Soiling Related Abrasion and the Development of a PV Abrasion Standard

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International PV Soiling Workshop

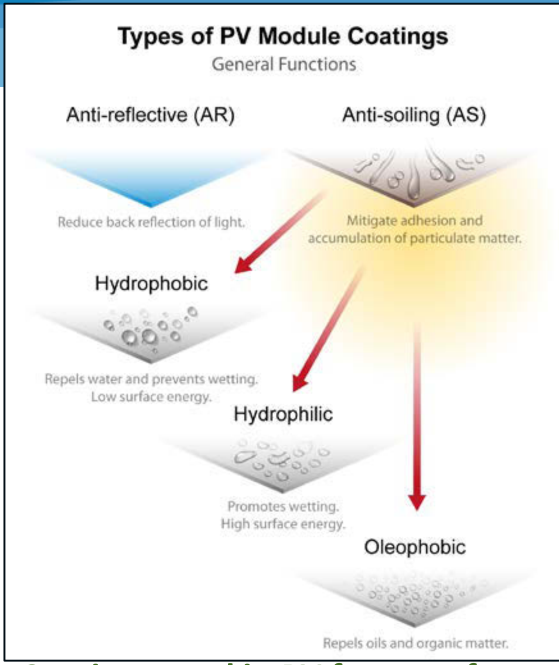
Golden Ballroom Salon D, Denver West Marriott hotel, Golden CO

08:40-09:00 Thursday, November 01, 2018

NREL/PR-5K00-72850

Motivation

- AR and/or AS coatings are applied to PV to directly increase e^- generation and/or reduce effects of soiling.
- Coated modules are typically cleaned.
- The degradation and durability of popular coatings remains to be understood.



Coatings used in PV front surfaces.
Einhorn et. al., J PV, in review.

- Much of the damage to coatings results from cleaning (equipment and/or contamination as abrasive).
- PV leverages cleaning methods and equipment from the building glazing industry.

- Goal: develop an industry standard concerning abrasion.

Vendor cleaning building glazings (at NREL campus).

IEC 62788-7-3 (PV Abrasion) Standard Is Under Development

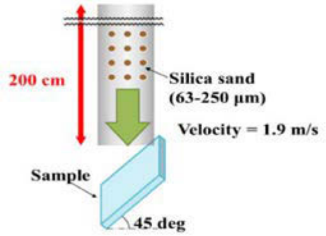
•On review, no existing standard from other industries was found readily suited for PV.
-Example: frosted –glass- specimens. See: Miller et. al., NREL/TP-5J00-66334, 2016, 1-25.
⇒Accelerated abrasion standard for PV surfaces is presently being developed in IEC WG2.

Methods

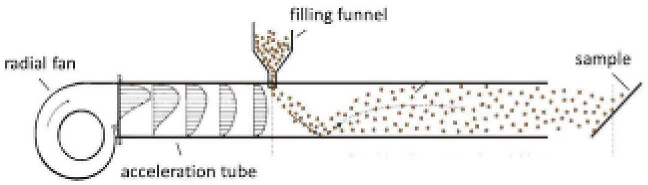
•Falling sand test.
-Natural abrasion (wear from typical meteorological conditions).
-Front surface coatings & backsheets.

•Forced sand impingement test.
-Covers severe storms (infrequent, but high velocity wind).
-Front surface coatings & backsheets & vehicle integrated PV.

•Artificial machine abrasion.
-Cleaning of PV.
-Includes slurry or dry dust abrasive.
-Linear translation or rotating brush.



Schematic of falling sand test. From Nishioka et. al., Proc. Asian PVSEC 2013.



Schematic of forced sand impingement test. From Klimm et. al., Proc. Euro. Weathering Symp. 2015.

Example (PB-8100) linear machine abrasion tester. www.byk.com

Key Details of the Linear Brush Test for Artificial Machine Abrasion

Some details can be leveraged from standards for other industries.

Abrasive

- Consider contamination (size & composition) present on a PV module.
- AZ test dust: ISO 12103 A3 (“medium” particle size distribution).

Brush bristle

- Consider common/existing equipment.
- Material: Nylon 6,12 (other standards use/moving towards this material).
- Length: 3.8 cm (many water fed brushes use longer bristles).
- Geometry: round, extruded bristles with no taper (standardize).

Brush geometry

- Standardize to legacy methods: area (3.5 x 8.5 cm), bristle count, tuft pattern.

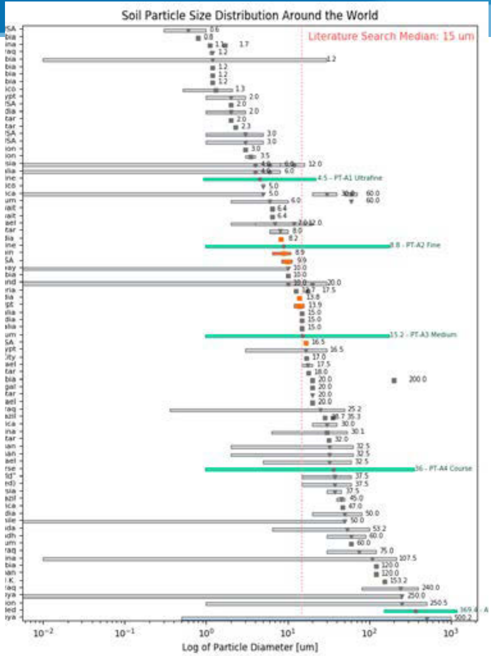
Machine

- Standardize to legacy methods.

-454 g contact force; 255 mm brush stroke length; 37 cpm test rate.

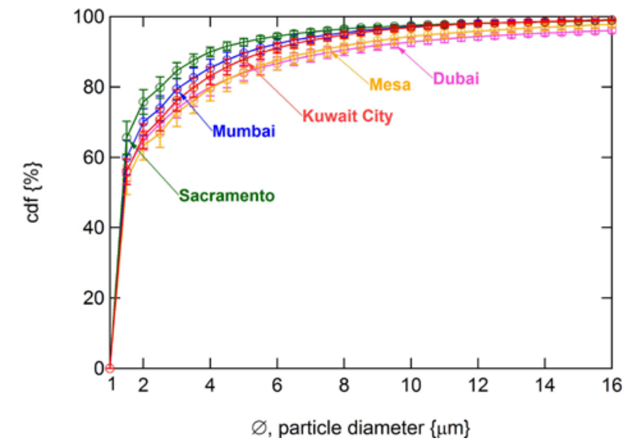
Next slides: explore aforementioned aspects in detail.

What Size of “Abrasive” is Typically Found on PV Surfaces?

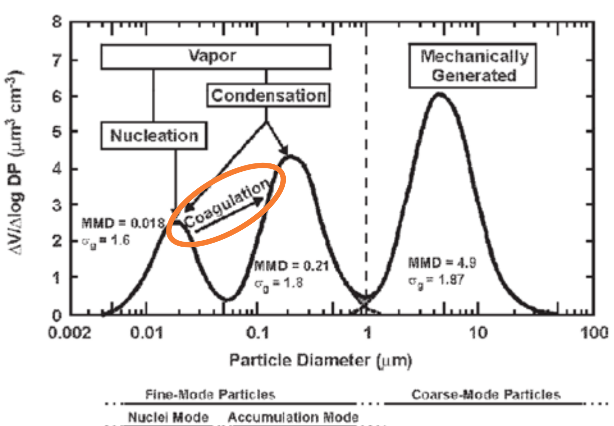


Nayshevsky et. al.,
Proc Intl Soiling Work., 2018.

- 15 μm ∅ (median) in PV literature.
- 1.5 μm ∅ (50th percentile) in NREL field studies was < 15 μm PV literature.
-Results repeatable, Keyence & ImageJ.
-Loss of large particles during shipping?
-Cementation (e.g., Dubai & Kuwait)?
-Characterization methods & reporting is not standardized.

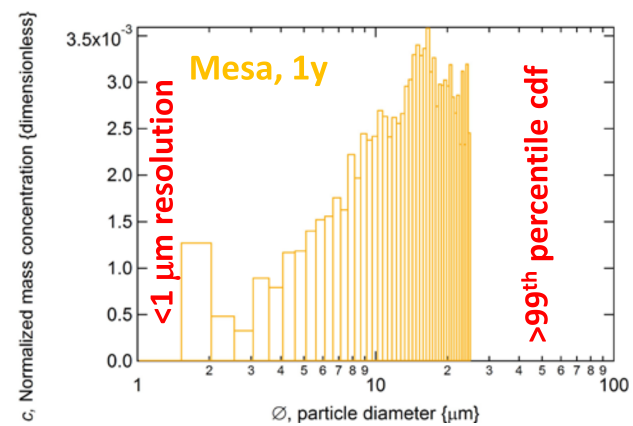


cdf of particulate population of field sites (NC samples, 1y) verified at NREL.



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

- PM2.5: from combustion, chemical processes.
- Airborne mass concentration of PM2.5 subject to evolution.
- PM10: from mechanical origins.
- Mass concentration field sites similar to expected airborne.



Mass concentration of Mesa field site (NC sample).

“Abrasives” Used in the PV Community

- ”Sands” have greater ∅ than “dust”.
- Sands have a more limited composition than dust. (Sands mostly silica)
- Grain morphology may vary between the sands.

Chemical composition for DIN 52348 sand. Busch GmbH.

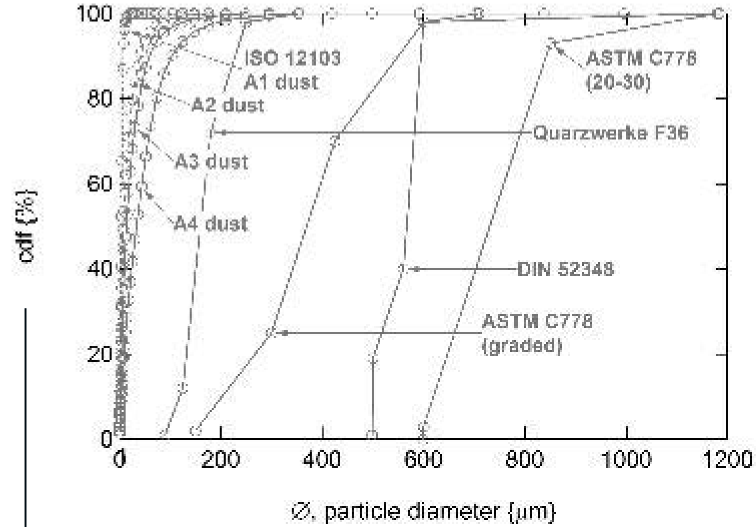
MATERIAL	CONCENTRATION {%}
SiO_2	96.20
Al_2O_3	0.90
Fe_2O_3	0.02
TiO_2	0.06
CaO + MgO	0.05
$K_2O + Na_2O$	0.55
Ignition loss	0.20

Chemical composition for F36 sand. Quarzwerke GmbH.

MATERIAL	CONCENTRATION {%}
SiO_2	99.3
Al_2O_3	0.5
Fe_2O_3	0.06
Ignition loss	0.2

Chemical composition for ISO 12103 test dust. PTI Inc, Safety Data Sheet.

Components	Quantity
silica (fine dust)	69-77 %
aluminium oxide	8-14 %
calcium oxide (mineral)	2.5-5.5 %
potassium oxide (mineral)	2-5 %
sodium oxide (mineral)	1-4 %
Iron(III) oxide (hematite)	4-7 %
magnesium oxide	1-2 %
titanium dioxide	0-1 %



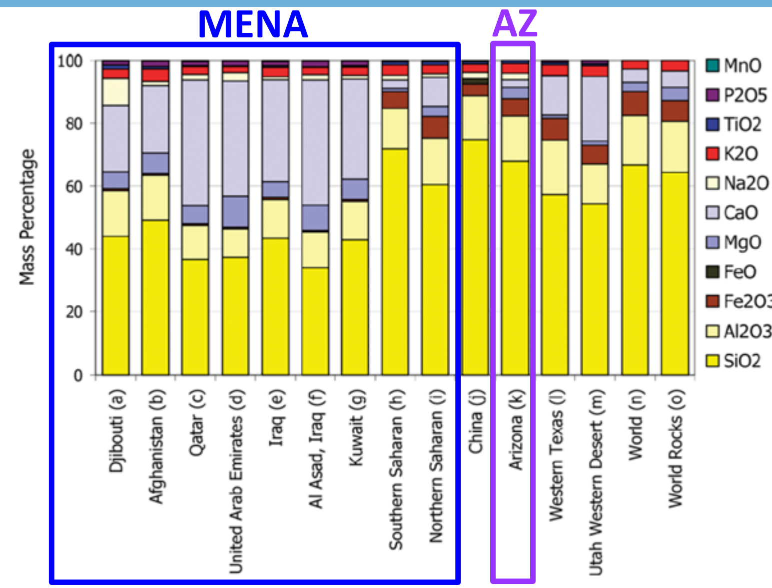
Cumulative distribution function for “abrasives” examined in the PV community. (Supplier’s data).

	SAMPLE	SIZE, 5th PERCENTILE {μm}	SIZE, 50th PERCENTILE {μm}	SIZE, 95th PERCENTILE {μm}
ISO 12103 (PTI)	A1 dust	1.0	4.5	9.5
	A2 dust	1.0	8.0	58.8
	A3 dust	1.6	14.2	84.5
	A4 dust	2.4	34.2	140.3
standard	ASTM C778 graded	170	369	581
	ASTM C778 20-30	607	732	960
	DIN 52348	499	567	598
	Qarzwerke F36	103	160	242

Range of particle diameters for “abrasives” examined in the PV community. (Supplier’s data).

Abrasive Composition: Additional Varieties May Ultimately Be Required

- Local composition of soil (therefore PM10) varies between world locations.
- "Compared with the Sahara, China, US, and world dusts, Middle East samples had lower proportions of SiO_2 and higher proportions of CaO and MgO", Engelbrecht et. al.
- Palygorskite [$(Mg,Al)_2Si_4O_{10}(OH)\cdot 4(H_2O)$] is a mineral commonly found in MENA locations (and SE USA), but not in AZ (ISO 12103 test dust).
- Palygorskite is affected considerably by water (including dew cycles), contributing to cementation.



Comparison of dust from various locations.
Engelbrecht et. al., Inhalation Toxicology, 21, 2009.

- A future standardized "MENA test dust" may be appropriate.
- Location specific differences also exist within MENA.
- What location might be the benchmark for MENA?
- MENA dust products presently exist.

Components	Quantity
silica (fine dust)	69-77 %
aluminium oxide	8-14 %
calcium oxide (mineral)	2.5-5.5 %
potassium oxide (mineral)	2-5 %
sodium oxide (mineral)	1-4 %
Iron(III) oxide (hematite)	4-7 %
magnesium oxide	1-2 %
titanium dioxide	0-1 %

Chemical composition for ISO 12103 AZ test dust.
PTI Inc, Safety Data Sheet.

Bristle Materials Typically Used for PV and Their Characteristics

Nylon

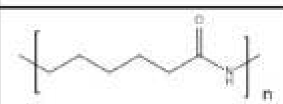
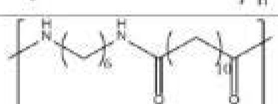
- Hardest material. Slow wear rate ⇒ low cost of use.
- Easiest bristle material to clean ⇒ low cost of use.
- Nylon 6,6 swells more with water, may fatigue faster than Nylon 6,12.

Hog bristle

- Natural: obtained from along the spine of a boar's back. Premium price.
- Preferred in automotive industry (will not scratch clearcoat/paint).
- Not commonly used in MENA for cultural reasons.

Other synthetics

- Includes: polyester, polystyrene, and polypropylene.
- Low cost resins.
- Softer materials ⇒ faster wear rate.

Polymer	Chemical structure	No. of CH2 units
Nylon 6,6		5
Nylon 6,12		16

Comparison of molecular structure of Nylons.

http://nxt-ubiquity.s3.amazonaws.com/wiley/plasticsengineering/april2016/UPLOADED_ASSETS/technicalpaper/T2.jpg

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

Representative Brushes for the PV Industry

- Examine five brushes marketed to the PV industry (building glazing cleaning equipment vendors).
- Goal: verify characteristics to provide feedback to IEC 62788-7-3.

(1) *(2)* *(3)* *(4)* *(5)*

Images of representative brushes examined.

<u>Characterizations</u>

-Physical dimensions

-Chemical composition

-Glass & phase transition temperature(s)

Not considered: rotary disc style brush (manufacturer: Kärcher).

Not Examined:

-Proprietary brushes.

-Microfiber/fabric “bristles”.

-Surfactants/liquids/solvents.

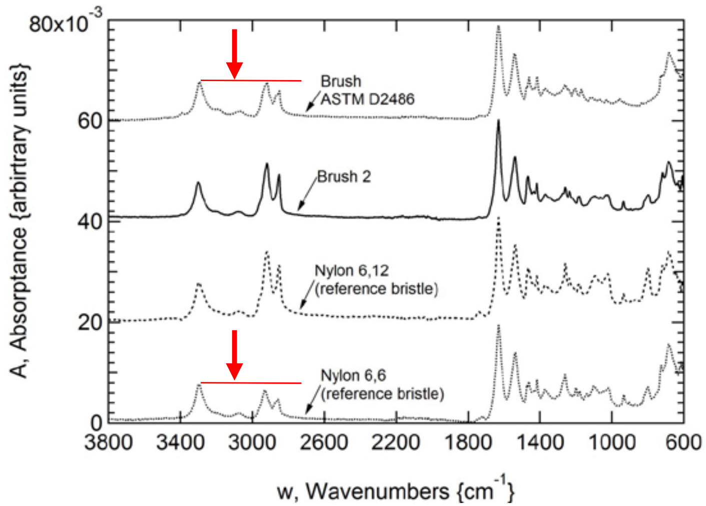
(detergents & anti-spotting agents are not allowed in CA water reclamation laws)

Lessons Learned From the Representative Brushes

- Materials used do not always match catalog information. (PE and horse hair are cheap).
- Bristle diameter > 0.23 mm. $k_{bend} \propto \varnothing^4$
- Bristle length(s) > 38 mm. $k_{bend} \propto L^{-3}$

INDEX	BRISTLE COLOR	BRISTLE MATERIAL: COMPOSITION	BRISTLE MATERIAL: SAME AS IN VENDOR CATALOG?	BRISTLE DIAMETER {mm}	BRISTLE LENGTH (OUTER) {mm}	BRISTLE LENGTH (INNER) {mm}
1	yellow or gray	polyester	yes	**0.34**	**75**	50
2	clear	Nylon 6,12	yes	**0.30**	**51**	41
3	brown	hog bristle	yes	**0.27**	**71**	N/A
4	red	polyester	no	**0.25**	**43**	N/A
5	blue	Nylon & polyester	no	**0.50**	**31**	N/A
6	black	horsehair	yes	NREL field study		

Key physical characteristics (bristle-diameter & -length) were verified.
The base material was verified against known reference materials



Example: the FTIR peaks ~3300 and ~2900 cm-1 may be used to verify the structure of Nylon.

INDEX	$T_{g1}=T_{\alpha 1}$ {°C}	T_{c1} {°C}	T_{m1} {°C}
1	44	180	216
2	157	189	216
3	N/A	N/A	N/A
4	N/A	202	218
5	N/A	200	224
6	153	N/A	N/A

- Bristle material's phase transition temperature may limit the local temperature on the specimen (dry brush test).
- Nylon and PE have similar T_{melt}, $T_{crystallization}$
- Natural fibers may have T_g, will decompose at higher T. (No melt).

Measured phase transition temperatures for the same brushes.

A Comparison of the Bristle Materials in Linear Abrasion

What is the quantitative significance of the bristle material in cleaning abrasion?

- Compare popular bristle materials (Nylon 6,12; hog bristle; polyester) in dry linear abrasion test.
- Correlate optical performance (transmittance), surface energy (contact angle), and surface roughness.

Photo of the brushes used in the comparative study.

Brushes

- 38.1 mm long bristles (some deceleration, longest length possible in abrasion tester).
- Identical brush blocks → similar packing pattern & density.

Experiments

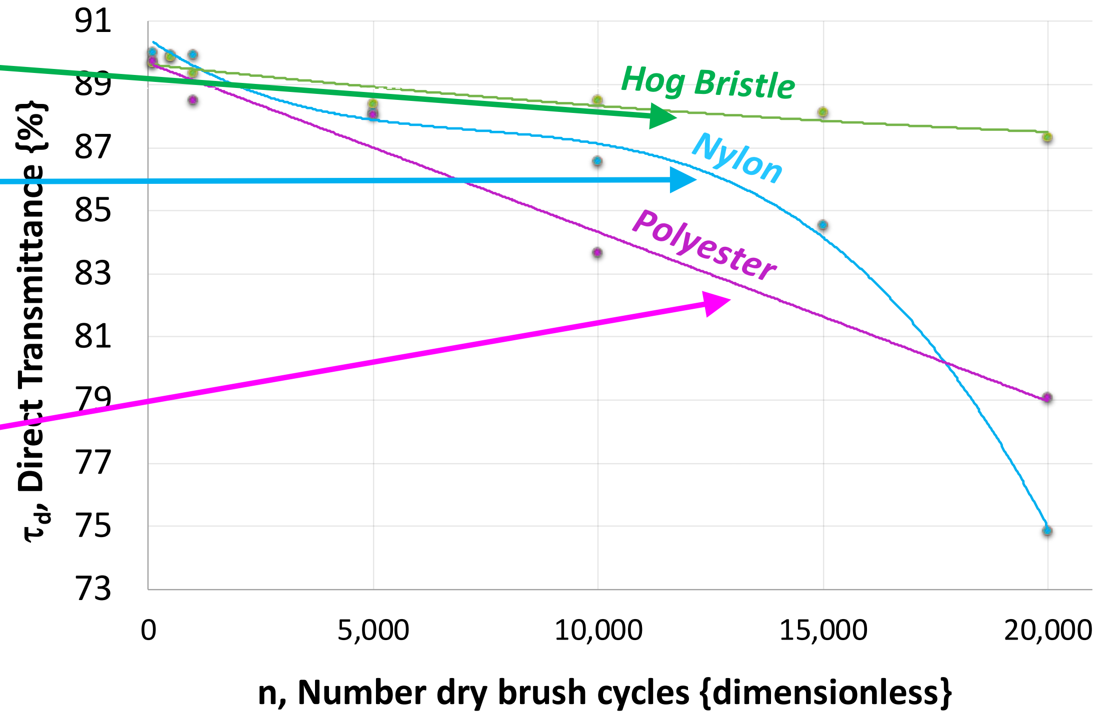
- Brush test performed using A4 (coarse) AZ test dust on reference ("J") glass.
- Up to 20k cycles (clean 1x daily for 25y, 20kc also used in other industries' standards).

BRISTLE MATERIAL: COMPOSITION	$T_{g1}=T_{\alpha 1}$ {°C}	T_{c1} {°C}	T_{m1} {°C}	BRISTLE DIAMETER {mm}	BRISTLE LENGTH (OUTER) {mm}
Nylon 6,12	125	188	215	0.30	38.1
hog bristle	176	N/A	N/A	0.11	38.1
polyester	106	196	224	0.61	38.1

Characteristics of the brushes used in the comparative study.

Bristle Materials Readily Distinguished For Dry Brush Test (1)

- Hog bristle minimally affects glass. ($\Delta\tau_d$ ~ 2.5%)
- Nylon maximum affect on glass. ($\Delta\tau_d$ ~ 15%).
- Polyester gave significant damage.
- Only large ∅ bristle available from our vendor.

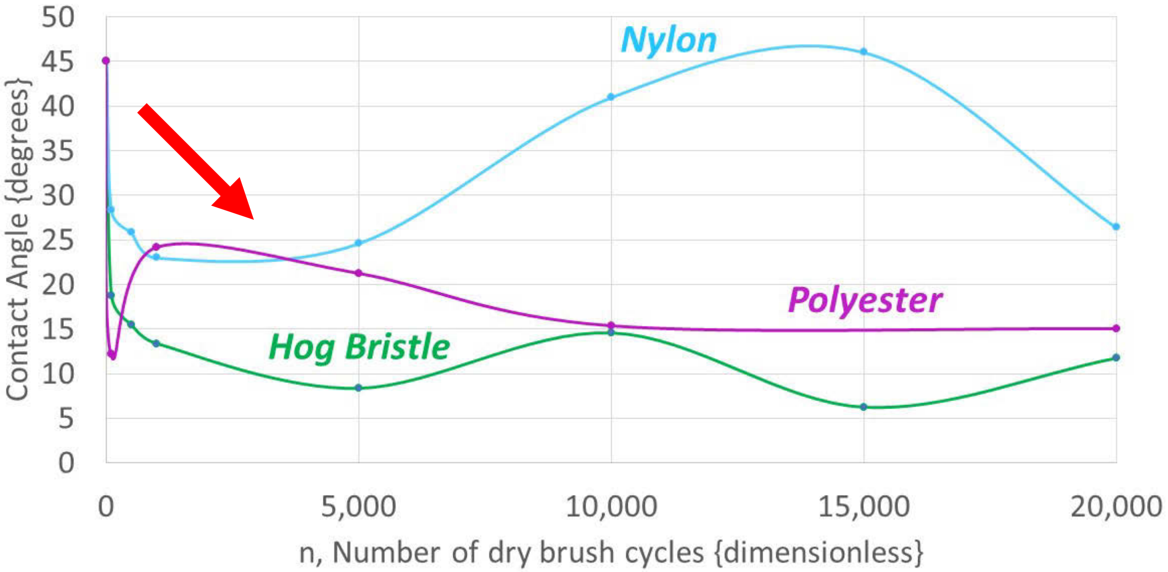


Effect of linear abrasion on direct transmittance results for J (reference glass).

- Results here quantify the feedback from the industry (hog bristle least damaging; Nylon most damaging).
- Results for glass can be used as reference for artificial abrasion study and standard development.
- Next step: dry brush testing of coated specimens.

Bristle Materials Readily Distinguished For Dry Brush Test (2)

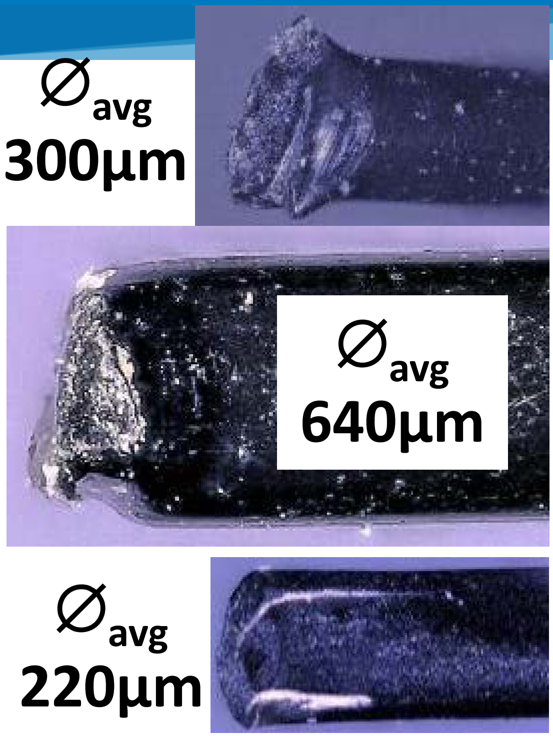
- Contact angle greatly reduced from baseline value with dry brushing for all bristle materials.
- Contact angle remained reduced (hydrophilic) through experiment for hog bristle and polyester.
- Contact angle evolved in complex manner with *n* for Nylon.



Effect of linear abrasion on surface energy (contact angle) for J (reference glass).

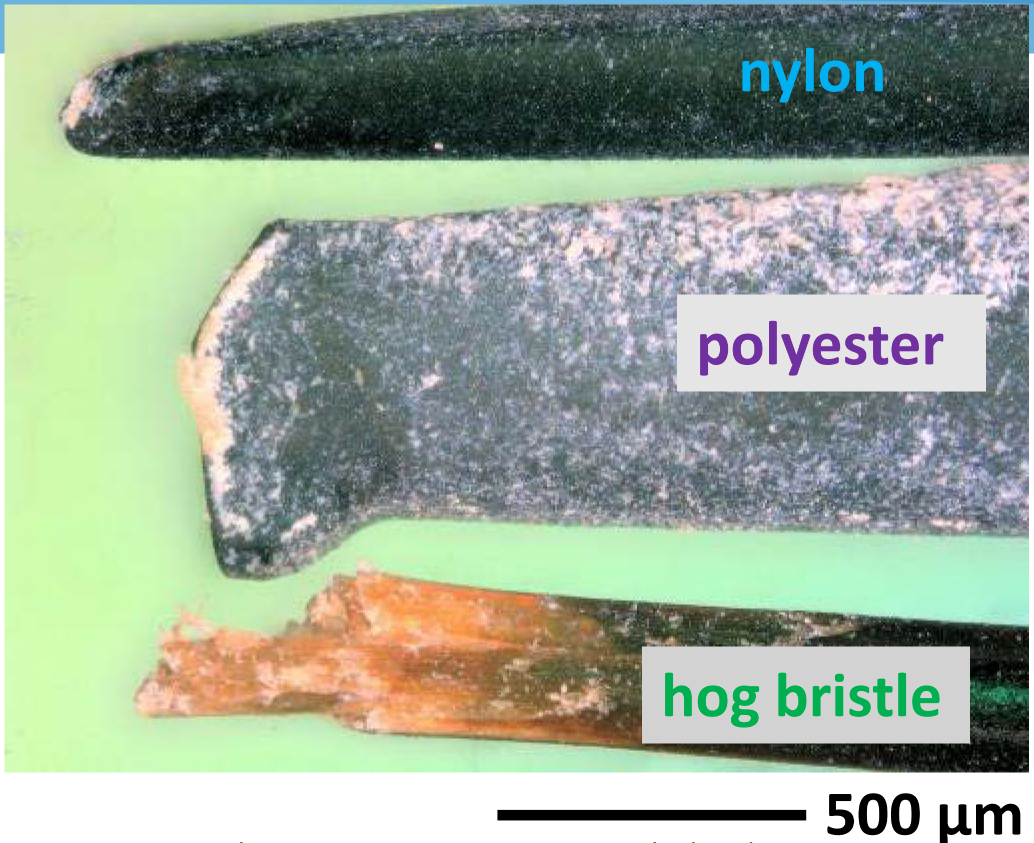
- Additional characterization (surface roughness, SEM, XPS) should clarify if abrasion, contamination, or diffusion contribute to the surface energy.

Brush Bristles Are Readily Distinguished For Dry Brush Test



Optical microscope image comparing the bristle types
***before** 20k cycles of dry brush test.*

20k cycles



Optical microscope image comparing the bristle types
***after** 20k cycles of dry brush test.*

- Morphology after 20,000 cycles evidences:
  bristle erosion (hog bristle);
  bristle rounding (nylon, temperature or electrostatic discharge);
  bristle deformation (polyester).

Field Coupon Study (Background and Progress)

Original specimen set deployed in Sacramento.

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.

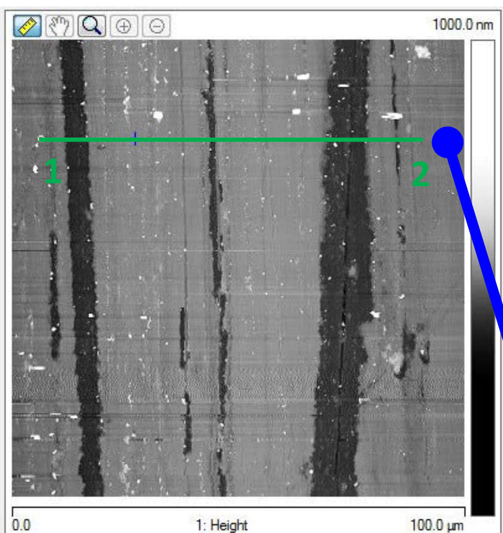
Status:
•y1 specimens recently returned from all sites. Some y2 specimens have returned.
•Quantifying soiling performance (PAC) to down-select sites & cleaning methods of interest.
•Future: F/A, RE: abrasion, cleaning, and soiling.

Abrasion Observed in the Field Study

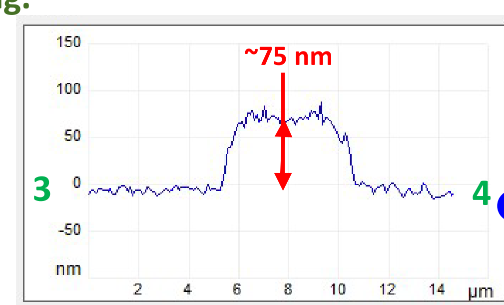
- The efficacy of cleaning was readily distinguished after 1 year.
- DB cleaning method greatly damaged some coatings after 1 year (12 cleanings) in Dubai.
  - -Example: coating D extensive damage. B relatively intact.
  - -More frequent cleaning may help.
- WSS cleaning method much less damaging.
- Quantification & comparison between sites presently underway for DB.

AFM to asses damage regions for Dubai
B specimen (left) and D specimen (right) for DB cleaning.

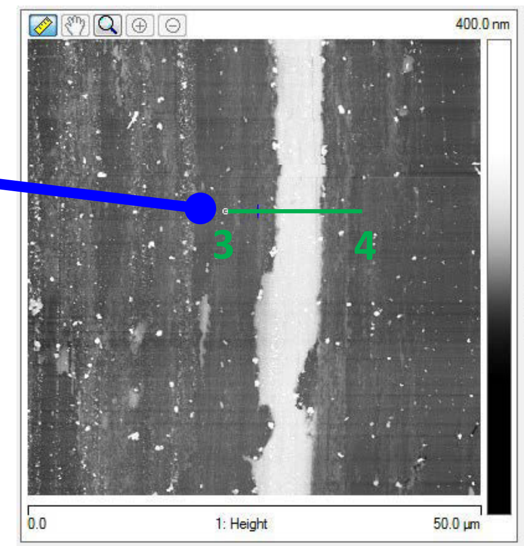
Einhorn et. al., JPV, in press.



B: relatively intact

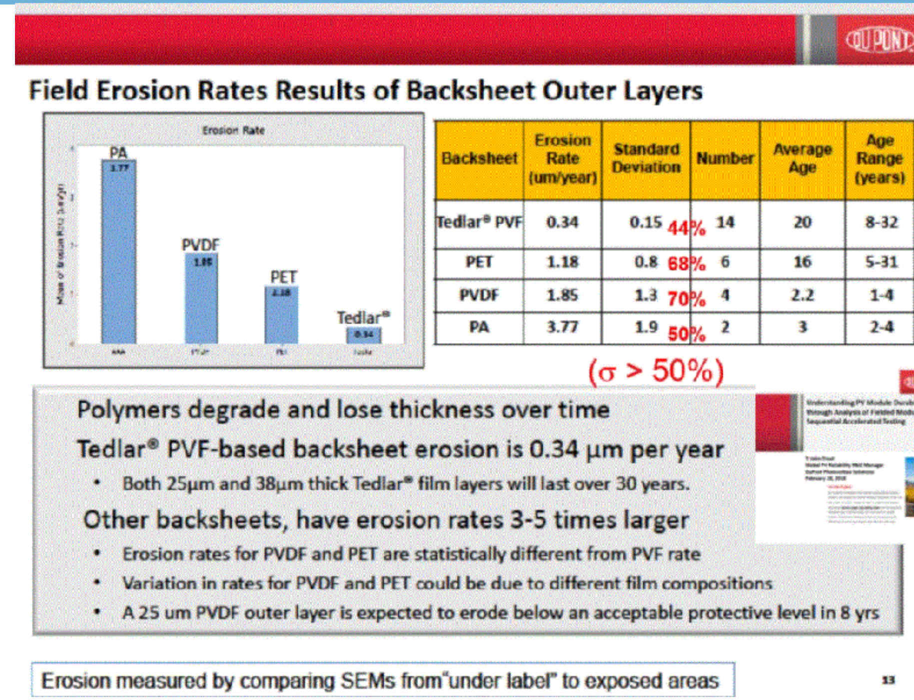


D: relatively damaged



“The Abrasion of Backsheets & VIPV May Also Be Addressed”

- The erosion of backsheets was recently identified in veteran PV modules.
- Caveat: polymers may erode from photodegradation (loss of volatiles) in addition to physical abrasion.
- More evidence & understanding is sought within IEC 62788-2 (backsheet standard group).



Backsheet	Erosion Rate (um/year)	Standard Deviation	Number	Average Age	Age Range (years)
Tedlar® PVF	0.34	0.15 44%	14	20	8-32
PET	1.18	0.8 68%	6	16	5-31
PVDF	1.85	1.3 70%	4	2.2	1-4
PA	3.77	1.9 50%	2	3	2-4

Roy Choudhury et. al., IEEE PVSC, 2018.

- IEC WG2: consider backsheets within the scope of IEC 62788-7-3.
- Accelerated test sequence for PV modules may ultimately include abrasion, in a test sequence (e.g., UV → abrasion → TC200 → HF10)

☞To participate in the backsheet abrasion survey, contact:
Jürgen JUNG <juergen.jung@agfa.com>

- IEC WG7: consider vehicle integrated PV within IEC 62788-7-3.

Summary

- An IEC abrasion test standard is being developed for the PV industry.
- Suite of: falling sand, forced sand impingement, and machine abrasion tests.
- Originally just for coatings, but may eventually address backsheets & VIPV.

- ISO 12103 AZ test dust may be used for machine abrasion tests.

- Nylon (most damaging) and hog bristle (least damaging) were readily distinguished in dry machine abrasion tests (transmittance, surface energy).
- Popular Nylon 6,12 recommended as bristle material for machine abrasion.
- Abrasion depends on tribology and bristle materials (T_{melt}) characteristics.

- Please contact me if you are interested in the abrasion standard.

Acknowledgements

- Thanks to field site collaborators: Bader Alabdulrazzaq, Ayman Al-Qattan, Pedro Banda, Ben Bourne, Telia Curtis, Zoe Defreitas, Jim J. John, Greg Kimball, Anil Kottantharayil, Marco Stefancich, Pr. Govindasamy Tamizhmani, Juzer Vasi, and Sonali Warade
- There has been fantastic participation in PVQAT TG12 webinars & TG12-3.

  *Thank you to the **many** participants for your ongoing support!!!*
- If interested in the TG12-3 activities or IEC 62788-7-3 standard, please contact David.Miller@nrel.gov

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NREL STM campus, Dennis Schroeder

- Your questions and feedback are much appreciated! Please help me to cover the important details & perspectives.

Standards Discussion Session (1)

- What are the highest impact soiling problems that presently need to be addressed?

- Are existing standards sufficient? What new standards are needed?

- What scientific information is needed to help address soiling?

Standards Discussion Session (2)

- Are the PVQAT TG12 groups sufficient to address the most pressing issues?

- What do you believe is the future of:

 (a) soiling monitoring

 (b) soiling assessment

 (c) prediction

 (d) mitigation?

What issues need to be resolved?

What innovations are needed?

The Subgroups of PVQAT TG12 (Soiling)

PVQAT
International PV Quality Assurance Task Force

Task Group 12 Webinars (**all general topics**)

- Monthly webinars on soiling topics. 2nd Tuesday of each month.
- Contact: Greg SMESTAD <smestad@solideas.com>

Task Group 12-1 (**sensors** and the **monitoring** of soiling)

- Contributed to IEC 61724-1 (quantifying effect of soiling on PV systems).
- Contact: YuePeng DENG <Yuepeng.Deng@FIRSTSOLAR.COM>.

Task Group 12-2 (solutions for **cleaning**)

- Much recent interest. Goal: module cleaning standard (manual & robotic methods).
- Contact: Lin SIMPSON <Lin.Simpson@nrel.gov>

Task Group 12-3 (antireflective and/or anti-soiling **coatings**)

- Recent focus on abrasion.
- Web study group, including abrasion and characterization methods.
- Reference: Miller et. al., NREL/TP-5J00-66334, 2016, 1-25.
  http://www.nrel.gov/docs/fy16osti/66334.pdf
- Goal: international artificial soiling test standard, e.g., used for R&D purposes.
- Contact: David MILLER <David.Miller@nrel.gov>

Task Group 12-4 (**modeling/analysis** of effects of soiling on **PV systems**)

- Example: analysis of power production data from PV installations
- Reference: Deceglie et. al., Proc. IEEE J PV, 2018. also:
  http://www.nrel.gov/docs/fy16osti/65763.pdf
- Contact: Leo MICHELI <Leonardo.Micheli@nrel.gov>