PREDICTING FIELD PERFORMANCE OF PHOTOVOLTAIC MODULES FROM ACCELERATED THERMAL AND ULTRAVIOLET AGING DATA*

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ABSTRACT

A 30-year lifetime for photovoltaic (PV) modules is necessary for such applications as central-station power generation. A key to the achievement of this target is an understanding of the failure mechanisms related to aging-induced degradation of materials in field environments, including the ability to forecast long-term effects of exposure to high temperature and ultraviolet (UV) light. Some results of a research program at the Jet Propulsion Laboratory, aimed at characterizing aging mechanisms in polymeric PV encapsulant materials, are described. The development of an analytical structure for assessing the significance of thermal-UV-induced transmission losses in ethylene vinyl acetate in simulated 30-year field exposure at various U.S. sites is discussed.

KEY WORDS

Photovoltaic module; polymeric encapsulant; material aging; failure mechanisms; accelerated testing; thermal-ultraviolet aging; analytical model.

BACKGROUND

The use of photovoltaics as an electric power source for applications such as central stations depends on a lifetime for photovoltaic (PV) modules ≥30 years. One source of concern in this regard is the deterioration of module encapsulation materials. This paper describes the results of one portion of a research program at the Jet Propulsion Laboratory aimed at detailed characterization of aging mechanisms in polymeric PV encapsulant materials [1, 2]. The total program involves studies of electrochemical corrosion in the module as determined by sorption of moisture and changes in transparency

*This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the U.S. Department of Energy, through an agreement with the National Aeronautics and Space Administration.

Presented at the International Solar Energy Society Meeting in Montreal, Canada, June 22-29, 1985

of the encapsulant, cracking and delamination (all due to photothermal aging), and electrical breakdown of the encapsulant material due to voltage stresses.

INTRODUCTION

The first step in predicting 30-year life is to implement a parametric test program to collect data to characterize the material's aging dependencies accurately over the time allowed for material and module development. Normally, measurable degradation cannot be effected by exposure to field-level environments within the time allocated, so accelerated testing must be used. The approach considered here involves the acceleration of time and stress level by exposure in an environmental test chamber.

A key part of any test approach is to control and measure the environmental parameters precisely. Failure to do so leads to inaccurate data, or to such large data scatter that understanding parameter dependencies becomes difficult if not impossible.

In accelerated testing, relationships must be developed to allow extrapolation back to ambient stress levels. Key issues here include the sequence of stress levels (diurnal and seasonal cycles introduce certain sequences), and nonlinearities in degradation vs stress level. Avoiding such phenomena as phase changes is important.

The approach used to obtain accurate extrapolation of accelerated test results to 30-year field conditions is discussed here for the problem of thermal and ultraviolet (UV) aging of a polymeric encapsulant, ethylene vinyl acetate (EVA), a widely used encapsulant for PV modules.

The procedure involves first a least-squares fitting of a mathematical function to available parametric aging data to allow interpolation and extrapolation of the measured degradation rates to field stress levels. Next the mathematical function is used, with histories of expected field stress levels, to predict the incremental degradation for each hour (hourly rate times one hour) over the array lifetime. The hourly degradation increments are them summed to yield the final 30-year degradation level.

For the case of photothermal degradation, a model of optical transmission loss vs temperature and UV level was developed. An attempt was made to fit a mathematical function with physical significance in hopes that the fitting constants determined could be related to actual physical constants. In constructing the equations for the model it was assumed that the encapsulant's optical transmission can be expressed as a function of the concentration Q of a given reactive species. The rate of variation of the concentration, Q/t, is therefore the reaction rate.

The EVA test data indicate that competing reactions occur simultaneously, one causing increase of yellowing from thermal exposure only, one causing an increse of yellowing from UV exposure, and one bleaching out the yellowing. Thus, a logical component of the equations is a thermal-only term plus two UV radiation-dependent terms of opposite sign, one modeling the production of yellowing and one the bleaching. The thermal term is modeled as an Arrhenius type term because reaction rates leading to material degradation show a temperature dependence closely resembling an Arrhenius relationship. The resultant mathematical function is defined by Eqns. 1 and 2 below. The arbitrary constants, a_1 to a_{10}, are determined by least-squares fitting

the model to the experimental optical-transmission-versus-time data obtained over a period of time at JPL using accelerated thermal-UV environments.

$$\tau/\tau_o = 1 + a_1 Q + a_2 Q^2 + a_3 Q^3 \quad (1)$$

$$Q/t = e^{(a_4/T)} + a_5 e^{(a_6/T)} S^{a_7} - a_8 e^{(a_9 T)} S^{a_{10}} \quad (2)$$

where

τ = transmission at 440 nm
τ_o = initial transmission at 440 nm
Q = concentration
a_i = constant
t = time
T = temperature, K
S = UV level, suns

As this model is a function of both temperature and UV level, it is instructive to plot Q/t from Eqn. 2 vs these two parameters. Figure 1 shows an Arrhenius plot for two UV levels that demonstrates the Arrhenius dependence, which is well modeled by a rate that doubles with every 10°C increase in temperature. Figure 2 shows a plot of Q/t vs UV level as a function of temperature. The striking aspect of Fig. 2 is the nonlinear dependence of reaction rate on UV level, with a minimum occurring around the 2-sun exposure level. A unit sun level is the amount of UV present when insolation is 100 mW/cm2. The UV level is modeled as a fixed 5% of the insolation level.

The value sought is the optical transmission through the encapsulant, which varies with Q, as a function of time. Since Q/t varies with temperature and UV level, it must be integrated over time. To determine the transmission in a field environment, it is necessary to develop a model of the environment that provides the values of temperature and UV level at the site of interest. This was done using solar radiation surface meteorological observations (SOLMET) typical meteorological year weather data for various sites and modul mounting configurations. The hourly PV cell temperature was computed based on the irradiance level incident on the array, and the hourly ambient air temperature from the SOLMET datatape. An assumption is made in this use of the model that the order in which environmental levels occur is not important.

The number of annual hours spent at a given site in a given range of UV radiation levels and module operating temperatures is determined by scanning the SOLMET tape for a complete year, which results in a matrix of numbers of hours at the various combinations of UV radiation and temperature levels. The product is then taken of the elements of this matrix with the elements of a matrix of reaction rates, Q/t, determined for the same temperature and UV levels (using Eqn. 2). The sum of the products of the elements yields the concentration Q at the end of one year; this is multiplied by 30 to obtain the 30-year value. Equation 1 is then used to determine the transmission loss at the end of 30 years.

The final determination of PV performance degradation requires a convolution of the encapsulant transmission curve with a cell-response curve (Fig. 3) and a solar-distribution curve. The cell-response curve is representative of crystalline silicon; other types of devices have their own response curves.

An example of the results obtained with this approach is the 30-year PV power loss determined for EVA-encapsulated modules in Phoenix, Arizona. Two types of module mounting, ground-mounted and roof-mounted, were considered, each with crystalline silicon cells. The mounting configuration affects the module operating temperature, which in turn affects the reaction rates and subsequent yellowing. The 30-year transmission loss for crystalline modules

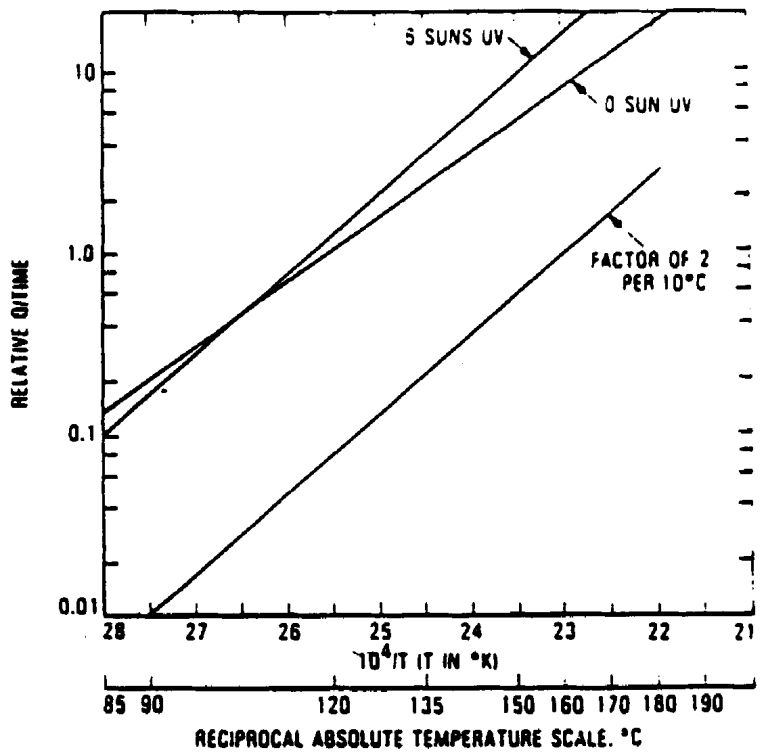

Fig. 1. Arrhenius plots of reaction rate (Q/time) versus temperature for EVA.

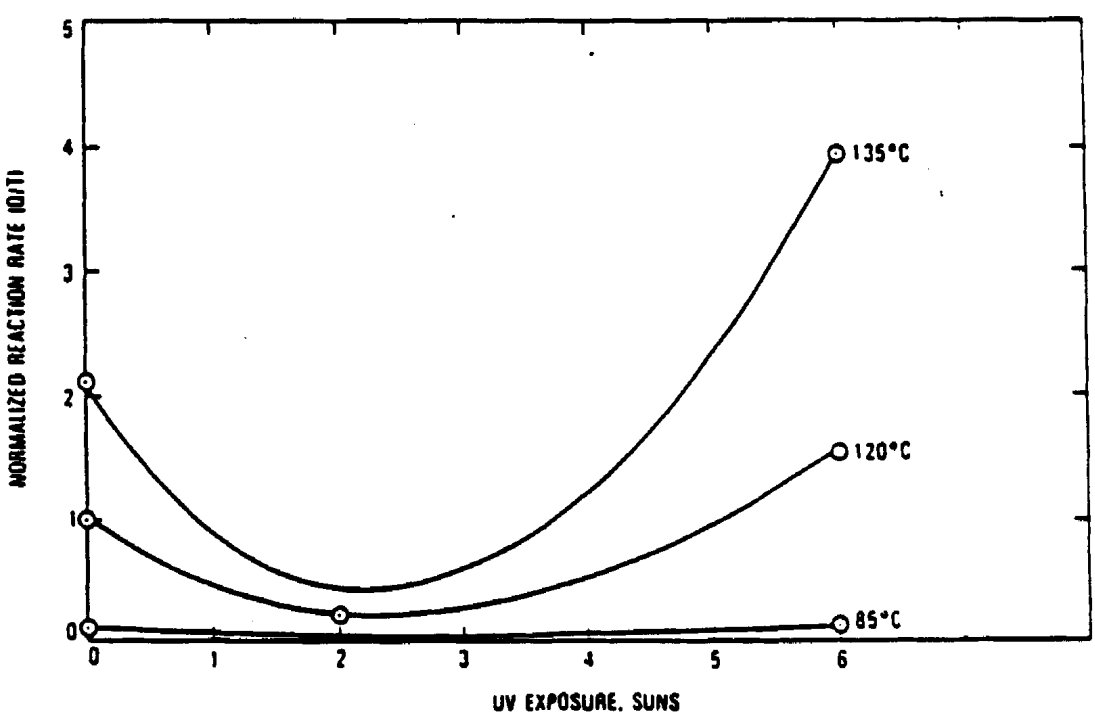

Fig. 2. Reaction rate (Q/time) versus UV level as a function of temperature for EVA.

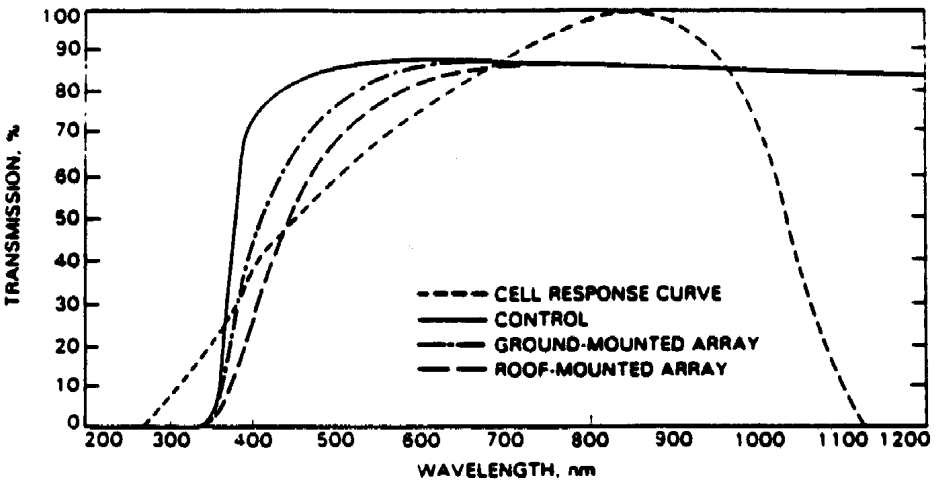

Fig. 3. Thirty-year percentage of transmission versus wavelength for three samples of EVA with a typical spectral response curve of a crystalline silicon cell.

reached a very acceptable level of from 3.5% to 8%; roof-mounted modules had the greater losses due to higher operating temperatures.

CONCLUSIONS

A key finding is that the reaction rate for photothermal yellowing is a highly non-linear function of the UV level, with the thermal-only rate (UV = 0) greater than the rate for full sunshine. Bleaching of the yellowing products appears to be an important reaction at typical 1-sun UV levels. Temperature is probably the key driver in photothermally induced transmission loss; temperature dependencies are well approximated by Arrhenius relationships with a rate doubling approximately every 10°C.

The importance of obtaining a complete characterization of parameter dependencies, precisly measured and controlled, cannot be overemphasized. As noted above, when reaction rates proceed slowly at ambient conditions, accelerated testing becomes necessary. The case considered here had two stress variables; the degradation of polymeric encapsulation with temperature is better understood than that with UV radiation.

This approach is applicable to studies of the photothermal degradation of materials other than PV encapsulants and should be of interest to researchers involved with long-term reliability of products exposed to the sun.

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