What Are Appropriate Accelerated Tests For New Module Components?

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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?
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

“Accelerated Testing of Module Level Power Electronics for Long-Term Reliability”
Flicker et al., IEEE JPV 2017

“Humid Environment Stability of LPCVD ZnO:B”
Steinhauser et al., TSF 2011

85% RH, 85 °C

Thermal cycles from -40 to + 85 °C

........Why? What is special about these conditions?
<table>
<thead>
<tr>
<th>Test</th>
<th>Block I</th>
<th>Block II</th>
<th>Block III</th>
<th>Block IV</th>
<th>Block V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Cycles</td>
<td>100 -40 to +90°C</td>
<td>50 -40 to +90°C</td>
<td>50 -40 to +90°C</td>
<td>50 -40 to +90°C</td>
<td>200 -40 to +90°C</td>
</tr>
<tr>
<td>Humidity (humidity/freeze)</td>
<td>70°C, 90% 68 hrs</td>
<td>5 cycles 40°C, 90%RH to -23°C</td>
<td>5 cycles 40°C, 90%RH to -23°C</td>
<td>5 cycles 54°C, 90%RH to -23°C</td>
<td>10 cycles: 20 h at 85°C / 85% RH, 4 h excursion to -40°C</td>
</tr>
<tr>
<td>Hot Spot (intrusive)</td>
<td></td>
<td></td>
<td></td>
<td>3 cells 100 hrs</td>
<td></td>
</tr>
<tr>
<td>Mechanical Load</td>
<td>100 cycles ± 2400 Pa</td>
<td>100 cycles ± 2400 Pa</td>
<td>10000 ± 2400 Pa</td>
<td>10000 ± 2400 Pa</td>
<td></td>
</tr>
<tr>
<td>Hail</td>
<td></td>
<td></td>
<td>9 impacts ¾” –45 mph</td>
<td>10 impacts 1” – 52 mph</td>
<td></td>
</tr>
<tr>
<td>High Pot</td>
<td>&lt;15 µA 1500 V</td>
<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 1500 V</td>
<td>&lt; 50 µA 2*Vs+1000</td>
<td></td>
</tr>
</tbody>
</table>

Aspects of these test conditions look familiar from today’s literature and standards.
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.
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.
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
1. Identify failure or degradation mechanism
   - What measurable property changes?
   - What stress conditions contribute?
   - What physical processes occur?

Example:

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

Lee et al., CAP, 2015
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Example:
The effect is accelerated by higher relative humidity and T.
Steps for Predicting Degradation or Failure Rate Via Accelerated Testing

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   - What physical processes occur?

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

Alkali rich $t=165$ hours

Optical micrographs showing ZnO morphology

Pern et al., IEEE, 2008

DH 0 h 2.5X

DH 480 h 20X
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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

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.

Note: There is not always a single activation energy.
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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.
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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.
Steps for Predicting Degradation or Failure Rate Via Accelerated Testing

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2. Hypothesize physical model
3. Define accelerated tests
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)

   - 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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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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2. Hypothesize physical model

3. Define accelerated tests

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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:
     o Uncertainty not published
     o 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.