PREDICTING PHOTOTHERMAL FIELD PERFORMANCE

JET PROPULSION LABORATORY

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Objective and Approach

- Extrapolate photothermal accelerated test data to simulate 30-year field exposure
  - Develop an analytical model incorporating the measured dependency between transmittance loss and UV and temperature exposure levels
  - Exercise the model using SOLMET weather data extrapolated to 30 years for various sites and module-mounting configurations

Analytical Model Assumptions and Characteristics

- Encapsulant optical transmittance can be expressed as a function of the concentration of a given reactive species, Q
- Rate of variation of concentration, Q/t, is a reaction rate
- Standard reaction-rate equations, Arrhenius and power-law relationships are used to relate Q/t to the stress levels
- Two competing reactions occur simultaneously, one causing the increase of yellowing and one bleaching out the yellowing
  - Principle of superposition is assumed; order in which environmental levels occur not important
- Arbitrary constants a_1 to a_{10} determined by least-squares fitting of experimental optical transmittance (as a function of temperature and UV) versus time data
Analytical Model

- Two equations developed:
  \[
  \frac{\tau}{\tau_0} = 1 + a_1 Q + a_2 Q^2 + a_3 Q^3
  \]
  \[
  \frac{Q}{t} = e^{(a_4/T)} + a_6 e^{(a_8/T)} S^{a_7} - a_9 e^{(a_{10}/T)} S^{a_{10}}
  \]

Where:
- \( \tau \) = transmittance at 440 nm
- \( \tau_0 \) = initial transmittance at 440 nm
- \( Q \) = concentration
- \( a_i \) = constant
- \( t \) = time
- \( T \) = temperature in °K
- \( S \) = UV level in suns

Reaction Rate (Q/Time) vs UV Level
As a Function of Temperature (EVA)
Transmittance Loss vs Concentration, $Q$ (EVA)

Transmittance Loss vs Time (EVA)

Temperature = 135°C
Arrhenius Plot of Reaction Rate (Q/Time) vs Temperature (EVA)

Derivation of Photovoltaic Degradation From 440-nm Transmittance Loss

- 440-nm transmittance loss defines unique spectral transmittance curve for encapsulant
- Photovoltaic response requires convolution of encapsulant transmittance curve, cell spectral response curve, and solar distribution curve (global spectrum)
- Two-cell spectral response models used, one for crystalline silicon and one for amorphous silicon cells
30-Year Transmittance, %, vs Wavelength for EVA

Spectral Response Curves of Crystalline and Amorphous Silicon Cells
Determining 30-Year Degradation Using Photothermal Degradation Simulation Model

- Calculate 30-year field exposure environment using hourly SOLMET weather data tapes
  - Encapsulant operating temperatures computed as a function of irradiance level on tilted surface and ambient air temperature
  - UV level computed as a fixed 5% of the solar irradiance level
  - Results presented as matrix of annual number of exposure hours at each combination of temperature and UV level

- Simulate 30-year photothermal degradation using simulation model and environmental stress matrix
  - Matrix of reaction rates, Q/t, determined for temperature and UV levels in exposure-hours matrix
  - The product is taken of the two matrices
  - The sum of the values in each element of the last matrix yields the concentration Q at the end of a year
  - 30-year concentration is 30 times annual value
Annual Hours of Exposure of a Ground-Mounted Array to Various Cell Temperatures and UV Levels (Phoenix)

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<th>Cell temperature, °C</th>
<th>UV level in suns</th>
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<th>0.15</th>
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Relative Values of Reaction Rates (Q/Time) for Various Cell Temperatures and UV Levels

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<th>Relative values of reaction rates, Q/time</th>
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## Photovoltaic Power Loss After 30 Years in Phoenix* (EVA)

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Ground-mounted array</th>
<th>Roof-mounted array</th>
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<tbody>
<tr>
<td>Crystalline cell</td>
<td>3.5%</td>
<td>7.9%</td>
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<tr>
<td>Amorphous cell**</td>
<td>8.1%</td>
<td>17.8%</td>
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</table>

30-year allocation for this degradation mode is 6%

*Based on assumed UV acceleration factor distribution near one sun

**Only when EVA is between module front surface and cells

## Conclusions

- Temperature is key driver to photothermally induced transmittance loss (approximate doubling of rate per 10°C)
- Sensitivity of transmittance loss to UV level is highly nonlinear with minimum in curve near one sun
- EVA results consistent with 30-year life allocation

## Future Work

- Refine analytical model using additional data taken in region of one sun
- Repeat the thermal-UV exposure tests with the addition of humidity to study the impact of this variable
- Investigate the use of techniques similar to those discussed here for determining the photothermal degradation of encapsulant mechanical properties over 30-year life