ENVIRONMENTAL TESTING OF TERRESTRIAL FLAT PLATE PHOTOVOLTAIC MODULES

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ABSTRACT

The Low-Cost Solar Array (LSA) Project at the Jet Propulsion Laboratory has as one objective: the development and implementation of environmental tests for flat plate photovoltaic modules as part of the Department of Energy's terrestrial photovoltaic program. Modules procured under this program have been subjected to a variety of laboratory tests intended to simulate service environments, and the results of these tests have been compared to available data from actual field service. This comparison indicates that certain tests (notably temperature cycling, humidity cycling, and cyclic pressure loading) are effective indicators of some forms of field failures. Other tests have yielded results useful in formulating module design guidelines. Not all effects noted in field service have been successfully reproduced in the laboratory, however, and work is continuing in order to improve the value of the test program as a tool for evaluating module design and workmanship. This paper contains a review of these ongoing efforts and an assessment of significant test results to date.

THE LOW-COST SOLAR ARRAY (LSA) PROJECT is a part of the Department of Energy's national photovoltaic program. By means of technology development and stimulation of the terrestrial photovoltaic industry, the Project objectives are, by 1986, to:

(1) Reduce the selling price of photovoltaic arrays to $500/kW (peak).

(2) Achieve array efficiencies of greater than 10%.

(3) Achieve array lifetimes of 20 years.

(4) Reach a national manufacturing capability for terrestrial photovoltaics of 500 MW/year.

These objectives were formulated at Project inception in 1975, at which time the Jet Propulsion Laboratory (JPL) was given the management responsibility for their implementation. Over 100 contracts have been issued to the industrial organizations and educational institutions where the technological and manufacturing developments have been centered.

To evaluate the design and workmanship for both current and candidate photovoltaic module types, the LSA Project has instituted an ongoing module test and evaluation effort. Elements of this task include the generation of test requirements, the development of test facilities and procedures, the performance of tests under both real and simulated environments, the measurement of electrical performance before and after such tests, and the evaluation of results.

Most of the test results given herein are for modules procured by the Project for the test and applications projects of the Department of Defense (DOD), the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL), and the NASA Lewis Research Center (LeRC). Three separate procurements of solar-cell modules have been made for this purpose: Block I was a 58-kW purchase of off-the-shelf module types, with deliveries mainly in 1976; Block II was a 110-kW purchase of modules to uniform design and test requirements, with deliveries mainly in 1977; Block III is the current purchase of 205-kW of modules to Block II design and test requirements but more uniform quality standards, with deliveries mainly in 1978. The next major DOE procurements of flat plate photovoltaic modules are being accomplished via the Albuquerque Operations Office's Program Research and Development Announcement (PRDA) for Flat Panel Applications Experiments (1)* and the Block IV procurements (2, 3). Delivery of preproduction qualification modules for these procurements is occurring in 1979. Production deliveries will occur in 1980. Further information on the Block I, II, and III modules is given in Table 1 and these modules are shown in Figs. 1 through 3.

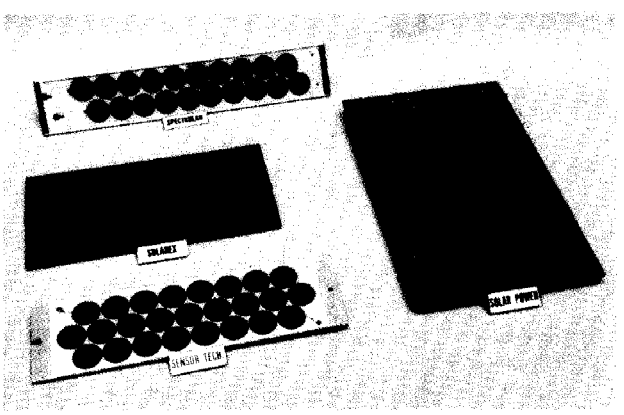

Fig. 1 - Block I flat plate photovoltaic modules

The remainder of this paper discusses the generation of environmental test requirements, the implementation of the tests, the test results, and the correlation between the tests and field observations.

ENVIRONMENTAL TEST REQUIREMENTS GENERATION

The development of environmental test requirements for flat plate photovoltaic modules is proceeding along two parallel and complementary paths. The first is to subject early production versions of the modules to sets of environmental tests for verifying adequacy of design, fabrication processes, and workmanship. The

*Numbers in parentheses designate References at end of paper.

Proceedings of the 14th Intersociety Energy Conversion Engineering Conference
Boston, MA, August 5-10, 1979, Volume 1. (A79-51726 23-44), p. 230-238.

Table 1 - Large-Scale Module Procurements

Manufacturer	Maximum Power Watts*	Dimensions mm	Physical Features
Block I (1976)			
Sensor Technology, Inc. Chatsworth, CA	5.8	571 x 165 x 11	Finned Al extrusion substrate 2.3-mm silicone encapsulant 25 cells, 50-mm diameter
Solar Power Corp. N. Billerica, MA	15.0	610 x 375 x 6	Epoxy fiberglass substrate 3.2-mm silicone encapsulant 22 cells, 87-mm diameter
Solarex Corp. Rockville, MD	9.4	508 x 260 x 5	Epoxy fiberglass substrate 2.3-mm silicone encapsulant 18 cells, 75-mm diameter
Spectrolab, Inc. Sylmar, CA	5.2	663 x 124 x 69	Al "I-beam" extrusion substrate 2.3-mm glass over silicone encapsulant 20 cells, 50-mm diameter
Block II (1977)			
Sensor Technology, Inc. Chatsworth, CA	10.4	589 x 290 x 25	Stamped Al substrate 3.2-mm silicone encapsulant 44 cells, 56-mm diameter
Solar Power Corp. N. Billerica, MA	31.3	1168 x 389 x 48	Molded polyester fiberglass substrate 2.8-mm silicone encapsulant 40 cells, 100-mm diameter
Solarex Corp. Rockville, MD	18.7	582 x 582 x 33	Polyester fiberglass substrate, Al frame 2.3-mm silicone encapsulant 42 cells, 75-mm diameter
Spectrolab, Inc. Sylmar, CA	28.5	1168 x 384 x 36	Formed Al frame 4.3-mm glass over PVB encapsulant 120 cells, 50-mm diameter
Block III (1978)			
Arco Solar, Inc. Chatsworth, CA	19.3	1160 x 232 x 36	Formed Al box frame 10-mm glass/PVB/Tedlar laminate 41 cells, 75-mm diameter
Motorola, Inc. Phoenix, AZ	23.1	580 x 580 x 50	Formed stainless steel pan 4.3-mm glass front, silicone gel encapsulant 48 cells, 75-mm diameter
Sensor Technology, Inc. Chatsworth, CA	10.1	582 x 287 x 48	Finned Al extrusion substrate 5-mm silicone rubber encapsulant 44 cells, 56-mm diameter
Solar Power Corp. N. Billerica, MA	31.4	1168 x 389 x 48	Molded polyester fiberglass substrate 2.8-mm silicone encapsulant 40 cells, 100-mm diameter
Solarex Corp. Rockville, MD	19.1	582 x 582 x 33	Polyester fiberglass substrate, Al frame 2.3-mm silicone encapsulant 42 cells, 75-mm diameter

*Average maximum power for a module

second is to develop approaches and procedures for accelerated life testing of encapsulant materials. This paper addresses only the former test activity.

The approach being used at JPL for developing qualification test requirements is a multiple iterative process consisting of identifying an environmental problem, fabricating experimental test apparatus, performing exploratory tests with varying levels and procedures, and reviewing resultant requirements with industry and other organizations (4).

The environmental 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). An expanded interface with national standards writing organizations is evolving from these efforts, with resulting benefits for the entire photovoltaic community.

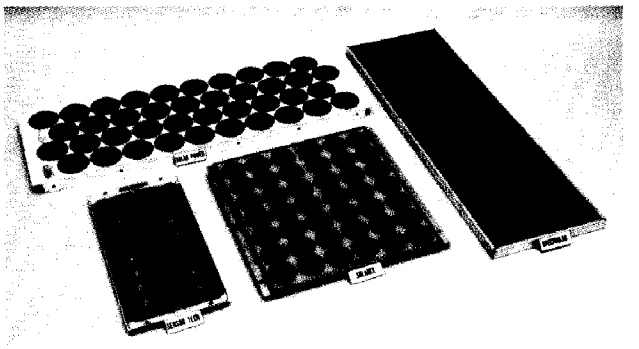

Fig. 2 - Block II flat plate photovoltaic modules

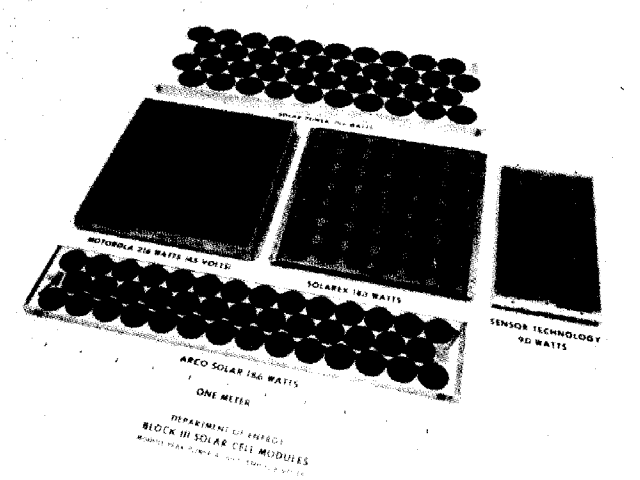

Fig. 3 - Block III flat plate photovoltaic modules

The environmental requirements currently being used to qualify modules are summarized in Table 2. The rationale for the selection of these tests, their levels, and their durations have been described previously (4).

ENVIRONMENTAL TEST IMPLEMENTATION

The flow plan for the qualification testing of flat plate photovoltaic modules is shown in Fig. 4. The diagram indicates the sequence of tests after initial inspection and the performance of baseline electrical measurements.

Several of these tests required equipment that was not readily available in-house or at commercial test labs at the outset of the Project. The necessary testing equipment was obtained by either modifying an existing testing facility or fabricating new testing equipment, as described below.

Temperature cycling and humidity tests were developed to simulate the diurnal and climatic variations of temperature and humidity which any solar energy conversion device must withstand. Standard temperature/humidity chambers are used for these tests. In order to simulate the effect of differential thermal expansion between the modules and their mounting structure, a special 1.2 x 1.2 m (4 x 4 ft) steel subarray frame was designed and fabricated such that equal mounting stresses were seen by each module in the test subarray. This frame was first used for the Block II procurement.

The cyclic pressure load test was developed to simulate module mechanical stresses due to wind to uncover design weaknesses of cell interconnects, encapsulation systems, and cells. To perform this test, a new test apparatus (5) was developed. This apparatus induces uniform loads across the modules of 2400 pascals and automatically alternates the pressure loading between the front and back sides.

A different wind resistance test is being specified for residential shingle-type modules (i.e., a specially designed flat plate module that also functions as a roof covering). The apparatus and pro-

Table 2 - Environmental Qualification Tests for Flat Plate Photovoltaic Modules

Tests	Modules: Block I (1976)	Block II (1977)	Block III (1978)	PRDA** (1978-'79)	Block IV (1979)	Present Environmental Test Levels
Temperature cycling	X	X	X	X	X	-40°C, +90°C, 100°C/h, 50 cycles
Humidity cycling	X	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*	X	±2400 Pa (±50 lb/ft^2), 10,000 cycles (Blk. II, III, 100 cycles)
Wind resistance (Shingles only)				X*	X	Underwriters Lab Standard UL 997
Warped mounting surface		X	X	X	X	±2 cm/m (±1/4 in./ft)
Hail impact				X*	X*	3 hits at each of 3 points on module
Electrical isolation		X	X	X*	X	Leakage current ≤50 μA at application-dependent voltage (e.g., 1500 Vdc) (Blk. II, ≤15 μA at 1500 Vdc)

*Test levels are application dependent

**PRDA — Program Research and Development Announcement

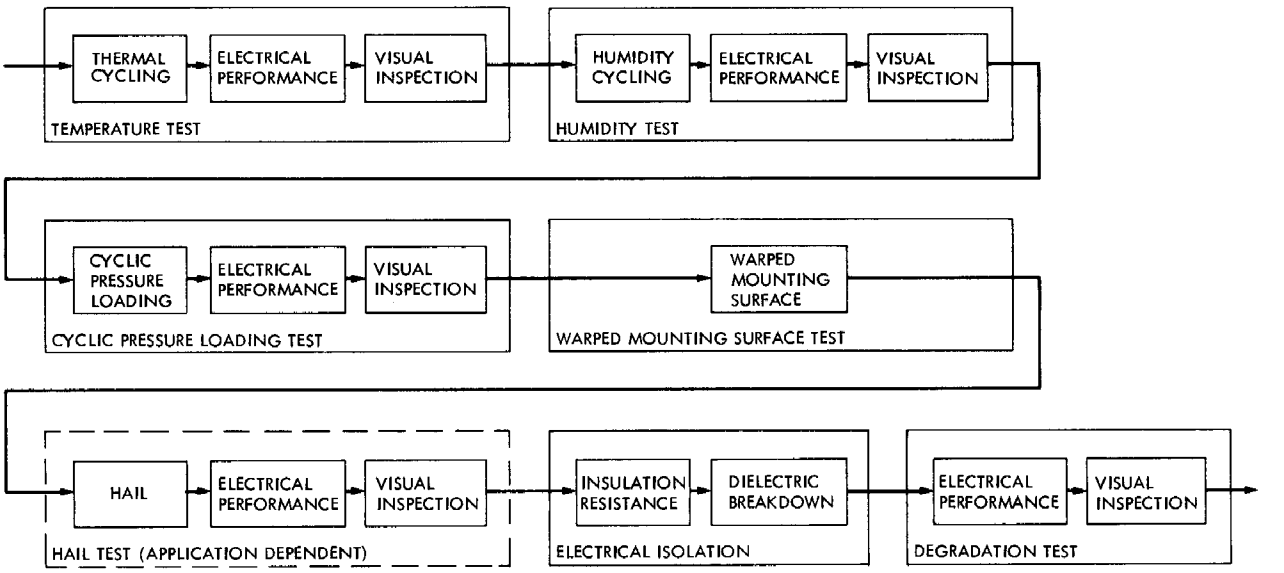

Fig. 4 - Qualification test sequence for flat plate photovoltaic modules

cedures given in Underwriters Laboratories Standard UL 997, "Standard for Wind Resistance Testing of Prepared Roof Covering Materials," form the basis of this test.

The warped mounting surface test was developed 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. A simple test jig for conducting this test was built. This apparatus permits one corner of the module to be raised and lowered a specified distance while holding the other corners fixed (2, 3).

The most recent addition to the environmental qualification requirements (2, 3) is hail testing. The hail test has been developed to characterize the susceptibility of a module's encapsulant, cells, and overall design to high-impact loading associated with hailstorms (6). The key element of the test apparatus is a device for propelling ice balls of the required hailstone diameter at terminal velocities 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.

Insulation resistance and high-voltage withstanding tests are intended to verify the adequacy of the module design for working voltages. These electrical breakdown tests, performed with commercially available power supplies and instrumentation, apply voltage between the cell string and module frame (if any).

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. These tests are summarized in Table 3. 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.

For Block II and subsequent procurements, preproduction prototype modules were used for qualification testing. Production was approved only after implementation of design changes shown necessary by this test series. Production samples taken at random throughout the production run were also subjected to qualification testing. Production modules were also used for exploratory testing.

TEST RESULTS

Full environmental test programs (i.e., qualification and exploratory tests) have been completed for Block I and II modules. The qualification test program for Block III modules has been completed. Block III exploratory tests are in progress. Applicable levels and durations for the test programs are noted in Tables 2 and 3. Production module qualification test results are summarized in Tables 4-6. The severity of problems resulting from qualification test exposure has been roughly indicated by the size of the "bullets."

The Block II and III module test results indicate that these modules are much superior to those of Block I. Delamination was greatly reduced throughout, and the humidity exposure resulted in very few discrepancies for Block II and III modules. Electric degradation occurred less frequently, and individual power loss percentages were also lower. Problems with interconnects were virtually eliminated. However, cell cracking was at least as prevalent for Block II as it was for Block I. It should be noted that cracked cells have been observed to some degree in all types of modules. Investigations are in progress to understand the module or cell design features contributing to cracking. The effects of cell cracking in the field can be circumvented by designing into the modules and arrays protective diodes or series paralleling circuits.

The Block I and II exploratory test results (Tables 7 and 8) show that salt fog could be a degradation concern for modules intended for marine applications. Humidity-freezing tests showed this environment is important in simulating delaminating effects. The other results are inconclusive. Some Block I modules showed less degradation than their Block II counterparts for certain tests and vice versa for other tests.

DISCUSSION

The essential indicator of the ability of an environmental test program to pinpoint potential problems is the degree of correlation between test and in-service degradation. Obtaining needed data from field tests and applications to make such a correlation is a significant task in itself, entailing identifica-

Table 3 - Exploratory Environmental Tests for Flat Plate Solar Cell Modules

	Tests	Modules: Block I	Modules: Block II	Modules: Planned Block III	Test Levels and Test Equipment
1.	Heat-rain	X	X	X	Modules allowed to reach maximum temperature on a clear warm day; hard rain simulated with deionized water spray until modules reach equilibrium (about 8 min.), 5 cycles. Specially designed water spray equipment.
2.	Wind-driven rain	X	X	X	Spray of deionized water at 40 mph and 2 mm average droplet size; modules slowly rotated in heavy spray for 15 minutes. Specially designed equipment.
3.	Humidity-freezing	X	X	X	MIL-STD-202E, Meth. 106D (no vibration). 2 cycles 23 to 65°C at 95% RH for 16 h; then, -13°C for 3 hours. 10 cycles. Standard temperature-humidity test chamber.
4.	Humidity-heat	X	X	X	Modules are water-saturated in a chamber for 6 h at 70°C, 95% relative humidity; then removed and irradiated at full simulated sun to stable temperature. 10 cycles. Standard temperature-humidity chamber and 3400 K lamp bank.
5.	Humidity with voltage bias	X	X	X	Levels being developed. Standard temperature-humidity test chamber.
6.	Salt fog	X	X	X	MIL-STD-810C, Meth. 509.1. Salt spray, 35°C, 95% R.H. for 48 h. Salt fog chamber.
7.	Hail impact	X	X	X	Iceballs of 1 to 5 cm diameter impact the modules at terminal velocities. Specially designed gas gun.
8.	Fungus	X			MIL-STD-810B, Test Method 508.1. Modules sprayed with salt and fungal culture and placed in humidity chamber at 30°C and 95% RH for 28 days.
9.	Combined environment: temperature, humidity, UV			X	Levels and equipment being developed.
10.	Optical surface soiling			X	Levels and equipment being developed.

Table 4 - Block I Qualification Test Results

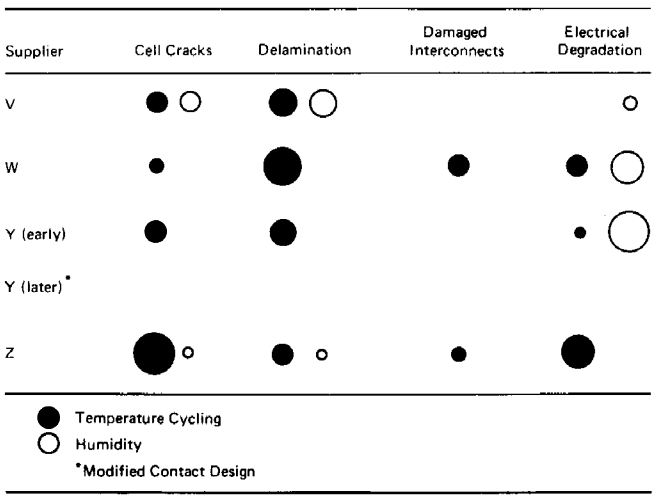

Table 5 - Block II Production Samples Qualification Test Results

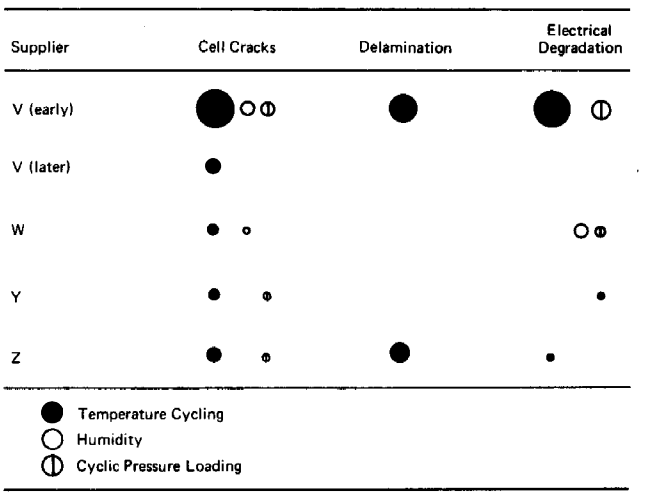

Table 6 - Block III Production Samples Qualification Test Results

Supplier	Cell Cracks	Encapsulant: Bubbles	Encapsulant: Delam	Encapsulant: Leaks	Corrosion	Workmanship, Electrical	Electrical Degradation
R	●	●		●		□	
U							
V					○	●	
Y			∘				
Y Hi-Density							
Z	○ ◐		● ○				

● Temperature Cycling
○ Humidity Cycling
◐ Cyclic Pressure Loading
□ Discovered Pretest

Table 7 - Results of Exploratory Testing of Block I Modules

Supplier	Humidity-Freezing	Salt Fog	Hard Rain	Heat-Rain	Humidity-Heat	Fungus
V	Discoloration, delamination	Slight corrosion	Pass	Pass	Delamination	Pass
W	Delamination, cracked terminals	Slight corrosion	Pass	Pass	Pass	Pass
Y	Pass	Pass	Pass	Pass	Pass	Pass
Z	Delamination, electrical degradation	Minor delamination	Pass	Pass	Pass	Pass

Table 8 - Results of Exploratory Testing of Block II Modules

Supplier	Humidity-Freezing	Salt Fog	Heat-Rain	Wind-Driven Rain	Humidity-Heat
V	Electrical degradation, discoloration, delamination	Oxidation	Electrical degradation	Pass	Cracked cell
W	Pass	Electrical isolation	Cell cracked	Pass	Pass
Y	Delamination	Corrosion	Pass	Pass	Pass
Z	Minor delamination	Pass	Electrical degradation, split encapsulant	Pass	Electrical degradation

tion of the parameters to be monitored, acquisition of in-situ measurements, and reduction and interpretation of results. The uncontrolled, application-peculiar nature of the environmental and system-related stresses imposed on the module introduces uncertainties in attempting to establish the cause of the observed problems, which complicates the field versus test correlation.

The LSA Project, in cooperation with the test and applications projects, has established a problem/failure reporting and analysis system to provide a mechanism for identifying and correcting design and workmanship defects which lead to module problem/failures during test or service. The elements of this system are shown in Fig. 5. An analysis of the data archived in this system, together with other available reports on module performance, shows the main causes of in-service degradation to be those

Table 9 - 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 (temperature cycling, humidity, 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

summarized in Table 9. Where the results of the various tests described above show similar effects, this correspondence is also noted in the table.

Examination of Table 9 shows that suitable qualification tests for two real-world effects — optical surface soiling and encapsulant delamination — remain to be developed; however, work is progressing in these areas. Vandalism, although a significant field problem, is a site security problem more appropriately addressed at the system level than by a module qualification test.

It will also be noted that the other phenomena relate to macroscopic physical degradation, which may in turn induce electrical degradation. For cracked or mismatched cells or interconnect problems the temperature cycling test appears to be the best indicator, with the humidity cycling test also showing fair correlation. These results suggest that the electrical failures observed in the field to date are mainly induced by differential thermal stress acting on the more fragile circuit elements within the module.

Encapsulant delamination has been observed to some degree at surfaces to which silicone rubber encapsulants (RTV 615 and Sylgard 184) have been bonded. The most severe examples have occurred at epoxy-fiberglass substrates of Blocks I and II modules. Figure 6 shows an extreme example from the field, in which the accumulation of liquid water in the resultant void is evident. Poor initial adhesion due to inadequate surface preparation may have been a contributing factor in such cases, but changes in surface energetics caused by environmental stresses are more important (i.e., a UV weakened bond may undergo delamination on exposure to moisture, Ref. 7).

The thin metallic interconnects between solar cells have proven susceptible to fatigue failures unless the interconnect design provides stress relief. When cells are series-connected to provide high voltage levels with no provision for current bypass around such faults, a sustained arc can be drawn across the fracture with destructive effect to the surrounding material. Figure 7 shows an example of a Block I module which failed in this fashion, charring the encapsulant and substrate near the point of failure. Temperature cycling and cyclic pressure loading tests are an effective screen for design problems of this sort. Early Block I modules exhibited these failures both in test and in service; Block II and III modules have not experienced failures in either case.

Since high-purity crystalline silicon is a brittle material, solar cells fracture rather easily under mechanical stress, particularly when the cells have edge chips or other flaws. Extreme cases lead to cell overheating or open-circuit conditions, while hairline cracks may have little or no effect. Temperature cycling tests have proven to be the most effective of the current environmental simulations in inducing this failure mode, although any test which subjects the module to mechanical stress may cause occasional random cell cracks.

If significant mechanical stress such as from a hailstorm is encountered, the cell fracturing is quite dramatic. Modules at the MIT/LL's Irrigation Project near Mead, NE, were subjected to a hailstorm in May 1978. Significant cell fracturing was noted on some of the modules (Fig. 8). Similar damage had been observed during laboratory hail tests on identical modules (Fig. 9).

In reviewing these results, it is clear that the temperature cycling test is the most valuable of the current series of environmental tests when evaluated on the basis of the ability to reproduce common field problems. The humidity test and the cyclic pressure loading tests have served well enough to merit retention, perhaps in modified form. The hail test is a valuable application-dependent test for modules being installed in hail-prone areas. The most serious shortcoming of the current qualification test series is the inability of these tests to reproduce the most common form of performance degradation — soiling. Further efforts to isolate the nature and cause of this phenomenon are in progress.

A forecast of near-term testing activity is given in Table 10. 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.

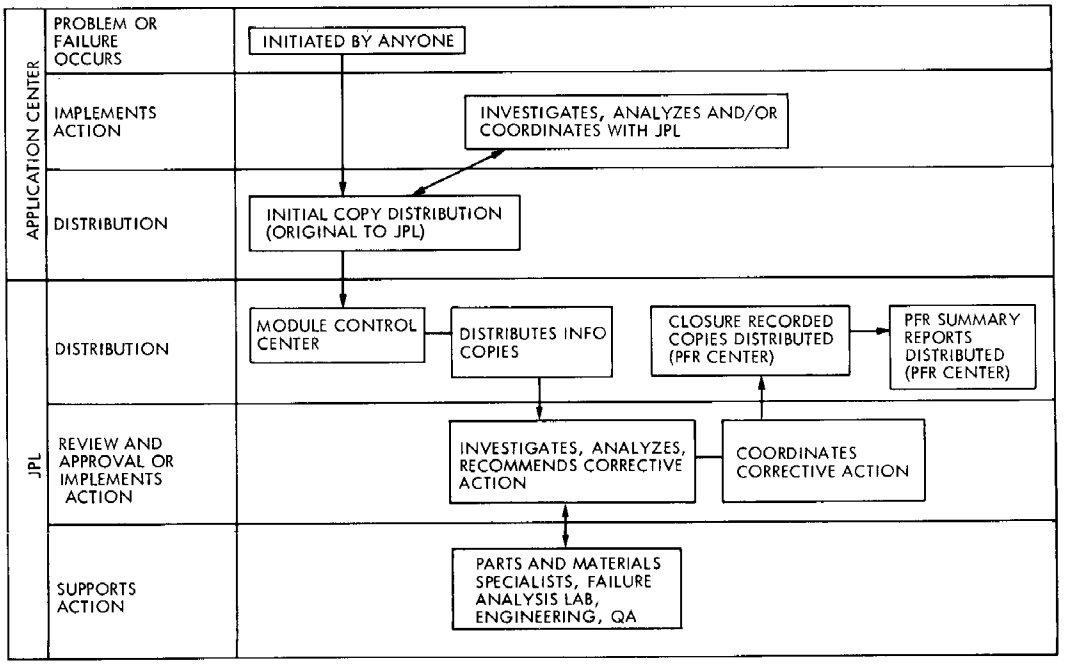

Fig. 5 - Problem/failure report flow diagram

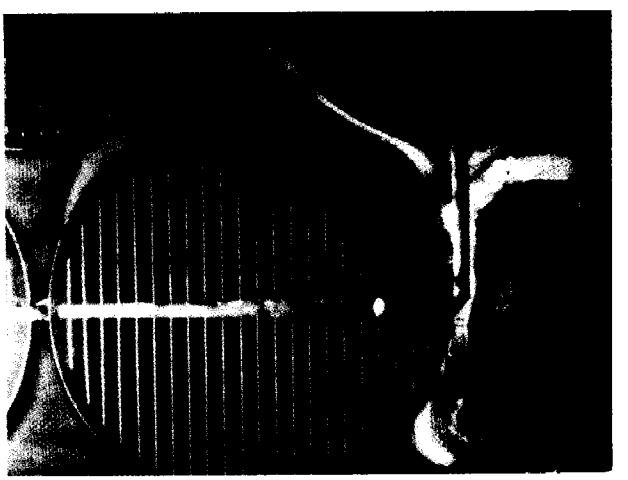

Fig. 6 - Example of solar cell module encapsulant delamination

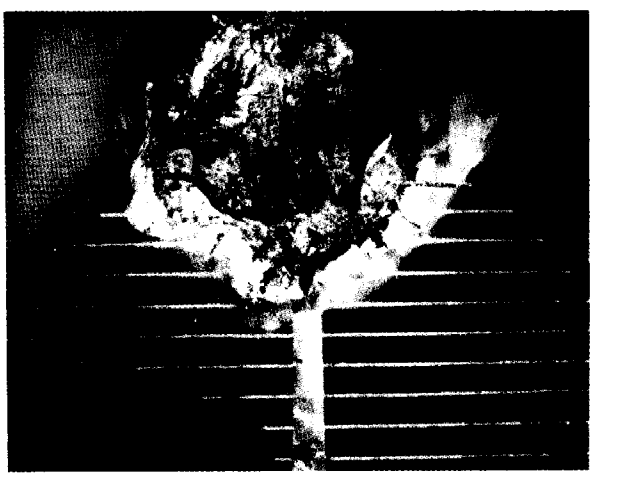

Fig. 7 - Interconnect failure with charred encapsulant

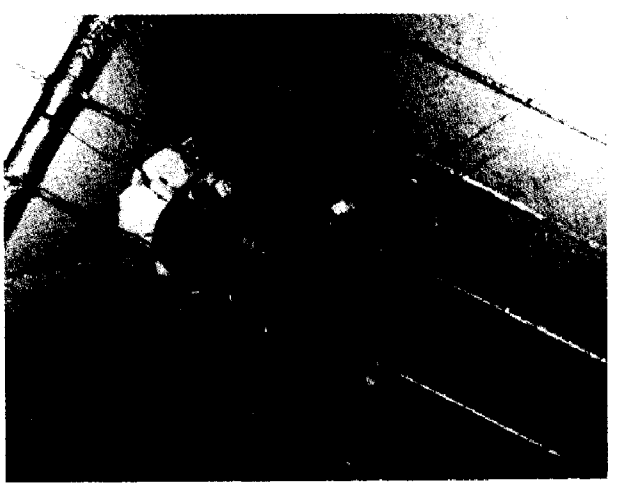

Fig. 8 - Hail damage on module from Mead, NE

Fig. 9 - Laboratory-induced hail damage on identical module

Table 10 - Environmental Testing Forecast for Solar Cell Modules

Environment	Forecast	Remarks
Present qualification tests (Ref. 1)		
Temperature cycling	○	
Humidity cycling	○	
Cyclic pressure load	○	
Warped mounting surface	○	
Hail impact	△	Applicability site-dependent
Present exploratory tests		
Heat-rain	○	
Wind-driven rain	⊗	
Humidity-freezing	○	May be combined
Humidity-heat	○	May be combined
Humidity with voltage bias	○	May be combined with humidity cycling when better understood
Salt fog	○△	Applicability as a qualification test, site dependent. May be made more severe.
Hail impact	○	
Other tests		
Fungus	△	Applicability site-dependent
Combined environment (temperature, humidity, UV)	●	Qualification test if proper test conditions are found to simulate field-type degradations
Optical surface soiling	●	Qualification test if representative test conditions can be developed

○ continue

⊗ discontinue

△ special qualification test

● qualification test needed and being developed

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. 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. The hail test is a useful application-dependent test.

Field experience to date (approx. 2 years) indicates that the failure rate of modules at endurance and application sites is very low (approximately one percent). Many of the observed field effects (e.g., power loss) are showing a positive correlation with qualification-test-induced degradation. The limited field experience available does not warrant the assumption that all important failure modes have been identified. Continuing analysis of problem/failure reports and other field data is needed to improve the understanding of failure modes as they become evident.

Module soiling is currently the most significant field-related problem that is not adequately accelerated and duplicated under controlled test conditions in the laboratory. Natural removal mechanics are key parameters in determining soiling retention differences between different module surfaces.

ACKNOWLEDGMENT

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