LIFETIME PREDICTION FOR DEGRADATION OF SOLAR MIRRORS USING STEP-STRESS ACCELERATED TESTING

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Outline

- Concentrating Solar Power
  - Reflectors of CSP
  - Testing facility (Ultra-accelerated Weathering System)
  - Optimal measurements
- Testing for lifetime prediction
  - Step-stress accelerated degradation testing (SSADT)
  - Multiple constant-stress accelerated degradation testing (MCSADT)
  - Testing plans for UAWS
- Statistical procedure for lifetime prediction
  - Degradation models for reflectors
  - Statistical approaches for lifetime prediction
  - Obtainable outputs
- Summary

Objective of The Current Project

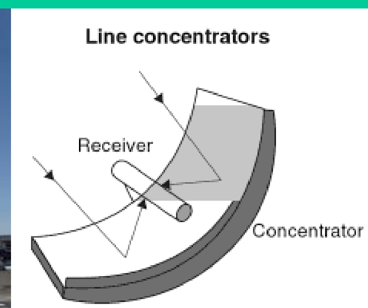
- Introduce a cutting-edge life-testing technique, accelerated degradation testing (ADT) and its advanced testing technique, step-stress accelerated degradation testing (SSADT), for reliability testing of solar reflectors
- Design a durability testing plan for solar mirrors (3M's new improved silvered acrylic "Solar Mirror Film (SMF) 1100") through the ultra-accelerated weathering system (UAWS)
- Develop statistical models for use of SSADT with the thermal-humidity-intensity stress condition through the cumulative damage model (CDM)
- Provide quantitative models for prediction of 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
- Define degradation paths of optical performance based on the SSADT model which is accelerated by high UV-radiant exposure,
- Investigate appropriate physical degradation of reflectors

Concentrating Solar Power (CSP)

- CSP has currently four common Concentrating technologies:

Parabolic trough

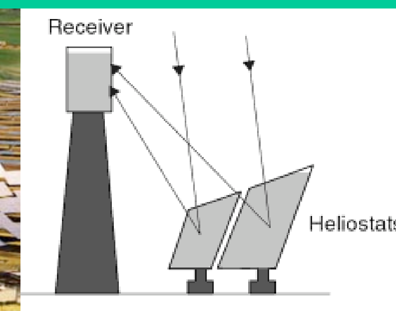
Source: NREL



Source: R. Paal (2008) [1]

Solar power tower

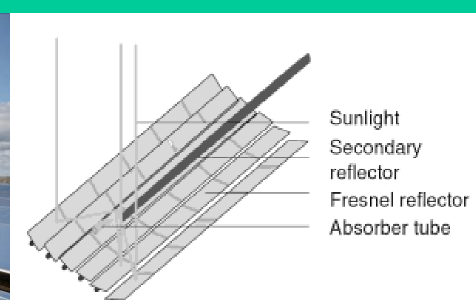
Source: NREL



Source: R. Paal (2008) [1]

Linear Fresnel reflector

Source: NREL



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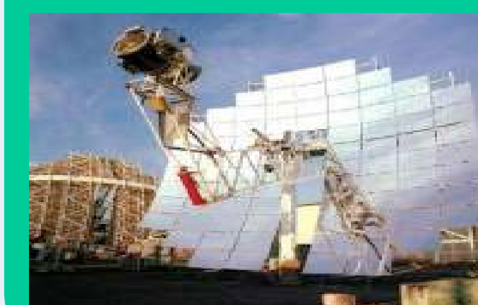
Dish-engine



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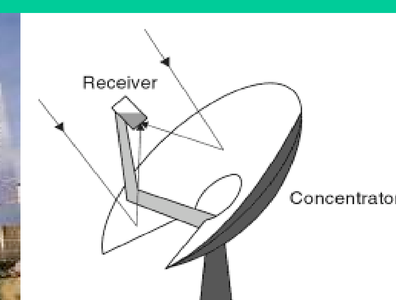
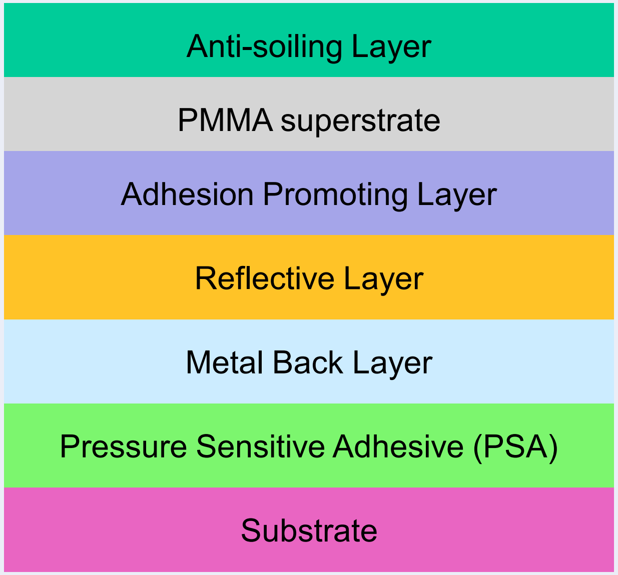


Source: R. Paal (2008) [1]

CSP Reflectors

- Reflectors (mirrors) and receiver tube coatings are the major components of the solar field of CSP systems.
- In evaluating the performance of these materials, we can help to improve the overall efficiency of CSP plants. Because the solar field accounts for nearly half the total plants construction cost, an increase in optical efficiency can be a significant step toward making CSP competitive with fossil fuels as a utility-scale energy source.
- Three common reflective materials are commonly used for solar mirrors:
  - Silvered Glass Mirrors (Thick and Thin Glass)
  - Aluminized Mirrors
  - Silvered Polymers

Structure of 3M Polymer Reflector



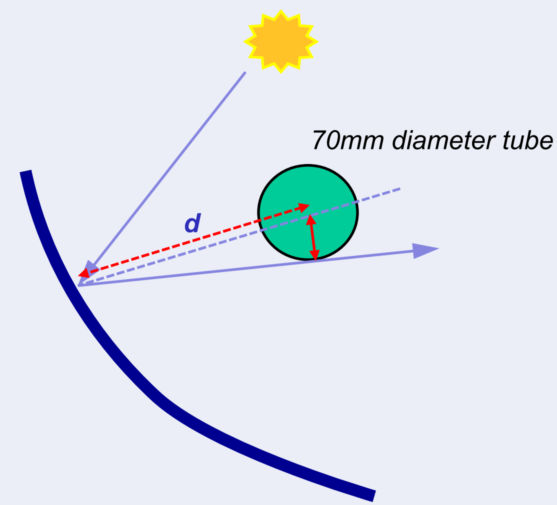
Based on prior 3M/NREL collaborations
Source: Cheryl Kennedy, Advance CSP R&D, Solar Energy Technologies Program Peer Review, 2010

Ultra-Accelerated Weathering System (UAWS)

- The UAWS is an outdoor weathering system, which dramatically increases the UV radiant exposure per unit time over what is attainable with current moderately accelerated techniques. [1]
- The system allows a 63-year (approximate) equivalent South Florida 45 UV-radiant exposure within a single year of ultra-accelerated exposure. [1]
- The system provides high fidelity to natural solar UV spectral power distributions while attenuating visible and IR wavelengths to maintain acceptable specimen exposure temperatures. [1]
- Polymer silvered reflectors are known to be susceptible to degradation mechanisms associated with exposure to UV radiation.

Optical Measurements

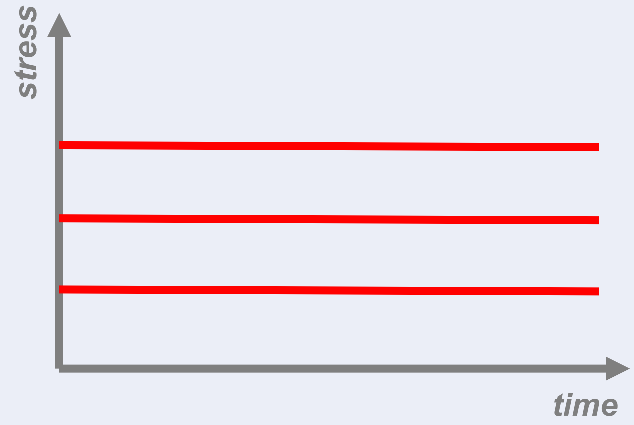
- Measure both hemispherical and specular reflectance using ultraviolet-visible-near infrared (UV-Vis-NIR) spectrophotometers and specular reflectometers.
  - Spectral hemispherical reflectance ($\rho_{2\pi}(\lambda)$)
  - Specular reflectance ($\rho_S(\theta, \lambda)$)
- Optical performance is characterized in terms of specular reflectance, the degree to which a reflector is capable of transferring directed radiation to a target receiver surface.
- Microroughness of a reflector surface, crazing of protective top coats, or both can result in scattering of light outside a specified angle, defined as the half angle (θ) subtended by the receiver as viewed from the reflector surface.
- The quantity $\rho_{2\pi}(\lambda)$ is measured in the wavelength range $250 < \lambda < 2500$ nm
- The specular reflectance is measured at a wavelength of 660 nm



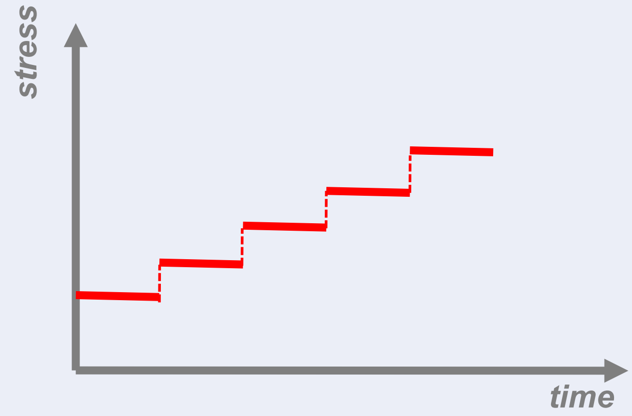
e.g., if d=4667mm
θ=sin-1(35mm/4667mm)
then acceptance angle (2θ) =15mrad

ADT & SSADT

- **Multiple Constant-Stress Accelerated Degradation Test (MCSADT)**
  - The accelerated life testing (ALT) technique may offer little help for highly reliable products which are not likely to fail during a rather short period time.
  - ADT relies on the degradation data instead of failure data when it is more difficult to obtain sufficient failure data for ALT but when degradation can be used to make acceptable prediction of failure.
  - Single constant-stress testing (e.g., Damp-Heat Test) can be used for qualification testing with a specific durability criteria
  - MCSADT can be used for life-time prediction of products.

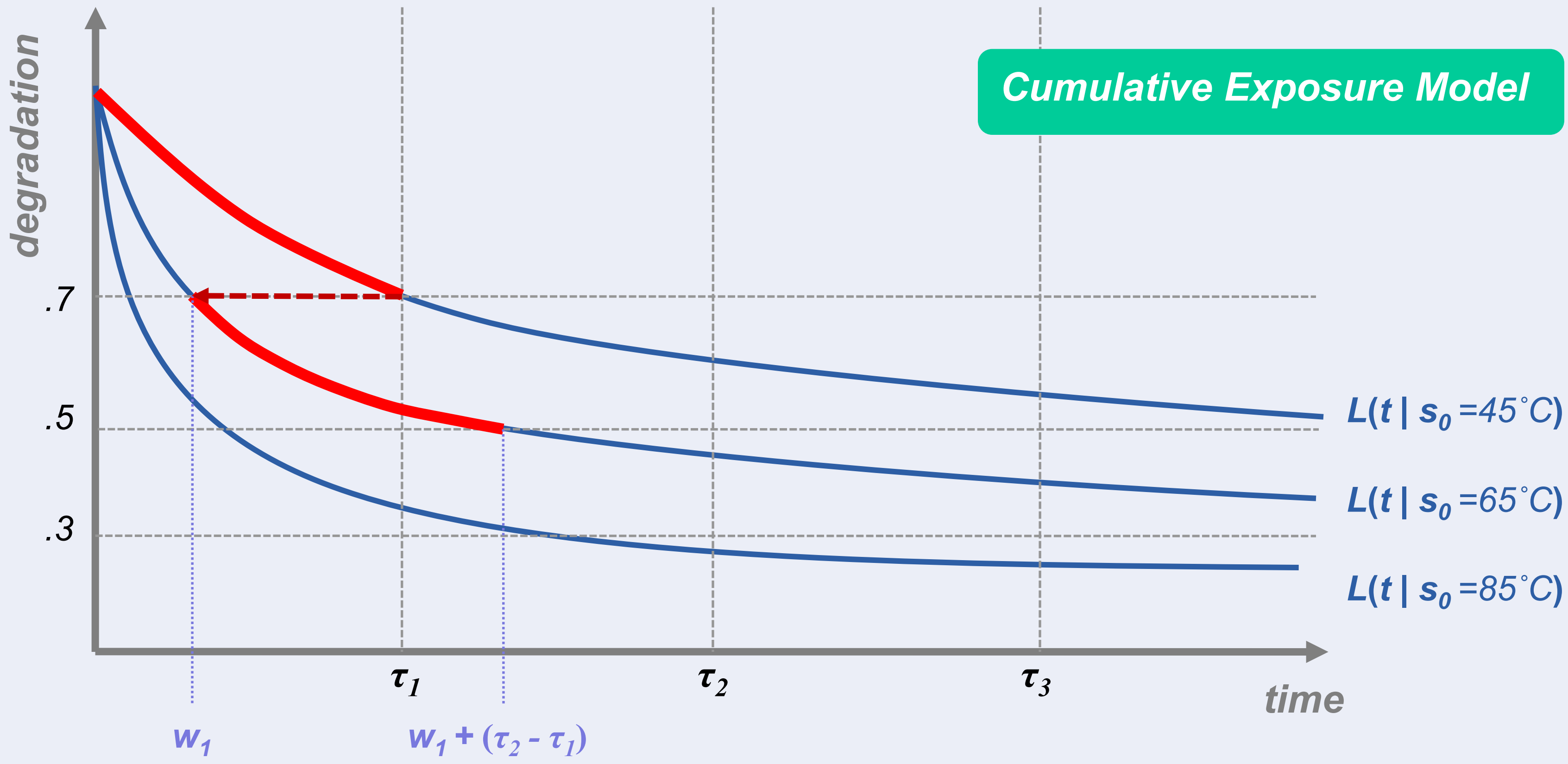


- **Step-Stress Accelerated Degradation Test (SSADT)**
  - Step-stress testing is one of the most basic time-varying stress tests. In a step-stress test, multiple samples in one or more sets are exposed to several stress conditions over time.
  - Step-stress testing is an advanced reliability testing technique for high reliability products.
    - **Economical:** suitable when we are constrained by test facilities, conditions, or samples
    - **Flexible:** useful for developing products where there is not enough knowledge for test conditions



What is SSADT ?

- Degradation vs. Time plot



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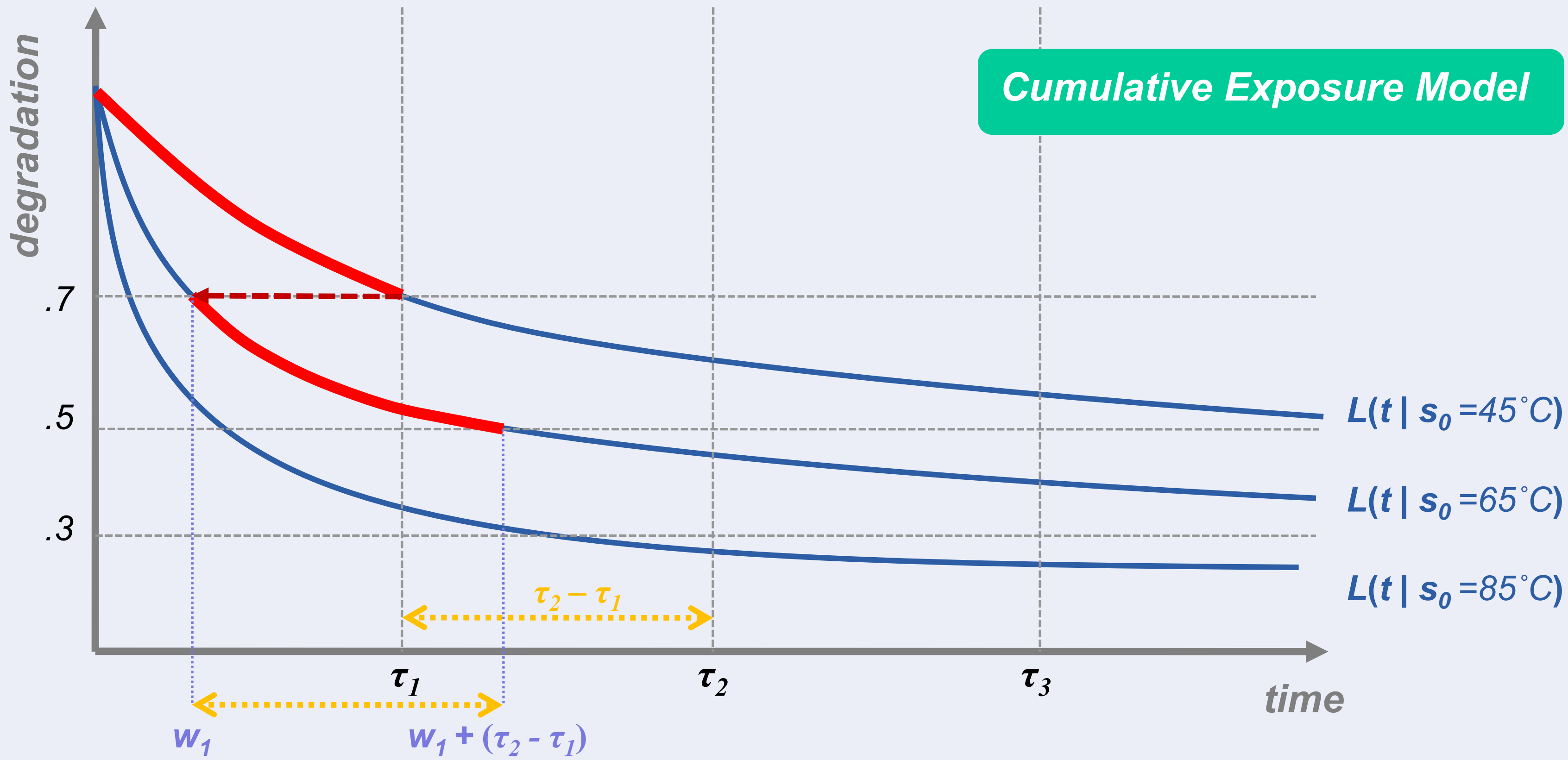

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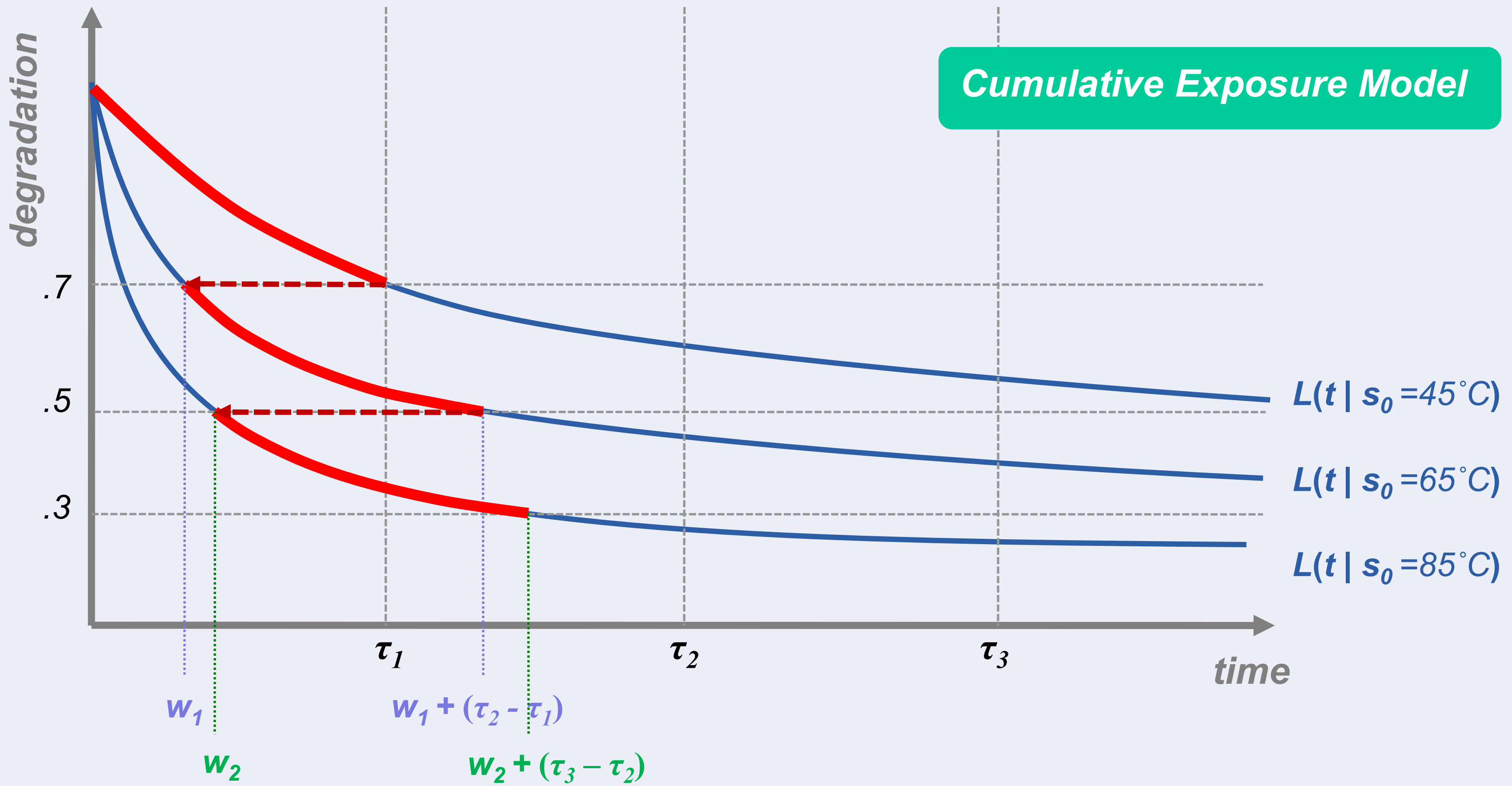

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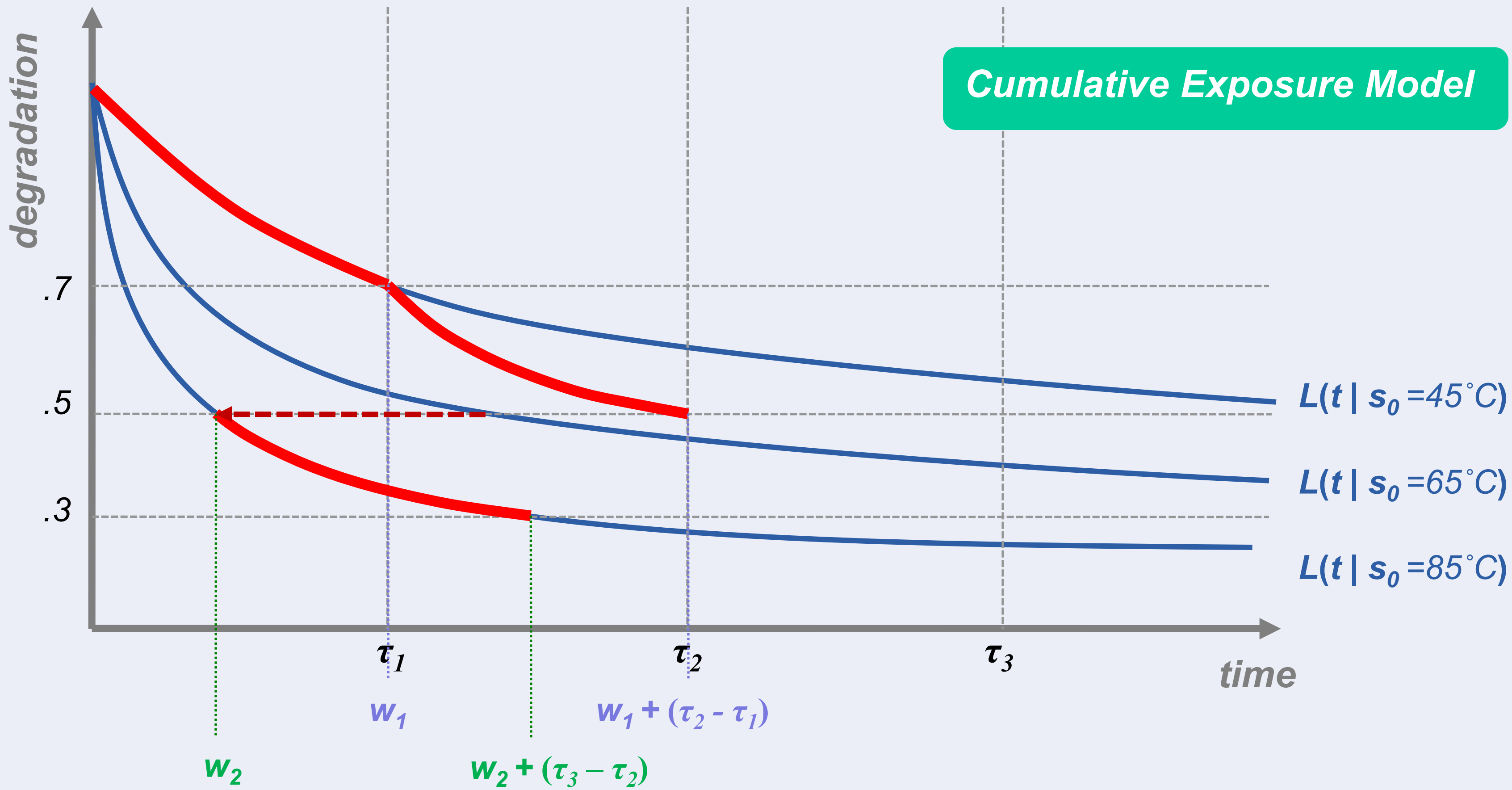

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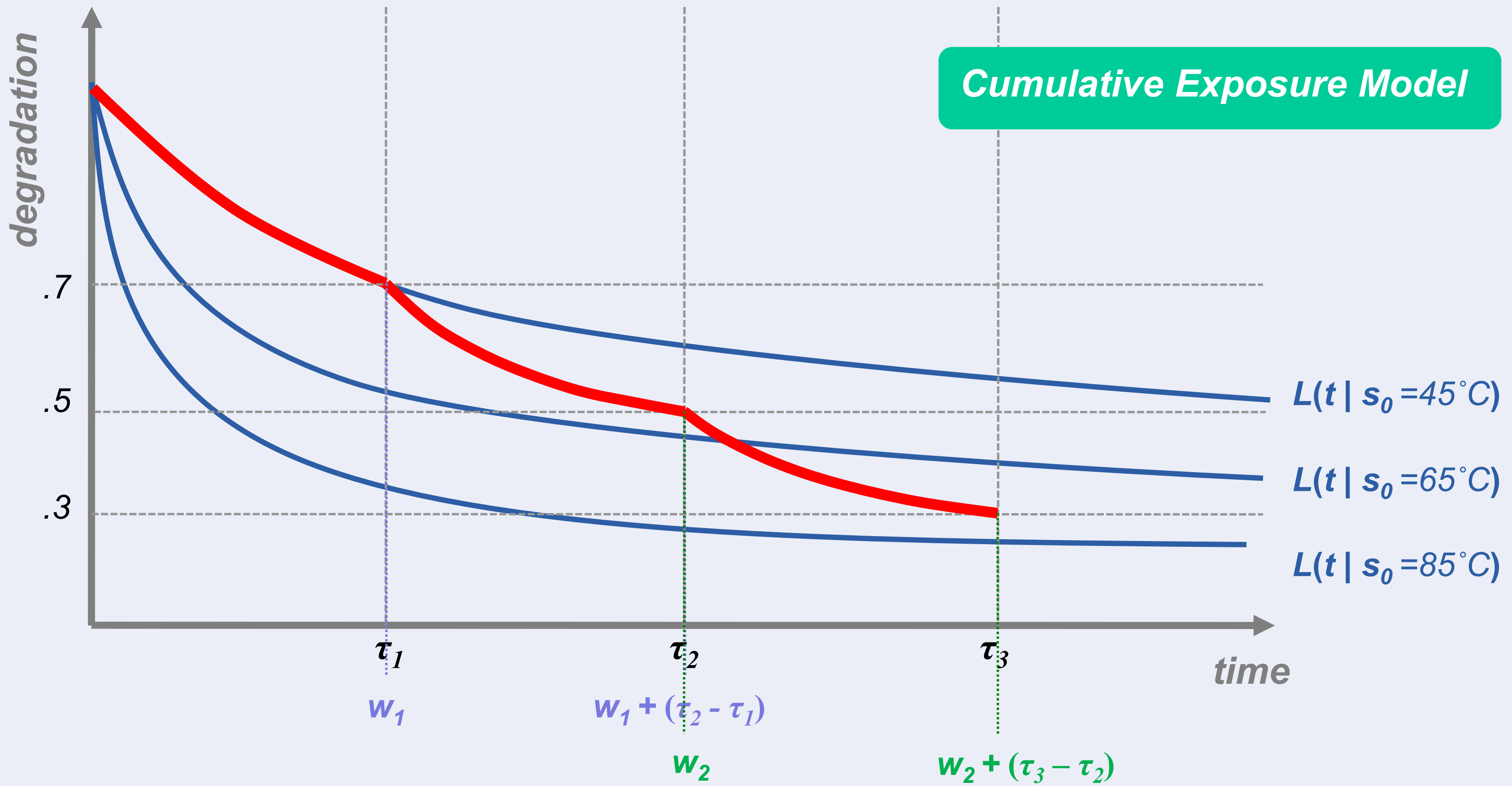
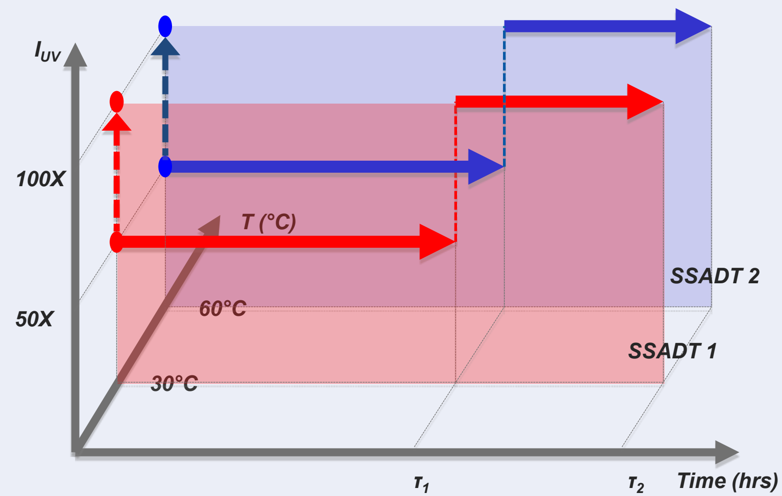
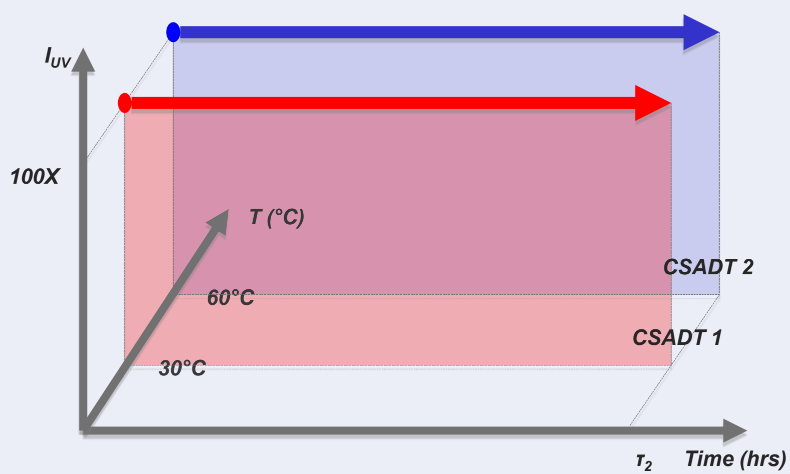


Testing Plan





SSADT

- Adopt two separate SSADT plans, each of which is designed with two UV-radiant exposure
- Reflector samples are initially tested at 50X intensity until reaching a pre-determined switch time
- The stress is increased to 100X and the test continues as before
- During the testing, the specular reflectance of each sample is measured at pre-specified inspection times

MCSADT

- Also consider a MCSADT plan, where two constant stress ADTs are deigned at two exposure temperatures of 30°C and 60°C, respectively
- Each test is subjected to 100X intensity throughout the pre-determined testing time

Degradation Model for Polymer Reflectors

- **Stage 1: Define a physical relationship of stress for degradation rate**
  - UV radiance
  - Temperature
  - Humidity

$$b = c \cdot I_{UV} \cdot \exp(-d \cdot RH) \cdot \exp\left(\frac{E_a}{k \cdot (273+T)}\right)$$

- **Stage 2: Identify the degradation pattern**
  - Linear $d(t) = a \cdot t + b$
  - Exponential $d(t) = b \cdot e^{a \cdot t}$
  - Power $d(t) = b \cdot t^{a}$
  - Logarithmic $d(t) = a \cdot \ln(t) + b$
  - others $d(t) = e^{-bt^{a}}$ *(Tseng and Wen, 2000)*
    $d(t) = a + bt^{0.55}$ *(Vehicle Battery)*

Choose "Power" with a = 1

(Jorgensen et al., 1999 & Jorgensen 2003)

- **Stage 3: Build a proper degradation model**

$$d(t) = A \quad I_{UV} e^{-E/kT} e^{C \cdot RH} \cdot t$$

Statistical Approach for Lifetime Prediction (Using SSADT)

- **Inference of SSADT through Least Square Estimation (LSE)**
  - Construct the expected degradation for SSADT at each temperature

$$d(t)=\begin{cases} d(t\mid s_1) & \text{if } 0\le t<\tau_1 \\ d(t+w_1-\tau_1\mid s_2) & \text{if } \tau_1\le t<\tau_2 \end{cases}$$

  - Minimize the sum of square error

$$SSE(\alpha,a,b)=\sum_{t}\{\ln(-\ln d_0(t))-\ln(-\ln H_0(t))\}^2$$

  - Estimate the product lifetime, Activation Energy, degradation rate
  - Detect the violation for the constant assumption with $|\hat{\alpha}(i)-\hat{\alpha}(j)|<\delta$ by minimizing

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

  - Determine the upper limit condition

Statistical Approach for Lifetime Prediction (Using SSADT)

- **Inference of SSADT through Maximum Likelihood Estimation (MLE)**
  - Construct the likelihood function using the transformed data based on failure distributions

$$LIK = \prod_{i=1}^{I}\prod_{q=1}^{Q_i}\left(1-R(\varphi_{i,q})\right)^{r_{i,q}}\left(R(\varphi_{i,q})\right)^{k_{i,q}-r_{i,q}}$$

$$= \prod_{i=1}^{I}\prod_{j=1}^{Q_i}\left(1-\exp(-\lambda_{i,q}\varphi_{i,q})\right)^{r_{i,q}}\left(\exp(-\lambda_{i,q}\varphi_{i,q})\right)^{k_{i,q}-r_{i,q}}$$

  - (Alternative option) Transform to a generalized linear model form with the Bernoulli trial and solve the problem through the iterative weighted least square (IWLS) method

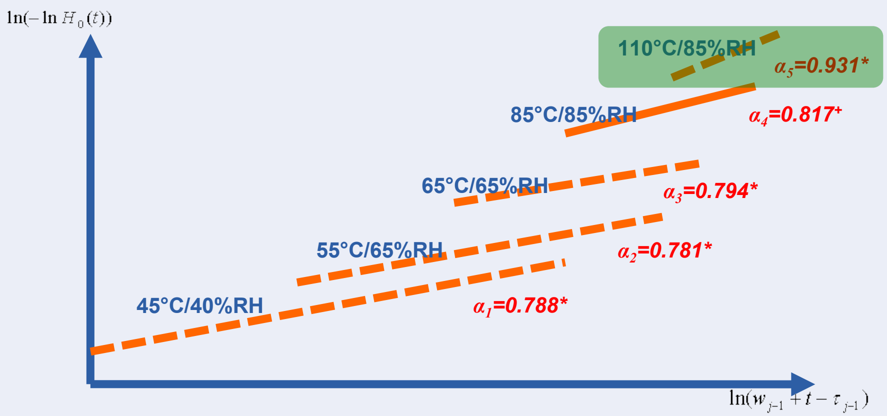
$$LIK = \prod_{d=1}^{D}\left(p_d\right)^{r_d}\left(1-p_d\right)^{k_d-r_d}$$

  - Estimate the product lifetime (including warranty time and mean-time-to failure (MTTF)), Activation Energy, failure rate, etc.

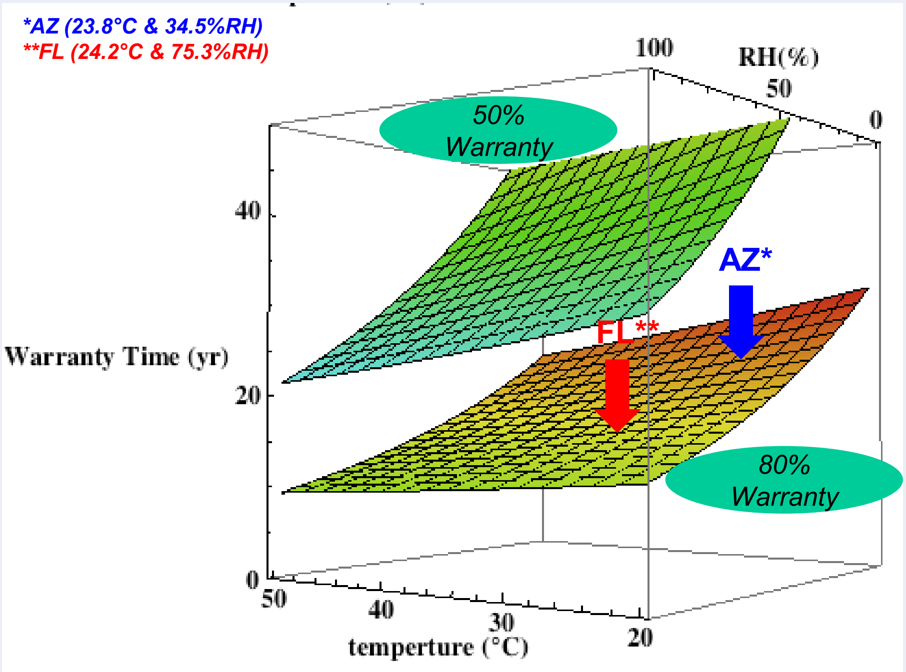
What Can be Estimated from SSADT?

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

❖ Example for Upper Limit Level of Stresses



❖ Example for Warranty Time



Summary

- Discuss lifetime prediction for metalized polymer reflectors
- Study the physical degradation models in optical performance, including UV-radiant exposure and thermal and moisture effects as relevant environmental stresses
- Develop accelerated testing plans for using the Ultra-Accelerated Weathering System (UAWS): considering step-stress accelerated degradation testing (SSADT) and multiple constant-stress accelerated degradation testing (MCSADT) techniques
- Develop statistical procedures for SSADT in order to predict lifetime of polymer reflectors
- Discuss several statistical approaches to enhance the lifetime prediction of reflectors

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Acknowledgements

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Thank You !!!