LONG TERM RELIABILITY OF PV MODULES

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ABSTRACT: This paper discusses how BP Solar utilizes long term module exposure data and field return data to determine module lifetimes, expected failure rates and to identify failure mechanisms. Accelerated stress tests are then utilized to test new materials and processes before they are implemented in production. Long term module reliability is assessed using a three pronged approach. 1) A small number of modules have been deployed outdoors for long time periods with periodic measurements of performance in order to establish degradation rates. 2) Field returns are reviewed for both overall return rates and to identify the failure mechanism that caused the return. 3) Accelerated stress tests are utilized to evaluate the present products and all new materials, processes and designs against known failure mechanisms. The data from all three cases indicate that today's PV modules are extrememly reliable and have projected lifetimes well in excess of the warranties.
Keywords: Reliability, Environmental Effects, PV Module

1 INTRODUCTION

The long term reliability of photovoltaic (PV) modules is critical to the cost effectiveness and the commercial success of PV. Publications on photovoltaic system reliability often state that the PV modules are the most reliable part of the system. [1,2] However, there are continuing questions about the average yearly degradation of the modules and concerns that as lower cost processes and materials are introduced that the reliability and useful lifetime will suffer. This paper will detail BP Solar's efforts to provide data on long term module degradation and describe the program to assure that changes in process and materials will not adversely affect module reliability and lifetime.

Today BP Solar offers a 25 year warranty on most of its crystalline silicon PV modules. This is a long time considering that the terrestrial PV industry is at most 35 years old. While the modules have to last for 25 years of outdoor exposure, we can not wait 25 years to see how they perform. Since Solarex did not extend the module warranty to 25 years until 1999, no BP Solar/Solarex module with a 25 year warranty has been in the field for more than 6 years. Even the oldest 20 year warranty modules have only been in the field for 12 years. Therefore a combination of field experiments, statistical data analysis from field returns of commercial products and accelerated stress testing must be used to assess module reliability and lifetime.

2 FIELD EXPERIENCE

Field data must be a critical component of any PV module reliability program. Without field data there is no way to identify failure mechanisms in order to develop accelerated stress tests. BP Solar is collecting module field data in three different ways:

- Analyzing commercial warranty returns.
- Deploying and monitoring individual modules over long time periods.
- Monitoring the performance of PV systems over time. [3,4]

Unfortunately the systems monitoring effort has not been in operation long enough to provide information on long term module reliability. The following subsections discuss the other two efforts.

2.1 Commercial Product Returns

BP Solar has a data base that includes all field returns of BP Solar/Solarex multicrystalline silicon modules since 1994. The total number of returns over this period was 0.13%*. This represents approximately one module failure every 4200 module years of operation. [5]

Besides measuring the overall rate of failure it is also very important to learn why modules fail so that accelerated tests can be developed for those failure mechanisms. Then it is possible to develop materials, designs and construction practices that will eliminate those failures. Table 1 lists the observed field failures as a percentage of the total number of failures observed.

Types of Failures	% of Total Failures
Corrosion	45.3
Cell or Interconnect Break	40.7
Output Lead Problem	3.9
Junction Box Problem	3.6
Delamination	3.4
Overheated wires, diodes or terminal strip	1.5
Mechanical Damage	1.4
Defective Bypass Diodes	0.2

Table 1: Types of Field Failures Observed

Several observations can be made from this data.

- The types of failures with the highest percentages (corrosion and cell or interconnect break) are assessed as part of our accelerated stress test sequence.
- Many of the failures (for example output lead and junction box problems) are more likely related to workmanship and process control than to design or materials.
- The last 3 types of failures may be a result of systems problems, namely how the modules are connected and mounted rather than being purely module problems.

2.2 Outdoor Monitoring

As part of their long term module aging program, Sandia National Laboratories has been measuring a Solarex MSX-60 module since 1991. Data from the module is shown in Figure 1. [6] Over the course of 14 years the module has an average power loss of 0.3%/year.

* Returns from one single occurrence, a know cause early in the period have been removed to give a clearer picture of normal operations.

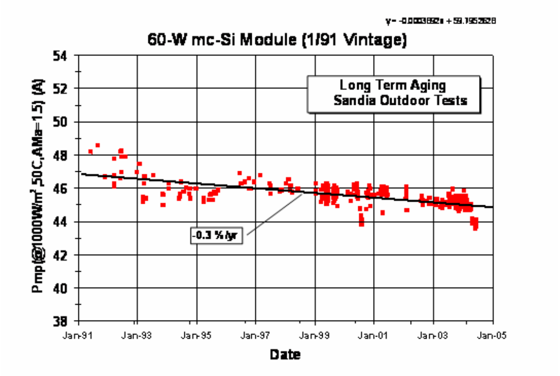

Figure 1: Long Term Module Performance at Sandia

Solarex has deployed 5 multicrystalline silicon modules in the Arizona desert since 1994, first at Quarter Circle U Technology and after 1998 at Arizona State University. The modules have typically been measured four times a year. Table 2 compares the power measurements in 1994 with the last set taken in January, 2005. The overall data shows almost no change over more than ten years of exposure. If we specifically look at the detailed data on one module, Figure 2 shows the short circuit current as a function of time for module # 4960. The trend line equates to a degradation rate of -0.02%/year. So there is really no current loss due to EVA yellowing, which was one of the mechanisms postulated as causing module degradation. Figure 3 shows the maximum power as a function of time for module # 4960. The trend line equates to a power degradation rate of -0.06%/year.

Module	1994 Power (W)	2005 Power (W)	Change (%)
4968	57.6	57.8	+.35
4961	58.1	59.3	+2.1
002	54.8	55.5	+1.3
4960	58.3	57.9	-0.7
003	58.4	55.0	-5.8
Average	57.4	57.1	-0.5%

Table 2: Change in Module Power after long term exposure in Arizona.

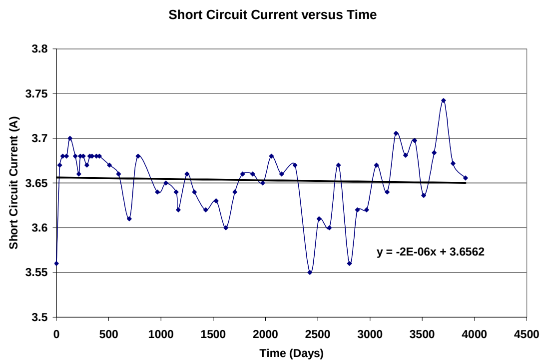

Figure 2: Change in Short Circuit Current for one module fielded in Arizona for more than 10 years.

The long term outdoor testing indicates that PV modules can survive for more than 10 years with very little degradation. This set of data is especially interesting to BP Solar because the data spans the change from manual to machine soldering. The module at Sandia was soldered by hand. The modules at ASU were soldered using automated equipment.

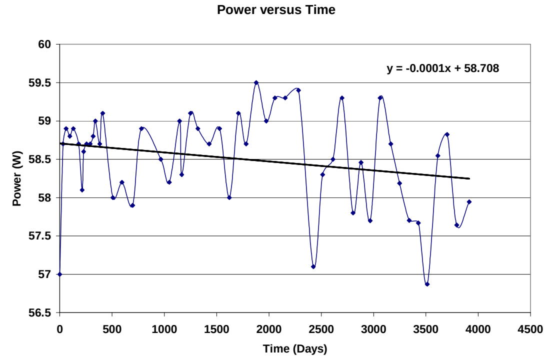

Figure 3: Change in Maximum Power for one module fielded in Arizona for 10 years.

3 ACCELERATED STRESS TESTS

3.1 Stress Testing

Stress testing is environmental testing that accelerates the stresses associated with known environmental conditions and/or known failure mechanisms. Development of such tests must be guided by the results of outdoor testing. The stress levels must accelerate the same failure mechanisms observed in the field. This limits the levels of stress that should be utilized as we do not wish to cause failures that don't occur naturally outdoors.

The goal with accelerated stress tests is to evaluate performance against a particular failure mechanism in a reasonably short amount of time. This allows for comparison of different technologies, materials and processes as well as letting us establish qualification tests.

3.2 Qualification Tests

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. Good examples of these tests are IEC 61215 "Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval" and IEC 61646 "Thin-Film terrestrial photovoltaic (PV) modules - Design qualification and type approval".

IEC 61215 and IEC 61646 include the following stress tests:

- 200 Thermal cycles from -40°C to +85°.
- Damp heat exposure at 85°C and 85% relative humidity for 1000 hours.
- A combined leg of UV Preconditioning (15 $K{\cdot}wh{\cdot}m^{-2}$), 50 thermal cycles from -40°C to +85°, and 10 humidity freeze cycles from +85°C, 85 % RH to -40 °C.
- Wet leakage current test at the rated systems voltage.
- Mechanical load test of 3 cycles of 2,400 Pa uniform load, applied for 1 hour to front and back surfaces in turn.

- Hail test with 25 mm diameter ice ball at 23 m ·s^{-1}, directed at 11 impact locations.
- And new in the second edition of IEC 61215, a bypass diode thermal test, with one hour at short circuit current and 75°C and one hour at 1.25 times short circuit current and 75°C

While Qualification tests are important they have limitations because the stress levels are by design limited and the goal is to have all (most) commercially available products capable of passing the test sequence. So 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. Similarly because the Qualification tests are based on known field failure mechanisms they likely will not identify failure mechanisms that:

- Appear after longer term exposure outdoors, so called end of life failures.
- Can be caused by combinations of stresses.
- Occur with new technologies for which field data does not exist.

In order to establish a qualification test sequence for new technologies, to compare the degradation rates and lifetimes of different products or to address any of the above issues, a reliability test program must be utilized.

3.3 Reliability Tests

Reliability tests also use accelerated stress tests with guidance from field experience. However, in reliability testing we wish to cause degradation so that we can learn about module failures and then hopefully do something about the failures. Several approaches to this include:

- Extending the time or cycles of the same tests used in the Qualification test sequence.
- Increasing (or decreasing) the acceleration factors in the same tests used in the Qualification test sequence (for example using a higher or lower temperature in the damp heat test). Of course when doing this, care must be taken to ensure that the failure mechanism observed in the accelerated test is the same one that was observed in the field.
- Combining stresses during the testing. This can be done by adding a stress to one of the tests already utilized, like running current through the module during thermal cycling or by running different stress tests in series e.g. doing humidity freeze after 1000 hours of damp heat.
- Utilizing different accelerated stresses that aren't included in the Qualification tests, but may be indicated from field results.
- Using accelerated stress tests to precondition modules for outdoor exposure. For example taking modules after 1000 hours of damp heat and installing them in a monitored system in a humid climate.

It is critical with reliability testing that any observed failure mechanisms be consistent with those observed in the field.

BP Solar uses reliability testing during product development to assure that new products are at least as good as the ones being replaced and to verify the results of any process or material changes implemented in production.

The following sections describe some of the reliability testing conducted at BP Solar.

4 DAMP HEAT TESTING

4.1 Development of Test

Clearly one of the stresses modules will experience in the field is humidity or damp heat. Some of the earliest work on damp heat exposure of PV modules was performed at the Jet Propulsion Laboratory as part of the US Department of Energy (DOE) Flat Plate Solar Array Project in the later 1970's and early 1980's. Indeed, the first JPL module procurement, Block I, included a damp heat soak as one of the qualification tests. [7, 8] The later procurements, Blocks II through V did not include damp heat testing, but just a humidity-freeze cycle. However, a Block VI qualification sequence that included a long term damp heat test was in preparation when the Block procurement program fell victim to DOE budget cuts. [8]

As part of JPL's reliability program an effort was made to develop a relationship between the rate of cell metallization corrosion and stress levels during damp heat exposure. By performing tests at a number of different temperatures and humidities JPL determined that the rate of the reaction doubled for every 10 degree C rise in temperature. They also determined that a 1% increase in Relative Humidity was equivalent to a 1°C rise in temperature. [9] In addition, the JPL effort included modeling of various environments in order to estimate the expected outdoor exposure of the module. From the combination of these two efforts JPL provided a relationship between different accelerated damp heat test conditions and the environments in several US cities. Using these degradation rates they were able to equate 1000 hours at 85°C/85% RH to 20 years outdoor exposure in Miami, Florida.

This work was the basis for selecting 1000 hours of damp heat at 85°C/85% RH for the damp heat test in IEC 61215 and IEC 61646. Most of today's commercial PV modules are tested at this level.

4.2 Damp Heat Testing to Failure

Since most of today's modules do pass 1000 hours at 85°C/85% RH with little power loss, there is not much information that can be gained from this test relative to predicted module lifetime. To use damp heat testing to predict module lifetime requires testing of modules for much longer times. Figure 4 shows the data for a multi-crystalline silicon, screen print technology module damp heat tested for 5000 hours or based on JPL's relationship, for 100 years of exposure in Miami.

In this case it took more than 2000 hours of damp heat or a predicted 40 years of exposure in Miami to reach a 5% degradation level, the standard pass/fail criteria in the qualification test sequence. This module type carries a 25 year, 20% power loss warranty. According to the results of this test, it should take more than 50 years of field exposure in a humid climate, before this module falls below the warranty level, a substantial safety margin.

4.3 Other Failure Mechanisms

Do all of the humidity induced failure mechanisms observed in modules have the same reaction rate? In one particular module construction the adhesion between the backsheet and the EVA drops rapidly during damp heat testing at 85°C/85% RH. If the same reaction rate holds for this failure mechanism as for the metallization corrosion, the adhesion would drop below acceptable levels within the 25 year warranty period, an unacceptable risk. To evaluate the reaction rate, a humidity test has been conducted at a lower temperature. If the same reaction rate holds, reducing the test temperature from 85° C to 65° C should slow the reaction down by a factor of four, so it should take four times as long to see the same effect. Figure 5 shows the adhesion strength as a function of time for both the 85°C/85% RH exposure and the 65°C/85% RH exposure. Clearly the reaction rate at 65° C is not one quarter the rate at 85°. In fact there is little if any degradation at all of the adhesion strength after 3000 hours at 65°C/85% RH. It appears as though there is a threshold temperature (or higher activation energy) below which there is almost no measurable degradation. For this mechanism 85°C/85% RH is not a valid accelerated stress test and is a more extreme condition than the modules would see over 25 years in the field.

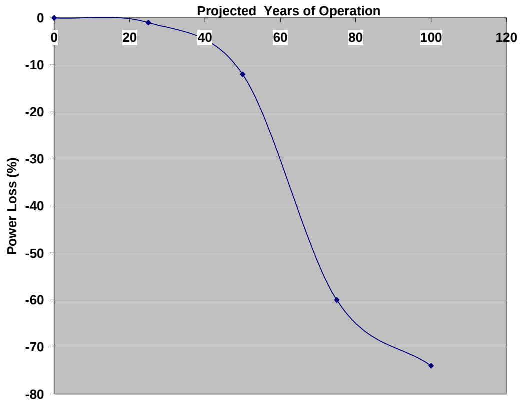

Figure 4: Projected Long Term Performance of Module Based on Damp Heat Testing

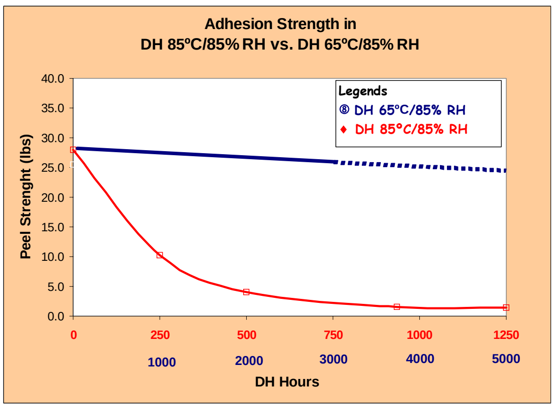

Figure 5: Adhesion of back sheet to EVA after testing at 85°C/85% RH and 65°C/85% RH.

5 THERMAL CYCLE TESTING

5.1 Development of the Test

From the earliest days of PV it was understood that thermal cycling was a useful stress test for evaluation of module performance. The initial JPL Block I program required 100 thermal cycles from -40 to + 90° C. This was reduced to 50 cycles for Blocks II through IV because during Block I testing all of the observed failures occurred during the first 50 cycles. [7] However, during the subsequent outdoor field testing some of the earlier Block modules began to suffer from interconnect fatigue. Therefore in Block V, JPL increased the number of thermal cycles to 200. This work and parallel efforts around the world lead to inclusion of 200 thermal cycles from -40 to +85° C in IEC 61215 and 61646.

5.2 Testing for Longer Warranties

In the 1990's when Solarex was transitioning from a 10 year warranty to a 20 year warranty, the question was raised as to whether longer term thermal cycle testing was necessary to ensure that the modules could last for 20 years. Field results from two older module types were evaluated to better understand the relationship between thermal cycling and field performance.

1. Block 2 modules built on fibreboard substrates successfully completed the 50 thermal cycles required in that program. These modules did fine in the field for about 2 or 2.5 years. After 2.5 years failures (open interconnects) began to appear in hot dry climates. Subsequent thermal cycle tests resulted in most of the modules failing before they reached 100 cycles.
2. Module built on metal substrates do not survive 200 thermal cycles due to broken interconnects. Experimenting with the number of thermal cycles provided evidence that this construction could survive 100 cycles. Subsequent field results indicated that most of these modules failed in the 7 to 10 year range.

From these results Solarex/BP Solar concluded that 200 thermal cycles, represented a valid test for a 10 year module life, but not for 20 years. So Solarex/BP Solar switched to 400 thermal cycles for a 20 year warranty and subsequently to 500 thermal cycles for a 25 year warranty. To verify that the modules could survive a large scale test was performed. Table 3 shows the data from the test. There is very little change out to 600 cycles, so the construction can survive these long cycle tests.

Module	214 TC	300 TC	400 TC	500 TC	600 TC
001	-1.1	-1.9	-2.1	-2.7	-2.8
002	-1.2	-1.4	-1.4	-2.1	-2.3
003	-1.1	-1.0	-1.1	-1.4	-1.8
004	-0.3	-0.5	-0.5	-0.7	-0.7
005	-1.4	-1.8	-1.8	-2.3	-2.3
006	-0.9	-1.1	-1.1	-1.6	-1.4

Table 3: Power loss in percentage as a function of thermal cycles

5.3 Adding Current Flow

In real world operation the modules will be subjected to current flow at or above module Imp for at least part of most thermal cycles. This added stress can cause failures that are not observed during thermal cycling alone.

- If solder bonds are too small, the current flow through the solder bonds may cause them to over heat, melt and become disconnected.
- If an interconnect begins to crack during cycling the current flow through it will overheat it and accelerate the failure.

Both of these effects have been observed as the mechanism leading to some field failures.

Current flow during the above room temperature part of the cycle has been included in BP Solar's qualification test sequence for many years. It has been added to IEC 61215 in the second edition published in 2005.

6 FUTURE WORK

A number of additional reliability studies are underway to expand our knowledge of failures mechanisms and ultimately to improve module reliability and lifetime. These include:

- Doing damp heat tests at 85°C/65% RH to verify the assumption that 1% in RH is equivalent to a 1° C rise in temperature for corrosion of cell metallization.
- Applying voltage during damp heat testing to determine how modules will react to being utilized in high voltage systems in humid environments.
- Revisit the weather exposure models. Recent outdoor data has shown that module leakage current actually reduces as the modules heat up during the day. (See Figure 6.) [10] In most cases as the modules are heated by the sun to high temperatures the moisture is driven out of them into the surrounding ambient. So even in a hot humid environment the modules may be operating at lower humidity than traditionally has been modeled.
- A model is needed to equate thermal cycles in the laboratory with outdoor performance in various climates. This is a difficult task because the modules survive so long in the field and for so many thermal cycles.

7 SUMMARY

Field returns indicate that a very low percentage of modules fail within the warranty period. Long term testing of power levels of a few modules show degradation rates that are considerably lower than typically reported for PV systems. The higher degradation rates often reported for PV systems are likely not due to overall degradation of the modules. Such degradation may be a result of failure of a few isolated modules or degradation associated with other components of the system e.g. increasing series resistance in the connectors.

Finally, accelerated testing indicates that the modules are robust against those field failure mechanisms that have been identified and incorporated into the accelerated testing programs. Correct use of the long term reliability tests can verify that new module designs, materials and processes do not negatively affect the module reliability and lifetime.

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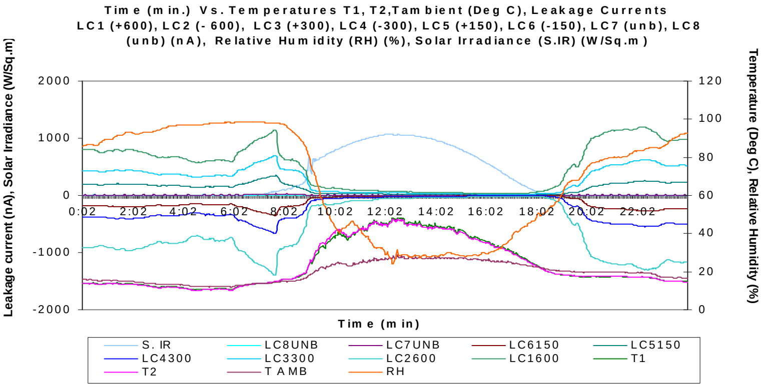

Figure 6: Variation of leakage current, solar irradiance, temperatures, and relative humidity versus time of day.