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

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2010/10/21 (Thurs)
17:00 – 17:20 (Germany)
9:00-9:20 (US)

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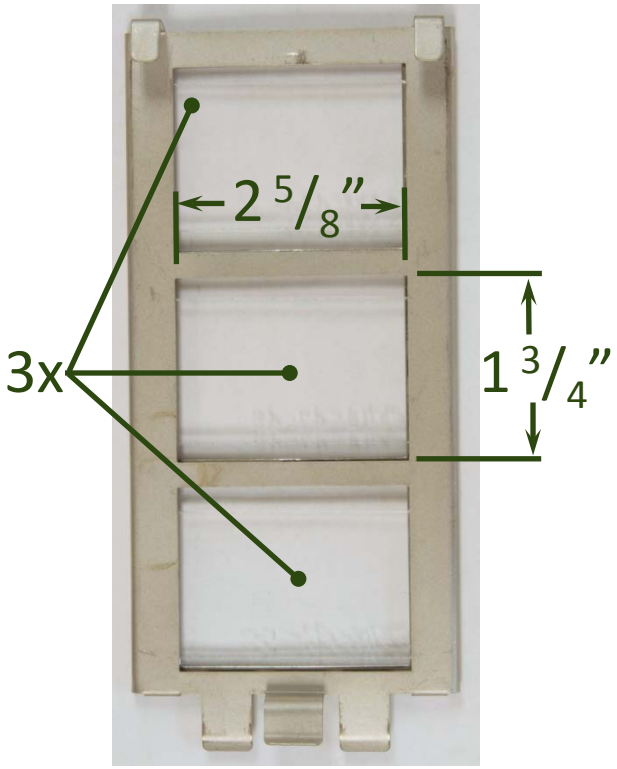
Purpose- and Details- of Screen Test at NREL

- Literature ⇒ studies initiated ≥20 years ago
- Goal here: characterize the durability of a broad range of ***contemporary*** specimens subject to indoor HAST



Test specimens (4.4 x 6.7 cm²)

DESCRIPTION	SPECIMEN TYPES
stock (unpatterned)	11
linear focus lens	1
spot focus lens	8
veteran (fielded) lens	3

- Veteran specimens on tracker in desert site, seldom cleaned (8, 22, 27 yrs)

- Test instrument: ATLAS Ci4000 Weather-ometer (Xenon-arc lamp @ 2.5x UV suns. Chamber @ 60°C/60%RH); *1 exception

Details of NREL Screen Test

- Measurands:

  Periodic

  optical appearance (photograph)

  → optical transmittance (hemispherical)

  mass

  → contact angle (sessile drop, H_2O on 1st surface)

  "**End of life**"

  haze (from direct transmittance)

  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, before & after cleaning)

- Test schedule:

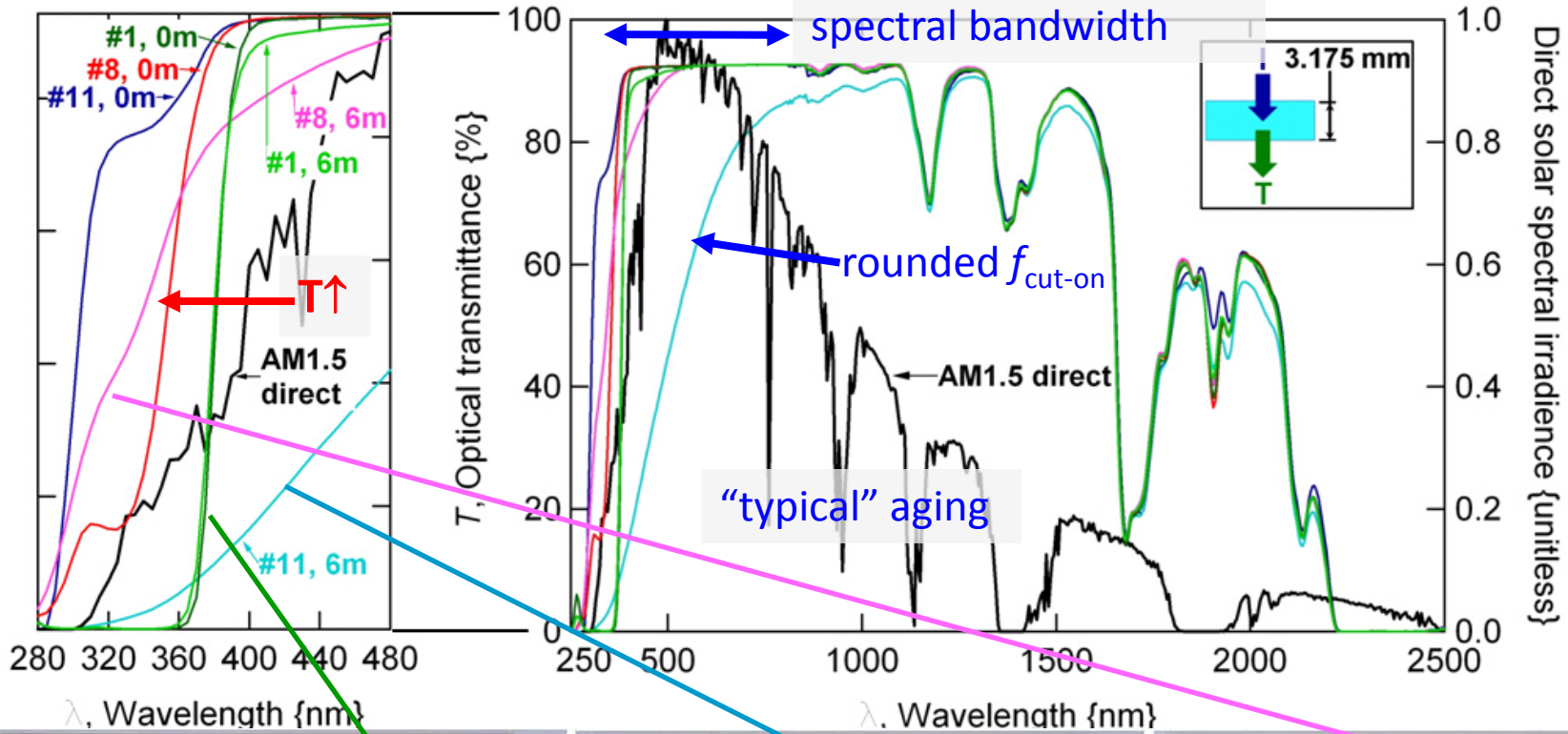
  0, 1, 2, 4, **6**, 12, 18, 24, 30, 36 months

  ≥8 acceleration factor (irradiance and 24 hour operation)

  pull 1 of replicates every 12 months

Transmittance is Reduced by Aging

- "Optical Durability" = transmittance as f[t]
- Lambda 900 (Perkin-Elmer) spectrophotometer (w/ integrating-sphere)

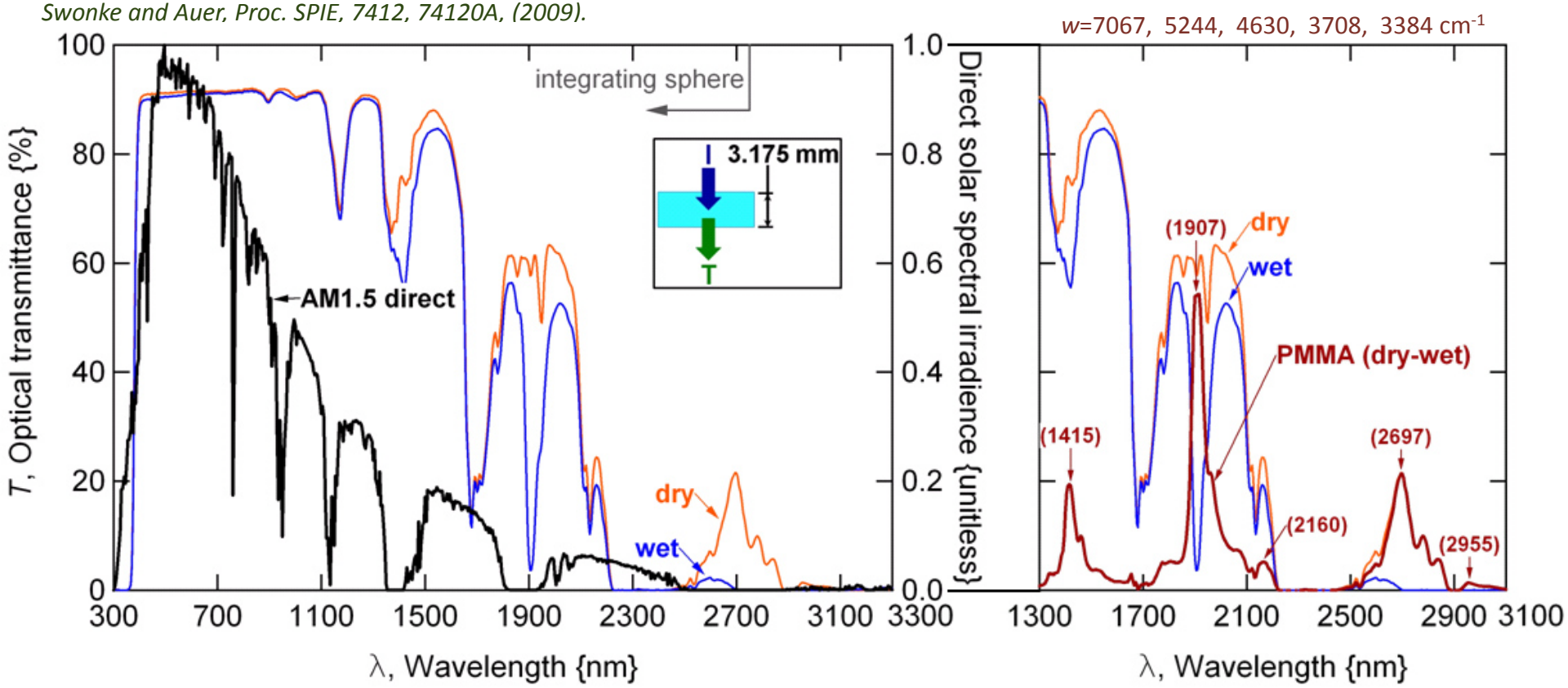


Measured transmittance at 0, 6 months for best and worst sheet stock specimens

Effect of H_2O on Transmittance

- Specimens maintained for >1 month in dry box (≤0.1 ppm H_2O) or DI
- Traditional λ's to estimate H_2O dissolved in polymers: 1.9, 2.7 μm

Kapur, et. al., Proc. IEEE PVSC, 001210-001214 (2009).
Swonke and Auer, Proc. SPIE, 7412, 74120A, (2009).



- Verified in direct- & hemispherical-T measurements
- H_2O solubility (≤2.5 wt.%) primarily affects unharvested IR λ's
- UV & vis (PV) unaffected; weathering results are *not* H_2O absorption!

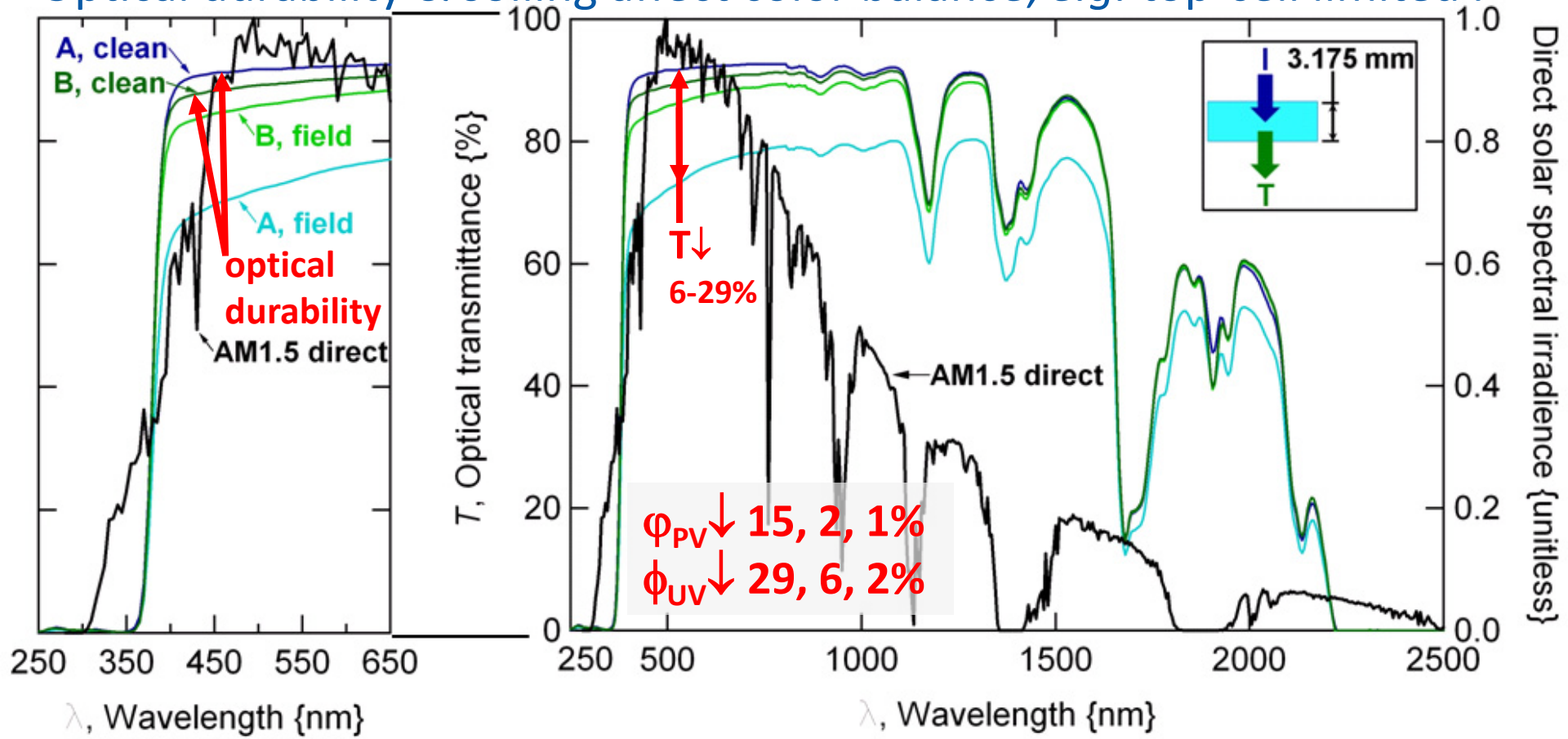
Measured transmittance for wet & dry stock specimens (unaged)

Transmittance is Reduced by Soiling

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

***Remember also**:

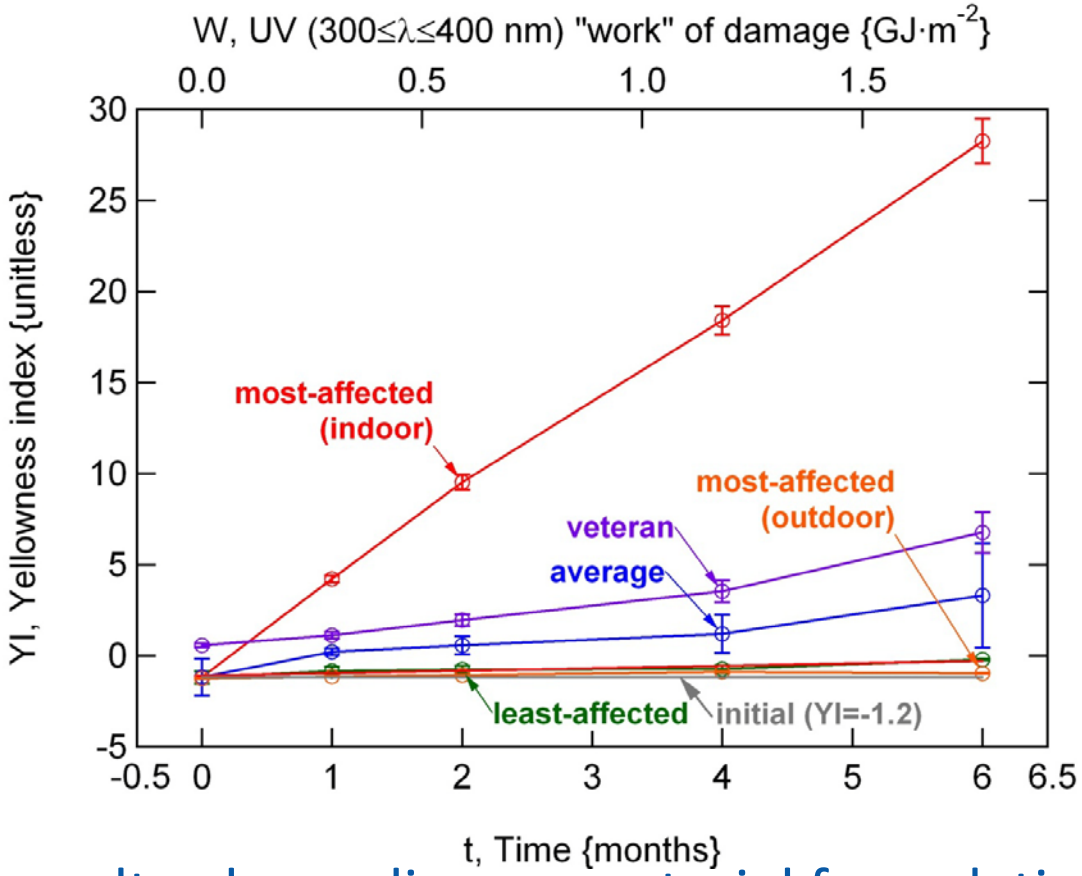
- Direct light (CPV) more severely affected than hemispherical (FP-PV)
- Optical durability & soiling affect color balance, *e.g.* top-cell limited I



Measured transmittance, as-received and after cleaning for 22, 8 year old Fresnel lens specimens

Yellowness Index (YI) Distinguishes Formulations, Aging Methods

- YI (ASTM E313 & E308 [D65 source, 10° observer]) quickly quantifies degradation



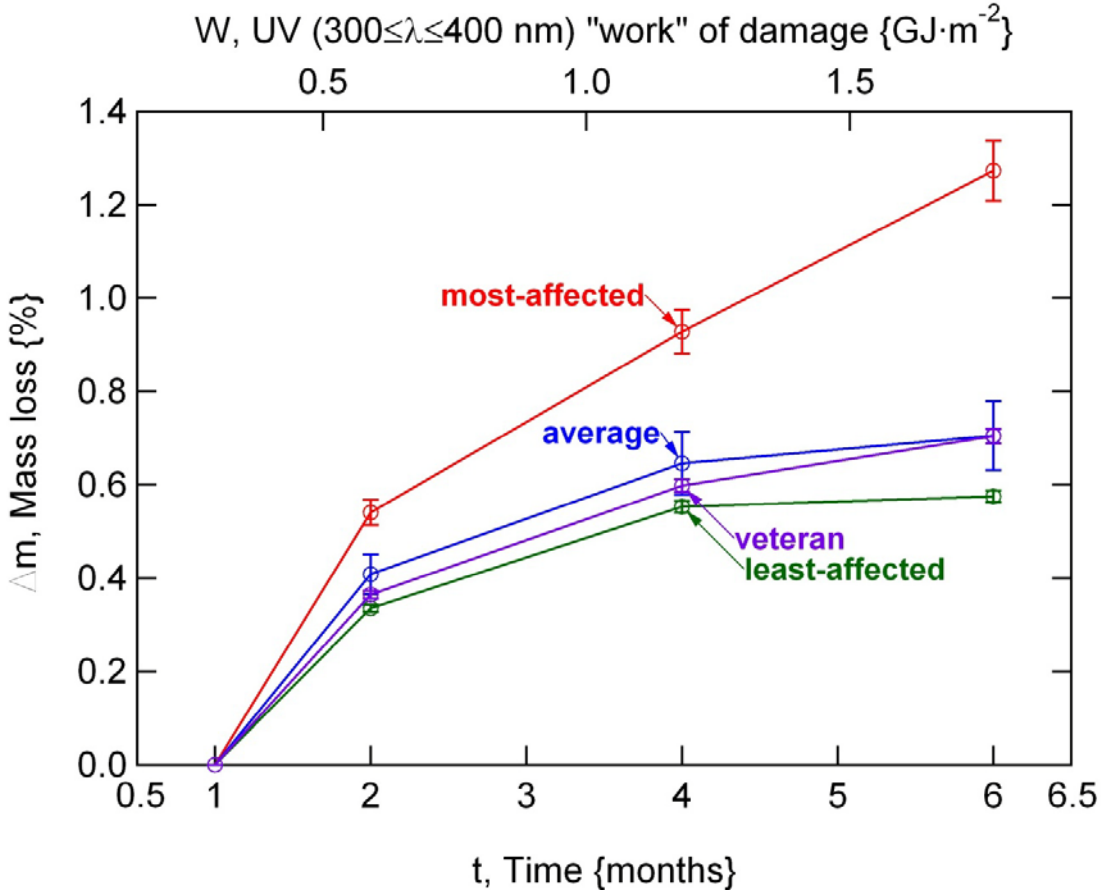
- Range of results, depending on material formulation. Not all the same!
- Damage rate indoors/outdoors = 220x for same (unstabilized) material
- Suggests synergy between UV, temperature, and/or humidity

*YI determined from raw hemispherical transmittance measurements (proportional to visual appearance). *Outdoor YI plotted for time only.*

Volatile Species (Mass Loss) Resulting From Aging

- Non-linear asymptotic trend (as great as 1.27%)
- Process of outward diffusion? (Degradation products and/or additives).
- Literature: 4.4% mass loss for chain scission (70 hours @ 300 nm)

  Abouelezz and Waters, Studies on the Photodegradation of Poly(Methyl Methacrylate), NBSIR 78-1463, (1978), 1-55.
- If photolysis, then volatile content proportional to cumulative damage



mass loss determined , starting after 1 month indoor aging.

The Expected Correlation Between YI, and UV/ PV Flux

- Table summarizes the 9 *standard* transmitting stock specimens

		t, TIME {months}				
CHARACTERISTIC	UNIT	0	1	2	4	6
PV photon flux	$\gamma \cdot m^{-2} \cdot s^{-1}$	723±3	724±3	721±4	725±3	719±6
UV energy flux	$W \cdot m^{-2}$	14±8	17±8	17±7	17±8	16±9
IR energy flux	$W \cdot m^{-2}$	7±0	7±0	7±0	7±0	7±0
YI	unitless	-1.2±0.1	0.2±1.4	0.6±1.4	1.2±1.7	3.3±2.9
$\lambda_{cut\text{-}on}$	nm	363±36	369±28	370±28	364±33	379±24
Δm, MASS LOSS	%	N/A	0.000±0.000	0.408±0.048	0.646±0.059	0.705±0.074
Θ, CONTACT ANGLE	degrees	N/A	66±1	60±1	58±2	61±4

Contact Angle is Reduced by Aging

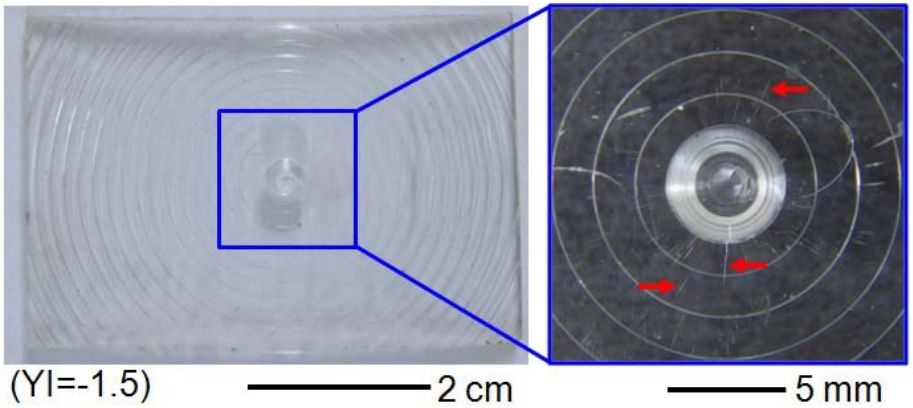
- Θ relates to accumulation and retention of particulate matter
- Θ: 66 → 58 → 43° (for unaged → aged → veteran)
- More easily cleaned, but more rapid to accumulate soil

- Partially restored by cleaning at 6 months … surface accumulation?

Mechanical Damage from Aging: Cracks and Haze

Cracks:

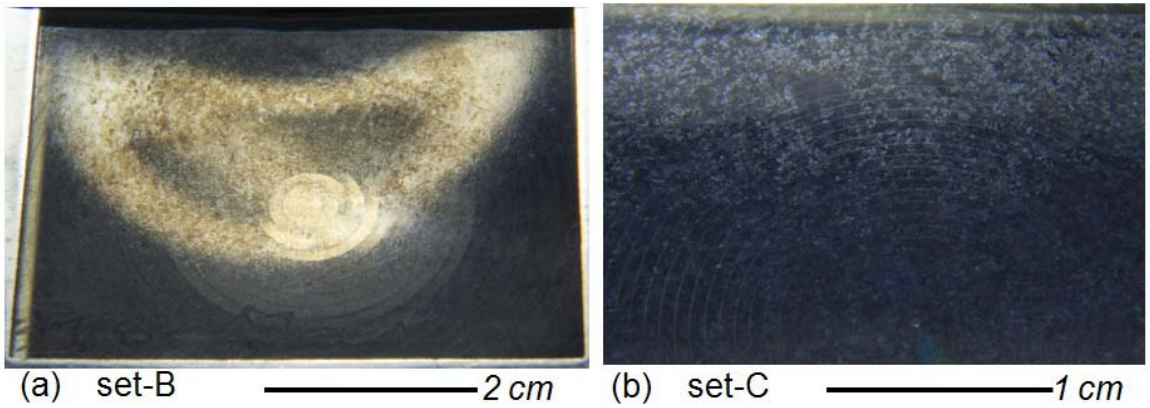
- Radial cracks in domed spot-focus lens (85°/85%RH)
- Cracks could motivate failure on impact; could grow via fatigue



Optical photograph , where arrows indicate cracks (3/3 specimens)

Haze:

- As-received veteran specimens demonstrate haze
- Surface erosion or microcracks detrimental to direct solar flux

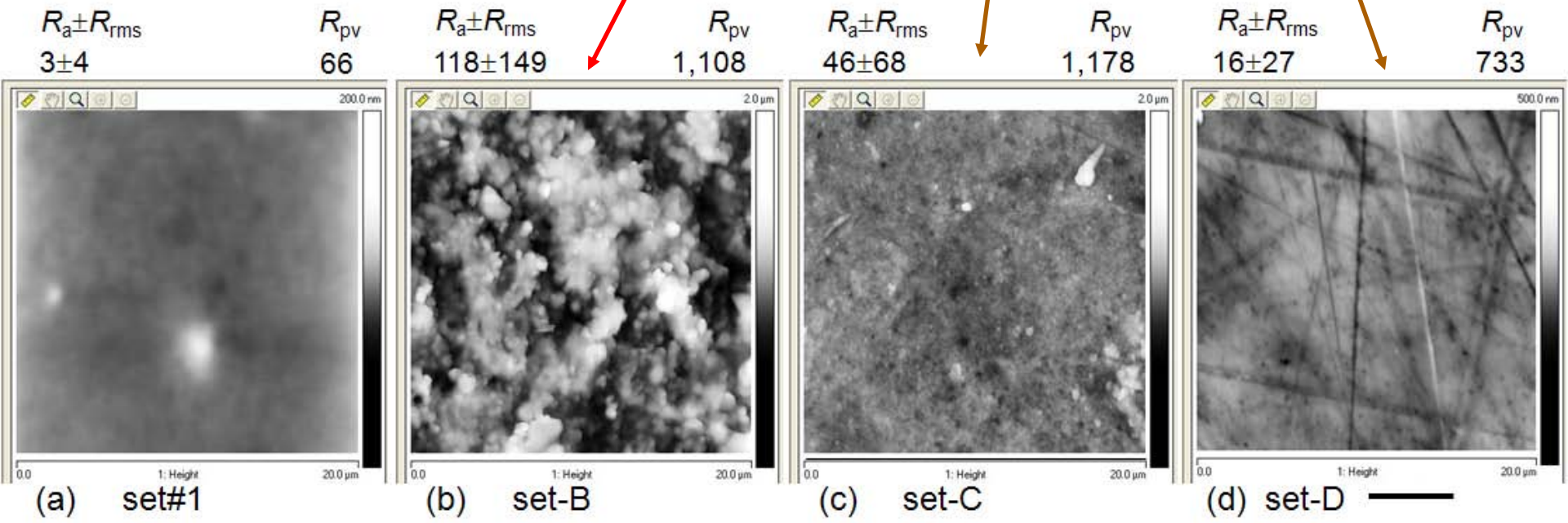


Optical photograph , where contrast indicates surface damage (each, 3/3 specimens)

Surface Roughness Identifies the Causes of Haze

- 90x90 & 20x20 μm^2 topography atomic force microscopy (AFM) scans
- Largest features (width/depth): 3850/340, 1540/88, 2350/72 nm
- Veteran specimens:
  - (a) abrasion/erosion, (b) scratches from cleaning,
  - (c) embedded material (Si) in set-B
- Erosion much less significant for mounting ≥2m (less airborne PM).

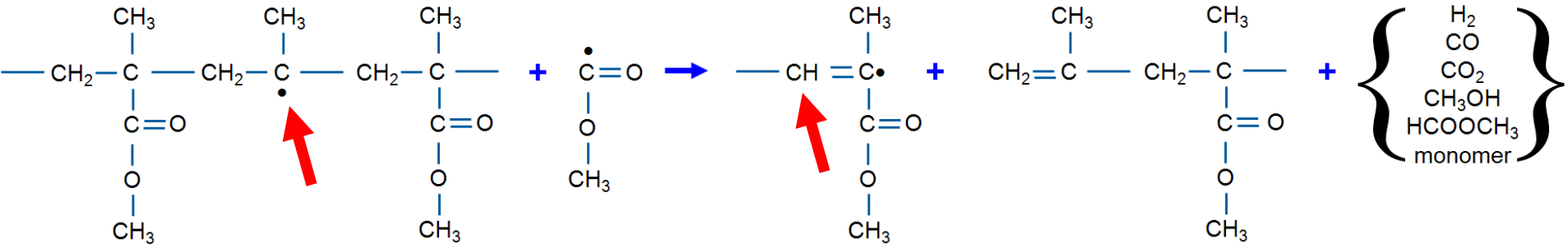
Thornton, "The Effect of Sandstorms on PV Arrays and Components", Proc. Solar, 81-85, (1992).



Roughness of unaged stock specimen relative to as-received (but cleaned) veteran specimens (27, 8, 8 years service)

A Summary of Photolysis From the Literature

- Dominant mechanism suggested in literature & suspected here



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

- Random main chain scission by UV (photolysis) $\Rightarrow M_w$ therefore T_g reduced
- T_g reduced $\downarrow$~5°C after 18 years outdoors

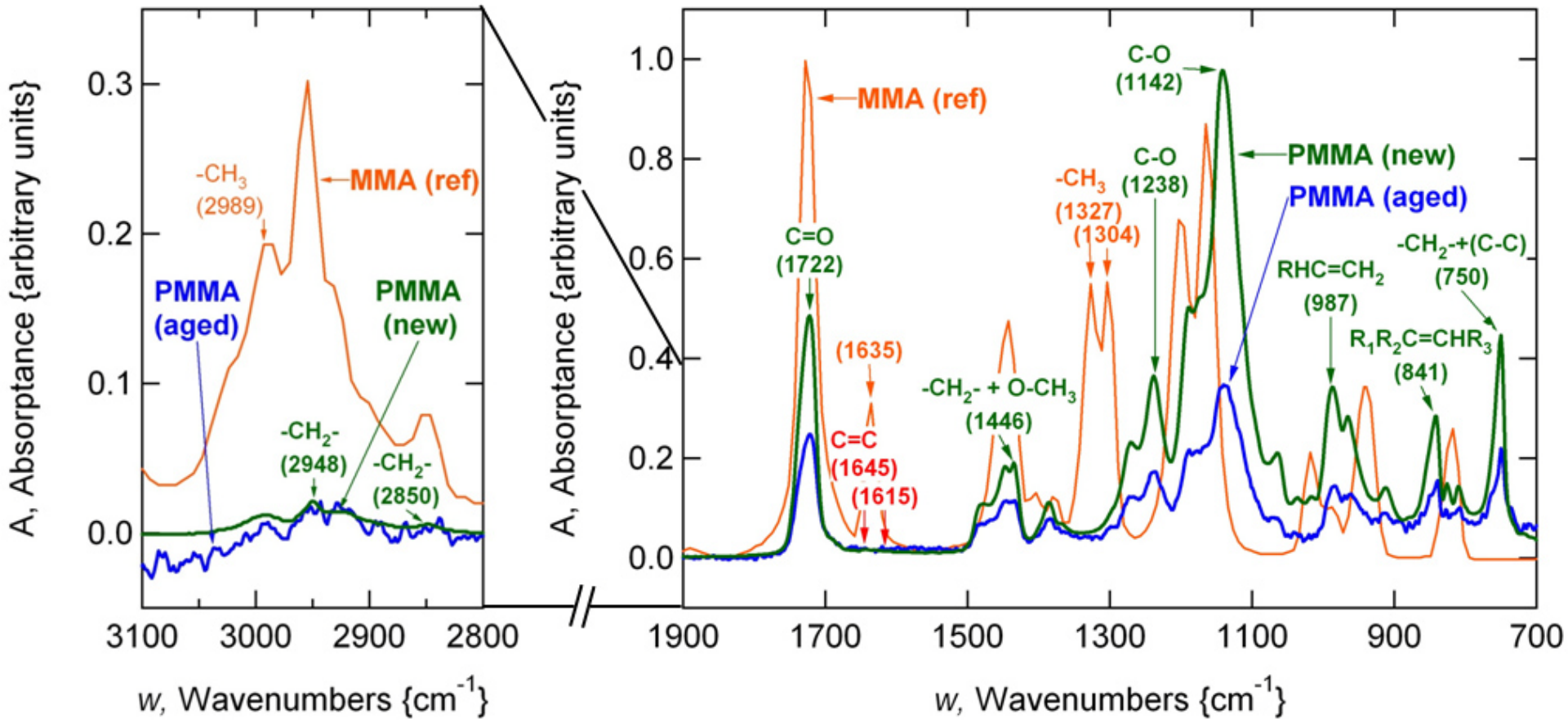
  L.G. Rainhart & W. P Schimmel, SAND 74-0241, 1974.

- $M_w\downarrow$ likewise affects mechanical durability: $K_{IC}\downarrow \Rightarrow \sigma_f\downarrow$ … $\partial a/\partial N\uparrow$

Fourier Transform Infrared (FTIR) Spectroscopy

*May identify changes in the molecular structure, but not vulnerability

- Magnitude major peaks reduced, consistent with chain scission
- All major peaks related to ester (C=O), (C-O), or methylene (-CH_2-)
- Technique not recommended for regular diagnosis of PMMA



Surface spectra of unaged and aged specimens (set#11) obtained using FTIR-ATR relative to reference spectrum for PMA monomer

The Progress Report … (Summary)

- Transmittance:
  - UV cut-on *f* , spectral bandwidth compromised by aging
  - Notable IR absorption @ 1415, 1907, 2697 nm from H_2O
  - Soiling⇒trends as in optical durability. (Blue) current limited?
- YI: This figure of merit may imply a synergy between UV, T, and/or RH
- Mass loss (on order of x%) may result from photolysis
- Θ decreases with time. Formation of water soluble surface layer?
- Erosion, scratching of surface quantified for veteran specimens
- FTIR: changes after 6 months consistent with chain scission… will verify

"Theme": from change in characteristics examined, photolysis suspected from the literature … will verify in future with "end of life" (12 month) measurements

*Future: Work with a SOG lens? Your participation solicited for round 2!

Acknowledgements

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

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

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See also:

This study: D.C. Miller, L.M. Gedvilas, B. To , C.E. Kennedy, and S.R. Kurtz, "Durability of Poly(Methyl Methacrylate) Lenses Used in Concentrating Photovoltaics", Proc. SPIE, 2010, 7773-02.

Literature review: D.C. Miller and S.R. Kurtz, "Durability of Fresnel Lenses: A Review Specific to the Concentrating Photovoltaic Application", submitted to Solar Energy Materials and Solar Cells

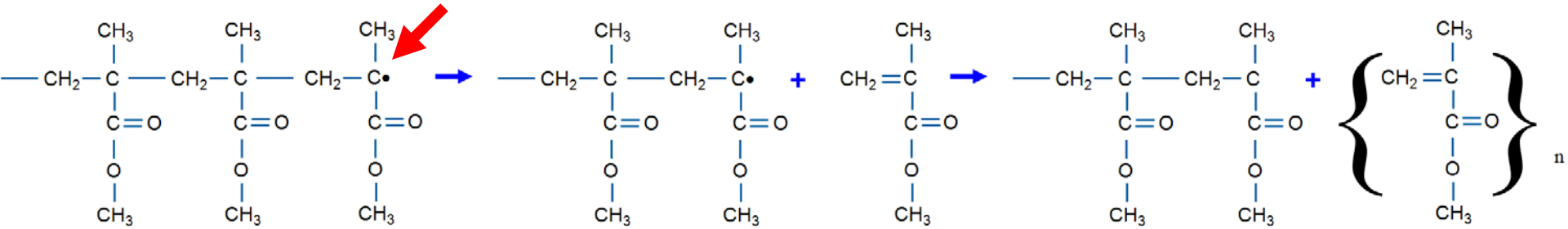
Questions

- Have you specifically studied the affects of cleaning (abrasion)?
- What about acid rain (the chemsitry of outdoor rain)
- What can be learned/said about the (chemistry/additiives/mW) most durable formulations
- Is there a change in the refractive index?
- XXX
- XXX
- XXX
- XXX
- XXX

XXX

Thermal Decomposition

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



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

- 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