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

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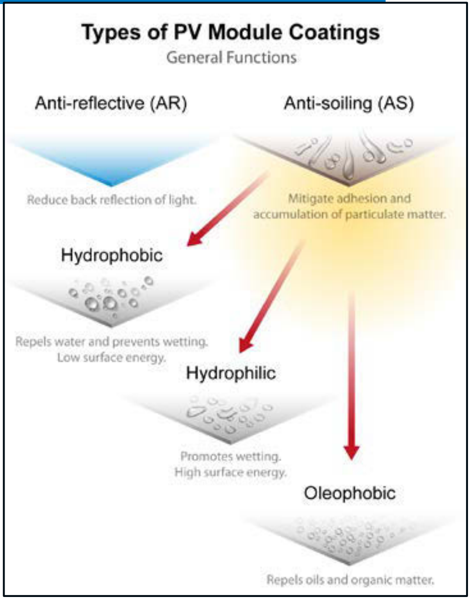
Motivation

•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.

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.

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

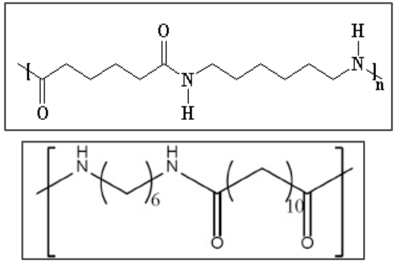
Typical PV Bristle Materials and Their Characteristics

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.

Nylon 6,6

Nylon 6,12



Comparison of molecular structure of PA.
http://nxt-ubiquity.s3.amazonaws.com/wiley/plasticsengineering/april2016/UPLOADED_ASSETS/technicalpaper/T2.jpg
https://www.quora.com/Why-is-the-melting-point-of-nylon-6-lower-than-nylon-66

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.

Representative boar artwork.
http://www.nedgallagher.com/journal/archives/000841.html

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.

Field Coupon Study (Background and Progress)

Original specimen set deployed at Sacramento.
Einhorn et. al., J PV 2019, 233-239.
Toth et. al., SOLMAT, 185, 2018, 375-384.

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

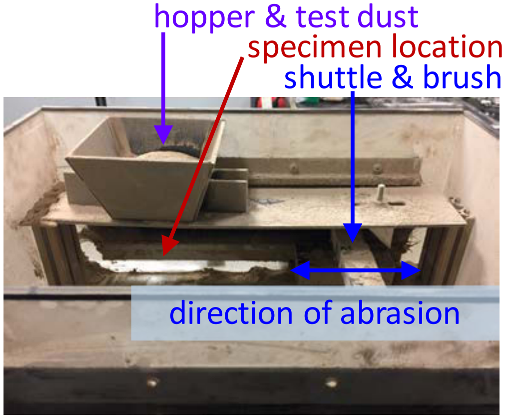
Test sites:
- Contamination and abrasion prone locations.
- **Mesa**, Arizona; **Sacramento**, California; **Mumbai**, India; **Kuwait City**, Kuwait; **Dubai**, United Arab Emirates.

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).

Details of the Linear Artificial Brush Abrasion Study

front view (lid removed)



back view

Experiments:

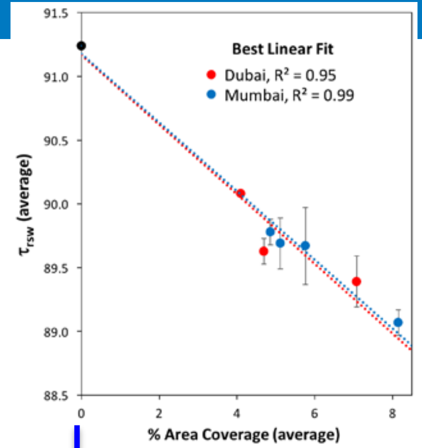
- Custom dry dust chamber added to commercial tester.
- A4 “coarse” AZ test dust abrasive (ISO 12103).
- Dust dispensed with each cycle.
- Compare polyamide (Nylon 6,12), hog bristle, polyester bristles. 3.8 cm length.

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.



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

Einhorn et. al., J PV 2019, 233-239.

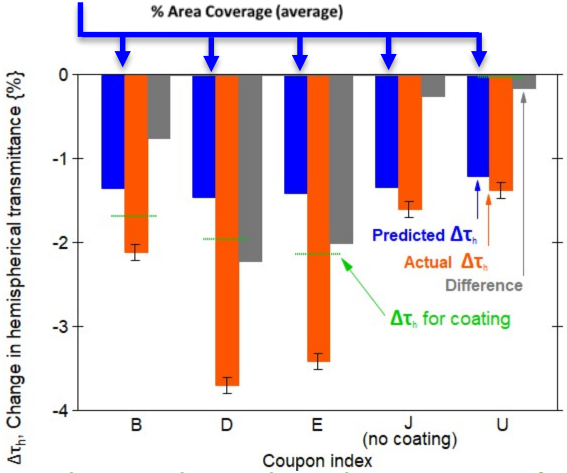
<u>Example: Dry Brush cleaning in Dubai, 1y:</u>

- $\Delta\tau_h$ *Predicted*: linear correlation between particle area coverage and τ_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 $\Delta\tau_h$.

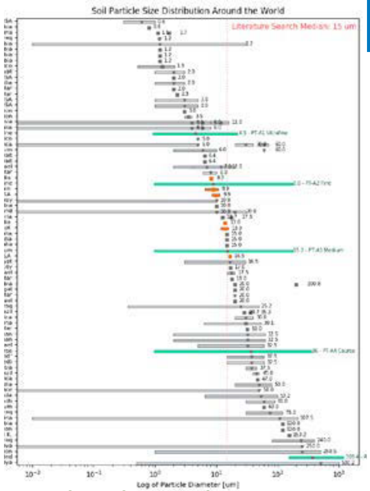
⇒coating abrasion damage and/or removal.

⇒results from: optical-scattering, -absorption, and cemented surface layer.



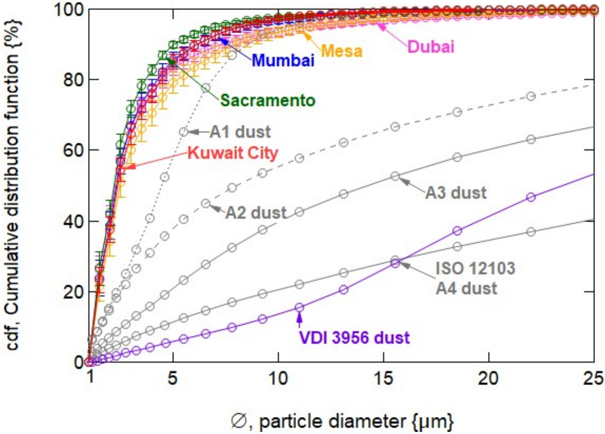
Change in hemispherical transmittance for Dry Brush cleaned specimens after 1 year in Dubai.

Example: PSD of the Field Contamination

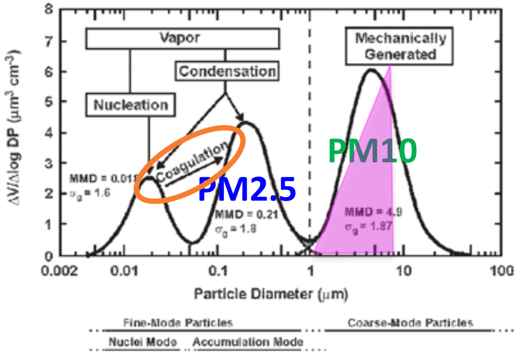


Nayshevsky et. al.,
Proc. Intl. Soiling Work., 2018.

- 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.

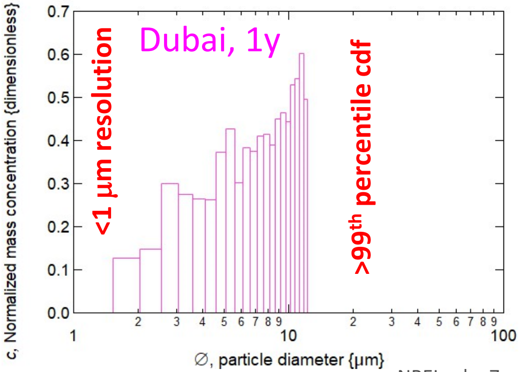


Miller et. al., J PV, in press.



Mass concentration of airborne PM.
Wilson & Suh, J. Air & Waste Manage. Assoc., 1997.

- 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.



Measured mass concentration (“Q_3”)for the Dubai No Clean field coupon.

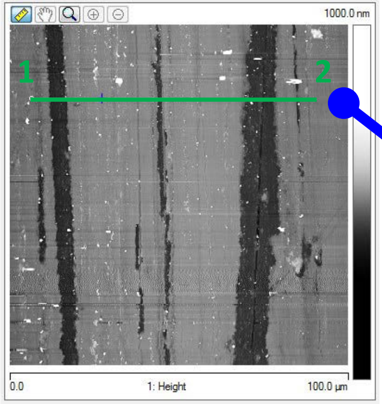
Surface Quantifications Confirm Coating Damage

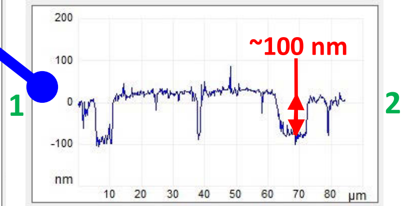
- Wide range of scratch-width and -depth observed after 12 cleanings. min-**avg**-max presented.
- Depth often less than, but sometimes greater than h_n.
- Scratches extend into surface of J (no coating) coupons.
- Brush bristle diameter was 154-**246**-335 μm. (5%-**50**%-95% cdf).

COUPON INDEX	w_s, SCRATCH WIDTH {μm}	h_s, SCRATCH DEPTH {nm}	h_n, NOMINAL COATING THICKNESS {nm}
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

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

- w_s comparable to ∅ of contamination present on coupon surfaces ⇒ contamination acts as localized abrasive.
- Field PSD believed to be more similar to A2 dust. (scratch width ≤35 μm exceeds PSD ∅ ≤12 μm).

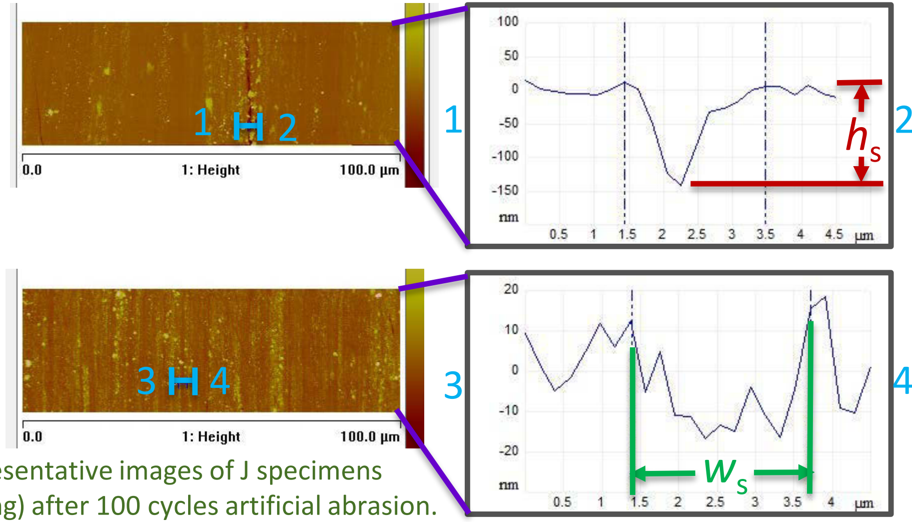




AFM to assess damage regions for Dubai B specimen (relatively intact).

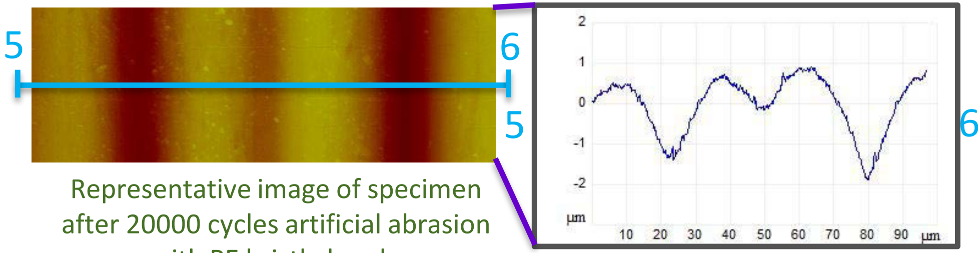
Artificial Test Also Heavily Affected By Abrasive

- Large individual scratches → max h_s at 100 cycles.
- Numerous subtle scratches → 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.



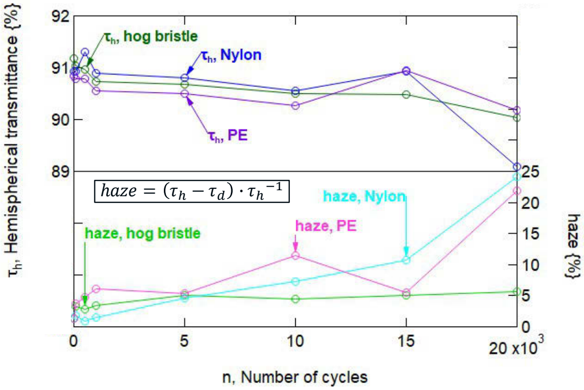
Representative image of specimen after 20000 cycles artificial abrasion with PE bristle brush.

Correlating Between Optical Performance, Roughness, and Surface Energy for Artificial Abrasion

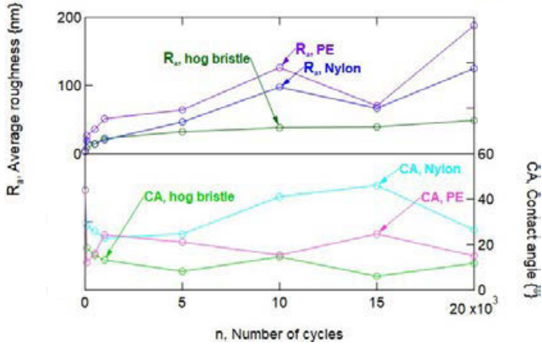
- τ_h decreased, optical scattering increased with *n*.
  - τ_h decreased for n<500.

- 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 τ_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

•τ_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 μm.
$\Rightarrow$*“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.*

Acknowledgements

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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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NREL STM campus, Dennis Schroeder

Complete Field Coupon Scratch Morphology Dataset

FIELD SITE LOCATION	COUPON INDEX	w_s, SCRATCH WIDTH {μm}	h_s, SCRATCH DEPTH {nm}	h_n, NOMINAL COATING THICKNESS {nm}
Dubai	B	5.1-**7.3**-11.7	38-**105**-137	125
Dubai	D	4.7-**16.9**-34.2	40-**64**-74	140
Dubai	E	3.1-**12.7**-27.4	6-**94**-130	130
Dubai	J	0.6-**9.3**-34.8	23-**37**-60	0 (no coating)
Dubai	U	0.6-**1.5**-2.3	33-**106**-170	25
Kuwait City	B	0.8-**6.9**-29.6	74-**130**-171	125
Kuwait City	D	0.4-**1.4**-7.8	14-**60**-205	140
Kuwait City	E	1.2-**6.7**-13.3	46-**97**-137	130
Kuwait City	J	0.8-**1.9**-3.0	37-**161**-328	0 (no coating)
Kuwait City	U	0.2-**1.9**-3.0	24-**126**-320	25
Mesa	B	2.5-**15.1**-95.1	3-**89**-211	125
Mesa	D	2.3-**8.0**-17.3	120-**142**-185	140
Mesa	J	1.6-**2.0**-2.5	53-**159**-253	0 (no coating)
Mesa	U	1.4-**9.3**-20.4	5-**44**-128	25
Mumbai	B	0.8-**3.1**-4.1	125-**165**-192	125
Mumbai	D	1.0-**3.0**-8.4	91-**144**-180	140
Mumbai	E	1.4-**7.4**-23.5	17-**65**-113	130
Mumbai	J	0.8-**1.8**-4.4	11-**105**-236	0 (no coating)
Mumbai	U	1.2-**3.1**-5.7	97-**125**-142	25
Sacramento	B	1.8-**5.8**-10.6	121-**153**-237	125
Sacramento	D	1.0-**8.2**-30.3	106-**117**-132	140
Sacramento	J	0.4-**3.6**-16.0	5-**22**-76	0 (no coating)
Sacramento	U	0.8-**2.0**-5.1	6-**39**-170	25

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.