# ENVIRONMENTAL QUALIFICATION

# TESTING OF TERRESTRIAL SOLAR CELL MODULES*

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## SUMMARY

The placement of solar cell modules in various climates and locations throughout the world results in different degrees and combinations of environmental stresses. Coupled with a design lifetime goal of 20 years, early detection and correction of module design deficiencies can result in significantly better long-term economics. This paper describes an environmental test research program for developing qualification requirements and procedures for flat-plate solar cell modules. A multiple iterative approach for establishing and evaluating test requirements is discussed as well as the rationale for the selection of levels and durations for the current qualification tests. The status of study efforts involving optical surface soiling, encapsulation delamination, and voltage bias-humidity testing is reviewed.

## INTRODUCTION

The use of photovoltaics to provide a primary source of power for space vehicles resulted in the development of environmental qualification and acceptance test requirements and procedures, which were dominated by the vibration, temperature, humidity, ultraviolet, and particle radiation requirements. These environmental tests have served the space industry well as the successful unmanned lunar and planetary missions with solar arrays, such as Mariner and Viking, attest. The application of photovoltaics for terrestrial use introduces an entirely different set of environmental conditions that render many of the previously developed tests and procedures inappropriate.

The placement of modules in various climates and locations throughout the world results in different degrees and combinations of environmental stresses. When a design lifetime goal of 20 years is imposed on top of these widely varying environments, the challenge to materials, design, and test engineers is indeed immense. A primary objective of the Low-Cost Solar Array Project (LSA) at the Jet Propulsion Laboratory is the timely development of low-cost, commercial-quality photovoltaic arrays through an active program of industrial and academic involvement. Development of environmental test technology for flat-plate solar cell modules has been an important and necessary step toward meeting this objective.

The environmental test activity described in this paper will in the future be closely coordinated with and integrated into the recently introduced overall Photovoltaic Design Criteria and Standards effort led by the Solar Energy Research Institute (SERI). An expanded interface with national standards writing organizations is anticipated from these efforts, with resulting benefits for the entire photovoltaic community.

## QUALIFICATION TEST DEVELOPMENT

As a first step in qualification test development, it is important to define the objectives of the tests and clarify the distinction between qualification tests and other tests relating to reliability and life prediction. In many cases the same test procedure developed for qualification testing can be used in each of these other areas.

### Qualification Test 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.

*This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology for the U.S. Department of Energy, by agreement with the National Aeronautics and Space Administration.

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. When developing tests, it is desirable to err on the side of identifying too many failures, but precautions should be taken to avoid initiating costly redesigns based on a failure subsequently attributed to a testing artifact.

In contrast with qualification tests, reliability and life-prediction tests are designed to provide quantitative information on projected mean-time-between-failures or lifetimes. Such analyses are generally site or mission specific and often lengthy for products requiring MTBF's or lifetimes of many years. Life prediction test development for terrestrial arrays is also ongoing at JPL(1).

Approach

The approach being used at JPL for developing qualification test requirements is a multiple iterative process consisting of the six basic steps outlined in Fig. 1. The initial step is the identification of an important failure mode

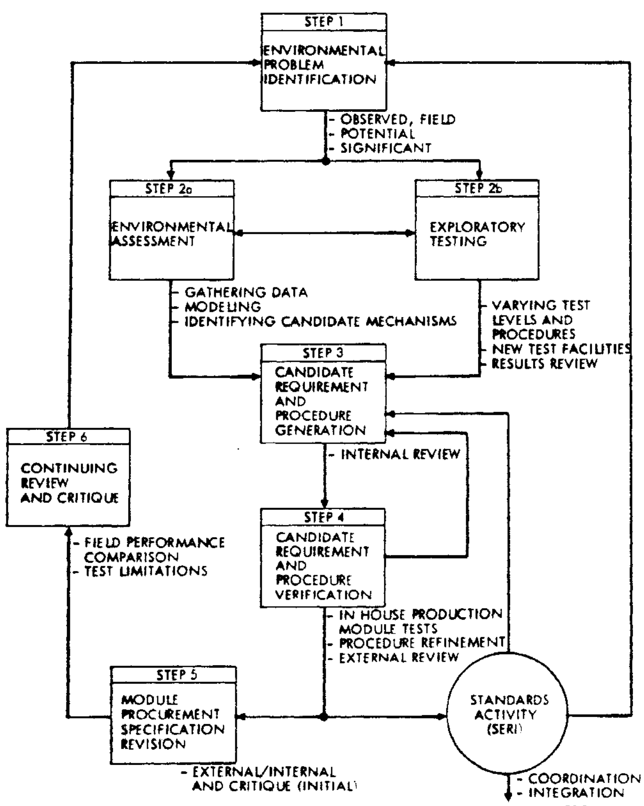


**Figure 1. Flow diagram of approach for developing environmental qualification test requirements and procedures for flat plate solar cell modules**

or environmental stress. The identification can be the result of a field failure observation such as encapsulant delamination, or can be the result of an envisioned problem, such as hail damage, not yet observed in the field. Before proceeding into Step 2, a judgement of the significance of the problem must be established. That is, a decision is rendered for determining whether the problem requires high priority and immediate attention, or whether it can be assigned a lower priority and placed in the queue for later environmental evaluation.

Depending on the specifics of the problem, the next step may consist of two efforts. One effort is the environmental assessment, which involves gathering, interpreting, and modeling, as appropriate, pertinent environmental data, and also involves identifying candidate failure mechanisms. The other effort in Step 2 is exploratory testing, which consists of subjecting modules, or module components, to environmental exposures with the expressed purpose of characterising the problem, and hopefully, duplicating the failure mechanism. As part of this step, new test facilities may be designed and evaluated. The test results are reviewed and iterated with the environmental assessment effort.

The outputs from Step 2 are used to generate candidate requirements and test procedures. The objective here is generally not to simulate the field environment, but to create a stress that will excite the same failure or degradation modes. After such a test is developed, the verification step (Step 4) is initiated. This typically consists of subjecting representative production modules to the candidate test. During this step the procedure details may 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 Design Criteria and Standards effort occurs throughout all of these steps, but is especially important at this phase. Then the module specification is revised (Step 5) with critiques being requested from a wide spectrum of organizations, such as manufacturers, users, and testing labs.

The last step in the approach is the continuing review and critique of the test. This is where the field results are compared to the test results. For example, if a hailstorm encounters an array field with two types of modules, A and B, both may behave as anticipated based on the results of the hail test. However, if either module responds unexpectedly, there is a hail test deficiency, or something unusual occurred during the hailstorm event. In either case, a problem is identified that needs to be addressed (i.e., Step 1).

CURRENT QUALIFICATION TESTS

Many of the current qualification tests have been developed using the approach outlined in the previous section. However, 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 the following failure modes: interconnect breakage, delamination, and electrical termination corrosion. This led to the development of additional qualification tests. This section discusses the rationale for the levels and durations of each of these tests.

## Temperature Cycling

Temperature cycling was one of the initial tests selected for qualifying terrestrial modules. In the space program, temperature cycling was associated with the wide temperature excursions that a solar array experienced when it was occluded from the sun, and when the sun was reacquired or shone on the back side. The problems noted with these kinds of thermal stresses included: broken cover glass, adhesion failure, broken cells, and broken interconnects. The temperature cycling test for terrestrial modules is intended to represent a stress that the modules encounter as a result of diurnal and climatic temperature excursions.

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 to not eliminate reasonable material candidates by excessively exceeding the anticipated operating temperature range.

The upper temperature limit for the test of 90°C was based on engineering judgement. The appropriateness of this level can be shown by determining the cell temperature of a typical photovoltaic module with a nominal operating cell temperature of 47°C. On a hot summer day (40°C) in the southwestern USA with good solar insolation (110 $mW/cm^2$), the cell temperature is calculated to be 77°C. This allows only a 13°C qualification temperature stress margin.

The lower limit -40°C was determined by considering (a) the low temperatures used in military specifications, (b) the subfreezing temperatures that can and do occur within the 48 contiguous states, and (c) a realistic low temperature near, but not below the nil ductility temperature (i.e., glass transition temperature) for polymer materials and glass. The number of cycles designated based on engineering judgement was 100.

In initial testing, two problems were identified: the lack of a specified ramp rate (i.e., the number of °C/h) affected test uniformity, and the test duration (approximately two weeks) resulted in a slow turnaround for design improvement verification. 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 military specifications (2) and 3°C/min in spacecraft component specifications. 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 Fig. 2.

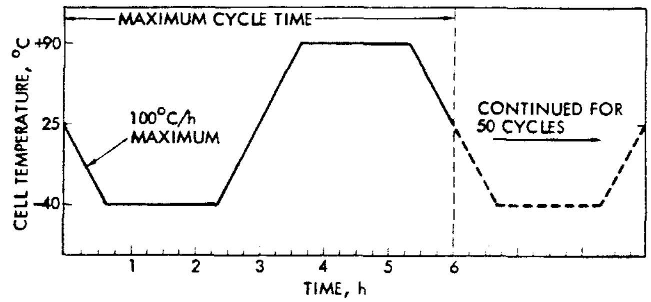


Figure 2. Temperature cycling test profile

To establish an appropriate number of temperature cycles, a special exploratory study was initiated. Modules from the first JPL Large Scale Procurement were subjected to the temperature cycling test. After exposure to a given number of cycles, they were visually and electrically examined. This was repeated until 100 cycles was achieved. Figure 3 shows that the principal degradation modes could be observed during the first 50 cycles. No significant new degradation modes occurred between 50 and 100 cycles. As a result of this exploratory investigation, a revised qualification requirement was proposed that reduced the required number of cycles from 100 to 50. This change was incorporated into subsequent module specifications.

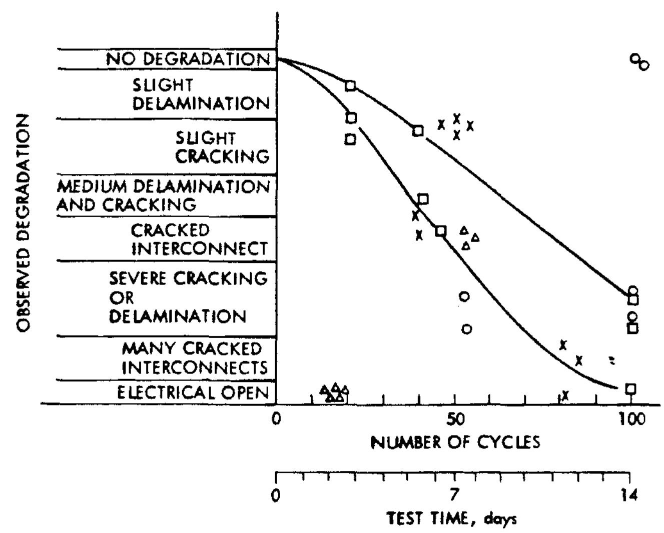


Figure 3. Observed temperature cycling degradation

## Humidity

Humidity related degrading effects on solar cells and modules are well known from both space and terrestrial experience. Solution of the metalization delamination problem associated with unsoldered silver-titanium contacts was an important contribution of the space program (3).

Building on this experience, a humidity soak test similar to that used in the space program was incorporated into the first set of terrestrial qualification tests. Subsequently the test was modified to introduce humidity cycling that was felt to be more appropriate for the types of encapsulation used for terrestrial modules. A review of standard military test procedures led to the selection of Method 507.1, Procedure V, from MIL STD 810C (2). The humidity cycling test profile is shown in Fig. 4. Both tests have served well in identifying potential metalization as well as encapsulant delamination problems.

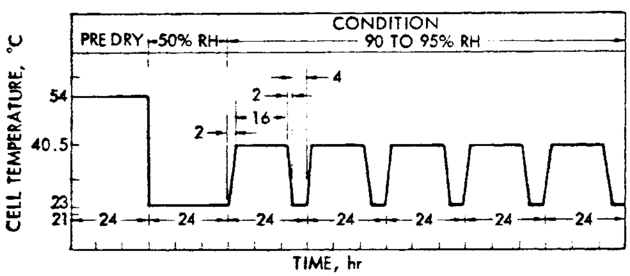


Figure 4. Humidity cycling test profile

## Cyclic Pressure Loading

Another common field failure in early photovoltaic systems was broken interconnects. Many field engineers attributed this problem to mechanical fatigue from long-term response to wind gusting as well as thermal cycling.

An environmental assessment was conducted consisting of evaluating the wind fluctuations and gusting at given locations throughout the country and interpreting wind loading building standards. The exploratory investigation consisted of developing a test apparatus (4) that could apply a pressure load on one side of the module then on the other and repeat. An interim test requirement was established that consisted of applying a pressure load of ±2400 pascals (±50 $lb/ft^2$) 100 times. As part of an exploratory test on representative early module designs, the number of cycles was increased to 35,000 cycles (5). The results for one module design as measured by the number of interconnect open circuits are shown in Fig. 5. The interim requirement of 100 cycles was not sufficient for detecting most of the interconnect open circuits that were subsequently seen in field exposure tests. However, all of the fatigue effects were noted before 10,000 cycles. Consequently, the number of cycles for the cyclic pressure load test was increased to 10,000 in subsequent specifications.

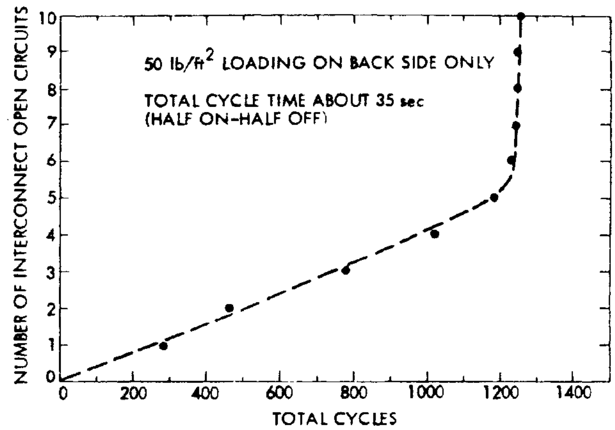


Figure 5. Observed structural cycling degradation

## Warped Mounting Surface

The rationale for establishing a warped mounting surface test is to account for the possible twisting of the module substrate when installed on a primary structure that is not entirely planar. An alternate approach would be to specify a stringent planar requirement for the primary structure. However, when module costs are reduced, structure costs with such a requirement would be unreasonably high.

The test consists of raising and lowering one corner of the module ±2 cm/m, (±1/4 in./ft) measured along either mounting surface. Current modules have had no difficulty in passing this test. The test has the potential for detecting design deficiencies in interconnects and cells, although its primary target is the encapsulation system.

## Hail

When key, large-scale demonstration projects (such as the Massachusetts Institute of Technology Lincoln Lab's irrigation project in Mead, Nebraska,) were located in regions of the country with large numbers of hailstorms, a hail assessment and testing program (6,7) was conducted.

The exploratory tests consisted of projecting ice balls of 1 to 5 cm in diameter at terminal velocities against the front face of the flat plate solar cell modules. Test results on the hail impact strength of commercially available flat-plate solar cell modules utilizing silicon rubber front surface indicate that module designs are capable of withstanding hail up to 2.5 cm (1 in.) diameter. Present glass modules were found to be slightly more rugged than modules with silicone rubber front surfaces, but not as rugged as modules made from acrylic sheet. Two simplified test methods were evaluated: dropped and statically loaded steel balls. The simplified methods did not provide acceptable correlation with the simulated hail impact tests.

As a result of the exploratory testing and the environmental assessment, a candidate hail test requirement and test procedure was generated, (i.e., Step 3 of Fig. 1 methodology). The verification (Step 4) and the inclusion in the PRDA (8) specification (Step 5) are occurring simultaneously during the spring and summer of 1978.

The qualification test consists of propelling ice balls of the required hailstone diameter at terminal velocity at the three most sensitive points on the test specimen. 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 to not perform a hail test. For solar collectors, HUD recommends a hailstone diameter equal to 0.3 inches times the average number of hail-days per year at the application site (9).

## Electrical Isolation

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 1000 Vdc must not exceed a specified limit, ($\leq$50μA). 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.

## Summary of Current Test Levels and Their Evolution

The environmental requirements currently being used to qualify modules are summarized in Table 1. As additional information has been learned from earlier procurements coupled with new electrical performance, mechanical configuration, and environmental characterization needs, the specification requirements have changed. Current environmental requirements are significantly different from those initially applied to Block I modules (Table 1). For Block II, new and improved requirements were added including reducing the number of temperature cycles, changing the humidity soak test to humidity cycling, adding a cyclic pressure load test, adding a warped mounting surface test, and adding electric isolation requirements. For Block III, the only change was relaxation of the leakage current requirement. For the PRDA modules (8) there were two changes: an increase in the number of cycles for the cyclic pressure loading, and the adding of an application dependent hail test.

## QUALIFICATION TESTS UNDER DEVELOPMENT

A measure of the adequacy of the existing qualification tests to detect module design and workmanship deficiencies is to examine the degree of correlation between test and in-service degradation. The main causes of in-service degradation as noted from reports and information that the

Table 1. Required environmental qualification tests for flat-plate solar cell modules

| Tests | Modules | | | | Present environmental test levels (from 8) |
|---|---|---|---|---|---|
| | Block I | Block II | Block III | PRDA (from 8) | |
| Temperature cycling | X | X | X | X | $-40^{\circ}$C, $+90^{\circ}$C, $100^{\circ}$C/h, 50 cycles (Blk. I, 100 cycles) |
| Humidity cycling | X | X | X | X | +40°C, +23°C, 90% RH, 24 h/cycle, 5 cycles (Blk. I, 70°C at 90% RH, 68 h |
| Cyclic pressure loading | | X | X | X | ±2400 Pa (±50 lb/ft$^2$), 10,000 cycles (Blk. II, III 100 cycles) |
| Warped mounting surface | | X | X | X | ±2 cm/m (±1/4 in./ft) |
| Hail impact | | | | X | 3 hits at each of 3 points on module, application dependent |
| Electrical isolation | | X | X | X | Leakage current $\leq$50μA at application dependent voltage (e.g., 1500 Vdc) (Blk. II, $\leq$15μA at 1500 Vdc) |

LSA Project has obtained in cooperation with the test and application projects are summarized in Table 2. Correspondence with existing qualification tests is noted. This correspondence is especially good for temperature cycling, cyclic pressure loading, and humidity cycling(4). Two phenomenon — optical surface soiling (i.e., dirt) and encapsulant delamination — are not adequately reproduced by any of the current qualification tests. Test procedures for these two field-related problems are needed and are being developed. In addition, another study is directed toward developing a combined voltage bias-humidity test. The impetus for this latter effort is based on favorable reports of correlation between field experience and bias humidity testing in the semiconductor and electronics industries.

Soiling

Soiling of optical surfaces is causing the largest single degradation of power of field modules, up to 30% (10). 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. The test development effort is in the middle of data gathering and exploratory testing (i.e., Steps 2a, 2b of Fig. 1).

The following discussion summarizes some of the principal adhesion and deposition mechanisms for particles under atmospheric conditions. There are five forces acting on particles. One principal force is water surface tension (i.e., moisture adhesion). Others include van der Wals forces, electrostatic forces, contact potential difference forces (related to occupation bands) and chemical bonding. Four mechanisms for depositing particles on module surfaces include: gravitational settling, thermophoresis (i.e., accumulation of particles on a cold surface such as dust from a hot air duct attaching to an adjacent cold wall), electrostatic attraction, and wind.

The adhesion and deposition mechanisms acting on modules in the field are likely to be site dependent. For example, modules in an industrial site may have water surface tension and chemical bonding as the principle adhesion forces, whereas modules in desert locations may have electrostatic forces due to dry winds as the principal force.

Recent exploratory tests using mini-modules and a standard air filter test have been performed. A given amount of dust (120 ml) was distributed uniformly over the face of the module, the module was rapped to remove loosley adhered particles, and then measured electrically. Preliminary results do

Table 2. 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) |
| 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*) |
| Severely cracked or mismatched cell | Cell back-biasing and overheating; reduced module power output | Yes, (humidity temperature cycling, cyclic pressure loading) |

*Application dependent qualification test.

not correlate with field experience (Table 3). Additional exploratory testing is in progress.

Table 3. Minimodule laboratory dust test results (preliminary)

| Minimodule encapsulant exterior surface | Output power degradation | |
|---|---|---|
| | Dry, % | Fogged, % |
| Float glass | <2 | 66 |
| Semiflexible silicone conformal coating | 4 | 49 |
| Silicone RTV rubber compound Type 1 | 64 | 68 |
| Silicone RTV rubber compound Type 2 | 46 | 52 |

Although the test dust does not have characteristics identical to field dust (eg., no organic constituents), it is well characterized (11), is available commercially, and has small lot-to-lot variation. A typical example of the rate at which dust accumulates on flat surfaces (a glass witness plate in this case) near the JPL test site is shown in Fig. 6. This information was obtained by using image enhancement techniques, and determining a relative measure of light blockage. The figure also shows the cleansing effect of a hard rain on the surface. Another field observation worthy of note is that dirt adhesion is omnidirectional. Encapsulant materials subjected to accelerated sunlight testing at Desert Sunshine Exposure Tests, Inc., where the samples are positioned upside down in the test configuration, accumulated visible dust on the test surface. However, the rate of dirt adhesion appeared to be relatively slow in this position although quantitative measurements have not been made.

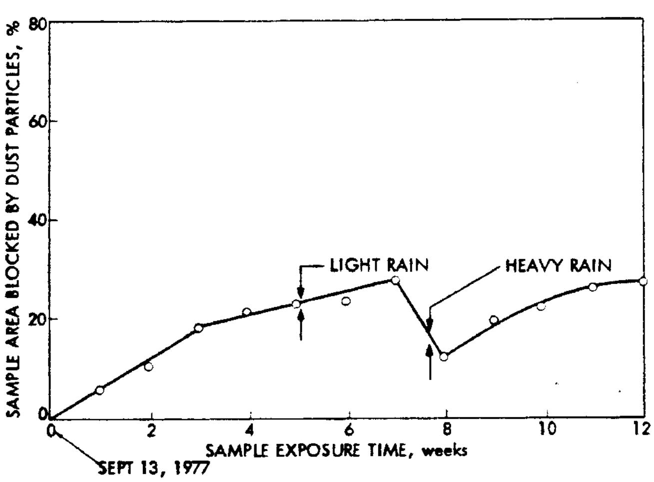


Figure 6. Dust accumulation near JPL Field Site No. 1

Since the environmental assessment and exploratory testing is just beginning, a candidate qualification test is several months in the future.

Encapsulant Delamination

The problem on encapsulant delamination has been observed to some degree at all surfaces to which silicone rubber encapsulants (RTV 615 and Sylgard 184) have bonded, but the most severe examples have occurred with epoxy-fiberglass module substrates (4). Poor initial adhesion due to inadequate surface preparation is probably a contributing factor in some cases, but environmental stresses appear to be important. While some encapsulant delamination has been observed to result from laboratory tests performed to date, the nature and extent of field delamination has not been duplicated. Ongoing investigations into this phenomenon have centered on the combined effects of exposure to ultraviolet light and high humidity levels as possible causative agents. An initial exploratory test for delamination was to subject a set of Block II minimodules to a standard "weatherometer" test [ASTM Test G 23-69 (Reapproved 1975)] for five hundred hours. The results were negative. Small delamination areas near the output terminals of one module and one cracked cell on another module were the only effects noted. Another exploratory test has been performed in which radiant (xenon lamp) heating and humidity were cyclically applied to minimodules. Again, no delamination was produced, however, a significant yellowing of one module was noted. A corresponding yellowing in the field has not been observed. Further work is planned with different ultraviolet sources.

Voltage Bias-Humidity

The bias-humidity test is being studied at JPL as a candidate for module qualification with respect to moisture related failure mechanisms that are enhanced by the presence of an electrical potential between the solar cells and between the cells and the module frame. Ion-migration and galvanic corrosion effects are of particular interest. In the first phase test, four Block II modules (one from each manufacturer) were subjected to 30 days of humidity cycling in the presence of a 250-volt reverse-bias voltage and a 100-volt bias to frame. Two of the four modules showed visible changes associated with material transfer and discoloration. In before-and-after measurements, it was found that the shunt resistance of solar cells increased about 50% on the average (Fig. 7). In general however, the test had little effect on power output as indicated by a maximum power loss of less than 5%. In the second phase test, three minimodules from four manufacturers (12 total) have been exposed to 20 days of humidity cycling with and without ground plane biasing, and with and without reverse biasing. As with the phase one test, discolorations and corrosion were the visible changes noted. The discoloration

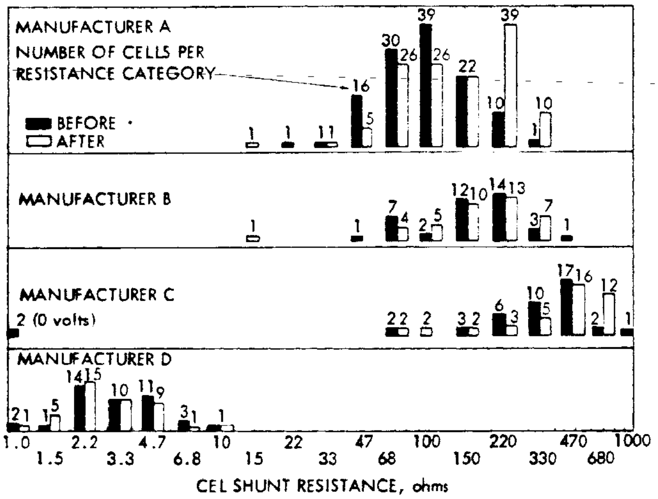


Figure 7. Cell shunt resistance before and after bias humidity testing

common to both tests occurred in the second test for the module with the +250-V ground plane bias. The material migration observed on one module in the first test did not repeat in the second test. The discoloration and material migration observed during these tests have not been observed on modules in the field (18 months exposure to date). Because of this lack of correlation between test results and field experience, an argument can be offered for not requiring a bias humidity qualification test for modules. However, the test has detected design or workmanship problems on some modules that have not been detected by other qualification tests. Modifying the existing humidity test to include voltage biasing is straightforward for both specifications and implementation. It is likely that a voltage bias requirement will be added to the current humidity test for the qualification of new module design approaches.

## CONCLUSIONS

A methodology based on a multiple iterative process for establishing and updating environmental qualification requirements for terrestrial solar cell modules has been developed and is being applied to candidate qualification tests. The current set of qualification tests are proving useful for detecting design-process, and workmanship deficiencies. Temperature cycling, cyclic pressure loading, and humidity cycling have been especially useful. There is positive correlation between some of the observed field effects and qualification-test-induced degradation. Test procedures for two field-related problems are needed and are being developed. The two problems are optical surface soiling (i.e., dirt) and encapsulant delamination.

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