Application of the NREL Test-to-Failure Protocol for PV Modules

Peter Hacke, David Trudell, Kent Terwilliger, Nick Bosco, Edward Gelak, and Sarah Kurtz

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Peter Hacke, David Trudell, Kent Terwilliger, Nick Bosco, Edward Gelak, and Sarah Kurtz

National Renewable Energy Laboratory, Golden, CO 80401

Abstract

Initial results of application of the NREL Test-to-Failure Protocol are presented and discussed. Six commercially available multicrystalline Si-cell flat-plate modules were subjected to the protocol with controls. The samples were divided among three test sequences, (1) 1000 hours of 85°C/85% relative humidity with positive or negative 600 V bias to the active layers with respect to the grounded frame, (2) -40/85°C thermal cycling with electrical load at the rated module power, and (3) an alternating sequence between tests (1) and (2). Application of the protocol manifested in the acceleration of degradation mechanisms seen in the field including backsheet delamination, corrosion, bubble formation within the laminate, discoloration of the antireflective coating, and localized heating with degradation of the backsheet as a result of moisture ingress, corrosion, and concentrated current flow. Significant differences in performance after one round of the protocol are seen in damp heat depending on the polarity of the bias applied to the active layer (the short-circuited power leads of the module). The protocol is found to successfully accelerate module degradation mechanisms that have been observed in the field and will help to differentiate the performance and reliability of various module technologies.

Introduction

Passing International Electrotechnical Commission certifications such as IEC 61215 and IEC 61646 for crystalline and thin-film silicon PV modules, respectively, are important thresholds to demonstrate the ability of modules to withstand a prescribed environmental exposure. The pass/fail criteria provided by such certifications however do not go far in differentiating which module technologies are better, nor do they provide a measure of module reliability over 25 or more years in the field. NREL has proposed a Test-to-Failure (TTF) protocol [1] that implements a series of accelerated environmental chamber testing procedures. The protocol's utility includes the following:

- Test new module technologies for product qualification on a comparative basis in a highly accelerated manner
- Spot-check performance and reliability of module designs that, in the past, may have obtained certifications
- Perform due diligence between various module technologies before large capital outlays for PV power plants are committed
- Characterize potential performance and reliability problems for high voltages systems
- Accelerate the onset of failure so that failure mechanisms can be studied, compared to field failures, and then addressed
- Qualify modules to minimize costly field diagnostics and servicing

While the performance of modules undergoing this protocol does not quantify module lifetime in the field, the information obtained is useful for the comparison of the reliability of different module technologies in an accelerated manner and on a quantitative basis.

The majority of field failures in the collective inventory of modules described in the literature across test laboratories and PV installations are not from arrays reaching the modern 600 V system voltage limit of the US, and even fewer are from those reaching the 1000 system voltage limit of the EU, and beyond. Similarly, for a recent publication indicating favorable performance of fielded modules, the modules were not specified to be from high voltage arrays [2]. Further, this study indicated a statistically significantly higher failure rate when modules were placed in inverter-connected arrays vs. being fielded in the open-circuit condition. In other detailed analyses of module degradation rates, measurements were taken on individual modules [3]. While it has been reported that warranty returns for major module manufacture are low [3], the cost of finding degraded modules in modern PV power plants involving hundreds of thousands of PV modules becomes cost prohibitive, except in the case of complete open circuit failure of the string [4]. The TTF protocol prescribes testing at the rated system voltage of a module under damp heat to simulate the high potential voltage that can exist between the active layers and the module packaging.

In this work, we report the results after one round of testing of a group of multicrystalline silicon cell-based modules undergoing the TTF protocol. We report on the in-situ monitoring, quantify the degradation under accelerated testing, discuss some of the failure mechanisms observed under the different stress factors applied, and begin to discuss the results in view of enhancements to this newly developed protocol.

Experimental

Eight nominally identical commercially available flat plate crystalline silicon modules of a given model from a single manufacturer were obtained. The eight modules were divided between the accelerated lifetime test stressors as described by the protocol [1] in Table 1. There are 4 sequences: (1) damp heat (2) thermal cycling (3) alternating damp heat and thermal cycling, and (4) control.

Table 1. The organization of the modules within the accelerated lifetime test sequences in the Test-to-Failure protocol.

Round	1. DH 1000 Hrs. 85°C/85%RH		2. TC 200 cyc. -40/85C		3. Alt DH/TC		4. Control	
Module	1A	1B	2A	2B	3A	3B	4A	4B
	5 kW hrs/m^2 light soak							
1	DH+	DH-	TC	TC	DH+	DH -		
2	DH+	DH-	TC	TC	TC	TC		
3	DH+	DH-	TC	TC	DH+	DH -		
4	DH+	DH-	TC	TC	TC	TC		
…								
15	DH+	DH-	TC	TC	DH+	DH -		

DH refers to 1000 hrs 85°C 85% relative humidity, ASTM E 1171 sec. 6.7
DH+(-) indicates +(-) voltage bias of 600 V or module's rated system voltage (whichever is greater) on shorted module leads with respect to the grounded frame

TC refers to 200 cycles between -40°C and 85°C with bias, IEC 61215 Sec. 10.11

Alt DH/TC refers to a sequence of alternating 1000 hrs. DH and TC 200 stress cycles described above

The damp heat sequence (1) of 1000 hrs in 85°C 85% relative humidity includes a voltage bias of 600 V or the module manufacturers specified system voltage, whichever is greater, applied to the shorted module leads with respect to the designated module ground point (in this case, the module frame). If there is no specific information for required polarity of the active layers of modules in a string with respect to ground in the specification sheet of the module, then modules are divided for test in positive and negative polarities (DH+, DH-) as indicated in Table 1. The current that flows through each module under bias is monitored continuously over the course of the damp heat test.

The thermal cycle sequence (2) as described in IEC 61215 Sec. 10.11, is implemented with current controlled forward bias load at maximum power (I_{mp}) applied when the module is above 25° C. The voltage is monitored in-situ for any open or short circuits that may develop during the course of the test. The alternating damp heat and thermal cycling sequence (3) requires alternating the modules between damp heat as prescribed in sequence (1) and thermal cycling as prescribed by sequence (2). While the protocol calls for one control module, we used two controls for this path-finding application of the TTF protocol in sequence (4)

At the start of the test, the modules were exposed to 5 kWh/m^2 light soaking according to Sec. 5 of IEC 61215. An initial inspection and measurement of each module was carried out; the modules were visually inspected, tested under NREL ISO-certified test and measurement procedures, tested for dielectric withstand, wet insulation resistance, thermal imaging and electroluminescent imaging. The measurements are repeated between each test round and the results are compared against the failure criteria (Table 2).

Table 2. Failure criteria of the Test-to-Failure Protocol.

1.	Loss of 50% of initial power output (x-Si)
2.	Power output less than 50% of the manufacturer's rating (a-Si, CdTe, CIGS)
3.	Arcing in module circuitry or junction box
4.	Failure of dielectric withstand or wet insulation resistance tests at end of test segment
5.	Leakage current greater than 50 μA during biased DH exposure
6.	Open-circuit fault during forward-biased TC
7.	Development of major visual defects.

Results and Discussion

Initial inspection and measurement

Eight modules were run through the initial inspection and measurement procedure. One module failed the wet leakage current test as received (Table 3). It was originally envisioned that any failure in Table 2 would mean ending of the test of a module design, in this case, at round 0 based on failure criterion #4. With a small sample size, the TTF protocol is not a statistically comprehensive test; therefore, a failure of one of the modules constitutes failure of the set. As this is a path-finding experiment, we nevertheless continued the testing to gather more information about degradation rates of the modules. It must however be considered based on the results of round 0 (the initial inspection) that there is a potential weakness in this module design or construction that can lead to faster degradation of the modules subjected to the protocol.

Damp heat (DH+ DH-)

The first round involved four samples in damp heat—two following sequence 1 (dedicated damp heat) and two others from sequence 3 (alternating damp heat and thermal cycling). In an

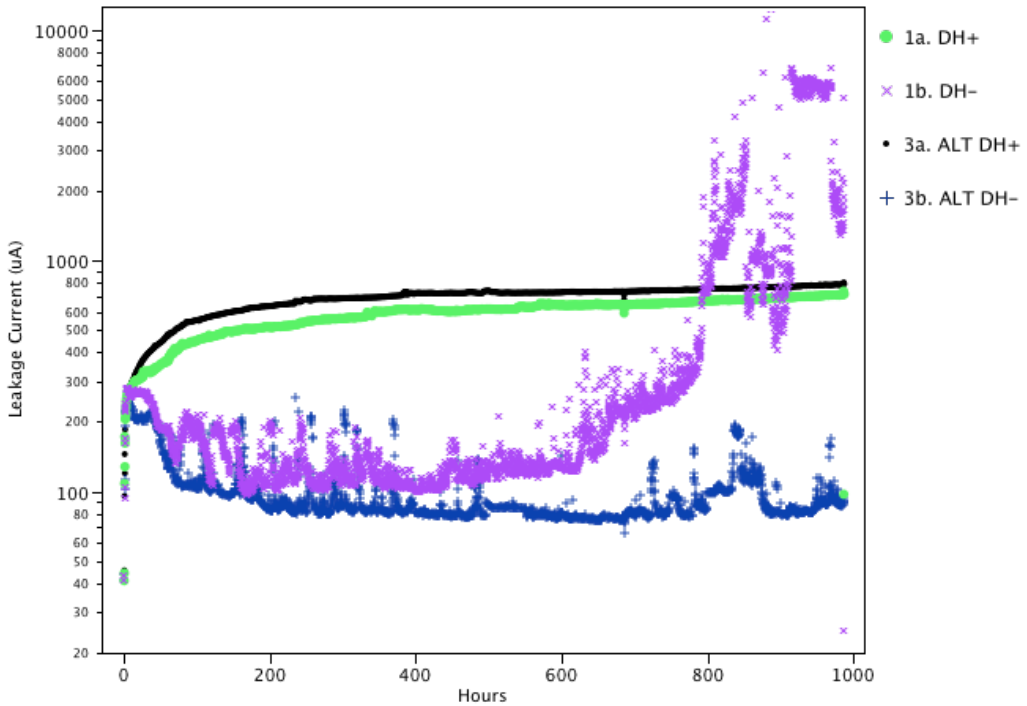

Fig. 1. In-situ monitoring of leakage current of modules undergoing 85°C /85% relative humidity stress testing with +/- 600 V bias.

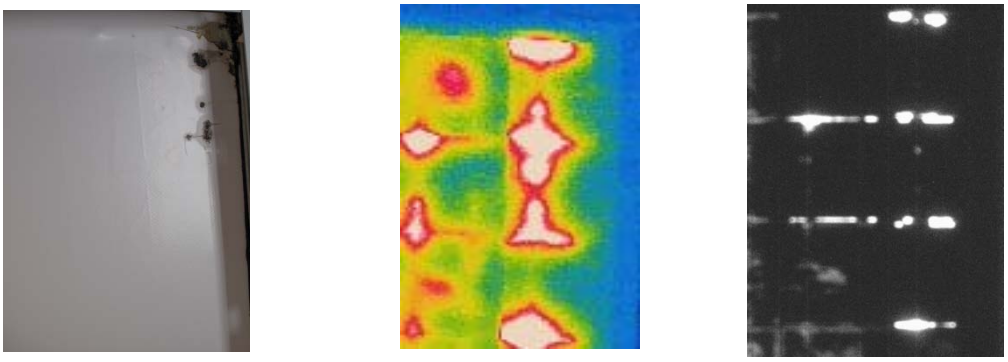

Fig. 2. An approximately 2 cell by 3 cell area of the upper right-hand corner of module 1b after the DH– stress test. From left to right, optical, thermal, and electroluminescence imaging of the same region. The electroluminescence image, taken from the front side of the module, was mirrored to achieve the same orientation as the other two images. Delamination and burning of the backsheet are seen over interconnects at the corner of the module in the optical imaging. The thermal imaging (3.8 A forward bias) indicates localized current flow, especially around cell interconnects and edges. The lack of electroluminescence signal over the active region of the cells and emission around the cell edges suggests luminescent discharge associated with shunt paths.

environmental chamber, +600 V was applied to the active layer with respect to ground for modules 1a and 3a, -600 V for 1b and 3b. The magnitude of the resultant current flow was recorded and charted (Fig. 1). For the bias of +600 V, the current increased steadily saturating toward about 800 μA. With -600 V bias applied to the active layer, the magnitude of the leakage current was normally lower overall; however, the nature of the current flow was marked by spikes. Module 3b exhibited severe spikes in current in the 600-800 hr window.

Visual examination of sample 1b indicated penetration of the back sheet associated with localized heating damage and delamination. While detailed failure analysis remains to be done, there is evidence of moisture ingress associated with delamination at the upper-right corner of the module. Thermal imaging shows hot spot formation, especially at the cell edges in between the cells of the string and at interconnects, which indicates localized current flow and shunting. This behavior can be seen in various fielded modules suggesting relevance to field failures. Results of the comparison will be presented in a subsequent publication.

Within just hours, the in-situ-monitored leakage current of all modules in DH+ or DH- exceeded the failure criterion #5 in Table 2 of 50 μA. 50 μA corresponds to the upper current limit of the UL 1703 dielectric voltage withstand test, but conductivity of encapsulants and their interfaces with common module materials increase many orders of magnitude moving from room temperature to 85°C. [5] The TTF protocol must therefore be adjusted to accommodate this greater conductivity. For the time being, the 50 μA failure limit specified in Table 2 is not recognized.

The 1000 hrs of 85°C and 85 % damp heat followed by the wet leakage current test is the most severe of the IEC 61215 and 61646 tests, whereby 30% of crystalline silicon and 70% of flat plate modules have been reported to fail at the Arizona State University Phoenix Testing Laboratory (Now TUV).[6] Addition of the stress of a system voltage bias to damp heat in the present TTF protocol is a significant further challenge. Application of this voltage is believed to be required to replicate the voltage bias that modules may see in the field.

The effects of application of a positive vs. negative voltage bias to the active layer of modules has been previously reported.[5, 7] With the active layer positive relative to the frame, cell metallization is dissolved. These metallic ions migrate toward the frame where they deposit as dendritic crystallites. The metallization ions also react with the encapsulant, discoloring it. With negative voltage applied to the active layer, anodic corrosion salts and the evolution of gas bubbles at the cell's metallization-silicon interface have been observed leading to delamination of the metallization and increased series resistance. The leakage current measured indicates the rate at which the corrosion process is occurring.

Among the items identified after round 1 for the DH samples by visual, thermal, or electroluminescence inspection are degradation of antireflective coating, shunting at edges of cells (between them), shunting at cell center, delamination, tab separation from cell, and corrosion.

Module 3b (Alt, DH-) exhibited 26% power loss. With significant visual defects, the module has been removed from the test by criterion #7 in Table 2 and will be subject to failure analysis. Modules under the DH+ regime (1a, 3a) exhibited comparatively lesser power loss, 3% and 17%, indicating the modules are more able to withstand this test configuration. Inverters in the United States are generally (but not always) connected to the positive terminal of the array (with the

negative terminal of the array to ground), which is the more reliable configuration considering our damp heat with bias test results. Nevertheless, both DH+ and DH- need to be considered because

Table 3. Table of results

	Sequences							
Round	1. DH		2. TC		3. Alternating		4. Control	
	1a	1b	2a	2b	3a	3b	4a	4b
pre-inspection	pass	pass	pass	pass	pass	pass	failed wet leak	pass
1	DH+	DH-	TC	TC	DH+	DH -		
measurement	Pass, P_m -3%	Failed,P_m -60%	Pass, P_m -5.3%	Failed wet leak	Pass, P_m-17%	Failed visual, P_m-26%		
2(ongoing)	DH+	removed	TC	TC	TC	removed		

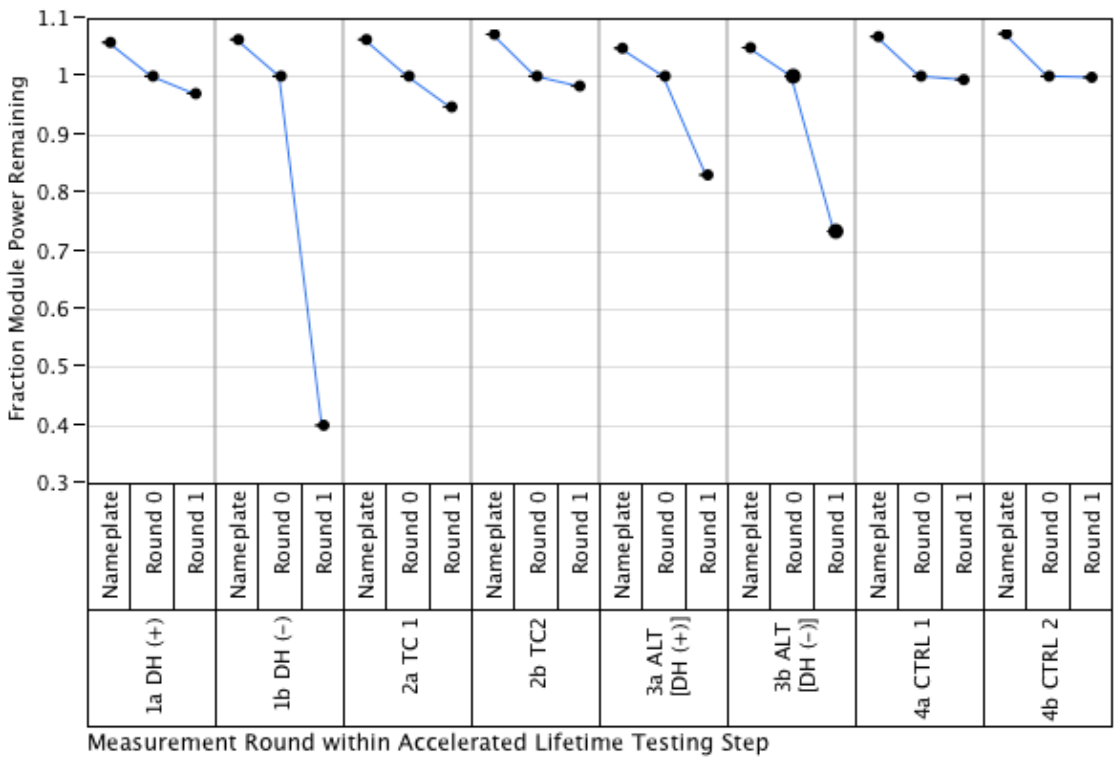

Fig. 3. Power (normalized P_{max}) for the modules tested in this study; the nameplate values, the initial inspection (round 0) and after round 1.

the module manufacturer did not give any information about the polarity for connection of the module.

Thermal cycling (TC)

Two modules (2a, 2b) underwent 200 -40°/85° C thermal cycles. Voltage monitoring across the terminals of the module while applying the nameplate I_{mp} load indicated no short or open circuit at any time during the course of this first round of environmental stressing. Module 2a exhibited a power reduction of 5.3% between round 1 and the initial inspection. While this does not constitute a failure in the TTF Protocol, it would constitute a failure according to IEC 61215.

This module was examined by imaging techniques before and after the environmental stressing. While also seen in thermal imaging, most salient is the electroluminescence imaging that indicates the breakage of a cell, which will to some extent contribute to a reduction of the module's power (Fig. 4).

Module 2b did not display any significant power loss (1.7%); however, the module failed the wet leakage current test after the thermal cycling, displaying resistance of 10 MΩ, about one-third the passing value. We elected to continue thermal cycling this module in this path-finding experiment to better clarify the effects of the failure.

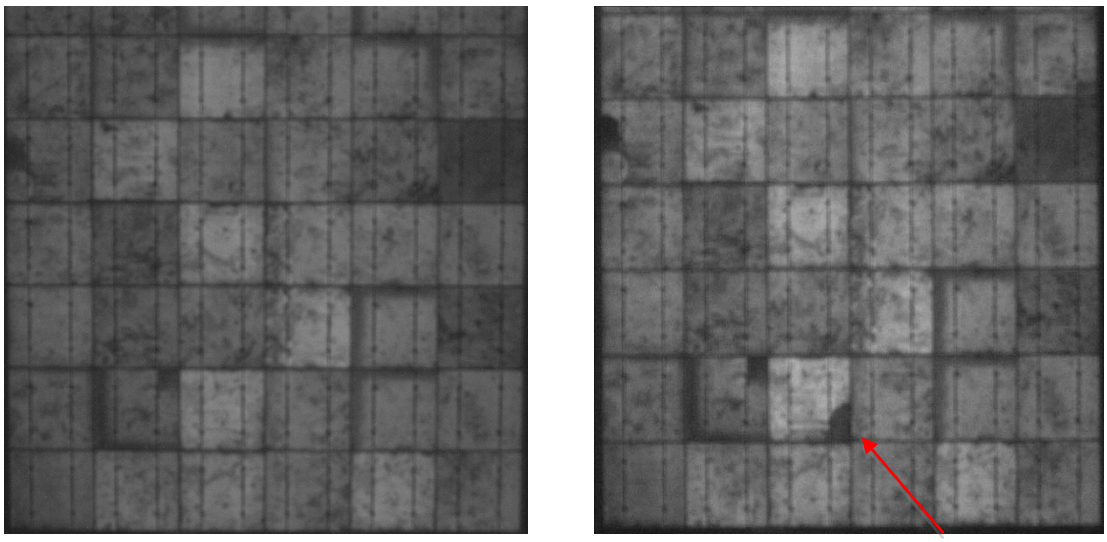

Fig. 4 Electroluminescence image (left, at initial visual inspection; right, after first round of thermal cycling) of a portion of module 1a that exhibited 5.3% power loss. Development of a cell fracture can be seen.

Summary

A PV module design that has passed IEC 61215 certification at some point in the past, may not necessarily continue to do so. Wet leakage current test failures out of the box and after 200 thermal cycles were found in these IEC-certified module designs. This validates a motivation for the test-to-failure protocol, namely, the benefit of spot-checking of modules to determine if quality of the manufacture is being sustained. We determined that the 50 μA limit for current under system voltage bias is not reasonable considering the increased conductivity of encapsulants at higher temperature. Two modules with + 600V bias to the active layer with respect to the grounded frame passed after one round, however, two modules with –600 V bias to the active layer with respect to the grounded frame both failed with significant measured power loss and visual defects created. Future studies will further ascertain how failures obtained in the TTF protocol compare to those in the field; however, many similar issues are seen, such as backsheet delamination, corrosion, bubble formation within the laminate, discoloration of the antireflective coating, and localized heating with degradation of the backsheet as a result of moisture ingress, corrosion, and concentrated current flow. This work is an initial round of tests of one module technology. Further testing will be carried out to further develop the failure criteria and build a statistical knowledge-base of test-to-failure protocol results.

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