NATIONAL RENEWABLE ENERGY LABORATORY

1977 - 2017





What Are Appropriate Accelerated Tests For New Module Components?

Ingrid Repins (NREL Reliability Group)

Duramat Workshop
May 22, 2017

Appropriate Accelerated Tests For New Module Components

I have a new material for PV modules.

Will it last 25 years?

How about 50 years?

Will 1000 hours of damp heat give me the answer?

Outline

1. Standard PV module accelerated tests for design qualification
   - Origins, purpose, limitations

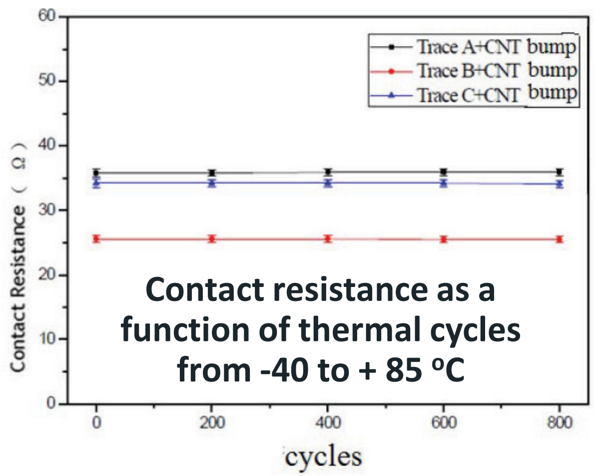
2. Steps toward predictive model-based accelerated tests (with an example)

Origins of Standard PV Module Accelerated Tests

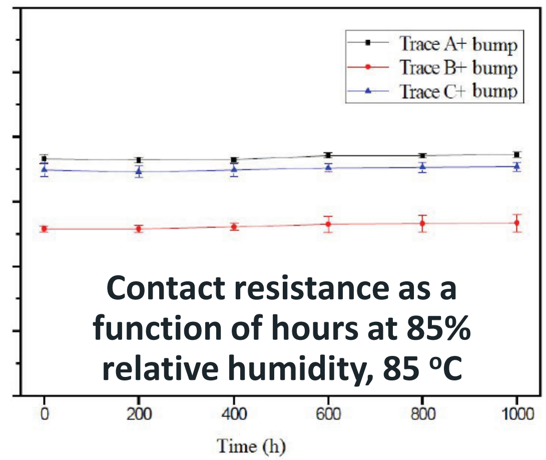
In the literature, a lot of PV materials and structures are subjected to similar accelerated tests, for example……

"Reliability of Carbon Nanotube Bumps for Chip on Glass Application"

Fan et al., IEEE 2014



Contact resistance as a function of thermal cycles from -40 to + 85 °C



Contact resistance as a function of hours at 85% relative humidity, 85 °C

MLPE unit	Time to failure (hours)
M1-1	Did Not Fail
M1-2	Did Not Fail
M2-1	Did Not Fail
M2-2	Did Not Fail
M3-1	Worked up to 710 cycles

"Accelerated Testing of Module Level Power Electronics for Long-Term Reliability"

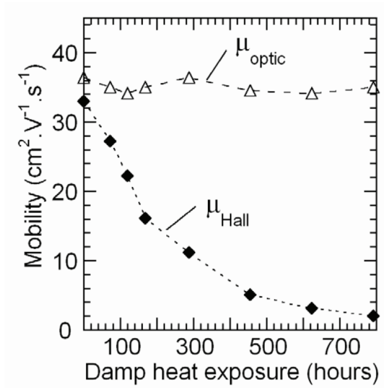
Flicker et al., IEEE JPV 2017

Thermal cycles from -40 to + 85 °C

"Humid Environment Stability of LPCVD ZnO:B"

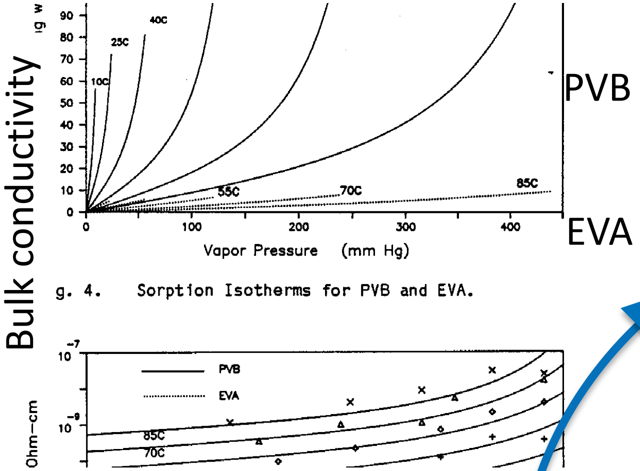
Steinhauser et al., TSF 2011

85% RH, 85 °C

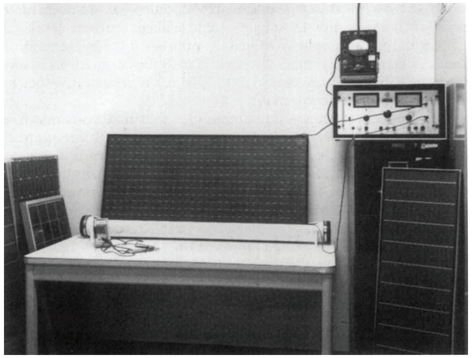


…….Why? What is special about these conditions?

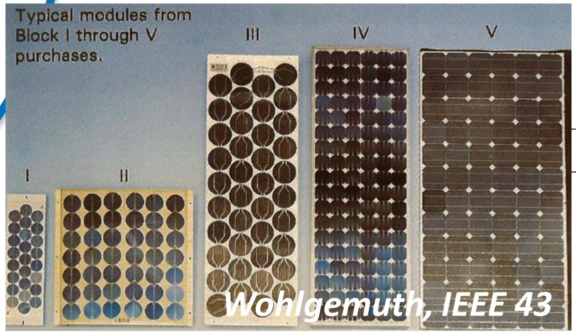
Origins of Standard PV Module Accelerated Tests



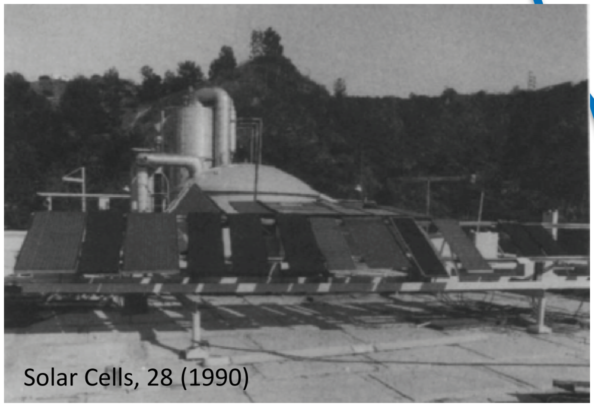
Define associated accelerated tests



Design modules to pass tests



Deploy modules



Identify failures

Jet Propulsion Laboratory executed a series of "block buys" in 1975-1986

Origins of Standard PV Module Accelerated Tests

Test	Block I	Block II	Block III	Block IV	Block V
Thermal Cycles	100 -40 to +90C	50 -40 to +90C	50 -40 to +90C	50 -40 to +90C	200 -40 to + 90C
Humidity (humidity/freeze)	70C,90% 68 hrs	5 cycles 40 C, 90%RH to -23 C	5 cycles 40 C, 90%RH to -23 C	5 cycles 54C, 90%RH to -23 C	10 cycles: 20 h at 85 C / 85% RH, 4 h excursion to -40°C
Hot Spot (intrusive)					3 cells 100 hrs
Mechanical Load		100 cycles ± 2400 Pa	100 cycles ± 2400 Pa	10000 ± 2400 Pa	10000 ± 2400 Pa
Hail				9 impacts ¾" –45 mph	10 impacts 1" – 52 mph
High Pot		<15 μA 1500 V	< 50 μA 1500 V	< 50 μA 1500 V	< 50 μA 2*Vs+1000

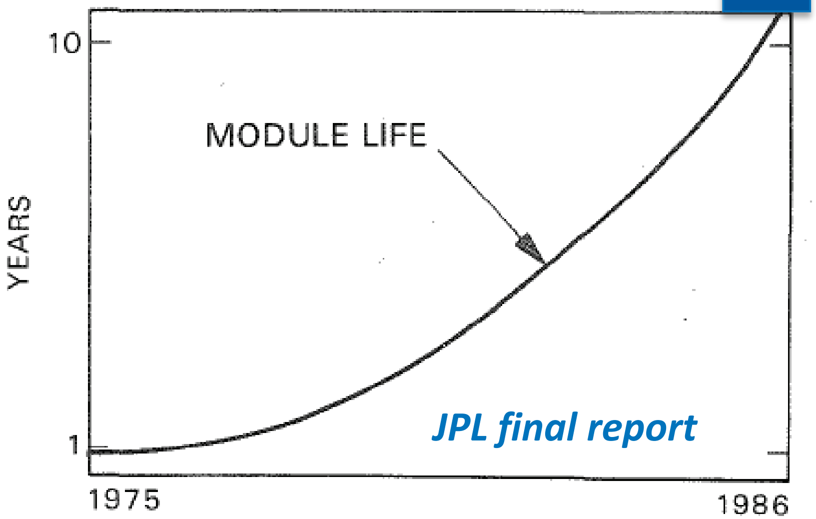
Aspects of these test conditions look familiar from today's literature and standards.

Origins and Success of Standard PV Module Accelerated Tests

Incorporation of these accelerated tests and related work into IEC 61215 (design qualification) and IEC 61730 (safety) standards has resulted in typical performance warranties around 25 years (and climbing).

IEC 61215 includes 1,000 hours at 85% RH, 85 °C, 200 thermal cycles from -40 to + 85 °C, humidity freeze from -40 to + 85 °C at 85% RH, and more, for a total of 19 tests.

The tests developed in the block buy program increased deployed module lifetime dramatically.



Typical module lifetimes were less than 1 year but are now estimated to be greater than 10 years. (Ten-year warranties are now available.)

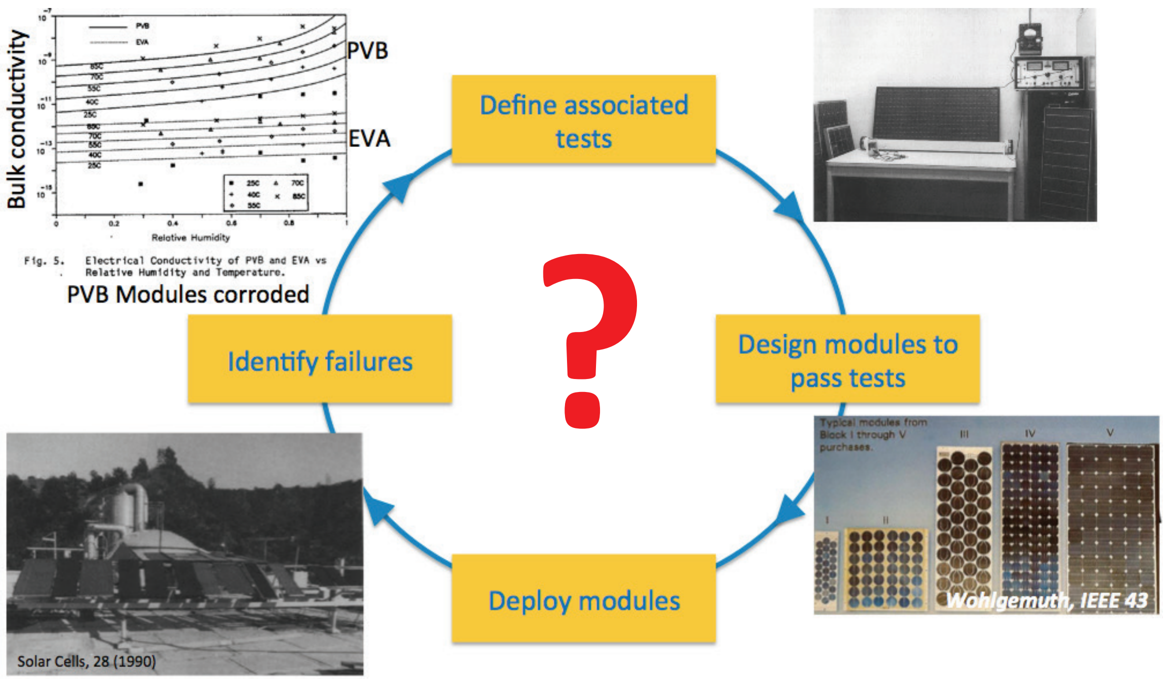
Limitations of Standard PV Module Accelerated Tests

So, if my new component or material passes those 19 tests, it's good for 25 years, right?

No:

- The tests in the standards screen for failure mechanisms in the types of products for which data were gathered.
- New materials and structures may have different failure mechanisms and acceleration factors.
- The tests in the standards screen for early (first few years of product life) failures, similar to the timeline of JPL block buy study.
- They do not predict quantitatively (10 years vs. 15 years)

Can I use a JPL block buy approach?

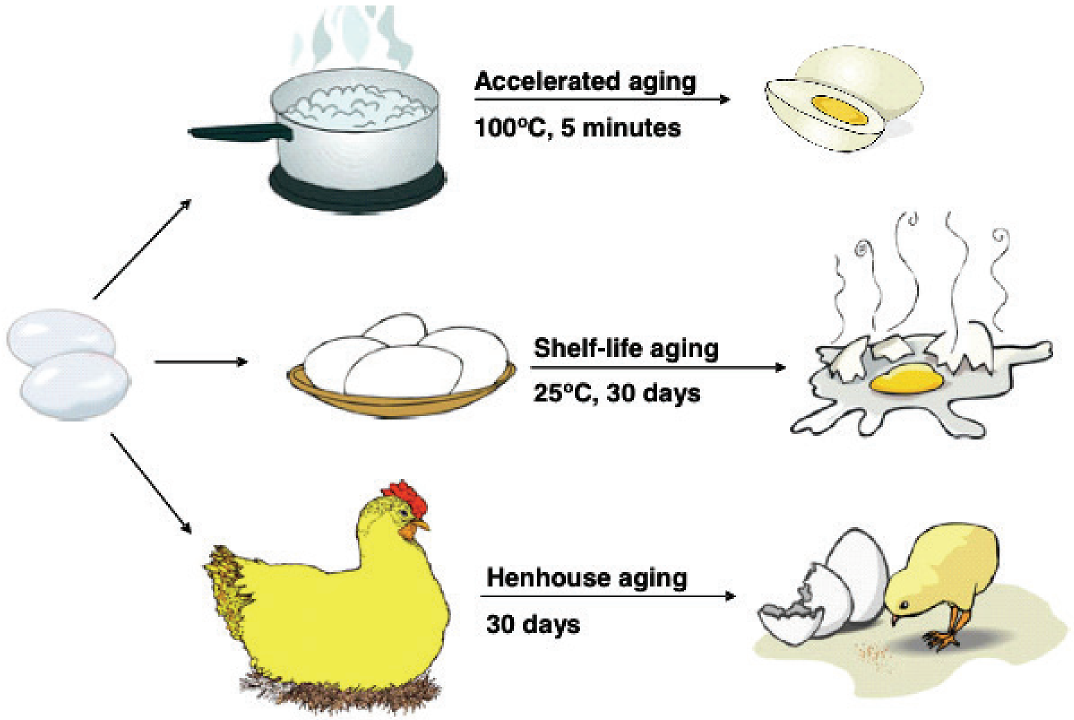


- Only if deployed time to failure is much shorter than development cycle.
- With targeted product lifetimes in the range of 25 to 50 years, this approach is practical only in early development stages.
- Can be useful early in development cycle for identifying failure modes associated with new material or component.

Where to Go From Here for Accelerated Tests on New Material

Can I just increase stress levels or times during accelerated tests?

Maybe. Possible issues:

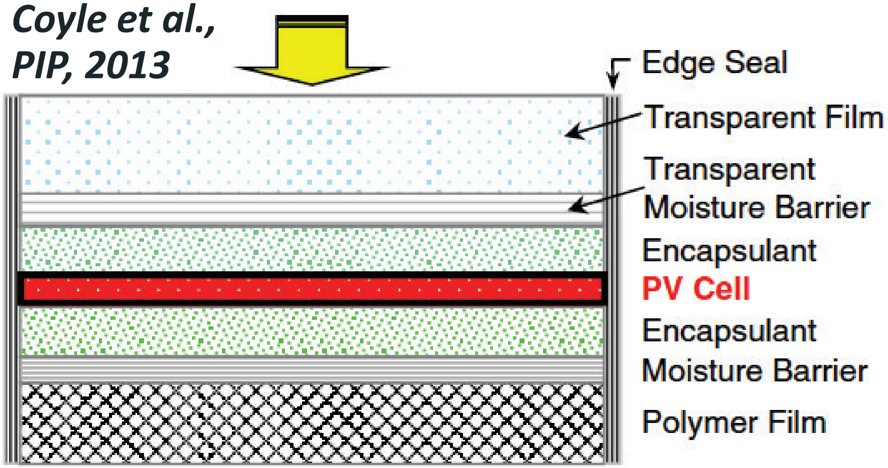


- You might apply the right stress, but accelerate an irrelevant process
- Your new material may have a failure mechanism that requires a new stress or combination of stresses
- The results are still not quantitatively related to product lifetime

Steps for Predicting Degradation or Failure Rate Via Accelerated Testing

1. Identify failure or degradation mechanism
2. Hypothesize physical model
3. Define accelerated tests
4. Verify the tests reproduce failure and fit model
5. Define use environment
6. Apply model, including uncertainty

Coyle et al., PIP, 2013



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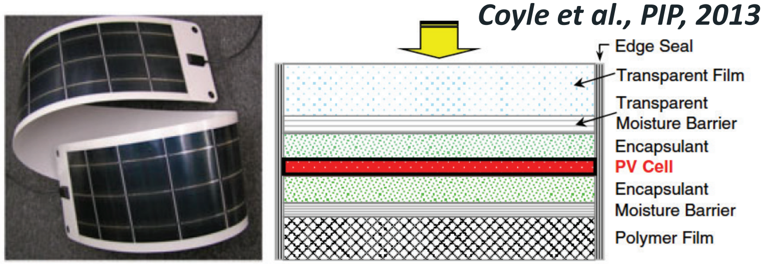
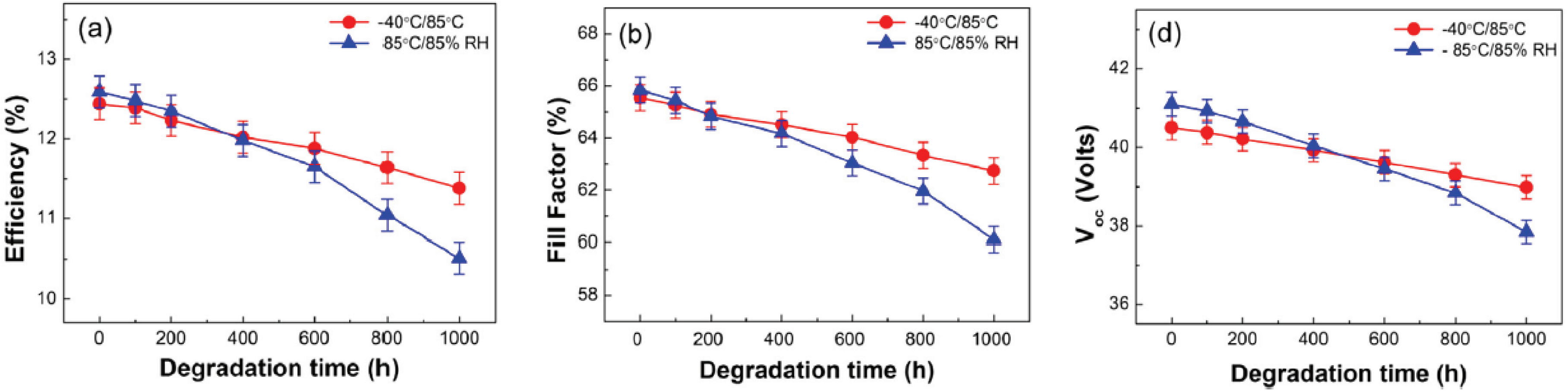


Example:

For CIGS devices exposed to damp heat, efficiency, voltage, and fill factor decrease.

Lee et al., CAP, 2015



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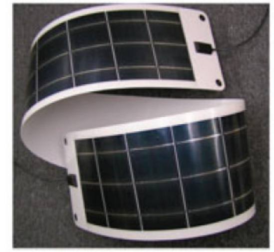
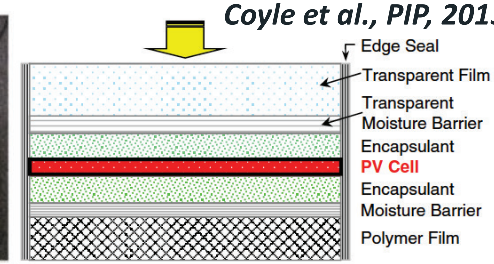
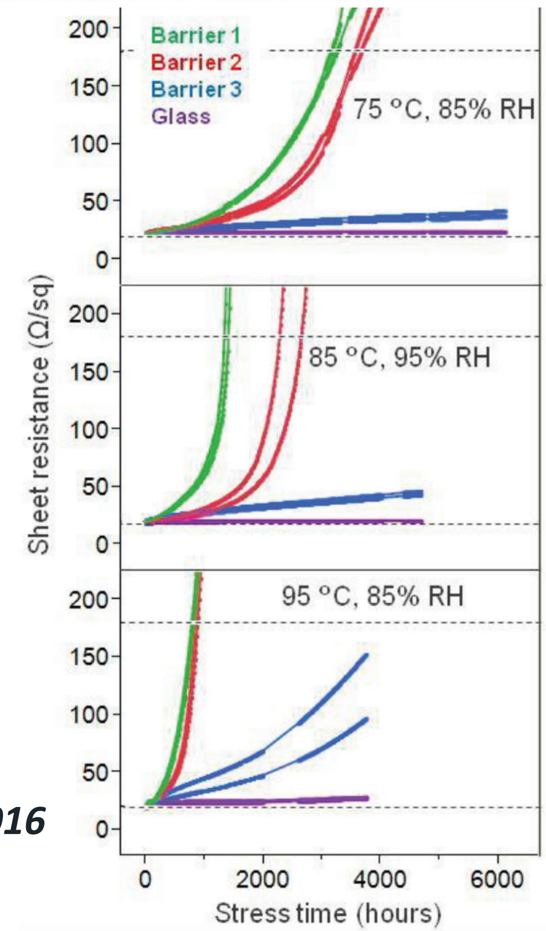




Coyle et al., PIP, 2013

Example:

The effect is accelerated by higher relative humidity and T.



Cao et al., IEEE, 2016

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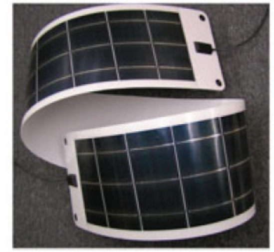
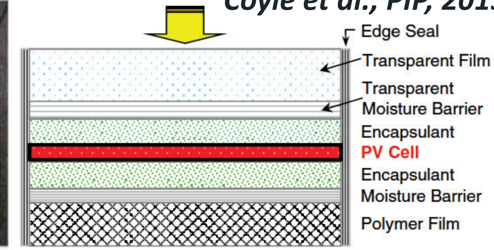


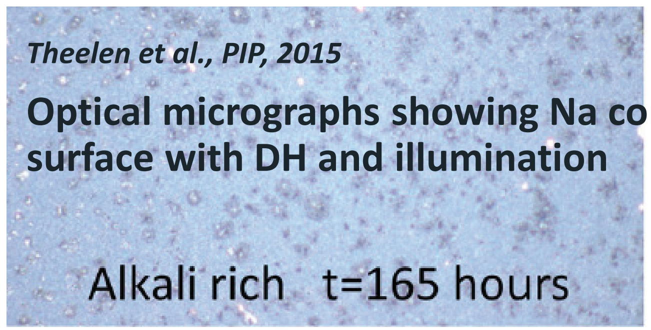


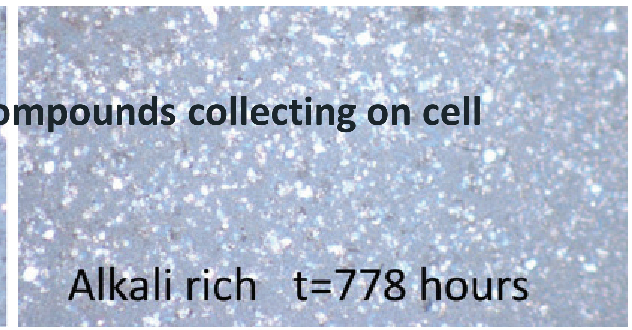
Example:

- Diffusion through moisture barrier
- Diffusion through and saturation of encapsulant
- Device degradation through reaction of water with transparent conducting oxide and Na

Theelen et al., PIP, 2015

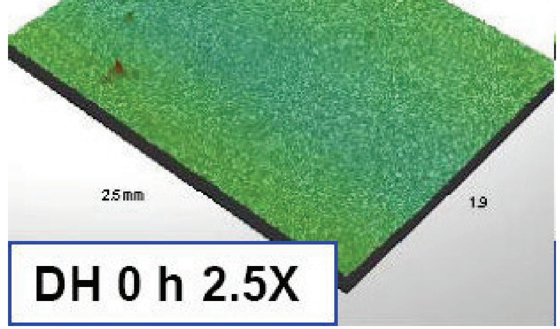
Optical micrographs showing Na compounds collecting on cell surface with DH and illumination

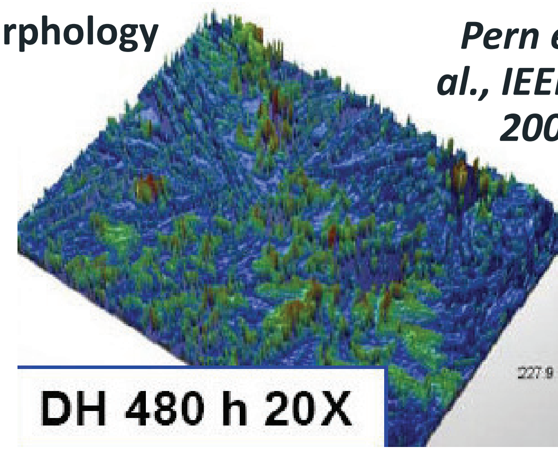




Optical micrographs showing ZnO morphology

Pern et al., IEEE, 2008





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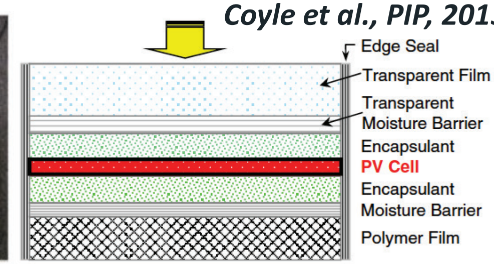

Example:

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- Diffusion thro and saturatio encapsulant
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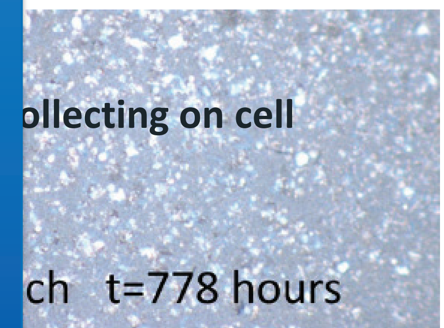
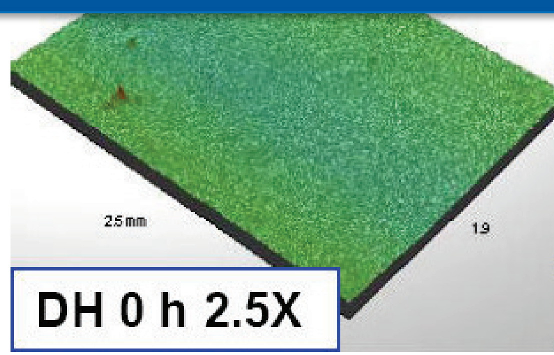
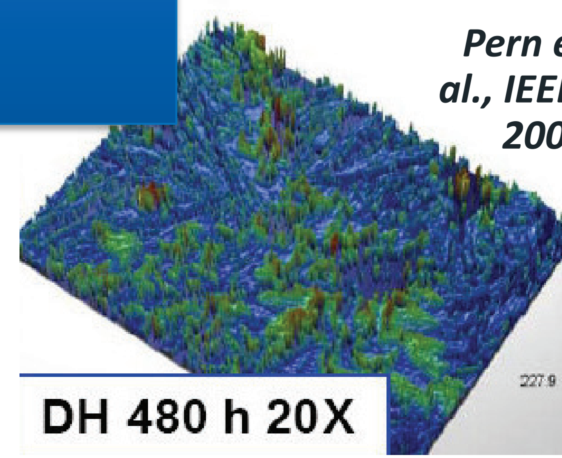
Note: Performing just step one involves several papers. Predicting degradation rates is a lot of work, even just for one failure mechanism!







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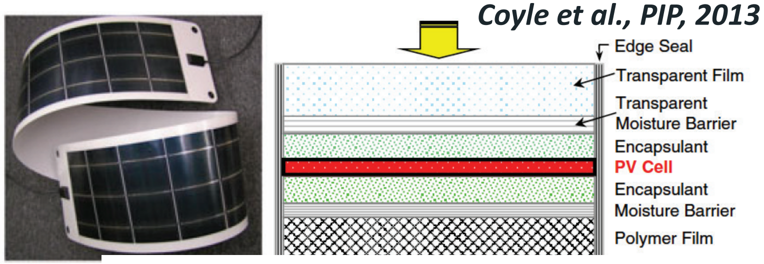
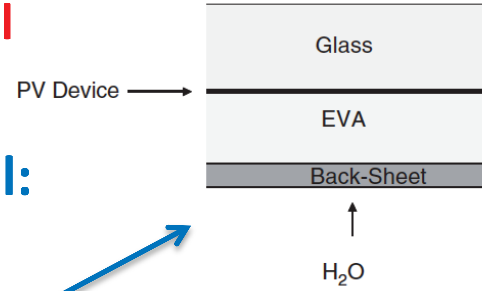
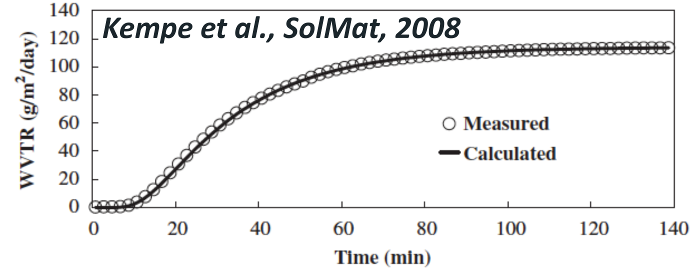


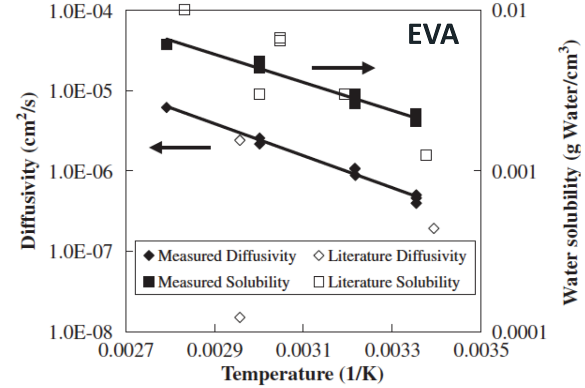
2. **Hypothesize physical model**





Example – Multi-step model:

- Fickian diffusion in front sheet and encapsulant
- Arrhenius T dependencies of solubilities and diffusivities
- Form of cell reaction with water at cell surface based on work in microelectronic packaging.



Klinger et al., QREI, 1991
Brunauer et al., JACS, 1938

$$R_D = k_o e^{\left(\frac{-E_{a,deg}}{RT}\right)} \left[\frac{RH_{cell}}{1 - RH_{cell} + \varepsilon}\right]$$

Note: There is not always a single activation energy.

Steps for Predicting Degradation or Failure Rate Via Accelerated Testing

1. **Identify failure or degradation mechanism**
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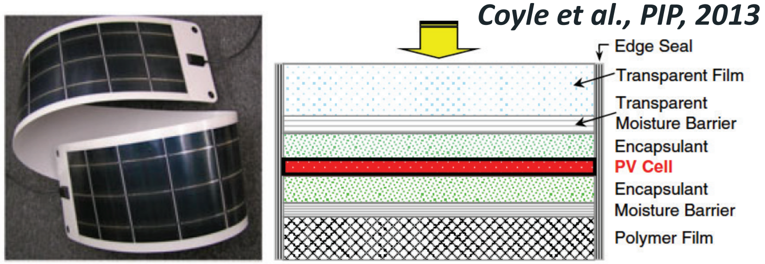
3. **Define accelerated tests**

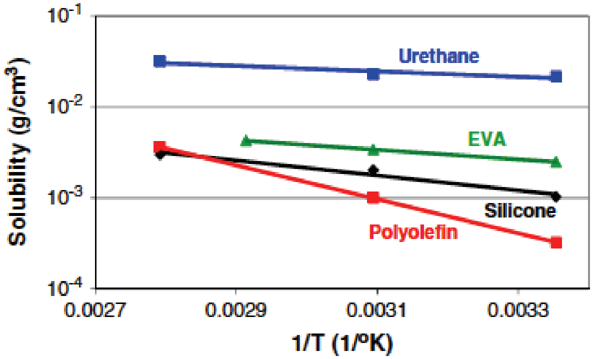
Example:

Varying exposures of temperature, time, and humidity to

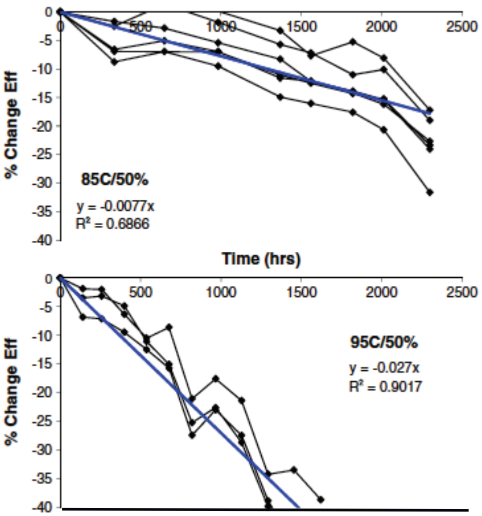
- **Define diffusion and solubility of moisture in packaging materials as a function of T.**
- **Define device degradation constants as a function of RH and T**
- **Document behavior of module in accelerated test**

Coyle et al., PIP, 2013





Encapsulants



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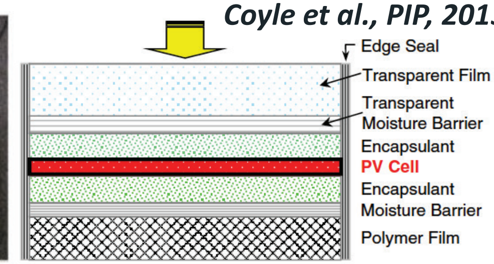
4. **Verify the tests reproduce failure and fit model**

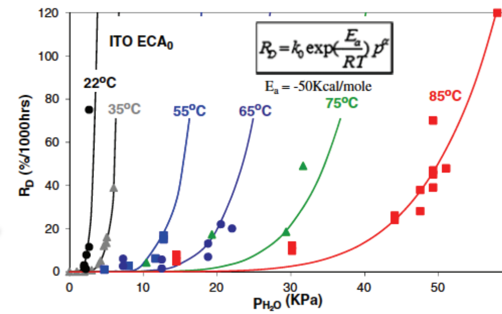
Example – Verified that:

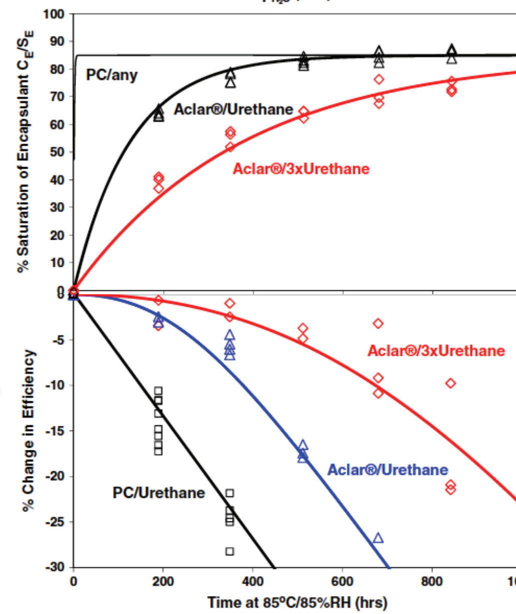
- Degradation of bare devices as a function of RH and T fits model
- Saturation of package with water (measured by weight) , as a function of RH, T, and package type fits model.
- Degradation of module as a function of RH, T, and package type fits model

Outdoor exposure was underway at time of publication.

Coyle et al., PIP, 2013







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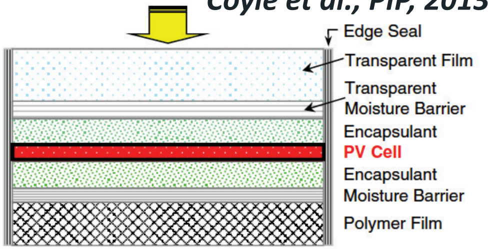
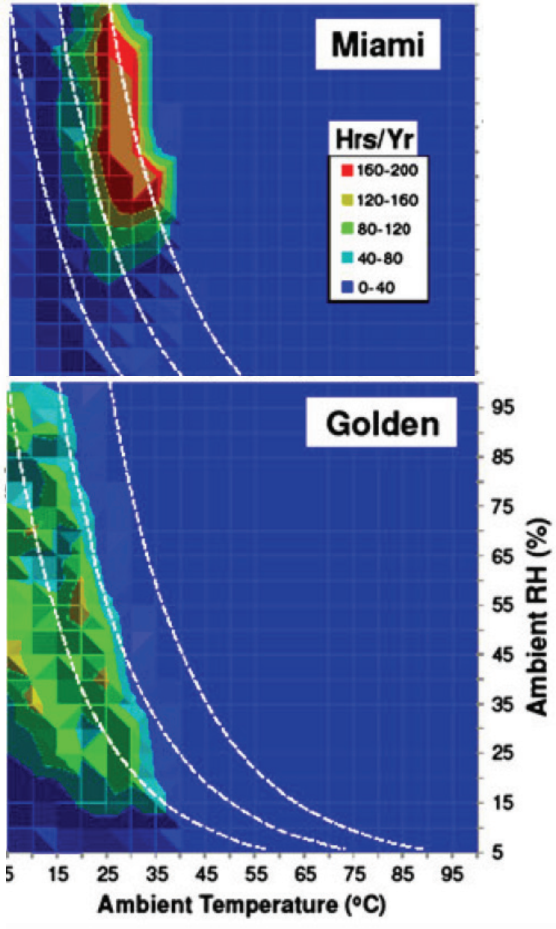
4. **Verify the tests reproduce failure and fit model**
5. **Define use environment**
   - **Historical weather file for the specific or worst-case location**
   - **Relationship between the ambient weather conditions and the actual product exposure. (e.g. effect of mounting configuration on temperature)**

Coyle et al., PIP, 2013





- **Meteorological data describing all important stress factors.**
- **Coyle: Hours at different RH and T for various locations**
- **On-line data sets can help (e.g. https://nsrdb.nrel.gov/)**

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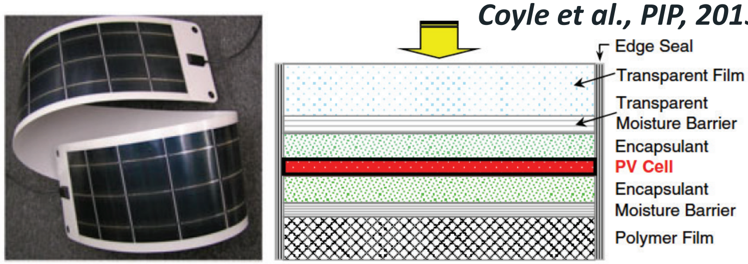
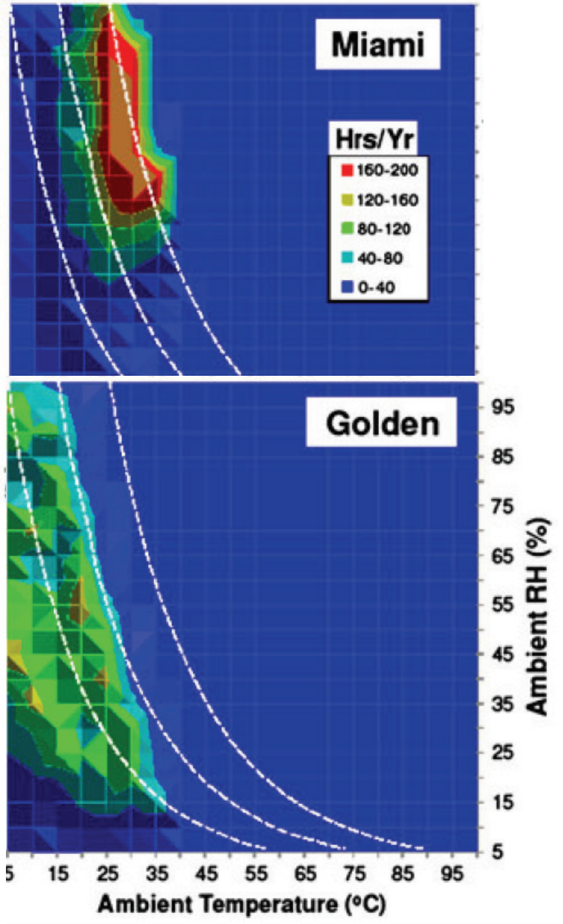
Coyle et al., PIP, 2013

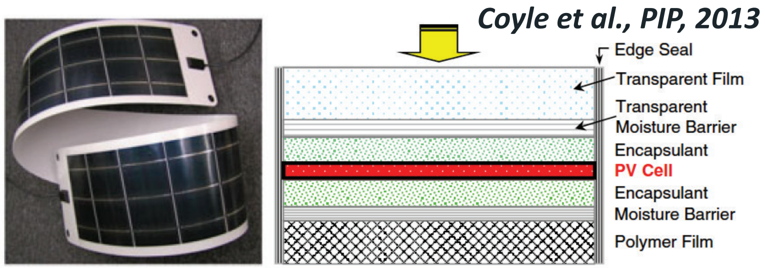




Example:

- Coyle used heat transfer model for flexible model on roofing membrane.
- Other models for relating ambient and module T in literature. (e.g. King et al., SAND2004-3535, 2004.)

Steps for Predicting Degradation or Failure Rate Via Accelerated Testing



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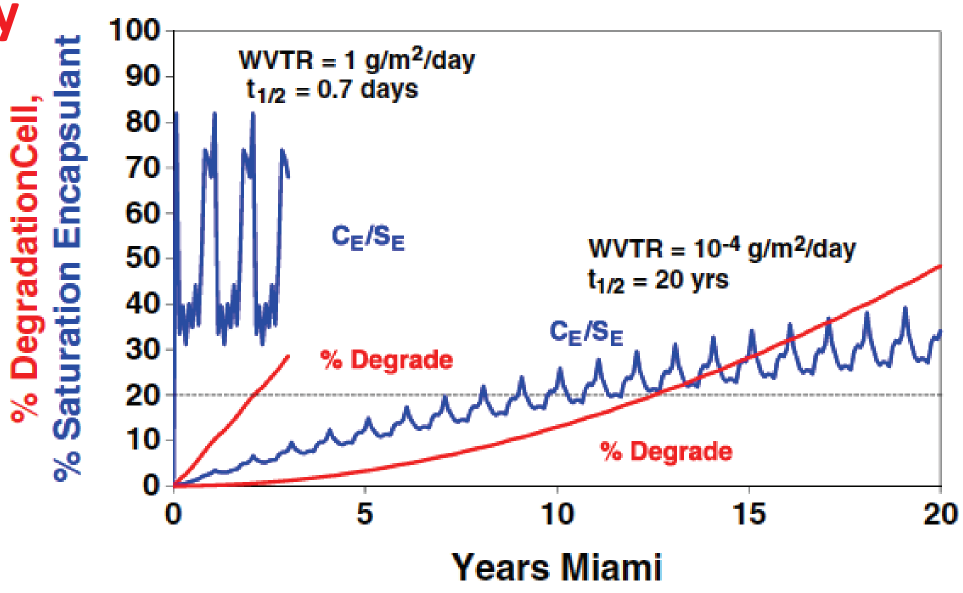
6. **Apply model, including uncertainty**

Example:

- **Result is predicted encapsulant saturation and module degradation from moisture ingress as a function of time for different package types and use climates.**
- **Still work to do, even on this one failure mechanism:**
  - **Uncertainty not published**
  - **Constants will be different for different TCO, contact type, alkali content, etc.**



Conclusions: Accelerated Tests on New Materials

- Accelerated tests described in IEC 61215 (for PV module design qualification) have been applied to a variety of PV structures or components.
- The tests are useful for
  - Screening for known early-life failures in field-tested PV modules
  - Identifying possible failure mechanisms in new materials or components
- The tests
  - Do not provide quantitative prediction of failure rates
  - Do not guarantee service life to warranty period
  - May not screen for early life failures in new module or component designs
- To predict failure or degradation rate for a new design:
  1. Identify failure or degradation mechanism
  2. Hypothesize physical model
  3. Define accelerated tests
  4. Verify the tests reproduce the failure and fit the model
  5. Define use environment
  6. Apply model, including uncertainty
- Each model-based prediction for just one failure mechanism on one module design involves a lot of work.
- There is fertile ground for much new work in PV related to quantitative prediction of degradation or failure rates.