Qualification Testing of Flat-Plate Photovoltaic Modules

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Abstract—**The placement of photovoltaic modules in various applications, in climates and locations throughout the world, results in different degrees and combinations of environmental and electrical stress. Early detection of module reliability deficiencies via laboratory testing is necessary for achieving long, satisfactory field service. This overview paper describes qualification testing techniques being used in the US Department of Energy's flat-plate terrestrial photovoltaic development program in terms of their significance, rationale for specified levels and durations, and test results.**

INTRODUCTION

As part of its Photovoltaic Energy Systems Program, the US Department of Energy (DOE) is supporting the development and testing of flat-plate photovoltaic modules and systems in experimental applications throughout the USA. Several different kinds of testing are being used by the Low-Cost Solar Array Project at the Jet Propulsion Laboratory (JPL) to assess the suitability of array elements and materials, and more specifically to identify key environmental factors, design features and failure mechanisms which effect the attainment of a satisfactory service life [1]. These include outdoor module testing at the system level; real-time and accelerated outdoor testing at the module and material level; and laboratory testing at the module, material, and cell level.

The qualification tests (which are the subject of this paper) are conducted to assess rapidly the importance of failure or degradation modes that can adversely affect the ability of the tested item to achieve satisfactory reliability performance. Although the most common use of qualification tests is in assessing the durability of a final product design before mass production is initiated, qualification tests are also valuable in the design, development, and process control phases of product generation. In the development testing phase, qualification tests are needed to provide rapid feedback of the *relative* strengths and acceptabilities of design alternatives. In process-control applications, qualification tests are useful to indicate out-of-tolerance materials or processes.

The key characteristics of qualification tests are quick turnaround and comprehensive failure-mode identification. To meet the latter need, the goal is to excite all failure modes that will result in unacceptable field performance while not exciting failure modes that are not related to field performance (i.e., test artifacts). To achieve this goal, careful selection of the test techniques, levels, and durations is necessary. This paper describes the various environmental qualification tests used in the DOE flat-plate terrestrial photovoltaic program [2, 3] in terms of their importance, rationale for specified levels and durations, and test results.

TEST DEVELOPMENT APPROACH

JPL is developing qualification test requirements by a multiple iterative process consisting of the six basic steps outlined in figure 1. Step 1 is the identification of an important failure mode or environmental stress. The identification can be the result of a field failure observation such as interconnect fatigue, or an envisioned problem not yet observed in the field.

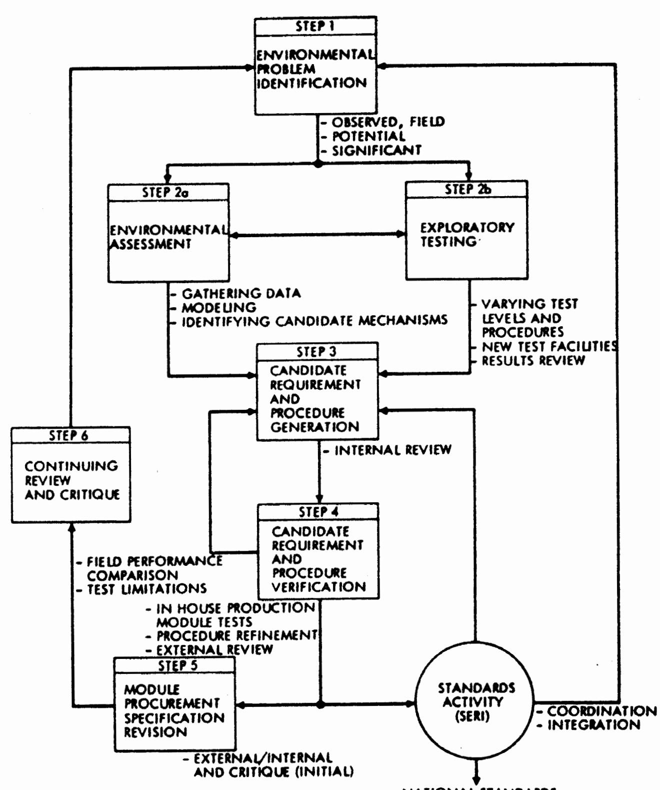

Fig. 1. Flow diagram of approach for developing qualification test requirements and procedures for flat-plate photovoltaic modules.

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Depending on the specifics of the problem, step #2 may consist of two efforts: 1) Environmental assessment which involves gathering, interpreting, and modeling, as appropriate, pertinent environmental data, and also involves identifying candidate failure mechanisms. 2) Exploratory testing which consists of subjecting modules, or module components to environmental exposures with the expressed purpose of characterizing the problem, and (one hopes) duplicating the failure mechanism. As part of this step, new test facilities might be designed and evaluated. The test results are reviewed and iterated with the environmental assessment effort.

Step #3. The outputs from step 2 are used to generate candidate requirements and test procedures. The objective is generally not to simulate the field environment, but to create a stress that will excite the same failure or degradation modes in as short a time as possible without exciting extraneous failure mechanisms.

Step #4. After such a test is developed, verification is initiated. Verification typically consists of subjecting representative production modules to the candidate test. During this step the procedure details can be refined and clarified. As the requirement or procedure matures, review comments from knowledgeable people are solicited and another iteration process ensues. Coordination and integration with the overall Photovoltaic Performance Criteria and Test Methods effort [4] led by the Solar Energy Research Institute (SERI) occurs throughout all of these steps, but is especially important at this phase.

Step #5. Then the module specification is revised with critiques being requested from a wide spectrum of organizations, such as manufacturers, users, and testing labs.

Step #6 is the continuing review and critique of the test. For example, if extreme diurnal temperature excursions are experienced by an array field with two types of modules, A and B, both may behave as anticipated based on the results of the temperature cycling test. However, if either module responds unexpectedly, there is a temperature cycling test deficiency, or something unusual is occurring at the site. In either case, a problem is identified that needs to be addressed (go to step #1).

REQUIREMENTS RATIONALE

The qualification tests being applied to flat-plate module designs [2, 3] have been developed using the approach outlined in the previous section and are summarized in table 1. This section summarizes the rationale for the levels and durations of each of these tests.

In addition to test levels and procedures, another important aspect of qualification testing involve the sequence of testing, failure detection, and pass-fail criteria. In the JPL qualification testing program, the tests are conducted in the order: electrical isolation, temperature cycling, humidity-freeze, cyclic pressure loading, twisted-mounting surface, hail impact, and electrical isolation. The order of the tests attempts to recognize possible synergistic effects between temperature-cycling damage and subsequent sensitivity to humidity-freezing. Tests which can be highly destructive, such as hail impact, are conducted at the end of the sequence. Because the hot-spot endurance tests require penetration of the encapsulation system, it is performed on a separate dedicated module. Electrical isolation testing is performed at the beginning and at the end of the test sequence to assess the insulation durability following environmental exposure. Modules are instrumented during temperature cycling, humidity-freezing, and cyclic pressure loading to detect intermittent cell strings, open circuits, or shorts to module ground. Module endurance is assessed by conducting visual inspections and electrical performance measurements before and after each test. Greater than 5% degradation in output power of a tested module at the completion of the test sequence as compared to its baseline measurement is considered a failure. Rejection criteria for visual inspections is more subjective and is based on the guidelines given in "Acceptance/Rejection Criteria for JPL/LSA Modules," JPL Document 5101-21 revision B. The number of replicate modules subjected to qualification testing is typically four to eight.

TABLE 1.
Qualification Test Levels for Flat-Plate Photovoltaic Modules

Tests	Levels and Duration
Temperature cycling	−40 °C, +90 °C, 100 °C/hour 200 cycles
Humidity-freeze	+85 °C, 85% RH with −40 °C freeze cycle, 24/hour cycle, 10 cycles
Cyclic pressure loading	±2400 Pa (± 50 lb/ft^2), 10^4 cycles
Wind resistance (shingles only)	Underwriters Lab Standard UL 997 1.7 k Pa (35 lb/ft^2)
Hail impact	10 sensitive points, 25.4 mm (1 in.) iceball at 23.2 m/sec (52 mph)
Electrical isolation	Leakage current <50 μA at twice worst-case open circuit voltage plus 1000 V
Hot-spot endurance	3 cells back-biased and heated for 100 hour of on-time

Temperature Cycling. This test is intended to accelerate thermal differential-expansion stress effects so that design weaknesses associated with the encapsulant system, cells, interconnects, and bonding materials can be detected as a direct result of the test. A key consideration in selecting the temperature range (figure 2) was to maximize the temperature excursion for accelerating the thermal stress effects so as to minimize the required test duration. A second moderating consideration was the desire not to eliminate reasonable material candidates by excessively exceeding the anticipated operating temperature range. The upper temperature limit (90 °C) represents a relatively small temperature stress margin (13 °C) above the

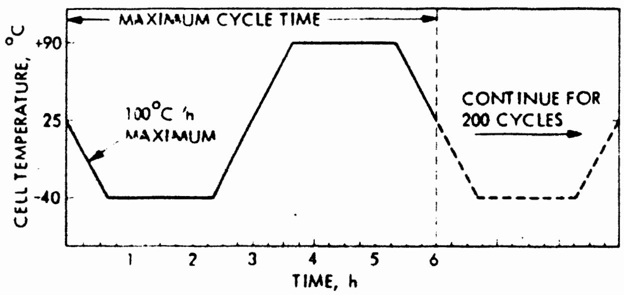

Fig. 2. Temperature cycling test profile.

estimated cell temperature (77 °C) of a typical operating module on a hot summer day in the southwestern USA with good insolation. The lower limit (−40 °C) was determined by considering the subfreezing temperatures within the USA, and the nil ductility (glass transition) temperatures for polymer materials. To establish an appropriate ramp rate, applicable military specifications were reviewed and facility capabilities examined. A rate of 1 °C/min is commonly applied in US military standards [5] and 3 °C/min in aerospace component standards. Since one of the primary purposes of this test is to detect problems caused by materials with different temperature coefficients of expansion, but not to induce testing-caused thermal shock or thermal-gradient problems, a maximum ramp rate of 100 °C/hour was selected. To establish an appropriate number of temperature cycles, empirical and analytic material fatigue relationships have been used in combination with the results from the field, and laboratory testing of complete modules. The most recent updating of this test is based on two isolated applications (in Africa and Arizona) which exhibited a much higher rate of interconnect fatigue than had been observed during qualification testing. To understand the fatigue problem further, an interconnect cycling apparatus was designed and used to establish fatigue curves for representative interconnect designs. The cycle motion impressed on the interconnect is a mechanical simulation of the idealized cyclic motions resulting from diurnal temperature variations. The test results were evaluated in conjunction with algorithms and metal fatigue results in the literature. The conclusion was that 20 years of interconnect fatigue induced by diurnal temperature variations would require approximately 700 cycles for the temperature cycling test. The time required to perform such a test would be 3.5 months, a lengthy time which violates a principal feature of qualification testing, namely rapid turnaround. In addition, other types of temperature-cycling degradation are observed to be substantially accelerated by significantly fewer cycles than interconnect fatigue. Previous test results indicate that the principal degradation modes other than interconnect fatigue are observed during the first 50 cycles. Thus, a two tier compromise test has been recommended. All environmental test modules, typically six or more, receive 50 cycles of exposure. Two modules are returned to test after the initial 50 cycles for a total accumulation of 200 cycles while 50-cycle-only samples (two modules, minimum) are subjected to the other environmental tests to assess synergistic effects.

The Humidity-Freeze Test. This test is intended to accelerate moisture-induced degradation of encapsulants, cell contacts, interconnects, terminations, and bonding materials. This new test is a combination of the standard 85 °C/85% relative humidity test from the electronics industry and a periodic, short duration freeze cycle. The selection of 85 °C/85% relative humidity for the test level is to maximize humidity stress factors so as to minimize test duration. A higher level was avoided because many of the encapsulant materials develop extraneous degradation mechanisms around 100 °C. Another consideration for choosing 85 °C/85% RH is to relate the photovoltaic module testing to a widely used component test in the semiconducter industry which is being used to test unencapsulated cells. A pronounced freeze cycle (i.e. to −40 °C) of short duration (≈30 minutes) has been selected to provide mechanical stressing of the moisture laden encapsulant system and to exaggerate and accelerate the adverse effects of absorbed moisture freezing within the module. To separate the moisture stress effects from the thermal cycling stress (e.g., fatigue) the number of cycles of the humidity freeze test is substantially less than that of the temperature cycling test. The number of cycles for the humidity-freeze test is ten, which is typical of electronic and military specifications. The resultant test profile is shown in figure 3.

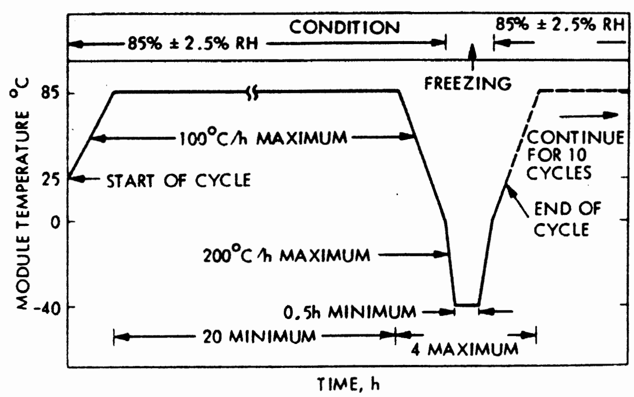

Fig. 3. Humidity freeze test profile.

Cyclic Pressure Loading. This test is intended to uncover structural design weaknesses of cell interconnects, encapsulant systems, and cells. Broken interconnects, a common field failure in photovoltaic modules, have been attributed in some cases to mechanical fatigue from long-term response to wind gusting. To address this failure mode, an analysis of wind, snow, and ice loads throughout the USA as reflected in the Uniform Building Code was performed. The specified level 2.4 kPa (50 lb/ft^2) satisfies the wind load code in 95% of the USA for heights ≥24 m (80 ft) and allows 0.6 kPa (12 lb/ft^2) snow and ice load. An assessment of field and exploratory test results indicated that 1000 cycles of testing were necessary to have a similar degree of fatigue failure as experienced in the field in one year [6]. To provide for a reasonable field life 10^4 cycles was selected, and an automatic cyclic pressure loading test apparatus was developed [6]. This apparatus is capable of performing the 10^4 cycles in less than 24 hours.

Twisted-Mounting Surface. This test is intended to detect mechanical weaknesses of encapsulants, cells, and interconnects which could result in module degradation or failure when mounted on a nonplanar primary structure in the field. Tolerance of the module to small deflections is a desirable characteristic so that flatness requirements on the support structure can be relaxed with a resultant reduction in costs. The deviation from a true flat surface during the test has been chosen based on engineering judgment, to be 20 mm/m (0.25 in. per foot) measured along either mounting in the direction of the module's width.

Hail Impact. This test is intended to characterize the susceptibility of a module's encapsulant, cells, and overall design to high-impact loading associated with hailstorms. The qualification test, which evolved from an exploratory testing program [7, 8], consists of propelling ice balls of the required diameter at terminal velocity towards at least 10 most sensitive points on the test specimen. Candidate points include module corners and edges, cell edges, and substrate supports. Hail-storm experience with modules in field application sites indicated that certain module designs, even though successfully passing a 19 mm (3/4 inch) iceball test, were suffering important hail damage. An evaluation of exploratory test data as represented in figure 4 led to the selection of a 25.4 mm (1 inch) iceball traveling at terminal velocity of 23.2 m/sec (52 mph) as the minimum hailstone tolerance level.

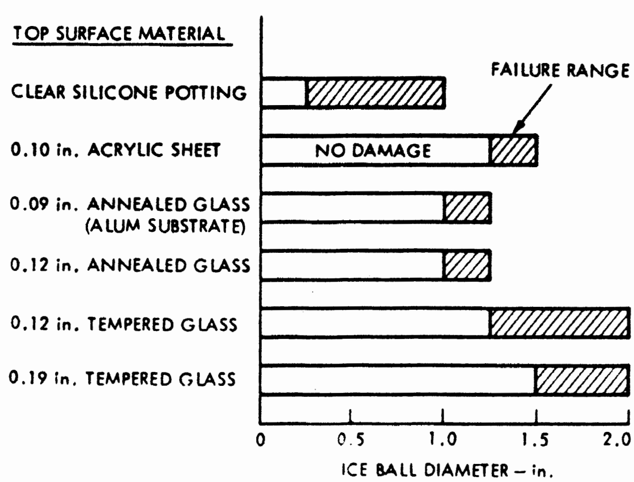

Fig. 4. Resistance of modules to iceball impact.

Electrical Isolation (Insulation resistance and high-voltage withstand). These tests are intended to verify the adequacy of the module insulation design for working voltages. As photovoltaic applications have become larger, the working voltages have gradually increased, with voltages as high as 1500 V expected in future large applications. As a result, safety and insulation reliability considerations have become more important.

The electrical insulation stress tests are performed with commercially available power supplies and instrumentation and apply high voltage between the cell string and module frame (if any). Based on historical precedent the test voltage level is selected as twice the worst-case open-circuit voltage above ground plus 1000 volts. Current leakage at the test voltage must not exceed a specified limit ($<50\ \mu A$).

Hot-spot Endurance. This recent addition to the test series was found to be necessary from a review of field failures. This test is intended to evaluate the ability of a module to endure the long-term effects of periodic hot-spot heating associated with common fault conditions such as severely cracked or mismatched cells, single-point open-circuit failures, or non-uniform illumination. Field experience indicates that fault conditions are expected even in highly reliable arrays. Under these fault conditions it is desirable to ensure that possible hot-spot heating due to reverse biasing does not cause propagation of the fault or electrical safety hazards through such mechanisms as solder melting or encapsulant deterioration. Hot-spot heating is caused when the operating current level exceeds the reduced short-circuit current capability of an individual cell or group of cells in an array circuit. The reduced short-circuit current fault condition can be the result of a variety of causes including non-uniform illumination (local shadowing), individual cell degradation due to cracking or soiling, or loss of a portion of a series-parallel circuit due to individual interconnect or cell open circuits. Under one or more of these conditions the cell(s) carrying the excess current dissipate power equal to the product of the current and the reversed voltage that develops across the cell(s), which can heat the cell(s) to elevated temperatures.

The hot spot endurance qualification test evolved from a series of analytical and experimental studies of the problem [9]. The test consists of selecting and instrumenting three appropriate cells within the module; determining the appropriate levels of heating, irradiation, and back bias power dissipation unique to the module electrical design; and subjecting the three cells to cyclic hot-spot heating for a period of 100 hours total on-time [2, 3]. The cyclic heating (one hour on and followed by sufficient off-time to allow the test cells to cool to within 10 °C of the nominal operating temperature) is intended to simulate the cyclic stress caused by the periodic occurrence of hot-spot heating conditions within the module. The 100 hour is based on the results of the exploratory tests run to determine the time required to spot known field hot-spot failures, and in recognition that most field hot-spot conditions are transient. The 100 hour test duration is expected to provide reasonable assurance against hot-spot heating effects, including delamination, outgassing or blistering of encapsulants, cell cracking, or solder melting. However, as

TABLE 2
In-Service Degradation Modes

Phenomenon	Electrical Effect	Qualification Tests Which excite similar degradation
Interconnect or interconnect/contact failure.	Arcing or open circuit.	Temperature cycling, cyclic pressure loading.
Wire, terminals, and cell metalization corrosion.	Open circuit, if severe; reduced power output.	Humidity-freeze, salt fog* but not to degree observed in field.
Severely cracked or mismatched cell.	Cell back-biasing & overheating; (ie hot-spot heating); reduced power output.	Temperature cycling, humidity freeze, cyclic pressure loading, hot-spot endurance.
Encapsulation delamination.	No short term electrical degradation observed; long-term delamination leads to corrosion.	Temperature cycling, humidity freeze.
Cell metallization delamination.	Reduced power output, or open circuit.	Humidity-freeze.
UV weathering.	Reduced power output caused by optical material degradation and aging.	Laboratory test Under development.
Hail impact.	Reduced power output because of cracked cells or subsequent corrosion.	Hail.
Insulation breakdown.	Arcing or open circuit.	Electrical isolation.
Optical surface soiling.	Temporary loss 5 to 60% power output.	No test, but natural or artificial washing restores power output.

*Application-dependent qualification test.

field experience with newly qualified designs is obtained, reevaluation of these test levels might be necessary.

Wind Resistance Test. This test is intended to accelerate wind-induced fatigue of encapsulant systems, substrates, interconnects and cells of shingle-type modules (i.e., a specially designed flat plate module that also functions as a residential roof covering). The cyclic pressure loading test described above is inadequate for shingle modules because shingles receive support on one side from the underlying roof structure, but can be blown upward by wind loads. After reviewing wind-loading literature from the American National Standards Institute, American Society of Testing & Materials, Underwriters Laboratories, and others, the testing requirements and procedures given in Underwriters Laboratories, Standard UL 997, "Standard for Wind Resistance Testing of Prepared Roof Covering Materials," were selected. This test involves the use of a fan-driven wind directed on to a built-up roof section incorporating the modules to be tested.

Exploratory Qualification Tests. In addition to the qualification tests described above which are typically applied as part of a module procurement effort, JPL performs a variety of exploratory qualification tests. These include ultraviolet, salt fog, fungus, and several combined environments such as humidity & heat and voltage-bias & humidity. Some of these tests are precursors of future qualification tests, while others are intended to evaluate performance in unusual environments or under specified operating conditions.

QUALIFICATION TEST RESULTS

Environmental qualification testing for the Low-Cost Solar Array Project's "Block Procurement" modules (Blocks I-IV, 1976-1980) have been completed and results are available [1, 10, 11, 12]. To provide for the continuing review and critique of the qualification tests (i.e. types, levels, and durations) in-service degradation modes and resultant effects are qualitatively compared to those that were induced during qualification testing (table 2). Two in-service degradation modes, corrosion and encapsulant delamination, have been observed to occur during the laboratory qualification test series but not to the degree observed in the field. Soiling, a significant degradation mode, can cause a temporary loss in electrical output. But with proper selection of top cover materials and an appropriate cleaning strategy (relying heavily on natural removal) this degradation mode becomes a minor problem [13].

The limited field experience available does not warrant the assumption that all important failure modes, a) have been identified and b) can be readily detected by the current set of qualification tests. Indeed, it is likely that more complex and subtle degradation mechanisms such as cell metallization corrosion will only become evident after several years of field exposure. Innovative materials and packaging concepts being incorporated into new module designs can also result in entirely different types of degradation modes. Continuing critique and review of test and service experience will be needed.

ACKNOWLEDGMENT

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