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RELIABILITY OF TERRESTRIAL PHOTOVOLTAIC MODULES AT  
VARIOUS DOE/MIT LINCOLN LABORATORY TEST SITES\*\* \*

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ABSTRACT

During the past four years, acting under the auspices of the U. S. Department of Energy, Massachusetts Institute of Technology Lincoln Laboratory has built and operated in the United States photovoltaic power-generating systems ranging in size from less than 1 kWp to 100 kWp. Slightly more than 11,000 modules from several manufacturers have been utilized at these sites with a cumulative number of electrical failures of approximately 2%. Discussion is presented of module performance at two of these sites: a 25-kWp array field at Mead, Nebraska, and a 100-kWp array field at Natural Bridges National Monument, Utah. Data and photographs of module failures, failure modes, physical and electrical degradation, and array diagnostics are presented for each of the five different types of modules utilized at these sites.

INTRODUCTION

MIT Lincoln Laboratory serves as a Field Tests and Applications Center for the U. S. Department of Energy (DOE) in order to evaluate the energy potential of photovoltaic (PV) components in various test applications. As part of the DOE/Jet Propulsion Laboratory's (JPL) Large-Scale Procurement Program, Lincoln Laboratory receives from various manufacturers, PV modules containing silicon solar cells for use at its experimental test sites. (The names of the module manufacturers are not relevant to this report, and the module types discussed are referred to as Models A, C, D, E and F.) Data are presented for the modules utilized in two experimental PV systems: a 25-kWp PV power-generation system at Mead, Nebraska, and a 100-kWp system at Natural Bridges National Monument, Utah.

DOE has set a 20-year lifetime goal for terrestrial PV modules. In the absence of meaningful accelerated tests to predict performance for various intervals of time, real-time test data have provided the only indication of module performance and reliability in terrestrial environments. At all Lincoln Laboratory's PV test sites, a total of 11,117 modules have been placed in service and only 250 (2.25%) have failed electrically. At the Mead, Nebraska, and Natural Bridges National Monument sites, 6,764 modules have been used and 128 have failed electrically (1.89%). Specific details are given in the following sections on module failures and failure rates, the electrical and physical degradation of modules due to weathering, and the diagnostics used to locate electrically degraded modules.

NATURAL BRIDGES NATIONAL MONUMENT TEST SITE

During 1980, a 100-kWp PV power-generating system was installed at Natural Bridges National Monument (NBNM). While the system was officially dedicated in June, the array field was installed in January. A complete description of the system is contained in Reference 1 and only details pertaining to the array field are presented here.

An aerial view of the array field is shown in Fig. 1. There are 1,740 Model E modules in the front of the array field, 2,064 Model F modules in the center, and 720 Model A modules at the rear. The Models E and F modules were purchased as part of Block III and the Model A modules are from Block II. All three types are glass covered. [Modules were purchased by JPL for DOE in three "Block" buys: I (1975-76); II (1977-78); and III (1979-80).]

Of the three types of modules present in the array field, the most significant electrical problems have been incurred by the Model F modules. During the first year of operation, 31 of these modules (1.5%) suffered short circuits between the electrically active cells and the metal

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+ Presented at the 15th IEEE PV Specialists' Conference, Orlando, FL, 11-15 May 1981.

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substrates of the modules. A brief description of the module and the failure mode is given below.

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Fig. 1. Aerial view of NBNM.

The Model F module consists of 48 three-inch-diameter cells (12 in series by 4 in parallel) potted in a silicone gel, with a glass cover, kapton-insulated copper foil to provide cell interconnection immediately beneath the cells, and a stainless steel substrate and frame to complete the packaging. Each array frame contains 48 of these modules wired into a series branch circuit. Under normal circumstances the array frames are grounded as part of the lightning protection system; the negative side of the branch circuit is grounded; the cells are electrically isolated from the stainless steel module substrates but the substrates themselves are grounded to the array frames. When a cell shorts to a module substrate, a second ground is introduced into the branch circuit, causing a reduction in circuit voltage and power. Sizeable currents can also occur in the array frame grounding network.

Photographs of the damage caused by shorting, to a module in the area of its terminals, are shown in Figs. 2 and 3. In Fig. 2, a large scorch mark is shown under the glass. In Fig. 3, similar scorching is shown about the module terminals on its rear side. Closer examination near the terminals indicates a blast hole through the stainless steel. A better example of the latter condition is shown in Figs. 4 and 5, where two large holes through the substrate can be seen. In two of the 31 failures, arcing and subsequent heat were sufficient to shatter the front glass on the modules.

Destructive analysis of several shorted modules of this type revealed that in each module examined the interconnect foil under the cells contained sharp edges of bare copper which shorted to the substrate during diurnal temperature cycling.

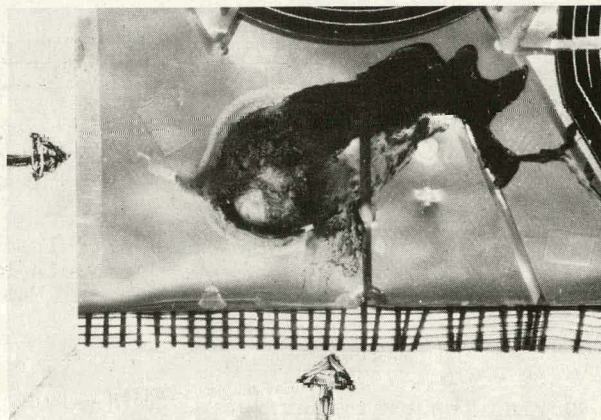


Fig. 2. Shorted Model F module, front side.

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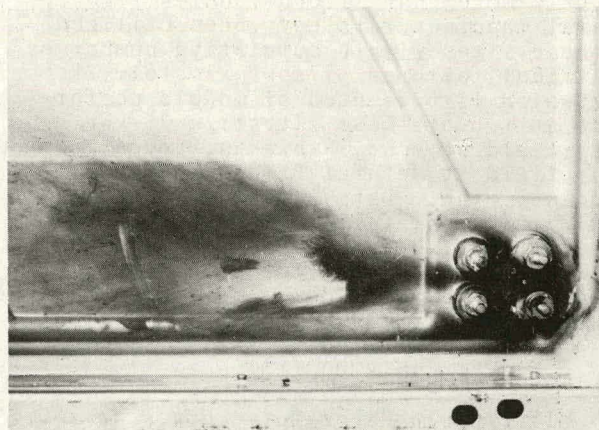


Fig. 3. Shorted Model F module, back side.

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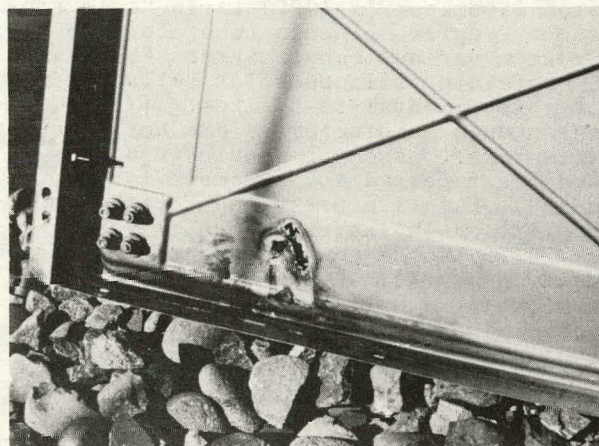


Fig. 4. Results of shorting Model F module.

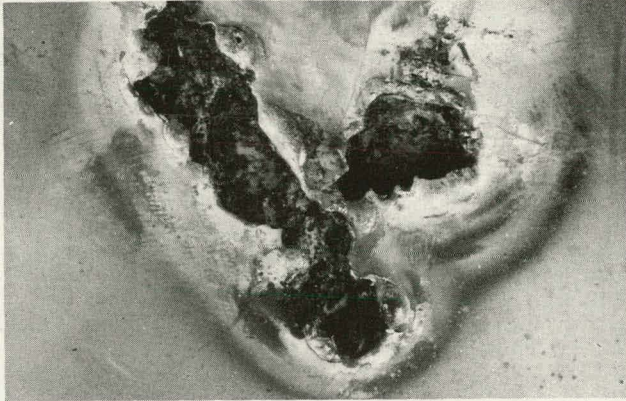


Fig. 5. Results of shorting a Model F module.

Electrical shorts to ground, of the type incurred by these modules, can be detected by using one of two techniques. In the first, the branch circuit containing the suspect module is electrically floated from ground in an open-circuit mode. The leakage currents between the positive and negative leads of the circuit and ground are then measured with a suitable measurement device. The normal leakage current for branch circuits of these modules at NBNM is about 15 to 20 microamps. A dead short will cause currents in the 1 to 5-amp range, depending on the level of sunlight at the time of measurement. (Isc is 4.91 amps at 100 mW/cm<sup>2</sup> insolation and 28°C cell temperature for Model F modules.) The second technique involves generating an I-V curve of a branch circuit with the negative lead of the circuit grounded. When a short-circuited module is contained in the branch circuit, the open-circuit voltage will be reduced by an amount dependent on the electrical location of the module in the series circuit. Both techniques have been used satisfactorily at NBNM.

During the first year of operation, only one of 1,740 Model E modules failed electrically. The module became open-circuited when an interconnect solder joint on the rear side of a cell failed.

The problems incurred by Models E and F modules affected their immediate electrical performance, but a different type of problem was found in the Model A modules. These modules are fabricated by sandwiching the solar cells into a laminate consisting of a glass cover sheet, two layers of polyvinyl butyrate (PVB) and a layer of Mylar. The cells are placed between the two layers of PVB, a rubber gasket is placed around the periphery of the laminate and then an aluminum frame is affixed in place. The module contains 120 two-inch-diameter cells.

Shortly after installation (January 1980), it was noted that the glass covers on 25 modules were cracked. During a later visit in March, 27 more modules were found with cracked cover sheets. The cracks always emanated from a long edge of a module. The center module in Fig. 6 illustrates two cracks starting from opposite long edges, running toward the center and then changing direction and running parallel to the long edges. The cracks caused no immediate electrical degradation in the module's output.

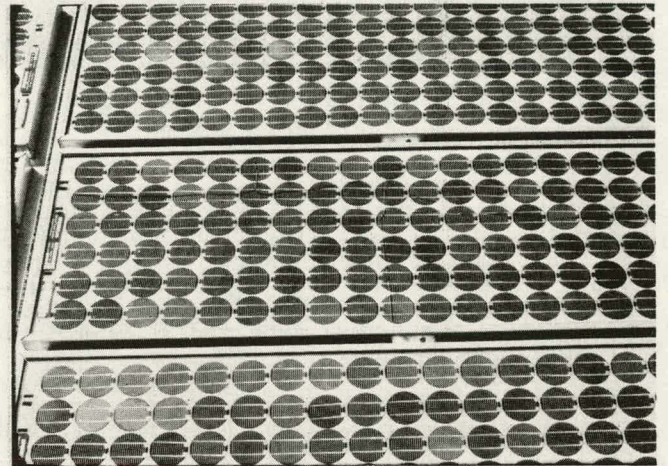


Fig. 6. Cracks in glass cover sheet, Model A.

Close examination of three modules removed from the site indicated that each crack emanated from a flaw on one of the long edges of the untempered glass. It is believed that the cracks occurred during diurnal temperature cycling which caused excessive tensile stresses at the flaw sites. Subsequent observations in November, 1980, indicated no new cracking, however the PVB along the cracks was starting to yellow due to moisture penetration. The long-term effect of these cracks on module electrical performance is not known.

In the next section, details of module physical and electrical degradation at the Mead Test Site are presented.

#### MEAD, NEBRASKA, TEST SITE

A 25-kWp photovoltaic power-generating system was installed at the Mead Field Station of the University of Nebraska in the late spring and early summer of 1977, beginning operations in July. A detailed description of the system is contained in Reference 2 and an aerial photograph is displayed in Fig. 7.

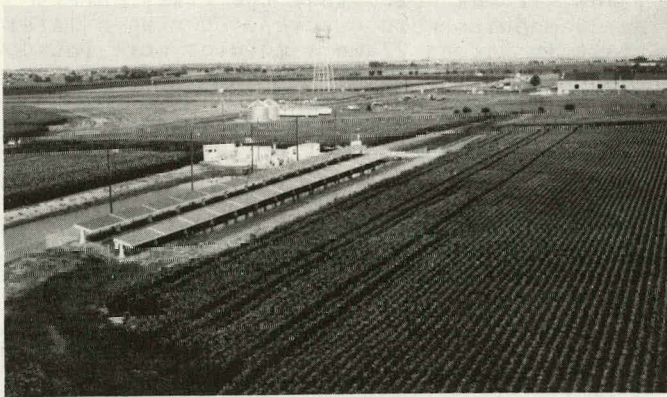


Fig. 7. Aerial view of Mead, Nebraska, Test Site.

The array field consists of 28 arrays of PV modules, separated by module type into two equal rows. The front row consists of 728 silicone-encapsulated Model D modules, while the back row consists of 1,512 silicone-encapsulated Model C modules. Both module types are from the JPL/DOE Block II procurement.

The predominate cause of electrically failed modules at Mead has been the cracked cell. Each module is a series assemblage of cells and it only takes one cell, cracked in the right way, to interrupt the series flow of current. A module is considered to be an electrical failure when it produces less than 75% of its nominal short-circuit current under the prevailing conditions. Twelve searches for electrically failed modules have been conducted since system turn-on. The results of these searches are summarized in Table I.

TABLE I

MODULE FAILURES AT MEAD TEST SITE

Front Row - 728 Modules (Model C)  
 Back Row = 1512 Modules (Model D)  
 Starting Date: July 1977

Date of Search	No. of Failures	
	Front Row	Back Row
Oct. 1977	0	1
Nov. 1977	1	1
Feb. 1978	0	3
Mar. 1978	0	0
Jul. 1978	6	3
Sep. 1978	3	1
Feb. 1979	2	0
Mar. 1979	1	2
Jul. 1979	6	7
Oct. 1979	1	10
Jul. 1980	11	7
Oct. 1980	4	26
TOTALS	35	61

The data of Table I are plotted in Fig. 8, where each data point represents the cumulative percentage of failed modules after a particular period of operation. In 39 months of operation, 96 of 2,240 modules (4.28%) have failed. Since the hailstorm of May, 1978, the slope of this curve has been steadily increasing. As indicated in Reference 3, there are still many cracked cells which have not yet caused modules to fail. In order to disrupt current flow, a crack must penetrate through the entire thickness of a cell. This phenomenon can happen in days or years after the initial cracking.

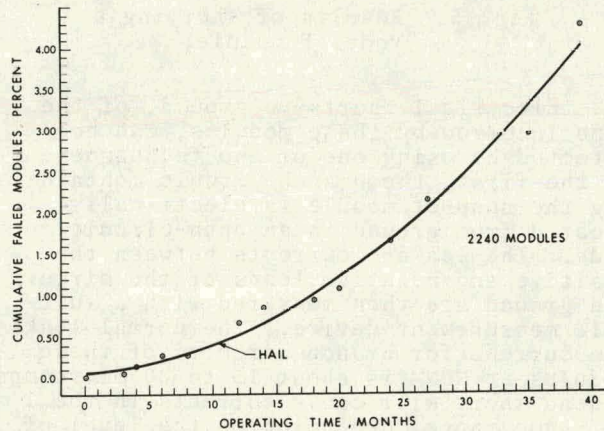


Fig. 8. In-service performance record for Mead PV modules.

During the 1980 visits to Mead, I-V curves were generated for each branch circuit in the array field. The electrical failures caused the occurrence of steps in the I-V curves, similar to those displayed in Reference 3. Various shadowing techniques were utilized to determine the specific locations of the defective modules. It is interesting to note that half of the failures occurred during 1980, a full two years after the 1978 hailstorm.

Four of the Model D failures found in 1980 contained a different type of failure mode--a pair of broken interconnects on one cell, as shown in Fig. 9. This type of failure mode has been observed at Bryan, Ohio, and Concord, Massachusetts, in the Block III version of this module. It is caused by differential thermal expansion of the polyester substrate, metal interconnects, and silicon cells which occurs during diurnal temperature cycling. The likelihood of failure is increased when inadequate strain-relief loops are placed on the interconnect.

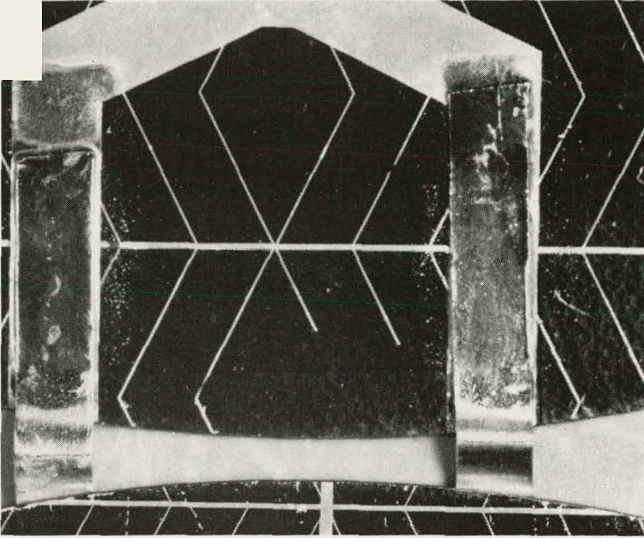


Fig. 9. Model D failure with pair of broken interconnects.

#### SUMMARY

During the past four years, Lincoln Laboratory has deployed over 11,000 modules at various test sites in the United States. To date, slightly more than 2% have failed electrically. Of the 6,764 modules placed at Mead and NBNM, 128, or 1.9%, have failed electrically.

At NBNM the predominate failure mode has been cell/interconnect shorts to ground in Model F modules. In addition several Model A modules have incurred cracks in their glass covers due to diurnal temperature cycling. At Mead the predominant failure mode has been cracked cells caused by either natural weathering or a 1978 hailstorm. Recent failures have been found with pairs of broken interconnects.

Thus far, the PV modules used at almost all Lincoln Laboratory test sites have proved to be exceptionally reliable sources of electric power. This is quite remarkable since these modules represent the infant stage of terrestrial PV module development.

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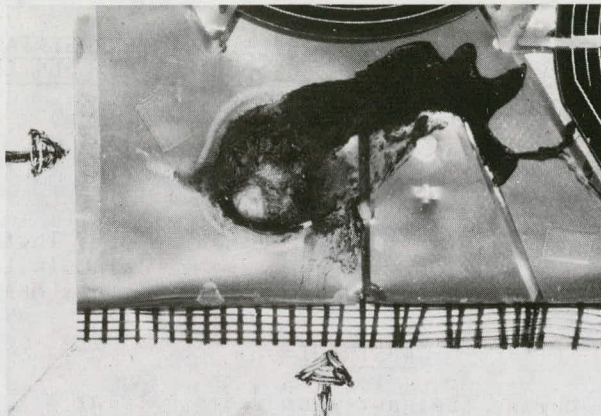


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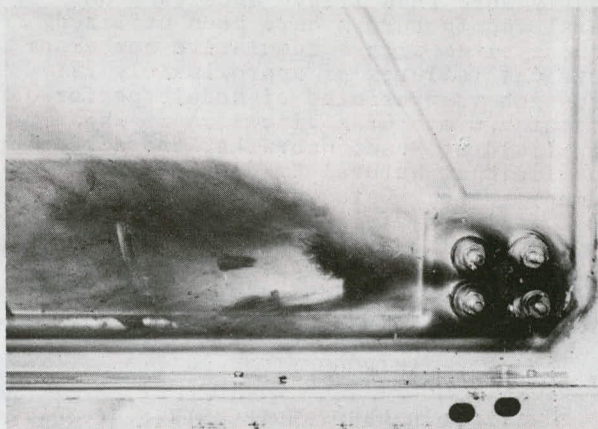


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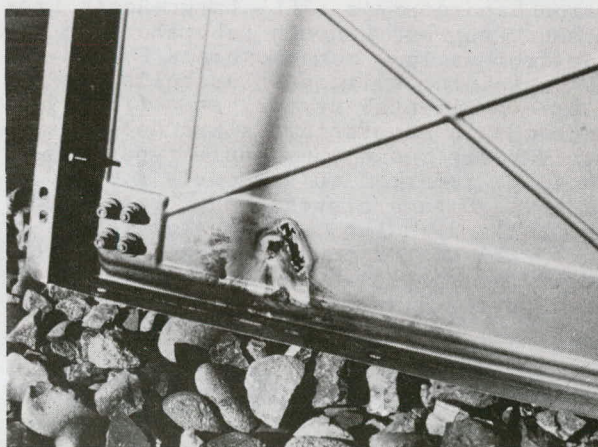


Fig. 4. Results of shorting Model F module.