Photovoltaic Lifetime & Degradation Science Statistical Pathway Development: Acrylic Degradation

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ABSTRACT

In order to optimize and extend the life of photovoltaics (PV) modules, scientific and mechanistic statistical analytics must be performed on a large sample of materials, components and systems. Statistically significant relationships were investigated between different mechanistically based variables to develop a statistical pathway diagram for the degradation of acrylic that is important in concentrating photovoltaics. The statistically significant relationships were investigated using lifetime and degradation science using a domain knowledge semi-supervised generalized structural equation modeling (*semi-gSEM*. Predictive analytics and prognostics are informed from the statistical pathway diagram in order to predictively understand the lifetime of PV modules in different stress conditions and help with these critical lifetime technologies.

Keywords: Domain Analytics, Statistical Analytics, Acrylic, Degradation, semi-gSEM, Lifetime and Degradation Science

1. INTRODUCTION

The durability and lifetime performance of photovoltaic (PV) systems has been identified as a key hurdle for further widespread adoption of these promising energy technologies.[1,2] A successful guarantee of the industry standard minimal 25 year lifespan depends upon informed engineering design and performance prediction based upon a strong scientific foundation. Unfortunately for the bankability of PV, current qualification standards and testing procedures, and consequently the technology solutions designed to accommodate them, do not reflect this reality.[3] A more reasonable approach to assessing the performance capacity of these systems, underpinned with a sound theoretical basis, is necessary to meet the needs of the growing PV industry.

1.1 Lifetime and Degradation Science (L&DS)

Lifetime and Degradation Science (L&DS) is based on mechanistic insights into degradation and moves beyond observational studies into domain-guided statistical analytics. Quantifying contributors to overall system performance loss is a complex problem, as even individual degradation effects within PV systems are not fully understood, and multiple effects acting in concert can become even more complicated. This necessitates the development of a methodical approach that incorporates both domain knowledge guidance as well as statistical techniques to correlate observed degradation to existent stressors, relate these modes and mechanisms to known physical processes, and quantify their rates both within and between a wide range of stress levels.[4–6] This reliance upon the physics of failure for analysis and prediction is the cornerstone of L&DS.[7–9] System performance loss is quantified in terms of stresses and responses, which provides useful diagnostic information for continuous system improvement and performance forecasting.[10–21] This can be contrasted to conventional reliability methods which only extrapolate upon a single dominant failure mode to quantify product quality and predict rates of binary failure.[3,10–12,22,23]

Reliability of Photovoltaic Cells, Modules, Components, and Systems VI,
edited by Neelkanth G. Dhere, John H. Wohlgemuth, Kevin W. Lynn, Proc. of SPIE
Vol. 8825, 88250D · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2024717

1.2 Structuring Studies for Good Statistical Practice

In order to facilitate the unbiased analysis necessary for good scientific practice, solid statistical evidence must be present in collected data to support claims about active degradation pathways operating within systems under study. All measured aspects of the system are treated as variables, with each measured value considered an observation. Observations of variables are grouped by sample of origin and the simultaneous value of a common variable such as a particular stressor. These coincident observations, tracking several variables across multiple samples as their common variable changes, are compared to one another to draw statistical conclusions about the relationships between measured variables. The number of variables that can be included in the final analysis is limited by the formula $v \leq n - 2$, where n is the number of coincident observations, and v is the number of variables that can be included. In other words, n-2 is the absolute upper limit for v. More often, one would hope that n$\gg$v, i.e. n is much bigger than v to have a large residual degrees of freedom to accommodate the complexity of true underline structure and assess the significance of parameters efficiently. In the different case when the number of possible predictors, p is much much larger than the number of observations, n, such as, in the case of gene expression data with thousands of genes from a few samples (subjects), a dimension reduction or feature selection technique must be used first to overcome this large-p-small-n problem, an on-going hot research topic. After that, a final model relating the data with ν (as a function of the reduced p) variables can be built. This is a different research topic not covered in this paper. Thus, a study must be pre-structured to contain an amount of samples adequate to allow the coincident observations necessary to accommodate the number of variables being measured[24]

1.3 Role of Acrylic in Photovoltaics

Photovoltaic systems are comprised of many distinct technologies working together. The use of reflectors to intensify the irradiance available to PV cells is a technique utilized for boosting the performance of high concentration, low concentration and mirror augmented photovoltaics. Under such circumstances, the durability of the acrylic material ties directly to the performance of the entire PV system.[7,8]

2. EXPERIMENTAL PROCEDURE

2.1 Samples and Exposures

Two formulations of PMMA (fabricated with evacuated extrusion to reduce residual monomer) used in the present study are UV transparent (UVT) and multipurpose absorbing (MPA) acrylic samples from Replex Plastics, Inc.[25] Each contains different amounts of a Tinuvin type UV stabilizer. The thicknesses of the acrylic samples were approximately 3 mm. The two formulations of PMMA acrylic were exposed in a Q-Lab QUV accelerated weathering tester[26] to a modified-ASTM G154 cycle 4[27] of $1.55\text{W/m}^2\text{/nm}$ of UVA 340 irradiance at 70° (irradiance only QUV). For the irradiance only exposure, there were 19 samples exposed to four dose steps, a sample was retained at every dose step and there were two additional base line samples. The four exposure steps consisted of 100, 192, 288 and 1000 hours.

2.2 Evaluations

Transmission plus reflectance spectra were taken on a Filmetrics PARTS-UV instrument for each sample from 245 to 700 nm. Transmission plus reflectance measurements were converted into absorbance per centimeter for a volumetric property for each sample. Average and incremental induced absorbance to dose curves were calculated for the absorbance per centimeter spectra for each sample as described in Murray et. al.[4] Four IAD values were chosen at particular wavelengths for mechanistic metrics (IAD1 at 274 nm, IAD2 at 297 nm, IAD2p at 339 nm and IAD3 at 440 nm). IAD1 represents the degradation at the fundamental absorption edge. IAD2 and IAD2p show the degradation of the UV stablizer package. IAD3 is a metric for the yellowing region.[4] YI values were calculated for the transmission plus reflectance spectra using the Filmetrics software according to ASTM E313.[28]

2.3 Initial Acrylic Degradation Pathway Library

A degradation pathway library for acrylic PMMA is shown in Figure 1 as an example of degradation due to UV absorber bleaching, PMMA degradation and water absorption.[4, 29–40] Many degradation pathways are not currently shown for ease of viewing. This degradation pathway library was used for an initial understanding of the statistical degradation pathway.

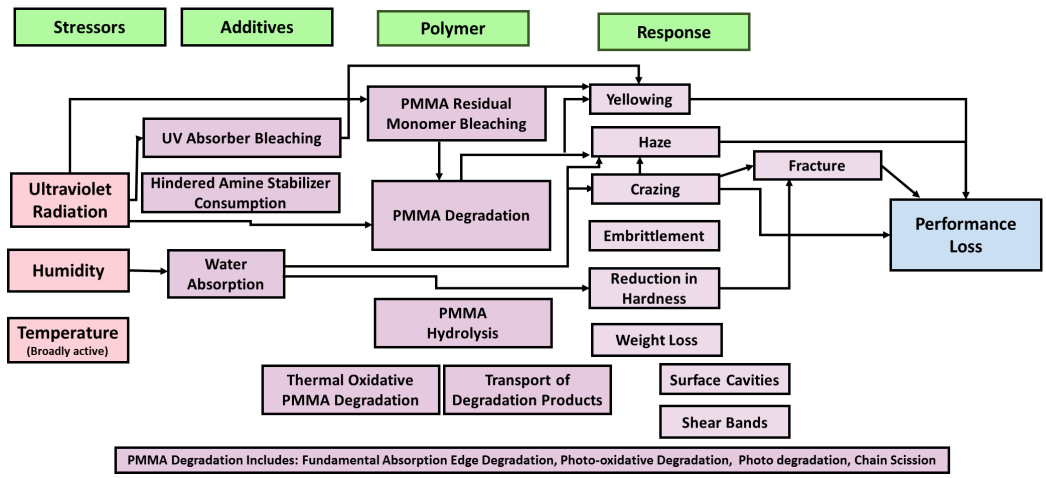

Figure 1. Example Acrylic Degradation Pathway informed by domain analytic shows a sampling of degradation pathways for acrylic based from different stressors.

2.4 Semi-Supervised Generalized Structural Equation (*semi-gSEM*) Methodology

Principle 1 of the *semi-gSEM* methodology[24] was applied to the entire data set for each exposure condition and acrylic formulation. Principle 1 looks at each relationship in the Markovian spirit; therefore, examines relationships between a pair of variables without influence from the previous variables once the current predictor variable is observed in the statistical pathway diagram. The functional forms that were used in the analysis included simple linear, quadratic, simple quadratic, exponential, logarithmic, and linear change point. Mechanistic variables included in the analysis were IAD1, IAD2, IAD2p and IAD3. The performance metric was YI and the stress condition was total UVA-340 dose in MJ/m^2.

3. RESULTS

The absorbance per centimeter (Abs/cm) spectra for UVT (Figure 2 (left)) and MPA (Figure 3 (left)) show the change in the volumetric properties of the sample after exposure to the irridiance only QUV exposure for baseline and 0-4 dose steps.

The performance metric YI values are shown in Figure 4 for UVT and MPA formulations of acrylic. The UVT acrylic had a faster yellowing rate than the MPA acrylic.

The statistical pathway diagram for UVT acrylic in the irradiance only exposure is shown in Figure 5. IAD1 and IAD3 were used as the mechanistic variables in this statistical pathway diagram. IAD2 and IAD2p could not be included because the UVT acrylic contained no measurable UV stabilizer. The statistical pathway diagram for UVT shows a strong statistically significant relationship (SSR) (adjusted R^2 of 0.93) from the stress (IrradTot) of UVA-340 irradiance to IAD1. There is a statistically significant relationship from IAD1 to YI (adjusted R^2 of 0.94). The SSR between IAD1 and IAD3 is weak (adjusted R^2).

The statistical pathway diagram for MPA acrylic in the irradiance only exposure is shown in Figure 6. IAD1, IAD2, IAD2p and IAD3 were used as the mechanistic variables in this statistical pathway diagram. There is a SSR between stress (IrradTot) and IAD1 (adjusted R^2 of 0.34), but with 2 small and 1 large p-values. The SSR between IrradTot and IAD2 shows a low adjusted R^2, but all low p-values. There is a significant relationship between IAD1 and YI.

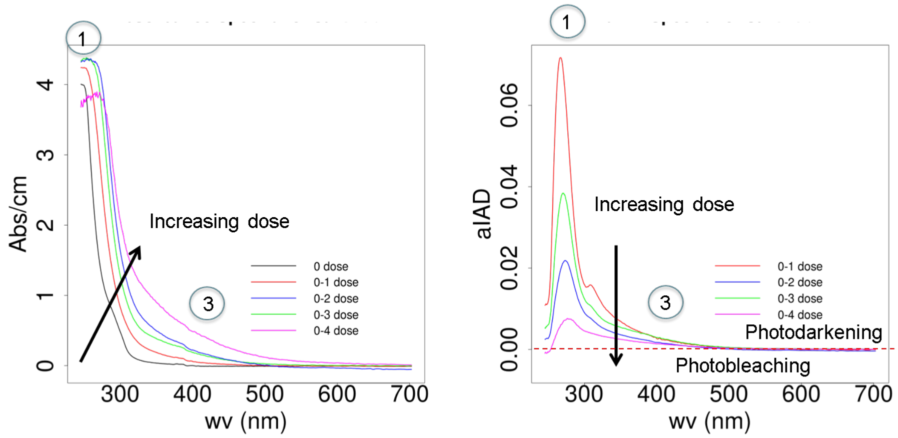

Figure 2. Abs/cm for ultraviolet transparent (UVT) grade poly(methyl methacrylate) (PMMA) for exposures in the QUV accelerated weathering tester to UVA-340 irradiance (irradiance only QUV exposure) for baseline, one to four dose for 1 example samples (left). The corresponding average IAD for UVT grade acrylic (right).

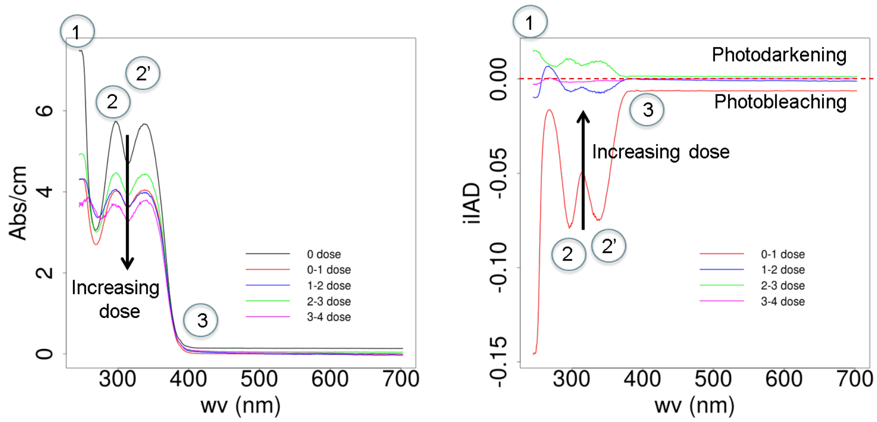

Figure 3. Abs/cm for multipurpose absorbing (MPA) grade poly(methyl methacrylate) (PMMA) for exposures in the QUV accelerated weathering tester to UVA-340 irradiance (irradiance only QUV exposure) for baseline, one to four dose for 1 example samples (left). The corresponding incremental IAD for MPA grade acrylic (right).

4. DISCUSSION

The Abs/cm spectra for UVT acrylic shows degradation at the fundamental absorption edge of the base acrylic resin (Region 1) and an increase in the yellowing of the sample (Region 3) (Figure 2 left). The average IAD for UVT shows a higher rate of photodarkening from the base line to 1 dose sample shown the larger positive IAD values. The rate of photodarkening begins to decrease for subsequent dose steps. The IAD curve from 0-3 dose shows an increase in the photodarkening rate compared to 0-2 dose and 0-4 dose (Figure 2 right). The average IAD is a good metric for showing continuous degradation such as the degradation of the fundamental absorption edge and yellowing. The YI has a large increase in yellowing from baseline to dose 4 (Figure 4) which is visibly apparent in the samples. The statistical pathway diagram shows a strong relationship between the stress and IAD1 (Figure 5). This relationship represents the fundamental absorption edge degradation of the base acrylic resin due to the UV irradiance. The strong SSR between IAD1 and yellowing shows that the degradation of the base resin contributes strongly to the yellowing of the bulk acrylic material. The relationship between IAD1 and IAD3 show a much less SSR. Although IAD3 represents yellowing, it is only evaluated at 440 nm while the YI is integrated over a large region; therefore, IAD3 is not the best metric for yellowing in the acrylic samples.

The Abs/cm spectra for MPA acrylic shows minimal degradation at the fundamental absorption edge of the base acrylic resin (Region 1) and the yellowing region (Region 3) (Figure 3). This is due to the protective nature of the stabilizer package. The stabilizer package begins to photobleach prior the degradation of the fundamental

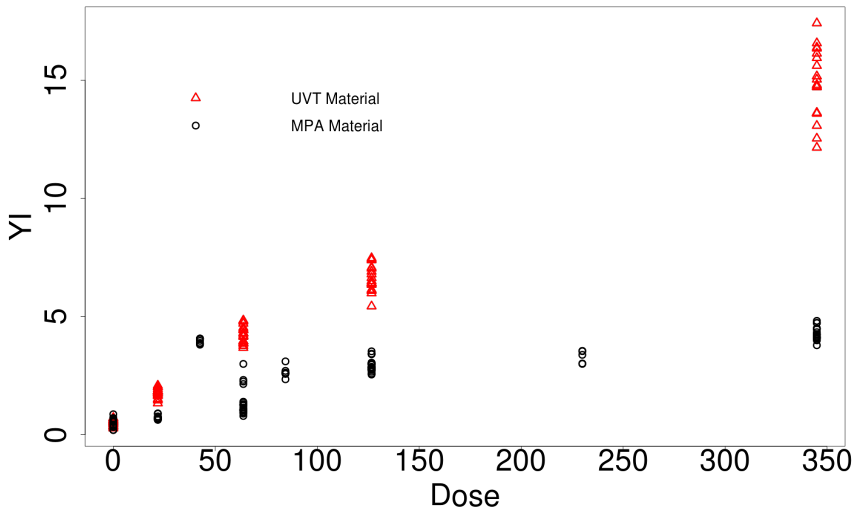

Figure 4. YI values for UVT (triangle) and MPA (circle) grade acrylics for baseline, and one to four dose for all samples.

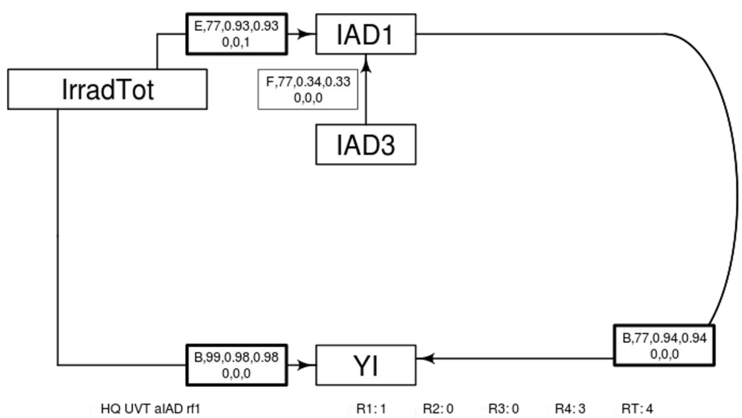

Figure 5. Statistical pathway diagram generated for UVT grade acrylic degradation in the irradiance only QUV exposure with the most relationships shown for Principle 1 with the average mechanistic variables IAD1 and IAD3 and the performance metric of YI. Information on each relationship is described in the box. The information contained is functional form, number of observations, R^2, adjusted R^2, P-value 1, P-value 2 and P-value 3, respectively. The strength of the SSR is summarized by the line width of the SSR border based on the R2 value to aide visualization (below 0.2 not shown, R1 has the thinnest border (0.2-0.5), R2 (0.5-0.7), R3 (0.7-0.9) and R4 the thickest ($\geq$0.9)). The functional forms are designated as A (simple linear), B (quadratic), C (simple quadratic), D (exponential), E (logarithmic), and F (linear change point).

absorption edge. The incremental IAD shows an initial high rate of photobleaching from the baseline to the 1 dose. Subsequent dose steps do not have an increase in the rate between 1-2, 2-3 and 2-4 dose steps. Incremental IAD is good metric to see transient degradation such as photobleaching of residual monomer or UV stabilizer. The statistical pathway diagram for MPA (Figure 6) shows less significant relationships between total irradiace to IAD1 and total irradiance to IAD2. These SSR do not seem to show a significant relationship between stress and IAD1 or IAD2, due to the protective nature of the UV stabilizer package, there was not a large amount of degradation in the material. However, the low p-values for the relationship between total irradiance and IAD2 suggests that there is a strong significant relationship that will appear as more degradation occurs (low p-values

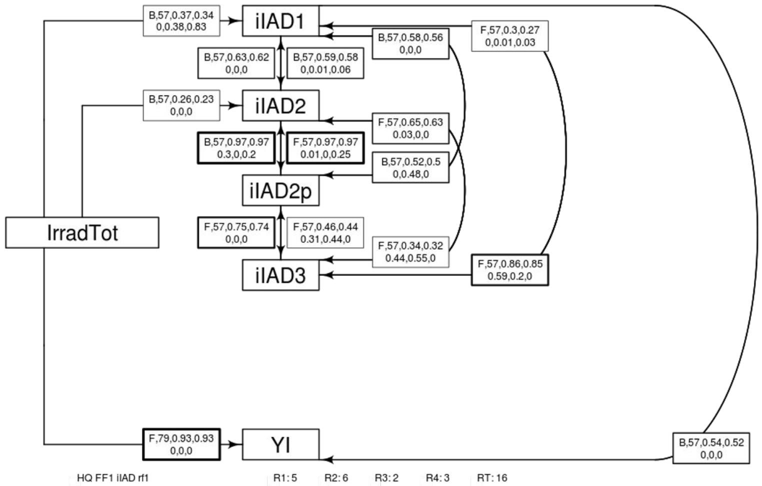

Figure 6. Statistical pathway diagram generated for MPA grade acrylic degradation in the irradiance only QUV exposure with the most relationships shown for Principle 1 with the incremental mechanistic variables IAD1, IAD2, IAD2p and IAD3 and the performance metric of YI. Information on each relationship is described in the box. The information contained is functional form, number of observations, R^2, adjusted R^2, P-value 1, P-value 2 and P-value 3, respectively. The strength of the SSR is summarized by the line width of the SSR border based on the R2 value to aide visualization (below 0.2 not shown, R1 has the thinnest border (0.2-0.5), R2 (0.5-0.7), R3 (0.7-0.9) and R4 the thickest ($\geq$0.9)). The functional forms are designated as A (simple linear), B (quadratic), C (simple quadratic), D (exponential), E (logarithmic), and F (linear change point)

indicate significant relationships). As more stress is applied to the sample there will be more degradation of the fundamental absorption edge. The volumetric metrics show that the UV stabilizer is protecting the base resin, which reduces the yellowing rate of MPA compared to he UVT grade. There is a significant relationship between IAD1 and YI, which further indicates that the degradation of the fundamental absorption edge initiates the yellowing of the material.

5. CONCLUSIONS

This data science approach for critical technology challenges, including lifetime and degradation science and the semi-gSEM methodology, moves studies from observational to domain-guided statistical analytics which is unbiased, reproducible and scientifically founded. The statistical analytics includes the development of a degradation pathway libraries, exploratory data analysis, degradation mechanisms and statistically significant relationships. The next step is to extend from statistical analytics to predictive analytics and prognostics.

In the case of the acrylic degradation, the semi-gSEM statistical pathway diagram suggests that the degradation of the fundamental absorption edge (IAD1) led to yellowing (YI) in the sample. The Tinuvin type stabilizer package (IAD2 and IAD2p) were being photobleached which protected the fundamental absorption edge degradation and therefore prevented extreme yellowing of the sample.

ACKNOWLEDGMENTS

Funding for the statistical analytics reported here from the Bay Area Photovoltaic Consortium Prime Award No. DE-EE0004946 and the Subaward Agreement No. is 60220829-51077-T on acrylic exposures from Ohio Third Frontier, Photovoltaic Program Award Tech 11-060. Research was performed at the SDLE Center at Case Western Reserve University, which was established through funding through the Ohio Third Frontier, Wright Project Program Award Tech 12-004. We appreciate the diligent efforts of Mark Schuetz of Replex Plastics, Sean Fowler of Q-Labs. Sample tracking and data management support was provided by REDCap[41] funded by the Clinical and Translational Science Collaborative (CTSC) grant support (1 UL1 RR024989 from NCRR/NIH).

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