Early Detection of Encapsulant Discoloration by UV Fluorescence Imaging and Yellowness Index Measurements

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Abstract — The early detection of encapsulant discoloration in the indoor accelerated UV-stressed mini-modules were carried out using non-destructive methods, such as UV fluorescence (UVf) imaging, yellowness index (YI), and IV measurements. Eight lab-fabricated 9-cell mini-modules having glass/backsheet construction with two kinds of EVA, UV-cut EVA and UV-pass EVA, were experimented. Mini-modules with UV-cut EVA suffered from yellowing, which is clearly evident from UVf images and ΔYI (not to the naked eyes), whereas mini-modules with UV-pass EVA showed the signs of delamination above the cell area without any discoloration in the UVf images. Also, the activation energy for encapsulant discoloration was determined based on %Isc drop and ΔYI data.

Index Terms — accelerated stress testing, activation energy, colorimetry, delamination, encapsulant discoloration, UV fluorescence.

I. INTRODUCTION

Encapsulant is a key component of photovoltaic (PV) module structure, which protects the solar cells from harsh external stresses. Environmental stressors such as UV radiation, high temperature and moisture influence the chemical, mechanical, optical and electrical properties of encapsulant. As a consequence, there is a gradual decrease in transparency and/or loss of interfacial adhesion [1]. Ethyl vinyl acetate (EVA) is the popular choice of encapsulant for crystalline-silicon PV modules. Some additives such as UV absorber and adhesion promoter are added to EVA matrix to minimize the discoloration and loss of adhesion due to UV radiation and temperature. EVA browning and delamination are few of the most commonly observed degradation modes in the field-deployed modules, particularly in hot climates [2]. Suleske has reported that about 89% of 1865 investigated modules have browning defect at APS-STAR, Phoenix, AZ, United States [3].

The transparent EVA degrades under long exposure to UV radiation and high temperature, and induce yellow color that converts to dark brown as degradation progresses over time. Discoloration is generally visible from naked eyes only after the color becomes darker. Moreover, its quantification is subjective to the person doing visual inspection. Many researchers performed the current-voltage (I-V) measurements to quantify the performance loss due to discoloration through the reduction in output power (P_{max}). However, P_{max} could be influenced by many degradation modes from which it would be difficult to isolate the effects of discoloration [4]. For example, the reduction in fill factor (FF) due to solder bond degradation mode is very common in almost all climates and it may affect only power without affecting short-circuit current (I_{sc}). Hence, it becomes vital to include other performance parameters (such as I_{sc}, V_{oc} and FF) and characterization tools, which would provide early and reliable detection of discoloration and delamination in the field and accelerated stress tests.

Delamination is another major degradation mode observed in the field deployed PV modules. The major drivers for the delamination are- 1) the stress exerted at the interface from residual thermal stresses or from external mechanical stress applied on the module, 2) the deteriorated interfacial bonding due to attack from heat, UV and moisture. Delamination creates new interfaces- a) glass/air and air/EVA in case of glass/EVA delamination, b) EVA/air and air/cell front in case of cell front/EVA delamination[5]. Delamination causes the optical decoupling between the solar cell and encapsulant which reduces I_{sc}. It also allows more accumulation of moisture and acetic acid which leads to corrosion of cell metallization. Sánchez-Friera et al. observed power loss of 11.5% in 12 years exposed PV modules due to delamination[6].

In this work, the photo-thermal degradation of mini-modules with UV-cut and UV-pass EVA was investigated by the means of non-destructive characterization tools, such as UV fluorescence (UVf) imaging, yellowness index (YI), and I-V measurements. The activation energy (E_a) for encapsulant discoloration was also calculated using Arrhenius model on ΔYI data and compared with that obtained from %Isc drop under accelerated UV testing. Miller et al. quantified the activation energy based on transmittance loss, which lies in the order of 30-60 kJ/mol (or 0.31-0.62 eV) [7].

II. METHODOLOGY

The samples used for this study were eight lab-fabricated mini-modules of the representative glass/EVA/cell/EVA/ backsheet construction rather than glass/EVA/glass coupon construction conventionally used by the other researchers in their accelerated test setup [3].

Encapsulant Used: These mini-modules were categorized into two sets based on EVA type used to encapsulate the solar cells: UV-cut EVA (UVC) and UV-pass EVA (UVP). As shown in Fig. 1 the UV-cut EVA absorbs the radiation below 360 nm wavelength and protects the anti-reflective coating (ARC) of cells and the backsheet from severe degradation, whereas UV-pass EVA allows the transmission of UV light to
the cell to slightly improve the cell performance at the risk of ARC and backsheet degradation.

Three mini-modules from each set underwent accelerated UV exposure testing while one is kept as a control module to ensure the repeatability of measurements to avoid random errors. As shown in Fig. 3, the backsheet of mini-modules and the laminate edges were covered by wide aluminum tape to prevent the oxygen diffusion into the laminate. This approach prevents the bleaching action of oxygen and accelerates the browning degradation due to UV, temperature and possibly acetic acid generated during lamination and UV exposure. Further, as shown in Fig. 4, three different module temperatures (64°C, 73°C and 78°C) were achieved simultaneously in the same UV chamber by attaching an insulation material of varying thickness at the backsheet. This novel technique of achieving three different temperatures in a single chamber helps in reducing test time, cost and resources.

Module Fabrication: As shown in Fig.2, the nine cells in each mini-module were obtained by laser cutting of a single mono-Si cell. Each cell in the module are individually accessed through individual cell ribbons for performance measurements. The EVA was cured at a temperature of 150°C for 20 minutes. Tedlar-Polyester-Tedlar (TPT) backsheet was used at the back while a tempered glass of 8 x 8 inches² dimension from Solite was used at the front. These mini-modules were tested using a solar simulator at STC to obtain their electrical parameters. $I_{sc}$, $V_{oc}$ and FF of the cells in all these mini-modules were around 1 A, 0.6 V and 73%, respectively.

Accelerated UV Testing: The accelerated UV stress testing was performed in a walk-in UV chamber equipped with rack housing for test samples as shown in Fig. 5. A total UV irradiance sensor was placed inside the chamber coplanar to module surface to measure the UV irradiance intensity. The two
sets of mini-modules were stacked next to each other on the test rack inside the UV chamber to reduce variations in the test conditions. The mini-modules were exposed to UV irradiance (300-395 nm) of 215 W/m² at a chamber temperature of 50°C under dry heat. A T-type thermocouple was attached on the backsheet (between backsheet and aluminum tape) behind the center cell of each module. The module temperature was continuously monitored using a data acquisition system at an interval of one minute.

Measurements: UV-fluorescence (UVf) imaging is a non-contact and non-destructive method that allows the fast and early detection of the discolored encapsulant, especially during the early stages of yellowing which is not visible to the naked eyes. The UV excitable chromophores present in yellow region of encapsulant emit fluorescence when irradiated under black/UV light. As shown in Fig. 6, the UVf imaging setup consists of a visual camera and a UV illumination system comprising of two arrays of 15 UV lamps (385-395 nm) each inclined at an angle of 45° w.r.t. the module surface. This is done to minimize glare in the visual images due to UV light reflection.

The colorimetric measurements were performed on the mini-modules to quantify YI by using a calibrated Xrite Ci-60 spectral radiometer. YI is a metric designated to measure the change in color of EVA. YI was measured on both sides of the busbar-ribbon in each cell to increase the statistical reliability of collected data as well as to capture any irregularity in the browning pattern. The change in YI under accelerated stress testing at three different module temperatures was used in Arrhenius model to calculate the activation energy for encapsulant browning. Another method applied for $E_a$ estimation was based on cell $I_{sc}$ degradation.

III. RESULTS AND DISCUSSION

Fig. 7 shows the UVf images of 3 mini-modules with UV-cut EVA taken at different stages of UV exposure testing. After 200 kWh/m² of UV dosage, there is yellowing at the cell center but not at the cell edges in the module with oxygen diffusion-prevented backsheet. In the test module, the cell area is hotter than the inter-cell area because of solar gain in the semiconductor material due to thermalization effect. It seems the acetic acid, a catalyst for encapsulant discoloration formed at the hot cell center does not diffuse to the cool inter-cell area whereas the acetic acid formed at the hot cell edges diffuse to the inter-cell area. The change in color is more pronounced in modules operating at higher temperature, which is also evident from YI data. This indicates that the degradation rate aggravates with increase in temperature. The yellowing is further enhanced with longer UV exposure of 400 kWh/m².

<table>
<thead>
<tr>
<th>UVC-cut Mini-module</th>
<th>UV dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 kWh/m²</td>
<td>200 kWh/m²</td>
</tr>
<tr>
<td>UVC-1 (Low T) 64°C</td>
<td><img src="fig7a.jpg" alt="Image" /></td>
</tr>
<tr>
<td>UVC-2 (Mid T) 73°C</td>
<td><img src="fig7d.jpg" alt="Image" /></td>
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<tr>
<td>UVC-3 (High T) 78°C</td>
<td><img src="fig7g.jpg" alt="Image" /></td>
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Fig. 7. UVf images of UVC mini-modules at different temperatures and UV dosage levels under accelerated UV testing.

Fig. 8 shows the UVf images of 3 mini-modules with UV-pass EVA taken at different stages of UV exposure testing. It shows no yellowing over the cell area or the non-cell area.
However, a complete delamination of encapsulant was observed over the cell area in UVf images but not in visual inspection. This effect was more pronounced in the mini-module operating at higher temperatures and becomes more noticeable in the third stage of UVf images. The delamination could be due to the different or no adhesion promoting additives used in the EVA. The results infer that UVf technique has also the capability to detect delamination in module at a very early stage.

Encapsulant yellowing should cause a reduction in $I_{sc}$ due to loss in transmission of light to the solar cells. Fig. 9 shows a drop, though small, in $I_{sc}$ for both UVC and UVP modules with increase in UV dosage. $I_{sc}$ drop is higher in the UVC module operating at higher temperature. This result supports the UVf findings. It also demonstrates that the UVf imaging technique is a powerful tool to detect the early sign of discoloration, which is neither visible to the naked eyes nor fully quantified by $I_{sc}$ loss. On the other hand, the $I_{sc}$ loss is significantly higher at low temperature for the UVP module as compared to the UVC module and also, more importantly, is nearly the same for the UVP modules irrespective of temperatures indicating that the optical decoupling due to delamination is nearly the same irrespective of its delamination severity.

Fig. 10 and 11 show the comparison of $\Delta YI$ of each cell of mini-module with UV-cut and UV-pass EVA respectively along with the control module. The center cell shows a higher $\Delta YI$ across all the UVC modules. This could be due to less available area for the acetic acid to diffuse out of the cell for the center cell as compared to the edge cells. Fig. 12 shows the $\Delta YI$ of the mini-modules with UV-cut EVA and UV-pass EVA, respectively. $\Delta YI$ of all UVC modules is positive and increases with the increase in module temperature. It confirms the occurrence of yellowing, which is in close correspondence with the UVf results. While $\Delta YI$ values of all UVP modules are negligibly small and close to each other. This indicates that there is not much change in color in these modules over or between the cells.

![Figure 8](image1.png)

Fig. 8. UVf images of UVP mini-modules at different temperatures and UV dosage levels under accelerated UV testing.

![Figure 9](image2.png)

Fig. 9. Percent $I_{sc}$ degradation of mini-modules after 400 kWh/m$^2$ UV exposure in the chamber testing at low, mid and high temperatures.

![Figure 10](image3.png)

Fig. 10. $\Delta YI$ values for cells of different UVC modules along with control module (UVC 1 low temperature; UVC 2 mid temperature; UVC 3 high temperature).

![Figure 11](image4.png)

Fig. 11. $\Delta YI$ values for cells of different UVP modules along with control module (UVP 1 low temperature; UVP 2 mid temperature; UVP 3 high temperature).
In the early degradation stage, the $I_{sc}$ drop is too small to give clear indication of encapsulant browning. As shown in Fig. 13, the change in $I_{sc}$ and $P_{max}$ is too small as compared to change in yellowness index for UVC modules. Thus, YI could be used as early detectors even before $P_{max}$ is affected. But, in case of UVP modules, as shown in Fig. 14, $I_{sc}$ drop is insignificant as there is no browning in these modules.

The activation energy for encapsulant discoloration was determined by two different approaches using Arrhenius model: cell $I_{sc}$ degradation and change in YI. A linear regression model is fitted for the stress testing as shown in Fig. 15. Activation energy estimated from $I_{sc}$ drop is 0.81 eV while from YI is 0.61 eV. The reason for the difference is that the $I_{sc}$ is dictated by whole cell area (yellowed and non-yellowed region) while YI is taken only at the yellowed region. This also infers that YI provides better estimation of activation energy compared to that from the cell $I_{sc}$ drop. However, if $I_{sc}$ is measured only in the yellow region using a mask technique or is normalized for the yellow area only using an image processing technique, the correlation between YI and $I_{sc}$ can be significantly improved.

Limited correlation in UV-cut EVA: Overall, $I_{sc}$ is dictated by both yellowed (at the cell center) and non-yellowed (cell edges) areas whereas YI is measured only by the yellow area at the center. So, only limited linear correlation exists between $I_{sc}$ and YI when yellowing is only at the cell center and can be detected only by UVf method, not by naked eyes or visual camera.

No correlation in UV-pass EVA: Overall, this material does not undergo yellowing but the interface between cell front-surface and EVA is clearly delaminated as observed in the UVf study. The delamination severely affects $I_{sc}$ but not the YI. Therefore, no correlation could be expected between $I_{sc}$ loss and yellowness index increase.
IV. Conclusion

An indoor accelerated UV testing was performed on mini-modules with different EVA types while blocking the oxygen diffusion and maintaining at different temperatures in a single chamber run. UVf technique provides visual evidence of discoloration in mini-modules with UV-cut EVA and traces of delamination in mini-modules with UV-pass EVA at the very early stage of the issues. It is also verified from YI data. The correlation between YI and $I_{sc}$ can be improved by normalizing $I_{sc}$ value for the yellow-only area using an image processing technique. The activation energy is calculated using both $I_{sc}$ drop and YI increase. This study clearly indicates that UVf images and YI values can be used as very early detectors of forthcoming encapsulant browning and delamination problems.

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REFERENCES


