TESTING FLAT PLATE PHOTOVOLTAIC MODULES FOR TERRESTRIAL ENVIRONMENTS

A.R. HOFFMAN, J.C.ARNETT, and R.G. ROSS, JR.

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California, USA

Summary

The development of test requirements, equipment, and procedures for flat plate photovoltaic modules has been one part of the Jet Propulsion Laboratory's Low-Cost Solar Array Project. A primary objective of the project, which is being performed for the United States Department of Energy, is the timely development of low-cost, commercial-quality photovoltaic arrays through an active program of industrial and academic involvement. Development of test technology for modules is an important and necessary step toward meeting this objective. Various electrical performance and environmental testing requirements are discussed in terms of their significance as well as the rationale for the specified levels and durations. Comparisons between field-observed degradation and test-induced degradation are showing a positive correlation with some of the observed field effects. The status of research efforts for the development of test methodology for field-related problems is reviewed.

Proceedings of 2nd E.C. Photovoltaic Solar Energy Conference, (A80-46694 20-44)
Dordrecht, D. Reidel Publishing Co., Berlin, Germany, 23-26 April, 1979, pp. 978-986.

1. INTRODUCTION

As part of the National Photovoltaic Conversion Program, the United States Department of Energy is supporting the development and deployment of flat plate photovoltaic modules and concentrator systems for experimental applications throughout the United States. To provide reasonable assurance of satisfactory performance of the flat plate modules in these and future field applications, a set of qualification test requirements has been developed by the Jet Propulsion Laboratory's Low-Cost Solar Array (LSA) Project. The test activity described in this paper is being closely coordinated with and integrated into the overall Photovoltaic Performance Criteria and Test Standards effort led by the Solar Energy Research Institute (SERI), Golden, Colorado.

2. TESTING OBJECTIVES

The purpose of the qualification tests described in this paper is to rapidly detect the presence of failure or degradation modes that may adversely affect the ability of the tested item to serve its intended function in the intended environment. The most common use of qualification tests is in verifying the durability of a final product design before mass production is initiated. The philosophy is that if the item passes the test with an acceptable level of degradation, the item is satisfactory as is. If an unacceptable level of degradation occurs, a failure analysis is conducted to determine whether the observed degradation is important to the item's intended use and, if so, to provide insight for a design modification. In addition to product verification uses, qualification tests serve a valuable need 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 may be used 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 uncorrelated with field performance.

3. REQUIREMENTS RATIONALE

The approach being used at JPL for developing qualification test requirements is a multiple iterative process consisting of identifying a module performance/environmental problem, fabricating experimental test apparatus, performing exploratory tests with varying levels and procedures, and reviewing resultant requirements with industry and other organizations (1).

The test requirements currently being used to qualify modules are summarized in Table I. The initial qualification tests for terrestrial solar cell modules were based on the experience gained during the development of solar arrays for the space program. Concurrent with the selection of the initial qualification tests, surveys of existing photovoltaic systems in the field revealed that arrays were experiencing interconnect breakage, delamination, and electrical termination corrosion. These observations led to the development of additional qualification tests. This section summarizes the rationale for the levels and durations of each of these tests.

The temperature cycling test is intended to accelerate thermal 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 the selection of the temperature range 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 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 military specifications, the subfreezing temperatures within the United States, and nil ductility temperatures for polymer materials and glass. 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 problems, a maximum ramp rate of 100°C/h was selected. The resultant test profile is shown in Figure 1. The number of temperature cycles was based on the results of a special exploratory study which showed that the principal thermal stress degradation modes for modules could be detected during 50

repetitions of the six-hour high/low temperature profile (1).

The humidity test is intended to accelerate moisture-induced degradation of encapsulants, metallization and interconnects, and bonding materials. A review of standard military test procedures and consideration of the types of encapsulation used for terrestrial modules led to the selection of a modified version of Method 507.1, Procedure V, from MIL STD 810 C (2), which is a humidity cycling test of seven days' duration. The humidity cycle test profile is shown in Figure 2.

The cyclic pressure load test is intended to uncover design weaknesses of cell interconnects, encapsulant systems, and cells. Broken interconnects, a common field failure in early photovoltaic modules, were attributed by some people to mechanical fatigue from long-term response to wind gusting. The pressure loading level was based on an analysis of wind, snow, and ice loads throughout the United States as reflected in the Uniform Building Code. The specified level 2.4 kPa (50 lb/ft^2) satisfies the wind load code in 95% of the United States for heights $\leq$24 m (80 ft) and allows 0.6 kPa (12 lb/ft^2) snow and ice load. The requirement for the number of pressure cycles was based on the results of special exploratory studies which showed that all of the fatigue effects were noted before 10,000 cycles (3).

The warped mounting test is intended to detect mechanical weaknesses of encapsulants, cells, and interconnects which could result in module failure when mounted on a nonplanar primary structure in the field. The height (±2 cm/m) that one corner of the module is raised is based on engineering judgment.

The hail 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 (4, 5), consists of propelling ice balls of the required hailstone diameter at terminal velocity at the three most sensitive points on the test specimen. Candidate points may include module corners and edges, cell edges, and substrate supports. The selection of hail diameter is determined by the user, based on his assessment of the hailstorm likelihood at his particular application. If his application is not in a hail region, he may elect not to perform a hail test. For solar collectors HUD recommends a hailstone diameter equal to 0.3 in. times the average number of hail-days per year at the application site (6).

Insulation resistance and high-voltage withstanding tests are intended to verify the adequacy of the module design for working voltages. Previous small arrays were primarily used to charge batteries with low working voltages, up to 24 volts. As the applications have become larger, the working voltages have increased. Working voltages as high as 1500 volts could be expected in large applications. As a result, safety considerations have become more prominent.

These electrical breakdown tests, performed with commercially available power supplies and instrumentation, apply voltage between the cell string and module frame (if any). Current leakage at 1500 Vdc must not exceed a specified limit ($\leq 50\ \mu A$). This limit was selected as being representative of unacceptable insulation integrity while also providing a current limiting level to prevent further damage to the module from excessive arcing or breakdown.

The wind resistance test is intended to accelerate wind-induced fatigue of cell interconnects, encapsulant systems, substrates, and cells of shingle-type modules (i.e., a specially designed flat plate module that also functions as a roof covering). After reviewing wind-loading literature from the American National Standards Institute, American Society of Testing Materials, Underwriter 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.

In addition to the qualification tests described above, several exploratory environmental tests have been performed, including rain, freezing, salt fog, fungus, and several combined environments such as humidity-heat and bias-humidity. Some of these tests are precursors of future qualification tests, while others are intended for evaluation of performance in unusual environments or under specified operating conditions. A test description and test results for Block I and II modules have been published (7, 8).

4. TEST RESULTS

Environmental qualification testing for Block I, II, and III modules has been completed. Comparisons between test results of Block I and II modules (7) indicate that the Block II modules had fewer design and fabrication deficiencies than Block I. Decreases in the frequency of occurrence of certain types of degradation were noted, especially delamination

and damaged interconnects. However, the frequency of occurrence of cell cracking did not decrease. Comparison of Block III test results with those of Block II indicated similar trends: some decreases in frequency of occurrence of delamination and damaged interconnects, no decrease in cell cracking. When observed in-service degradation modes are compared to qualification-test-induced degradation, significant agreement has been noted (1,7). This is summarized in Table II. Three phenomena - optical surface soiling, encapsulant delamination, and vandalism - are not adequately reproduced by any of the current qualification tests. These improvements in environmental ruggedness, as noted on the Block II and Block III modules test and most importantly in the field, reflect a maturing of photovoltaic module designs and fabrication processes. Thus, the program for developing (and conducting) qualification tests on flat plate modules is performing its intended function, i.e., to provide reasonable assurance of satisfactory performance in field applications.

5. ONGOING STUDIES

Soiling of optical surfaces is causing the largest single degradation of power in field modules, up to 30%. The degradation has been especially evident in modules that have used silicone polymers as encapsulants. A qualification test to aid manufacturers and their customers in assessing the "dust affinity" of flat plate modules is one of the most important needs of the current research and development efforts. Because of the complex interactions between contaminants, environment, and surface characteristics, initial simplified testing approaches have been unsuccessful. Investigations are being directed toward building a substantial data base and understanding techniques for simulating removal mechanics.

The effects on the insulation capability of the encapsulation system when a high voltage is applied over a long period of time in a natural environment are unknown. To determine long-duration high-voltage tolerance, an outdoor experiment was initiated at JPL recently (December 1978). Four-month results show no significant changes from the initial voltage withstand capability. This test is expected to continue for at least one year.

6. CONCLUSIONS

Improvements in environmental test tolerance by second- and third-generation photovoltaic modules indicate a maturing of the designs and fabrication processes. Thus, the qualification test program for flat plate modules should provide reasonable assurance of satisfactory performance in the field. It should be stressed that the limited field experience available does not warrant the assumption that all important failure modes have been identified. 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; continuing comparison of test and service experience will be needed to account for such phenomena. New qualification tests developed for flat plate modules are proving useful for detecting design and fabrication deficiencies. Temperature cycling, cyclic pressure load, and humidity have been especially useful. There is positive correlation between many of the observed field effects (e.g., power loss) and qualification-test-induced degradation.

Module soiling is currently the most significant field-related problem that is not adequately accelerated and duplicated under controlled test conditions in the laboratory.

7. ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the United States Department of Energy through an agreement with NASA.

8. REFERENCES

1. Hoffman, A. and Ross, R., "Environmental Qualification Testing of Terrestrial Solar Cell Modules," Thirteenth IEEE Photovoltaic Specialists Conference, 78CH1319-3, 1978, pp. 835-842.

2. Military Standard Environmental Test Standards, MIL STD 810C, 10 March 1975.

3. Moore, D., "Cyclic Pressure-Load Development Testing of Solar Panels," LSSA Project Task Report 5101-19 (JPL Internal Document), Jet Propulsion Laboratory, Pasadena, CA, 28 February 1977.

4. Gonzalez, C.C., "Hail Risk Model for Solar Collectors," in 1978 Proceedings of the 24th Annual Technical Meeting, Institute of Environmental Sciences, 18-20 April 1978, pp. 278-286.

5. Moore, D., Wilson, A. and Ross, R., "Simulated Hail Impact Testing of Photovoltaic Solar Panels," in 1978 Proceedings of 24th Annual Technical Meeting, Institute of Environmental Sciences, 18-20 April 1978, pp. 419-430.

6. "HUD Intermediate Minimum Property Standard Supplement for Solar Heating and Domestic Hot Water Systems," Document 4930.2, Vol. 5, Department of Housing and Urban Development, Washington, D.C., 1977.

7. Griffith, J., Dumas, L., and Hoffman, A., "Environmental Testing of Flat Plate Solar Cell Modules," in Proceedings of the Solar Seminar on Testing Solar Energy Materials and Systems, 22-24 May 1978.

8. Hoffman, A. and Miller, E., "Bias-Humidity Testing of Solar Cell Modules," LSA Project Task Report 5101-84 (JPL Internal Document), DOE/JPL 1012-78/11, Jet Propulsion Laboratory, Pasadena, CA, 15 October 1978.

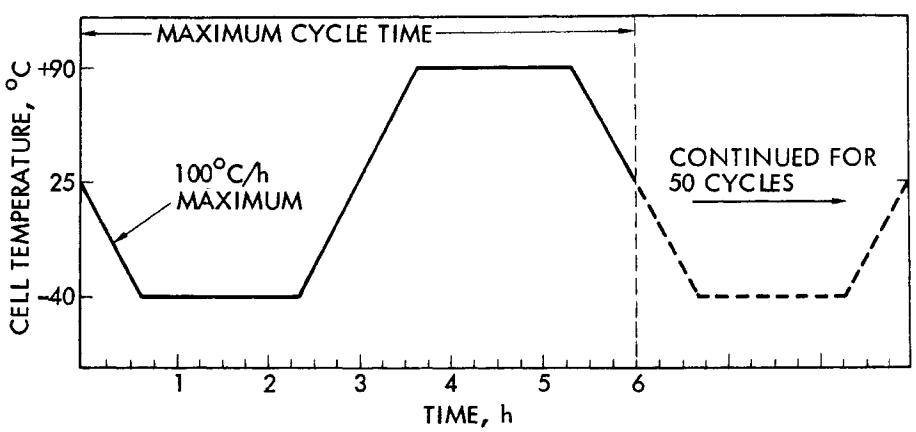

Fig. 1. Temperature cycling test profile

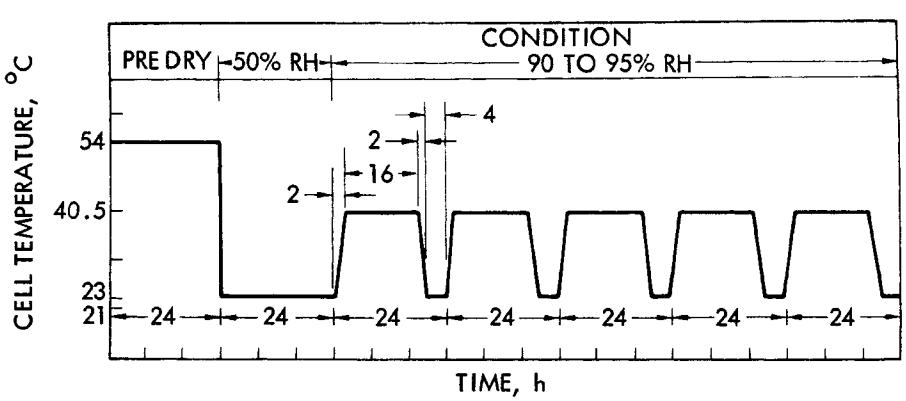

Fig. 2. Humidity cycling test profile

Table I. Environmental Qualification Tests for Flat Plate Photovoltaic Modules

Tests	Present Environmental Test Levels
Temperature cycling	+90°C, -40°C, 100°C/h, 50 cycles
Humidity cycling	+40°C, +23°C, 90% RH, 24 h/cycle 5 cycles
Cyclic pressure loading	±2400 Pa (±50 lb/ft^2) 10,000 cycles
Warped mounting surface	±2 cm/m (±1/4" per ft)
Hail impact	3 hits at each of 3 points on module, application-dependent
Electrical isolation	Leakage current $\leq$50 μA @ application voltage, e.g., 1500 Vdc
Wind resistance (shingle modules only)	Underwriters Lab Standard UL 997

Table II. In-Service Degradation Modes

Phenomenon	Field Effect	Similar Phenomenon/Effect Observed in Present Qualification Tests
Optical surface soiling	5 to 30% power output reduction	No
Encapsulant delamination	No short-term power degradation observed. Long-term effects unknown.	Yes, some delamination but not to the degree observed in the field (humidity cycling, temperature cycling)
Vandalism (i.e., thrown or projected objects)	Reduced power output or open circuit (i.e., cracked cells)	Yes, but not to the degree observed in the field (hail*)
Hail impact	Reduced power output or open circuit (i.e., cracked cells)	Yes (hail*)
Severely cracked or mismatched cell	Cell backbiasing and overheating; reduced module power output	Yes (humidity temperature cycling, cyclic pressure loading)
Interconnect or interconnect/contact failure	Arcing and/or open circuit	Yes (temperature cycling, cyclic pressure loading)
Electrical termination corrosion	Open circuit	Yes (humidity cycling, salt fog*)

*Application-dependent qualification test