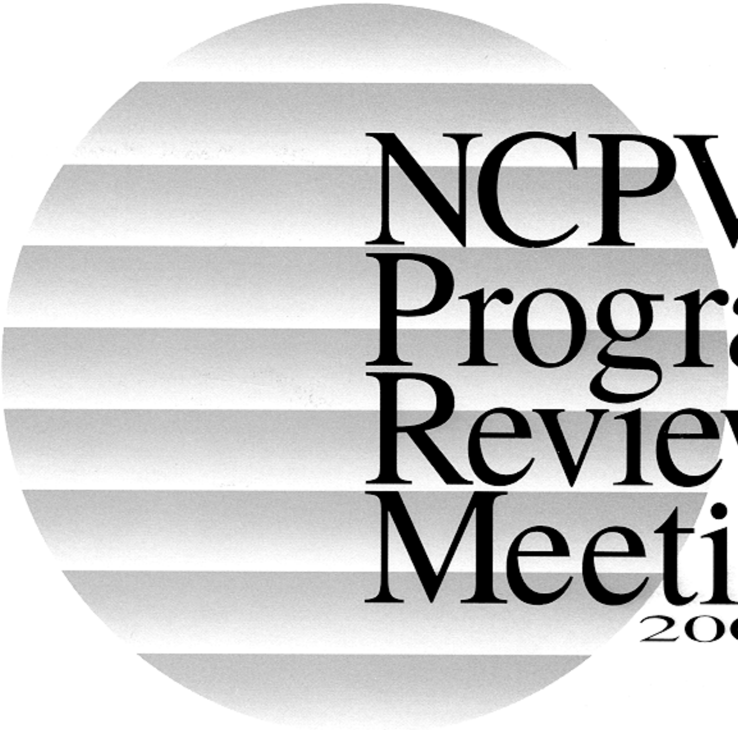
PROGRAM AND PROCEEDINGS



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Module 30 Year Life : What Does it Mean and Is it Predictable/Achievable?

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ABSTRACT

We define what we mean by a 30-year module life and the testing protocol that we believe is involved in achieving such a prediction. However, we do not believe that a universal test (or series of tests) will allow for such a prediction to be made. We can test for a lot of things, but we believe it is impossible to provide a 30-year certification for any arbitrary photovoltaic (PV) module submitted for test. We explain our belief in this paper.

1. Introduction

The photovoltaic (PV) industry wants a module technology that will last 30 years in the field as well as a means by which to certify that a module technology will, indeed, last 30 years. First, we must define what we mean by a 30-year life. Second, we will lay out the accelerated environmental test (AET) protocol involved in such a prediction. Third, we will discuss the time-to-failure calculation and the likelihood of such a certification process. And finally, short of such a certification process, we discuss an approach for rank ordering and testing of failure modes. The rank ordering would be similar to the "Life-Cycle Energy Cost Impact" analysis proposed by R.G. Ross [1].

2. Thirty-Year Life

The language used here is critical. It is clearly impossible to expect that for a given module type, every one will last 30 year without failure. The issue is reliability. What constitutes a failure for one person may not be a failure for others. As a starting point we paraphrase a textbook definition of reliability: [2] "a reliable PV module has a high probability that it will perform its intended purpose adequately for 30 years, under the operating conditions encountered." For simplicity we will say a PV module fails to provide service if its power output decreases by more than 30% after 30 years in its use environment. Also, "a high probability" means that 95% of the modules in the field will achieve this success. By "use environment" we mean any and all use environments that the PV module will experience during service. Site meteorology, handling, and installation are included in use-environment considerations.

3. Accelerated Environmental Testing

A life-prediction approach specifically designed for PV cells and minimodules is outlined elsewhere [3]. Lifetime- prediction tests appropriate for full-sized modules would be possible only when a final module design is defined, all failure modes are identified for that module design, and acceleration parameters for each relevant environmental stress are known. The AET's chosen must use stress or combinations of stresses that will accelerate failure modes that actually occur in the real world. Module lifetime in Florida may be very different than in Arizona. We must decide which performance parameter(s) should be measured to best monitor the failure mode being evaluated and then define what constitutes a failure for that performance parameter.

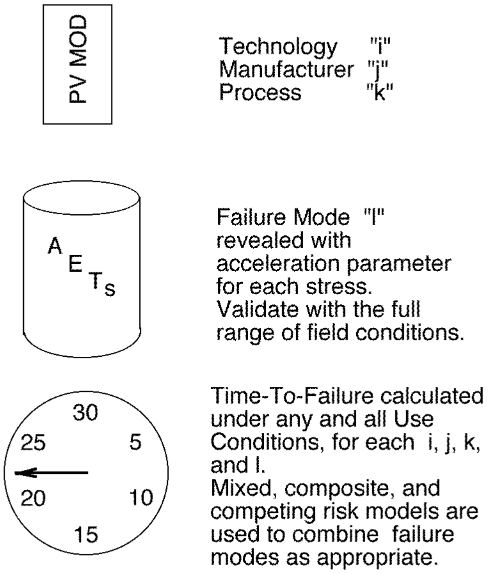

Fig. 1. Diagram of Life Prediction Process

To use AETs for life-prediction testing we divide the protocol into five steps: (1) Identify and isolate all failure modes, e.g., in a c-Si module we might look at solder-bond fatigue or in a thin-film module it might be film adhesion or moisture intrusion.; (2) Design and perform AETs, e.g. thermal cycling with series resistance as a metric or damp heat with visual inspection as a metric; (3) Use appropriate statistical distributions to model specific failure rates; (4) Choose and apply relevant acceleration models to transform failure rates; (5) Develop a total module failure rate as a composite of individual rates to allow service lifetime prediction for each use condition. Fig. 1 outlines this process.

In step (1) above, all of the failure modes designated by "l" must be determined for each module submitted for test. The materials technology and cell design are denoted by the subscript "i". If multiple manufacturers are using that technology, we need a second subscript "j" to denote the manufacturer and probable differences in material processing and/or cell design. If there are different processes or designs used by the same manufacturer, then we need a third subscript "k". For each module, $MOD_{i,j,k}$, the l^{th} failure mode must be identified and, ideally, the underlying failure mechanism (cause) found.

4. Life-Prediction Modeling

Steps (2) through (4) fix the acceleration parameter for the failure model used for the l^{th}-mode under test for each $MOD_{i,j,k}$; call this acceleration parameter $a_{l(i,j,k)}$. The time-to-failure (TTF) under outdoor use is equated to the TTF under accelerated stress by

$$TTF^{use}_{l(i,j,k)} = a_{l(i,j,k)} \bullet TTF^{stress}_{l(i,j,k)} . \qquad (1)$$

If the mechanism changes, the acceleration and failure model need to be changed. A hazard function is developed from the failure model and $a_{l(i,j,k)}$ used for equation (1). If the different TTFs associated with each of M failure modes are statistically independent, then the hazard rate-function, h(t), follows the addition rule [2]:

$$h_{(i,j,k)}(t) = \sum_{l(i,j,k)=1}^{M} h_{l(i,j,k)}(t) . \qquad (2)$$

The M failure modes include anything that can fail with the cell, interconnects, bus, encapsulation, leads, J-boxes, etc. A unique hazard function is obtained for each module. Equation (2) combines each failure-mode hazard function into a composite and allows a life prediction. We use the following identity found on p. 118 of reference [2]:

$$1 - F(t) = \exp\left[-\int_0^t h_{(i,j,k)}(t')\,dt' \right] . \qquad (3)$$

For a 95% survival rate after 30 years equation (3) becomes:

$$Ln(1 - 0.95) \geq \int_0^{30yr} h_{(i,j,k)}(t)\,dt . \qquad (4)$$

For each use condition (site), all of the stress conditions must be known throughout the year. The hazard rate for a given (i,j,k) must be low enough that for all use conditions, equation (4) is obeyed. Is it possible to have a series of tests that could predict h-values for any module (i,j,k) submitted for test under all possible use conditions? In principle this may be possible, but a quick consideration of possible combinations of (i,j,k,l) indicates literally hundreds of potentially unique situations- too many handle in practice.

5. Alternative Approach

It is quite clear that a universal 30-year life prediction protocol will be impossible to obtain. We must look for a testing protocol short of a 30-year certification that will still serve our industry well. A series of AETs need to be developed that produce the most critical yet realistic failure modes. Some AETs will produce failure caused by known failure modes, and other tests will be used to discover new, unknown failure modes. For life prediction, we also need to test for "wear-out" mechanisms, as well as failure mechanisms whose rate decreases with time. The Weibull distribution function [2] has the broadest application for modeling TTFs for rates of failure that increase with time. Other statistical distributions can be used if the mechanism is known [3]. We need to establish the relative importance of the mechanism for which we are testing, i.e. rank order, and determine the TTF distributions to estimate life expectancy for the dominant failure modes. Of course the possibility of unexpected, life-limiting, catastrophic mechanisms must be considered.

The testing we propose will be more involved than the usual standardized qualification tests, which are more appropriate for identifying poor designs and manufacturing flaws [4]. Results of our proposed life-prediction testing need to determine the acceleration factors associated with the failure mechanisms being investigated.

6. Rank-Ordering Failure Mechanisms

As a criterion for rank-ordering failure modes, we can choose those that have the greatest effect on system-energy-output. An approach used by R.G. Ross for crystalline modules [1] and later for thin-film modules [5] is an attempt at doing this. He lists known failure mechanisms and assigns values for "system life-cycle energy cost impact" based on, in his words, 'the author's best judgement in light of likely achievable levels." He assigned a constant rate of system-energy-loss (%/yr) for some mechanisms and a linearly increasing rate of energy loss (%/yr^2) for others. This may be a way to start rank ordering, but ultimately, these are not the functional dependencies typically used to model failure mechanisms [2].

A more objective system of rank-ordering failure modes needs to be developed. We need to understand relative impact to energy production of each failure mode on a module-by-module basis. Then we have to test for those mechanisms that cause the most life-limiting modes in equation (3).

7. Conclusion

Based on known failure mechanisms, we can use AET's to estimate TTF for what we determine to be the most damaging failure modes relative to system-energy output. Unfortunately, appropriate values for acceleration factors in testing will depend on many variables (i,j,k), and TTF will depend on the environmental stresses at the location of use. The development of a universal 30-year pass/fail certification for all PV module types cannot be expected.

8. Acknowledgements

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