NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Durability of Poly(Methyl Methacrylate) Lenses Used in Concentrated Photovoltaics

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*speaker

PV Reliability Workshop

Denver West Marriot

2010/02/19 1:20 PM

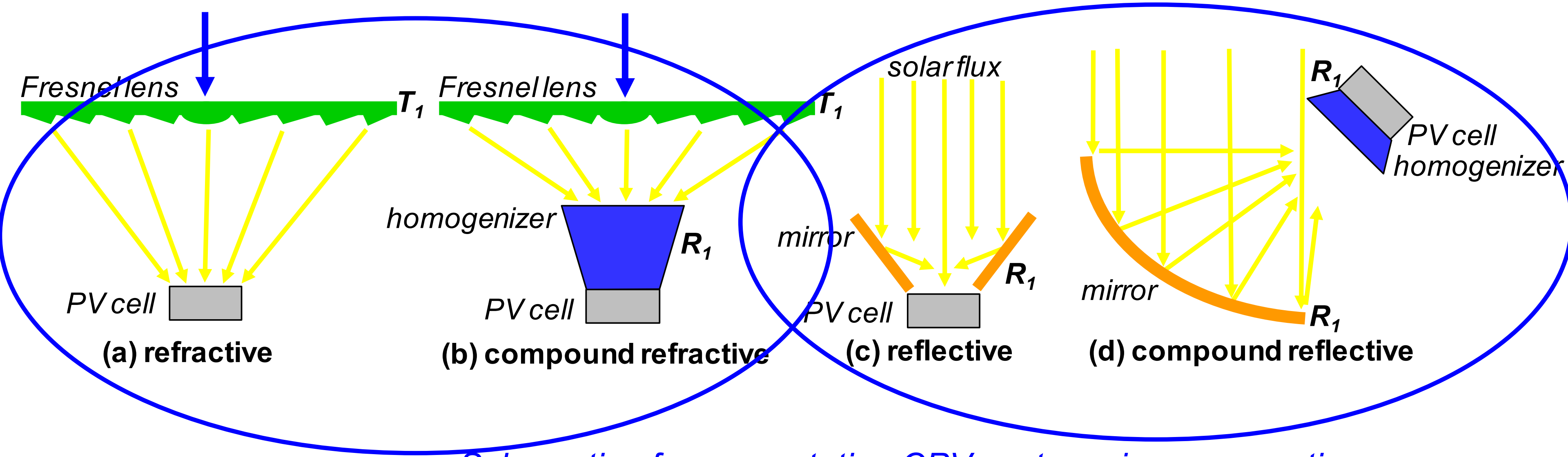
Overview

- Introduction/scope/terminology
- Experiment (@ NREL) vs. literature
- Failure *modes*
    - Optical durability
    - Mechanical durability
    - Soiling
- Failure *mechanisms*
    - Photodegradation
    - Thermal decomposition
- Summary

Scope

- Focus: Fresnel lens component in refractive CPV system
- Opto-mechanical component expected to last 30 years

- Direct solar resource (*for reference*)
  - solar disc: ±4.65 mrad (±0.27°)
  - circumsolar region: ±50 mrad (±2.9°)
  - reference spectrum: ASTM G173 direct

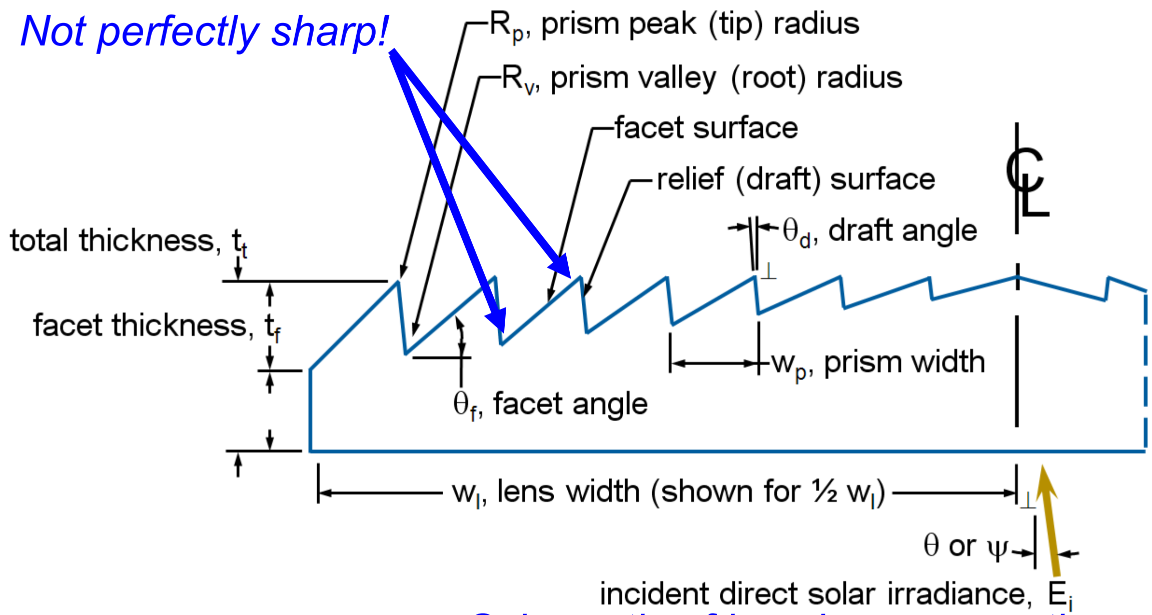


Schematic of representative CPV systems in cross-section

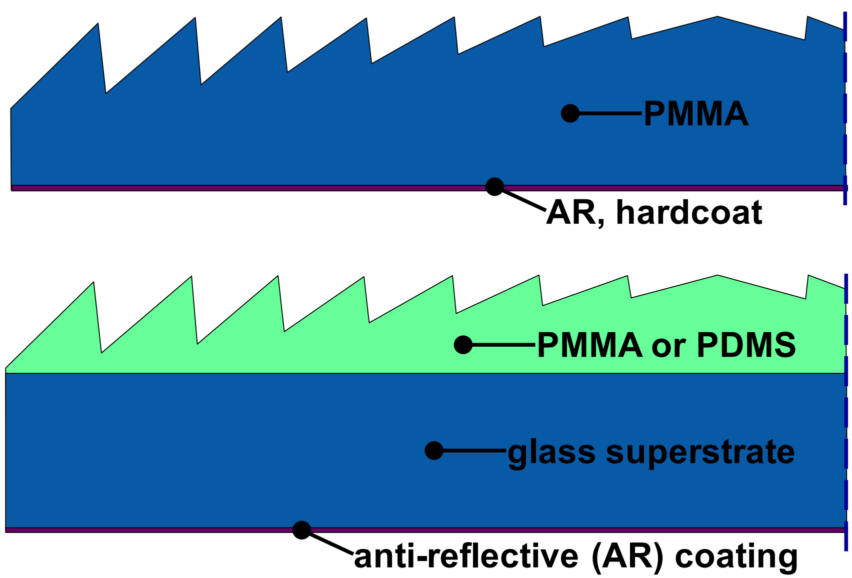
Terminology

<u>Fabrication methods</u>:

hot-embossing *(low σ)*
casting
extruding
laminating
compression-molding
injection-molding *(low \$)*



Schematic of lens in cross-section



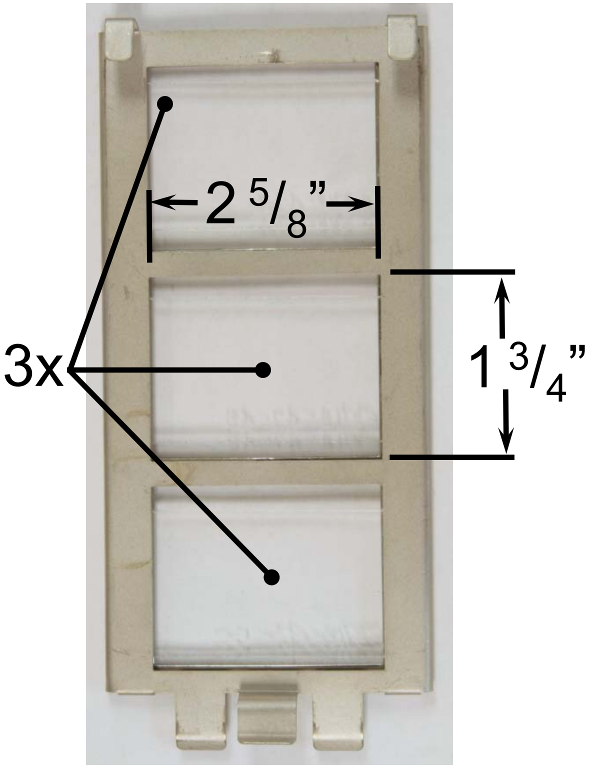
Materials implementation (monolithic vs. composite)

PARAMETER	REPRESENTATIVE VALUE
t_f	0.1-0.5 mm
t_s	2.0-5.4 mm
t_t	2.5-5.5 mm
R_p	2-30 μm
R_v	1-30 μm
θ_f	1.0-1.6 rad
θ_d	35-52 mrad
w_p	0.01-1.0 mm
w_l	2-30 cm
θ	$\pm$5-150 mrad
C	5-1000
f/	0.5-1.5
η	78-86%

*Figures of merit**

NREL Screen Test (1)

- Literature ⇒ initiated ≥20 years ago
- Characterize the durability of a broad range of contemporary specimens subject to indoor HALT



Test specimens, (3) ea

DESCRIPTION	SPECIMEN TYPES
stock sheet	11
linear lens	1
spot lens	8
veteran lens	3

- Test instrument: ATLAS Ci4000 Weather-ometer (Xenon-arc lamp @ 2.5x UV suns. Chamber @ 60°C/60%RH)

NREL Screen Test (2)

- Measurands:

  Periodic

  - optical appearance
  - → optical transmittance (hemispherical)
  - mass
  - → contact angle (sessile drop, 1st surface)

  "End of life"

  - prism facet geometry (lenses: section then SEM)
  - surface morphology (SEM or AFM)
  - → indentation (Vicker's hardness, toughness)
  - → rheometry (E', E'', T_g)
  - XPS or ESCA (surface chemistry)

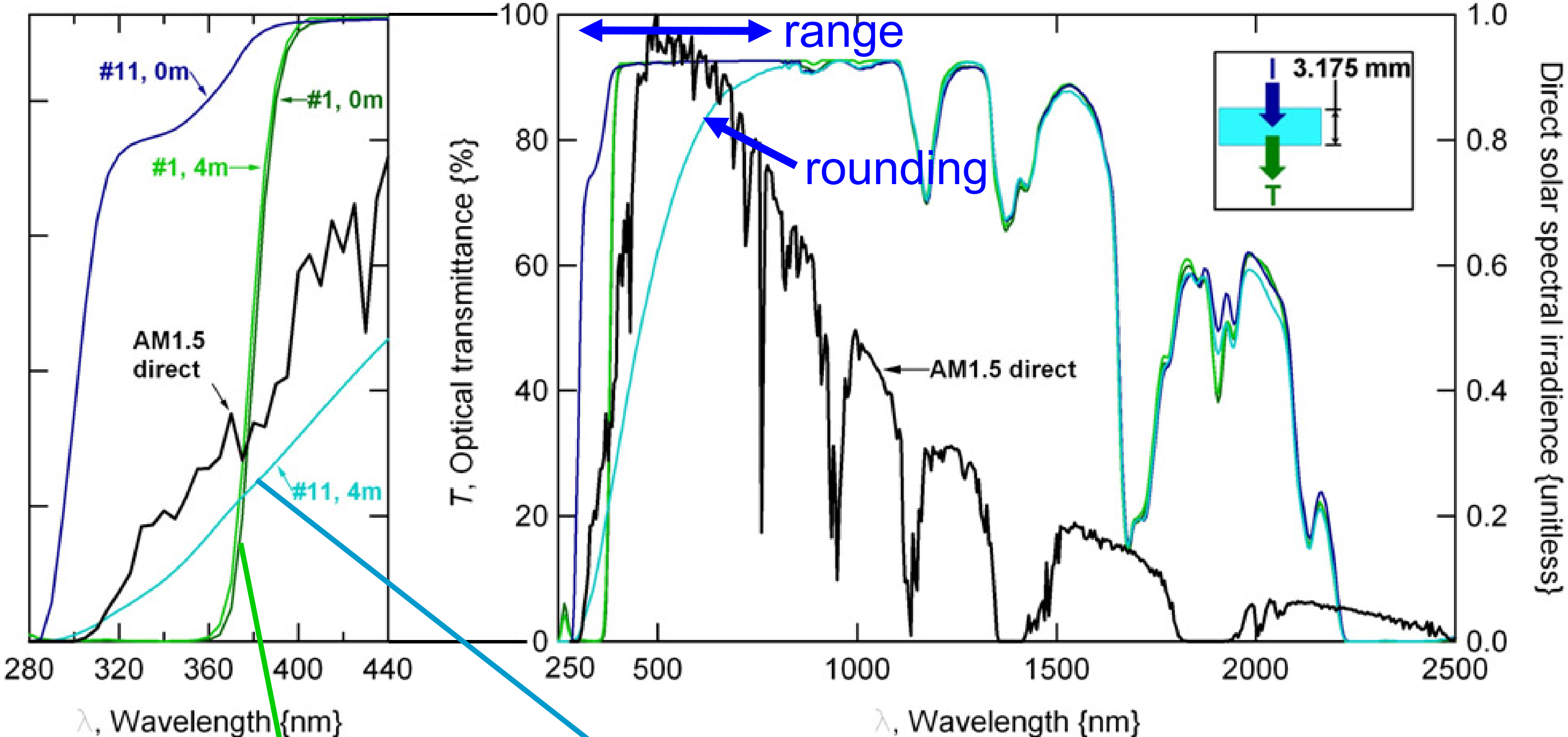
- Test schedule:

  0, 1, 2, 4, 6, 12, 18, 24, 30, 36, 42 months

  ≥8 acceleration factor

Optical Durability

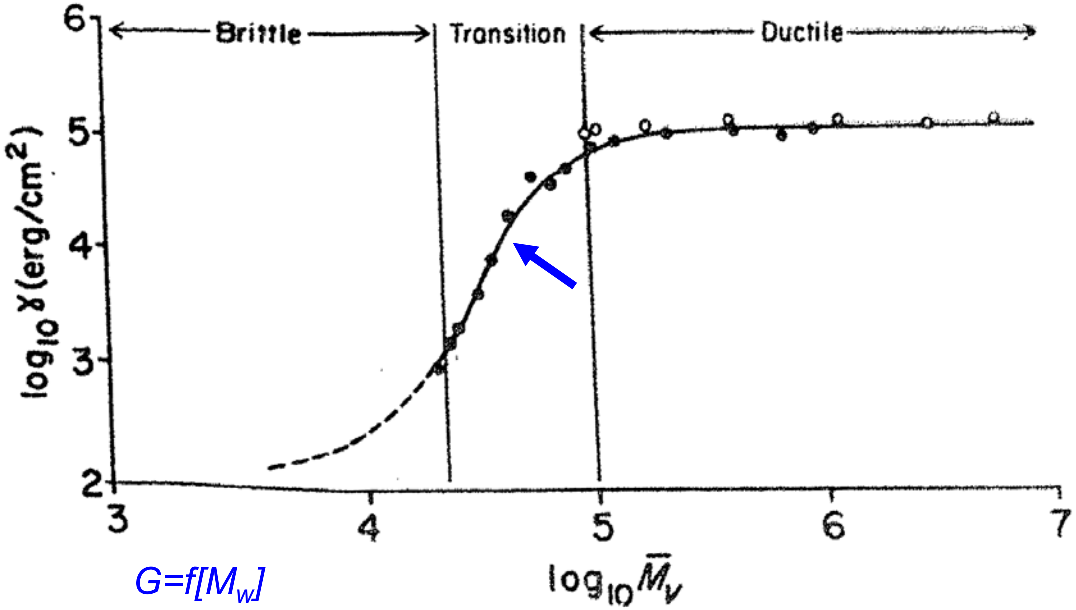
- Transmittance of PMMA
- Lambda 900 (Perkin-Elmer) spectrophotometer (w/ I-sphere)



Yellowness index (ASTM D65,1964)
YI: -1.1 → -0.9-18.4

Comparison of transmittance at 0, 4 months for best and worst sheet stock specimens

Mechanical Durability (Fracture/Toughness)



G=f[M_w]

Kusy, J. Non-Cryst. Sol., 24, 1977.

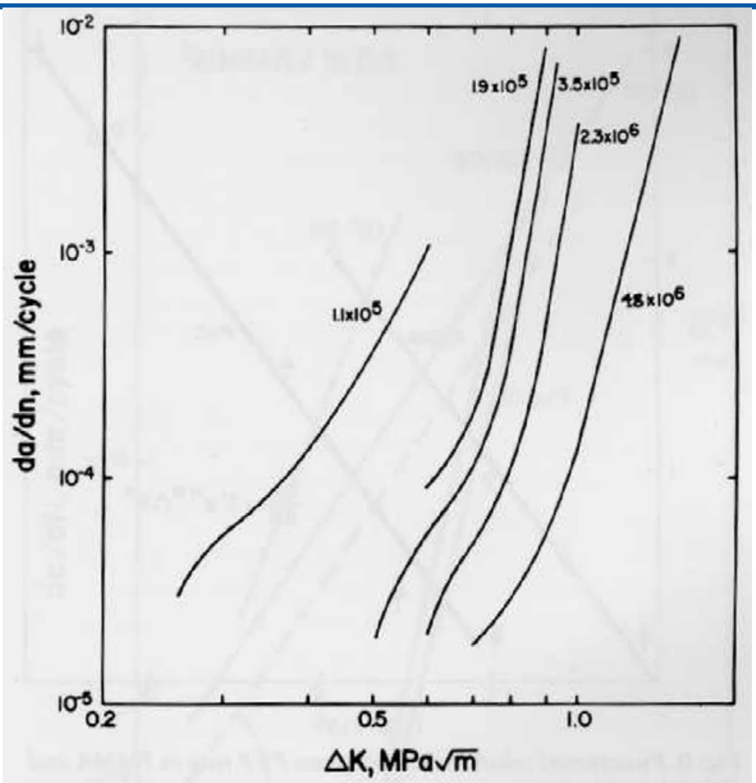
$$G = \frac{K_{IC}^2}{E} = \frac{\pi a_o Y^2 \sigma_f^2}{E} = 2(\gamma_s + \gamma_p)$$

Fracture mechanics: Griffith representation

- Unstable crack propagation (σ_f) depends on toughness (K_{IC}), greatest critical flaw (a_o)
- Embrittlement: K_{IC} varies with M_w, which decreases over time in the field
- Critical molecular weight, M_w, 10,000-100,000 (<10^4 not machinable)
- Mirror/mist/hackle fracture morphology for $M_w>10^5$

- Related mechanical concerns:
    - Buckling ⇒ fracture
    - Abrasion (tribology = *f*[*H,E*]); *H*=f[σ_y]; σ_y=f[M_w}

Mechanical Durability (Fatigue)



$\partial a/\partial N = f[M_w]$
Kim et. al., Polym. Eng. Sci., 19, 1977.

$$\frac{\partial a}{\partial N} = C \Delta K^m$$

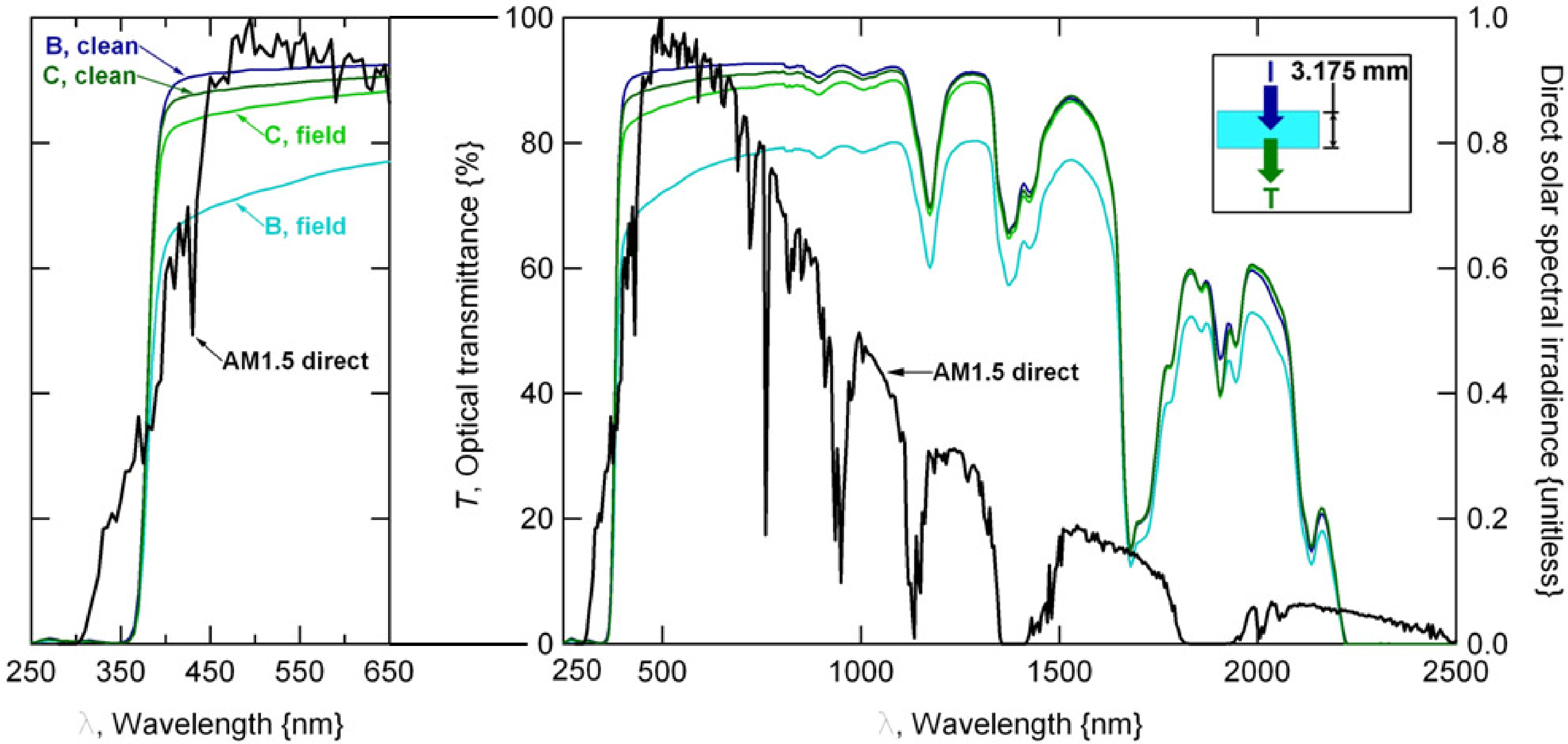
"Paris law" for crack growth rate

- Steady-state crack propagation modeled by log-linear relationship
- Hystertic heating above ~5 Hz
- Like unstable fracture, M_w & H_2O absorption can be influential

Soiling

- Contamination absorbs, scatters, and back-reflects light
- Effect most significant as $\lambda\downarrow$ (Mie scattering: $0.6/n<\pi\varnothing/\lambda<5$)
- Direct/specular light more severely affected than hemispherical

Contact angle (sessile drop) θ: 66 → 58 → 43°



Comparison of transmittance as-received and after cleaning for 19, 8 year old Fresnel lens specimens

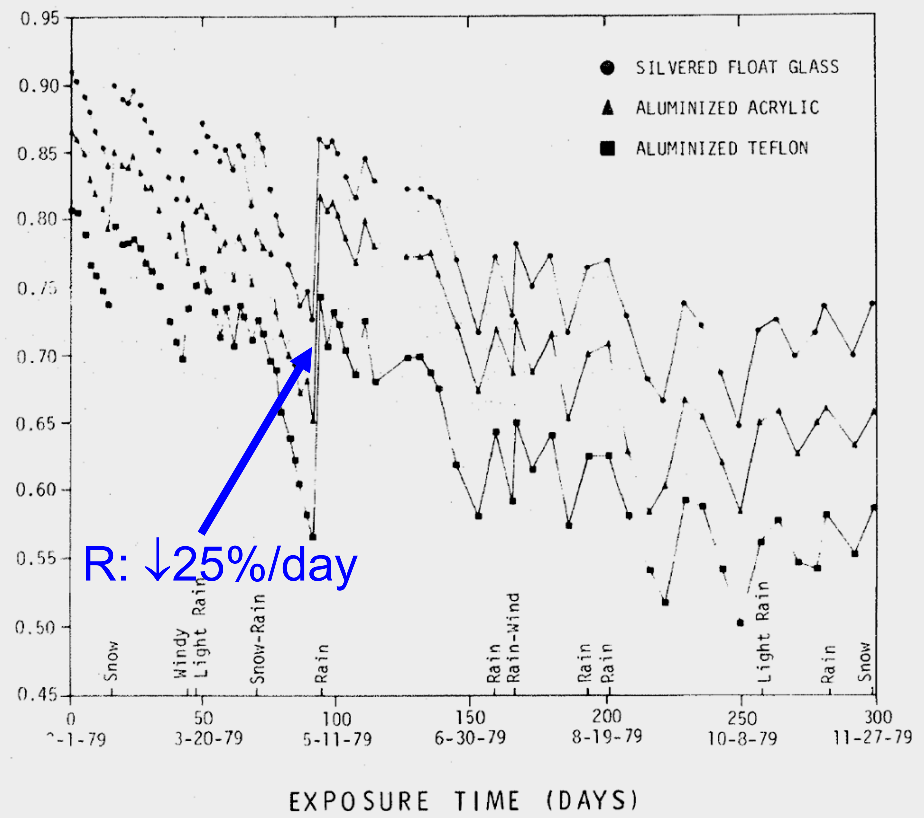
Soiling (Literature Summary)

- Issue of soiling is significant (could compromise η_{module})!
- Data from: Baja Mexico (*ocean & desert*), Europe (Spain & Italy), North & South *Africa*, *Australia*, West China might add perspective

	↓T, typical {%}	↓T, max {%}
↓T, AVG {%}	9	34
↓T, ST DEV {%}	7	26
↓T, MAX {%}	35	100

YEAR	REFERENCE	LOCATION	ENVIRONMENT	SPECIMEN(S) (FIRST SURFACE)	SPECIMEN TYPE	DURATION	↓T, typical {%}	↓T, max {%}	RECOMMENDED *f* CLEANING
1971	Hamberg []		laboratory	glass	mirror	N/A	3	42	
1974	Garg []	Roorkie, India	urban, continental	glass, PMMA	sheet	30 days	14	63	
1977	Pettit [], 1978 []	Albuquerque, NM, USA	rural, desert	glass, PMMA, Al	mirror	5 weeks	5	23	
1978	Berg []	Albuquerque, NM, USA	desert	glass	mirror	1 month	4	13	
1978	Blackmon [], []	CA, USA; NM, USA	rural, desert	glass, PMMA	mirror	1.5 years	7	14	
1978	Freese []	Albuquerque, NM, USA	desert	glass	mirror	7 months	5	[illegible]	
1979	Freese []	Albuquerqu	[illegible]	[illegible]	[illegible]	[illegible]	4	[illegible]	
1979	Nimmo []	Dhahran, S	[illegible]	[illegible]	[illegible]	[illegible]	15	N/A	
1979	Sheratte []	CA, USA; GA,	[illegible]	[illegible]	[illegible]	[illegible]	4	10	
1980, 1983	Cuddihy [], []	CA, U	[illegible]	[illegible]	[illegible]	[illegible]	9	19	
1980	Hoffman []	CA, NM, NY,	[illegible]	[illegible]	[illegible]	[illegible]	8	21	
1980	Pettit []	Albuquerqu	[illegible]	[illegible]	[illegible]	[illegible]	7.5	12	
1980	Roth [], []	Albuquerqu	[illegible]	[illegible]	[illegible]	[illegible]	10	18	
1981	Bethea []	Crosbyton	[illegible]	[illegible]	[illegible]	[illegible]	8	9.4	
1981	Morris []	A, HI, NM, NV,	[illegible]	[illegible]	[illegible]	[illegible]	15	100	
1983	Bethea []	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		44.5	
1984	Cuddihy []	AK, WA, US	[illegible]	[illegible]	[illegible]	[illegible]	6	19	
1984	Khoshaim []	Riyadh, Sa	[illegible]	[illegible]	[illegible]	[illegible]	22	33	
1985	El-Shobokshy	Riyadh, Sa	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	55	
1985	Sayingh []	Safat,	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	80	3 days
1986	Deffenbaugh []	TX,	[illegible]	[illegible]	[illegible]	[illegible]			
1987	Al-Busari []	Safat,	[illegible]	[illegible]	[illegible]	[illegible]	9	57	2/ month
1990	Nahar []	Jodphu	[illegible]	[illegible]	[illegible]	[illegible]	4	62	daily
1990	Said []	Dhahran, S	[illegible]	[illegible]	[illegible]	[illegible]	7	65	1 month
1992	Hasan []	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16	35	
1992	Pande []	Jodphur, India	arid	glass	PV module	1 year	8	30	
1993	El-Shobokshy		laboratory	glass	PV module	N/A		90	
1995	Bonvin []	Morges, Switzerland	urban	glass	sheet	1 year	5	25	
1997	Becker []	Köln, Germany	urban	glass	PV module	5 years	4	24	
1997	Hammond [], []	Phoenix, AZ, USA	urban, desert	glass	PV module	3 years	1	3	
1998	Al-Hasan []		laboratory	glass	sheet	N/A		73	
1998	Haeberlin []	Burgdorf, Switzerland	urban	glass	PV module	3 years		10	
1999	Goosens []		laboratory	glass	PV module	N/A		90	
2001	Hegazy []	Minia, Egypt	rural, desert	glass	sheet	1 month	15	26	
2003	El-Nashar []	Abu Dhabi, UAE	urban, desert	glass	desalination plant	1 year		29	
2005	Sahm []	Las Vegas, NV, USA	urban, desert	PMMA	sheet	1 year	11	24	2-4 weeks
2006	Kimber []	CA, USA	urban, desert	glass	PV site	1 year	6	27	
2008	Ruesch [], []	Davos, CH; Raperswil, CH	urban + rural, temperate	glass, PMMA, others	sheet	20 years	4.5	14	
2008	Vivar []	Madrid, Spain	rural, continental	glass, PMMA	CPV module	4 months	12	26	
2009	Banchik []	Las Vegas, NV, USA	urban, desert	PMMA	sheet	1 month	10	12	

Soiling (Over Time)



Pettit and Freese, Solar Energy Mat., 3, 1980.

- Asymptotic degradation w/ time

$$\left(\frac{1-T}{T_{clean}}\right) = d_1 erf\left[d_2 \omega^{d_3}\right]$$

(Hegazy, Renewable Energy, 22, 2001)

- *T* cannot be 100% restored to T_i
- Greater permanent retention for PMMA vs. glass

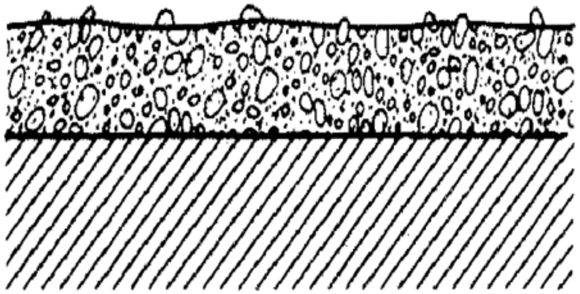
Subject to synoptic events:

- Rain: intense vs. evanescent
- Scraping effect from snow

Subject to tilt angle:

- Horizontal inclination ⇒ most soiling; vertical ⇒ least soiling
- Relates to accumulation and natural cleaning processes
- Trackers: store them face down overnight
- Uniformity… accumulation at the bottom ⇒ partial shading

Soiling (Mechanisms)



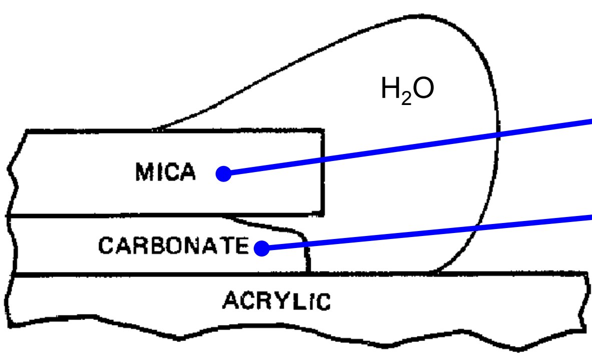
C: large ∅ (<50μm); inert; easily removed by rain
B: fine ∅ sediment; scrub to remove
A: ‘cementing’ matter; tenacious (abrasives)

In theory: Cuddihy, Solar Energy Mats, 3, 1980.

energetic gradients:
coarse ∅, non-polar organics, low γ
↑
fine ∅, polar inorganics, high γ

CPV environment:

- Great insolation, little precipitation ⇒ more prone to soiling
- Alkaline (desert) vs. acidic (temperate) soils

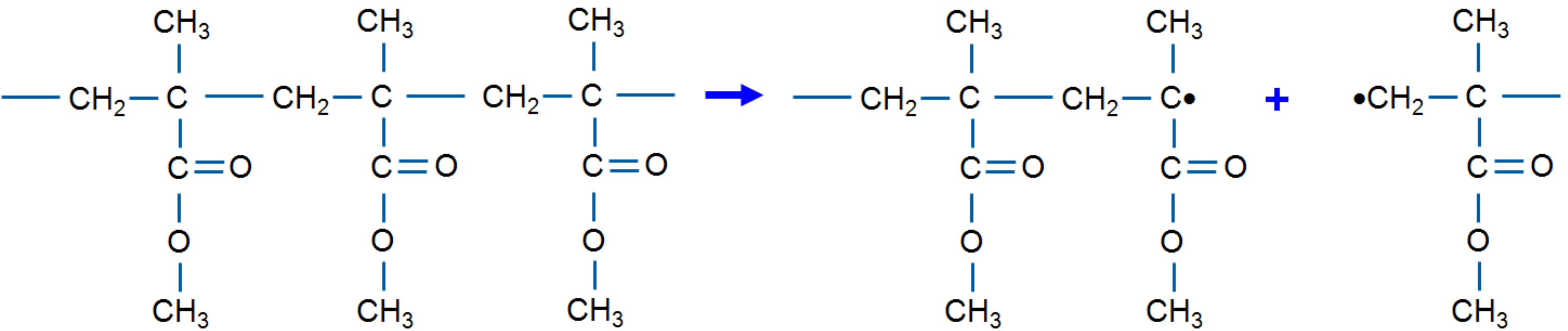


mica, quartz, feldspar

carbonates, sulfates (calcite, gypsum, halite, sylvite)
salts (external or from glass)
montmorillonoid clay

In practice: Sheratte et. al., SAND79-7052, 1979.

Photodegradation



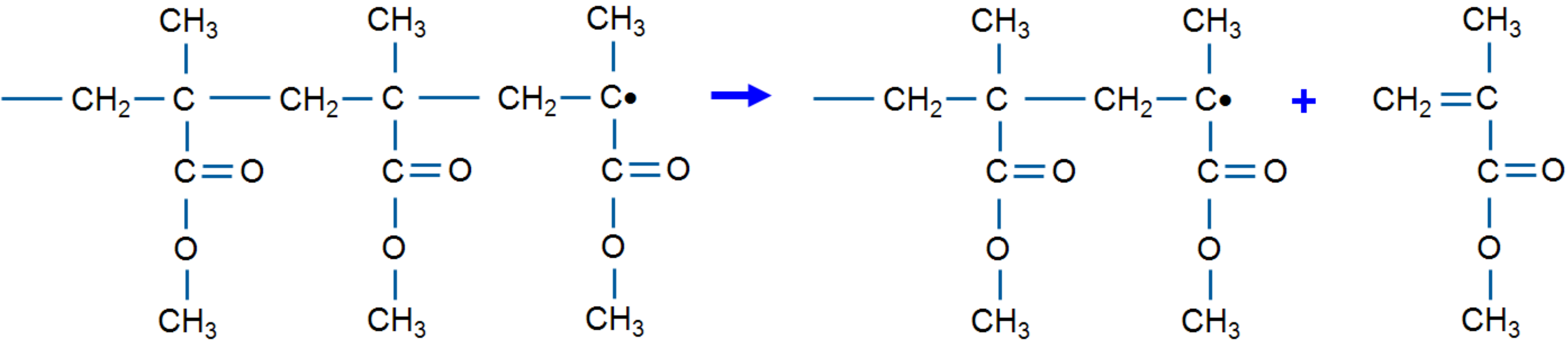
main chain scission after Aboulezz and Waters, "Studies on the Photodegradation of Poly(Methyl Methacrylate)", 1978

- Random main chain scission by UV (photolysis) ⇒ M_w therefore T_g reduced
- T_g reduced ↓~5°C after 18 years outdoors

  L.G. Rainhart & W. P Schimmel, SAND 74-0241, 1974.
- Likewise affects mechanical durability: $K_{IC}\downarrow \Rightarrow \sigma_f\downarrow$ … $\partial a/\partial N\uparrow$

- Many classic studies of quantum yield vs. λ, atmopshere
- Volatile products (vacuum): methyl formate, methanol, methyl methacrylate, plus(in air): methane, hydrogen, carbon monoxide, carbon dioxide
- Potential chromophores: residual monomer, formulation additives, co-polymers

Thermal Decomposition



chain unzipping after Aboulezz and Waters, "Studies on the Photodegradation of Poly(Methyl Methacrylate)", 1978

- Unzipping of main chain in methyl methacrylate (monomer)
- Autocatalytic process (zip length on order of 1000)
- Significant weight loss (vs. minimal in chain scission)

- Occurs readily for T>200°C
- Synergistic effect w/ irradiation (UV)⇒occurs at T<200°C
- Many classic studies of E_a vs. heating rate, atmopshere
  - O_2 suppresses decomposition

Unknowns

- Mechanical (fracture & fatigue):
  - General material characteristics understood;
    - application specific data is not available
  - Size/morphology of field-developed critical flaws
  - Dimension stability, *e.g.* facets
- Soiling (lots!):
  - Comparison between key world sites
  - Solution methods (fluorination, roughening, or doping the first surface)
  - Tracking vs. fixed modules
- SOG:
  - No literature (concerning durability)
  - Significant $\Delta\alpha \Rightarrow$ delamination?

Summary

NREL study:
- Identify key issues for contemporary specimens

Optical durability:
- Evolution of location & distinctness of cut-on frequency

Mechanical durability (K_{IC}, $\partial a/\partial N$):
- Fracture, fatigue strongly depend on M_w
- Embrittlement over time

Soiling:
- Complex issue that may vary significantly over time w/ location

Photodegradation:
- Chain scission $\Rightarrow$ decreased M_w

Thermal decomposition:
- Chain unzipping $\Rightarrow$ decreased mass

SOG:
- Probably physically robust against soiling; limited existing literature

Acknowledgements

- NREL: Daryl Myers, Marc Oddo, Robert Tirawat, Bryan Price, Matt Beach, Christa Loux, Kent Terwilliger

- Others: Ralf Leutz (Concentrator Optics Inc.), John Wiedner, Michael Longyear, Scott Steele (Arizona Public Service, S.T.A.R. facility)

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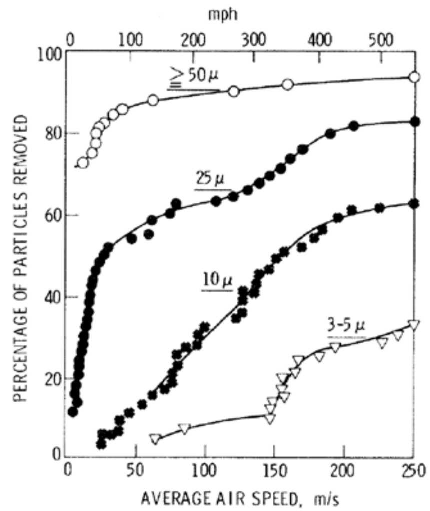
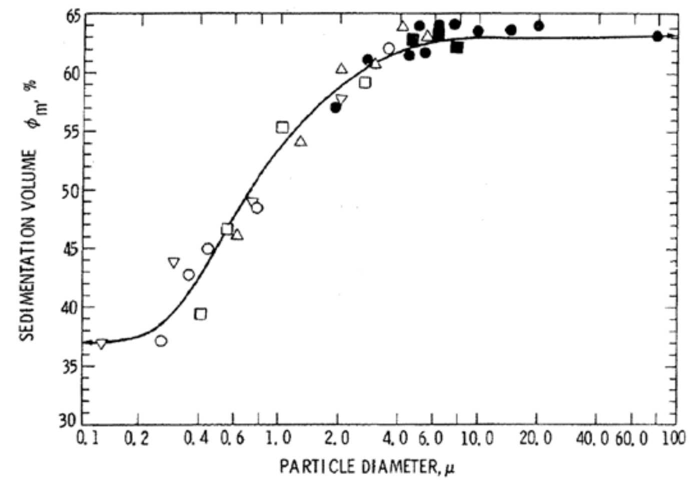
This work was supported by the U.S. Department of Energy under Contract No. DOE-AC36-08GO28308 with the National Renewable Energy Laboratory.

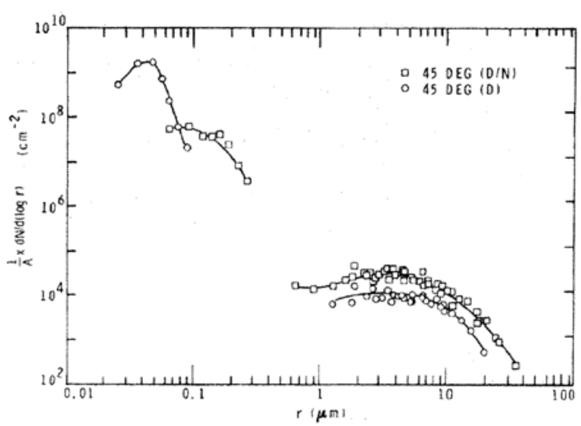
Xtras

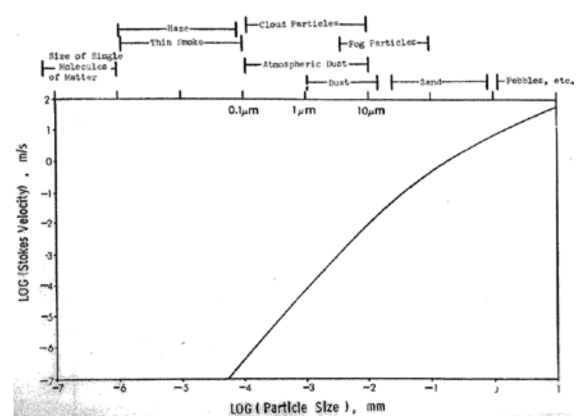
- Some useful additional figures…





Cuddihy, Solar Energy Mats, 3, 1980.





Particle size for natural cleaning; day only (152) vs. day & night (396 hr)
Roth and Anaya, Trans. ASME, 1980.

Berg, SAND78-0510, 1978.

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