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ABSTRACT

Lunar base activity, particularly rocket launch and landing, will suspend and transport lunar dust. From preliminary models, the resulting dust accumulation can be significant, even as far as 2 km from the source. For example, at 2 km approximately 0.28 mg/cm^2 of dust is anticipated to accumulate after only 10 surface missions with a 26,800 N excursion vehicle. The possible associated penalties in photovoltaic array performance were therefore the subject of experimental as well as theoretical investigation.

To evaluate effects of dust accumulation on relative power output, current-voltage characteristics of dust-covered silicon cells were determined under the illumination of a Spectrolab X-25L solar simulator. The dust material used in these experiments was a terrestrial basalt which approximated lunar soil in particle size and composition. Cell short circuit current, an indicator of the penetrating light intensity, was found to decrease exponentially with dust accumulation. This was predicted independently by modeling the light occlusion caused by a growing layer of dust particles. Moreover, the maximum power output of dust-covered cells, derived from the I-V curves, was also found to degrade exponentially. Experimental results are presented and potential implications discussed.

INTRODUCTION

The suspension and transport of lunar dust can occur by many processes. These include natural mechanisms, such as ejection during meteoroid impact (ref. 1-3) and electrostatic levitation (ref. 4-7), as well as mechanisms associated with human activity on the lunar surface (ref. 8). Disturbance can result from any activity, including walking, rover transport, mining/construction, and rocket launch and landing. Once lunar dust is suspended, it follows pure Newtonian motion in the absence of any atmospheric effects, and thus has the ability to travel great distances and accumulate indiscriminately. Vulnerable power system components such as photovoltaic arrays and radiator surfaces may be at risk of performance reductions due to lunar dust accumulation. Therefore the potential effects of dust accumulation on these surfaces may impact future lunar base design and perhaps even advanced component concepts.

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Of all the mechanisms for lunar dust suspension, the launch and landing of lunar excursion vehicles is anticipated to disturb the greatest amount of lunar dust, and transport it the furthest. Therefore an effort was made to assess the amount of dust that may be expected to accumulate as a result of launch and landing, both as a function of distance from the launch pad, and as a function of the number of supply missions from Earth. To generate an understanding of lunar dust transport behavior, available information from the Apollo experiences was collected and analyzed. Particularly important were the clues provided by the Surveyor III, an unmanned lunar exploratory craft which experienced the nearby landing of the Apollo 12 lunar module (LM). The Apollo 12 astronauts returned some of the Surveyor's components for analysis, and it was discovered that significant dust accumulations, directly related to the LM's engine blast, occurred even at a distance of 155 m (ref. 9). In general the craft acquired roughly 1 mg/cm^2 of lunar dust (ref. 10), and some parts collected a layer as thick as 8.7 μm (ref. 11). The investigators who examined the components were able to estimate that the dust was ejected almost horizontally at an average velocity on the order of 40 - 100 m/s, but with some particles travelling as fast as 2000 m/s in order to cause the observed pitting in glass (ref. 9, 12, 13).

Based on this information, a particle velocity distribution was generated for the landing LM. The relationship between velocity and distance was introduced to convert the relative number of particles of a given velocity to the relative number of particles travelling a given distance. The resulting function was integrated over angles from 0° to 1° to produce a lunar particle accumulation distribution for the 13,400 N LM engine. The accumulation distribution was subsequently scaled to a future possible lunar excursion vehicle employing O_2/H_2 propulsion at a thrust of 26,800 N. As the thrust is doubled, particles attain twice the distance and the number of particles disturbed (flux) is squared. Finally, assuming that the dust trajectories resulting from launch are equivalent to those from landing, and assuming that two service or supply missions are required each year during normal lunar base operations, the anticipated dust accumulations with time were determined for various distances from the landing site (see Figure 1). By this optimistic model, surfaces within 1000 m can be expected to acquire accumulations in excess of 2 mg/cm^2 after 10 missions (5 years). At 2 km, cells would collect 0.28 mg/cm^2 over the same time period. The development of this model is described in more detail in Reference 8.

To address the potential implications of this level of lunar dust accumulation on a photovoltaic array, a light occlusion model was developed. This model was generated by incorporating particle overlap probabilities and particle optical absorption to calculate the attenuation of light by a growing layer of dust. The reduced light intensity into a cell is associated with a reduction in relative short circuit current, which is in turn an indicator of relative cell power reductions. The preliminary occlusion model was based on a fixed particle size and shape, and was confirmed by laboratory measurement of the transmittance of dust-covered glass coverslips under the illumination of a tungsten filament light source. The lunar dust simulant used in these experiments, "Minnesota Lunar Simulant-1," or MLS-1, is a basaltic material mined from a quarry in Duluth, MN, for its close compositional match to the material from the lunar lowlands, or "maria." Both the occlusion model and the experiments showed an exponential decay in relative transmittance, and therefore relative cell power, with lunar dust accumulation (see Figure 2). The model was then generalized to describe the occlusion caused by a continuous distribution of particle sizes, more representative of lunar soil. Two particle morphologies were considered: spherical and cubic. The predicted decay in relative transmittance with increasing dust accumulation is shown in Figure 3. As expected, particles with a greater surface area-to-volume ratio are more mass-efficient at light attenuation. Lunar particle morphologies have been observed to vary from spherical to very highly pocketed and irregular due to the unusual erosion processes on the moon. Therefore, the curve representing actual lunar soil is likely to fall below that for cubic particles. The evolution of the occlusion model is described in Reference 8.

The predicted relative transmittance for cubic particles was combined with the anticipated launch/landing-related dust accumulation described above to estimate the amount of solar power incident upon a photovoltaic array as a function of time for arrays located at various distances from the landing site. The predicted reduction in available solar power relative to that for a dust-free cell is shown in Figure 4. It can be seen that over 5 years the dust coverage attenuates more than 10 % of the solar intensity at 2000 m, and more than 60 % at 1000 m. Arrays within 500 m will experience a 50 % reduction in available solar power in one year. It is important to note that these estimates do not include to dust suspended from the host of other sources. As the lunar base is expected to survive 30 years of operation, it is clear that the issue of lunar dust management must receive attention during the design stages.

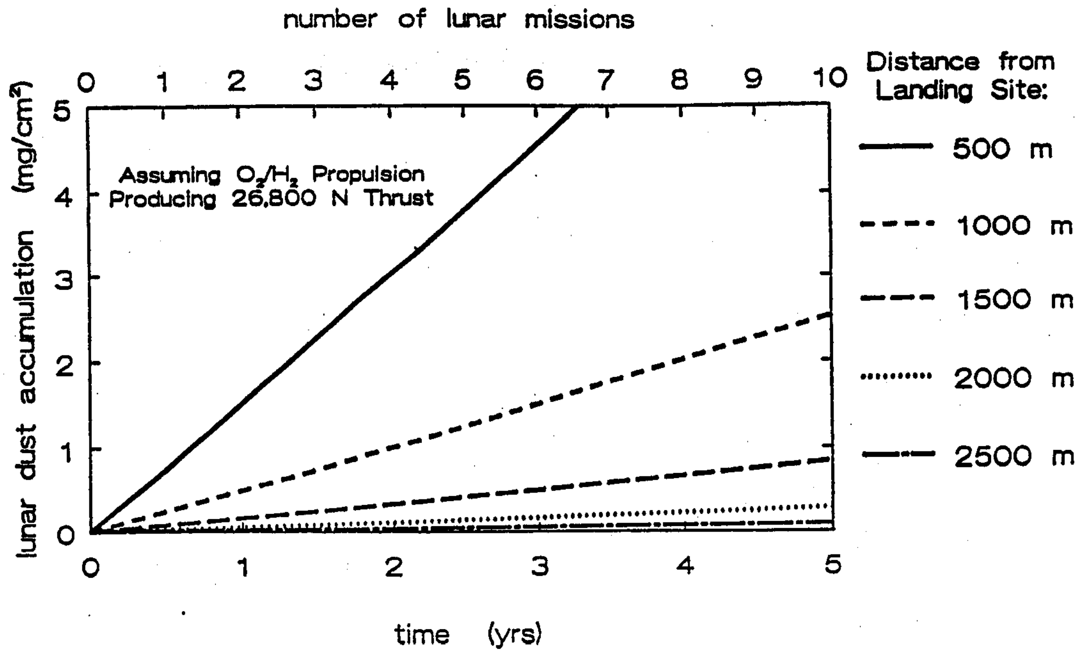

Figure 1. Predicted lunar dust accumulation distribution resulting from launch and landing of a 26,800 N lunar excursion vehicle as a function of time for different distances from the landing site.

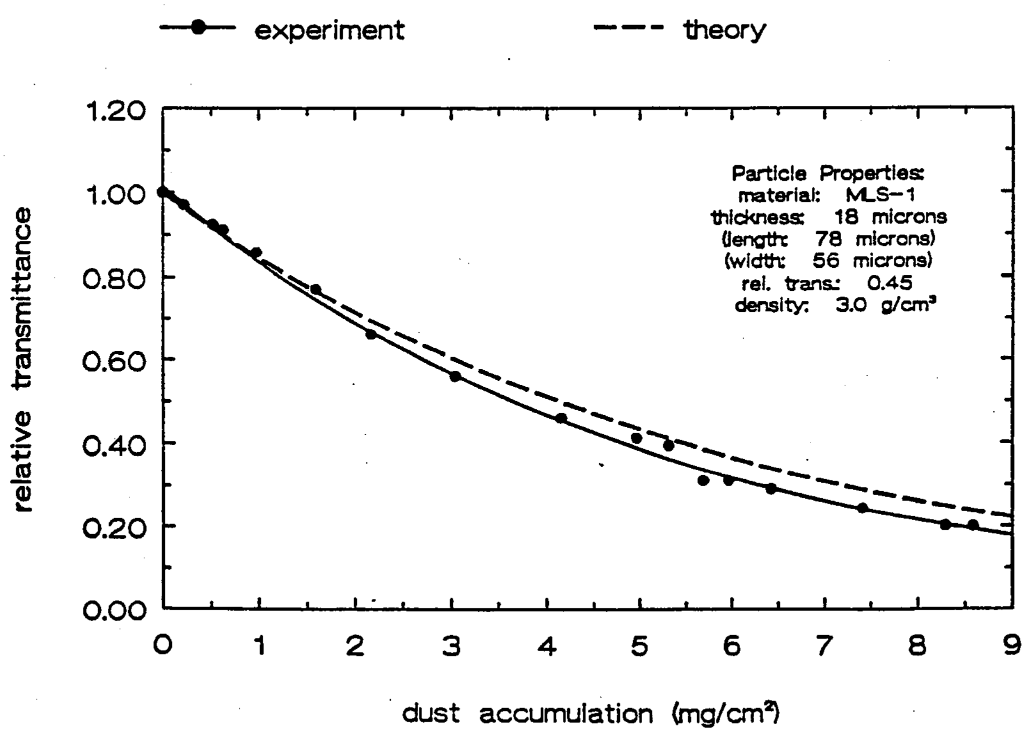

Figure 2. Transmittance of a glass coverslip with varying amounts of dust. Theory and experiment are compared for a specific particle size and shape.

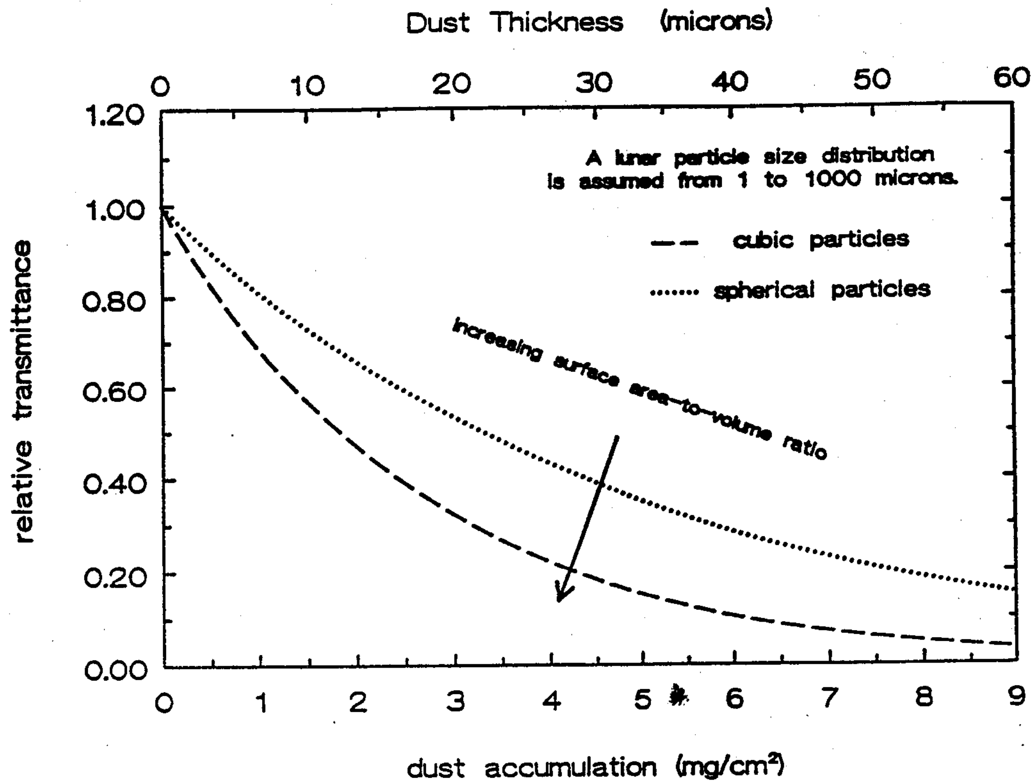

Figure 3. Predicted transmittance of a glass coverslip with varying amounts of dust which includes the range of particle sizes found in lunar dust. Spherical and cubic particles are compared.

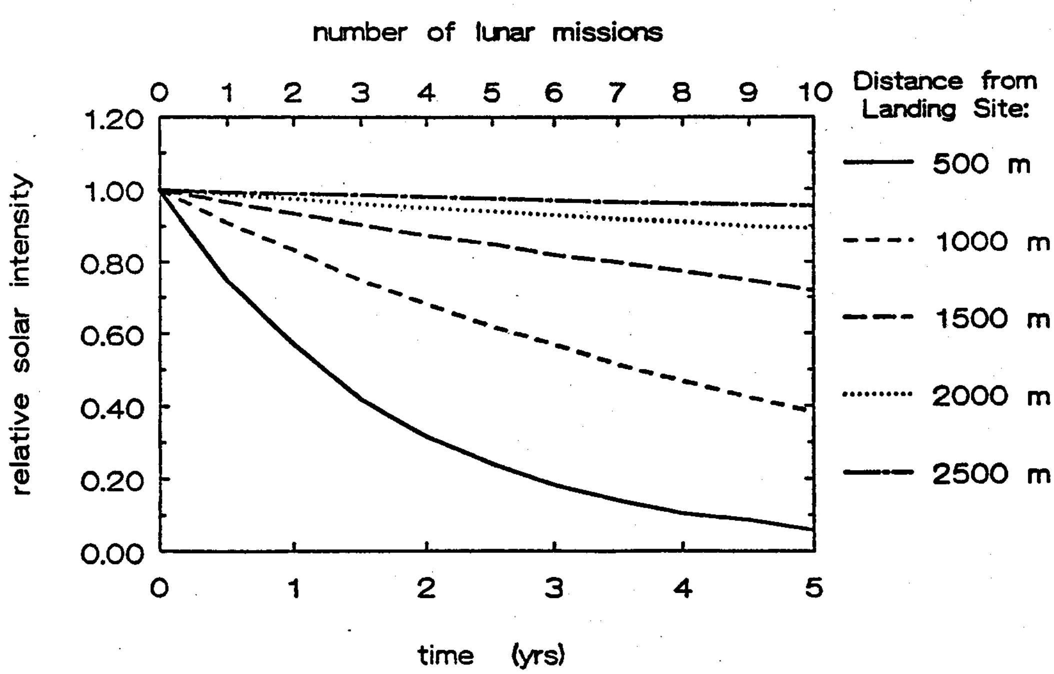

Figure 4. Predicted temporal dependence of relative solar intensity entering solar cells due to accumulated dust resulting from the launch and landing of 26,800 N lunar supply vehicles.

I-V CURVES OF DUST-COVERED CELLS

In order to more directly determine the effects of dust accumulation on the power output of photovoltaic arrays, current-voltage characteristics were measured for solar cells covered with differing amounts of dust. Small silicon space solar cells (2x4 cm^2) were used so that the mass of applied dust would be detectable by means of a Sartorius microbalance. The cells, provided by Applied Solar Energy Corporation, had antireflective coatings, fused silica coverslips bonded with Dow-Corning 93-500 adhesive, and ultraviolet filters.

The illuminated cell characteristics were measured prior to and after dusting in a Spectrolab X-25L xenon arc solar simulator. Air mass zero calibration was assured by the use of an aircraft calibrated silicon reference standard.

The dust material, MLS-1, was ground and dry-sieved with stainless steel mesh. The sieve fraction used in these experiments was collected between 20 μm and 38 μm meshes, but it was observed that the diagonal dimension of the mesh openings allowed passage of somewhat larger particles. In addition, very fine particles were present due to electrostatic effects created during sieving. The charge was allowed several weeks to drain, and the dust material was held at 200 °C when not in use in order to eliminate the clumping effects of moisture.

Dust layers were applied to the cells by a simple sedimentation procedure which produced homogeneous sub-monolayers of simulant particles with a minimum of clumping. Before and after dusting, each cell was weighed and the complete I-V curve was measured, proceeding from open-circuit voltage to short circuit current, with computer-controlled increments in voltage. Short circuit current and maximum power for each cell were determined from the I-V curves.

RESULTS AND DISCUSSION

While the occlusion model and measured transmittance of coverslips provide a useful estimation of the effects of dust, the I-V curves directly demonstrate the impact of dust accumulation on photovoltaic array performance. Cell short circuit current more accurately represents the exponential decrease in light intensity penetrating the cell. As can be seen in Figure 5, a difference exists between the measured relative transmittance of glass coverslips with MLS-1 of 20-38 μm and the relative short circuit current of cells with the same type and amount of dust. The difference would indicate that in fact more light enters the cell than suggested by tungsten source transmittance measurements. This is thought to be attributable to spectral differences in the light sources; the xenon arc source provides wavelengths in the blue-ultraviolet end of the spectrum which are not represented in tungsten illumination. The results suggest that these short wavelengths are not as significantly absorbed or reflected by the lunar simulant particles, as are the redder wavelengths. An evaluation of the spectral absorption of both the simulant and actual lunar dust, as well as the spectral response of the cells, may elucidate these subtleties. Other factors which may also be involved include cell optics and illumination intensity.

It is possible to adjust the optical absorption coefficient used in the occlusion model to more closely match the model to the observed change in relative short circuit current (See Figure 5). Ideally, the best correction would incorporate the spectral properties of both cell and dust, which is beyond the scope of this paper. The improvements, however, would not significantly affect the predictions of Figure 4.

The I-V curves also allow direct observation of the exponential decay in relative maximum cell power as a function of dust accumulation for the specific silicon cells used (Figure 6). The data show that an accumulation of 5 mg/cm^2 of MLS-1 in the size range 20-38 μm will reduce power output to less than 40 %. Smaller particles, such as those most readily disturbed and transported in the lunar environment, would be expected to cause greater reductions because dust monolayer coverage can be achieved at a lower mass per unit area with smaller particles.

Unfortunately, once lunar dust has accumulated it may be very difficult to remove. According to Apollo observations, lunar dust adhesive forces are very strong (0.01 to 0.1 N/cm^2 (ref. 9)), dominated by electrostatics with van der Waals contributions. Dust removal may be labor-intensive and at best only partially successful. Therefore, a defensive position is recommended to prevent array surfaces from collecting dust. The location and placement of

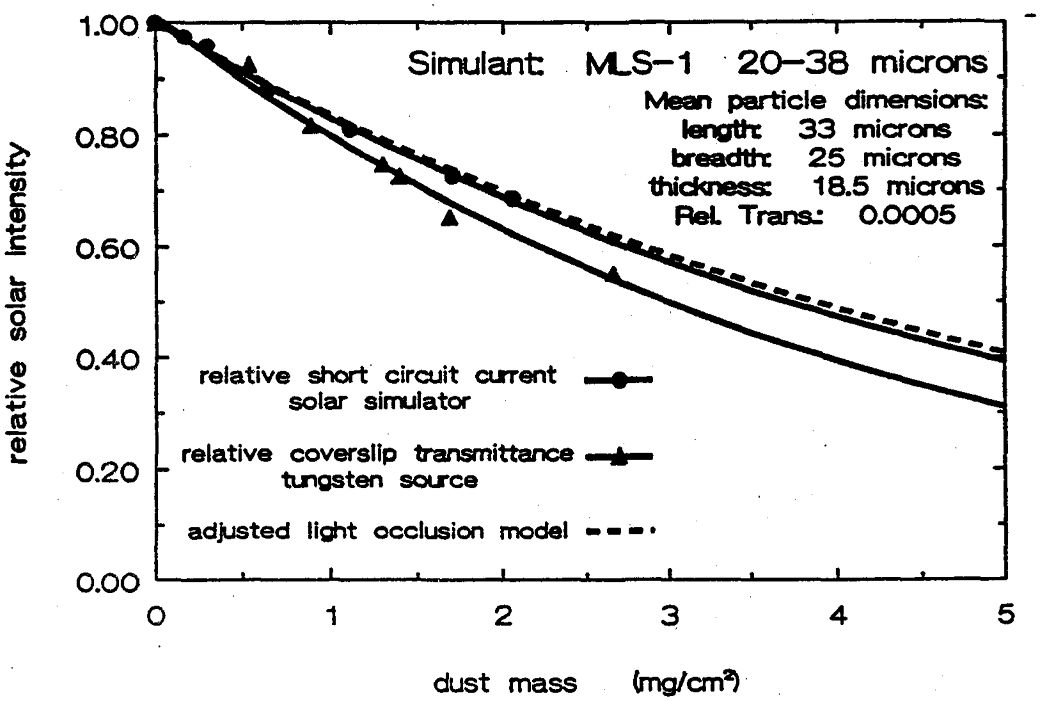

Figure 5. Relative light intensity entering a solar cell through an accumulation of dust, as predicted by three methods: relative short circuit current measurements of dusted cells under simulated solar illumination, relative transmittance measurements of dusted coverslips under tungsten illumination, and predictions of a light occlusion model.

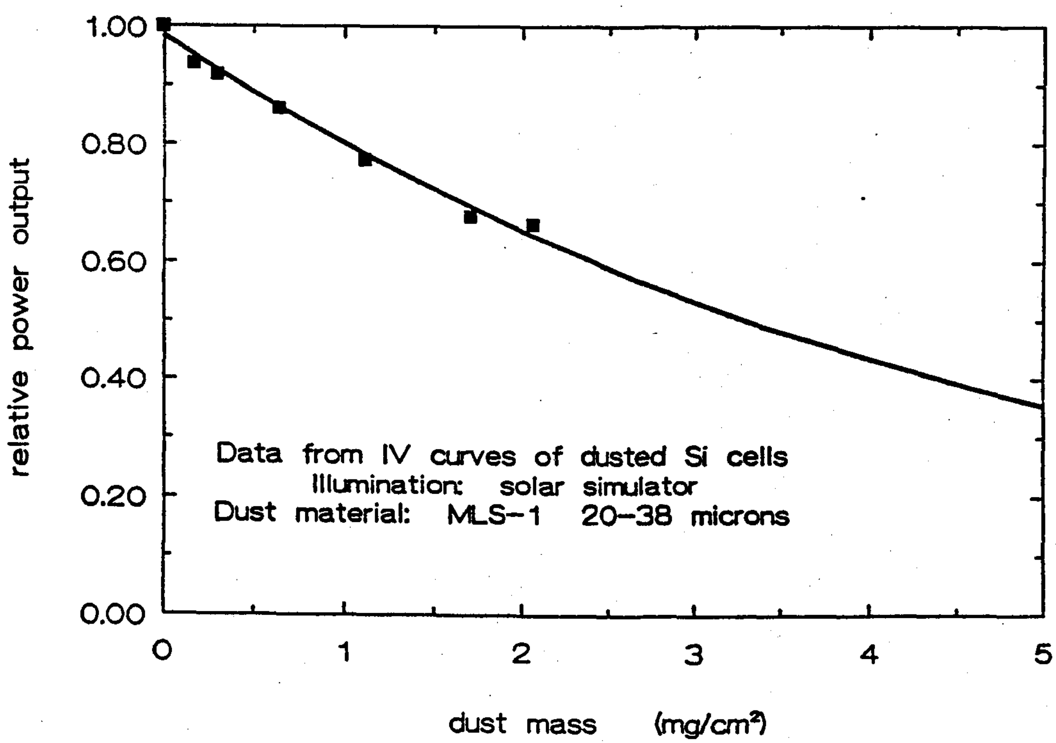

Figure 6. Relative power output as determined from the IV curves of dust-covered silicon cells.

arrays at a lunar base with respect to launch pads and other major sources of suspended dust is an important consideration. Advanced array design concepts may be found which incorporate array materials, operating voltages, or mounting arrangements to reduce the tendencies for particles to collect. However, these may not be enough to eliminate dust accumulation. Unless it becomes feasible for arrays to be compensationally oversized, it is likely that additional strategies must be implemented to reduce the amount of dust generated. These might include glazing launch pad areas, refining rocket approach patterns, improving rover fenders, laying packed-earth roads, restricting traffic in array zones, and even improving space suit mobility. Moreover, supplementary measures, such as mechanical or electrostatic fences, may be necessary to divert the dust that is inevitably suspended from accumulating on important surfaces.

CONCLUSIONS

Lunar dust accumulations resulting from the launch and landing of a 26,800 N surface vehicle have been anticipated, using available Surveyor III data. Substantial dust accumulations are predicted for surfaces within a 2 km radius of the landing site over a 5 year period. Therefore, the impact of dust accumulation on the performance of photovoltaic arrays has been addressed both theoretically and experimentally; both a light occlusion model and transmittance measurements indicate that the attenuation of light by dust accumulations at 1 km may be in excess of 60 %, and at 2 km more than 10 % after 10 surface missions.

Relative cell short circuit current changes derived from I-V measurements confirmed the predictions of the light occlusion model and transmittance measurements: an exponential decay in solar intensity results from the accumulation of dust particles. However, the relative short circuit current data suggests that solar ultraviolet is not as significantly attenuated by the dust simulant as the visible wavelengths produced by a tungsten source, and therefore indicates a more gradual exponential decay than predicted by the model or transmittance data.

Cell power output was directly determined from the I-V curves of silicon space cells covered with MLS-1 particles in the 20-38 μm size range. This also degrades exponentially with dust accumulation such that 50 % reductions result when accumulations reach 3 mg/cm^2. As actual accumulations of lunar dust will likely be comprised of even smaller particles, power output is expected to degrade more dramatically.

The findings of this investigation indicate that the performance of photovoltaic arrays on a lunar base is so threatened by the potential accumulation of lunar dust that measures must be incorporated into design to minimize degradation. As lunar dust adhesive forces have been observed by Apollo astronauts to be very strong, driven by electrostatic as well as van der Waals forces, dust removal appears to be a difficult solution. Instead, a preventative strategy is recommended to protect vulnerable surfaces such as photovoltaic arrays from ever acquiring enough dust to significantly affect performance. Such measures might include special attention to array orientation and location on a lunar base, as well as improved rover fenders, glazed launch pads, and perhaps even electrostatic fences.

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