NREL
NATIONAL RENEWABLE ENERGY LABORATORY

"The Durability of Polymeric Encapsulation Materials for Concentrating Photovoltaic Systems"

David C. Miller[1], Matt Muller[1], Michael D. Kempe[1], Kenji Araki[2], Cheryl E. Kennedy[1], and Sarah R. Kurtz[1]*

1. National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO, USA 80401
2. Daido Steel Co., Ltd. 2-30 Daido-cho, Minami, Nagoya 457-8545, Japan
* David.Miller@nrel.gov

2012 PV Module Reliability Workshop

(Denver West Marriot, Golden, CO)

8:30-8:50 am, 2012/3/01 (Thursday)

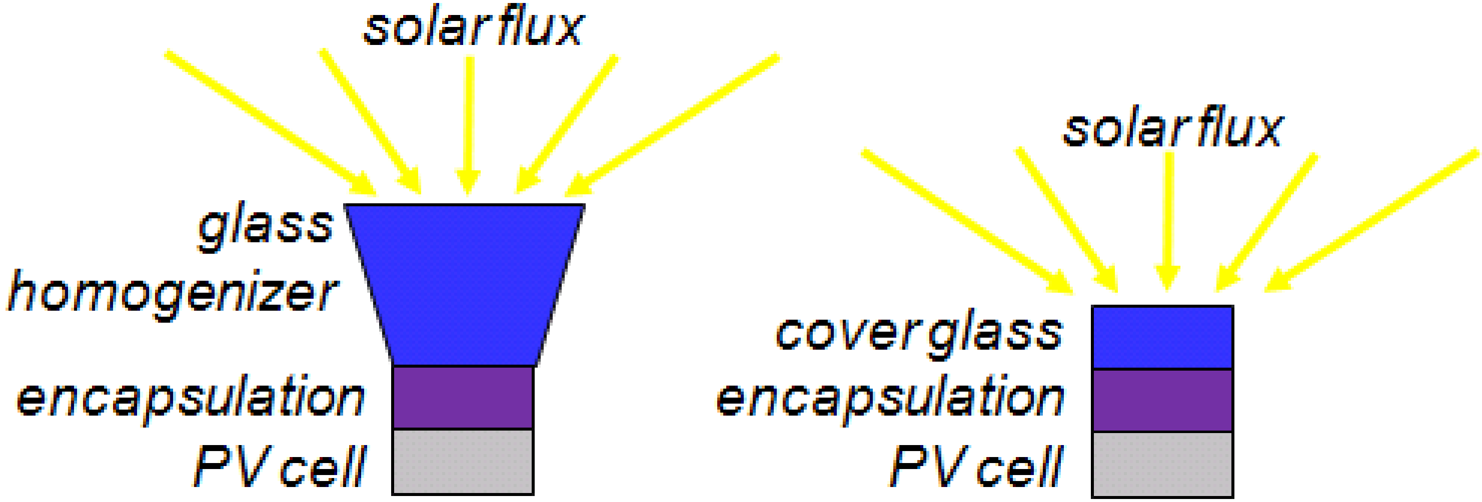
Golden Ballroom

-this presentation contains no proprietary information-

NREL/PR 5200 54524

Motivation for the NREL Field Study

- Concentrating Photovoltaic (CPV) modules use cost effective optics ($) to focus light onto high efficiency (η=44%) multijunction cells ($$$$$)



cross-sectional schematic of the components near the cell in CPV systems (not to scale)

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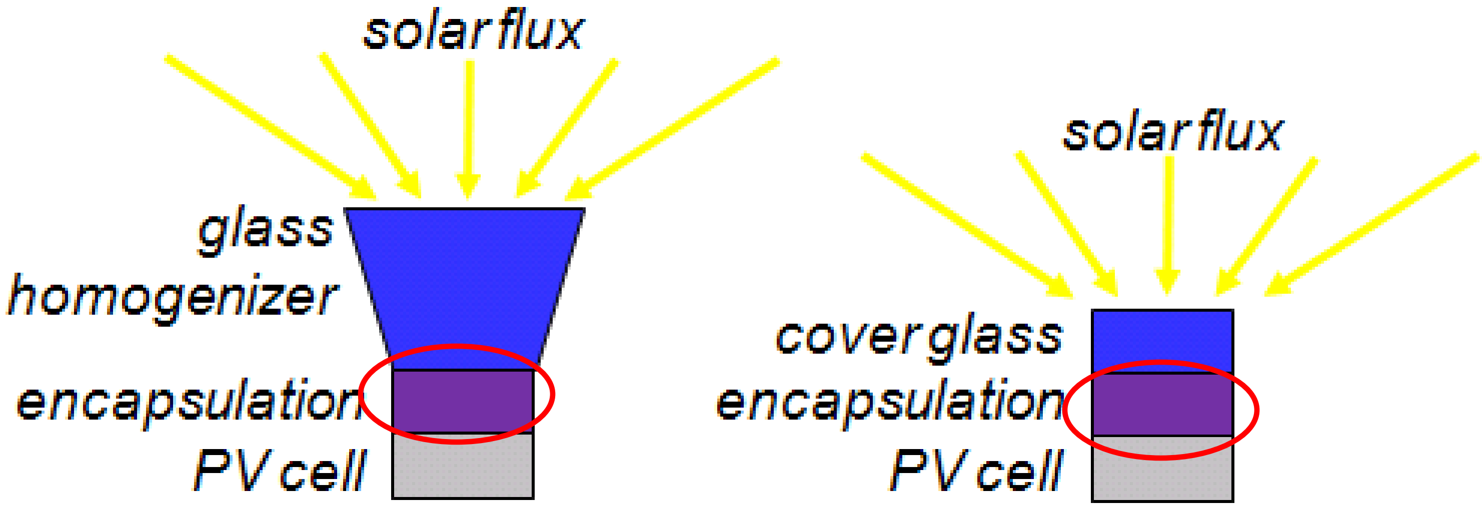

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corrosion prevention, optical coupling : CPV systems typically use encapsulation to adhere optical component(s) or cover glass to the cell

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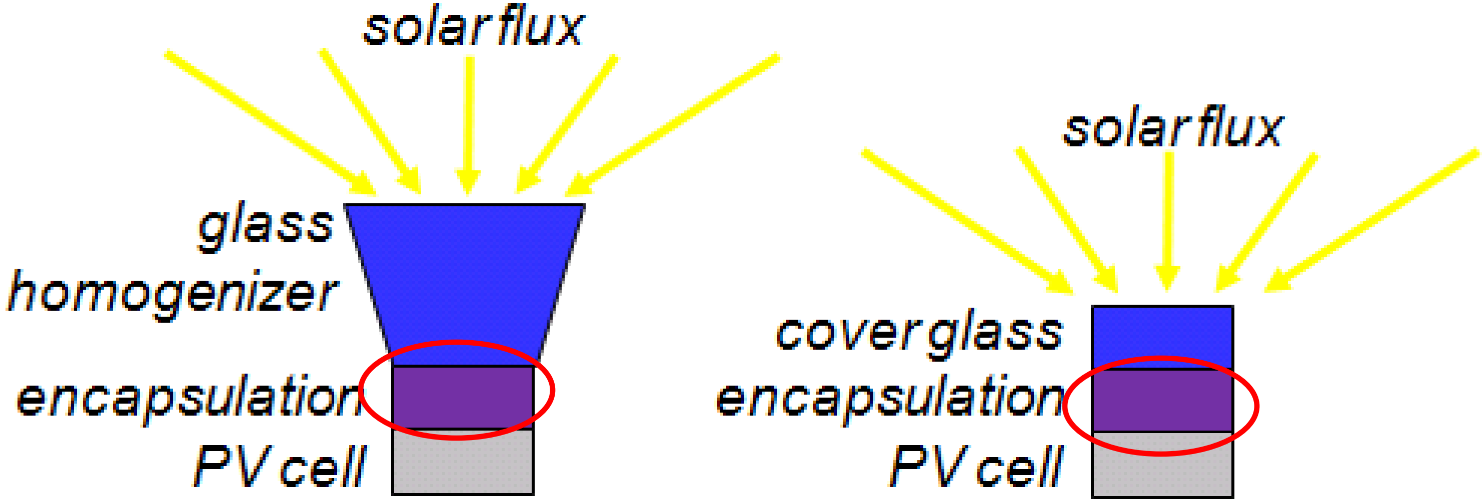

cross-sectional schematic of the components near the cell in CPV systems (not to scale)

corrosion prevention, optical coupling : CPV systems typically use encapsulation to adhere optical component(s) or cover glass to the cell

encapsulation durability (30 year field deployment) is unknown:

- identify field failure modes
- gain insight related to failure mechanisms
- distinguish between material types
- identify materials for future study (HALT & qualification tests)

Details of the Experiment (Specimens & Apparatus)

Miller et. al., PIP, DOI: 10.1002/pip.1241.

	MATERIAL	ON-TEST	IN QUEUE
hydrocarbons (representative types)	EVA	6	2
	ionomer	2	0
	polyolefin	1	1
	PVB	2	0
	TPU	1	2
silicones (representative grades)	PDMS	11	5
	PPMS	2	1
	TOTAL	25	11

test coupons are mounted in a modified CPV module product on a 2-axis tracker in Golden, CO

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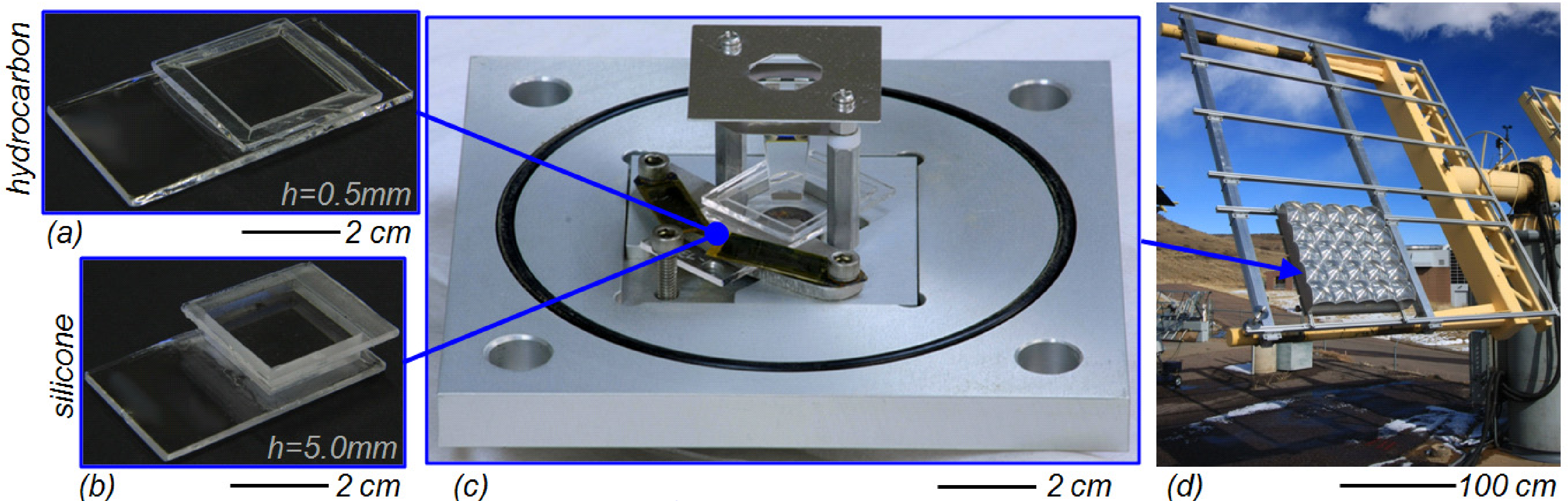

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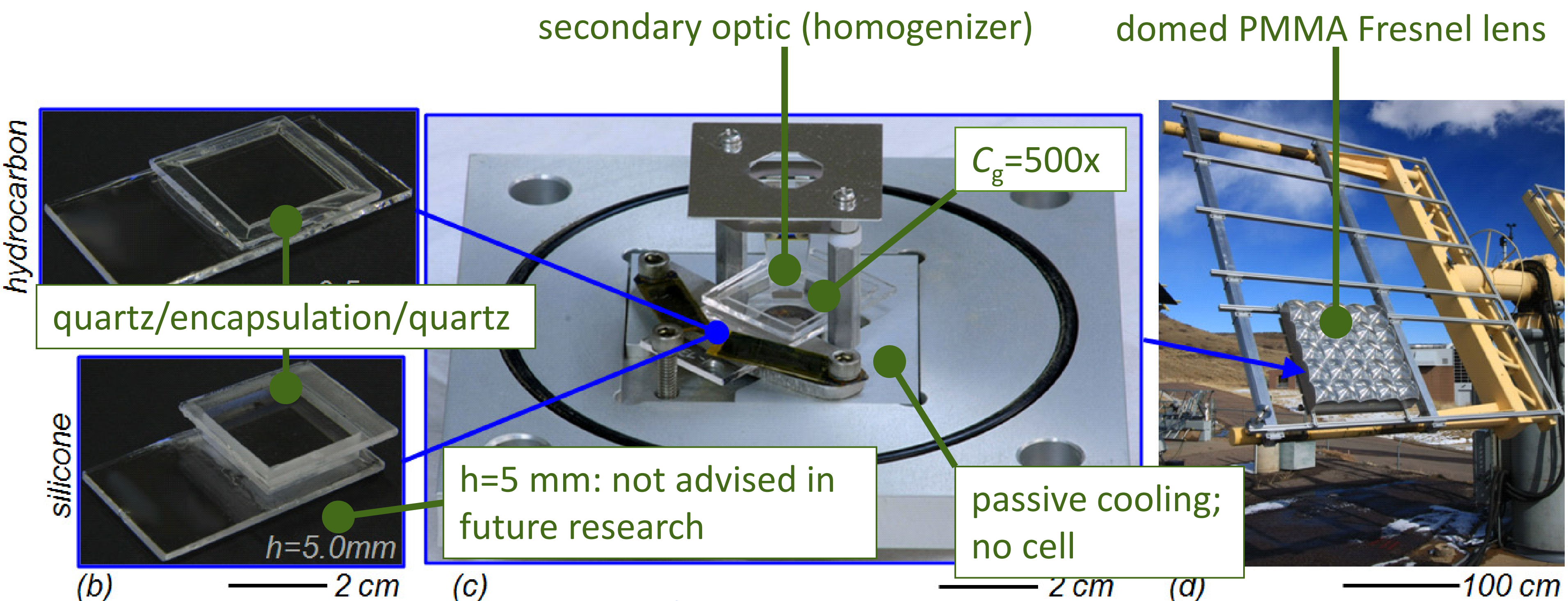

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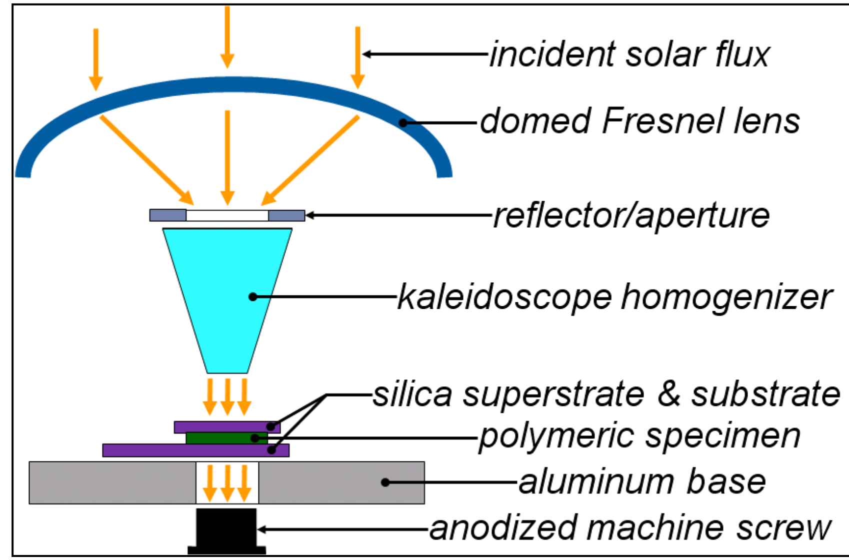
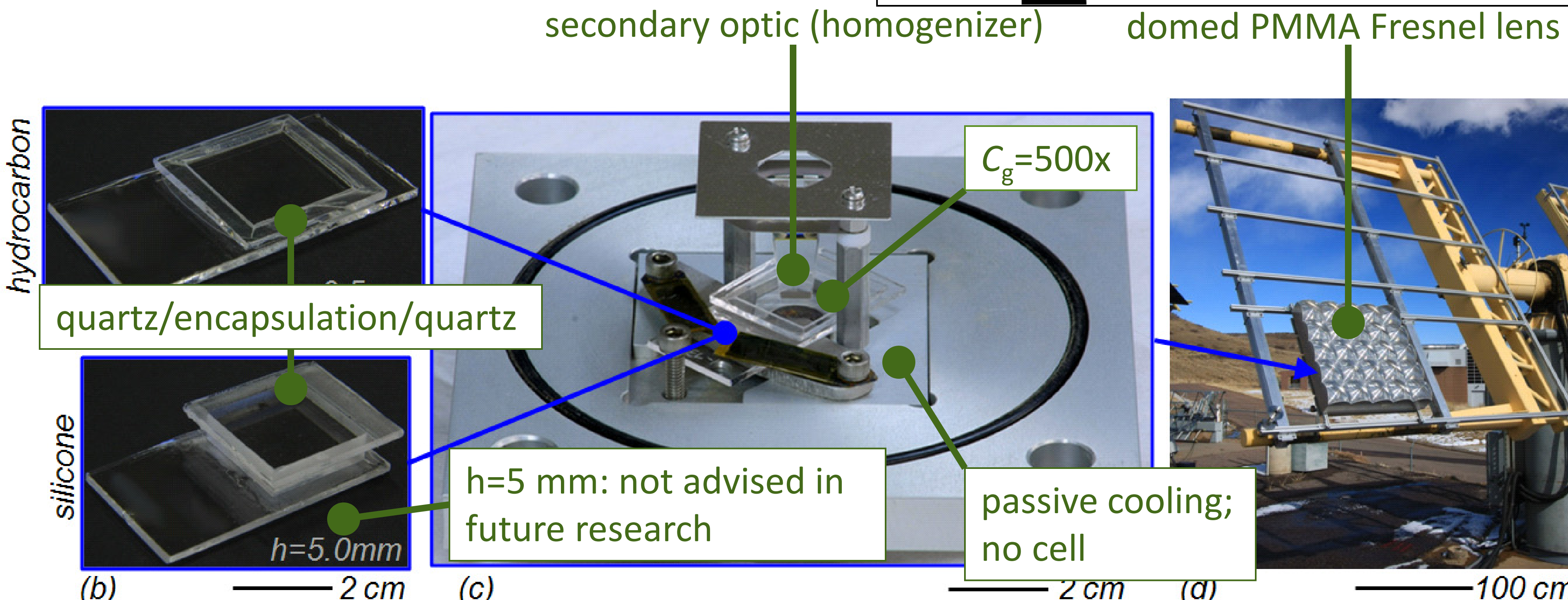




test coupons are mounted in a modified CPV module product on a 2-axis tracker in Golden, CO

Details of the Experiment (Measurands & Schedule)

"Continuous" measurements:

ambient conditions (irradiance, temperature, wind…)
fixture temperature (via thermocouple)

Periodic measurements:

→ transmittance ($T[\lambda]$, hemispherical & direct)
mass
appearance (photograph)

⇒ from $T[\lambda]$, calculate: yellowness index (D65 source,1964 10° observer), haze, $\lambda_{cut\text{-}on}$ …

→ fluorescence spectroscopy

Final measurements:

FTIR, RAMAN, NMR
TGA, DSC (polymer physics)

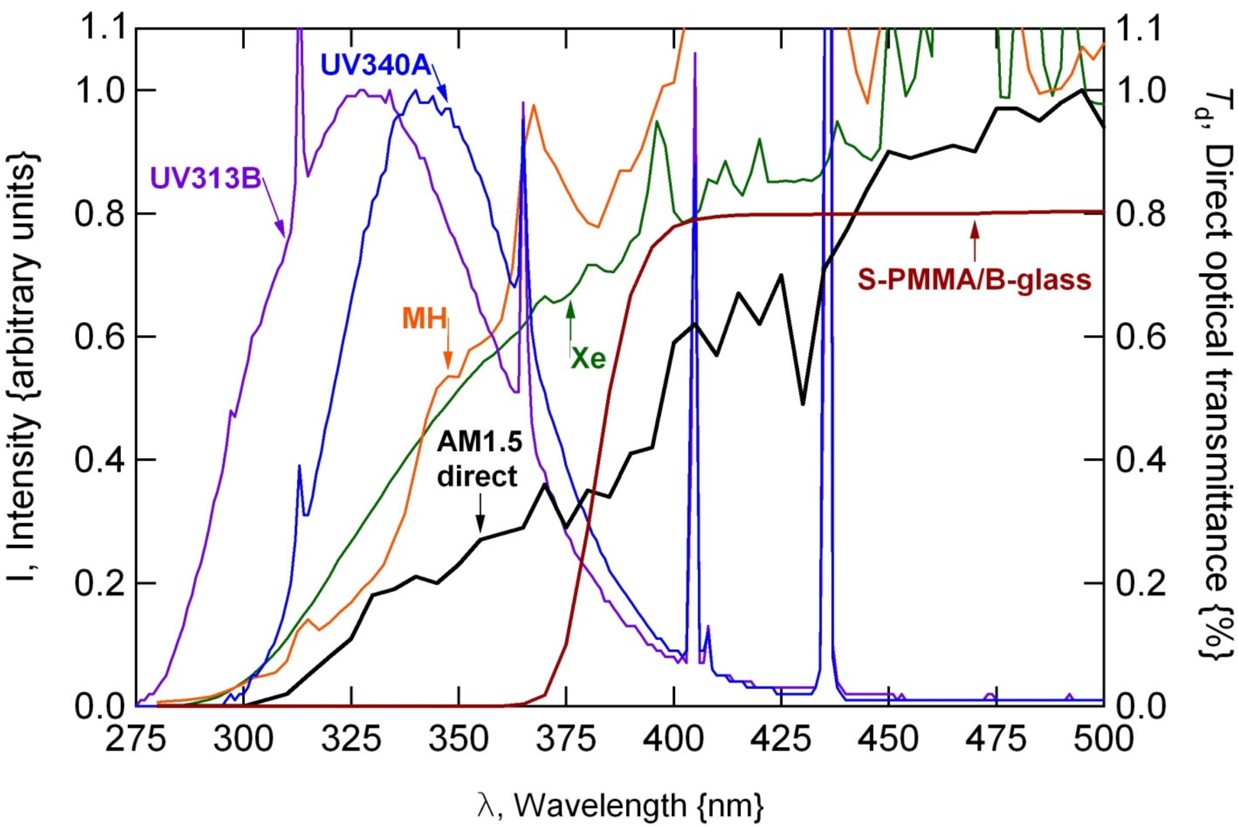
Test schedule:

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

Optical Irradiance May Vary from CPV Transmittance

•PMMA transmits little (T=1%) UV flux, λ>390 nm

•Thermal content therefore has increased significance (coupled UV & thermal degradation)



•Some popular indoor sources (UV 313V, UV340A) are completely inappropriate for a PMMA-enabled CPV system

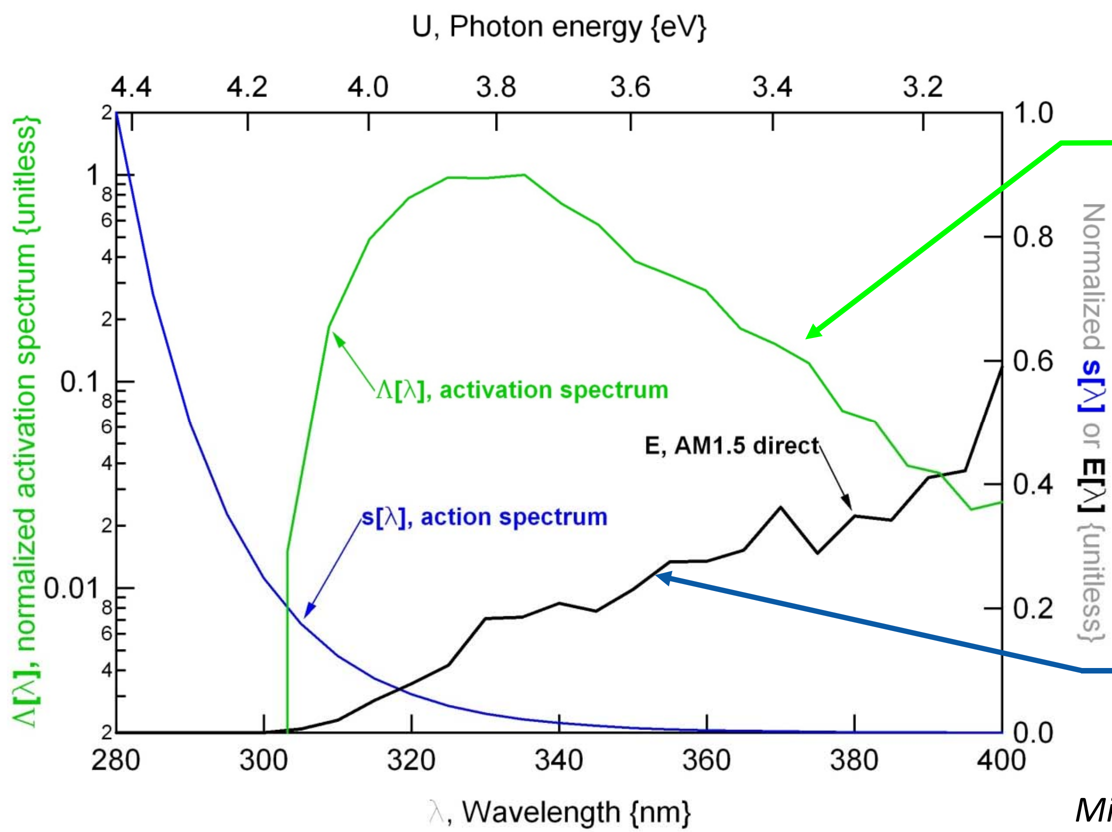
•SoG Fresnel lens is substantially more transmitting (T=89%) of UV

Miller et. al., PIP, DOI: 10.1002/pip.1241

Irradiance for popular optical sources (including the sun) relative to the CPV optical system

UV Radiation: Damaging Dose

- Early weathering studies ⇒ total UV dose (damage vs. Joules or hours)
- Activation spectrum instead considers:
    1. characteristics of source & optical system
    2. effectiveness of damage at each λ ("action spectrum")
    3. may be unique to each characteristic (+ and -)



$$\Lambda[\lambda] = E[\lambda]s[\lambda] = E[\lambda]c_1 e^{-c_2\lambda}$$

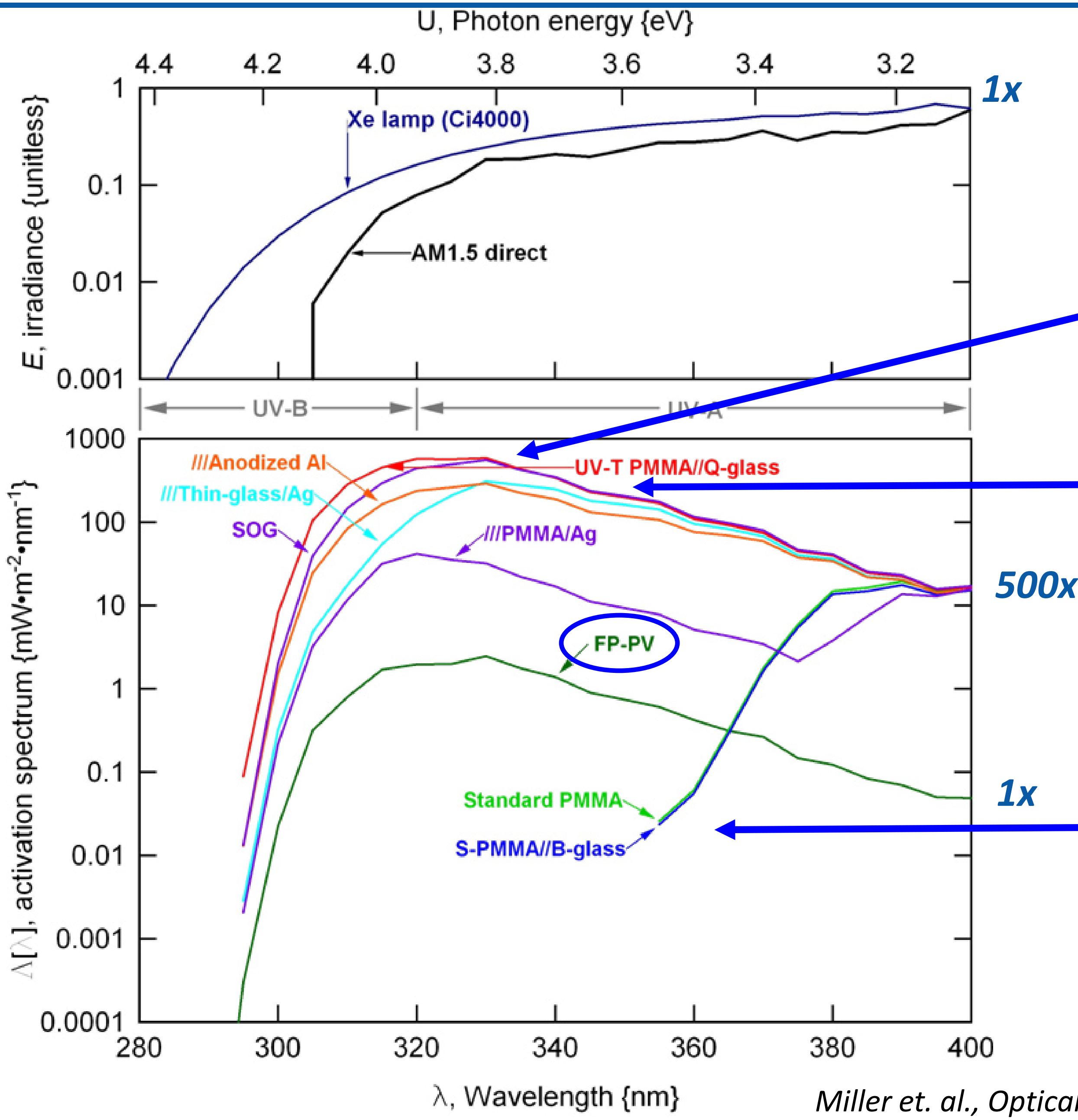
sun

optical system

$$E[\lambda] = E_I[\lambda]C_g \prod_{i=1}^{i=j} \eta_i T_i[\lambda] \prod_{k=1}^{k=l} \eta_k R_k[\lambda]$$

*Miller et. al., Optical Engineering, **50** (1), 2011, 013003*

The Optical System Readily Affects UV & IR Dose



accelerated test fixture

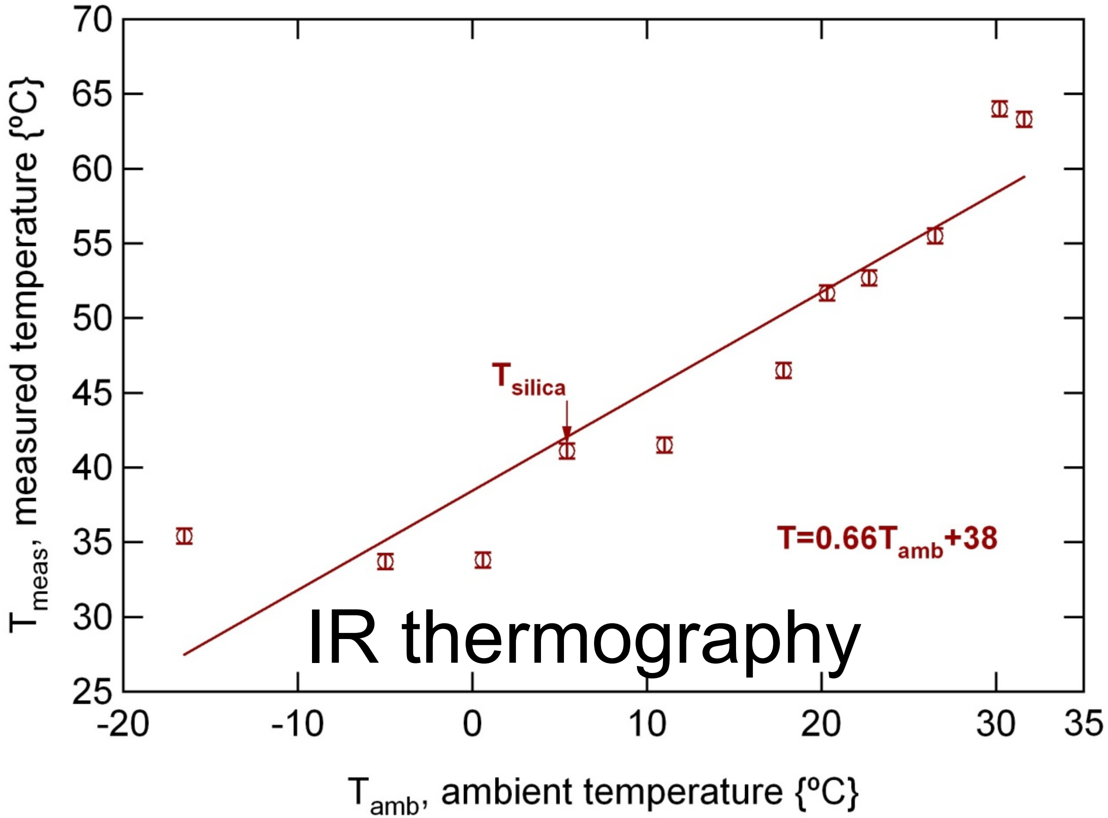
reflective systems or SoG

PMMA refractive systems: reduced UV

Miller et. al., Optical Engineering, ***50*** *(1), 2011, 013003.*

The Field Conditions (Specimen Temperature)

- Specimen temperature proportional to optical (IR) absorptance (thermal management "system": conduction to the frame.)
- Measured at solar noon. Factors: T_{amb}, irradiance, wind speed
- ~40°C temperature rise observed. T_{max} 70-80°C in summer.



PDMS specimen temperature, determined using optical thermography

Miller et. al., PIP, DOI: 10.1002/pip.1241.

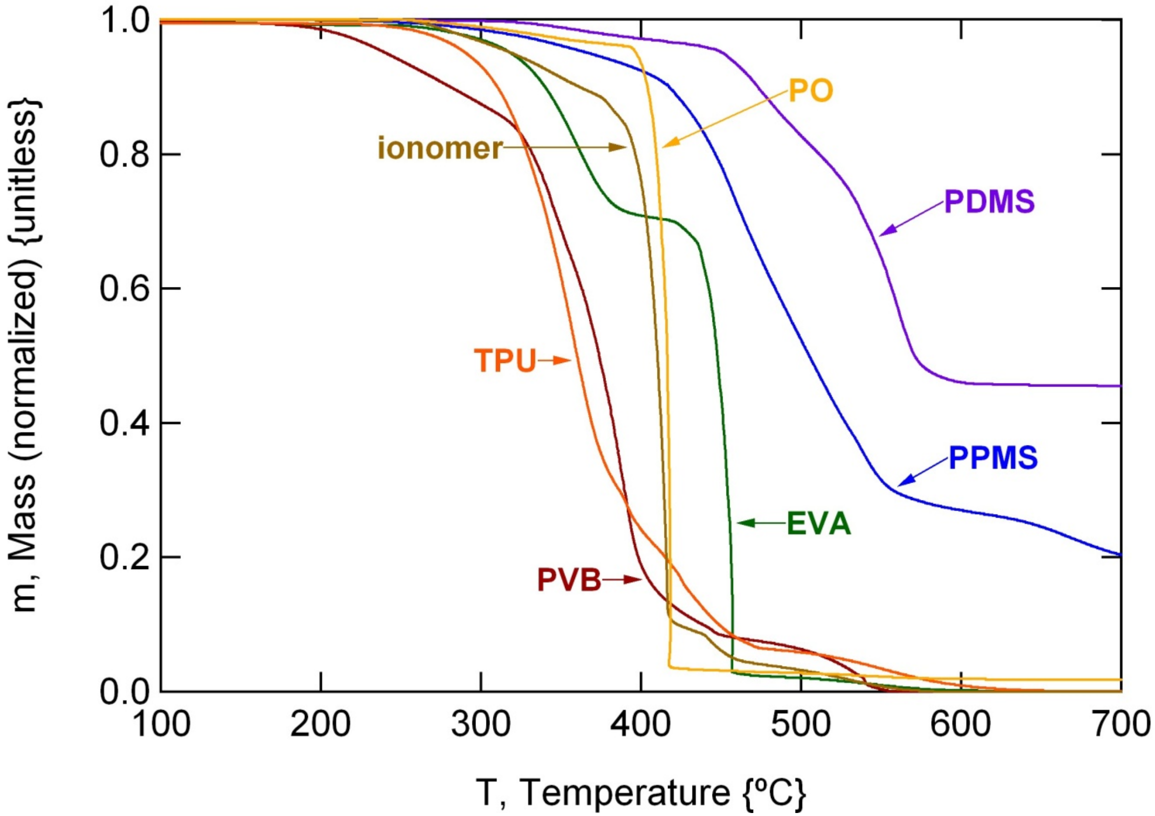
Thermal Decomposition of the Encapsulation May Occur at High Temperature

- Thermal stability compared using thermogravimetric analysis (TGA) @20°C·min^{-1}

- Onset of decomposition for hydrocarbons: 200-300°C

- Silicones more thermally stable: T_{onset} 300-400°C

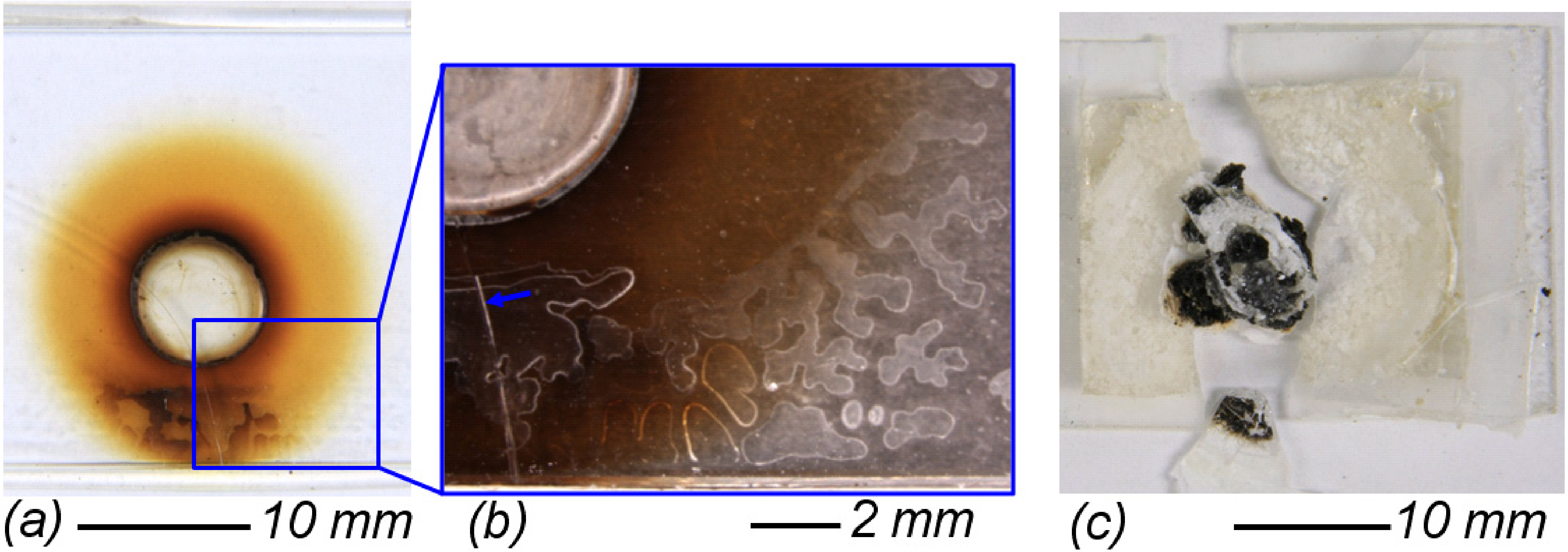
*Remember *T*'s for later!



Thermography data for representative materials from the study
Miller et. al., PIP, DOI: 10.1002/pip.1241

Results of Discovery Experiments
(The Homogenizer)

EVA: without homogenizer, rapid discoloration ⇒ combustion



optical images of EVA in (a) & (b), and PDMS in (c).
inset shows: voided center, char, cracked cover-glass, discoloration, delamination

silicone: without homogenizer ⇒ combustion

- Likely motivated by local hot spots (10^1 to $10^3 \cdot C_g$)

D.C. Miller, S.R. Kurtz, Solar Energy Materials and Solar Cells, 2011.

Results of Discovery Experiments

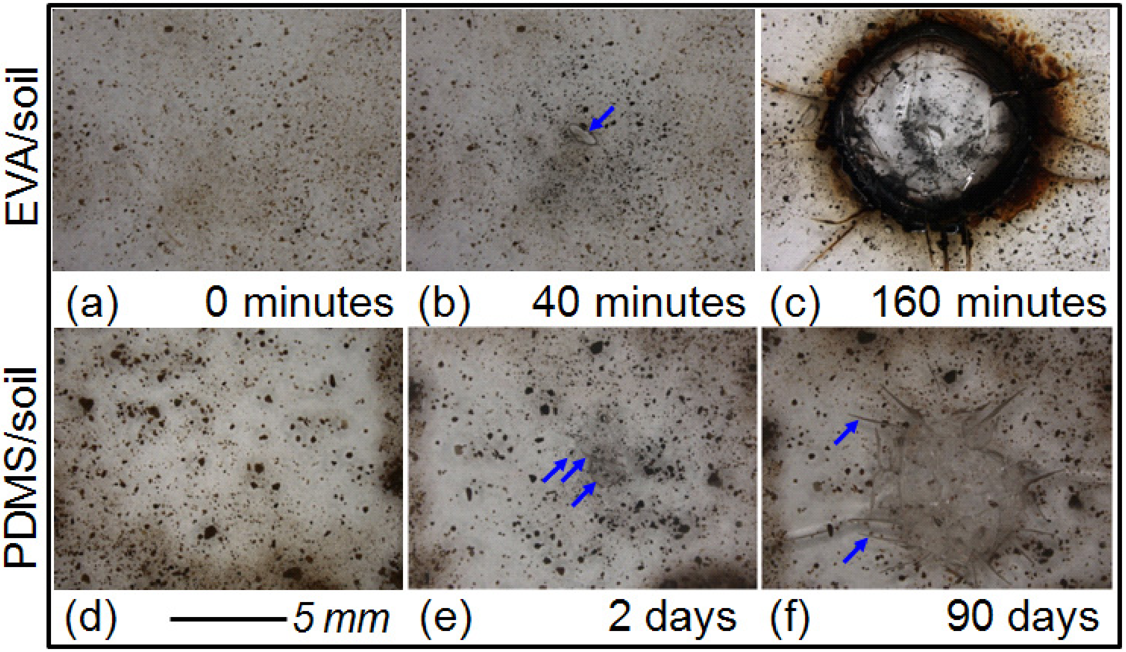
The Effect of Contamination)

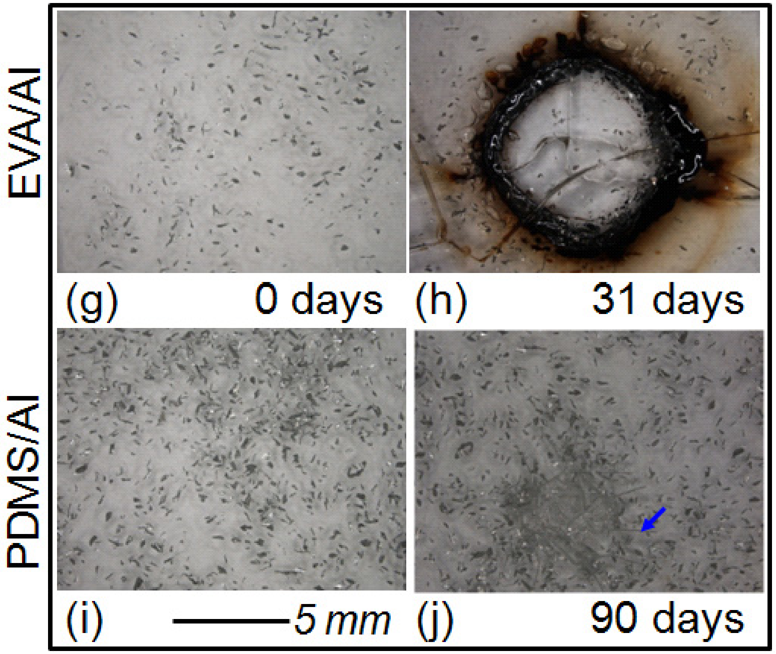
- Intentionally introduce soil, Al, PE, or bubbles into EVA or silicone

EVA: soil, Al, PE motivated localized discoloration ⇒ combustion

silicone: soil, Al ⇒ localized cracking. (no primer present)

- elapsed time: minutes – days/weeks
- bubbles: no failure @C_g=500, despite 4% measured $T[\lambda]$ reduction





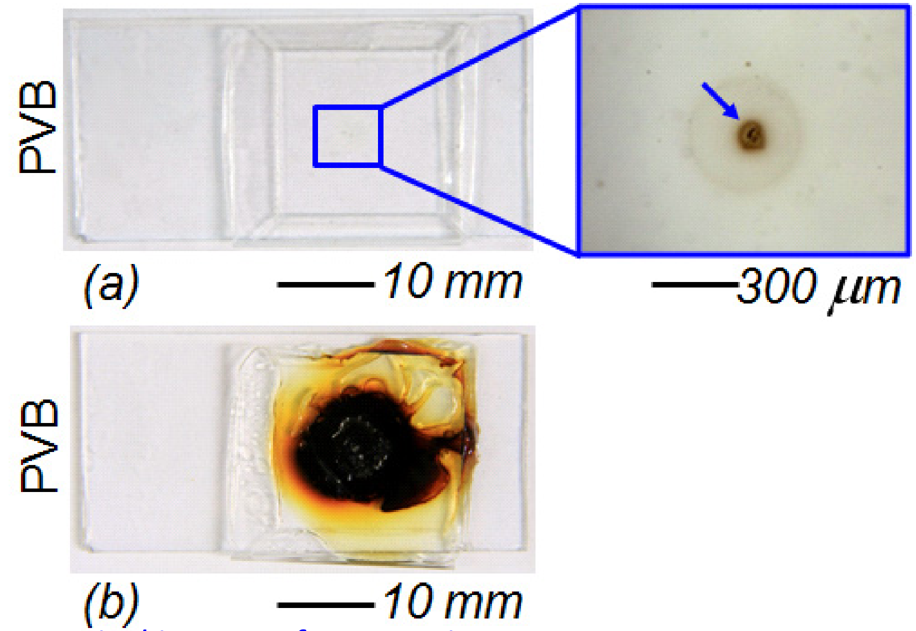
time sequence: optical images of test specimens

Miller et. al., PIP, DOI: 10.1002/pip.1241

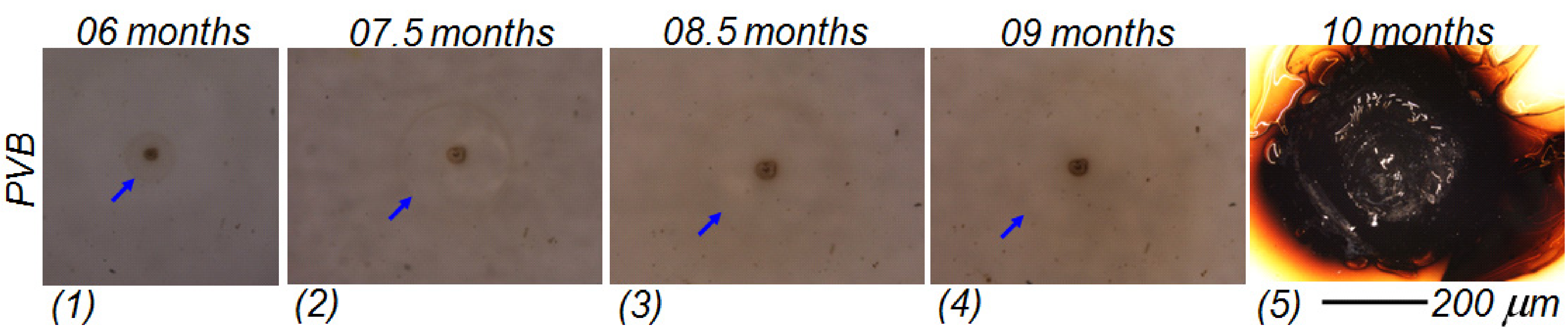
Results of the Formal Experiment
(Hydrocarbon Specimens)

- PVB was the first material to demonstrate thermal runaway mediated failure

- The radius of the affected region was seen to slowly grow during the cold winter months



optical images of test specimen at:
(a) 6 months and (b) 10 months



time sequence: optical images of test specimen

Miller et. al., PIP, DOI: 10.1002/pip.1241

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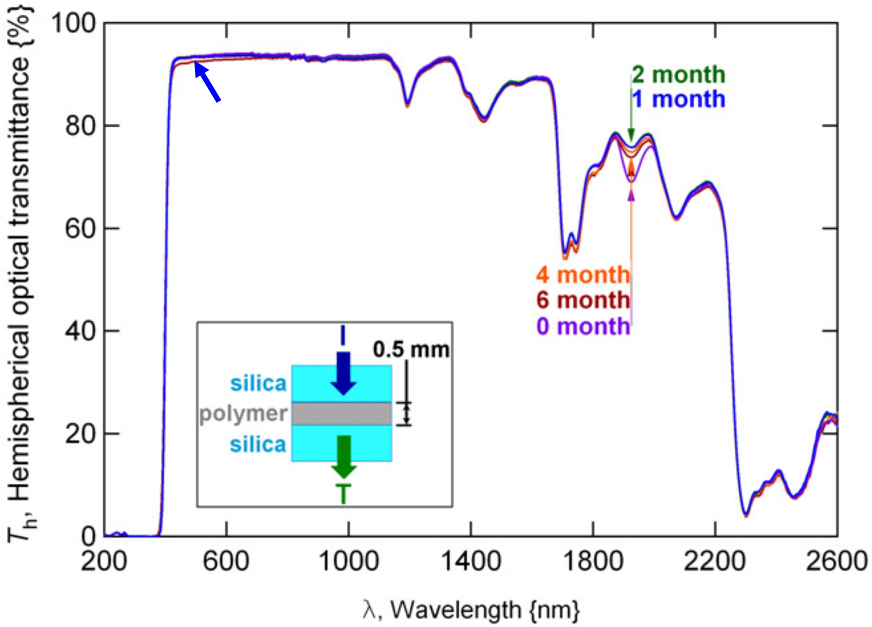


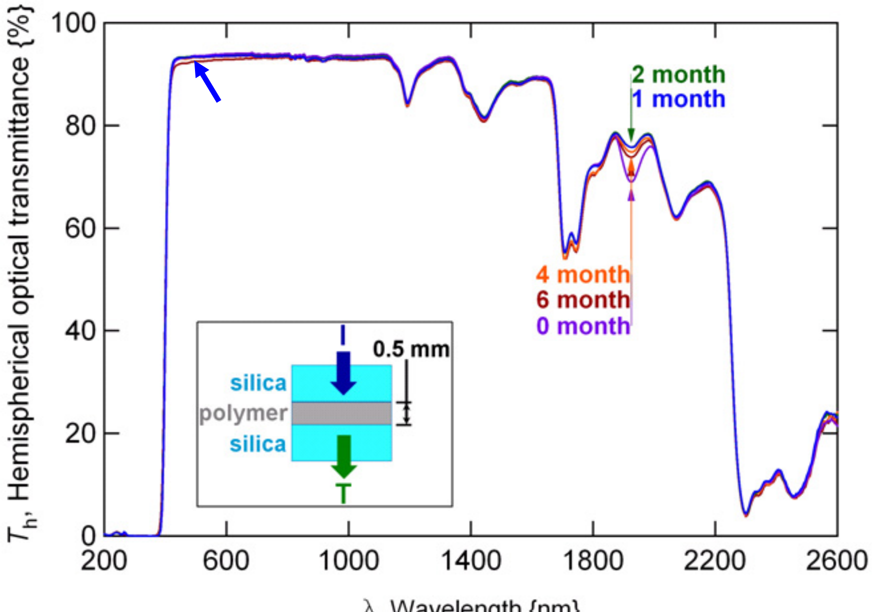
time sequence: transmittance of the PVB specimen

- Transmittance & YI not significantly affected, despite impending failure

- A diagnostic characteristic with predictive capability is preferred!!!

optical fluorescence spectrum of PVB, for λ_I= 280 nm

Results of the Formal Experiment
(Hydrocarbon Specimens)



time sequence: transmittance of the PVB specimen

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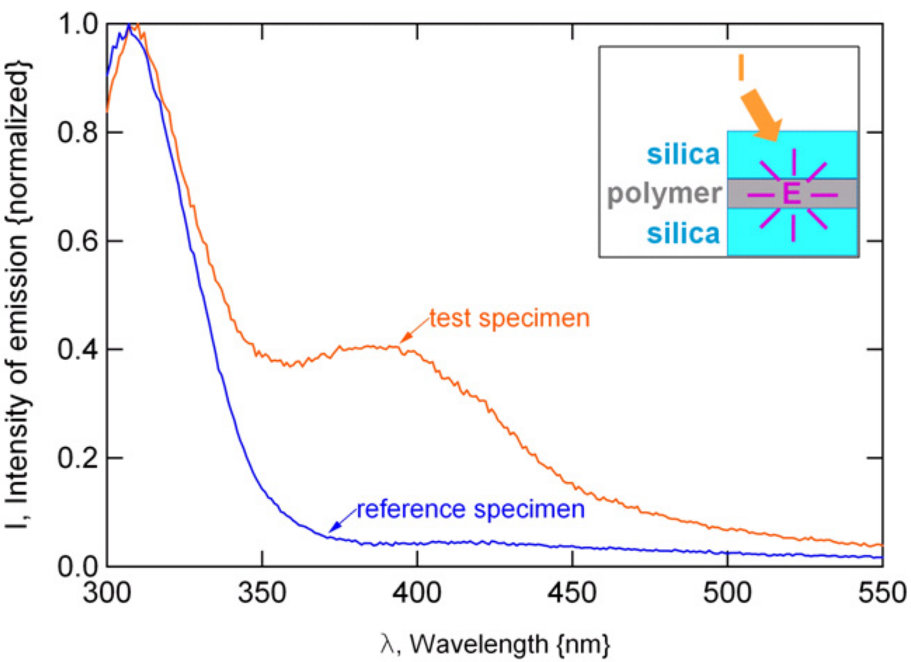
- A diagnostic characteristic with predictive capability is preferred!!!

- Optical & Raman spectroscopy clearly indicate fluorescence

- These techniques may help understand the degradation mechanism (*e.g.*, chromophores)



optical fluorescence spectrum of PVB, for λ_I= 280 nm

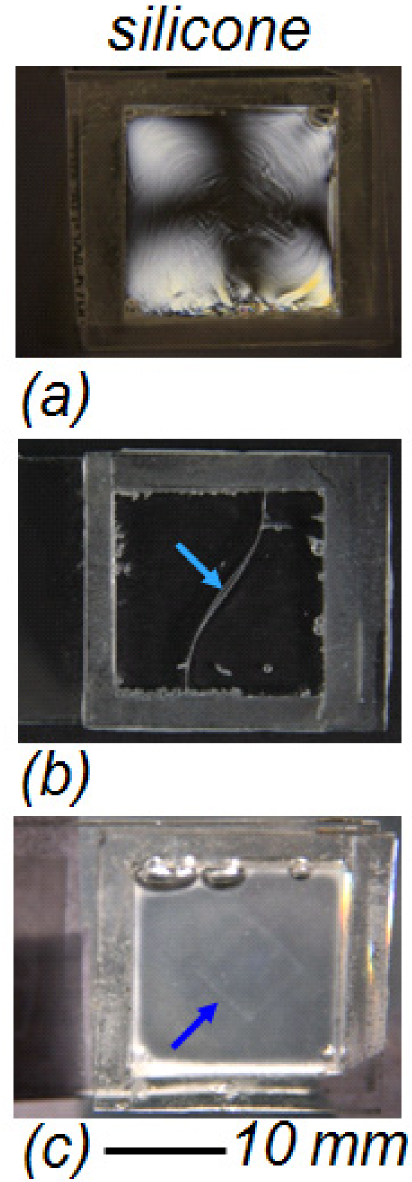
Results of the Formal Experiment
(Silicone Specimens)

- Observations of silicone specimens include: (a) densification, (b) cracking, and (c) haze formation

No mass change with time for the (5) **densified** specimens $\Rightarrow$ likely occurred during molding

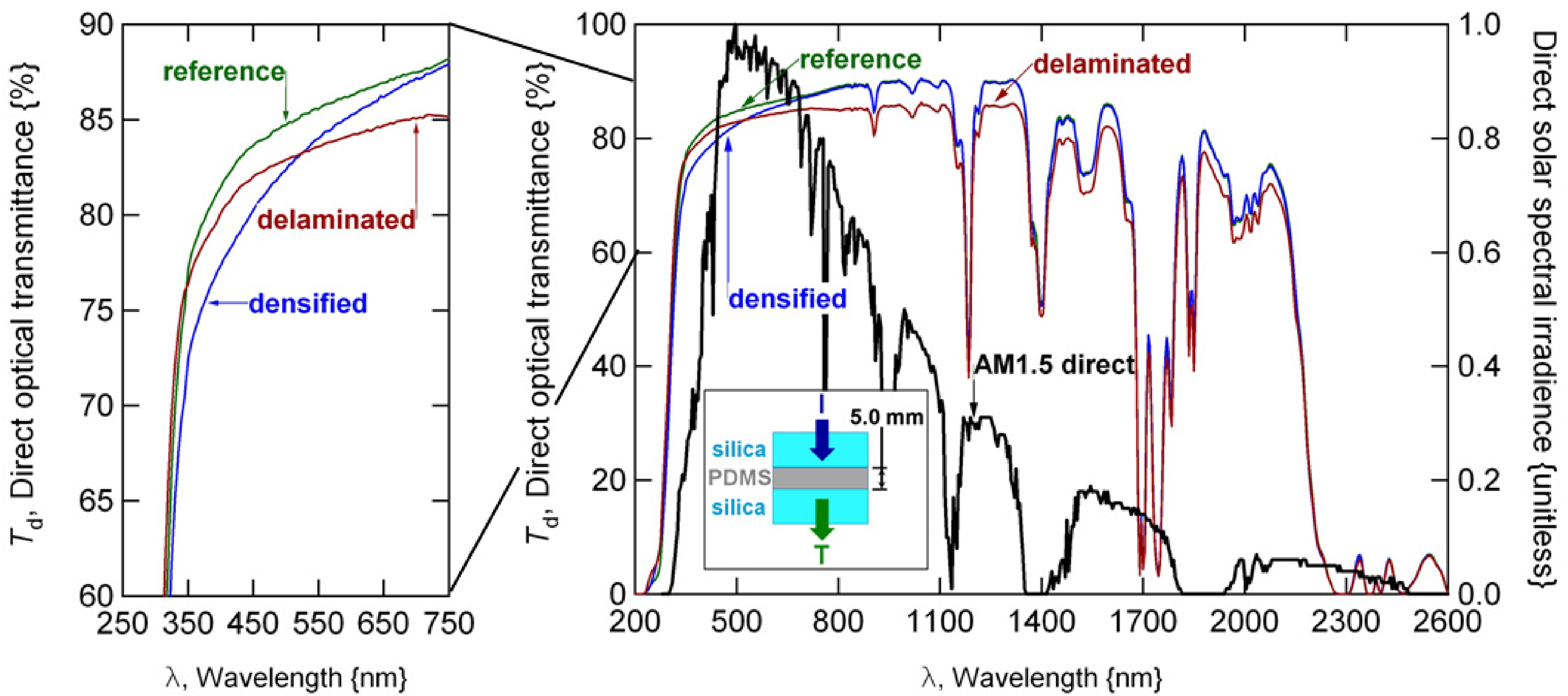
- **Crack** advancement occurred during cold weather periods only $\Rightarrow$ likely motivated by CTE misfit
- Additional fractured specimens may be emerging

Haze formation is attributed to one material's unique formulation



optical images of silicone specimens, including those obtained using (a) cross-polarization or (c) back-lighting

Results of the Formal Experiment
(Densified Silicone Specimens)



- Densification is not delamination
- Densification does scatter direct light

Problematic for CPV?

- Current limited condition (blue light) •Optical attenuation (less power)

⇒May not be significant in thin bond layers

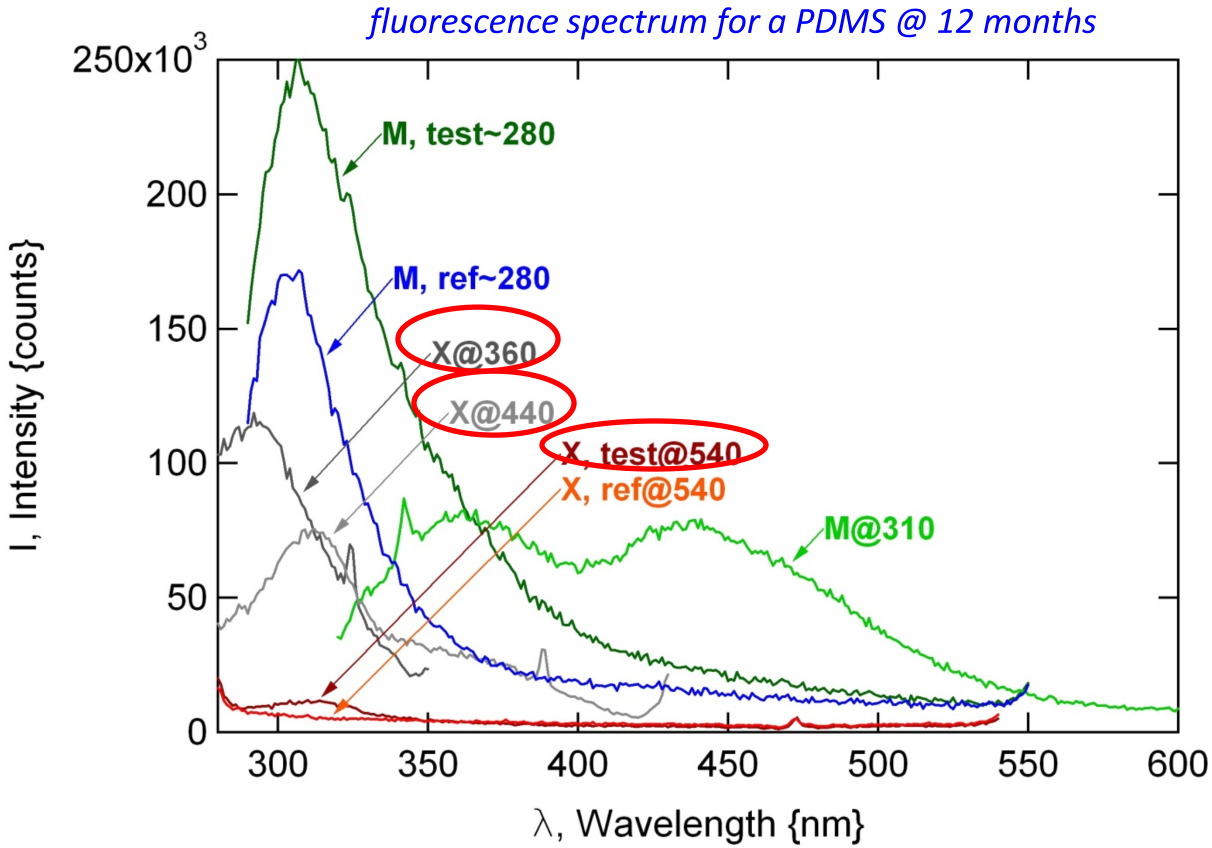
Miller et. al., PIP, DOI: 10.1002/pip.1241

Fluorescence Identifies the Silicones Are Affected!

- Unexpected new peaks identified for all silicone specimens!

- The particular details location and relative intensity of the new M_t peaks varied with formulation

- Attributed to Pt catalyst (working to verify)

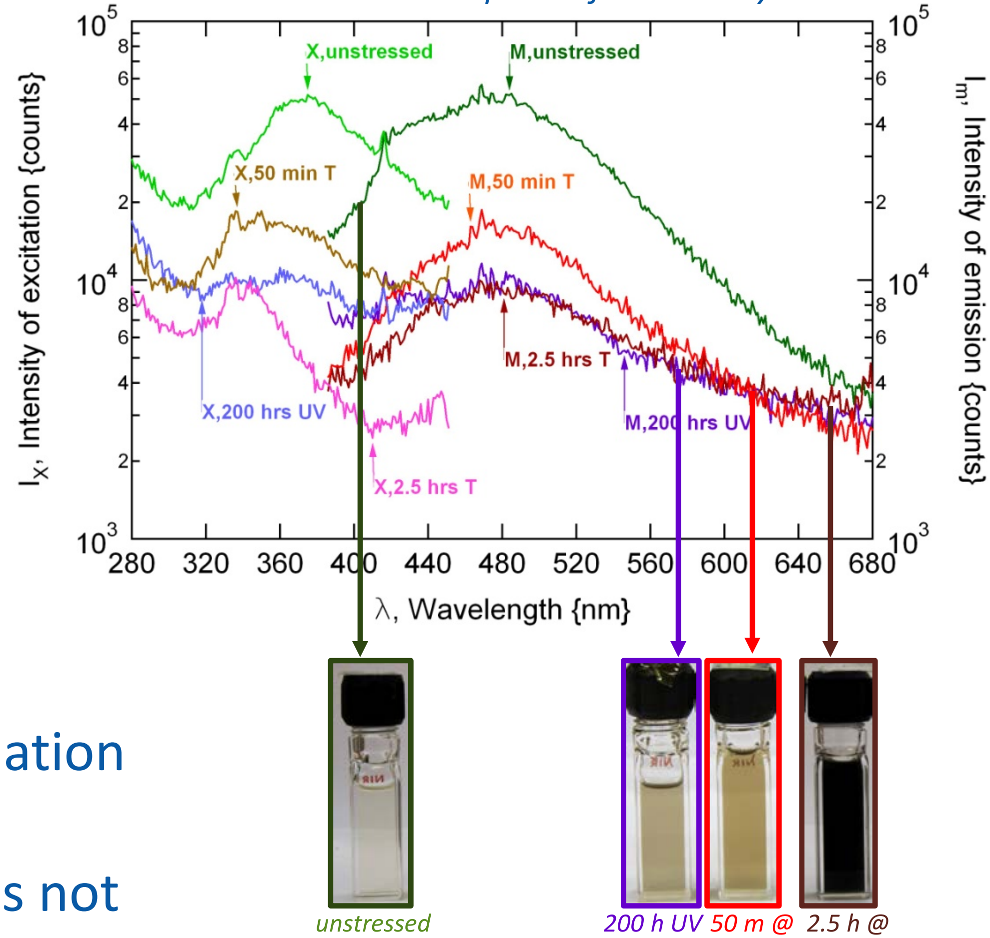


- The implications are unclear. PDMS is historically robust in extreme environments. λ_X… <390 nm for PMMA, ~320 nm for SoG

UV and/or Temperature Can Degrade Pt Catalyst

- Karstedt's catalyst, Pt(0), examined in tetramethyldivinyldisiloxane
- Catalyst loses fluorescence with UV or T
- Organometallic literature: mononuclear Pt with ligands → colloidal Pt, 3-5 nm ∅
- Discoloration (optical absorptance) could motivate thermal runaway
- No evidence to date of optical degradation in NREL specimens
- Fluorescence of catalyst solution does not correspond to that in x-linked PDMS

excitation and emission spectra for Pt catalyst solutions



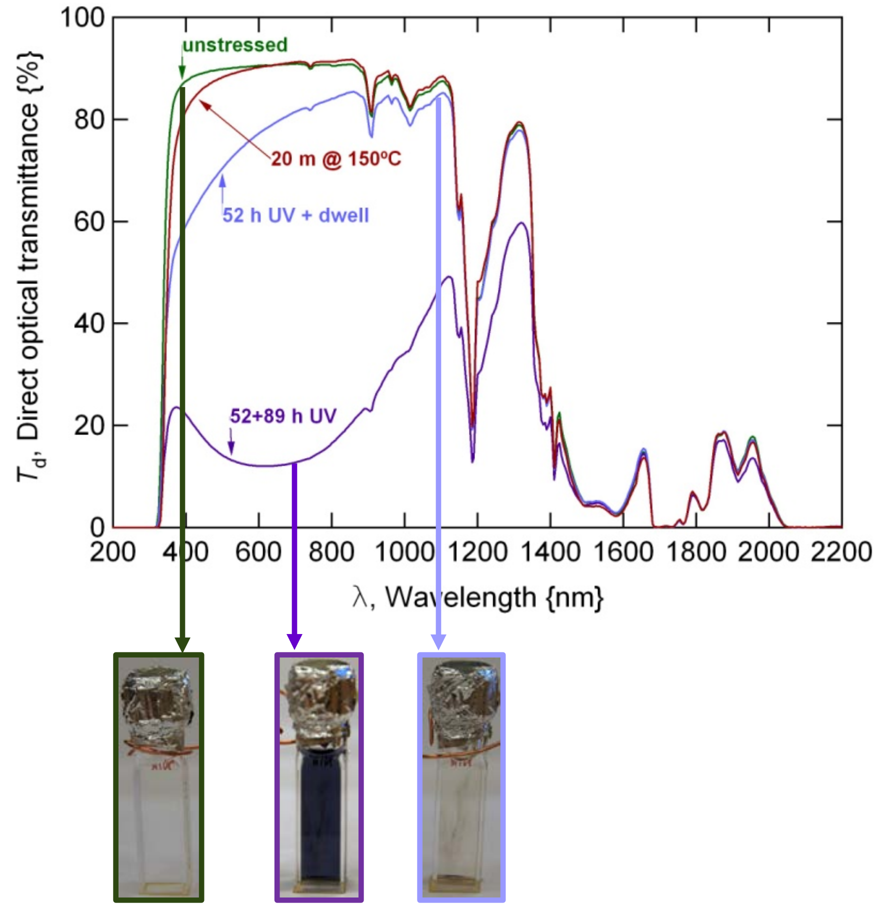
color-corrected specimen photographs

- Alternate pathways: different catalyst type (ligands), peroxide cured silicone, PMMA on glass (PoG) lenses, AR coatings

UV Can Degrade Silicone Primers

- Dow-Corning 92-023 used in all NREL PDMS specimens
- The Ti based primer (on glass) reduces UV transmittance for $\lambda < 300$ nm (n TiO_2 = 2.5)

transmittance for primer solutions (in IPA)



unstressed 52+89h UV 52 h UV + dwell

- Experiments identify primer is quite photoactive:
  discoloration with minor fluorescence
- Transparency recovered with time (O_2 facilitated?)

- TiO_2 used in self cleaning coatings.
(UV driven consumption of organic contamination). Affect on PDMS is unclear.
- Alternate pathway: Sn catalyzed primers (n SnO=2.1)

Summary & Conclusions

Field study of the durability of polymeric encapsulation materials for CPV

Discovery experiments:

- Quickly confirmed the importance of an optical homogenizer
- Al, soil, polymeric contamination ⇒ *T* runaway & combustion of EVA
- Al, soil contamination ⇒ cracking of silicone

Formal experiment:

- 17 of 25 specimens not discussed today!
- 3 of 25 specimens "failed".

PVB: localized discoloration ⇒ thermal runaway ⇒ combustion

Fluorescence & Raman spectroscopy may diagnose & provide prediction

Silicone: densification, cracking, haze-formation

Densification affects the direct transmittance

PDMS Fluorescence:

- Working to understand observed peaks; alternative "solutions" identified

*Transmittance of optical system and corresponding activation spectrum of the encapsulation are critical to encapsulation durability

Acknowledgements

- NREL: Dr. Keith Emery, Dr. Daryl Myers, Dr. John Pern, Matt Beach, Christa Loux, Tom Moricone, Marc Oddo, Bryan Price, Kent Terwilliger, Robert Tirawat

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Paper: "The Durability of Polymeric Encapsulation Materials for Concentrating Photovoltaic Systems", Prog. Photovoltaics, *DOI: 10.1002/pip.1241*.