Testing the reliability and safety of photovoltaic modules: failure rates and temperature effects

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ABSTRACT

Photovoltaic modules are designed to meet the reliability and safety requirements of national and international test standards. Qualification testing is a short-duration (typically, 60-90 days) accelerated testing protocol, and it may be considered as a minimum requirement to undertake reliability testing. The goal of qualification testing is to identify the initial short-term reliability issues in the field, while the qualification testing/certification is primarily driven by marketplace requirements. Safety testing, however, is a regulatory requirement where the modules are assessed for the prevention of electrical shock, fire hazards, and personal injury due to electrical, mechanical, and environmental stresses in the field. This paper examines recent reliability and safety studies conducted at TÜV Rheinland PTL's solar module testing facility in Arizona.

Introduction

TÜV Rheinland PTL (formerly Arizona State University Photovoltaic Testing Laboratory) has been involved in PV testing and standards development activities for over 18 years. TÜV Rheinland PTL, a joint venture between TÜV Rheinland and ASU, is one of six TÜV Rheinland laboratories around the globe. The Arizona branch was created in October 2008 with additional testing services, capabilities, test/engineering personnel, and indoor (40,000 square feet) and outdoor test areas (five acres). The PV module testing and applied research activities at TÜV Rheinland PTL and ASU include:

- Performance at standard test conditions
- Performance at nonstandard test conditions
- Performance characterizations as per Sandia National Laboratory method
- Design qualification testing of flat-plate PV modules (IEC 61215, IEC 1646)
- Design qualification testing of concentrator PV modules (IEC 62108)
- Safety testing of flat-plate modules (IEC 61730, ANSI/UL 1703)
- Evaluation of polymeric components used in PV modules
- Reliability research to predict lifetime of modules in the field.

The results of various qualification and safety testing conducted at TÜV PTL are presented in this paper. The first section discusses the failure rates obtained in the qualification testing of flat-plate modules (per IEC 61215 and IEC 1646 standards) over 13 years [1,2]. The second discussion centres on one of the major safety tests (per IEC 61730 and ANSI/UL 1703 standards) – the 'temperature test' [3,4]

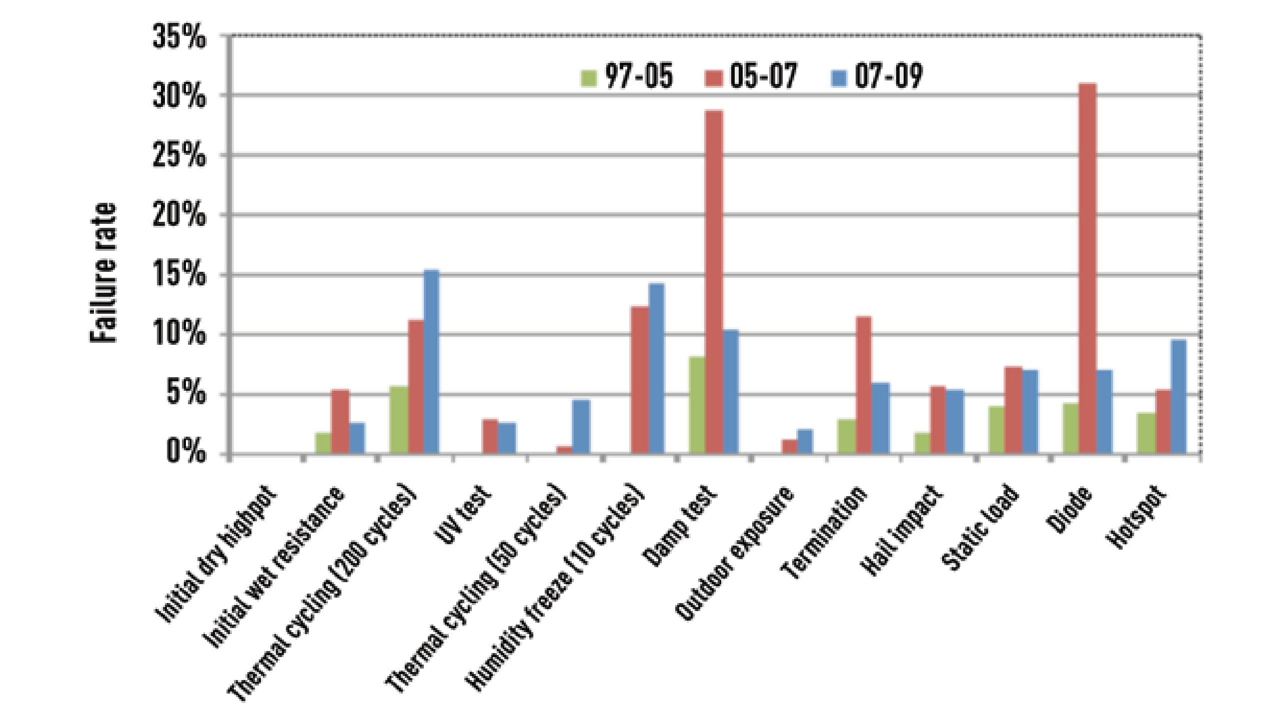

Figure 1. Failure rate comparison of crystalline silicon modules for 1997-2005, 2005-2007 & 2007-2009.

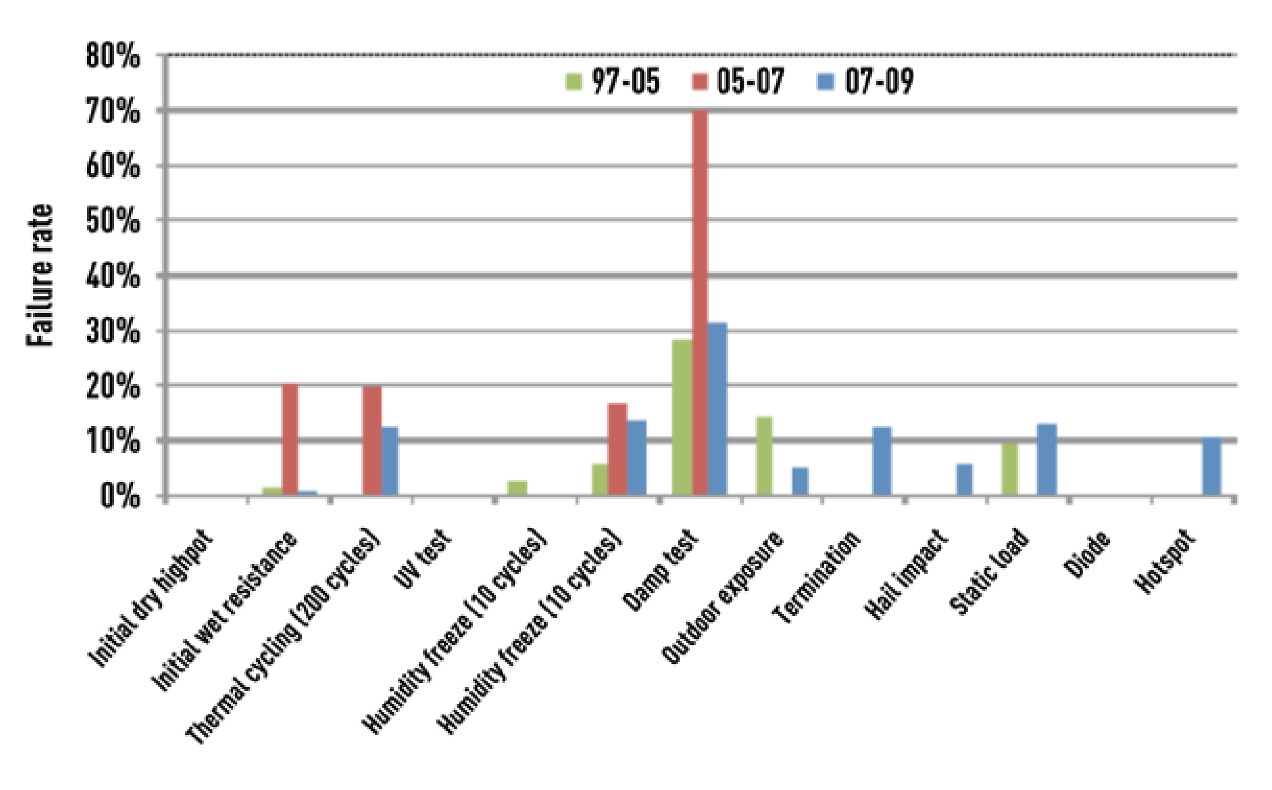

Figure 2. Failure rate comparison of thin-film modules for 1997-2005, 2005-2007, and 2007-2009.

– with results obtained for more than 140 modules compared with data obtained on actual rooftop PV modules.

Module reliability: failure rates in qualification testing

Qualification testing is a set of well-defined accelerated stress tests – irradiation, environmental, mechanical and electrical – with strict pass-fail criteria based on functionality/performance, safety/insulation, and visual requirements. The qualification testing does not, as anticipated, identify all the possible lifetime/reliability issues that would be encountered in the field; however, it does identify the major/catastrophic design quality issues that would initially occur in the field. The type, extent, limits, and sequence of the accelerated stress tests of the qualification standards have been stipulated with two goals in mind: one, accelerate the same failure mechanisms as observed in the field but without introducing other unknown failures that do not occur in the actual field; and two, induce these failure mechanisms in a reasonably short period of time (60-90 days) to reduce testing time and cost. As an ISO 17025 accredited laboratory, TÜV Rheinland PTL has tested more than 5,000 photovoltaic modules from nearly 20 different countries and issued several hundred qualification certificates.

The following section presents a failure analysis of the design qualification testing of both crystalline silicon and thin-film modules for three consecutive, multiyear periods: 1997-2005, 2005-2007 & 2007-2009. A detailed analysis of the failure rates in the qualification testing is presented elsewhere [5].

> "About 3% of the crystalline silicon modules failed in the initial wet resistance test right out of the box."

In the 1997-2005, 2005-2007, and 2007-2009 periods, about 1,200 (87% c-Si), 1,000 (93% c-Si), and 1,470 (83% c-Si) modules, respectively, were tested for the qualification certification. In the latter two periods, about 52% and 39% of them, respectively, were manufacturers that were new to the test laboratory.

Fig. 1 shows a comparison of the failure rates of crystalline silicon modules in various initial and stress tests for the 1997-2005, 2005-2007, and 2007-2009 periods. For the latest timeframe, the thermal cycling 200 test, humidity freeze test, damp heat test, and hot spot test showed the highest failure rates of 15%, 14%, 10%, and 10%, respectively. About 3% of the crystalline

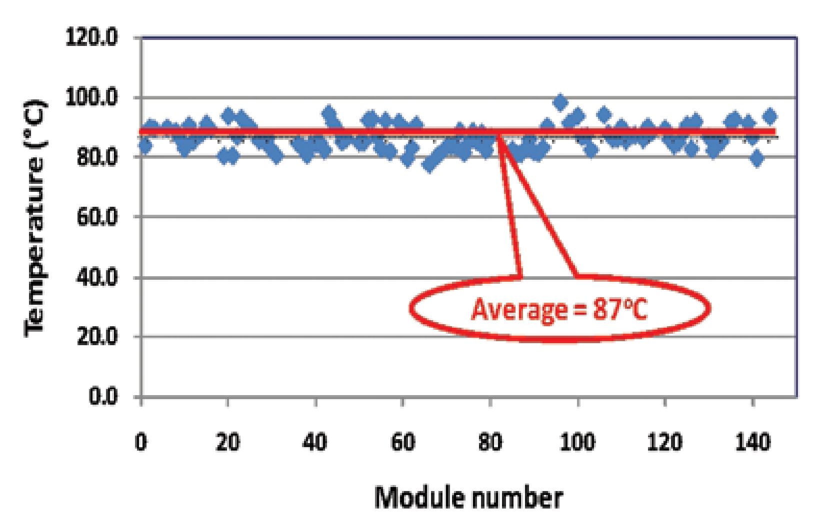

Figure 3. Normalized cell temperature, standard testing (ambient temperature 40°C; irradiance 1000W/m²).

silicon modules failed in the initial wet resistance test right out of the box, a result that could have been easily avoided if the module manufacturers had implemented the wet resistance test in the production line.

For the purposes of this paper, the analysis represented in Fig. 1 is limited to only the two longest duration (about 42 days) but most stringent tests for the three time periods, namely, the damp heat test and the thermal cycling 200 test. While it is interesting and comforting to see that there has been a decrease in failure rates in damp heat testing from 29% (2005-2007) to 10% (2007-2009), this 10% failure rate is still higher than the rate of the modules tested in the 1997-2005 period (8%). Considering that these modules are expected to have 20-25 years of lifetime in humid climatic conditions, the 10% failure rate may not be acceptable to consumers.

As for the thermal cycling 200 test results, it is a little discouraging to see an increase in the failure rate from 11% (2005-2007) to 15% (2007-2009). When the testing data from the entire 13 years are examined, the top four test failure categories in the qualification testing of c-Si modules have been determined to be damp heat, thermal cycling, humidity freeze, and diode.

Figure 4. Simulated rooftop structure in the testing yard (front view, bottom row = 0-in. air gap; top row = 4-in. air gap).

Fig. 2 shows the failure rate of thin-film PV modules in various initial and stress tests for the 1997-2005, 2005-2007, and 2007-2009 periods. For the most recent timeframe, the damp heat test (31%) and humidity freeze test (14%) showed the highest failure rates, followed by the static load, termination, and thermal cycling 200 tests (12-13%). About 1% of the thin-film modules failed in the initial, right-out-of-the-box wet resistance test.

As in the c-Si module analysis, for the purposes of this article, the comparative analysis for thin-film modules is limited to only the longest duration tests – damp heat and thermal cycling 200. A dramatic decrease in failure rate in the damp heat

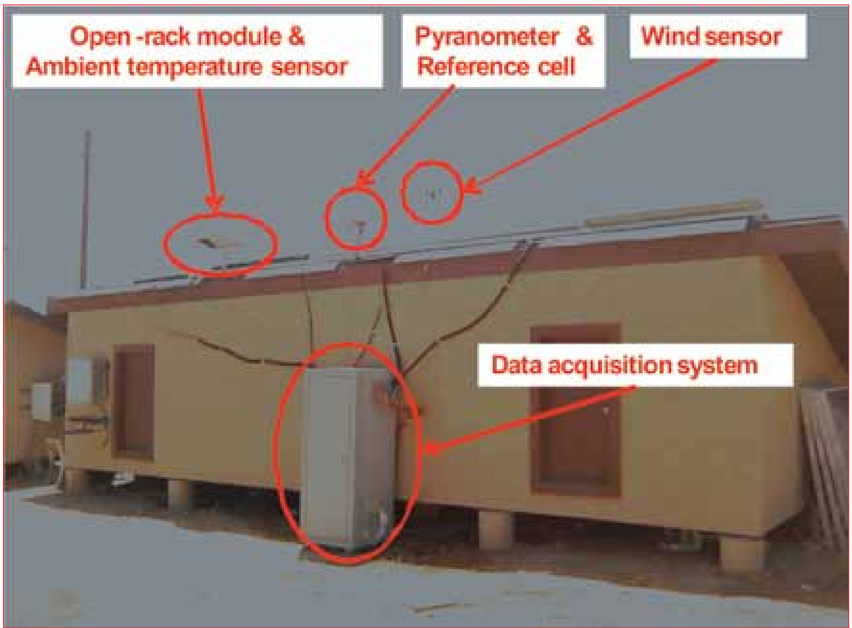

Figure 5. Simulated rooftop structure in the testing yard (rear view, with various sensors and DAS).

test can be seen, going from 70% (2005-2007) to 31% (2007-2009). Since the modules are expected to have 10-20 years of lifetime in humid climates, this 31% failure rate will certainly not be acceptable to consumers.

Encouragingly, the failure rate for the thermal cycling 200 test has fallen from 20% (2005-2007) to 12% (2007-2009). An examination of the data from the 13 years of testing reveals that the top four test failure mechanisms in the qualification testing of thin-film modules are damp heat, thermal cycling, humidity freeze, and static load.

Rooftop PV module safety: temperature effects

The operating temperatures of various components of rooftop PV modules are dictated by various parameters, including ambient temperature, irradiance, wind speed, bias condition (open-circuit, short-circuit, maximum-power point and shading), and installation configuration (air gap between module and roof surface). In hot climatic conditions, such as Arizona, the module temperature could reach as high as 85°-95°C, depending on the mounting configuration. In the following section, a brief comparison of the test results obtained during the temperature tests (per IEC 61730 and ANSI/UL 1703 standards) and the test results obtained on the actual rooftop installed modules are presented. The detailed results related to these studies are discussed elsewhere [6,7].

The purpose of the temperature test identified in the safety standards is to ensure that no part of the module attains a temperature that would ignite materials or components, exceed the temperature limits of materials, and cause creeping, distortion, sagging, or charring. The IEC 61730 and UL 1703 temperature test method closely mimics the close-roof (direct mounting) model. During the temperature test, the operating temperatures of nine components of each module were monitored and recorded under prevailing field conditions. These components include front glass (superstrate), substrate (polymer backsheet), cell, junction-box ambient (inside volume), junction-box surface (inside surface), positive terminal (inside the junction box), junction-box backsheet (polymer backsheet inside the junction box or bottom surface of the J-box), field wiring, and diodes. The component temperatures were then normalized, as shown in Equation 1, to those expected for an ambient temperature of 40°C and 1000W/m² plane-of-array irradiance as required by the standards.

The normalized temperature (in °C) of each component was calculated using the following equation:

$$T_{norm} = (T_{max} - \text{Mean } T_{amb}) \times \frac{1000}{\text{Mean Irradiance}} + 40 \qquad (1)$$

where T_{norm} is the normalized temperature, T_{max} is the maximum component temperature during the test, and T_{amb} is the ambient temperature during the test.

In this paper, only the normalized cell temperatures obtained under open-circuit condition (standard testing) are compared with the monitored cell temperatures of rooftop modules under open-circuit condition (rooftop testing). Fig. 3 shows the temperature test results for the open-circuit condition obtained for approximately 140 c-Si modules (with glass/cell/polymer packaging) from approximately 60 different manufacturers during 2006-2009.

A simulated rooftop structure was designed and installed at ASU's Photovoltaic Reliability Laboratory in Mesa, Arizona. The concrete flat-tile roof was 32 feet by 17.5 feet, with a south-facing orientation and a pitch from horizontal of 23 degrees. Front- and rear-view photographs of the simulated rooftop structure are shown in Figs. 4 and 5, respectively.

The array and module installation specifications of the roof were as follows:

- Test technologies: mono-Si and poly-Si
- Module electrical termination: open circuit

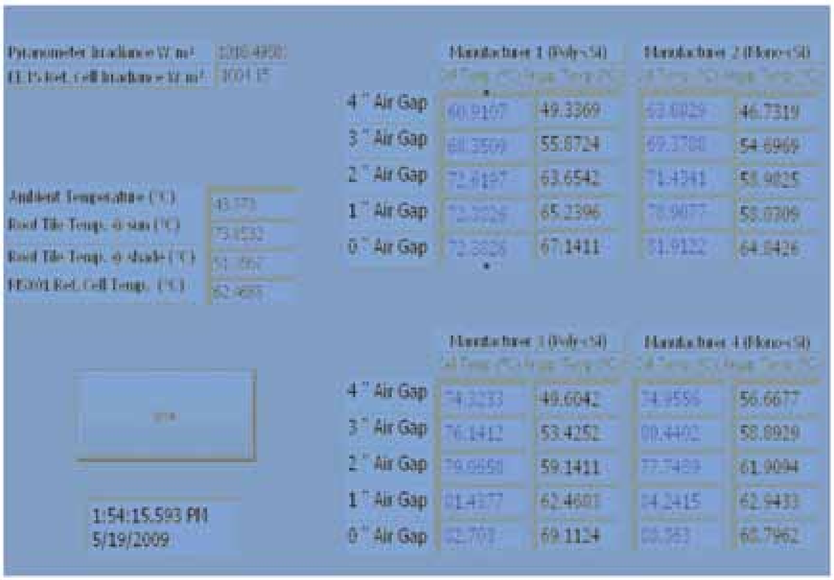

Figure 6. A screenshot of front panel of data acquisition system (cell temperature = thermocouple under the cell; air-gap temperature = temperature between module laminate and roof tile).

PV Modules

- Number of test modules: 20 (10 mono-Si; 10 poly-Si)
- Array matrix: four columns (five modules each) x five rows (four modules each):
  - Column 1: poly-Si (manufacturer 1)
  - Column 2: mono-Si (manufacturer 2)
  - Column 3: poly-Si (manufacturer 3)
  - Column 4: mono-Si (manufacturer 4)
  - Row 1 (bottom row): 0-in. air gap
  - Row 2: 1-in. air gap
  - Row 3: 2-in. air gap
  - Row 4: 3-in. air gap
  - Row 5 (top row): 4-in. air gap
- Distance between modules in each column: 2-6 in.
- Distance between modules in each row: 1 in.
- Depth of module frame: ~2 in.

The monitored parameters on the rooftop test bed and details of data acquisition system (DAS) were as follows:

- Irradiance:
  - Plane-of-array irradiance using a pyranometer (Eko, Japan)
  - Plane-of-array irradiance using a c-Si reference cell (EETS, UK)
- Ambient temperature
- Wind speed
- Wind direction
- Roof-tile temperature exposed to sunlight
- Roof-tile temperature shaded by a module
- Backsheet temperature of an open-rack module (installed at the top edge of roof structure)
- Air-gap temperature under each of the 20 modules
- Cell temperature: average temperature of two middle cells (through backsheet cut)
- Data collection: recorded every minute; averaged and saved every six minutes
- DAS: National Instruments NI-9172
- DAS software: a dedicated LabView-based software developed in this work.

Fig. 6 features a real-time screenshot of monitored data on a hot sunny day when the ambient temperature was 43°C and irradiance was about 1000W/m^2. It shows that the lower air gaps significantly increase the module temperatures as compared to higher air gaps. The average daily temperature of tiles under PV modules is lower by about 15°C when compared to tiles exposed to direct sunlight. This indicates that the rooftop PV modules help significantly reduce the summer cooling load of the buildings just by simply shading the roof tiles.

The temperature test (Fig. 3) indicates an average cell temperature of 87°C, while the rooftop results for the 0-inch air gap modules noted in Fig. 6 show cell temperature ranging between 72°C and 88°C, depending on the module column number. Because of wind direction from left to right, the first column (left) modules experienced lower temperatures compared to the fourth column (right) modules. This study and a yearlong extension of this study clearly suggest that the temperature testing of the test standards closely simulates the temperatures of real-world rooftop modules.

Conclusion

The comparative failure analysis testing showed that the fraction of new manufacturers in the 2005-2007 period was about 52%, and the failure rate dramatically increased in the 2005-2007 period as compared to the 1997-2005 period. The fraction of new manufacturers in 2007-2009 period was about 39% but, encouragingly, the failure rates for most of the major stress tests have dramatically decreased for the 2007-2009 period compared to the previous period of 2005-2007. As for the temperature testing method of the safety test standards (ANSI/UL 1703 and IEC 61730), the lab's findings reveal that it closely simulates the temperatures of real-world rooftop modules.

References

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