NATIONAL RENEWABLE ENERGY LABORATORY

Using Uncertainty Analysis to Guide the development of Accelerated Stress Tests

NREL Photovoltaic Module Reliability Workshop (PVMRW)

Michael Kempe

Golden, Colorado
Tuesday, February 25, 2014

NREL/PR-5200-61539

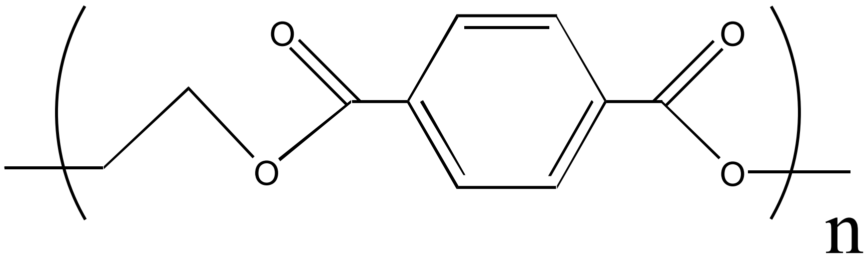
Introduction

- **PV modules degrade in response to environmental stresses such as heat, humidity, UV irradiation, CTE mismatch, high voltage, and etc..**
- **Many degradation processes are driven by complex combinations of these stress factors.**
- **For generalized accelerated stress tests, a significant amount of uncertainty is inherent.**
- **A better understanding of the uncertainty in the relevant stress factors will aid in the development of accelerated stress tests.**

Outline

- Look at the hydrolysis of a typical back-sheet made of PET as a case study for a material with an unusually high level of understanding of degradation.
- Apply kinetic models of paints and coatings degradation to backsheets.
- Discuss concerns with developing a single test for all degradation modes.

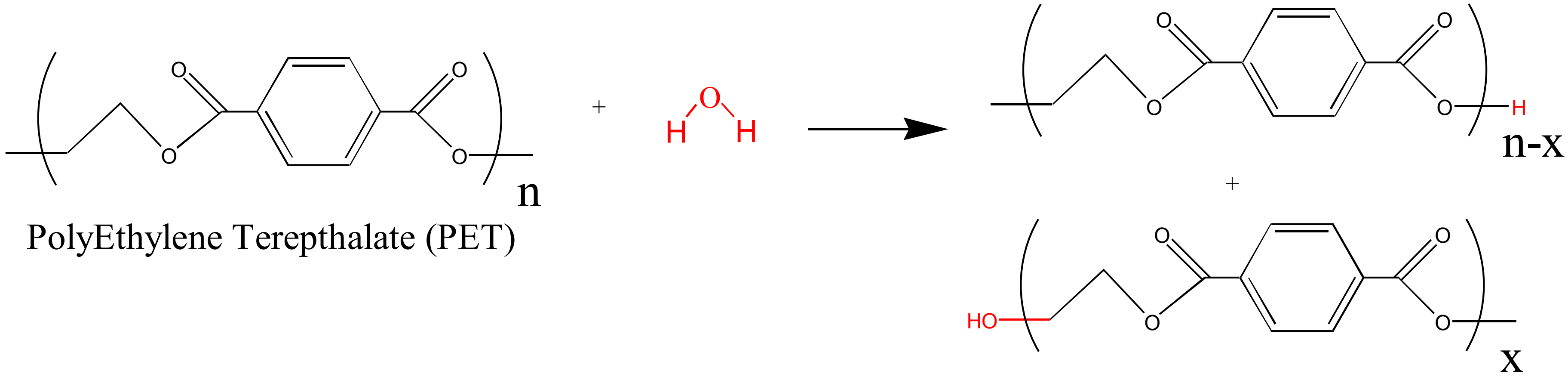
PET Hydrolysis Modeling



PolyEthylene Terepthalate (PET)

- **PET is commonly used in back-sheet materials:**
  - Low cost
  - Good electrical insulator
  - Long term track record
- **Hydrolysis results in embrittlement of PET which can lead to cracking and back-sheet failure.**
- **However, hydrolysis is only one potentially relevant failure mechanism, but it is extremely well understood.**

PET Hydrolysis Kinetics



PolyEthylene Terepthalate (PET)

$$t_{fail} = \frac{e^{\left(\frac{E_a}{RT}\right)}}{A[RH]^2}$$

Pickett *et. al***

Ea=129±3.4 kJ/mol

A=$1.2 \cdot 10^{17} \pm 1.3 \cdot 10^{17}$h

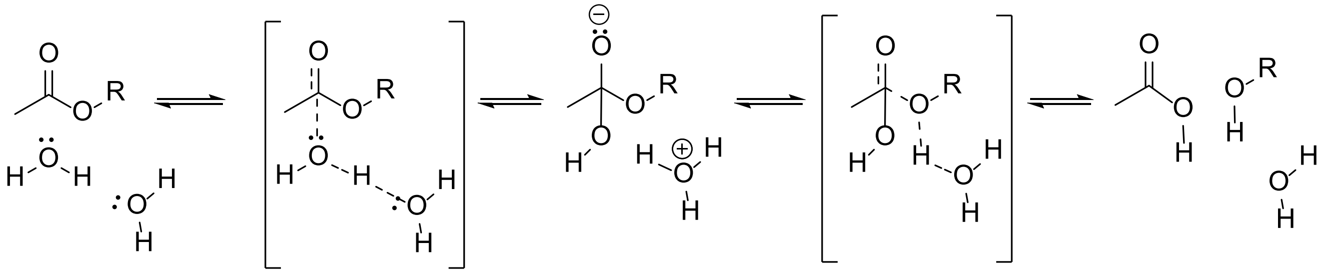
RH expressed as a percentage.

*PET becomes brittle (1/3 initial tensile strength) and "failed" when about 0.55% hydrolysis of ester bonds.

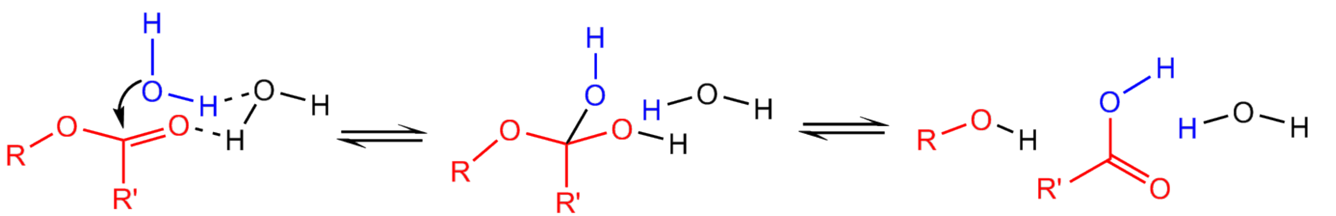
*W. McMahon, H. A. Birdsall, G. R. Johnson, and C. T. Camilli, "Degradation Studies of Polyethylene Terephthalate," Journal of Chemical & Engineering Data, vol. 4, pp. 57-79, 1959.

**J. E. Pickett and D. J. Coyle, "Hydrolysis Kinetics of Condensation Polymers Under Humidity Aging Conditions," Polymer Degradation and Stability, vol. 98, pp. 1311-1320, 2013.

Hydrolysis Mechanism is Well Understood



Scheme 4*



Scheme 6*

- **Picket *et. al** * proposed these mechanisms and reaction intermediates as possible hydrolysis pathways.**

*J. E. Pickett and D. J. Coyle, "Hydrolysis Kinetics of Condensation Polymers Under Humidity Aging Conditions," Polymer Degradation and Stability, vol. 98, pp. 1311-1320, 2013.

**Shi Z, Hsieh Y-H, Weinberg N, Wolfe S. The neutral hydrolysis of methyl acetate—Part 2. Is there a tetrahedral intermediate? Can J Chem 2009: 87; 544-555.
Euranto EK, Cleve NJ. Kinetics of the neutral hydrolysis of chloromethyl chloroacetate. Acta Chemica Scand. 1963: 17; 1584-1594.

Site Specific Equivalent T and RH

$$t_{fail} = \frac{e^{\left(\frac{E_a}{RT}\right)}}{A[RH]^2}$$

$$RH_{weighted\ average} = RH_{WA} = \left[\frac{\sum RH^n e^{\left(-\frac{Ea}{kT}\right)}}{\sum e^{\left(-\frac{Ea}{kT}\right)}}\right]^{\frac{1}{n}}$$

RH_{WA} is an average effective relative humidity weighted towards higher temperatures where most of the damage occurs.

$$T_{eq} = -\frac{Ea}{k\ln\left[\frac{\sum e^{\left(-\frac{Ea}{kT}\right)}}{N}\right]}$$

The equivalent temperature (T_{eq}) gives the temperature at RH_{WA} for which constant conditions will produce a degradation rate equivalent to the yearly average.

Uncertainty Propagation

$$\sigma_f{}^2 \approx \left|\frac{\partial f}{\partial a}\right|^2 \sigma_a{}^2 + \left|\frac{\partial f}{\partial b}\right|^2 \sigma_b{}^2 + 2\frac{\partial f}{\partial a}\frac{\partial f}{\partial b} COV_{ab} \ldots$$

Assumes f(a,b,…) has normally distributed uncertainties and ignores higher order terms.

$$T_{eq} = -\frac{Ea}{kln\left[\frac{\sum e^{\left(-\frac{Ea}{kT}\right)}}{N}\right]}$$

$$\sigma_{T_{eq}} = \left\{-\frac{1}{kln\left[\frac{\sum e^{\left(-\frac{Ea}{KT}\right)}}{N}\right]} - \frac{Ea}{k^2}\frac{\sum \frac{e^{\left(-\frac{Ea}{KT}\right)}}{T}}{\sum e^{\left(-\frac{Ea}{KT}\right)}}\right\}\sigma_{Ea}$$

Pet Hydrolysis Uncertainty

	Years to failure	Teq for Ea=129 kJ/mol	Effictive RH_{WA}, at T_{eq}
	(y)	T	RH
		(°C)	(%)
Denver, Colorado	10500±1600	32.9±0.3	14.2±0.3
Munich, Germany	8400±1300	27.5±0.4	25.3±0.5
Albuquerque, New Mexico	7000±1100	36.7±0.3	12.6±0.2
Riyadh, Saudi Arabia	6400±1000	47.7±0.3	5.6±0.1
Phoenix, Arizona	2700±400	46.1±0.3	9.8±0.2
Miami, Florida	870±130	36.7±0.2	36.4±0.5
Bangkok, Thailand	530±80	40.9±0.2	33.4±0.5

- The uncertainty in the service life was a function of the uncertainty in the prefactor A and Ea, with a significant correlation between the two.
- The uncertainty in all other terms is dependent only on σ_{Ea}.
- The uncertainty in the order parameter n was assume to be zero.
- The uncertainty in the weather, materials, microclimate, and etc was ignored.
- Thus this represents a minimal estimate of uncertainty.

Pet Hydrolysis Uncertainty

	Years to failure	Teq for Ea=129 kJ/mol	Effictive RH_{WA}, at T_{eq}	Conditions for a test Equivalent to 25 y for Ea=129±3.4 kJ/mol and n=2, for a rack mounted system				
				1000 Hour Test				
				Thermal Only		50:50 Split		
		T	RH	$T_{100\%}$	Years	T	RH	Years
	(y)	(°C)	(%)	(°C)	(y)	(°C)	(%)	(y)
Denver, Colorado	10500±1600	32.9±0.3	14.2±0.3	69.3±-0.7	25±3.1	50.1±-0.1	54.5±1.2	25±1.4
Munich, Germany	8400±1300	27.5±0.4	25.3±0.5	62.5±-0.6	25±3.1	44±-0.1	97.4±2.3	25±1.3
Albuquerque, New Mexico	7000±1100	36.7±0.3	12.6±0.2	74.1±-0.7	25±3.1	54.4±-0.2	48.6±0.8	25±1.3
Riyadh, Saudi Arabia	6400±1000	47.7±0.3	5.6±0.1	87.9±-0.8	25±3.6	66.6±-0.2	21.7±0.5	25±1.8
Phoenix, Arizona	2700±400	46.1±0.3	9.8±0.2	86±-0.8	25±3.3	64.9±-0.2	37.7±0.7	25±1.5
Miami, Florida	870±130	36.7±0.2	36.4±0.5	74.1±-0.9	25±3.5	54.3±-0.3	140±2	25±1.7
Bangkok, Thailand	530±80	40.9±0.2	33.4±0.5	79.4±-0.9	25±3.6	59.1±-0.3	128±2.1	25±1.8

- **A 1000 h 25 y equivalent test can be designed by using only thermal acceleration.**
- **Alternatively, the acceleration can be split between higher temperature and higher humidity.**

Pet Hydrolysis Uncertainty

	Years to failure	Teq for Ea=129 kJ/mol	Effictive RH_{WA}, at T_{eq}	Conditions for a test Equivalent to 25 y for Ea=129±3.4 kJ/mol and n=2, for a rack mounted system														
				1000 Hour Test					6 Month Test					2.5 Year Test				
				Thermal Only		50:50 Split			Thermal Only		50:50 Split			Thermal Only		50:50 Split		
	(y)	T	RH	$T_{100\%}$	Years	T	RH	Years	$T_{100\%}$	Years	T	RH	Years	$T_{100\%}$	Years	T	RH	Years
		(°C)	(%)	(°C)	(y)	(°C)	(%)	(y)	(°C)	(y)	(°C)	(%)	(y)	(°C)	(y)	(°C)	(%)	(y)
Denver, Colorado	10500±1600	32.9±0.3	14.2±0.3	69.3±-0.7	25±3.1	50.1±-0.1	54.5±1.2	25±1.4	58.5±-0.3	25±2.2	45.2±0.02	37.7±0.6	25±0.9	47.5±0	25±1.1	40±0.16	25.2±0.3	25±0.3
Munich, Germany	8400±1300	27.5±0.4	25.3±0.5	62.5±-0.6	25±3.1	44±-0.1	97.4±2.3	25±1.3	52.1±-0.3	25±2.1	39.3±0.07	67.3±1.1	25±0.8	41.5±0	25±1	34.3±0.19	45±0.5	25±0.3
Albuquerque, New Mexico	7000±1100	36.7±0.3	12.6±0.2	74.1±-0.7	25±3.1	54.4±-0.2	48.6±0.8	25±1.3	63±-0.4	25±2.1	49.3±-0.02	33.6±0.4	25±0.8	51.7±-0.1	25±1	44±0.12	22.4±0.2	25±0.3
Riyadh, Saudi Arabia	6400±1000	47.7±0.3	5.6±0.1	87.9±-0.8	25±3.6	66.6±-0.2	21.7±0.5	25±1.8	75.9±-0.5	25±2.6	61.2±-0.07	15±0.3	25±1.3	63.7±-0.1	25±1.6	55.5±0.08	10±0.1	25±0.8
Phoenix, Arizona	2700±400	46.1±0.3	9.8±0.2	86±-0.8	25±3.3	64.9±-0.2	37.7±0.7	25±1.5	74.1±-0.5	25±2.3	59.5±-0.06	26.1±0.3	25±1	62±-0.1	25±1.2	53.9±0.09	17.4±0.1	25±0.5
Miami, Florida	870±130	36.7±0.2	36.4±0.5	74.1±-0.9	25±3.5	54.3±-0.3	140±2	25±1.7	63±-0.5	25±2.5	49.3±-0.14	96.8±1	25±1.2	51.6±-0.2	25±1.4	44±-0.0005	64.7±0.4	25±0.6
Bangkok, Thailand	530±80	40.9±0.2	33.4±0.5	79.4±-0.9	25±3.6	59.1±-0.3	128±2.1	25±1.8	67.9±-0.6	25±2.6	53.9±-0.15	88.7±1	25±1.3	56.3±-0.2	25±1.5	48.4±-0.01	59.3±0.4	25±0.7

- **A 1000 h test is suitable for screening tests or qualification tests.**
- **A 6 month test provides more flexibility in a reasonable amount of time.**
- **A 2.5 y test is an acceleration factor of 10× which is generally believed to provide reasonable accelerations for unknown processes.**

Reduced Uncertainty for Longer Test Times

Uncertainty in Equivalent Length of 25 y test for Rack Mounted System for PET Hydrolysis	Conditions for a test Equivalent to 25 y for Ea=129±3.4 kJ/mol and n=2, for a rack mounted system					
	1000 Hour Test		6 Month Test		2.5 Year Test	
	Thermal	50:50	Thermal	50:50 Split	Thermal	50:50
Denver, Colorado	3.1	1.4	2.2	0.9	1.1	0.3
Munich, Germany	3.1	1.3	2.1	0.8	1.0	0.3
Albuquerque, New Mexico	3.1	1.3	2.1	0.8	1.0	0.3
Riyadh, Saudi Arabia	3.6	1.8	2.6	1.3	1.6	0.8
Phoenix, Arizona	3.3	1.5	2.3	1.0	1.2	0.5
Miami, Florida	3.5	1.7	2.5	1.2	1.4	0.6
Bangkok, Thailand	3.6	1.8	2.6	1.3	1.5	0.7

- **This represents the smallest amount of uncertainty possible. It ignores variability from exposure, construction and other test specific sources, and assumes the failure mode is directly related to PET hydrolysis.**

Kinetics of Paints and Coatings Degradation

$$R_D \sim I^x \cdot (b + m \cdot TOW) \cdot T_f^{\frac{T - T_o}{10}}$$

*Fischer *et. al*

T_f=1.41±0.23 Acceleration per 10°C increase.

X=0.64±0.2 Irradiance acceleration exponent.

m=-0.0015±0.12 Time of Wetness (TOW) factor.

b=1.071±0.0026

- **50 coatings with respect to color shift, cracking, gloss loss, fluorescence loss, retroreflectance loss, adhesive transfer, and shrinkage.**

*R. M. Fischer and W. D. Ketola, "Error Analyses and Associated Risk for Accelerated Weathering Results," *Third International Service Life Symposium, Sedona, AZ February 2004,* 2004.

Modeling Assumptions for a PV Backsheet

- **Assume UV on back of rack mounted system is 0.5% of global horizontal irradiance.**
- **Ignore TOW**
  - Very high uncertainty with a low mean value indicating a very small effect.
  - Condensation is predominantly on the front making application of this effect dubious on the back.

Location Specific Effective Conditions

Rack Mounted Modules	I_{WA}		T_{oeq}
	(W/m² from 295 to 385)	(W/m²/nm @340 nm)	(°C)
Munich, Germany	0.753±0.339	0.0095±0.0043	14.4±1.5
Denver, Colorado	1.17±0.48	0.0148±0.006	19.0±2.1
Albuquerque, New Mexico	1.44±0.55	0.0181±0.0069	24.0±2.0
Miami, Florida	1.01±0.36	0.0127±0.0046	30.8±0.8
Bangkok, Thailand	1.05±0.38	0.0131±0.0047	35.2±0.8
Phoenix, Arizona	1.52±0.57	0.0191±0.0071	34.6±2.0
Riyadh, Saudi Arabia	1.57±0.58	0.0197±0.0073	36.7±1.9

ASTM G173 has 35.6 W/m² between 295 and 385 nm

$$T_{oeq}=\frac{10}{ln(T_f)}\,ln\left(\frac{\sum T_f^{\frac{T}{10}}}{N}\right)$$

$$I_{WA}=\left[\frac{\sum I^x T_f^{\frac{T-T_{oeq}}{10}}}{N}\right]^{\frac{1}{x}}$$

Much Greater Uncertainty in 25 y Tests

Uncertainty in Acceleration Factor for Optimized Data			
Uncertainty in 25 y Equivalent Test	Accelerated Stress Test Duration		
	1000 h	6 month	2.5 y
Munich, Germany	27	18	7.3
Denver, Colorado	28	18	7.8
Albuquerque, New Mexico	28	19	8.3
Miami, Florida	29	19	8.9
Bangkok, Thailand	29	19	8.9
Phoenix, Arizona	29	19	8.4
Riyadh, Saudi Arabia	29	19	8.4

- **Temperature and irradiance optimized to minimize the uncertainty in a 25 y equivalent stress test.**

Optimal Exposure Conditions

Irradiance optimized Data						
Uncertainty in 25 y Equivalent Test	Accelerated Stress Test Duration					
	1000 h		6 month		2.5 y	
	T_o (°C)	($W/m^2/nm$ @340 nm)	T_o (°C)	($W/m^2/nm$ @340 nm)	T_o (°C)	($W/m^2/nm$ @340 nm)
Munich, Germany	68	2.5	55	0.50	40.4	0.086
Denver, Colorado	74	3.6	61	0.71	46.4	0.12
Albuquerque, New Mexico	78	4.4	65	0.89	51.2	0.15
Miami, Florida	80	4.1	67	0.81	53.1	0.14
Bangkok, Thailand	85	4.2	72	0.83	57.7	0.14
Phoenix, Arizona	89	4.7	76	0.94	61.7	0.16
Riyadh, Saudi Arabia	90	5.0	77	1.01	63.2	0.17

- **ASTM G173 using 0.5018 $W/m^2/nm$ @340 nm**
  - 1000 h test - 5 to 10 UV suns
  - 6 month test - 1 to 2 UV suns
  - 2.5 y test - 0.17 to 0.33 UV suns

Conclusion

- **With an extremely good understanding of the degradation kinetics, one can design a 25 y equivalent test to within ~±1 y. Unfortunately, this is an unusual occurrence and produces results with a very narrow scope.**
- **For backsheet materials, a generic and long, ~2.5 y, test may yield reasonable uncertainties of ~± 8 y.**
- **Accelerated stress tests must be very targeted at specific materials and failure modes, or be of a very long duration.**
- **Estimates for irradiance for a 25 y backsheet test:**
  - 1000 h test - 5 to 10 UV suns
  - 6 month test - 1 to 2 UV suns
  - 2.5 y test - 0.17 to 0.33 UV suns

Acknowledgements

Sarah Kurtz

John Wholgemuth

David Miller

Peter Hacke

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