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MATERIALS, PROCESSES AND TESTING LABORATORY
RESIDENTIAL TECHNICAL PROGRESS REPORT
OCTOBER - DECEMBER 1980, JANUARY AND FEBRUARY 1981

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15 April 1981

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ABSTRACT

The U. S. Department of Energy has set a 20-year lifetime goal for terrestrial photovoltaic modules. In its capacity as a Residential Photovoltaic Field Test and Applications Center, Massachusetts Institute of Technology Lincoln Laboratory has established and is monitoring experimental residential test sites in various locations of the United States. These sites contain either real or simulated residences coupled with photovoltaic modules from several manufacturers, as well as the necessary balance-of-system components. This report, the first in a series of ensuing reports, summarizes the activities of the Materials, Processes and Testing Laboratory of the Solar Photovoltaic Field Tests and Applications Project (as they apply to residences) during the period of October 1980 through February 1981.

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1. INTRODUCTION

This is the first technical progress report of the Materials Processes and Testing Laboratory which describes Massachusetts Institute of Technology Lincoln Laboratory (MIT LL) test experience with photovoltaic (PV) modules intended for residential applications. Similar reports (see References) dealing with experience with PV modules at various MIT LL experimental PV facilities, will continue to be published under separate cover.

This report covers the period of October 1980 through February 1981, and details the work of the MP&TL for that period. During this time, work was progressing on the erection of several residential prototypes at the Northeast Residential Experiment Station (NERES) in Concord, Mass., and a prospective lived-in house in Carlisle, Mass. This report covers the inspection, analysis, and testing of PV modules to be installed at these locations.

MIT LL presently serves as a Residential Field Test and Applications Center for the U. S. Department of Energy (DOE) to evaluate the energy potential of PV components in various residential applications. The modules used in the residential experiments described here were procured by MIT LL through a competitive bidding process. (The names of the module manufacturers are not relevant to this report. Module types will be designated as Model A, Model B, etc.)

At the time of this printing, three prototypes were completed at the NERES: (1) TriSolarCorp, (2) Westinghouse, and (3) MIT LL; and construction of two others was under way: (4) General Electric and (5) Solarex. A similar experiment was also initiated at New Mexico Solar Energy Institute (NMSEI) and is called the Southwest Residential Experiment Station (SWRES). At that site, construction has been initiated on five prototypes: (1) General Electric, (2) Westinghouse, (3) BDM, (4) TEA, and (5) TriSolarCorp. More complete descriptions of each of the prototypes are contained in references 9 and 10.

2. I-V CURVES FOR TRISOLARCORP PROTOTYPE—MODEL H MODULES

In early December 1980, members of the MP&TL conducted an acceptance test on Model H modules installed at the TriSolarCorp Prototype at NERES in Concord, Mass.

The array consists of 36 modules, wired two in parallel by 18 in series. They are designed to be installed directly on the

rafters of the prototype house. A photograph of the prototype is shown in Fig. 1.

Fig. 1. TriSolarCorp Prototype—NERES.

The measurements took place between 11 a.m. and 12:30 p.m. under ideal weather conditions: the insolation (measured by an Eppley PSP₂ pyranometer) varied from 92.5 to 93.5 mw/cm^2 ; the ambient temperature varied from -1.7° to -0.04°C ; the wind speed varied from 7 to 20 mph.

An MIT LL-developed curve tracer was used to generate the I-V curves, which were recorded on tape as well as printed by an Hewlett-Packard 85 computer. Module temperature was measured by a thermocouple placed on the rear of one module, behind a cell, for the duration of the test. An I-V curve was made for each module and then for the entire array.

The average module peak power of the 36 modules was 128.2 watts (W) at 93 mw/cm^2 and a cell temperature of 30°C . The power ranged from 122.6 to 134.2 w at these same conditions over all the modules. The vendor specifications quote a nominal power of 133 w at 100 mw/cm^2 and 28°C optional test conditions (OTC). When correction coefficients become available to make an exact calculation, it is expected that the measured average power will be greater than the quoted nominal value at OTC.

A total array peak power of 4350 W was measured at 91.7 mw/cm^2 and 30°C . When correction coefficients become available, the array peak power at 28°C and 100 mw/cm^2 will be calculated. A typical Model H I-V curve is shown in Fig. 2, while the Model H array I-V curve is shown in Fig. 3.

3. MODEL H MODULE ANALYSIS

In October 1980, two preproduction Model H models for NERES were electrically and visually examined in detail.

Since the short-circuit current of this module exceeds 10 amperes (A), the modules could not be flashed in the Large-Area

Fig. 3. Model H array I-V curve.

Pulsed Solar Simulator (LAPSS). Instead, using a curve tracer, an I-V curve was obtained for each of the modules by placing them on a frame outdoors in the sun. With an ambient temperature of 16.1°C and an insolation of 90 mw/cm², the first Model H module had an open-circuit voltage of 12.5 volts and a short-circuit current of 12.1 A. At the same conditions the second Model H module had an open-circuit voltage of 12.5 V with a short-circuit current of 11.9 A.

Each module measures 32 inches in width by 60 inches in length, with two large terminal boxes located on their rear, one at each corner of one end of the module. There are a total of 253 cells arranged in 11 rows of 23 cells each.

Examination revealed the following defects in the Model H modules: bared copper, debris, bubbles, delamination, scratches, excess interconnect material, stains, collector splash, excess solder, solder splash, edge chips, edge cracks, cracked cells.

Spots of bared copper were found along the sides and across the ends of the web-like interconnects where they terminate at the center of a cell. This condition was found on a majority of the cells of both modules. An area of bared copper was also found on the edge of the busbar on one of the modules.

Pieces of debris, such as hair, unknown matter, and a metal fragment from an interconnect were found on several cells of each module.

One cell of one module and two cells on the other module were found to have bubbles between the cells and the glass front cover.

One small spot of delamination, approximately 1/16 of an inch in diameter, was found on one cell.

Numerous scratches were found around the end of the interconnect where it terminates at the center of the cell. This condition was found on a majority of the cells on both modules.

Excess interconnect was found on three cells; a piece of the interconnect (approximately 1/8 inch long) was found to be folded back on itself at the end near the center of the cell.

Ninety-five cells were found with stains; the cause of this condition is unknown.

A combination of titanium, palladium and silver (known as Trimet) is used to form the collector lines on these cells. When this material is sputtered on, it sometimes splashes onto other parts of the cell. On the two modules, 367 cells were affected.

On the two modules, 64 cells were found to have excess solder on the end of the interconnect.

During the process of soldering the interconnects onto the cells, the solder tends to splatter and leave small blotches on the cell surface. This condition was found on 102 cells.

Six cells were found with small chips broken from the edge of the cell.

Two cells were found on one module which had edge cracks propagating approximately 1/8 inch into the cell area, with one of the cracks starting from an edge chip.

A total of three cracked cells were found, one on one of the modules and two on the other. The former started at the edge of a cell under an interconnect and ran completely up the cell to the opposite edge. The two cells on the latter were cracked in a different manner: one of the cracks started at the edge of the cell under the interconnect and then progressed in a diagonal line to the edge of the cell in one corner; the second cell had a crack which started at one edge, ran horizontally across the cell, passing under the main interconnect, and exited at the opposite edge of the cell. A second crack on this cell started at the edge under the interconnect and diagonally intersected the first crack just beyond the edge of the interconnect. This second crack also had a short crack branching from it.

Fig. 4. Peak power distribution for 120 Block IV residential Model D modules.

Except for the cracked cells and edge cracks that were found on these modules, the other defects appear to be relatively insignificant. Overall the modules look attractive from an aesthetic viewpoint.

4. FLASH TESTING MODEL D MODULES FOR MIT LL PROTOTYPE

In late December 1980, 120 Block IV Model D modules intended for use at the MIT LL Prototype at NERES in Concord, Mass., were flashed in the MP&TL. The modules were received in four groups: first shipment of 20 modules; second shipment of 30 modules; third shipment of 30 modules; fourth shipment of 40 modules.

The first group data showed that the lowest peak power was 58.5 W and the highest was 66.2 W with an average peak power of 62.7 W. The second group data showed that the lowest peak power was 60.5 W and the highest was 68.4 W with an average peak power of 64.7 W. The third group data showed that the lowest peak power was 60.2 W and the highest was 73.6 W with an average peak power of 67.5 W. The fourth group data showed that the lowest peak power was 61.3 W and the highest was 75.3 W with an average peak power of 68.5 W. All data were normalized to 100 mw/cm² insolation at 28°C.

Analysis of these data reveals a constantly increasing power output for each shipment. The overall average peak power for all 120 modules was 66.3 W, higher than the manufacturer's claim of 62.6 W at the same conditions. A bar graph of the peak power distribution is shown in Fig. 4.

After flash testing, the modules were hi-pot tested at 1500 VDC. Only one module failed, and was returned to the manufacturer for replacement.

5. MODEL D MODULE INSPECTION

Twenty Model D modules were inspected on a random basis prior to installation in the MIT LL Prototype at NERES. Inspection was conducted with the use of 5 to 35 power microscope. The glass front surfaces were prepared with a film of isopropyl alcohol or glycerol to more clearly define cracks and scratches from the grain boundary lines on the cell surface below the glass.

A number of visual anomalies were found. The quality of the soldering was poor at most of the interconnects. One module had a bare minimum of solder on all interconnects. A few of the main collectors had large voids in their patterns.

A greater number of the interconnects

were found to be badly twisted in later shipments compared to the first shipment. One panel had two interconnects on top of each other, and another had a broken interconnect. Interconnects were found to be extremely short, which allowed only a small surface area to be soldered to the top of the cell.

Numerous large chips were found at the corners of the cells and loose chips were also common under the interconnects. Loose chips were also found to be flipped over and lying on the cell surface.

A few cells were very close to each other (0.01 inch apart) and two cells were found touching. It was not uncommon to find the fine grid lines to be broken loose and crossing over from cell to cell. In one case, grid lines passed from the top of one cell to the bottom of the adjacent cell.

One module had four rework areas on the tedlar back side and another had one rework area, with much debris found along the cut edges.

Instead of using white wires with red stripes as positive leads, the vendor painted white wires with red paint that subsequently peeled off.

The stippled glass on four modules was reversed such that the stippled side was placed next to the cell surface.

6. PROTOTYPE MODEL D MODULE ANALYSIS

Prior to deployment of Block IV Model D modules in MIT LL's Prototype at NERES, two preproduction prototypes were received for evaluation. In addition, a slightly different version of this module was received for the Solarex Prototype at NERES. Two of the modules had gold metal frames (MIT LL Prototype) and two had rubber gaskets around the edges (Solarex Prototype).

Using a standard cell, the four modules were flashed in the LAPSS and a normal curve was obtained for each module. The results were as follows:

Module	Short-Circuit Current (A)	Open-Circuit Voltage (V)	Peak Power (W)
1 (gold)	4.43	20.20	60.9
2 (gold)	4.48	20.22	63.8
3 (rubber)	4.51	19.84	59.8
4 (rubber)	4.41	20.26	61.8

Although the modules are similar electrically, they differ in the pattern of the cell main collectors. The framed modules have cells with three main collectors that

run parallel to the short side of the module. These main collectors measure 3/32-inch wide at the cell edges and then taper to 1/31-inch near the center of the cell. An interconnect, attached to a terminal strip beneath each side of the cell, is folded onto the main collector, where it is soldered. This method occurs in six places on each cell.

The rubber gasketed modules have cells that have three collectors arranged in a trident pattern, with the lines running parallel to the long edge of the module. The collector is 1/8-inch wide on one end and tapers to 1/32-inch at the opposite end. Two interconnects obtained from either a previous cell in the string or a busbar are soldered onto the main collectors at their widest end. The cells are also connected laterally, with two interconnects from the rear, to the rear of the cell in the adjoining row; i.e., cells in row 1 are connected laterally to cells in row 2; cells in row 3 are connected laterally to cells in row 4; etc. Both types of modules consist of 72 square polycrystalline cells (six rows of 12 cells each) on a white background; they are wired 36 in series by two in parallel.

Visual examination revealed the following defects in each type of module:

Module Type	Defect	Commentary
1 & 2 (gold frame)	Bared copper on interconnects	Module 1 had 186 interconnects with spots of bared copper. Module 2 had 202 interconnects with the same problem. A portion of this problem was caused by the absence of proper solder flow, while the remainder was caused by the tools used during assembly.
	Stains	Module 1 had eight cells with stains and module 2 had seven cells with stains.
	Delamination	Numerous areas of rear-surface tedlar delamination were found between the cells and along the periphery of the modules. A small spot of delamination was found on one cell of one module between the front cover glass and the cell.
	Air bubbles	Air bubbles were found in the ethyl vinyl acetate (EVA) over and between the cells on both modules, as well as along the periphery of the modules.
	Debris	A piece of bus wire was found lying on a cell in Module 1. A long piece of bus wire was

Module Type	Defect	Commentary	Module Type	Defect	Commentary
		also found lying between another cell and the frame of the module.		Solder splash	One cell of one module was found to have some solder splash on its surface. Solder balls, as well as solder splash, were found on four cells of the other module.
	Excess grid	Pieces of excess grid material were found on two cells of one module and on one cell of the second module.		Chips	One module was found to have 114 places on 62 cells where chips of silicon had been broken out of the edges of the cells. This condition was found in 106 places on 60 cells of the other module.
	Collector splash	The material used for the main collectors was splashed onto the active parts of 34 cells of Module 1 and six cells of Module 2.		Damaged interconnects	Three cells on one module were found to have damaged or partially broken interconnects. Four interconnects appeared to be broken on four cells of the second module, as well as 14 additional cells on which 20 damaged interconnects were found. Damaged interconnects are those which are partially broken, nicked or twisted. One interconnect was found that had been twisted upside down and then soldered onto a cell. This condition is caused by the careless use of tools during assembly.
	Scratches	Deep scratches were found around the periphery of numerous cells on both modules.		Cracks	On the two modules, 15 cells had cracks that started at chips at the edges of the cells. An example was a crack that started from a chip at the midpoint of one side of the cell and ran diagonally across the cell to the opposite edge, cutting the cell in half. Two smashed cells were found on one module; one cell had its central two-thirds area shattered, while the other cell was smashed in the lower left quadrant, with a radial crack running diagonally up the cell, through one main collector and terminating two-thirds of the way up the cell. Six edge cracks, which terminated a short distance into the cell, were found on both modules. Three randomly cracked cells were found on both modules; in one the crack started at the corner of the cell, ran diagonally into the cell, through two of the main collectors, and then cut vertically up the cell to the top edge, isolating two-thirds of the cell. A second cell on this module had a Y-shaped crack that straddled a rear interconnect.
	Chips	On Module 1, 12 cells were found with chips removed from their peripheries. On module 2, six cells have this problem. Some of the chipped areas were larger than 1/8-inch long; in one case a corner of a cell approximately 1/2-inch long was missing.			
	Cracks	Six cells on one module were found to have cracks starting at the edge of the cell by an interconnect and terminating a short distance into the cell.			
	Rework areas	Module 1 had two cells that had been reworked. Module 2 had seven reworked cells.			
3 & 4 (rub-ber gasket)	Bared copper on interconnects	Module 3 had 63 interconnects with bared copper, while Module 4 had 109 interconnects with the same problem. Bared copper was also found along the edges of the terminal strips on both modules.			
	Delamination	Several spots of delamination were found over one cell of one module between the front cover glass and the cell.			
	Air bubbles	Air bubbles were found over cells, between cells, and near the terminal strips of both modules.			
	Debris	Five cells were found to have hair and other unknown pieces of debris on their surfaces.			
	Excess grid	Three cells of one module were found to have loose or excess grid material on their surfaces.			
	Collector splash	The material used in forming the main collector lines were found splashed onto the active part of 67 cells on one module. This condition was found on 59 cells of the second module.			

Since the cells of both types of modules are made of polycrystalline silicon, it is difficult to discern cracks from the grain boundaries of the surface pattern of the silicon. It is necessary to use a layer of isopropyl alcohol to make a clear image through the stippled glass covering the cells.

The soldering of the interconnects was poor. There were lumps of solder in some places and insufficient solder in others. The solder flow around the interconnects was poor; solder had been permitted to flow onto the bends of some of the interconnects, thus "freezing" or eliminating any available strain relief.

Numerous interconnects had been twisted and damaged by tools which would tend to fatigue the metal.

There were no identifying marks to distinguish between the positive and negative terminals on the rear of the modules.

7. PROTOTYPE MODEL E MODULE ANALYSIS

In October 1980 three Block IV Model E modules were received as preproduction prototypes for the Westinghouse Prototype at NERES. All the modules were electrically and visually examined. These modules are 12-inches wide by 48-inches long and contain 35, 4-inch cells, with two rows of 12 cells and one row of 11 cells. The cells are wired to form one series string.

The modules were flashed in the LAPSS and a normal I-V curve was obtained for each module. For each module the short-circuit current measured approximately 2.4 A, while the open-circuit voltage measured approximately 20.5 V.

Visual examination revealed the following defects:

Module Type	Defect	Commentary
E, Block IV	Bubbles	Small bubbles were found over and around most of the cells on the three modules.
	Solder splash	During the soldering of the main collector strips onto the cells, solder is apt to splatter and leave small blotches on the cell surface. This condition was found on 62 cells on the three modules. Solder balls, also caused by solder splattering, were found near seven cells of the three modules.

Debris A metal fragment was found between two cells on one module. On another module a piece of hair was found on a cell, and a paint chip was found lying between another cell and the frame of the module.

Stains The stains found on these cells resemble the stains found on the Block I Model A modules. They could possibly be caused by some type of solvent used during manufacturing. Most of the stains were found on the cells of one module; the other two modules had only a half dozen cells with this condition.

Collector splash A total of 25 cells were found which had some of the collector line material splashed onto the active part of the cell.

Scratches A total of 54 cells were found with surface scratches.

Bare copper on interconnects Areas of bared copper were found on 56 of the 212 interconnects on the three modules. This condition is caused by the misuse of tools during assembly. Areas of bared copper were found on the metal bars used for the main collectors on 47 cells of the three modules. Nine areas of bared copper were also found on the busbars of the three modules.

Bent main collector On six cells of two modules one of the main collector strips was bent back on itself for approximately 1/8 inch.

Chips Small chips were found around the periphery of 90 of the 105 cells of the three modules.

Cracked cells On the first module, six cells were found to have cracks. The second module was found to have five cracked cells. The third module had one cell which had a crack running in an arc, from an edge chip near the interconnect to the edge of the cell along one side.

8. MODEL E MODULE ACCEPTANCE TEST AT WESTINGHOUSE PROTOTYPE AT NERES

In late January 1981, I-V curves of 40 quads of Model E modules at the Westinghouse Prototype at NERES were generated. Each quad consisted of four Model E modules in parallel.

The insolation, as measured by a PSP pyranometer at a 45-degree tilt, varied from 95 to 100 mw/cm^2 . The ambient temperature varied from 5° to 8°C with a cloudless sky. The backs of the modules were inaccessible for temperature measurements as they were covered with panels of Sheetrock. A photograph of this prototype during assembly is shown in Fig. 5.

Fig. 5. Westinghouse Prototype at NERES.

Referring to Fig. 6, the average power over the 40 quads was 125.7 W (normalized to 100 mw/cm^2 insolation and an ambient temperature of 5–8°C). The variance in measurements was between 117.7 W and 132.0 W. Since the nominal power of the preproduction prototypes at 28°C ranged from 32 to 35 W, the output for each quad was deemed acceptable.

It is expected that further acceptance tests will be conducted when the modules are wired together to form an array.

Fig. 6. Peak power distribution for 40 quads of residential Model E modules.

9. MODEL E I-V CURVE GENERATION AT WESTINGHOUSE PROTOTYPE

In mid-February 1981, I-V curves were generated for Block IV Model E modules installed on the Westinghouse Prototype at the NERES.

The modules were connected electrically 12 in parallel by 13 in series. I-V curves were generated for the 13 series portions of the array as well as for the entire array (Figs. 7–10). During the measurements the sky was clear blue, the insolation varied from 102 to 103 mw/cm^2 , the ambient temperature varied from 2° to 5°C, and the temperature of the modules varied from 30° to 32°C. Insolation was measured by means of a PSP pyranometer and cell temperature was monitored from a permanently affixed thermocouple mounted on the rear of a module near the center of the array.

A summary of the power data for each 12-module block and the entire array is presented in Table 1. Two data points are presented for the entire array.

10. FLASH TESTING MODEL D MODULES FOR CARLISLE ISEE

In late January 1981, 132 Block IV Model D modules intended for use at the Carlisle ISEE were flashed in the LAPSS.

Three shipments of modules were received: first shipment of 41 modules; second shipment of 52 modules; third shipment of 39 modules. Data are presented for each group as well as all 132.

The first group data showed that the lowest peak power was 62.5 W and the highest was 73.8 W with an average peak power of 67.5 W. The second group data showed the lowest peak power was 61.3 W and the highest was 75.8 W with an average peak power of 67.7 W. The third group data showed the lowest peak power was 56.6 W and the highest was 74.4 W with an average peak power of 66.8 W. All data were normalized to 100 mw/cm^2 insolation at 28°C.

The overall average peak power for all 132 modules was 67.4 W, a higher value by 1.1 W over the modules used at the NERES. A bar graph of the peak

Fig. 7. Model E I-V curves 1-4.

Fig. 8. Model E I-V curves 5-8.

Fig. 9. Model E I-V curves 9-12.

Fig. 10. Model E I-V curve 13 and array curves.

Table 1
Model E Prototype NERES Powers of
Each 12-Module Block

Block	Insolation (mw/cm ²)	Module Temperature (°C)	Peak Power (W)
1	102	31.1	392.8
2	102	31.1	408.7
3	102	30.5	416.6
4	102	31.1	408.7
5	102	31.1	414.0
6	103	31.6	419.2
7	103	31.6	419.6
8	102	31.6	408.8
9	102	31.6	406.1
10	103	31.1	408.7
11	103	30.5	408.8
12	103	30.5	395.3
13	103	30.5	390.2
Total			5297.5
Array	103	30.0	5213
	102	31.1	5134

power distribution is shown in Fig. 11.

Fig. 11. Peak power distribution for 132 Block IV residential Model D modules for Carlisle House.

In regard to the first shipment, two modules produced no output when flashed and were sent back to the vendor for repair. These two modules were included as part of the third shipment, at which time they were tested and found to be operational.

After flash testing, all the modules were hi-pot tested at 1500 VDC. No failures were recorded. The nominal leakage current was less than 0.1 microamperes (μ A). Two modules were sent to Jet Propulsion Laboratory (JPL) for qualification testing and evaluation. One module was returned to the vendor for replacement because the frame pulled away from the glass around the entire periphery.

11. MODEL D MODULE INSPECTION FOR CARLISLE ISEE

Twelve of the 132 Model D modules intended for installation at the Carlisle ISEE (refer to Paragraph 10) were inspected in a manner similar to that described in Paragraph 5.

The quality of the soldering was poor at most of the interconnects throughout all the lots. Most modules had the bare minimum of solder on the interconnects. In a few cases the interconnects had lifted completely off the surface of the cell, removing all connection. There was no evidence of any solder under the interconnects.

The quality of the interconnects had not improved since the earlier inspection. One cell had one interconnect missing.

Numerous large chips were found at the corners of the cells. In several instances, cracks were found radiating into the cells from the chips. A few cracks were found under the interconnects.

A great number of cells were found to be very close to each other (0.01-inch apart). A marked increase was found in the number of cells touching each other with respect to the cells inspected in Paragraph 5. One module had cells touching in six different places, while another had cells touching in three different places. The tedlar backs of these modules are dyed blue, very similar to the color of the cells, and it is very difficult to see defects near the edges of cells.

Holes in the tedlar were found which had been patched with white caulking compound on the back surface.

On several modules the stippled glass was found to be reversed, as described in Paragraph 5.

Other minor conditions found to exist on almost all modules included air bubbles, stains, collector splash, debris, scratches, and bared copper on the interconnects.

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