Acceleration Factor Modeling for Degradation Rate Prediction of Photovoltaic Encapsulant Discoloration

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Acceleration Factor Modeling for Degradation Rate Prediction of Photovoltaic Encapsulant Discoloration

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Abstract — An acceleration factor modeling approach to predict the degradation rate for climate-specific encapsulant discoloration in glass/polymer construction modules is presented. The modeling has two different routes of determining the acceleration factor and activation energy for encapsulant browning, which is governed by the degradation data obtained from either the outdoor field or the indoor accelerated UV stress testing. The model developed based on the modified Arrhenius equation uses hourly meteorological data in conjunction with the degradation data. An acceleration factor of 23 is determined for encapsulant browning of c-Si modules exposed to Arizona climate (Hot and Dry) and the degradation rate predicted due only to encapsulant browning is about 0.37±0.04% per year.

Index Terms — acceleration factor, Arrhenius model, degradation rate, encapsulant discoloration, lifetime prediction, photovoltaic module.

I. INTRODUCTION

Reliability of field-installed photovoltaic (PV) modules is a key metric for sustained energy yield and lower levelized cost of energy (LCOE). Many manufacturers give 25+ year service lifetime warranty in the outdoor environment. However, the modules suffer from several degradation modes, which are dictated by various factors, such as climate, PV technology, installation (roof or ground mounted), PV materials and construction type. It is reported that the primary cause for module degradation in crystalline-silicon (c-Si) technology is associated with the encapsulant degradation from the field survey carried out on around 56,000 modules installed in four different climatic regions of USA [1].

Ethyl vinyl acetate (EVA) is the most dominant encapsulant used for wafer based c-Si modules. Discoloration and delamination are two common degradation modes, which affect the transparency and adhesion of EVA layer, respectively. Encapsulant discoloration, ranging from light yellow to golden brown, occurs due to the decomposition of UV absorber formulated in EVA matrix and generation of chromophores under the action of UV radiation and high temperature [2]. Browning directly reduces light transmission decreasing the short-circuit current (Isc) and hence the module power (Pmax). The degradation escalates in the presence of humidity through the EVA hydrolysis and deacetylation reaction. The acetic acid produced leads to the corrosion of metallic contacts and the reduction of interfacial adhesion leading to delamination. It also accelerates the encapsulant degradation either through the catalytic pathway or being a part of chemical reaction.

Assessment of degradation rate is useful in evaluating the lifetime and bankability of installed PV systems. Determining the acceleration factor (AF) for the most prevalent degradation mechanisms is necessary for predicting module lifetime in the field. Different approaches have been reported for determining AF of potential induced degradation [3], corrosion [4], solder bond failures [5]; however, the literature on the correlation of accelerated test data and field data for encapsulant discoloration is scarce. In this work, a climate-specific degradation rate modeling approach for encapsulant discoloration is presented, which is supported by physical model equations. It employs the degradation data obtained from outdoor field and/or indoor accelerated test, which helps in module lifetime prediction, as depicted in Fig. 1. It also involves the determination of activation energy (Ea) and AF for this degradation mode, which is described in the following section.

II. ACCELERATION FACTOR MODELING

A. AF modeling using F2F approach

The field measured data provide the realistic evaluation of module degradation rate. One field is considered as an accelerated testing site to estimate the degradation rate in another field. In our work, Arizona is regarded as the accelerated testing site. Isc is the most affected metric by encapsulant browning. Therefore, AF is defined as the ratio of Isc degradation in field-1 to that in field-2, as per equation (1).
Envelop discoloration is a photo-thermal degradation where the chemical reaction mechanism is governed by UV intensity, temperature and humidity. The individual or synergistic effect of micro-climatic factors on the encapsulant discoloration have been studied using three different physical models: the Arrhenius equation, the Modified Arrhenius equation, and the Modified Peck’s equation.

The Arrhenius equation gives the basic relationship between the degradation rate, temperature and activation energy, as given in equation (2)

\[ R = Ae^{-\frac{E_a}{kT}} \]  

The Arrhenius equation has been modified to account for the effect of UV radiation as per equation (3).

\[ R = Ae^{-\frac{E_a}{kT}}(UV)^n \]  

Similarly, UV term has been incorporated in standard Peck’s equation, which considers the effect of humidity in a chemical reaction. It is represented by equation (4) as follows

\[ R = Ae^{-\frac{E_a}{kT}}(UV)^n(RH)^m \]  

where \( R \) = \( I_{sc} \) degradation rate (%), \( A \) = pre-exponential factor, \( E_a \) = activation energy (eV), \( m \) = UV exponent, \( n \) = RH exponent, \( k \) = Boltzmann constant (\( 8.617 \times 10^{-5} \text{ eV/K} \)), \( T \) = module temperature (K), \( UV \) = UV irradiance (W/m²), \( RH \) = relative humidity (%).
The hourly weather data such as global irradiance, ambient temperature and humidity were obtained from the Typical Meteorological Year (TMY) database. The ambient temperature data were taken from the weather stations closest to the site. The module temperature in field was calculated using the Sandia model [6], given in equation (5).

\[ T_{\text{mod}} = E e^{a+b(WS)} + T_{\text{amb}} \quad (5) \]

where \( WS \) = wind speed (m/s), \( T_{\text{amb}} \) = ambient temperature (K), and \( E \) = plane of array (POA) irradiance (W/m²). \( a \) and \( b \) are empirically determined coefficients dependent on the module types and mounting configurations. For open rack mounting and modules with glass/cell/polymeric backsheet construction, the values of \( a \) and \( b \) are -3.56 and -0.075 respectively [6].

The UV irradiance for any site is assumed to be 5% of POA [7]. Only the daytime (POA irradiance \( \geq 40 \text{ W/m}^2 \)) weather data is considered for our analysis since the modules are subjected to UV light only during the sunshine hours. The module’s RH is calculated using the model used by Kempe [7].

B. AF modeling using A2F approach

The field testing offers the realistic evaluation of any degradation mode and its mechanism, however, it takes a long time for that degradation to occur at a significant level. In order to save the time, accelerated stress tests are designed to simulate the module degradation similar to field-induced failure modes and mechanisms. It also facilitates to study the influence of an individual stressor under controlled condition, which is generally not possible in the outdoor environment. The acceleration factor is determined from models relating time-to-failure (TTF) in an accelerated testing environment to TTF in the field. The IEC 61215 qualification test includes an UV pre-conditioning test where modules are exposed to UV light with total UV dosage is equivalent to 15 kWh/m² in 280-400 nm with at least 5 kWh/m² in 280-320 nm at module temperature 60°C±5°C. This UV dose is not enough to meet 20+ years of field exposure.

An accelerated UV stress test was performed in Ci4000 Atlas Xenon-arc Weather-Ometer where eight MSX-05 mini-modules were exposed to UV light. Three different module temperatures were maintained by attaching insulation of varying thicknesses on the module backsheet. The chamber RH was kept constant at 65%±3%. The module temperature was measured at the center. The measured \( I_{\text{sc}} \) degradation corresponding to three specified temperatures are used to calculate the activation energy. The details of this work is presented in another paper of this conference.

III. RESULTS AND DISCUSSION

The results obtained from the two approaches of modeling are described below:

A. Field to field degradation

The models stated in previous section were applied to degradation data retrieved from some 18-21 year-old discolored modules installed in Arizona (AZ), New York (NY) and Colorado (CO). These modules were characterized with outdoor I-V tracing and translated to STC condition. The annual degradation rate in \( I_{\text{sc}} \) was calculated from their nameplate ratings and the age of the module. Fig. 3 presents the individual distribution of module \( I_{\text{sc}} \) degradation rate under different climate fields.

![Fig. 3 Distribution of \( I_{\text{sc}} \) degradation rate (%/year) of field-deployed modules at Arizona (AZ), New York (NY) and Colorado (CO) sites.](image)

Fig. 4 shows the UV fluorescence images of modules deployed at Arizona (AZ) and New York (NY) climates. The discoloration area in AZ module is limited within the cell busbars, whereas it is spread over a larger region and extended beyond the busbar interconnects of NY module. The reason for shrink discolored region in AZ module is due to high temperature, which enhances the oxygen diffusion rate into the laminate and hence lesser discoloration. On the other hand, NY module was operated at lower temperature and under high ambient humidity. Both these factors have impacted to greater discoloration area. It demonstrates that the oxygen bleaching plays an important role in encapsulant degradation.

![Fig. 4 UV fluorescence images of a cell from the modules installed at (a) Arizona and (b) New York climates.](image)
The acceleration factor for two climate types – Cold and Dry (NY) and Temperate (CO) when compared to Hot and Dry (AZ) is calculated using equation (1) and the results are presented in TABLE I. It also shows the obtained values of Ea, which are calculated from three model equations given in (2)-(4).

### TABLE I

<table>
<thead>
<tr>
<th>Field-1</th>
<th>Field-2</th>
<th>Ea (eV)</th>
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</thead>
<tbody>
<tr>
<td>AZ</td>
<td>NY</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.28</td>
</tr>
</tbody>
</table>

As shown in Table I, the Arrhenius model yields negative Ea for both NY and CO due to higher I_sc degradation rate in NY when compared to AZ. Though AZ modules experiencing higher UV irradiance and operating temperatures, the oxygen bleaching process also dominates in AZ, countering the discoloration. The rate of oxygen diffusion into the module increases with temperature. Again, the RH is greater in NY causing faster discoloration. Hence, this model accounting only temperature does not fit for this degradation mechanism. The Ea estimated from modified Arrhenius equation is around 0.31 eV, which lies in the range reported by others [8]. The Ea from Modified Peck’s equation is much higher. The Modified Arrhenius model better estimates the Ea for encapsulant discoloration and hence is used for further analysis.

After substituting Ea in modified Arrhenius equation (2), the hourly acceleration factor for NY and CO climates was determined and plotted in Fig. 5(a) and (b), respectively. The plots indicate a marginal increase in acceleration factors over the winter as compared to summer. This is because Arizona receives more UV light in the winter as compared to Colorado and New York. The degradation rate predicted for NY and CO climates is 0.10%/year and 0.055%/year, respectively.

![Fig. 5 Hourly variation of acceleration factor during daytime for Arizona field to (a) New York field, and (b) Colorado field.](image)

### B. Accelerated testing to field degradation

Fig. 6 shows the percent hourly I_sc degradation at different module temperatures (77°C, 107°C and 123°C). This result is analyzed in detail in another paper of this conference.

![Fig. 6 Percent I_sc degradation for mini-modules after four weeks of UV stress testing as a function of temperature](image)

Generally, high temperature (>120°C) could invoke other degradation modes along with discoloration. Due to these reasons, data corresponding to 123°C were disregarded. The linear model is fitted and the activation energy is computed from slope. The estimated value of activation energy is 0.27±0.11 eV, which aligns with the reported values in literature [8].

The acceleration factor is determined by substituting the experimentally-obtained value of activation energy in equation (6). The annual daytime (plane of array irradiance > 40 W/m²) for AZ site is 4105 hours, which is equivalent to an average of 11.24 hours/day.
where $T_{\text{acc}}$ = module temperature under accelerated testing (K), $T_{\text{field}}$ = module temperature at field operating condition (K), and $UV_{\text{acc}}$ = UV intensity falling over the front surface of module under accelerated testing (W/m²), and $UV_{\text{field}}$ = UV intensity over module surface installed at outdoor field (W/m²).

Fig. 7 shows the hourly variation of AF for Arizona field during the daytime. The mean value of AF is 15.4. There are several spikes that represent AF as high as 250 and this are attributed to low temperatures and low UV intensity, particularly at the dawn.

The mean $I_{sc}$ degradation rate in the accelerated UV testing at 77°C is 0.0021% per hour. The predicted degradation rate for encapsulant discoloration in Arizona climate is 0.000136% per hour. While considering the daytime of 4105 hours in a year and uncertainty errors, the degradation rate is predicted to be 0.37±0.04%/year, which falls within expected range of actual field-measured value (0.42%/year). The field degradation rate was computed from modules exposed to around 20 years in Arizona field. The model is validated against the field measured data and can be used to predict the degradation rate for any location, provided the hourly weather data is available.

**IV. CONCLUSIONS**

A modeling approach has been presented to determine the acceleration factor and the degradation rate for encapsulant discoloration in climate-specific field. It utilizes the degradation data from outdoor field and indoor accelerated tests, each of these methods has their own advantages and limitations. Different physical models have been tested and it is found that Modified Arrhenius model gives good fit to obtain the activation energy for browning mechanism. Activation energy estimated using accelerated UV testing was 0.27±0.11 eV. The $I_{sc}$ degradation rate predicted from A2F approach for encapsulant browning for Arizona field is 0.37±0.04% per year. Such prediction will be useful to ensure 25+ years warranty limit in the field under different climate zones.

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**REFERENCES**