Predictive Mechanics and Photochemical Degradation Kinetics Modeling for Polymeric Encapsulants

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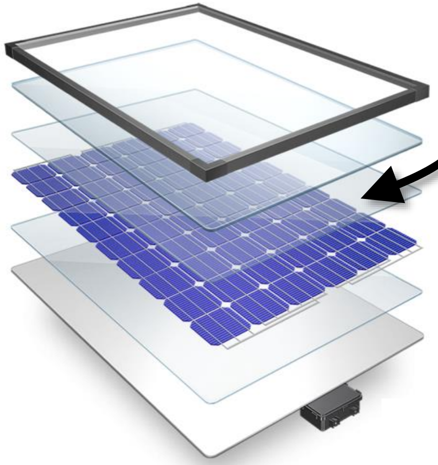
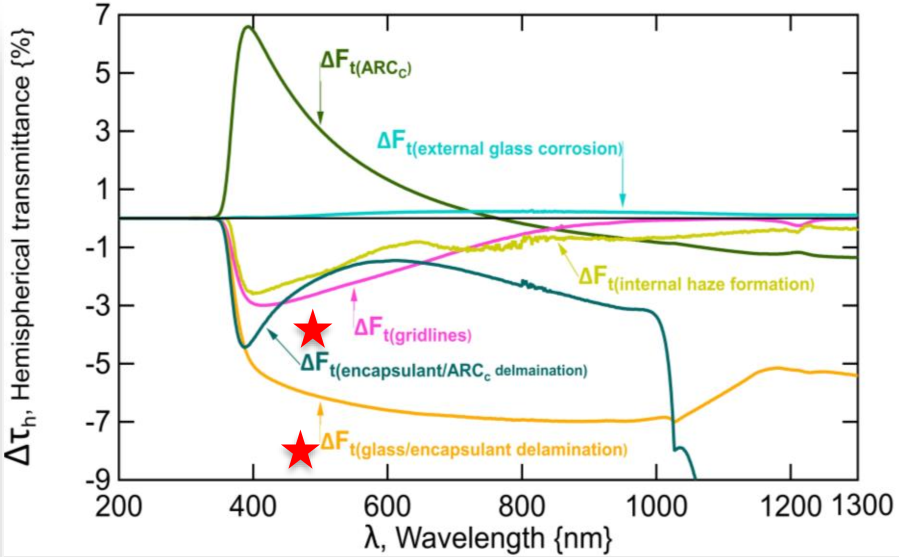
Photovoltaic Reliability Workshop (PVRW) – February 2024

Delamination – A Long Term Reliability Concern

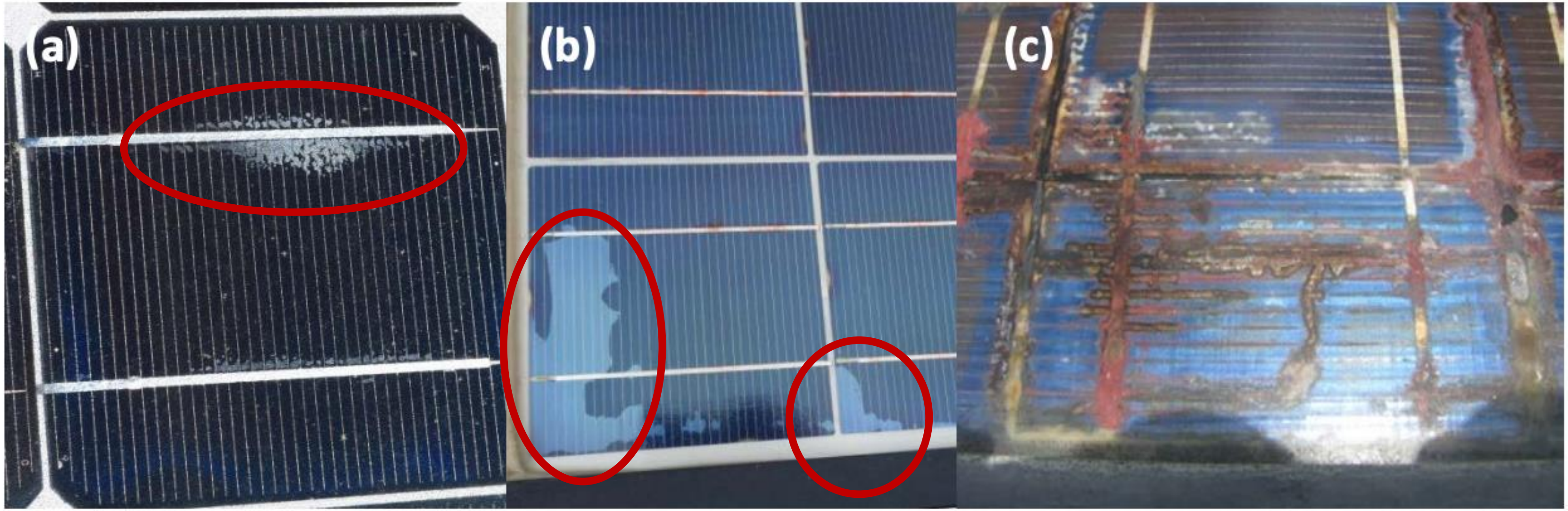




The optical loss from **glass/encapsulant** and **ARC/encapsulant** delamination is significant [1].

[1] DOI:10.1002/pip.3690, https://www.nrel.gov/docs/fy23osti/82324.pdf

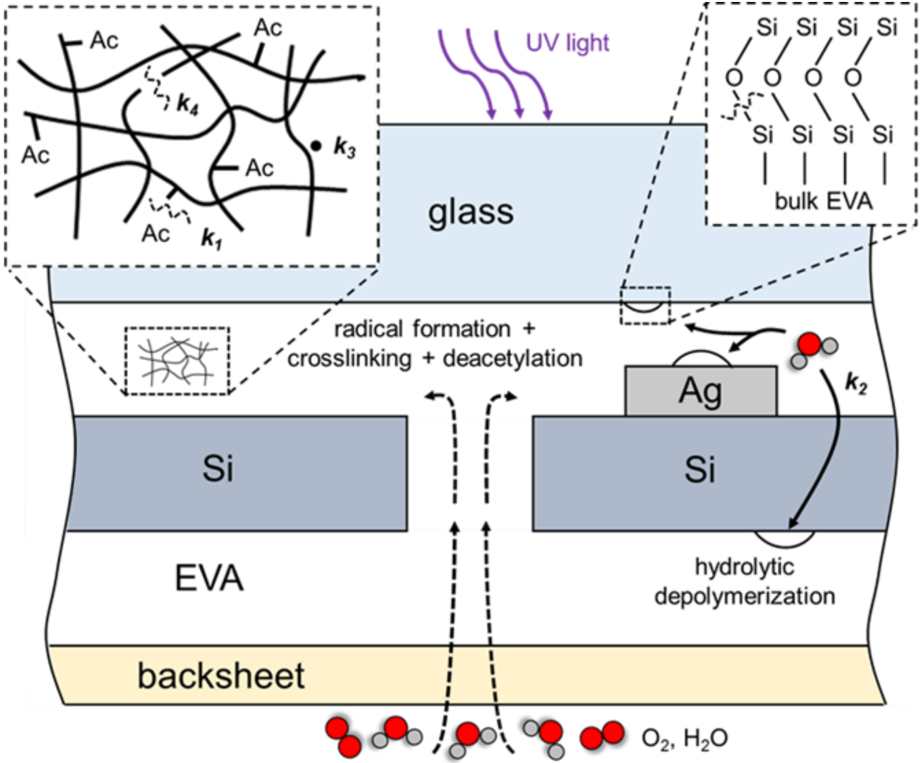
Delamination – A Long Term Reliability Concern

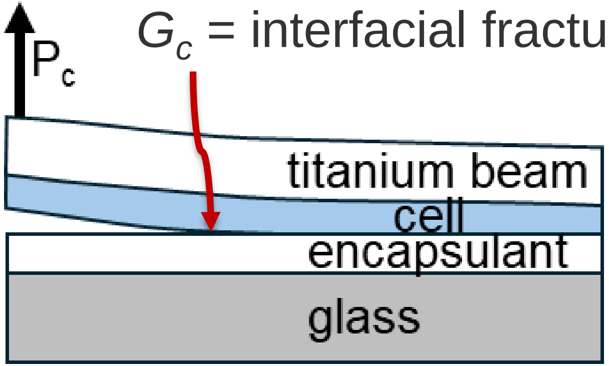


Delamination at the silicon interface	Delamination at the glass interface	Severe corrosion/ discoloration of circuitry

- Moisture diffusion and corrosion from delamination events lead to performance drop, not matching required manufacturer- and cell-specific performance.

Degradation Modeling of Interfacial Adhesion





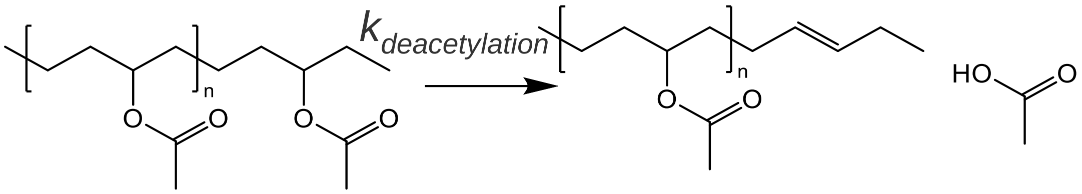
G_c = interfacial fracture toughness

Goals:

- Develop and experimentally validate a module encapsulant degradation model.
- Incorporate fundamental degradation and crosslinking pathways and their dependence on environmental stressors (UV, temperature, humidity).

Connecting Molecular Degradation Kinetics to Fracture Properties with Multiscale Modeling

I. Deacetylation → loss of vinyl acetate (VA) moieties in EVA

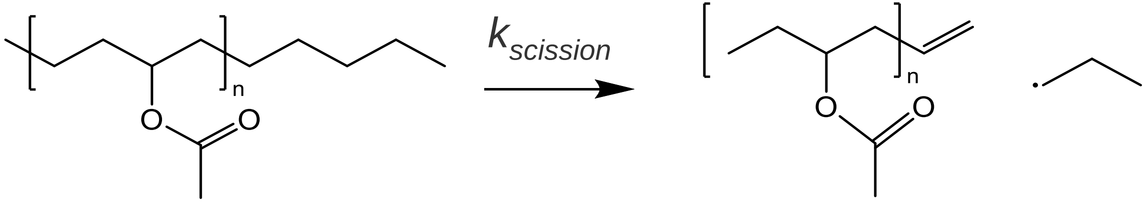


N = *bond densities*

$$N(t) = N_o exp(-\boldsymbol{k}t)$$

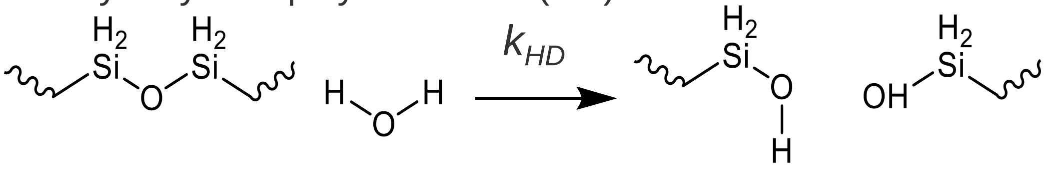
$\boldsymbol{k_{deacetylation}}$ (bulk EVA)

II. Beta-scission → loss of polyethylene (PE) moieties in EVA



$\boldsymbol{k_{scission}}$ (bulk EVA)

III. Hydrolytic depolymerization (HD) → loss of silane bonds



$\boldsymbol{k_{HD}}$ (EVA/cell, EVA/glass)

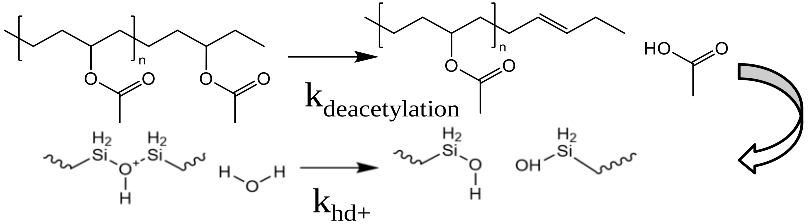
$\boldsymbol{k_{CL}}$

$$C_{CL}(t) = C_{CL,max} - \left(C_{CL,max} - C_{CL}(0)\right) \mathrm{e}^{-\boldsymbol{k_{CL}}t}$$

IV. Crosslinking → formation of bonds due to heat/UV

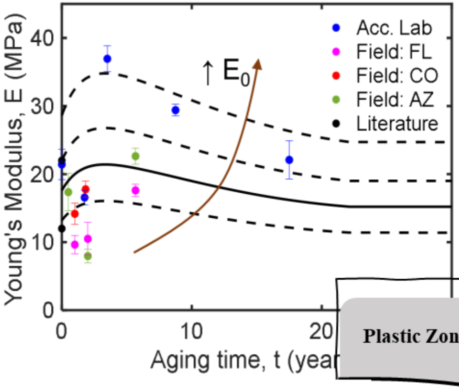
Connecting Molecular Degradation Kinetics to Fracture Properties with Multiscale Modeling

2.



coupled auto-catalytic effect

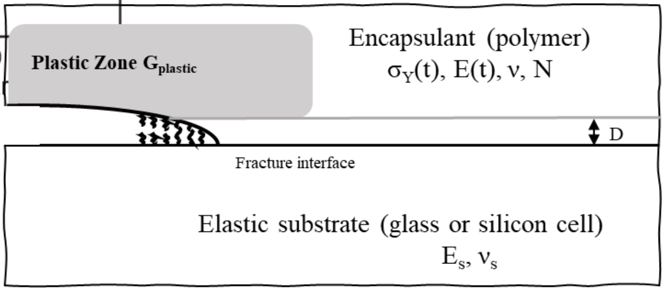
3.



$$E(t) = E_0\left(\alpha_{PE}\frac{N_{PE}(t)}{N_{PE}(0)} + \alpha_{VA}\frac{N_{VA}(t)}{N_{VA}(0)}\right) + w_{CL}E_0C_{CL}(t)$$

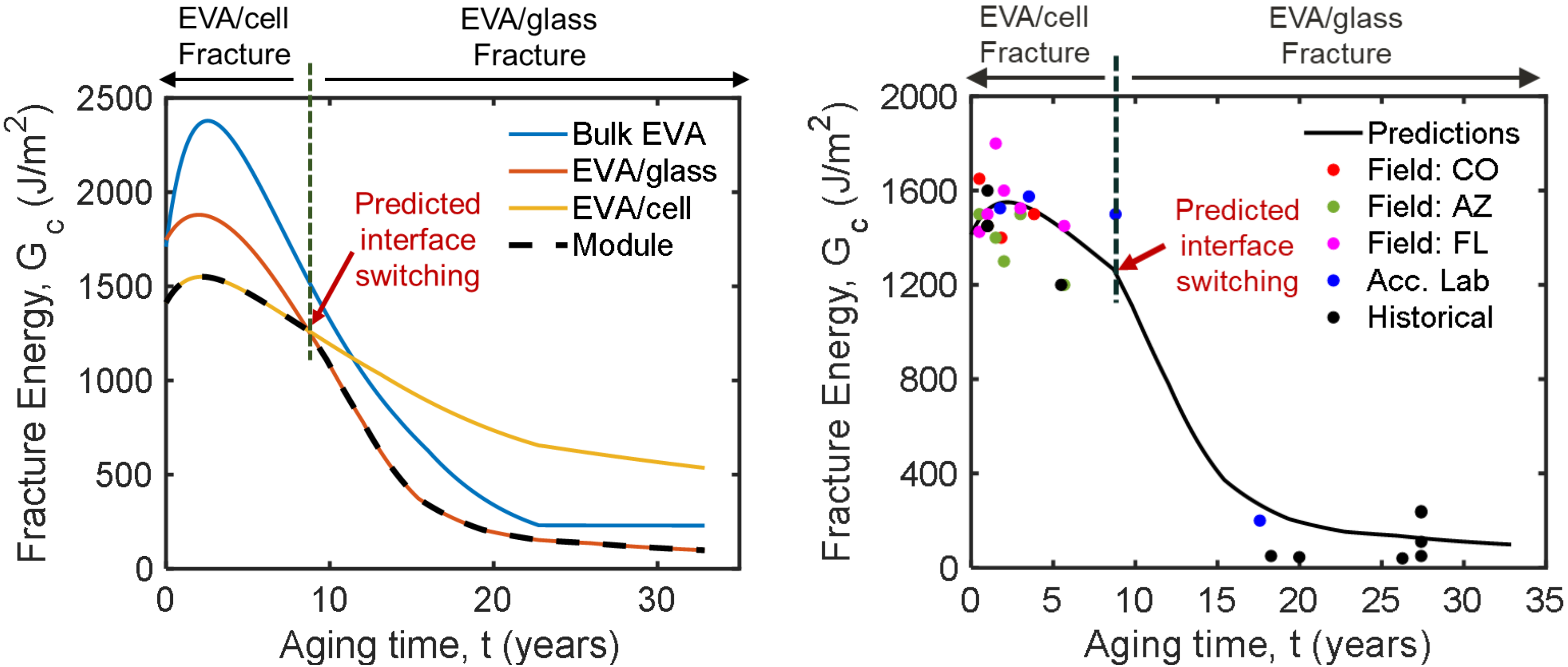
$$\sigma_{ys}(t) = \sigma_{ys,0}\left(\alpha_{PE}\frac{N_{PE}(t)}{N_{PE}(0)} + \alpha_{VA}\frac{N_{VA}(t)}{N_{VA}(0)}\right) + w_{CL}\sigma_{ys,0}C_{CL}(t)$$

4.



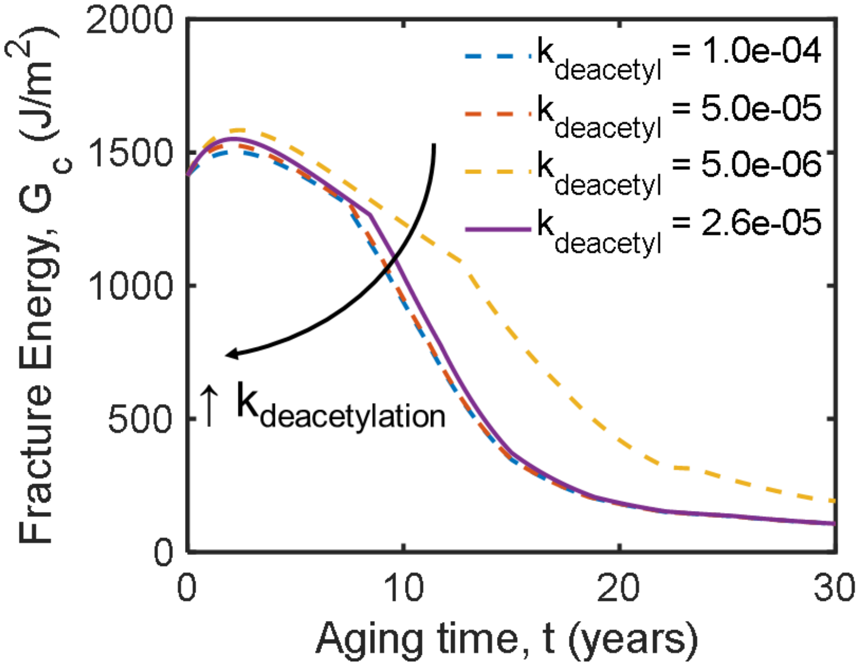
1. Molecular crosslinking in the field - Formation of new bonds
2. Synergistic interactions between separate degradation mechanisms
3. Computing encapsulant mechanical properties from bond densities
4. Rigorous treatment of plasticity during fracture process

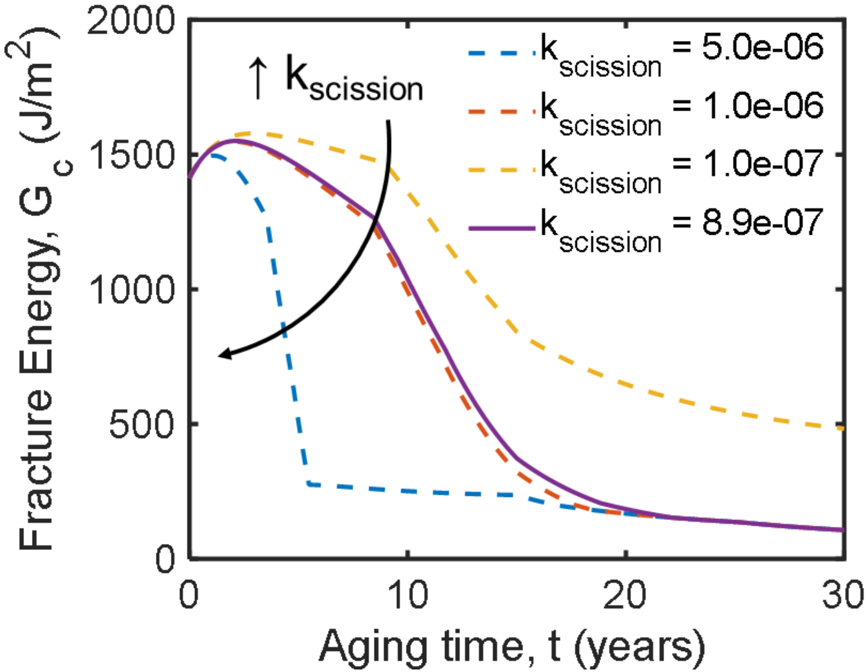
Refined Model-Comparison with Experimental Data (Limited Variation in Exposure Conditions)



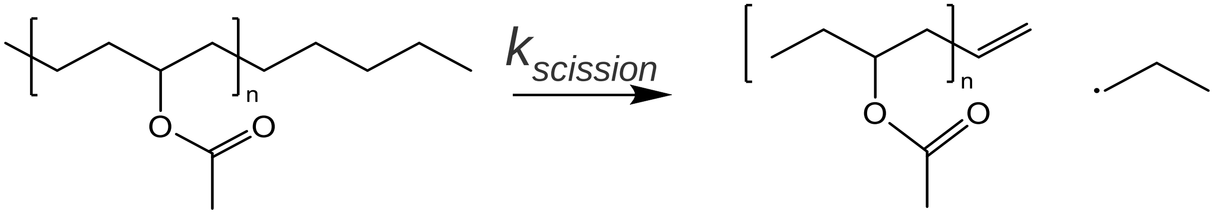
How to Extend The Model to Any Field Exposure Condition?

- Changing $k_{degradation}$ and k_{CL} changes $G_c(t)$ model predictions
- Goal: Determine how k changes with UV intensity, temperature, humidity

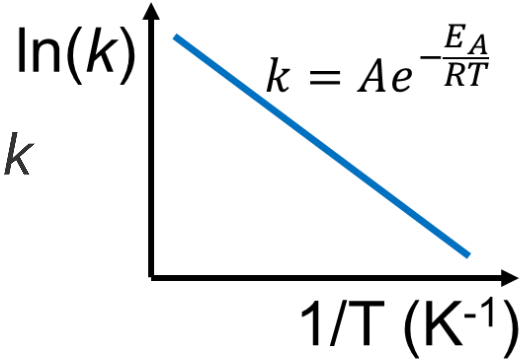


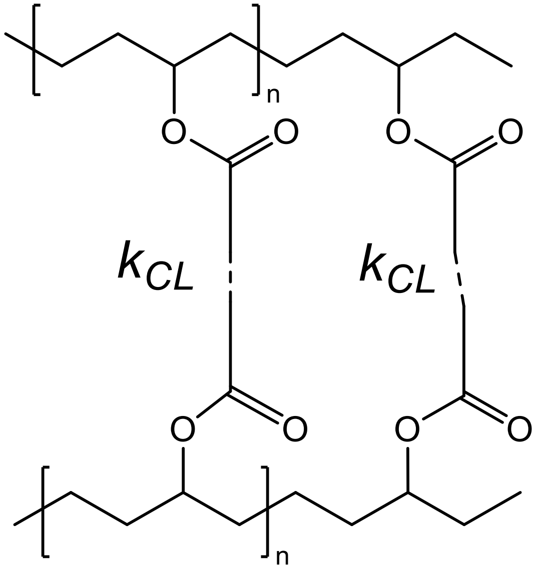


Ongoing Work: Determining Degradation and Crosslinking Reaction Rates (Kinetics) Under Different Environmental Stressors



Example of how *k* varies with temperature





Ex: $k_{scission}$, $k_{crosslinking}$ = *f(UV intensity, temperature, humidity)*

- Using accelerated aging (varying the stressors), characterize the degradation and crosslinking rates.

Ongoing Work

Encapsulant Accelerated Aging Test Matrix

		READ POINT (CUMULATIVE DURATION)						
TEST TYPE	TEST CONDITION	#1	#2	#3	#4	#5	#6	# Encapsulants (EVA, POE, EPE)
UV photodegradation: Oxidative vs. inert environment	65°C, 22% RH (or chamber RH), oxidative, with UV	500 hr	1000 hr	2000 hr	3000 hr	4000 hr	5000 hr	18
	65°C, inert glovebox air, with UV							
	85°C, 22% RH (or chamber RH), oxidative, with UV							
Hygrometric aging.	90°C/60%RH, oxidative, no UV	2500 hr	5000 hr	6250 hr	7500 hr	8750 hr	10000 hr	Laminated coupon (9)
	60°C/60%RH, oxidative, no UV			N/A		N/A		
Thermal aging: Oxidative vs. inert environment	90°C, 22% RH, oxidative, no UV	2 wk	4 wk	8 wk	14 wk	20 wk	30 wk	18
	90°C, inert glovebox air, no UV							
	65°C, inert glovebox air, no UV							

Ongoing Work

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	60°C/60%RH, oxidative, no UV			N/A		N/A		
Thermal aging: Oxidative vs. inert environment	90°C, 22% RH, oxidative, no UV	2 wk	4 wk	8 wk	14 wk	20 wk	30 wk	18
	90°C, inert glovebox air, no UV							
	65°C, inert glovebox air, no UV							

Thermal Effects on Crosslinking in Encapsulants Revealed by High-Temperature Aging (90^{o}C, no UV)

EVA, POE, EPE from commercial source

- Fully cured (145^{o}C for 45 minutes “5x cured”) before aging
- No residual crosslinking initiators (DSC verified)
- EPE = EVA/POE/EVA composite

Additional crosslinking of encapsulants may occur in the field under high temperatures and UV exposure, even after being fully cured [1], [2]

High-temperature aging experiments (90^{o}C) allow us to isolate the thermal effects on the crosslinking kinetics of fully cured encapsulants.

[1] Oreski, G., Rauschenbach, A., Hirschl, C., Kraft, M., Eder, G. C., & Pinter, G. G. (2017). *J. of App. Polymer Sci.*, *134.2017*(23), Article 44912.
[2] Michael D. Kempe, David C. Miller,…, Energy Sci. Eng., 4 (1), 2016, 40-51.

Method for Measuring Encapsulant Degree of Crosslinking: Soxhlet Extraction

- Sample: Encapsulant aged at various times
- Solvent: mixed xylenes (~220 mL), BHT antioxidant (~20 mg)
- Reflux for 10 hours in Soxhlet extractor (>180 cycles)
- Sample held in a cellulose thimble in extraction chamber

Measure gel content: $G_{\%} = \frac{m_f - m_t}{m_i} 100$

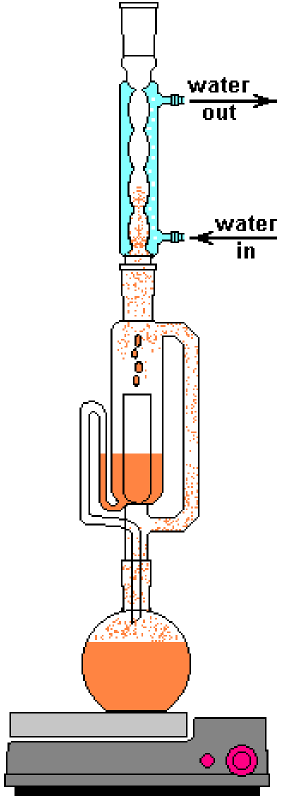
m_t = initial mass of dried thimble

m_i = initial encapsulant mass before extraction experiment

m_f = (thimble + encapsulant) mass post-extraction

In other words: $G_{\%} = \frac{insoluble\ mass}{total\ mass} = \frac{heavily\ crosslinked\ mass}{total\ mass}$

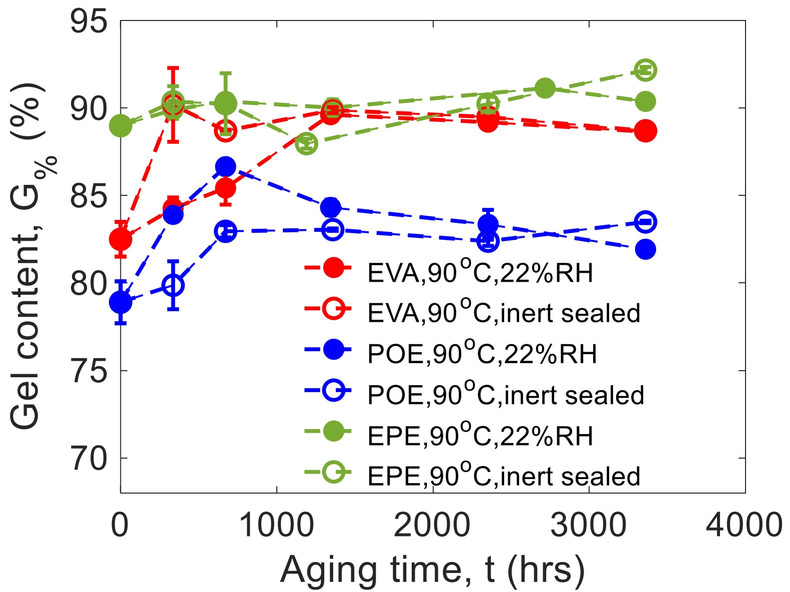
$G_{\%}$ increases as the degree of crosslinking increases



Thermal Effects on Crosslinking in Encapsulants Revealed by High-Temperature Aging (90^{o}C, no UV)

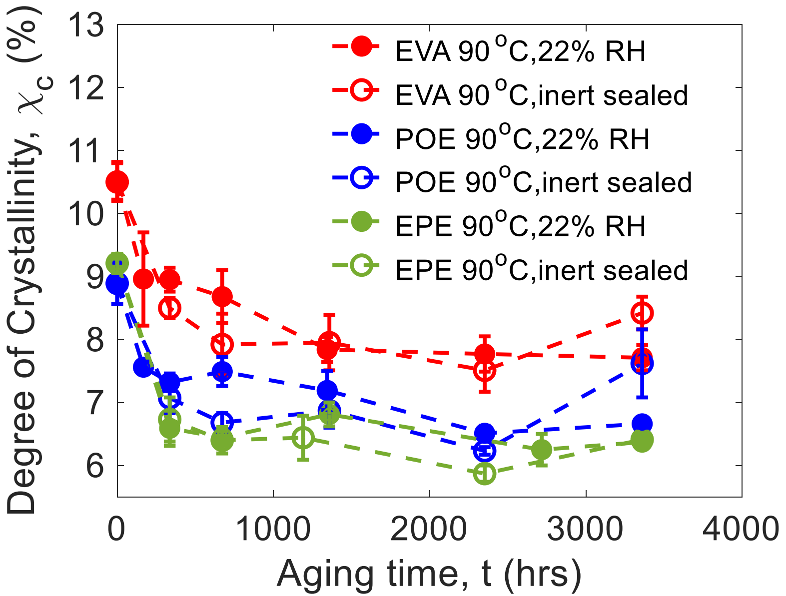
Solid dots: 90^{o}C, 22% RH, no UV
Open dots: 90^{o}C, inert air test tube sealed

$G_{\%}$ measures the degree of crosslinking

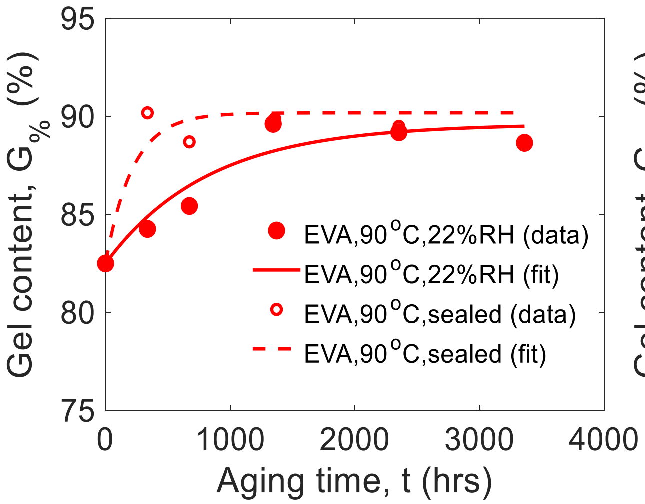


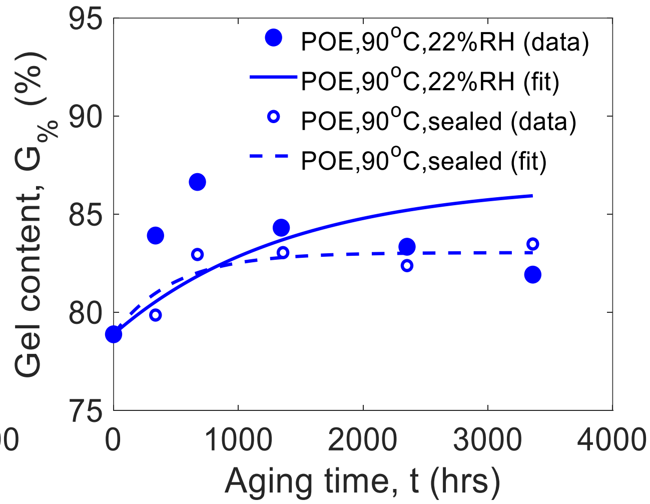
Degree of crystallinity decreases with an increase in degree of crosslinking

Changes consistent with gel content



Kinetics of Thermal-Induced Crosslinking in Encapsulants





$G_{\%}$ correlates with degree of crosslinking.

First-order kinetics model [1]:

$$G(t) = G_{max} + (G_0 - G_{max})e^{-k_{CL}t}$$

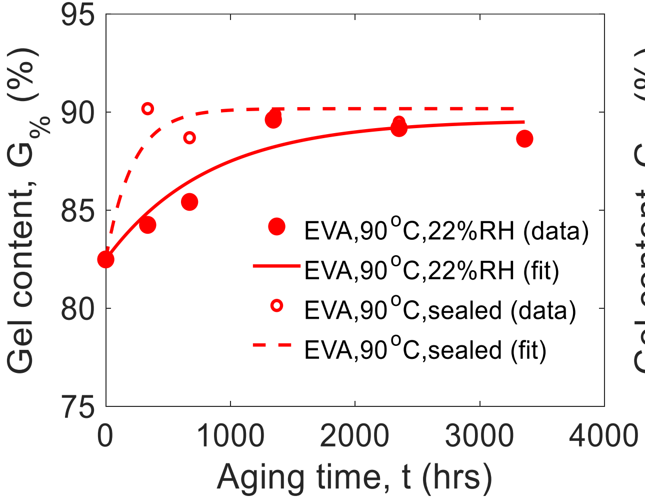
Determine k_{CL} from line of best fit

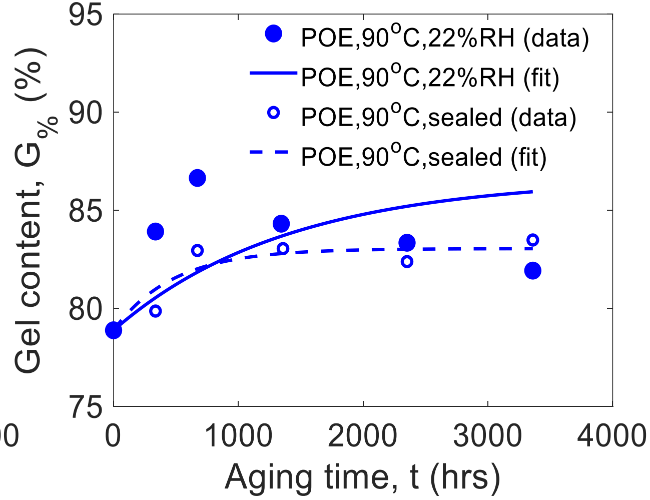
EVA	k_{CL}
EVA, 90^{0}C 22% RH	1.21E-3
EVA, 90^{0}C inert sealed	4.60E-3

POE	k_{CL}
POE, 90^{0}C 22% RH	7.15E-4
POE, 90^{0}C inert sealed	2.08E-3

[1] Liu, Thornton, D'hooge, Dauskardt. Prog Photovolt Res Appl. 2023;1-13.doi:10.1002/pip.3771

Kinetics of Thermal-Induced Crosslinking in Encapsulants





k_{CL} ~ 7.4E-5 under FL, CO, AZ field conditions [1]

k_{CL} computed for EVA and POE at 90°C is about an order of magnitude higher

$$k_{CL} = Ae^{-\frac{E_{A,crosslinking}}{RT}}$$

EVA	k_{CL}
EVA, 90^{0}C 22% RH	1.21E-3
EVA, 90^{0}C inert sealed	4.60E-3

POE	k_{CL}
POE, 90^{0}C 22% RH	7.15E-4
POE, 90^{0}C inert sealed	2.08E-3

Repeat experiment with 65°C aging to get thermal $E_{A,crosslinking}$

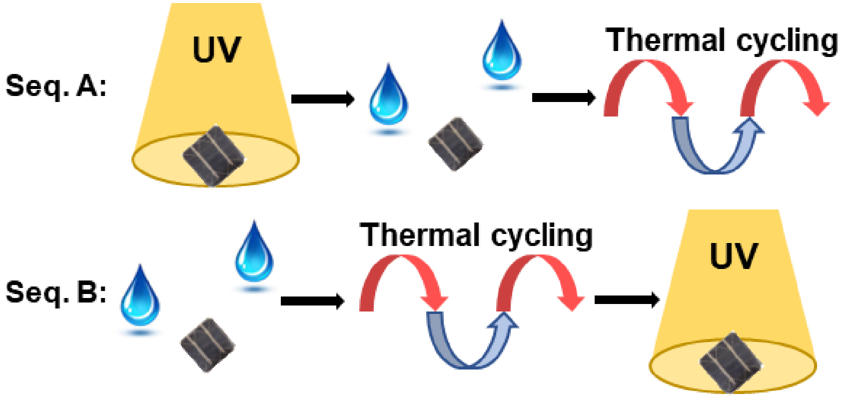
[1] Liu, Thornton, D'hooge, Dauskardt. Prog Photovolt Res Appl. 2023;1-13.doi:10.1002/pip.3771

What Is the Role of Sequenced Accelerated Testing on Interfacial Degradation (Interfacial G_c) ?

Test matrix for sequences of accelerated aging of cell/encapsulant/glass laminates

		DURATION (hours)			
TEST TYPE	TEST CONDITION	2500	5000	7500	10000
steady state aging	UV (IEC 62788-7-2 A3)				
	hot-humid (60°C/60%RH)				
	hot-dry (90°C/~0%RH)				
sequential aging	UV → hot-humid (h-h)	UV	h-h		
	repeat[UV → hot-humid]	UV	h-h	UV	h-h
	hot-humid → UV	h-h	UV		
	repeat[hot-humid → UV]	h-h	UV	h-h	UV
	UV → hot-dry → hot-humid	UV	h-d	h-h	

Further Refinement of G_c Model with Adhesion Testing and Characterization of Laminated Coupons



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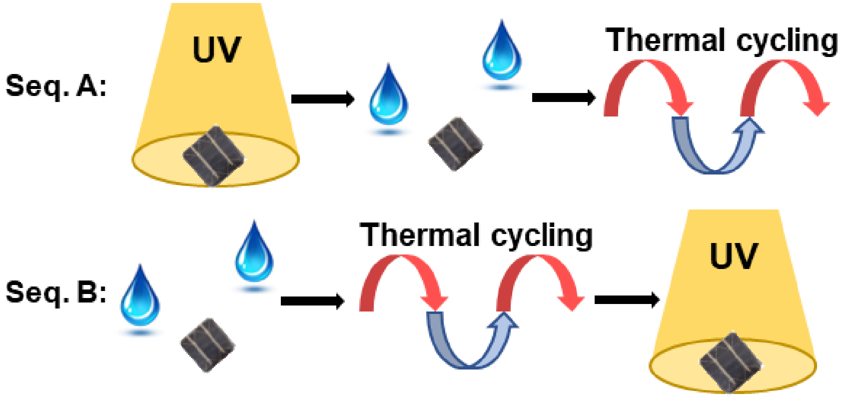
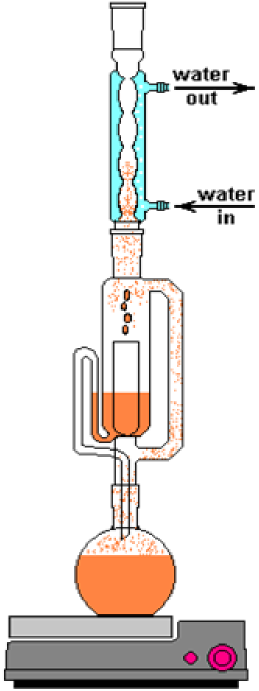
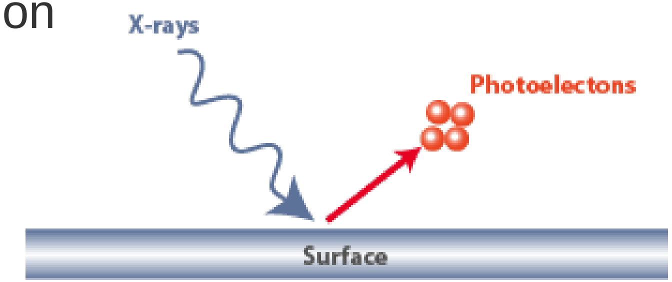


Soxhlet extraction



XPS



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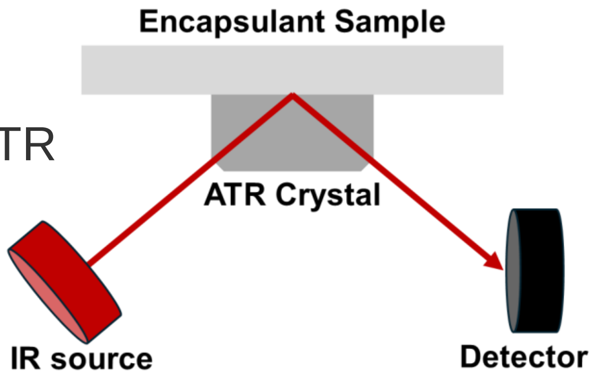
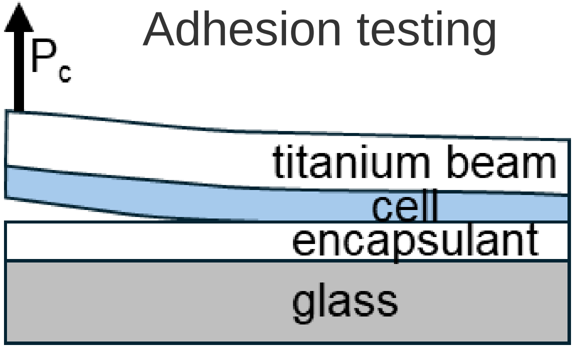


Adhesion testing



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- Professor Dagmar D’hooge

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DuraMAT
Durable Module Materials Consortium

Q/A

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