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PHYSICAL AND ELECTRICAL DEGRADATION OF PHOTOVOLTAIC MODULES AFTER EXPOSURE IN TERRESTRIAL ENVIRONMENTS[†] [‡]

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ABSTRACT

Between March, 1977 and March, 1979, MIT/Lincoln Laboratory, in conjunction with the U. S. Department of Energy, placed 75 kW of photovoltaic modules at various experimental test sites in the United States. The largest of these include a 25 kW array field in Mead, Nebraska, used to power corn irrigation and crop drying equipment; a ground level 25 kW array field in Lexington, used as a residential system test bed; a 15 kW rooftop test bed in Lexington, used to evaluate components of photovoltaic systems prior to field installation. To date only 44 modules (amounting to 600 watts) out of 6,000 have experienced electrical failures. This report summarizes the performance of the photovoltaic modules at the Mead test site and describes the physical and electrical changes which have occurred due to weathering and soil accumulation since start-up in July 1977. Where relevant, comparisons will be made with modules at the other test sites.

IN A PREVIOUS REPORT (1*), test experience with photovoltaic modules at various MIT/Lincoln Laboratory (MIT/LL) experimental photovoltaic test facilities during the eight-month period (5/77-12/77) was detailed by the authors. In this report, data will be presented for the following period of 15 months (1/78-3/79), with specific details given regarding module performance, electrical degradation, power loss due to soil accumulation and physical degradation.

MIT/LL, serving as a Field Tests and Applications Center for the U. S. Department of Energy, evaluates the energy potential of photovoltaic devices in various applications. As part of the DOE/Jet Propulsion Laboratory's (JPL) Large Scale Array Procurement Program, MIT/LL receives, from various manufacturers, photovoltaic modules for use at several experimental test sites. Each module is visually inspected at the factory of origin and a road map outlining its physical appearance and various workmanship-related anomalies is completed in the manner previously discussed by one of the authors (2).

During field deployment, most modules are placed at experimental test sites called Systems Test Facilities (STF), where, in addition to the modules, many components of a PV system are evaluated. During the report period discussed here, there were five test sites in existence: a 25 kW array field at the Mead Field Station of the University of Nebraska; a 25 kW array field at Lexington, Massachusetts; a 15 kW rooftop test bed on one of MIT/LL's buildings in Lexington, Massachusetts; a 7 kW array field at the University of Texas at Arlington, and a 1.5 kW array on the roof of the Chicago Museum of Science and Industry.

At each of these sites, data on module performance and degradation relative to the DOE 20-year lifetime goal, has been obtained. To date, of 6,000 modules deployed at various sites for periods of up to 24 months, only 44 have failed. This is an outstanding performance record. Specific details of module performance at the Mead, Nebraska, array field are given below. Where relevant, data from other sites is enumerated for comparison purposes.

The names of the module manufacturers are not relevant to this report, and the two module types at Nebraska will be referred to as models B and C. Model B is covered with RTV 615 and Model C is covered with Sylgard 184.

MEAD, NEBRASKA TEST SITE

The Mead, Nebraska test site consists of 28 arrays of photovoltaic modules, separated by model type into two equal rows. The eastern-most arrays in each row serve as test beds for module performance analysis. Modules are periodically removed from these arrays and returned to the Materials, Processes and Testing Laboratory (MP&T) of the Solar Photovoltaic Project. In the MP&T Laboratory, the modules undergo detailed visual examination to detect physical changes, and are subject to soil accumulation analysis to measure power loss due to dirt and exposure. In addition, field inspections are conducted twice a year so that every module in the array is inspected at least once a year. In this way, the kinds of changes and degradation which modules undergo can be carefully recorded and related to the DOE 20-year lifetime goal.

Results of field inspections conducted in March and September of 1978 and March of 1979, degradation analysis of modules with seven, nine, twelve and fourteen months of field service, and soil accumulation data for modules with the same lengths of service are presented here.

During March and September of 1978 and March of 1979, field inspections of modules in 26 of the 28 array frames were performed. Hand-held magnifying glasses were used to view the solar cells. Every cell on these frames was inspected at least once. Prior to inspection, each module in the array field was washed, using the techniques described in Reference 3. For the most part, field washing leaves the silicone encapsulant outer surface of the modules optically clear and cells can be viewed easily.

An attempt was made to accumulate as much data as possible on defects which could be observed visually. At present, there is little or no correlation between many of these defects and electrical degradation, however evidence of real time changes is indicated. A breakdown by model, type of defect and number of occurrences is given in Table 1. The principal types of defects observed in the field are: electrical elements protruding through the encapsulant; encapsulant delamination from the substrate, cells, or interconnects; discoloration, and cracked cells.

*Numbers in parentheses designate References at end of paper.

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DISCLAIMER

TABLE 1

CUMULATIVE FIELD INSPECTION RESULTS AT MEAD TEST SITE SINCE JULY 1977

Model B	Number of Occurrences
Modules inspected	1400 mods
Edge-seal delamination	409 mods
Terminal post area delamination	1097 mods
Delamination over cells	300 mods
Delamination over or around interconnects (IC)	28 mods
Split encapsulant over IC or cell	27 mods
Encapsulant delamination or torn around mounting boss	384 mods
Protruding IC or cell	15 mods
Protruding ground screw	4 mods
Newly-cracked cells	686 mods
Model C	
Modules inspected	684 mods
Edge-seal delamination	628 mods
Delamination over cells	86 mods
Delamination over or around IC	37 mods
Split encapsulant over IC or cell	27 mods
Protruding interconnects	20 mods
Cracked interconnects	4 mods
Newly-cracked cells	47 mods

Electrical elements protruding through the encapsulant represent a safety hazard and modules with this defect must be removed from the array. In most instances, the element becomes exposed because of weathering of an initially thin layer of covering or because of the loss of a surface repair area due to exposure and/or washing. To date, 39 modules have been removed because of exposed electrical elements; all were repaired in the MP&T Lab and returned to field service.

Encapsulant delamination of varying degrees was found on almost all observed modules. The various types of delamination are enumerated by model in Table 1. An example of edge-seal delamination is shown in Fig. 1. The large arrow is under the entire layer of encapsulant, and dirt has penetrated up to the smaller arrows. An example of delamination over a cell is shown in Fig. 2, where a repair area over a cell has delaminated.

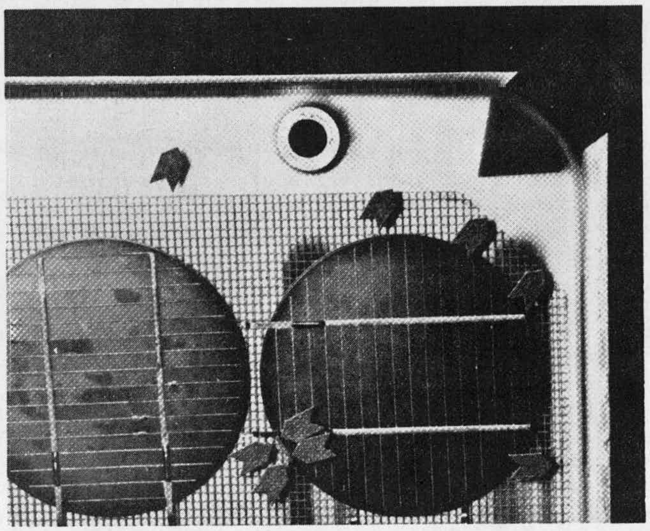

Fig. 1

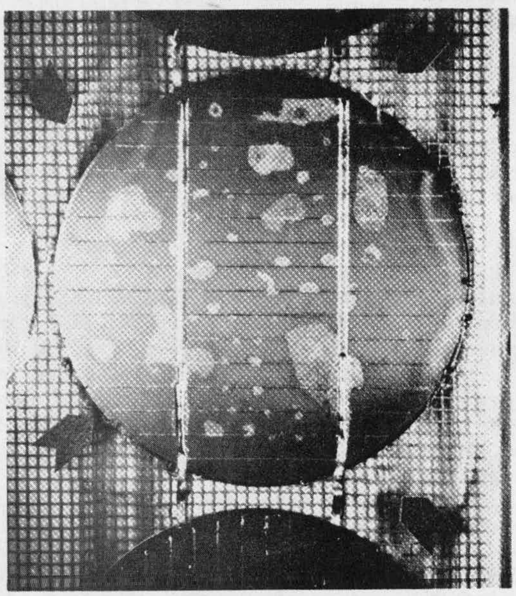

Fig. 2

During the receiving inspection of each module, all areas with appreciable delamination were repaired; what is observed in the field occurs after installation. It is clear from Table 1 that a significant amount of delamination has occurred since system turn-on in July 1977. This is especially true for the Model B module, where 300 of these modules were found with delaminated areas over cells.

An increasing number of modules are being found with splits in the encapsulant. These occur because of broken surface bubbles as well as weathering and can eventually expose electrical elements to moisture and contaminants. In addition, there is evidence of discoloration in terminal post areas of almost all Model B modules and on main collectors of many cells on almost all Model C modules.

To date, almost one third of the modules in the array field have been found with at least one cracked cell; this amounts to over 1000 cracked cells.

Two typical cracked cells on a Model B module are shown in Figs. 3 and 4. In the former, the crack crosses both interconnects and may ultimately cause a failure if it penetrates through the thickness. In the latter, a zigzag crack splits the cell in half. In Fig. 5, a cracked cell on a Model C module is shown. If it penetrates through the thickness, it may cut an edge off a cell and reduce the active cell area.

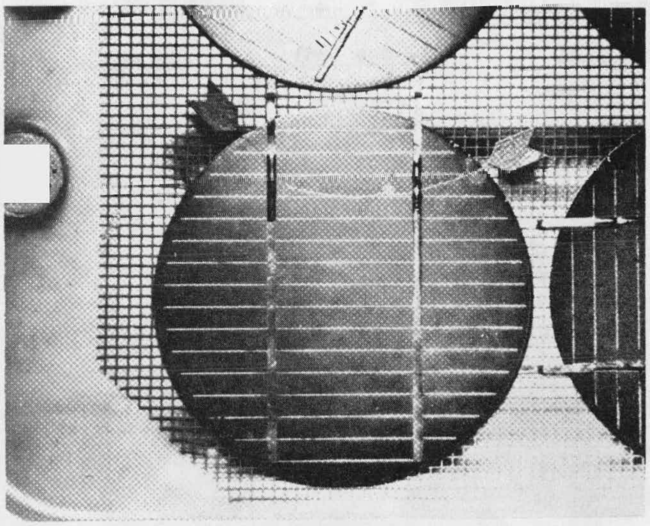

Fig. 3

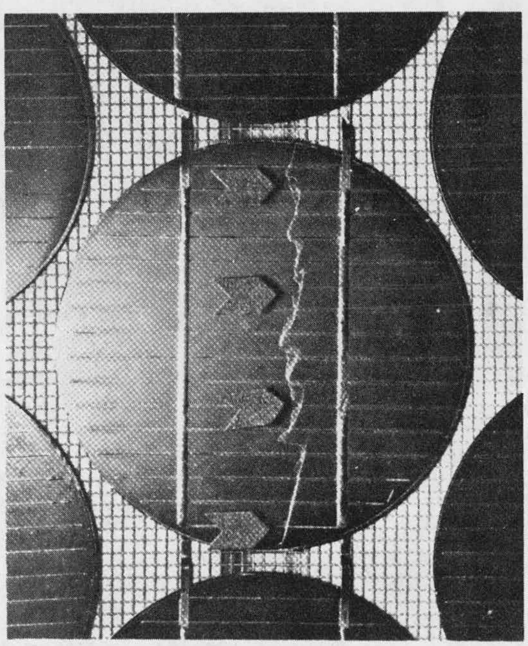

Fig. 4

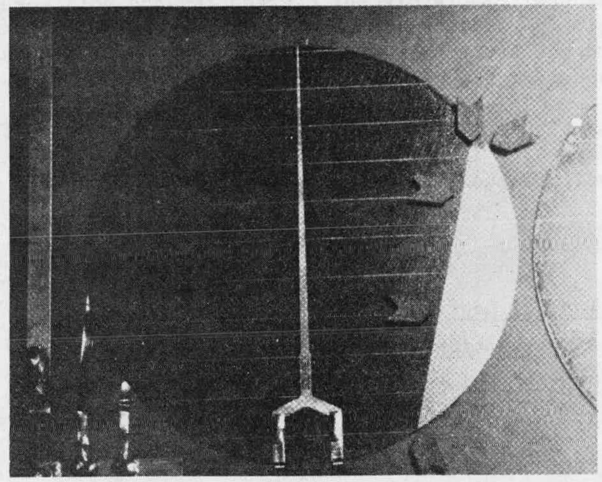

Fig. 5

Many of the cracked cells were found with impact damage such as what might have been caused by an airborne projectile. A typical example is shown in Fig. 6, where a cell on a Model B module has sustained two impact hits. These impact cracks were caused by a hailstorm in May. On-site observers reported that one inch of rain fell in a 15-minute period, along with five minutes of hail, and that hailstones 1/4 inch to 3/4 inch in diameter were found. The modules appeared to have marks in the surface dirt, with a density of approximately 5-10 marks/ft^2. The high incidence of cracked cells has caused many modules to operate at reduced short-circuit current.

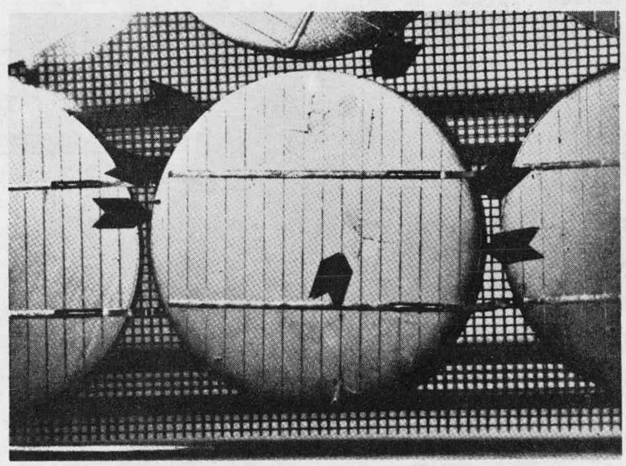

Fig. 6

Searches for electrically-defective modules have been conducted several times during the 19 months of the Mead test site's operation. The procedure has been described in Reference 1. To date, of 1,512 Model B modules, eleven have failed; of 728 Model C modules, 13 have failed. Most of the failures were due to cells cracked across one or both main collectors; one was caused by interconnects left unsoldered on a cell backside, and one was due to interconnects becoming unsoldered on the front side. The hailstorm appears to have caused at least six of the cracked cell failures.

After seven, nine, twelve and fourteen months of field service, 46, 40, 40 and 43 modules were returned to the MP&T Laboratory for degradation and soil accumulation analysis. These modules underwent a very detailed microscopic examination to determine what changes had occurred beyond those observed during field inspection.

A tabulation of types of degradation is shown for each model in Tables 2 and 3. The numbers in parentheses indicate the number of modules observed.

TABLE 2

VISUAL DEFECTS IN MODEL B MODULES

Type of Degradation	7 mos (32)	9 mos (28)	12 mos (28)	14 mos (31)
1. Discoloration				
Of terminal post areas	30 mods	25 mods	25 mods	31 mods
Along collector or grid lines	3	28	28	31
2. Delamination				
Repair areas	4	5	9	2
Over and around interconnects	6	5	5	4
Over cells	9	12	14	16
Terminal area	14	17	16	24
Around mounting bosses	14	6	17	8
Edge seal	13	6	9	6
3. Broken Surface Bubbles	7	7	9	11
4. Cracked Cells				
Totals	8 mods (11 cells)	7 mods (11 cells)	24 mods (54 cells)	26 mods (65 cells)
Impact Cracks	--	--	18 mods (38 cells)	24 mods (41 cells)

TABLE 3

VISUAL DEFECTS IN MODEL C MODULES

Type of Degradation	7 mos (14)	9 mos (12)	12 mos (12)	14 mos (12)
1. Discoloration				
Along collector or grid lines	14 mods	12 mods	12 mods	12 mods
2. Delamination				
Over or along interconnects	--	2	1	4
Edge seal	14	12	11	12
3. Broken Surface Bubbles	14	11	12	11
4. Cracked Cells				
Totals	--	--	5 mods (13 cells)	3 mods (5 cells)
Impact cracks	--	--	4 mods (12 cells)	2 mods (3 cells)

These types of degradation parallel those described in Reference 1 and reported in the field inspection. The staining along collector lines in the Model B module appears to be more prevalent than previously observed. An example of this is shown in Fig. 7. Here the anti-reflective coating has changed from the normal dark blue color to a rusty brown color. In Fig. 8, there appears to be a crystalline residue with some dendritic growth between grid lines. Delamination also seems to be more prevalent in Model B than in Model C modules.

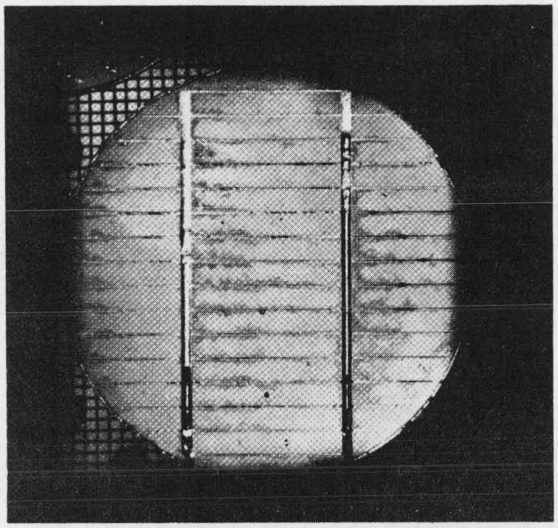

Fig. 7

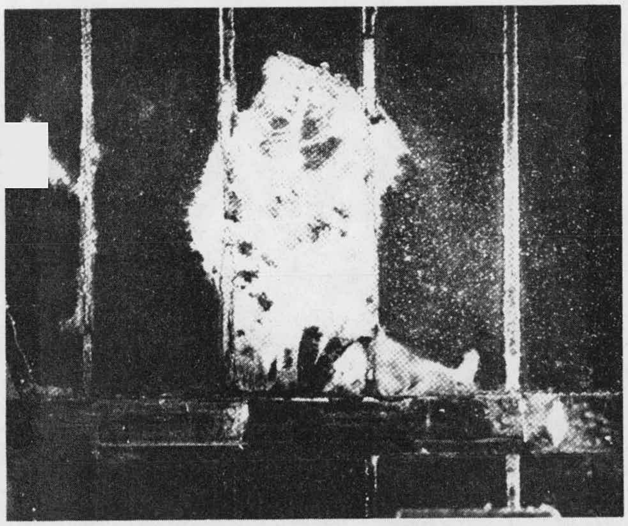

Fig. 8

Closer examination indicates a higher proportion of cracked cells than was observed in the field. Impact damage was observed on 198 cells, indicating that many cells with impact damage were overlooked in the field inspection because of difficulty in observing them in-situ.

In addition to undergoing a highly detailed visual examination, the aforementioned modules were tested to determine the effects of soil accumulation on module output power. The I-V characteristics of each module were determined by flashing the module clean and dirty in a Large Area Pulsed Solar Simulator (LAPSS). The modules were cleaned using one of the techniques described in Reference 3. Data is available for Model B and C modules after various lengths of exposure at the Mead Test Site and is shown in the following table (the starting date is 15 July 1977).

	Average % Power Loss	
Length of Exposure	Model B	Model C
2 months	--	4.2 (11)
5	7.7 (8)	7.5 (5)
7	9.9 (22)	7.2 (12)
9	6.3 (28)	5.5 (12)
12	9.2 (28)	8.7 (12)
14	12.4 (28)	12.5 (11)

The numbers in parentheses indicate the number of modules tested.

The data indicates a steady rise in percent power loss up to the nine-month measurement which corresponds to March, 1978. This month was close to being the wettest in Nebraska's history and constant rain appears to have removed some dirt. The 12-month data shows continued increase almost to the level of the seven-month data. The 14-month data shows further increase. There is little difference between the two encapsulants (RTV 615 and Sylgard 184), and, subsequently, there is very little difference in power loss due to dirt between one module and the other.

Similar data has been obtained for these modules at other test sites. Typically, for a one-year exposure period, modules at Lexington, Massachusetts, Cambridge, Massachusetts and New York City experienced power losses of 10%, 18% and 35% respectively due to soil accumulation. At the latter two sites, soiling due to airborne pollutants and particulates is the prime cause of the increased power loss. Glass-covered modules at the same sites during the same test period experienced power losses of 3%, 3.5% and 12%, which are significantly less than those of the RTV-covered modules. The glass covers are more prone to self cleaning.

While power loss due to soil accumulation is recoverable, that due to degradation is not. For Model B, the average unrecoverable power loss after 12 to 14 months of service at Mead is 3 to 4%. For Model C, the average was slightly less, 1.5 to 2.5%. Since these modules had been carefully cleaned, the effects of dirt on these values are considered minimal.

SUMMARY AND CONCLUSIONS

In this section a summary of results and observations at the Mead test site is presented. In 19 months of operation, only 24 of 2,240 Model B and C modules have failed electrically, which is an outstanding record. Most of the failures have been due to cracked cells. The most prominent types of physical degradation are cracked cells, encapsulant delamination, exposed electrical elements, discoloration of cells and broken surface bubbles. These have been common also at other MIT/LL photovoltaic test facilities. In one year, peak power losses due to soil accumulation have been measured at between 1 to 14%, with the variation depending on length of service or amount of rain. A hailstorm, ten months after installation, caused the occurrence of several hundred cracked cells which led to at least six failures. These cracked cells have also caused several modules to operate at reduced short circuit current.

In conclusion, the performance of current generation photovoltaic modules at Mead, Nebraska, as well at other MIT/LL test sites has been excellent in the period governed by this report. The overall number of failures at Mead is slightly more than 1% and the cumulative total at all sites is less than 1%. The most significant cause of power loss has been soil accumulation, which is highly site dependent. Electrical degradation has averaged between 1.5 and 4% for modules exposed for 12 to 14 months at Mead.

REFERENCES

1. Forman, S. E., "Summary of Field Experience of Photovoltaic Modules at Various MIT/LL Test Sites," MIT/LL COO/4094-8, 22 March 1978.

2. Forman, S. E., "Visual Defects in Terrestrial Photovoltaic Modules," MIT/LL COO/4094-6, 21 March 1978.

3. Murphy, E. B., and Forman, S. E., "Measuring Dirt on Photovoltaic Modules," MIT/LL COO-4094-37, 12 March 1979.