



Quantifying Adhesion in PV modules: A Historical Survey and Degradation Processes

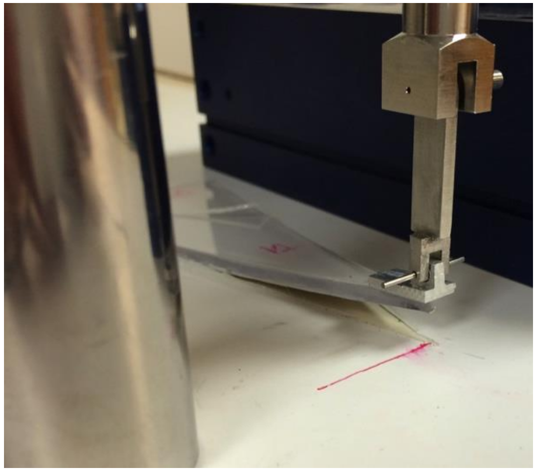
Nick Bosco

NREL

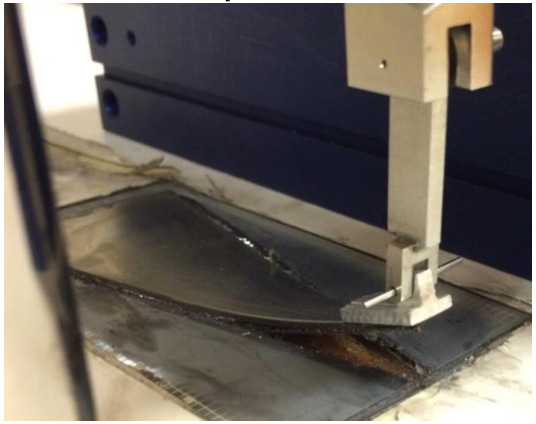
Quantifying Adhesion

width-tapered cantilever beam method

backsheet

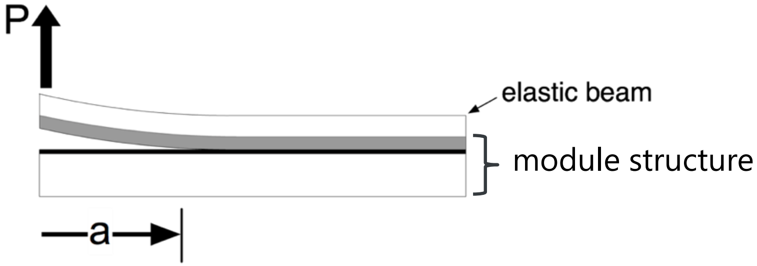


front encapsulant



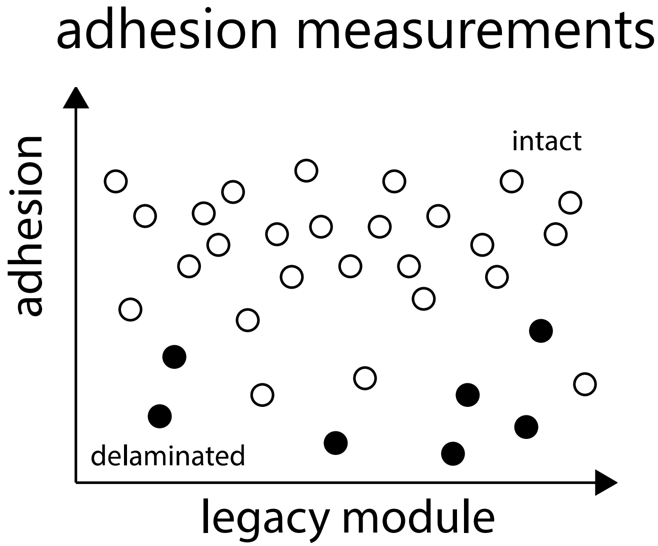
- Only the strain energy temporarily stored in the beam is available to drive delamination
- Measurements of beam compliance allow us to quantify this energy very accurately

$$G_c = \frac{P^2}{2b}\frac{dC}{da}$$



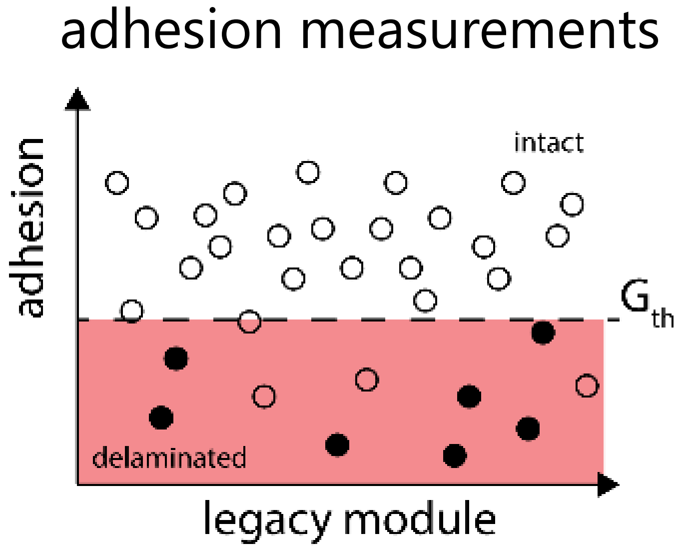
- The measurement is identical at the coupon and module level
- Every interface within the PV module laminate may be measured
- The result is the quantification of a material property

Threshold Adhesion Values



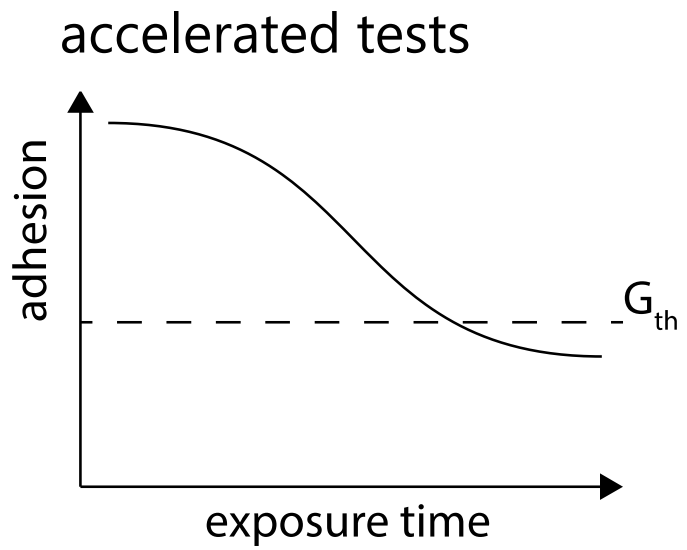
- an adhesion value above which a module should remain intact throughout its lifetime

Threshold Adhesion Values



- an adhesion value above which a module should remain intact throughout its lifetime

Threshold Adhesion Values



- an adhesion value above which a module should remain intact throughout its lifetime

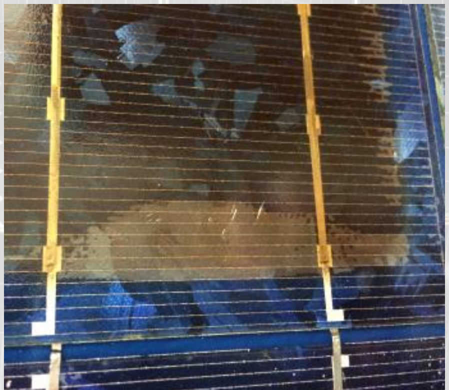
Module Population

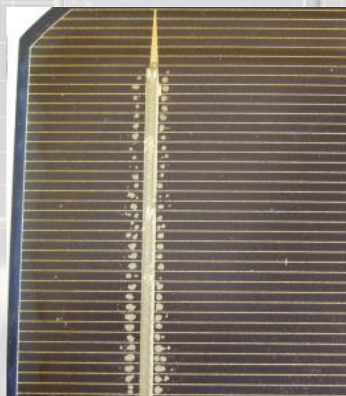
- 32 crystalline silicon modules
- 11 manufactures
- Deployed or stored from two – 27 years
- 16 locations world wide
- Include pre-existing delamination

N. Bosco, J. Eafanti, S. Kurtz, J. Tracy and R. Dauskardt, "Defining Threshold Values of Encapsulant and Backsheet Adhesion for PV Module Reliability," in ***IEEE Journal of Photovoltaics***, vol. 7, no. 6, pp. 1536-1540, Nov. 2017.

Module Population

examples of pre-existing front encapsulant delamination





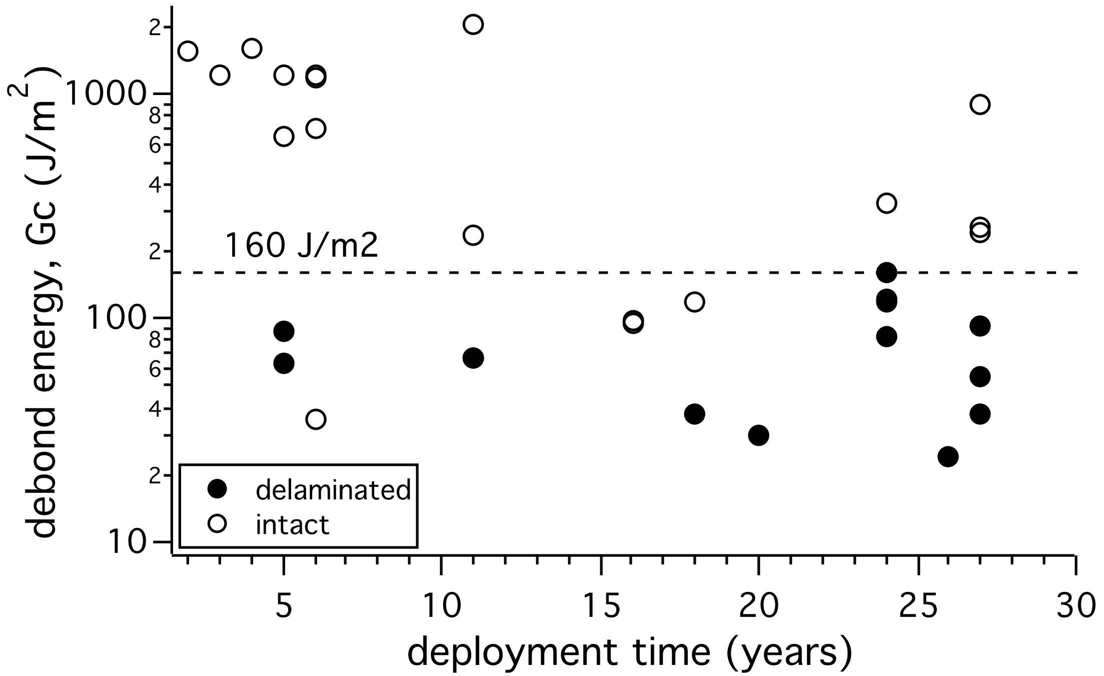
- measurements primarily made away from debonded area
- likely results in a more conservative estimate of G_{th}

examples of pre-existing backsheet delamination

Photo: John Wohlgemuth

- measurements made at delamination front
- results in a more accurate estimate of G_{th}

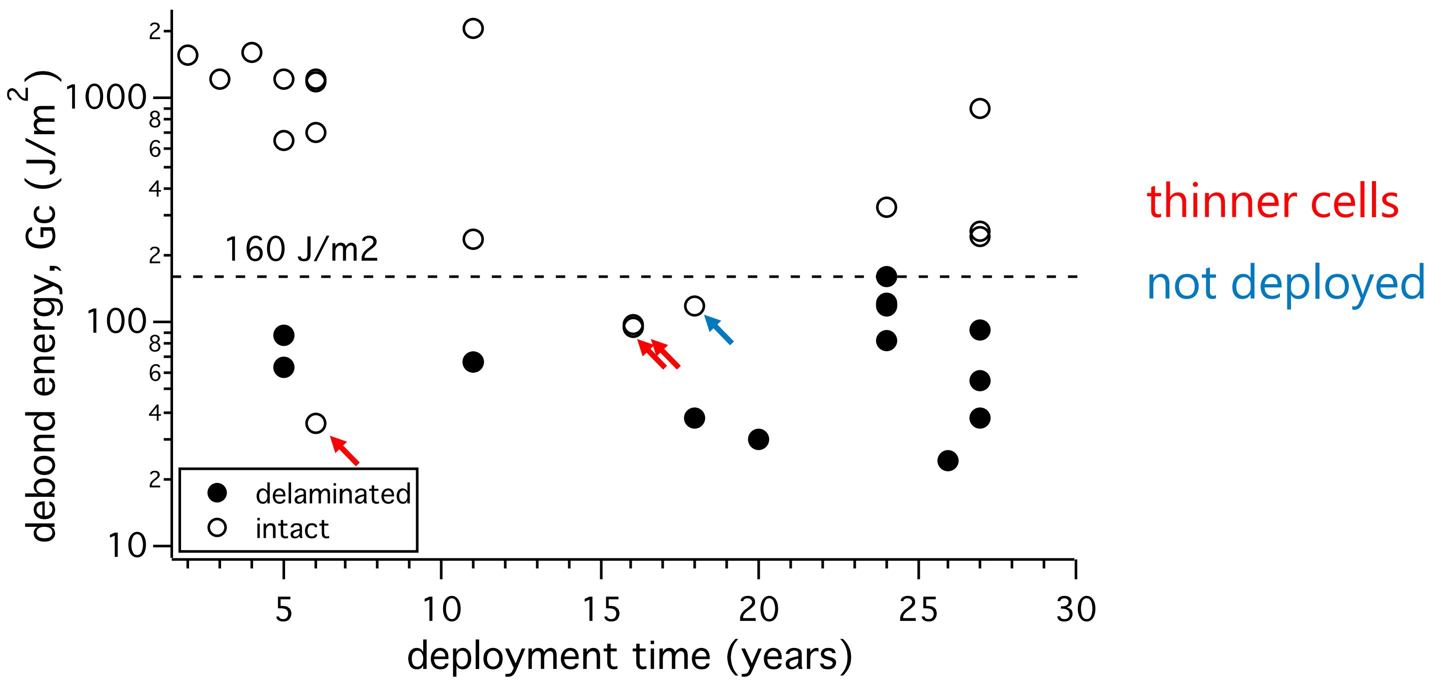
Encapsulant Adhesion Survey



- Front encapsulant adhesion threshold is ~ **160 J/m²**

Results

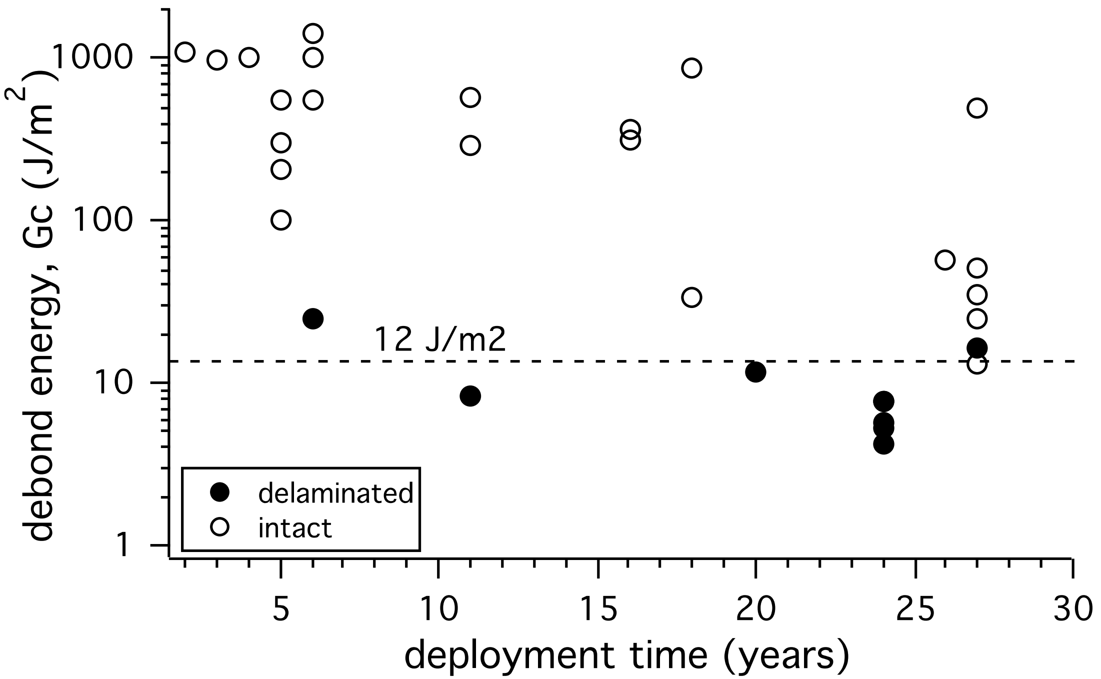
Encapsulant Adhesion Survey



- Front encapsulant adhesion threshold is ~ **160 J/m²**
- Newer modules with thinner cells can accommodate lower debond energies without delaminating

Results

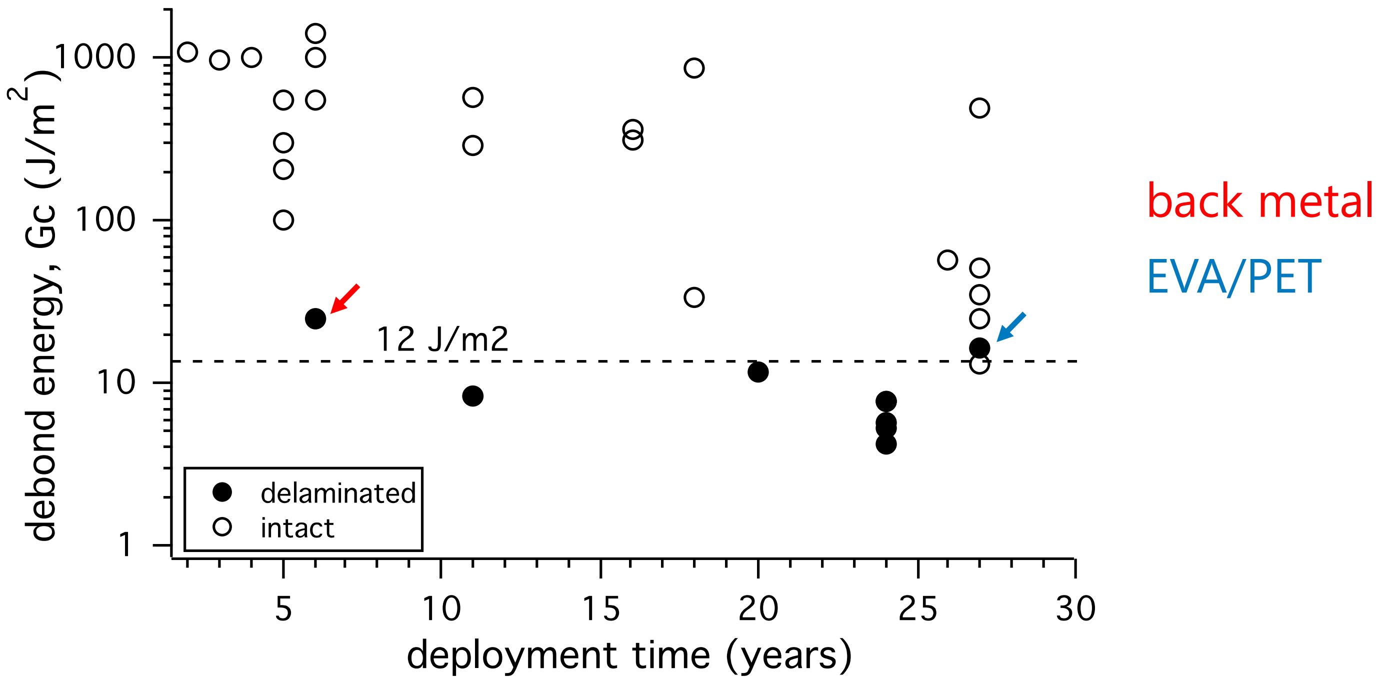
Backsheet Adhesion Survey



- backsheet adhesion threshold is ~ **12 J/m²**
- Most delamination occurred at the outer PET/ PVF interface
- Only a lower limit (>300 J/m^2) of adhesion was measurable on some modules

Results

Backsheet Adhesion Survey



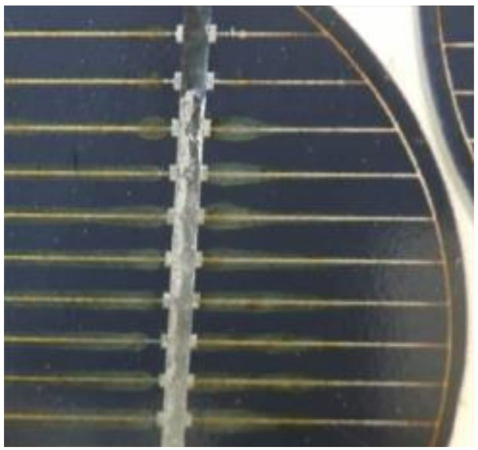
- backsheet adhesion threshold is ~ **12 J/m²**
- Most delamination occurred at the outer PET/ PVF interface
- Only a lower limit (>300 J/m^2) of adhesion was measurable on some modules

Conclusions

- Front encapsulant adhesion threshold is: **~160 J/m²**
- Backsheet adhesion threshold is: **~12 J/m²**
- These values should evolve as the sample population increases
- A safety factor should be assigned when developing and evaluating materials
- Some aspects of module design will influence G_{th}

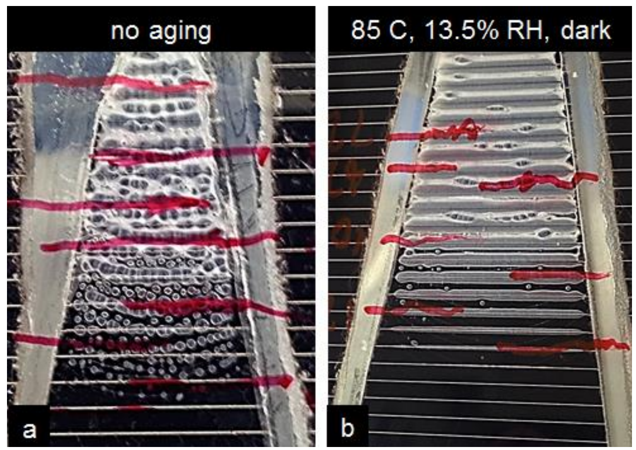
motivating observations

field observation



Arco Solar

adhesion measurement

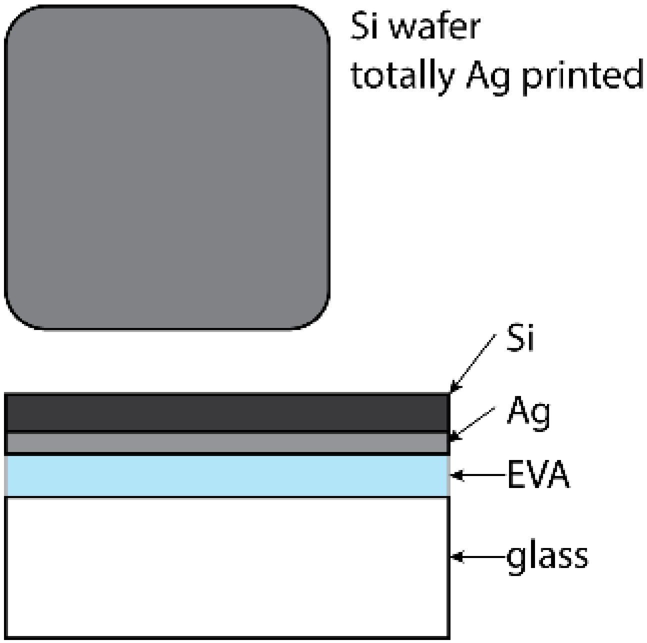


85°C, 13.5% RH

accelerated stress

85°C, 85% RH: 1000 h
followed by
72°C, 95%, -1000 V :156h

experimental design



sample	temp C	RH %	bias V
Ag/ EVA 1	85	0	0
Ag/ EVA 2	85	13.5	0
Ag/ EVA 3	85	40	0
Ag/ EVA 4	85	85	0
Ag/ EVA 5		on-sun	
Ag/ EVA 6	85	85	0
	85	85	-1000
Ag/ EVA 7	85	85	-1000
Ag/ EVA 8	85	0	-1000
Cell/ EVA 1	85	85	0
Cell/ EVA 2	85	0	0
	85	0	-1000
Cell/ EVA 3	85	85	0
	85	85	-1000
Cell/ EVA 4	85	0	0
	85	0	-2000
Cell/ EVA 5	85	85	0
	85	85	-2000

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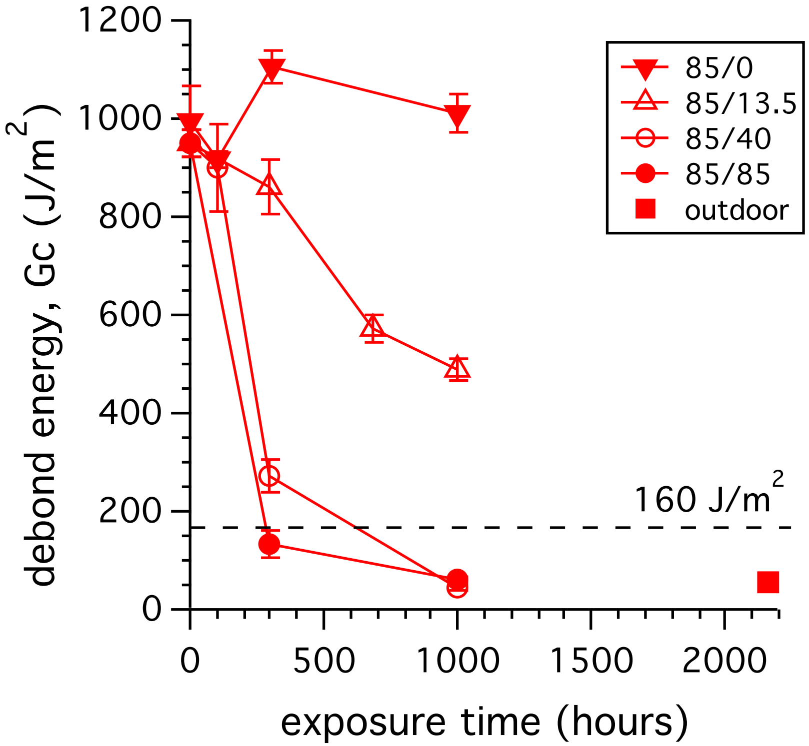
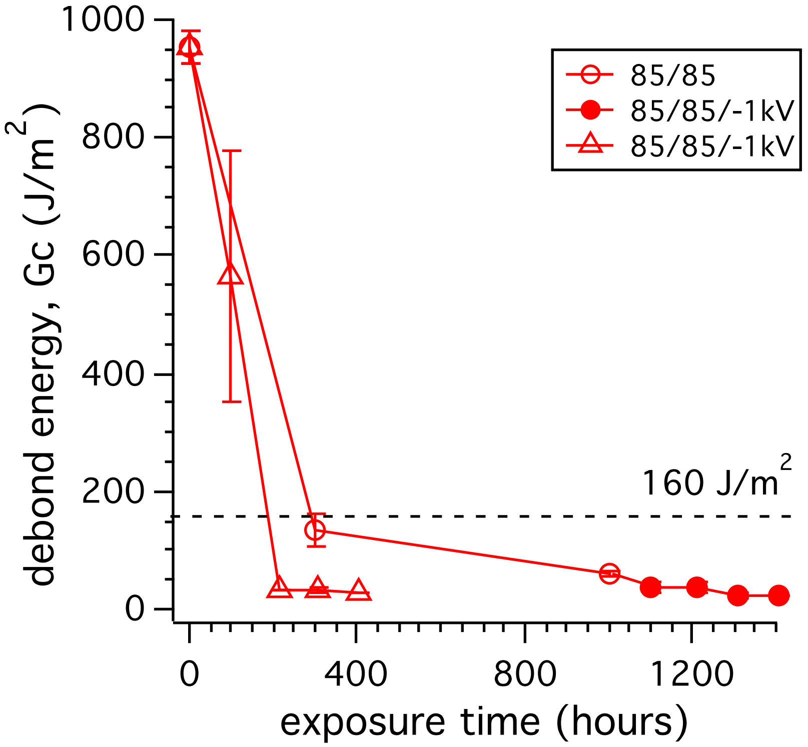
Georgia Tech University, USA

Ag/ EVA humidity series



- adhesion rapidly degrades in the presence of humidity
- accelerated conditions are representative of a short on-sun exposure

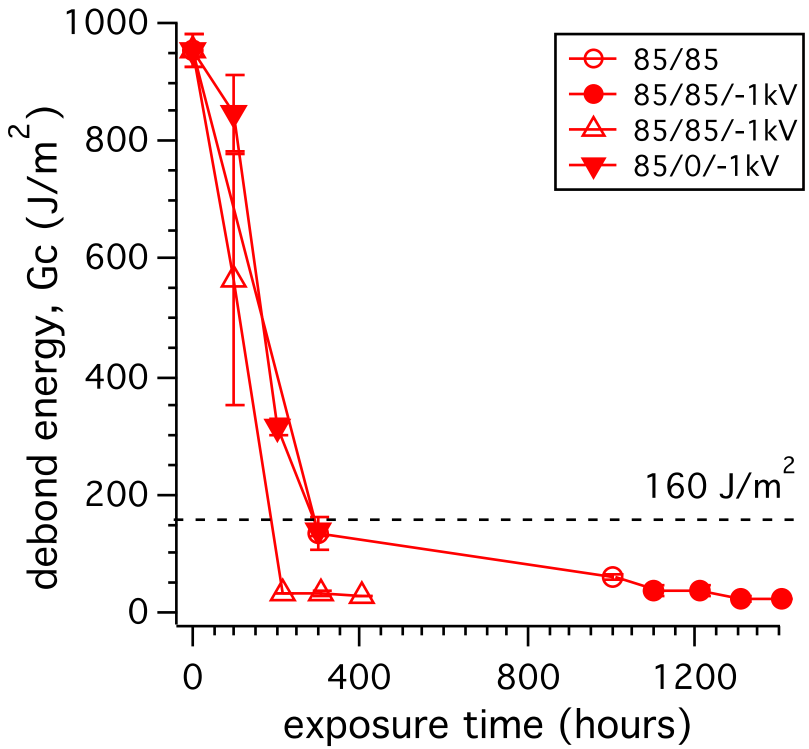
Ag/ EVA bias series



- parallel damp heat and bias exposure is more effective than a serial exposure

results

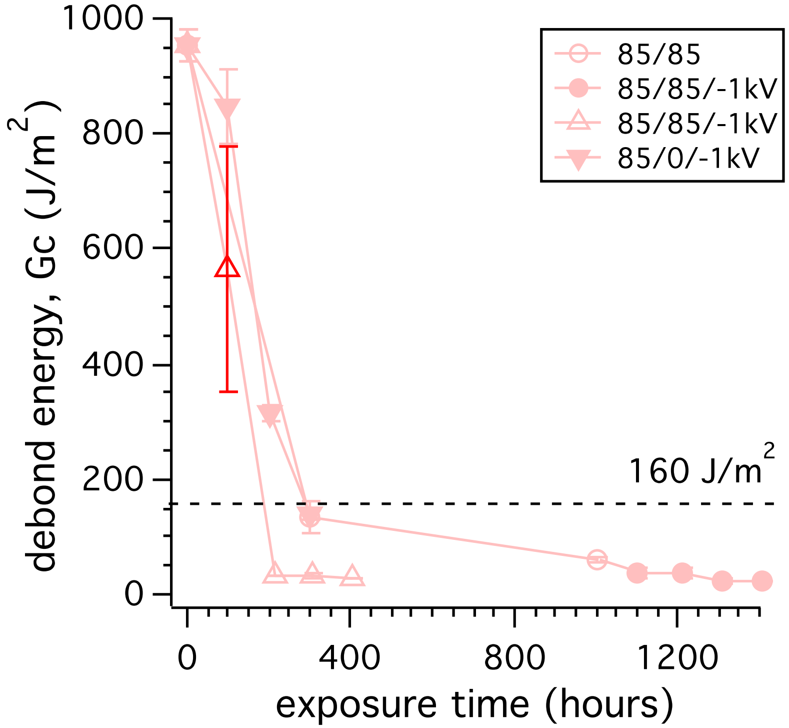
Ag/ EVA bias series

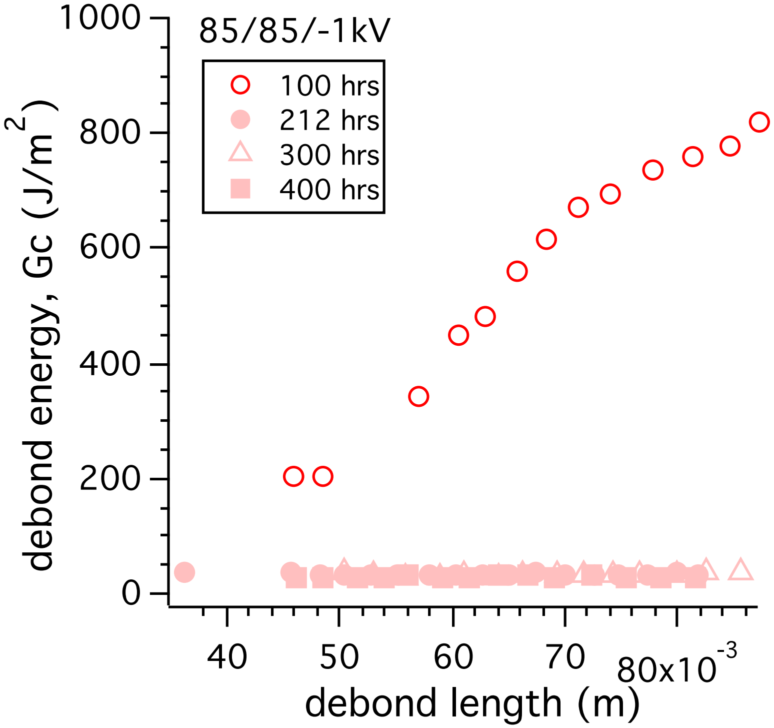


- damp heat and bias exposure is more effective than a serial exposure
- independent voltage mechanism observed
- bias mechanism accelerated in the presence of moisture

results

Ag/ EVA bias series

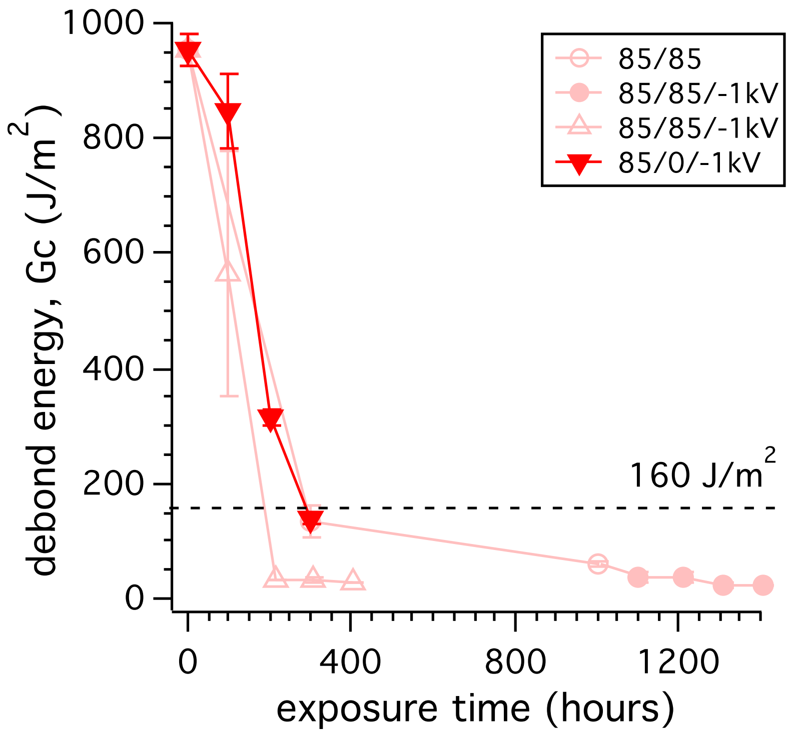


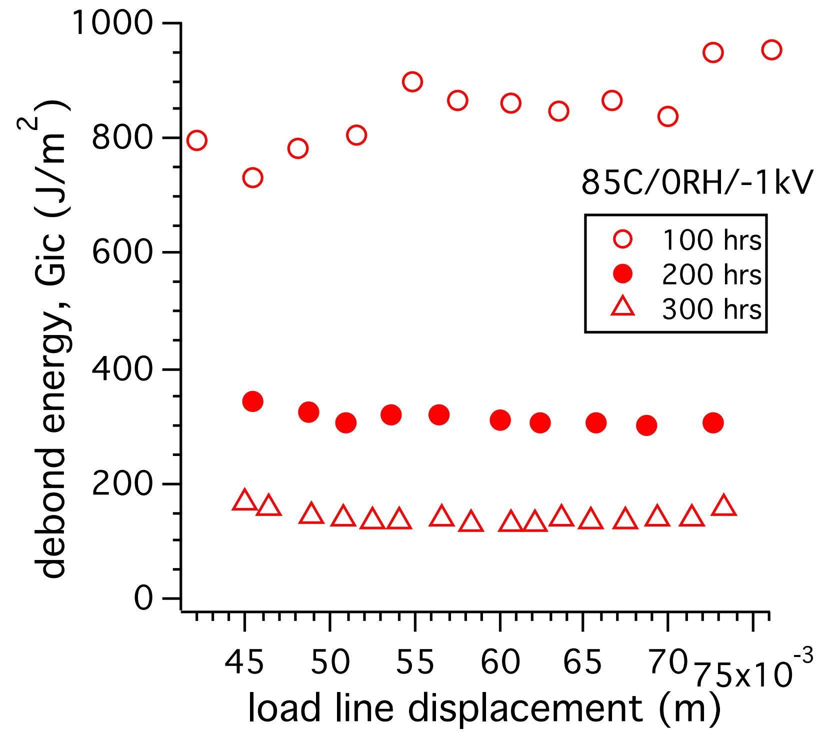


- adhesion gradient observed for short exposure times
- suggests moisture diffusion is the limiting mechanism

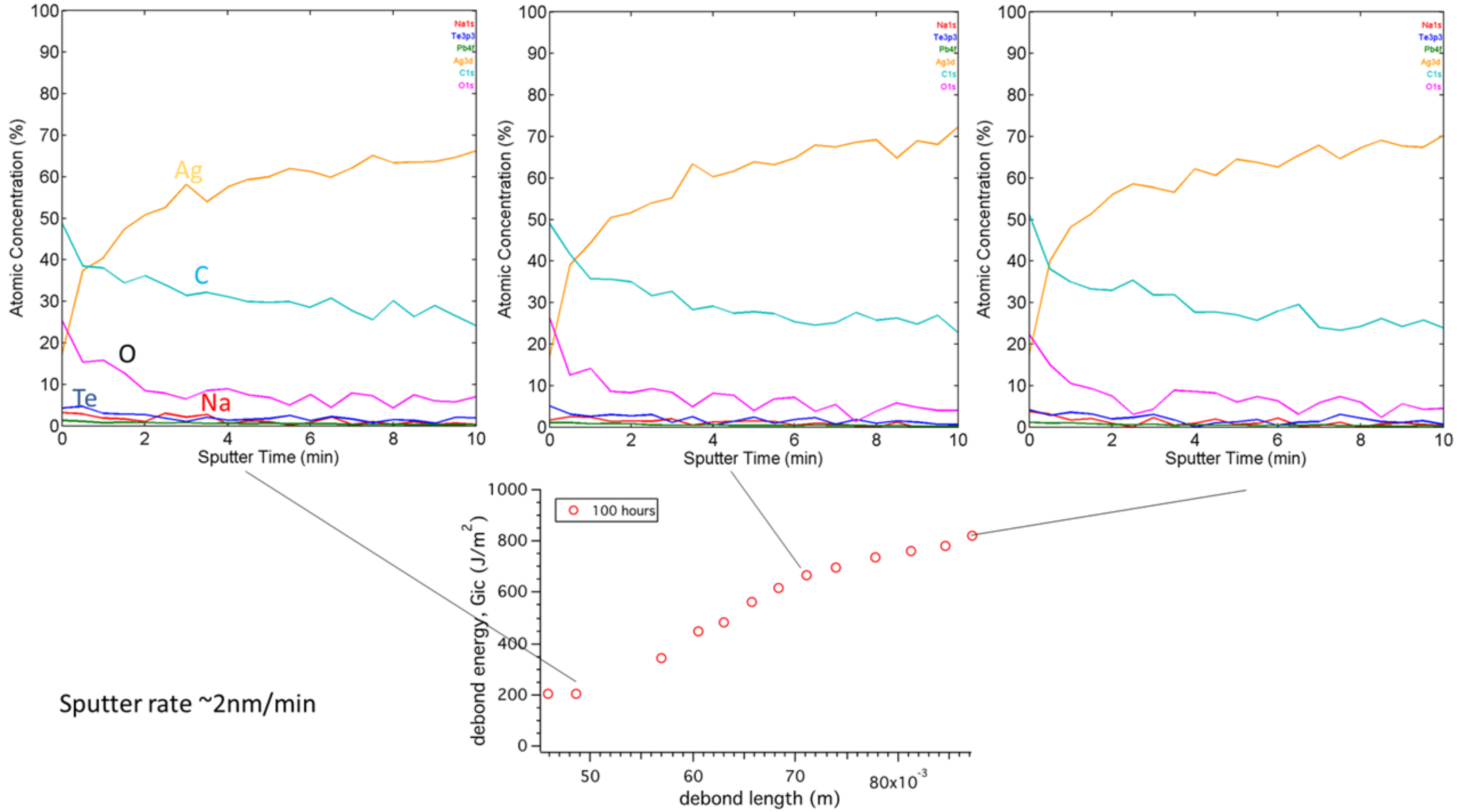
results

Ag/ EVA bias series



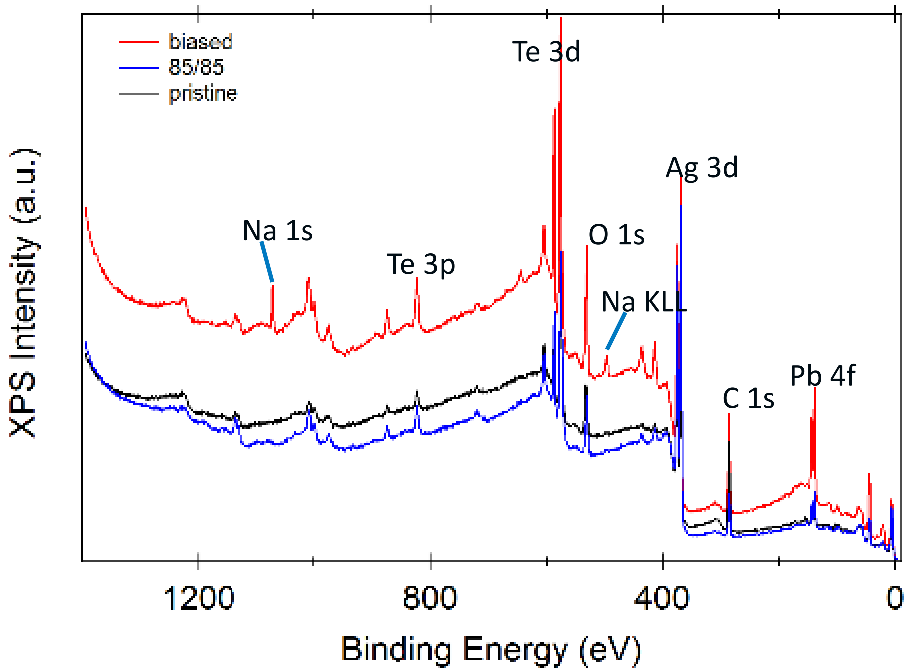


- uniform adhesion consistent with bias mechanism



- XPS depth profiling does NOT show oxide formation responsible for decreased level of adhesion.

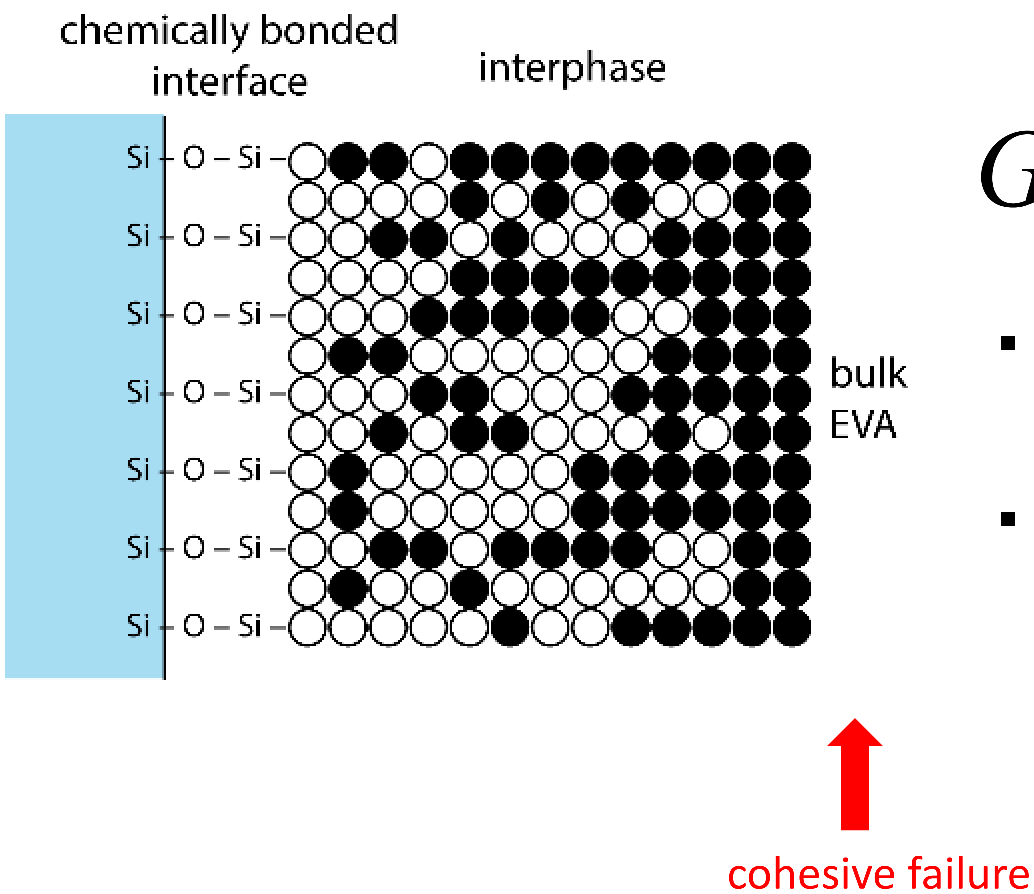
results



Sample	XPS file	Atomic Concentration (%)						
		C	O	Si	Ag	Te	Pb	Na
pristine	x170811_1	60	22	3.9	11	2.3	0.8	---
85/85	x170807_4	37	27	5.0	23	5.4	1.9	---
Biased	x170907_6	49	27	1.0	11	4	3.0	4.0

- Evidence of change in failure mode: cohesive to adhesive
- Na^{+} is detected, but what is it doing?

analysis

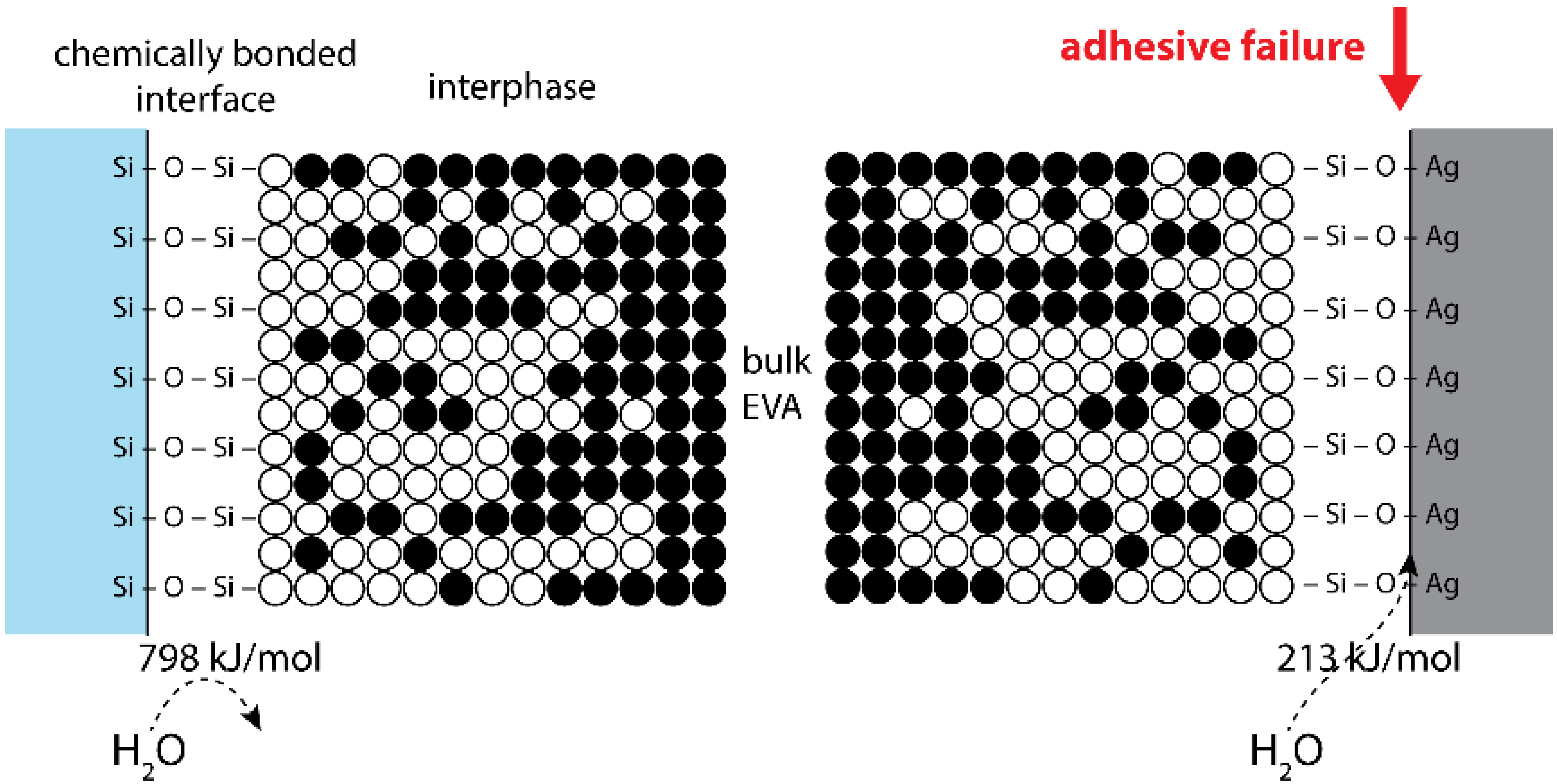


$$G_{c,siloxane} > G_{c,EVA}$$

- cohesive failure in the EVA occurs when siloxane bonded interface is intact.
- failure mode switches to adhesive when chemically bonded interface is degraded

D.R. Coulter, E.F. Cuddihy, and E.P. Plueddemann, "Chemical Bonding Technology for Terrestrial Photovoltaic Modules," DOE/JPL-1012-91) JPL Publication 83-86, Nov. 15, 1983.

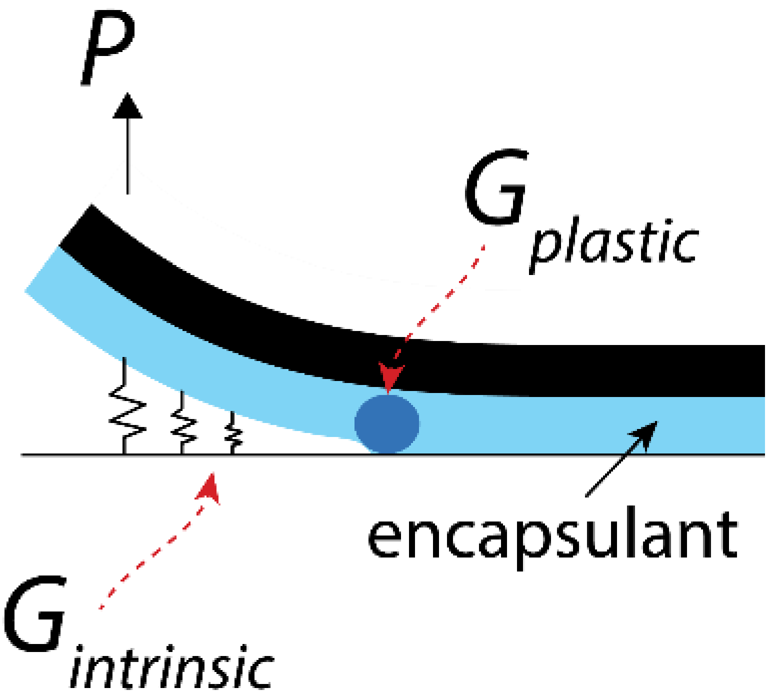
analysis

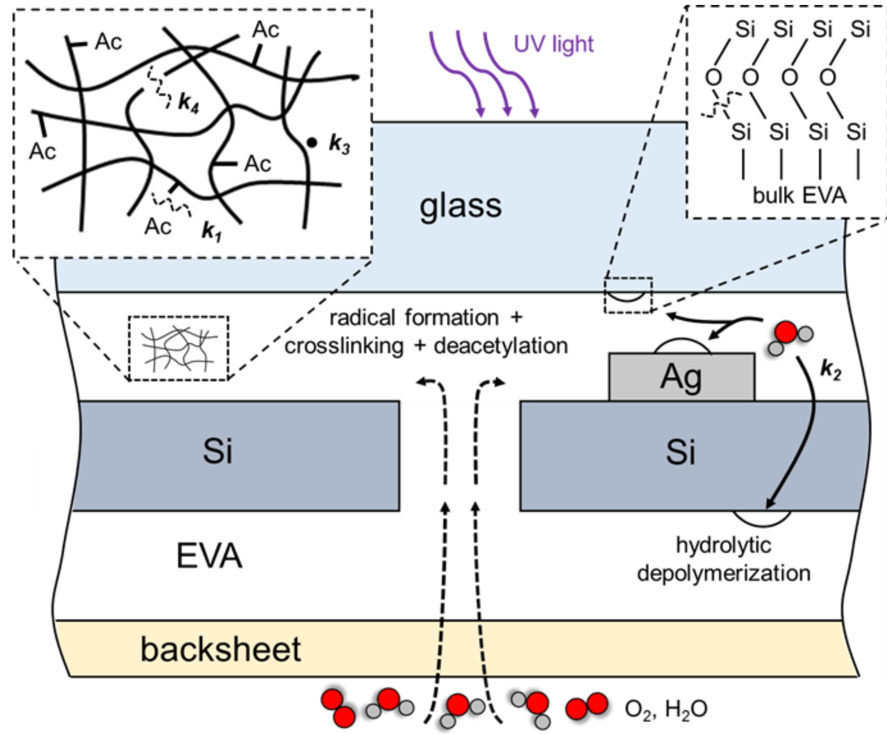


- dissociation via moisture ingress
- changes failure mode from cohesive to adhesive failure at the Ag interface

D.R. Coulter, E.F. Cuddihy, and E.P. Plueddemann, "Chemical Bonding Technology for Terrestrial Photovoltaic Modules," DOE/JPL-1012-91) JPL Publication 83-86, Nov. 15, 1983.

analysis





$$G_c(t) = \sum_{i}^{n} G_{c,\text{int},i}(t) + G_{c,PL}(t)$$

- Analytical model development: modular and extendable

Prof. Dagmar D'Hooge, Ghent University

Analytical model development: modular and extendable

Prof. Dagmar D' Hooge, Ghent University, Belgium

$$(\ ) = \sum \ ,\ \ ,(\ ) + \ ,\ (\ )$$

Intrinsic Contribution

$$G_{c,intr,i}(t) = G_{c,intr,i}(0) f_i(t)$$

$$f_i(t) = exp\left(-a_i\left(1 - \frac{b_i(t)}{b_i(0)}\right)\right)$$

- $b_i(t)$: # bonds after rupture
- $b_i(0)$: # bonds initially
- a_i: intensity factor of intrinsic process

Non-linear Contribution

$$G_{c,PL}(t) = \sum_i^n G_{c,intr,i}(t)\, d(t)$$

- $d(t)$: proportionality factor

$$d(t) = d(0)\left(1 - \frac{t}{t_\infty}\right)$$

$$d(0) = \frac{G_c(0)}{\sum_i^n G_{c,intr,i}(0)} - 1$$

Analytical model development: governing equations and functional form

$$\boldsymbol{f_i(t) = exp\left(-a_i\left(1 - \frac{b_i(t)}{b_i(0)}\right)\right)}$$

( ) = ∑ , , ( ) + , ( )

$$\frac{dc_{\mathrm{VAc}}(t)}{dt} = -k_1 c_{\mathrm{VAc}}(t)$$

deacetylation (I)

$$\frac{b_1(t)}{b_1(0)} = \exp(-k_1 t)$$

$$\frac{dc_{SiOSi}(t)}{dt} = -k_2 c_{SiOSi}(t) c_w(t)$$

hydr. depolym. (III)

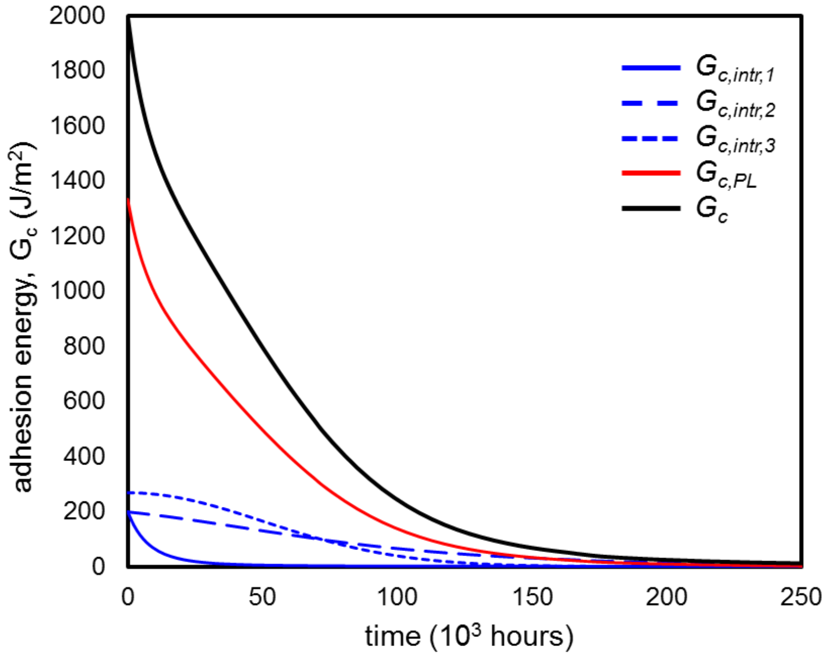
$$\frac{b_2(t)}{b_2(0)} = \exp(-k_2 c_{w,eq} t)$$

$$\frac{dc_{MCR}(t)}{dt} = k_3\mu_1 - k_4\, c_{MCR}(t)$$

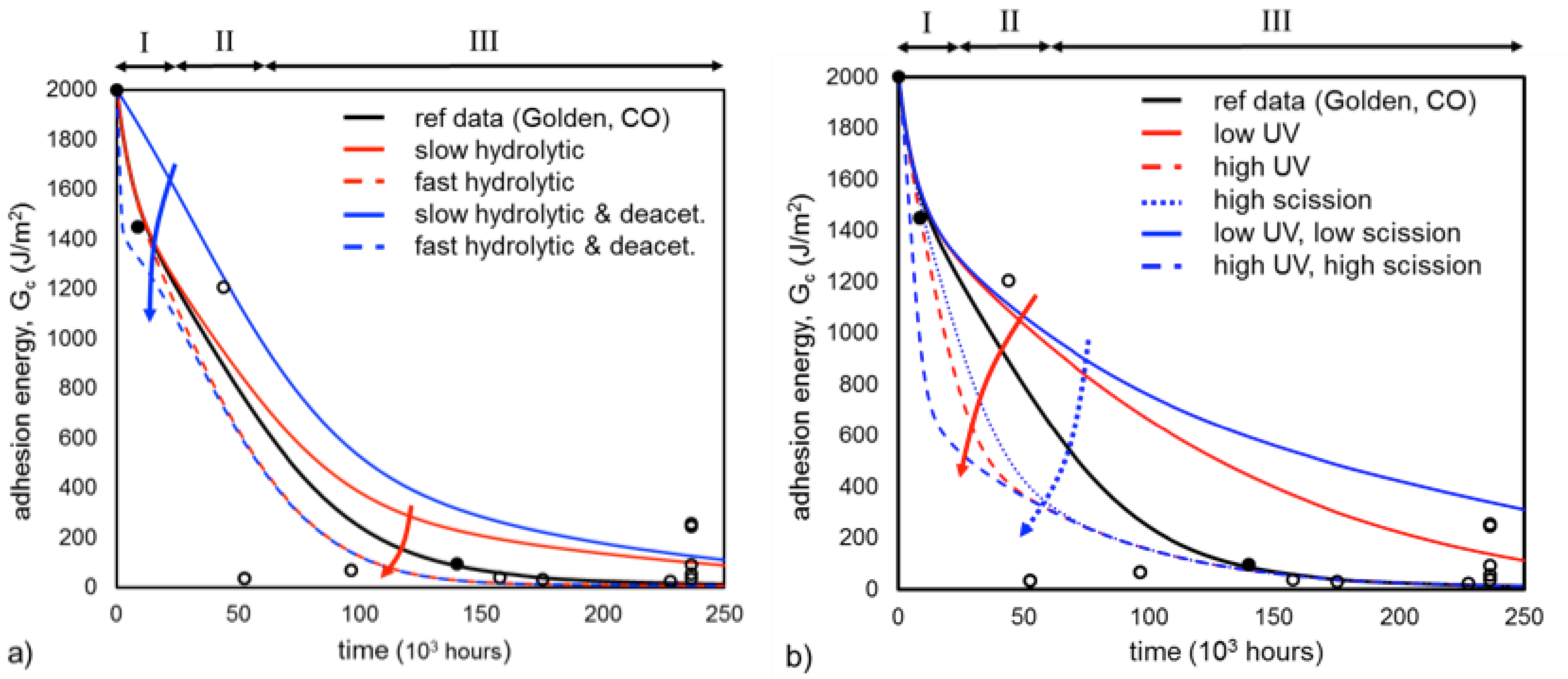
$$\frac{dc_{MM}(t)}{dt} = k_4 c_{MCR}(t)$$

radical formation and scission (II)

$$\frac{b_3(t)}{b_3(0)} = \frac{c_{CL}(t)}{c_{CL}(0)} = \frac{k_3\mu_1}{c_{CL}(0)}\left(\mathrm{t} - \left(\frac{1}{k_4} + c_{MCR}(0)\right)(1 - \exp(-k_4 t))\right)$$



Analytical model development: parameter tuning



I. deacetylation II. UV radicals + scission III. hydrolytic depolymerization

analysis

- Quantifying the material property of adhesion
- Developing a modular and extendable model for adhesion degradation
- Current experiments to define degradation mechanisms and refine rate equations
- Work will enable accelerated tests to predict long-term adhesion performance
- A similar approach may be applied to all adhesive systems

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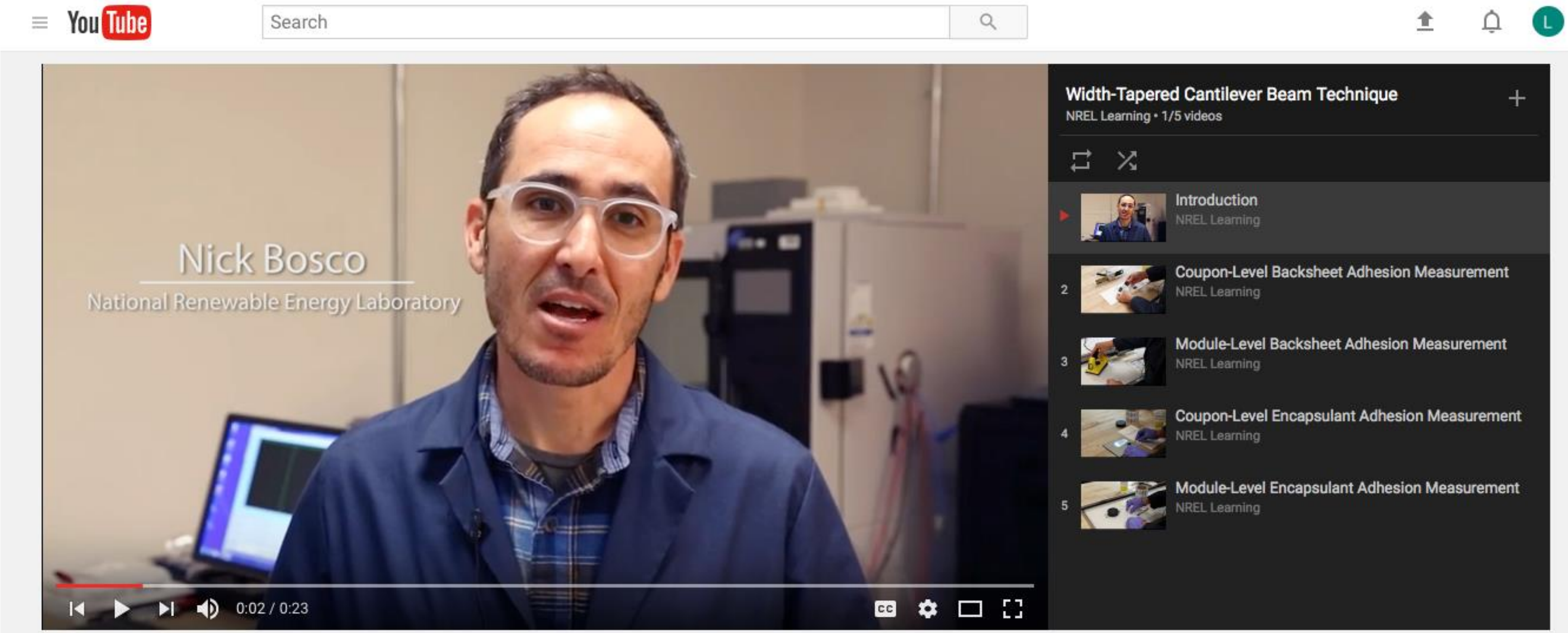
Quantifying Adhesion

instructional videos



https://youtu.be/ql9li68J60c?list=PLmIn8Hncs7bFpFFBpUQnKXzzx54wucPp1

- Tracy, J., Bosco, N., Novoa, F., Dauskardt, R., "Encapsulant and backsheet Adhesion Metrology for Photovoltaic Modules", ***Progress in Photovoltaics***, 25:87-96, Sept 2016
- Bosco, N., Kurtz, S., Tracy, J., Dauskardt, R. "Development and First Results of the Tapered Width Beam Method for Adhesion Testing of Photovoltaic Material Systems***", IEEE Journal of Photovoltaics*** ,2016
- N. Bosco, J. Eafanti, S. Kurtz, J. Tracy and R. Dauskardt, "Defining Threshold Values of Encapsulant and Backsheet Adhesion for PV Module Reliability," in ***IEEE Journal of Photovoltaics***, vol. 7, no. 6, pp. 1536-1540, Nov. 2017.
- J. Tracy, N. Bosco and R. Dauskardt, "Encapsulant Adhesion to Surface Metallization on Photovoltaic Cells," in ***IEEE Journal of Photovoltaics***, vol. 7, no. 6, pp. 1635-1639, Nov. 2017.