ASSESSING PHOTOVOLTAIC MODULE LIFE FROM LONG-TERM ENVIRONMENTAL TESTS

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ABSTRACT

A 20-to-30-year lifetime for photovoltaic modules is a necessary element of a viable technology base addressed to large scale terrestrial photovoltaic applications such as residential or central station power generation. An important ingredient in the successful achievement of this lifetime target is understanding failure mechanisms related to temperature, humidity and electrical bias, including forecasting their long-term effects in different application environments. This paper describes updated information from an ongoing research program aimed at identifying key temperature-humidity-bias degradation mechanisms and assessing the significance of the mechanisms relative to long-term operation at various sites in the United States.

Assessing product lifetime from accelerated tests involves developing a correlation between accelerated test levels and duration and application stress levels and durations. The analytical procedure for correlating time-varying field exposures to constant stress accelerated environments was described in a previous IES paper (Ref. 1). Its application requires a detailed knowledge of product failure-mechanism stress dependencies and field-site stress levels. In the previous paper the site specific nature of the procedure was readily developed with the use of SOLMET weather data. However, the product failure-mechanism rates were obtained from early parametric testing results on a variety of module designs. The series of long-term tests described in the previous paper have now been successfully completed on a number of generic module designs. A thorough updated review of failure-mechanism rate dependencies and life assessments have been completed for both temperature and combined temperature/humidity environment testing.

Key Words: Accelerated, Degradation, Lifetime, Aging, Environmental Qualification

I. INTRODUCTION

As part of the U.S. Department of Energy's national photovoltaics program, the Jet Propulsion Laboratory's Flat-Plate Solar Array Project is conducting research directed at achieving the technology base required for future large-scale photovoltaic applications. An important element of this technology base is the availability of photovoltaic module designs with 20 to 30-year lifetimes. To understand the temperature-humidity and electrical-bias degradation mechanisms of typical photovoltaic modules and materials and to be able to forecast relative product lifetimes at various field sites, a series of long-term accelerated environmental tests has been conducted on 80 flat-plate modules. Twelve design configurations were represented in the module test set. In parallel with the testing activities an analytical structure was developed to correlate various field site exposures and accelerated test levels based upon the detailed knowledge of module failure-mechanism stress dependencies and site stress levels. Ref. 1 presents the resulting procedure for reducing a time-varying field exposure to an equivalent duration at a simplified or constant stress so that correlations can be made between field site exposures and accelerated tests. The next step, also described in Ref. 1, is the application of accelerated parametric tests on photovoltaic modules to identify significant failure mechanisms and to obtain degradation-rate dependencies. Section II of this paper briefly reviews the scope of the parametric test series and includes refinements in inspection methods to characterize failure mechanisms. Also discussed in Section II are densitometric measurements on color negatives to obtain color degradation rates in encapsulant materials and the effectiveness of using specific electrical tests such as insulation resistance, capacitance and dissipation factor to characterize failure mechanisms.

The previous paper illustrated the combined analytical and accelerated parametric test concept by using limited temperature-humidity test results from early environments. The current focus is on complete failure-rate determinations for temperature and combined environments and how failure-rates and module degradation change when humidity is incrementally added to temperature. The results given in Section III, represent an updated assessment of product lifetimes for a wide cross section of generic module designs. Section III also gives module power performance data including the determination of 20-year equivalent field values associated with module degradation rates and the specific contribution of encapsulant transmission losses and solar cell corrosion mechanisms to total power loss.

The results presented will aid designers in choosing the appropriate and most cost-effective qualification test levels for equivalent long-term field site exposures for photovoltaic modules. Additionally, generic module designs can be selected to ensure maximum product life.

II. MODULE PARAMETRIC TESTING

A series of long-term module tests was begun in August 1981 at Wyle Laboratories (Huntsville, AL) to identify the key temperature-humidity failure mechanisms of photovoltaic modules and obtaining their rate dependencies. Completing this task required over two years of extensive parametric testing and included twelve module design types at various stress levels. The test set of eighty PV modules from six different manufacturers represented a variety of common designs.

Specific objectives of the Wyle parametric tests were first to understand the temperature/humidity and electrical bias degradation mechanisms of typical photovoltaic modules and materials. This included significant degradation mechanisms that would result in module failure or reduced performance such as corrosion of the metalized cell grids used for current collection, discoloration of the encapsulant, corrosion of cell-to-cell interconnects, delamination or embrittlement of back covers, and diffusion of edge seals into the encapsulant. Second, the tests would establish generic functional relationships among temperature, humidity, electrical-bias and time for the observed module degradation mechanisms. Rate dependencies could then be derived for the key degradation mechanisms.

Rationale and selection of acceleration test environments, exposure durations for the parametric tests and test schedules were presented in the previous paper, Ref. 1. In general, the environments were aligned with those typically used in the semi conductor industry and with stress levels used in reliability and endurance temperature-humidity testing in existing (parallel) PV research program activity. The six environments implemented at Wyle Laboratories included temperature-only (85°C and 100°C) and temperature-humidity (85°C/85% RH, 85°C/70% RH, 70°C/85% RH and 40°C/93% RH). Two modules of each type were subjected to the listed environments; one subjected to an additional forward voltage-bias stress and one with its positive and negative terminals joined to electrically short the module. Details of the voltage-bias circuit were presented in the previous paper, Ref. 1.

Inspection Improvements

The visual and electrical performance methods of inspection used in observing and recording module degradation mechanisms were an important and integral part of the parametric testing. Inspection frequency, matched to equal increments of exposure on a log scale, and the basic means of visually monitoring and recording module performance via examinations and individual module "road maps" remained unchanged for the duration of the test series, see Ref. 1 for details. However, significant improvements were achieved in generating more quantitative measures of degradation by improving the primary means of recording and comparing module visual and electrical performance. The use of color photography at each inspection point, implemented near the beginning of the parametric test program, has provided a historical record of visible mechanisms such as encapsulant discoloration with exposure time. The photographs with a color key standard adjacent to the frame, allowed the magnitude of degradation on one module in an 85°C/85% RH chamber to be directly compared with that of other modules of the same type in the 70°C/85% RH, 85°C/70% RH or 40°C/93% RH chambers. Correlating the failure data in this manner resulted in generating early visible mechanism rates based upon qualitative data, which was subject to variations in photo print exposures and photo comparisons with the unaided eye. To eliminate these latter variables and rely more precisely on the color key standard, the photograph negatives were compared using a densitometer. Referring to Fig. 1, a full spectrum light source is directed via a 1 mm diameter aperature through the module negative and then into a filter selector assembly and electronic sensor. The sensor then digitizes the value of diffuse and filtered (red, green or blue) light. The color density value is inversely proportional to a function of the transmittance, equation (1),

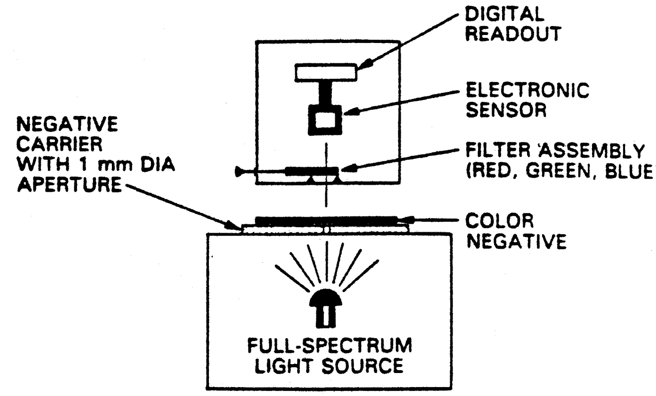

Figure 1. Densitometer detail.

$$\text{Color Density} = f\left(\frac{1}{\text{Transmittance}}\right) \quad (1)$$

and decreases as the negative area under examination becomes lighter. For example, a module failure mechanism such as encapsulant discoloration (darkening) would result in progressively lighter values on the module negative during accelerated aging and exhibit decreasing color density values. Since the predominate visual module degradation mechanism in the test set was a yellow to orange discoloration of the encapsulant, the desitometers blue filter with a range from 400 to 500 nanometers was sensitive to the corresponding subtle color changes in the negative. The densitometer data therefore provided a more quantitative approach to track color degradation and improved the confidence in failure rate determinations for the above mechanism.

In addition to the visual inspections, two types of electrical performance measurements were conducted on each module. Current-voltage (I-V) curves, normalized to standard reference conditions of 25°C and 100 mW/cm^2 in a solar simulator, provided the primary quantitative electrical measure of degradation associated with various mechanisms. A secondary set of measurements typically used in the insulation systems and coatings industries were implemented to track the aging characteristics and corrosion protection performance of the encapsulant. At each inspection point, a module capacitance and dissipation factor (ratio of energy dissipated to energy stored per cycle) was obtained with a digibridge to monitor thermal aging. Research conducted by Fort and Pletsch, has shown that thermal aging of typical insulating materials resulted in similar changes for these measured properties. During aging, these properties increase in value with a tip-up characteristic described in Ref. 4. In addition, if the resulting data for these properties corresponded to either a separation of test environments or module construction, then aging rates could be determined for various encapsulant systems by using this electrical method.

Recording the insulation resistance values at applied voltages of 200 vdc and 1000 vdc was also included at inspection points to evaluate an encapsulant's ability to protect against corrosion of the solar cell surface, metallization and interconnect materials. From the coatings industry, work by Leidheiser, Ref 5, shows that in order for organic coatings or polymer films to protect a metallic substrate against corrosion they should have a high electrolytic resistance. This correlation prompted the use of the above insulation resistance measurements as an alternate method for characterizing corrosion failure mechanisms.

III. RESULTS

The predominate visual degradation on all module types was encapsulant yellowing which reduces light transmittance to the solar cells and its rate is primarily temperature-dependent. The 85°C and 100°C temperature-only environments along with densitometric measurements were used to determine degradation rates for two popular encapsulant systems that feature ethyl vinyl acetate (EVA) or polyvinyl butyral (PVB) as pottant materials. Other module designs with either a silicone rubber or PVB encapsulant that was protected from the environment by a thin aluminum foil back cover were also included in the test set. However, the visual degradation for these types was negligible and failure rates were not obtained. Fig. 2 compares the time history response of various encapsulant systems using normalized color density measurements. Separation of the 100°C and 85°C temperature-only data for PVB and EVA encapsulated modules provided a means of identifying equal magnitudes of discoloration (yellowing) and collectivily define the rate of degradation for this failure mechanism. Note that the color of silicone rubber and foil protected PVB encapsulants remained unchanged after 1 year of constant temperature. Also, the limits of the densitometer to identify color density in dark saturated areas on the negative is reflected by the hysteresis in the PVB data.

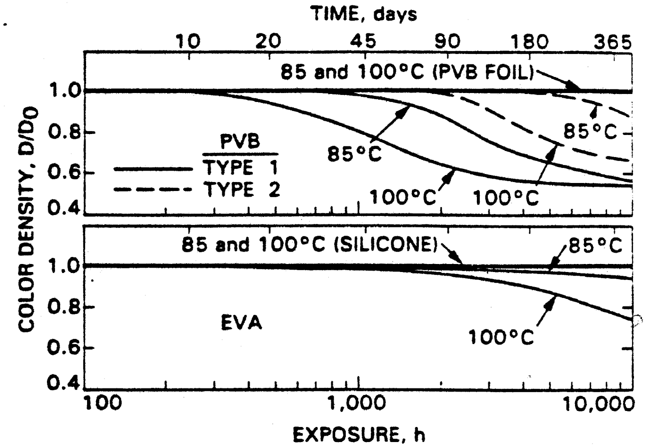

Figure 2. Time history of various encapsulant systems in temperature-only environments using normalized color density.

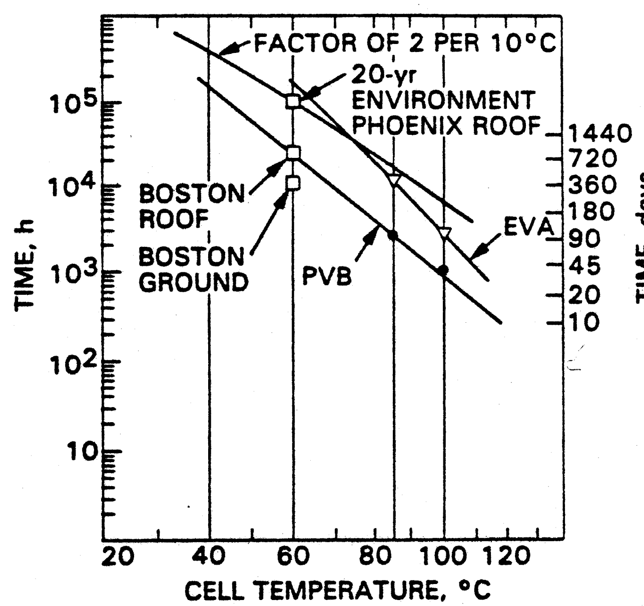

Figure 3. PVB and EVA exposure rate dependence of encapsulant discoloration using color density measurements from 85°C and 100°C test environments.

Referring to Fig. 3 the PVB and EVA rate dependance can now be used to correlate the 20-year field exposure stress for arrays in Phoenix or Boston to equivalent accelerated exposures. This is accomplished by translating the PVB or EVA rates to any one of the three 20-year equivalent environments (Phoenix, Boston roof or Boston ground). For example, modules subjected to 90 days of 85°C for PVB designs or 12 days of 85°C for EVA designs correspond to a 20-year Boston roof exposure for encapsulant discoloration.

Subjecting module designs to several combined temperature-humidity environments resulted in separating the temperature and humidity dependence of the discoloration mechanism for each encapsulant system. Figs. 4 and 5 show that temperature is the major factor in PVB discoloration and the addition of high levels of humidity at high temperature increases the degradation. The same result is observed with the foil protected PVB encapsulant system, but the rate of degradation is proportionally reduced. EVA encapsulant discoloration is solely temperature-dependent as shown by the overlap of temperature-humidity data and has the least failure-rate except for silicone rubber. Figures 4 and 5 clearly indicate the combined environment encapsulant color degradation rate does not follow the relationship documented in Refs. 1 and 2 where the addition of one percentage point change in relative humidity has the same effect as 1°C temperature change. Data from a lower humidity level in a combined environment, such as 85°C/40% RH, would establish the contributing value of relative humidity and correctly model the rate dependence in combined environments.

An example of degradation synergisms related to visual discoloration in a combined temperature-humidity environment is shown in Fig. 6. Failure of an edge seal resulted in accelerated discoloration on the Type I module in an 85°C/85% RH environment compared to two other generic designs (Type II and III) that showed consistant performance. Without a thorough understanding of the failure-mechanism and visual behavior, degradation synergisms can limit failure-rate information.

Secondary electrical measurements, which included capacitance, dissipation factor and insulation resistance data are presented in Figures 7 to 9. Separation of module encapsulant systems resulted from capacitance data and an increased moisture take-up with exposure for silicone and PVB designs, Fig 7. Although no EVA data was available, research by G. Mon et al, Ref. 3, has shown silicone rubber and EVA capacitance data in 85%/85% RH and 85%/98% RH environments to be of the same

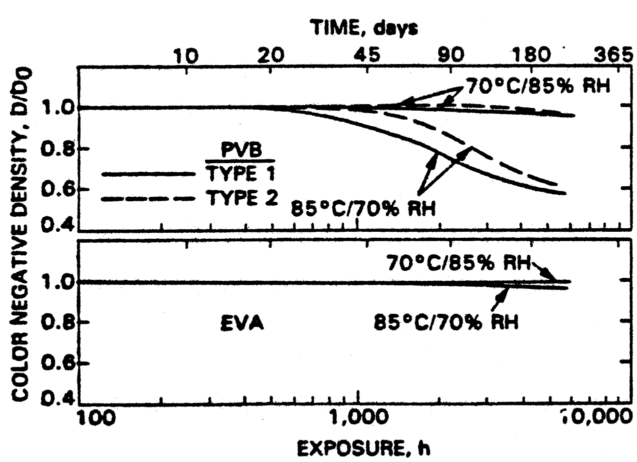

Figure 4. The temperature and humidity dependencies of PVB and EVA discoloration from reciprocal environments of 85°C/70% RH and 70°C/85% RH.

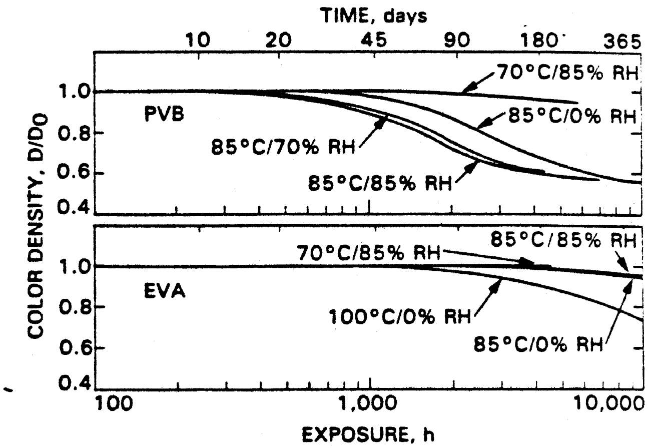

Figure 5. PVB and EVA encapsulant discoloration characterized by temperature-only and combined environments.

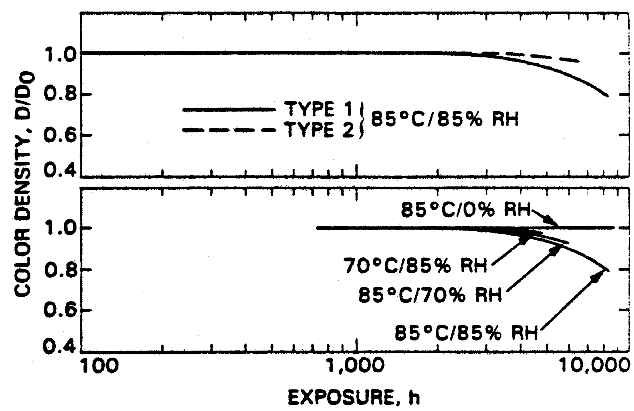

Figure 6. Foil-protected PVB encapsulant discoloration characterized by temperature-only and combined environments.

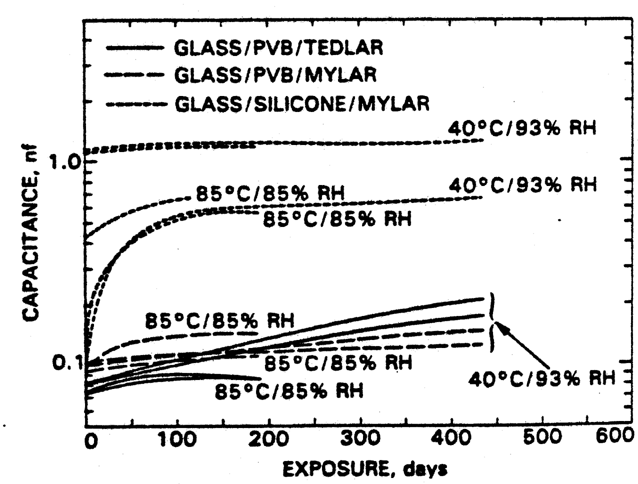

Figure 7. Separation of encapsulant systems using capacitance measurements.

magnitude. Using this reference, the results are consistant with the visual degradation that indicates the insensitivity of EVA-encapsulant modules to humidity.

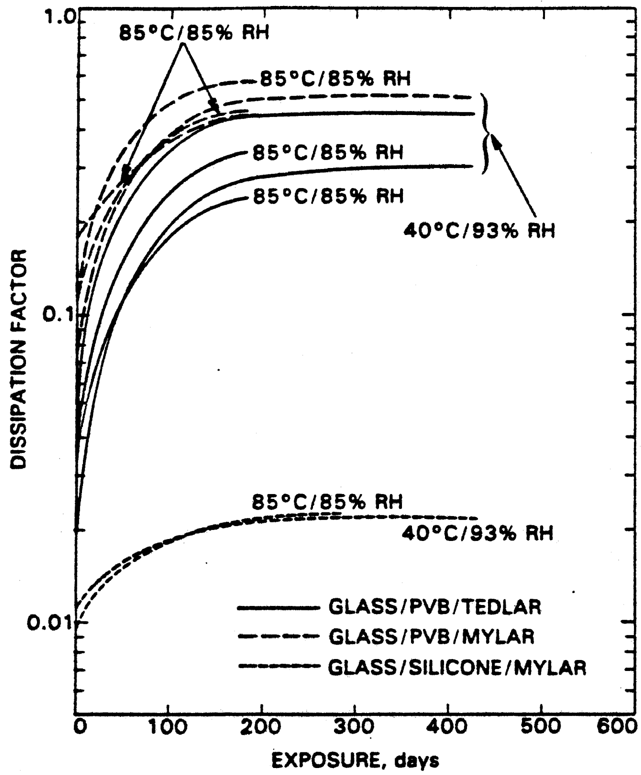

Figure 8. Separation of encapsulant systems from dissipation factor measurements.

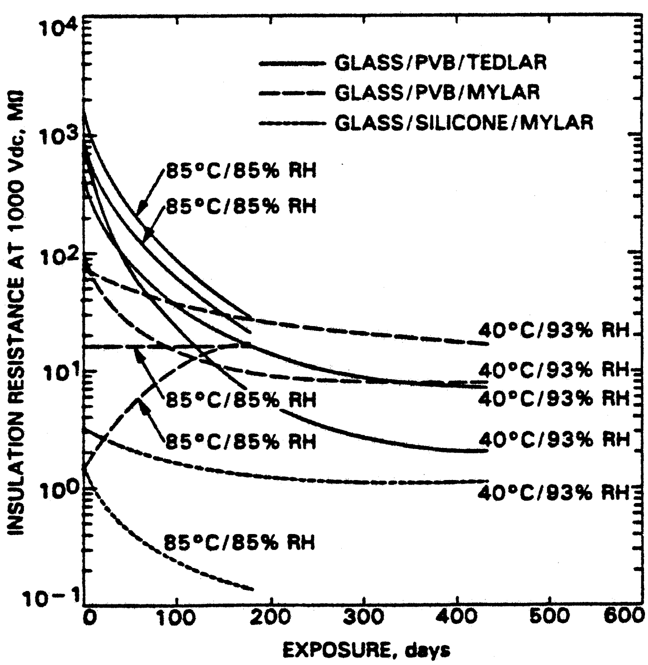

Figure 9. Insulation resistance at 1000 Vdc of various encapsulant systems.

Encapsulant yellowing is typically considered to be a thermal oxidation mechanism and the resistance to moisture is evident when noting the order of magnitude difference between silicone rubber and PVB encapsulants. The dissipation factor data, Fig. 8, is inversely related in that higher values of capacitance reduce the ratio of energy stored to energy dissipated. The result shows the separation of encapsulant systems. Both measurement techniques were insensitive to differences in environments and failed to provide module degradation rates.

As encapsulant moisture take-up increased, the insulation resistance values were reduced. Measurements at the 200 vdc level failed to identify any separation of module construction or test environment. However, at the 1000 vdc measurement level Fig. 9 the silicon rubber values tend toward lower megohm levels. The measurements were useful and aided ones understanding of a failure mechanism but failed to establish environment separations required for obtaining degradation rates.

Module Power Degradation

The specific contribution of encapsulant yellowing and solar cell metallization corrosion mechanisms to the total power loss of various module designs is tabulated in Figure 10. These results, based on I-V curve electrical measurements, compare the effect of temperature-only and combined environments in degrading module electrical performance. The reduction in total module power is due to corrosion (increasing series resistance) and encapsulant yellowing (transmittance). Referring to Figure 10, the benefit of foil protected PVB and EVA in reducing transmittance losses and corrosion mechanisms for three types of metallizations is readily seen. Also, note that PVB/Tedlar designs are more sensitive to high temperature and humidity values as well as to the application of forward electrical-bias than PVB/foil/Tedlar and EVA systems. In high temperature and low humidity environments Titanium-Palladium-Silver metallization offers a slight improvement over Nickel-Solder or printed-Silver contacts. In general, the 85°C/85% RH environment provided the greater degradation, but the overall total electrical performance power reduction is within the project goal of 6%. Also, combined environments accelerated failure mechanisms more readily than temperature-only stresses at temperature levels above 70°C.

IV. SUMMARY AND CONCLUSIONS

Both encapsulant discoloration and metallization corrosion degradation mechanisms for various module designs were characterized from temperature-only and combined temperature-humidity environments. The temperature-humidity environments have led to additional degradation modes and greater degradation than temperature environments. The quantification of long-term temperature-humidity degradation for encapsulant discoloration on a limited number of module designs requires additional data and analysis. The degradation rates that were established were used to correlate accelerated test levels to equivalent 20-year field site exposures for product life assessments.

The use of densitometric measurements to characterize encapsulant discoloration proved to be a more quantitative approach over photo comparisons in determining degradation rates. The densitometer provided the required sensitivity to evaluate the incremental addition of humidity to temperature and added confidence in the rate determinations. The use of second order electrical measurements including capacitance, dissipation factor and insulation resistance only clarified the fundamental understanding of failure mechanisms and failed to provide degradation rate information.

The quantitative (electrical I-V curve) measure of degradation associated with the key failure mechanisms was separated into transmittance (encapsulant yellowing) and series resistance (solar cell metallization corrosion) values. The results presented will aid designers in choosing the appropriate and most cost-effective qualification test levels for equivalent 20-year field site exposures. Additionally, generic module designs can be selected to ensure maximum product life.

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			P/P_O Power Loss									
			Due to Decreased Transmittance					Due to Increased Series Resistance				
Encapsulant	Metallization	Bias	°C/% RH 85/0*	85/70	85/85	70/85	40/93	°C/% RH 85/0*	85/70	85/85	70/85	40/93
Glass/PVB/Tedlar	Ti-Pd-Ag	-	0.97	0.96	0.95	0.98	-	0.97	0.94	0.96	0.98	-
	Print-Ag	yes	0.96	0.93	0.81	0.96	1.00	0.97	0.86	0.85	0.91	0.94
		-	0.95	0.94	-	0.96	1.00	0.99	0.67	-	0.64	0.98
		yes	0.96	0.91	0.85	0.99	1.00	0.99	0.68	0.73	0.80	0.99
Glass/PVB/Foil	Print-Ag	-	0.99	1.00	-	0.99	-	1.00	0.99	-	0.97	-
		yes	0.96	0.98	0.95	1.00	-	1.00	0.96	0.68†	0.95	-
	Ni-Solder	-	0.98	0.99	0.96	0.99	0.99	0.98	0.98	1.00	0.99	1.00
		yes	0.98	0.98	0.95	0.98	-	0.98	1.00	1.00	0.98	-
Glass/EVA/Tedlar	Ti-Pd-Ag	-	0.96	0.99	0.94*	1.00	1.00	0.93	0.95	0.96*	0.97	1.00
		yes	0.96	0.99	0.99	-	-	1.00	0.95	0.91	-	-
Glass/Silicon/Mylar	Ni-Solder	yes	0.99	0.90	0.50†	0.98	-	0.89	0.97	0.97	0.93	-

* Day 365 Results
† Back Cover Failure

Figure 10. Performance Degradation at Day 180.

(4320 hrs).