Statistical Modeling of Photovoltaic Reliability Using Accelerated Degradation Techniques

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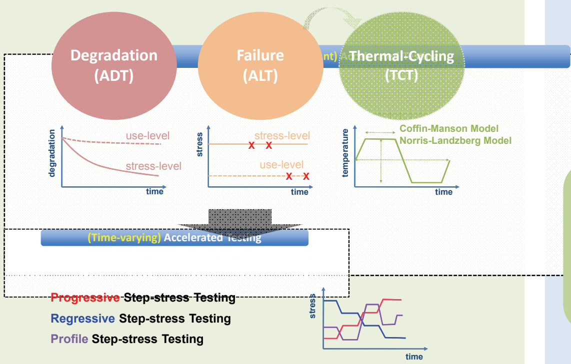
Introduction & Objective

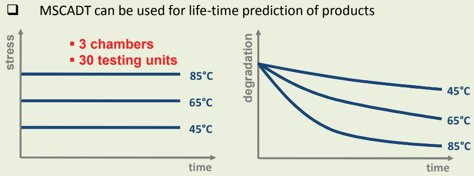
- Introduce cutting-edge life-testing technique, accelerated degradation testing (ADT), for PV reliability testing
- Apply two common types of ADT for life-time prediction of PV modules: multiple constant-stress ADT (MCSADT) and step-stress ADT (SSADT)
- Develop statistical models for use of SSADT with the thermal-humidity stress condition through the cumulative damage model (CDM)
- Provide quantitative models for prediction of PV module life-time including mean-time-to-failure (MTTF), warranty time and failure/degradation rates
- Estimate accelerated testing parameters, such as activation energy, acceleration factors, upper limit condition of stress via statistical inference procedure

Accelerated Testing



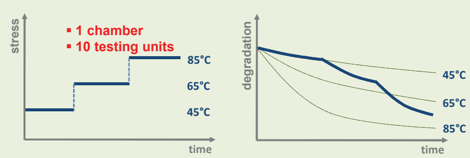
Multiple Constant-Stress ADT (MCSADT)

- The accelerated life testing (ALT) technique may offer little help for high reliable products which are not likely to fail during a rather short period time
- ADT collects the degradation data instead of failure data when it is more difficult to obtain sufficient failure data for ALT
- Single constant-stress testing (e.g, Damp-Heat Test) can be used for qualification testing with a specific durability criteria
- MSCADT can be used for life-time prediction of products



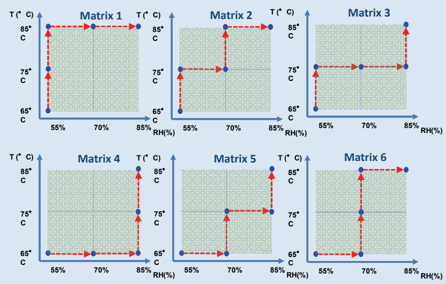
Step-Stress ADT (SSADT)

- Step-stress testing is one of the most basic time-varying stress tests. In a step-stress test, multiple samples in one or more sets are exposed to several stress conditions over time.
- Step-stress testing is an advanced reliability testing technique for high reliability products
  - **Economical:** suitable for limited test facility and condition
  - **Flexible:** useful for new developing products where there is not enough knowledge for test conditions
- SSADT can be constructed based on the cumulative damage model (CDM), which assumes that the remaining test units are failed according to the cumulative density function of current stress level regardless of the history on previous stress levels.



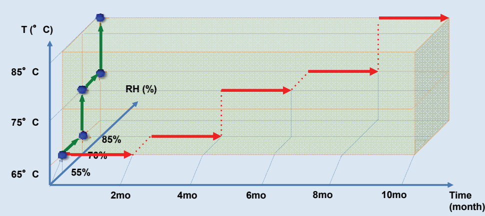
Statistical Models for SSADT

Test Matrix



- The thermal-humidity condition
  - Temperature (T): 3 levels (65°C, 75°C, 85°C)
  - Relative Humidity (RH): 3 levels (55%, 70%, 85%)
  - **No interaction** between T and RH
- 6 possible test matrices can be considered for the SSADT plan

Test Design



- This plot depicts a test design based on "Test Matrix 5" which has five stress levels
  - Level 1 (s_1): 65°C & 55%RH
  - Level 2 (s_2): 65°C & 70%RH
  - Level 3 (s_3): 75°C & 70%RH
  - Level 4 (s_4): 75°C & 85%RH
  - Level 5 (s_5): 85°C & 85%RH

Degradation Model

Stage 1: Defining a degradation pattern

- Linear: $L(t)=a\cdot t+b(s)$
- Exponential: $L(t)=b(s)\cdot \exp[a\cdot t]$
- Power: $L(t)=b(s)\cdot t^a$
- Logarithmic: $L(t)=a\cdot \ln t+b(s)$
- And some used: $L(t)=\exp[-b(s)t^a]$ (Tseng and Wen, 2000)
  $L(t)=\left(1+b(s)\cdot t^a\right)^{-1}$ (Mitsuo, 1991)

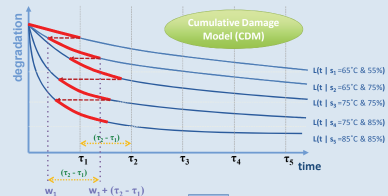
Stage 2: Defining a physical model for stress

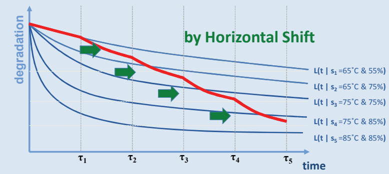
- Temp: $b(s;\ T)=\exp\left(c-\frac{E_a}{k\cdot(273+T)}\right)$
- Temp & RH: $b(s;\ T,RH)=c\cdot\exp\left(-\frac{d}{RH}\right)\cdot\exp\left(\frac{E_a}{k\cdot(273+T)}\right)$
  $b(s;\ T,RH)=c\cdot\exp(-d\cdot RH)\cdot\exp\left(\frac{E_a}{k\cdot(273+T)}\right)$
- Other two stresses
- Three stresses

SSADT Model

- Expected degradation for SSADT

$$L(t)=\begin{cases} L(t\mid s_1) & if\ 0\le t<\tau_1 \\ L(t+w_1-\tau_1\mid s_2) & if\ \tau_1\le t<\tau_2 \\ L(t+w_2-\tau_2\mid s_3) & if\ \tau_2\le t<\tau_3 \\ L(t+w_3-\tau_3\mid s_4) & if\ \tau_3\le t<\tau_4 \\ L(t+w_4-\tau_4\mid s_5) & if\ \tau_4\le t<\tau_5 \end{cases}$$





Statistical Process for Lifetime Prediction

Statistical Model

Least square estimation by minimizing

$$SSE(\alpha,a,b)=\sum_t\{\ln(-\ln L_0(t))-\ln(-\ln H_0(t))\}^2$$

Expected value ($L_0(t)$) — Observed data ($H_0(t)$)

Estimate α ; β_i (a, b, E_a)

Given D= criteria for failure,

$$\hat{t}_f=\left(-\ln D/\hat{\beta}_0\right)^{1/\hat{\alpha}}$$

Estimate Product's lifetime; E_a; degradation rate

Least square estimation by minimizing

$$SSE(\beta_0,\alpha(j),\omega_1,\cdots,\omega_{j-1})=\sum_{t=t_j-1}^{t_j}\left\{\ln(-\ln H_0(t))-A_j-\alpha(j)\left[\ln(\omega_{j-1}+t-\tau_{j-1})\right]\right\}^2$$

Estimate at each stress level

Detect Upper limit condition

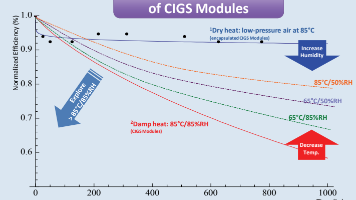
Detect the violation for the constant assumption with $|\hat{\alpha}(i)-\hat{\alpha}(j)|<\delta$

References:
[1] J. Lee and R. Pan, "Analyzing Step-Stress accelerated Life Testing Data Using Generalized Linear Models," *IIE Transactions*, 42, 2010, pp589-598.
[2] S.-T. Tseng and Z.-C. Wen, "Step-Stress Accelerated Degradation Analysis For Highly Reliable Products, *Journal of Quality Technology*, 32, 2000, pp209-216.
[3] W. Nelson, Accelerated Testing – Statistical Models, Test Plans, and Data Analysis, Wiley & Sons, New York, 1990.

Measurement for Degradation of PV Modules

- **J-V measurement System**
  - Open-circuit voltage (*Voc*)
  - Short-circuit current (*Isc*)
  - Fill factor (*FF*)
  - Conversion efficiency of the device (η)
  - Series resistance (*Rs*)
  - Shunt resistance (*Rsh*)

Degradation for Efficiency of CIGS Modules

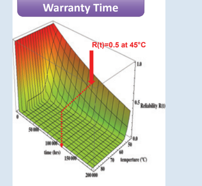


[1]Data source: J. Wennerberg, "Design and Stability of Cu(In,Ga)Se2-Based Solar Cell Modules," Dissertation, ACTA Universitatis Upsaliensis, 2002.
[2]Data source: J. Wennerberg et al., "Cu(In,Ga)Se2-Based thin-film photovoltaic modules optimized for long-term performance," Solar Energy Materials & Solar Cells, 75, 2003, pp47-55.

Outputs from SSADT

- **Product lifetime parameters** at various use-conditions
  - Mean time to failure
  - Reliability (Warranty) time
  - Failure rate
- **Degradation rate** at various use-conditions
- **Activation Energy** (E_a)
- **Upper limit level of stress** (tolerable stress level)

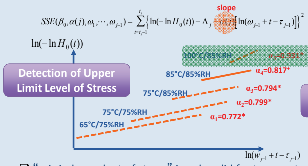
Prediction of Warranty Time



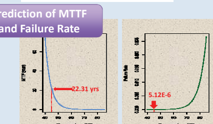
Detection of Upper Limit Level of Stress

$$SSE(\beta_0,\alpha(j),\omega_1,\cdots,\omega_{j-1})=\sum_{t=t_j-1}^{t_j}\left\{\ln(-\ln H_0(t))-A_j-\alpha(j)\left[\ln(\omega_{j-1}+t-\tau_{j-1})\right]\right\}^2$$

(slope: $\alpha(j)$)



Prediction of MTTF and Failure Rate



- "α is independent of stress" is only valid for temperature less than or equal 85°C
  - The issue of "over-stress" can lead to misleading results

Note, + : estimated value from Wennerberg et al. (2003)
* : assumed value

References:
[2] S.-T. Tseng and Z.-C. Wen, "Step-Stress Accelerated Degradation Analysis For Highly Reliable Products, *Journal of Quality Technology*, 32, 2000, pp209-216.

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