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Technical Report
NREL/TP-5200-60950
December 2013

Contract No. DE-AC36-08GO28308

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Prepared under Task No. SS13.5510

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Acknowledgments

This work identifies standards that are being developed around the world and, therefore, is based on the efforts of many people. We are especially grateful for support from William Gambogi (DuPont), Kurt Scott (Atlas), Sean Fowler (Q-Lab Corporation), Charles Reid (STR), Govindasamy Tamizhmani (TUV Rheinland), Danny Cunningham (BP Solar), Jeanne Schwarz (Assurant), Tony Sample (European Commission, Joint Research Centre), Vivek Gade (Jabil), George Kelly (IEC), Paul Robusto (Miasole), Nathan Schweller (SunPower), Andy Nguyen (CNPV), and others for their reviews of the concepts and/or report. We are especially indebted to the U.S. members of the IEC backsheet weathering group for their efforts to identify the best UV test for backsheets. The portion of this work completed at the National Renewable Energy Laboratory was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308.

Acronyms

ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
DML	Dynamic mechanical load
DHWB	Damp heat with bias
ESD	Electrostatic discharge
EVA	Ethylene vinyl acetate
IEC	International Electrotechnical Commission
IECEE	Worldwide System for Conformity Testing and Certification of Electrotechnical Equipment and Components
ILAC	International Laboratory Accreditation Corporation
ISO	International Organization for Standardization
JPL	Jet Propulsion Lab
NREL	National Renewable Energy Laboratory
OTF	Outdoor test facility
PET	Polyethylene terephthalate
PV	Photovoltaic
QMS	Quality management system
SAE	Society of Automotive Engineers
STR	Specialized Technology Resources, Inc.

Executive Summary

Reliability is a critical element of continued growth of the photovoltaic (PV) industry. Solar electricity can be cost competitive in many electricity markets today if solar panels can perform to warranted specifications for the length of their warranty, which is typically 25 years. Design qualification test protocols, such as IEC 61215 and IEC 61730, have been key to mitigating infant mortality, but continued improvements to these standards and beyond are necessary to ensure the overall reliability and durability of products going into the field. Because the adoption process of new standards can take years, it is desirable to make updated test methods available as soon as possible, even before they may be adopted as standards.

This report summarizes some of the test methods that are in the midst of being adopted as standards and some that are being prepared for submission into the standards process. These "Qualification Plus" test methods support the following goals:

- Detect product weaknesses observed in the field that might not be caught by IEC 61215 and IEC 61730 before they cause failures in the field
- Optimize these test procedures more fully before they become standards
- Encourage manufacturers to begin to use the new tests in anticipation of the new standards
- Provide customers with additional information for choosing products that will last longer in the field.

The proposal contains three parts:

1. New or revised accelerated tests for components and modules including tests applying system-voltage bias, ultra-violet (UV) light, and mechanical stress
2. Revised sampling procedures, including the requirement of random sampling from the production line
3. Required audit of the quality management system.

Incentive programs, PV customers, and insurance companies are encouraged to consider the results of these tests, but are cautioned against using them as a requirement for all types of solar energy collection equipment. The Qualification Plus tests are being recommended specifically for crystalline silicon modules with glass/polymeric backsheet construction. Thin-film and concentrator PV modules may also achieve improved durability and reliability by demonstrating similar attributes with tests not addressed in this report. The authors propose that these tests should be considered as optional at this time, and that thin-film and concentrator products may demonstrate similar durability in other ways.

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1 Introduction

1.1 Motivation

As the photovoltaic (PV) industry continues to develop, the vast size of deployments today requires optimization of product reliability. The safe operation, requisite service life, reliability, and durability of PV modules become increasingly important as incentives are reduced and the value of an investment in PV is reflected in the kilowatt hours (kWh) generated over the lifetime of the product. Solar electricity can be cost competitive in many electricity markets today [1] if solar panels can perform to warranted specifications for at least the length of their warranty, which is typically 25 years. But, it can be difficult to identify which PV modules will meet their warrantied performance level. Design qualification testing using tests such as IEC 61215 [2] and IEC 61730 [3,4] has been key for achieving high reliability. The continued maintenance of these standards and the development of new standards that address wear-out mechanisms will continue to improve the durability and reliability of products going into the field. However, the adoption of new standards can take multiple years and it is desirable for the PV community to be able to use the updated test methods as soon as possible, even before they may be adopted as standards.

1.2 Purpose of This Report

This report proposes a set of tests for Qualification Plus verification. It summarizes the motivation and logic behind each of the proposed tests based on degradation observed in the field and evidence that a new test could identify technical weakness that might lead to failure, and therefore prevent failure. Most of the proposed test methods are in the midst of being adopted as standards or are being prepared for submission into the standards process. This report also summarizes the proposed methods for sampling methodology and provides a review of the quality management system.

2 Background

2.1 Origin of Current Design Qualification Tests

Today's design qualification tests (IEC 61215, IEC 61646, and IEC 62108 [2,5,6]) were developed by the international PV community over several decades using field observations and scientific investigations of the observed failure modes. In the late 1970s, as an example of one of the contributors to the development of these tests, the Jet Propulsion Lab (JPL) executed a series of block buys of PV modules that passed successively harsher accelerated tests [7-12], providing the early basis for the development of today's qualification test. The JPL tests were originally based on procedures used to qualify PV modules for use in space. With each block buy, the tests were modified to reflect failures that were observed in the terrestrial deployments. A dramatic reduction in module infant mortality occurred between Block IV and Block V [7,13]. Table 1 [10-12] highlights the primary differences between Blocks IV and V in bold, which include:

- An increase in the number of thermal cycles
- A more stressful humidity freeze test
- The addition of a hot-spot test.

Table 1. Comparison of JPL Blocks IV and V Tests

Test	Block IV	Block V
Thermal Cycling	50 cycles (-40 to +90°C)	**200** cycles (-40 to +90°C)
Humidity (Freeze)	5 cycles 54°C/90%RH to -23°C	**10** cycles **85°C**/85%RH to **-40**°C
Hot Spots	**None**	3 cells, 100 h
Mechanical Load	10,000 cycles, ± 2400 Pa	10,000 cycles, ± 2400 Pa
Hail	9 impacts 20 mm @ 20 m/s	10 impacts 25 mm @ 23 m/s
Electrical Isolation	<50 μA @ 1500 V	<50 μA @ 2*Vs+1000
Reported Field Failures	>50% [13]	~ 1% [13]

The thermal-cycling test induces mechanical fatigue, which can lead to failures of interconnect ribbons, solder bonds, and multiple other interfaces. A hard freeze after exposure to high humidity causes the expansion of water as it freezes, stressing interfaces and promoting delamination. The Block V version of the humidity (freeze) test caused more stress than the Block IV version. The hot-spot test motivated manufacturers to use bypass diodes, which protect the modules when the photocurrent generated by each cell shows variations because of partial shading or cell damage. These three changes helped to avoid important design flaws, thus dramatically decreasing failure rates. It is notable that the 1000-h damp heat test, which often is viewed as a critical element of today's qualification tests, was not included in Block V testing. Nevertheless, the changes between the Block IV and Block V tests dramatically improved the tests' ability to identify infant mortality [7,13].

2.2 Testing Beyond IEC 61215 for Differentiation of PV Products

Many test laboratories now offer accelerated testing designed to differentiate PV products, as summarized in Table 2. These test programs generally apply many of the same tests as the qualification tests, but apply them for a longer duration or combine existing tests in a particular sequence. The primary themes observed in a review of this collection of tests include:

1. Extended-duration of the individual qualification tests
2. Additional sequences of existing or novel tests
3. Quantification of module condition after each of the individual qualification tests
4. Additional characterization measurements (e.g., electroluminescence)
5. Addition of voltage bias during damp heat.

A majority of these tests identify the modules and module components that last longer in the chamber, but there are few data directly indicating the value of these longer tests for differentiating field performance. The comparison of accelerated test results with field data is challenging because of the extremely different time scales. However, early PV systems have now been in the field for longer than 30 years. Each year, more data become available from veteran systems [14], guiding the knowledge of wear-out mechanisms to the extent that these early modules are similar to today's modules.

Table 2. Accelerated Test Programs Available Commercially Today

DH: Damp heat, TC: Thermal cycling, DML: Dynamic mechanical load, DHWB: Damp heat with bias, HF: Humidity freeze, HS: Hot spot.

Program Name	Extra Test Sequences*	Key Features	Test Length (Months)**
Holistic QA [15,16]	DH, TC, DML	Extended 61215	~4
Thresher [17]	DHWB, TC, HF	Document degradation after each test cycle	~6
Reliability Demonstration [18]	DHWB, HS	Comprehensive	~6
Durability Initiative [19]	DHWB, Outdoor, UV, HS, DML, TC	Durability assessment	~6+
Test to Failure [20,21]	DHWB, TC	Test to failure	>12
Long-Term Sequential [22]	UV, DH, TC, HF	Sequential (pass-fail)	~12+
PV+Test [23]	DHWB, TC, ML	Assign rating	~4
Weather [24,25]	Multiple***	Simulates weather	~12

* Beyond IEC 61215 or IEC 61646 test sequences
** A "+" indicates additional testing in the field
*** Not based on IEC 61215/61646 test sequences

2.3 Identification of Failures Seen Today

Field experience with PV is increasing exponentially with the rapidly growing volume of installation. Although information is often lacking about the testing methods used to qualify a design or the manufacturing quality control, researchers have assembled some statistical data (Table 3) indicating an opportunity for improvement. A key goal of today's standards development is to identify tests that will avoid these observed failures in the future.

Table 3. Summary of Selected Field Studies

Observation	Sample Size	Reference
~2% of modules failed after 8 years. 36% of failures were due to laminate internal electrical circuit; glass 33%; j-box and cables 12%; cells 10%; encapsulant and backsheet 8%.	21 manufacturers; ~0.9 GW	DeGraaff [26]
16% of systems required replacement of some or all modules because of a variety of failures, with many showing breaks in the electrical circuitry.	483 systems	Kato [27,28]
3% developed hot spot after <7 years; 47% had non-working diodes.	1232-module system	Kato [27,28]
6.5% of modules failed after 10 years. 54% BOS*, 38% mismatch, 6% wiring, 1% failed, 0.5% shattered.	68,739 modules	Rosenthal [13]
35 modules degraded outside of warranty. Large power loss (>20%) came from decrease in FF because of increased series resistance; smaller power loss was from reduced transmission of glass and encapsulant and light-induced degradation. Glass/encapsulant designs showed less degradation than glass/glass designs.	204 modules from 20 manufacturers	Skoczek [29]
For problems reported: encapsulant discoloration 66%; delamination 60%; corrosion 26%; glass breakage 23%; j-box 20%; broken cells 15%.	~2000 reports	Jordan [30]
200 thermal cycles design qualification testing correlated to ~10 years in the field	>10 years of manufacturing	Wohlgemuth [31,32]

* BOS included switches, fuses, blocking diodes, surge protectors, and dc contactors.

DeGraaff summarized data from SunPower's >1.5 gigawatts (GW) of installations, including PV modules from 21 manufacturers [26]. The most common failure type involved failed solder bonds or other internal electrical interconnection issues. Problems with the glass, such as delamination of the anti-reflective coating, were the second most common failure type. About 12% of the failures were related to the junction boxes or cabling, often causing arcing that could lead to fires.

Kato [27,28] reported the need for module replacement after 5–12 years in ~16% of the systems studied, with most of those cases showing electrical failures (interconnects or bypass diodes). Rosenthal reported on Block IV and V modules, some of which were in the field for a full 10 years [13] with minimal (<1.3%) failures, implying that 200 thermal cycles may be adequate for a 10-year lifetime. Jordan's literature review [30] showed that discoloration and delamination were most frequently reported; corrosion, glass breakage, cell breakage, and many other problems were also observed.

Noteworthy themes from the data in Table 3 are:

- Degradation or safety issues caused by failure of cell interconnects, solder bonds, or the bypass diodes that protect in case of shading
- Early degradation in the short-circuit current related to light-induced degradation and changes in transmittance associated with changes in anti-reflection coatings, encapsulation discoloration, and delamination
- Corrosion of cells and ribbons (often associated with delamination in the field)
- Junction-box failures, including non-functioning bypass diodes.

Additional failures associated with system voltage bias have been observed. [33,34]

2.4 Current Efforts to Improve Qualification Test Standards

Test standards are typically revised every few years to reflect new knowledge. In response to the observations of failures in the field, the standards committees have developed or are developing a number of new standards. Some of these are summarized in Table 4.

There is a need to gather data correlating field performance with outcomes from accelerated testing. A long-term goal is to have enough details to be able to provide quantitative predictions of field performance and service life.

Table 4. Summary of Standards Under Development or Not Usually Included in Type Testing

Standard or Proposal	Description	Status
Standards that are generally applicable		
IEC 62782 Dynamic Mechanical Load Testing for PV Modules EN 12211 Windows and doors. Resistance to wind load. Test method.	Apply ±1000 Pa at a rate of 1 to 10 cycles/min for 1000 cycles with current flow; quantify power loss	IEC is refining draft; EN is published
IEC 62804 Test Method for Detection of Potential Induced Degradation of Photovoltaic (PV) Modules	Apply system voltage in configuration such that leakage current may flow; quantify power loss	Refining draft
ASTM E2481-06 Hot Spot Protection Testing of Photovoltaic Modules	Longer stress: *e.g.* 50 h at 1 kW/m^2 [35] Selection of susceptible cells and worst case shadowing	ASTM is published; IEC is planning a 5-hour test for Ed. 3 of IEC 61215
IEC 62852 Connectors for DC-Application in Photovoltaic Systems – Safety Requirements and Tests EN 50521 Connectors for Photovoltaic Systems – Safety Requirements and Tests	Set of tests for electrical, thermal, and mechanical performance	IEC is refining draft; EN is published
IEC 62790 Junction Boxes for Photovoltaic Modules – Safety Requirements and Tests EN 50548 Junction Boxes for Photovoltaic Modules	Set of tests for electrical, thermal, and mechanical performance	IEC is refining draft; EN is published
IEC 61730-2 Revision for 2nd Edition – Addition of MST 94 Weathering Resistance Test	Weathering test	Under development based on ISO 4892-2:2013 and ASTM D7869
IEC 62759 Transportation Testing of PV Modules – Part 1: Transportation and Shipping of PV Module Stacks	Mechanical test	IEC is refining draft
Weighted Junction Box Test [36]	Tests robustness of junction box mounting	IEC is refining draft for inclusion in Ed. 3 of IEC 61215
IEC 61788-x Polymeric Component Standards	Determine material parameters for prescreening	Concept stage
Bypass Diodes Electrostatic Susceptibility	Determine the susceptibility of bypass diode failure from an electrostatic event in the factory or field	IEC initiated a new work item in August 2013
Standards that apply to specific applications		
IEC 61701 Salt Mist Corrosion Testing of PV Modules	Tests durability for marine environments	Ed. 2 published
IEC 62716 Ammonia Corrosion Testing of PV Modules	Tests durability for farm or other conditions with ammonia	IEC 62716 is published
Non-uniform Snow Load Testing for PV Modules	Tests durability for bearing a snow load for a tilted module	IEC is refining draft; ANSI is developing TUV-R 71730

3 Application of the Qualification Plus Testing

Incentive programs, PV customers, and insurance companies are encouraged to consider the results of Qualification Plus tests, but are cautioned against using them as a broad requirement for all types of solar energy collection equipment. The Qualification Plus tests are being recommended specifically for crystalline silicon modules with glass/polymeric backsheet construction using ethylene vinyl acetate (EVA) encapsulant. Other silicon, thin-film and concentrator PV modules may also demonstrate improved durability and reliability through these or similar tests not described in this report. The authors propose that these tests should be considered as optional at this time, and that products that have not passed these tests may demonstrate similar confidence in other ways. Nevertheless, it is anticipated that module manufacturers will find these tests to be useful as part of an excellent quality management system.

If the Qualification Plus approach is well received as a means for accelerating the adoption of new standards, this set of tests may be updated periodically.

4 Rationale for Proposal

This proposal is not meant to circumvent the consensus building that is essential to developing useful international standards. Every effort has been made to build upon and align with existing standards development efforts.

4.1 Selection of New or Modified Accelerated Test Procedures

The philosophy driving the choice of requirements in this proposal reflects the need to:

- Address failures that are being seen in the field
- Align with existing or contemplated test standards (national and international)
- Avoid extended tests unless they have technical basis as being relevant to field performance.

The accelerated tests proposed for the Qualification Plus testing are summarized in Table 5, which also describes the failure mechanisms associated with each test and the origin or technical basis of each test procedure.

The IEC Polymeric Materials Weathering Group is evaluating different weathering cycles to establish the best conditions and may revise the details of each of the UV-exposure tests.

Table 5. Accelerated tests proposed for Qualification Plus

Test	Associated Failure	Origin or Technical Basis for Test
Component Tests		
1. UV exposure for encapsulants	Discoloration and delamination of the encapsulant sometimes dominate the observed failures and cause power degradation	STR and other companies have successfully used this test to select EVA formulations for decades.
2. UV exposure for backsheets	Cracked backsheets have been observed and can lead to safety issues	Field studies have shown backsheet cracking failures well short of expected lifetime. Backside solar exposure from albedo can be significant, and photolysis is a recognized degradation mechanism for many materials, for example PET. UV testing can identify materials exhibiting this failure.
3. UV exposure for connectors/cables	Cracked connectors or cables	EN 50521 and draft for IEC 62852
4. UV exposure for junction boxes	Loss of mechanical integrity for junction box	EN 50548 and draft for IEC 62790
5. Bypass diode and junction box thermal test	Failed bypass diodes and thermal degradation of junction box and/or potting	This is an extension of an existing test to avoid junction box and diode failures that have been observed in the field.
Module Tests		
1. Thermal cycling	Solder bond or ribbon failure, usually associated with thermal fatigue	This is an extension of IEC 61215. Thermal cycling is known to identify this failure; field and modeling studies imply that longer testing may be beneficial.
2. Dynamic mechanical load (DML)	Cracked cells that cause hot spots and power loss	IEC 62782. Studies have shown that the combination of DML and thermal cycling can uncover this failure.
3. Enhanced hot spot test	Localized heating from partial shading conditions	ASTM E2481-06
4. System voltage (potential-induced degradation)	Power loss for modules operating at large (positive or negative) bias voltage	Test method: IEC 62804; Pass criteria: studies correlating test with field results.
Quality Management System		
1. PV-specific quality management system	Add PV requirements to ISO 9001	Submitted to IEC and available at www.nrel.gov/docs/fy13osti/58940.pdf.

4.1.1 UV Exposure for Encapsulant Materials

Discoloration of module encapsulation in fielded modules has been frequently reported, as summarized in Table 3. Notably, of approximately 2,000 reports in the literature [30], close to two-thirds of the papers reporting problems identified encapsulant discoloration as being noticeable. The loss of short-circuit current that largely drives degradation in silicon modules [30] is partially caused by this discoloration.

This problem was recognized in the 1990s. Researchers were successful in finding a test that could quickly identify the basis for discoloration and verify subsequent EVA encapsulation formulations that greatly reduced the rate of discoloration. [37] Now, decades later, the strong correlation between the results of this test and field deployments for multiple encapsulant formulations supports the relevance of this test for screening EVA formulations. [37] Because the degradation chemistry is expected to be primarily dependent on the additives in the encapsulant, this test may be relevant to other encapsulant materials using similar stabilization chemistry. The technical basis described above included multiple EVA formulations, but the quantitative correlation may vary with different stabilization chemistry. The application of UV and temperature should be relevant as a general weathering tool.

A technical basis for this test has been published, [37,38] and documentation is in progress for submission to the IEC. The UV dose specified for encapsulant testing is less than that specified for the backsheet testing, but because the test is conducted at elevated temperatures, the discoloration is accelerated.

To facilitate the convenience of using a single chamber for simultaneously testing encapsulants and backsheets, the UV exposure for both may be completed at the higher irradiance specified for the backsheet test as described in the Appendix.

4.1.2 UV Exposure for Backsheets

Backsheets can cause safety issues if their electrical integrity is compromised and a ground fault or shock hazard develops. As the number of candidate backsheet products increases, it is reasonable to expect a divergence of the types of backsheets used, along with a possible corresponding increase in the failure rates. The present qualification and safety standards are inadequate for UV testing of the backsheet material. The Qualification Plus test proposed here applies a longer UV exposure at a moderately low temperature.

This set of tests recognizes both service life and “delta test” philosophies, and uses both. The annual UV dose in Phoenix is typically found to be between 300 and 350 MJ/m^2.[1] Converting units and assuming ~10% albedo, for the back of the backsheet the dose of 320 kWh/m^2 (for 300–400 nm) provides approximately a service-life dose in Phoenix. The front-side exposure was limited to a six-month test time, resulting in a modeled dose of about 3 years in Phoenix, which is not a full service life, but is substantially longer than many of today’s tests. Compared to the encapsulant test, a lower test temperature is used because the thermal activation energies of the degradation processes for the backsheet materials are poorly characterized.

[1] http://atlas-mts.com/online-tools/weather-summary-reports/

The visual inspection is designed to identify issues with obvious material degradation and adhesion problems. In addition, the backsheet needs to retain mechanical properties adequate to ensure safe operation of the module. Specifically, the backsheet should be able to stretch in response to strain from thermal coefficient of expansion mismatch or other mechanical stresses. Typically, these strains are expected to be < 2%, but local strain associated with the junction box, at the edges of the cell, or other stress concentrators may be substantially greater. Functioning backsheets harvested from fielded modules typically exhibit > 70% elongation at break. Thus, the pass criterion after the UV exposure should be chosen to be between 2% and 70%.

In absence of more definitive technical data 50% extent of elongation at break was chosen as a reasonable estimation of the amount of elongation required in the application. For simplicity, the same performance criterion is used for both front and backside exposures.

To facilitate the convenience of using a single chamber for simultaneously testing encapsulants and backsheets, the test temperature may be increased to the higher values specified for the encapsulant test.

4.1.3 UV Exposure for Cables and Connectors

Connectors and junction boxes sometimes fail in the field. The IEC Working Group 2 is developing two new standards for these components, as described in Table 4. Module manufacturers may use these tests to select connectors or junction boxes for inclusion in products. Issues with cables and connectors are often detected by module-level testing required in IEC 61215 and IEC 61730, as well as the Qualification Plus tests described here. However, the UV exposure required for 61215 is inadequate to test for a full lifetime, even for substantially shaded components on the module's backside that receive less than 20% of the UV light the front of the module receives. Furthermore, cables and connectors occasionally are positioned in ways that expose them to as much direct sunlight as the front of a module. This test aims to evaluate high-exposure situations by providing the same UV dose as used for encapsulant materials. The tests completed after weathering are taken from EN 50521, which is very similar to the draft currently in discussion by the International Electrotechnical Commission (IEC 62852). The Qualification Plus approach attempts to be consistent with the existing standards while including some additional details to clarify the procedure.

4.1.4 UV Exposure for Junction Boxes

The current qualification tests do not require UV exposure of the junction box. EN 50548 and the similar draft IEC 62790 both define aging conditions as well as useful tests to characterize whether the junction box survived adequately. The Qualification Plus approach attempts to be consistent with the current tests while including some additional details to clarify the procedure.

4.1.5 Bypass Diode Thermal Test

Failed diodes and junction boxes appear in several of the surveys summarized in Table 3. For example, Kato reported that in one system with >1,200 modules, roughly half had diodes that were not functioning. [27,28] Although there is no publication demonstrating the value of the specific test proposed here, the potential effects of failure (including module fires) justify additional testing. The proposed test is a quick, inexpensive and logical step toward identifying hardware that can survive temperatures that are likely to be experienced by some modules at some time during their service. Additionally, the Quality Management System (see section 4.3) requires control of electrostatic discharge within the factory to prevent damage of the diodes during module fabrication.

4.1.6 Thermal Cycling

Failures of solder bonds and ribbons in the module laminate have dominated the failure Pareto charts in a number of studies. While it is possible that the 0.1%–3% failure rates reported by Degraaff [26] could be infant mortality associated with poor quality control, the high failure rates of this sort reported by Kato [27,28] imply that an improvement in the initial design would be beneficial.

Fatigue associated with the mechanical strains encountered during thermal cycling in the field is known to accumulate in a predictable manner. There is some evidence that the 200 cycles required by IEC 61215 corresponds to about 10 years in the field. [31] The increase to 500 cycles was chosen with the intent of aligning the test more closely with product warranties. Many of today's modules can survive far more than 500 thermal cycles, but application of 400 to 800 has sometimes been reported to cause additional failures. [39] Thermal cycling is recommended as one of the longest test times because of the frequency with which this type of failure is still observed in the field.

The requirement of 500 thermal cycles extends the time required for module testing from about 6 weeks to 13 weeks, though a chamber that cycles quickly could complete the test in 2 months. Concern about the length of time that this test requires is motivating the community to investigate how to increase the rate of thermal cycling beyond the ~8 cycles/day allowed by IEC 61215 or otherwise decrease the duration of the test. One option is to use mechanical load as the source of the mechanical strain.

The proposed test also includes an assessment of the junction box adhesion by hanging a weight on the junction box. This approach is based on the studies of Miller et al. [36] with modifications to address community feedback that it would be better to apply weight during the thermal cycling than during the damp-heat test. The size of the weight is greater than the weight of the cables themselves, but modules are sometimes installed with added tension on the cables. A vertical test configuration is chosen for convenience and is frequently consistent with the general orientation in which stress is applied.

4.1.7 Dynamic (Cyclic) Mechanical Load

A reduction in the thickness of silicon solar cells has helped to lower module costs. However, the thinner cells are more prone to fracture, especially during events of extreme mechanical loading. [40-43] Initially, these cracks may not be obvious and may have no effect on performance of the module, but after subsequent thermal cycling, the weakened structure may be more susceptible to failures of metal interconnections between the pieces of silicon. Three studies [40-42] have each shown the value of first applying a mechanical load and then subsequent thermal cycling.

The number of cycles and the applied load could be varied, but were chosen to align with the draft standard currently being considered by the IEC. The rate of cycling specified for the test has a very wide spread, reflecting an insensitivity of the test to this parameter because the test is inducing cracks in the silicon and/or in the ribbon interconnections (which are insensitive to dwell time). This test does not attempt to address the creep that occurs in solder bonds during thermal cycling, which are dependent on the cycling frequency.

4.1.8 Enhanced Hot Spot

As noted above, the addition of a hot spot test was one of the critical improvements to the qualification test developed by JPL for the Block Buys. When a module is partially shaded, the shaded cells are usually forced into reverse bias. If bypass diodes are not used to protect the cells in the module, the current flowing in reverse bias can cause extreme heating, leading to catastrophic failure. The localized temperature can exceed 150°C or even 300°C for minutes or hours, causing permanent damage within the module package. [27]

Wohlgemuth and Herrmann [44] described why the hot spot test in the second edition of IEC 61215 was not adequate. Their proposed modifications have been incorporated into ASTM E2481-06 and proposed for the third edition of IEC 61215. Tamizhmani and Sharma [35] compared three hot spot tests, concluding that the IEC 61215 method is the most economical. Because IEC 61215 selects only the cell with the largest shunt resistance for testing and lasts only five hours, it sometimes overlooks problematic cells. In contrast, the ASTM test method chooses to test the cell with the highest shunt resistance in addition to the three cells with the lowest shunt resistance. It also applies current for a longer time (50 h), providing a better test of the cells most likely to fail. The third test (UL hot spot test) compared by Tamizhmani [35] can be implemented either intrusively by making contacts directly to each cell or nonintrusively, much like the ASTM method. It applies stress for even longer (100 h).

ASTM E2481-06 is the test method recommended here to take the IEC 61215 test to the next level.

4.1.9 Potential-Induced Degradation Testing

Although Table 3 does not reflect failures caused by the effects of system voltage, recent data [45] have shown that this mechanism can cause degradation of large systems by tens of percent in a single year. SunPower reported power loss caused by polarization when their modules were operated with a negative ground. [33] They found that the problem could be addressed by grounding the positive end of the system or by redesigning the module. In conventional silicon PV modules, the problem appears in the reverse polarity and is frequently associated with sodium migration from glass. With the introduction of inverters that allow a portion of the system to operate at negative bias with respect to ground, this degradation has become more common. It is easy to reproduce in the laboratory or in individual modules biased as though in a system outdoors. [34,45,46] In general, the problem can be solved for conventional modules by adjusting the chemistry of the silicon nitride layer on the cells, by using a high-resistance encapsulant, or by adjusting the system voltage so that sodium ions present in the glass move away from the cells.

The IEC is developing a test method to characterize potential-induced degradation and has identified several options for determining whether there may be a problem, but has not yet defined pass criteria. Because this type of degradation has only been observed recently and because the effect depends on the weather, the requirements have not yet been well defined. The test proposed here has been examined in a round robin study [47] and validated in fielded modules. [48] Light exposure during application of the bias stress may be appropriate in order to more closely simulate the field conditions, but data on the degradation observed in this sort of test is not available. Metal foil may also be used to apply the voltage bias, but the basis for the pass criteria needs to be established, so this option is not included here, but will be included in the IEC test method.

4.2 Selection of Sampling and Test Procedures

Although testing of engineering samples or modules that have been carefully selected from a manufacturing line gives an indication of the durability of a PV module design at its best, substantially greater confidence is obtained when the samples are selected randomly from the production line. While it is essential to certify engineering samples from a pilot line as a basis for construction of the subsequent large-volume production line, there is also value in recertifying the design as it is reproduced on the large-volume production line in case small differences in the production equipment affect the final results.

Similarly, testing a larger sample set increases confidence. The increase from two to five modules per leg proposed in this report was chosen to increase confidence without a substantial increase in test cost.

4.3 Audit of Quality Management System

The delivery of a durable and reliable product requires both qualification of the design and consistent control of the manufacturing process. Task Group 1 of the International PV Module Quality Assurance Task Force has developed a guideline for PV manufacturing Quality Management Systems (QMS). [49] Key features of this guide require that the company provide:

- Resources to maintain the product warranty system
- An electrostatic discharge (ESD) safe environment program, as required for raw material storage, processing, and assembly areas
- A product realization that includes appropriate certification (e.g. IEC qualification, including both type approval and safety testing), a design lifetime that enables compliance with warranty, and recycling provisions
- Previous failure information incorporated into the requirements of the QMS
- Product and manufacturing traceability
- A method for selection of vendors that can provide quality materials or products
- Incoming inspections of materials and sub assemblies
- Routine tests on 100% of product to ensure consistency of initial quality
- An ongoing, periodic monitoring program to ensure consistency of aspects of manufacturing that may affect safety, performance, and reliability.

Although the accelerated tests that are defined in this proposal are specific for conventional silicon modules, oversight of the QMS may be applied to all PV products, including thin-film and concentrator PV.

5 Conclusions

The philosophy and technical bases for the design of the Qualification Plus tests were described in this proposal. These methods are recommended as optional tests that increase confidence in the durability and reliability of PV modules. PV customers are encouraged to look for completion of these or similar tests as they are considering PV acquisitions. The description of the tests and other requirements are given in the Appendix.

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Appendix: Test Requirements for Qualification Plus Testing

The Qualification Plus set of tests is intended for implementation after certification to IEC 61215. If the module design or any material or component source is changed, retest is required, consistent with the retest guidelines established for IEC 61215.

The Qualification Plus tests are being recommended specifically for crystalline silicon modules with glass/encapsulant/polymeric backsheet construction. Other silicon, thin-film and concentrator PV modules may also demonstrate improved durability and reliability through these or similar tests not described in this report but are not eligible for the Qualification Plus certification.

Component Tests

All component tests may be documented by/through the component or the module manufacturer, depending on which is more convenient (see note below about how to certify the test results). Certification for Qualification Plus requires documentation that these tests have been completed initially and any time the module design changes or the source of these components changes. Qualification Plus also requires ongoing qualification of materials received into the factory, but does not specify the frequency and type of acceptance testing. These details are reviewed during the factory audit.

1. **UV Exposure for Encapsulants**: Extended UV exposure for frontsheets and encapsulants that transmit light to the solar cells in the PV module.
    a. Five sample coupons must be tested in the configuration in which they will be deployed.
        i. If the encapsulant will be mounted behind glass, it must be tested behind the same type of glass used in the module or a glass shall be chosen that is as transparent or more transparent (within 5%) to UV (between 300 and 400 nm) than the glass used in the module. The choice of glass, including the UV cut-off (10% transmission) of the glass used, shall be noted and included in the test report.
        ii. If the encapsulant has restricted availability of oxygen and moisture (for example between glass and cells), it must be tested in a glass/glass or similar package (minimum of 5 cm x 5 cm) in order to simulate the lack of oxygen availability in the final product.
        iii. The package design for this test will depend on the module design, but the underlying principle in the design of the test coupon is to expose samples to the relevant dose of UV and maintain the oxygen concentrations in a range of relevance.
    b. Test Conditions
        i. Irradiance of 56 ± 5 W/m^2 between 300 and 400 nm, or 0.55 ± 0.05 $W \cdot m^{-2} \cdot nm^{-1}$ at 340 nm, using a xenon arc source with filters complying with the latest version of ASTM D7869 Daylight filter. For convenience, the irradiance specified in 2.a.ii.1. may be used.

ii. Chamber controlled to ambient air temperature of 70°C ± 5°C.
iii. Chamber humidity of 50% ± 10% at air temperature.
iv. Corresponding Black Panel (uninsulated) Temperature [50] of 90 ± 5°C.
v. Duration of exposure: ~ 4000 hours to achieve at least 224 kWh/m^2 total UV (300–400 nm). The exposure may be interrupted for system maintenance. If the irradiance of 2.a.ii.1. is used, the exposure may completed in less time as long as the 224 kWh/m^2 dose is completed.

c. Measurements
   i. Measure transmittance (T) as a function of wavelength [51], from a location in the center of the samples, in 5-nm steps.
   ii. Report changes in the solar-weighted photon transmittance (T_{sw}) using global photon flux values from Table 1 of IEC 60904-3 in the wavelength range 300-1250 nm.

d. Pass/fail criteria: <2% decrease in T_{sw} for all samples as measured in c.ii.

2. **UV Exposure for Backsheets:** Backsheet materials will be exposed to UV light and evaluated using visual inspection to assess the weathering durability and safe use of these materials.
   a. **Matched Component Coupon Test with Visual Inspection Only**
      i. Twelve samples of backsheet will be laminated, using two layers of encapsulant, to a glass sample. The sample dimensions will be at least 6.4 cm × 4.4 cm. The choice of glass and encapsulant, including the UV cut-off (10% transmission) of the glass and encapsulant used, shall be noted and included in the test report. Two samples shall be retained as controls.
      ii. Five samples will be exposed from the glass side as:
         1. Irradiance of 81 ± 8 W/m^2 between 300 and 400 nm, or 0.8 ± 0.08 W/m^2/nm at 340 nm, using a xenon arc source with filters complying with the latest version of ASTM D7869 Daylight filter.
         2. Chamber controlled to Black Panel (uninsulated) Temperature [50] of 70°C ± 5°C. For convenience, temperature may be controlled as in 1.b.iv.
         3. Ambient temperature of 50°C ± 5°C. For convenience, temperature may be controlled as in 1.b.ii.
         4. Ambient air relative humidity of 50% ± 10%.
         5. Duration: ~ 4000 hours to achieve at least 320 kWh/m^2 total UV (300–400 nm). The exposure may be interrupted for system maintenance.
      iii. Five samples will be exposed from the backsheet side using the same conditions specified in a.ii, to achieve a total dose of at least 320 kWh/m^2 total UV (300–400 nm).
      iv. Both sets of 5 samples must pass the visual inspection according to IEC 61215 10.1, as no major visual defects such as broken, cracked, torn external surfaces, bubbles, or delamination that could form a continuous path between a cell and the edge of a module if the sample were within a module. Color change shall be noted for reference only.
   b. **Matched Component Coupon Test with Visual Inspection and Physical Property Measurement**

i. Twelve samples of backsheet will be laminated to a glass sample, using two layers of encapsulant, with a transparent release film inserted between the backsheet and encapsulant. The release film must be transparent (>85% transmission at all wavelengths from 300 nm to 400 nm) and retain its transparency in this wavelength range during the exposure. The sample dimensions will be at least 6.4 cm × 4.4 cm. The choice of glass, encapsulant, and release liner including the UV cut-off (10% transmission) shall be noted and included in the test report. Two samples shall be retained as controls.
ii. Expose five samples, with the backside facing the light, to UV light as in section a.iii.
iii. Expose five samples, with the glass side facing the light, to UV light as in section a.ii.
iv. After exposure, remove the backsheet sample from the release sheet. Both sets of five samples must pass the visual inspection according to IEC 61215 10.1, as no major visual defects such as broken, cracked, torn external surfaces, bubbles or delaminations that would be expected to form a continuous path between a cell and the edge of a module if this were within a module. Color change shall be noted.
v. Remove the backsheet films from the release sheet and measure elongation at break according to ASTM D 882.
vi. Pass/fail criteria: The average elongation at break of the exposed samples must not be less than 50%.

3. **UV Exposure for Cables and Connectors**
    a. Three samples of cables with connectors will be made with a male and female connector on opposite sides of a cable of sufficient length to perform the analysis indicated below. The connectors on a single cable will be connected together.
    b. Samples will be exposed to the UV conditions prescribed for encapsulant materials in section 1.b. To facilitate mounting in the test chamber, the cables may be coiled and clipped onto a sample holder provided that the connectors and 80% of the cable length are completely exposed to UV light on one side.
    c. After exposure, samples will be tested according to EN 50521, 6.3.4 Temperature rise, 6.3.5 Mechanical operation, 6.3.6 Bending (flexing) test, and 6.3.8 Dielectric strength. The bending test will be performed on both sides of the cables after disconnecting the connectors.
    d. Pass/fail criteria. All samples must pass the visual inspection according to IEC 61215 10.1 such that no damage likely to impair function can be seen. For 6.3.4, the temperature rise may not exceed the rated temperature limits of the materials. For 6.3.8, there may be no breakdown or flashover.
4. **UV Exposure of Junction Box**
    a. Five samples of the junction box will be obtained complete with cables and diodes, and fixed to a substrate representative of the module according to EN 50548 5.2.5.
    b. Test conditions as per EN 50548 or EN ISO 4892-3

i. Irradiance of 60 ± 6 W/m^2 between 300 and 400 nm, or 0.59 ± 0.06 W/m^2/nm at 340 nm, using a xenon arc source with filters complying with the latest version of ASTM D7869 Daylight filter.
ii. Chamber controlled to Black Standard (insulated) Temperature [50] of 65°C ± 5°C.
iii. Ambient temperature of 50°C± 5°C.
iv. Ambient air relative humidity of 65% ± 10% during the "dry" cycle.
v. Cycles: 18 min. spraying, 102 min. dry.
vi. Duration: ~500 h to achieve at least 30 kWh/m^2 total UV dose between 300 and 400 nm.

c. After exposure, samples will be tested according to EN 50548, 5.3.3 Fixing of lid at rewireable junction box, 5.3.19 Test of terminations and connection methods, 5.3.21 Test of cord anchorage, 5.3.22 Retention of the mounting surface, 5.3.16 Wet leakage current test, and 5.3.20 Knock-out inlets (outlets) intended to be removed by mechanical impact. Tests will be conducted in the order listed above.
d. Pass/fail criteria. All samples must pass the visual inspection according to IEC 61215 10.1 such that no damage likely to impair function can be seen. For 5.3.16 the insulation resistance must be greater than 400 MΩ. For all the other tests, the respective requirements of EN 50548 will be fulfilled.

5. **Bypass Diode and Junction Box Thermal Test**
   a. Increase time for bypass diode thermal test Section 10.18 of IEC 61215.
   b. Test five samples, where a sample is a junction box with the relevant number of diodes in the configuration used by the manufacturer (this test is completed under the direction of the module manufacturer because it needs to reflect the module design). As in Section 10.18, heat the diodes mounted in the junction box as in a regular module in a 75°C ± 5°C ambient and apply a current through all diodes using a current equal to the short circuit current under Standard Test Conditions for one hour. Measure the junction temperature of each diode. None of these should exceed the diode manufacturer's recommended operating temperature during the test and the diodes should continue to be operational after the test. Increase the time of the test (the time at 75°C ± 5°C with short circuit current flow) from 1 hour to 96 hours. After at least 96 hours of exposure, increase the current flow to 1.25 times short circuit current for 1 hour as described in section 10.18.3(f).
   c. The pass/fail criteria of IEC 61215 are used with the addition of the requirement of verification of the integrity of the junction box housing and function of all diodes.

Module Tests

Before initiating tests, modules may be preconditioned according to Clause 5 of IEC 61215.

1. **Thermal Cycling**: Test five modules and increase the total number of thermal cycles in IEC 61215 Section 10.11 from 200 cycles to 500 cycles. The test procedure and pass/fail criteria follow Section 10.11 of IEC 61215 with the addition that the diodes are still functioning. A 0.5 kg weight is hung from each junction box during the temperature

cycling (the module is assumed to be in a vertical configuration). This test may be interrupted for interim testing.

2. **Dynamic (Cyclic) Mechanical Load (DML)**: Add DML testing in the UV/50TC/10 HF test sequence as described by IEC 61215 using five modules. The DML test shall be performed after the UV preconditioning exposure and before the 50 thermal cycles/10 humidity freeze cycles. Apply the dynamic mechanical load and cycle it 1,000 times using a pressure of ± 1000 Pa (with a tolerance of ± 100 Pa) and a rate between 1 and 10 cycles per minute. (Each cycle consists of one positive and one negative load application). Pass/fail criteria: <5% power loss after each of the tests in the sequence, <8% power loss after the entire sequence, no open circuit during the test, no major visual defects, and meeting the requirements of the insulation resistance and wet leakage current tests.
3. **System Voltage (Potential Induced Degradation and Polarization)**
   a. Five modules shall be exposed to the following stress test conditions:
      i. Chamber air temperature: 60°C ± 2°C
      ii. Chamber relative humidity: 85% ± 3% RH
      iii. Test duration: at least 96 h dwell at the designated temperature and relative humidity
      iv. Voltage: Module rated system voltage and polarities are applied to the shorted module leads. The module frame or mounting points shall be grounded.
   b. Test Procedure
      i. The modules shall be at temperature before relative humidity is ramped and voltage shall be applied for the test duration after the modules reach the specified stress levels.
      ii. The testing shall reasonably accommodate requests by the module manufacturer to simulate manufacturer-specified mounting and grounding configurations when deployed while ensuring the stress levels and factors specified here are maintained.
   c. Pass/Fail Criteria
      i. The Standard Test Condition maximum power <5% degradation
      ii. No major visual defects (IEC 61215 Ed. 2 Clause 10.1),
      iii. Wet leakage current test (IEC 61215 Ed. 2. Clause 10.15) results meet all requirements initially and after stress testing.
4. **Hot Spot Test**
   a. Test five modules.
   b. Use Hot Spot procedure from ASTM E2481-06.
   c. The quality system must specify a continuing sampling program for hot spots.

Sampling Requirements

1. All test modules (for the module tests described here) must be chosen at random from a production line that is shipping product—no engineering or preproduction samples are allowed.
2. If any module fails any Qualification Plus test, the overall test is failed and the manufacturer must address the deficiency (by a change in the design or in the QMS)

before retest to the entire test (with five modules for each test) or according to the retest guidelines used for IEC 61215 in the event that most of the initial test was passed.

3. The quality system must specify a continuing sampling program with a repeat of module tests 1–4 at least once a year.

Requirement for Quality Management System

Add the recommendations from "Guide for Quality Management System for PV Module Manufacturing: Supplemental Requirements to ISO 9001-2008" into the quality assurance system and ensure inclusion of these requirements [49] in an audit by a Certification Body approved by ANSI-ASQ National Accreditation Board (ANAB) to conduct ISO 9001 Quality System Audits or Certification Body approved by a similar organization under the International Accreditation Forum (IAF) (an IAF-accredited Certification Body inside or outside the United States may be used to conduct this audit).

Certification Requirements

1. Testing to Qualification Plus requirements shall be certified (using these specifications and the relevant sections of IEC 61215, EN or ASTM standards) by an International Laboratory Accreditation Corporation (ILAC) accredited laboratory or a laboratory accredited by IECEE for testing per IEC 61215. If the test data for the component testing is accepted by the independent test lab from the component manufacturers, both the certificate and test report shall indicate that these data were accepted by the test lab according to their data acceptance procedure.
2. Annual documentation of compliance with these standards is required to retain Qualification Plus status.