Understanding the Variability in Extrapolation from Lab to Field Conditions

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2021 NIST-UL Workshop for PV Materials Durability

Background

- There is a desire to design PV modules capable of being fielded for 50 y.
- The main impediment to achieving this is the ability to know if a particular design and manufacturing process can meet adequate degradation rate targets.
- To have reasonable confidence in long term performance, accelerated stress testing factors ideally should not be greater than 10×, but a 5-y test is not usually reasonable.
- Therefore, tests are designed with much higher acceleration factors and/or designed to target specific failure mechanisms.
- With such high acceleration factors, >100×, the potential variability in the equivalent time between different materials in a given module construction can be very large.

Monte Carlo Method

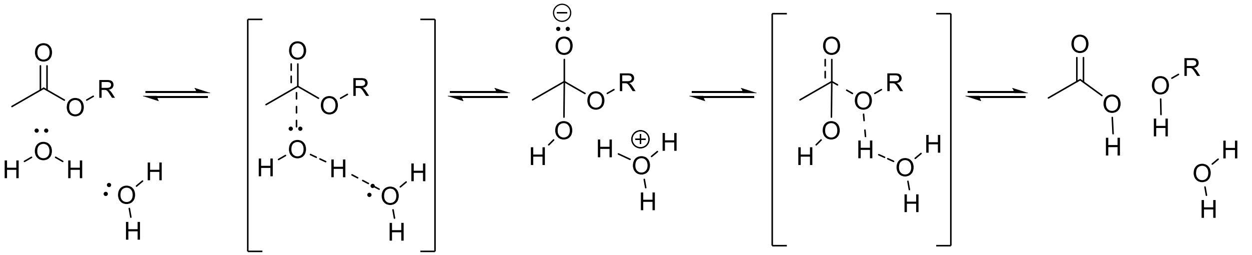
- We used hourly typical meterological year data for Miami Florida and for Riyadh Saudi Arabia as extreme examples of representative hot and humid and hot and dry environments.
- For module temperature we used a single axis tracker system with the King* model for rack mounted glass front/polymer back module.
- A random number generator produced sets of 20,000 acceleration parameters (e.g. activation energy) with the appropriates means, standard deviations, and correlation coefficients.
- Lastly, each set of parameters is then run through the hourly module environmental data to generate a distribution of acceleration factors from the field extrapolation.

*D. L. King, W. E. Byoson, J. A. Kratochvil, Photovoltaic Array Performance Model, SAND2004-3535 (2004)

There is Uncertainty in Degradation Parameters

- Under the best circumstances, when degradation parameters are determined, there is some inherent uncertainty.
- Frequently, the specifics of the degradation mechanism are largely unknown and we only know the general range of degradation values to be expected in broad terms.

PET Hydrolysis Kinetics



Pickett *et. al***

It is understood at a mechanistic level and known to be second order with respect to water. Therefore, no uncertainty is assumed in the RH power.

$$R_D = R_0 \cdot RH^n \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

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

Ea=129±3.4 kJ/mol

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

n=2

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.

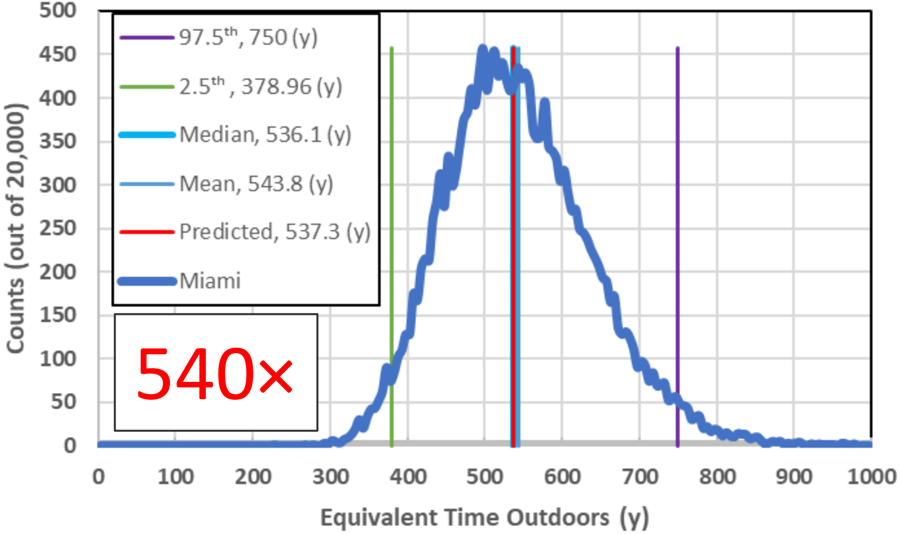
**J. E. Pickett and D. J. Coyle, "Hydrolysis Kinetics of Condensation Polymers Under Humidity Aging Conditions," Polymer Degradation and Stability, vol. 98, pp. 1311-1320, 2013.

PET hydrolysis:

Best case extrapolation

Single-axis tracker
Polymer back module

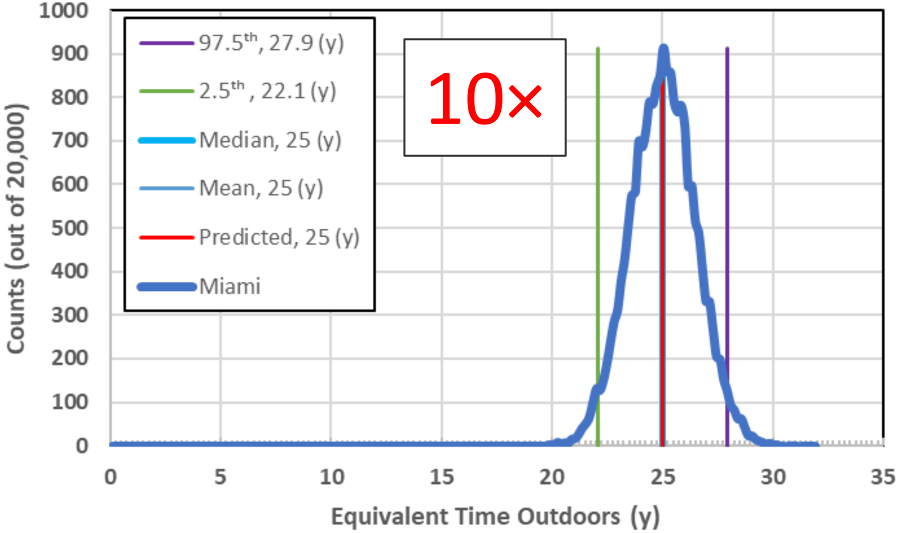
Miami, 1000 (h), 85 (%), 85(°C)
Ea=129±3.4 (kJ/mol), n=2



540×

$$R_D = R_0 \cdot RH^n \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

Miami, 2.5 y, 33% RH, 53°C
Ea=129±3.4 kJ/mol, n=2



10×

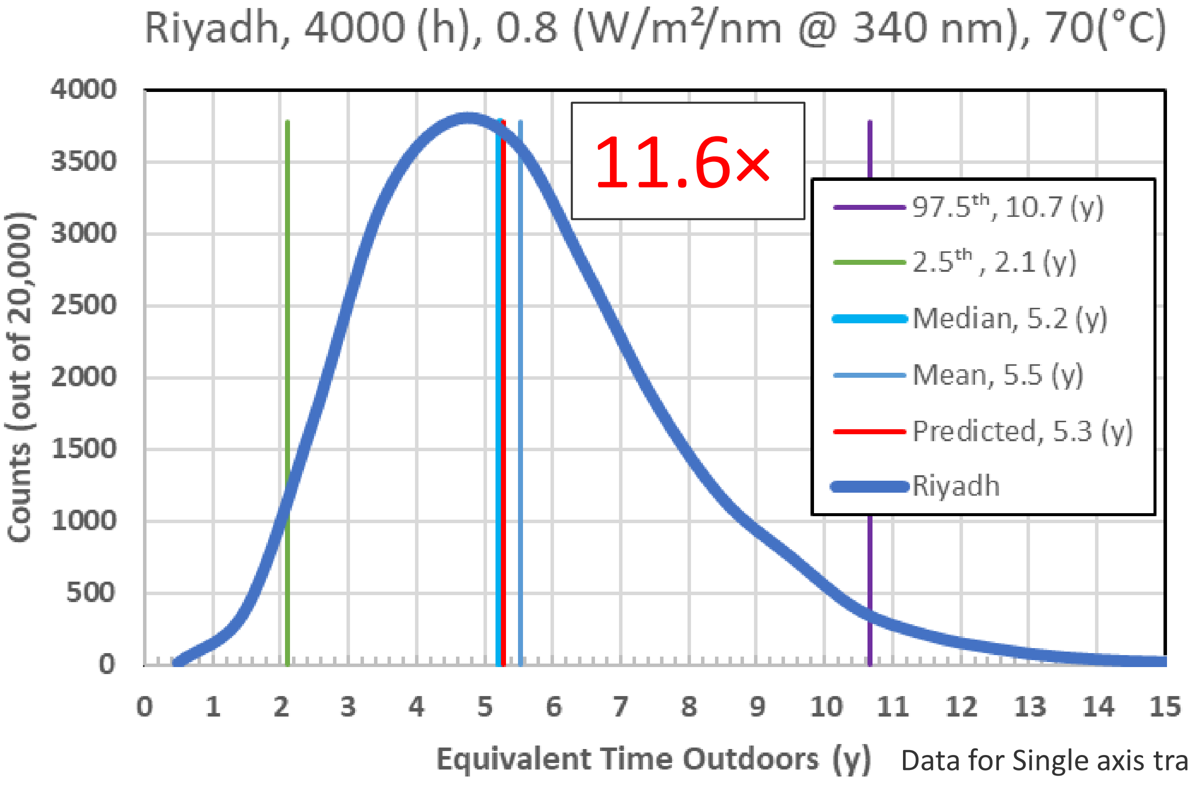
- Extrapolation can be for extreme amounts of time for highly thermally accelerated processes like PET hydrolysis.
- When the acceleration is kept low, the uncertainty in the extrapolation is low.

Most degradation modes have many degradation mechanisms

- It is unusual that one can describe a degradation mode by a single or even a single dominant mechanism.
- In an experiment looking at 15 different transparent frontsheets and looking at several different failure modes, we found the range of degradation processes to be described as:
- Frontsheet Degradation**
  - Ea=38±21 kJ/mol
  - X=0.49±0.22
  - Correlation(*X* to *Ea*)=-0.606

$$R_D = R_0 \cdot I^X \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

Long-Term UV Exposure is only equivalent to a few years



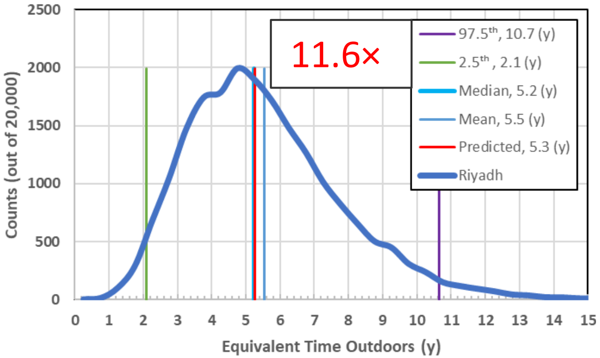
Data for Single axis tracking.

- The condition of A3 from IEC 62788-7-2 is only equivalent to a few years of frontside exposure in Riyadh on a single axis tracker.
- Even with a reasonable 11.6× acceleration factor, there is a >5× range in equivalent time.

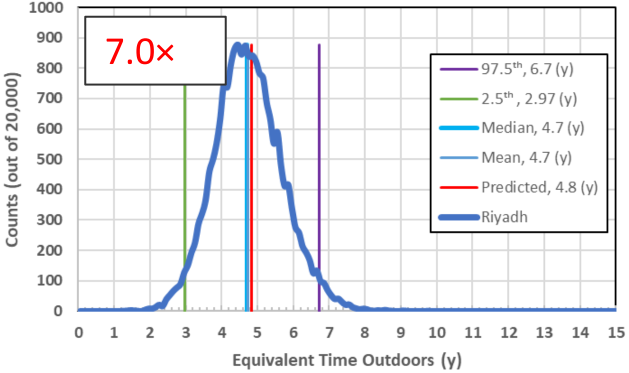
*M. D. Kempe et al., "Highly Accelerated UV Stress Testing for Transparent Flexible Frontsheets," in 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), 2020, pp. 1823-1823.

Optional proposals for IEC 63126 high system testing exposure

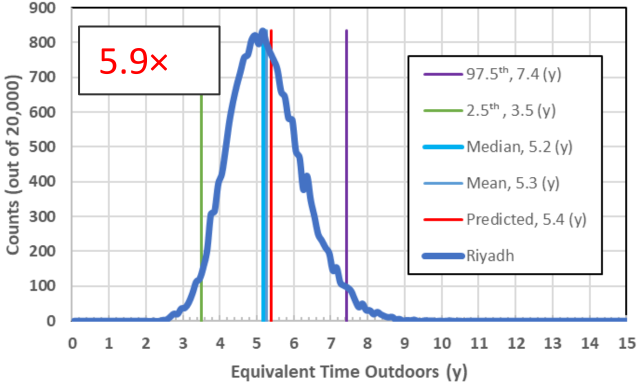
Riyadh Saudi Arabia



A3 (65°C), 4000 h, Rack, T_{98}<70°C



A3 (75°C), 6000 h, Close Roof, T_{98}<80°C



A3 (85°C), 8000 h, Insulated, T_{98}<90°C

These are proposed exposures for qualification of encapsulants or frontsheets to temperatures of T_{98}<70°C, 80°C or 90°C.

If longer times are used for the extrapolation, there is less variability in the results.

Without a mechanistic understanding of degradation, acceleration factors of 6× or 7× may be needed to accurately compare different materials unless their total degradation is dramatically different.

Humidity promoting degradation

- Using lots of humidity to accelerate degradation can be difficult.
  - Very good at promoting delamination and oxidation of inorganic materials.
  - For organic materials humidity may decrease or may increase degradation.
  - In studying paints and coatings, Fisher et al.* found that degradation depended on the "Time of Wetness" with an average value that was negative (slowing down degradation) and was half the magnitude of the standard deviation. Therefore, there isn't a "typical" response to moisture and each material should be considered specifically.

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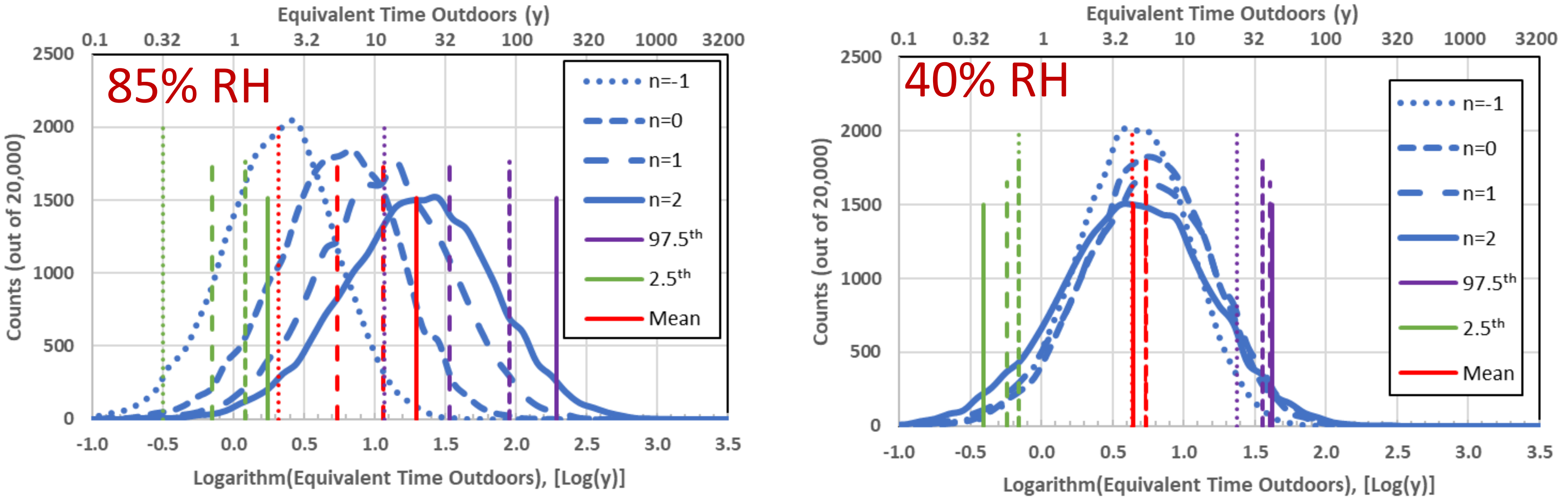
*Richard Fischer and Warren Ketola, "Error Analyses and Associated Risk for Accelerated Weathering Results", Third International Service Life Symposium, Sedona, AZ February 2004.

Representative humidity reduces scatter in extrapolation

$$R_D = R_0 \cdot RH^n \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

Miami, open rack, Single axis Tracking, 1000 h, 85°C, Ea=70±20 kJ/mol



- Choosing the right humidity improves field extrapolation to a specific site by making the results almost independent of the response to humidity.

Considerations for Humidity Choice

- Unfortunately, there is not an ideal humidity choice that works everywhere.
- Ideal test humidity ranges between ~5% for Saudia Arabia to 40% for Florida with minor dependence on activation energy but a relevant dependence on mounting configuration and subsequent module temperature.
- For most locations, values between 20% and 30% RH would be appropriate.
- One should also be aware that a given degradation mode may have several mechanisms with different humidity dependencies.
- Within a single module there may be several different contributors to failure. If the acceleration factors from the different stressors are better balanced, there is a higher probability that the most important failure modes, or the best material combinations will be identified.

Conclusions: Reasons to use lower acceleration factors

- If acceleration factors are too great, one will simply see the most highly accelerated pathways which are not necessarily the relevant ones.
- Unless the degradation mechanism of interest is well understood and precisely quantified, there will be large variability in the extrapolation to the field.
- Longer tests at lower acceleration factors are needed to compare unknown materials to each other unless the total degradation is dramatically different.
- Using field representative humidity levels can eliminate the need to separately evaluate the effect of humidity on degradation.

*M. D. Kempe et al., "Highly Accelerated UV Stress Testing for Transparent Flexible Frontsheets," in 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), 2020, pp. 1823-1823.

Abstract

- Understanding the Variability in Extrapolation from Lab to Field Conditions
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- Carefully controlled laboratory experiments and measurements can enable the determination of acceleration factors suitable for extrapolation to durability and performance when fielded. Ideally, a single mechanism can be identified with appropriate acceleration factors for extrapolation to the field. However, even with a single mechanism, the inherent uncertainty in these factors leads to uncertainty in the extrapolation which is greater the higher the acceleration factor. But when designing generic accelerated stress tests for standards, or for even a simple rank ordering, one must compare processes where not only the acceleration factors are unknown, but the acceleration factors are most likely different for the different materials. In this case, the best that can be done is to gain a general understanding of the range of typical acceleration factors for the degradation processes causing the degradation modes of interest after which significant difference must be seen to have confidence in the results. Because of the wide range of acceleration factor for a given degradation mode, utilizing acceleration factors greater than about 10× will typically lead to unacceptable uncertainty in the results. Therefore, if even just a rank ordering of materials is desired, acceleration factors must be minimized which requires a good general understanding of the scale of the different acceleration factors for the degradation mode of interest.