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Effect of Particle Size of Martian Dust on the Degradation of Photovoltaic Cell Performance

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EFFECT OF PARTICLE SIZE OF MARTIAN DUST ON THE DEGRADATION OF PHOTOVOLTAIC CELL PERFORMANCE

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SUMMARY

Glass coverglass, and SiO_2 covered and uncovered silicon photovoltaic (PV) cells were subjected to conditions simulating a Martian dust storm, using the Martian Surface Wind Tunnel, to assess the effect of particle size on the performance of PV cells in the Martian environment. The dust used was an artificial mineral of the approximate elemental composition of Martian soil, which was sorted into four different size ranges. Samples were tested both initially clean and initially dusted. The samples were exposed to clear and dust laden winds, with velocities varying from 23 to 116 m/s, and attack angles from 0° to 90°. It was found that transmittance through the coverglass approximates the power produced by a dusty PV cell. Occultation by the dust was found to dominate the performance degradation for wind velocities below 50 m/s, whereas abrasion dominates the degradation at wind velocities above 85 m/s. Occultation is most severe at 0° (parallel to the wind), is less pronounced from 22.5° to 67.5°, and is somewhat larger at 90° (perpendicular to the wind). Abrasion is negligible at 0°, and increases to a maximum at 90°. Occultation is more of a problem with small particles, whereas large particles (unless they are agglomerates) cause more abrasion.

INTRODUCTION

Consensus has been growing that one of NASA's primary missions over the next several decades will be further exploration of the planet Mars. To this end, NASA is developing the technology to place a manned expedition on the surface of Mars in the early part of the twenty-first century. The role of developing new technologies for power on the planetary surface has been assigned to the Lewis Research Center.

There will be substantial power requirements for the surface base, and there is little doubt that photovoltaic (PV) arrays will play an important role. Mars has a diurnal cycle (24 hr, 37 min.) similar to that of Earth, and although it receives a little more than 40 percent sunlight that Earth receives (580 W/m^2)[1], there is still sufficient solar flux to make photovoltaic power an important option. However, there are some concerns about the durability of PV arrays in the Martian environment. Although there are a number of considerations such as large daily thermal cycles, ultra-violet radiation, and highly corrosive species in the soil, the predominant threat appears to be dust.

Dust is pervasive in the Martian environment. Suspended dust is thought to cause the pink color of the sky seen in photographs from the surface taken by the Viking Landers. The low pressure but high speed Martian winds can transport large amounts of dust during huge global dust storms. That the top layer of soil from the Viking Lander 1 and 2 sites were virtually identical even though the landers were several thousand miles apart [2] is further evidence of the scale of dust transport around the planet. The dust could result in occlusion or abrasion of PV surfaces, but any attempt to assess the possible harmful effects is hampered by the paucity of knowledge about the composition and particle size distribution of the dust. Thus, parametric studies may be the most helpful type to determine which factors are most important to the degradation of PV arrays.

The distribution of particle sizes in the Martian atmosphere and on the loose surface has not been well constrained by experiments to date. Best estimates of particle size distributions suggest 0.1 to 2000 μm diameter particles at the Viking Lander sites [3]. The smallest particles (0.1 to 10 μm) remain suspended in the atmosphere indefinitely, and sand-size particles (60 - 2000 μm) will not rise more than a few meters from the surface; however, dust particles between these extremes (about 5 - 100 μm) are expected to be elevated during dust storms and quickly settle out, covering, among other things, PV arrays. The focus of this study is the effect of particle size within this sensitive range on the degradation of PV performance.

METHODS AND MATERIALS

At this time no decision has been made about the type of PV cell which will be used in the early Mars exploration missions. The PV cells will probably be protected with a coverglass, and a likely coverglass material is SiO_2. Since the coverglass will probably protect the PV cells from adverse chemical reactions with the Martian environment, the most important modes of performance degradation would be occlusion of incoming light by dust particles, and abrasive degradation of the transparency of the coverglass. Thus, square glass coverglass, 2.54 cm on a side and 0.13 mm thick were used for the sample substrates. Although it may be advantageous to apply coatings to the coverglass, previous tests suggest that the coatings have little effect on dust removal mechanisms [4], though they may affect coverglass abrasion. These substrates were mounted on sample holders capable of maintaining the substrate horizontally for characterization and initial dusting, and at an angle of attack of 0°, 22.5°, 45°, 67.5° or 90° for the test. The angle of attack is measured from the wind direction, that is at 0° the plate surface is parallel to the wind, and at 90° the surface is normal to the wind. Some of the samples were gold coated and imaged in a Cambridge Model 200 Scanning Electron Microscope (SEM).

Conventional SiO_2 covered and uncovered N/P silicon PV cells (Spectrolab) were affixed to the sample holders described above in place of one of the coverglass. All PV cells were mounted on 45° attack angle sample holders. Damage was assessed by inspection using optical and scanning electron microscopes. The illuminated (AM0) cell characteristics were also measured using a Spectrolab X-25L xenon arc solar simulator calibrated by an aircraft calibrated silicon reference standard.

The dust used to coat the samples was a synthetic mineral manufactured by Ferro Corporation (Independence, OH) to have a chemical composition similar to Martian soil. It was not the purpose of these experiments to accurately simulate the Martian soil, but to generate several different dust samples with the same chemical composition, relevant to Martian dust, varying only in size. Table I compares the composition of this material to the soil composition found at the Viking Lander sites. The dust was dry sieved into four different ranges with nominal diameters of 10, 30, 60, and > 75 μm. There was not a sufficient amount of the 60 μm material to include it in our tests.

An initial layer of dust was deposited on half of the sample holders by placing them in a dusting chamber where the dust was elevated using dry air and allowed to settle out onto the samples. Details about the method of dusting are described in detail elsewhere.[5] The uniformity and extent of the dust deposition was monitored optically. The specular transmittance was used as a probe of the extent of occlusion and abrasion. Power is also generated in PV cells from diffuse light, so the specular transmittance cannot be converted directly into PV cell performance. Further references to transmittance in this work will refer only to the specular component. The specular transmittance was measured using an incandescent light source that shines into the photo-sensor of a Coherent Model 212 Power Meter. The sample coverglass was then placed between the source and the sensor and the percent decrease in the power was recorded.

In the case of initially clear samples the ratio of the final to initial transmittance (Tf/To) was calculated. Note that this function ranges from 0.00, when so much dust has accumulated that no light can be detected, to 1.00, when the slide totally clears.

In the case of the initially dusted samples, the situation is more complex. When assessing the clearing of a pre-dusted slide with clear air, the dust clearing parameter (Tf-Td)/(To-Td), where Td is the transmittance of initially dusted samples before being subjected to the wind, is a useful indicator. This function goes to 1.00 if all of the dust is cleared off, and goes to 0.00 if none of the dust is removed. If there is a net accumulation of dust, this parameter becomes negative. Note that these are not the same conditions as the equation for the initially clear sample.

The winds on Mars were simulated using the Martian Surface Wind Tunnel (MARSWIT) at NASA Ames Research Center. The MARSWIT is a low pressure ($\approx 10^2$ Pa) wind tunnel 14 m in length with a 1 m by 1.1 m by 1.1 m test section located 5 m from the tunnel's entrance. This flow-through wind tunnel is located within a 4,000 m^3 vacuum chamber. The characteristics of the MARSWIT are described in detail elsewhere.[6] The samples were placed in the MARSWIT and tested under the conditions listed in table II.

The method used to simulate a Martian dust storm is illustrated in figure 1. The test dust was fed through a hopper into the top of the MARSWIT, near the entrance. First the wind was generated in the MARSWIT at a velocity below that which would clear dust off of the pre-dusted samples. Then the hopper feed was started, dropping the dust into the air stream. Immediately thereafter the wind velocity was increased to the test conditions. The time reported in table II is the time spent at the maximum speed. The finer particles were carried along the wind stream and struck the samples, much as would happen during a dust storm on Mars. The MARSWIT was shut down before the hopper was turned off, consequently there was no time when high velocity clear air hit the samples. Both initially clean and initially dusted samples were included in these tests.

RESULTS AND DISCUSSION

Large Particle Sizes

The largest particle sizes used in this study, being larger than 75 μm, might be better described as sand than dust. The smaller particles, having high adhesion to the sample plates, could be tipped to 90° or even inverted with no significant loss of particles. Particles larger than 75 μm however, would slide off of the plates when tipped to a high angle. Our measurements indicate that the angle of repose for these particles was about 27°. However, these measurement were done in a gravity field of 1.0 g. On Mars, with a gravity of 0.377 g, a sliding force this strong could not be developed at any angle, so this material would be expected to be dust-like. In fact, any particles with an angle of repose greater than about 22° would be expected to exhibit dust-like behavior. Therefore, particles larger than 75 μm were not used to dust sample plates, but were used in the wind stream to examine the effects of particle size on clearing, deposition, and abrasion.

Coverglass Tests

The first series of tests examined the effect of particle size on the ability of clear Martian winds to remove dust from pre-dusted surfaces. In a previous study it was found that wind velocities of about 90 m/s were required to clear small particles (2 μm) of ferric oxide, whereas much larger (30 μm) aluminum oxide and basalt particles were removed at about 35 m/s [5]. Although it was suspected that particle size effects were a major cause of variation, differences in the surface chemistry of the particles could be responsible. Thus, in this study different sizes (nominally 10 μm and 30 μm) of the same particles were used. The results, shown in figure 2, show that particle size effects are important in determining the threshold clearing velocity for dust. This is shown most dramatically in figure 2b, illustrating the effects of dust clearing in 40 m/s winds. This is clearly above the threshold clearing velocity for the 30 μm particles (except for the 0° samples), but in the transition region for the 10 μm particles. Except for the 67.5° data, which are similar, the 30 μm particles clear to about twice the extent. In the 95 m/s data, shown in figure 2c, clearing was nearly complete in both cases. Inspection of the coverglass reveals evidence of abrasion. In addition, as the attack angle increased there was an increase both in the number of abrasion sites (fig. 3) and in the depth of the sites (fig. 4). Transmittance data, shown in figure 5a, bear out that the abrasion does have a detrimental effect on the transmittance of the coverglass, albeit a small one. It is also apparent from these data that the 30 μm particles did more damage when removed by clear wind than did the 10 μm.

The second series of tests studied the deposition and abrasion effect on initially clean samples subjected to dust laden winds. Degradation of the transmittance was found to increase with angle of attack, as is shown in figure 6. This is not surprising since both occultation and abrasion have been shown to increase with angle of attack.[7] Since the ratio of the final to the initial transmission increases with increasing velocity, occultation is expected to be the primary degradive mechanism. Additionally, when basaltic dust is blown across the samples at velocities as high as 58 m/s, abrasion of glass coverglass has been shown to be minimal [7]. Thus only the samples subjected to velocities greater than 58 m/s would be expected to experience significant abrasion. In order to test these speculations, accumulated dust was carefully removed from two samples subjected to each velocity. The transmittance of these samples was then remeasured, and they were inspected under an optical microscope. Only those samples which were subjected to 89 m/s winds and higher had evidence of abrasion.

The effects of particle size vary with wind velocity. When the wind velocity was very high (89 - 116 m/s) there was no significant difference between the degradation caused by large particles (> 75 μm) and that caused by small particles (30 μm). In both cases there was little degradation. This is in contrast to a previous study which found large particles to be less abrasive than their smaller counterparts [7]. The authors speculated that perhaps the larger particles were agglomerates which broke up upon collision, dissipating much of their energy. If that is the case then one would think that these particles agglomerate significantly less than the basaltic dust used in that study. When figure 5b is compared to figure 6, it is apparent that abrasion caused most of the losses. It should be noted that wind velocities were measured, and that particle velocities, especially for the large particles, may have been significantly (as much as 40 percent) lower.[8] At lower wind velocity (23 - 24 m/s) there was a much greater particle size effect. At an attack angle of 0° there was no significant difference, but at 45° the transmission ratio was about 12 percent lower for smaller particles and at 90° nearly 20 percent lower. Since occlusion is the only significant mechanism of degradation at these velocities, the implication is that smaller particles stick better to the surfaces. Larger particles but not smaller may be removed by the low velocity winds, whereas both are removed in the high velocity winds.

The third series of tests examined the effects of dust-laden winds blowing across pre-dusted samples. One might expect the results to be a linear combination of effects of clear wind over dusty samples, and dusty wind over clear samples. Deposition increases with increasing angle, decreasing velocity, and decreasing particle size. Clearing is lowest at 0°, peaks near 45°, and lowers at 90°; and increases with increasing velocity, and increasing particle size.

At 0°, with significant deposition and minimum clearing, low transmittance values would be expected, especially for small particles. Figure 7 shows this to be the case. However, if the particle size is increased, or if the velocity is increased, the 0° samples cleared about 80 percent. Thus dust laden wind cleared to a much greater extent at the same velocity than did the clear wind. We speculate that this is due to particle-particle collisions which elevate the particles so that they can be swept away.

At 45° particle size appeared to have a very large effect. Small particles were cleared off of surface by an 89 m/s wind to about the same extent as large particles by a 24 m/s wind.

At 90° deposition should be at its highest and clearing should be somewhat lower than at 45°. Particle size effects appeared to be smaller under these conditions. The smaller particles were cleared to a greater extent than at 45°, and the larger particles to a lesser extent. Abrasion was found to account for about half of the transmission degradation (see fig. 5c.). Larger particles caused somewhat more abrasion than did smaller particles.

PV Cell Performance

The important issue is not, of course, how is coverglass transmittance effected during a Martian dust storm, it is how does the power produced by a PV cell change. Katzan et al. have related coverglass specular transmittance, as measured in the transmission measurement device used in this study, to N/P silicon PV cell performance at AM0.[9] Their data are reformatted in figure 8. The result is that, within the error of the measurement, the normalized transmittance correlates with PV power (calculated from the current as a function of voltage curves.)

For the degradation mechanism of occlusion (which is what Katzan et al. measured), the degradation of the transmittance as measured through the coverglass should accurately reflect the degradation of PV cells. Abrasion, however, might not follow the same relation. As with the coverglass tests, abrasion of PV cell surfaces was only observed in those samples subjected to 89 m/s winds and higher. Figure 9 shows that the abrasion pits on the SiO_2 covered PV cells look like the abrasion pits in the coverglass. The efficiencies calculated from the current-voltage characteristics of PV cells subjected to the MARSWIT were measured after the tests (Table III). Although the efficiencies were not determined before the tests, the samples subjected to 23 m/s winds showed no visible signs of damage, and thus were assumed to reflect the initial conversion efficiencies. Given that assumption, there was no significant loss in the efficiencies of any of the PV cells except perhaps for sample PV - 7. Measurement of the transmittance of cleaned and abraded coverglass reveals a consistent four percent drop in the transmittance. In fact, the coverglass run with sample PV - 7 had a slightly smaller drop in transmittance. This leads to the suspicion that PV - 7 probably had a lower initial efficiency than the other cells.

Bowman et al. have reported degradation in PV cell performance from coverglass abrasion caused by hypervelocity particle impact of about 5 percent.[10] These tests had very high impact densities which perhaps set an upper bound for the abrasive component of the cells. Wade reported that erosional effects of the contacts could be an important factor in the degradation, but with covered cells, and not inter-cell contacts such effects were not observed in the present study.[11]

CONCLUSIONS

An artificial mineral of the approximate elemental composition of Martian soil was manufactured, crushed, and sorted into four different size ranges. Particles larger than 75 μm did not have sufficient adhesive forces to adhere to the samples at angles greater than about 27°. Glass coverglass, and covered and uncovered PV cells were dusted with the remaining sizes and subjected to clear air, air laden with fine particles (30 μm), and air laden with coarse particles (greater than 75 μm) at angles of attack of 0°, 22.5°, 45°, 67.5°, or 90°. Initially clear samples were also subjected to the two sizes of dust laden winds. A previous study verified that specular transmittance through the coverglass predicts the degradation due to occlusion of power generated by a dusty PV cell. Abrasive losses, even in the worst cases, were only a few percent and did not significantly degrade PV power production.

Occultation by the dust was found to dominate the performance degradation for wind velocities below 50 m/s, whereas abrasion dominates the degradation at wind velocities above 85 m/s. Occultation is most severe at 0°, is less pronounced from 22.5° to 67.5°, and is somewhat larger at 90°. Abrasion is negligible at 0°, and increases to a maximum at 90°. Occlusion is more of a problem with small particles, and large particles (unless they are agglomerates) cause more abrasion. Abrasive losses were similar for initially clear and initially dusted coverglass, and for clear wind and dust-laden wind alike.

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10. R.L. Bowman, M.J. Mirtich, and J.R. Jack, *"Performance of N/P Silicon and Cadmium Sulfide Solar Cells as Affected by Hypervelocity Impact"*, NASA Technical Note D-5133 (1969).

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Table I -- Composition of Dust Used in MARSWIT Test

MINERAL	VIKING LANDERS	TEST DUST
SiO_2	44.7 %	53.5 %
Fe_2O_3	18.1	21.7
MgO	8.3	9.9
Al_2O_3	5.7	6.8
CaO	5.6	0.0 ?
TiO_2	0.9	1.1
Na_2O	?	6.7 ?
K_2O	0.0	0.3
CO_2	?	0.0
TOTAL	**83.3**	**100.0**

"?" indicates species not detectable by Viking Landers

Table II -- Test Conditions for MARSWIT Tests

Run Number	Sample Dust	Wind Dust	Wind Velocity
1	30 μm	Clear	44 m/s
2	30	Clear	23
3	30	Clear	95
4	10	Clear	43
5	10	Clear	32
6	10	Clear	96
7	10	Clear	25
8	10	30 μm	23
9	10	30	89
10	10	> 75	40
11	10	> 75	24
12	10	> 75	116

Table III -- Performance of PV Cells

Sample	Cover Glass	Sample Dust Size	Suspended Dust Size	Wind Velocity	Damage seen in SEM	Eff AM0 PV	Tf/To 45° Cover
PV - 1	none	30	none	23 m/s	No	9.6	1.0
PV - 2	none	10	none	32	No	9.1	1.0
PV - 3	SiO_2	30	none	95	Yes	9.6	0.97
PV - 4	SiO_2	10	none	96	Yes	9.5	0.97
PV - 5	none	10	15 μm	23	No	----	1.0
PV - 6	none	none	15	23	No	9.3	1.0
PV - 7	SiO_2	10	15	89	Yes	8.5	0.98
PV - 8	SiO_2	none	15	89	Yes	9.4	0.95

1. Chamber pumped down to 1 kPa
2. Dust dropped past MARSWIT mouth
3. Flow initiated in MARSWIT
4. Dust laden wind strikes samples

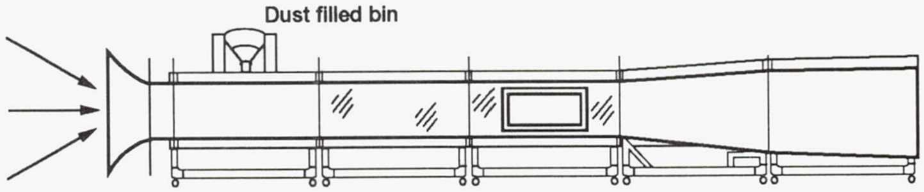
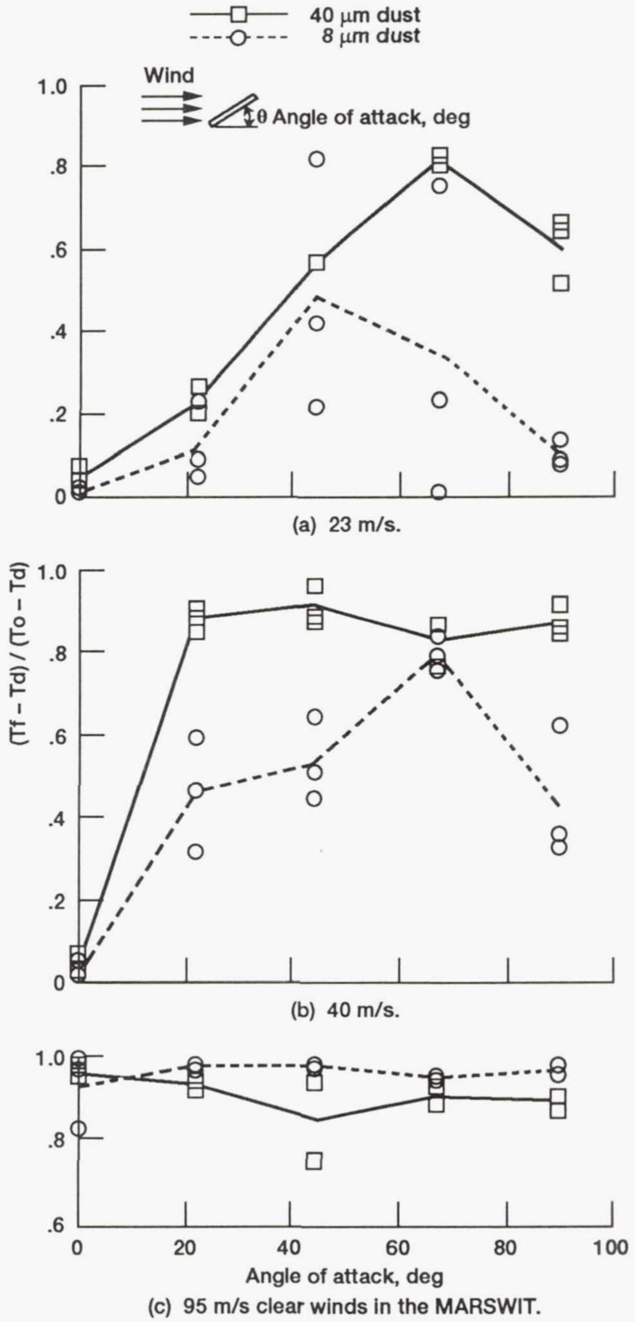


Figure 1.—Experimental set-up to simulate a Martian dust storm.

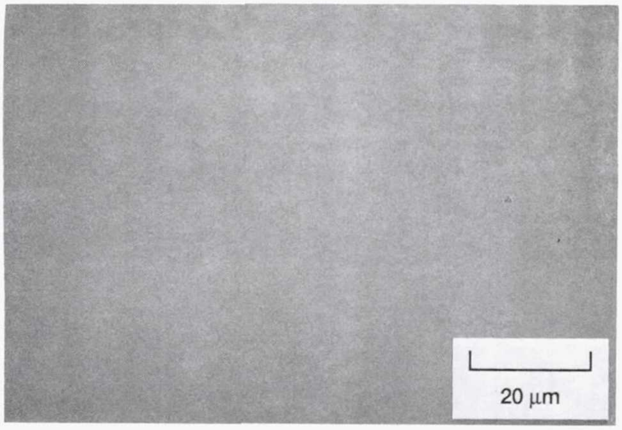


(a) 23 m/s.

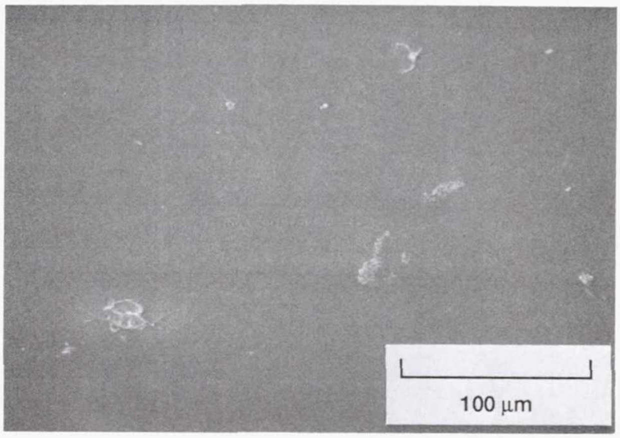
(b) 40 m/s.

(c) 95 m/s clear winds in the MARSWIT.

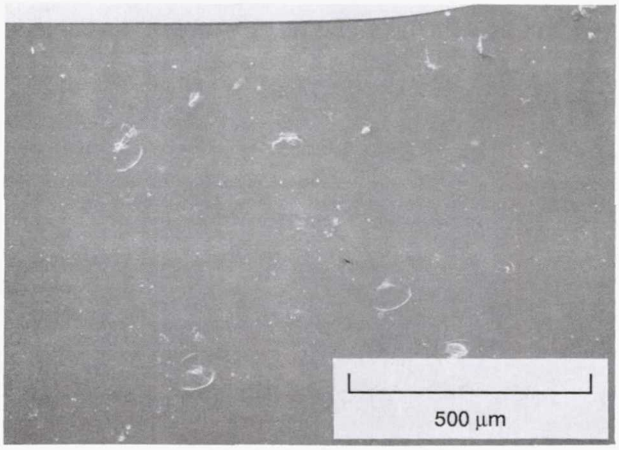
Figure 2.—Dust clearing from initially dusted samples.



(a) 0°.

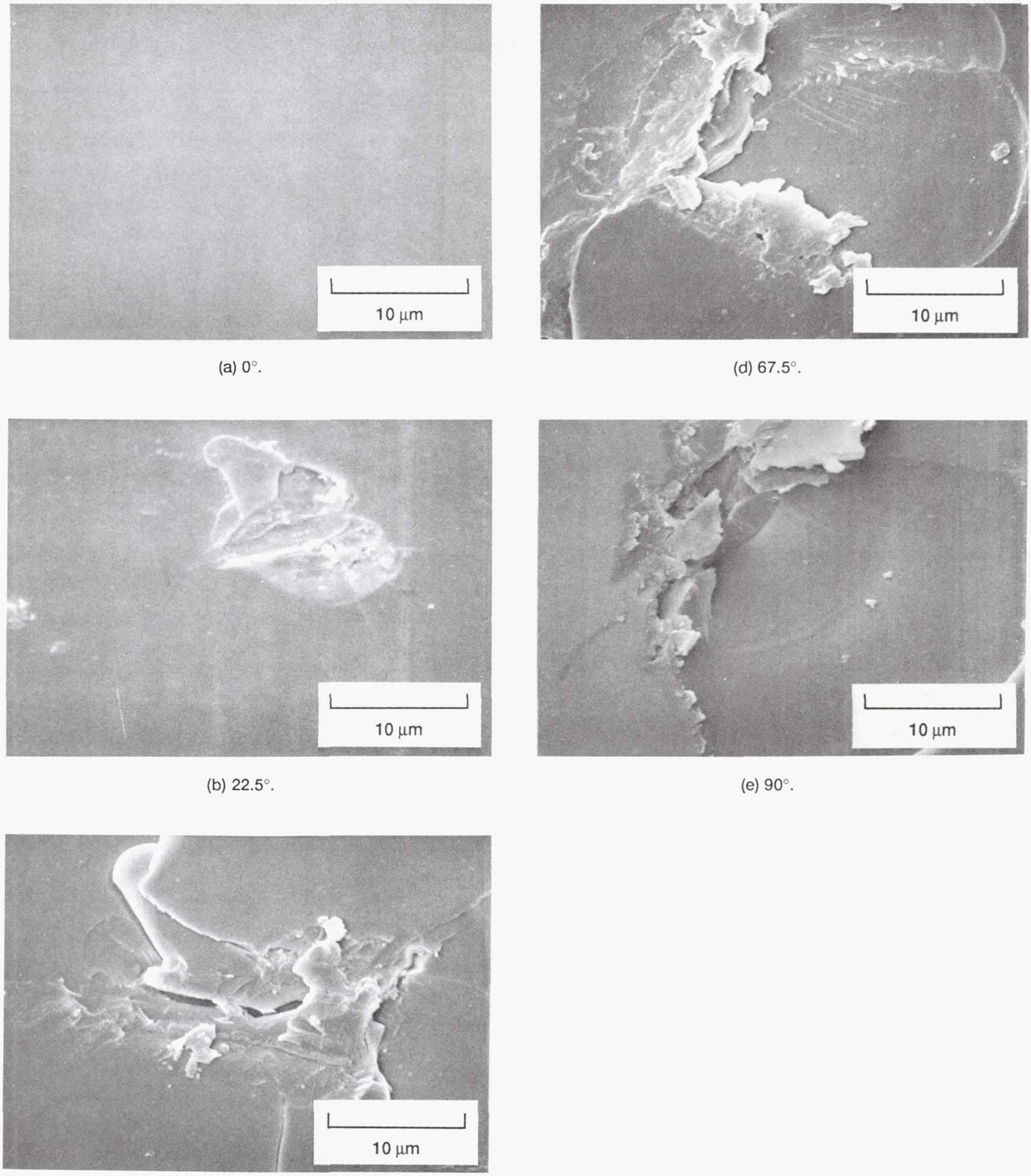


(b) 45°.



(c) 90°.

Figure 3.—Electron photomicrographs of coverslip surfaces which were predusted with 10 μm dust and subjected to 96 m/s clear air attack angles.



(a) 0°.

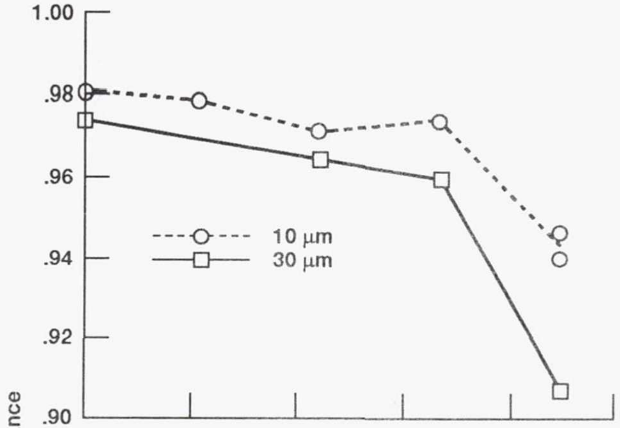
(d) 67.5°.

(b) 22.5°.

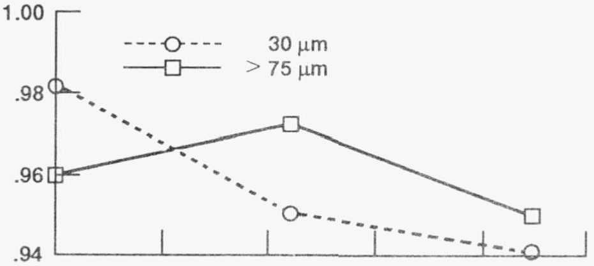
(e) 90°.

(c) 45°.

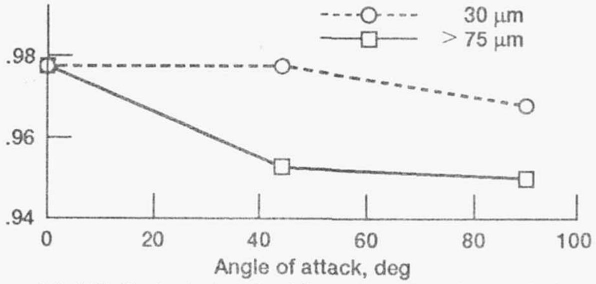
Figure 4.—Electron photomicrographs of coverslip surfaces which were predusted with 10 μm dust and subjected to 96 m/s clear air attack angles.



(a) Initially clear and subjected to 95 m/s clear winds.

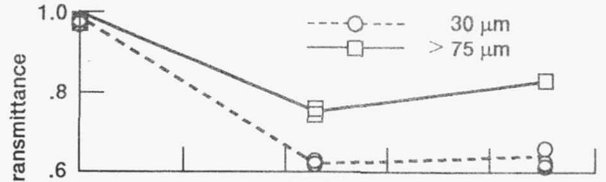


(b) Initially clear and subjected to 100 m/s dust laden winds.

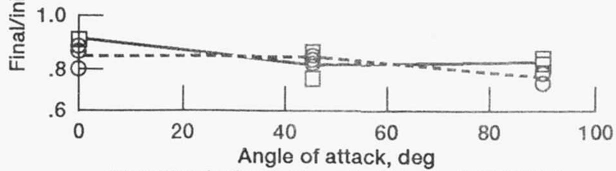


(c) Initially dusted and subjected to 100 m/s dust laden winds in the MARSWIT.

Figure 5.—Abrasion of coverslips.

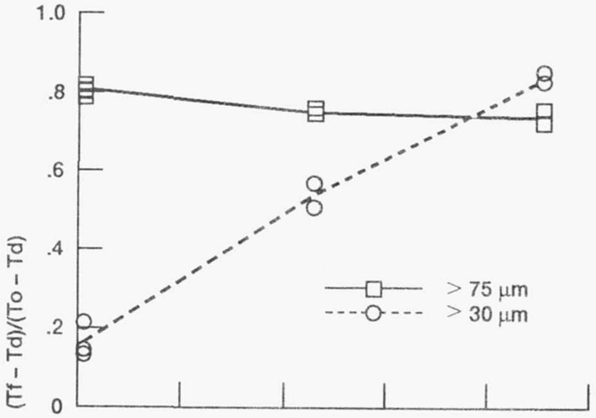


(a) 24 m/s.

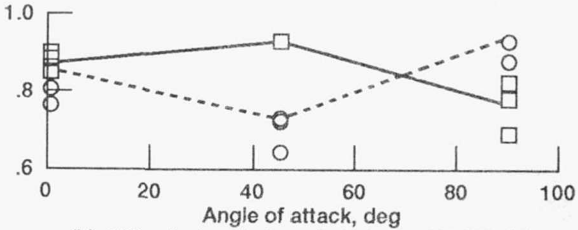


(b) 100 m/s dust laden winds in the MARSWIT.

Figure 6.—Dust accumulation from initially clean samples.



(a) 24 m/s.



(b) 100 m/s dust laden winds in the MARSWIT.

Figure 7.—Dust clearing from initially dusted samples.

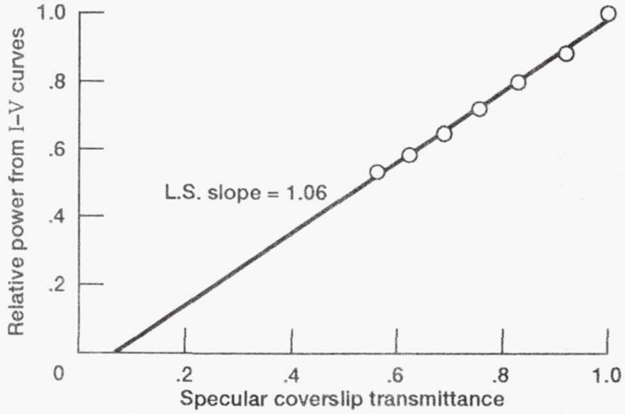


Figure 8.—Relationship between specular coverslip transmittance as measured in this study and PV power calculated from I–V curves on n–doped on p–doped silicon cells at AM0.

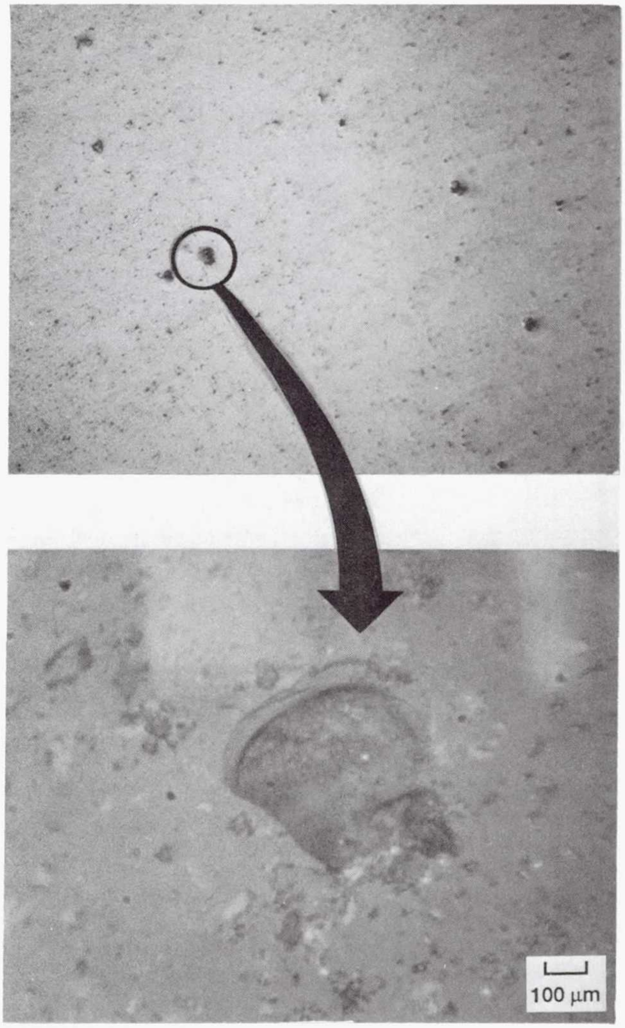


Figure 9.—Electron photomicro-graphs of coverslip surface of a photovoltaic cell which was pre-dusted with 10 μm dust and subjected to 96 m/s clear air attack angle of 45°.

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13. ABSTRACT ***(Maximum 200 words)***

Glass coverglass, and SiO_2 covered and uncovered silicon photovoltaic (PV) cells were subjected to conditions simulating a Martian dust storm, using the Martian Surface Wind Tunnel, to assess the effect of particle size on the performance of PV cells in the Martian environment. The dust used was an artificial mineral of the approximate elemental composition of Martian soil, which was sorted into four different size ranges. Samples were tested both initially clean and initially dusted. The samples were exposed to clear and dust laden winds, with velocities varying from 23 to 116 m/s, and attack angles from 0° to 90°. It was found that transmittance through the coverglass approximates the power produced by a dusty PV cell. Occultation by the dust was found to dominate the performance degradation for wind velocities below 50 m/s, whereas abrasion dominates the degradation at wind velocities above 85 m/s. Occultation is most severe at 0° (parallel to the wind), is less pronounced from 22.5° to 67.5°, and is somewhat larger at 90° (perpendicular to the wind). Abrasion is negligible at 0°, and increases to a maximum at 90°. Occultation is more of a problem with small particles, whereas large particles (unless they are agglomerates) cause more abrasion.

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