VALIDATING PHOTOVOLTAIC MODULE DURABILITY TESTS

Prepared by

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EXECUTIVE SUMMARY

The reliability of photovoltaic (PV) modules for their intended service lifetime, currently based on a 20- to 25-year minimum, is a key requirement of financial stakeholders. The current generally accepted minimum testing and performance requirements are described in the design qualification and safety tests of the International Electrotechnical Commission (IEC). Although these standardized requirements have been largely successful in keeping poor quality modules out of the marketplace, field failures of installed modules still occur. These may range from catastrophic failures occurring early in a module's life to long-term degradation and power loss or safety concerns later in the module's life.

It is widely recognized that the existing basic qualification tests are not lifetime reliability assurance tests, which is what the industry needs. Therefore, considerable research into module degradation and failure modes has been and continues to be performed by manufacturers, national laboratories, private and public research institutions, and academia. These efforts have greatly contributed to the present scientific understanding of module degradation and failure mechanisms, and the industry continues to learn new things as it gains more and longer field experience with current module technologies and designs.

This increased knowledge has led the ongoing industry efforts to develop and standardize more comprehensive tests that move beyond basic qualification testing to tests that can better predict long-term reliability or better compare and rate different modules for various attributes. Over the past several years, this effort has gained considerable momentum, and PV module and system reliability issues are now the subject of numerous specialized symposia and workshops and a key topic at PV and solar energy technical and investment conferences.

These efforts currently fall into three major categories. The first can be described as "IEC 61215 on steroids," consisting of protocols that are derivatives of the current IEC 61215 tests, either by extending the durations or combining the tests in new sequences or cycles. The second category is "weather" testing—test programs that primarily use weather durability testing principles and methods. The third is "new tests," which are either add-ons or modifications to a more comprehensive test protocol. Additionally, efforts are underway to establish PV materials tests. The key activities in these areas are summarized in this report.

Accelerated testing has been ongoing for about 35 years, leading to the current IEC qualification standards. However, there has not been a systematic effort to identify short- and long-term degradation and failure modes and to use that information to develop and validate a comprehensive testing methodology. Further, no definitive models exist that fully link test results with long-term performance—a service life prediction model, for example. The final missing standards piece is a quality assurance program to assure stakeholders that current production models are of the same or better quality as those passing the qualification tests.

This report details a comprehensive long-term multi-step effort required to develop and validate both current and new tests and a roadmap to develop a service life prediction methodology. Finally, the report recommends an interim solution using the current standards process.

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Allen Zielnik has degrees in electronics engineering and analytical chemistry. For the first 19 years of his career, he was involved with various scientific instrument companies dealing with chemical and physical methods of analysis, specializing in polymer molecular weight determination and separations science. For the past 19 years, he has been with Atlas Material Testing Technology, in Ametek's Measurement and Calibration Technology division. He serves as Senior Consultant—Weathering Science in Atlas' Global Consulting group as well as a senior member of Atlas' Solar Energy Competence Center. He has been involved with supplying durability test equipment to the PV industry since 1994 and has authored more than 100 articles on materials weather durability and testing technology.

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TABLE OF CONTENTS

INTRODUCTION

The need for durability and reliability in photovoltaic (PV) modules and systems is well recognized. At the module level, solar panels must be both durable and reliable for many reasons. The term "bankability" is often used to describe a number of aggregate properties, including:

- power degradation over product lifetime that affects revenue generation;
- engineering, procurement, and construction and operations and maintenance considerations that affects overall system cost; and
- safety of life and property that affects insurance costs and regulatory compliance.

A relative comparison of good versus poorer performing systems is provided by Kurtz (Kurtz, 2009) in Figure 1.

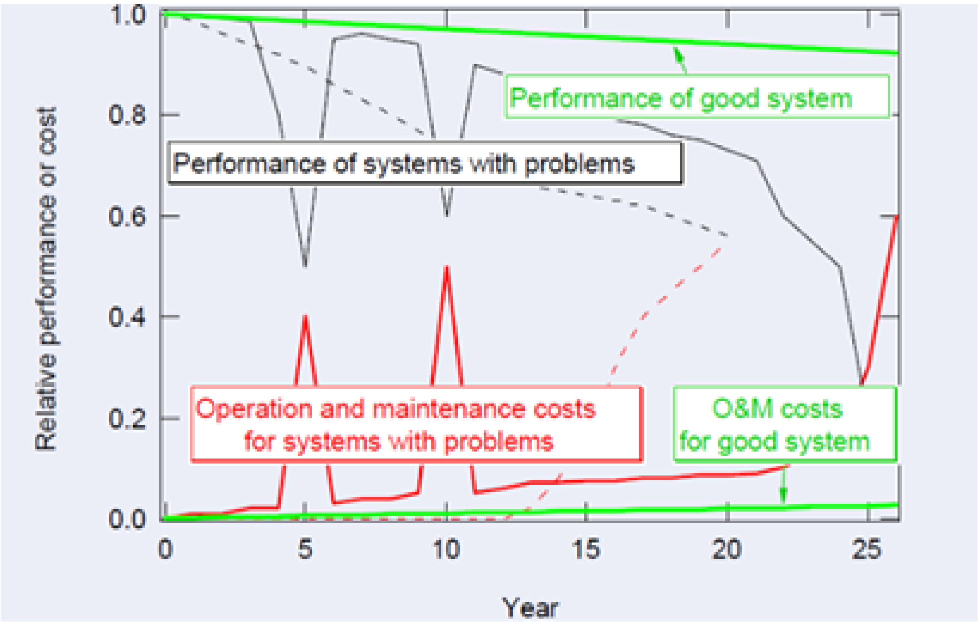


Figure 1. Comparison of "good" systems vs. those with problems (Kurtz, 2009).

There are documented cases of PV installations ten, twenty, or more years old that are performing well with low failure rates. There are also, however, reported instances of arrays requiring high levels of module replacement within several years of installation (Carus, 2013; Hibberd, 2011; Kato, 2012; Kuhn, 2011; Mayer &Meydbray, 2012; Wang, 2012). Although some of these are likely limited to specific module manufacturers or models, or may be related to installation or other issues, the PV industry needs a way to more accurately assess fielded module durability. Therefore, the term "module failure" clearly depends on many factors, including:

- device technology, materials, design, and manufacturing;
- end use climate; and
- transportation, installation, and maintenance.

It is tempting to rely on overall past industry success, but there are several factors that work against this:

- Many current module designs, especially those manufactured after about 2004, are substantially different from earlier designs in materials and construction (Bradley, 2013). These include thinner silicon (Si) cells and encapsulant layers, frameless designs, and alternative backsheet materials and cell interconnects. It is not clear whether these changes have affected durability and reliability when compared to earlier designs.
- The use of lower cost materials and manufacturing methods in new modules may negatively impact quality.
- Many new, often low-cost, manufacturers with no or limited prior history or experience are entering the marketplace.

Manufacturer warranties may be of limited value if the module manufacturer is no longer in business. Even with third party insurance, replacing modules often requires reconfiguring arrays and incurring additional costs if identical replacement modules (power rating, electrical characteristics, and physical size) are no longer available.

Meeting International Electrotechnical Commission (IEC) design type qualification (IEC, 2005; IEC, 2008) is not a guarantee of either long-term performance or service lifetime. Although these tests have proven effective at weeding out weak designs, many type-approved modules still fail in service. It is now widely, though not universally, recognized that the IEC qualification standards do not currently go far enough to demonstrate long-term durability and reliability, or to predict service life (Wohlgemuth, 2012). Further, the IEC tests address design qualification, not whether the module manufacturer has an adequate quality assurance system to consistently produce modules that will perform like qualified modules, as described by Mikonowicz (Mikonowicz, 2011).

This paper explains basic concepts and principles of durability and reliability testing, service life prediction methodology, and test validation. It summarizes the development rationale leading to the current IEC module qualification standards and what is generally believed to be their strengths and weaknesses. Further, it summarizes the main known or suspected failure modes of PV modules as well as currently proposed alternative test protocols and highlights ongoing industry and standards activities. The report also includes a gap analysis on these items and a process framework for validating these various tests.

The focus here is primarily on mono- and multi-crystalline silicon terrestrial flat-plate collectors, because most installed and currently produced modules fall into these categories and the outlook is for this to continue into the foreseeable future. This encompasses a broad range of cell and interconnect technologies, materials, and module designs.

The fundamental principles described here also apply to thin films (TF). However, due to the small number of manufacturers, the small size of the currently installed base, and the relative time in service, less is known regarding TF degradation and failure mechanisms. Where possible, specific TF issues will be noted.

These principles also generally apply to other PV technologies such as organic PV and dye-sensitized solar cells, although the degradation mechanisms are often substantially different from Si. Further, general principles apply to various exterior building-integrated PV products although these usually have their own specific issues as both a functional building element and a PV device.

In addition, the use of onboard active electronic direct current/alternating current (DC/AC) microinverters (AC modules) or DC/DC power optimizers, some with digital communications capability, is growing rapidly. Originally externally attached, these electronics are increasingly being incorporated directly into the module laminate package. The use of in-module laminated bypass diodes has also re-emerged in some designs. The specific effects of these devices on module durability and performance, the effects of environmental and service use stresses on these components, and the possible need for different testing methodologies are just beginning to be investigated. At present, these are not treated differently from traditional module designs in terms of testing standards.

Finally, for testing and qualification purposes, a “line of demarcation” must be drawn between factors that affect standalone modules (including in test) and those involved with interconnected modules in strings and arrays. Also, the effects of various electrical loads may have an impact, but mostly are not considered as factors in current module tests.

WHAT DEFINES "FAILURE"?

The most commonly used description of what constitutes PV module "failure" involves three independent parameters:

- catastrophic failure (no output),
- power loss beyond a defined limit, and
- safety of life or property issues.

From the user's perspective, other factors not affecting performance—aesthetic issues, for example—may also be a consideration. The first two parameters noted above primarily involve durability or reliability issues intrinsic to the module design, materials, or manufacturing, or resulting from the effects of environmental exposure or other extrinsic in-service conditions. These failures may be catastrophic, immediately resulting in a dead module, or may degrade with time in some manner that affects power output beyond an expected level. The third failure type involves safety risks that cause the module to be taken out of service prematurely.

At present, IEC and related PV design type qualification and safety tests are performed on modules that have only been stressed through accelerated tests. There are no retest requirements for field-aged modules.

SERVICE LIFE EXPECTATIONS

It seems logical to expect PV service life to be at least partially dependent upon the severity of the climate where the module is used, because some degradation modes can be related to specific climate stresses. However, most current test standards do not test or tie module performance to different climates. Also, current qualification and safety standards do not specify any module durability, reliability, or performance minimums beyond the initial qualifications. In addition, they do not specify any minimum required service life.

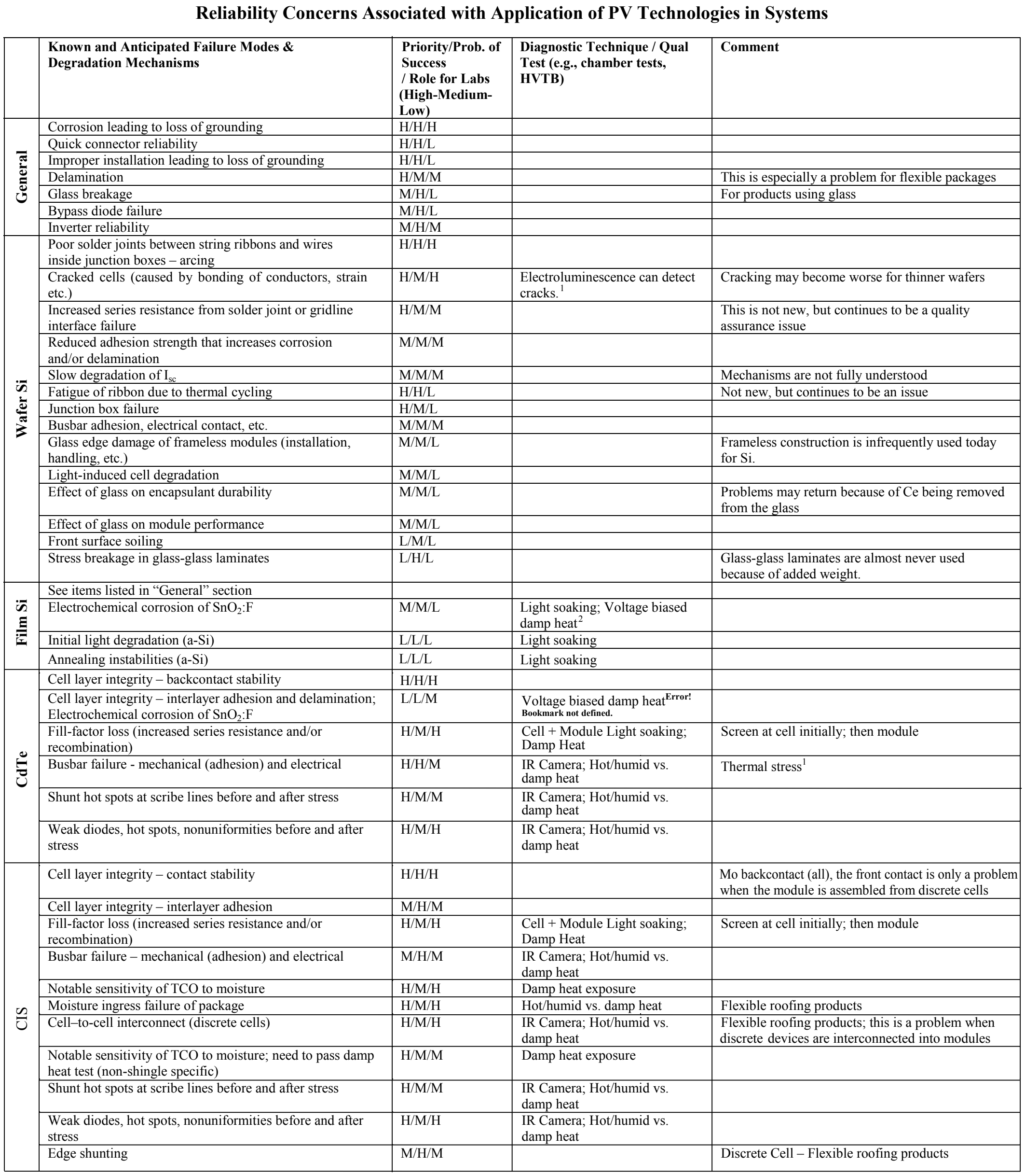
Manufacturers determine module warranties. Due to market competition, most module warranties fall within a general range, typically based on two independent parameters:

- **Repair, replace, or refund warranties** cover defects in materials or workmanship, and presently have durations of 5 to 10 years.
- **Lost power replacement warranties** typically offer remedies such as supplying additional modules to supplement for the power loss, repairing or replacing modules, or providing monetary compensation. Typical values are minimum peak power of more than 90% at 10 to 12 years, and more than 80% up to 20 to 25 years, although some manufacturers go beyond this. Both step-wise and straight line depreciation methods are used, depending on the manufacturer. A warranty may also be provided by a third-party insurer as a hedge against manufacturer insolvency.

Terms and conditions of warranties are manufacturer-specific. Minimum power performance is typically based on the minimum power rating, less tolerances, of the nameplate rating. These ratings are under laboratory standard test conditions and are not necessarily indicative of output performance at installation or over time. The general industry expectation of service life most commonly quoted is a minimum of 25 years power generation at more than 80%, although “useable” life expectations by users and investors can exceed 40 to 50 years or more, even at lower power levels.

COMMON PHOTOVOLTAIC FAILURE MODES

Many failure modes have been identified in PV modules over the years. In 1977, the U.S. Department of Energy (DOE) established the Solar Energy Research Institute (SERI) in Golden, Colorado, subsequently renaming it the National Renewable Energy Laboratory (NREL) in 1991. NREL maintains a running summary of quality and reliability issues by PV technology (Bosco, 2010). Key findings are included in Figure 2.



Reliability Concerns Associated with Application of PV Technologies in Systems

	Known and Anticipated Failure Modes & Degradation Mechanisms	**Priority/Prob. of Success / Role for Labs (High-Medium-Low)**	**Diagnostic Technique / Qual Test (e.g., chamber tests, HVTB)**	**Comment**
General	Corrosion leading to loss of grounding	H/H/H		
	Quick connector reliability	H/H/L		
	Improper installation leading to loss of grounding	H/H/L		
	Delamination	H/M/M		This is especially a problem for flexible packages
	Glass breakage	M/H/L		For products using glass
	Bypass diode failure	M/H/L		
	Inverter reliability	M/H/M		
Wafer Si	Poor solder joints between string ribbons and wires inside junction boxes – arcing	H/H/H		
	Cracked cells (caused by bonding of conductors, strain etc.)	H/M/H	Electroluminescence can detect cracks.[1]	Cracking may become worse for thinner wafers
	Increased series resistance from solder joint or gridline interface failure	H/M/M		This is not new, but continues to be a quality assurance issue
	Reduced adhesion strength that increases corrosion and/or delamination	M/M/M		
	Slow degradation of I_{sc}	M/M/M		Mechanisms are not fully understood
	Fatigue of ribbon due to thermal cycling	H/H/L		Not new, but continues to be an issue
	Junction box failure	H/M/L		
	Busbar adhesion, electrical contact, etc.	M/M/M		
	Glass edge damage of frameless modules (installation, handling, etc.)	M/M/L		Frameless construction is infrequently used today for Si.
	Light-induced cell degradation	M/M/L		
	Effect of glass on encapsulant durability	M/M/L		Problems may return because of Ce being removed from the glass
	Effect of glass on module performance	M/M/L		
	Front surface soiling	L/M/L		
	Stress breakage in glass-glass laminates	L/H/L		Glass-glass laminates are almost never used because of added weight.
Film Si	See items listed in "General" section			
	Electrochemical corrosion of SnO_2:F	M/M/L	Light soaking; Voltage biased damp heat[2]	
	Initial light degradation (a-Si)	L/L/L	Light soaking	
	Annealing instabilities (a-Si)	L/L/L	Light soaking	
CdTe	Cell layer integrity – backcontact stability	H/H/H		
	Cell layer integrity – interlayer adhesion and delamination; Electrochemical corrosion of SnO_2:F	L/L/M	Voltage biased damp heat**Error! Bookmark not defined.**	
	Fill-factor loss (increased series resistance and/or recombination)	H/M/H	Cell + Module Light soaking; Damp Heat	Screen at cell initially; then module
	Busbar failure - mechanical (adhesion) and electrical	H/H/M	IR Camera; Hot/humid vs. damp heat	Thermal stress[1]
	Shunt hot spots at scribe lines before and after stress	H/M/M	IR Camera; Hot/humid vs. damp heat	
	Weak diodes, hot spots, nonuniformities before and after stress	H/M/H	IR Camera; Hot/humid vs. damp heat	
CIS	Cell layer integrity – contact stability	H/H/H		Mo backcontact (all), the front contact is only a problem when the module is assembled from discrete cells
	Cell layer integrity – interlayer adhesion	M/H/M		
	Fill-factor loss (increased series resistance and/or recombination)	H/M/H	Cell + Module Light soaking; Damp Heat	Screen at cell initially; then module
	Busbar failure – mechanical (adhesion) and electrical	M/H/M	IR Camera; Hot/humid vs. damp heat	
	Notable sensitivity of TCO to moisture	H/M/H	Damp heat exposure	
	Moisture ingress failure of package	H/M/H	Hot/humid vs. damp heat	Flexible roofing products
	Cell–to-cell interconnect (discrete cells)	H/M/H	IR Camera; Hot/humid vs. damp heat	Flexible roofing products; this is a problem when discrete devices are interconnected into modules
	Notable sensitivity of TCO to moisture; need to pass damp heat test (non-shingle specific)	H/M/M	Damp heat exposure	
	Shunt hot spots at scribe lines before and after stress	H/M/M	IR Camera; Hot/humid vs. damp heat	
	Weak diodes, hot spots, nonuniformities before and after stress	H/M/H	IR Camera; Hot/humid vs. damp heat	
	Edge shunting	M/H/M		Discrete Cell – Flexible roofing products

Figure 2. Common PV failure modes by technology as reported by NREL (Bosco, 2010). Note that TCO = transparent conducting oxide, I_{sc} = short circuit current, a-Si = amorphous silicon, Ce = cerium, and IR = infrared.

Although these are the bulk of the known issues, the root causes of a particular failure may not be completely known. It is possible for a given failure to have multiple initiating modes, or to result from a combination of simultaneous or sequential degradation or failure mechanisms that current tests may not adequately detect. Certainly, new failure modes may surface with future module designs and materials.

THE PATH TO IEC 61215/61646

IEC 61215 and IEC 61646 design type qualification tests are the currently accepted minimum testing requirements in most of the world, although they are not mandated in the United States. They specify certain tests, including various module environmental exposure tests, as a minimum qualification for acceptance. They do not purport to be performance, durability, or reliability indicators beyond initial qualification, despite being often mistaken for or portrayed as such.

Nonetheless, because they serve as the de facto basis for much of the current and proposed durability/reliability testing methodologies, it is important to examine their key tests and the process leading to their development. With this understanding, it is easier to identify their advantages and disadvantages relative to what is being proposed to address long-term PV durability and reliability issues, tests, and standards.

NREL's Carl Osterwald and Thomas McMahon (Osterwald & McMahon, 2009) published a landmark review, *History of Accelerated and Qualification Testing of Terrestrial Photovoltaic Modules: A Literature Review,* spanning the 30+ year period from 1975 to 2008. The reader is referred to this document and the 170 references cited for greater detail than can be described here.

Since the 1970s, there have been a number of PV qualification test sequences developed by various entities, each successively building on the knowledge gained in an attempt to detect the presence of known failure or degradation modes in the intended environments. These have evolved into a series of tests paths, successful completion of which at least implies that a module will last a minimum number of years. That is, these test paths should avoid out-of-box or early service failure.

Starting in 1975, the Flat-Plate Solar Array project was begun by the Energy Research and Development Administration, which in 1977 was integrated into the U.S. Department of Energy. Under this program, the National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory (JPL) organized a series of purchases of PV modules from manufacturers designated as JPL "Block Buys I through V." All modules were crystalline silicon. Based on field experience and failure analysis of degraded modules, each of the five block buys generally placed increasingly stringent accelerated stress tests on the modules through additional tests, altered test parameters, and varied test durations to reach the current IEC 61215 qualification tests.

A summary of the tests used in the block buy program (Ross, 1982-1983) is shown in Figure 3.

Test	Block I	Block II	Block III	Block IV	Block V
Thermal Cycle	100 -40 to +90°C	50 -40 to +90°C	50 -40 to +90°C	50 -40 to +90°C	200 -40 to +90°C
Humidity Cycle	70°C, 90%RH 68 hours	5 -23 to 40°C 95%RH	5 -23 to 40°C 95%RH	5 -23 to 40°C 95%RH	10 -40 to +85°C 85%RH
Mechanical Loading Cycle		100 2400Pa	100 2400Pa	10000 2400Pa	10000 2400Pa
Wind Resistance				X UL997	X UL997
Hail Impact				9 impacts ¾", 45mph	10 impacts 1", 52mph
High Potential		<15µA 1500	<50µA 1500V	<50µA 1500V	<50µA 2xVs+1000V

Figure 3. Summary of key JPL Block qualification tests. Note that Block I used 100 thermal cycles, Blocks II-IV used 50 cycles, and Block V increased to 200 cycles (Ross, 1982-1983). Note that RH = relative humidity and µA = microamperes.

As Wohlgemuth explains (Wohlgemuth, 2011):

- Block I tests were based on NASA tests used on space arrays. Thermal cycle extremes were selected as -40 and +90°C based on estimates of worst case terrestrial environmental conditions. Humidity testing for space arrays was short duration due to the limited pre-launch exposure time. Block I exhibited many early failures due to cracked cells; one cracked cell resulted in total power loss due to the designs. Non-glass superstrate modules exhibited significant soiling and delamination, usually due to solar ultraviolet (UV) exposure.
- Block II added 100 mechanical load cycles, likely influenced by NASA experience with space launch damage. It added an electrical high potential (Hipot) test to ensure electrical insulation, and reduced the thermal cycles from 100 to 50, although the rationale for the reduction is unknown. The humidity test was changed from a constant level to 5 cycles of -23°C to 40°C.
- Block III changed the Hipot failure level as module size increased. Block II and III modules were used in some larger systems, many in desert environments, and exhibited new failure modes. Modules that passed 50 thermal cycles failed in the desert due to broken cells or interconnects, resulting in total power loss. Most new modules used glass superstrates, reducing thermal expansion and contraction.
- Block IV increased the mechanical load cycles and added hail impact, because hail was found to cause broken cells and superstrate glass breakage unless tempered glass was used.
- Some modules built without bypass diodes exhibited hot-spot failures, so a hot-spot test was added in Block V, and the thermal cycles were increased to 200. The humidity freeze test was also increased from five to ten cycles between Blocks IV and V. As Whipple (Whipple, 1993) described, this appears to have helped dramatically reduce ten-year failure rates.
- A sixth block buy was scheduled but never implemented due to funding cuts. Additions planned for 1985 included bypass diode, UV exposure, and damp heat (85°C/85% relative humidity [RH]) tests.

Wohlgemuth further details the activity leading to the current second editions of IEC 61215 and 62646 (Wohlgemuth, 2012). In Europe, the European Solar Test Installation, now part of the European Commission's (EC's) Joint Research Centre (JRC) in Ispra, Italy, simultaneously worked on a PV qualification standard at the time of the JPL work. European Standards 501 and 502 had some similarities to the Block V tests with the addition of a UV test, outdoor exposure, and a reduction in the thermal cycle high temperature from 90°C to 85°C. EU 503 was a draft of IEC 61215 before it became official.

- Block VI was the basis for IEC 61215. Several tests from Block VI were not included in 61215—the dynamic mechanical load test defined in Block V because it was unsuitable for large modules, and the bypass diode thermal test because the international community did not consider it adequately developed.

- SERI work on TF modules, mostly amorphous silicon (a-Si), led to an interim qualification test (IQT). A significant issue was high leakage current resulting from inadequate edge isolation of the transparent conducting oxide (TCO) on the glass, and a wet insulation resistance test was added as well as ground continuity and cut susceptibility tests from UL 1703 and the Block VI bypass diode test. The IQT led to IEEE 1262. It was a hybrid of elements of IEC 61215 and the IQT, addressing light-induced degradation (LID) in a-Si. IEEE 1262 subsequently led to the development of IEC 61646 and was then withdrawn as being redundant. Other changes in the IQT from IEC 61215 include the addition of wet leakage current, light soak and anneal cycles, and added maximum power output under standard test conditions after a final light soak as a pass/fail criteria.
- IEC 61215 Edition 2 (2005) eliminated the twist test, added the IEC 61646 wet leakage current test, added the IEEE 1262 bypass diode thermal test, and changed the pass criteria for dielectric withstand and wet leakage current test to be dependent on the test module area. It added the requirement to run peak power current through the module during the 200 thermal cycles to evaluate field observed solder bond failures, and clearly labeled the UV test as only a preconditioning test.
- IEC 61646 Edition 2 (2008), in an attempt to adapt to non-a-Si thin film technologies, modified the pass/fail criteria by requiring modules meet the rated power after all tests have been completed and the modules have been light-soak stabilized, and to eliminate meeting a power criterion before and after each test. It also eliminated the twist test, made the dielectric withstand and wet leakage current tests dependent on test module area, rewrote the hot-spot test, added the bypass diode thermal test, and relabeled the UV tests as only a preconditioning test.

Description of Key IEC Durability-Related Tests

The key accelerated stress tests for PV modules (Wohlgemuth, 2011) are detailed in Figure 4.

Accelerated Stress Test	Failure Mode	Technology
Thermal Cycles	Broken interconnect	c-Si
	Broken cells	c-Si
	Electrical bond failure	All
	Junction box adhesion	All
	Module open circuit—potential for arcing	All
Damp Heat	Corrosion	All
	Delamination	All
	Encapsulantloss of adhesion &elasticity	All
	Junction box adhesion	All
	Electrochemical corrosion of TCO	TF
	Inadequate edge deletion	TF
Humidity Freeze	Delamination	All
	Junction box adhesion	All
	Inadequate edge deletion	TF
UV Test	Delamination	All
	Encapsulant loss of adhesion & elasticity	All
	Encapsulant and backsheet discoloration	All
	Ground fault due to backsheet degradation	All
Static Mechanical Load	Structural failures	All
	Broken glass	c-Si & TF
	Broken interconnect ribbons	All
	Broken cells	c-Si
	Electrical bond failures	All
Dynamic Mechanical Load	Broken glass	c-Si & TF
	Broken interconnect ribbons	All
	Broken cells	c-Si
	Electrical bond failures	All
Hail Test	Broken glass	c-Si & TF
	Broken cells	c-Si
Bypass Diode Thermal Test	Bypass diode failures	All
	Overheating of diode causing degradation ofencapsulants, backsheet, or junction box	All
Salt Spray	Corrosion due to salt water or salt mist	All
	Corrosion due to salt used for snow and ice removal	All

Figure 4. Accelerated stress tests for common PV module failures (Wohlgemuth, 2011). Note that TF = thin film, TCO = transparent conducting oxide, and c-Si = monocrystalline silicon.

The IEC 61215 and 61646 qualification tests now include the following stress tests (Wohlgemuth, 2011):

- damp heat exposure at 85°C and 85% RH for 1,000 hours;
- 200 thermal cycles from -40°C to +85°C with peak power current flow above room temperature;
- a combined leg of UV preconditioning (15 kWh/m^2), 50 thermal cycles from -40°C to +85°C, and humidity freeze (HF) cycles from +85°C, 85% RH to -40°C;

- wet leakage current test at the rated system voltage;
- mechanical load test of three cycles of 2,400 Pascals uniform load, applied for 1 hour to front and back surfaces in turn;
- hail test with 25mm diameter ice ball @ 23 m/sec directed at 11 impact locations;
- a bypass diode thermal test, with one hour at short circuit current at 75°C and one hour at 1.25X short circuit current at 75°C; and
- hot-spot test with 3 lowest shunt resistance cells subjected to one-hour exposure to 1,000 W/m^2 irradiance in worst-case hot-spot condition and highest shunt cell subjected to five hours of 1,000 W/m^2 irradiance in worst-case hot-spot condition.

Based on field experience and failure analysis of degraded modules, each of the five block buys placed increasingly stringent accelerated stress tests on the modules through additional tests, altered test parameters, and varied test durations to reach the current IEC 61215 qualification test sequence in Figure 5.

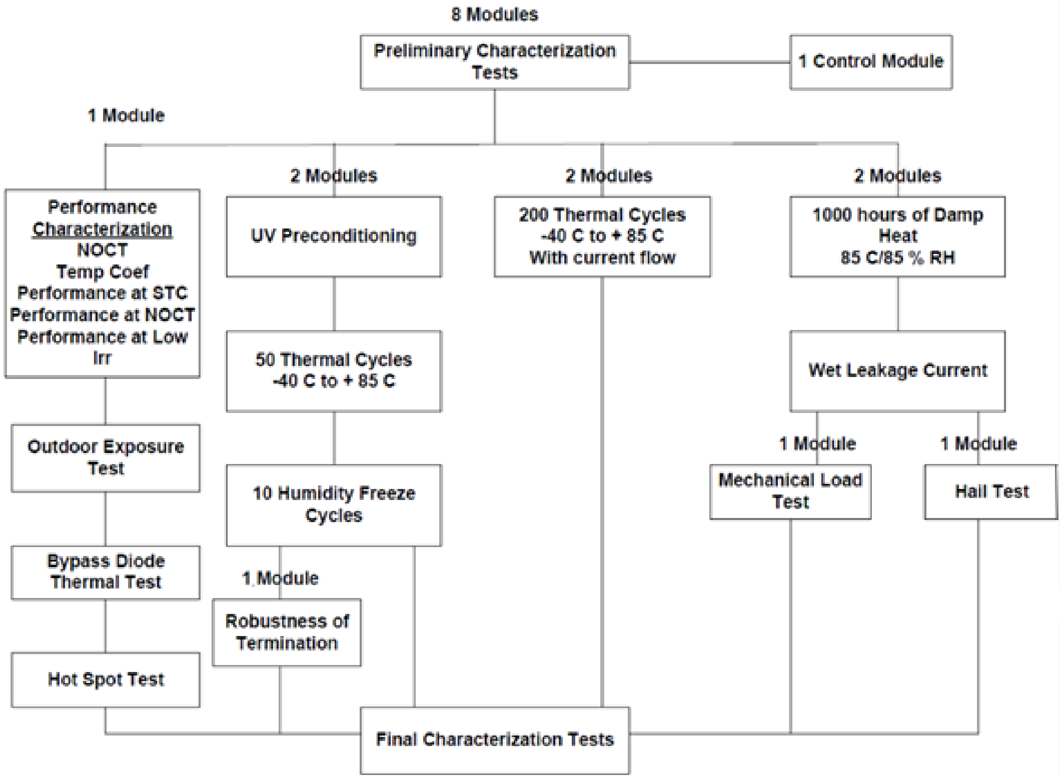


Figure 5. IEC 6125 2nd edition qualification test sequence (Wohlgemuth, 2012).

In IEC qualification testing, the types and ratios of failures seen prior to module changes circa 2004-2005 and those manufactured since has shifted somewhat (Figure 6) (TamizhMani, 2010). A significant portion of this change can be attributed to several factors. First, there was a large influx of new module manufacturers trying to quickly introduce products into the market during this timeframe. As Wohlgemuth notes (Wohlgemuth, 2012),the qualification tests became more stringent at that time. Adding the wet Hipot test after the damp heat test contributed to many of the new damp heat failures for monocrystalline silicon (c-Si) in the 2005 to 2007 period. Adding current flow also increased the thermal cycling and diode failures in this interval.

However, this does raise the question of whether current module designs and materials may also now perform somewhat differently either in accelerated testing or in actual long-term service from earlier models. For example, as noted by Bradley (Bradley, 2013), Si wafer thickness has decreased from 300 to 350 microns or more to about 150 to 180 microns. When a cell breaks, it starts to get hot, which can accelerate the degradation of polymers such as encapsulants. If the susceptibility of current modules to long-term environmental and service use stresses has changed, the appropriateness of some current or extended tests based on prior materials and designs may be questioned. However, it is not completely clear whether this is actually the case.

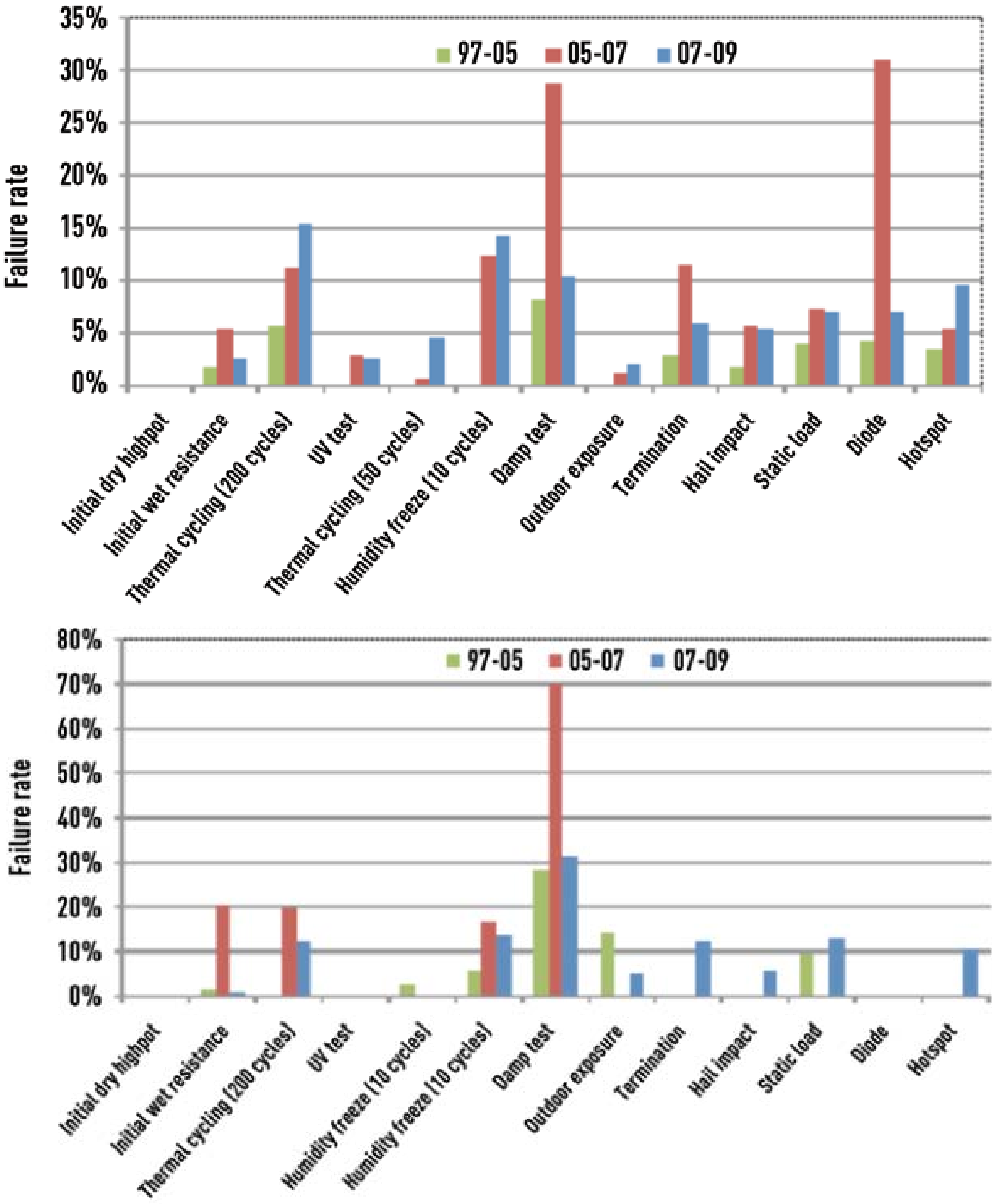


Figure 6. IEC qualification test failure rates of c-Si (top) and TF (bottom) modules for periods 1997 to 2005, 2005 to 2007, and 2007 to 2009 (TamizhMani, 2010). Note that UV = ultraviolet.

Note that most of the IEC qualification tests are primarily directed at the module package—the principal source of module problems—and the interconnections between components. Tests such as the thermal cycling and damp heat have their origins in the industrial and military electronics and semiconductor device industry, in which the direct outdoor exposure of the semiconductor or packaging to the elements, including sunlight, is relatively uncommon. It is notable that during most of the IEC environmental tests, the module does not produce electricity from light exposure, which is the purpose of the device. It is known that failure mechanisms such as LID can be attributed to module operation in sunlight (Sopori et al., 2012). Of the failure mechanisms identified in Figure 2, it is not clear what fraction may be directly caused or influenced by sunlight exposure.

In an extensive PV systems survey, Rosenthal and Thomas (Rosenthal, Thomas, & Durand, 1993) found that failure rates in pre-Block V modules decreased significantly from 45% to less than 0.1% for Block V. Degradation rates for 10 selected systems were found to be larger than 1% per year, although c-Si systems deployed in Florida had degradation rates well below that.

Programs similar to the above were conducted during that time in Europe, Australia, and Japan by other organizations. Jordan and Kurtz (Jordan & Kurtz, 2012) have conducted a systematic analysis of nearly 2,000 PV degradation rates found in the literature over a span of 40 years. Jordan reports that 78% of all data reported a degradation rate of less than 1%/year, and often significantly less than that. Older TF technologies were statistically closer to 1%/year, but more recently produced TF modules had significantly reduced degradation rates. A value closer to less than 0.5%/year is necessary to meet 25-year commercial warranties. Also, only a few of the module types fielded had reached their 25-year anniversary.

Currently, most power degradation models are based on field studies. As stated, there is insufficient field history on many current module types to accurately model and predict power loss behavior as a function of materials or design. Several models have been proposed, such as that by Válquez and Rey-Stolle (Válquez & Rey-Stolle, 2008). These primarily have been developed based on long-term fielded modules and attempts to determine power loss based on accelerated testing. These models require validation for a variety of module designs and climates.

It is possible that some of the more recently fielded module designs have not yet reached the wear-out phase (Figure 7). If so, power degradation models based on early life performance may not properly predict that of longer term service. Also, the performance of individual modules may not equate to their performance in strings and arrays at system voltage. This may become more critical, because the industry trend is to move to increasingly higher system voltages.

As Válquez and Rey-Stolle note, at the beginning of a module's operational life, the most common failure mechanism is catastrophic failure, while thereafter degradation will take over as the main failure mechanism. Failures resulting from degradation can start to appear after a few years or up to 50 years depending on the degradation rate. This can be demonstrated in the standard "bathtub" reliability curve (Figure 7), which is a composite of several failure distributions (Válquez & Rey-Stolle, 2008).

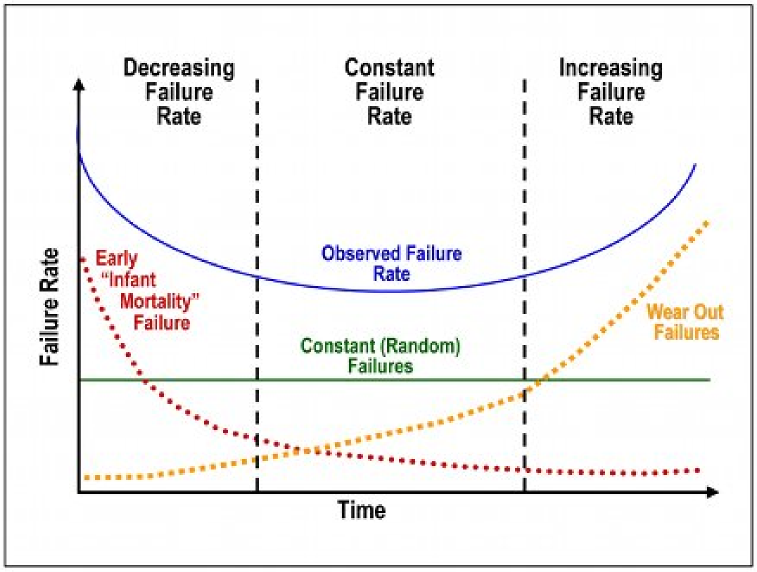


Figure 7. Typical "bathtub" product reliability curve consists of three main failure distributions (Válquez & Rey-Stolle, 2008).

For electronic equipment, the failure rate over the life of the equipment typically has three distinct periods (Klutke, Kiessler, & Wortman, 2003). For mechanical equipment, a similar curve exists, but with a less pronounced constant failure rate region.

- **Infant Mortality.** In this first phase of the bathtub curve, the failure rate is relatively high because some of the parts used in the manufacturing process are out of tolerance or the processes used in manufacturing are inadequate. The shape of the failure rate curve is decreasing, with its rate of decrease dependent on the maturity of the design and manufacturing process as well as the applied stresses.
- **Useful Life.** The second phase of the bathtub curve is known as the "useful life" and is characterized by a relatively constant failure rate caused by randomly occurring defects. It should be noted that the failure rate is only related to the height of the curve, not to the length of the curve, which is a representation of system life.
- **Wear Out.** The last part of the curve is the wear-out portion. This is where components start to deteriorate to such a degree that they have reached the end of their useful life. Durability is defined as the length of the failure-free or maintenance-free operation period. The basic assumption is that all failures are caused by applied stresses and there are no failures before the end of the failure-free period (useful life) is reached. This process is predicated on being able to quantify the loads or stresses that are applied to the electronic or mechanical components and relate these conditions to cycles to failure for repeating and varying load conditions. Wear out is the process that results in an increase of failure rate or probability of failure as the number of life units increase.

The difference in the durability function is the initial part of the life operation up to the point where failure starts. Wear out is the next step after durability. Reliability descriptions and definitions are contained in the *Reliability Toolkit: Commercial Practices Edition* (Morris, 1993) and in *MIL-HDBK-338 Electronic Reliability Design Handbook* (DOD, 1998). However, "failure" must be carefully defined when discussing PV modules. As Wohlgemuth notes (Wohlgemuth, 2013), for example, individual cell interconnects may fail, but built-in redundancy may prevent any change in module performance even though some specific elements may have "failed." So "failure" may be at either the single interconnect level or the module level depending on the criteria.

BEYOND CURRENT IEC QUALIFICATION TESTING

As noted by Wohlgemuth and Kurtz (Wohlgemuth & Kurtz, 2011b) and demonstrated by the PV industry's rapid growth, the current IEC tests have been fairly successful in weeding out poor modules. The degradation rates reported by Jordan and Kurtz (Jordan & Kurtz, 2012) indicate that the tests have been quite successful in identifying and eliminating module types that suffer large degradation rates early in their lifetime.

By design, however, the qualification tests have limitations. A significant number of commercially available products must be able to pass the test sequence, but the tests do not say anything about which product performs better over the long term. For example, when 10 c-Si module types, all qualified to IEC 61215, were tested beyond the qualification level (500 v. 200 thermal cycles and 1250 v. 1,000 hours of damp heat), only two of them passed the extended test (Wohlgemuth et al., 2006).

The qualification tests do not specifically test for wear-out mechanisms, but instead focus principally on early failure mechanisms. Properly designed test-to-failure (TTF) protocols may serve as better indicators of wear out, whatever the impact of combined stresses. The tests primarily identify single cause-and-effect failure mechanisms, do not represent or distinguish the kind of varying and multiple combined stresses present in multiple climates, and are not accelerated enough to determine long-term performance. The PV industry does not know what combined set of stress tests would be a good predictor of a 25-year lifetime, and does not take into account that when the protocols are determined, they are likely to depend on the geographic location where the module is deployed as well as how it is mounted (Wohlgemuth et al., 2006). Some manufacturers (Hasselbrink, 2012) have developed their own internal models based on combined stress tests.

As stated by Wohlgemuth and Kurtz (Wohlgemuth & Kurtz, 2011b), the IEC qualification tests may serve as the basis for longer term reliability purposes given the following preconditions:

- increasing test duration (time or number of cycles);
- using higher stress levels, but making sure that they do not cause failures that are not seen in the field;
- combining stresses;
- evaluating new methods to accelerate the failures;
- using material or coupon tests where it would be impractical or too expensive to use full size modules; and
- using step stresses in which the initial stress starts at the qualification level, then increases to failure, taking care to ensure that the failures are the same ones identified from field exposure.

They also suggest that instead of a simple pass/fail criterion, actual performance be reported to directly compare modules and that the following measurements be considered:

- visual inspections for defects;
- infrared thermography for heat dissipation and to identify high series resistance, hot spots, overheated bypass diodes, etc.;
- electroluminescence to identify discontinuities such as cell cracks or breaks in the junction; and
- dark IV curves to identify small changes in series and shunt resistance.

While modified or completely new individual tests or test sequences may be required, Wohlgemuth and Kurtz provide guidance on extending the existing IEC tests as a possible first step, at least for the comparative evaluation of older fielded designs with current module designs and potential new materials. Wohlgemuth and Kurtz (Wohlgemuth & Kurtz, 2011a) propose:

- **Thermal Cycling.** The current 200 thermal cycles (TC) in the IEC test does not appear to represent 25 years service in most climates. Various levels of cycles from 400 to 1,000 have been proposed, although it has been shown that well designed and manufactured modules can survive 1,500 TC without appreciable power loss (Wohlgemuth & Kurtz, 2011b). If extended to a preset number of cycles at many times the qualification level or run until one of two module types begins to degrade in output or exhibit other detrimental changes, it could serve as a differentiator. If no changes are seen, then it is presumed the two constructions would have similar field performance for failure modes caused by thermal cycling.

- **Damp Heat.** The 85°C/85%RH 1,000 hour test is likely at the practical limits for acceleration for damp heat, because these conditions probably do not happen in the real world. Different module technologies and designs perform quite differently in the damp heat 1000 (DH1000) test, and the correlation to field performance is questionable. For comparative testing, reporting the hours to some measureable degradation such as power loss is likely the most that can be expected. As Kurtz (Kurtz, 2013) notes, “Ultimately, it may be appropriate to apply different versions of the damp heat test to different module constructions.”

- **UV/TC50/HF-10.** This leg of the IEC test sequence consists of UV-A/UV-B exposure, followed by 50 TC and 10 HF cycles. It is primarily a module package test with failures usually indicating inadequate interlayer adhesion or encapsulant cure. Wohlgemuth and Kurtz recommend not extending the 10 HF cycles, because it is not really an identified wear-out mechanism, and adding dynamic mechanical load to the sequence leg.

- **Dynamic Mechanical Load.** IEC 61215 only contains a static mechanical load test following the accelerated stress tests. Wohlgemuth and Kurtz suggest that a dynamic mechanical test would better identify modules with cells prone to breakage and power loss. Static loading has often been equated to the mechanical load effects of built-up snow, while dynamic loading is probably closer to the multi-axial irregular frequency of variable wind force. Although neither has been thoroughly defined, there are models from the building materials and other industries that may be of value to the PV community regarding wind load simulation.

- **UV Materials Test.** The UV exposure in IEC qualification is only a pre-screening test to identify UV-sensitive bonding issues and is not long enough to address the UV stability of module polymeric materials in a 25-year lifetime. As there is no agreement between UV dose and years in the field, a comparative test between old and new materials for a proposed 26 weeks or until observed degradation could be a starting point, based on prior work by Wohlgemuth et al. at BP Solar (Wohlgemuth et al., 2006).

- **Potential Induced Degradation (PID).** There are recent reports of significant degradation of modules mounted at the negative-voltage end of high voltage strings. Degradation appears to be related to voltage-induced migration of ions along current paths, exacerbated by the presence of high humidity or water. Preliminary indications are that module design influences the susceptibility to this effect. Hacke (Hacke, 2012) has proposed one test methodology. Adding a combined temperature/humidity/voltage-bias element to the IEC test sequence is recommended at a minimum, and this is included in draft standard IEC 62804 Ed. 1.0, *System Voltage Durability Test for Crystalline Silicon Modules.*

Alternate Durability Test Proposals

To address the gap between IEC qualification tests addressing infant mortality and longer term performance/durability/reliability testing, a number of global research and standards development activities are currently underway. Some of these enjoy open participation while others are closed or otherwise proprietary. It is beyond the scope and ability of this report to address all of these activities, but the most notable and applicable at the time of this report will be summarized.

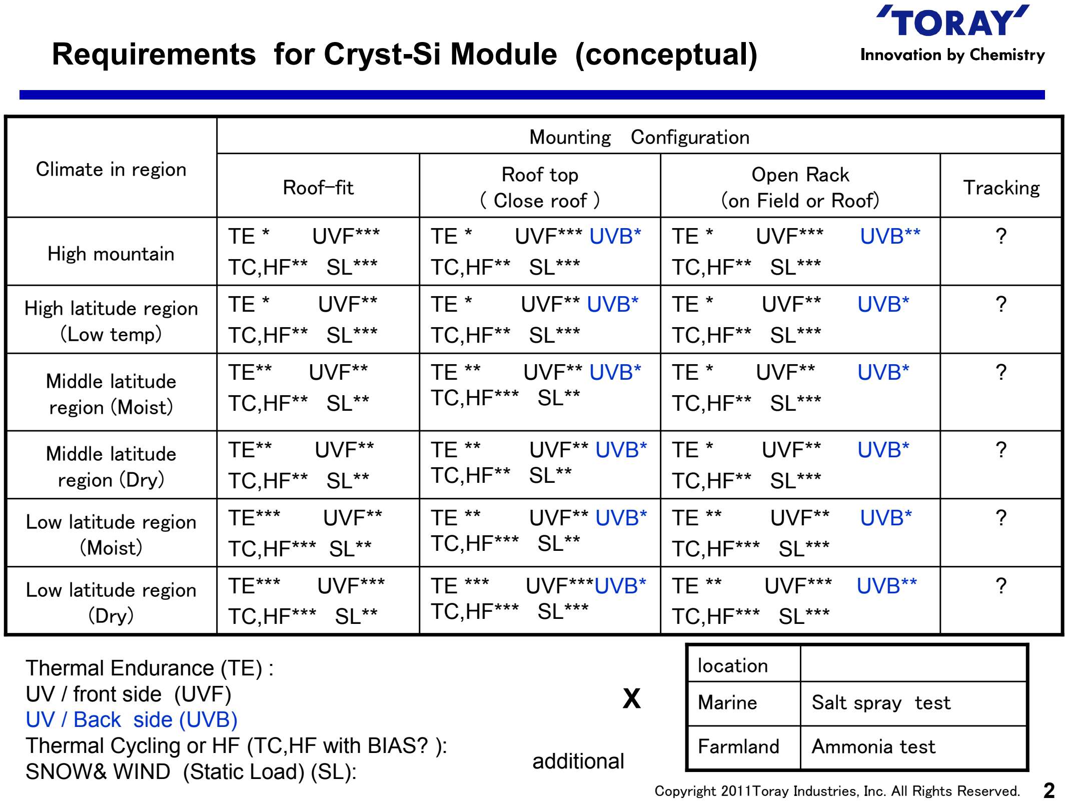
One of the principal efforts currently underway to address PV durability, performance, and reliability was initiated through a cooperative effort between NREL in the United States, the European Commission's JRC, and Japan's National Institute of Advanced Industrial Science and Technology to form the International Photovoltaic Module Quality Assurance Task Force (IPVMQATF). The purpose of the initiative is to develop improved testing in support of standards development, and to develop a comprehensive quality assurance (QA) manufacturing guideline, including a PV module rating system and a guideline for a PV module manufacturing QA system.

Participants include a large number of interested parties from all sectors of the industry—materials suppliers, module manufacturers, academic and research organizations, and testing and standards development organizations (SDOs). Many of the principals are key members of IEC and other standards committees. Due to time zone and travel logistics, the effort is divided into several working groups (Figure 8) in three main geographic theaters: Japan and eastern Asia, Europe, and the Americas. All work will then be compiled and participant consensus sought. The task groups include:

- Task Group 1: PV QA guideline for manufacturing consistency—leaders Ivan Sinicco, Yoshihito Eguchi, Gunnar Brueggemann, Alex Mikonowicz, Zhou Wei
- Task Group 2: PV QA testing for thermal and mechanical fatigue including vibration—leaders Chris Flueckiger, Tadanori Tanahashi
- Task Group 3: PV QA testing for humidity, temperature, and voltage—leaders John Wohlgemuth, Takuya Doi, Neelkanth Dhere
- Task Group 4: PV QA testing for diodes, shading, and reverse bias—leaders Vivek Gade, Yasunori Uchida, Paul Robusto
- Task Group 5: PV QA testing for UV, temperature, and humidity—leaders Michael Koehl, Kusato Hirota, Jasbir Bath
- Task Group 6: Communication of PV QA ratings to the community—leader David Williams
- Task Group 7: PV QA testing for wind and snow loading—leader Jorge Althaus
- Task Group 8: PV QA testing for thin-film PV—leaders Neelkanth Dhere, Veronica Bermudez, Shuuji Tokuda
- Task Group 9: PV QA testing for CPV—leaders Itai Suez and Nick Bosco

Figure 8. International PV Module Quality Assurance Task Force working groups.

One stated goal of the IPVMQATF is to develop a climate-related PV module rating system. An example of such a system has been proposed by Hirota (Hirota, 2011) (Figure 9).



Requirements for Cryst-Si Module (conceptual)

'TORAY'
Innovation by Chemistry

Climate in region	Mounting Configuration			
	Roof-fit	Roof top (Close roof)	Open Rack (on Field or Roof)	Tracking
High mountain	TE * UVF*** TC,HF** SL***	TE * UVF*** UVB* TC,HF** SL***	TE * UVF*** UVB** TC,HF** SL***	?
High latitude region (Low temp)	TE * UVF** TC,HF** SL***	TE * UVF** UVB* TC,HF** SL***	TE * UVF** UVB* TC,HF** SL***	?
Middle latitude region (Moist)	TE** UVF** TC,HF** SL**	TE ** UVF** UVB* TC,HF*** SL**	TE * UVF** UVB* TC,HF** SL***	?
Middle latitude region (Dry)	TE** UVF** TC,HF** SL**	TE ** UVF** UVB* TC,HF** SL**	TE * UVF** UVB* TC,HF** SL***	?
Low latitude region (Moist)	TE*** UVF** TC,HF*** SL**	TE ** UVF** UVB* TC,HF*** SL**	TE ** UVF** UVB* TC,HF*** SL***	?
Low latitude region (Dry)	TE*** UVF*** TC,HF*** SL**	TE *** UVF***UVB* TC,HF*** SL***	TE ** UVF*** UVB** TC,HF*** SL***	?

Thermal Endurance (TE) :
UV / front side (UVF)
UV / Back side (UVB)
Thermal Cycling or HF (TC,HF with BIAS?):
SNOW& WIND (Static Load) (SL):

X

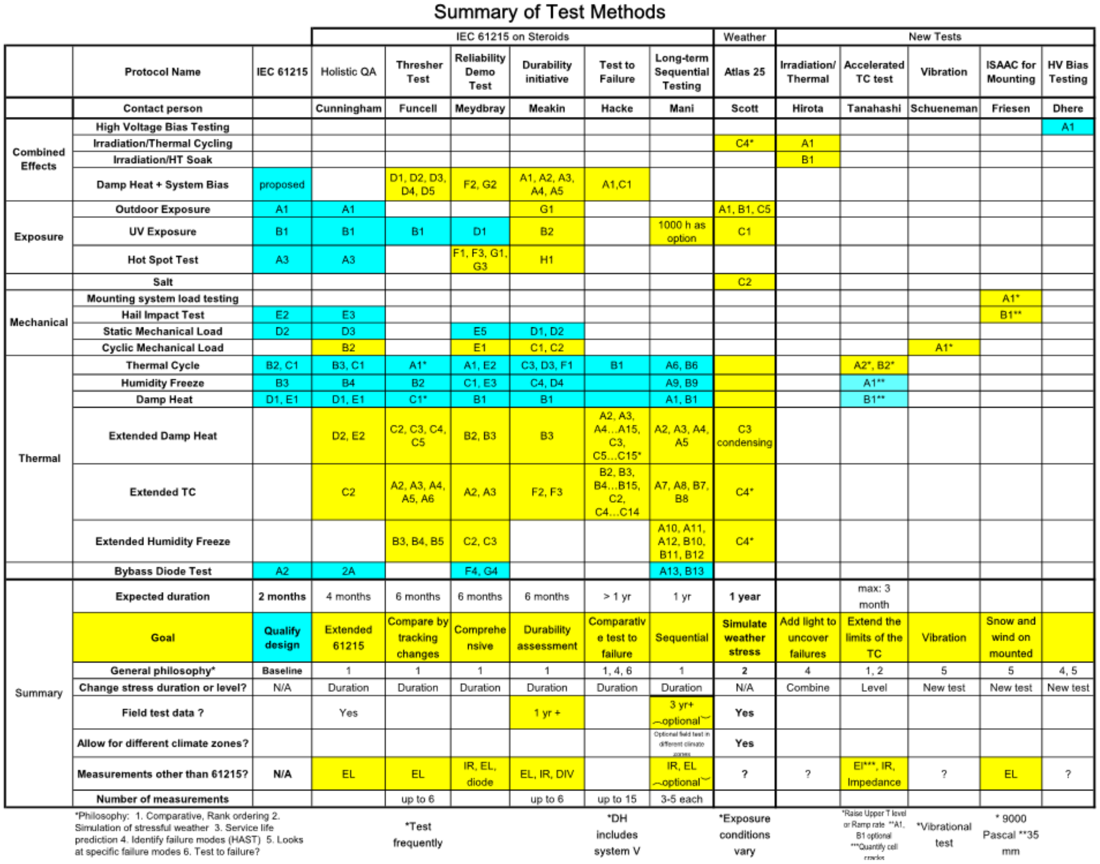
additional

location	
Marine	Salt spray test
Farmland	Ammonia test

2

Figure 9. Example of what a climate-based module rating system might include (Hirota, 2011).

The first major effort was to compile a list of testing needs and alternative test methods and testing schemes to address the IEC deficits in long-term prediction of PV module durability. A number of alternative test protocols have been identified in this effort. An abbreviated guide is included here for reference (Figure 10), but is not intended for detailed examination. At the time of this report, only c-Si has been considered; work is just beginning on thin films.



Summary of Test Methods

			IEC 61215 on Steroids						Weather	New Tests				
	Protocol Name	IEC 61215	Holistic QA	Thresher Test	Reliability Demo Test	Durability initiative	Test to Failure	Long-term Sequential Testing	Atlas 25	Irradiation/ Thermal	Accelerated TC test	Vibration	ISAAC for Mounting	HV Bias Testing
	Contact person		Cunningham	Funcell	Meydbray	Meakin	Hacke	Mani	Scott	Hirota	Tanahashi	Schueneman	Friesen	Dhere
Combined Effects	High Voltage Bias Testing													A1
	Irradiation/Thermal Cycling								C4*	A1				
	Irradiation/HT Soak									B1				
	Damp Heat + System Bias	proposed		D1, D2, D3, D4, D5	F2, G2	A1, A2, A3, A4, A5	A1,C1							
Exposure	Outdoor Exposure	A1	A1			G1			A1, B1, C5					
	UV Exposure	B1	B1	B1	D1	B2		1000 h as option	C1					
	Hot Spot Test	A3	A3		F1, F3, G1, G3	H1								
	Salt								C2					
Mechanical	Mounting system load testing												A1*	
	Hail Impact Test	E2	E3										B1**	
	Static Mechanical Load	D2	D3		E5	D1, D2								
	Cyclic Mechanical Load		B2		E1	C1, C2						A1*		
Thermal	Thermal Cycle	B2, C1	B3, C1	A1*	A1, E2	C3, D3, F1	B1	A6, B6			A2*, B2*			
	Humidity Freeze	B3	B4	B2	C1, E3	C4, D4		A9, B9			A1**			
	Damp Heat	D1, E1	D1, E1	C1*	B1	B1		A1, B1			B1**			
	Extended Damp Heat		D2, E2	C2, C3, C4, C5	B2, B3	B3	A2, A3, A4...A15, C3, C5...C15*	A2, A3, A4, A5	C3 condensing					
	Extended TC		C2	A2, A3, A4, A5, A6	A2, A3	F2, F3	B2, B3, B4...B15, C2, C4...C14	A7, A8, B7, B8	C4*					
	Extended Humidity Freeze			B3, B4, B5	C2, C3			A10, A11, A12, B10, B11, B12	C4*					
	Bybass Diode Test	A2	2A		F4, G4			A13, B13						
Summary	Expected duration	2 months	4 months	6 months	6 months	6 months	> 1 yr	1 yr	1 year		max: 3 month			
	Goal	Qualify design	Extended 61215	Compare by tracking changes	Comprehensive	Durability assessment	Comparative test to failure	Sequential	Simulate weather stress	Add light to uncover failures	Extend the limits of the TC	Vibration	Snow and wind on mounted	
	General philosophy*	Baseline	1	1	1	1	1, 4, 6	1	2	4	1, 2	5	5	4, 5
	Change stress duration or level?	N/A	Duration	Duration	Duration	Duration	Duration	Duration	N/A	Combine	Level	New test	New test	New test
	Field test data ?		Yes			1 yr +		3 yr+ ⌢optional⌣	Yes					
	Allow for different climate zones?							Optional field test in different climate zones	Yes					
	Measurements other than 61215?	N/A	EL	EL	IR, EL, diode	EL, IR, DIV		IR, EL ⌢optional⌣	?	?	EI***, IR, Impedance	?	EL	?
	Number of measurements			up to 6		up to 6	up to 15	3-5 each						
	*Philosophy: 1. Comparative, Rank ordering 2. Simulation of stressful weather 3. Service life prediction 4. Identify failure modes (HAST) 5. Looks at specific failure modes 6. Test to failure?			*Test frequently			*DH includes system V		*Exposure conditions vary		*Raise Upper T level or Ramp rate **A1, B1 optional ***Quantify cell cracks	*Vibrational test	* 9000 Pascal **35 mm	

Figure 10. Alternative testing approaches examined in the International PV Module Quality Assurance Forum. Blue indicates similarity to IEC 61215 tests, yellow indicates it goes beyond IEC 61215 or differs in some other way. The letters indicate the specific "leg" of each test and the number following is the step in the leg sequence. Designations are provided only to show which tests are included in the various schemes for comparative purposes and do not detail test specifics (Aeby, 2012).

In summary (Wohlgemuth& Kurtz, 2012), the alternative proposals fall into three major categories. The first classification is described as "IEC 61215 on steroids." This consists of protocols that are derivatives of the current IEC 61215 tests either by extending the durations or combining the tests in new sequences or cycles. The second classification is "weather" testing, i.e., test programs that primarily use weather durability testing principles and methods. The third classification is "new tests," which are either add-ons or modifications to a more comprehensive test protocol. A description of the highlights, rationale, and comments for several of the key tests follows.

"IEC 61215 on Steroids"

Holistic QA (BP Solar, Q-Cells, VDE) (Cunningham, Jaeckel, & Roth, 2012; Jaeckel, 2011)

This consists of three components: 1) robustness of design testing, 2) inline quality monitoring, and 3) offline product quality assurance. The requirements are based on IEC 61215/61730 and UL 1703. Conditions were extended to better validate reliability and safety as well as to activate potential latent failure mechanisms, and are based on real failure modes/mechanisms from field data.

The test program consists of the following elements (Figures 11a, 11b, and 12).

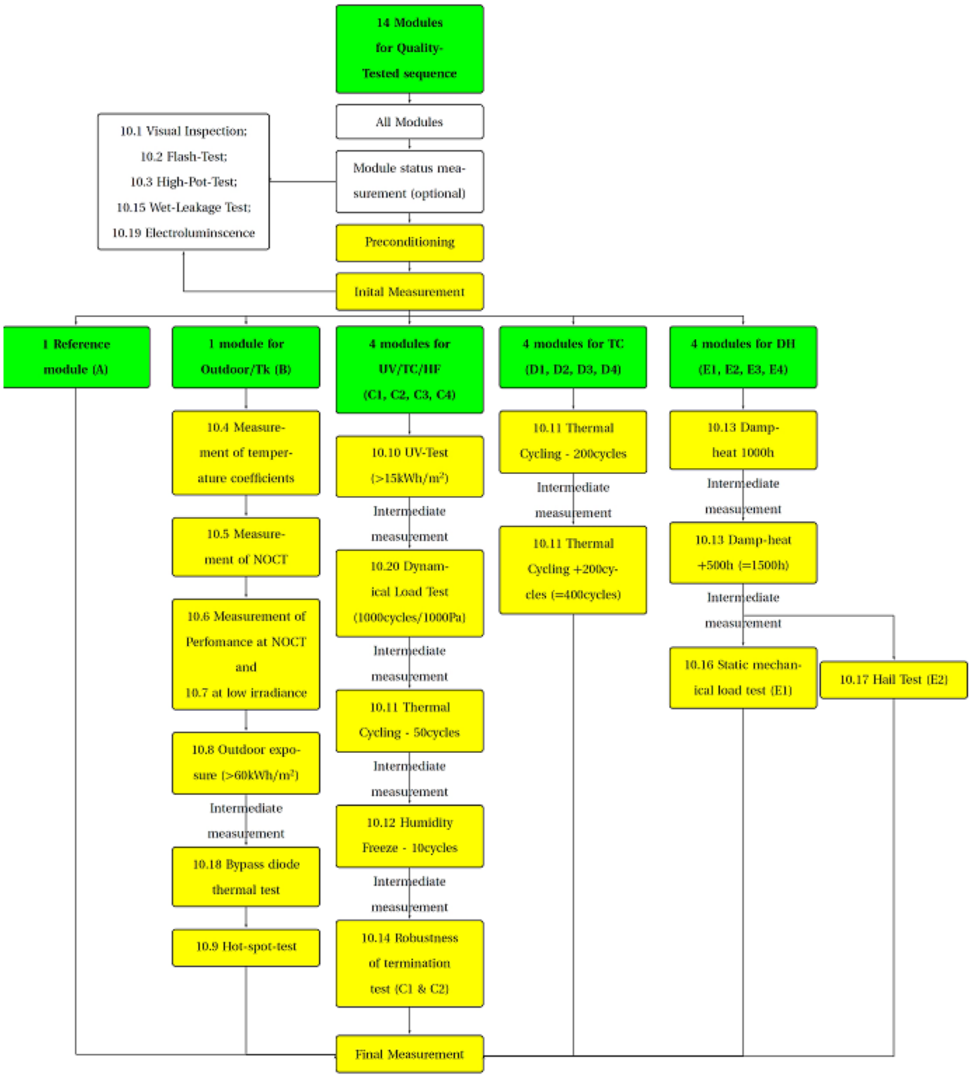
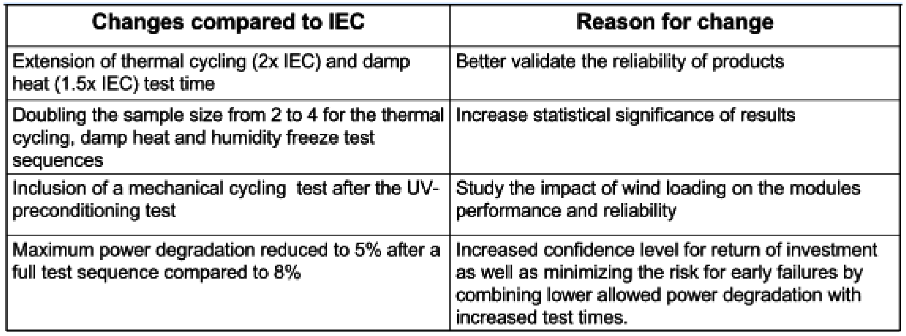
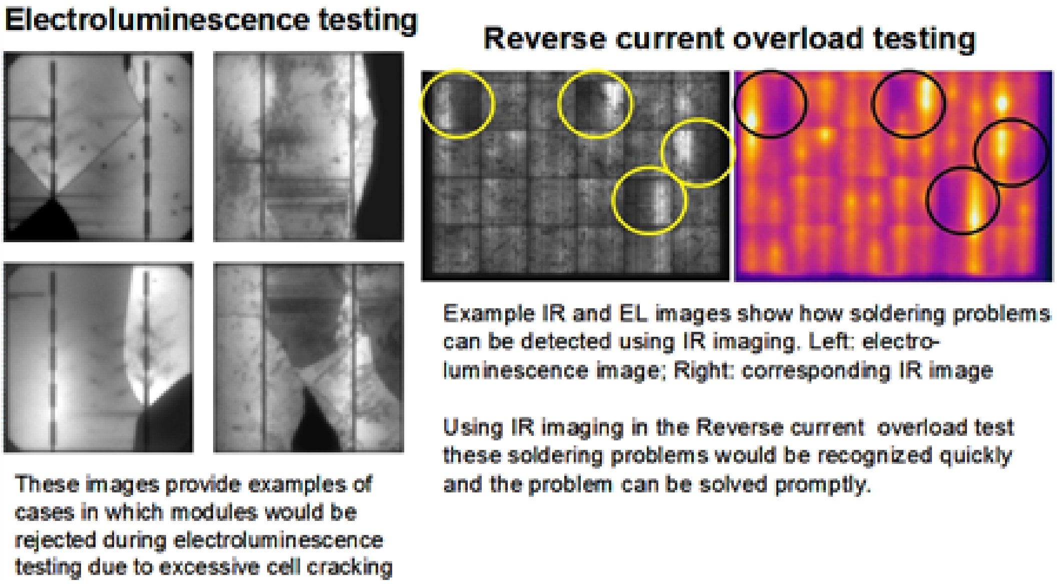


Figure 11a. Holistic robustness of design test sequence flowchart (Cunningham, Jaeckel, & Roth, 2012).



Changes compared to IEC	Reason for change
Extension of thermal cycling (2x IEC) and damp heat (1.5x IEC) test time	Better validate the reliability of products
Doubling the sample size from 2 to 4 for the thermal cycling, damp heat and humidity freeze test sequences	Increase statistical significance of results
Inclusion of a mechanical cycling test after the UV-preconditioning test	Study the impact of wind loading on the modules performance and reliability
Maximum power degradation reduced to 5% after a full test sequence compared to 8%	Increased confidence level for return of investment as well as minimizing the risk for early failures by combining lower allowed power degradation with increased test times.

Figure 11b. Holistic robustness of design test compared to IEC (Cunningham, Jaeckel, & Roth, 2012). Note that IEC = International Electrotechnical Commission and UV = ultraviolet.



These images provide examples of cases in which modules would be rejected during electroluminescence testing due to excessive cell cracking

Example IR and EL images show how soldering problems can be detected using IR imaging. Left: electroluminescence image; Right: corresponding IR image

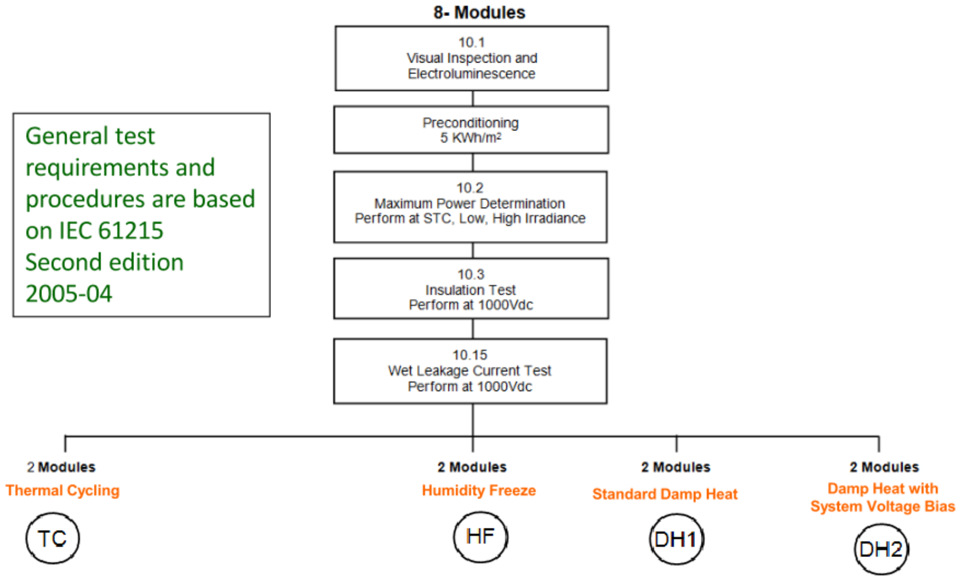
Using IR imaging in the Reverse current overload test these soldering problems would be recognized quickly and the problem can be solved promptly.

Figure 12. Holistic inline quality monitoring measurements (Cunningham, Jaeckel,& Roth, 2012). Note that IR = infrared and EL = electroluminescence.

Information on Part 3, offline product quality assurance of the holistic robustness program, has not been included, because it is not a durability/reliability test addressed in the scope of this report. Advantages of this program include increased number of modules, extended thermal cycling and damp heat tests, electroluminescence and infrared imaging, and more comprehensive interim measurements.

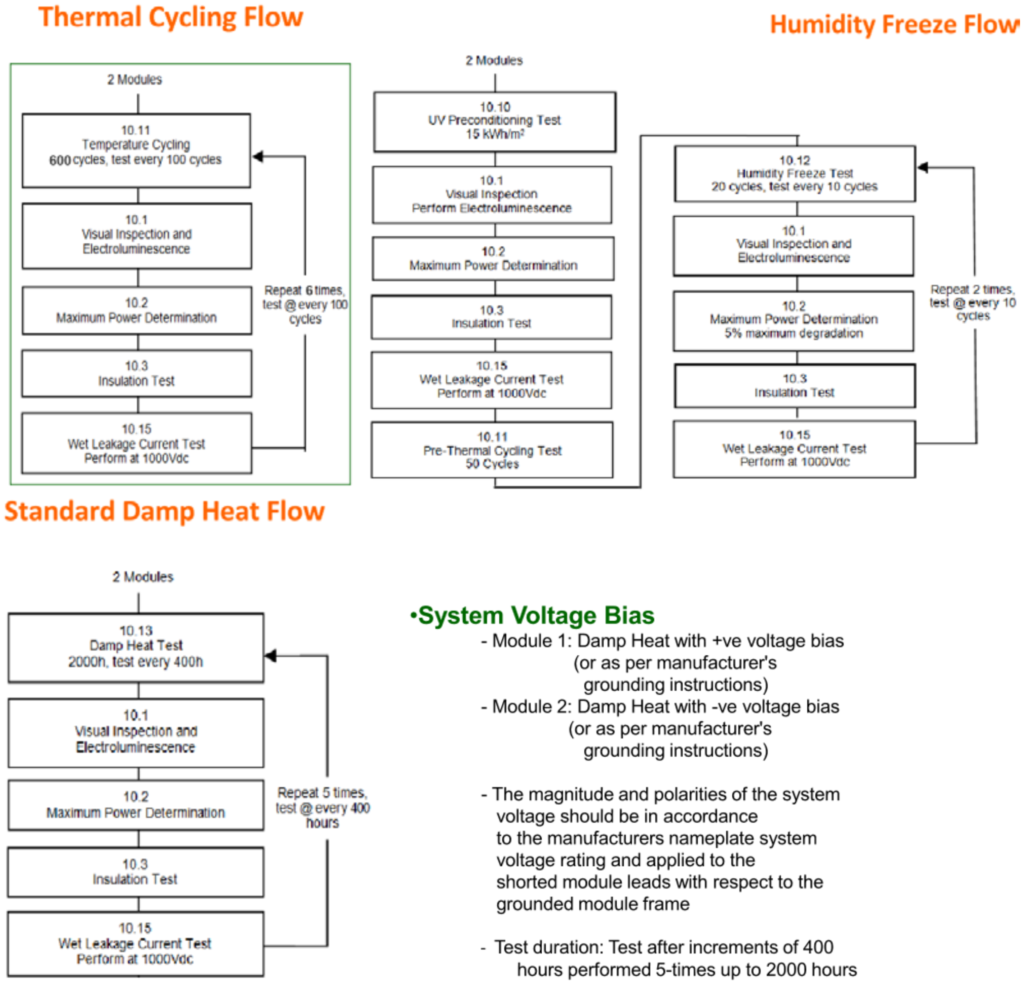
Thresher Test (Kuhn & Funcell, 2011)

So named to refer to "separating the wheat from the chaff." Based on IEC 61215 tests using eight modules with data taken at interim pulls plus initial and final (Figures 13, 14).



General test requirements and procedures are based on IEC 61215 Second edition 2005-04

Figure 13. "Thresher test" process flow (Kuhn & Funcell, 2011). Note that IEC = International Electrotechnical Commission, STC = standard test conditions, and Vdc = direct current voltage.



•System Voltage Bias

- Module 1: Damp Heat with +ve voltage bias (or as per manufacturer's grounding instructions)
- Module 2: Damp Heat with -ve voltage bias (or as per manufacturer's grounding instructions)

- The magnitude and polarities of the system voltage should be in accordance to the manufacturers nameplate system voltage rating and applied to the shorted module leads with respect to the grounded module frame

- Test duration: Test after increments of 400 hours performed 5-times up to 2000 hours

Figure 14. “Thresher test” details (Kuhn & Funcell, 2011).

The “Thresher Test” is designed to gather and report degradation through the course of the test sequences rather than being a pass/fail test. The test is terminated if power output degrades more than 20% from initial test data. At the beginning and end of each test sequence, the power drop, leakage current reading, visual observations, and defects (per IEC 62125, Clause-7) are reported. It is designed as a third-party test with data reported to the manufacturer.

Key differences from standard IEC testing include additional interim inspections and measurements such as electroluminescence, maximum power, insulation, and wet leakage current tests. The thermal cycling is extended from 200 to 600 cycles with measurements every 100 cycles. UV preconditioning and 50 thermal cycles as in IEC 61215 are followed by 10 humidity freeze cycles repeated twice with measurements every 10 cycles. Damp heat is doubled to 2,000 hours with measurements every 400 hours. An additional 2,000 hour damp heat test and measure cycle, as above, is performed with module frames at plus and minus rated system voltage relative to ground (Hacke, 2011).

TÜV Rheinland Long-Term Sequential Test (LST) (TamizhMani, 2011)

A commercially developed test sequence (Sopori, 2012) within TÜV's larger performance scheme offering and described as mid-level "to verify quality for medium confidence." The sequence is shown in Figure 15.

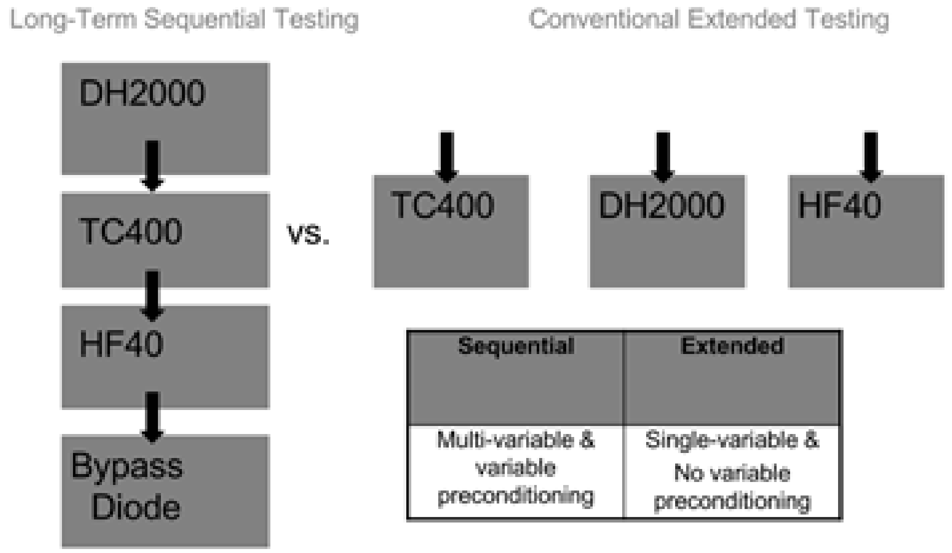
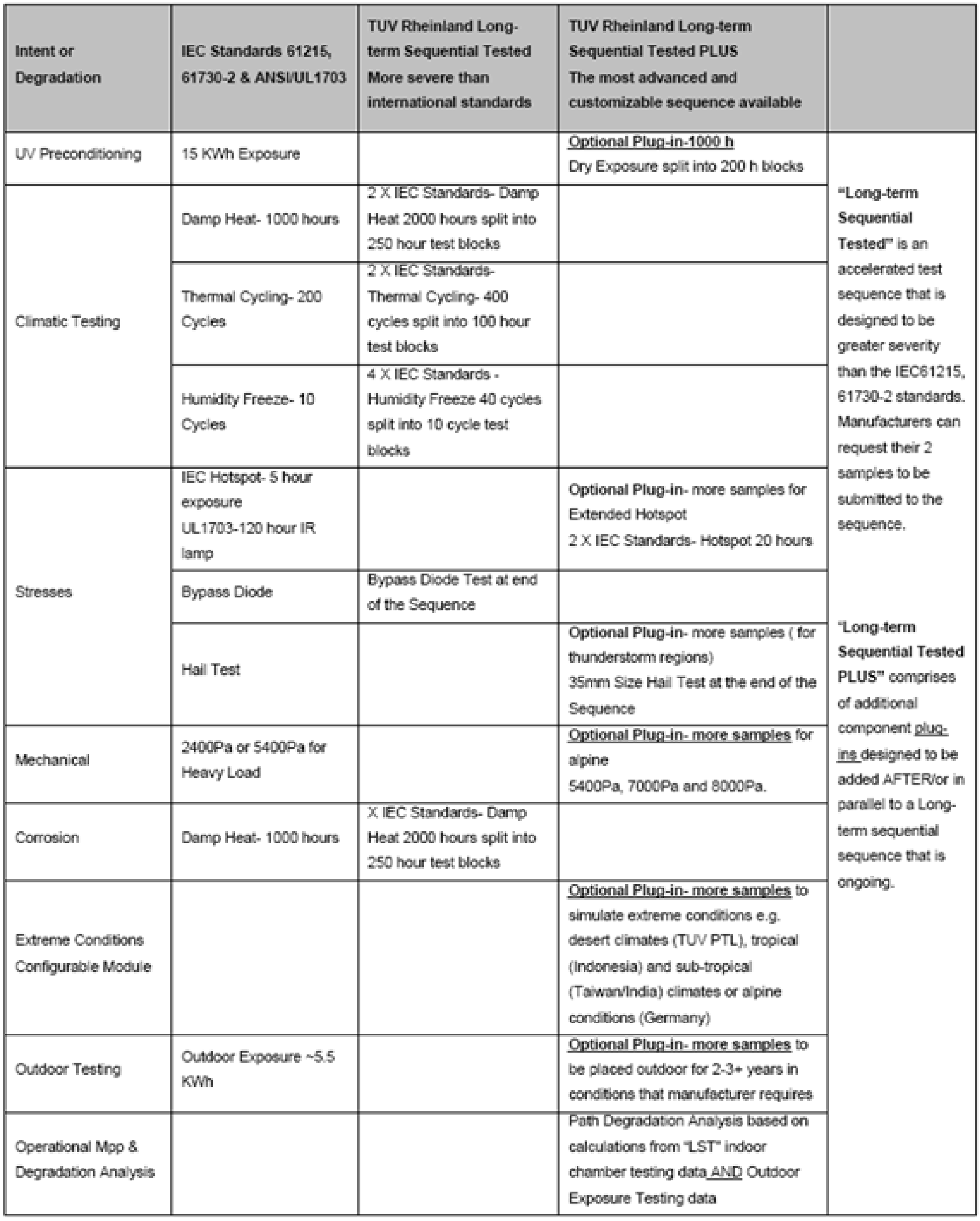


Figure 15. TÜV Rheinland Long-Term Sequential Test sequence compared to conventional extended testing (TamizhMani, 2011). Note that DH = damp heat, TC = thermal cycles, and HF = humidity freeze.

IEC 61215 test in which each one primarily undergoes only one stress test. In addition, each test step is extended, and is therefore two to four times more severe than in IEC 61215. Pre- and post- tests consist of current-voltage (IV) parameters, dry Hipot, wet resistance, and visual inspections. Interim measurements (as above) are made on the following schedule with interim measurements at each interval (dielectric withstand, wet leakage current, maximum power, and visual inspections):

- damp heat: 1,000, 1,250, 1,500, 1,750, and 2,000 hours;
- thermal cycling at 200, 300, and 400 cycles;
- humidity freeze at 10, 20, 30, and 40 cycles; and
- bypass diode test at end of sequence.

Failure is based on more than 20% power loss. The test sequence is estimated to take one year and involves three modules. A "plus" version is offered that adds a dry exposure to UV-A/UV-B light in the test sequence. Following standard IEC pre-conditioning, interim measurements (as above) are made at 200, 300, 600, 800, and 1,000 hours. Also available in "plus" are optional outdoor exposures of test sequenced modules at TÜV locations in Japan, Arizona, Germany, Shanghai, Taiwan, and India for two to three years or more. "Plus" also has additional "plus" options as shown in Figure 16.



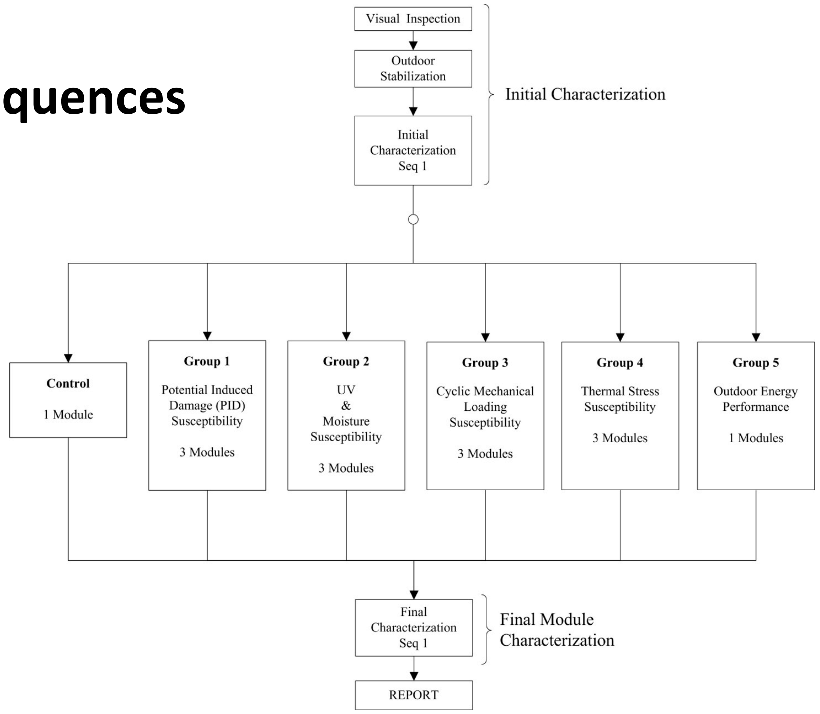
Intent or Degradation	IEC Standards 61215, 61730-2 & ANSI/UL1703	TUV Rheinland Long-term Sequential Tested More severe than international standards	TUV Rheinland Long-term Sequential Tested PLUS The most advanced and customizable sequence available	
UV Preconditioning	15 KWh Exposure		Optional Plug-in-1000 h Dry Exposure split into 200 h blocks	**"Long-term Sequential Tested"** is an accelerated test sequence that is designed to be greater severity than the IEC61215, 61730-2 standards. Manufacturers can request their 2 samples to be submitted to the sequence. "Long-term **Sequential Tested PLUS"** comprises of additional component plug-ins designed to be added AFTER/or in parallel to a Long-term sequential sequence that is ongoing.
Climatic Testing	Damp Heat- 1000 hours	2 X IEC Standards- Damp Heat 2000 hours split into 250 hour test blocks		
	Thermal Cycling- 200 Cycles	2 X IEC Standards- Thermal Cycling- 400 cycles split into 100 hour test blocks		
	Humidity Freeze- 10 Cycles	4 X IEC Standards - Humidity Freeze 40 cycles split into 10 cycle test blocks		
Stresses	IEC Hotspot- 5 hour exposure UL1703-120 hour IR lamp		Optional Plug-in- more samples for Extended Hotspot 2 X IEC Standards- Hotspot 20 hours	
	Bypass Diode	Bypass Diode Test at end of the Sequence		
	Hail Test		Optional Plug-in- more samples (for thunderstorm regions) 35mm Size Hail Test at the end of the Sequence	
Mechanical	2400Pa or 5400Pa for Heavy Load		Optional Plug-in- more samples for alpine 5400Pa, 7000Pa and 8000Pa.	
Corrosion	Damp Heat- 1000 hours	X IEC Standards- Damp Heat 2000 hours split into 250 hour test blocks		
Extreme Conditions Configurable Module			Optional Plug-in- more samples to simulate extreme conditions e.g. desert climates (TUV PTL), tropical (Indonesia) and sub-tropical (Taiwan/India) climates or alpine conditions (Germany)	
Outdoor Testing	Outdoor Exposure ~5.5 KWh		Optional Plug-in- more samples to be placed outdoor for 2-3+ years in conditions that manufacturer requires	
Operational Mpp & Degradation Analysis			Path Degradation Analysis based on calculations from "LST" indoor chamber testing data AND Outdoor Exposure Testing data	

Figure 16. TÜV Rheinland Long-Term Sequential Test (LST) and "LST-plus" comparison to IEC 61215 (TÜV RheinlandEnergie & Umwelt GmbH, 2011). Note that IEC = International Electrotechnical Commission, LST = long-term sequential test, PTL = Photovoltaic Testing Laboratory, and UL = Underwriters Laboratories.

Fraunhofer Photovoltaic Durability Initiative (PVDI) (Fraunhofer ISE & CSE joint project) (Meakin, 2011).

The Fraunhofer Photovoltaic Durability Initiative (PVDI) (PVDI, 2011) seeks to "provide ranking of PV modules relative to their likelihood to perform reliably over their rated service life." A goal of the program is to regularly publish durability reports and rankings. The PVDI program is intended to test and generate comparative ratings on commercially purchased modules. The test sequence is described in Figure 17.

PVDI Test Sequences



Module Component Testing

- Diode
- Junction Box
- Hotspot

Fraunhofer USA

Figure 17. Fraunhofer Photovoltaic Durability Initiative (PVDI) test sequences (PVDI, 2011). Note that UV = ultraviolet.

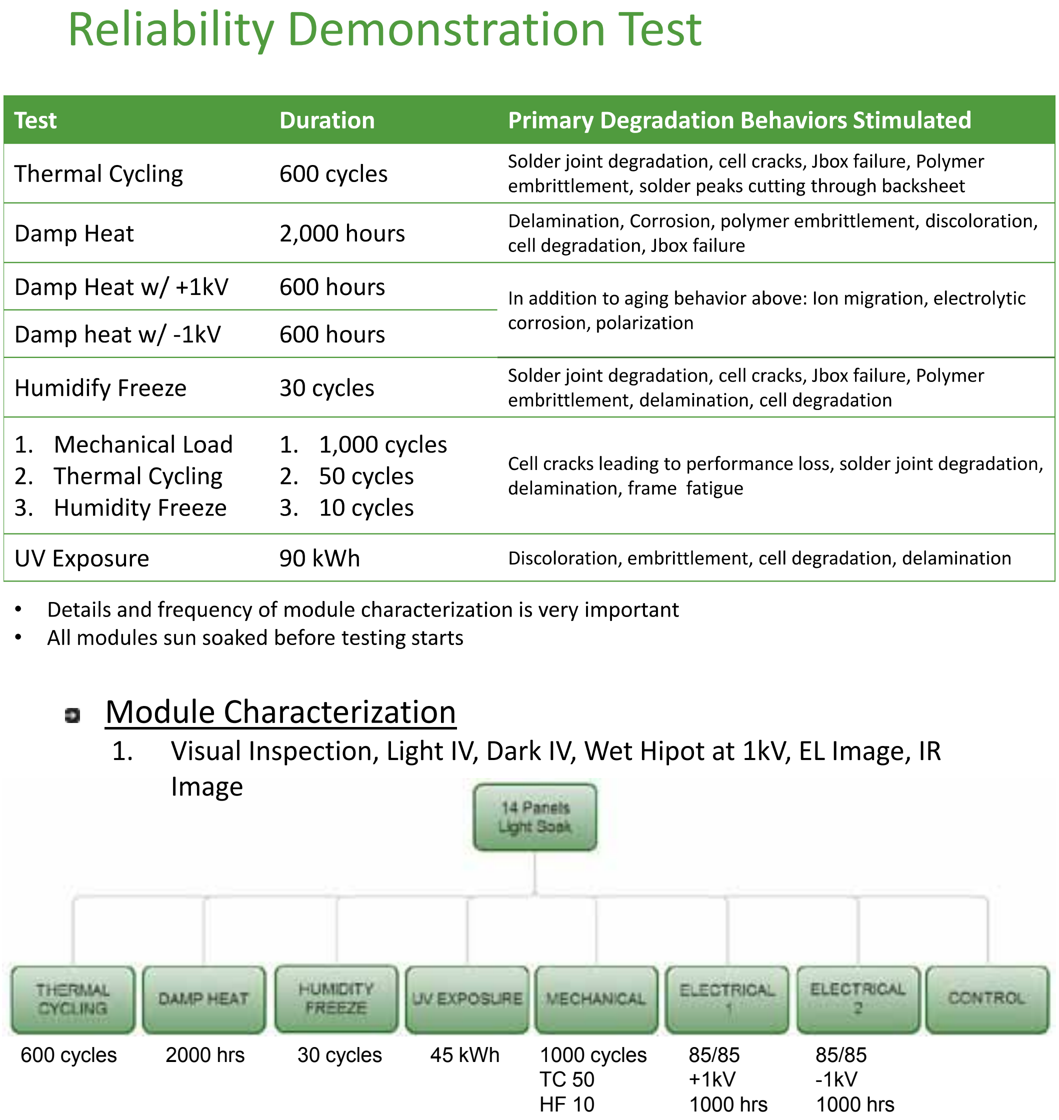
Key features of the PVDI test sequence include:

- potential-induced degradation test sequence, positive and negative grounding;
- UV combined with damp heat—UV exposure equivalent to at least one year with partial saturation;
- cyclic loading at -40°C followed by thermal cycling to exacerbate crack separation;
- extended thermal cycling;
- long-term exposure at maximum power point (MPP) with intermittent IV measurements
- infrared (IR), electroluminescence (EL), and dark IV measurements;
- 6 month test time (except continued outdoor testing);
- evaluation of commercially purchased modules, results quantitative rather than pass/fail; and
- test sequences designed to provide durability assessments of four operational environments:
    - high voltage stress;
    - high UV radiation stress;
    - thermal-mechanical stress (high wind, high snow load); and
    - thermal stress with high temperature variance.

A key feature of the PVDI is the use of 13 modules (plus one control) for somewhat improved statistics and outlier identification compared with IEC 61215.

PV Evolution Labs Reliability Demonstration Test (PV Evolution Labs)

This is a commercial test program (Meydbray, 2012) designed to “provide the industry a robust and comprehensive test protocol to evaluate long-term PV modules aging behavior….” and is primarily based on extending individual IEC 61215 tests and adding electrically biased damp heat and mechanical load sequenced with thermal cycling and humidity freeze as described in Figure 18.



Reliability Demonstration Test

Test	Duration	Primary Degradation Behaviors Stimulated
Thermal Cycling	600 cycles	Solder joint degradation, cell cracks, Jbox failure, Polymer embrittlement, solder peaks cutting through backsheet
Damp Heat	2,000 hours	Delamination, Corrosion, polymer embrittlement, discoloration, cell degradation, Jbox failure
Damp Heat w/ +1kV	600 hours	In addition to aging behavior above: Ion migration, electrolytic corrosion, polarization
Damp heat w/ -1kV	600 hours	
Humidify Freeze	30 cycles	Solder joint degradation, cell cracks, Jbox failure, Polymer embrittlement, delamination, cell degradation
1. Mechanical Load 2. Thermal Cycling 3. Humidity Freeze	1. 1,000 cycles 2. 50 cycles 3. 10 cycles	Cell cracks leading to performance loss, solder joint degradation, delamination, frame fatigue
UV Exposure	90 kWh	Discoloration, embrittlement, cell degradation, delamination

- Details and frequency of module characterization is very important
- All modules sun soaked before testing starts

Module Characterization

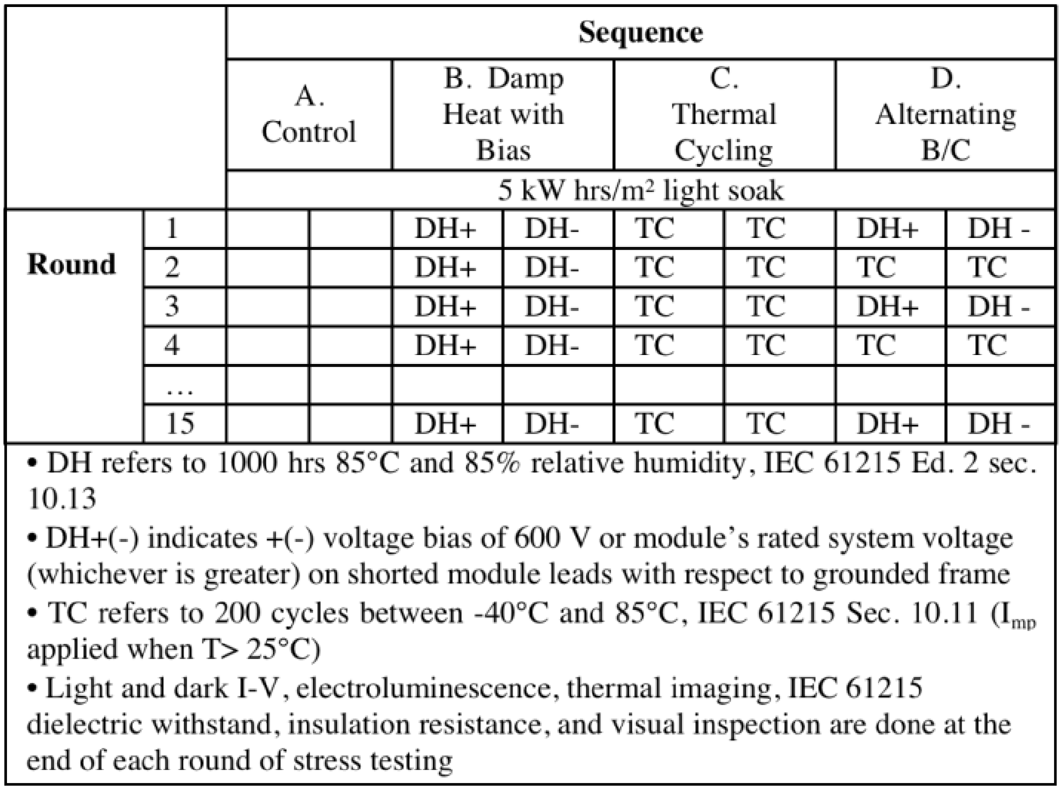
1. Visual Inspection, Light IV, Dark IV, Wet Hipot at 1kV, EL Image, IR Image

Figure 18. PV Evolution Labs reliability demonstration test protocol (Meydbray, 2012). Note that kV = kilovolt, kWh = kilowatt-hour, IV = current-voltage, Hipot = high potential, EL = electroluminescence, IR = infrared, TC = thermal cycles, and HF = humidity freeze.

NREL Test-To-Failure Protocol (Hacke, 2012)

NREL’s Carl Osterwald (Osterwald, 2008) originally proposed a methodology that may be used to obtain more quantitative information about PV module reliability than the existing IEC 61215 tests. The TTF protocol falls somewhere between qualification testing and true accelerated life testing. TTF extends the artificial indoor stresses by continuing the environmental chamber testing until module failure is detected. “These lengths are not module lifetimes, but they can be used to compare the reliability of different modules on a quantitative basis.” Six modules are tested, plus one unexposed control.

Thermal cycling and damp heat were selected for the TTF protocol because these stresses have been reported by laboratories performing standard qualification testing to cause the highest numbers of failures. Electrical forward biased thermal cycling is used for both c-Si and thin films. In damp heat testing for test sequences B & D (Figure 19) a system bias voltage is applied between the module's frame grounding points and the shorted output leads, at both polarities. Measurements consist of MPP, dielectric withstand, wet insulation resistance, visual inspection, and optional infrared imaging. Originally, power output less than 50% (different measurements for c-Si and thin films) and other parameters were included as definitions of failure, but that was later revised (Hacke, Terwilliger, Glick, Trudell, Bosco, Johnson, & Kurtz, 2010) to power loss of 20% among other parameters to better correspond to today's average 25-year module warranties. Wet leakage current failure was also redefined from 50 microamperes (μA) to 1mA.



		Sequence							
		A. Control		B. Damp Heat with Bias		C. Thermal Cycling		D. Alternating B/C	
		5 kW hrs/m^2 light soak							
Round	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 -

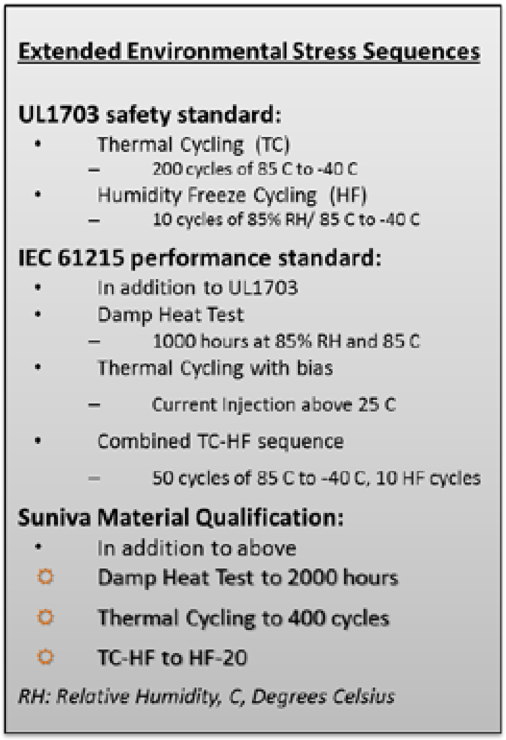
- DH refers to 1000 hrs 85°C and 85% relative humidity, IEC 61215 Ed. 2 sec. 10.13
- DH+(-) indicates +(-) voltage bias of 600 V or module's rated system voltage (whichever is greater) on shorted module leads with respect to grounded frame
- TC refers to 200 cycles between -40°C and 85°C, IEC 61215 Sec. 10.11 (I_{mp} applied when T> 25°C)
- Light and dark I-V, electroluminescence, thermal imaging, IEC 61215 dielectric withstand, insulation resistance, and visual inspection are done at the end of each round of stress testing

Figure 19. NREL Test-to-failure protocol test sequence (Hacke, 2012). Note that DH = damp heat, TC = thermal cycle, IEC = International Electrotechnical Commission, and I-V = current-voltage.

Other Extended Tests

Over the years, a number of manufacturers and others have also modified or extended the IEC test sequence in an attempt to better test for durability and reliability. The following are two representative examples:

- BP Solar (Wohlgemuth, 2003) increased the IEC 61215 tests to 500 thermal cycles with peak power current flow and 1,250 hours of damp heat.
- Suniva (O'Neill, 2012) extended damp heat and thermal cycling (Figure 20).



Extended Environmental Stress Sequences

UL1703 safety standard:

- Thermal Cycling (TC)
  - 200 cycles of 85 C to -40 C
- Humidity Freeze Cycling (HF)
  - 10 cycles of 85% RH/ 85 C to -40 C

IEC 61215 performance standard:

- In addition to UL1703
- Damp Heat Test
  - 1000 hours at 85% RH and 85 C
- Thermal Cycling with bias
  - Current Injection above 25 C
- Combined TC-HF sequence
  - 50 cycles of 85 C to -40 C, 10 HF cycles

Suniva Material Qualification:

- In addition to above
- **Damp Heat Test to 2000 hours**
- **Thermal Cycling to 400 cycles**
- **TC-HF to HF-20**

RH: Relative Humidity, C, Degrees Celsius

Figure 20. Suniva extended testing (O'Neill, 2012). Note that IEC = International Electrotechnical Commission and UL = Underwriters Laboratories.

SunPower (Kim & Bunea, 2012) extends IEC 61215 to 500 thermal cycles, 4,000 hours damp heat, and 110 cycles humidity freeze, and performs static load (2,400 Pa). SunPower also performs multi-climate outdoor and ISO 4892-3 UV testing to 10 years (AM1.5 @ 6 hours/day). Extended hot-spot shading and ± voltage-induced degradation tests are also performed. Additional materials tests such as backsheet and encapsulant thermal and UV stability, and 2,200 thermal cycles (-40°C to- 90°C) for solder joints are performed.

Schott Solar (Mills & Schonfield, 2009) performs more than 2X static loading (5,400 Pa), 400 thermal cycles (-40°C to- 90°C), 2,000 hours damp heat, 20 week "combi" test (3 days thermal cycling and 4 days damp heat), and 20 weeks outdoor exposure.

Summary of Extended IEC Tests Approaches

The extended IEC 61215 tests focus on several key areas (Wohlgemuth & Kurtz, 2011):

- increasing the number of cycles, or test duration, typically by a factor of about 2X;
- increasing the stress limits (e.g., 90°C v. 85°C upper limit in thermal cycling);
- sequencing several tests on the same module(s) to provide multiple rather than single stresses;
- adding system high voltage bias representative of in-service conditions, especially during high humidity tests;
- adding static or dynamic load to represent snow load and wind mechanical stresses; and
- increasing both the frequency and type of evaluations (such as electroluminescence, thermal imaging, dielectric withstand, and wet leakage current).

Potential advantages of this approach include:

- it builds on a body of prior experience in replicating many known field failures,
- it is relatively easy to implement with commonly available equipment used in IEC qualification testing, and
- some extended approaches (those not requiring new test sequencing) may be implemented at the same time on the same modules as current IEC 61215/61646 qualification testing.

Potential disadvantages include:

- This approach may not represent multiple simultaneous stresses of in-service conditions required to reproduce some degradation mechanisms. This approach has, however, proven effective for some degradation mechanisms, for example voltage-temperature-humidity for PID.
- This approach may not induce some longer term degradation and failure mechanisms. Some tests, however, such as extended thermal cycling, do appears effective for reproducing thermo-mechanical wear out.
- Modeling power loss and correlating accelerated test to field conditions is still elusive.
- This approach does not correlate to specific climates.
- There may be inadequate UV/solar radiation exposure; most tests are conducted in the dark or with externally applied electrical bias, and may not reproduce sunlight effects in operating modules.

A simple extension of existing tests may or may not shift the focus from infant mortality problems to wear out mechanisms. As Kurtz notes, it is useful to find field data to identify the most common wear-out mechanisms and then revisit the test design to see if these are the right tests (Kurtz, 2013).

Weather Tests

The second category of identified tests, “Weather,” is designed to address several of these shortcomings, most notably performance, durability, and reliability in specific climates. This category also relates these shortcomings to accelerated test conditions or combines more stresses simultaneously as Wohlgemuth and Kurtz recommend (Wohlgemuth & Kurtz, 2011). Due to the long times required for normal outdoor exposure tests, accelerated tests need to be developed that are likely to replicate longer term degradation and wear out resulting from external environmental stresses, device metastability issues, and/or normal (and transient) in-service electrical operation.

Presently, there are several research efforts underway to understand current PV module degradation through long-term outdoor exposures in various climates. There are also several comparative PV demonstration projects underway. Some of these efforts are described elsewhere in this report. The goal of some of these efforts is to link identified long-term field failure mechanisms to short-term accelerated tests, similar to the development of the current IEC qualification tests linking to infant mortality failures. Most of this work is in early stages. One test sequence, identified in the International PV Module Quality Assurance Forum (Figure 9) is currently focused on weather degradation.

Atlas 25+ PV Module Long-Term Durability Test (Scott, 2011; Zielnik, 2010)

The standard test sequence is shown in Figure 21.

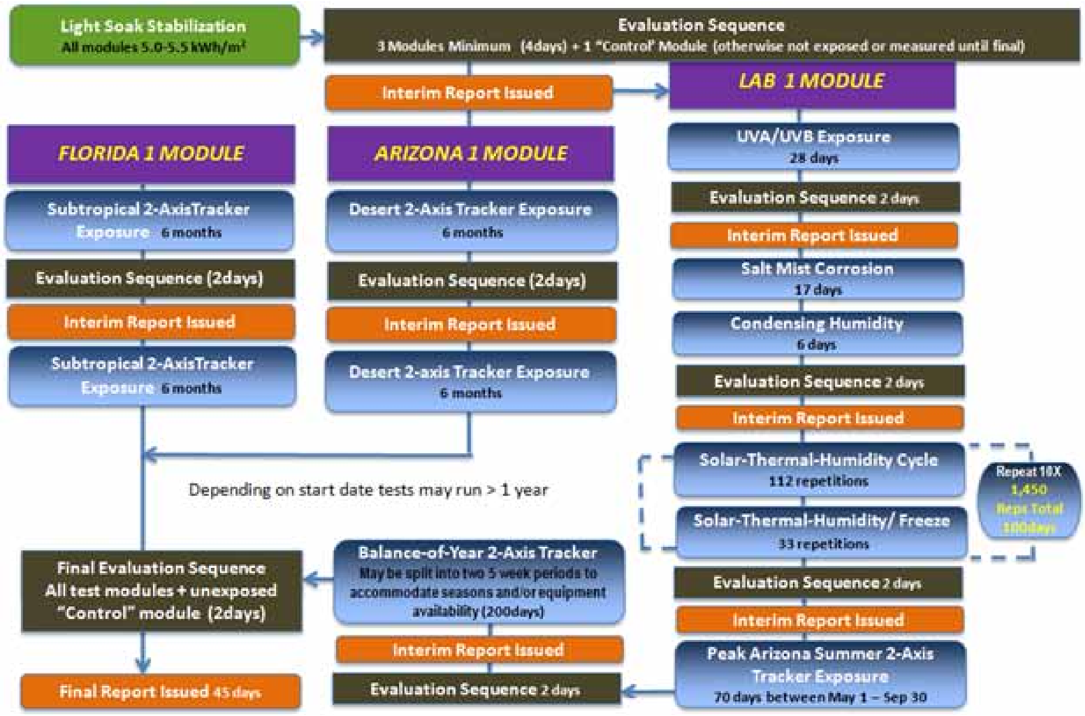


Figure 21. Atlas 25+ "standard" test sequence (Zielnik, 2010).

The sequence uses two modules for outdoor two-axis tracking, one each in south Florida and Arizona for one year. A third "lab" module goes through a sequence of UVA/UVB exposure (2X IEC duration), salt fog corrosion (17 days), condensing humidity (6 days), combined solar/environmental chamber cycles (100 days), Arizona peak summer two-axis tracking (10 weeks), and outdoor Arizona solar tracking for the balance of the year. Measurements include IV curves, digital, IR and EL images, visual inspection, and wet leakage current.

Atlas describes the core solar/environmental chamber sequence as consisting of climate-based conditions in two alternating cycles representing spring/summer/autumn and winter and characterized by a high number of cycles (1,450). Apart from some PV-specific considerations, modules are essentially treated as a "black box"—i.e., tests reproduce climate conditions and not specific failure modes. Modules operate under resistive load at MPP during all outdoor and solar/environmental chamber tests.

The addition of class BBA solar simulation in the diurnal cycles to one of four climates—hot/arid, northern temperate, hot/humid, and a "composite" of the three as a default—is unique. A "plus" version adds additional modules, outdoor climates such as "coastal-marine," and other options. SGS, a global commercial testing organization, incorporates the Atlas protocol into their PV performance and certification scheme.

Potential advantages of this approach include:

- It builds on the body of prior experience in long-term weather durability testing of complex structures.
- It incorporates multiple stresses in a high number of climate-derived cycles.

- It may induce longer term weather related degradation, such as that seen in about 10 years of service.

The module generates power whenever tested under natural or simulated sunlight. Potential disadvantages include:

- It may require longer test times to induce the degradation typical of a module with a 25-year warranty.
- A limited number of modules (typically one) are tested in the full sequence.
- Resistive loading does not produce the higher system voltages of arrays.
- It requires specialized environmental chambers with full solar simulation.
- It typically extends the test time to about four times that of current IEC qualification tests.
- Because this test method is not related to duplicating any observed field failures, it is not clear if the results have any relationship to actual long-term field performance.

Other Tests

The third category of accelerated tests identified in the IPVMQATF (Figure 10) is "add-ons" to IEC tests for specific failure modes. One example is a UV-thermal combined stress acceleration test (Doi, 2011). This test notes that standard thermal cycling and constant temperature stress tests are performed with light irradiated stress (up to three times UV). A second is a rapid thermal cycling (400°C/hour) proposed by Tanahashi (Tanahashi, 2011). Another is the incorporation of wind-induced vibration simulation (Schueneman, 2012).

These add-on tests are largely experimental or in development at this time, so they will not be detailed in this report. The various approaches to specific testing schemes do, however, point to the fact that in terms of moving from basic qualification to mid-level durability assessment, much is still unknown. Here are examples of uncertainties related to the current IEC 85°C/85%RH damp heat test as described by Wohlgemuth (Wohlgemuth, 2012):

- There are multiple humidity and humidity/electrical bias degradation modes with widely varying acceleration factors.
- Eight-five degrees Celsius and 85%RH never occur in the real world, nor do steady-state conditions.
- Failure modes occurring after long-term 85/85 testing are not observed in the field.
- The industry needs field data, samples, and analysis methods
- The industry needs to determine what mechanisms are leading to module degradation in the field.
- The industry will have to perform modeling to understand those degradation mechanisms and how they can be accelerated (Kempe, 2013).
- Then the industry will have to design new accelerated stress tests that can duplicate the field failures.

Clearly, much work remains in fundamental research and understanding of module degradation and failure mechanisms for various module designs and technologies in order to develop true predictive durability tests leading to module and system reliability assessment. A key aspect of this is developing statistical degradation and failure mode data from a large assortment of fielded module designs and technologies. This presents a problem, in that most of the current designs have only been in service for 10 to 15 years, although for c-Si some basic designs and materials have a longer track record. An example is to perform comparative testing more severe than the qualification tests on long-term fielded ethylene vinyl acetate (EVA) encapsulated modules and those with new encapsulants in an attempt to duplicate wear-out mechanisms (Wohlgemuth & Kurtz, 2011b). Of course, many original equipment manufacturers are reluctant to share commercial failure information. In any event, the linkage between long-term field degradation and performance in various climates and laboratory tests must be made. Some of the existing efforts underway in this area will be mentioned in this report, although it must be pointed out that there is no large scale long-term effort presently underway and certainly none on a comprehensive scale.

Demonstration Projects and Field Tests

The Japan Electrical Safety and Environment Technology Laboratories have been conducting limited exposures (Masuda, 2011) of several Si module types at four locations in Japan with some dating from the early 1990s. In addition, 67,000 modules (mostly poly-silicon) at 32 sites—some of which have been operating for about 30 years—have been visually inspected.

DOE has very recently established three regional test centers (Granta, Stein, & Lynn, 2012) in the United States (in New Mexico, Colorado, and Florida) where manufacturers can set up systems for monitoring by DOE laboratories to assess all aspects of a PV system throughout its lifetime. This effort is organized in four main areas:

- design evaluation and acceptance testing,
- performance and system monitoring,
- analysis and monitoring, and
- reliability and safety.

TÜV Rheinland and Fraunhofer Institute for Solar Energy Systems are conducting exposures (Köhl, 2011b; Bogdanski, 2011) of three replicas of seven module types under resistive load in urban Germany, the Alps, Israel (desert), Indonesia (tropical), and the Canary Islands (maritime). Apart from special-cause failures (glass breakage, soiling, etc.), power loss at three years is generally within the measurement error. Note, however, that different degradation mechanisms impact different module parameters. The study notes that:

- degradation indication by power loss requires more than three years of outdoor weathering;
- only the determination of significant outdoor degradation data enables a reliable correlation of lab and outdoor degradation;
- power degradation is actually a superposition of several degradation mechanisms, which should be evaluated (measured) separately to correlate them to lab values; and
- outdoor exposure is important to reveal degradation that will not occur in lab testing.

DURABILITY AND RELIABILITY TESTING CONCEPTS

The term “reliability” is frequently used in the PV industry. In order to define a methodology to predict or achieve reliability, the term itself must be adequately understood. Bajaria (Bajaria, 2000) provides a reasonably practical definition as “the measure of unanticipated interruptions during customer use. These interruptions typically arise from unexpected failures. During a reliability test, one important goal is to maximize the opportunities for unexpected failures, so that they can be fixed. A test may appear to be a reliability test and actually be a durability test when opportunities for discovering unscheduled interruptions are unintentionally minimized.”

Durability is classically defined as the length of failure-free or maintenance-free operation period. A simpler definition is the amount of use one gets from a product before it deteriorates to a point where it is no longer economical to operate (Tenner & DeToro, 2012).

For PV, this must be more clearly defined. In some circumstances, a power loss of 10 % may be as important as a complete failure. In others, any output requiring minimum maintenance may have value. The basic assumption in durability is that all failures are caused by applied electrical, mechanical, thermal, or other stress and there are no failures before the end of the failure-free period (useful life) is reached.

This process is predicated on being able to quantify the loads or stresses that are applied to the electronic or mechanical components and relate these conditions to cycles or duration to failure for repeating and varying load conditions. Therefore, a durability test is a test to failure to determine the length of the failure-free period. Units are stressed as expected in the operating environment or are accelerated by increasing the stress levels. Testing is stopped at failure of all the units.

Adams (Adams, 2011) simplifies durability and reliability further:

- In a formal manner, reliability is the probability (likelihood) that an item (e.g., system, subsystem, component, part) will perform its intended function with no failures for a given time period under a set of operating conditions (environment).
- In brief, reliability is the likelihood of failure-free performance for stated conditions (function, time, environment).
- A durable component is designed to have a longer “useful life” or is designed for damage tolerance.

Bajaria (Bajaria, 2000) notes that to assess reliability or durability, we rely on internal qualification tests because it is not possible to calculate either reliability or durability from first principles alone. Even if we can generate mathematical models to estimate reliability or durability, the models still need to be verified by testing. A durability test is a subset of a reliability test. We may be able to estimate durability from a reliability test but not vice versa. Both these tests appear very similar from a testing mechanics’ viewpoint and it is often difficult to discern any differences. Bajaria provides a good reference for what constitutes a true reliability test (Figure 22).

Reliability test should be	Actual industry practice	Best practice
Reliability test should reflect a true customer. Actual likely users in an actual environment should be testing products.	In most instances, industry uses expert or well-trained employees to simulate customers' feedback. Well-trained employees are not a true reflection of potential customers. Employees have vested interest and therefore, one cannot consider the data as 100% valid.	Use actual users and actual environments for tests whenever possible.
If testing must be done in a laboratory, a reliability test should reflect a true user environment.	Many tests are conducted in a laboratory under a simulated, single environment. The outcome of such tests most likely represents durability rather than reliability.	If only laboratory tests are possible, measure customer environments and design tests accordingly, so that all environments and the operating profile are included simultaneously.
The reliability test should reflect a sample coming from a true production environment.	In many instances, prototype parts are used for the test. Prototype parts may exhibit the validity of physical principles but may not necessarily reflect reliability.	Define reliability at two levels: 1) hardware level D (design level) and 2) hardware level P (production level). Design engineering is considered complete only when both the D level and P level are proven.
Reliability tests should use random samples.	Industry practice is to use pre-qualified test samples. That means, the test samples are inspected and assured to be within specifications before they are subjected to the tests. This, in turn, reduces the chances of observing premature failures. Pre-qualified samples most likely measure durability not reliability.	Use random samples. Or, if pre-qualified samples have to be used, make the pre-qualification scheme a part of the production control plan.
The reliability test should be a validation test, not just a verification test.	Most tests are designed to verify design requirements. These requirements are supposedly a translation of customer requirements. Such tests can be labeled as verification tests. The outcome of such tests most likely measures durability rather than reliability. Additionally, the tests do not reflect the fact that some customer environments may be inadequately translated or some customer environments may be omitted altogether.	Perform verification tests on a smaller sample. Perform validation tests on a larger sample.

Figure 22. Reliability testing concepts and best practices (Bajaria, 2000).

Klyatis (Klyatis, 2012) further points out that the vast majority of literature references to reliability tests are actually true durability tests, or stop short of failure at a finite duration as a qualification test.

Despite extensive use of the term “reliability,” most of what is being done in the PV industry at best falls under the realm of trying to assess “durability.” As Klyatis notes, many types of environmental influences act on a product in real life. Some influences are studied, but many are not. The factors responsible for the influences of environmental stresses in the field are very complicated. One of the most complicated problems is the integrated cause-and-effect relationship of different factor steps including stress influences, effect on output parameters, and degradation.

In accelerated testing, we have two primary means of test acceleration. The first is overstress where one or more levels of a stress condition (such as temperature cycling) are applied at levels in excess of the intended normal service use. The test results are then used to extrapolate estimated performance at the normal stress level. Care must be taken not to exceed the stress strength of the product and induce unrealistic failure.

The second is time compression, where the stress is applied for shorter periods of time to estimate normal service use. This method works best on cyclic fatigue failures, and often a combination of the two approaches is used, such as rapid thermal cycling over an extended range.

Accelerated laboratory tests for durability and reliability fall into several categories. The U.S. Department of Defense Information Analysis Center (Criscimagna, 2013) defines two main categories of accelerated testing:

- Accelerated life testing (ALT) uses a model relating the reliability (or life) measured under high stress conditions to that which is expected under normal operation to determine length of life. It requires:
  - an understanding of the anticipated failure mechanism(s) and
  - a knowledge of the magnitude of the acceleration of this failure mechanism, as a function of the accelerating stress.
- Accelerated stress testing uses accelerated environmental stresses to precipitate latent defects or design weaknesses into actual failures to identify design, part, or manufacturing process problems that could cause subsequent failures in the field. It requires:
  - a thorough understanding, or at least a working knowledge, of the basic failure mechanisms; and
  - an estimation of item life, which may or may not be a concern.

Accelerated testing may be performed at either the component or equipment level. Accelerated test models relate the failure rate of the life of a component to a given stress such that measurements taken during accelerated testing can then be extrapolated back to the expected performance under normal operating conditions. The implicit working assumption here is that the stress will not change the shape of the failure distribution. Typical models include the Inverse Power Law, Arrhenius Acceleration Model, and Miner's Rule (Fatigue Damage), although there are others. In selecting a model, the key criterion is that it accurately models the reliability or life under the accelerated conditions to that under normal operating conditions. Constant single stress profiles are the easiest to implement, but both non-constant stress profiles and multi-stress profiles can be used.

An accelerated test model is derived by testing the item of interest at a normal stress level and also at one or more accelerated stress levels. Extreme care must be taken when using accelerated environments to recognize and properly identify the failures that occur in normal field use and conversely those that are not typical of normal use. Because an accelerated environment typically means applying a stress level well above the anticipated field stress, accelerated stress can induce false failure mechanisms that are not possible in actual field use. For example, raising the temperature of the test item to a point where the material properties change or where a dormant activation threshold is exceeded could identify failures that cannot occur during normal field use. In this situation, fixing the failure may only add to the product cost without an associated increase in reliability. Understanding the true failure mechanism is paramount to eliminating the root cause of the failure.

Not all degradation stresses can be "accelerated" (in terms of the applied stress, not material response) at the same rate. For example, irradiance can be easily increased, but time to reach moisture equilibrium may be more difficult. Therefore, any accelerated test has the potential to alter the normal balance of stresses compared to the service environment. This, in turn, may affect or alter specific degradation mechanisms. Further, many stresses in the outdoor environment are interrelated. Unidirectional solar load, for example, may cause a temperature gradient within a module stack that in turn may affect moisture levels and provide thermo-mechanical stress different from exposure in an environmental chamber. Diurnal cycles typically result in an inverse relation of relative humidity and temperature, a relationship not always achieved in climate chamber tests.

In addition, laboratory test steady-state conditions really do not exist outdoors, and longer term chemical degradation mechanisms, such as corrosion of TCO, may not be able to be accelerated with current tests. Degradation or failure modes resulting from combined stress in service, or those resulting from simultaneous or sequential degradation modes, also may be difficult to reproduce or accelerate with single or limited-stress tests. As a result, a fundamental tenet is that any accelerated laboratory tests must be validated with real time service condition exposures and cause-and-effect correlation established. Degradation or failure modes resulting from combined in-service stresses, or those resulting from simultaneous or sequential degradation modes involving different stresses, are often difficult to reproduce or accelerate with single or limited-stress tests.

As this report demonstrates, the current IEC qualification tests overall are generally recognized as insufficient to assess true long-term durability and wear out, although some of them (in current or extended versions) are effective in reproducing many observed PV failure mechanisms. However, as Kurtz points out (Kurtz, 2013), some degradation and failure modes have not been reproduced by the current test approaches, and it is probable that other problems will surface with the continued introduction of new materials and designs.

Because realistic accelerated multiple-stress testing of full-size modules can be quite expensive, there is substantial interest in supplementing full-module testing with materials-level testing. This is predicated on relying more on materials pre-qualification, on the premise that starting with high quality durable materials will more likely result in durable modules. IEC TC 82 Working Group (WG) 2, a standards writing body, has established a materials working group that is looking at material properties and relevant tests. At this time, only polymeric non-balance of systems materials are being addressed. Several parallel groups are working on backsheets and frontsheets, encapsulants, adhesives for attachment, and edge sealants and potting materials to establish durability tests and specifications. An additional overarching weathering/accelerated aging group is providing input and expertise to the materials groups. The goal of the materials group within IEC WG2 is to define uniform and meaningful methods for testing materials. Those tests may eventually be incorporated into standards that define acceptable limits, such as the PV safety standard IEC 61730-1.

Acceleration Factors

Accelerated tests often report calculated or apparent test acceleration factors. These factors are simply a numerical value relating the relative test time to an equivalent in-service time based on the degree of change in a specific property. It is important to note that in most cases acceleration factors for any test condition are only valid for a particular material or product design, a specific end-use climate or service condition, and a specific measurement parameter. In some cases there is a non-linearity of property change with exposure due to increasing stress sensitivity with product age and wear out, deviations from test reciprocity, overlapping or synergistic degradation mechanisms, and other factors. Therefore, apparent acceleration factors may not be constant across all measurement intervals due to non-linearity in either the field or accelerated test parameter response.

Assuming that test acceleration is linear often results in over- or underestimating product life. Acceleration factors must be determined based on equivalent amounts of measureable product change between the test and service environment at multiple points and for each parameter, such as EVA yellowing. Historically, experience in accelerated testing has usually shown an inverse relation between test acceleration and field correlation, i.e., “highly” accelerated (a relative term) tests typically show low correlation and therefore predictive ability. In general, the more highly accelerated a test, the greater the lack of correlation with field results.

TESTING IN OTHER INDUSTRIES

Other industries such as aerospace, electronics, and automotive systems have developed strong durability and reliability testing methodologies, although failures still occur. Most of these programs rely on strong physics-of-failure (or chemistry-of-failure) principles. This consists of robust root cause failure analyses and determination of cause and effect failure mechanisms and the variable factors that make them appear to be irregular events. The effort combines material science, physics, and chemistry with statistics, variation theory, and probabilistic mechanics (McLeish, 2012). As noted earlier, the PV industry is just beginning to understand some of the physics-of-failure mechanisms of modules needed to evolve beyond empirical test development.

The military requires durable and reliable products. Since the early 1970s, the U.S. Department of Defense and the North Atlantic Treaty Organization have been developing improved laboratory tests and test methodologies. MIL STD 810G (DOD, 2008), now in its seventh major revision, is often used for commercial products as well. It addresses a broad range of global environmental and use stress conditions. The method does not impose design or test specifications, but rather describes the environmental tailoring process that results in realistic materiel designs and test methods based on system performance requirements. Figure 23 is a simplification of the key test concepts and Figures 24 and 25 illustrate some of the environmental and service use stresses that may need to be considered. The 810G document details the factors that must weighed when designing an appropriate durability/reliability test methodology. This may serve as a valuable template for the PV industry.

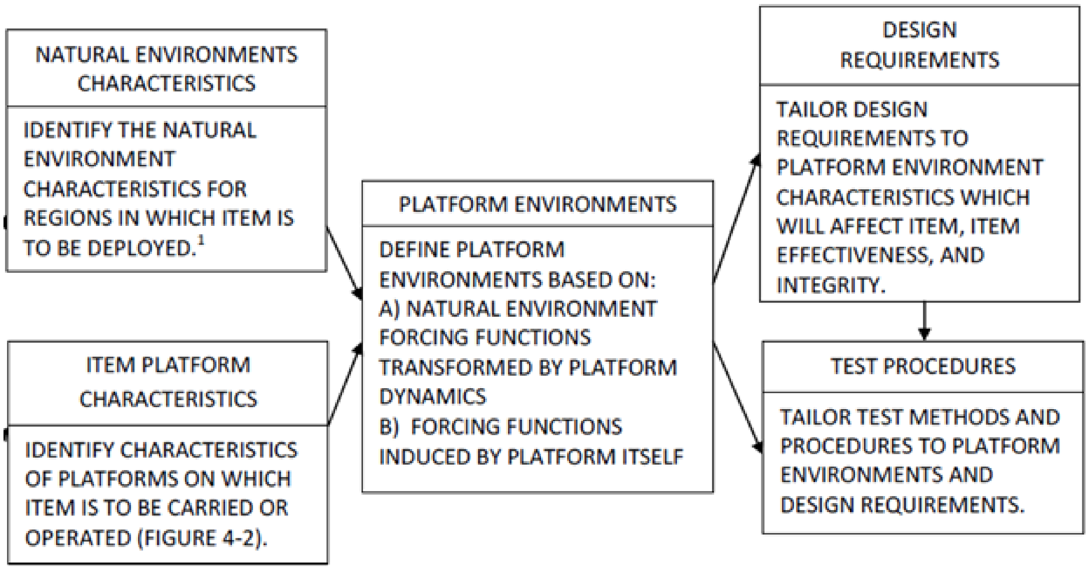
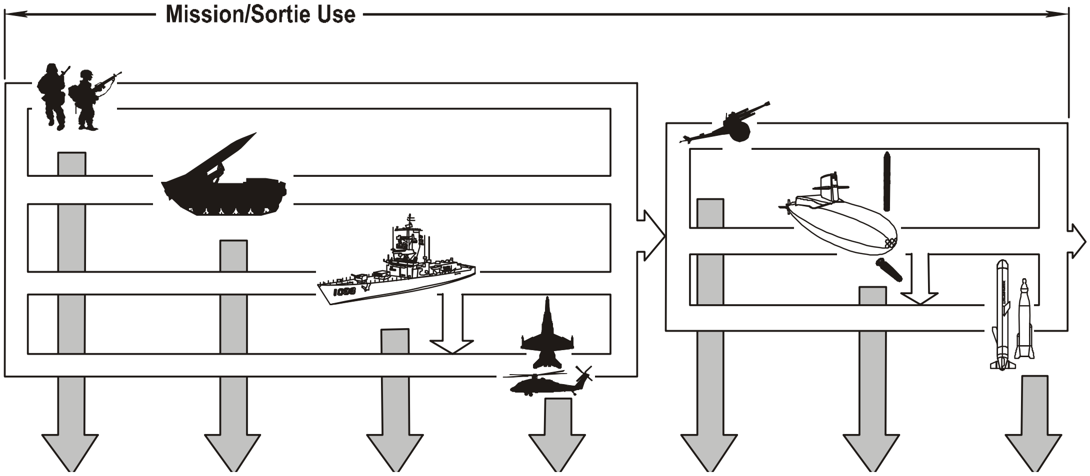


Figure 23. MIL STD 810G test tailoring considerations overview (DOD, 2008).



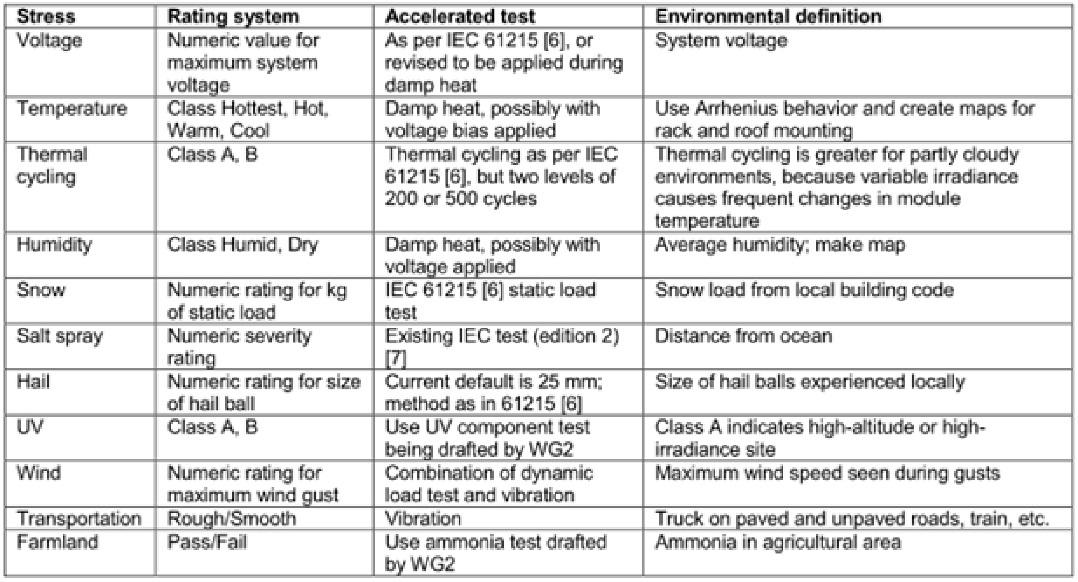
High Temperature (Dry/Humid) Low Temperature/ Freezing Thermal Shock (Storage to Use) Rain/Hail Sand/Dust/Mud Salt Fog Solar Radiation Fungus Growth Chemical Attack	High Temperature (Dry/Humid) Low Temperature/ Freezing Thermal Shock (Storage to Use) Rain/Hail Sand/Dust/Mud Salt Fog Solar Radiation Fungus Growth Chemical Attack	High Temperature (Dry/Humid) Low Temperature/ Freezing Thermal Shock (Storage to Use) Rain Salt Fog Solar Radiation Fungus Growth Chemical Attack	High Temperature (Dry/Humid) Low Temperature/ Freezing Thermal Shock (Storage to Use) Rain Salt Fog Solar Radiation Rain Impingement Sand/Dust Impingement Fungus Growth Chemical Attack	Thermal Shock (Storage to Use) Rain Impingement Sand/Dust Impingement	Immersion Thermal Shock	Rain Impingement Sand/Dust Impingement

Figure 24. MIL STD 810 example of natural stresses to be considered in test design (DOD, 2008).

Handling Shock (Dropping/Slamming/ Overturning) Firing/Blast Shock Acoustic Noise Explosive Atmosphere Electromagnetic Interference	Road/Off-Road Vibration (Surface Irregularities/ Tread Laying) Engine-Induced Vibration Acoustic Noise Handling Shock (Including Bench) Road/Off-Road Shock (Large Bumps/Holes) Land Mine/Blast Shock Weapon Firing Shock/ Vibration Explosive Atmosphere Electromagnetic Interference	Wave Induced Vibration (Sinusoidal) Engine-Induced Vibration Acoustic Noise Wave-Slam Shock Mine/Blast Shock Weapon Firing Shock Explosive Atmosphere Electromagnetic Interference Increased Pressure (Submarine)	Runway-Induced Vibration Aerodynamic Turbulence (Random Vibration) Maneuver Buffet Vibration Gunfire Vibration Engine-Induced Vibration Acoustic Noise Take-Off/Landing/ Maneuver Acceleration Air Blast Shock Catapult Launch/ Arrested Landing Shock Handling Shock (Including Bench) Aerodynamic Heating Explosive Atmosphere Electromagnetic Interference	Firing Shock Firing Acceleration Handling/Loading Shock Acoustic Noise Aerodynamic Heating Explosive Atmosphere Electromagnetic Interference	Launch Acceleration Handling/Launch Shock Engine-Induced Vibration Acoustic Noise Pyrotechnic Shock (Booster Separation) Explosive Atmosphere Electromagnetic Interference	Launch/Maneuver Acceleration Handling/Launch Shock Engine-Induce Vibration Aerodynamic Turbulence (Random Vibration) Acoustic Noise Aerodynamic Heating Explosive Atmosphere Electromagnetic Interference

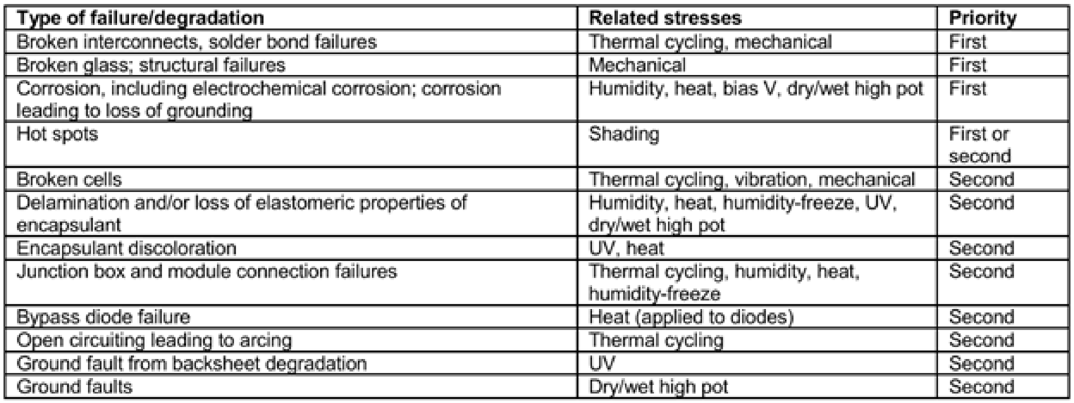
Figure 25. MIL STD 810 example of use-induced stresses to be considered in test design (DOD, 2008).

For PV modules, Kurtz et al. (Kurtz et al., 2011) provide guidance regarding the types of stresses to be considered for durability testing (Figures 26, 27), similar to the MIL STD 810 required approach.



Stress	Rating system	Accelerated test	Environmental definition
Voltage	Numeric value for maximum system voltage	As per IEC 61215 [6], or revised to be applied during damp heat	System voltage
Temperature	Class Hottest, Hot, Warm, Cool	Damp heat, possibly with voltage bias applied	Use Arrhenius behavior and create maps for rack and roof mounting
Thermal cycling	Class A, B	Thermal cycling as per IEC 61215 [6], but two levels of 200 or 500 cycles	Thermal cycling is greater for partly cloudy environments, because variable irradiance causes frequent changes in module temperature
Humidity	Class Humid, Dry	Damp heat, possibly with voltage applied	Average humidity; make map
Snow	Numeric rating for kg of static load	IEC 61215 [6] static load test	Snow load from local building code
Salt spray	Numeric severity rating	Existing IEC test (edition 2) [7]	Distance from ocean
Hail	Numeric rating for size of hail ball	Current default is 25 mm; method as in 61215 [6]	Size of hail balls experienced locally
UV	Class A, B	Use UV component test being drafted by WG2	Class A indicates high-altitude or high-irradiance site
Wind	Numeric rating for maximum wind gust	Combination of dynamic load test and vibration	Maximum wind speed seen during gusts
Transportation	Rough/Smooth	Vibration	Truck on paved and unpaved roads, train, etc.
Farmland	Pass/Fail	Use ammonia test drafted by WG2	Ammonia in agricultural area

Figure 26. Typical stresses encountered by PV modules and proposed system for rating modules (Kurtz et al., 2011). Note that IEC = International Electrotechnical Commission, UV = ultraviolet, and WG2 = IEC TC 82 Working Group 2.



Type of failure/degradation	Related stresses	Priority
Broken interconnects, solder bond failures	Thermal cycling, mechanical	First
Broken glass; structural failures	Mechanical	First
Corrosion, including electrochemical corrosion; corrosion leading to loss of grounding	Humidity, heat, bias V, dry/wet high pot	First
Hot spots	Shading	First or second
Broken cells	Thermal cycling, vibration, mechanical	Second
Delamination and/or loss of elastomeric properties of encapsulant	Humidity, heat, humidity-freeze, UV, dry/wet high pot	Second
Encapsulant discoloration	UV, heat	Second
Junction box and module connection failures	Thermal cycling, humidity, heat, humidity-freeze	Second
Bypass diode failure	Heat (applied to diodes)	Second
Open circuiting leading to arcing	Thermal cycling	Second
Ground fault from backsheet degradation	UV	Second
Ground faults	Dry/wet high pot	Second

Figure 27. Partial list of failure or degradation mechanisms and the related stresses (Kurtz et al., 2011). Note that UV = ultraviolet.

SERVICE LIFE ASSESSMENT AND SERVICE LIFE PREDICTION

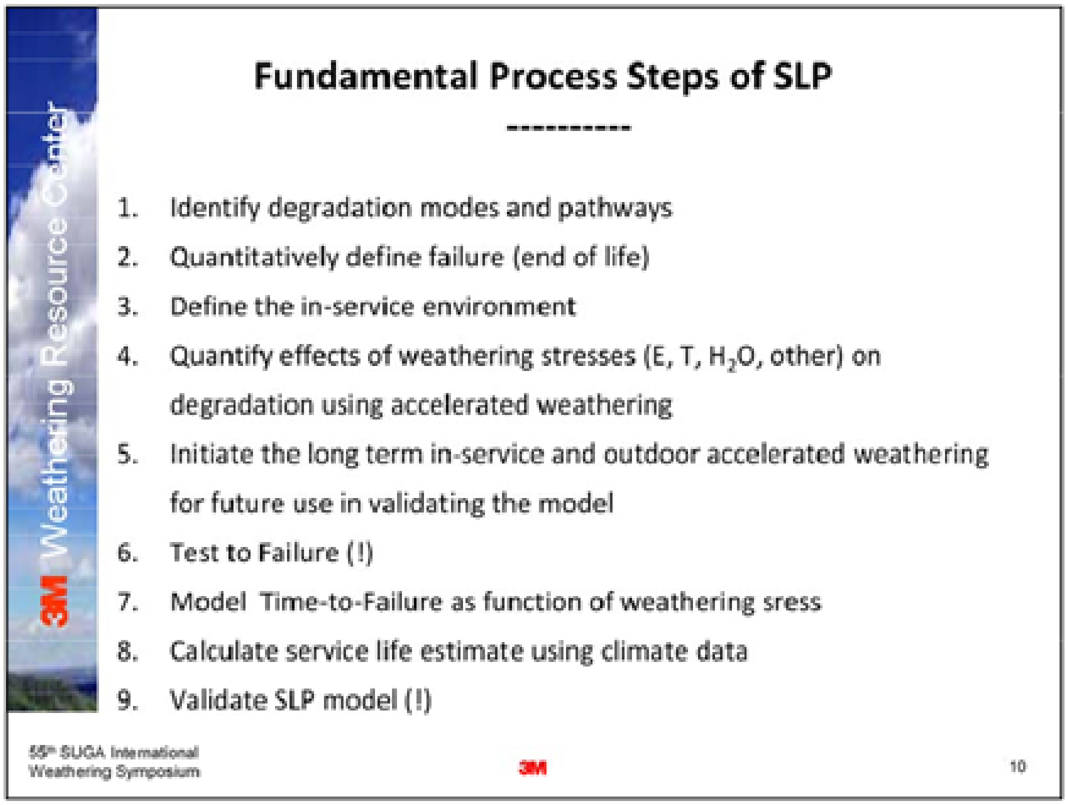
The fundamental principles of true service life prediction (SLP) are well accepted in the testing community. The fundamental concepts have been well documented but fully implemented only for a relatively limited number of materials and products. The methodology has been implemented and reported most notably by Fischer (Fischer, 2006), Ketola (Ketola, 2007), and Burns (Burns, 2012) at 3M Company and by Martin (Martin, Saunders, Floyd, &Wineburg, 1994), White (White, Huntson, & Tan, 2012), and Chin (Chin, Byrd, Gu, & White, 2000) at the U.S. National Institute for Science and Technology, to name only a few. Czanderna and Jorgensen (Czanderna & Jorgensen, 1997) reported on applying this approach to PV lifetime prediction.

SLP is a methodology for estimating the functional life of a product in service by mathematical modeling of degradation and time-to-failure as a function of the cumulative effects of the external and use stresses. The service life of a material product or system can be defined as the time required for any critical functional properties to degrade to the minimum acceptable level required for the application. For PV, this minimum is often defined in terms of the maximum allowed drop in output power.

Burns (Burns, 2012) explains that there is a key conceptual difference between SLP tests and those of the current IEC tests or those protocols based on extending them. ALT is a general methodology to evaluate the robustness of a specific product design by forcing failure using very high stresses, often in combinations not possible in the real world. It assumes that survival under exceptionally high stress can directly predict service life. Meeker (Meeker, 1998) and Escobar (Escobar & Meeker, 2006; Escobar & Meeker, 2009) have further commented on the limitations of and proper statistical design of accelerated tests and the analysis of results. As noted by Wohlgemuth (Wohlgemuth, 2013), the IEC 61215 ALT tests have demonstrated the ability to duplicate one or more field observed failure modes.

SLP and ALT require that the accelerated testing reproduce the same failure modes and degradation pathways encountered in service. True SLP requires that the test stresses correlate directly with the in-service climatic stresses. By relating the same failure modes arising from the same degradation pathways, SLP is capable of providing a quantitative lifetime estimate for any location given the corresponding data. However, ALT provides only information on the ability of a system to survive severe stress, which may or may not be encountered in actual use.

Burns (Burns, 2012) identifies the fundamental process steps required in SLP methodology (Figure 28).



Fundamental Process Steps of SLP

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1. Identify degradation modes and pathways
2. Quantitatively define failure (end of life)
3. Define the in-service environment
4. Quantify effects of weathering stresses (E, T, H_2O, other) on degradation using accelerated weathering
5. Initiate the long term in-service and outdoor accelerated weathering for future use in validating the model
6. Test to Failure (!)
7. Model Time-to-Failure as function of weathering sress
8. Calculate service life estimate using climate data
9. Validate SLP model (!)

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3M

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Figure 28. Steps in SLP methodology as implemented by 3M Company (Burns, 2012). Note that SLP = service life prediction.

It must be noted that this process requires rigorous discipline and detailed knowledge regarding all degradation mechanisms. At present, full SLP is beyond reach, given the multiple degradation mechanisms, complex laminate structure, and varied use climates of PV modules. In addition, there may be failure modes that have not yet been identified. Nonetheless, the methodology has direct application to all durability/reliability test schemes—environmental and use stresses must be quantified and realistic, the degradation mechanisms must correlate to field use, and the test results and models used must be validated with real time service exposures.

TEST METHOD VALIDATION

Regardless of the specific test methodology used, such as those described in this report, a fundamental requirement is that each individual test and test program must be validated to be of any practical use. This presents the industry with a fundamental and significant dilemma. As noted previously, testing must move beyond the current levels of basic qualification. Despite the significant progress in testing that is being made at the research level, there are several hindrances to developing a thorough test standard, including:

- uncertain knowledge of all longer term failure mechanisms for current product materials and designs;
- lack of 25-year field history for many current product designs (may require real time testing, but we can't wait 25 years);
- different degradation rates and failure modes for various module technologies and designs;
- different tests or test parameters may be required for individual climates;
- need for much longer test times due to the practical limits of test acceleration;
- need for multiple combined stress delivery for better simulation of the service and use environments;
- correlation must be established, i.e., same physics of failure(s) between test and field;
- apparatus limitations of current and proposed tests (technology, capacity, expense);
- need for better statistics (i.e., larger sample populations); and
- lack of comprehensive validated transfer models relating test to field results.

Current field demonstration tests and some known field history, at least for c-Si modules, may provide useful information if the data is made available.

As Köhl (Köhl, 2011a) aptly notes, the question from a pragmatic point of view becomes "Is it possible to design accelerated service life tests for PV modules?". He goes on to provide a generally practical and implementable approach, though it stops short of what is required for true validation.

First he starts with several "assumptions":

1. only long-term wear-out degradation is considered;
2. the primary degradation factors are due to weathering;
3. the stress levels depend on local climate and installation;
4. the stress levels depend on the microclimate at the module;
5. the test samples (PV modules or components) have to be considered as a "black-box," i.e., the natural applied stresses are not dependent on PV device technology or failure modes;
6. the modeling is based on investigation of the degradation kinetics of real state-of-the-art modules and is therefore device technology dependent; and
7. a service life of 25 years should result.

Köhl points out that accelerated life test parameters must be realistically derived from multi-climate outdoor monitoring and module exposure performance over time to validate the accelerated tests. The second step is to characterize the individual module microclimates including:

1. module temperature modeled by solar irradiation, ambient temperature, and wind speed;
2. module surface humidity modeled by module and ambient temperatures and humidity;
3. UV radiation modeled from solar irradiation and spectral transmittance of laminated materials;
4. temperature cycles of module temperature;
5. leakage current as a function of voltage, module temperature, and surface humidity; and
6. salt concentration correlated with wetting/drying.

He then models the module temperature for each module type using one-year outdoor data for module temperature, solar radiation, ambient temperature, wind velocity, and solar radiation to determine module-dependent parameters followed by leakage current as a function of potential, relative humidity, and temperature.

Köhl's third step is to model the degradation processes as a function of the degradation factor using various time-transformation functions (Köhl, 2001a):

1. module temperature: Arrhenius, Eyring models;
2. module surface humidity impact: power law, time-of-wetness;
3. UV radiation: dose function, reciprocity effect;
4. module temperature cycles: Coffin-Manson;
5. potential induced degradation; and
6. salt concentration correlated with wet/dry cycles.

In step four, he determines the accelerated life test conditions, such as test time at 85°C calculated as necessary to produce the equivalent damage, based on activation energies, for the various modeled climates and module types. This is repeated for other stresses such as UV exposure, humidity, etc.

Step five involves accelerated testing (e.g. 85°C/85% RH damp heat), using various commercial modules (c-Si were used in his study) comparing power output. From this he estimates equivalent testing times necessary to achieve 25 years in various climates to determine the climate suitability of the individual modules. However, note that acceleration factors are valid only for a specific module design, material set, and evaluation criteria.

Next Köhl uses analytical tools such as Raman spectroscopy and electroluminescence to characterize the degradation followed by numerical simulation of materials degradation, such as water vapor permeation and diffusion in the backsheet and encapsulant during the accelerated tests. Lastly, various combined multiple stress tests (within the given limits of equipment technology, capacity, etc.) are performed with the intent of iterative improvements in design. This approach comes closer to key aspects of true service life prediction methodology, but still requires many assumptions, mathematical models, and performance degradation measurements over time until failure. Further, many real-world stresses such as dynamic mechanical (i.e., wind) load and other variables have not yet been included. Still, by using accepted models for key environmental stresses, basing test parameters on actual climate and module measurements, and moving toward more realistic dynamic multiple stress tests with results verified by outdoor testing, improved module durability estimates should be achieved.

RECOMMENDATIONS FOR TEST VALIDATION

Key Requirements

To advance beyond the current situation and develop PV methods and standards leading to a comprehensive PV reliability framework that serves the needs of the stakeholders and helps ensure the viability of the industry, the community needs to work together to share knowledge and systematically develop a comprehensive approach. This effort must be made without regard to the short-term logistics of funding, implementation, or geopolitical concerns. Once identified, the individual elements of such a framework (many of which are already now being performed) can be coordinated. A roadmap can be developed and efforts directed towards a common goal. This will require several key actions:

1. Accelerated test development (in standards) must be driven by correlation with field observations. Field data must be continuously collected, analyzed, and prioritized so as to focus resources where they can make the most difference. Specific details that need to be quantified and understood include but are not limited to:
   i. intrinsic module issues that are not being detected with current tests;
   ii. environmental stress effects resulting from various climates;
   iii. system service use conditions (e.g., string size, inverter technology);
   iv. module transportation damage;
   v. module installation effects (mounting, wiring, handling); and
   vi. operation and maintenance effects (module washing, re-cabling, off-line strings).

   These need to be categorized not only by type, age, and location, but also by relevant module characteristics (e.g., semiconductor technology, number and type of cells/strings, mounting configuration, cell interconnect method, encapsulant and backsheet type, power and electrical characteristics, etc.).

2. Tackling each identified failure/degradation mechanism according to how it has been prioritized in step #1, we must thoroughly understand the cause and the related stresses and use modeling based on those to estimate the testing that provides confidence that the mechanism is adequately mitigated. The common approach of simply extending the time of tests should be based on correlation with field observations and/or physics-based models. New tests that can achieve higher acceleration factors without introducing larger uncertainty in the meaning of the tests should be developed whenever possible. However, the key goal is to develop tests that can reduce the uncertainty, regardless of test time.

3. The critical climatic service environments of concern need to be accurately identified and characterized as a key input to the modeling in #2. Secondly, most modules are not standalone; the modeling done in #2 should include system-related stresses (e.g., system electrical characteristics) that can easily be neglected during module-level testing. These may or may not be adequately represented in existing tests, or may lead to combined or new tests. Including the variable stresses seen in each use environment (e.g., climate, mounting configuration, and system design) is an important step should industry wish to develop suitability ratings for specific climates or performance ratings for modules. This may result in lower module cost if modules are designed to perform in specific markets rather than the worldwide approach used for most products today.

4. Once items (2) and (3) are accomplished and implemented into test standards for the prioritized failure mechanisms, the effects of the individual climate parameters, their levels, combinations, and cycles can be investigated by tracking field results relative to the new test results. These results will serve as a continuing framework as new module materials, technologies, and designs are developed. The current lack of consistent correlation between accelerated testing and field observations slows the validation and refinement of testing procedures.
5. A systematic set of experiments to correlate accelerated and field testing of module designs that are known to be both robust and flawed could be implemented through the DOE regional test centers and/or other test laboratories to hasten the development and validation of improved test methods. The results from these tests can continue to feed the work above as all failure mechanisms are tackled.
6. In parallel with the above steps, mathematical models should be developed relating degradation rates and field failures to accelerated testing. Models must be validated against actual field performance. Further, the results of accelerated testing can then be modeled to climate stresses to estimate service life. With comprehensive models, it may be possible to estimate how changes in module materials or design may impact performance, durability, and reliability.

Short-Term Needs and Recommendations

A critical concern within the industry relates to module manufacturing QA as an ongoing process. Will changes in materials vendors or specifications, manufacturing lines or process affect product quality or performance? The first step we need to take addresses manufacturing variability to assure stakeholders that production modules are of the same quality as those from qualification testing. Current qualification testing goes a long way to providing durable products if consistently implemented. The PV-specific version of the ISO 9000 series that is being submitted for consideration by IEC TC82 WG2 is a first start. The community should discuss how this can best be implemented and whether there is a conflict of interest in audits paid for by the factory compared with audits paid for by a coalition of customers or other community organization. Models exist in other industries; one example is the Good Manufacturing Practice system used in the pharmaceutical industry (WHO, 2007).

The second step is to systematically identify those accelerated stresses that have demonstrated some degree of predictive ability, many of which are implemented in the schemes detailed in this document, to better assess module long-term durability and performance. Their use should be promoted on a voluntary basis. This will serve as a relative comparison basis until full consensus standards can be developed.

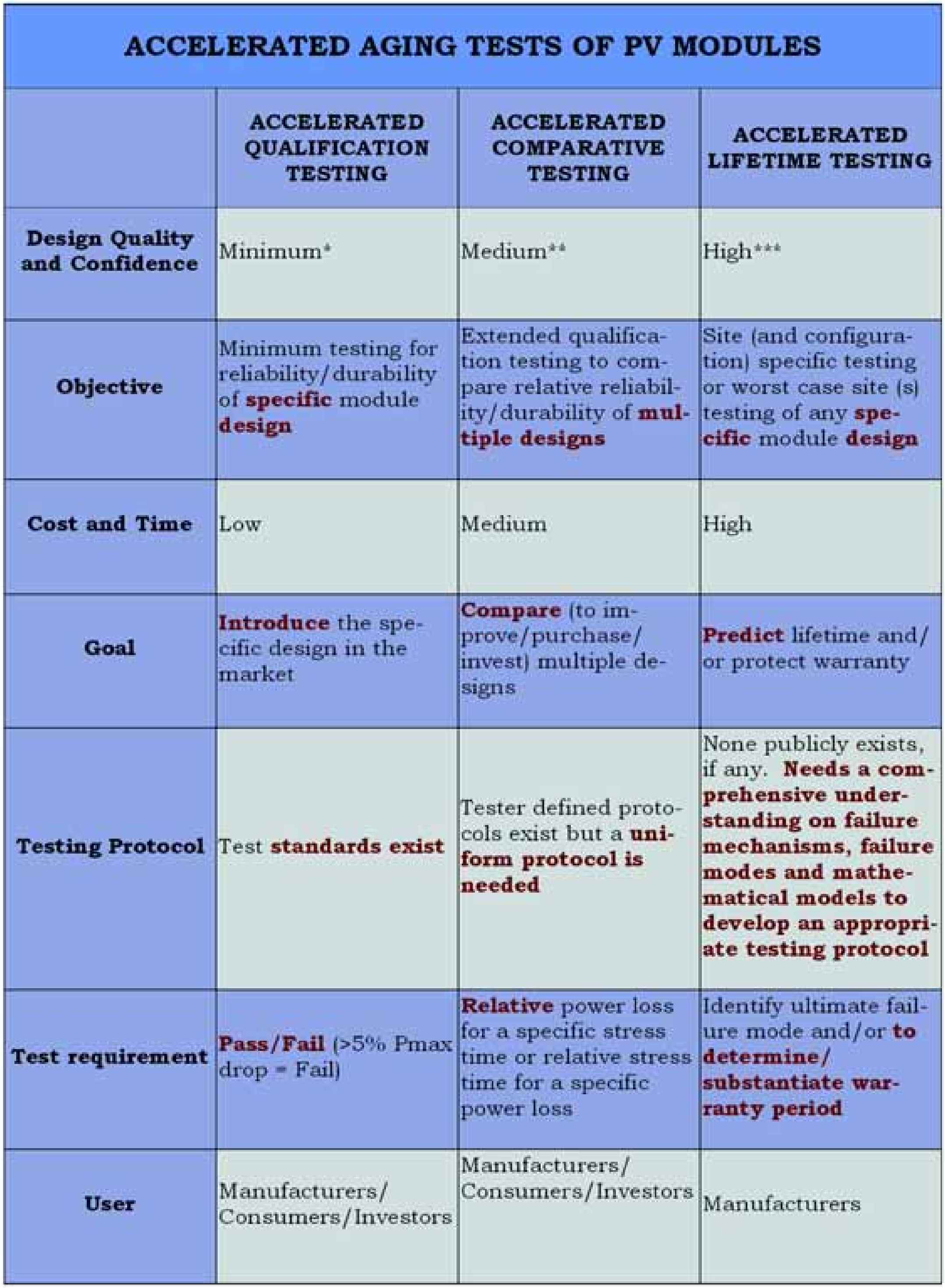
The IPVMQATF is currently the only overarching short-term global effort underway to support recommended steps 1-6, so the third step is to actively support and participate in the Task Force and its working groups (Solar ABCs, 2013).

SUMMARY

The current level of IEC design type qualification tests has served reasonably well as a basic screen for key early failure issues over the past 30 years. Extending specific tests may be effective in providing longer term wear-out and end-of life estimations. In their present form, these tests have generally proven insufficient, however, to predict either long-term service durability or lifetime. Further, current tests may not adequately detect some degradation mechanisms, particularly those that are longer term or climate-specific.

This has resulted in an effort to improve standard qualification testing to better predict long-term performance, durability, and reliability. Currently, the most common approaches are to (1) modify or extend existing IEC tests; (2) combine IEC tests in new combinations, cycles, or sequences; (3) augment IEC tests with multi-stress accelerated weathering tests on modules or materials; (4) add specific tests such as potential induced degradation to the current or "extended" IEC tests; (5) perform extended outdoor exposures in demonstration projects; and (6) move beyond existing IEC tests to a service life prediction methodology. Each level involves a different degree of knowledge and sophistication, time and effort, and cost. These must be balanced with scientific validity, rapid technology changes, and the ever changing market conditions and needs of the various stakeholders.

TamizhMani (TamizhMani, 2010; TamizhMani, 2009) describes three levels of testing (Figure 29) for PV modules: (1) current accelerated qualification tests, (2) accelerated comparative testing, and (3) true accelerated lifetime tests. Currently, the industry is at the first level of testing and standards and attempting to move to the second. The third is currently beyond the state of the art in the industry, although incremental progress is being made.



ACCELERATED AGING TESTS OF PV MODULES			
	ACCELERATED QUALIFICATION TESTING	ACCELERATED COMPARATIVE TESTING	ACCELERATED LIFETIME TESTING
Design Quality and Confidence	Minimum*	Medium**	High***
Objective	Minimum testing for reliability/durability of **specific** module **design**	Extended qualification testing to compare relative reliability/durability of **multiple designs**	Site (and configuration) specific testing or worst case site (s) testing of any **specific** module **design**
Cost and Time	Low	Medium	High
Goal	**Introduce** the specific design in the market	**Compare** (to improve/purchase/invest) multiple designs	**Predict** lifetime and/or protect warranty
Testing Protocol	Test **standards exist**	Tester defined protocols exist but a **uniform protocol is needed**	None publicly exists, if any. **Needs a comprehensive understanding on failure mechanisms, failure modes and mathematical models to develop an appropriate testing protocol**
Test requirement	**Pass/Fail** (>5% Pmax drop = Fail)	**Relative** power loss for a specific stress time or relative stress time for a specific power loss	Identify ultimate failure mode and/or **to determine/substantiate warranty period**
User	Manufacturers/ Consumers/Investors	Manufacturers/ Consumers/Investors	Manufacturers

Figure 29. Three distinct levels of accelerated PV module accelerated testing (TamizhMani, 2010).

Several efforts are underway to push testing to the second level as described above, but the results of these efforts cannot be predicted at this time. However, it is important that these efforts are productive, meaning that they produce tests and knowledge that advance the industry and serve the needs of stakeholders. However, the current semi-empirical approach is suboptimal in efficiency, and is not always rigorously validated.

The development of such tests requires understanding the science behind the observed failure modes. Existing initial qualification tests are insufficient to assure durability and reliability. As DeGraaff (DeGraaff, 2011) notes, the ". . . majority of failures can be attributed to inadequate manufacturing QA and/or not testing when materials or processes are changed." Therefore, retest requirements may need to be imposed whenever a material or design fundamentally changes, and requirements for ongoing manufacturing quality assurance will need to follow.

The experience of other industries and scientific research has resulted in a proven service life prediction methodology. Although technically difficult to implement on a large multi-component laminate structure that must last 25 years or more with little or no degradation or catastrophic premature failure or safety concerns in many different and severe climates, the effort is likely to result in improved market competiveness for PV. Such an effort would require extensive coordination, participation, and support from PV manufacturers, academia, national and other research laboratories, testing facilities, and other stakeholders. This requires a multi-step approach:

1. Establish a consolidated database of module degradation and field failures.
2. Conduct systematic review of module degradation and failure modes.
3. Characterize the key climatic service and system environmental variables.
4. Implement design of experiment to determine stress-failure interactions.
5. Execute real time testing exposures in various climates with key module technologies.
6. Establish models and transfer functions for service exposures and accelerated lab testing.
7. Establish an ongoing manufacturing quality assurance audit program.

Given market economics and other conditions, this comprehensive approach may be unlikely in the foreseeable future. However, many efforts currently underway could be more closely coordinated and aligned to support the key elements of this approach, yielding substantial improvements in the short term even if the full approach is beyond reach.

Alternatively, a more expedient short-term approach is the development of comparative module data. This approach is gaining some traction as a competitive tool, but to be effective industry-wide, it needs to be expanded, even if on a voluntary basis. This may be possible through standards requiring module manufacturers to report hard data rather than using a generic pass/fail approach. Some module manufacturers and buyers already advocate hard data reporting, and this may serve industry needs while a true SLP methodology is implemented over the next few decades.

Thirty years from now, we can go into the field and collect statistics to convert the comparative test standard data into a more quantitative SLP. There would likely be wide variation in the data, but if the methodology applies stresses that are relevant to the use environment, it should be possible to use those results to make statistical predictions about how long modules will last in each location as a function of the comparative test results.

The practice of effectively using a test standard as the basis of a worldwide experiment could be practical. This may be a way to accomplish "extensive coordination" without the huge budget required to have researchers execute a similar project. Similar to distinguishing "reliability" from "durability" testing, moving studies out of carefully controlled test fields and turning the whole world into a laboratory may be way to finally answer the question "How long will my module last?" and connect with the real needs of the customer.

ACRONYMS

a-Si	amorphous silicon
AC	alternating current
ALT	accelerated life testing
c-Si	monocrystalline silicon
DC	direct current
DOE	U.S. Department of Energy
DH	damp heat
EC	European Commission
EL	electroluminescence
EVA	ethylene vinyl acetate
HF	humidity freeze
Hipot	high potential
IEC	International Electrotechnical Commission
IPVMQATF	International PV Module Quality Assurance Task Force
IQT	interim qualification test
IR	infrared
IV	current-voltage
JPL	Jet Propulsion Laboratory
JRC	EC's Joint Research Centre
LID	light-induced degradation
LST	long-term sequential test
MPP	maximum power point
NREL	National Renewable Energy Laboratory
Pa	Pascal
PID	potential induced degradation
PV	photovoltaic
PVDI	Photovoltaic Durability Initiative
QA	quality assurance
RH	relative humidity
SERI	Solar Energy Research Institute
Si	silicon
SLP	service life prediction
TCO	transparent conducting oxide
TC	thermal cycles
TTF	test to failure
UV	ultraviolet
WG	working group

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