STEP-STRESS ACCELERATED DEGRADATION TESTING (SSADT) FOR PHOTOVOLTAIC (PV) DEVICES AND CELLS

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Outline

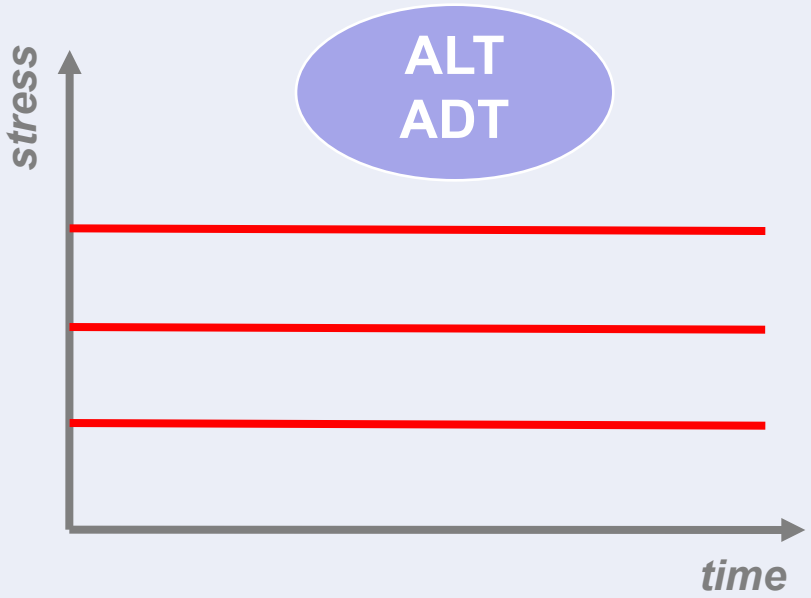
- Introduction of SSADT
  - ✓ What is SSADT?
  - ✓ Why do we need SSADT?
  - ✓ What can be estimated from SSADT?
- Reliability testing for PV
  - ✓ Current reliability testing
  - ✓ How to apply SSADT to PV area (e.g,. CIGS)
- Statistical process for SSADT
  - ✓ Inference using the lifetime prediction model
- Discussion

Objective

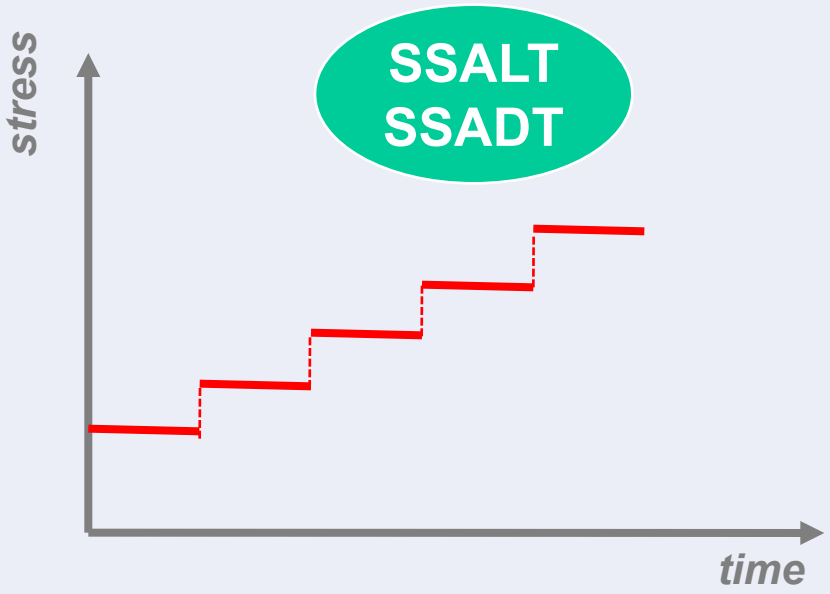
- Develop a step-stress degradation testing (SSADT) for PV reliability tests
  - Stage 1: construct a statistical model for SSADT **- current**
  - Stage 2: apply to reliability testing for thin film PV
- Develop a lifetime prediction model for PV products (cell level, but expandable to module level)
  - estimate lifetime characteristics (mean time, warranty time, failure rate) and activation energies
- Explore the current performance tests for Cu(In,Ga)Se_2, CIGS, device and cells; and provide physical and statistical models for their degradation

What is SSADT ?

- **Stress vs. Time plot**



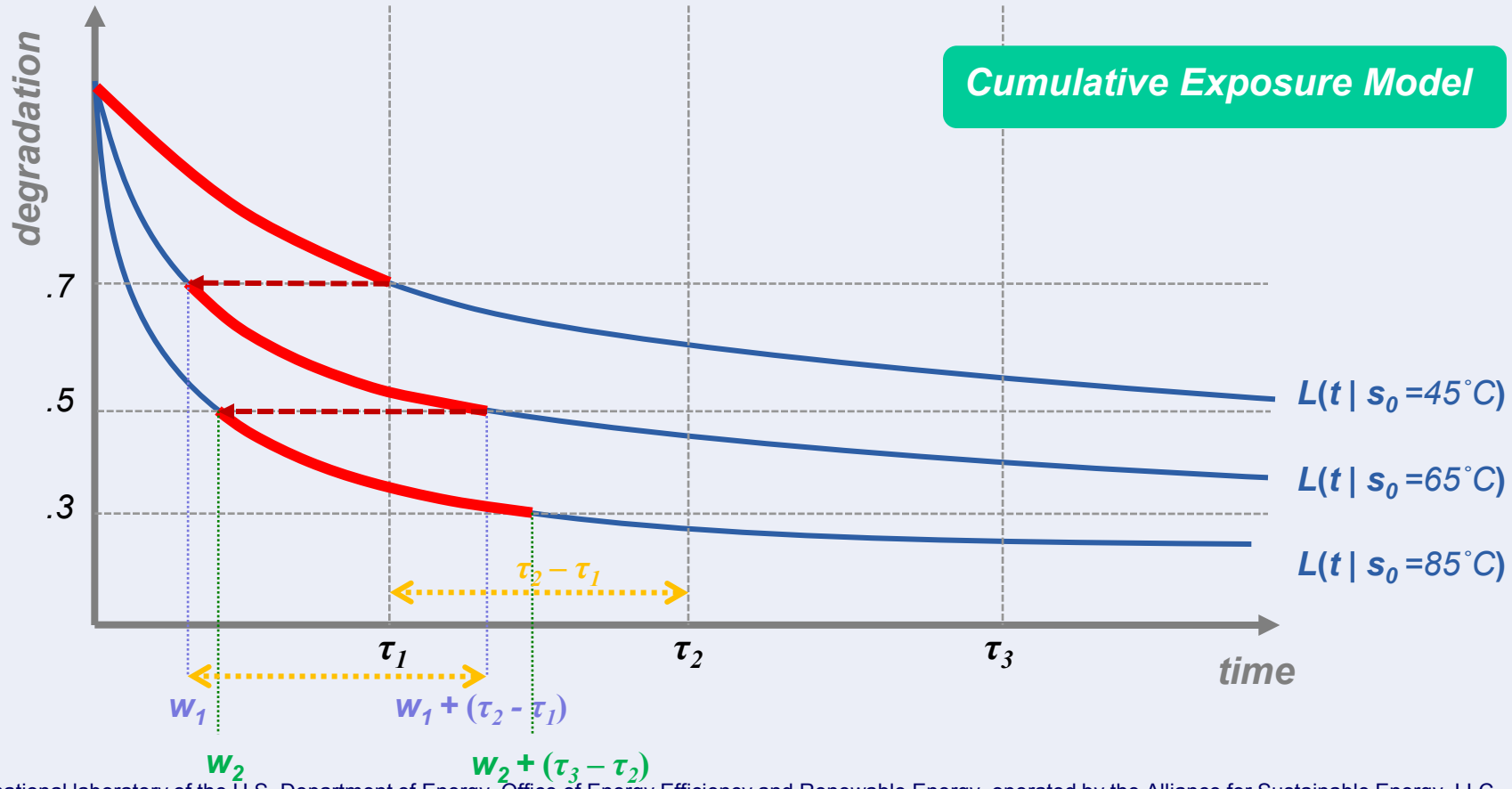
- 3 chambers
- 30 testing units



- 1 chamber
- 10 testing units

What is SSADT ?

❑ Degradation vs. Time plot



Why do we need SSADT?

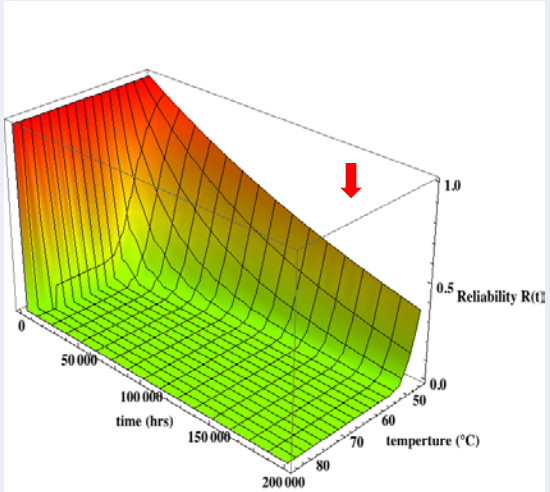
- ALT may offer little help for highly reliable products which are not likely to fail during a rather short period of time
- ADT collects the degradation data at higher levels of stress and then uses these data to predict the product's lifetime at a use-condition

- SSADT is an economical and flexible test plan

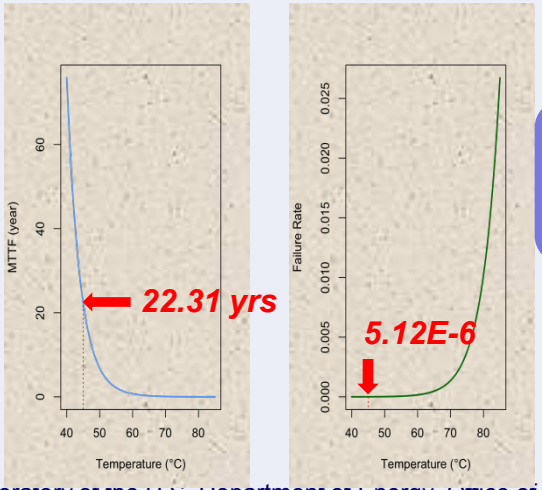
  - In particular, it is not easy to determine suitable test stress levels in ALT/ADT for new developing products where we don't have knowledge of appropriate stress levels.

What can be estimated 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



Prediction of Mean time to failure & Failure rate

Reliability Testing for $Cu(In,Ga)Se_2$, CIGS-based Thin film PV

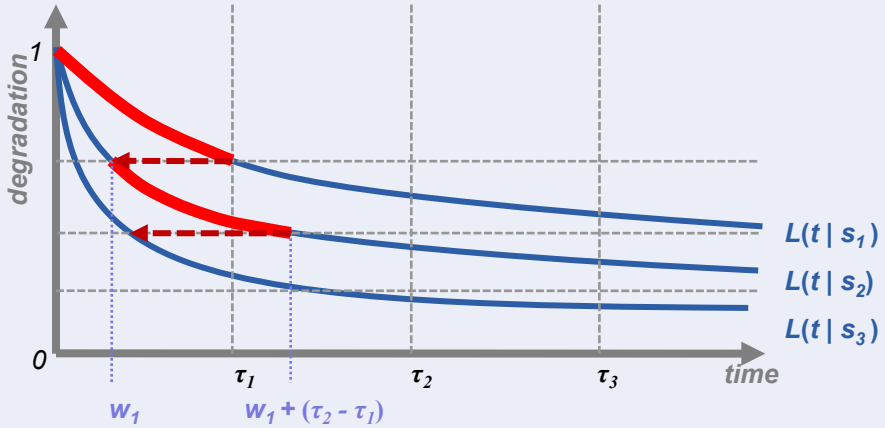
- **Performance Testing for CIGS (CIGS, NREL, leaded by John Pern)**
  1. Damp Heat Test: 85° C/85%RH
  2. Dry Heat Test: 85° C/4-10%RH
  3. Pressure Cooker: 110° C/100%RH/~6psi
  4. SSADT

- **Measurement for Degradation (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)

Statistical Models

- Expected degradation for SSADT (by using **CEM**)

$$L(t) = \begin{cases} L(t \mid s_1) & \text{if } 0 \le t < \tau_1 \\ L(t + w_1 - \tau_1 \mid s_2) & \text{if } \tau_1 \le t < \tau_2 \\ \quad \text{M} & \\ L(t + w_{m-1} - \tau_{m-1} \mid s_m) & \text{if } \tau_{m-1} \le t < \tau_m \end{cases}$$



- Degradation model over time

$$L(t \mid s_i) = L(0) \cdot \exp[-\beta_i t^{\alpha}], \quad i = 1, 2, \text{L}, m$$

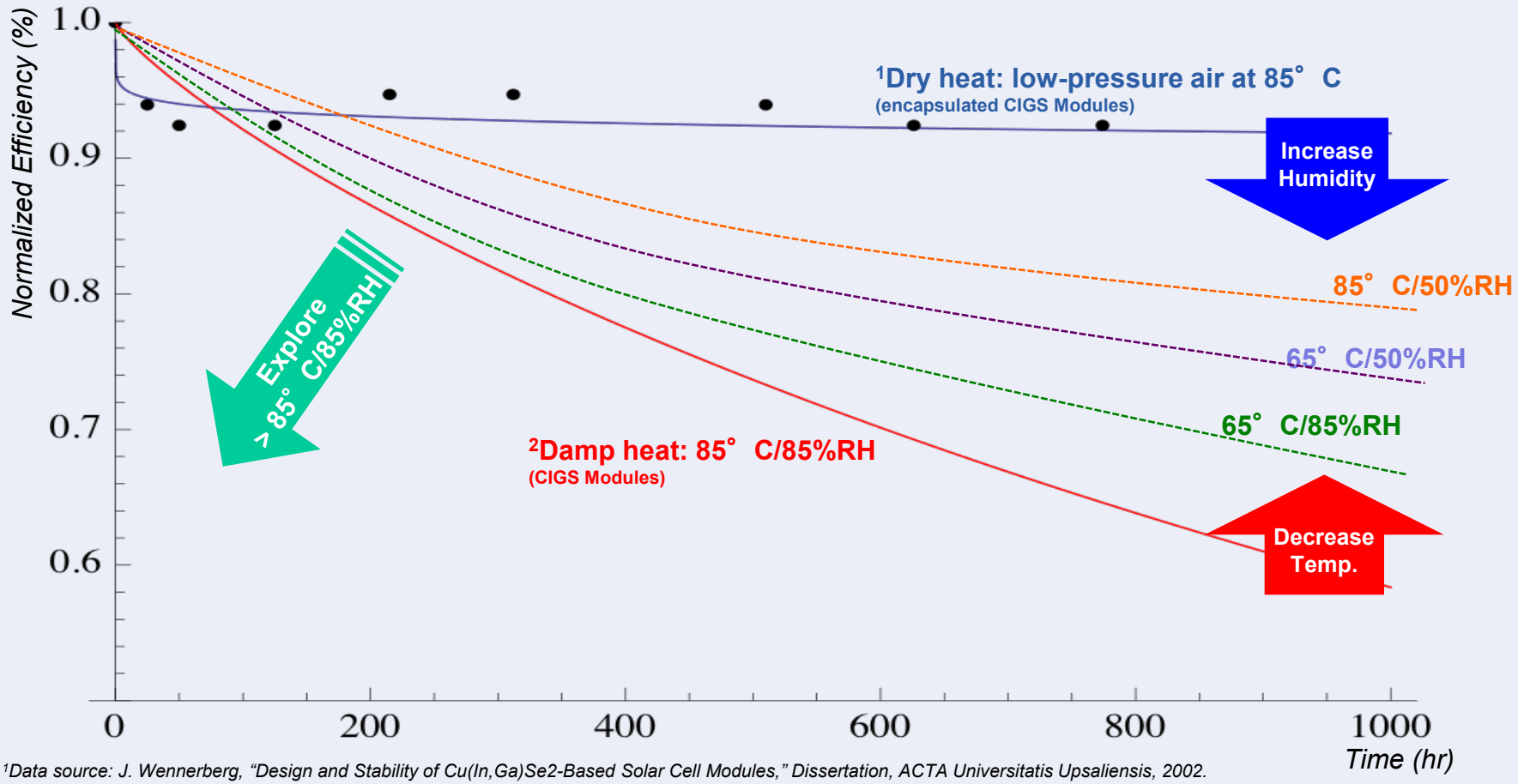
- Physical model for temperature and humidity (**Generalized Eyring Model**)

$$\beta_i = a \cdot \exp\left(-\frac{b}{RH_i}\right) \cdot \exp\left(\frac{E_a}{k \cdot (273 + T_i)}\right)$$

* ***Arrhenius Model*** *for* ***Temperature***

$$\beta_i = \exp\left(a - \frac{E_a}{k \cdot (273 + T_i)}\right)$$

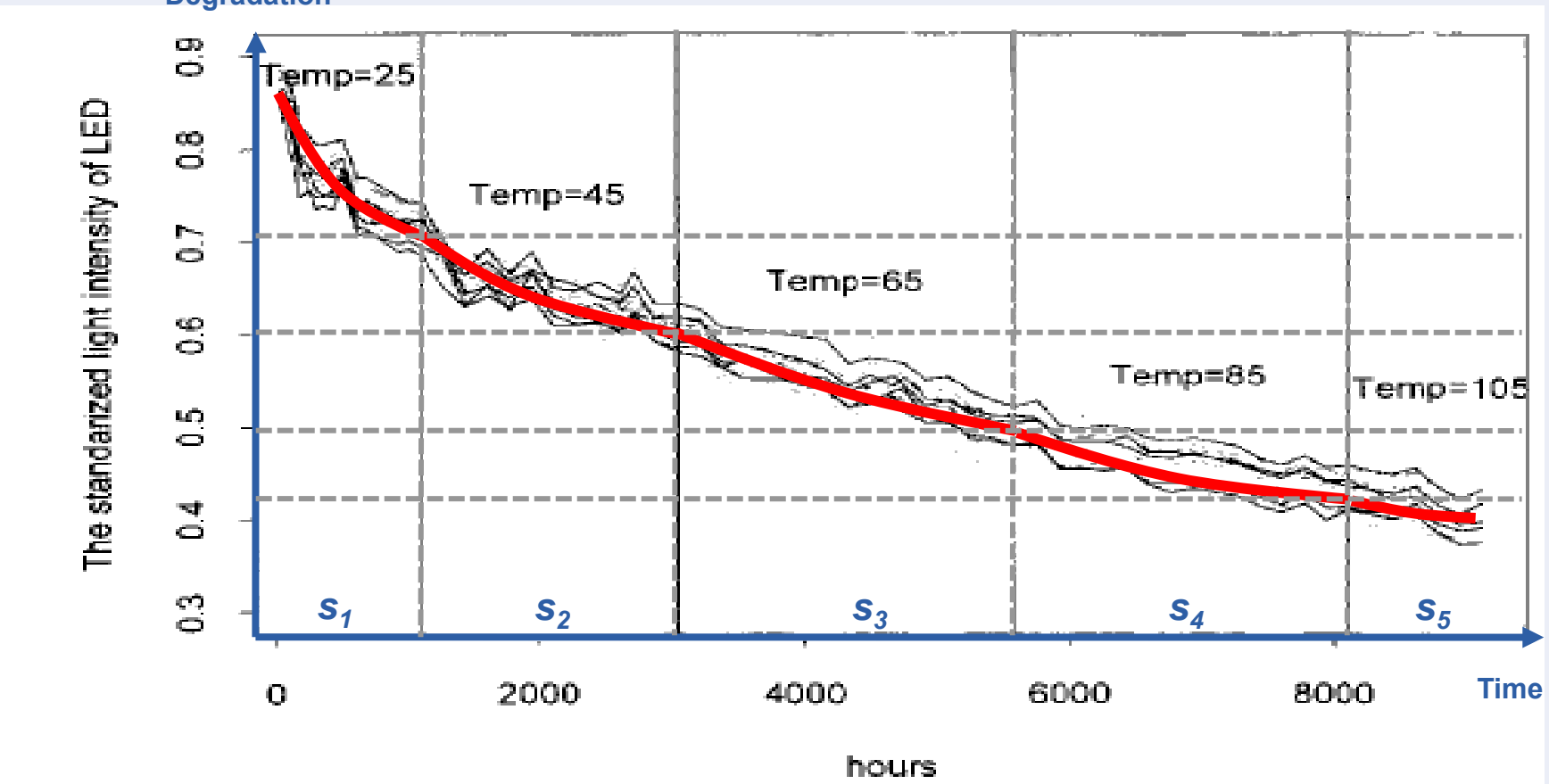
Degradation of CIGS



[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.

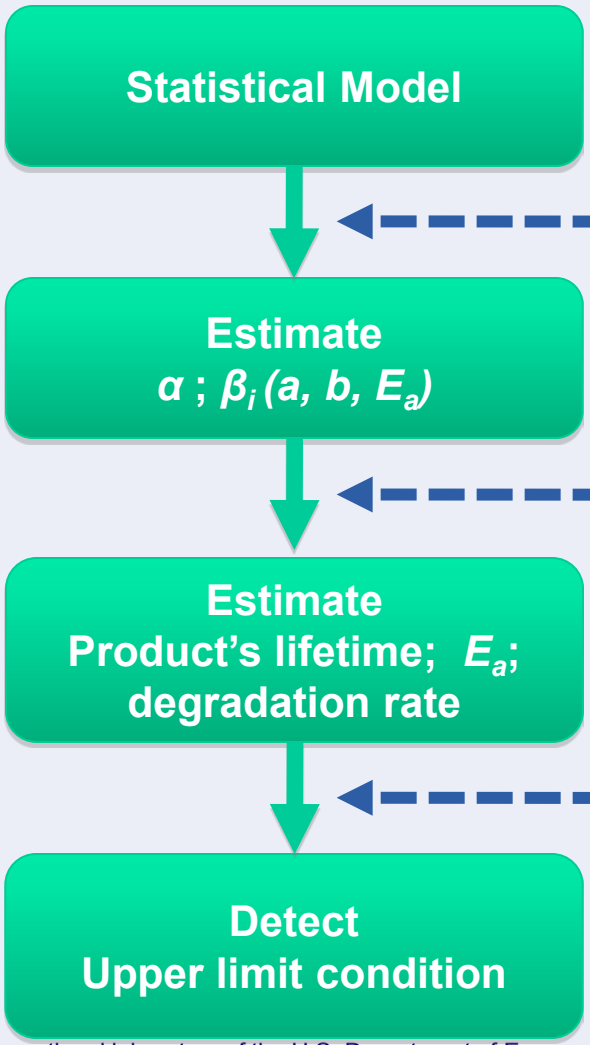
Example of SSADT Data

(LED lamps of fax machine (Tseng & Wen 2000))



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

Overall Process of Statistical Analysis



Least square estimation by minimizing

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

Observed data

Given D= criteria for failure,

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

Least square estimation by minimizing

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

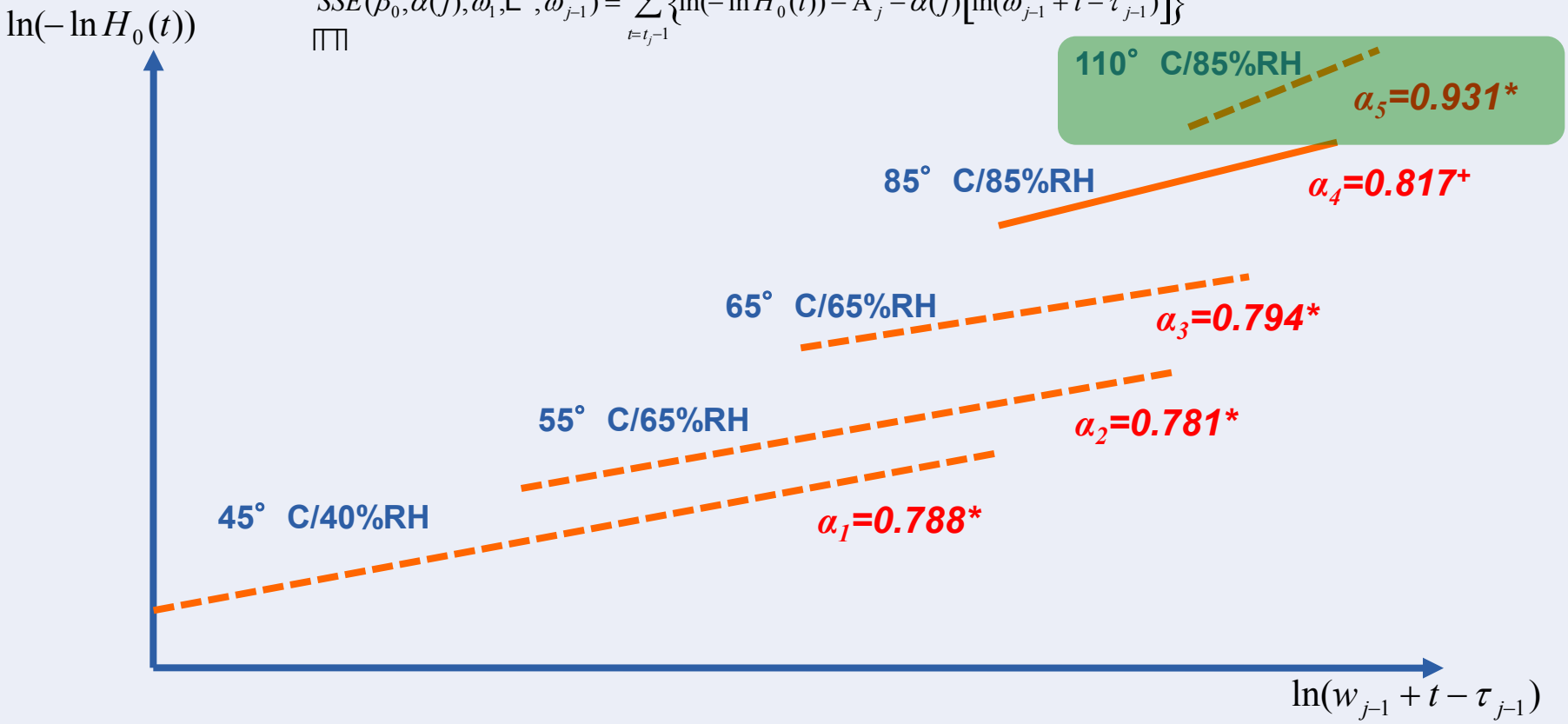
Estimate at each stress level

Detect the violation for the constant assumption with

$$|\hat{\alpha}(i)-\hat{\alpha}(j)|<\delta$$

Example for detecting a upper limit of stress

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



- *"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

Discussion

- Develop statistical models for a cutting-edge life-testing technique, SSADT, with temperature-humidity condition for PV reliability testing
  - applicable to all PV reliability testing (including module levels and all PV technologies)
- Discuss the benefits of SSADT
- Consider other applicable degradation models (discussed by Nelson (1990)): e.g., some temperature-humidity models
- Study two main areas for SSADT: Statistical inference and Optimal planning
- Discuss about other statistical methods to build a SSADT model and analyze its data – e.g., LSE vs. MLE, Bayesian inference, generalized linear models, etc.

Key Reference

- S.-T. Tseng and Z.-C. Wen, “Step-Stress Accelerated Degradation Analysis For Highly Reliable Products, *Journal of Quality Technology*, 32, 2000, pp209-216.
- 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.
- W. Nelson, Accelerated Testing – Statistical Models, Test Plans, and Data Analysis, Wiley & Sons, New York, 1990.
- J. Lee and R. Pan, “Bayesian inference model for step-stress accelerated life testing with type-II censoring, *in Proc. The Annual Reliability and Maintainability Symposium*, Las Vegas, NV, 2008.
- J. Lee and R. Pan, “Analyzing Step-Stress accelerated Life Testing Data Using Generalized Linear Models,” *IIE Transactions*, 42, 2010, pp589-598.