MEASURING DIRT ON PHOTOVOLTAIC MODULES

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Abstract

Soil accumulation has been the most significant factor in the degradation of the output power of photovoltaic modules used in experimental solar power generating systems. One method of measuring dirt accumulation and the subsequent power loss is to return photovoltaic modules to the laboratory for thorough examination. This paper describes the use of a Glossmeter as a practical alternative to laboratory examination in making quantitative measurements of dirt accumulation on PV modules. Of particular value for in-situ measurements, this instrument has been used successfully to monitor dirt build-up on the front surfaces of several types of modules before and after cleaning. Surface gloss has been correlated with peak power and short-circuit current. It has also been used as an indication of the extent of dirt accumulation and the effectiveness of a cleaning process. Data obtained from Glossmeter readings taken on photovoltaic modules with over a year's exposure at photovoltaic field test sites in Nebraska; New York City; and MIT, Cambridge, are presented.

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MEASURING DIRT ON PHOTOVOLTAIC MODULES

I. INTRODUCTION

As part of the Department of Energy's Photovoltaic Program, MIT/Lincoln Laboratory serves as a Field Tests and Applications Center to evaluate the performance of photovoltaic power systems in various terrestrial applications. Photovoltaic (PV) modules, each containing 20 to 120 electrically connected silicon solar cells, have been assembled into arrays and installed in urban, suburban, agricultural and rural areas in a wide variety of environments. At each site the effects of exposure time on the durability and electrical behavior of these modules are being determined. In 18 months of testing, the most significant factor in the degradation of module performance has been power loss due to dirt accumulation.

The purpose of this report is to detail the use of a Glossmeter in measuring the effects of dirt accumulation on photovoltaic modules in the field and in the Laboratory.

II. MEASURING POWER OUTPUT OF PV MODULES IN THE LABORATORY

Within minutes of installation, the front surface of a PV module begins to accumulate airborne dirt particles. These particles continue to accumulate as part of the normal weathering process and eventually cut down the amount of solar radiation impinging on the solar cells, thereby reducing power output. The customary procedure used for quantitatively measuring the subsequent extent of power degradation is to return the weathered PV module to the Laboratory for thorough macro- and micro-examination. Under precise conditions (28°C , 100 mw/cm^2), the PV module is "flashed" in a solar simulator in the "as removed" dirty state, then cleaned and reflashed.

The device used to "flash" modules at MIT/LL is a Spectrolab Large Area Pulsed Solar Simulator (LAPSS) which emits a light pulse of millisecond duration that simulates solar radiation at Air Mass 1.5. Because of this short interval of illumination, there is no heat buildup in the module, which would lower its output.

Fig. 1. Glossmeter.

The data acquisition system of the LAPSS generates a current-voltage curve (IV curve) which can be used to determine the short-circuit current, I_{sc} , and the peak power, PP, of a module. These parameters are used to quantify the electrical characteristics of each module in the dirty and clean conditions. The I_{sc} is the current at zero voltage. The PP is the

maximum product of the current and voltage in watts as determined from the IV curve. Since returning modules to the Laboratory for this type of evaluation is expensive and time-consuming, there is a need for a technique that would quantify the effects of dirt in the field. In the following sections the materials used for encapsulating PV modules are described, as well as a simple field technique to "measure" surface dirt on them.

III. SOLAR CELL ENCAPSULATION MATERIALS FOR PV MODULES

Two types of front surface coverings are used to protect solar cells in current PV modules, i.e., glass and RTV silicone rubber. For both types, the silicon solar cells are normally encapsulated in a transparent elastomeric material, usually RTV silicone, to minimize the effect of thermal mismatch between the thin brittle silicon cells and the tray supporting the cells (substrate). Of the two types of front surfaces, the RTV silicone tends to retain more dirt and is more difficult to clean after several months in the field. It was found that a Glossmeter is a convenient tool for quantifying dirt buildup on both types of front surfaces.

IV. THE GLOSSMETER

The Glossmeter is a portable optical measuring instrument which has been used for many years by paint chemists to evaluate the surface shine and gloss of their formulations¹. Its use has been standardized by several ASTM documents². It consists of a collimated light source, a photocell at the specular angle, and a 100-division scale as shown in Figure 1. Each unit of this scale is called a "g".

Calibration is provided by the manufacturer with two secondary standards: a shiny black tile for which the Glossmeter is adjusted to a value of 92 g's, and a white diffuse tile for which the glossmeter is adjusted to a reading of 45 g's. The sensitivity of the Glossmeter is such that particles as small as 1 micron cause scattering of the collimated light reflection and cause deflections of the meter.

Glossmeters are commercially available at more than one angle of illumination³. The proper angle is contingent on the quality of the surface under investigation. Three angles were evaluated in this study, namely:

<u>Illumination Angle</u>	<u>Recommended Usage</u>
20°	High-Gloss
45°	Low-Gloss
60°	Intermediate

The 20° Glossmeter (Gardner model #GG7220A) was found to be the most appropriate because the module surfaces on both the glass and RTV-covered types are quite shiny.

The Glossmeter measurement procedure consists of taking 10 readings randomly over the individual silicon solar cells in a module. The average gloss of new, clean RTV-encapsulated modules is 50-70 g's while for smooth glass-covered modules the average is 75-90 g's. Gloss readings of dirty RTV-covered modules have been measured as low as 5-30 g's, whereas for glass modules the low readings are rarely less than 60-65 g's.

V. LOCATION OF MIT/LL FIELD TEST SITES

The Glossmeter data presented in this report have been obtained from modules which were located at three test sites: (1) University of Nebraska Field Station at Mead, Nebraska; (2) New York and Columbia Universities in New York City; and (3) MIT in Cambridge, Massachusetts. The Mead site is one of several experimental System Test Facilities operated by MIT/LL for DOE. It consists of a 25-kw array field containing 2240 modules, as well as power conditioning, control and storage systems. It is used to provide electrical power for corn irrigation and crop drying. The latter two are small environmental test installations on the roofs of buildings at each school. Each of these sites contains at least three pairs of modules from several vendors.

Photographs of the Mead installation and the NYU test site are shown in Figures 2 and 3.

Fig. 2. 25-kw array at Mead, Nebraska.

Fig. 3. Urban New York City test site.

VI. FIELD DATA - MEAD, NEBRASKA

The Nebraska installation (which was the largest PV power system in the world at the time of its inception in July 1977) has had the most careful and frequent attention. Electrical data and Glossmeter readings for a number of PV modules which were returned to Lincoln Laboratory at various intervals are shown in Table I. None of these returned modules had received any field cleaning prior to removal.

In the first column, the field exposure time in months is listed. In the second column, the vendor's code name is listed and the number of modules sampled is placed in parenthesis. In columns 3 and 4 the Glossmeter readings are listed in g units. It can be seen that the "dirty" g readings steadily decreased until the dirt saturated after 12 to 14 months with low values of 4 to 5 g's.

In column 4, the "clean" Glossmeter readings are listed. After cleaning modules with nine months of field service, the gloss readings increased to just over 50 g's. However, after one year the dirt became extremely difficult to remove by standard cleaning methods and the 12-month clean values are only 32 to 40 g's. The 14-month values of 44 to 49 g's are misleading because these modules were cleaned using special techniques. Prior to using these techniques, the cleaned modules were also in the 30 to 40 g range (this will be discussed further in the section on 'Cleaning PV Modules').

TABLE I
AGRICULTURAL EXPERIENCE - NEBRASKA

Columns					
1	2	3	4	5	6
Exposure Time(mos.)	Module (Type + Qty.)	Glossmeter Readings Dirty Clean (g units)		%PP* Loss	%I _{sc} Loss
3	A (12)	33	53	3.8	5
	B (16)	28	51	--	--
7	A (12)	17	57	7.2	--
	B (21)	11	53	4.3	--
9	A (12)	17	52	5.0	5.2
	B (14)	12	49	6.6	5.6
12	A (12)	5	32	8.8	8.2
	B (28)	4	40	9.1	10.4
14	A (16)	4	44	14.6	13.4
	B (31)	4	49	12.1	12.0

$$* \% PP_{loss} = \frac{PP_{clean} - PP_{dirty}}{PP_{clean}} \times 100$$

In column 5, the peak power (PP), i.e., the maximum product of current and voltage, has been computed for both the dirty and clean states and the percentage difference between the clean and dirty states has been presented. In this experiment, there have been no significant differences between decreases in PP and I_{sc} due to dirt accumulation.

There was an excessive amount of rain at the time the 9-month data were obtained and, as a result, the percent changes in PP and short-circuit current both decreased from the 7-month values. A plot of gloss readings as a function of peak power loss due to dirt is given in Figure 4. A linear relationship was found when logarithmic scales were used to plot the data. Decreases in gloss clearly lead to decreases in power (additional information is given under the section on 'Urban Sites - New York City').

Fig. 4. % PP loss vs. Glossmeter readings.

VII. URBAN SITE - MIT, CAMBRIDGE, ROOF

In contrast to the rural farm land environment of Mead, Nebraska, an experiment was initiated in the urban, industrial environment of MIT in Cambridge, Massachusetts. At this experimental rooftop installation, two modules from each of four vendors were exposed to the elements. These consisted of modules covered with glass, a hard-coated RTV, and two kinds of RTV. The soil accumulation data obtained from the MIT Cambridge Urban Test Site is summarized in Table II.

TABLE II
URBAN DATA, M.I.T., CAMBRIDGE, ROOFTOP

Exposure Time(mos.)	Module Type	Glossmeter Readings			%PP Loss *
		Dirty	Clean	New	
6 (7/77-1/78)	A (RTV)	22	56	62	14.2
	B (RTV)	21	45	54	13.2
	C (Glass)	81	93	84	6.1
	D (RTV + Hardcoat)	38	62	67	10.8
6 (2/78-8/78)	A	11	40	62	13.1
	B	10	37	54	14.6
	C	77	94	84	2.1
	D	30	60	67	3.9
12 (7/77-8/78)	A	7	39	57	18.7
	B	6	32	60	17.8
	C	66	85	76	3.4
	D	24	61	67	7.3

* Dirty to Clean

After the first six months of exposure, cleaning of the RTV-covered modules returned the gloss readings to within 6-9 g's of the initial readings. Cleaning the RTV-hardcoat module returned it to within 5 g's of the initial reading. Cleaning the glass-covered module increased the gloss to a value 9 g's greater than the initial value. This indicates that the module already had a dirt film prior to installation.

Cleaning the two plain RTV-covered modules after the first six months of exposure restored them to nearly the original gloss condition, 45-60 g's. However, the cleaning after the second six months was ineffective because of the tenacity of the dirt and produced low "clean" g values of only 37-40.

During this second six-month period, the model B panels exhibited a lower "dirty" g value of 10 as compared to a "dirty" g value of 21 for the first six months. The additional dirt showed up as a corresponding loss in PP, i.e., 14.5% as compared to 13.2% during the first period.

The glass did not accumulate a significant amount of dirt. After twelve months, the initial 76 g's was reduced to 66 g's and the resulting percentage PP decrease was 3%. After cleaning, the gloss was higher than the original value, indicating an initial dirt film. For this urban environment, use of a hardcoat over the RTV appears to offer a better self-cleaning surface than use of RTV alone. After six months, the power loss was 11% for the hardcoated model D as compared to 13-14% for RTV-covered models A and B. After 12 months, the power loss was 7% compared to about 18% for the plain RTV-covered modules. Cleaning the model D hardcoated surface after one year of exposure returned the surface g value to within 6 g's of the original 67 g value. This was consistent for all the periods studied. The reduced values may be due to scratching of the hardcoat during the cleaning process.

VIII. URBAN SITES - NEW YORK CITY

At both the Columbia and New York University rooftop environmental test sites, the output of PV modules showed a greater reduction due to soil accumulation than was the case at the previously mentioned sites. Gloss and % PP losses are presented in Tables III-A and -B.

Two observations can be made from Table III-A. First, thoroughly cleaned RTV-covered modules should have gloss values between 50 and 60 g's;

TABLE III-A
URBAN DATA, N.Y.C.

NYC Modules	Glossmeter Readings			%PP Loss*
	Dirty	Clean	New	
<u>RTV Type</u>				
A(2) (6 months)	9	41	62	27
A(2) (1 year)	4	30	62	38
B(2) (6 months)	7	26	54	27
B(2) (1 year)	4	24	54	31
<u>Glass Type</u>				
C(2) (6 months)	37	88	84	10

*Clean to Dirty

TABLE III-B
URBAN DATA, N.Y.C.

N.Y.C. 6-MONTH EXPOSURE -- 6/78 to 12/78									
Module Type	History	Gloss		First Clean		Second Clean		Third Clean	
		Initial 6/78	Dirty 12/78	Gloss	%PP Loss	Gloss	%PP Loss	Gloss	%PP Loss
A (RTV)	Initial Exposure	57	12	33	21	40	24.4	54	24.5
B (RTV)	Initial Exposure	46	18	40	14.2	58	14.4	61	19.5
C Glass	Prev. Exp. 6 mos.	85	59	91	5.7	92	7.2	92	7.1
D Hard-coat	Initial Exposure	61	23	59	15.8	59*	14	56	16.9

*No pumice used; scratch sensitive

First Clean - Hot H₂O + Alconox (A)

Second Clean - Hot H₂O + A + Pumice (P)

Third Clean - Isopropyl Alcohol

however, values between 24 and 41 g's were obtained for modules A and B, indicating ineffective cleaning. Secondly, low dirty gloss readings in NYC which are similar to readings at other sites give rise to higher losses in peak power. This is evident in Figure 4 where loss in peak power is plotted as a function of gloss for NYC as well as Nebraska. Where $g = 4$ in Nebraska, the % PP loss was about 14% whereas in NYC it was over 30%. This indicates that the types of dirt particles in NYC may be more opaque to sunlight than those in Nebraska. The output of the Glossmeter is a function of the number and size of particles rather than their transmissivity to light. In the same way that power loss due to soil accumulation is site dependent, the relationship of gloss to power loss is also site dependent.

More recent data from the NYC test site is shown in Table III-B. During this six-month interval, the modules did not get as dirty as during the six-month interval reported in Table III-A. During the latter period, the dirty gloss readings for plain RTV-covered modules was 7-9 g's and the power loss was 27%. During the former period, similar modules had dirty gloss readings of 12 to 18 g's with an accompanying power loss of only 14-21%. This "reduced dirt accumulation" is due to either more frequent rain or a change in air contamination levels. The use of special cleaning techniques to further improve the output and gloss of these modules is described in the next section.

IX. CLEANING PV MODULES

RTV-covered PV modules which have been in the field longer than nine months to a year become very difficult to clean using only a solution of cold water and a laboratory detergent, Alconox, the normal cleaning agent. The dirt particles appear to become impregnated into the RTV surface.

It is surmised that within the exposure time, the sun's ultraviolet energy and the dirt catalyst have converted a migrating, low-molecular-weight ingredient in the RTV silicone encapsulant into a tenacious dirt film. RTV silicones have high vacuum outgassing characteristics (almost 2% by weight loss in 24 hours at 10^{-5} Torr at 120°C).⁴ In a field environ-

ment, these low-molecular-weight silicon compounds migrate⁵ rather than volatilize. They capture the dirt particles and become polymerized by the dirt and solar radiation. This film is extremely difficult to remove by standard washing.

A cleaning experiment was performed with Nebraska modules which had been exposed for 14 months. Glossmeter and field observations indicated that these modules, which were RTV covered, did not clean well (see Table IV). The g value after field cleaning was only 18. Pumice, which is used in the cosmetic industry for removing rough skin, was utilized as a cleaning aid. The use of harsher solvents or cleaning agents was not considered because of possible harmful side effects, such as silicone encapsulant delamination. The results of field cleaning, conventional lab cleaning and pumice cleaning are shown in Table IV. Six modules were removed from Nebraska after field cleaning with cold water and Alconox. Five of these were cleaned with hot water and Alconox and the gloss improved from 18 to 38 g's. The sixth module was cleaned with hot water, Alconox and pumice and the gloss improved further to 55 g's. It is shown in Table V that the use of pumice provided an improvement in PP of about 1.5% for Nebraska modules washed with hot water and Alconox only.

TABLE IV
GLOSS OF VARIOUS CLEANING TECHNIQUES
ON RTV-COVERED MODULES

Modules	Glossmeter Readings	Condition
6	18	Nebraska Field Cleaned Cold H ₂ O and Alconox (A)
5	38	Lab Cleaned, Hot H ₂ O + A
1 (of 6 above)	55	Lab Cleaned, Hot H ₂ O, A, plus Pumice

TABLE V
THE EFFECT OF CLEANING WITH PUMICE

Modules	Glossmeter Readings		% PP Loss	Condition
	Dirty	Clean		
B(7)	6	43	9.4	Hot H ₂ O + A
B(7)		52	10.9	Hot H ₂ O + A plus Pumice

A similar experiment was performed with the NYU modules exposed from 6/78 to 12/78, as shown in the right-hand side of Table III-B. Each module was first cleaned with Alconox and hot water only. Cleaning was repeated with the addition of pumice (except where it might scratch the hard-coat). For RTV-hardcoat and glass, one cleaning with hot water was sufficient to return the initial gloss. For plain RTV, two cleanings still could not remove the dirt and a third wash with isopropyl alcohol was necessary. For the type A module, a final gloss of 54 g's was achieved compared to the initial value of 57 g's. For type B, the second cleaning improved the gloss to 58 g's or 12 units higher than the initial "clean" value. This indicates the presence of a dirt film prior to installation. Use of alcohol further increased the gloss to 61 g's.

The progress made with each cleaning process is shown in Table III-B. The increase in power gained by further cleaning illustrates the need for some indication that a module is indeed clean. The surface gloss before and after exposure serves as such an indicator.

X. CONCLUSIONS

The soil accumulation and module cleaning experiments performed by MIT/LL for the DOE Photovoltaic Program during the past 18 months lead to the following conclusions:

- (1) The Glossmeter can be used to assign a quantitative value to the amount of soil accumulated on a PV module's surface. These measurements can be correlated with either short-circuit current (I_{sc}) or peak power (PP). The correlations are site dependent as shown in Figure 4. Even though the gloss of two dirty modules from different sites is the same, the loss in peak power may be quite different.
- (2) The Glossmeter can be used to establish the quantitative efficiency of a cleaning procedure. The effectiveness of various PV module washing operations can be judged by determining how close the gloss readings are to the original readings taken prior to field installation.
- (3) Glossmeter readings have the potential to provide a measure of the extent of surface erosion on a module's front surface over a period of years.
- (4) More work still needs to be performed over large statistical samplings of modules from various sites to better correlate loss in gloss with loss in peak power and the effect of dirt particle size and type.

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