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John H. Wohlgemuth and Sarah Kurtz

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USING ACCELERATED TESTING TO PREDICT MODULE RELIABILITY

John H. Wohlgemuth and Sarah Kurtz
National Renewable Energy Laboratory, Golden, CO

ABSTRACT

Long-term reliability is critical to the cost effectiveness and commercial success of photovoltaic (PV) products. Today most PV modules are warranted for 25 years, but there is no accepted test protocol to validate a 25-year lifetime. The qualification tests do an excellent job of identifying design, materials, and process flaws that are likely to lead to premature failure (infant mortality), but they are not designed to test for wear-out mechanisms that limit lifetime. This paper presents a method for evaluating the ability of a new PV module technology to survive long-term exposure to specific stresses. The authors propose the use of baseline technologies with proven long-term field performance as controls in the accelerated stress tests. The performance of new-technology modules can then be evaluated versus that of proven-technology modules. If the new-technology demonstrates equivalent or superior performance to the proven one, there is a high likelihood that they will survive versus the tested stress in the real world.

INTRODUCTION

The commercial success of photovoltaics is based on long-term reliability of the PV modules that comprise the PV systems. Today most PV modules are warranted for a 25-year life. These modules are typically qualified to either IEC 61215 [1] or IEC 61646 [2], which do an excellent job of identifying design, materials, and process flaws that are likely to lead to premature failure (infant mortality). However, the qualification tests are not designed to address wear-out mechanisms that will limit module lifetime.

Analysis of field data available in the literature indicates that the durability of PV modules available commercially over the last 10 or even 15 years has been adequate to meet the needs of the commercial PV industry. Figure 1 shows a plot of degradation rate per year versus the frequency of that level being reported in the literature [3]. This curve represents data from 1920 literature sources. The average annual degradation rate is 0.8% per year, whereas the most frequently reported value is 0.5% per year. So there are many examples of module technologies that have proven durability.

However, lower module prices are necessary for the PV industry to continue to grow and ultimately reach grid parity. The U.S. Department of Energy (DOE) recently announced the new SunShot initiative [4], which aims to reduce the cost of PV systems to $1/ peak watt, with $0.50 of this expected to come from the module. This represents a significant decrease from the present selling price for all PV technologies. Achieving such a large reduction in selling price will likely require major changes to the module design, materials, and processing. These lower module costs must be achieved without adversely affecting PV module reliability and durability.

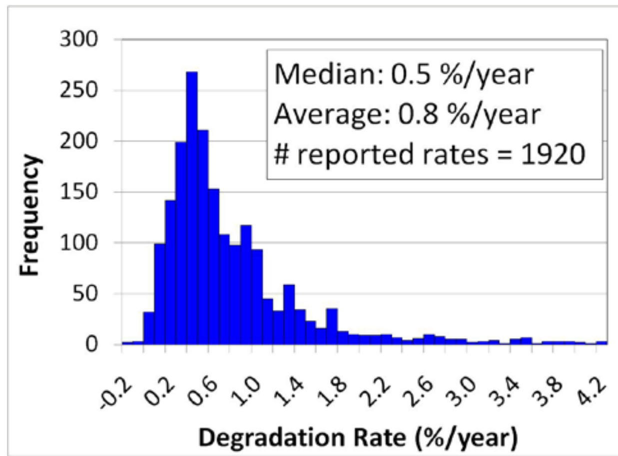

Figure 1. Module degradation rate from the literature

So how can we ensure that changes in design, materials, and/or processes do not adversely affect module reliability? We cannot wait 20 or 25 years to see what happens to the lower-cost modules after they are deployed in the field. Accelerated reliability tests must be used to evaluate the potential of these lower-cost modules to survive without increased degradation of output power. However no existing accelerated stress tests that we know of can determine whether a module type will survive 25 years wherever it is deployed.

This paper proposes a process that utilizes the past field experience of a module type along with comparative accelerated stress tests to compare the performance of known baseline module types with new-technology, lower-cost module types. The new module types are evaluated against the older design using accelerated stress tests that go beyond those used in qualification test sequences. Comparison of the performance between the old and the new module types can give an excellent indication of how well the new design is likely to perform outdoors compared to the older design.

LIMITATION OF QUALIFICATION TESTING

Qualification tests are a set of well-defined accelerated stress tests developed out of a reliability testing program. Qualification tests incorporate strict pass/fail criteria. Such tests are used by customers to qualify modules for purchase and by manufacturers as a means of demonstrating a degree of product reliability. These test sequences were developed based on the identification of field failure mechanisms.

Once typical field failure mechanisms were identified, accelerated stress tests were developed that would duplicate these failure modes in a reasonably short amount of time. Table 1 provides a list of some of the accelerated stress tests that have been used along with the failure modes that they accelerate. The list in Table 1 was used to establish the initial PV module qualification test sequences that grew into IEC 61215. [5]

Table 1. Accelerated Stress Tests for PV

Accelerated Stress	Failure Mode
Thermal Cycle	Broken interconnect Broken cell Solder bond failures Junction box adhesion Module connection open circuits Open circuits leading to arcing
Damp Heat Exposure	Corrosion Delamination of encapsulant Encapsulant loss of adhesion & elasticity Junction box adhesion Electrochemical corrosion of TCO Inadequate edge deletion
Humidity Freeze	Delamination of encapsulant Junction box adhesion Inadequate edge deletion
UV Test	Delamination of encapsulant Encapsulant loss of adhesion & elasticity Encapsulant discoloration Ground fault due to backsheet degradation
Mechanical Load	Broken interconnect Broken cell Solder bond failures Broken glass Structural failures
Dry and Wet Insulation Resistance	Delamination of encapsulant Ground faults Electrochemical corrosion of TCO Inadequate edge deletion
Hot Spot Test	Hot spots Shunts at the scribe lines
Hail Test	Broken cells Broken glass
Bypass Diode Thermal Test	Bypass diode failures

Although qualification tests like IEC 61215 and IEC 61646 are important and valuable, they have limitations because the stress levels are by design limited. A significant number of commercially available products must be capable of passing the qualification test sequence or the commercial PV business would be severely limited. Passing the qualification test means the product has met a specific set of requirements, but doesn't say anything about which product is better for long-term performance. Most of today's commercial modules pass the qualification sequence with minimal change, meaning that they suffer almost no degradation in power output from the test sequence. When 10 crystalline-silicon module types, all previously qualified to IEC 61215, were tested beyond the qualification level (500 versus 200 thermal cycles and 1250 hours versus 1000 hours of damp heat) only two of them passed the extended test [6]. From the results of the qualification test there was no way to know that only two module types out of 10 could pass 1250 hours of damp heat without exceeding 5% power loss.

So the qualification test itself could not distinguish between the performances of these 10 module types. Similarly, the qualification test is not a good tool for determining whether a change in materials, processing, or design is likely to reduce the module's lifetime or increase the annual degradation rate. However, the qualification test sequence can be used to determine that a new design will not suffer from infant mortality, and it can provide a good starting point for developing a methodology to evaluate the impact of new lower-cost designs, materials, and processes on the modules' long-term reliability and lifetime.

RELIABILITY TESTING

The accelerated testing required for evaluation of the impact of cost reducing changes in module construction on module durability must address the observed field failure modes and must cause degradation of the product to prove that the tests are addressing the same failures as seen in the field. Because the accelerated stress tests from the qualification tests are designed to address the identified field failure modes, they are a good starting point for developing these reliability tests. How can the qualification tests be turned into reliability tests? The following approaches may all contribute to the development of a test sequence evaluating a module's ability to survive for 25 years in a particular terrestrial environment.

- Increase the test duration, for example do more thermal cycles or expose the modules to damp heat for a longer time.
- Use higher stress levels, but making sure that the higher stress levels do not cause failures that are not seen in the field.
- Combine stresses, for example by applying voltage to the module during damp heat.
- Evaluate new methods to accelerate the failure modes identified in the field, for example by using the dynamic mechanical load test to accelerate cell breakage caused by wind-induced vibrations [7].
- Use material or coupon tests in situations where it would be too expensive to test full-sized modules. For example, long-term ultraviolet (UV) testing at high temperature to evaluate material discoloration and degradation is better performed on small coupons of the same cross-sectional construction as the module.
- Use step stresses in which the initial stress starts with the stress level from the qualification test and increases until failures are seen. Once again, care

must be taken to ensure that the failures seen are the same failure modes identified from field exposure.

In the qualification tests, pass/fail measurements include peak power at Standard Test Conditions (STC) and the dry and wet leakage currents. The first way to increase the available information about new lower-cost technologies is to eliminate pass/fail and report the actual performance so that products can be compared directly with each other. There are additional measurement tools that can be used to observe problems, often before they impact the power or leakage currents. The following measurement tools can be valuable for identifying failure modes before they are serious enough to cause measureable power loss.

- Visual inspection can be used to observe discoloration of encapsulant, corrosion of metals, and delamination of the encapsulant or backsheet.
- Infrared (IR) cameras show heat dissipation, so they can be used to determine areas where collection of current has been disrupted (higher series resistance) or where current is flowing where it shouldn't (shunting). An IR camera can also be used to show whether the current path through a string of cells is intact and whether the module bypass diodes are carrying current during normal operation or only during shaded operation as designed.
- Electroluminescence looks at the near-IR light generated by carriers transitioning across the cell p-n junction. So electroluminescence can be used to see discontinuities in the junction such as cracks in the cell or breaks in the junction itself.
- When testing for adhesion of the package layers, the junction box and the frame can identify possible weaknesses in the packaging technology.
- Dark I-V curves can identify small changes in series and shunt resistance before they are large enough to change the light I-V curve appreciably.

A number of publications have suggested adopting more aggressive test protocols. Some of these have been proposed by PV module manufacturers [8 and 9], some by test laboratories [10], and others by groups organized by customers [11]. In most cases, they call for increasing the test durations. Although most of these suggested test protocols are based on equating field experience with results of accelerated testing, none purport to predict 25-year life.

An effort is now underway to establish a methodology for making the accelerated stress tests more quantitative [12]. The long-term goal is to determine the acceleration rates to use for many of the long-term wear-out mechanisms. For some, such as thermal cycling of crystalline-silicon modules, existing analyses of field data [13] and modeling [14] of weather data can be used to provide an estimate of the acceleration rate and therefore give a better estimate of the number of thermal cycles we should run for a 25-year lifetime.

For many of the other long-term stresses that lead to module wear-out, the appropriate acceleration factors are unknown. The impacts of combined stresses on the module lifetime are also unknown. Therefore, both real-time and accelerated stress tests are needed in order to evaluate the changes made to modules and to develop tests that can help us elucidate the modules' long-term performance in the variety of terrestrial environments in which they are deployed.

ESTABLISHING A BASELINE

We do not know how to test modules for a 25-year lifetime, but we cannot wait 25 years to find out how they will perform. We do have module types that have already survived long time periods, in some cases more than 25 years in the field with acceptable degradation rates. These module types can provide a valuable baseline. Analyses of modules that have survived for a long time in the field have provided a great deal of data on failure rates, degradation rates, and failure modes [15]. The materials group of Working Group 2 (Modules) of IEC TC-82 on PV has begun an effort to evaluate modules that have been exposed in the field for long time periods. In parallel with this effort, new modules and samples are being constructed using materials, processes and designs that are as similar as possible to those used in construction of the original fielded modules. These new modules are then subjected to various accelerated stress tests to see what levels of accelerated stress duplicate the field failures.

However, there is one more way to gain knowledge from the baseline module types. Because they can survive for long time periods, their construction can be used as a baseline in accelerated stress testing. For example, assume that a module manufacturer wants to change encapsulants from one with proven field performance that the company has been using for years to a new-lower cost material. What testing should be performed? The first step would be to perform the qualification tests on the new material. Assuming it passes that without problems, the second step is to test both the new material and the old material through more severe environmental tests (with guidance given in the next section) in an attempt to duplicate wear-out mechanisms. The results from the old and new encapsulant can then be compared. If the new encapsulant performs as well as the old one in the appropriate accelerated stress tests, then it is likely to perform as well as the old material in the field.

DEVELOPING THE EXTENDED TEST SEQUENCE

Thermal Cycling

The 200 thermal cycles in the Qualification test does not appear to represent 25 years outdoors in most terrestrial environments [13 and 14] depending on the site. Various levels of cycles (from 400 up to 1000) have been proposed by different authors. Interestingly, it has been shown that well designed and constructed modules can survive 1500 thermal cycles without appreciable power loss. [16] To assess a new technology's ability to survive thermal cycles, it should be cycled along with the control module type until either one or the other begins to degrade or to some preset number of cycles many times the qualification level. Assessment of performance should be based on a comparison of both the change in output power and on observations of detrimental changes (e.g. broken interconnects). If the two technologies exhibit similar thermal cycle performance, then the two constructions should have similar field performance for failure modes caused by thermal cycling.

Damp Heat

The 85°C/85% relative humidity exposure is as accelerated as necessary and probably at the practical limit for acceleration of damp heat. These conditions probably never happen in the real world as the modules tend to dry out at their highest temperatures, but absorb moisture at lower temperatures. It is difficult to judge what outdoor exposure the 1000-hour exposure at 85/85 represents particularly as different module designs will experience very different stress from this exposure. So rather than specify a particular length of time, it seems appropriate to test the control technology and the new technology through enough hours of damp heat that both begin to lose some power (say to 90% of the original) in order to verify that the new technology is no worse and has no additional failure modes than the old module technology it will replace.

UV/TC50/HF10

This sequence of tests (UV exposure, followed by 50 thermal cycles and 10 humidity-freeze cycles) is mainly a test for the package. The module failing this test indicates inadequate adhesion between layers or inadequate cure level in the encapsulant. Humidity freeze is not really a lifetime test for a particular wear out mechanism so typically does not need to be enhanced for reliability testing. Although some people have recommended repeating the humidity freeze test a number of times, it is not clear what wear-out failure modes they are trying to accelerate. So our recommendation is to test both the new and the old module construction to the sequence defined in IEC 61215/61646, but with the addition of the dynamic mechanical load test, which is discussed in the following section.

Dynamic Mechanical Load Test

The only mechanical test in IEC 61215 is a static mechanical load test that is performed after the accelerated stress tests. A dynamic mechanical load test followed by 50TC/10HF does a much better job of identifying modules with cells that are prone to breakage and would cause subsequent power loss [7]. There is an available DIN Standard (EN12211) [17] that can be used for this test until IEC Working Group 2 can finish preparation of a dynamic mechanical load test for PV modules.

UV Material Test

Although IEC 61215 contains a UV test, it is intended only as a pre-screening test to address UV-sensitive bonding issues. This test is not long enough to assess whether the polymeric materials used in a module are capable of surviving the UV exposure expected during the lifetime of the module. Specialized Technology Resources, Inc. (STR) developed a long-term UV exposure protocol during its work evaluating the causes of EVA yellowing [18]. BP Solar reported the use of a similar UV exposure protocol for 26 weeks to verify a 25-year lifetime [19]. A similar UV testing protocol should be used to evaluate any new polymeric material for use in a PV module. The material should be exposed to the UV within the standard package in which it will be used. Because there is no agreement between UV dose and years in the field, it would be best to perform the test with the new material side-by-side with the material it is to replace. The test should proceed for at least the proposed 26 weeks or until one or both of the materials begin to discolor or degrade. At that point, a comparison between the old and new materials will indicate whether the new material will perform as well as the one it is design to replace.

Potential Induced Degradation

There have been recent reports of significant module degradation associated with being mounted at the negative-voltage end of a high-voltage string [20]. The failure mechanism appears to be related to voltage-induced ionic current flow, which is made worse in the presence of high humidity or liquid water. Preliminary results indicate that some module types are susceptible to this degradation mechanism, whereas others are not. Although no standard test has been developed for this failure mode, adding a combined temperature/humidity/voltage-bias component to the test sequence should verify that the new-technology module type doesn't introduce this failure mode.

CONCLUSIONS

A method for assessing the long-term reliability and durability of new lower-cost PV modules has been proposed. Because the new approach compares the results of the accelerated testing with modules that have a known long lifetime, a new module type qualified through this procedure has a high likelihood of also being able to survive in the field. The recommendations given in this paper can serve as a guideline for the establishment of a specific program of reliability testing for each major cost-reduction proposed. Use of this methodology will reduce the risk that a change made to lower costs will have a major, negative impact on module lifetime or degradation rate.

Going forward, this method can also provide valuable input into the development of accelerated test procedures that can predict 25-year lifetime.

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