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Abstract— **With increasingly large-scale deployments of photovoltaic (PV) modules to meet global energy demands, interest in better establishing modules' lifespans is growing. We report on the performance of co-extruded polyolefin- (PO)-based backsheets as environmentally friendly alternatives to fluoropolymer-reinforced polyethylene-terephthalate (PET)-based backsheets using three hygrometric accelerated test conditions. After completing cumulative 4000 hours of aging, we analyzed data from electrical performance (I-V), surface roughness (gloss), and appearance (L, a*, b* color) characterizations to quantify degradation rates, quantify the corresponding activation energy, and cross-correlate between the characteristics examined, thereby providing insights into the relationship between physical characteristics and operating performance.**

Keywords—BackFLIP, photovoltaic (PV), backsheet, damp heat testing, durability, DuraMAT, IEC TS 62788-7-2, PET, polyolefin, polyamide, UV weathering

I. BACKGROUND AND INTRODUCTION

Photovoltaic (PV) backsheets play an important role in the durability of PV modules. They are cost effective packaging materials with enhanced mechanical strength that also protect the electrical components of the modules against physical and chemical stresses such as UV radiation, temperature variation, humidity, electrical shunting, moisture, and fires. Backsheets themselves must withstand different environmental conditions during their service life outdoors [1]–[3]. Thus, their weathering stability is also critical.

Backsheets are often three-layer laminates consisting of an adhesive inner layer, an electrically insulating core layer, and a weather-resistant outer layer [4]. In some cases, they have been observed in field inspections to be vulnerable to cracking and delamination, thereby compromising module insulation and performance, in addition to presenting unsafe working conditions for personnel maintaining PV systems [5]. Furthermore, photodegradation of poly(ethylene-co-vinyl acetate) (EVA) encapsulant can generate acid species,

accelerating chemical degradation and facilitating cracking of the inner backsheet layer [4].

Backsheets are typically made with an electrically insulating polyethylene-terephthalate (PET) core. It is further layered with adhesives and fluoropolymers for improved durability. A common backsheet construction is laminated layers of PET film with poly-vinyl fluoride (PVF, named "Tedlar") in a three-layer PVF/PET/PVF configuration, or "TPT". Due to difficulty of decomposing and recycling fluoropolymers and to lower production environmental footprint, efforts have been made to develop fluorine-free backsheets. Polyolefins (POs) have been shown to be environmentally friendly alternatives to PET [6], that when co-extruded, also reduce the risk of delamination and fabrication cost.

Using steady state aging experiments, we investigate the durability of developmental PO-based backsheets relative to traditional PET- and polyamide (PA)-based backsheets on the market. To evaluate the degradation modes and rates of degradation of commercial and novel backsheets, we performed accelerated stress experiments in a double-blind study. Seven different backsheets in coupon and mini-module (MiMo) form were subjected to three hygrometric and four photolytic aging conditions for 4000 hours[7]. Degradation models were developed by correlating accelerated aging with changes in electrical performance, appearance, mechanical performance, polymer chemical structure, crystal structure, and degree of crystallinity. Accelerated testing will be compared with natural weathering in Albuquerque, NM, and Cocoa, FL, to identify characteristics common to artificial and natural aging so we can predict degradation. For conciseness, this abstract focuses on the Arrhenius modeling of thermal degradation of backsheets induced in the three hygrometric tests.

II. EXPERIMENTAL

A. Test Specimens

Seven different backsheets from three groups of polymers *for the core layer were used to fabricate coupon and MiMo*

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samples. Table 1 lists the backsheets studied: three traditional ("TPT," "PPE," and "KPf"); one known bad ("AAA"); and three novel PO-based backsheets (PO-1, PO-2, and APO). PPE is a laminate of pigmented PET/unpigmented PET/EVA; KPf is a laminate of polyvinylidene fluoride (PVDF)/PET/fluorinated coating; and AAA is a coextruded backsheet composed of PA/blended PA and polypropylene (PP)/PA layers.

TABLE 1: POLYMER BACKSHEETS INVESTIGATED IN THIS STUDY.

Arbitrary Index	Backsheet	Construction	Comment
BS-1	PO-1	Coextruded	New
BS-2	PO-2	Coextruded	New
BS-3	TPT	Laminate	Traditional (reference)
BS-4	APO	Coextruded	New
BS-5	PPE	Laminate	Traditional (contemporary)
BS-6	AAA	Coextruded	Known bad
BS-7	KPf	Laminate	Traditional (contemporary)

MiMos were prepared using non-tempered float glass (Planibel Clearvision, AGC Inc.) with no antireflective coating. A single 156-mm, stabilized Si-Cz, p-PERC solar cell (diced into four equal pieces) was connected with ribbon to an edge-mounted junction box. EVA encapsulant of a UV-transparent front layer and a UV-blocking rear layer was laminated to attach the MiMo components. They were first outdoor light-soaked and then verified using electroluminescence (EL) imaging and electrical performance (I-V) measurements.

Coupon specimens consisted of polymer backsheet that was run through the same lamination process to provide the same thermal history as the MiMos.

B. Accelerated Testing

In this abstract, we focus on samples weathered in the three hygrometric accelerated test conditions listed in Table 2. Combined temperature/humidity chambers (e.g., BTX-475, ESPEC North America Inc.) were used, and weathering was performed at read points of 0, 1000, 2000, 3000, and 4000 hours of cumulative duration.

TABLE 2. HYGROMETRIC TEST CONDITIONS EVALUATED IN THIS STUDY.

Arbitrary Experiment Index	UV Irradiance (Wm^{-2} at 340 nm)	Temperature (°C)	Relative Humidity (%)
1	0	85	85
2	0	65	85
3	0	45	85

C. Characterization Methods

As described in Ref. [7], MiMo and coupon samples were characterized for: color (L, a*, and b*), gloss (at 20°, 60°, and 85°), visual appearance, optical microscopy, wide-angle X-ray scattering (WAXS) of the polymer crystalline structure, and Fourier transform infrared (FTIR) polymer chemical structure. Electrical performance of the MiMos was characterized using I-V flash testing (at 1000 W·m^{-2}) followed by EL imaging. Destructive characterization, including mechanical tensile testing, DC breakdown voltage, and differential scanning calorimetry (DSC) of the crystalline content, were conducted after cutting the coupons into smaller specimens. For this presentation, we will focus on the I-V characteristics.

D. Arrhenius Modeling of Degradation

The degradation of certain characteristics is thermally activated, and the effective rate-limiting reaction of a degradation mode can be modeled with an Arrhenius fit:

$$k = A \, e \left[\frac{-E_a}{RT} \right] \qquad (1)$$

where k is the degradation rate (units s^{-1}), A is the frequency factor (units s^{-1}), E_a is the activation energy (kJ mol^{-1}), R is the gas constant (8.3145 J mol^{-1}K^{-1}), and T is the temperature (K). Where applicable, the change in maximum power will be evaluated to determine the activation energy of degradation induced by the accelerated tests.

III. RESULTS AND DISCUSSION

The electrical performance, as change in maximum power ΔP_{max}, averaged for all seven backsheets over 4000 hours in the three hygrometric test conditions, is shown in Fig. 1. P_{max} decreases with increased exposure time with the most damage observed in test condition 1 at 85 °C and 85% relative humidity. P_{max} degradation is similar up to 2000 hours, beyond which PET-based backsheets 3, 5, and 7 degrade significantly more (~3x), indicated by a steeper inflection. From analysis of the
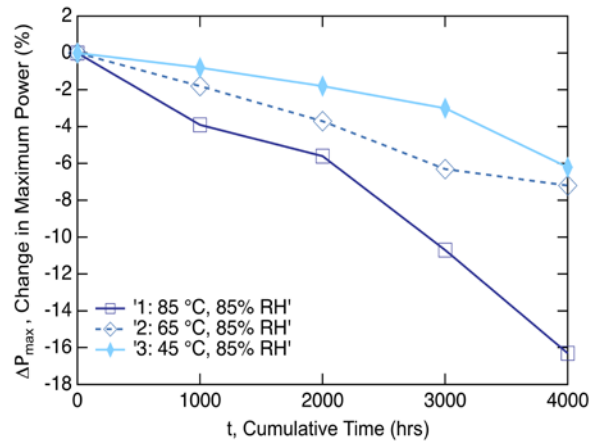

Fig. 1. Performance, ΔP_{max}, averaged for all seven backsheets, in the three hygrometric aging experiments. It decreases with increased exposure time for all hygrometric tests, with test 1 at 85 °C and 85% relative humidity being the most damaging. Modified from Ref [7].

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series and shunt resistance, performance degradation (ΔP_{max}) results from corrosion of the busbars, ribbons, and solder in addition to damage to the cell [7].

Hygrometric degradation of P_{max} is thermally activated. Thus, the rate-limiting reaction can be modeled with an Arrhenius fit (Equation 1). Using backsheet 4 (coextruded APO) MiMo as an example, we consider the linear relationship of change in P_{max} with time (Fig. 2). From Equation 1, the slopes of these lines are then analyzed to determine their relationship with inverse temperature (of the three hygrometric test conditions, as shown in the Fig. 2 inset). The slope in the Fig. 2 inset is multiplied by R to obtain E_a for the P_{max} degradation. The E_a values for the MiMos of each backsheet are listed in Table 3. It is important to note that as ΔP_{max} of backsheets 3, 5, and 7 degraded more beyond 2000 hours, a different rate and, therefore, a different mode of degradation was assumed. Hence, data points beyond 2000 hours were not considered for these backsheets.
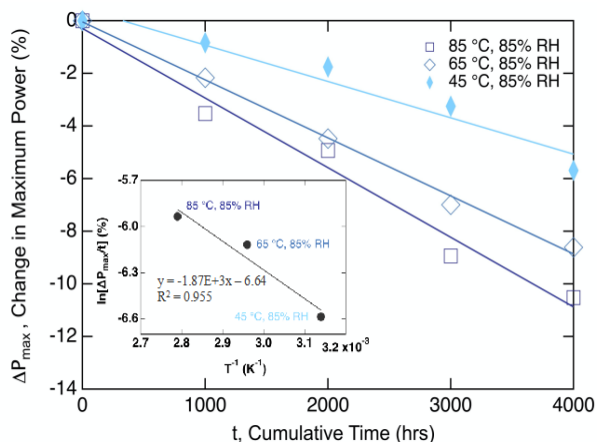

Fig. 2. Change in maximum power, ΔP_{max}, of the recent PO-based backsheet 4 over time in the three hygrometric tests. Inset: Change in natural log of the slopes from Fig. 2 with inverse temperature of the three hygrometric tests. Activation energy, E_a, for P_{max} is obtained from the slope of this graph.

From the table, E_a ranges from 15 kJ mol^{-1} to 28 kJ mol^{-1}, being similar within the range of variation for two standard deviations. The activation energy of diffusion of water has been reported to be 18 kJ mol^{-1} [8] and 129 kJ mol^{-1} for hydrolysis of PET [9]. For all backsheets, E_a is consistent with the diffusion of water. This suggests ΔP_{max} in Fig. 1 results from the mass transport of water through the backsheets, rather than the degradation of the backsheet materials. Minor variation in E_a in Table 3 may result from differences in the backsheets (diffusivity of water, porosity, etc).

IV. SUMMARY

To extend the lifespan of PV modules, it is important to understand the long-term effects of operating conditions on physical characteristics and thus on, PV module performance. Here, we have described initial calculations of E_a for P_{max} degradation of new and traditional backsheets after 4000 hours

of accelerated hygrometric aging. The BackFLIP study will compare E_a for each of the characteristics examined (gloss, color, etc) so that the effect of each degradation mode can be predicted and compared relative to MiMo performance. The most significantly affected characteristics and test conditions will be identified and correlated to provide a comprehensive picture of backsheet degradation.

TABLE 3. E_a FROM P_{MAX} IN FIG.1.

	Backsheet	E_a, effective activation energy [kJ mol^{-1}]
1	PO-1	15.3 ± 15
2	PO-2	19.7 ± 15
3	TPT	23.9 ± 13
4	APO	15.6 ± 15
5	PPE	20.5 ± 14
6	AAA	28.4 ± 15
7	KPf	10.1 ± 14

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