“The Abrasion of Photovoltaic Glass: A Comparison of the Effects of Natural and Artificial Aging”

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Motivation

• PV now uses AR and/or AS coatings to increase electricity generation and reduce effects of soiling.
• ~1%·day⁻¹ performance loss in MENA ⇒ clean PV modules daily.

Coatings used on PV front surfaces. Einhorn et. al., J PV, 9, 2018, 233-239.

Help develop IEC 62788-7-3 PV industry abrasion standard:
⇒ Quantify field contamination.
⇒ Quantify field abrasion damage.
⇒ Compare field- & artificial-abrasion damage.

Vendor cleaning building glazings (at NREL campus).

• Much of the damage to coatings results from cleaning.
• PV leverages cleaning methods and equipment from the building glazing industry.
Typical PV Bristle Materials and Their Characteristics

Polyamide (e.g., Nylon)
• Hardest material. Slow wear rate ⇒ low cost of use.
• Easiest material to clean ⇒ low cost of use.
• Nylon 6,6 swells more with water, may fatigue faster than Nylon 6,12.

Hog bristle
• Natural: obtained from along the spine of a boar's back. Premium price.
• Preferred in automotive industry (prevent scratching clearcoat/paint).
• Not commonly used in MENA PV for religious & cultural reasons.

Other synthetics
• Includes: polyester, polystyrene, and polypropylene.
• Low cost resins.
• Softer materials ⇒ faster wear rate.
• Sometimes unofficially substituted for other materials!

Example PE pole fed water jet brush marketed to the PV industry.

Representative boar artwork.

Comparison of molecular structure of PA.
Field Coupon Study (Background and Progress)

Samples:
- 7.5 cm x 7.5 cm coupons.
- Includes AR, AS (-phobic & -philic), reference glass.
- Black backpane (similar temperature to PV).

Cleaning methods:
- No clean (NC); dry brush (DB); low-pressure water spray (WS); wet sponge and squeegee (WSS).
- Clean 1x/month.
- Examine 1 set of duplicates each year for 5 years.

Characterize:
- Particulate contamination (particle-size distribution, -area coverage, and -mass concentration).
- Optical performance (hemispherical transmittance).
- Damage morphology (scratch-width & -depth).

Test sites:
- Contamination and abrasion prone locations.
- Mesa, Arizona; Sacramento, California; Mumbai, India; Kuwait City, Kuwait; Dubai, United Arab Emirates.

Original specimen set deployed at Sacramento.
Einhorn et. al., J PV 2019, 233-239.
Toth et. al., SOLMAT, 185, 2018, 375-384.
Details of the Linear Artificial Brush Abrasion Study

Experiments:
- Custom dry dust chamber added to commercial tester.
- A4 “coarse” AZ test dust abrasive (ISO 12103).
- Dust dispensed with each cycle.
- Compare polyamide (Nylon 6,12), hog bristle, polyester bristles. 3.8 cm length.

Correlate:
- Surface energy (water contact angle, goniometer).
- Surface roughness (white light interferometer).
- Optical performance (spectrophotometer with integrating sphere).
- Damage morphology (AFM).
Surface Damage Implied From Optical Performance Analysis

- Transmittance previously correlated to particle area coverage for No Clean specimens.

Example: Dry Brush cleaning in Dubai, 1y:
- $\Delta \tau_h$ Predicted: linear correlation between particle area coverage and $\tau_h$ for non-contact cleaned specimens.
- Actual $\Delta \tau_h$ measured for DB using spectrophotometer.
- $\Delta \tau_h$ (performance change if coating was removed) measured for coated specimens relative to uncoated glass.

- Actual $\Delta \tau_h$ consistently exceeds $\Delta \tau_h$.
  ⇒ coating abrasion damage and/or removal.
  ⇒ results from: optical-scattering, -absorption, and cemented surface layer.

Correlation between particle area coverage and transmittance after 1 year in Dubai and Mumbai.

Einhorn et. al., J PV 2019, 233-239.
Example: PSD of the Field Contamination

- **15 μm ∅ (median)** in PV literature.
- **2.5 μm ∅ (50th percentile)** in field study. ???
  - ∅ > 2.5 μm reported for Dubai & Mumbai.
  - Cementation observed (e.g., Dubai & Kuwait).
  - Size limited by natural cleaning (timeliness of wind & rain) as well as return shipment.
  - Variation between measurement methods.

- PM2.5: from combustion, chemical processes.
- Airborne fine particulate evolves to PM2.5.
- PM10: from mechanical origins.
- Mass concentration distribution of field sites resembles airborne PM10 contamination, if maximum ∅ limited by cleaning & transportation.

Mass concentration of airborne PM.

Measured mass concentration (“Q₃”) for the Dubai No Clean field coupon.


Miller et. al., J PV, in press.
Surface Quantifications Confirm Coating Damage

• Wide range of scratch-width and -depth observed after 12 cleanings. min-avg-max presented.
• Depth often less than, but sometimes greater than \( h_n \).
• Scratches extend into surface of J (no coating) coupons.
• Brush bristle diameter was 154-246-335 µm. (5%-50%-95% cdf).

\[
\begin{array}{|c|c|c|c|}
\hline
\text{COUPON} & \text{\( w_s \)} & \text{\( h_s \)} & \text{\( h_n \)} \\
\text{INDEX} & \text{SCRATCH} & \text{SCRATCH} & \text{NOMINAL} \\
& \text{WIDTH} & \text{DEPTH} & \text{COATING} \\
& (\mu m) & (nm) & \text{THICKNESS} \\
& & & (nm) \\
\hline
B & 5.1-7.3-11.7 & 38-105-137 & 125 \\
D & 4.7-16.9-34.2 & 40-64-74 & 140 \\
E & 3.1-12.7-27.4 & 6-94-130 & 130 \\
J & 0.6-9.3-34.8 & 23-37-60 & 0 (no coating) \\
U & 0.6-1.5-2.3 & 33-106-170 & 25 \\
\hline
\end{array}
\]

\( w_s \) comparable to \( \varnothing \) of contamination present on coupon surfaces \( \Rightarrow \) contamination acts as localized abrasive.
• Field PSD believed to be more similar to A2 dust. (scratch width \( \leq 35 \) µm exceeds PSD \( \varnothing \leq 12 \) µm ).

Measured scratch geometry for the Dry Brush cleaned specimens after 1 year in Dubai.

AFM to assess damage regions for Dubai B specimen (relatively intact).
Artificial Test Also Heavily Affected By Abrasive

- Large individual scratches $\rightarrow$ max $h_s$ at 100 cycles.
- Numerous subtle scratches $\rightarrow$ avg $w_s$ and $h_s$.
- Scratches in field coupon study wider (5x, on average).
- Scratches in artificial abrasion study deeper (2x).
- Bristle diameter $>> w_s$ and $h_s$.

Representative images of J specimens (no coating) after 100 cycles artificial abrasion.

- Large $w_s$ & $h_s$ observed at 20k cycles, from individual scratches for PA and PE bristles.
- Tribological deposition of a thin film of contamination suspected for dry brush test.

Representative image of specimen after 20000 cycles artificial abrasion with PE bristle brush.
Correlating Between Optical Performance, Roughness, and Surface Energy for Artificial Abrasion

- $\tau_h$ decreased, optical scattering increased with $n$.
  - $\tau_h$ decreased for $n<500$.

- Complex evolution of $R_a$ & CA with $n$ for PA & PE.
  - CA decreased from initial 43°. (Surface energy increased).
  - Peak and valley trend at large $n$ was repeatable. (multiple measurements and replicate specimens).

- Corresponding loss of $\tau_h$ & increased haze consistent with increased $R_a$.

- Immediate decrease in CA may result from surface cleaning, e.g., pumice scrub cleaning.

- Increase in haze for $n>10000 \Rightarrow$ glass (no coating) can be cleaned many times (e.g., over years) with minimal $\Delta \tau_h$.

- Complex evolution: tribological deposition of thin film of contamination.

Hemispherical transmittance and haze as a function of the number of dry-brush cycles for J (no coating) glass.

Surface roughness and surface energy as a function of the number of dry-brush cycles for J (no coating) glass.
Summary & Conclusions

- $\tau_h$ field coupons at one year (12 cleanings) reduced greater than predicted from contamination area coverage, exceeding enhancement from antireflective coatings.

  $\Rightarrow$ Coating abrasion damage and/or removal.

- $\varnothing$ contamination on field coupons was 1–12 $\mu$m.

  $\Rightarrow$ “Fine” A2 ISO 12103 AZ test dust recommended as artificial abrasive in accelerated tests.

- Scratch-width and -depth identify surface contamination (not bristle $\varnothing$) is a primary factor affecting the field- and artificial-abrasion damage.

- Bristle materials distinguished in artificial abrasion, at $n > 10000$.

  $\Rightarrow$ Standardization of bristle material (Nylon 6,12) and geometry (<3.8 cm) is recommended.
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If interested in the PVQAT TG12-3 activities or IEC 62788-7-3 PV abrasion standard, please contact: David.Miller@nrel.gov Participants wanted.

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Complete set of measured scratch geometry for the Dry Brush cleaned specimens after 1 year, including minimum, **average**, and maximum values. Default cleaning was performed monthly (12 cleanings).

Note: Kuwait was cleaned daily (365 cleanings) rather than monthly.