Indoor Soil Deposition Chamber
Evaluating Effectiveness of Antisoiling Coatings

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Indoor Soil Deposition Chamber: Evaluating Effectiveness of Antisoiling Coatings

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Abstract—An indoor soil deposition method has been developed to simulate natural soil deposition on glass coupons or one-cell and multicell photovoltaic (PV) modules. This method uses variable ambient humidity, coupon/module temperature, and dust composition within a single custom-made chamber to create a natural and uniform soil deposition layer. Antisoiling (AS) coatings from two different manufacturers were applied on two one-cell monocrystalline silicon modules. Three layers of Arizona road dust have been deposited on the one-cell modules with AS coatings and an uncoated one-cell reference module at varied humidity levels. The soiled modules were exposed to an open-circuit subsonic wind tunnel at varying speeds and the effectiveness of AS coatings have been quantified using the transmittance gain. Transmittance loss resulting from the AS coating has been measured and compared with the transmittance of the uncoated reference module using a reflectance spectrophotometer. Reflectance measurements have also been taken to compare the transmittance loss of Arizona road dust and soil collected from PV modules’ superstrates. The soiled one-cell modules were then exposed to rain from a rain simulator. The transmittance gain due to rain exposure is quantified using a rain gain and rain coefficient. These tests cumulatively may be used to help develop a test standard for evaluating the effectiveness of AS coatings.

Index Terms—Antisoiling (AS) coating, rain coefficient, rain gain, transmittance, soiling loss, wind coefficient, wind gain.

I. INTRODUCTION

Soiling on a photovoltaic (PV) module superstrate has a significant detrimental effect on the module and string performance. The dust particles on the PV module absorb, scatter, and reflect incident photons, thus, reducing the power output. Soil deposited on the surface of the modules can be visualized as three layers. Soil layer A is the first layer of soil, which is chemically bonded to the surface of the PV module. This is the tenacious, primary surface layer of soil, which is very hard to remove. The second layer of soil, layer B, is not as tightly attached to the surface as layer A and the topmost layer of soil, layer C, is very loosely bound and can be easily removed [1]. The typical power loss due to soiling is 0.06% per day for a module with a 20° tilt angle facing due South in Arizona desert climatic conditions, as reported by this research group previously [2]. Anti-soiling (AS) coatings can be used to reduce the impact of soiling on module output power. For development of an international standard, a consistent technique to verify the effectiveness of AS coatings, validate AS coating vendor claims, and standardize the artificial soil deposition conditions is needed. Standardization requires acceptable repeatability of deposition within a lab and the deposition methodology to be reproducible and accurate across independent test facilities.

Two of the artificial soil deposition techniques reported in the literature utilized either an organic solvent or water as soil carrier medium [3], [4].

A 9-cell mini-module and three one-cell modules have been fabricated in a glass/EVA/Cell/EVA/Tedlar construction. The first one-cell module (20 cm × 20 cm) was used as the uncoated reference module in this study. Among the remaining two one-cell modules, one module (20 cm × 20 cm) was shipped to an AS coating manufacturer who coated the module (AS1) with their AS coating. An AS coating liquid was purchased from a different manufacturer and manually applied on the third one-cell module (AS2) (20 cm × 28 cm).

The primary soil used for this study was: Arizona road dust (ISO 12103-1, AZ fine test dust), which is formulated artificially by Powder Technology Inc. Soil has also been collected from surfaces of modules’ superstrates located at a PV power plant in Mesa, Arizona. The surface collected soil (CS) was also used in this study.

II. METHODOLOGY

A. In-Situ Soil Deposition Chamber

ASU Photovoltaic Reliability Lab has designed and fabricated soil deposition stations and developed the following three soil deposition methods.

1) 3 Chamber - Dew Method.
2) 2 Chamber - Humidity Method.
3) 1 Chamber - In-situ Method.

The 3 Chamber-Dew Method involves placing the coupon in a cooling chamber for cooling, separate chamber for deposition, and, finally, a chamber for baking. The 2 Chamber–Humidity
Fig. 1. Photograph of one-chamber soil deposition method (above); 9-cell monocrystalline silicon split-cell module for the uniformity measurements (below).

method does not require a separate cooling chamber, but still utilizes the deposition and baking chambers. The deposition chamber was saturated with humidity prior to soil deposition and then the coupon is baked in the baking chamber. The results obtained in these two methods are presented elsewhere [5], [6].

In the 1 Chamber-In-situ method, all four processes (cooling, humidifying, soil deposition, and heating), are performed in a single chamber as shown in Fig. 1 [7], [8]. First, the coupon was cooled for about 10 min to 11 °C using Peltier elements. Next, a humidifier was used to bring the humidity level of the chamber to the desired level. Then, a 1-s burst of compressed nitrogen at 40 psi was released into a small soil dispensing compartment containing the measured soil sample, generating a dust cloud. After allowing a 3-min settling time for deposition, the coupon was heated to 65 °C for 10 min using Peltier elements to create a uniform soiling layer.

B. In-Situ $I_{sc}$ Measurements

One of the most important factors used to determine soiling loss is the short-circuit current ($I_{sc}$). The $I_{sc}$ was measured after each soil deposition cycle within the soil deposition chamber itself. Honeywell’s 3500 Lumen portable LED light was used as the light source to measure $I_{sc}$ of the one-cell modules. After the heating cycle was complete, the LED light was turned ON for the $I_{sc}$ measurements. The terminals of the one-cell module were connected to a Fluke multimeter and the $I_{sc}$ was measured with the module still inside the chamber.

$I_{sc}$ was measured before and after each soiling cycle and the soiling loss was evaluated

$$\text{Soiling loss(\%) = } \frac{I_{sc,b} - I_{sc,a}}{I_{sc,b}} \times 100$$ (1)

$I_{sc,b}$ = $I_{sc}$ before soiling.
$I_{sc,a}$ = $I_{sc}$ after soiling.

C. Soiling Density and Uniformity Determination

The weight of the one-cell module was measured before and after the soil deposition cycle using a Radwag 1000 R1 precision balance and the soil deposition density was evaluated by dividing the amount of soil deposited by the area of the one-cell module

$$\text{Soil deposition density (g/m}^2\text{) = } \frac{W_b - W_a}{A}$$ (2)

$W_b$ = weight of (one-cell) module before soiling.
$W_a$ = weight of (one-cell) module after soiling.
$A$ = area of (one-cell) module in m$^2$.

D. Soil Uniformity Determination

A 9-cell monocrystalline silicon mini-module shown in Fig. 1 was used to verify the uniformity of soiling. The dimension of each cell was 52 mm × 52 mm and the dimension of the entire arrangement is 203.2 mm × 203.2 mm. The $I_{sc}$ of each individual cell was measured before and after the soil deposition. The percentage drop in $I_{sc}$ was used as a measure of soil deposition uniformity.

E. Particle Size Determination

A clear piece of PV glass (20 cm × 20 cm) was placed over the module and 0.5 g of AZ road dust was deposited on the glass as per the standard operating procedure. After each soil deposition cycle, the glass with the soil deposited was taken into a dark room and measured. For this, a KLAREN 1000× 8 LED 2MP USB Digital Microscope was held on the surface of the glass (at the center of each edge) and images were captured in the dark room. The images were imported in ImageJ, to obtain particle size distribution and count.

F. Reflectance Measurements

A split-cell (two half cells from a single cell) mono-Si module was fabricated and AS coating (AS2) has been applied on one half cell. The other half-cell was left uncoated. To obtain transmittance data, reflectance measurements using a handheld reflectance spectrometer were taken on the uncoated half-cell and the half-cell with AS coating to observe the transmission loss, from 300 to 1100 nm, due to application of the coating. The transmission loss has also been evaluated by measuring in-situ $I_{sc}$ before and after applying the coating.

A total of three cycles of AZ road dust (2 g per cycle) were deposited on the split cell module. Reflectance was then measured
I was noted before and after each soiling cycle. The velocity maintained during the wind gain testing are the two
variables investigated in this study. The different soil deposition RH levels tested were 30%, 50%, 70%, and 90% to mimic soil accumulation across different geographic regions. The wind velocity in the wind tunnel was set at various speeds between 5 and 11 m/s with an increment of 2 m/s for each humidity level. The tests at different humidity levels and wind velocities were performed on UC, AS1, and AS2 one-cell modules.

A rain test setup has been developed to simulate rain and evaluate the transmission gain obtained when the soiled one-cell modules are exposed to rain. A 3.18 mm HH-05 (1/8” HH05) nozzle manufactured by iSpray Technologies has been used to simulate rain. The inlet pressure was maintained at 7 psig with a cone spray angle of 59° and a flow rate of 0.36 gpm. A 356 mm (14”) Stratus Precision Gauge was used to measure the amount of rain. Three cycles of AZ road dust were deposited on the one-cell modules. The soiled one-cell modules were then placed at a 30° tilt and exposed to 1 mm of simulated rain. \( I_{sc} \) values before and after rain exposure were used to calculate the rain gain and rain coefficient.

\[
\text{Rain Gain} = \left( \frac{I_{sc,ar} - I_{sc,a3}}{I_{sc,a3}} \right) \times 100
\]

\[
ra = \text{rain amount (mm)}
\]

\[
I_{sc,ar} = I_{sc} \text{ after rain.}
\]

### III. Results and Discussion

Uniformity is an important characteristic of any testing protocol. Fig. 3 shows the drop in \( I_{sc} \) of each of the nine cells after a 2 g soil deposition. The mean percentage drop in \( I_{sc} \) was 4.79% with a standard deviation of 0.17%. This shows that the soil deposition is uniform.

Fig. 4 compares the wind gain of AS1 and AS2 with the uncoated reference module when the humidity inside the soil chamber was at 30%, 50%, 70%, and 90%. Fig. 5 compares the wind coefficient for the one-cell modules. The wind gain is a measure of transmittance gain, due to the removal of soil by wind. At 30% RH, we can see that the wind gain for AS coated modules is higher than the uncoated reference module for all wind velocities. This gap lessens as the humidity increases due to the layers becoming stuck to the surface. The wind gain for UC at 30% RH and 11 m/s wind velocity was 5.83%, whereas
the wind gain for AS1 and AS2 were 12.85% and 13.13%, respectively.

At 70% RH and a wind velocity of 11 m/s, the wind gain for UC, AS1, and AS2 were 4.37%, 9.21%, and 8.88%, respectively. Thus, there is a decrease in wind gain with increase in humidity, for a specific wind velocity. At 90% RH, there is zero transmittance gain, even at 11 m/s, for all three one-cell modules.

The wind coefficient is higher for higher velocities due to the higher associated transmittance gain. Similarly, the wind coefficient is lower during higher humidity instances because the layers are more firmly bonded to the module superstrate at higher humidity.

Fig. 6 compares the reflectance of clean UC and AS2 half cells. The reflectance of AS coated half-cell was higher than the reflectance of uncoated half-cell at all wavelengths. The transmission loss in AS2 due to the application of AS coating evaluated using the in-situ method was 0.60%. The transmission loss in AS1 was evaluated to be 0.62%.

Fig. 7 compares the reflectance of AZ road dust and CS. No significant difference in the reflectance behavior of AZ road dust and CS were observed. This could be because the CS was collected from modules’ superstrates in Arizona.

Fig. 8 shows the particle size distribution when 2 g of AZ road dust was deposited on clear PV glass. The mean particle size is 5.85 µm and the standard deviation is 4.29 µm. This gives an estimate of the particle sizes after one cycle of soiling for AZ road dust. Different soil types yield different particle sizes and thereby different effects on the light transmission in PV modules.
Fig. 6. Reflectance: Uncoated and AS coated.

Fig. 7. Reflectance measurements comparison for AZ road dust and CS. (a) Uncoated module. (b) AS coated module.

Fig. 8. Particle size distribution.

Fig. 9. Comparative rain gain for UC, AS1, and AS2 at 30% RH and 1 mm rain.

Fig. 10. UC, AS1, and AS2 before and after exposure to 1 mm rain.

Fig. 9 shows the comparison of rain gain for UC, AS1, and AS2 when three cycles of AZ test dust were deposited on the modules at 30% RH exposed to 1 mm rain in the rain test setup. The rain gain for the one-cell modules with AS coating is higher than the uncoated reference module. Among the two modules with AS coatings, AS1 and AS2, AS1 has a higher rain gain of 18.65% and AS2 has a rain gain of 16.29% under the given test conditions.

From Fig. 10, we can see that the first layer of soil, which is chemically bonded, has been impacted the least in removal from the uncoated module.

IV. CONCLUSION

An artificial indoor soiling deposition method has been developed as a recreation of the soiling deposition sequence found in nature, where the drop in $I_{sc}$ was used to quantify soiling loss. Uniformity of soil deposition has been verified by depositing soil on the 9-cell mini-module and measuring percentage drop in $I_{sc}$ in the 9-cells. Image processing techniques were used to characterize the soil particle size deposited.

A procedure to evaluate the effectiveness of AS coatings based on wind and rain cleaning has been proposed. The trans-
mission losses due to the AS coatings tested were about 0.6%.

In the wind test, the soiled modules were exposed to subsonic open-circuit wind tunnel and the transmittance gain was measured in the uncoated and AS coated modules. The soiled modules were exposed to 1 mm rain using a rain test setup and the transmittance gain was evaluated.

The transmittance gain can be used as a metric to compare different AS coatings. The transmittance loss or gain due to application of coating can be subtracted or added to the transmittance gain from the rain and wind test for better comparison.

This study focused on evaluating the performance of the AS coatings. Future work will focus on both performance and durability of AS coatings. Durability and life-time of AS coatings play a major role in economic feasibility. Hence, the future work will include accelerated testing of PV modules with AS coatings.

REFERENCES