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Research

History of Accelerated and Qualification Testing of Terrestrial Photovoltaic Modules: A Literature Review

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We review published literature from 1975 to the present for accelerated stress testing of flat-plate terrestrial photovoltaic (PV) modules. An important facet of this subject is the standard module test sequences that have been adopted by national and international standards organizations, especially those of the International Electrotechnical Commission (IEC). The intent and history of these qualification tests, provided in this review, shows that standard module qualification test results cannot be used to obtain or infer a product lifetime. Closely related subjects also discussed include: other limitations of qualification testing, definitions of module lifetime, module product certification, and accelerated life testing. Copyright © 2008 John Wiley & Sons, Ltd.

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INTRODUCTION

From the early days of photovoltaics (PV) following the invention of the silicon solar cell at Bell Laboratories[1] and since silicon solar cells were first soldered together into series strings to produce power from sunlight,[2] two key questions have been: how long will these string assemblies, now called modules, deliver useful power? And can accelerated testing can provide this information? Over the past 30-plus years, much research and testing has been done on PV reliability by government laboratories, third-party laboratories, and PV manufacturers. This work has resulted in the development of standardized module testing sequences commonly called qualification or type-approval tests. These sequences are relatively short in duration, about 3–4 months, and include tests such as accelerated temperature and humidity stresses inside climatic environmental chambers. Adoption of the sequences as national and international standards has led to their widespread use as the final hurdle in product development.

In 2006, electrical arcing and fires inside module junction boxes caused failures in a number of PV systems; these failures were reported in the trade magazine *PHOTON International*.[3] The modules in question were produced by a reputable PV manufacturer with over 30 years of experience, and had passed all of the standard qualification and safety tests. Later reports indicated that the problem was not restricted to this manufacturer.[4] An obvious question is then: how could these failures have occurred after all of this careful design and testing? Subsequent investigations appeared to indicate the arcing was

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the result of an inadequate manual soldering step during manufacturing. Because the flaw was unknown prior to the occurrences of the junction-box fires, the qualification tests were not designed to test for susceptibility to the problem. Therefore, these standard tests cannot be expected to catch all module problems.

The objective of this paper is to document how these qualification tests have evolved over time by presenting a roughly chronological literature review, and thereby showing that the individual elements are designed to stress modules in ways that uncover susceptibility to known failure mechanisms. The review will also include the numerous accelerated tests that have been applied to PV modules. To these ends, it will be helpful to first discuss some major terms that are commonly used and associated with PV.

Although the history attempts to summarize major points and conclusions, it cannot be a substitute for reading and studying the reviewed publications. With more than 170 references here, much information has been omitted of necessity.

Qualification testing of concentrator modules is a complex subject with very different issues and was therefore judged to be beyond the scope of this review.

Modules

A PV module can be defined as a collection of individual solar cells integrated into a package that protects them from the environment in which the module is installed for a long period of time. Modules must be manufactured as inexpensively as possible because their price is a significant portion of the cost of electricity generated by a system, yet they must be capable of operating in many climates such as maritime tropical, high-temperature, high-irradiance deserts, and dirty urban rooftops. The solar cells must be protected from degradation caused by stresses and effects such as:

- Corrosion of materials, especially metals
- Water-vapor intrusion
- Delamination of encapsulant materials, especially polymers
- Physical damage from wind, hail, and installation
- Thermal excursions, including coefficient of thermal expansion mismatches
- Ultraviolet (UV) radiation
- Deterioration of or damage to external components such as junction boxes, wiring, and frames.

Because of the imperative to minimize module cost, the degree of protection from these effects must necessarily be imperfect, and a design trade-off between cost and protection exists. Typically, the costs of the materials used for protecting the internal solar calls (packaging costs) are roughly 50% of the total materials cost.

Module designs continue to evolve and change, which presents continuing challenges to testing procedures. Crystalline-Si (x-Si) cells are becoming thinner and thinner, new thin-film devices with exotic materials are being developed, and building-integrated PV (BIPV) is challenging ideas about what constitutes a module.[5] Devising adequate qualification tests that may be needed to stress new failure mechanisms in these products requires on-going research with real-time outdoor testing to discover the mechanisms, and indoor accelerated testing to simulate them.

Qualification testing

Since the late 1970s, there have been a number of PV qualification test sequences, first published by government laboratories and then later by national and international standards organizations, intended to gauge the ability of module designs to protect solar cells from the environment. Each in succession has built on previous tests as new information is learned, and the older tests are made obsolete. As the PV industry has grown and become an international commodity market, the International Electrotechnical Commission (IEC) test standards[6] are now the only tests accepted by both module manufacturers and buyers.

Hoffman and Ross[7] defined the purpose of qualification testing as being a means of rapidly detecting the presence of known failure or degradation modes in the intended environment(s). It also provides ''rapid feedback of the relative strengths and acceptabilities of design alternatives'' during product development.

The test sequences are relatively short in duration, a few months, and are separated into several ''legs'' performed on different modules that can be done in parallel. At the end of the sequences, test modules must retain a specified percentage of their initial output power in order to be judged as having passed the qualification. Figure 1 shows an example of a

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typical module qualification sequence organized with legs containing major tests such as UV exposure, thermal cycling (TC), humidity-freeze (HF) cycling, damp-heat (DH) exposure, and outdoor exposure (OE).

It is quite difficult or impossible to equate these stresses with those experienced by a module operating in the field as part of a PV system on a quantitative basis. Nevertheless, some segments of the PV industry desire relatively short testing regimens that can provide a numeric value for the lifetime of a module or system, or that implies or provides confidence that a system will last at least a minimum number of years. Regardless of these desires, the standard sequences are not intended to be life tests.

Another limitation of the qualification tests is that they are performed on a very small number of modules, typically less than 10. When compared with the thousands of modules that a single PV production line can produce in a year, this is a statistically insignificant number, and passing a qualification sequence cannot be used to infer that all production modules will pass. However, the converse is not true—a failure of even one module during a qualification test is significant and the module design should be investigated and corrected.

Module lifetime

The lifetime of a PV module can be defined as a point in time when the module is no longer acceptable for any reason such as safety, appearance, a catastrophic event, or when the output power has fallen below a minimum acceptable value. This latter criterion, power degradation, makes a formal definition of module lifetime difficult to quantify. For a manufacturer, the lifetime will be the number of years for which the module is guaranteed with an output power above a certain value, such as 80% of the initial power (called the ''degradation limit'' below).[8] At the end of this warranty period, a module is past its useful lifetime because it no longer is a financial liability.

To the user of a module, the situation is much less clear, and it is probable that most PV system owners have no set criteria for deciding when a module is no longer serving its purpose. Without careful measurements of the direct current (DC) output of a system, tracking the performance over time is quite difficult or impossible for many users. In addition, many

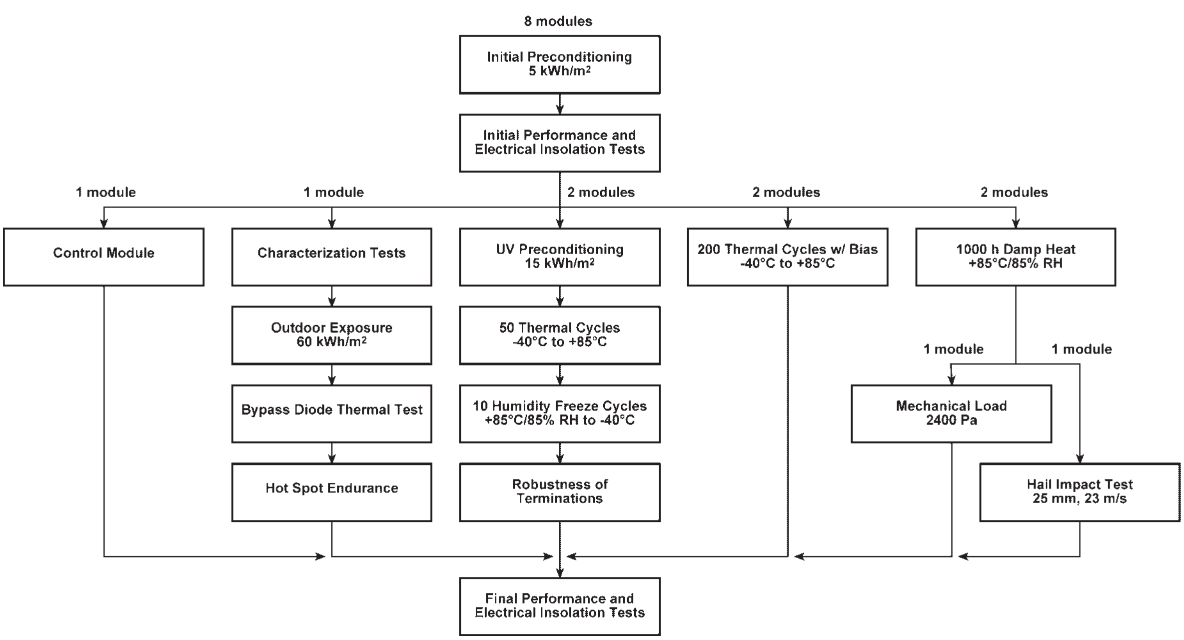

Figure 1. Typical qualification testing sequence for crystalline-Si modules (adapted from IEC 61215 2nd edition, Figure 1).[158] Test modules must retain a specified percentage of their initial output power to pass, in addition to other requirements

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applications may have criteria for usability that are very different from the manufacturer's warranty.

Important issues with module lifetime are discussed by McMahon *et al*.,[9] who believed that it is impossible to provide a 30-year lifetime certification for any given module based on a single test. While presenting the conflicting viewpoints of manufacturers and users, Schlumberger[10] wrote in *PHOTON International* that "...experts can't even agree on what constitutes the end of a module's product life." Note that it is impossible to state what the lifetime of a module is without a formal definition of the end-of-life.

Continuous measurements of performance have shown that degradation of output power in PV modules and systems tends to be linear with time, especially for periods of several years and longer.[11] If the degradation rate is known and remains linear for the entire life, a straightforward calculation can predict the lifetime if the degradation limit is known

$$t_L = \frac{100\% - L_D}{R_D} \qquad (1)$$

where t_L is the lifetime in years, R_D the degradation rate in percent per year, and L_D the degradation limit in percent. Figure 2 illustrates this calculation for two

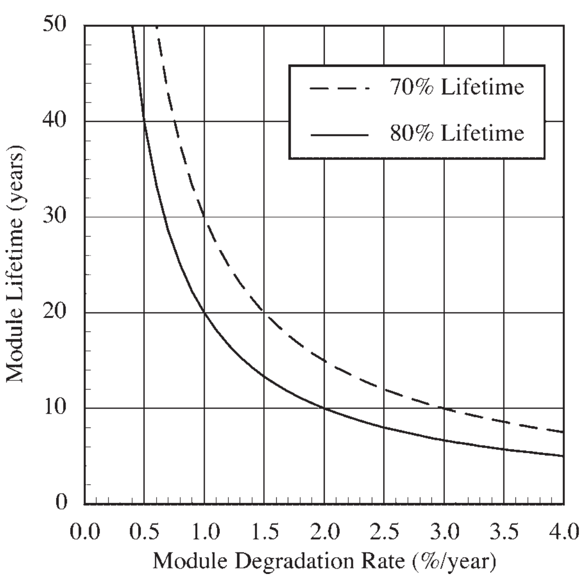

Figure 2. Module lifetime versus degradation rate for two values of module degradation end-of-life definitions, assuming linear degradation for the entire life of the module. This calculation also applies to PV systems with similar behavior

degradation limits, 70 and 80%. Notice that at the slower rates of power loss, the lifetime is a strong function of the degradation limit.

Lifetime and warranty issues were recently discussed in a paper by Vázquez and Rey-Stolle[12] in the context of a proposed numerical reliability model for PV modules that is based on slow degradation. They concluded that R_D must be less than 0·5% per year for any module with a 25-year warranty.

Certification

The word *certification* has a much different meaning inside the PV industry compared to many other industries with manufactured products. The standard definition of a certified product is one that has been approved through a *third-party certification* program, which includes elements such as third-party testing, random selection of product for testing, evaluation of the factory and the product design, periodic retests, and the issuance of a license to apply the certification program's *certification mark* to the product.[13–16] Examples of third-party certification marks in the PV industry include the Underwriters Laboratories (UL) mark for PV module safety,[17] and the Global Approval Program for Photovoltaics (PV GAP) certification mark.[15,18] PV GAP operates under the Worldwide System for Conformity Testing and Certification of Electrotechnical Equipment and Components (IECEE)[19] of the IEC.

However, in the common language of the PV industry, a "certified" module has come to refer to one that has merely passed a standard qualification sequence, and the test report generated by a laboratory is called a "certification." Phrases such as "IEC certificate" or "IEC certification" are also used.[20–23] Module labels attached by manufacturers use phrases such as "IEC 61215 Certified." This usage is misleading and incorrect for two reasons: (1) the IEC itself does not certify any products; rather, it is a standards organization responsible for publishing and maintaining test procedures[6] and (2) there was no license issued by a certification body.

A serious flaw with identifying a test report as a certification is that the product quality requirements normally enforced by an outside agency are missing. A manufacturer is free to make changes to a module, such as changing the supplier of the encapsulation material, and still claim that the module is "certified." It is not difficult to imagine scenarios in which such manu-

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facturing changes could adversely affect the lifetime of a PV module.

Accelerated life testing

One example of an accelerated life test is to apply stress to a test sample until failure.[24,25] Note the difference here from that of qualification testing, which applies stress for only a prescribed and limited duration. Hoffman and Ross emphasized that, unlike qualification tests, reliability and life-prediction tests must be designed ''to provide quantitative information on mean-time-between-failures [MTBFs] or lifetimes.''[7] In a tutorial on PV qualification testing, Wohlgemuth[26] reiterated this distinction by stating that ''qualification testing does not provide a prediction of product lifetime.''

For PV, there are only a limited number of use and stress factors that can be accelerated, namely: illumination duty cycle, total irradiance, UV irradiance, temperature, humidity, or combinations of these factors. However, applying stresses to modules that result in temperatures higher than about 90°C can result in damage to materials that may never occur in actual use, and temperature cannot easily be used as an acceleration factor for thin-film devices because output power can increase and decrease as a result of previous thermal and illumination states. PV acceleration factors for temperature and humidity have proven to be quite unwieldy to determine, and little is published on the subject (the Jet Propulsion Laboratory [JPL] work in this area will be outlined below). For accelerated UV irradiance, if the applied UV spectral irradiance contains significant numbers of high-energy photons that are not present in terrestrial sunlight, unrelated damage may be induced.

One practical accelerated life test for PV could be continuous light-soaking (100% duty cycle) without elevated irradiance (continuous light-soaking has been used extensively for a-Si initial light-induced degradation determinations).[27,28] Such a test can be directly correlated with real-time exposure using the average daily irradiance profiles from a target site; this results in acceleration factors in the range of 3× to 5×, depending on the geographical location.

Another approach is to use the standard qualification stress tests, but extend them until failure of the test modules, known as test-to-failure (TTF). BP Solar has employed this technique as part of an overall module reliability program, primarily with TC.[25] Such tests can provide qualitative information about ultimate failure modes, but do not provide numeric lifetime data.

MODULE QUALIFICATION AND ACCELERATED TESTING: HISTORY AND LITERATURE REVIEW

The review is approximately chronological, and is divided into sections 5 years in length. Year 1975 was selected as the starting point of the history, even though module technology began at Bell Laboratories in the mid-1950s. Prior to 1975, the literature is nearly silent on module stress testing, and terrestrial modules were low power (Green authored a review in 2005 that documents the history of x-Si module technology).[2] Publications on related subjects such as cell lifetime or materials testing are included, especially if they have a bearing on the development of the standard tests.

As will be seen, two bodies of work are especially important. The first is the Flat-Plate Solar Array Project (FSA) at JPL (the program had several titles, including the Low-Cost Silicon Solar Array Project, the Low-Cost Solar Array Project, as well as the FSA Project). The second is that of the Joint Research Center (JRC) of the European Commission, Ispra, Italy (also known as the European Solar Test Installation, ESTI); JRC has been very active in both developing and applying the standard qualification sequences. The Solar Energy Research Institute (SERI, later the National Renewable Energy Laboratory, NREL) held a series of workshops over the 1985–1999 period on PV performance and reliability where advancements in module testing were presented.

One element of module qualification are the hot-spot (HS) endurance tests, which are intended to determine if a module design is protected from excessive and destructive heating caused by cells forced to dissipate power in reverse bias. Although the tests are documented here, they are too complex to be described in any detail.

A potential source of confusion about the IEC standards is that in 1997 the number 60 000 was added to all the designation numbers. Thus, IEC 1215 became IEC 61215, although the two designations refer to the same document.

Finally, a shorthand notation for temperature–humidity conditions is used: 85/65 DH indicates a stress level of 85°C module temperature and 65% relative humidity.

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1975–1979

Serious development of terrestrial PV modules in the United States began in the mid-1970s under the sponsorship of the US Energy Research and Development Agency (ERDA),[29] which later became a part of the US Department of Energy (DOE). Because of its experience with spacecraft PV power systems, the National Aeronautics and Space Administration (NASA) had key roles through two of its laboratories: JPL in Pasadena, California, and the Lewis Research Center (LeRC) in Cleveland, Ohio.[30] JPL had responsibility for the FSA project.[31,32] LeRC developed the first terrestrial PV performance measurement techniques and operated an OE program at a number of sites.[33]

The FSA project was organized as a series of purchases of PV modules from manufacturers, designated as Block I through Block V (Block VI was planned, but not executed).[31,34] To qualify for one of the block procurements, manufacturers had to build modules that met the specification document, including a series of prescribed tests. Thus, the JPL specifications were the first qualification tests implemented for terrestrial PV. Purchased modules were transferred to LeRC, the Massachusetts Institute of Technology's Lincoln Laboratory, Wyle Laboratories (Huntsville, Alabama), and Clemson University for further testing with real-time OE[35] and parametric temperature–humidity testing.[36] A highlight of the FSA project was the development of ethylene vinyl acetate (EVA) as a replacement for silicones and polyvinyl butyral (PVB) encapsulants.[31,37–39]

The qualification test elements used in the FSA project changed considerably over Blocks I–V;[7,34] these elements included temperature cycling, humidity cycling, cyclic pressure loading, warped mounting surface (later called the twist test), hot spot endurance, hail impact, and electrical isolation. The testing for Block I consisted of just 100 thermal cycles and 7 days of humidity stress (70/90 DH).

The Hoffman and Ross article discussed how the upper and lower temperature limits (+90°C and −40°C), thermal ramp rate limit (100°C/h maximum), and number of cycles were selected.[7] The purpose of TC was to represent stress due to diurnal and climatic temperature excursions.

The humidity test used with the early procurements (II, III) changed from the short 70/90 DH exposure test in Block I to a cyclic test selected from existing military and space test specifications, and consisted of five 1-day cycles from +23 to +40·5°C cell temperature at 90–95% RH. Humidity testing was used to eliminate metal delamination of Ag–Ti contacts in space solar cells.[7]

All of the tests were performed sequentially; thus, the tests effectively consisted of only one leg as defined in the "Qualification Testing" section above. The complete qualification tests for Blocks II and III and development of the cyclic-load test were documented in several JPL internal reports.[40–42] Block IV was initiated in 1978.[31]

Using feedback from outdoor testing, Hoffman and Ross identified several degradation modes, and described some exploratory tests intended to replicate them: soiling, encapsulant delamination, ion migration, and galvanic corrosion.[7] Migration and corrosion were observed with voltage-biased humidity exposure, although these were of a different nature from that seen in modules exposed outdoors. Voltage bias detected problems that were not detected by other tests, and JPL wanted to add this requirement to Block VI.

Two JPL papers at the 1978 Washington, DC, IEEE PV Specialists Conference discussed possible and observed module failure modes, and analysis techniques used to study these problems.[43,44] Failures noted included open cell interconnects, cracked cells, delamination, dielectric breakdown, and corrosion. A subsequent 1981 JPL paper presented a summary of the field test results from Blocks I–III.[45] The failures listed were similar and included some specific observations of corrosion.

1980–1984

An early JRC paper in 1980 outlined the two tasks assigned to the Ispra Establishment, namely development of performance measurements on solar cells and modules and qualification testing of modules.[46] These procedures were developed through a European Working Group on PV Testing, and the qualification test procedures were called CEC Specification No. 201. This document was indicated as being a "final version in preparation," although few details of the testing sequence were provided. A one-paragraph outline listed the tests contained in CEC 201, which were:

- Hail impact
- UV exposure
- Wind pressure
- Temperature cycling: −40 to +85°C

DOI: 10.1002/pip

- "Smog"
- Humidity cycling: 20/10 DH–40/100 DH
- Thermal degradation, including shocks with cold-water spray.

A presentation at the 1980 EC conference in Cannes, France, by Desombre outlined a reliability study on PV modules and tried to show how lifetimes might be determined from acceleration factors of failure mechanisms.[47] Two models were discussed; the first was the Arrhenius relationship of absolute temperature and an activation energy. The second was an empirical function of the sum of two terms, the temperature in °C and the relative humidity in percent. A graph showed "time to contact corrosion" using this empirical function, but it is not clear from the text if the points on the graph were experimental data or not. Two test conditions were indicated on the graph: 55/95 DH and 85/85 DH. Later, the Desombre empirical temperature-plus-humidity acceleration model was used in the JPL corrosion model (see below).

The specifications and testing requirements for the last FSA procurement, Block V, were published in 1981 and became the *de facto* standard for module quality[48] and module safety[49,50] in the United States. The term "passed Block V" was commonly used to indicate that a module design had been subjected to and passed the JPL tests.

The Block V test sequence contained two legs: one with 200 thermal cycles, and the other required 50 thermal cycles, 10 HF cycles, 10 000 dynamic load cycles,[42] the twist test, and the hail impact test. Along with the longer TC leg, the Block V specification changed the temperature limits of the former "humidity" test in earlier specifications to the −40 to +85°C HF cycling test. Module performance degradation that resulted from the testing could not exceed 5%, and the specification included requirements for visual changes and electrical isolation. The leakage current during a 1-min electrical isolation ("hi-pot") test at ±3000 V between the shorted leads and the module grounding point could not exceed 50 μA. Qualification test results from Block V were published in 1982,[51] and an overview of the module development and test results were published in 1985.[52]

A HS endurance test that was included in the Block V specification was documented in a 1981 paper.[53] The complicated 100-h cyclic procedure consisted of selecting a number of individual cells based on their reverse bias *I–V* characteristics to be subjected to heating from infrared illumination, visible illumination, and a voltage bias.

Under subcontract to JPL, UL developed a recommendation for a module safety standard that was published in two parts, and was used for the Block V purchases.[49,50] The JPL interim safety standard was the first to use the $2 \times V_S + 1000$ dielectric voltage withstand test level specification, where V_S is the module maximum system voltage rating.

Year 1981 also saw the publication of the first European qualification test sequence, CEC Specification 501.[54] These tests were quite different from those indicated earlier for CEC 201.[46] CEC 501 used a twist test, nominal operating cell temperature (NOCT) determination, and hail test very similar to the JPL tests, and included several figures from the Block V specification. It also had a degradation limit requirement of 5%. Other tests included:

- Temperature cycling: –40 to +40°C + NOCT, 50 cycles
- Humidity-freezing: 40/93 DH for 48 h, then –40°C for 1 h, 1 cycle
- Mechanical load: 2400 Pa, and an optional 5400 Pa test for wind and snow
- DH long exposure: 40/93 DH, 720 h
- High-temperature long exposure: NOCT + 50°C, 2880 h
- UV exposure: NOCT + 30°C, 40 MJ/m^2
- Ozone test: 40°C, 55% RH, 120 h, 0·5 vpm O_3
- SO_2 test: 25°C, 75% RH, 120 h, 50 ppm SO_2
- Salt mist: 35°C, 96 h, 50 g NaCl/L
- Ice formation: +20 to –10°C with a water spray, 60 min
- HS heating: complex 1-h cyclic test repeated 50×.

Krebs published some experiences and results of applying the CEC 501 test in 1982,[55] and a subsequent 1983 paper[56] briefly reported results of the same tests, and stated that the test sequence had been modified as a consequence of testing experience. The new sequence had a block called "Temperature & Humidity Storage," and did not use the term damp heat. This terminology was included in the updated European qualification sequence, CEC 502, which was published the next year,[57] although the sequence in CEC 502 differed greatly from the JRC paper, and from CEC 501. An OE test was described for the first time, "outdoor pre-conditioning," and the atmospheric pollution-related tests were dropped, along with the 40/93 DH test. The "high-temperature storage" test

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consisted of 90°C for 20 days, while the ''high-temperature/high-humidity'' test required 20 days at 90/95 DH. The TC test in CEC 502 specified 10 cycles between –20 and +80°C. CEC 502 included a 1-h HS endurance test that was much simpler than the JPL test.[53] One cell was selected with infrared imaging while the test module was shorted and in 1-sun illumination; this cell was shadowed for 1 h.

The IEC established Technical Committee 82 (TC82) on Solar Photovoltaic Energy Systems in 1981, and gave oversight for international module-related standards to Working Group 2 (WG2), which included future module qualification standards.[58] Treble noted that such standards had to be an evolutionary process with improvements incorporated as experience is accumulated.

Ross published several considerations of predicting reliability or assuring lifetime of modules in this period.[59–61] A review of module degradation mechanisms concluded that a lack of known wearout mechanisms implies that module lifetimes in excess of 25 years is likely.[60] This paper mentioned that 85/85 DH is commonly used in the semiconductor industry and the PV cell-reliability testing at Clemson University. A description of the Clemson test program indicated that encapsulated cells were exposed to 85/85 DH and –40 to +100°C thermal cycles.[62]

The US Coast Guard developed a qualification test for modules intended to power offshore navigation aids.[63] The qualification consists of a pressure-immersion-temperature (PIT) cyclic test that simulates an environment where a module operating in full sunlight is quickly immersed to a depth of several meters in seawater as a result of wave action. The authors estimated the acceleration factor of the PIT test at 45:1.

Using the Desombre empirical acceleration model for temperature and humidity,[47] module indoor stress testing at several levels, and hourly weather data for the United States, Otth and Ross at JPL attempted to equate hours of damp heat testing with a 20-year module life at site-specific conditions,[64] and estimated 20 years exposure in Miami, Florida, is correlated with 144 h at 85/85 DH. This correlation was for just a single failure mechanism: galvanic or electrolytic corrosion of x-Si cells and metallization driven by the resistivity of polymeric encapsulants. An interesting aspect of this work was the use of color density measurements on photographs of stressed modules to determine degradation rates of the polymers.[36]

JPL published another study of electrochemical corrosion and metal migration in x-Si cells and modules in 1984 that included life predictions based on total charge transfer and hourly US weather data.[65] The paper ended with a discussion of water-vapor intrusion into modules with PVB and EVA encapsulants. Electrochemical degradation of a-Si modules was later performed with 85/85 DH exposure and a ±500 V bias between the frame and module leads while measuring leakage currents.[66] This accelerated test was able to duplicate corrosion and damage effects on a-Si modules that had been observed outdoors. An adjunct paper reported how temperature and humidity affects these leakage currents and included relevant data for PVB and EVA.[67]

1985–1989

In a review of the JPL Block programs, Smokler stated that several new qualification tests were proposed for the never-implemented Block VI program, including a UV exposure test, a bypass diode thermal test, and an electrochemical stress test at 85/85 DH and ±500 V.[31] Another JPL paper by Ross gave a review of the reliability testing lessons from the FSA project, and made recommendations for applying these to thin-film modules using qualification and laboratory stress testing, OE testing at both the module and system levels, and failure analyses.[68]

The first comprehensive safety standard for PV modules was published in 1986 by Underwriters Laboratories, UL 1703, and became the basis for UL's module listing and labeling program for safety in the United States.[17,69] The important difference between a safety test and a qualification test is that modules are not required to have any electrical output at the end of the stress testing; they only have to remain safe and not pose a hazard. UL 1703 is based largely on the earlier JPL Block V interim safety standard and includes the TC and HF tests.[50] It expanded the Block V HS test by defining ''intrusive'' (the JPL test) and ''non-instrusive'' options.

A 1986 paper by Chenlo *et al*. described the standard qualification sequence that was required for modules used in Spain, and outlined results from applying the sequence to 40 samples.[70] The sequence followed the CEC 501 Specification but without the HS, NOCT, atmospheric pollution, and high-temperature/high-humidity tests. The JPL Block V TC and HF tests were substituted, and the test included an indoor light-

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soak with illumination on both module surfaces for bifacial modules.

Treble wrote an update of the IEC TC82 standards development in 1986,[71] and stated that in the previous 2 years WG2 had been considering existing ''design qualification'' documents for inclusion in the future international qualification standard, and listed JPL Block V,[48] CEC Specifications 501 and 502,[54,57] and other national standards from Australia, France, and Japan (not referenced) as possible sources. A list of the tests identified included: HS endurance, robustness of terminations, mechanical loading, mounting twist, hail impact, TC, HF, DH, UV exposure, ''high-temperature storage'', salt-mist corrosion, and marine environment. At this time, it was hoped that several categories of environments would be included in the same standard.

JPL continued researching leakage currents and moisture ingress with respect to electrical isolation and electrochemical corrosion, especially for a-Si modules.[72–76] From this work, JPL proposed a corrosion susceptibility qualification test for a-Si modules using edge immersion into a surfactant solution while measuring the resistance at $\pm 500\ V_{DC}$ between the solution and the shorted module leads.[73] The test was intended to have a minimum resistance value, but it was undetermined in this description.

Cuddihy authored a JPL report that demonstrated how the empirical Desombre temperature and humidity acceleration model[47] can be derived from numerical PVB and EVA resistivity data using Taylor series expansions.[77]

At the 1986 SERI PV Thin-Film Module Testing Workshop, ECD/Sovonics showed results of light-soaking a-Si modules with metal-halide lamps to measure the initial light-induced degradation, and reported using a modified JPL Block V sequence that included an OE with ±1500 V bias.[78] UV weathering was used to stress different polymers needed for the top superstrates of these modules. The subsequent 1987 workshop had presentations from a number of thin-film manufacturers about module stress testing. Both Chronar[79] and Solarex[80] were using variations of the wet insulation resistance test pioneered by JPL, as well as wet hi-pot testing for determining susceptibility to a-Si corrosion.

In 1988, Solarex published recommendations for accelerating grid metalization corrosion in x-Si modules.[81] Using the previous JPL work,[36] this paper developed a model for relative humidity acceleration rates and compared the 90/95 DH condition against 85/85 DH. It was calculated that 135 h of exposure to 85/85 DH is equivalent to 20 years of 25/90 DH. The paper recommended 400 h of 85/85 DH for Solarex modules, and stated that DH on the order of 2000 h should be regarded as ''torture tests.''

Qualification testing of Solarex's a-Si modules was discussed by Carlson in 1988.[82] The list of tests used included the Block V tests plus a hot-water immersion test (40°C water while illuminated, 5 days) and 1 month of 85/85 DH. An electrochemical corrosion problem was corrected by switching from a metallic to a plastic frame.

Several papers at the 1988 EC conference in Florence, Italy, reported measuring initial light-induced degradation of a-Si modules with artificial light sources indoors while controlling module temperatures.[27,28,83]

Using the JPL work on insulation resistance, SERI in 1988 published a proposal for a qualification sequence intended for ''thin-film'' modules, which really meant a-Si modules.[84] The proposal was later published as the SERI Interim Qualification Tests, or IQT.[85] It included the JPL corrosion susceptibility wet resistance test with a 100 MΩ minimum to pass. A wet hi-pot test was also proposed using mist sprays of surfactant or with edge dipping. The IQT included the JPL intrusive HS test, but did not include DH. a-Si stabilization was characterized with a 400-h light-soak test. Other unique features of the IQT were a 20-cycle (3 cycles per day) HF test and a degradation limit of 10%; the wider limit was an allowance for the initial light-induced degradation of a-Si. A bypass diode thermal test was specified that required measurement of diode junction temperatures with the module operating in a fault condition of 1·25 times the short-circuit current (I_{sc}) at +40°C. Much of the final form of the IQT was shaped by presentations at the 1986 and 1987 SERI reliability workshops.[78–80]

Sumner reported on the performance of the world's largest PV system at the time, the ARCO (Atlantic-Richfield) Solar Carrisa Plains system in southern California, and stated that the efficiency declined about 20% during its fourth year of operation.[86] Modules in this system had a very pronounced browning of the encapsulation over the Si solar cells, which naturally led to concerns about the suitability of EVA. Sumner linked the power losses with the browning and stated the cause as thermal oxidation of EVA caused by higher operating temperatures due to the two-axis mirror concentration (this conclusion was later disputed by additional data). Photothermal degradation

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of EVA became an active research topic for at least the next 5–6 years.

The status of the draft IEC international qualification standard for x-Si modules, including a diagram of the test sequence, was presented by Wohlgemuth and Klein in 1988[87] and by Treble in 1989.[88] Treble stated that no accelerated environmental test in the laboratory can guarantee a lifetime, but also said the standard was to be "...aimed at a lifetime of over 20 years in general open-air climates, as defined in IEC 721-2-1."[89] The earlier goals for applicability to marine and equatorial climates were dropped. The sequence was organized around four legs with the following major tests:

- 60 kWh/m^2 (216 MJ/m^2) OE and HS endurance
- 15 kWh/m^2 (54 MJ/m^2) UV exposure, 50 TC, and 10 HF
- 200 TC
- 1000 h of 85/85 DH.

These legs were a combination of the JPL Block V and CEC Specification 502 tests. One notable change to the Block V tests was the reduction of the high-temperature limit of the thermal cycle from 90 to 85°C out of concerns about the melting points of common module encapsulants, especially EVA.

Although WG2 had a draft international standard for module qualification, in 1988 Standards Coordinating Committee 21 (SCC-21) of the IEEE began developing a comprehensive standard that would be applicable to both crystalline and amorphous Si, for a number of reasons:

- There were still no consensus standards for qualification testing
- The IEC document was intended for x-Si modules only, not a-Si
- A desire to standardize the SERI IQT
- The IEC draft was still years away from adoption.

SERI held another thin-film module reliability workshop in 1989 during which JPL discussed wet insulation resistance leakage current limits with regard to safety and corrosion.[90] Solarex had time-to-failure data from immersing a-Si modules in water under low illumination (0·1–0·3 suns) at three temperatures (60, 70, and 85°C) that produced failures from back metal corrosion.[91] Chronar was using partial submersion of a-Si modules biased to +250 V with respect to the water for 500 h as a corrosion susceptibility test, in addition to the SERI IQT sequence.[92]

A Japanese Industrial Standard for x-Si qualification testing was published in 1989.[93] JIS C 8917 contained the following individual tests, which could be performed individually or in a prescribed sequence:

- 200 thermal cycles: –40 to +90°C
- 10 HF cycles: 2·5 h at 85/85 DH and 1 h at –20°C, or 10 min at 85/85 DH and 1 h at –40°C
- Robustness of terminations
- Salt mist corrosion: NaCl mist at 40/93 DH for 168 h or 21 h
- Irradiation test: carbon-arc/water spray 500 h
- Wind resistance: pneumatic sinusoidal cyclic pressure, or 1422 Pa static load
- Hail resistance
- Waterproofing: water ingress with hi-pot testing
- Twist test
- Dry heat: 1000 h at +85°C
- Damp heat: 1000 h at 85/85 DH
- HS test: iterative shading procedure, 100 1·5-h illumination cycles.

Revisions of JIS C 8917 were published in 1998 and 2005.

1990–1994

The 1990 SERI module reliability workshop had a Solarex presentation that demonstrated correlation between 1000-h light-soaking of a-Si modules under high-pressure sodium-vapor lamps and 1 year of OE.[94] Hester described the qualification and field testing for the PV for Utility-Scale Applications (PVUSA) project in Davis, California.[95] PVUSA required that all modules pass a sequence similar to the IQT, and a wet resistance test for operating PV arrays was developed. The wet resistance test was demonstrated to reveal a number of manufacturing flaws in modules, including backsheet pinholes, delaminations, and bypass diode failures.[96] This work strongly influenced the wet insulation resistance and wet hi-pot tests that were formalized in the future IEEE qualification standard, and later IEC standards.

Additional reports of EVA browning in hot, dry climates motivated considerable research on the topic, including the role of UV stabilizers and Ce-containing glasses that block wavelengths less than 350 nm.[97–99] Contradicting earlier conclusions, Rosenthal showed that the Carrizo power losses must be attributed to more than just loss of short-circuit current due to EVA darkening,[100] and Wohlgemuth concluded that fill factor (FF) losses were caused by module *I–V* curve mismatches coupled with solder-joint degradation and

DOI: 10.1002/pip

inadequate use of bypass diodes that resulted in HS problems.[101]

Matshushita performed a series of accelerated stress tests on CdS/CdTe encapsulated mini-modules that were designed to reveal the effects of oxygen.[102] The tests performed included an 80°C dry exposure, an 80/90 DH soak, a –20°C to 85/85 DH HF test, a cold–hot (0 and 100°C) water-immersion ‘‘heat shock’’ test, and a cycling test of carbon arc illumination followed by water spray without illumination.

Siemens published some early reliability and qualification testing results on $CuInSe_2$ (CIS) modules using the JPL Block V procedures, and noted that adhesion of the CIS–Mo interface was correlated with stability in HF testing.[103] Later work used the IQT sequence, and the authors noted that heating the modules above normal operating temperatures during lamination or qualification testing caused temporary losses of output power that disappeared after about 30 days stored indoors.[104–106] Based on results from HF tests, the authors concluded that humidity does not cause power losses and that hermetic seals are not generally necessary for CIS.

The draft IEC qualification sequence[87,88] was adopted in Europe as CEC Specification 503;[107] CEC 503 defined a brief UV exposure prior to the TC/HF tests that was blank in the IEC draft. In this paper, Ossenbrink also presented results from applying the new sequence to eight module types.

Chronar used the IQT wet insulation test to measure leakage currents through a-Si module edges.[108] Sandblasting was used to remove conductive films (such as SnO_2:F) at module edges from the glass superstrates (a process known as edge-delete or edge isolation) and reduce the leakage currents.

The 1992 NREL Performance and Reliability Workshop had a number of presentations related to qualification and accelerated module testing. Solarex investigated the effects of different lamp spectra on triple-junction a-Si light-induced degradation.[109] United Solar Systems performed a salt-fog test on flexible a-Si modules;[110] full-immersion wet hi-pot testing was used because of problems wetting DuPont Tefzel fluoropolymer front sheets. In a tutorial of accelerated indoor and outdoor weathering of coatings, E. I. Dupont stated that lifetime projections are only partially successful.[111]

At the next NREL workshop in 1993, Azzam discussed Mobil Solar's reliability testing program that included 85/85 DH with voltage bias, 85/85 DH combined with interim TC and HF cycles, autoclave, and UV light-soaking;[112] temperature–humidity testing suggested that ‘‘. . .JPL's model[36] places too heavy a weight on the relative humidity factor. . .’’ Results from applying the IQT to early Solar Cells, Inc. CdTe double-glass laminate modules showed HF caused the most power degradation; this was attributed to edge delamination and ‘‘internal fingering’’ (probably corrosion).[113] Wohlgemuth gave a history of Solarex's x-Si module warranties and the testing used to support them, including extending the duration of the standard qualification tests.[8] Lastly, Klein reported that TC82 had begun work on a new thin-film module qualification sequence.[114]

In 1993, the IEC x-Si qualification standard, IEC 1215,[115] was issued and became the first formal qualification standard that was not published by a governmental body. The test sequence was identical to those reported in early drafts[87] and in the CEC 503 Specification.[107] It did not contain any wet insulation resistance or wet hi-pot testing. IEC 1215 included the optional 5400 Pa wind and snow load test that originated in CEC 501.[54] The HS endurance test was very similar to the one in CEC 502.[57]

The UV exposure test block in IEC 1215 contained the phrase ‘‘under consideration’’ as the details of the test remained a major disagreement among the member countries of WG2. The disagreement was a reflection of the realization in the PV industry that EVA browning is a serious problem, but that including a test for browning was not possible because of the time required to accumulate a sufficient UV dose. Also, the spectral irradiance of UV light sources is problematic.[116] UV fluorescent lamps are inexpensive, but their spectral irradiance curves are completely dissimilar to sunlight at wavelengths greater than 380 nm. Xe arc lamps can be closely matched, but are expensive.

These UV testing issues were discussed by Wohlgemuth in 1994, who stated that including a short exposure to UV fluorescent lamps prior to the TC and HF tests can replicate a delamination between adhesive tapes and EVA that had been observed in fielded modules.[117]

Also in 1994, in an overview of reliability testing of PV modules, Wohlgemuth emphasized the difference from qualification testing.[24] This paper identified two fallacies that can arise from well-accepted PV qualification test sequences: (1) that qualification tests tell everything needed to know about module reliability and (2) test sequences are relevant for modules types other than the ones for which they were developed.

DOI: 10.1002/pip

Research into solutions for EVA browning at Springborn Laboratories in the US continued to show that using fast-cure formulations was important, along with limiting UV exposure dose with cerium-containing glass.[118] Accelerated testing to demonstrate these newer configurations was done with small coupons in Xe arc chambers.

Burdick reported qualification test results on a variety of module technologies, including a-Si, CdTe, and CIS, using the draft IEEE qualification sequence.[119]

At the 12th EC conference in 1994, outdoor and indoor light-soaking of a-Si modules were compared at CIEMAT-IER in Spain, and extrapolations of the data were made to estimate module lifetimes.[120] Another paper measured degradation of a-Si series resistance and leakage current following salt-fog exposure testing.[121]

The JRC issued a qualification sequence for thin-film modules called CEC Specification No. 701 that was produced by the European Thin Film Qualification Task Force.[122] This document referenced CEC Specification No. 503[107] for most of the individual tests, but the overall test sequence was very different. To minimize test time, the 85/85 DH was reduced to 350 h and the 200 TC test was reduced to 50 cycles. Annealing and light-soaking were included, and the SERI IQT[85] wet insulation resistance test was added.

1995–1999

A series of presentations at the NREL workshops by Siemens again reported on reversible losses in Cu(In,Ga)Se_2 (CIGS) modules, termed "transients," that occur during lamination or TC.[123–125] Data were presented that showed FFs recovering with 20–30 days of OE. In contrast to what was stated in earlier Seimens' papers,[104] it was now reported that "moisture ingress causes permanent increases in the series resistance of modules."[124] By 1998, Siemens was investigating alternative module edge humidity seals for CIGS modules, and stated that for 1000-h 85/85 DH testing, "most packages fail; some designs pass with transient loss & recovery."[125] The Siemens module development included investigation of coatings over the CIGS cells such as SiN_x, SiO_x, and various plastics.

Year 1995 saw the completion of the IEEE qualification standard, IEEE 1262,[126] which was the first consensus standard for qualification testing of module types other than x-Si. The test sequences in IEEE 1262 are similar to those in IEC 1215, with a few exceptions. Wet insulation resistance and wet hi-pot testing were included, and the sequences contained provisions for light-induced degradation of a-Si module to separate power losses caused by the stress tests. This was accomplished by a succession of short thermal annealing steps where modules are annealed at 90°C for 24 h, and retested for performance. The annealing steps were continued until the output power changes by less than 2%. IEEE 1262 included a bypass diode thermal test, but the stress condition was raised from the +40°C module temperature in the SERI IQT to +75°C. Two separate HS endurance tests were given: a non-intrusive test similar to IEC 1215[115] and the intrusive test from the IQT.[85]

IEC TC82 published a module salt-mist corrosion test standard, IEC 61701;[127] this 96 h test subjects modules to an atmosphere of atomized 5% NaCl-water at 35°C while tilted at 15–30° from vertical.

Arizona State University presented a summary of qualification test results using IEEE 1262 on a number of Si modules made with different EVA formulations.[128] Almost all of these modules failed the DH test for reasons other than encapsulation problems. A common failure was deformation of junction boxes, usually caused by the use of non-UL-listed plastics, and corrosion of electrical terminals.

The IEC qualification standard for thin-film modules, IEC 1646, was approved in 1996.[129] Similarly to the IQT,[85] the term "thin-film" really meant a-Si, even though the scope stated that it may also be applicable to other thin-film modules. IEC 1646 included a wet insulation resistance test, but not the wet hi-pot from IEEE 1262. The most significant difference between the two standards, however, was the use of light-soaking, rather than thermal annealing. The IEC 1646 conditioning steps involved successive 48-h light-soaks at 0·8–1 sun and 40–50°C that are repeated until the output power does not change by more than 2%. Light-soaking before and after the stress tests made them expensive and time consuming for test laboratories to perform. HS endurance was identical to IEC 61215, even though shading narrow, individual cells in monolithically interconnected thin-film modules is quite difficult.

A fundamental study of water and sodium interactions with CIGS film semiconductors concluded that effective humidity barriers are important for the long-term stability of CIGS solar cells.[130]

JRC summarized qualification test results from 80 different module designs over a 5-year period using the

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CEC 503 sequence (essentially identical to IEC 1215) in 1996.[131] Nearly all of the failures involved visual defects and power losses that occurred during DH and TC.

A Solar Cells, Inc. paper recorded a study of light-soaking CdTe/CdS modules at several temperatures and loading conditions, and concluded that long-term testing is essential to ensure the stability of modules with a recommended minimum exposure time of 5000 h.[132]

In 1997, Dunlop of the JRC published results attempting to find a correlation between OE and DH testing in a-Si modules.[133] Rugged test modules survived 5000 h of 85/85 DH, but no correlation with 1 year of OE was found (likely because of light-induced degradation). A subsequent 1998 paper by Dunlop *et al*.[134] compared IEC 1646 with the European CEC Specification 701 sequence[122] for a-Si modules and recommended the HS endurance test be dropped. CdTe and CIS modules were mentioned briefly, and it was suggested that light-soaking, annealing, and HS testing could be eliminated for these module types.

Two papers by Wennerberg *et al*. of Uppsala University studied DH exposure in both individual cells and small modules of CIGS, with and without encapsulation.[135,136] Unencapsulated cells are shown to suffer large losses of open-circuit voltage (V_{oc}) and *FF*, with little change in short-circuit current (I_{sc}), and concluded that ZnO sheet resistance increases could only explain part of the losses.[135] Modules were shown to suffer degradation in damp heat greater than that seen in cells, which was attributed to the absorber (second) interconnect scribe lines.[136]

Pellegrino *et al*. measured insulation resistances of modules exposed to a cyclic salt-spray environment; modules with both glass and DuPont Tedlar backsheets were tested.[137] Surprisingly, the results showed that the loss rates of insulation resistance versus time for Tedlar backsheets were less than those of glass.

An IEC standard for UV exposure testing, IEC 61345, was published in 1998.[138] This test requires a UV exposure dose of 15 kWh/m^2 (54 MJ/m^2) for wavelengths between 320 and 400 nm, and 7·5 kWh/m^2 (27 MJ/m^2) for the higher-energy wavelength band between 280 and 320 nm. Acceptable UV light sources for the test include sunlight, Xe arc lamps, metal-halide lamps, and fluorescent UV lamps in the UV-A and UV-B ranges. IEC 61345 was intended to fill the void in the first edition of IEC 1215 in which the UV exposure test was not specified.[115]

2000–2004

While reviewing x-Si reliability and qualification testing, BP Solarex proposed changing the standard TC test to include 1-sun forward bias current while modules are above 20°C.[139] Also proposed was DH with the maximum system voltage applied between the shorted module leads and the grounding point; the modification was nearly identical to the electrochemical stress test proposed by JPL for Block VI.[31] NREL applied the TC with forward-bias test to three different x-Si module types and reported maximum power losses attributed to series-resistance increases.[140]

In 2000, Sandia National Laboratories (SNL) published two summaries of failure mechanisms observed in fielded modules, along with descriptions of tests that can be used to detect module failures.[141,142]

Light-soaking effects on thin-film modules (a-Si, CdTe, and CIGS) were compared at JRC[143] to determine the suitability of the IEC 1646[129] stabilization procedure for module types other than a-Si. Results indicated that the light-soaking behaviors of CdTe and CIGS were dissimilar enough from those of a-Si to warrant changes to IEC 1646.

Saly *et al*.[144] performed a study of module insulation degradation following an accelerated stress test somewhat similar to the JPL Block VI electrochemical stress test, although the 80/70 DH with 1500 V bias stress level was different. Test samples were small modules encapsulated with EVA, or single x-Si cells in a polycarbonate/silicone rubber sandwich. Both types experienced more than an order-of-magnitude decrease of insulation resistance after 120 days of exposure.

Light-soaking effects on CdTe modules at varying loading conditions using metal-halide illumination were studied in 2002 by Cunningham *et al*.,[145] and compared with real-time OE.

NREL published results of a 5-year x-Si light-soaking experiment under real-time outdoor, accelerated outdoor with mirror enhancement, UVA fluorescent, and Xe arc lamp illumination.[146,147] A correlation between the total UV exposure dose and module I_{sc} for all exposures showed that UV radiation caused losses of 0·25–0·6% per year.

Accelerated UV exposure using mirror-enhancement at Phoenix, Arizona, combined with HF testing was reported by Hanoka of Evergreen Solar as part of a development project to replace EVA with an unspecified thermoplastic encapsulant.[148] Test samples included both material coupons and small-sized modules.

A 2003 NREL study showed that internal module electric fields are able to drive electrochemical corrosion of SnO_2 layers in both a-Si and CdTe glass superstrate modules, and demonstrated that metallic frames around module edges play an important role in enhancing the electric fields.[149] This work was motivated by observations of damage to SnO_2 in modules used in high-voltage systems, as reported by Carlson *et al.* at Solarex.[150] Using a –100 V bias and a +85°C salt-water bath, the authors were able to reproduce the failure on coated glass samples in just a few days. Later, Jansen and Delahoy[151] at Energy PV devised a screening test for the problem that substituted a laboratory hot-plate and reduced the testing time to just a few minutes.

Tsuda *et al.*[152] developed an accelerated test program for x-Si that was intended to duplicate a number of failures observed in fielded modules that included ''milky white'' discolorations (possibly encapsulant delamination), series-resistance increases, and EVA yellowing. Individual stress tests used were 85/85 DH with Xe arc illumination, TC with constant and with intermittent illumination, thermal shock from pouring water onto hot modules, cyclic illumination, and an unspecified ''humidity test'' under illumination.

Another Uppsala University article studied the mechanisms of performance losses in CIGS modules, and demonstrated that humidity from DH testing is a major cause of degradation that results in losses of FF through series resistance increases and losses of V_{oc}.[153] The paper listed possible ways of reducing degradation through improved monolithic cell interconnect structures.

After exposing CIS mini-modules to a cyclic light/dark test without humidity, Yanagisawa *et al.*[154] also reported losses of *FF* and V_{oc}. Similar to light-soaking results on CdTe/CdS reported by Solar Cells, Inc.,[132] the CIS device performance initially improved before beginning to decrease.

Ossenbrink and Sample wrote a detailed summary of test results from 12 years of x-Si qualification tests on 125 module types performed at JRC, and included statistics for each individual test in IEC 61215.[155] Visual defects caused by the environmental chamber tests were the most common failures, and power losses were the second-most common. Fifty-four percent of new module designs failed the qualification sequence.

A 2004 review by McMahon discussed the stresses imposed by individual tests on thin-film modules, and diagnostic methods that can be used to detect failures.[156] Failure modes and mechanisms of many thin-film module types were reviewed with causes listed such as cells separating from module interconnects and packaging.

Palm *et al.*[157] of Shell Solar GmbH subjected $Cu(In,Ga)(S,Se)_2$ (CIGSS) modules to 2000 h of 85/85 DH, followed by a 110-h anneal in dry air. The modules retained 80% of their initial efficiency, and data from unencapsulated cells showed ZnO sheet resistance nearly doubling after 200 h of 85/85 DH exposure.

2005–2008

WG2 of IEC TC82 completed a second edition of the IEC 61215 x-Si qualification standard that incorporated several significant changes.[158] The twist test was removed because modules never failed this test, and wet insulation resistance and bypass diode thermal tests similar to those in IEEE 1262[126] were added. A forward-bias current equal to the module's current at maximum power under 1000 W/m^2 irradiance was made a requirement for the TC200 test when the module temperature is greater than 25°C. The formerly unspecified ''UV Test'' in the first edition was renamed the ''UV Preconditioning Test'' and filled with a procedure similar to that of IEC 61345,[138] although the exposure dose for the UV-B wavelength range (280–320 nm) was reduced by one-third.

A JRC study in 2005 authored by Dunlop *et al.* attempted to associate module lifetime with the stresses imposed by the standard qualification tests,[159,160] especially CEC 501.[54] Degradation rates of 0·4% per year were reported on two old x-Si systems, one dating from 1982 and the other from 1991.[159] This paper included a survey of the degradation modes and frequencies observed in both systems. Another JRC paper by Sample *et al.*[161] provided 15 years of statistical information for electrical performance losses in modules subjected to IEC 61215, which identified the TC200 and 85/85 DH tests as causing the largest numbers of power losses.

As a result of doubts about the efficacy of the IEC 61215 HS endurance test, BP Solar and the TÜV Rheinland Group proposed in 2005 a new method of selecting individual worst-case cells in x-Si modules to be subjected to HS testing,[162] for possible inclusion in a revision of IEC 61215. Murakami *et al.*[163] later

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presented a review and analysis of this method. The method was adopted as a standalone ASTM International standard, E 2481, in 2006.[164]

Wohlgemuth *et al*.[165] outlined how BP Solar estimates module lifetimes from a program that uses real-time outdoor testing, field returns, and accelerated stress tests. The stress tests included DH testing to failure and extended-duration TC with forward current bias. A later 2006 paper indicated that BP Solar typically runs 500 thermal cycles and 1250 h of 85/85 DH exposure.[25] This paper referenced the JPL corrosion acceleration model that equated 1000 h of 85/85 DH with 20 years of exposure in Miami, FL,[64] but DH testing results of a new module backsheet material at 65/85 DH and 85/85 DH did not follow the JPL acceleration rate prediction.

Using a numeric simulation for water-vapor transport in x-Si modules, Reisner *et al*.[166] calculated hydrolytic degradation rates of polymer molecular weights for x-Si modules mounted with open backs and sealed BIPV applications. For the BIPV case, the authors estimated that 1000 h of 85/85 DH corresponds to 16 years in a tropical environment, and more than 100 years in Berlin, Germany. In the open back case, the authors found no correlation between DH and outdoor conditions, thus the weathering results of DH have little relevance for outdoor weathering. Note that the polymer molecular weight degradation mechanism studied here is different from the corrosion study performed by JPL in the early 1980s.[64]

Field exposure by Carlsson and Brinkman of CdTe/CdS modules with Sb_2Te_3 back contacts and indium-tin-oxide (ITO)-SnO_2 transparent conductors showed output power degradation greater than 10% in 1·5 years, but 1000-h 85/85 DH testing of mini-modules fabricated with the same structure had no measurable power losses, thus indicating no correlation with the outdoor testing.[167]

A 2006 paper by Jorgensen *et al*.[168] of NREL compared properties of module encapsulants and backsheet materials for moisture barriers using DH. McMahon published a companion paper that showed degradation of adhesion strength of EVA following 85/85 DH testing and light exposure.[169]

In 2006, Showa Shell demonstrated CIGS modules with improved stability by performing 85/85 DH with about 200 W/m^2 illumination and in the dark.[170] Module performance of samples stressed without light was generally improved after a brief 1-day outdoor light-soak step.

The IECEE issued a series of retesting requirements for modules tested to the IEC standards.[171]

Stocks *et al*.[172] of Origin Energy Solar subjected SLIVER modules, which use micro-machined x-Si strip solar cells, to extended-duration TC and 85/85 DH testing, with minimal or no measurable power losses. Testing to 1400 thermal cycles and 4500 h of 85/85 DH showed degradation less than 5% of initial performance.

Authors from the Arizona State University PV Testing Laboratory presented module failure statistics from 9 years of standard qualification testing on a total of about 1200 modules at the 2006 European PV conference.[173] DH caused the most failures, with 8% for x-Si modules and 28% for thin-film modules.

Broek *et al*.[174] used TC and 85/85 DH up to 3000-h duration to evaluate electrical connections to thin-Si cells formed with conductive adhesives. Parameters monitored on special test samples included electrical resistance and adhesive, tensile, and sheer strengths.

Jorgensen and McMahon devised a method of determining toughness and shear strength of individual material interfaces in modules by measuring torque versus twist angle in circular module areas defined by coring.[175] Application of the technique to light-soaked x-Si modules[146] showed that toughness of the EVA–silicon interface declines by about 80% after just a few years of UV exposure.

IEC TC82 completed a second edition of the thin-film qualification sequence in 2007, IEC 61646.[176] Significant changes included the removal of the annealing step, and a new requirement that the output power of all modules be within 90% of the manufacturer's power rating at the end of a final light-soaking step. The UV preconditioning test is similar to the corresponding test in IEC 61215, although the UV-B energy requirement was reduced to 1/5th. Considerations were added to the HS endurance test for the difficulties with shading narrow, monolithically interconnected cells.

An NREL technical report published in 2008 documents a TTF protocol intended to provide a method to obtain quantitative reliability information for modules.[177] Three stresses are applied to modules under test until output power declines to 50% of initial, or until a catastrophic failure occurs; these stresses are TC with forward-current bias, 85/85 DH with voltage bias, and a combined TC/DH stress. Intermediate power measurements are used to determine if failure has occurred.

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SUMMARY AND CONCLUSIONS

Since 1975, considerable effort has been directed by PV testing laboratories and manufacturers toward developing and using accelerated stress tests for terrestrial PV modules. This effort has included the incremental development of standardized stress sequences intended to discover susceptibility of module designs to known failure mechanisms; these sequences have been adopted as national and international module qualification standards. The process has included tests that were deemed necessary in the early years but experience over time showed they were unnecessary.

Along with the standard tests, many specialized accelerated tests have been used as screening tests to investigate failures or potential problems unique to particular module designs; examples are the various light-soaking tests that have been necessary for thin-film module development.

Equating accelerated stress tests to in-use lifetimes requires knowledge of the acceleration factors involved, and the literature is quite sparse in this area. Desombre, Otth, and Ross attempted to correlate the number of hours at 85/85 DH with years of operation in a humid climate, and this model influenced the selection of 1000 h as the length of the standard DH test. However, this model is only applicable to a single failure mechanism: the corrosion of metal contacts driven by the resistivity of polymeric insulation materials. Acceleration factors for other mechanisms remain unknown. Therefore, it is not possible to state that a module that passes a standard qualification test will produce power for a certain number of years. Also, the standard tests cannot be used to determine lifetimes because they do not test for all failure mechanisms.

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