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Studying the lifetime of crystalline PV modules by interpreting the acceleration test data with statistical reliability models

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ABSTRACT

Crystalline silicon solar modules installed in the field are exposed to atmospheric conditions and experience stress, which induces a wear-out phenomenon in various parts of the modules and degrades performance over time. The performance eventually reaches a point where the output power falls below an acceptable level. Thermal cycling (TC) and damp heat (DH) are two important reliability tests for estimating infant failures related to materials and the manufacturing process, as well as providing the information on performance degradation with respect to time. In this study, modules composed of 156mm × 156mm multicrystalline silicon cells were subjected to TC and DH tests. By applying acceleration models, such as the Norris-Landzberg model for TC and the Hallberg-Peck model for DH, the minimum guaranteed life was calculated. The electrical and reliability results were interpreted and explained on the basis of the respective models.

Introduction

Photovoltaic (PV) technology has the advantage of being able to generate power by means of solar panels that can receive solar radiation irrespective of other environmental factors such as humidity, temperature and rainfall. Crystalline PV technology is a primary solution for energy generation in remote areas where conventional power is not feasible, and also becomes an alternative solution to the on-grid power option when power demand exceeds conventional power generation capacity. Solar panels installed in the field experience adverse environmental effects and degraded power generation capacity year in, year out. In today's solar market, module manufacturers offer a warranty of a minimum of 25 years of power generation and workmanship, up to a limit of 80–85% power.

> "With continuous exposure to solar radiation, EVA reacts with ultraviolet radiation in the solar spectrum."

As for the industry standard, solar module manufacturers have to follow International Electrotechnical Commission (IEC) 61215 guidelines [1] and obtain certification of their products from authorized certification institutes. During certification tests, modules will be subjected to an accelerated stress test for factors such as temperature and humidity to understand the types of failures that can occur and their relation to the quality of the process and materials used in module manufacturing. If either the process or the materials change, the new modules are required to be re-certified by following the IEC retest guidelines [2]. The solar industry needs to adhere to stringent quality standards due to the 25-year product warranty.

There are two kinds of power degradation: light-induced degradation and wear-out degradation. *Light-induced degradation* is related to EVA and the performance of a solar cell with respect to time. With continuous exposure to solar radiation, EVA reacts with ultraviolet radiation in the solar spectrum and hence light transmission to the solar cell through EVA will be reduced [3]. The rate of current generation of the solar cell will decrease after exposure to radiation because boron in the silicon substrate reacts with oxygen contamination and forms recombination centres [4]. *Wear-out degradation* – mainly due to thermal, mechanical and humidity-related stress factors and maximum test failures – is related to thermal cycling (TC) and damp heat (DH) stresses only [5]. There are various studies of TC and DH failures [6–8] in terms of failure analysis. This paper presents the results of studies focusing on TC and DH tests for modules manufactured at Tata BP (TBP) and these results are interpreted to determine the equivalent lifetime using statistical models.

For this study, seven 60-cell modules of multicrystalline 156mm × 156mm cells,

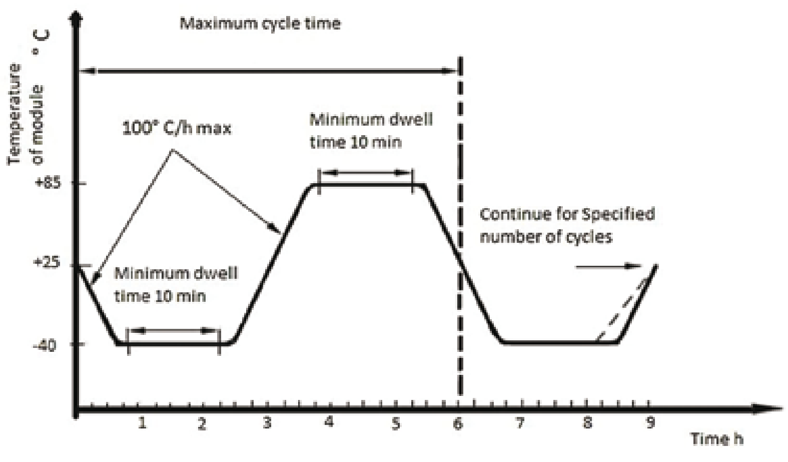

Figure 1. Thermal cycling profile in accordance with IEC guidelines.

manufactured by a standard process, were subjected to accelerated environmental tests. Four modules were subjected to the TC test for 500 hours, two modules were subjected to the DH test for 1140 hours and one module was used as a control sample. Test data were correlated with statistical models and the minimum guaranteed lifetime for the product was calculated. *IV* data measured at regular intervals during the TC test were converted to correspond to a real-time distribution.

> “Since the environmental conditions are outside of human control, manufacturers should ensure that their modules are robust for any eventual conditions.”

Background

As mentioned previously, during their operation in the field, crystalline silicon solar modules are exposed to atmospheric conditions such as radiation, temperature and humidity. These conditions are not constant and vary from minimum to maximum values in a cyclic manner, causing a build-up of stress in all parts of the module. The wear-out mechanism induced by stress leads to degradation of module performance; the rate of degradation increases with time and eventually reaches a point where the module fails to achieve an acceptable level of performance. The amount of time from the day of installation until a module begins to perform below the acceptable level depends for the most part on two factors: 1) the module process and material quality, and 2) the environmental conditions of the location where the module is installed. Since the environmental conditions are outside of human control, manufacturers should ensure that their modules are robust for any eventual conditions.

In order to withstand the environmental conditions, PV manufacturers use acceleration tests. The accelerated ageing test in indoor chambers uses a mixture of environmental conditions such as pressure, radiation, moisture and temperature, all at higher values than nominal product operating conditions. This kind of reliability testing has been in use in the solar industry since the day of inception of PV products. Accelerated tests proposed by IEC 61215 for design qualification of crystalline PV modules replicate the environmental conditions over 25 years in a short period to find out the failures related to design flaws, material quality and the manufacturing process [9]. There are six types of test:

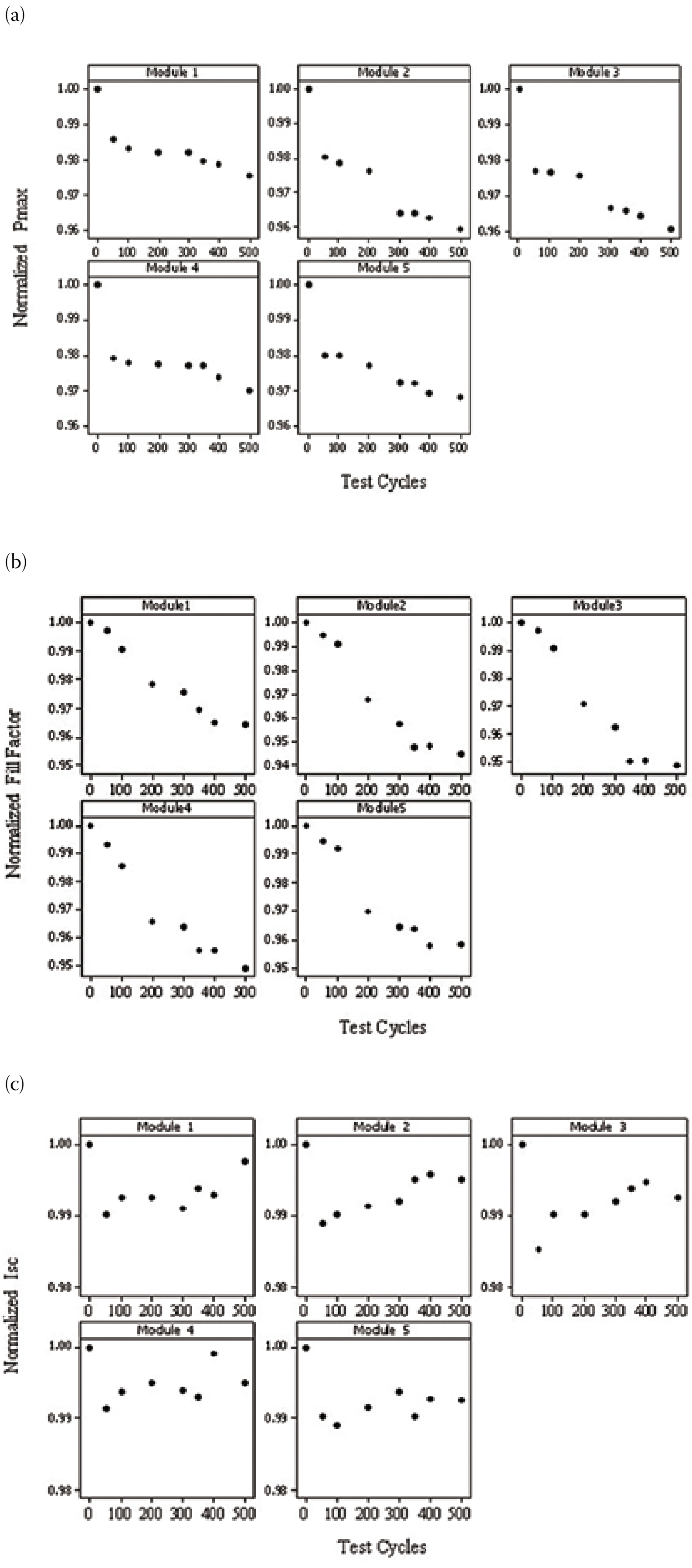

Figure 2. Relative changes in the characteristics of test modules at various test cycles of thermal cycling: (a) power drop; (b) fill factor drop; (c) short-circuit current drop.

- Electrical – insulation resistance and wet leakage current tests
- Performance – P_{max}, temperature coefficients and normal operating cell temperature (NOCT)
- Thermal – bypass diode and hot-spot tests
- Irradiance – outdoor exposure, UV exposure and light-soaking tests
- Environmental – TC, humidity, freeze and DH tests
- Mechanical – mechanical load and hail tests

Among the mentioned stress tests, the environmental ones are the most critical because according to a survey, most reports indicated that TC and DH failures were more numerous [10]. In this paper, TC studies and DH test results are correlated with a statistical model to estimate lifetime and reliability.

Experimental details

p-type boron-doped multicrystalline 156mm wafers were converted into solar cells by using standard screen-print technology; modules were then fabricated with these cells. Wafer to module conversion was performed at in-house manufacturing facilities. The steps involved in the module manufacturing process were:

- Tabbing the inspected cells by using interconnect ribbon
- Stringing the tabbed cells
- Making the lay-up by using standard lamination materials
- Laminating
- Fixing the junction box
- Framing
- Testing and grading the module

The *IV* characteristics of these modules were determined using standard operating procedures.

Modules were constructed using the conventional process and tested in accordance with IEC 61215 guidelines for TC and DH in the well-known module reliability test lab. One module was conserved as a control sample in order to compare the performance of the modules after the acceleration tests. Four modules were kept for TC tests and two modules subjected to the DH test. To minimize measurement errors, the control module was measured each time before measuring the test modules.

Acceleration models

A product is said to be aged when its characteristics (physical, mechanical, chemical, etc.) have changed as a result of the stress experienced in operation over a period of time and its performance or quality has degraded. Some products take longer to age, and it is difficult for product developers to collect failure and lifetime data for their products. The accelerated ageing test is a universally accepted method in industry for testing a product at higher stress levels under various conditions – such as temperature, radiation and humidity – than it normally encounters during its operation.

The accelerated test has two purposes: 1) to determine failures related to design and the manufacturing process, and 2) to estimate the useful lifespan of the product. Since the accelerated tests are carried out at higher levels of stress to evaluate the failure time, the test results cannot be interpreted directly for normal operating conditions. Appropriate acceleration models need to be used to convert the test results to normal operating conditions [11]. A linear time relationship will be assumed to use a transformation function

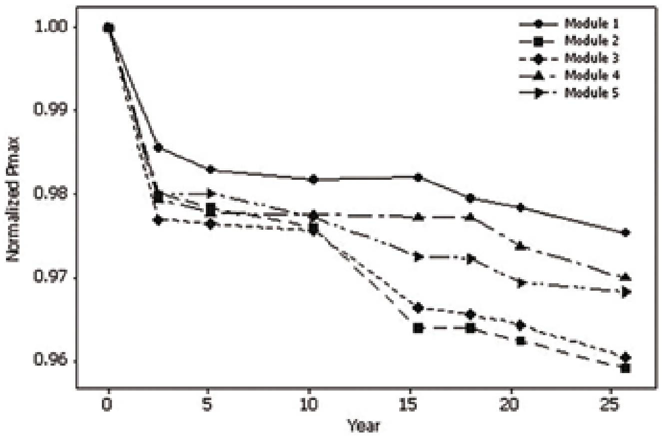

Figure 3. Power drop with respect to the equivalent years calculated using the acceleration factor.

for modelling acceleration results; the time to fail under normal operating conditions is therefore

$$T_o = A_f \, T_t \qquad (1)$$

where T_o is the minimum guaranteed lifetime, A_f is the acceleration factor and T_t is the time spent in the test.

Thermal cycling

When a product is exposed to different temperature conditions, not all of its parts will expand or contract at the same rate in all directions because of a mismatch in the temperature coefficients of expansion and contraction of different materials. The stress built up due to this mismatch is called thermal stress. Crystalline PV modules are subjected to TC to characterize the level of damage in solder joints. The temperature coefficients of tin-copper interconnects (TCIs) (17.5×10^{-6}/K), silver busbars (18.9×10^{-6}/K) and silicon (4.68×10^{-6}/K) are different, so the rates of expansion and contraction will be different when a module experiences cyclic changes in temperature. Due to this mismatch in temperature coefficients, the solder joints associated with TCIs, silver busbars and silicon will wear out and increase the series resistance.

> “The fill factor (*FF*) is strongly dependent on the series resistance and shunt resistance of the solar cell.”

It is well known that the fill factor (*FF*) is strongly dependent on the series resistance and shunt resistance of the solar cell, and hence any increase in contact resistance will reduce the fill factor significantly. For the study reported on in this paper, TBP multicrystalline 156mm 230W modules were tested for TC using the temperature range defined by IEC 61215 and held for 500 cycles, since the stress level will be increased if held for longer (Fig. 1).

Norris-Landzberg model (modified Coffin-Manson model)

The Coffin-Manson equation models the effects of thermally induced stress and follows an inverse power law relationship. In other words, as the magnitude of the induced stress increases, the number of cycles to failure decreases by a power of two. Norris-Landzberg modified the Coffin-Manson model by including time- and frequency-dependent anomalies [12,13]. The acceleration factor is calculated using the equation

$$A_{TC} = \left(\frac{\Delta T_L}{\Delta T_U}\right)^2 \left(\frac{F_U}{F_L}\right)^{1/3} \exp\left\{1414\left(\frac{1}{T_U}-\frac{1}{T_L}\right)\right\} \qquad (2)$$

where A_{TC} is the acceleration factor for the time duration (dimensionless), ΔT_L is thermal cycle temperature change in the accelerated lab environment, ΔT_U is the temperature change in the operating environment, F_U is the frequency (cycles/day) of the thermal cycles in the operating environment, F_L is the frequency (cycles/day) of the thermal cycles in the accelerated environment, T_U is the maximum temperature in the operating environment and T_L is the maximum temperature in the accelerated environment.

> “The temperature of the module starts to increase from 297K along with sun radiation.”

The parameters for the acceleration tests conducted in this study are ΔT_L = 398K, T_L = 358K and F_L = 4 cycles/day. Based on field data of TBP modules installed in the southern part of India, the maximum operating temperature (T_U) is 328K. The minimum temperature experienced by modules in the field before and after peak radiation during a day is normally 297K, and hence the difference in operating temperatures (ΔT_U) in a day is 304K. The temperature of the module starts to increase from 297K along with sun radiation and falls back down again to the nominal value when the sun sets. Assuming typical wind speeds and the cloudy behaviour of a particular tropical region, the estimated maximum number of thermal cycles (F_U) is four per day. The acceleration factor calculated for TC by substituting the given values and field conditions in Equation 2 is 37. The minimum guaranteed life is therefore equal

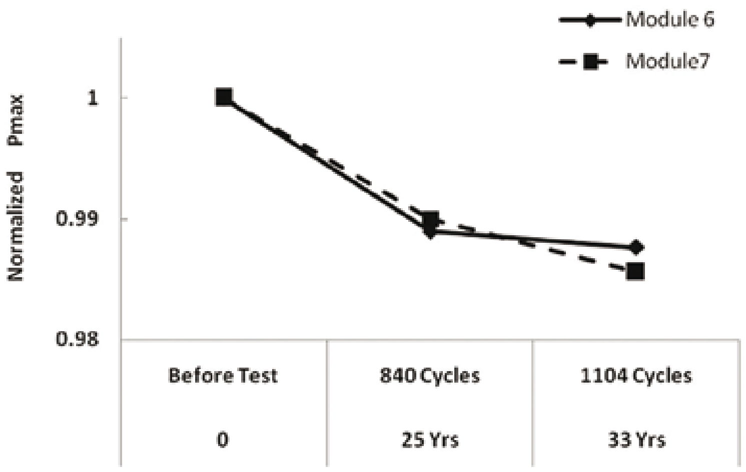

Figure 4. Power drop of test modules at various test cycles of the damp heat test (85°C, 85% RH).

to $A_{TC} \times T_t$ = acceleration factor × (number of cycles × 6 hours) = 37 × (500 × 6) hours = 25 years.

Results and discussion

Fig. 2 shows the relative change of maximum power P_{max}, fill factor FF and short-circuit current I_{sc} of test modules at various test cycles. Zero represents the results for an as-fabricated module, and the *IV* measurements of modules were carried out at regular intervals to understand the relative drop with respect to the level of stress experienced. The observed drop in power is linear with respect to the number of cycles, and the initial drop of 50 cycles is larger than for subsequent intervals. This is because the short-circuit current dropped significantly compared to the fill factor in the first 50 cycles; the reason for this drop is not yet understood.

As the stress increases with the number of cycles, the fill factor decreases, since the solder joints of the TCI, silver and silicon wear out due to the mismatch in thermal expansion coefficients. By using Equation 1, a number of test cycles were converted into equivalent years by substituting the acceleration factor and time. The power drop with respect to time in years is shown in Fig. 3. It is interesting to note that the contribution of the degradation of the solder joints to power drop in the crystalline solar module during its operation in the field is a maximum of 4% over a 25-year period. The observed decrease in power after 500 cycles of the TC test is quite reasonable for 25 years and can give a manufacturer confidence in their process and material quality.

Damp heat

The ageing of a material can be explained using the collision theory of particles, according to which particles in a material are in continuous collision, and a collision with sufficient energy will break existing bonds and form new bonds. This in turn leads to a change in the properties of the material in terms of its physical, mechanical and chemical attributes. The sufficiency energy, also known as activation energy, which decides the success rate of collision, can be increased by changing the temperature. It is well known that at higher temperatures, particles will have higher energy states and have the activation energy necessary to make a collision successful; for every 10°C rise in temperature, the reaction rate doubles [14].

As discussed earlier, the maximum temperature of PV modules in the field is 328K, so the acceleration test is conducted at 358K to increase the rate of reaction. Along with maintaining this temperature, the humidity is also kept at 85% RH, which is higher than normal operating conditions. High humidity in combination with high temperature causes moisture to diffuse through joints and accelerates the corrosion in metal parts of the product [15]. The main objective of the DH test is to assess the lamination process by observing moisture ingress and related corrosion in metallic parts such as silver contact fingers, busbars and interconnect ribbons.

> "At higher temperatures, particles will have higher energy states and have the activation energy necessary to make a collision successful."

Hallberg-Peck model

Arrhenius's equation was the first acceleration model developed for temperature-related stress modelling. This equation was subsequently modified by Hallberg and Peck to combine the effects of temperature and humidity [16] and is given by

$$A_{DH} = \left(\frac{RH_L}{RH_U}\right)^3 \exp\left\{\frac{E_a}{K}\left(\frac{1}{T_U} - \frac{1}{T_L}\right)\right\} \tag{3}$$

where A_{DH} is the acceleration factor, E_a is the activation energy (eV), K is Boltzmann's constant (8.617×10^{-5} Ev/Tk), T_U is the operating temperature (K), T_L is the acceleration test temperature (K), RH_L is the acceleration test humidity and RH_U is the operating humidity. The acceleration test was conducted at a temperature $T_L = 85 \pm 2°C$ with a relative humidity $RH_L = 85 \pm 5\%$ for 1000 hours. Based on field data, the nominal operating temperature and humidity is $T_U = 323K$ and $RH_U = 55\%$; the activation energy for EVA is taken to be 0.9eV [17]. The acceleration factor for the DH test was calculated by substituting the given parameters in Equation 3, yielding $A_{DH} = 87$. The minimum guaranteed life is therefore equal to $A_{DH} \times T_t = 87 \times 1000$ hours = 30 years.

Results and discussion

Fig. 4 shows the power degradation with respect to the number of test cycles and equivalent years. As the purpose of the test is to verify the stress in a continuous fashion without any discontinuity, the modules were only taken out of the chamber after 840 cycles, which equates to 25 years. The modules were inspected visually and no defects or corrosion in metallic parts was found. If the lamination is irregular, moisture will penetrate in between the layers and react with the metallic parts as well as EVA. Moreover, moisture penetration at higher temperatures will lead to aluminium and back-sheet delamination of the cell back surface, resulting in a significant reduction in module power. For the modules tested, a power drop of 1.3% after 1104 cycles of DH stress testing confirms that the lamination process is optimum and also proves that the quality materials used in module making justify a 25-year warranty.

> "The calculations based on reliability models confirmed that the IEC guidelines for acceleration testing are sufficient for providing a long-term warranty on the product."

Conclusions

Multicrystalline solar modules were subjected to TC and DH tests in accordance with IEC 61215 guidelines; the resulting power drop was correlated to the lifetime calculated from acceleration models. It was clear from reliability calculations that modules made using the standard TBP manufacturing process are able to withstand environmental stresses such as temperature and humidity, as well as delivering the power within acceptable limits for 25 years. This study also confirmed that the power degradation noticed during reliability testing correlated with actual observed performance in the field. The calculations based on reliability models confirmed that the IEC guidelines for acceleration testing are sufficient for providing a long-term warranty on the product. As part of future research in this area, it is envisaged that a detailed understanding and relative analysis of module degradation at various stages of IEC testing could provide an opportunity for manufacturers to improve lifetime and performance.

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