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Module Encapsulant Diagnostic and Modeling

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Presented at the 2004 DOE Solar Energy Technologies Program Review Meeting
October 25-28, 2004
Denver, Colorado

Conference Paper
NREL/CP-520-37027
January 2005

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Module Encapsulant Diagnostic and Modeling

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ABSTRACT

Encapsulant materials are used in photovoltaic devices for mechanical support, electrical isolation, and protection against corrosion. The ability of an encapsulant to protect against surface corrosion is related to its adhesional strength. The adhesion of candidate encapsulants under accelerated environmental stress was examined to determine what materials have the best hydrolytic stability and are more likely to reduce corrosion rates. Under environmental exposure, the ingress of water has been correlated with increased corrosion rates. The diffusivity of different encapsulants has been measured to determine how long it takes for water to enter a module. The high diffusivity of ethylene vinyl acetate indicates that, even with the use of an impermeable back-sheet, moisture from the sides will diffuse throughout the entire module. To significantly reduce moisture ingress requires a true hermetic seal, the use of an encapsulant loaded with desiccant, or the use of a very low diffusivity encapsulant.

1. Objectives

The processes that contribute to module failure must be understood to produce modules that will perform reliably for 20 years. Service in moist environments is known to be correlated with an increase in the failure rate of photovoltaic (PV) modules; therefore the effects of water are important for failure analysis. Materials must be evaluated to determine how much water can be kept out and if they protect a device against the moisture that does enter.

2. Technical Approach

Determining how long it takes water to enter a module requires knowledge of its diffusivity and solubility. This was accomplished by measuring the transient water vapor transmission rate (WVTR) through encapsulant films using a Mocon Permatron-W 3/31. Assuming Fickian diffusivity (diffusivity is independent of concentration), the transient WVTR can be described by

$$WVTR(t) = \frac{DC_S}{l}\left(1 + 2\sum_{n=1}^{\infty}(-1)^n e^{-\frac{Dn^2\pi^2 t}{l^2}}\right), \qquad (1)$$

where D is the diffusivity, C_s is the saturation concentration, t is time, and l is the sample thickness [i]. The diffusivity determines the time required to reach steady state after which the water saturation concentration is determined by the steady state WVTR. These physical constants permit the modeling of the ingress of moisture in a PV module.

Since the ability of an encapsulant to prevent corrosion is related to its adhesion to a surface, lap shear tests were performed to determine how different materials are affected by environmental stress.

3. Results and Accomplishments

The diffusivity and solubility of water in ethylene vinyl acetate (EVA) and a number of other back-sheet materials and encapsulants were measured so that the ingress of moisture can be modeled (Fig. 1). It was found that EVA had a high diffusivity relative to most materials measured.

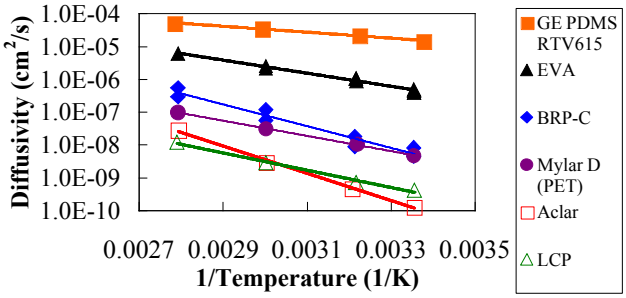

Fig. 1. Diffusivity measurement for several different types of polymers.

The high diffusivity of EVA enables water to enter PV modules rapidly. If a PV module with impermeable glass superstrates and substrates is analyzed with a one dimensional model (by assuming it is infinitely long with a width equal to $2l$), starting with an initially dry encapsulant, and holding the temperature and external humidity constant, then the moisture content as a function of time and distance from the edge can be represented as [i]

$$C(x,t) = C_S + \frac{4(C_s)}{\pi}\sum_{m=0}\frac{1}{2m+1}\sin\frac{(2m+1)\pi x}{l}\, e^{-\frac{D(2m+1)^2\pi^2 t}{l^2}} \qquad (2)$$

A finite element analysis using meterological data was used to determine that using the average temperature and atmospheric water concentration yields overlapping curves with Eq. 2 for long distances and times. For Miami Florida this corresponds to a temperature of 26.7 °C and a relative humidity of 71%.

Figure 2 shows water concentration profiles as a function of time calculated using Eq. 2 for EVA and an experimental encapsulant by BRP Manufacturing Company. The data show that the high diffusivity of EVA allows water to reach the center of the module in a few years. These results are for a 1-D model. For a 2-D model with a square shape, the ingress rate would be nearly twice as fast.

As shown in Fig. 1, the diffusivity of water varies by orders of magnitude for different materials. Since changes in diffusivity have the same effect on the concentration profile as changes in time (Eq. 2), a material with a diffusivity an order of magnitude slower than that of EVA would take an order of magnitude longer to saturate. This is shown in Fig. 2, where after 33 years the BRP material is still dry at distances greater than 8 or 10 cm into the module.

If EVA was replaced by materials with lower diffusivities, significant reductions in water content could be obtained.

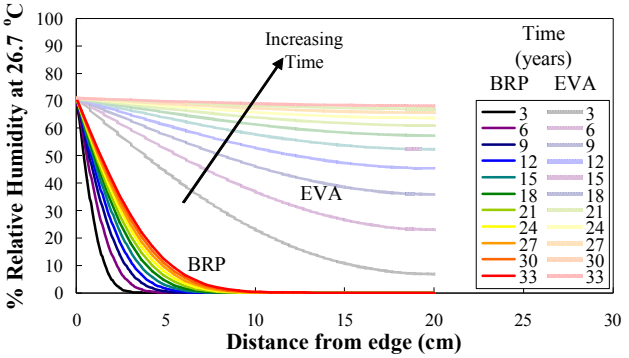

Fig. 2. Moisture ingress as a function of time for two different encapsulants for between 3 and 33 years. The lines were calculated using Eq. 2 and data from Fig. 1 at a temperature of 26.7 °C and 71% relative humidity.

For the case of a breathable back-sheet, water is able to enter a module extremely rapidly. Assuming that the water concentration in the encapsulant is uniform (i.e. $D_E >> D_B$, "D" refers to diffusivity, subscripts "B" and "E" refer to back-sheet and encapsulant properties, respectively) and that the WVTR across the back-sheet is proportional to the concentration change $\Delta C = C(0) - C(l_B)$, then the change in water concentration as a function of time is given by

$$\frac{dC_E}{dt} = \frac{WVTR_{B,Sat}}{C_{E,Sat}.l_E}[C_B(0) \quad C_B(l_B)], \qquad (3)$$

where "Sat" refers to maximum conditions in equilibrium liquid water. With an initially dry module exposed to constant environmental conditions, Eq. 3 can be integrated to determine the water content as a function of time as:

$$\frac{C(t)}{C(0)} = 1 \quad e^{\frac{C_{Sat,EVA}l_{EVA}t}{WVTR_{B,Sat}}} \qquad (4)$$

This yields a half-time for equilibration of [ii]

$$t_{1/2} = 0.693\frac{C_{Sat,E}l_E}{WVTR_{B,Sat}} \qquad (5)$$

As an example, a module consisting of a Tedlar®/ polyethylene terepthalate/EVA back-sheet (WVTR=1.13 g/m^2/day @ 25 °C) laminated to a 0.46 mm thick layer of EVA (C_{Sat}=0.0021 g/cm^3 @ 25 °C) would have an equilibration half-time of 14 hours. For a back-sheet to have an equilibration half-time on the order of 20 years, it would need a WVTR of approximately 1 10^{-4} g/m^2/day. If a WVTR this low was achieved, ingress from the sides would still be a concern as with a double glass laminate.

These calculations have demonstrated that the only way to keep moisture out of a module is to use a hermetic seal. Because of the prohibitive cost of this, the use of materials that resist the effects of moisture is more practical. Since the ability of a material to prevent corrosion is strongly correlated with the diffusion of ionic species within the polymer and the adhesional strength to the surface being protected, lap shear experiments under accelerated environmental conditions were conducted to determine which materials are more likely to give good protection against corrosion.

Figure 3 shows experimental data for the lap shear strength of encapsulant materials after exposure to 85 °C and 85% relative humidity. Here it can be seen that, although EVA has good initial strength, it quickly degrades, losing nearly half of its strength after 1000 hours exposure. This rapid loss in adhesion was probably enhanced by the presence of acetic acid produced as a decomposition product. The silicone polymers failed either cohesively or at the primer-to-polymer interface, leaving at least a primer layer on the glass. Comparison of the data sets using Dow Corning Sylgard 186 demonstrates the importance of the choice of primer on hydrolytic stability. Lastly, the experimental material from BRP had strong adhesion with hydrolytic stability, and it failed cohesively. A cohesive failure is preferential since it still leaves a protective coating on the substrate. The other consideration with a cohesive failure is that the actual adhesive strength could be significantly higher.

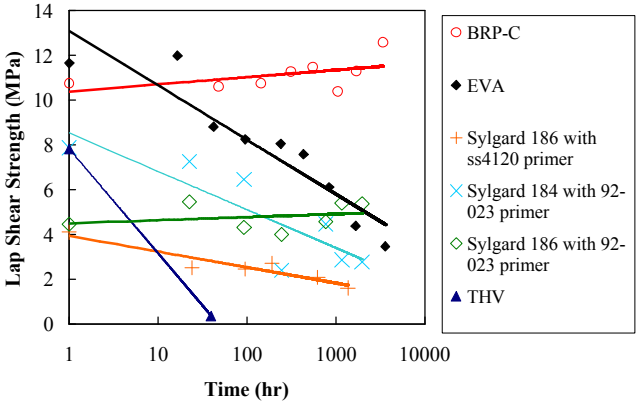

Fig. 3. Lap shear results for encapsulants exposed to 85 °C and 85% relative humidity. The dominate mode of failure is indicated by the symbol (filled=adhesive, open=cohesive, and "X" or "+"=primer to encapsulant interface).

4. Conclusions

Because of the high diffusivity of water in EVA, it is not possible to keep a module dry for a period of 20 years without incorporating large amounts of dessicant and/or creating a hermetic seal. The use of alternative encapsulants with lower diffusivities and better adhesion can reduce the amount of water that does enter and could provide better protection against hydrolytic reacitions. Furthermore, the production of acetic acid in EVA and its large number of polar groups give it some inherent problems with corrosion. By switching to a more non-polar polymer with better hydrolytic stability, better protection of module interfaces can be obtained, thereby creating a more durable product.

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[i] J. Crank, (1975) The Mathematics of Diffusion, p. 50, Clarendon Press, Oxford.

[ii] M. Tencer "Moisture Ingress inot Nonhermetic Enclosures and Packages," *Proc. Of the 1994 IEEE 44th Electronic and Technology Conference*, Washington, DC, pp. 196-209 (1994).

REPORT DOCUMENTATION PAGE

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1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
January 2005	Conference Paper	

4. TITLE AND SUBTITLE
Module Encapsulant Diagnostic and Modeling

5a. CONTRACT NUMBER
DE-AC36-99-GO10337

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
M. Kempe

5d. PROJECT NUMBER
NREL/CP-520-37027

5e. TASK NUMBER
PVB57201

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-520-37027

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

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15. SUBJECT TERMS
PV; electrical isolation; encapsulant materials; ethylene vinyl acetate (EVA); impermeable back-sheet; module; water vapor transmission rate (WVTR); hydrolytic stability;

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (*Include area code*)
Unclassified	Unclassified	Unclassified	UL		

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