spirit and Opportunity but cannot be the only dust removal strategy. An array that is substantially off the ground and is tilted has the best chance to avoid power loss due to dust accumulation. The curvature of the SLA's lens also reduces dust accumulation.

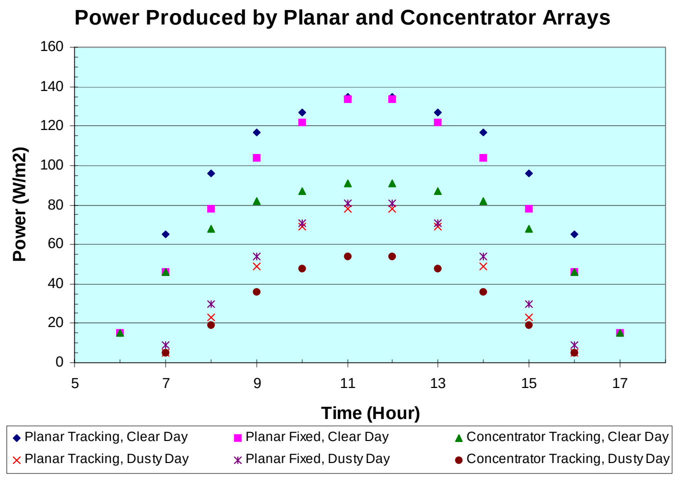

Figure 6. Impact of Mars Atmosphere Conditions on Power Produced by Planar and Concentrator Arrays

Another factor of the atmospheric dust on Mars is it causes the solar spectrum to be redder. The spectrum is blue-deficient, meaning it is enriched in the red and IR compared to the orbital AMO spectrum.[7] This affects the technology choice because of the reduced transmission of short wavelengths. As noted above, it leads to a loss in Isc of a current production TJ cell of about 10%. Thus for optimum performance on Mars, the solar cell must be redesigned. Materials which respond most to the red and IR are more desirable than cells responding to the blue end of the spectrum. This tends to favor lower band gap solar cells technologies.[7]

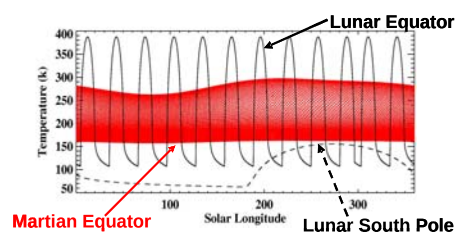

Figure 7. Lunar and Mars surface temperatures (Courtesy MIT & Draper)

B. Low Operating Temperature

Another issue with operation on Mars is the low operating temperature. The low operation temperature tends to favor lower band gap solar cell technology which was previously mentioned was best suited for the Mar's red spectrum.[7] This is desirable and will lead to higher efficiencies at Mar's temperatures.

Figure 7 shows typical lunar and Martian temperature profiles. Deployed PV arrays will typically operate in the temperature range between -100°C and 0°C.[10] Thermal considerations for SLA will be similar to those of a one-sun array on earth and will be discussed and shown to cause no difficulty in operation. Temperature

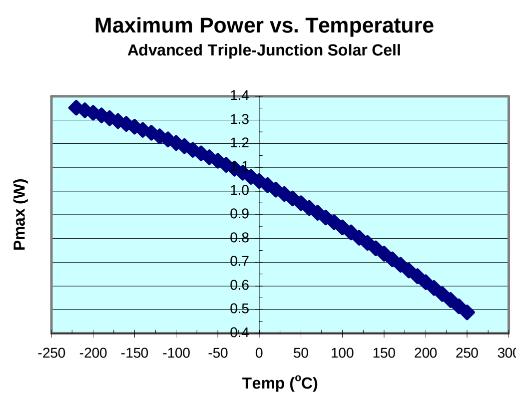

Figure 8. Effect of temperature on the maximum power of an ATJ solar cell

measurements on the SCARLET array on Deep Space 1 verified an operating cell temperature of about 70C at a 1 AU distance from the sun. SLA's cell temperature is typically about 10C warmer than for a high-efficiency one-sun cell array on the same orbit. For operation on Mars the operational temperature difference between a planar array and the SLA is expected to be even less.

Figure 8 shows the relationship between temperature and maximum power for an advanced triple-junction solar cell. This relationship is based upon the temperature coefficient for an advanced triple-junction high efficiency solar cell in space applications. It assumes the Martian temperature range with cell beginning of life performance with no radiation damage. The maximum power increases as the temperature of the cell decreases.

C. Radiation Environment

The Mars atmosphere is thick enough to provide effective shielding from micrometeoroids and solar proton/electron radiation.[11, 12, 13] At the surface of Mars, the atmosphere provides the equivalent of roughly 20 gram/cm2 of shielding from radiation, and thus radiation exposure is not a significant source of degradation and will therefore be ignored from the solar array standpoint.[14] Protection for human crews and electronics is still necessary but that is outside the scope of this paper.

D. High Voltage Operation

As Mars exploration expands and human missions become reachable; power levels will increase. The higher power levels make high voltage operation desirable in order to lower resistive losses. Electrostatic discharge becomes a problematic issue due to the Paschen breakdown effect in concurrence with the 7-9 mbar Martian atmospheric pressure. The Paschen discharge voltage is thought to be as low as 100 V.[15] The SLA is inherently designed to withstand arcing because the entire cell and cell edges are fully encapsulated providing a sealed environment. This is accomplished with minimal mass detriment due to the SLA's small cell size which is 85% smaller than planar high-efficiency arrays.

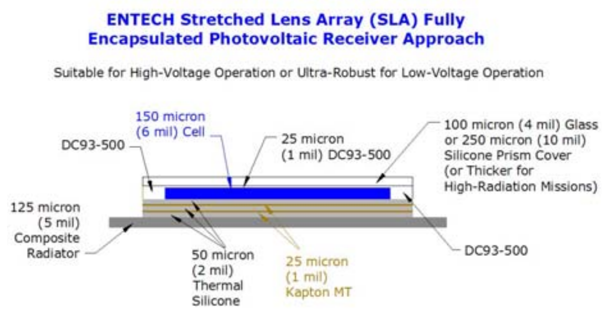

Figure 9. SLA receiver cross section

Ground testing of solar arrays at high voltages can determine potential charging issues that need to be addressed prior to launch. Testing should include corona discharge and hypervelocity testing, yet standardized testing procedures currently do not exist. Terrestrial test IEC 343 is the only basis on which guidelines can be determined for a corona test.[16] A receiver must be developed that can operate over the full mission durations without corona break-down. A fully encapsulated cell circuit, using redundant insulation layers below the cell and glass/silicone layers above the cell, is configured to provide moderate (3-5 V/micron) gradients through the insulating layers to minimize voltage endurance failures. A sample SLA receiver is shown in Fig. 9. ENTECH has fabricated and tested a number of such single-cell SLA receiver samples at very high voltage levels (2,250 to 4,500 V) in an underwater hi-pot test for very long periods of time. The water is a crude simulator of space plasma and is effective in finding insulation defects.

To complement ENTECH's underwater hi-pot testing, Auburn has conducted similar tests in vacuum using the same type of fully encapsulated receiver samples. The sample is maintained at room temperature under a vacuum of approximately 6×10^{-5} torr. This set-up tests the insulation properties of the cell sample under a DC voltage bias. A failure indicates that a path from the high voltage source to the ground has occurred through the insulation which could lead to failure of the array. Testing of high-voltage SLA photovoltaic receiver materials and assemblies started at Auburn in August 2006. No changes were seen in the samples for ten and a half months. At this point there was an equipment failure and the test was stopped. It is believed the samples would have continued to see no change if testing had continued for a long time period.

E. Wind Forces

Wind speeds in the upper atmosphere can exceed 100 m/sec.[17] However, on the Martian plains, the Viking Landers measured typical wind speeds of 2-7 m/sec and wind gusts up to only 26 m/sec at an elevation of 1.6 m.[18] Over the surface of a large, elevated PV array in the boundary layer, dust storm peak wind speeds could range from 3 m/sec at the surface to about 55 m/sec at the top (about 5-m elevation).[11]

The shape error tolerance of the ENTECH lens is critical to the excellent long-term performance of concentrator systems using this technology. In contrast, the lack of shape error tolerance has contributed to the poor performance of many reflective photovoltaic concentrator systems both on the ground and in space. Detailed analyses show that the symmetrical-refraction lens offers a shape error tolerance that is 200 times better than for any reflective concentrator and 100 times better than for a conventional flat Fresnel lens. A comparison of the shape error tolerance of refractive versus reflective concentrators is shown in Fig. 10.

A model of the SLA was placed in front of a floor fan to model the wind forces that might be seen on Mars. Even with the distortion of the lens material the light remained focused on the solar cells as seen in Fig. 11. Distortion of the lens material due to the wind on Mars will not affect SLA performance. The only time the light does not remain on target is if the lens flips over on itself.

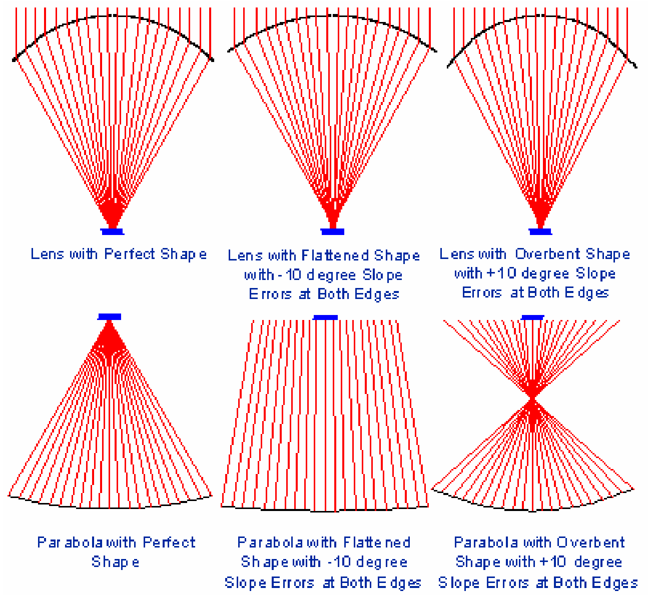

Figure 10. Direct Ray-Trace Comparison of Shape Error Tolerance of ENTECH's Lens versus Reflective Concentrator

IV. Conclusion

The Stretched Lens Array can effectively and reliably provide power on the Mars surface overcoming the environmental challenges, however, it can not compare to the power performance of a planar array due to the substantial dust suspended in the atmosphere. The SLA's main attributes are it is lightweight and the ability to provide reliable power without the risk of electrostatic discharge. These factors may be more important than overall power performance. Dust accumulation, wind forces, operating temperatures, and other challenges to solar array operation on the surface of Mars have been discussed and the SLA's solution to each factor was presented. To help alleviate dust settling on the array it should be tilted and raised substantially about the ground. Laboratory tests show the SLA's durability of lens material with simulated dust along with operation and flexure of the arrays due to wind. The lens' impressive shape error tolerance toward wind and vibration was demonstrated. Ground testing proves the SLA's durability in high voltage operations effectively fixing the problematic issue of electrostatic discharge due to the Paschen breakdown effect. In high dust circumstances the SLA has a lower power performance than a planar array, however, many mission factors determine the choice of an array on the Martian surface including mass, performance, and reliability. The SLA is capable of reliable operation on the Martian surface and is a suitable candidate for that use.

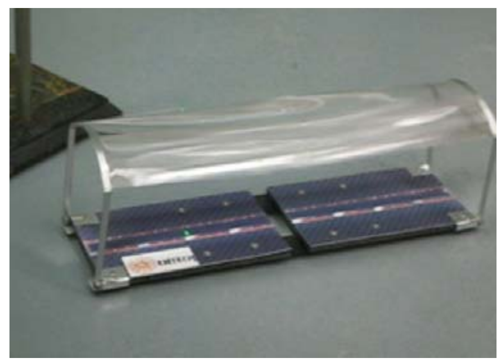

Figure 11. Picture of wind distortion to lens with light remaining focused on cells

Acknowledgments

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References

[1] O'Neill, M. J., "Silicon Low-Concentration, Line-Focus, Terrestrial Modules," Chapter 10 in Solar Cells and Their Applications, John Wiley & Sons, New York, 1995.

[2] Curtis, H. and Marvin, D., "Final Results from the PASP Plus Flight Experiment," 25th IEEE PVSC, Washington, 1996.

[3] Jones, P. A., Allen, D. M., Murphy, D. M., Piszczor, M. F., “The SCARLET Light Concentrating Solar Array,” 25th IEEE PVSC, Washington, 1996.

[4] O’Neill, M. J., “1,000 W/kg Solar Concentrator Arrays for Far-Term Space Missions, Space Technology & Applications International Forum (STAIF 2004),Albuquerque, 2004.

[5] *www.newmars.com/wiki/index.php/Solar_panels*

[6] Landis, G. A., and Jenkins, P. P., “Dust Mitigation for Mars Solar Arrays,” IEEE, 2002.

[7] Landis, G. A., “Solar Cell Selection for Mars,” *IEEE AES Systems Magazine, January 2000*

[8] Landis, G. A, and Appelbaum, J., “Design Considerations for Mars Photovoltaic Power Systems,” IEEE Publication, 1990.

[9] Landis, G. A., Hyatt, D., and the MER Athena Science Team, “The Solar Spectrum on the Martian Surface and its Effect on Photovoltaic Performance,” IEEE Publication, 2006.

[10]Jenkins, P.P, Scheiman, David A., Brinker, D.J., and Appelbaum, J., "Low Intensity, Low Temperature (LILT) Measurements on New Photovoltaic Structures," 30th Intersociety Energy Conversion Engineering Conference, paper 95353, Aug 1995.

[11] Kerslake, T. W., and Kohout, L. L., “Solar Electric Power System Analyses for Mars Surface Missions, NASA/TM—1999-209288, July 1999.

[12] Simonsen, L. C., Nealy, J. E., Townsend, L. W., and Wilson, J. W., "Radiation Exposure for Manned Mars Surface Missions," NASA TP 2979, Mar 1990.

[13] Simonsen, L. C. and Nealy, John E., "Mars Surface Radiation Exposure for Solar Maximum Conditions and 1989 Solar Proton Events," NASA TP 3300, Feb 1993.

[14] Landis, G. A, Kerslake, T. W., Jenkins, P. P, and Scheiman, D. A., “Mars Solar Power,” NASA/TM—2004-213367, November, 2004.

[15] Kolecki, J. C., "Electrostatic Charging of the Mars Pathfinder Rover and Charging Phenomena on the Planet Mars," 32th Intersociety Energy Conversion Engineering Conference, paper 97344, Aug 1997.

[16]IEC International Standard #343 (1991): “Recommended test methods for determining the relative resistance of insulating materials to breakdown by surface discharges.”

[17] Kaplan, David I., "Environment of Mars, 1988," NASA TM 100470, Oct 1988, pp. 2-10

[18] Ryan, J. A. and Henry, R. M., "Mars Atmospheric Phenomena During Major Dust Storms, as Measured at the Surface," Journal of Geophysical Research, Vol 84, No B6, Jun 10, 1979.