Experimental Considerations for Estimating Degradation in PV Modules

Michael Kempe
National Renewable Energy Laboratory (NREL)

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Outline

- Introduction
- Accelerated stress testing overview
- Uncertainty in testing
- Pitfalls of accelerated stress testing
- Examples of pitfalls and things to avoid or consider
- Discussion of some PV degradation stressors
- Considerations for quality test designs
- Conclusions

A little about me

- Michael Kempe
  - PhD in Chemical Engineering from the California Institute of Technology.
  - 20 years photovoltaic durability research at NREL.
  - 16 years as a Director for the CORE electric cooperative (formerly IREA).
    - This is a cooperative electric utility.
    - $1.5 B in assets.
    - ~$370 M in annual revenue.
    - Soon to go from 36% renewable to >56% when we cancel our contract with Xcel as our power purchase provider.

CORE™
ELECTRIC COOPERATIVE

Past work at NREL

- Expertise in polymer physics and chemistry.
- Moisture ingress Modelling
  - Backsheet ingress modelling.
  - High barrier e-Ca measurement method.
  - Edge seal modelling.
- UV light, heat, and humidity degradation measurements used for extrapolation to the use environment.
- Participating in many IEC standards projects.
  - Project leader for 63126 (high temperature modules).
  - Recently helped write significant parts of the new versions of IEC 62788-7-2, 62788-2, 62788-2-1, and many others.

Durability, Reliability, and Failure

- **Durability** refers to the ability of the object or system to endure physical damage from normal use.
  - Wear-out and gradual loss of performance
- **Reliability** refers to the ability of an object or system to perform its intended function under specified conditions over some defined period of time.
  - Glass or backsheet cracking
  - Safety concerns
  - Inverter failure
  - Described as mean time between failure (Weibull distribution more common)
- **Failure**
  - Defined on a case-by-case basis where either the performance is too low to be useful, or a reliability issue that is not economically repairable.

How Does Durability fit in

- The SunShot program is targeting 3¢/kWh by 2030.
- Improvements in durability and reliability are a significant component of the pathway to achieve this.
- Degradation rates are targeted to be reduced from 0.75%/y to 0.2%/y and/or to increase the lifetime from 30 y to 50 y.
- Achieving this, along with safe operation, are the main goals of the PV durability group.

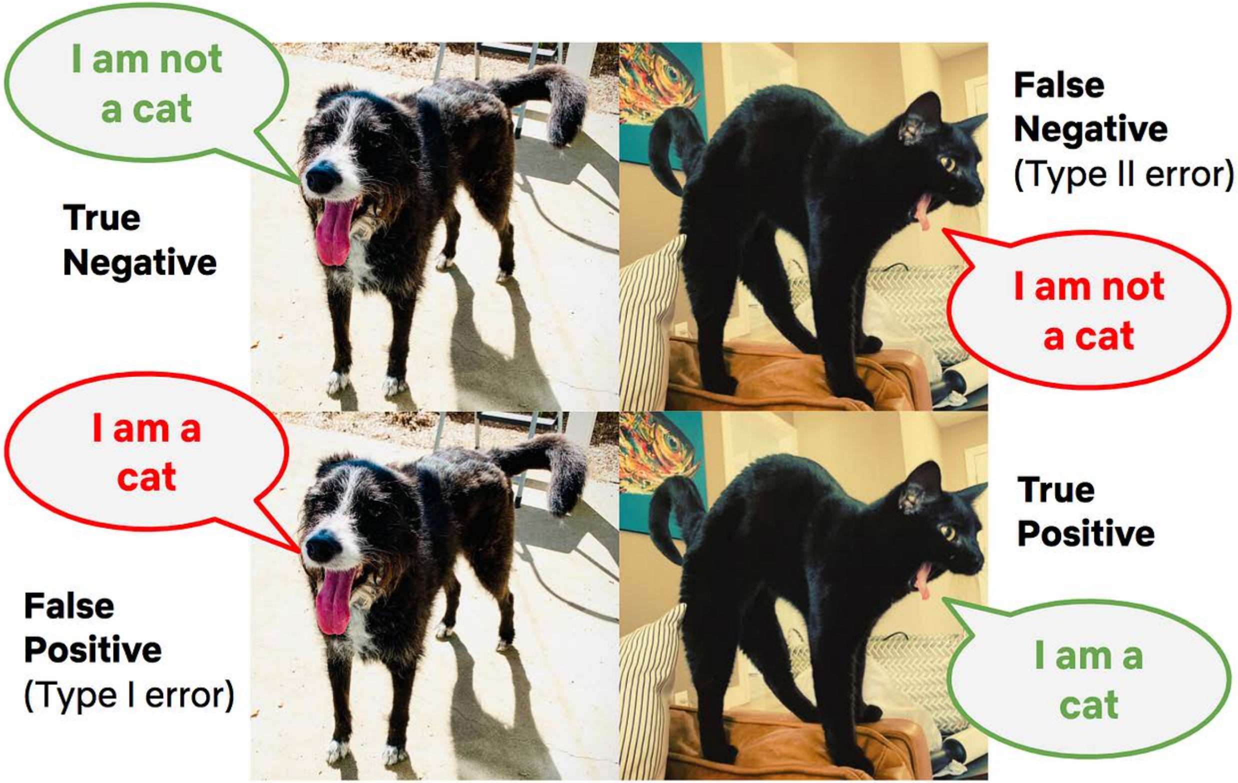
Figure 12. Example modeled pathway toward an LCOE target of 3 ¢/kWh for 100-MW utility-scale systems with 1,480 kWh/kW first-year performance

Woodhouse, Michael, Rebecca Jones-Albertus, David Feldman, Ran Fu, Kelsey Horowitz, Donald Chung, Dirk Jordan, and Sarah Kurtz. 2016. On the Path to SunShot: The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-65872. http://www.nrel.gov/docs/fy16osti/65872.pdf.

Accelerated Stress Testing Overview

- What are false positives and false negatives?
- What types of accelerated stress tests are there?
  - qualification, highly accelerated stress test (HAST), exploratory, rank ordering, service life prediction (SLP)
- Accelerated stress testing pitfalls
- Examples of errors
  - Diffusion limited stress tests
    - JPL EVA development
  - Masking of failures.
    - UL labs accelerated stress test

Testing Results



False positive:

May result in the use of a product or process that will fail prematurely.

False negative:

May result in elimination of the better or the less expensive material.

When would you prefer one over the other?

Qualification Testing

- IEC 61215: Terrestrial photovoltaic (PV) modules - Design qualification and type approval (For module durability)
- IEC 61730: Photovoltaic (PV) module safety qualification
- IEC 62752: Connectors for DC-application in photovoltaic systems - Safety requirements and tests
- IEC 62790: Junction Boxes for photovoltaic modules – Safety requirements and Tests

- These tests have been somewhat empirically determined over the years to screen out field failures.
- They also draw upon a much wider range of standards that are generally applied to electrical devices.
- They must not be an impediment to the industry; therefore, the duration of these tests is generally very short and inexpensive. (May force a bias to false-positive results).
- Represent minimum requirements for entry into the market and are not sufficient to ensure a durable product.
- Can be performed on engineering (not production) modules, and use a really small sample size of just a few modules or components. (very poor statistics)
- They do not address the ability of a company to have a quality manufacturing process.

- The result is primarily described as pass/fail.

Screening Tests

- When a large number of alternative materials or processes are available, a highly accelerated stress test (HAST) is often used to crudely distinguish between potentially good and bad materials.
  - Typically, a single condition test using very high temperature, voltage, or current.
  - Example: Damp heat: 85°C and 85% RH for 1000 h.
    - May be equal to between 1 and 10,000 years
    - Covers lots of failures not specifically addressed (e.g. adhesion)
  - Example: Potential Induced Degradation test
    - $V_{\text{sys,max}}$ for 96 h 85°C/85% RH
- Can work well if the cost of false-negatives is not great. This is typically designed to simply remove all bad or possibly bad options (i.e. low false-positive rate).
- But if the costs of more durable alternatives is high, then these tests can result in overdesign (e.g. hydrolytically stabilized PET).
- Single point tests like this will not tell you if one process/material is better than another unless you have a good understanding of the failure kinetics/mechanisms or if the degradation process.

Rank Ordering Tests

- A single point test only works for a rank ordering if the acceleration factors of **all** the pertinent modes and mechanisms are known or are known to be the same.
- The vast majority of the time, you need at least two stress levels to determine which material/method is best.
- If more than one stressor is involved, one must vary the level of every stressor and use stress levels that don’t overly emphasize one stressor over another, otherwise, you might mask the most relevant stressor and/or failure mode.

Exploratory Testing

- In these tests you are testing a wide variety of stressors with very high stresses or very long durations.
- Using HAST type of testing conditions.
- A good example of this is a Test to Failure.
  - Testing may continue until failure is seen under one condition.
  - Or the testing conditions (e.g. temperature) are increased in severity until all samples fail.
  - High probability of inducing a failure mode that is not relevant.
- Should be used to find out possible failure modes which will subsequently be tested with greater precision to determine if it is really a problem or to determine if one process/material is better than another.

Difficulties of Service Life Prediction

- Service life prediction from accelerated stress requires simultaneous acceleration of many different parameters (T, RH, UV, O_2) for many different materials and interfaces within the same system.
- This also requires that all failure modes or mechanisms are not just known, but separately evaluated.
- For a complex system (e.g. a PV module), it is not possible to equally accelerate all parameters at the same rate; thus a series of tests focusing on different failure modes is necessary for service life prediction.*
- However, for an individual failure mode control of these parameters may produce realistic accelerated stress testing and service life prediction.
- Generally speaking, acceleration factors greater than 10x are not useful because of the high probability of masking the important failure mode.

T.J. McMahon, G.J. Jorgensen, R.L. Hulstrom, D.L. King, M.A. Quintana, “Module 30 Year Life: What Does it Mean and Is it Predictable/Achievable?”, Proc of the IEEE PV Spec. Conf. (2000).
W. Q. Meeker, L.A. Escobar “Pitfalls of Accelerated Testing”, IEEE Transations on Reliability, Vol. 47, NO 2, (1998).

Pitfalls of Accelerated Aging

1. Multiple (unrecognized) Failure Modes.
2. Failure to Quantify Uncertainty Properly.
3. Multiple Time-Scales and Multiple Factors Affecting Degradation.
4. Masked Failure-Mode.
5. Faulty Comparison.
6. Accelerating Variables Can Cause Deceleration (i.e. reduce RH or oxygen ingress).
7. Beware of Untested Design/Production Changes.
8. Beware of Drawing Conclusion on the Basis of Specially Built Prototype Test Units.
9. It is Difficult to Use Accelerated Life Test to Predict Field Reliability.

W. Q. Meeker, L.A. Escobar “Pitfalls of Accelerated Testing”, IEEE Transations on Reliability, Vol. 47, NO 2, (1998).

1. Multiple (unrecognized) Failure Modes

- High levels of stress can result in failure modes that do not occur under normal operation.
  - Materials may melt in test but not in the field.
  - High temperatures may accelerate a failure mode, which does not occur in the field, enough to dominate the response.

2. Failure to Quantify Uncertainty Properly

- Smaller sample sizes will result in larger uncertainties.
- When extrapolated to the use environment, large uncertainties can result in the wrong decisions and conclusions being made.
  - The extrapolated difference in performance between alternatives may be much smaller than the uncertainty in the calculation.
  - In single point tests, the differences may be larger than the uncertainty.

3. Multiple Time-Scales and Multiple Factors Affecting Degradation

- There may be several different stressors all causing the same failure mode through different mechanisms.
- Each mechanism will have a different acceleration factor.
- If one stressor has a very high acceleration factor it is more likely to be the one that is seen.
- Ideally, all the stressors will have a similar acceleration in the experiment. If not, then each stressor will need to be varied separately to determine its acceleration factor.

4. Masked Failure-Mode

W. Q. Meeker, L.A. Escobar “Pitfalls of Accelerated Testing”, IEEE Transations on Reliability, Vol. 47, NO 2, (1998).

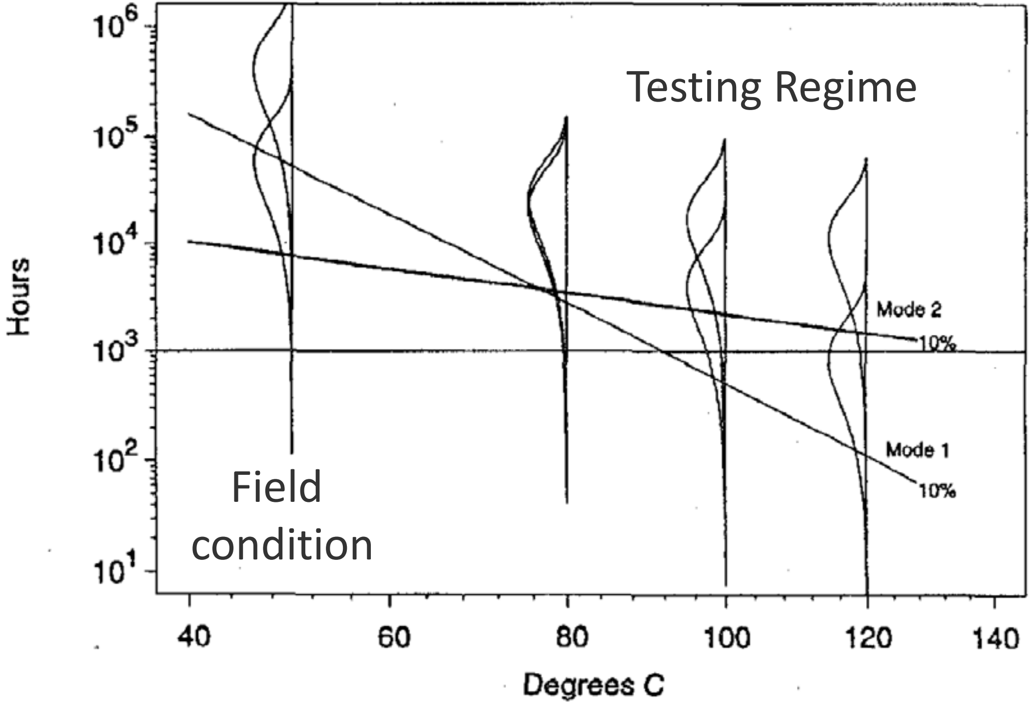


Figure 4: Unmasked Failure-Mode #2 With Lower Activation Energy

- When testing at high stress levels (e.g. high temperature), one may only detect the more highly accelerated failure mode which might not be the important one in the field.

5. Faulty Comparison

W. Q. Meeker, L.A. Escobar “Pitfalls of Accelerated Testing”, IEEE Transations on Reliability, Vol. 47, NO 2, (1998).

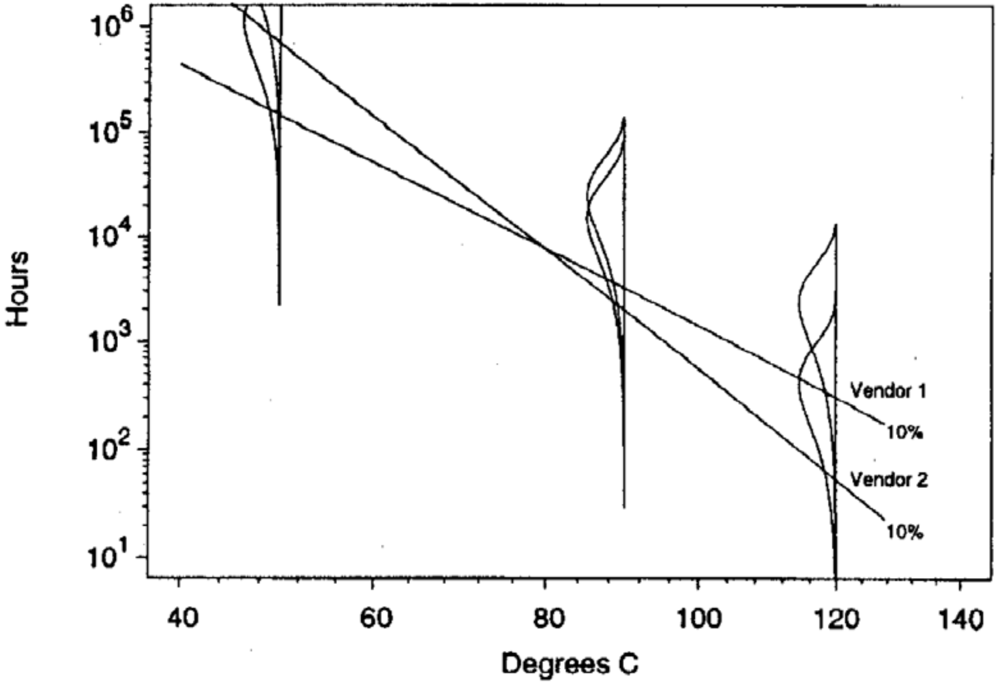


Figure 6: Comparison with Evidence of Different Failure Modes

- A rank ordering under accelerated stress conditions is not necessarily the same as what will be seen in the field, especially if the failure mode or mechanisms are different.
- This is similar to a masked failure mode.
- Comparisons are only likely to be valid if the acceleration factor is not large, or if the difference in performance is very large and much greater than the experimental uncertainty.
- In the figure, Vendor 1 performs better in the accelerated stress test, but Vendor 2 is the more reliable/durable option.

6. Accelerating Variables can Cause Deceleration

- Some failure modes will actually occur more slowly at higher stress levels.
  - Higher temperatures can cause the relative humidity to be lower decreasing the degradation rate.
  - Some degradation modes (e.g. chemical reactions that are equilibrium limited and produce water) will be slowed down by higher humidity.
  - Reactions that cause discoloration may be more easily bleached at higher temperatures or higher UV doses.
  - Degradation modes may be diffusion limited at high temperatures, but at the lower use temperatures, enough oxygen or water can diffuse into the material to degrade it.

7. Beware of Untested Design/Production Changes

- Frequently module components will be changed without a full durability assessment.
- Two components may individually be durable but not in combination with each other.
- A polyamide backsheet (AAA) was testing in ~2009 and found to be a low-cost alternative backsheet and passed all the qualification tests. But these tests do not actually evaluate long term field durability. They failed after about 4 years in the field. A test combining UV/heat with subsequent thermal cycling was needed to expose this weakness.*

*M. D. Kempe, T. Lockman, and J. Morse, "Development of Testing Methods to Predict Cracking in Photovoltaic Backsheets," in 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), 16-21 June 2019 2019, pp. 2411-2416, doi: 10.1109/PVSC40753.2019.8980818.

8. Beware of Drawing Conclusions on the Basis of Specially Built Prototype Test Units

- In IEC 61730 and IEC 61215, one may be using a production line but with laboratory materials or unusually carefully controlled process parameters which do not represent what will actually be made.
- Or worse yet, the design may be completely hand made in a laboratory and not possible to be made on the production line.
- Build up of minute contaminants after thousands of cycles of use in equipment may be needed for some failure modes to be seen.*

*M. D. Kempe and D. C. Jordan, "Evaluation and modeling of the potential effects of a module manufacturing anomaly," Progress in Photovoltaics: Research and Applications, vol. 25, no. 12, pp. 982-988, 2017, doi: 10.1002/pip.2908.

9. It Is Difficult to Use Accelerated Life Tests to Predict Field Reliability

- There are so many factors that go into predicting how long a product will last that for complicated products (such as a PV module), it is practically speaking not possible to reasonably accurately predict the performance.
- Because of all the pitfalls discussed here, one should ideally be testing at only a 6× to 10× acceleration factor of prediction is really needed. This translates into tests lasting 2.5y to 4.2y for a 25-y product. This is very rarely done while applying a full set of different and balanced stressors.
- You should be extremely skeptical of any proposal, funding call, or scientific paper claiming/aiming to predict the service life of a PV module. Nobody is actually doing this.

Quiz: What problems does RTI testing have?

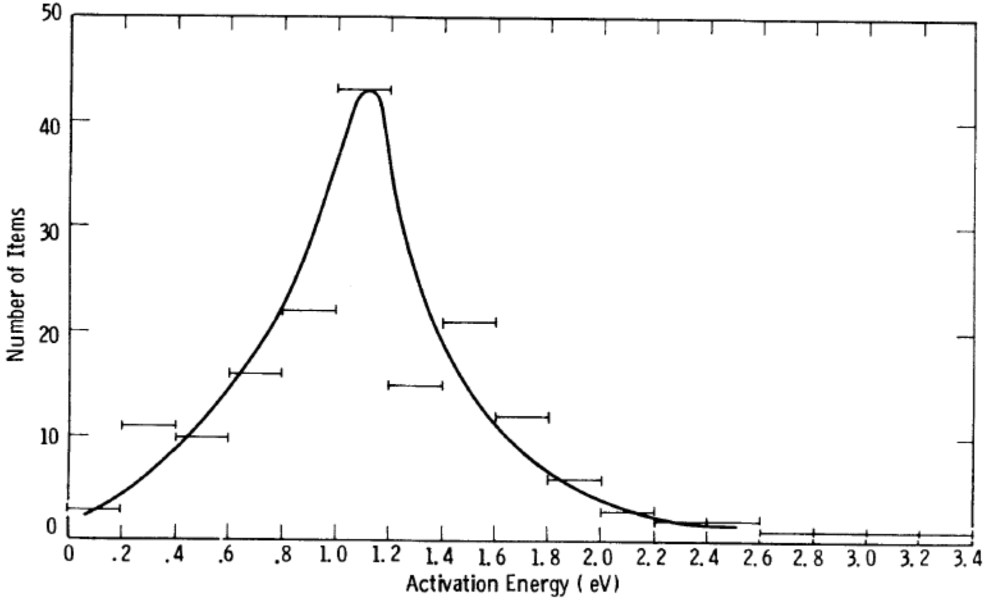


Fig. 3: Frequency distribution of activation energies of various components/materials (D. Cain - EPRI information)

- Activation Energy for:
  - Dielectric Strength
  - Elongation at Break
  - Oxidation
  - Flexural Strength
  - Weight Loss

Quiz:
What pitfalls
are active
here?

- Compiled from 170 polymeric properties.
- In Relative Thermal index testing, the activation energy is determined by looking for failure at different temperatures and extrapolating to the use environment as an Arrhenius dependence on temperature.
- The requirement that failure must be seen to produce data results in the temperature being raised in these experiments till a failure mechanism is seen. This creates a systematic bias to more highly activated processes with a high probability that the most important degradation mode might not be observed.

* R.R. Dixon “Thermal Aging Predictions From an Arrhenius Plot With Only one Data Point”, IEEE Transactions on Electric Insulation, Vol EI-15, No. 4, (1980).

Pitfall Example: Early JPL studies

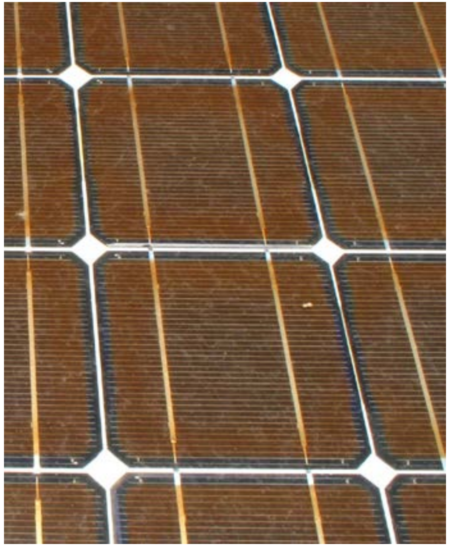
- Initial JPL EVA studies.*
    - Bare samples of EVA A-9918 withstood 30,000 h of 1.4 UV suns (Hg lamp) exposure at 55^{o}C without visible change.
    - Bare samples aged in the dark turned yellow after 800 h at 105^{o}C.
    - UV filtering glass encapsulated EVA A-9918 samples showed no yellowing after 800 h of 6 UV suns exposure at 105^{o}C.
    - Unformulated EVA exposed to 1500 h of 1.4 UV suns at 55^{o}C depolymerized and turned slightly yellow. When placed behind UV blocking films (block λ<360 nm) no degradation was seen.

- JPL concluded that UV light bleached out a thermally produced chromophore and that UV absorbers would effectively be sufficient.
- Thus a 20 to 30 y lifetime was expected at peak operating temperatures of 55^{o}C.

* E.F. Cuddihy, "applications of Ethylene Vinyl Acetate as an Encapsulation Material for Terrestrial Photovoltaic Modules", DOE/JPL-1012-87, (1983)

Carissa Plains PV

- 6 MW deployed 1983. World’s largest plant.
- 1982, worldwide production was 9.3 MW/y.
- Initially the **8-12% loss per year** was attributed to EVA yellowing*, but subsequent tests indicate cell metallization corrosion was a larger problem**.
- Accelerated stress at 125^{o}C caused EVA to brown around the cell perimeter rather than in the center as is typical.**
- These modules were constructed using UV transparent glass.



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* A.L. Rosenthal, C. G. Lane, “Field Test Results for the 6 MW Carrizo Solar Photovoltaic Power Plant”, Solar Cells, 30 (1991) 563.

** J. H. Wohlgemuth, R. C. Petersen, “Reliability of EVA Modules”, IEEE PVSC, pg 1090-1094, (1993).

EVA Degradation Modes

- In fielded modules, dark areas are less oxidized, therefore oxygen bleaches EVA.
- To accurately accelerate degradation, one must consider temperature, UV dose, UV spectrum, and the presence or absence of oxygen.

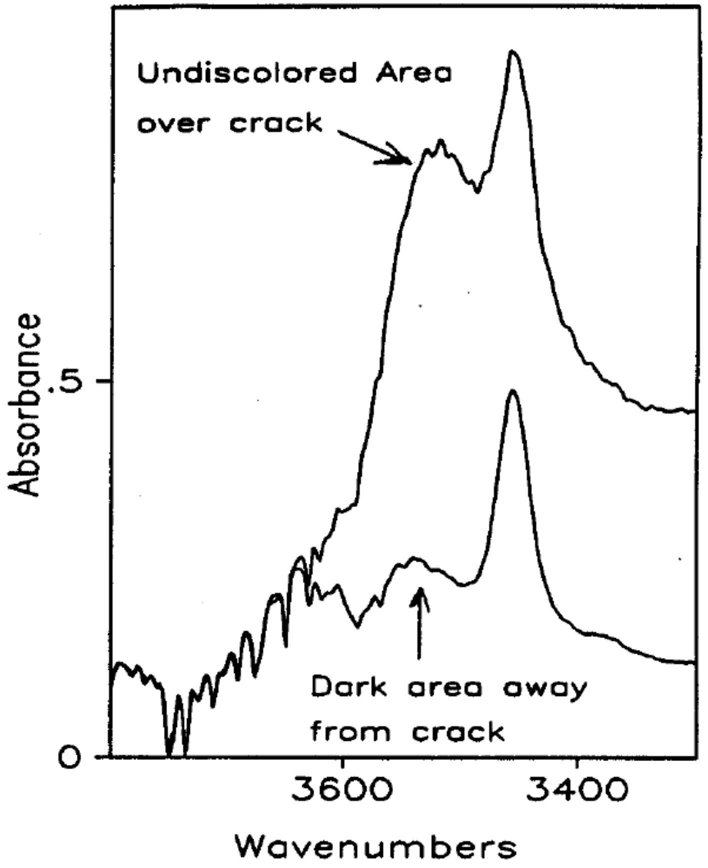

Figure 3 - Infrared spectra of hydroxyl region for field aged solar module EVA at an undiscolored crack and in discolored area away from crack.

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* M. Ezrin, G. Lavigne, P. Klemchuk, “Discoloration of EVA Encapsulant in Photovoltaic Cells”, Antec, 3959, (1995).

JPL Pitfalls

- Initial JPL EVA studies used “UV filtering Pyrex glass covers with open edges”.
  - I could not find a record of the dimension of the samples, but presumably it was significantly smaller than a cell not duplicating the anerobic conditions.*
  - Carissa plains modules used highly transmissive glass exposing sample to UV-B radiation.**
- Bare samples were tested where there was sufficient oxygen present to bleach out chromophores.
- Assumed high temperature (105^{o}C) thermally induced yellowing was representative of yellowing mechanism in the field.

*E.F. Cuddihy, “applications of Ethylene Vinyl Acetate as an Encapsulantion Material for Terrestrial Photovoltaic Modules”, DOE/JPL-1012-87, (1983)

** W. H. Holley, S. C. Agro, J. P. Galica, L. A. Thoma, R. S. Yorgensen, M. Ezrin, P Klemchuk, G. Lavigne, H. Thomas, “Investigation Into the Causes of Browning in EVA Encapsulated Flap Plate PV Modules”, First WCPEC, Dec. 5-9, Hawaii (1994).

JPL Encountered Pitfalls

1. Multiple (unrecoginzed Failure Modes.
2. Failure to Quantify Uncertainty Properly.
3. Multiple Time-Scales and Multiple Factors Affecting Degradation.
4. Masked Failure-Mode.
5. Faulty Comparison.
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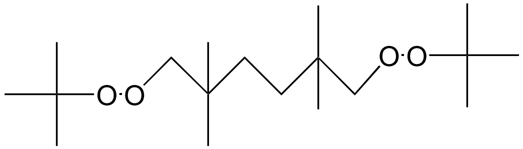
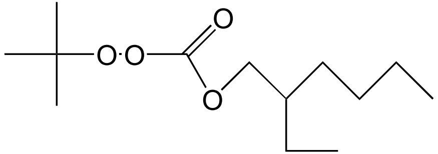
9. It is Difficult to Use Accelerated Life Test to Predict Field Reliability. (Accelerated stress may not duplicate the use environment).

W. Q. Meeker, L.A. Escobar “Pitfalls of Accelerated Testing”, IEEE Transations on Reliability, Vol. 47, NO 2, (1998).

Formulation Changes to Fix the problem



2,5-Dimethyl-2,5-Di(t-butylperoxy)Hexane (Lupersol 101)

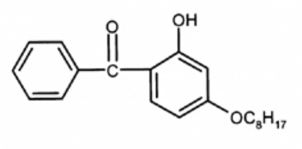


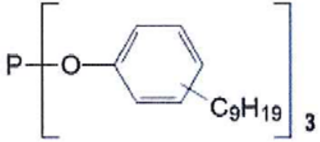
OO-t-Butyl-O-(2-ethylhexyl) monoperoxycarbonate (TBEC)

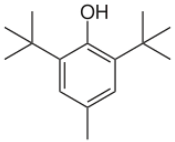
- Replaced the peroxide Lupersol 101 with TBEC

- Also important in yellowing:
- 2-Hydroxy-4-n-octoxybenzophenone (Cyasorb UV-531)
- Phenyl phosphonites (Naugard P)
- Butylated hydroxytoluene (BHT)

- Lupersol 101 cannot by itself produce a chromophore.







* W.W. Holley, S.C. Agro, “Advanced EVA-Based Encapsulants, Final Report, January 1993-June 1997, NREL/SR-520-25296 (1998).

UV-Blocking Glass Was Recommended

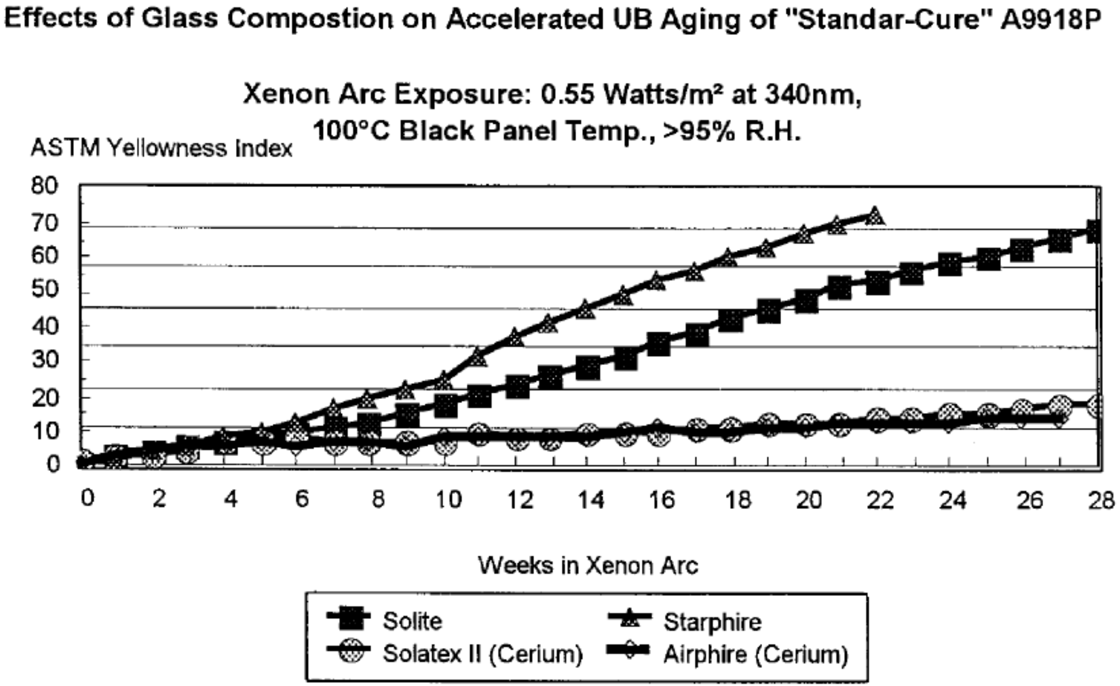
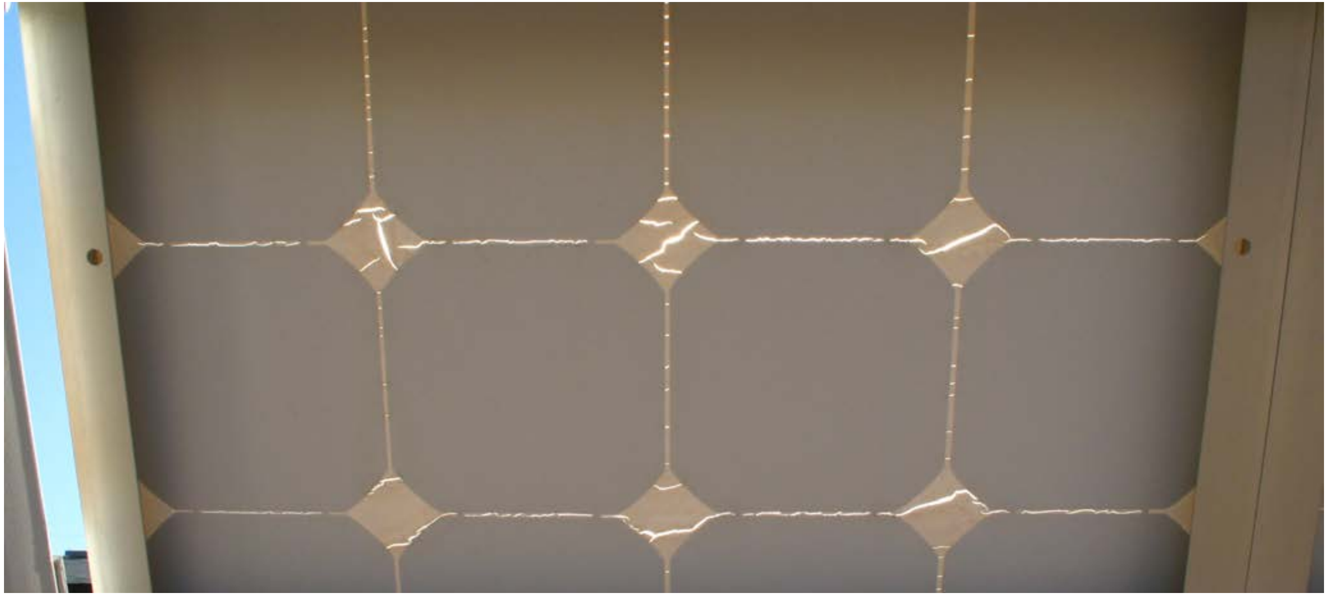


Figure 11 - Effects of Glass Composition on Accelerated UV Aging of "Standard-Cure" A9918P EVA

- The addition of Ce to glass cuts off UV-B light below ~320 nm.
- Unfortunately, it also absorbs in the IR which is good for glass manufacturing but bad for energy production.

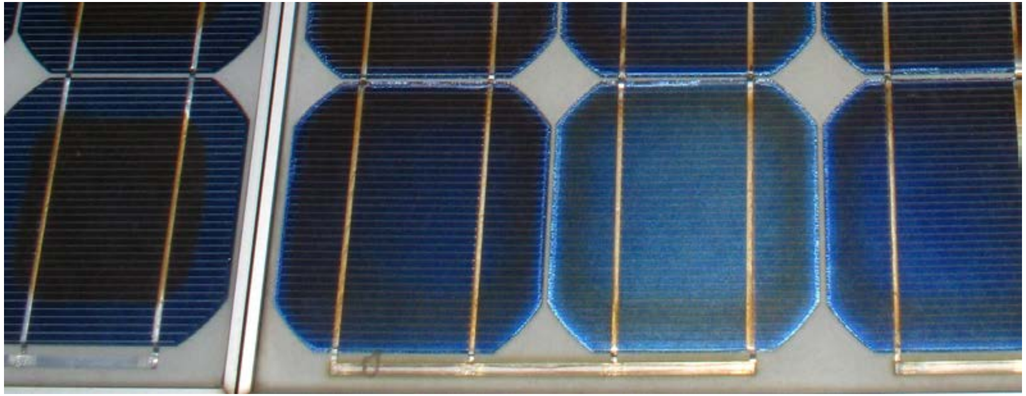
- W.W. Holley, S.C. Agro, "Advanced EVA-Based Encapsulants, Final Report, January 1993-June 1997, NREL/SR-520-25296 (1998).
- M. D. Kempe, "Ultraviolet light test and evaluation methods for encapsulants of photovoltaic modules," (in English), Solar Energy Materials and Solar Cells, vol. 94, no. 2, pp. 246-253, February 2010, doi: 10.1016/j.solmat.2009.09.009.
- M. D. Kempe, G. J. Jorgensen, K. M. Terwilliger, T. J. McMahon, C. E. Kennedy, and T. T. Borek, "Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices," Solar Energy Materials and Solar Cells, vol. 91, no. 4, pp. 315-329, 2007. [Online]. Available:

Example Pitfall #1



- What appears to be an obvious failure is not necessarily the cause.
- This failure is probably due to something such as inadequate UV absorber in the encapsulant, not a poorly designed backsheet.

Example Pitfall #2



There may be multiple mechanisms for the same degradation modes.

What is needed

(1) Outdoor real-time testing of samples to verify that the appropriate degradation modes are being evaluated.

(2) Testing on small representative samples (especially outdoors in real-time).

(3) When modules fail in the field, you must carefully identify the failure modes and develop accelerated tests to duplicate it. This requires knowledge of material makeup.

(4) You must know what type of accelerated test is being performed (e.g. SLP, Rank ordering, screening), and what “Pitfalls” are possible.

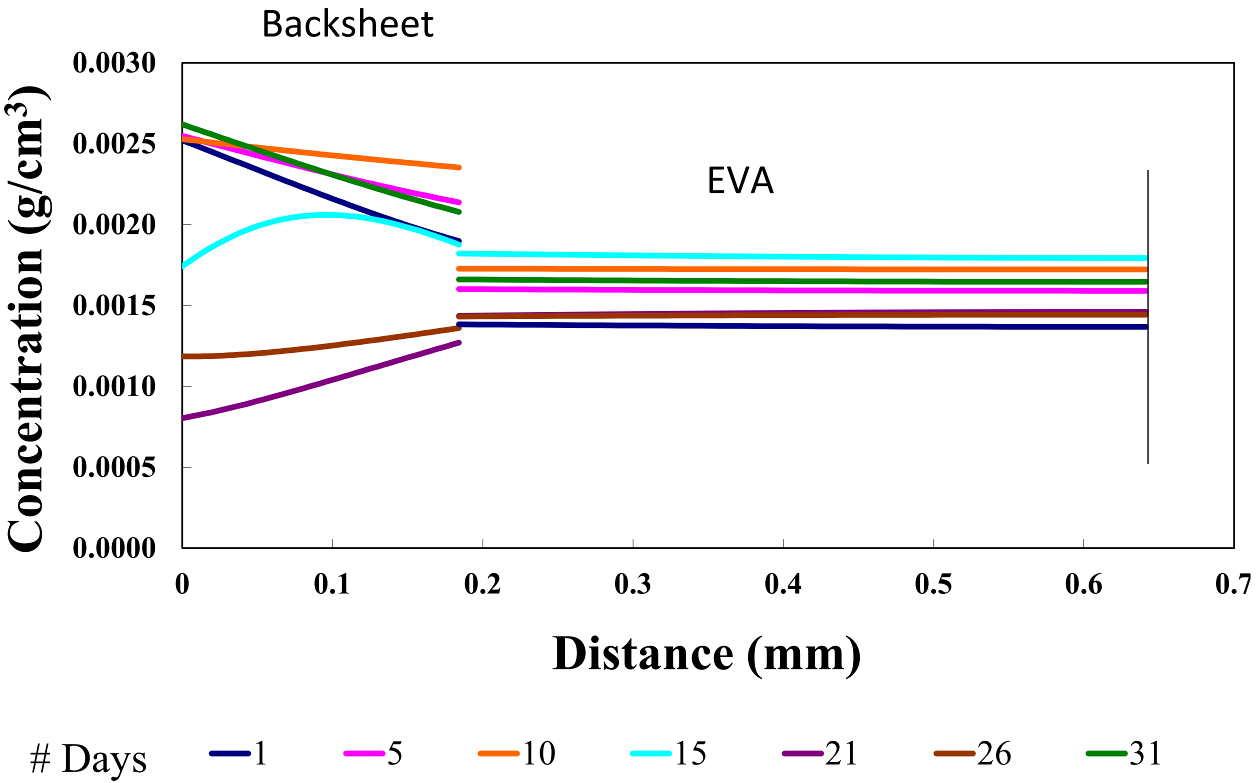
What is 1000h 85°C/85% RH?

- **It is:**
- This test comes out of the JPL block purchases of the 70s and 80s*.
- It was designed to duplicate electrolytic corrosion for crystalline silicon PV**.
- Part of the qualification standards (e.g. IEC 61215).
- A Highly Accelerated Stress Test (HAST)
- **It is NOT**:
- A 20-y service life prediction.
- It may severely over stress some components and under stress others.

*Smokler MI, Otth DH, Ross RG. The block program approach to photovoltaic module development. Proceedings of the 18th IEEE PV Specialists Conference, Las Vegas, Nevada, USA, 1985; 1150–1158.

** Otth DH, Ross RG. Assessing photovoltaic module degradation and lifetime from long-term environmental tests. Proceedings of the 29th Institute of Environmental Sciences Technical Meeting, Los Angeles, California, USA, 1983; 121–126..

Moisture Profile on Module Backside, FDM



Quasi-Steady State Solution

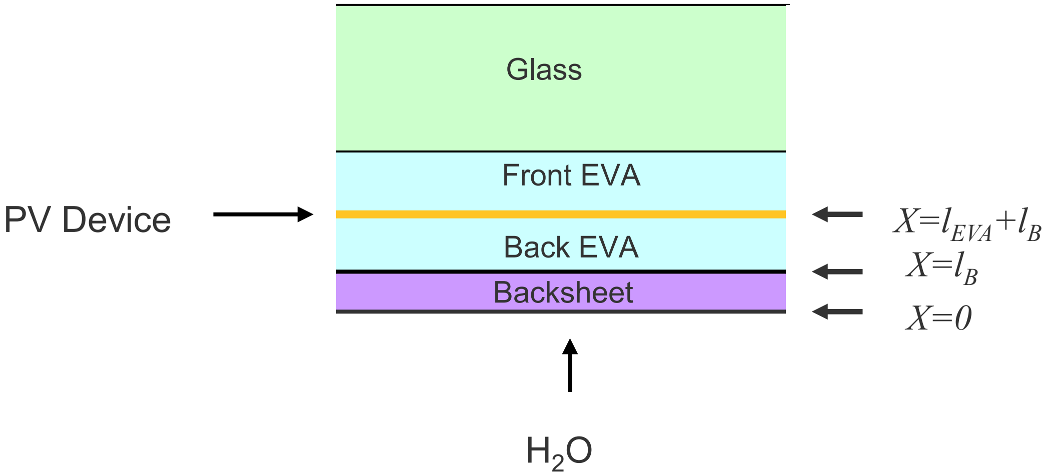
$$\frac{dC_E(t)}{dt} = \frac{WVTR_{B,Sat}(T)}{C_{E,Sat}(T)l_E}\left(C_{E,Eq}(t,RH) - C_E(t)\right)$$

- **Miami Florida**

- Finite difference solution for moisture content on the backside of a module.
- Started with an initially dry back-EVA.
- Ingress profile through the backsheet can be approximated by a straight-line ignoring transients.
- EVA diffusivity is much greater than typical backsheets, so the concentration profile can be ignored.

M. D. Kempe, "Modeling of rates of moisture ingress into photovoltaic modules," Solar Energy Materials and Solar Cells, vol. 90, pp. 2720-2738, 2006.

The Back-EVA Equilibrates quickly



Glass

Front EVA

PV Device

Back EVA

Backsheet

$X = l_{EVA} + l_B$

$X = l_B$

$X = 0$

H_2O

Quasi Steady State with Constant Conditions

$$C(t) = C_\infty \left(1 - e^{-\frac{WVTR_{B,Sat}\, t}{C_{Sat,EVA}\, l_{EVA}}} \right)$$

$$\tau_{1/2} = 0.693 \frac{C_{Sat,EVA}\, l_{EVA}}{WVTR_{B,Sat}} = 0.693 \frac{Amout\ of\ water\ EVA\ can\ hold}{Rate\ of\ moisture\ ingress}$$

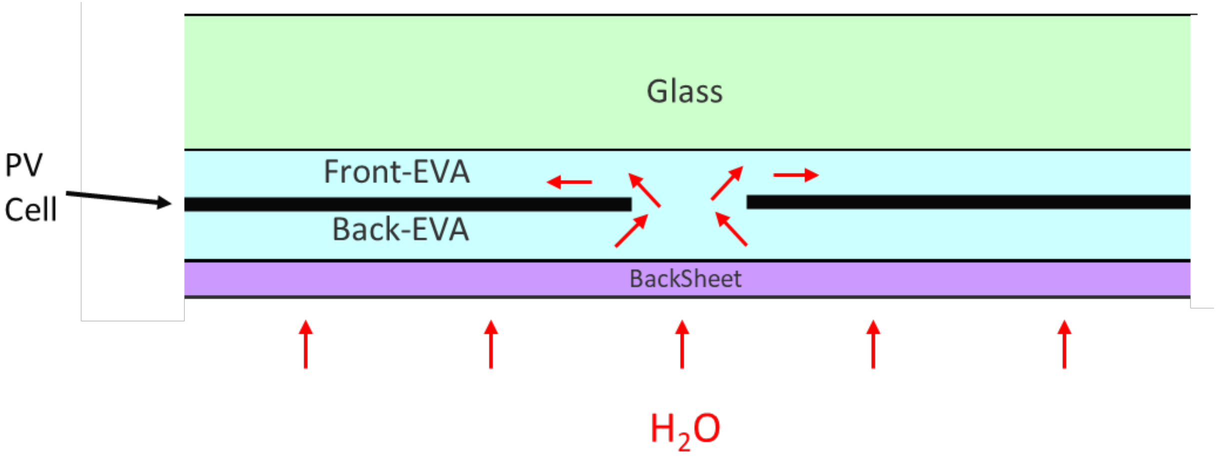
For $\tau_{1/2,PET}$~ 1 day

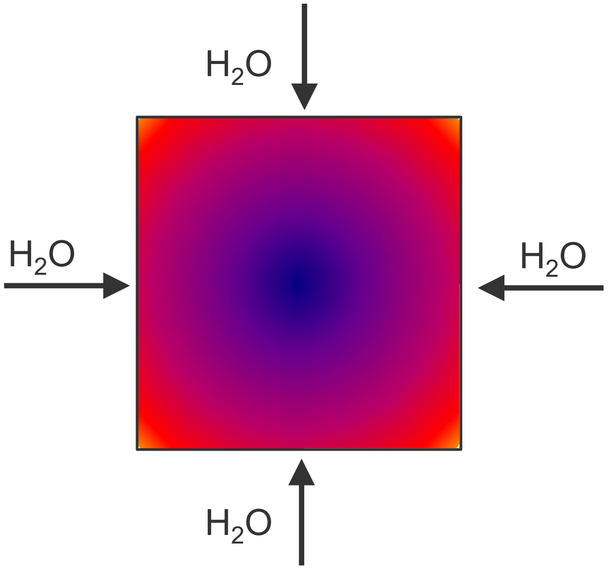
For $\tau_{1/2}$=20 years need 10^{-4} g/m^2/day

The Front EVA takes longer to equilibrate

For constant T and RH, an analytical solution exists for 2-D moisture ingress estimates. The key is to use a diffusivity weighted average equilibrium water concentration and temperature.*

$$C(X,t) = C_s - C_s \frac{16}{\pi^2}\left\{\sum_{m=0}^{\infty}\frac{1}{2m+1}\sin\left[\frac{(2m+1)\pi X}{l}\right]e^{\left(-\frac{D(2m+1)^2\pi^2 t}{l^2}\right)}\right\}^2$$



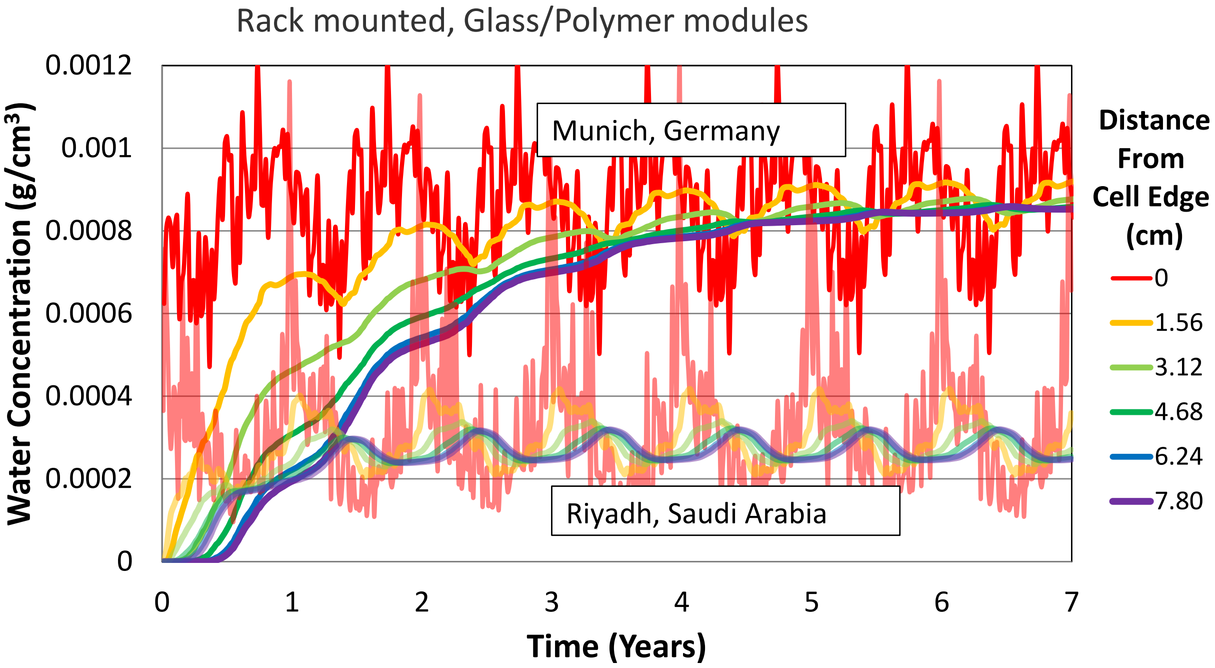


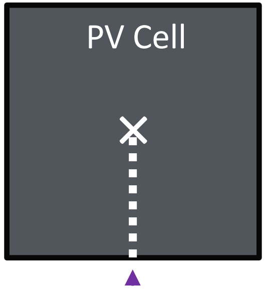
*Crank, “The Mathematics of Diffusion”

*M. D. Kempe, D. Panchagade, M. O. Reese, and A. A. Dameron, "Modeling moisture ingress through polyisobutylene-based edge-seals," Progress in Photovoltaics: Research and Applications, vol. 23, no. 5, pp. 570-581, 2015, doi: 10.1002/pip.2465.

*M. D. Kempe, D. L. Nobles, L. Postak, and J. A. Calderon, "Moisture ingress prediction in polyisobutylene-based edge seal with molecular sieve desiccant," Progress in Photovoltaics: Research and Applications, vol. 26, no. 2, pp. 93-101, 2018, doi: 10.1002/pip.2947.

Front Encapsulant Water Content



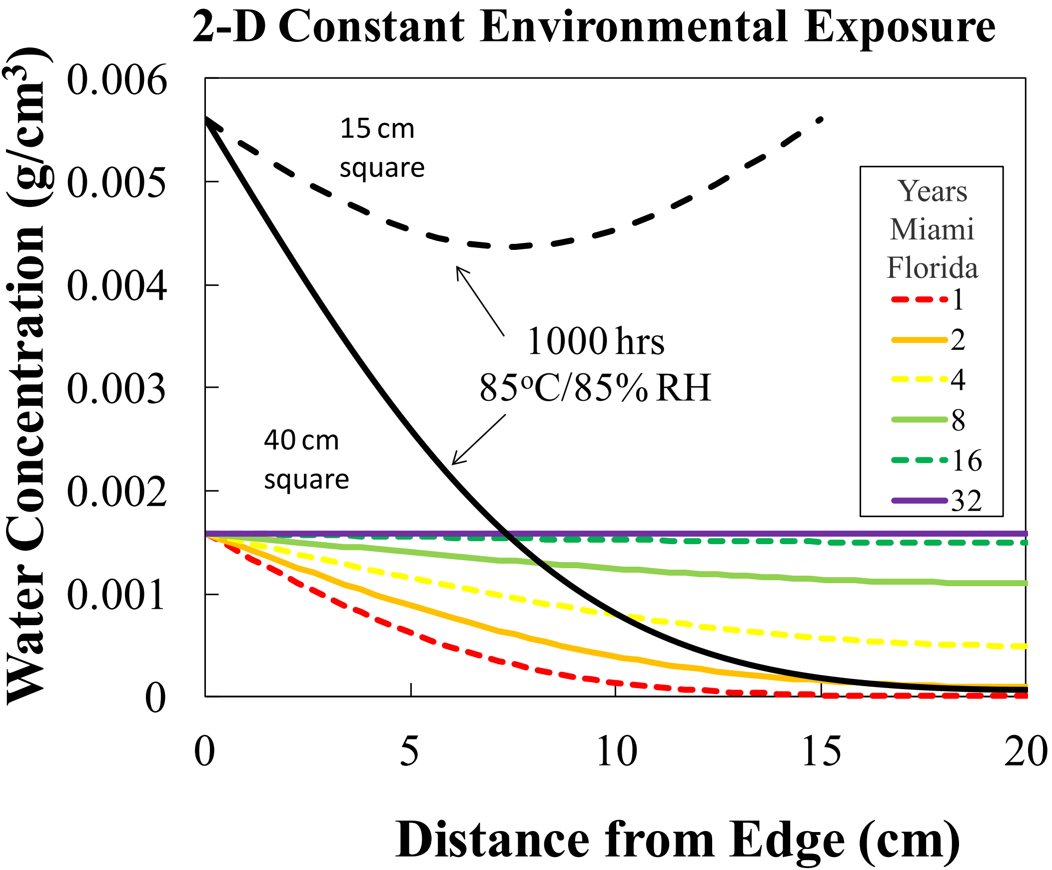


Profiles along this line are plotted.

- It takes just one to 3 years for the front encapsulant to reach equilibrium. Practically speaking, it can be assumed to always be at equilibrium.

Damp Heat vs Outdoor Expsosure

- For a small glass/glass module (represented by a 40-cm square), it takes 15 years to equilibrate. An 80-cm module would take 4× as long.
- The 15-cm square represents the front-EVA between the cell and glass on a module with a polymer backsheet.
- In both cases, water ingress is diffusion limited.
- One cannot consider the whole module to be at 85% RH during the test. Only the outside surfaces and the back-EVA on a polymer back module are at 85% RH.



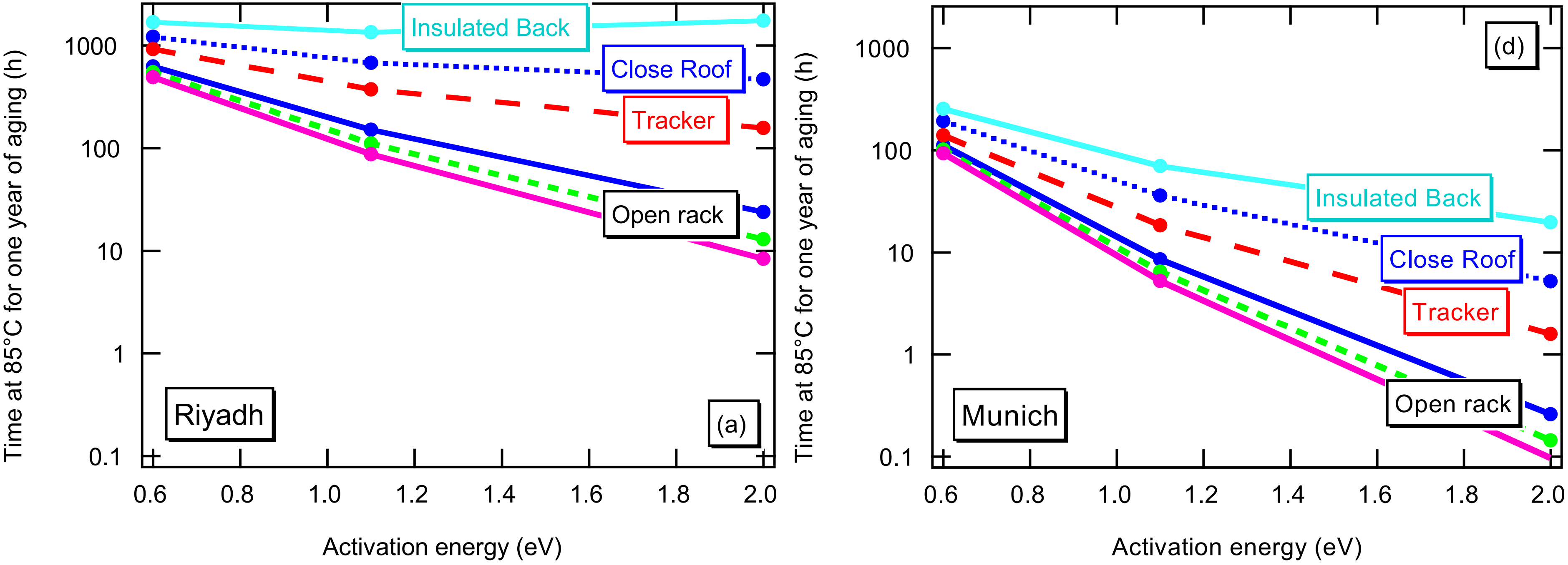
M. D. Kempe and D. C. Jordan, "Evaluation and modeling of the potential effects of a module manufacturing anomaly," Progress in Photovoltaics: Research and Applications, vol. 25, no. 12, pp. 982-988, 2017, doi: 10.1002/pip.2908.

What This Means for Modules Tests

- For a typical crystalline silicon module with a breathable backsheet at 85°C/85%RH;
- (a) Water vapor on the back side will equilibrate with a half-time of about 22 minutes (about the amount of time it takes to thermally equilibrate).
- (b) In front of the cells it will be mostly equilibrated in about 700 h.
- (c) The moisture content will be about 3 times higher than would be seen in the field. This is a concern for hydrolytically sensitive materials.

- For a glass/glass module moisture content be high near the edges and low in the center. Moisture will only penetrate about 10 cm.
- Depending on what part of the module is degrading, equating the exposure to 85°C/85% RH may be erroneous.

1000 h 85°C May Equal ½ to 10,000 years



- Even just considering the thermal aspect of damp heat can lead to a wide range in equivalence.
- Most thermal degradation processes will have activation energies between 0.6 and 1.0 eV.

S. Kurtz et al., "Evaluation of high-temperature exposure of photovoltaic modules," Progress in Photovoltaics: Research and Applications, 2011, doi: 10.1002/pip.1103

Question?

- When you hear that Damp Heat (1000 h, 85°C and 85% RH) is equivalent to 25 y of exposure, what pitfalls are likely being used?

Long Term UV Durability Is NOT Evaluated in IEC Standards

- IEC 61730-2 (MST 54) or IEC 61215-2 (MQT 10)
  - “UV Preconditioning Test”
  - 15 or 60 kWh/m^2 between 280 nm and 385 nm
    - At up to 250 W/m^2 or ~5.4 UV suns
    - Module at 60±5 °C
    - Equivalent to 17.7 or 71 days of AM 1.5
- IEC 62852 Connectors or IEC 62790 J-box
  - ISO 4892-2
  - 60 kWh/m^2 300 to 400 nm, ~1.3 UV suns
  - 500 h total, 425 h light, at 65°C black panel temperature
  - Equivalent to ~54 days of AM 1.5

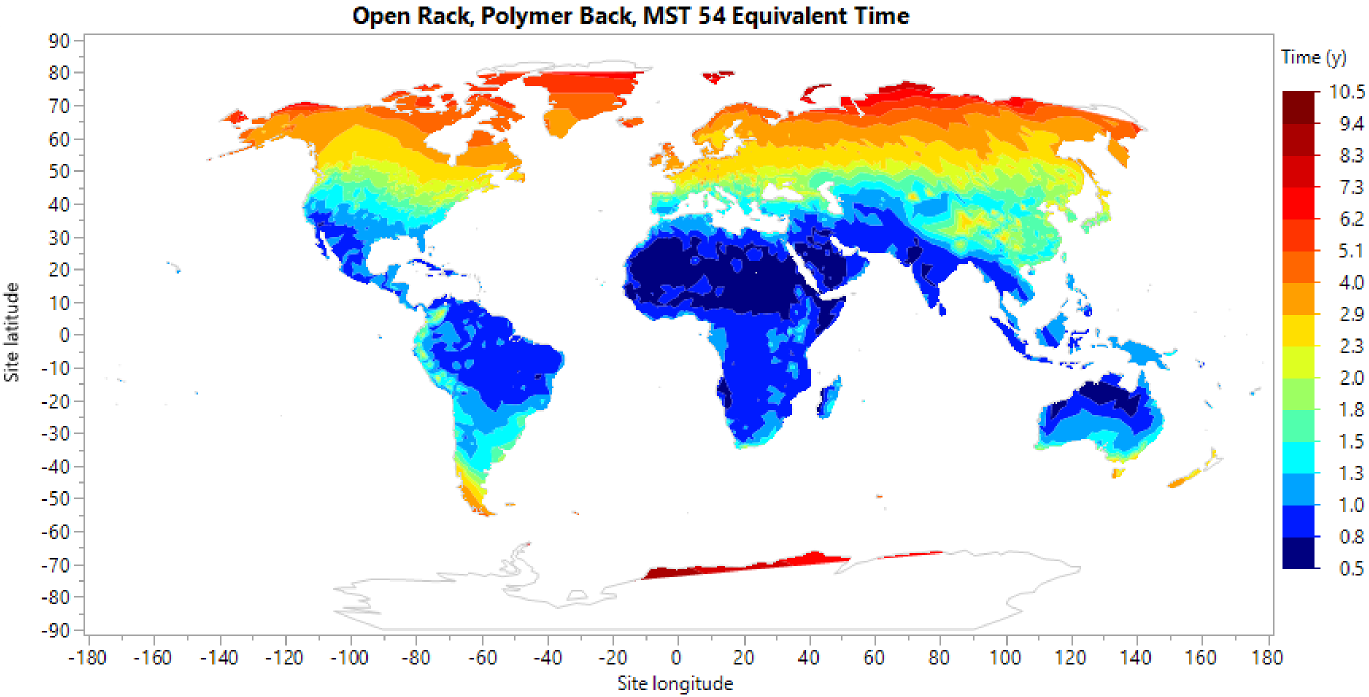
Example plot showing equivalence of MST 54

MST 54 modeled as:

1000 W/m² with 46.1 W/m² between 280 and 400nm.

1302 h exposure for a total of 60 kWh between 280 and 400 nm with 3.2% the UV between 280 and 320 nm.

Module temperature of 60°C.



$$R_D \sim I^x \cdot T_f^{\frac{T-T_o}{10}}$$

T_f=1.4 and x=0.64

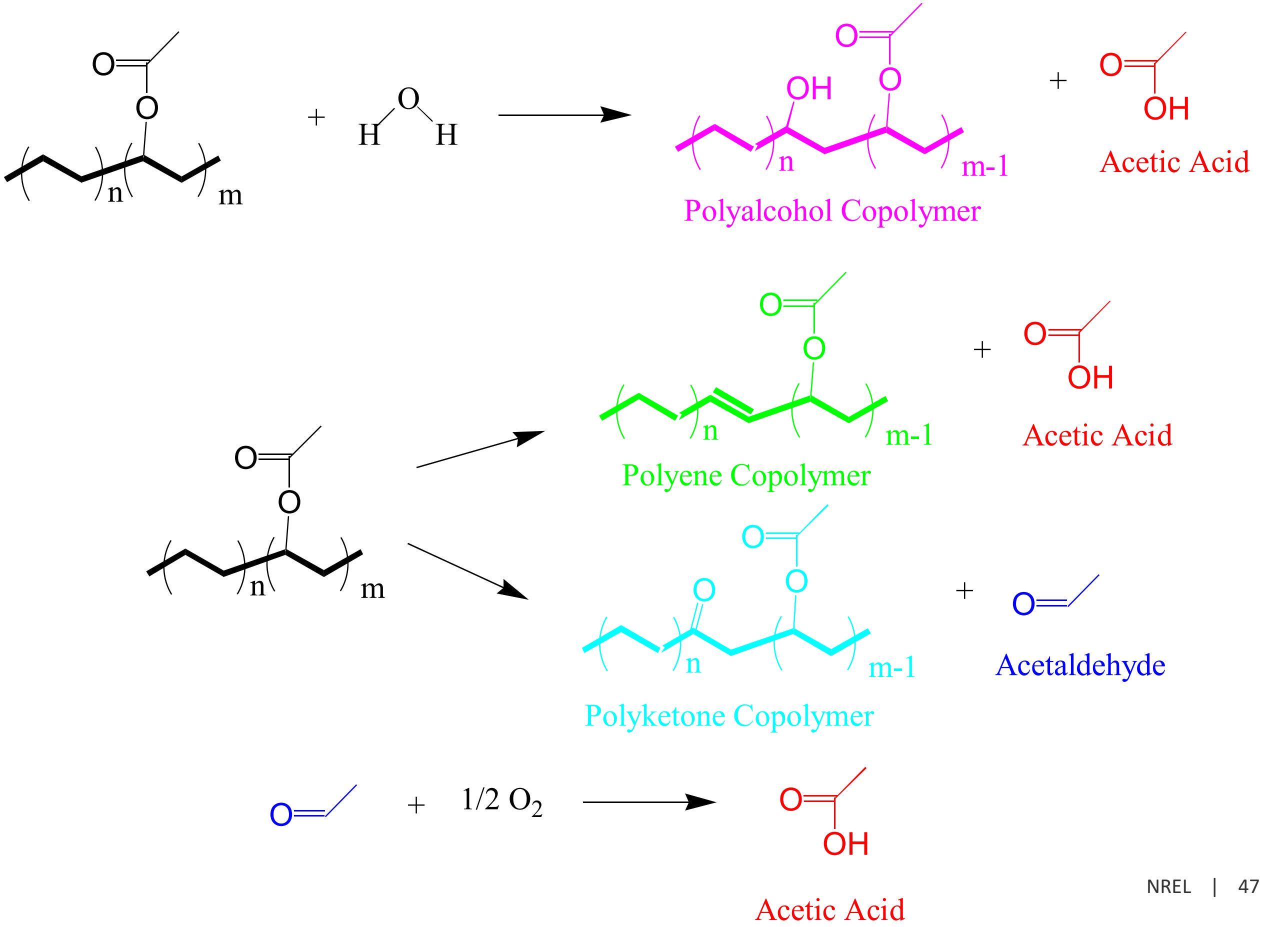
*R. M. Fischer and W. D. Ketola, "Error Analyses and Associated Risk for Accelerated Weathering Results," *Third International Service Life Symposium, Sedona, AZ February 2004*, 2004.

Acetic Acid in PV Devices

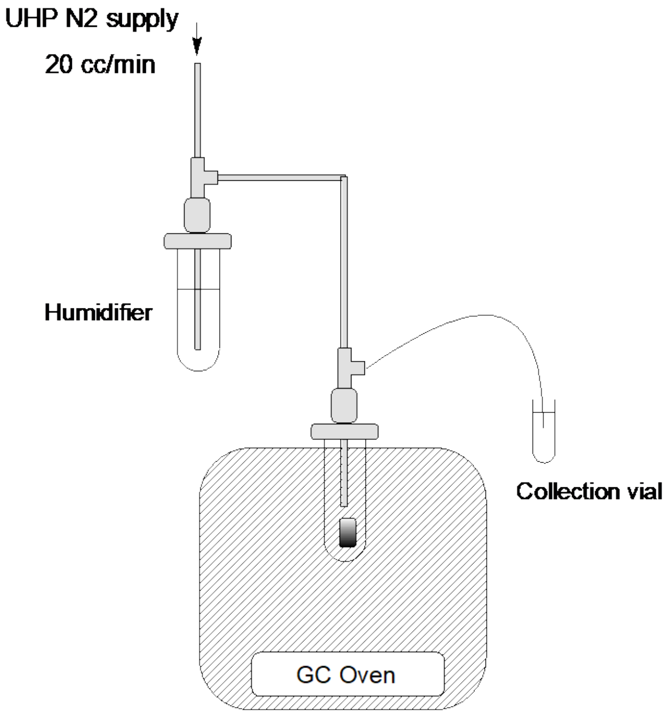
- Crystalline silicon modules are commonly constructed with a breathable backsheet using polyethylene-co-vinyl acetate (EVA) as an encapsulant.
- EVA dominates the industry because of a long history of use in PV devices, a low cost, and adequate processibility and performance.
- Some new “polyolefin” encapsulants are actually copolymers with EVA.
- It is now common to make encapsulants consisting of three layers of EVA/POE/EVA to have low cost and good electrical insulation.
- **EVA will produce acetic acid as a by-product.**
- **The presence of both water and acetic acid produce a corrosive environment.**
- **Question: How bad is acetic acid really?**

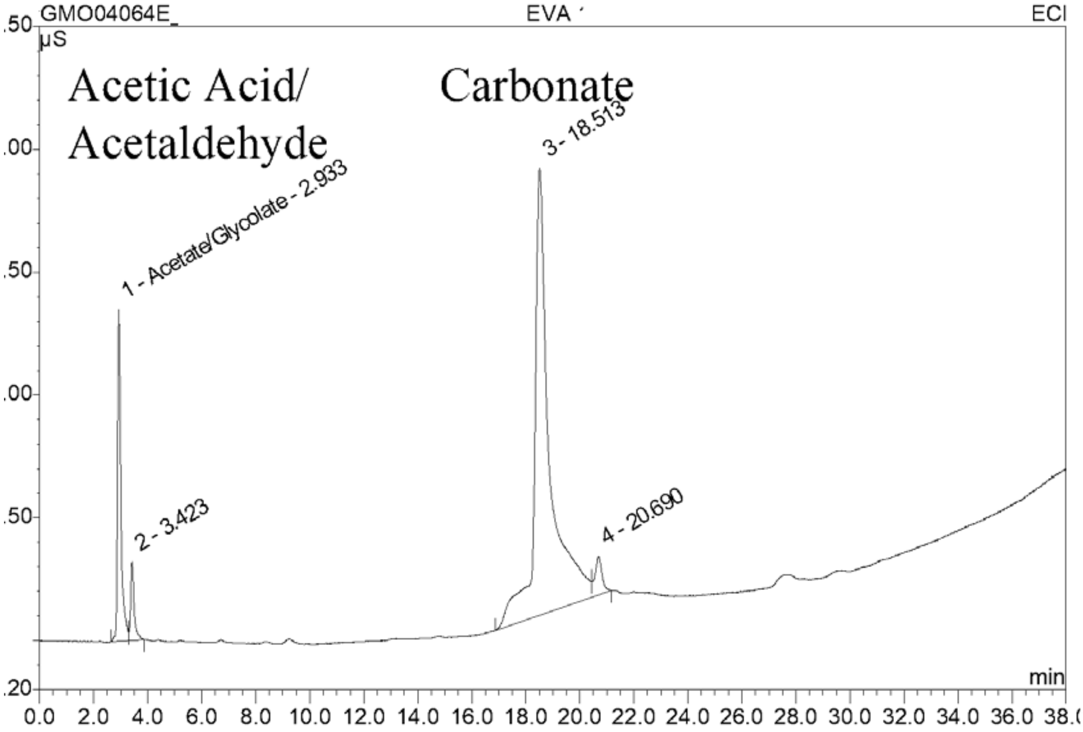
EVA Chemistry Deacetylation Pathways

- These reaction pathways are promoted by UV light and radical chemical pathways and by heat and humidity.
- None of these decomposition products will cause yellowing. Large conjugated moieties are needed to have enough blue light absorption to make a material look yellow.



Very Low Production of Acetate Measured





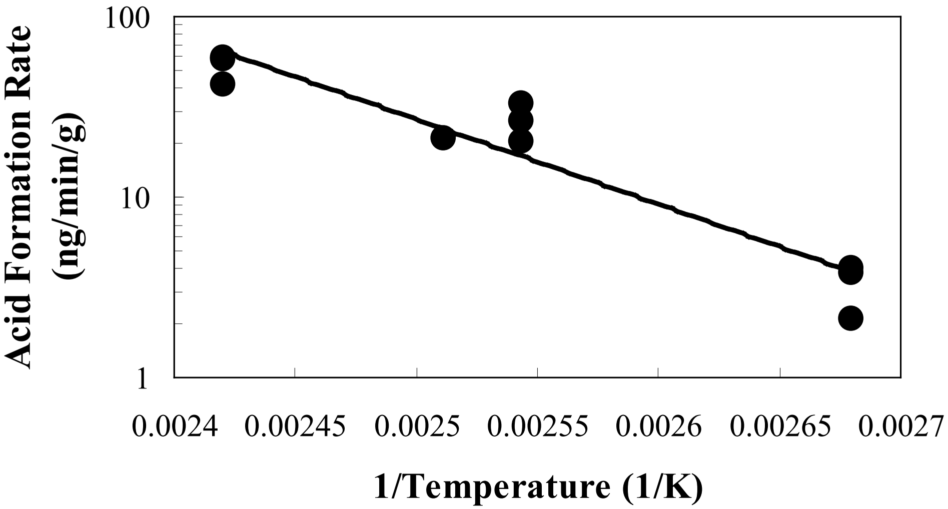
Slightly humidified air is blown over a temperature-controlled sample and generated acetic acid and acetaldhyde are collected in an NaOH solution.

Ion chromatography is used to analyze the solution to look for Acetic Acid. Capable of detecting very low concentrations of acid.

- M. D. Kempe, G. J. Jorgensen, K. M. Terwilliger, T. J. McMahon, C. E. Kennedy, and T. T. Borek, "Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices," *Solar Energy Materials and Solar Cells,* vol. 91, pp. 315-329, 2007.

Lower Bound for EVA Acid Formation Rate

- Similar activation energies were found for EVA, but different overall rates.
- Additionally, these methods remove generated acetic acid, underestimating the potential for autocatalytic generation of acid.



- M. D. Kempe, G. J. Jorgensen, K. M. Terwilliger, T. J. McMahon, C. E. Kennedy, and T. T. Borek, "Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices," *Solar Energy Materials and Solar Cells,* vol. 91, pp. 315-329, 2007.

Reprinted from Weber *et al.*

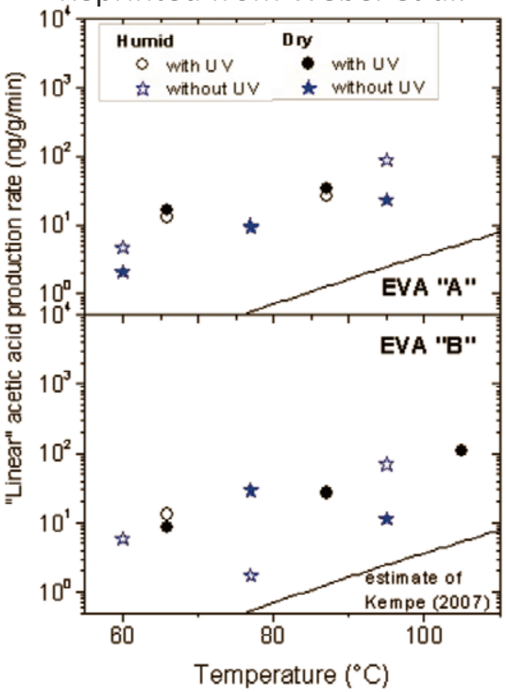


Figure 5: Average acetic acid production rates for two different types of EVA as a function of temperature for "humid" and "dry" conditions with and without UV irradiation

- U. Weber, R. Eiden, C. Strubel, T. Sogding, M. Heiss, P. Zachmann, K. Kattermann, H. Engelmann, A. Dethlefsen, and N. Lenck, "Acetic Acid Production, Migration and Corrosion Effects in Ethylene-Vinyl-Acetate- (EVA-) Based PV Modules," *27th European Photovoltaic Solar Energy Conference and Exhibition,* pp. 2992-2995, 2012.

Acetic Acid is Trapped in a Module

Reprinted from Weber *et al.*

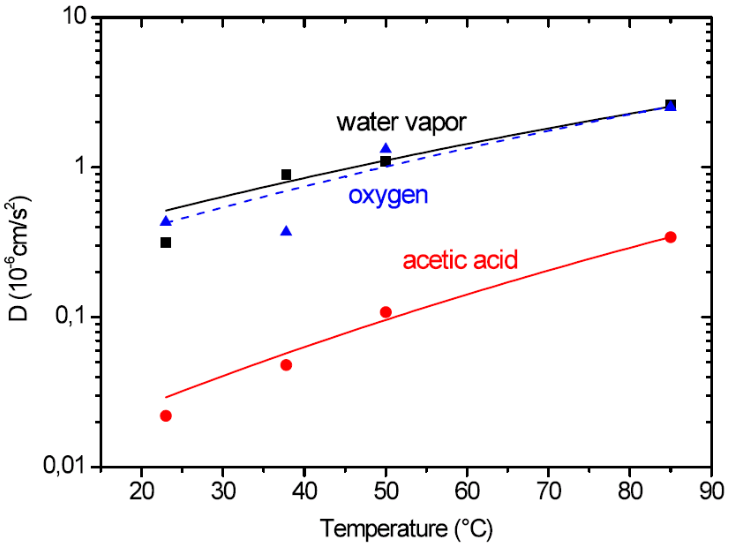


Figure 10: Diffusion coefficients of water, acetic acid, and oxygen within EVA at different temperatures, the lines are Arrhenius fits to the data (activation energies: 22,7 kJ/mol for water 25,4 kJ/mol for oxygen and 35,0 kJ/mol for acetic acid).

- With a >10× lower diffusivity, acetic acid is trapped in a module for 10 to 20 y rather than 1 to 2 y as with water.
- Acetic acid initially present in EVA may remain for the life of the module.
- There are lots of inexpensive ways to make EVA that result in increased free acid content.

- U. Weber, R. Eiden, C. Strubel, T. Sogding, M. Heiss, P. Zachmann, K. Kattermann, H. Engelmann, A. Dethlefsen, and N. Lenck, "Acetic Acid Production, Migration and Corrosion Effects in Ethylene-Vinyl-Acetate- (EVA-) Based PV Modules," *27th European Photovoltaic Solar Energy Conference and Exhibition,* pp. 2992-2995, 2012.

No Bulk Acetate Loss in Fielded EVA

- Klemchuk* measured deacetylation in fielded EVA samples and found the loss to be less than the experimental noise, ~±1%.
- Only small amounts of acetic acid are evolved in the life of a PV module.
- However, acetic acid has a pkA of 4.76 and will buffer the hydronium (H_3O^+) to that chemical potential which is equivalent to 330 ng/cm^{3}in water which is easily produced as decomposition.

Reprinted from Klemchuk *et al.*

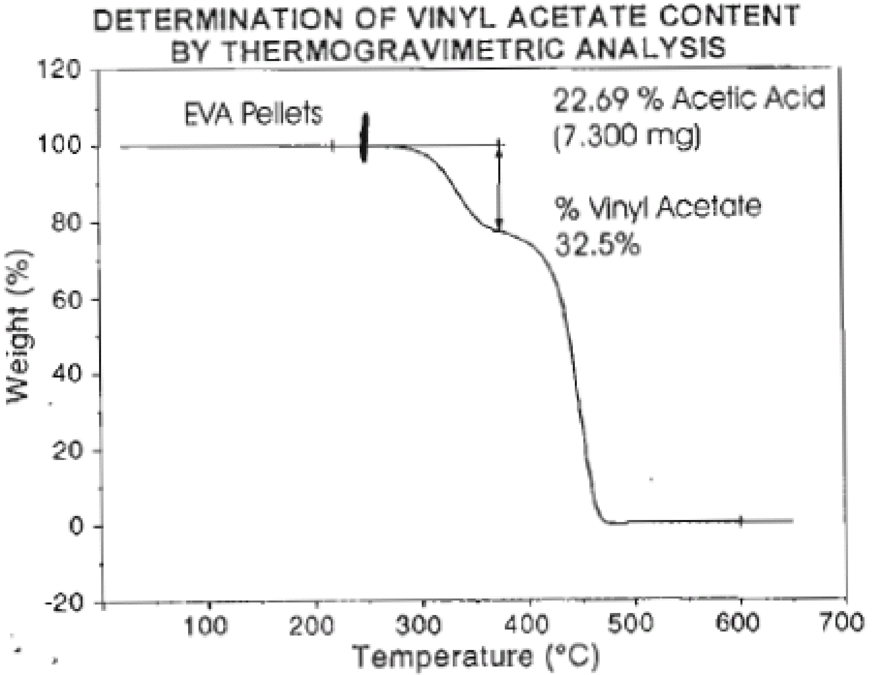


Fig. 3. Determination of vinyl acetate content of EVA by TGA.

- P. Klemchuk, M. Ezrin, G. Lavigne, W. Holley, J. Galica, and S. Agro, "Investigation of the degradation and stabilization of EVA-based encapsulant in field-aged solar energy modules," *Polymer Degradation and Stability,* vol. 55, pp. 347-365, 1997.

H_3O^+ Chemical Potential is Determined by Polarity

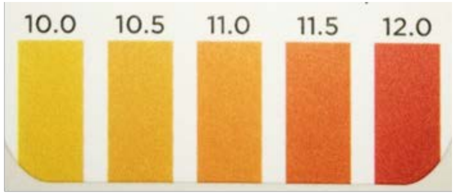


Fig. 9 Change in acidity as a function of voltage bias in EVA. Some samples were exposed to 168 h of damp heat before bias was turned on for an additional 300 h with bias. Other samples were put directly into damp heat with bias.

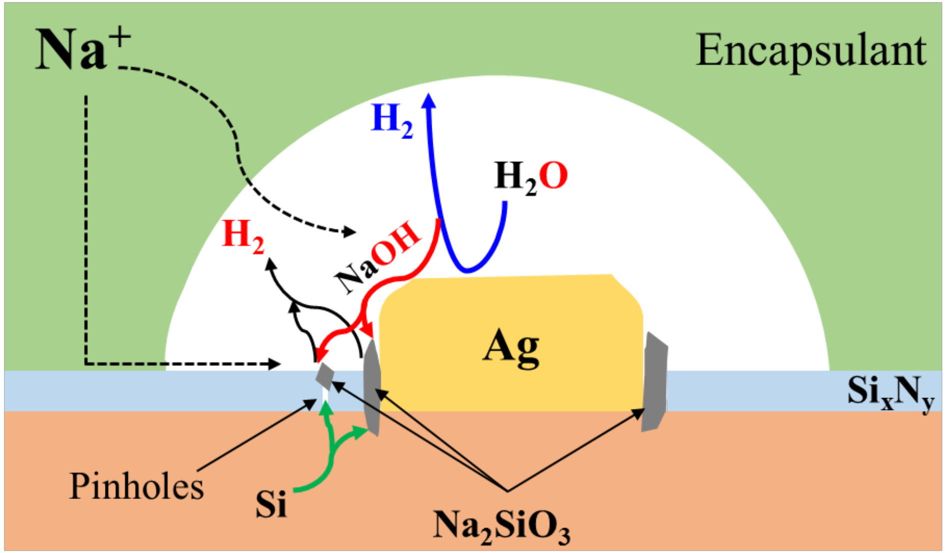


Fig. 10 Schematic diagram showing Si corrosion near Ag fingers and at defects or pinholes in the SiO_xN_y during negative bias testing.

- The effective pH or chemical activity of H_3O^+ is determined by deployment polarity not acetic acid generation.

J. Li, Y.-C. Shen, P. Hacke, and M. Kempe, "Electrochemical mechanisms of leakage-current-enhanced delamination and corrosion in Si photovoltaic modules," *Solar Energy Materials and Solar Cells,* vol. 188, pp. 273-279, 2018/12/15/ 2018, doi: https://doi.org/10.1016/j.solmat.2018.09.010.

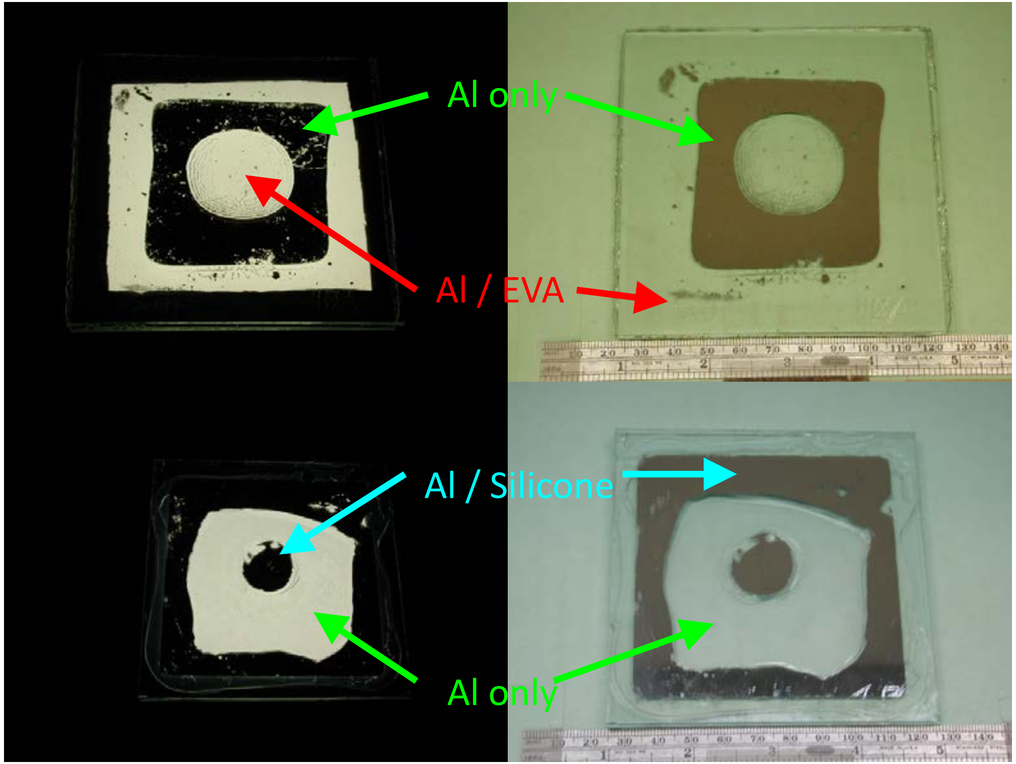
EVA Enhances Corrosion

Backlit photos

Front-lit Photos

EVA

Silicone
Acetic Acid
Condensation
Cure



1000 hours of 85°C and 85% RH

Polymer located only in the center and the outer ~25mm.

3.18 mm Glass
800 Å Al film
0.5 mm Polymer
3.18 mm Glass

- Both EVA and this condensation cure silicone produce acetic acid.
- But corrosion is larger where it is contacted with EVA.
- Silicone reduces oxidation of Al.
- For corrosion to happen, there must be oxidation and if the material forms protective oxides, removal of the ions to expose new metal surface.

G. J. Jorgensen *et al.*, "Moisture transport, adhesion, and corrosion protection of PV module packaging materials," *Solar Energy Materials and Solar Cells,* vol. 90, no. 16, pp. 2739-2775, Oct 2006.

M. D. Kempe, G. J. Jorgensen, K. M. Terwilliger, T. J. McMahon, C. E. Kennedy, and T. T. Borek, "Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices," *Solar Energy Materials and Solar Cells,* vol. 91, no. 4, pp. 315-329, 2007. [Online]. Available: http://www.sciencedirect.com/science/article/B6V51-4MFCW04-1/1/2a78374bee3f833856397ccfc9bc75b7.

EVA is Protective if Allowed to “Breath”

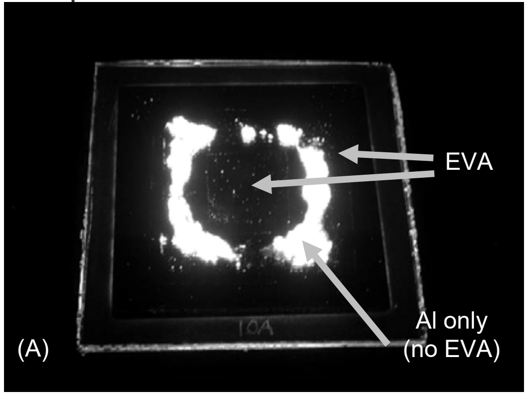
Breathable Backsheet

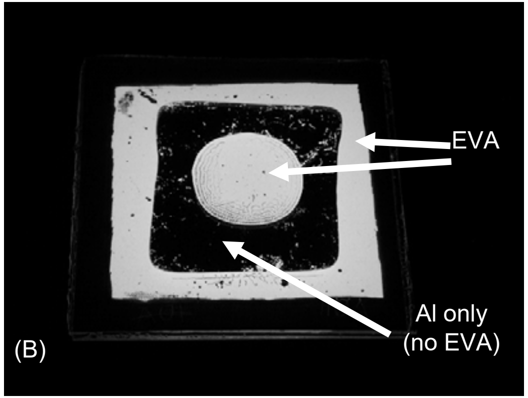
3.18 mm Glass
800 Å Al film
0.5 mm EVA
0.18 mm PET

Impermeable Backsheet

3.18 mm Glass
800 Å Al film
0.5 mm Polymer
3.18 mm Glass

Photo taken after 1000 h
exposure to 85 °C and 85% RH.





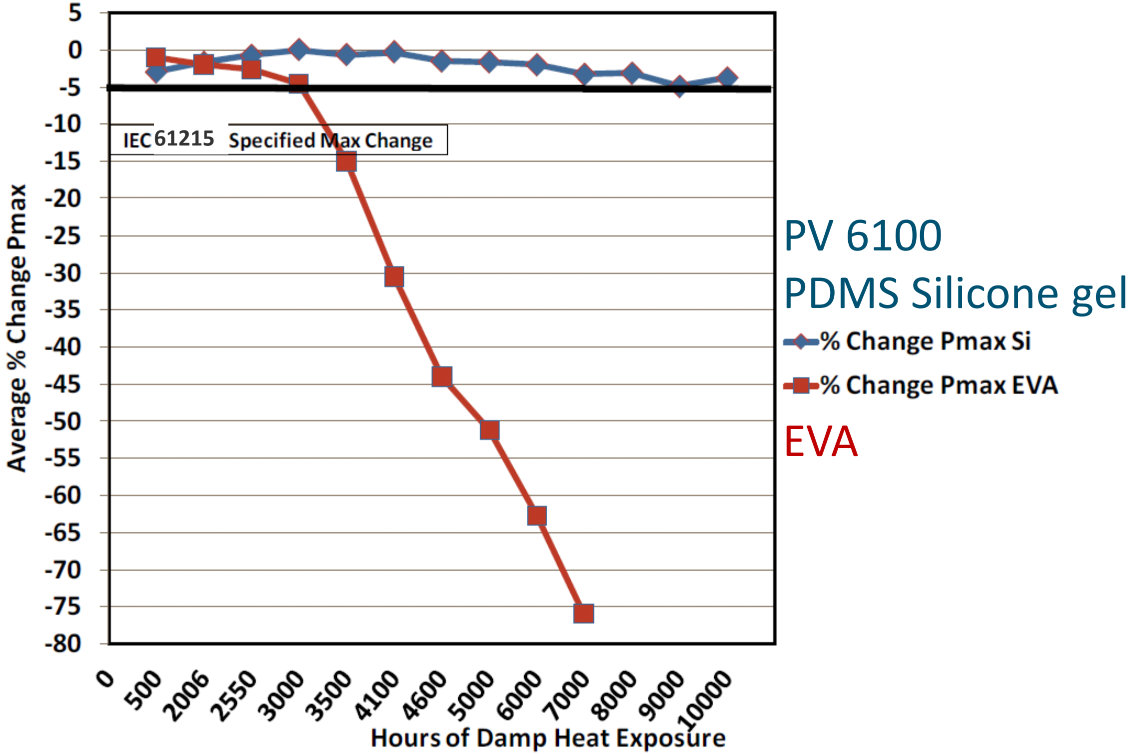
- The trapping of acetic acid increases corrosion rates.

G. J. Jorgensen *et al.*, "Moisture transport, adhesion, and corrosion protection of PV module packaging materials," *Solar Energy Materials and Solar Cells,* vol. 90, no. 16, pp. 2739-2775, Oct 2006.

M. D. Kempe, G. J. Jorgensen, K. M. Terwilliger, T. J. McMahon, C. E. Kennedy, and T. T. Borek, "Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices," *Solar Energy Materials and Solar Cells,* vol. 91, no. 4, pp. 315-329, 2007. [Online]. Available: http://www.sciencedirect.com/science/article/B6V51-4MFCW04-1/1/2a78374bee3f833856397ccfc9bc75b7.

Silicones Outperform EVA in Damp Heat

Reprinted from Ketola *et al.*



- The power reduction was driven by reduced Fill Factors (FF) and increased Series Resistance (Rs).
- In prolonged damp heat silicones perform better.
- Question: What are the potential interpretation pitfalls.

Ketola, B., Norris, A.; The Role of Encapsualnt Moisture Permeability in the Durability of Solar Photovoltaic Modules; Proceedings 25th EU PVSEC, 2010, Valencia, Spain.
B. Ketola and A. Norris, “Degradation mechanism investigation of extended damp heat aged PV modules” 26th *EUPVSEC,* 2011.

EVA Results in More Corrosion Relative to PDMS

- Silicone reduces corrosion.
- But is 7000 h equal to 1 year or 10,000 years?
- We cannot understand this question without more data.

Reprinted from Ketola *et al.*

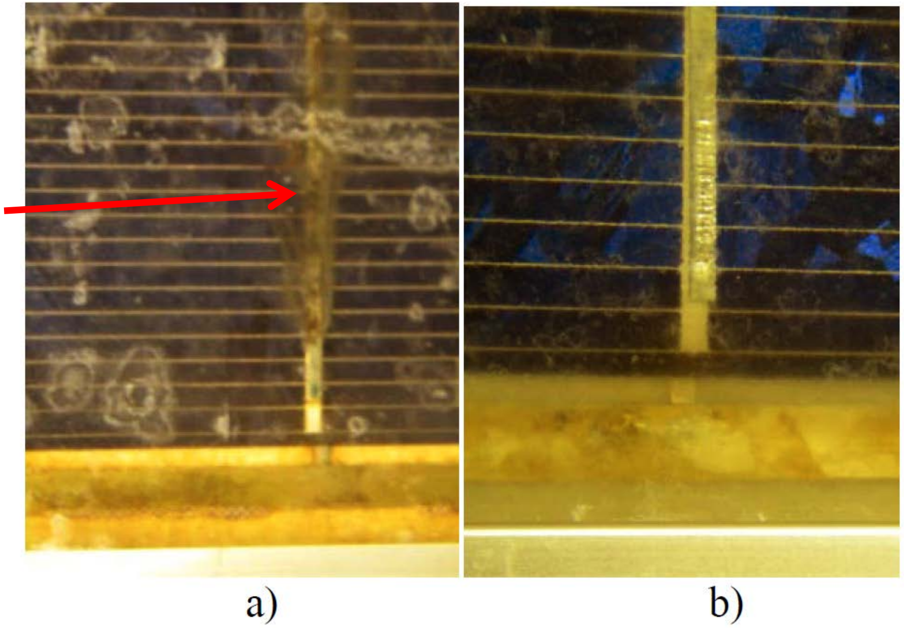
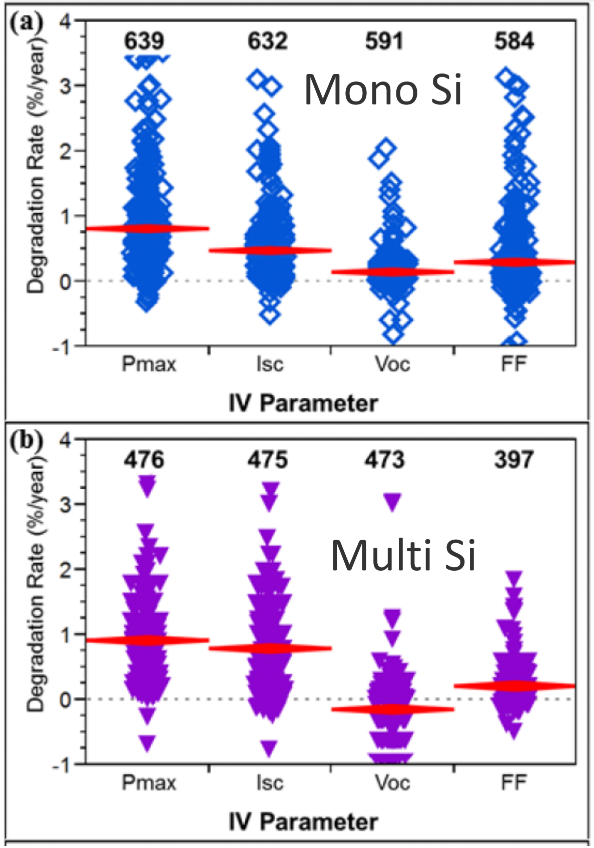


Figure 5: Picture of bus bars and tabbing of a) EVA and b) Silicone modules after 7000 and 10000 hours of Damp Heat Aging, respectively.

Ketola, B., Norris, A.; The Role of Encapsualnt Moisture Permeability in the Durability of Solar Photovoltaic Modules; Proceedings 25th EU PVSEC, 2010, Valencia, Spain.
B. Ketola and A. Norris, “Degradation mechanism investigation of extended damp heat aged PV modules” 26th *EUPVSEC,* 2011.

For Si-PV ISC Losses Dominate



Reprinted from Jordan *et al.*

a-Si, CIGS, CdTe

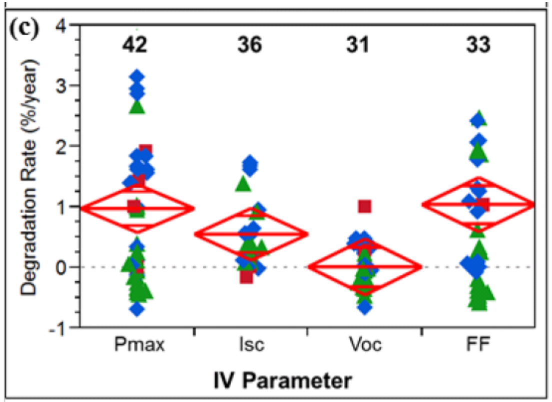


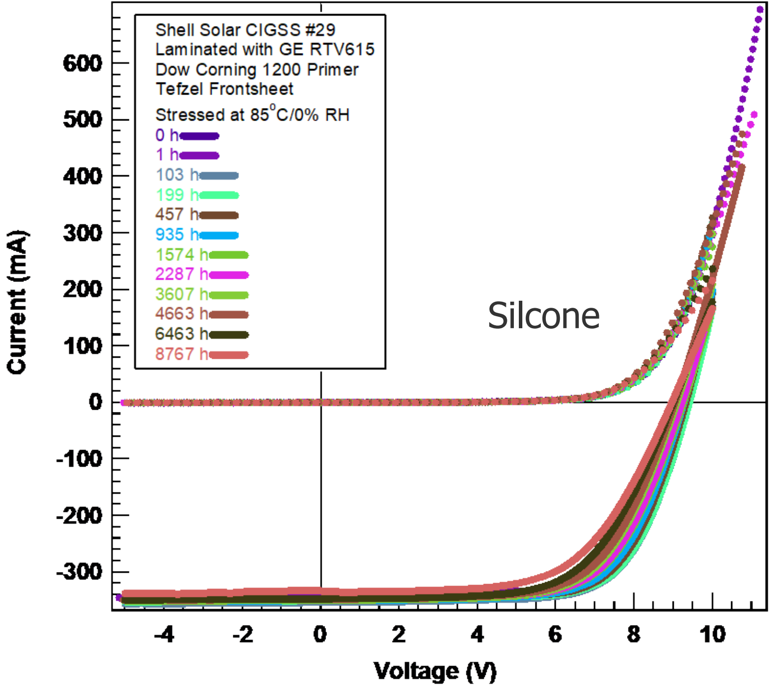
Figure 3: Pmax, Isc, FF and Voc degradation rates for mono-Si (a), multi-Si (b), and thin-film (c). The thin-film part is an overlay of a-Si (filled blue diamonds), CIGS (filled green triangles), and CdTe (filled red squares). As a guide for the eye, no degradation is indicated by a dashed line. The numbers at the top indicate the number of data points.

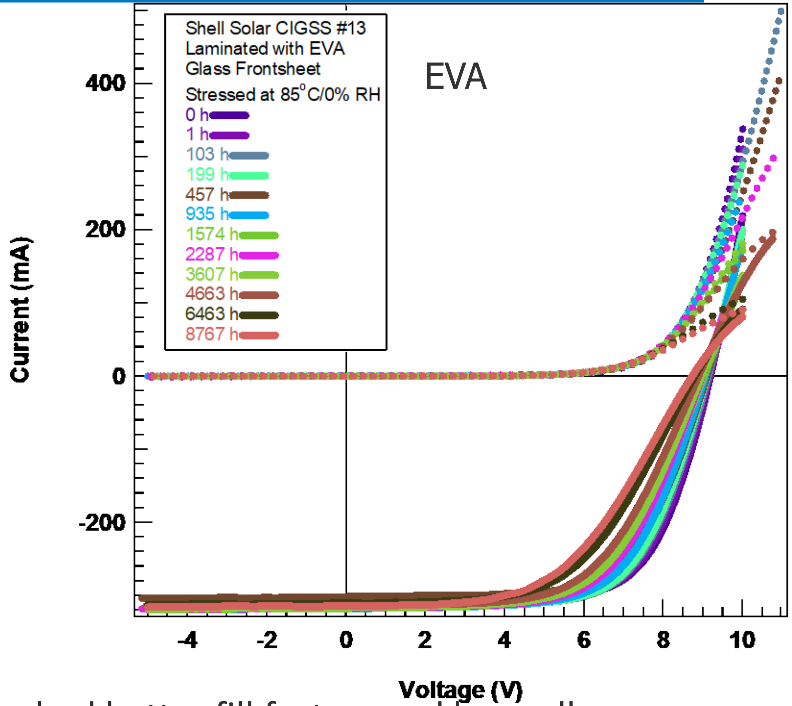
- The Failure mode in extended damp heat may not be the most important failure mode for Si PV.

The relevance of extended Damp Heat testing is highly suspect.

Jordan, Wohlgemuth, Kurtz, “Technology and Climate Trends in PV Module Degradation”, 27th European PVSEC, Frankfurt, Germany, September 24-28, 2012.

85°C and 0% RH Exposure Causes V_{oc} and FF Losses





- Silicone encapsulated cells performed better. They had better fill factors and less roll over.
- Here the failure mode is correct and starts immediately and is not dependent on unreasonably high levels of humidity. This is much more likely to be a relevant conclusion.
- It is frequently understood that CIGS and other thin film technologies will perform better when EVA is not used as the encapsulant.

M. D. Kempe, K. M. Terwilliger, and D. Tarrant, "Stress Induced Degradation Modes in CIGS Mini-Modules," *33rd IEEE Photovoltaic Specialist Conference Program*, 2008.

Study of Encapsulant Effects on CIGS

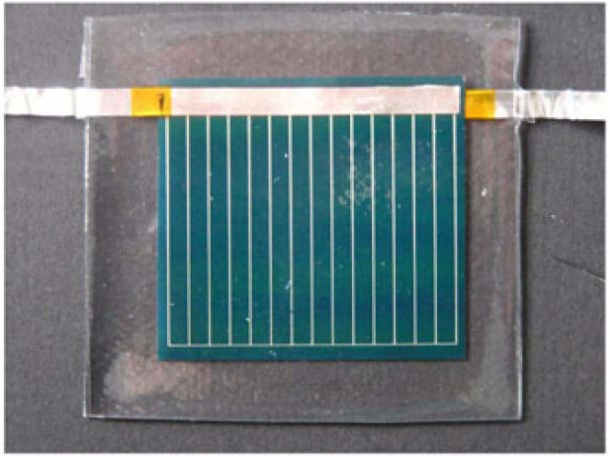


Figure 1. Global Solar Energy (GSE), Inc. Copper indium gallium selenide flexible cell for moisture degradation testing, tabbed and encapsulated.

Reprinted from Coyle *et al.*

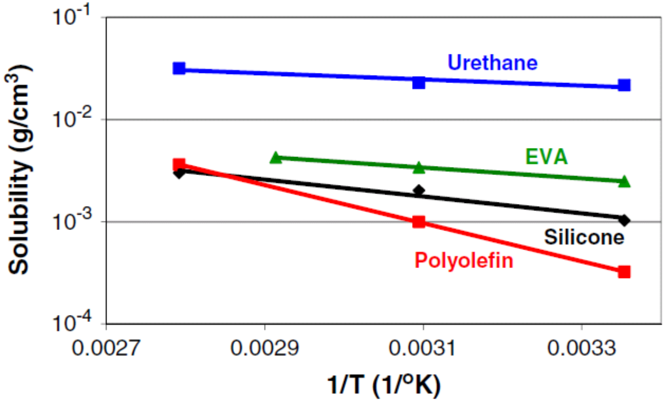


Figure 13. Solubility of experimental encapsulants.

$$t_c = \frac{S_E L_E}{WVTR_{max}}$$

Higher solubility and/or thicker encapsulants should delay moisture ingress prolonging the life of a cell.

D. J. Coyle, H. A. Blaydes, R. S. Northey, J. E. Pickett, K. R. Nagarkar, R.-A. Zhao, and J. O. Gardner, "Life prediction for CIGS solar modules part 2: degradation kinetics, accelerated testing, and encapsulant effects," *Progress in Photovoltaics: Research and Applications,* 2011.

CIGS Degradation Enhanced by EVA

Reprinted from Coyle *et al.*

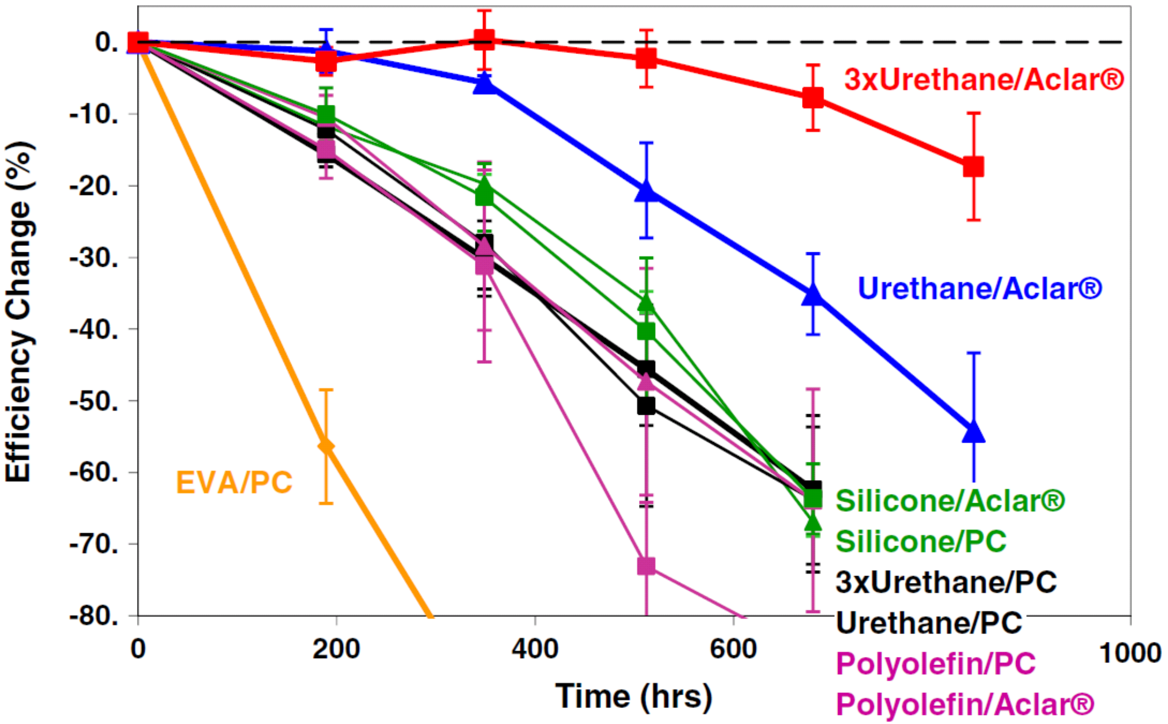


Figure 14. Degradation versus time at 85 C 85% *RH* for all packages, showing greatly extended life for the two urethane/Aclar® packages.

- In this experiment EVA will equilibrate with moisture much slower than with the Urethane, but faster than the silicone and polyolefin.
- CIGS with EVA degrades faster than other combinations.

D. J. Coyle, H. A. Blaydes, R. S. Northey, J. E. Pickett, K. R. Nagarkar, R.-A. Zhao, and J. O. Gardner, "Life prediction for CIGS solar modules part 2: degradation kinetics, accelerated testing, and encapsulant effects," *Progress in Photovoltaics: Research and Applications,* 2011.

Uncertainty and Variability in Extrapolation

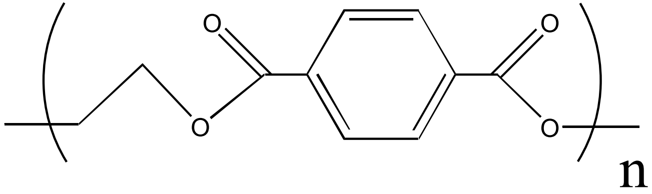
- Once modeling constants are obtained, one can extrapolate the time to failure or performance of a PV module or module component.
- Unfortunately not only are these parameters not typically found, but their uncertainty and even less the correlation between them is not always reported despite being integrated into the software doing the calculations.
- We are accustomed to considering the uncertainty in measurement of a specific degradation, but when people ask what is the equivalent time of a given stress test they want to know the variability in the value of the extrapolation for different materials and processing methods.

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)

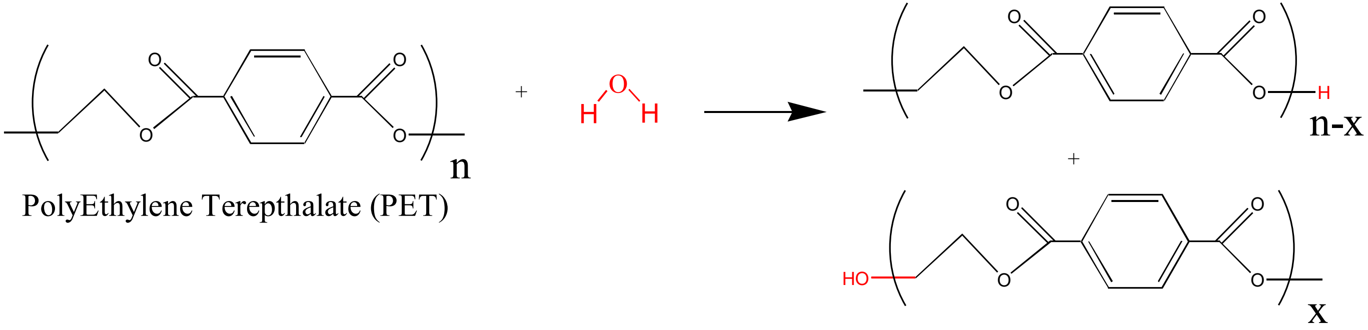
PET Hydrolysis Modeling



PolyEthylene Terepthalate (PET)

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

PET Hydrolysis Kinetics



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

Pickett *et. al***

Ea=129±3.4 kJ/mol

A=$1.2\cdot10^{17}\pm1.3\cdot10^{17}$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.

PET hydrolysis:

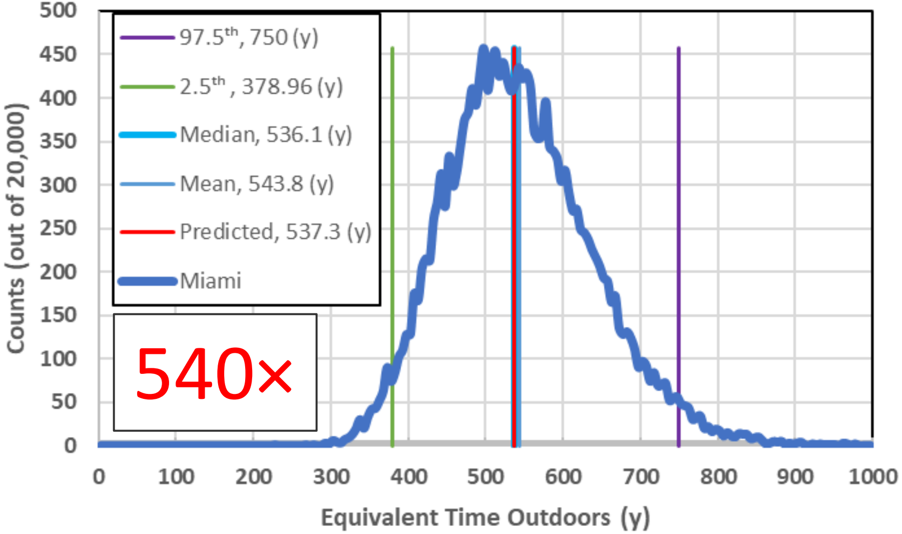
Best case extrapolation

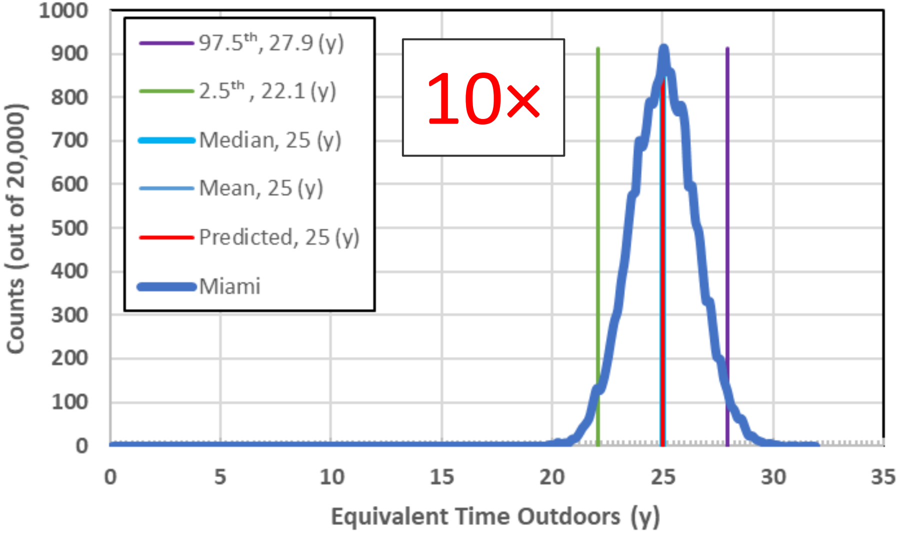
Single-axis tracker
Polymer back module

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

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

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





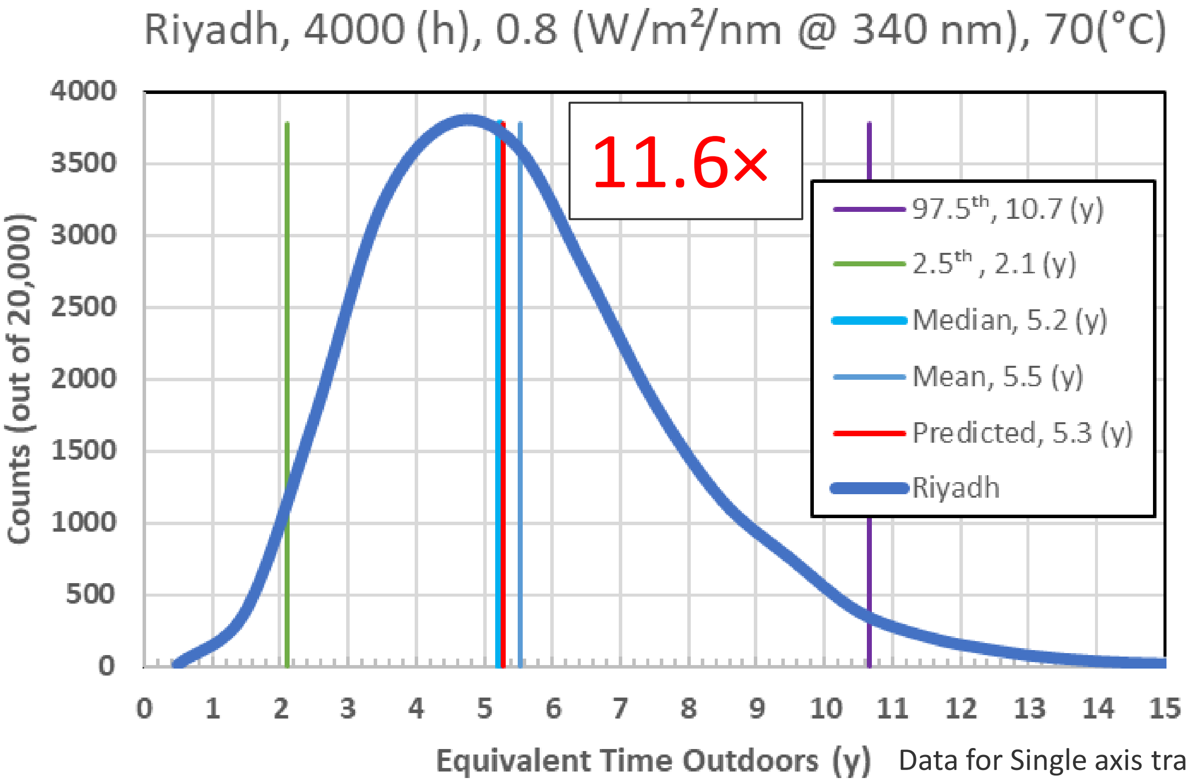
- Extrapolation can be for extreme amounts of time for highly thermally accelerated processes like PET hydrolysis.
- When the acceleration is kept low, the uncertainty in the extrapolation is low.

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.

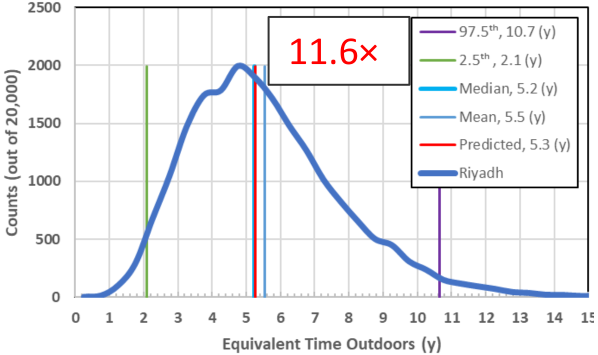
- The condition of A3 from IEC 62788-7-2 is only equivalent to a few years of frontside exposure in Riyadh on a single axis tracker.
- Even with a reasonable 11.6× acceleration factor, there is a >5× range in equivalent time.

*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.

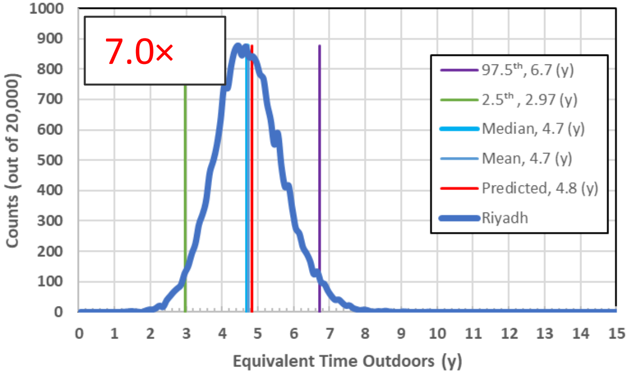
Optional proposals for IEC 63126 high system testing exposure

Riyadh Saudi Arabia

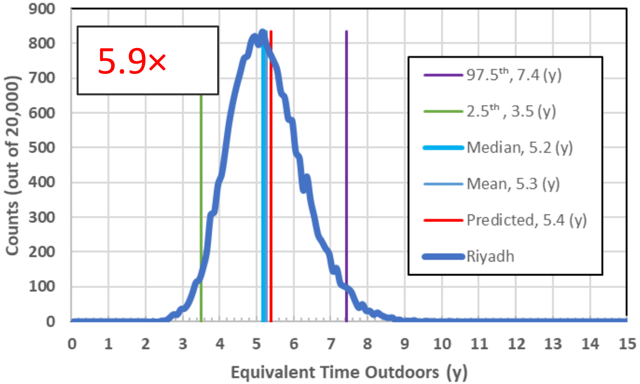
A3 (65°C), 4000 h, Rack, $T_{98}<70°C$



A3 (65°C), 6000 h, Close Roof, $T_{98}<80°C$



A3 (65°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. This will be implemented in the next version of IEC 63126.

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.

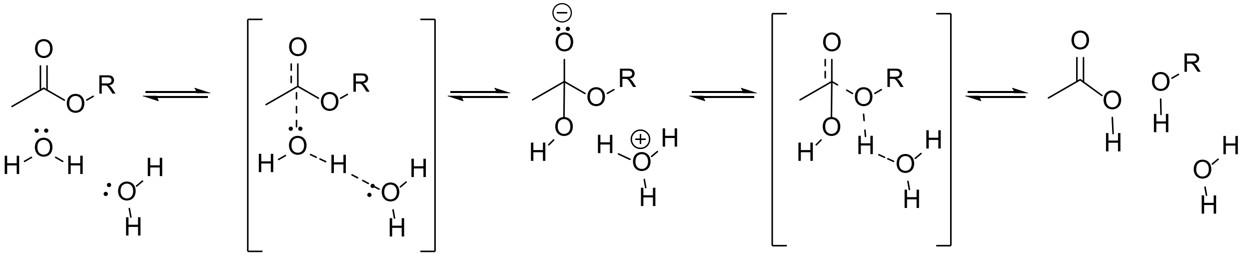
Considerations for quality test designs

- Qualification tests, such as damp heat, indicate design inadequacies, but do not to predict lifetime or assess relative durability.
- Many degradation processes are driven by complex combinations of stress factors making it easy for relevant failure modes to be missed.
- For generalized accelerated stress tests, a significant amount of uncertainty is inherent.
- A better understanding of the typical dependence of and uncertainty in the relevant stress factors will aid in the development of accelerated stress tests.

Outline

- Specific Mechanism - Look at the hydrolysis of a typical PV backsheet made of PET as a case study for a material with an unusually high level of understanding of degradation.
- Generalized Test - Apply kinetic models of paints and coatings degradation to backsheets.
- Accelerated Test Design - Show how good choices for RH can simplify the accelerated stress testing for a given environment when the humidity dependence is unknown.

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.

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

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

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.

How Arrhenius Data Should be Reported

- The Data was reported as:
  - Ea=129±3.4 kJ/mol
  - ln(A)=39.3±1.1 ln(1/days)
  - n=2±0

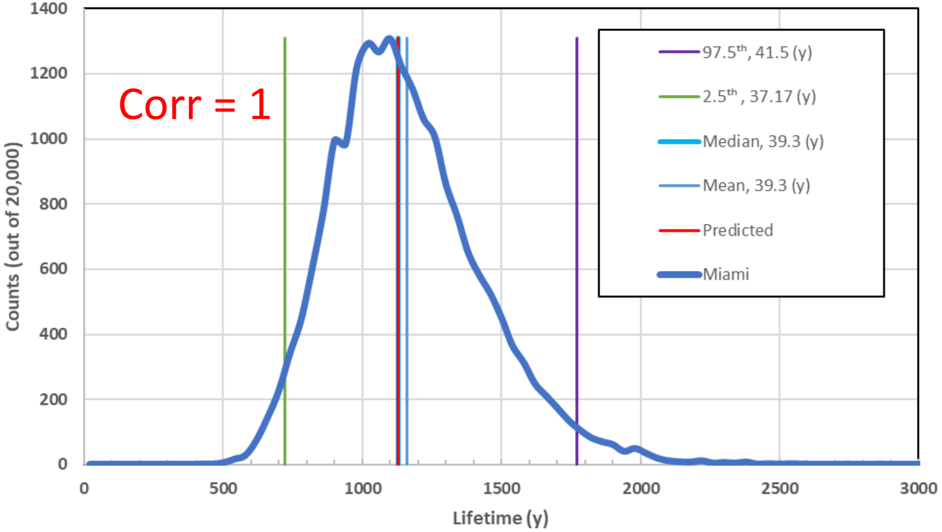
$$t_{fail} = \frac{e^{\left(\frac{E_a}{RT}\right)}}{A[RH]^2}$$

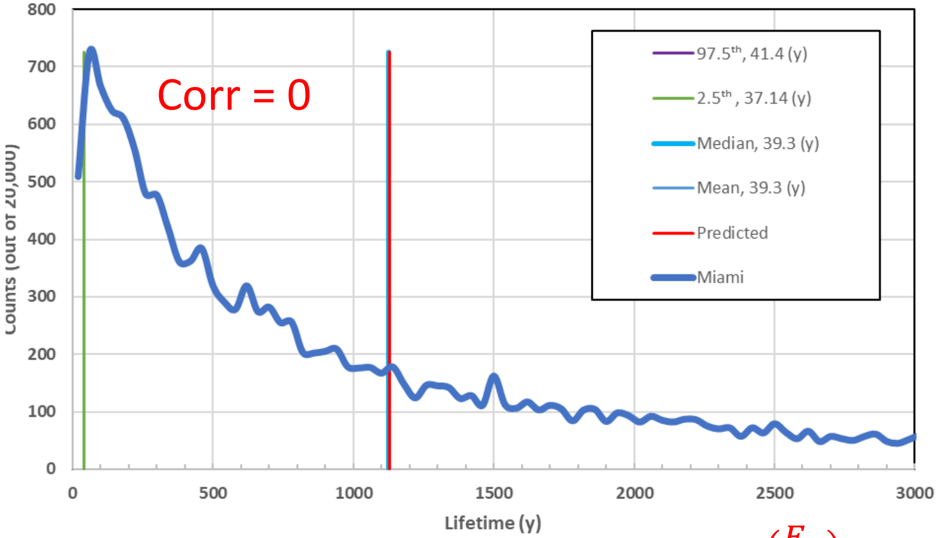
- The correlation between ln(A) and Ea should have also been reported. This is vitally important for calculating the uncertainty in the time to failure.
- Because these are both determined from the same Arrhenius plot, the correlation coefficient is 1.

*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.

Using Correlation Coefficients is Needed





PET Backsheet Hydrolysis failure For Miami Florida, single axis tracking

Ea=129±3.4 kJ/mol, ln(A)=39.3±1.1 ln(1/days), n=2±0

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

- Even with small uncertainties, the extrapolation is highly uncertain.
- PET Hydrolysis is not a problem for backsheets, but this is not the only stressor.
- If you don’t account for the correlation between different modelling constants, your results will be wrong.

Site and mechanism Specific Equivalent T and RH

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

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

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

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

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

- If you want to consider how hot a climate is in the context of degradation, average values are not useful.
- For humidity, degradation equations are typically written in terms of the relative humidity.
- By using T_{eq} in the equation, this provides constant conditions of T_{eq} and RH_{WA} that produce the same degradation as the use environment.

PET Hydrolysis Equivalent T and RH

$$\log\left(\frac{C}{C-x}\right) = A \cdot t \cdot RH^2 \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

	Years to 0.55% degradation (i.e. Hydrolysis Service Life) (y)		1000 Hours 85^{o}C/85% RH Years equivalent (y)		**Teq for Ea=129.3 kJ/mol (^{o}C)**		**RH, at Teq for 2nd order Kinetics of PET (%)**	
	Open Rack	Insulated Back	Open Rack	Insulated Back	**Open Rack**	**Insulated Back**	**Open Rack**	**Insulated Back**
Denver, Colorado	13,000	4,900	6,500	2,400	**33**	**54**	**14**	**4.6**
Munich, Germany	11,000	4,400	5,100	2,100	**28**	**46**	**25**	**8.4**
Albuquerque, New Mexico	9,000	3,200	4,400	1,500	**37**	**58**	**13**	**4.2**
Riyadh, Saudi Arabia	8,200	3,000	4,000	1,500	**48**	**70**	**5.6**	**2.0**
Phoenix, Arizona	3,400	1,300	1,700	630	**46**	**68**	**9.8**	**3.3**
Miami, Florida	1,100	510	530	250	**37**	**54**	**36**	**14**
Bangkok, Thailand	700	310	320	150	**41**	**59**	**33**	**12**

PET is predicted to “fail” (1/3rd initial tensile strength) after 2064 h of 85 ^{o}C and 85% RH.

*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.

M. D. Kempe and J. H. Wohlgemuth, "Evaluation of temperature and humidity on PV module component degradation," in 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC), 16-21 June 2013 2013, pp. 0120-0125, doi: 10.1109/PVSC.2013.6744112.

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.

- For Temperature, there is a 15% variability in the acceleration factor.
- For irradiance there is a 30% variability in the acceleration factor.
- The variability in TOW (the humidity factor), is 80× the average value. Be careful using humidity to accelerate degradation. You will be masking the non-humidity dependent degradation and may be over accelerating the degradation.
- This is much higher than the 2.6% uncertainty for PET.

- While this isn't explicitly for PV polymeric components, it should be similar in magnitude for a PV material with an unknown/untested composition and degradation kinetics.

---

*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 (GHI).
- This is roughly equal to 10% UV reflectance to the back of the module
- Ignore TOW
  - Condensation is predominantly on the front making application of this effect dubious on the back.
  - Very high uncertainty relative to the low mean value.
  - If used, optimized TOW be representative of the climate and not contribute to the acceleration, but this does result in reduced uncertainty.

$$R_D \sim I^x \cdot T_f^{\frac{T-T_o}{10}}$$

Optimal Exposure Conditions to Minimize Uncertainty

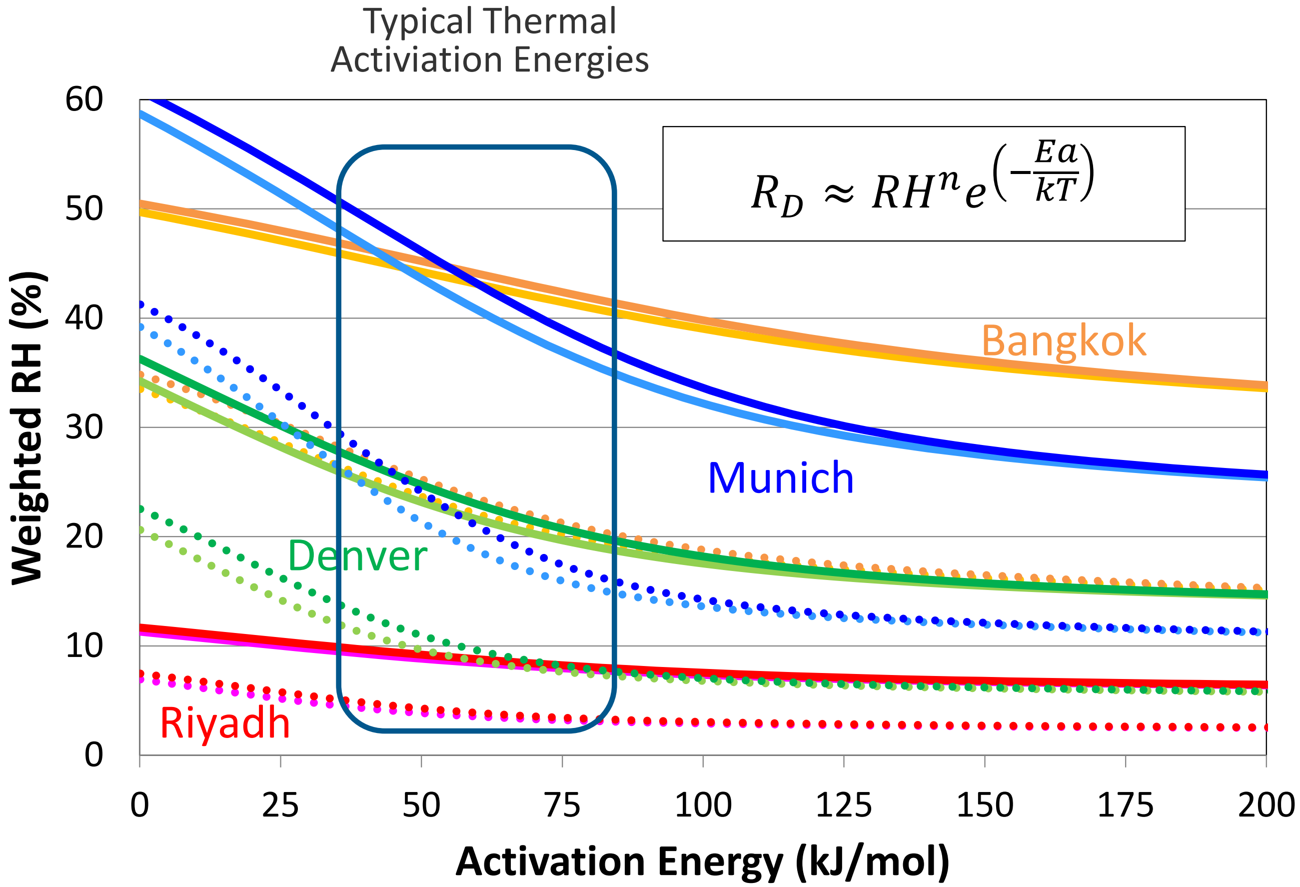
Temperature and Irradiance optimized Data	Accelerated Stress Test Duration					
	1000 h		6 month		2.5 y	
	T_o (ºC)	(W/m²/nm @340 nm)	T_o (ºC)	(W/m²/nm @340 nm)	T_o (ºC)	(W/m²/nm @340 nm)
Munich, Germany	67	2.5	54	0.50	40	0.086
Denver, Colorado	74	3.6	61	0.71	46	0.12
Albuquerque, New Mexico	78	4.4	65	0.89	51	0.15
Miami, Florida	80	4.1	67	0.81	53	0.14
Bangkok, Thailand	85	4.2	72	0.83	58	0.14
Phoenix, Arizona	89	4.7	76	0.94	62	0.16
Riyadh, Saudi Arabia	90	5.0	77	1.00	63	0.17

- Modeled for back sheet exposure assuming rear side irradiation intensity/damage is 1/10th the front, for a fixed latitude tilt and rack mounted.
- ASTM G173 using 0.5018 W/m^2/nm @340 nm

– 1000 h test -	5 to 10 UV suns	219× acceleration
– 6 month test -	1 to 2 UV suns	50× acceleration
– 2.5 y test -	0.17 to 0.33 UV suns	10× acceleration

M. D. Kempe, "Evaluation of the uncertainty in accelerated stress testing," in Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th, 8-13 June 2014 2014, pp. 2170-2175, doi: 10.1109/PVSC.2014.6925355.

The Effective RH is low



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

Solid Lines:
Rack Mounted

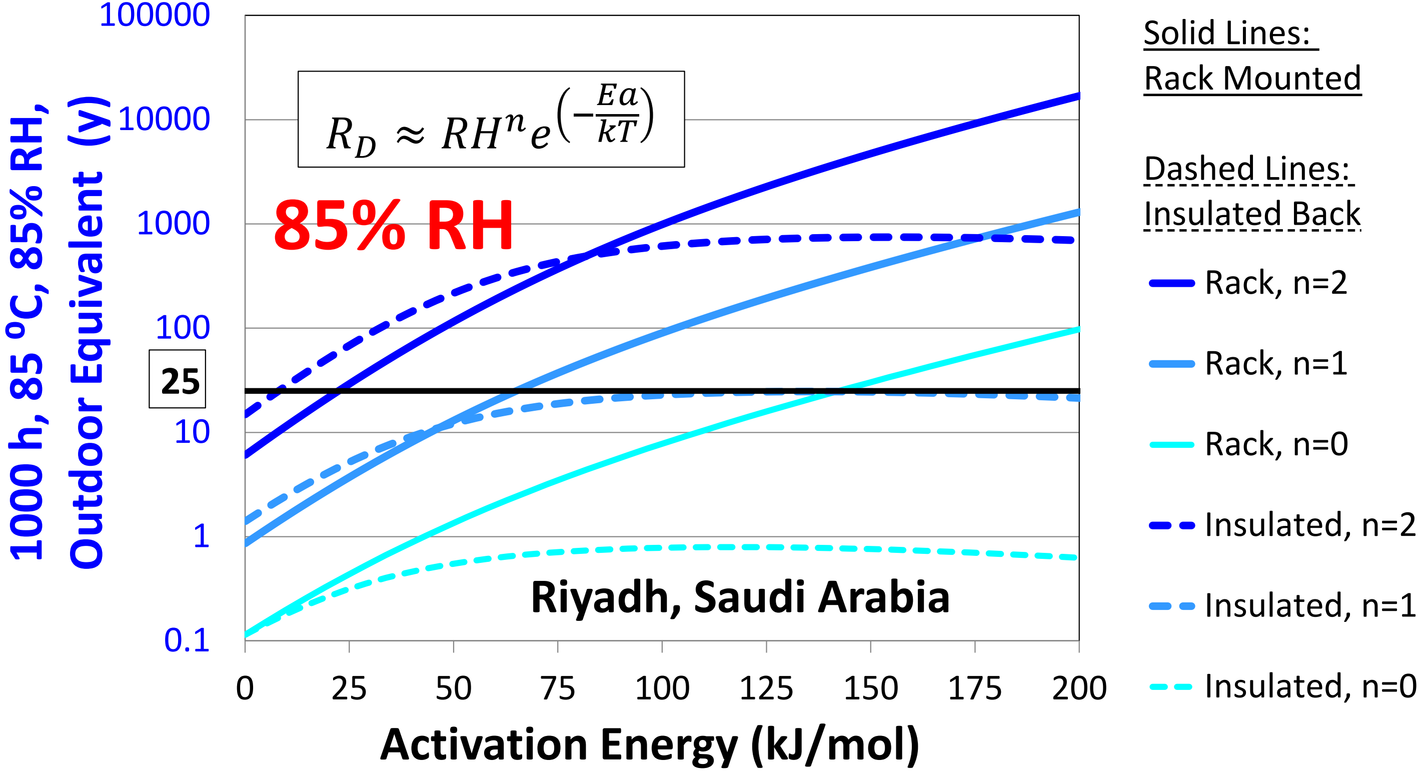
Dashed Lines:
Insulated Back

Darker Line:
n=2

Lighter Line:
n=1

M. D. Kempe and J. H. Wohlgemuth, "Evaluation of temperature and humidity on PV module component degradation," in Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th, 2013, pp. 0120-0125.

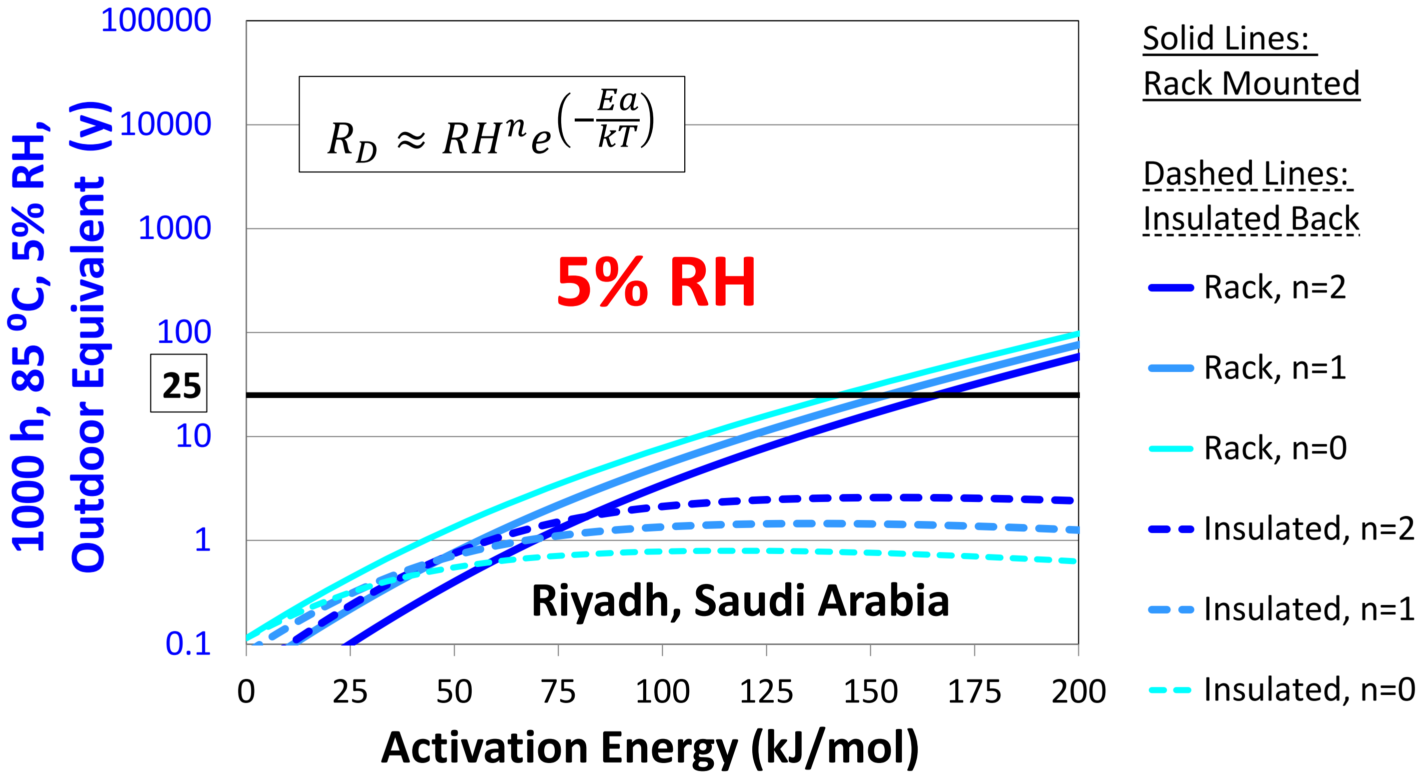
85°C/85% RH Equivalent Time-Riyadh



- The unknown humidity dependence results in a 1000× uncertainty in the acceleration

M. D. Kempe and J. H. Wohlgemuth, "Evaluation of temperature and humidity on PV module component degradation," in Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th, 2013, pp. 0120-0125.

Good RH Choice Reduces the Range of Values



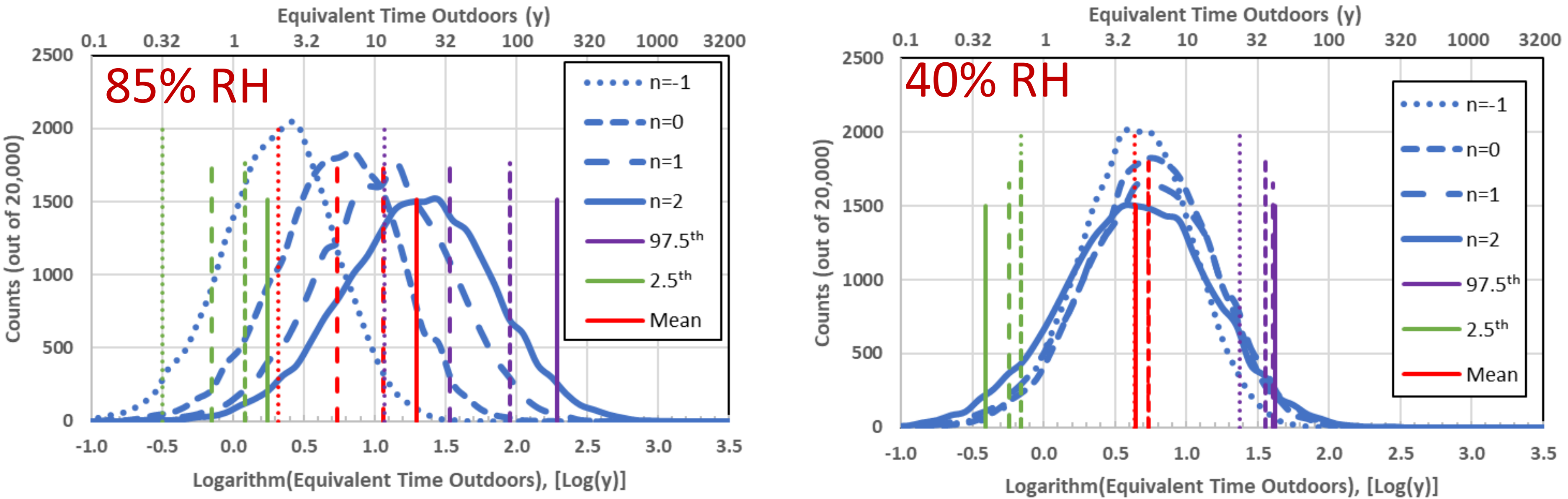
- Testing using a chamber humidity of 5% vs. 85% significantly reduces the variability in the acceleration factor. (For Bangkok Thailand, the ideal humidity is 25%).

M. D. Kempe and J. H. Wohlgemuth, "Evaluation of temperature and humidity on PV module component degradation," in Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th, 2013, pp. 0120-0125.

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.

RH Kinetic Dependencies Vary Widely

Ester Hydrolysis*

$$log\left(\frac{C}{C-x}\right) = A \cdot t \cdot RH^2 \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

Si Cell Metallic Corrosion**

$$\mathrm{TF} = F1 \cdot e^{-b \cdot RH} \cdot e^{\left(\frac{Ea}{kT}\right)}$$

CIGS Degradation*** BET model

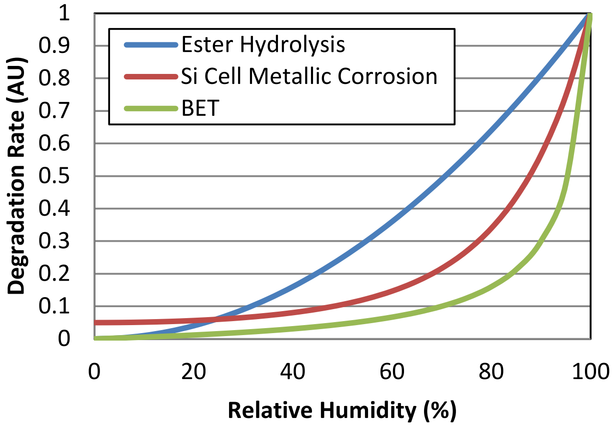
$$R = k_o \cdot \left[\frac{RH}{1-RH+\epsilon}\right] \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

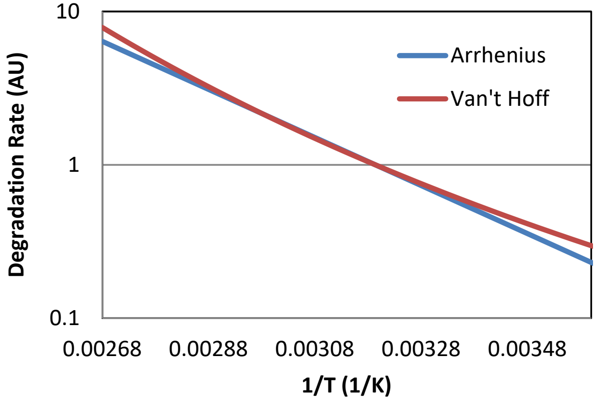
Arrhenius

$$\mathrm{R}=R_o \cdot e^{\left(\frac{-Ea}{kT}\right)}$$

Van’t Hoff****

$$\mathrm{R}=R_o \cdot T_f^{\frac{T-T_o}{10}}$$





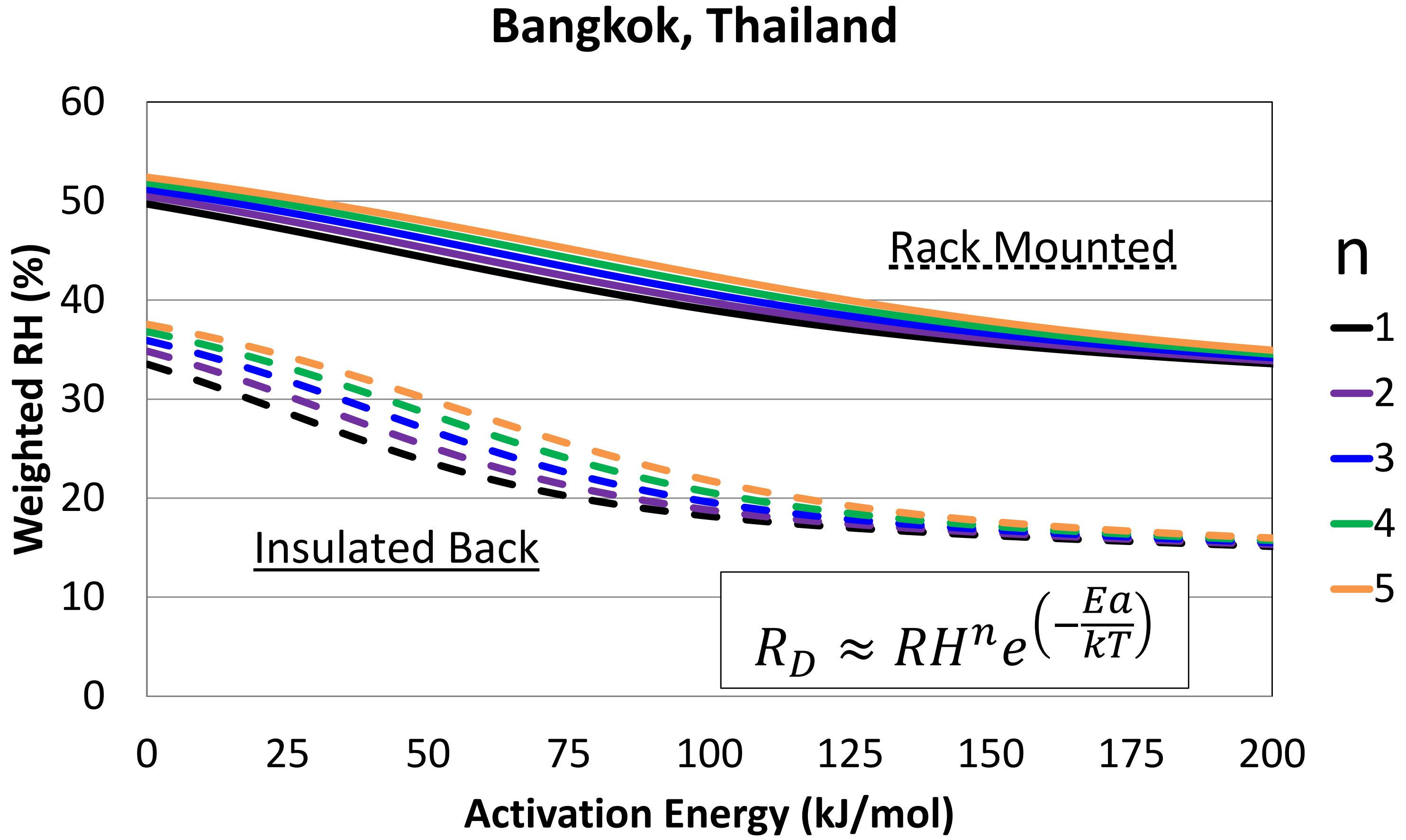
*J. E. Pickett and D. J. Coyle, "Hydrolysis kinetics of condensation polymers under humidity aging conditions," Polymer Degradation and Stability, vol. 98, no. 7, pp. 1311-1320, 2013,

**Whitfield, Salomon, Yang Suez, “Damp Heat versus Field Reliability for Crystalline Silicon”, 38th IEEE PVSC (2012).

***Coyle, Blaydes, Northey, Pickett, Nagarkar, Zhao, Gardner, “Life Prediction for CIGS solar modules part 1: modeling moisture ingress and degradation”, Prog. Photovolt: Res. Appl. (2011).

****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.

RH Not Very Dependent Kinetics or Ea



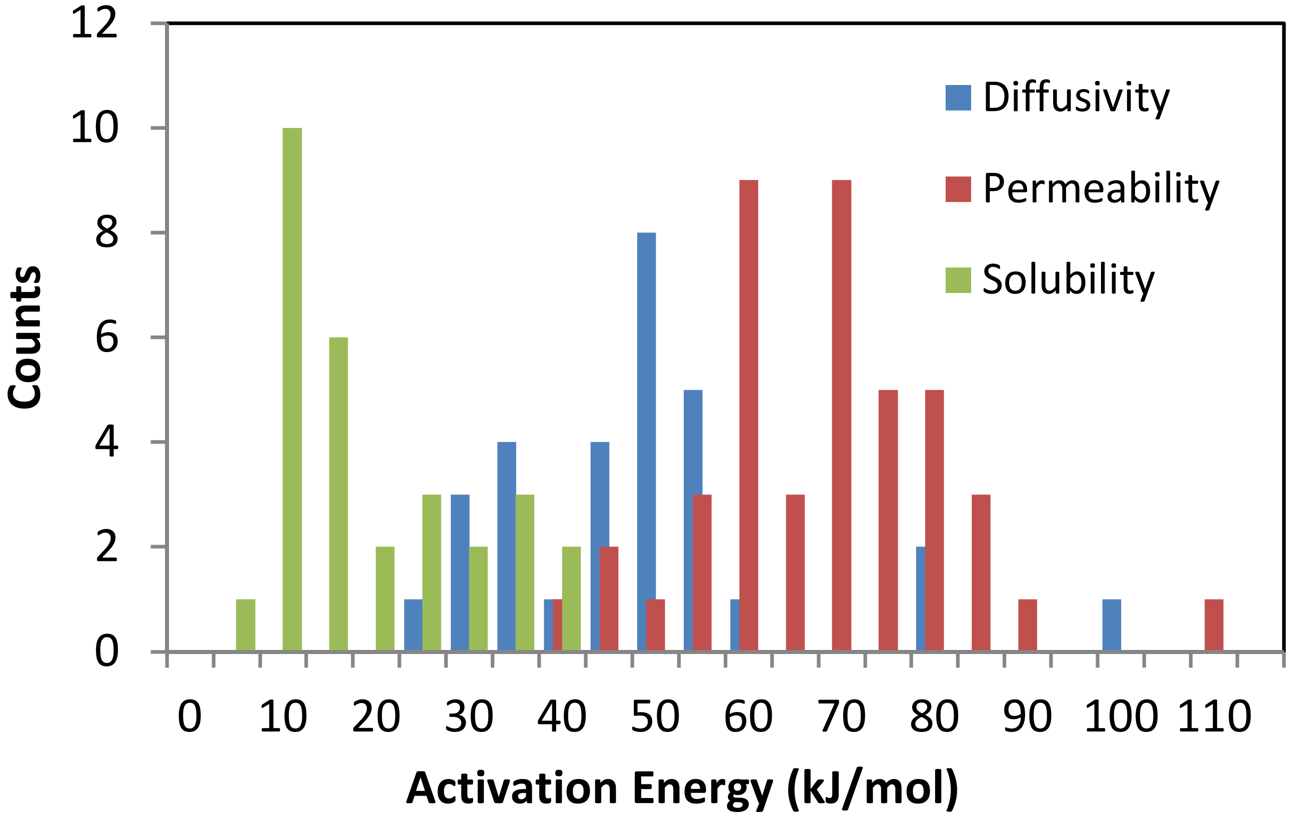
$$R_D \approx RH^n e^{\left(-\frac{Ea}{kT}\right)}$$

RH Dependence as a Taylor Series Expansion

- For n=1 to 5 results in ±2% variability for RH_{WA}.
- If the humidity dependence can be expressed as 5th order Taylor series expansion, then one does not need to be very concerned with the RH dependence of the degradation when determining RH_{WA}.
- If the humidity is set to represent the use environment, then experiments designed to predict durability do not need to test at different humidity levels which can significantly reduce the amount of testing needed to get relevant acceleration factors.

$\left[\frac{RH}{1-RH+\epsilon}\right]$? Or $e^{-b\cdot RH}$? Or RH^2 ? can be expressed as $\sim\sum_{n=0}^{5}\frac{a_n RH^n}{n!}$

Be Aware of studies that are Diffusion Limited

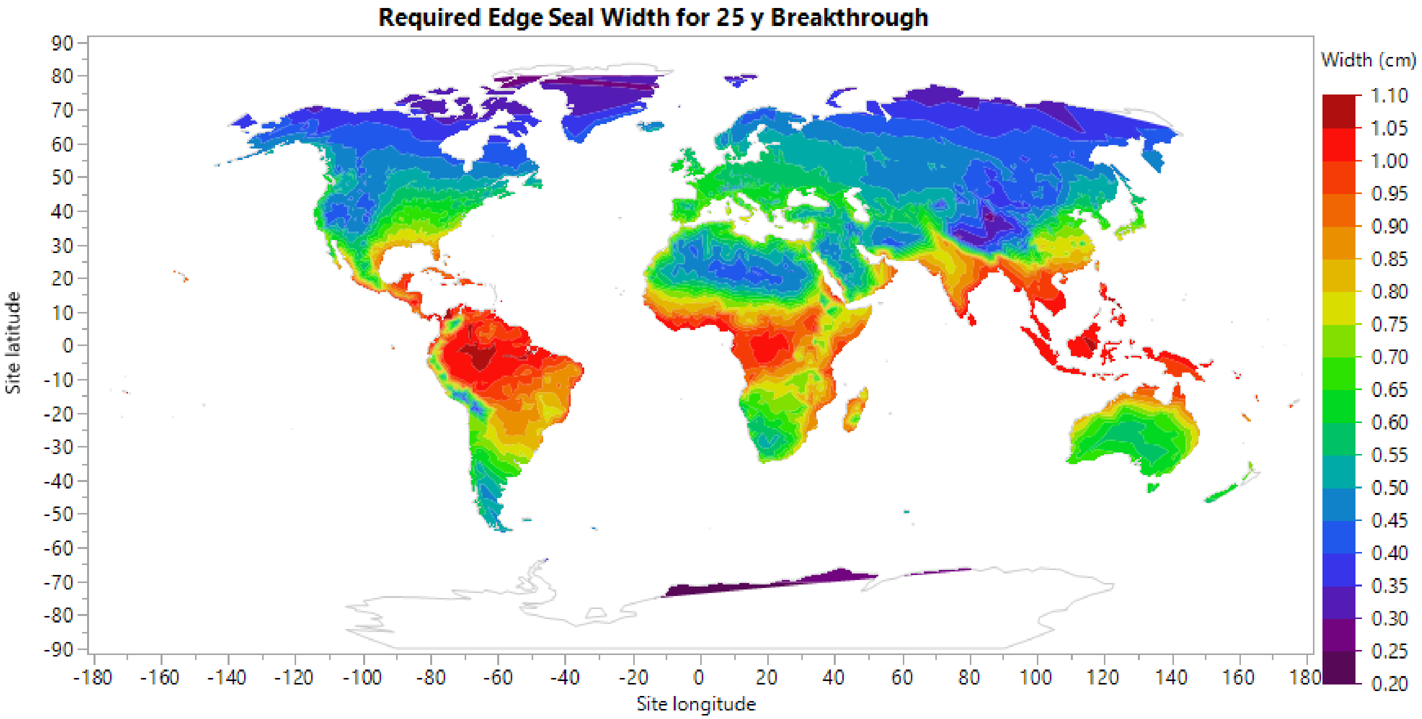


Histogram for moisture ingress activation energy for PV polymeric materials.

Watch out for publications where water or oxygen ingress is important and the activation energy for time to failure is around 40 kJ/mol or 50 kJ/mol.

Researchers will frequently mistakenly build samples that don’t fully equilibrate over the course of an experiment and assume the applied humidity is that of the chamber when the humidity is constantly changing or assume that moisture does not enter a package.

Edge Seals Can Keep Moisture out



- By measuring the moisture ingress rate on small samples, we were able to determine the relevant ingress parameters and extrapolate it to the world.
- If the application uses well designed edge seals, it may make sense to test samples in environments without water because they will not degrade in the field due to water ingress.

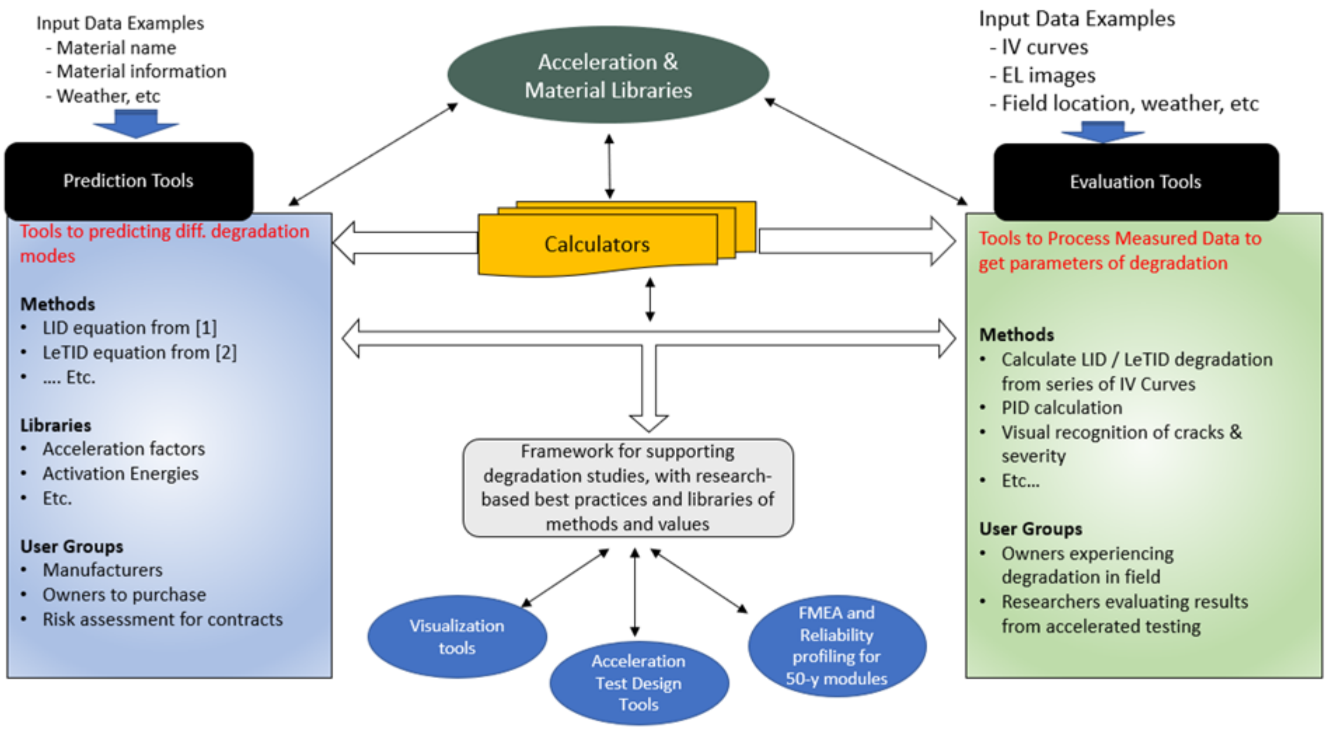
M. D. Kempe, D. Panchagade, M. O. Reese, and A. A. Dameron, "Modeling moisture ingress through polyisobutylene-based edge-seals," Progress in Photovoltaics: Research and Applications, vol. 23, no. 5, pp. 570-581, 2015, doi: 10.1002/pip.2465.
M. D. Kempe, D. L. Nobles, L. Postak, and J. A. Calderon, "Moisture ingress prediction in polyisobutylene-based edge seal with molecular sieve desiccant," Progress in Photovoltaics: Research and Applications, vol. 26, no. 2, pp. 93-101, 2018, doi: 10.1002/pip.2947.

Standards development and 50-year modules

- 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.
- This will be achieved by:
  - Learning how to test for all the major failure modes.
  - As much as possible test will be conducted on components with full size module testing being primarily used for qualification testing.
  - Empirically learning what processes work and do not work and fixing them.
  - Developing stress sequences that mimic very long term exposures.
  - Overdesigning components when the cost to do so is minimal.
  - Only the expensive to avoid weaknesses will be thoroughly studied and designed to last about 50 years.
  - It will not be achieved by a service life prediction study. That would require years of work on every bill of materials.

Industry Facing PV Degradation Prediction Tool and Degradation Database to Enable a 50 Year Life Module

- Searchable database of PV related degradation parameters.
- Online tool for running degradation calculations.
- Online visualization tool for communicating and understanding results.
- All Code available on GitHub.



Input Data Examples
- Material name
- Material information
- Weather, etc

Prediction Tools

Tools to predicting diff. degradation modes

Methods
- LID equation from [1]
- LeTID equation from [2]
- .... Etc.

Libraries
- Acceleration factors
- Activation Energies
- Etc.

User Groups
- Manufacturers
- Owners to purchase
- Risk assessment for contracts

Acceleration & Material Libraries

Calculators

Framework for supporting degradation studies, with research-based best practices and libraries of methods and values

Visualization tools

Acceleration Test Design Tools

FMEA and Reliability profiling for 50-y modules

Input Data Examples
- IV curves
- EL images
- Field location, weather, etc

Evaluation Tools

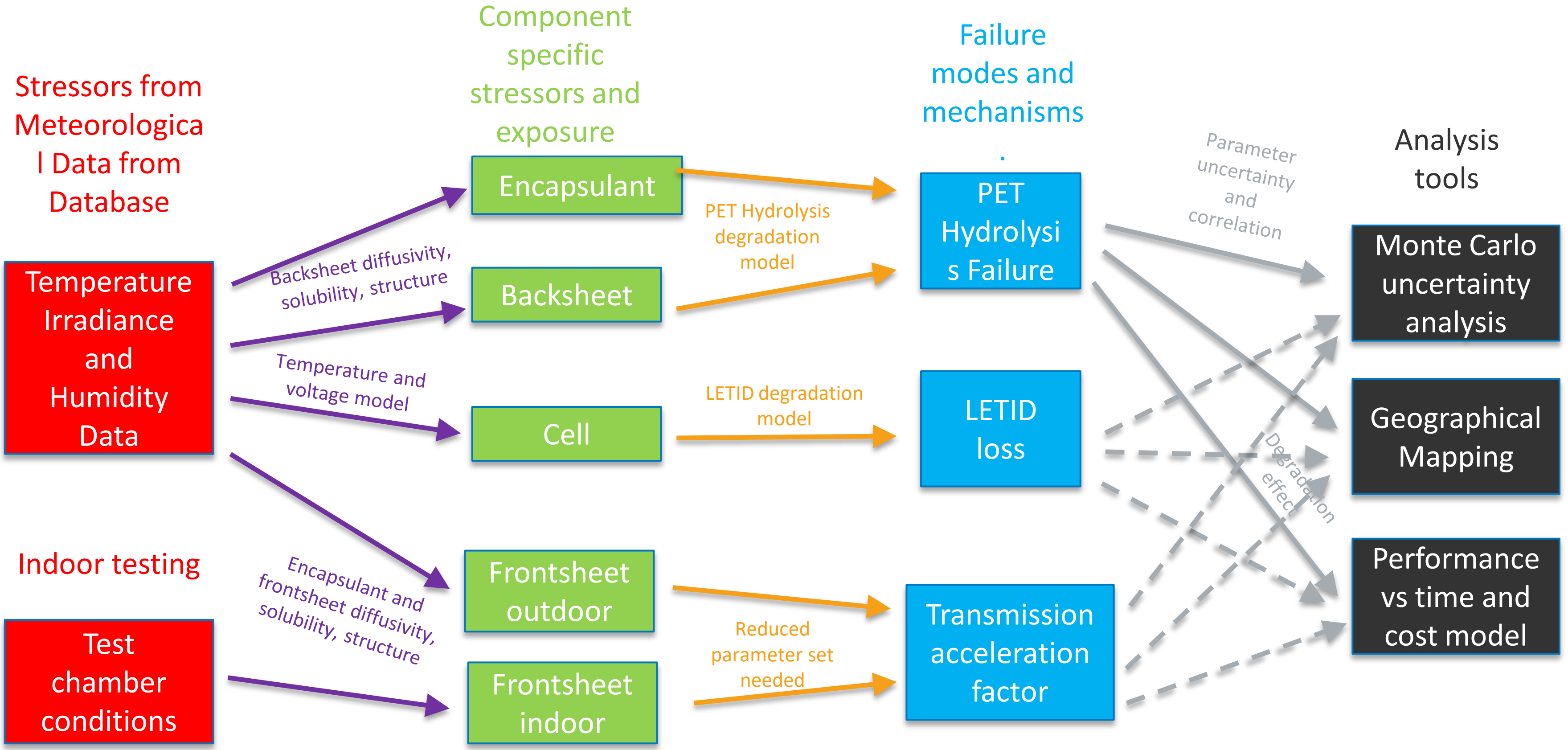
Tools to Process Measured Data to get parameters of degradation

Methods
- Calculate LID / LeTID degradation from series of IV Curves
- PID calculation
- Visual recognition of cracks & severity
- Etc...

User Groups
- Owners experiencing degradation in field
- Researchers evaluating results from accelerated testing

Schematic structure of the online tool for degradation calculations.

Block diagram of python code structure



Stressors from Meteorological Data from Database

Temperature Irradiance and Humidity Data

Indoor testing

Test chamber conditions

Backsheet diffusivity, solubility, structure

Temperature and voltage model

Encapsulant and frontsheet diffusivity, solubility, structure

Component specific stressors and exposure

Encapsulant

Backsheet

Cell

Frontsheet outdoor

Frontsheet indoor

PET Hydrolysis degradation model

LETID degradation model

Reduced parameter set needed

Failure modes and mechanisms

PET Hydrolysis Failure

LETID loss

Transmission acceleration factor

Parameter uncertainty and correlation

Degradation effect

Analysis tools

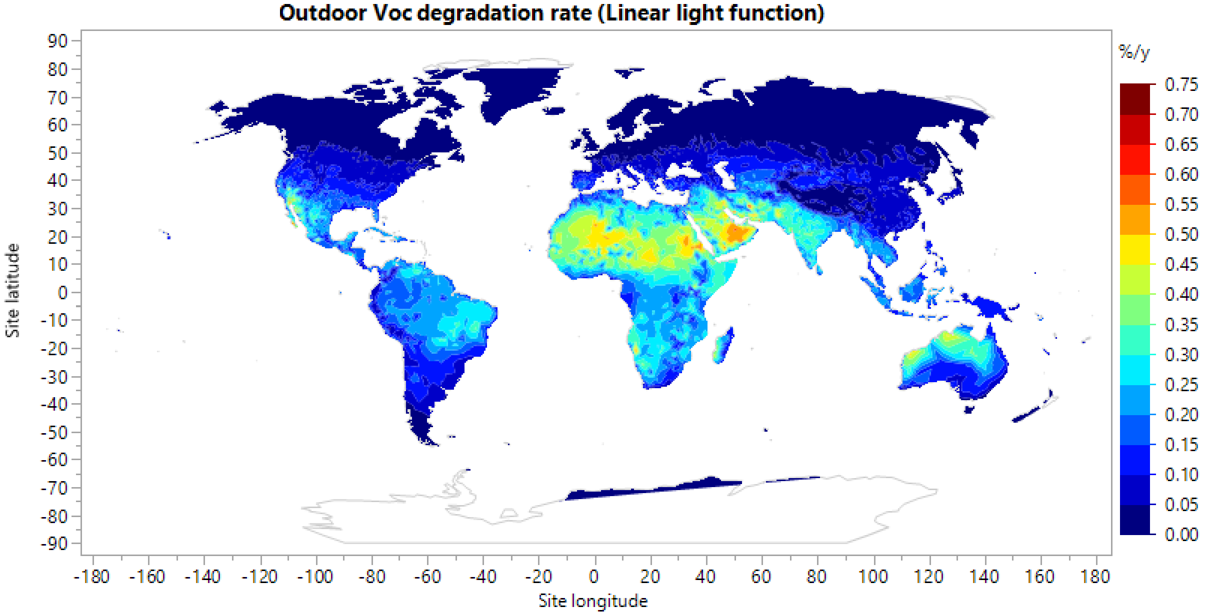
Monte Carlo uncertainty analysis

Geographical Mapping

Performance vs time and cost model

Example: Investigation of Interfacial Degradation in Glass/Glass PV Modules

- ***We will create an online tool that can be used to search for related degradation information and then utilize Python code to extrapolate to the field exposure. Then there will be visualization software to aid in the understanding of the results. Lastly, some components will be open for more input into calculations or to database information.***
- ***Creating a map like this will hopefully be a few minute process if your degradation equation is of a standard form.***



Taken from Xiao et al. [8]. Example of future output. World map visualization of PERC cell V_{oc} degradation using activation energy estimated by lab stress testing under illumination.

Summary

- Accelerated stress tests serve many purposes but only in very limited and focused situations are these actually service life prediction test.
- There are many pitfalls that are commonly done when interpreting accelerated stress tests. Even just saying a failure mode is relevant, and that a specific material/process is better than another requires substantial testing.
- Acceleration factors must be kept very low to have confidence in the relative performance of materials and processes.
- Stress test conditions should be designed to minimize the complexity of the testing, the uncertainty in the results, and to balance the effects relative to the use environment.

Questions?

PVSC 2023 Tutorials Survey

https://forms.gle/1VFccDmZmcSgnjaQA

Thank you for attending! Please help us keep improving

c.hages@ufl.edu

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Tutorial AM4: **Experimental Considerations for Estimating Degradation in PV Modules**

Instructor:

Michael D. Kempe, National Renewable Energy Laboratory, USA

Description

Carefully controlled laboratory experiments and measurements can enable the determination of acceleration factors suitable for extrapolation to durability and performance of a fielded PV module. 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. This course will explain how because of the wide range of acceleration factors 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.

In this tutorial we will discuss what the different purposes are for many of the accelerated stress tests used today. E.g., what is a qualification test, a highly accelerated stress test, a rank ordering test, or a service life prediction test. We will discuss how one can understand the relationship between test results and expected field performance. A single accelerated stress test condition cannot duplicate outdoor exposure for all possible degradation pathways; therefore, one must use targeted evaluation of material properties at different stress levels to determine the relevant acceleration factors and fit it to a model. We will also discuss how to interpret the results of experiments understanding what is relevant/not relevant, or not evaluated in a test. There are many common error people make in their test interpretations because they push the stress levels to be too harsh. This creates biases and can mask the relevant failure modes and mechanisms or will erroneously lead one to over design materials against things that aren’t relevant. Several case studies will be presented to illustrate appropriate interpretation of accelerated stress testing results.

Dr. Michael D. Kempe is a Senior Scientist in the PV Module Reliability Group at the National Renewable Energy Laboratory, where he studies the factors affecting the longevity of photovoltaic cells and modules. This includes both modelling and measuring moisture ingress into PV modules and studying its effect on polymer adhesion, device performance and component corrosion. This work also includes the development of a technique for measure the moisture permeation rates in films down at levels around 10^{-6} g/m^2/day and the evaluation of edge seal materials. He is also studying the effects of UV radiation and heat on the mechanical, chemical, and electrical stability of PV packaging components. This effort is tied into creating better qualification tests that more accurately assess safety and are better predictors of long-term durability, including development of the solder bump test for backsheet evaluation. He has been a central participant in the development of many IEC standards including those for safety, durability, backsheets, retesting, encapsulants, and high temperature exposure. Dr. Kempe graduated summa cum laude with an undergraduate degree in Chemical engineering from the University of Utah and from the California Institute of Technology with a Ph.D. in Chemical Engineering. In addition to working at NREL, he has served on the board of directors for CORE electric cooperative for 16 years. This is a large coop with over 170,000 meters. Here he has shaped policy working to modernize operations paving the way for integration of more renewable energy.