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FIELD TEST EXPERIENCE

R.W. Weaver
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

INTRODUCTION

As a part of the Flat-Plate Solar Array Project (FSA), a field-test program was developed to obtain solar photovoltaic (PV) module performance and endurance data. These data are used to identify the specific characteristics of module designs under various environmental conditions. The information obtained from field testing is useful to all participants in the National Photovoltaics Program, from the research planner to the life-cycle cost analyst.

TEST SITES AND DATA PROCESSING

The Field Test Program plan identified four Southern California test sites with characteristics ranging from oceanside to desert environments, including one with high urban pollution. Test facilities at these sites were constructed and modules were deployed in 1977. All of the modules deployed were first tested and inspected at the Jet Propulsion Laboratory (JPL). The testing was done using the Large-Area Pulsed Solar Simulator (LAPSS) to obtain I-V (current-voltage) data, at a reference irradiance level and module temperature, the results of which were used as baseline data whenever the module was returned to JPL for special testing. The pre-deployment inspection was a detailed visual examination of the modules, from which an original-condition report was generated. Subsequent inspection reports were compared with this report to discover and identify physical changes in the module.

In 1978 the FSA Field Test Activity assumed responsibility for 12 more test sites, which had been established originally by the National Aeronautics and Space Administration (NASA) Lewis Research Center as part of the NASA energy program. These sites were situated as far north as Alaska and as far south as the Canal Zone, and covered virtually all climatic conditions. The characteristics of these sites and those of the four JPL sites are shown in Figure 2. Lewis Research Center also furnished JPL with all of the data that had been acquired for the modules at the 12 sites. The resulting site network consisted of 15 remote (unattended) sites and one at JPL.

Two data acquisition systems were developed, one for the remote sites and one for the JPL site. The data system for the remote sites was a portable battery-operated unit that sampled I-V data and displayed the key parameters (e.g., sh t-circuit current, open-circuit voltage, peak power). After acquiring the data the unit stored it on an erasable storage medium, which is readable on the JPL site data system. Data were acquired periodically from the remote sites using this unit.

The JPL site data system was designed to sample module performance daily. The system also takes weather and irradiance data every five minutes. All of the data were stored on magnetic disks for processing by scheduled programs or by special programs on demand. This system could also process data from the remote sites.

The endurance data were obtained periodically from all of the sites by means of physical inspections by a JPL quality-assurance team. The results of these inspections were written up as detailed descriptions of the physical states of the modules. These descriptions were then compared with previous inspection reports to identify changes in the modules occurring during the test period.

FAILURE PROCESSING

The performance and endurance data were used to determine if a failure analysis of a module were warranted; if so, the module was removed from the field and returned to JPL for further analysis. The criterion for performance failure was failure to produce 75% or more power than it did when it was originally tested. If the module's physical state had deteriorated to the point that it had become hazardous, or when performance failure was imminent, the module was to considered to have failed. Failed modules were returned to the JPL failure analysis team for detailed analysis to determine the type and cause of the failure. The results were published as Problem/Failure Reports and were distributed to all concerned in the PV program, including the module manufacturer.

RESULTS

In the nearly five years of field testing Blocks I, II and III modules, almost 10% failed the performance test. Many more experienced physical degradation that did, or would eventually, result in an unserviceable module. The plot in Figure 5 depicts performance failures as a function of time in the field. The curves show that for the Blocks I and II modules · failure rate increased over the last 18 to 24 months. This means that m modules (per module deployed) were failing after the first three years than before that time. This leads to the conclusion that there is definitely a time-versus-design correlation for field failures.

The results of the physical inspections are shown in the chart in Figure 6 for the Blocks I and II modules (type refers to manufacturer). The defects are ranked by severity for each site and type. No site stands out as being more severe than any other in the chart. However, when the performance data are also considered, the sites with hot-humid climates clearly have more severe environments.

Some results from non-JPL sites are described in Figure 7. The causes of failure are basically the same as for the JPL tests; only the rate of failures is different. The notable exception is the number of burst cells observed at the Mount Laguna site. The ultimate effects of the three most prevalent defects are shown in Figure 8. All of these defects would eventually require that the module be replaced. Figures 9 and 10 describe several of the prime reasons for cell failure.

During the test period, changes in the cell grid and collector materials were observed. The most common was the discoloring, usually a browning, of the grid and collector material. Several of the modules were disassembled and the discolored area was analyzed. The probable cause was a reaction with some residual material from the manufacturing process. The "blossoming" effect found at the ends of some grid lines is attributed to the migration of the silver used in the grid material. This effect was seen only in modules that used silver in the grid material and that were configured so that the end of a grid line was near another part of the electrical circuit that was at much different electrical potential.

The test results also indicated other reasons for loss of power or module degradation. Some of these are presented in Figure 12. The most severe, relative to the loss of power, is the amount of dirt that is deposited on the module surface. Power losses of as much as 12% were observed within a three-month period. The best design for preventing power loss from soiling was that with a glass superstrate on the module.

SUMMARY

JPL field test results were compared with test and operational results from other centers in the PV program to determine if similar failures were occurring elsewhere. The consensus as to the principal causes of electrical failure was: (1) cracked cells, (2) broken interconnects, (3) various types of shorts. The principal types of physical degradation were: (1) delamination of encapsulants, (2) discoloration of encapsulants, (3) internal corrosion of interconnects and grid connectors, (4) external connector corrosion. There appears to be no correlation between the physical appearance of the module, dirt deposits excepted, and performance. The most severe environment is the hot-humid type.

A representative sample of the modules that were used in this test program have been relocated at the JPL Goldstone site. Data will be sampled annually to determine what effect further time in the field may have on the modules.

Figure 1. Objectives of Field-Test Activity

- To obtain in-field performance data for life-cycle endurance evaluation
- To determine degradation characteristics and failure modes as they relate to module design characteristics
- Provide verification data to qualification testing
- Develop improved in-situ diagnostic testing methods and analytical techniques

Figure 2. Field-Testing History

1977 • Establish four sites in Southern California

• Automatic data acquisition system installed at the JPL site (Block I and II modules)

1978 • Acquired 12 more test sites from Lewis Research Center (Block I and II modules)

• Developed a portable Module I-V data acquisition system

• Initiated semiannual inspections of remote sites

• Block III modules deployed to sites

1979 • Data analysis techniques developed and applied to all data available

1981 • Remote sites decommisioned

• Final data analysis for Blocks I, II, and III performed

1982 • Started Block IV deployment and testing

Figure 3. JPL Test Sites

CATEGORY	LOCATION	LATITUDE (degrees)	ALTITUDE (feet)	KEY FEATURES
EXTREME WEATHER	CANAL ZONE (FT. CLAYTON)	9	~0	TYPICAL TROPIC - HOT AND HUMID; 100 INCH-PER-YEAR RAINFALL
	ALASKA (FT. GREELY)	64	1,270	SEMI-ARCTIC - DRY, COLD AND WINDY; -30 F WINTERS
MARINE	POINT VICENTE, CA	34	~0	COOL, DAMP MORNINGS AND CLEAR AFTERNOONS; CORROSIVE SALT SPRAY
	KEY WEST, FLA.	25	~0	HOT AND HUMID; CORROSIVE SALT SPRAY
	SAN NICHOLAS ISLAND, CA	34	~0	SOMEWHAT MILDER THAN KEY WEST
MOUNTAIN	TABLE MOUNTAIN, CA	34	7,500	TYPICAL ALPINE ENVIRONMENT - HEAVY WINTER SNOWS AND MILD SUMMERS; HIGH-VELOCITY WINDS
	MINES PEAK, CO	40	13,000	CLEAR AND COLD; HIGH-VELOCITY WINDS, MAX. UV
HIGH DESERT	GOLDSTONE, CA	35	3,400	VERY HOT AND DRY SUMMERS; CLEAR SKIES
	ALBUQUERQUE, NM	35	5,200	DRY WITH CLEAR SKIES; AN ABUNDANCE OF UV
	DUGWAY, UTAH	40	4,300	COLD WINTERS, HOT SUMMERS; ALKALINE SOIL
MIDWEST	CRANE, INDIANA	39	~0	TYPICAL MIDWEST; HOT HUMID SUMMERS, COLD SNOWY WINTERS
NORTHWEST	SEATTLE (FT. LEWIS)	47	~0	TYPICAL NORTHWEST - MILD TEMPERATURES AND AN ABUNDANCE OF RAIN
UPPER GREAT LAKES	HOUGHTON, MICHIGAN	47	750	MILD SUMMERS, SEVERE WINTERS
URBAN SOUTHERN CALIFORNIA	JPL/PASADENA	34	1,250	PRIMARY TEST SITE - HOT SUMMERS AND MILD WINTERS; VERY HIGH POLLUTION ENVIRONMENT
URBAN COASTAL	NEW LONDON, CONNECTICUT	41	~0	TYPICAL NEW ENGLAND COASTAL
	NEW ORLEANS, LOUISIANA	30	~0	HOT AND VERY HUMID; HIGH POLLUTION ENVIRONMENT

Figure 4. Test and Inspection Procedures

Testing

- **Modules were "stressed" via fixed resistors**
- **Baseline I-V data acquired during installation**
- **Periodic I-V data taken**
- **Performance evaluated**

Inspection

- **Visual inspection prior to shipping to site**
- **Visual inspection during installation**
- **Periodic inspections**
- **Physical change description reports**

Figure 5. Blocks I, II and III Results

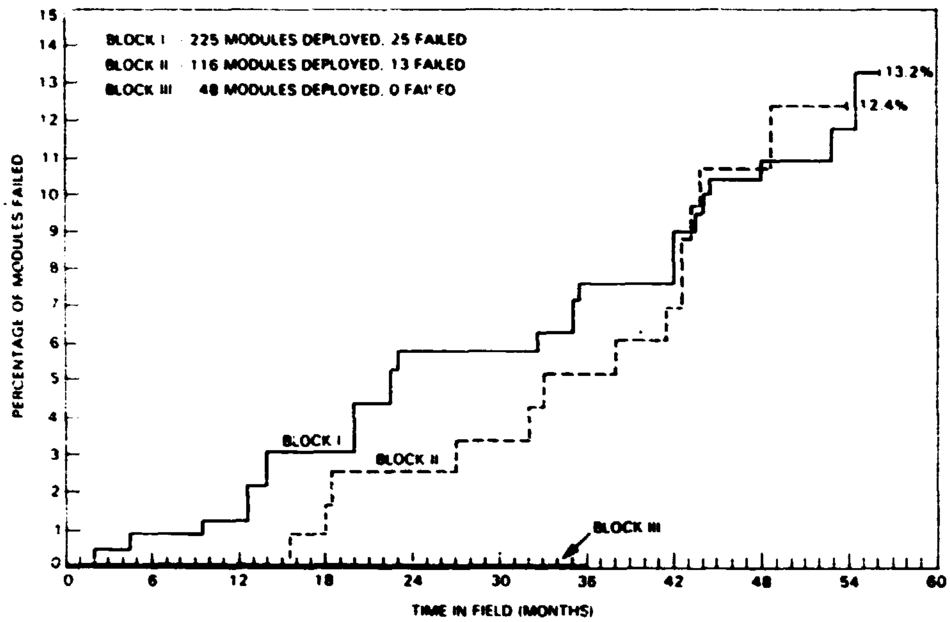

Figure 6. Physical Inspection Summary of Remote-Site Modules

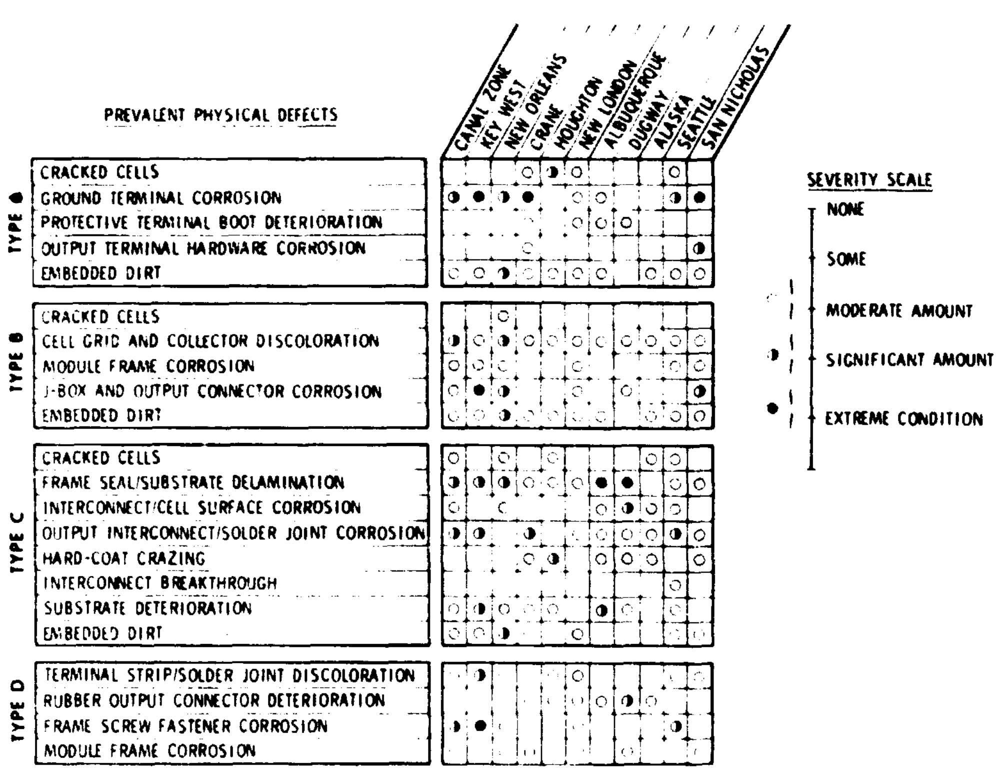

Figure 7. Results From Non-JPL Sites

Mount Laguna, CA (July 1979 - July 1981)

- Cracked cells: 1500 (950 "burst")
- Output: Down 55%
- Encapsulant: Delamination

MIT/LL

- In-field, over 30 months: 6.5% failed
- Causes: Cracked cells, broken interconnects and shorts
- Physical: Delamination, cracked glass

Figure 8. Failure Effects

TYPE	EFFECTS
Cracked cell	• Loss of power • Hot-spot heating • Loss of module
Broken interconnect	• Loss of power • Loss of module
Short circuit	• Loss of power • Loss of module • Hazardous condition

Figure 9. Causes of Cracked Cells

Impact type

- Hail storms
- Rocks
- Other

"Burst type"

- Outgassing of material between cell and substrate
- Moisture entrapment and subsequent heating

Other causes

- Manufacturing defects
- Hot spotting
- Module twisting

Figure 10. Observed Changes in Grids and Collectors

Discoloring

- Brown coloring - probably due to reaction with contaminants
- White streaking (GE) ??

Separating from cell

- Manufacturing problem

"Blossoming"

- Silver migrating to ends of grid that are at a high potential relative to nearby cell or circuit component

Figure 11. Other Reasons for Loss of Module Output

Dirt

- 2 to 12% loss
- Partially correctable via cleaning
- Glass is best self cleaner

Discoloring of encapsulant

- Select proper material-glass

Thermal related

- Cycling effects
- Expansion stress
- Match materials or compensate

NSMD

- San Nicolas Island, Mines Peak, Pt. Vicente

Hazards of field testing

Figure 12. Conclusions

- Electrical degradation or failure is not necessarily a function of physical appearance
- Three primary known causes of failures were cracked cells, broken interconnects, and electrical shorts
- Most severe environment is hot and humid

DISCUSSION

CAMPBELL: What percentage of Block I, II and III modules were glass superstrate?

WEAVER: I can't give you a percentage but I think there were only two manufacturers that we tested during that period that used glass.

LAVENDEL: You, in your failure analysis, mentioned discoloration several times. Is this really a hazard or is it mostly cosmetic?

WEAVER: I think it is mostly cosmetic. Like I said, we very seldom, if ever, could find an electrical performance degradation related to a discoloring of the system.

LAVENDEL: Have you ever tried to define the composition of this discolored film?

WEAVER: Yes, we did send it to our Failure Analysis group and I think they have found what other people have found, if they peel the encapsulant away. Brian (Gallagher), do you want to field that?

GALLAGHER: I am going to give a short presentation this afternoon on metal degradation of a very specific encapsulant, and to answer your first question, you will see this afternoon that the first property that degrades that is visible is transmission at 400 nanometers: it starts to turn yellow. To your question about whether it really degrades the modules or not -- if the yellow transmission at 400 nanometers degrades down to 10% of its original value, which looks like a lot, you only have from 5% to 10% degradation in the electrical properties of the module of the total integrated area from 400 nanometers to 1.1 micron. You would still only have 5% to 10% degradation. We will cover it a little more detail this afternoon.

AMICK: You showed that Block III modules are much better from the standpoint of reliability than I or II. Do you understand the reasons why the Block III modules have improved so dramatically? I and II look pretty much the same.

WEAVER: Well, we would like to think it because we told them what was wrong with I and II. Redundant interconnects came on very strongly in Block III, there were some in II, but basically in Block III. The redundant interconnects; a better understanding of stress relief in interconnects. Better encapsulation procedures, we think, came into effect there. Glass, more glass. There was a Block II contractor that used glass that I don't think is still in the business of terrestrial PV; I think they are still in the space business, and some of their Block II modules are actually putting out more now than when we originally put them in the field. That was a small cell. But they were so expensive there was no point in going on.

SCHWUTTKE: On the subject of electrical migration: was this typical of all modules? At what distance from anode to cathode did it occur, and is it typical for all metallurgies -- that is, for all modules?

WEAVER: I will defer that to either Ed (Royal) or Gordon (Mon), because they understand that better than I do.

ROYAL: Gordon (Mon) is going to talk about that this afternoon.

WEAVER: I can answer that to some extent -- no, we have not seen it in all of them. In the ones that we understand have silver, yes, we have seen it.

PROVANCE: Have you observed any phenomena with this discoloration per location -- in other words was it more prominent in one location than in another? The reason I ask that is that sulfur tends to sulfide in areas of high sulfur concentration, so if it is in an industrialized area some of the discoloration, I would think, would be from the sulfiding.

WEAVER: No, I don't think I could correlate that to an area. The site at JPL is the worst urban environment, pollution-wise, that we found. Mines Peak had almost none. Almost no discoloring at all.

SCHWUTTKE: But you lost all of your modules there--

WEAVER: On the last inspection.

PROVANCE: We have seen this quite prominently in other thick-film applications, in microelectronic circuits where silver or platinum-silver compositions will tend to discolor or sulfide very quickly in various areas of high concentration of industry. But much longer periods of time for the same discoloration to occur in very clean areas.

WEAVER: The worst case I have seen of it was at Cape Canaveral at the Florida Solar Energy Center. Very predominant in those modules there.