

QUARTERLY REPORT
SOLAR PHOTOVOLTAIC PROJECT,
MATERIALS, PROCESSES, AND TESTING ACTIVITIES,
FOR THE PERIOD
1 JANUARY TO 31 MARCH 1979

S.E. Forman
M.P. Themelis

COO-4094-55
30 June 1979

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

The Department of Energy has set a 20-year-lifetime goal for terrestrial photovoltaic modules. Massachusetts Institute of Technology's Lincoln Laboratory, in its capacity as a Photovoltaic Field Tests and Applications Center, has established throughout the United States various experimental test sites which range in size from 0.1 to 25 kW of peak power. These sites include modules from several manufacturers and serve as test beds for photovoltaic system components. This report summarizes the activities of the Materials, Processes, and Testing Laboratory of the Solar Photovoltaic Project during a three-month (1/1/79-3/31/79) period. During this period, an inspection trip was made to the Mead, Nebraska, test site. The modules were tested in the field to determine the extent of physical and electrical degradation which had taken place since previous inspections. In addition, several modules were removed from the site for more detailed laboratory examination. The results of both the field testing and laboratory analyses are reported here.

TABLE OF CONTENTS

	<u>Page</u>
Abstract	iii
List of Figures	vii
List of Charts	viii
List of Tables	viii
1.0 INTRODUCTION	1
2.0 ON-SITE INSPECTION AND TESTING - MEAD	2
2.1 Array Washing	2
2.2 Module Inspection	3
2.3 Degradation Analysis and Module Failures	4
2.4 Hail Detection	5
2.5 Safety Inspection	5
2.6 Infrared Heat Detection Tests	7
2.7 Corrosion Inspection	7
2.8 Summary	7
3.0 ON-SITE EXPERIMENT - LOON MOUNTAIN, NH	8
3.1 Method	8
3.2 Data	9
3.3 Conclusions	9
4.0 LABORATORY DEGRADATION ANALYSIS - NYU MODULES	12
4.1 Model A	12
4.2 Model B	14
4.3 Model C	16
4.4 Model D	18
5.0 LABORATORY DEGRADATION ANALYSIS - MEAD MODULES	19
5.1 Model D	19
5.1.1 Second Degradation Analysis	19
5.1.2 First Degradation Analysis	23
5.2 Model A	26
5.2.1 Second Degradation Analysis	26
5.2.2 First Degradation Analysis	31

Table of Contents (con'd)

	<u>Page</u>
6.0 LABORATORY FAILURE ANALYSIS	34
6.1 Lincoln Laboratory Rooftop Failures	35
6.2 Nebraska Failures	38
6.3 Use of X-ray and Infrared Detection	38
References	43

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Hail report card	6
2	Module power vs. snow depth - Model D	10
3	Module power vs. snow depth - Model E	11
4	Impact-cracked cell	28
5	Impact-cracked cell	29
6	52% reduction of ISC - Model B	36
7	46% reduction of ISC - Model B	37
8	ISC reduced to 1/3 the normal value (1) - Model A	39
9	ISC reduced to 1/3 the normal value (2) - Model A	40
10	X-ray of unsoldered interconnect	42

LIST OF CHARTS

<u>Chart</u>		<u>Page</u>
I	Comparative Analysis of Visual Defects Model D Block II Modules	20
II	Comparative Analysis of Visual Defects Model A Block II Modules	21

LIST OF TABLES

<u>Table</u>		<u>Page</u>
I	Comparative Table of Forward and Reverse Dark Curves	24
II	Comparative Table of Forward and Reverse Dark Curves and High-Voltage Leakage Current	32

1.0 INTRODUCTION

In previous reports (1, 2, 3), nineteen months (5/77-12/78) of test experience with photovoltaic modules at various MIT/Lincoln Laboratory (MIT/LL) experimental photovoltaic test facilities was detailed. In this report, further data will be presented for the next three-month period (1/79-3/79). Specific details will be given with regard to module failure rates, soil accumulation, cleaning methods, short-circuit current measurements, electrical degradation and physical degradation.

MIT/LL serves as a Field Tests and Applications Center for the Department of Energy (DOE) in order to evaluate 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 photovoltaic modules from various manufacturers for use at several experimental test sites. (The names of the module manufacturers are not relevant to this report, and the module types discussed will be referred to as models A, B, C, D and E.) 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 (4).

During field deployment, modules are placed in two types of experimental test facilities. The first has been designated as a Systems Test Facility where, in addition to modules, the many components of a PV system are evaluated. This report discusses two such sites: a 25-kW array field at the Mead Field Station of the University of Nebraska and a 10-kW rooftop test bed at Lexington, Massachusetts. The second type has been designated as an Endurance Test Site, where modules are placed to undergo weathering and soiling in special climates (urban rooftops and a Mount Washington, New Hampshire, weather station). Some of these test sites will be discussed in this report.

The Mead, Nebraska, test site consists of 28 arrays of photovoltaic modules, evenly divided by manufacturer into two rows. The easternmost arrays in each row serve as test beds for module performance analysis from which modules are periodically removed 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 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, a careful record of the kinds of changes and degradation which modules undergo can be developed and related to the DOE 20-year lifetime goal.

2.0 ON-SITE INSPECTION AND TESTING - MEAD

During the week of 26 March 1979, MIT/LL staff members visited the Mead, Nebraska test site to perform various tasks in connection with the Materials, Processes and Testing Program. These tasks included array washing, inspection of the lower half of 26 array frames, removal and installation of degradation analysis modules on frames 14 and 28, a search for electrically defective modules, and installation of new array junction boxes.

In addition, visits were made the same week by representatives of the MIT Safety Office, Rockwell Science Center, and JPL. All the activities carried out at the site are summarized below.

2.1 Array Washing

As in previous inspections, a local window-cleaning firm was retained to wash 26 of the 28 array frames. Improved techniques developed in the MP&T Laboratory were used for better results; whereas in September the arrays were washed with cold water andalconox, this time hot water,alconox and pumice were used.

The cleaning sequence was as follows: (1) application of a solution of hot water (160°F) andalconox to the module surface by a water-jet nozzle spray attached to a steamer; (2) brush cleaning of each module using the soapy solution applied to the modules; (3) cold water rinse; (4) brush cleaning of each module with pumice sprinkled on the brush bristles; (5) cold water rinse, and (6) squeegee drying of each module. This sequence resulted in dramatically cleaner modules than when cold water only was used. The hot water spray and the pumice scrub made a difference in cutting through the surface dirt on the RTV-covered modules. The cost difference was modest: \$850, as compared to \$600 for the less successful cold water process.

2.2 Module Inspection

The modules in the lower halves of 13 of the 14 frames in each row were inspected with hand-held magnifying glasses. In addition, the upper half of one frame in the back row (not inspected in September because of a frame level soil accumulation study) was inspected.

While the module-cleaning process described above removed most of the surface dirt, a thin film still remained which contained soap residue and dust from the morning dew. This was easily removed, however, with a sponge, squeegee and cold water. It was learned that leaving the module surface wet during inspection appeared to highlight surface defects.

Every module on 13 of 14 frames in each row has now been inspected at least once since the May, 1978, hailstorm. The cumulative number of defects in each row has been determined and is presented in tabular form below:

Front Row (Model D)

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 (64 cells)

Back Row (Model A)

Modules inspected	1404 mods
Edge-seal delamination	409 mods
Terminal-post-area delamination	1097 mods
Delamination over cells	300 mods
Delamination over or around IC	28 mods
Split encapsulant over IC or cells	27 mods

*Includes 7 modules found with this condition in March of 1978.

Encapsulant torn around mounting boss	384 mods
Protruding IC or cell	15 mods**
Protruding ground screw	5 mods***
Newly cracked cells	686 mods (962 cells)

In the Model D modules, the defects most prevalent after field exposure are delamination around the edge seal, over cells, and over or around interconnects. Twenty modules with protruding interconnects have been removed. Forty-seven modules have been found with cracked cells, mostly caused by the May, 1978, hailstorm. It should be noted here that these modules are extremely difficult to inspect in the field, especially for cracked cells. Based on the amount of impact damage found in the back row, it is suspected that several cracked cells are as yet undetected in the front row.

In the Model A modules, the most prevalent field-induced defects are terminal-post-area delamination, delamination around the edge seal and over cells, torn encapsulant around the mounting boss, and cracked cells. Nineteen modules with protruding electrical elements have been removed. Almost half the modules in the back row have one or more cracked cells due to hail damage and the expansion of RTV in structural ribs under cells. This will be discussed further in Section 2.3. Model A modules are considerably easier to inspect in the field than Model D modules.

2.3 Degradation Analysis and Module Failures

A search for electrically defective modules was conducted. For Model D, one open-circuited module was found, bringing the total to 13 of 728; for Model A, two open-circuited modules were found, bringing the total to 11 of 1512 modules. In addition, six Model A modules were found to be operating at from 50% to 60% of their normal short-circuit current because of cracked cells which cut down the current carrying capacity.

**Includes 10 mods found with this condition in March of 1978.

***Includes 3 mods found with this condition in March of 1978.

To gain some insight into failure rate, the date of each search for electrically defective modules and the number found are presented in the following table:

<u>Date of Search</u>	<u>Number of Failures Found</u>	
	<u>Front Row</u>	<u>Back Row</u>
October 1977	0	1
November 1977	1	1
February 1978	0	3
March 1978	0	0
July 1978	6	3
September 1978	3	1
February 1979	2	0
March 1979	1	2
	<hr/>	<hr/>
Totals	13	11

The aforementioned hailstorm occurred in May, 1978.

Fourteen Model D modules and twenty-eight Model A modules were removed for further degradation analysis in the MP&T Laboratory. They were replaced with an equivalent number of previously analyzed modules. In addition, sixteen modules used in a Battelle Life Prediction Study were re-installed.

2.4 Hail Detection

In view of the probability that hailstorms will occur again this year at the site, two hailpads were installed on the tops of frames 7 and 21. These pads are made of styrofoam wrapped with aluminum foil and are about one foot square. A data sheet, as shown in Figure 1, will be filled out at the time of the storm. The use of a larger (two feet by four feet) pad is being tested at the MIT/Lincoln Laboratory rooftop test bed and will be reported on at a later date.

2.5 Safety Inspection

A representative of the MIT Safety Department conducted a safety inspection of the site, and a report on his findings will be released shortly.

HAIL REPORT CARD - 1 Module Sites

- (1) Date of Storm: _____ Site _____
Day of week: _____
- (2) Hail began: _____ AM or _____ PM Daylight Savings Time
Hail lasted for _____ minutes
Rain lasted for _____ minutes and totalled _____ inches
Did rain fall at same time as the hail: yes no .
- (3) During this time there were the following number of distinct hail bursts:
1 2 3 4 5 6 more than 6 unknown
- (4) Size of largest hail: shot pea, grape, walnut, golfball, larger
Size of most common hail: shot pea, grape, walnut, golfball, larger
- (5) Average spacing of hailstones on the ground at end of storm was _____ inches
or depth of hail was _____ inches, or ground was just covered _____.
- (6) Hail began: before rain _____, at same time _____, after rain began _____, no rain _____.
- (7) Winds accompanying hail: light moderate strong severe
0-10 MPH 10-25 MPH 25-40 MPH over 40 MPH
- (8) Was any hail soft or slushy: yes no . If yes, what percentage of stones were soft _____
- (9) Shape of largest stones: conical _____, flattened _____, egg _____, round _____, other _____.
Surface structure of largest stones: smooth _____, flattened _____, egg _____, round _____ other _____.
- (10) (Optional) Estimate PV module damage at location _____.
Describe _____

NAME: _____ ADDRESS: _____

Check if you have a hail sample _____

Check if you require more cards _____

PLEASE RETURN PROMPTLY TO:

Dr. Steven E. Forman
MIT/Lincoln Laboratory (I-210)
P.O. Box 73
Lexington, MA 02173

Fig. 1. Hail report card.

It is anticipated that this type of safety inspection procedure will be followed in future installations. New frame junction boxes, which enable one to switch the array strings to open circuit, short circuit or on-line directly at the frame, were added to 15 array frames. These are compatible to a new test box which can be used to measure V_{oc} , I_{sc} and leakage to ground at the string level.

2.6 Infrared Heat Detection Tests

A representative of Jet Propulsion Laboratory field tested JPL's newly purchased infrared heat detection equipment. This portable system was used to find hot spots on modules. In the front row, hot spots (about 6) corresponded to cells which had cracked, lifted from the substrate and gone into reverse bias. It was not possible to detect the failed module mentioned earlier which was in the open-circuit mode. These results have also been determined in the MIT/Lincoln Laboratory MP&T Laboratory with our own AGA Thermo-vision (see Section 6.3). A short videotape of these efforts was made, showing several hot spots in the back row which probably correspond to cracked cells.

2.7 Corrosion Inspection

Rockwell Science Center has been subcontracted by JPL to determine the extent of corrosion in modules at Mead and to assess the future influence of corrosion on module performance. A representative of RSC spent a day at Mead inspecting corrosion on modules and holding discussions with an MIT/LL representative on the various types of discoloration noted. For Model A, there appears to be significant fading of anti-reflective coating as well as discoloration of and around grid lines. For Model D, there is extensive collector and grid line discoloration. Future cooperation with RSC is anticipated.

2.8 Summary

The results of this field inspection are summarized below:

- One Model D failure was found, bringing to 13 of 728 the total number of failures.
- Two Model A failures were found, bringing to 11 of 1512 the total number of failures.
- The most prevalent types of degradation are encapsulant delamination and cracked cells. Almost half the Model A modules now have at least one cracked cell.

- Washing with hot water, detergent and pumice instead of cold water and detergent greatly increases the surface cleanliness of the modules.
- Hail detection pads and data sheets have been added to record future hailstorms.
- Cracked cells are causing six Model A modules to operate at from 50% to 60% of their normal short-circuit current.
- New, safer frame junction boxes were added to 15 of 28 array frames. All array frames will soon be similarly equipped.
- Infrared heat detection can locate hot spots in modules but not necessarily failed modules in the open-circuit mode.

3.0 ON-SITE EXPERIMENT - LOON MOUNTAIN, NH

In the absence of sufficient snow during the first quarter of 1979 in Massachusetts, the Loon Mountain Ski Area in nearby New Hampshire provided the snowy conditions required for a module power loss experiment. The purpose of the experiment was to determine the effects of snow depth on module output power at various angles of tilt.

3.1 Method

A glass-covered Model E module and an RTV-covered Model D module were each fixed to the head of a heavy-duty tripod. A thin metallic frame, set at a specific height, was placed around the circumference of the module under test. Snow was then scooped onto the module surface and leveled off until it was even with the frame. It was then possible to tilt the module to any angle up to 45°. The snow started to slide off both modules at 30°; however, the frame was able to retain the snow. At 45° the snow could not be retained on either surface.

The output power of each module was measured with solar curve tracers developed at MIT/LL (5), one with a two-amp limit for Model D and one with a ten-amp limit for Model E. Insolation was measured with a portable solar meter, and temperature with a digital thermometer. Since 110 AC was available,

thermocouples could be used to monitor ambient and module temperatures, and the curve tracer did not require battery power. Acquisition of a battery-operated thermocouple output device for future tests (where 110 AC is not available) is being considered.

3.2 Data

The data for the RTV-covered Model D module and the glass-covered Model E module are displayed in Figures 2 and 3. Tilt angles of 0°, 10°, 20°, 30° and 40° from the horizontal were used, along with snow depths of 1/4", 1/2", 1", 1-1/2" and 2", to generate the data. All data has been normalized to a module temperature of 25°C and the average normal insolation at the particular angle of tilt. The Sandstrom equations were used to perform the current and voltage corrections with correction coefficients supplied by JPL.

For Model D, 1/4" of snow depth reduced the power by 50%; 1/2" of snow reduced the power by 60%; 1" of snow reduced the power by 80%; 1-1/2" of snow reduced the power by 90%; and 2" of snow reduced the power by 95%. These values appear to be almost invariant with tilt angle.

For Model E, 1/4" of snow depth reduced the power by 25% to 40%; 1/2" reduced the power by 45% to 60%; 1" reduced the power by 70%; 1-1/2" reduced the power by 80%; and 2" reduced the power by 90%.

3.3 Conclusions

From outward appearances, the glass cover of the Model E module appears to provide better optical coupling for the snow than RTV and, as a result, less power is lost. It may be, however, that the Model E cells are more responsive to the wavelengths which penetrate the snow than are Model D cells. For Model D, the percentage of power lost due to tilt varied very little; for Model E there seemed to be wider variations.

Though there was ample snow of coarse granular texture and a density of from .5 to .6 grams/cm³, this type of experiment needs to be performed with various densities of snow. The .5 to .6 gram/cc density range is almost like crushed ice. Next winter this experiment will be repeated with lighter snow

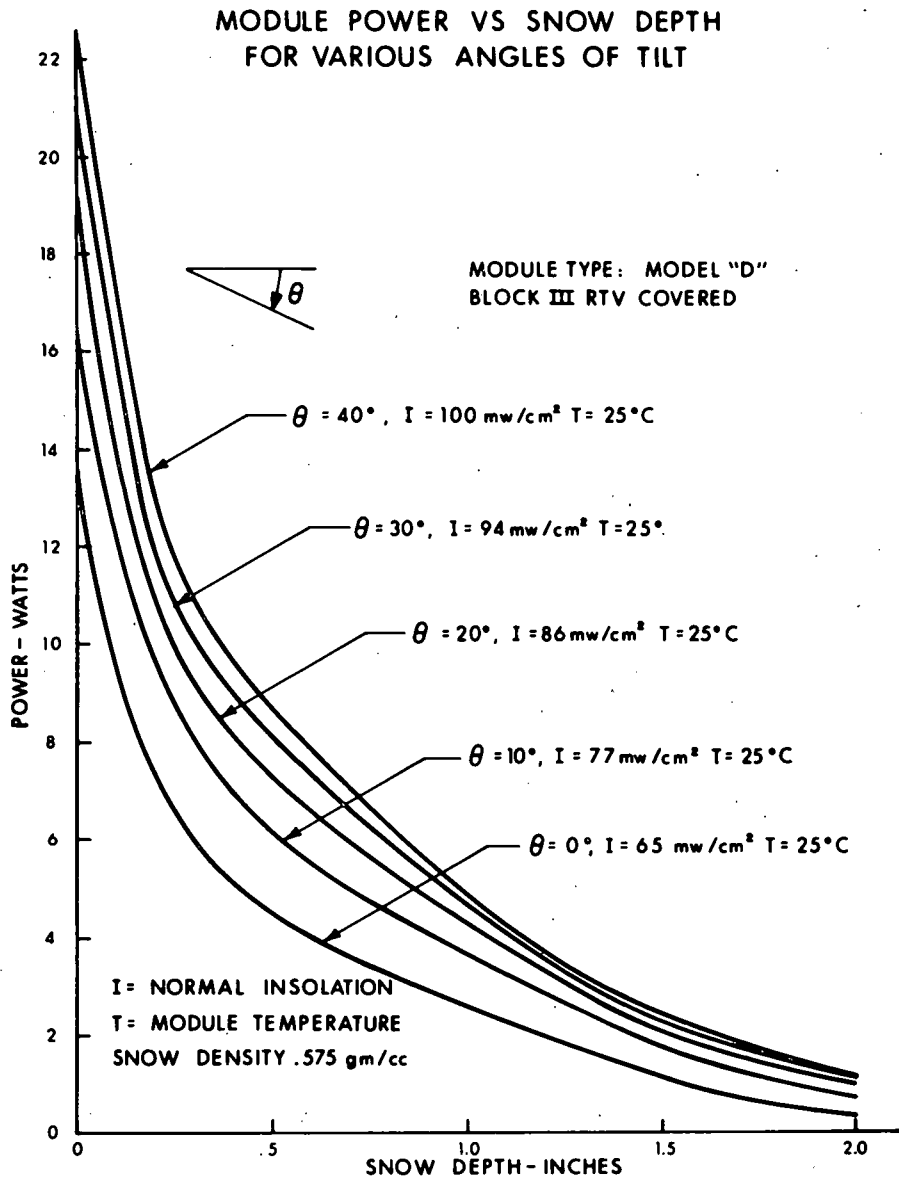


Fig. 2. Module power vs. snow depth - Model D.

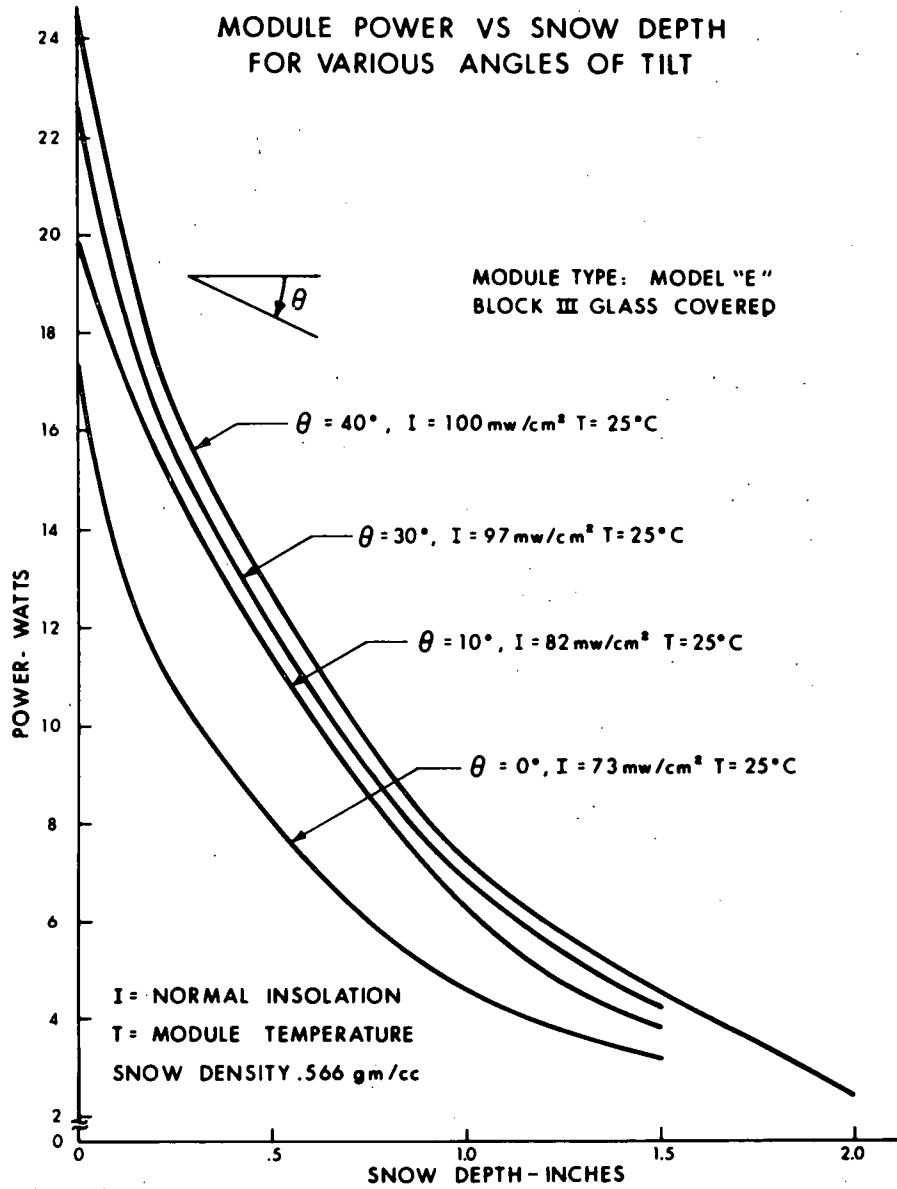


Fig. 3. Module power vs. snow depth — Model E.

densities. Loon Mountain staff say they are willing to help with an experiment by making snow and showering it on a module in bright sunlight so that we can monitor module output. This possibility will be given consideration next winter.

4.0 LABORATORY DEGRADATION ANALYSIS - NYU MODULES

During the period of 23 January 1979 through 5 February 1979, visual and electrical degradation analysis of nine modules was performed. These modules had been removed from New York University on 15 November 1978, after 21 weeks of soil accumulation and electrical degradation tests. The nine modules consisted of (2) Block I Model B, (2) Block II Model A, (3) Block II Model C and (2) Block II Model D. The following is a summary of conditions found in each type of module.

4.1 Model A

Delamination

Along most of the edge-seal area, one module had delamination which penetrated toward the cells as much as 3/4 inch at the positive end and 1/2 inch at the negative end. The encapsulant had loosened from the substrate across both end seals and along one side in the delaminated areas.

This module had an aluminum plate bonded to the substrate, which covered the structural ribs and extended to within 1/16 inch of the sides of the module. At the positive and negative ends, the plate was within 1/16 inch of the mounting bosses.

The adhesive used to bond the plate to the substrate had seeped out along the outer periphery of the plate. The cause of the excessive delamination found on this module was improper curing of the exposed adhesive to which the RTV could not adhere.

Delamination was present around the four mounting bosses on one module.

Areas of delamination along the interconnects, where they are soldered to the cell main collectors, were found on two cells of one module and on 18 cells of the second module. These areas of delamination ranged from 3/64 to 1/8 inch in diameter.

Slight delamination was found along the outer periphery of the positive terminal area on one module.

Discoloration

Both modules were found to have a yellowish discoloration, varying from light to moderate, in the terminal areas.

Fading of the cell anti-reflective coating to a gray and/or beige hue had taken place on both modules.

Stains, previously noted on the cells as dark in color, had changed to a reddish-brown color. This condition existed on both modules and involved 60 cells.

Staining of varied intensity was found along the grid lines of both modules and involved 88 cells.

Tarnish

Tarnishing of exposed copper on the interconnects was found in 20 places on one module and 16 places on the second module.

On one module, tarnish was found around the base of one terminal at the negative end.

On one module, some of the interconnects had darkened, possibly due to a loss of plating.

Residue

Flux, left on the interconnects of 3 cells, had turned green on one module.

Slits in RTV

A slit in the RTV, 1/8-inch long and 1/32-inch deep, was found over a cell on one module.

Cracked Cells

Edge cracks, not previously noted on receiving inspection road maps, were found on one cell of each module. The cracks penetrated 3/64 and 1/16 inch into the cells.

One module contained a newly cracked cell. The crack started between the interconnects at the top of the cell and emerged in the lower left quadrant of the cell, cutting through one of the main collectors.

One cell, cracked halfway across, had been noted on the receiving inspection road map of the second module. The crack has since cut through both main collectors and is approaching the opposite edge of the cell.

Electrical

Forward and reverse dark curve checks were taken. Typically, the voltage on the forward dark curve at 0.5 amps is on the order of 25 volts. One module showed an increase of 0.5 volts; the voltage of the second module remained the same as had been noted at receiving inspection.

On the reverse dark curve check, the current at 160 volts is noted. On the first module, a decrease of 6.5 milliamps from the value at receiving inspection was noted, while the second module showed a decrease of 0.4 milliamps.

High-voltage breakdown was performed at 500- and 1000-volts DC. The leakage current at 1000 volts decreased by 5.69 microamps on the first module and by 6.75 microamps on the second from values measured at receiving inspection.

4.2 Model B

The two Model B modules had already seen seven months of service in the Lincoln Laboratory Rooftop Test Bed before being installed at New York University for an additional 21 weeks of exposure. This report will include all changes found since receiving inspection.

Delamination

On one module, delamination was found around and on the positive terminal disc. On the second module, the areas around the negative and positive terminal discs were delaminated, with the delamination from the positive disc extending to the end seal.

Areas of delamination under the RTV along the end seal, opposite the terminal end, were found on one module. These areas measured from 1/64 to 1/4 inch in diameter.

Voids were found, along the side and end seals of both modules, where small pieces of the RTV had either fallen off or had been washed off. Entrapped dirt was also found in some of these areas.

Discoloration

Yellowing of the material used to bond the terminal discs to the substrate was found on both modules.

Yellow stains on the main collectors and grid lines were found on both modules and involved a total of 16 cells.

To some extent, staining along the grid lines was found on all the cells of both modules.

Rust-colored spots were found on the main collectors and grid lines of five cells on one module. Some of the gray stains on cells, previously noted on the receiving inspection road maps, had changed to a rusty hue. This condition existed on seven cells of one module and six cells of the second module.

Broken Surface Bubble

A broken surface bubble, 3/64 inch in diameter, was found in the end seal opposite the terminal end.

Tarnish

Exposed copper, on the interconnecting mesh between cells, had tarnished. This condition was found in three places on the two modules.

Chipped and Scratched Glass

On one module, a 1/16-inch chip from the protective glass cover was found along the edge near the positive terminal disc.

Multiple scratches were found on the surface of the protective glass cover of both modules. The scratches probably are due to shipping and handling rather than weathering.

Electrical

Forward dark curve checks were taken and there were no changes.

High-voltage breakdown was performed at 500 volts and 1000 volts. On one module, the leakage current at 500 volts was zero. The second module had a leakage current of 0.01 microamps.

At 1000 volts, both modules showed high-voltage breakdown. By starting at 500 volts again, the voltage was increased in 10-volt increments until the breakdown point was reached. On the first module, breakdown occurred at 720 volts. The current leakage to that point had been 0.01 microamps.

The breakdown voltage on the second module occurred initially at 940 volts. By decreasing the voltage in 10-volt increments, a stabilized voltage was reached at 600 volts. Starting again at 600 volts, the voltage was increased in 10-volt increments until a breakdown occurred at 700 volts. The current leakage at 600 volts was 0.01 microamps.

Normally, these modules would not be used in an application where the voltage would be as high as 500 volts.

4.3 Model C

Corrosion/Tarnish

Green corrosion on the interconnects between cells and on the positive and negative terminal strips was found in 34 places on the three modules.

Exposed copper, on the interconnects and the terminal strips, had tarnished in 13 places on the three modules. On all three modules, several interconnects with areas of sparse plating had darkened.

Debris/Residue

On one module, a piece of debris on a cell had turned green.

Due to poor cleaning techniques by the vendor, a white residue was left on the cells along the interconnects and collector grid lines. The anti-reflective coating in these areas had stained along the edges of this residue. This condition existed on 67 out of the three modules' 120 cells.

Delamination

Delamination was found in a vendor-repaired area beside the negative terminal strip on one module.

On one module, seal delamination was found measuring 1/2-inch long and 1/16-inch deep along the right-hand corner at the negative end.

Several dispersed spots of delamination were found on all three modules around the periphery of the cell nest, measuring approximately 1/4 to 1/64 to 1/32 inch in diameter.

Slits in RTV and Topcoat

Slits in the RTV, 9/32-to 3/8-inch long x 3/64-inch deep, were found over two cells on one module. This module also had a slit in the topcoat which measured 5/16-inch long.

The second module had three slits in the RTV, measuring 1/4-to 3/8-inch long and 1/4-inch deep, near the interconnect to the positive terminal. On the same module, a line of V-shaped splits, starting between cells and ending over a cell, was found. These splits ranged in length from 3/32 to 1/2 inch and 1/64 to 3/64 inch in depth. Three areas of missing topcoat measuring 1/32, 9/32 and 11/32 inch in diameter were found on the third module.

Discoloration

The anti-reflective coating on previously noted stained areas had changed from a dark brown to a copper hue. This condition existed on all three of the modules.

The encapsulant appeared to be yellowing slightly due to weathering.

Broken Interconnect

On one module, the interconnect joining the two negative terminal studs was broken in two. This probably was caused by over-tightening of the terminal screw in the rearside junction box during the electrical assembly process. This over-tightening caused the terminal stud to rotate, resulting in a break in the thin interconnect.

Cracked Cells

One module was found with a cell cracked across the area where the rearside interconnect is soldered.

Electrical

Forward and reverse dark curve measurements were taken and there were no significant changes.

High-voltage breakdown is not performed on these modules because they have a nonmetallic substrate.

4.4 Model D

Broken Surface Bubbles

Bubbles which had broken at the surface, leaving shallow holes, were found on both modules.

Corroded and Rusted Hardware

Screws, located in the terminal strip of the rearside junction box, had a light green corrosion on the heads. This condition was found on both modules. Rusted screw heads in this same area was found on one module.

Delamination

Slight seal delamination was found on both modules.

Delamination on a cell, near the rearside interconnect, was found on three cells of one module and ranged from 5/64 to 3/32 inch in diameter.

Stained Main Collectors

Eighty-one of 84 cells were found to have rust-colored main collectors.

Electrical

Forward and reverse dark curve checks were taken. No significant changes were found on the reverse dark curve.

On the forward dark curve the voltage at 0.5 amps is noted. Both modules showed increases of 1.0 volts and 1.5 volts, respectively.

High-voltage breakdown was performed at 500 volts and 1000 volts and the changes were negligible.

5.0 LABORATORY DEGRADATION ANALYSIS - MEAD MODULES

During the period 26 February 1979 through 8 March 1979, electrical and visual degradation analyses were performed on 32 Block II Model A and 14 Block II Model D modules. These modules were removed from the Mead, Nebraska, test site on 30 January 1979 after varied lengths of exposure in the field.

With the exception of two Model A and two Model D modules, all of the modules had been returned once previously to the MP&T Laboratory for electrical and visual degradation analyses.

An attempt has been made to determine the physical changes which had occurred between the first and second analyses by carefully comparing and correlating both sets of data. These comparisons are shown in Charts I and II.

New or deteriorating conditions found in each type of module, not noted on the charts, will be summarized in the following text.

5.1 Model D

5.1.1 Second Degradation Analysis

Discoloration of collector or grid lines, edge-seal delamination and broken surface bubbles were found on all twelve modules during the first and second degradation analyses. Two of seven modules, which were observed after two months of service and again after twelve more months of service, were found to have new areas of delamination over or along interconnects.

Of the seven modules exposed for two months and then an additional twelve, no cracked cells were found during the first analysis. However, six modules, with a total of ten cracked cells, were found during the latest analysis. All cracks were of the impact variety. Of five modules exposed for five months and then an additional twelve, only one was found with a cracked cell during the first analysis. Two more modules, however, with a total of three cracked cells, were found during the second analysis. The new cracks were all due to impact, caused by a hailstorm which occurred during May, 1978.

The results of the second analysis of degradation of Model D modules are described in detail below:

CHART I
COMPARATIVE ANALYSIS OF VISUAL DEFECTS

Type of Degradation	1st insp. (7) 2 mos	2nd insp. (7) 14 mos	1st insp. (5) 5 mos	2nd insp. (5) 17 mos
1. Discoloration of collector or grid lines	7	7	5	5
2. Delamination				
Edge Seal	7	7	5	5
Over or Along Interconnects	1	3	-	-
3. Broken Surface Bubbles	7	7	5	5
4. Cracked Cells				
5. Total Modules with Cracked Cells	-	6	1	3
Total Cracked Cells	-	10	1	4
Modules with Impact Cracks	-	6	-	2
Total Impact Cracked Cells	-	10	-	3

Numbers in parenthesis indicate the number of modules examined.

Model D Block II Modules

CHART II
COMPARATIVE ANALYSIS OF VISUAL DEFECTS

C74-569

Type of Degradation	1st Insp.	2nd Insp.	1st Insp.	2nd Insp.	1st Insp.	2nd Insp.	1st Insp.	2nd Insp.	1st Insp.	2nd Insp.
	(4) 2 mos.	(4) 14 mos.	(3) 3 mos.	(3) 15 mos.	(7) 5 mos.	(7) 17 mos.	(12) 6 mos.	(12) 16 mos.	(4) 8 mos.	(4) 14 mos.
1. <u>Discoloration</u> of Terminal Post Areas	MODS 4	MODS 4	MODS 3	MODS 3	MODS 7	MODS 7	11	11	3	4
Along Collectors or Grid Lines	-	4	-	3	-	7	1	12	4	4
2. <u>Delamination</u> Repair Areas	-	-	-	-	-	-	1	4	-	1
Over and Around Interconnects	-	1	-	-	-	1	2	1	1	-
Over Cells	-	3	-	2	-	-	2	5	2	3
Terminal Areas	3	3	2	2	6	6	8	8	2	2
Around Mounting Bosses	-	3	1	1	3	3	7	10	2	3
Edge Seal	-	1	-	-	-	1	2	4	1	1
3. <u>Broken Surface</u> <u>Bubbles</u>	2	3	2	2	1	3	-	2	-	-
4. <u>Cracked Cells</u>										
Total Modules	-	3	1	3	2	7	3	10	1	3
Total Cells	-	3	1	8	2	24	3	23	2	4
Modules w/Impact Cracks	-	3	-	3	-	7	-	10	-	10
Impact Cracked Cells	-	3	-	6	-	16	-	15	-	-

Numbers in parenthesis indicate number of modules.

Model A Block II Modules

Splits in the RTV

Ten of the twelve modules were found to have splits in the RTV, all of which occurred over cells. These splits ranged in length from 1/32 to 5/32 inch and from 1/64 to 3/32 inch in depth.

On two of the above modules, the RTV was split down to the surface of the cell. The split area was very small on one of the modules and is not considered an electrical hazard. This module will be returned to the field and carefully watched to determine whether accelerated degradation occurs.

The second module appeared to have been damaged in handling or shipping. The area of split encapsulant over a cell was so extensive as to be an electrical hazard. This module will be reworked in the MP&T Laboratory before returning it to the field.

Broken Surface Bubbles

Typically, bubbles which break at the surface leave a shallow hole 1/64 to 1/32 inch in diameter. Occasionally, there is a chain of bubbles, one on top of the other, which rise to the surface from the substrate. When the surface bubble breaks, it leaves an open path to the substrate through which moisture can penetrate.

One module contained a newly broken surface bubble which left an open path extending almost to the busbar.

Protruding Vendor ID Plate

On one module, the vendor identification plate had protruded through the encapsulant, leaving splits 3/8-inch x 1/8-inch long. This damage is not an electrical hazard and the module will be returned to the field.

Shore Hardness

As an indicator of degradation of the encapsulant, Shore hardness checks have been taken since August, 1978 on all modules returned to the MP&T Laboratory for analysis. Until modules are returned to their second analysis, a correlation cannot be made.

It is hard to determine at the present time if the length of exposure has much bearing on these readings. For example, two modules which had an

equal exposure time (one year and five months) had an entirely different range of readings. The first module ranged from 33 to 44 points while the other module ranged from 47 to 49 points.

A possible cause of this discrepancy may be the thickness of the RTV in the area where the readings were taken. Because of poor control of encapsulant flow during fabrication, the thickness of the RTV is highly irregular. There is no way to determine the exact thickness, short of cutting through the encapsulant.

Electrical

High-voltage breakdown, at 500 volts and 1000 volts, was performed and no significant changes were found.

Forward and reverse dark curve measurements were taken on all twelve modules. On eleven modules, the forward dark curve readings showed increases of from .5 to 1.0 volts over the previous readings. On ten modules, the reverse dark curve check showed decreases ranging from 5 to 60 milliamps.

Of the above modules showing changes on both the forward and reverse dark curve measurements, eight were found to contain impact-cracked cells.

The results of forward and reverse dark curve measurements at receiving inspection and after 2, 5, 14 and 17 months of field service are shown in Table I. Also included in the table are the readings for two modules which have seen 18 months of field service without prior return to the MP&T Laboratory.

5.1.2 First Degradation Analysis

The following is a summary of conditions found on two Model D Block II modules which have seen 18 months of continuous field service.

Stained Main Collectors

More than half of the cells on both modules had rust-colored main collectors.

Delamination

Slight seal delamination was found on both modules.

TABLE I

COMPARATIVE TABLE OF FORWARD AND REVERSE DARK CURVES

Model D Block II Modules

LL S/N	Receiv. Forward Dark	Inspect. Reverse Dark	2 Mos Forward Dark	Expos. Reverse Dark	5 Mos Forward Dark	Expos. Reverse Dark	14 Mos Forward Dark	Expos. Reverse Dark	17 Mos Forward Dark	Expos. Reverse Dark	18 Mos Forward Dark	Expos. Reverse Dark
1460	23.0V	160 ma.	23.0V	160 ma.			*23.5V	155 ma.				
1790	24.0	190			23.5V	190 ma.			24.5V	190 ma.		
1827	23.0	175	23.0	175			*24.0	170				
1832	23.0	220	23.5	170			*24.0	160				
1913	23.0	150	23.5	150			*24.0	140				
1970	23.0	200	23.0	200			*23.5	190				
2201	23.0	140			23.5	140			*24.0	130		
2203	23.0	140			23.5	135			*24.0	130		
3409	23.5	225	23.0	290			24.0	230				
3413	23.0	175	23.5	180			*24.0	170				
4164	22.5	128									23.5V	120 ma.
4166	22.0	130									23.5	120
4227	23.0	145			23.0	150			23.5	150		
4349	23.0	180			23.5	160			23.5	120		
* Designates modules with impact cracked cells												

24

Delamination in the area of the interconnects was found on one cell of one module.

Broken Surface Bubbles

Bubbles, which had broken at the surface, were found on both modules. Some of these had tiny surface splits running from them.

Repair Droplets

Shallow holes, left by vendor repair droplets which had fallen off and/or had been washed off, were found on both modules. Some of the holes had tiny splits running from them.

Splits in the RTV

Both modules contained splits in the RTV, over a cell, ranging in length from 1/32 to 9/64 inch and from 1/64 to 1/32 inch in depth.

Shore Hardness

The Shore hardness, taken at the four corners of each module, ranged from 46 to 52 points.

Electrical

High-voltage breakdown was taken and there were no changes when compared to the receiving inspection reports.

Forward and reverse dark curve measurements were taken. There was an increase of 1.0 volt on one module and 1.5 volts on the second module on the forward dark curve. The reverse dark curve check showed a decrease of 8 milliamps and 10 milliamps, respectively, as shown in Table I.

Note: Some of the modules, noted as having impact-cracked cells, contained cells which had multiple impact hits. One cell had received as many as four impact hits. In spite of the severe damage to the cell, the module was still working electrically. However, this cell has the potential to eventually open-circuit the module, thus causing failure. Several of the splits in the RTV were found over cells with impact cracks, which indicates that hail not only caused cells to crack but also split the encapsulant.

5.2 Model A

The most significant changes that occurred between the first and second analyses were discoloration along the grid lines, delamination in various areas and cracked cells.

Of the twelve modules exposed for six months, only one was found on the first analysis with discoloration along the grid lines. When these modules were again examined, after ten additional months of exposure, all twelve modules were found to be discolored along the grid lines.

Delamination in several areas is noted on Chart II. The following is an explanation of the extent of this condition.

5.2.1 Second Degradation Analysis

After six months of exposure, delamination around the mounting bosses was found on seven of twelve modules. With an additional ten months of field service, ten of the twelve modules were found with this problem. Rotation of the mounting bosses during removal and replacement of the modules for degradation analysis has, in all probability, been the reason for the increased delamination around the mounting holes.

Delamination, found on or around the interconnects, ranged from $1/64$ to $7/32$ inch in diameter. On two modules, previously noted delamination near the interconnects seems to have disappeared, leaving a stain on the A/R coating.

Areas of delamination, found randomly on cells, ranged from $1/32$ to $7/32$ inch in diameter. On reworked cells, the delamination was sometimes much larger, i.e., $1/2$ inch x 1 inch.

Delamination in the terminal areas of the Model A modules was generally found adjacent to the screws used to attach the rearside terminal knob to the substrate. These areas varied in size from $5/64$ to $17/64$ inch in length and $1/64$ to $1/32$ inch in width.

Some modules were found with a large portion or most of the terminal area delaminated. These areas ranged from $13/32$ to $3/4$ inch long and from $5/64$ to $9/32$ inch wide.

The largest change noted between the first and second degradation analyses is an increase in the number of cracked cells. The prime reason for this increase was the damage caused by the hailstorm mentioned earlier.

Two modules, containing two cells that had cracked over a structural rib, were found on the first analysis of seven modules with five months of exposure. A second analysis was performed after twelve additional months and five more modules were found containing 22 newly cracked cells, 16 of which were impact cracks.

The first look at twelve modules, with six months of exposure, revealed three cracked cells on three modules. Observations made after ten additional months of field service, showed that seven more modules contained 20 cracked cells, 15 of which were of the impact type.

The remaining newly cracked cells are summarized in Chart II.

Note: Several of the impact-cracked cells, noted on Charts I and II, had multiple impact "hits" on a cell, i.e., one cell was found which had been hit in four places.

Several of the impact-cracked cells had radial cracks which cut across the main collectors and/or across the area of the junction of the rearside interconnects. These cells have the potential to eventually open-circuit the string of cells in the module.

Examples of impact-cracked Model A cells, one with radial cracks cutting through a main collector, are shown in Figures 4 and 5.

Further details of degradation of Model A modules are given below:

Tarnish

Darkened solder was found on the grid lines of 146 cells on 15 modules.

Spots of exposed copper on interconnects, which were found in numerous places during the first analysis of all 30 modules, had tarnished. This condition is caused during fabrication by tools accidentally removing the plating on the interconnects and exposing the copper base.

Tarnish was found at the base of the positive and/or negative terminals on eleven modules.

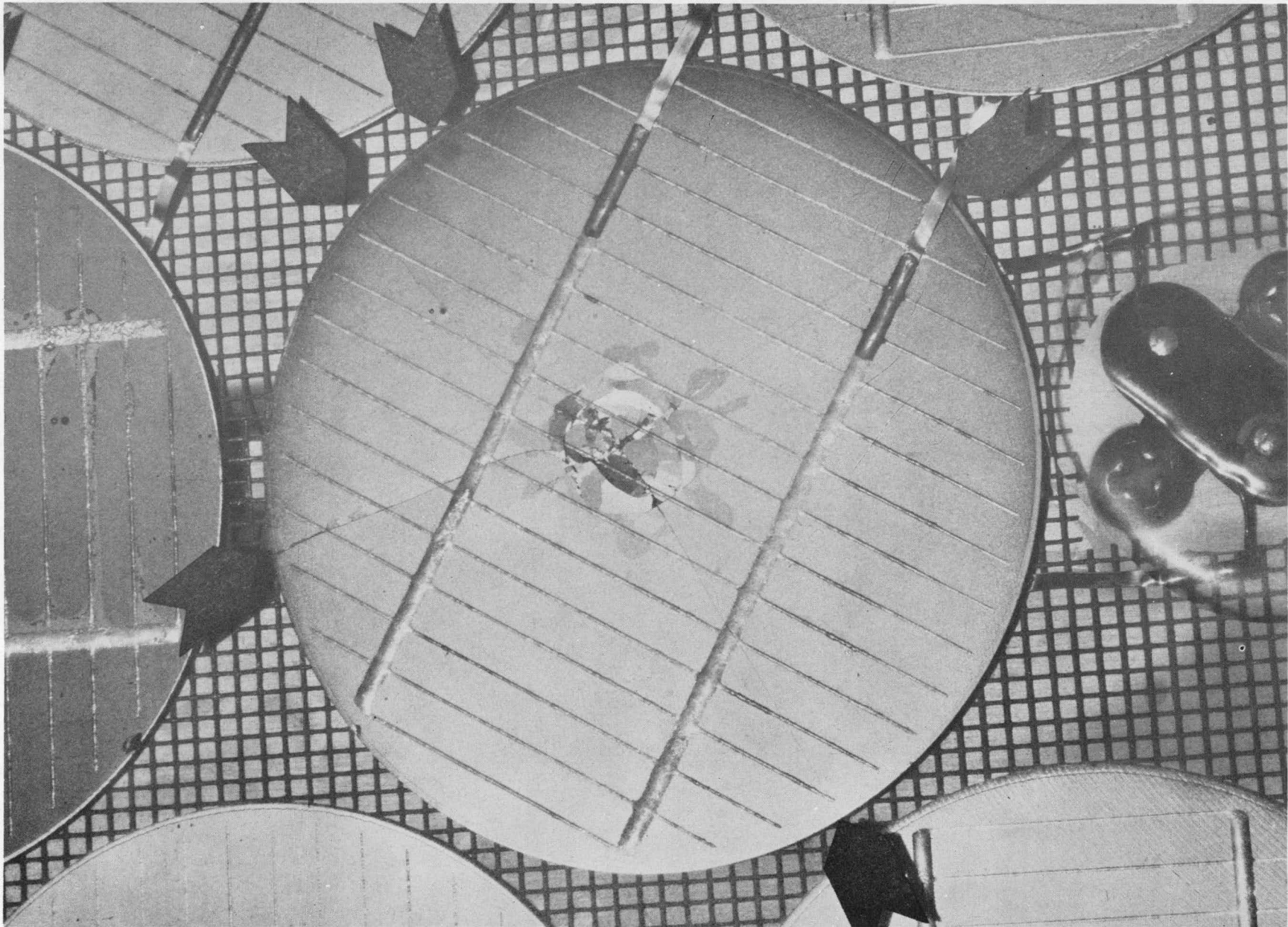


Figure 4. Impact-cracked cell.

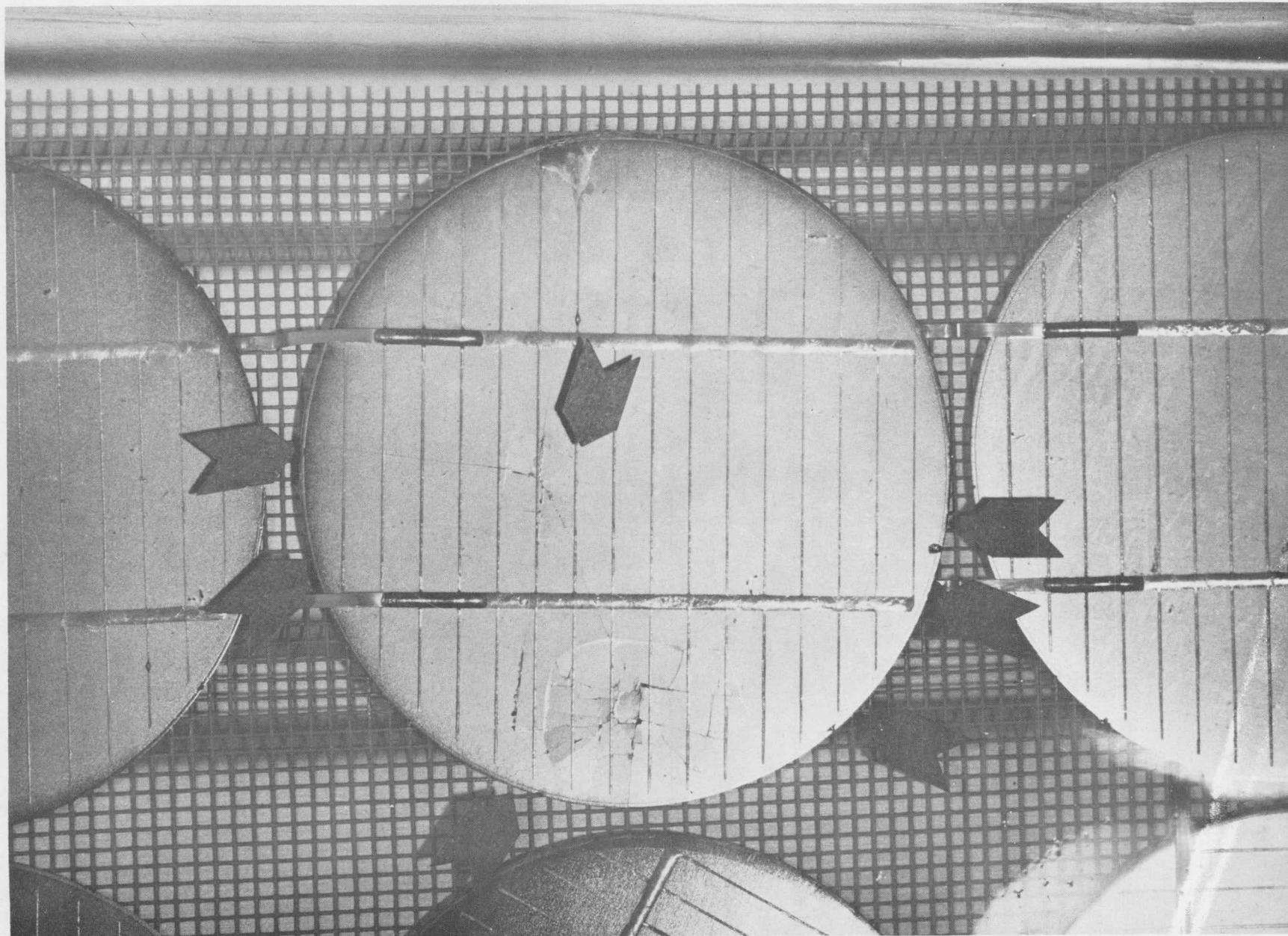


Figure 5. Impact-cracked cell.

Three modules were tarnished on top of the positive and/or negative terminals.

Exposed copper on the bus wires, at the negative and/or positive terminals, has become tarnished on four modules.

Flux Residue

Flux residue, found on the interconnects of eleven modules and around the base of the positive and/or negative terminals on two modules, had turned green.

Splits in the RTV

Small splits in the encapsulant were found over five cells on four modules. These splits ranged in length from 1/32 to 1/8 inch and from 1/64 to 3/64 inch in depth. It is possible that these splits were caused by hail striking the module during the May, 1978, hailstorm.

Discoloration of A/R Coating

At receiving inspection, it was noted that numerous cells had irregular dark stains on the anti-reflective (A/R) coating. These same stains, after field exposure, appear to be changing in color. They now range in color from light grey to various shades of rust.

The degree of change seems somewhat dependent upon the initial depth of color of the A/R coating. Stains on those cells with a pale blue A/R coating tend to range from pale gold to a rusty hue. Stains on cells with an initially dark blue/black A/R coating are inclined to become more of a brown shade. On a cell with grayish A/R coating, the staining will change to a silvery or pale gold shade, almost as if it is fading.

It has been noted that scratches in the A/R coating tend to discolor along the disturbed area.

The discoloration and staining conditions, described above, have been found on the majority of cells on all 30 modules.

Shore Hardness

The Shore hardness of the encapsulant was taken at the four corners of all the modules and ranged from 37 to 49 points.

Edge Cracks

Two modules were found containing one cell each with an edge crack. An edge crack is one that penetrates a short distance into the cell beyond the rim, which is 1/64-inch wide. Most edge cracks are from 1/32- to 3/32-inch long.

Electrical

Forward and reverse dark curve checks were taken on each module. Typically, the voltage on the forward dark curve at .5 amps is on the order of 25 volts. On 22 modules, the change from this value ranged from .5 to 1.0 volt of increase when compared to the first analysis.

On the reverse dark curve, the current at 160 volts is noted. Decreases on the order of .1 to 1.0 milliamps were found on twenty modules. One module showed a decrease of 6.8 milliamps.

On two modules, the current increased by 4.8 and 3.0 milliamps. The remaining seven modules showed no change.

High-voltage breakdown was performed at 500 volts and 1000 volts. Since the previous field return, the leakage current at 1000 volts on 22 modules has decreased to .6 to .94 of their values. It has increased, on five modules, by 1.03 to 1.22 times their former values, and remained unchanged on three other modules.

See Table II for a comparison of the results of initial, first field-return and second field-return readings.

5.2.2 First Degradation Analysis

Only two of the Model A Block II modules used for this degradation analysis have seen twelve months of continuous field exposure. The following is a summary of the conditions found on those modules:

Discoloration

Light yellow discoloration of the RTV around the positive terminal areas was found on both modules.

TABLE II

C74-571

MODEL A BLOCK II
 COMPARATIVE TABLE OF FORWARD AND REVERSE DARK CURVES
 AND HIGH-VOLTAGE LEAKAGE CURRENT

		Fwd. Dark	Rev. Dark	I Leakage at 1000 V			Fwd. Dark	Rev. Dark	I Leakage at 1000 V			Fwd. Dark	Rev. Dark	I Leakage at 1000 V		
*2736	A	25.5V	11.2ma	.50 μ a		*3918	A	24.0	23.0	1.10		*2385	A	25.5	8.8	.30
	2 mos B	25.5	12.0	.22			6 mos B	26.5	22.0	.31			1 year B	26.5	8.6	.11
	14 mos C	26.0	11.4	.19			16 mos C	26.5	22.0	.25						
2734	A	26.0	16.0	1.0		*2893	A	25.0V	6.3ma	.35 μ a		*2034	A	25.0	6.6	.35
	2 mos B	26.0	16.0	.21			5 mos B	25.5	6.4	.18			1 year B	26.5	5.5	.08
	14 mos C	26.5	15.2	.16			17 mos C	26.0	6.1	.15						
*2738	A	25.0	9.9	.50		*2895	A	25.5	6.3	.35		*3922	A	24.5V	37.0ma	.56 μ a
	2 mos B	25.5	10.0	.18			5 mos B	26.0	6.6	.16			6 mos B	26.0	32.0	.28
	14 mos C	26.5	9.6	.15			17 mos C	26.5	6.4	.13			16 mos C	26.5	32.0	.25
*2746	A	25.5	8.4	.80		*2896	A	25.5	7.5	.26		*3927	A	25.5	32.5	.86
	2 mos B	25.5	8.4	.13			5 mos B	25.8	7.5	.13			6 mos B	26.5	32.0	.32
	14 mos C	26.5	7.8	.10			17 mos C	26.5	7.0	.12			16 mos C	26.5	32.0	.30
*2263	A	25.5	7.4	.375		*2898	A	25.5	6.5	.28		*3933	A	25.5	18.0	.91
	3 mos B	26.5	7.0	.17			5 mos B	25.8	6.6	.08			6 mos B	26.0	18.0	.44
	15 mos C	26.5	6.8	.19			17 mos C	26.5	6.5	.08			16 mos C	26.5	18.0	.36
*2262	A	25.5	9.9	.50		2457	A	25.5	9.1	.25		*4060	A	25.0	26.5	1.60
	3 mos B	26.5	9.8	.30			6 mos B	26.0	9.2	.09			6 mos B	25.5	26.0	.54
	15 mos C	26.5	9.5	.31			16 mos C	26.5	8.8	.09			16 mos C	25.5	26.0	.58
*2266	A	25.5	12.0	.50		*3693	A	26.0	10.2	.80		3525	A	25.0	22.0	.85
	3 mos B	26.5	12.0	.19			6 mos B	26.5	21.0	.40			8 mos B	25.5	22.0	.62
	15 mos C	26.5	11.5	.16			16 mos C	26.5	21.0	.40			14 mos C	26.0	21.0	.37
*2317	A	25.5	10.5	.35		*3737	A	24.0	11.0	.80		3559	A	25.5	9.2	.79
	5 mos B	25.8	11.2	.16			6 mos B	25.5	11.0	.32			8 mos B	26.0	9.5	.35
	17 mos C	26.5	11.0	.17			16 mos C	26.5	15.8	.24			14 mos C	26.5	9.2	.23
*2334	A	25.0	11.0	.65		*3739	A	24.5	45.0	1.28		3536	A	25.5	16.0	1.10
	5 mos B	25.8	11.0	.14			6 mos B	26.5	40.0	.30			8 mos B	26.0	16.0	.51
	17 mos C	26.5	10.5	.13			16 mos C	26.5	43.0	.25			14 mos C	26.5	15.5	.34
*2335	A	25.5	10.5	1.05		*3744	A	25.0	34.0	1.20		3568	A	25.0	10.8	.99
	5 mos B	25.5	10.5	.27			6 mos B	25.5	32.0	.45			8 mos B	26.0	11.3	.58
	17 mos C	26.5	10.2	.33			16 mos C	26.0	32.0	.40			14 mos C	26.5	11.0	.38
3917	A	24.5	14.0	.72		*3713	A	26.0	15.9	.90						
	6 mos B	26.0	13.5	.31			6 mos B	26.5	17.0	.41						
	16 mos C	26.5	12.5	.28			16 mos C	26.0	10.2	.38						

*These are modules which have at least one impact cracked cell.

A = Receiving Inspection

B = First Field Return

C = Second Field Return

Grid Staining

Staining of the anti-reflective coating along the grid lines was found on 38 cells of one module and three cells of the second module. Each module contains 44 cells.

Tarnish

Tarnish of the solder on the grids was found on 39 cells of one module.

Copper on the interconnects, exposed during fabrication, was found to be tarnished in several places on both modules.

Tarnish was found at the base of the negative and/or positive terminals on both modules.

Stains on the A/R Coating

Stains, noted on cells at receiving inspection, are changing from a dark color to hues ranging from grey to rusty red. This condition was found on a total of 17 cells on the two modules.

Mounting Holes

The encapsulant was torn at the base of two mounting holes on one module. This condition is due to the rotation of the mounting boss during assembly to mounting frames.

Splits in the RTV

A T-shaped split, 9/32 inch x 3/32-inch long and approximately 1/32-inch deep, was found over an impact area on one cell of one module.

Shore Hardness

The Shore hardness, taken at the four corners of the modules, ranged from 42 to 49 points.

Cracked Cells

On the first module, three cracked cells were found, two of which were of the impact type. The third cell was cracked over a structural rib.

The second module contained three cracked cells, two over a structural rib and the third of the impact type.

Two of the impact-cracked cells had radial cracks that had cut through one of the main collectors. As Model A modules have ample interconnects, there does not seem to be, at this time, a potential for the modules to become open-circuited. Eventually, if the radial cracks continue across the cell during thermal expansion and contraction, the cells could open-circuit the string.

Electrical

Forward and reverse dark curve measurements were taken on both modules. On the forward dark curve, one module showed an increase of 1.5 volts while a 1.0 volt increase was found on the second module.

The reverse dark curve readings showed a decrease of 1.1 milliamps on the first module and a .2 milliamp decrease on the second.

These forward and reverse dark curve measurements are included in Table II for comparison with the other thirty modules.

High-voltage breakdown was performed at 500 volts and 1000 volts on both modules.

Decreases on the order of 23% and 37% from original values were found on the two modules. These readings are also included in Table II for comparison with the other thirty modules.

Note: Glossmeter readings, both dirty and clean, were taken of all the modules. The results of these readings are being analyzed.

6.0 LABORATORY FAILURE ANALYSIS

During the period of 23 April 1979 through 2 May 1979, electrical and visual failure analysis was completed on the following modules: (1) Block II Model C; (3) Block I Model B; (2) Block II Model A, and (1) Block II Model D.

The Model C and Model B modules were removed from the Lincoln Laboratory Rooftop Test Bed on 22 March 1979, where they were found to have reduced short-circuit current.

The Model A and Model D modules were electrical failures found during the March 1979 field inspection trip to the Mead, Nebraska, test site.

The following is a summary of conditions found in each type of module and the probable cause of failure.

6.1 Lincoln Laboratory Rooftop Failures

Model B:

Two of the Model B modules were found to be operating at reduced short-circuit current. When flashed in the Lincoln Laboratory Large Area Pulsed Solar Simulator (LAPSS), the short-circuit current was reduced by 52% and 46%, respectively, of the normal values, as shown in Figures 6 and 7.

Visual inspection showed that each module contained an edge-to-edge cracked cell with the crack cutting across the main collector.

The third Model B module was flashed in the LAPSS but no I-V curve could be obtained.

A forward dark curve measurement was taken and, again, no curve could be obtained.

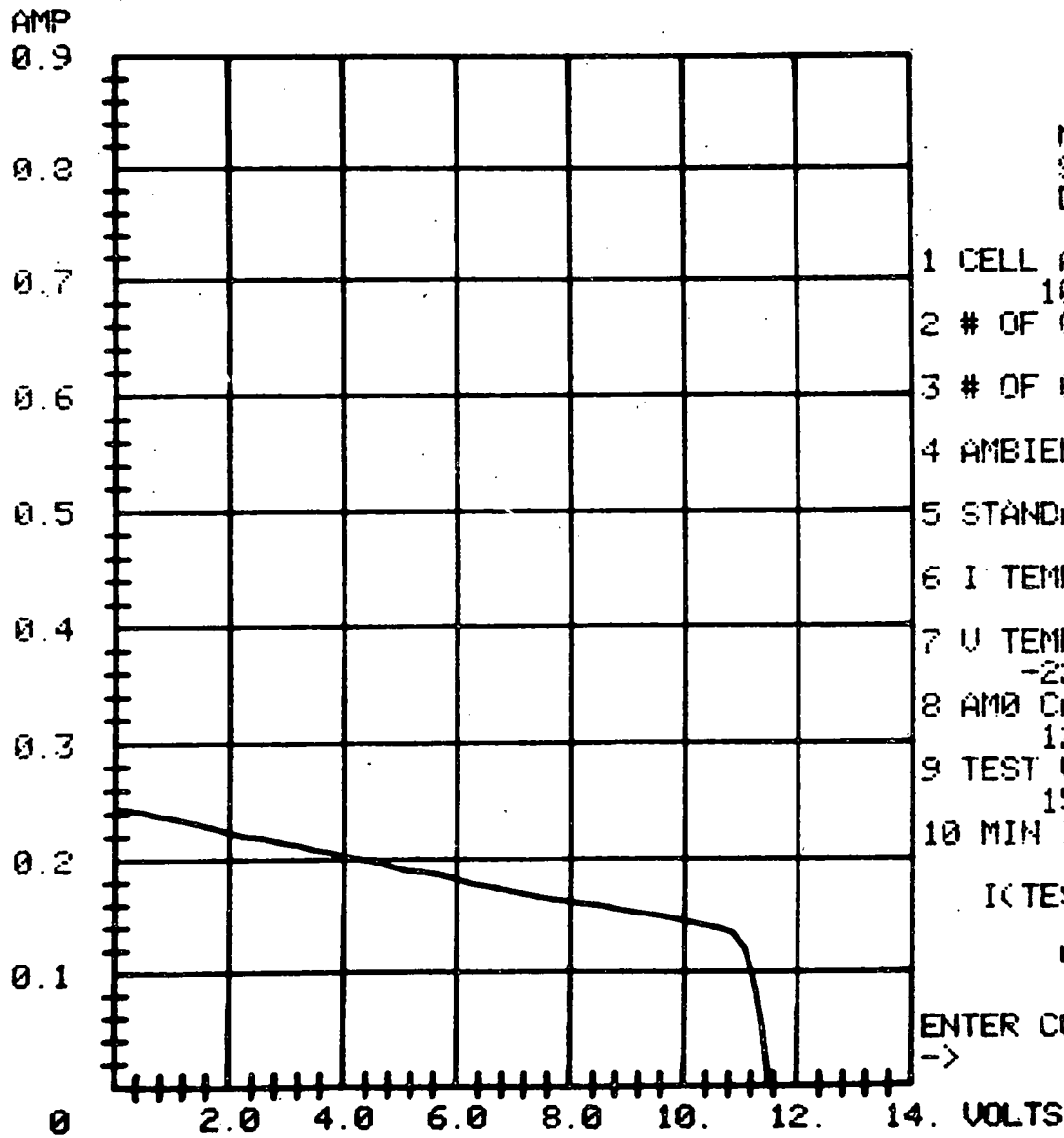
Upon visual inspection, it was found that the metal tab on top of the negative terminal had become unsoldered. This would account for the open-circuit condition of the module.

Model C:

The Model C module was flashed in the LAPSS and was found to have a normal I-V curve.

Closer examination under a microscope showed the module to have four cells that contained partial cracks, none of which could cause reduced short-circuit current. However, a fifth cell was found with an edge-to-edge crack that cut across both main collectors and the circular grid.

A ridge in the RTV was obvious along the cracked area. It appears that as the cell heated up, it pushed up from the substrate. As delamination was found along the lower edge of the cell, it is believed that air entrapped under the cell expanded, causing the cell to crack.



MODEL #I ROOF
 SERIAL 1105
 DATE 03/23/79

1 CELL AREA (SQ MM)
1001

2 # OF CELLS IN PARALLEL
1

3 # OF CELLS IN SERIES
20

4 AMBIENT TEMP (DEG C)
28

5 STANDARD TEMP (DEG C)
28

6 I TEMP COR(UA/SQ CM/DEG C)
25

7 U TEMP COR(U/DEG C/CELL)
-2204

8 AMØ CAL CURRENT (0.1'S MA)
1242

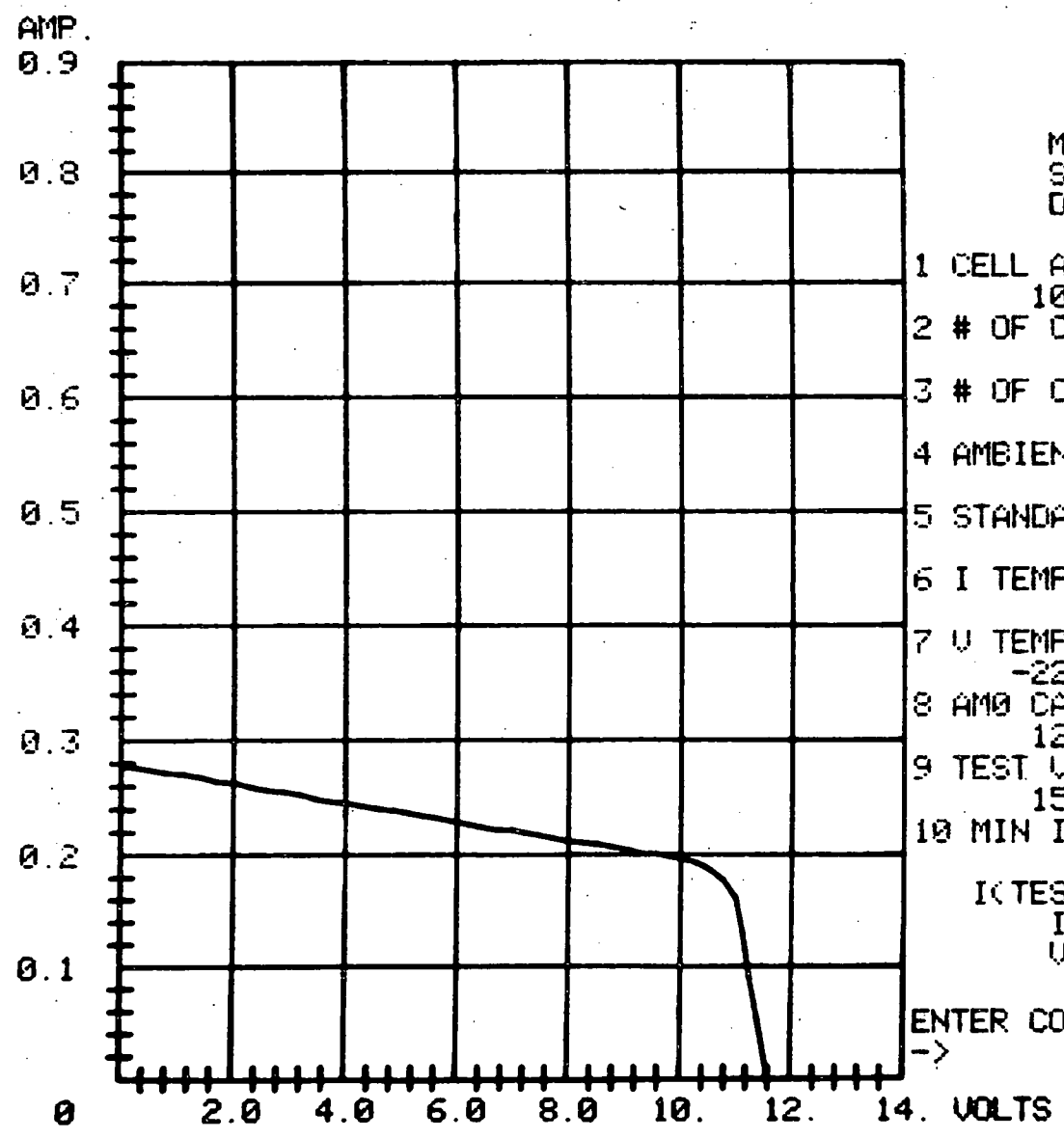
9 TEST VOLTAGE (0.01'S U)
1580

10 MIN I(TEST) (0.01'S A)
50

I(TEST) = ?? < 0
 ISC = 244500 UA
 UOC = 11518000 UU

ENTER COMMAND LETTER
 ->

Figure 6. Model B - 52% reduction of ISC.



MODEL #I ROOF
 SERIAL 683
 DATE 03/23/79

1 CELL AREA (SQ MM)
 1001

2 # OF CELLS IN PARALLEL
 1

3 # OF CELLS IN SERIES
 20

4 AMBIENT TEMP (DEG C)
 28

5 STANDARD TEMP (DEG C)
 28

6 I TEMP COR(UA/SQ CM/DEG C)
 25

7 U TEMP COR(UV/DEG C/CELL)
 -2204

8 AMØ CAL CURRENT (0.1'S MA)
 1242

9 TEST VOLTAGE (0.01'S V)
 1580

10 MIN I(TEST) (0.01'S A)
 50

I(TEST) = ?? < 0
 ISC = 277200 UA
 UOC = 1159200 UV

ENTER COMMAND LETTER
 ->

-37-

Figure 7. Model B - 46% reduction of ISC.

6.2 Nebraska Failures

Model D:

One Model D module was found to have zero short-circuit current at the Mead, Nebraska, test site on 28 March 1979.

Upon flashing in the LAPSS, an I-V curve could not be attained. A closer look at the wires in the rearside junction box revealed a broken negative wire which caused the open-circuit condition.

This module will be repaired in the MP&T Laboratory, retested, and then put back into the field.

Model A:

Both modules were found to have reduced short-circuit current at the Mead test site on 28 March 1979. Flashing in the LAPSS showed both modules to have dropped to 1/3 of their normal values, as shown in Figures 8 and 9.

Upon visual inspection, one module was found to have an impact-cracked cell, with radial cracks cutting through both main collectors.

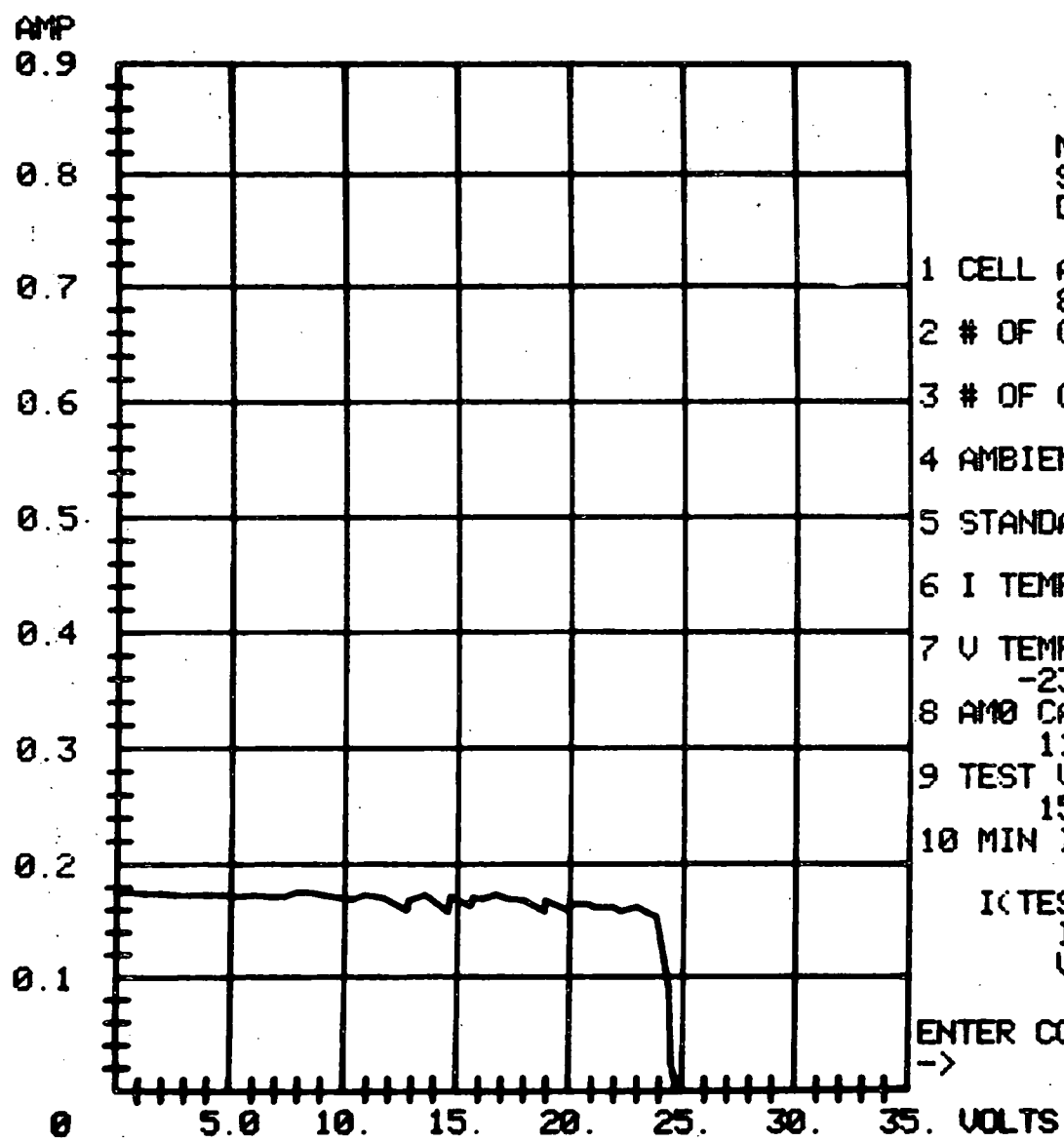
The other module was found to have a cell which had cracked over a structural rib. The crack cut across both lateral main collectors and isolated one of the interconnects going to the next cell in the string. A hairline crack, by the second interconnect going to the next cell, intersected the primary crack. This cell definitely has the potential to open-circuit the module.

All of the modules, except for Model D, have been photographed for future reference.

The above modules, along with MIT/Lincoln Laboratory findings, will be shipped to JPL for further failure analysis.

6.3 Use of X-ray and Infrared Detection

During February, six Block II Model A modules at the Residential Test Bed were found to have zero short-circuit current after only two months of service. Upon visual examination of each module, there was no visible evidence of the cause of failure. Each module was flashed in the LAPSS and had a



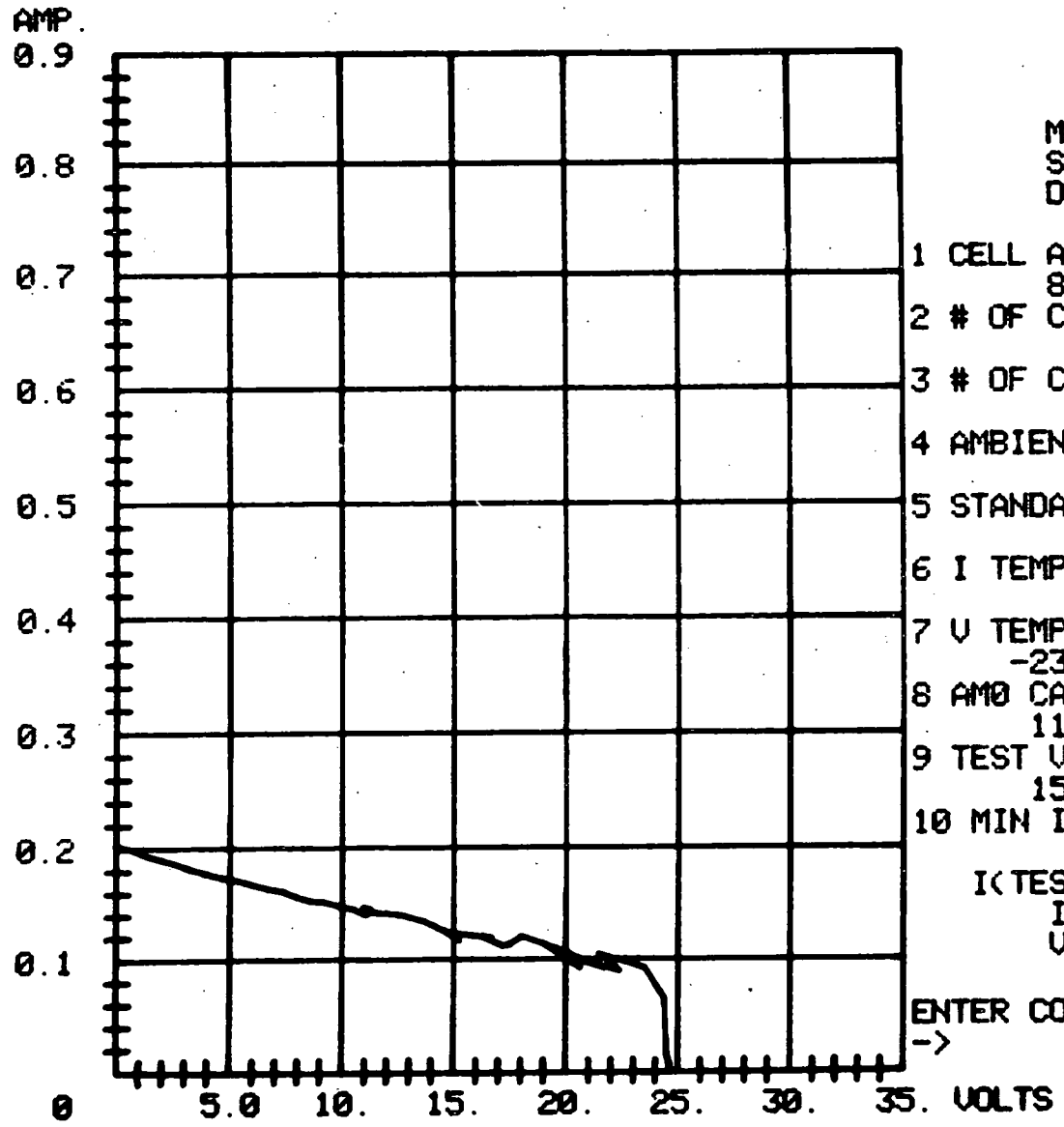
MODEL #NEB FAIL
 SERIAL 3770
 DATE 04/23/79

1 CELL AREA (SQ MM)
819
 2 # OF CELLS IN PARALLEL
1
 3 # OF CELLS IN SERIES
44
 4 AMBIENT TEMP (DEG C)
26
 5 STANDARD TEMP (DEG C)
28
 6 I TEMP COR (UA/SQ CM/DEG C)
25
 7 V TEMP COR (UV/DEG C/CELL)
-2307
 8 AMB CAL CURRENT (0.1'S MA)
1100
 9 TEST VOLTAGE (0.01'S V)
1580
 10 MIN I (TEST) (0.01'S A)
50

I (TEST) = 169100 UA
 ISC = 176200 UA
 UOC = 24700000 UV

ENTER COMMAND LETTER
->

Figure 8. Model A - ISC reduced to 1/3 the normal value (1).



MODEL #NEB FAIL
 SERIAL 4070
 DATE 04/23/79

1 CELL AREA (SQ MM)
819

2 # OF CELLS IN PARALLEL
1

3 # OF CELLS IN SERIES
44

4 AMBIENT TEMP (DEG C)
26

5 STANDARD TEMP (DEG C)
28

6 I TEMP COR(UA/SQ CM/DEG C)
25

7 V TEMP COR(UV/DEG C/CELL)
-2307

8 AMB CAL CURRENT (0.1'S MA)
1100

9 TEST VOLTAGE (0.01'S V)
1580

10 MIN I(TEST) (0.01'S A)
50

I(TEST) = 119100 UA
 ISC = 203000 UA
 UOC = 24625000 UV

ENTER COMMAND LETTER
->

Figure 9. Model A - ISC reduced to 1/3 the normal value (2).

flat I-V curve showing zero current. The same zero current response occurred when attempts to generate forward dark curve on a Tektronix 575 curve tracer were made.

The symptoms of the failures were similar to the very first module failure that occurred in Nebraska, i.e., on one cell the vendor neglected to solder the two interconnects to the backside. Using the curve tracer as a diagnostic tool, in the forward dark curve mode, light finger pressure was applied to each cell on the modules. Eventually, one cell was found which returned continuity to each module. The continuity was not totally retained, however, and upon release of pressure on the cell, the zero response condition returned from within a few seconds to thirty minutes at most.

The modules were brought to Arnold Greene Testing Lab in Natick, Massachusetts, for X-rays of suspect areas of the cells. The X-rays showed conclusively that the rearside interconnects on each suspect cell had indeed never been soldered at the factory. An example of this is shown in Figure 10. Normally, rearside solder joints show up as "dark blobs" against the gray of a cell. In the circled area, there is no sign of rearside solder.

The failure mode of these modules makes them perfect candidates for infrared detection of hot spots where poor continuity exists in the cell string. The module which retained continuity for the longest time was set up so that 1.25 amps of forward current was passed through it at a voltage of 28 volts. The nominal temperature of the module was found to be from 42 to 45°C; the hot spot, which appeared at the location of the unsoldered interconnects, was 53°C. In order to determine the amplitude of the hot spot temperature, a black body radiator was used and set at 50°C. The module emissivity was assumed to be 0.8.

As mentioned in Section 2.6, the use of infrared detection is a technique being explored by JPL and which they used at the Mead test site.

C00-4094-55-10

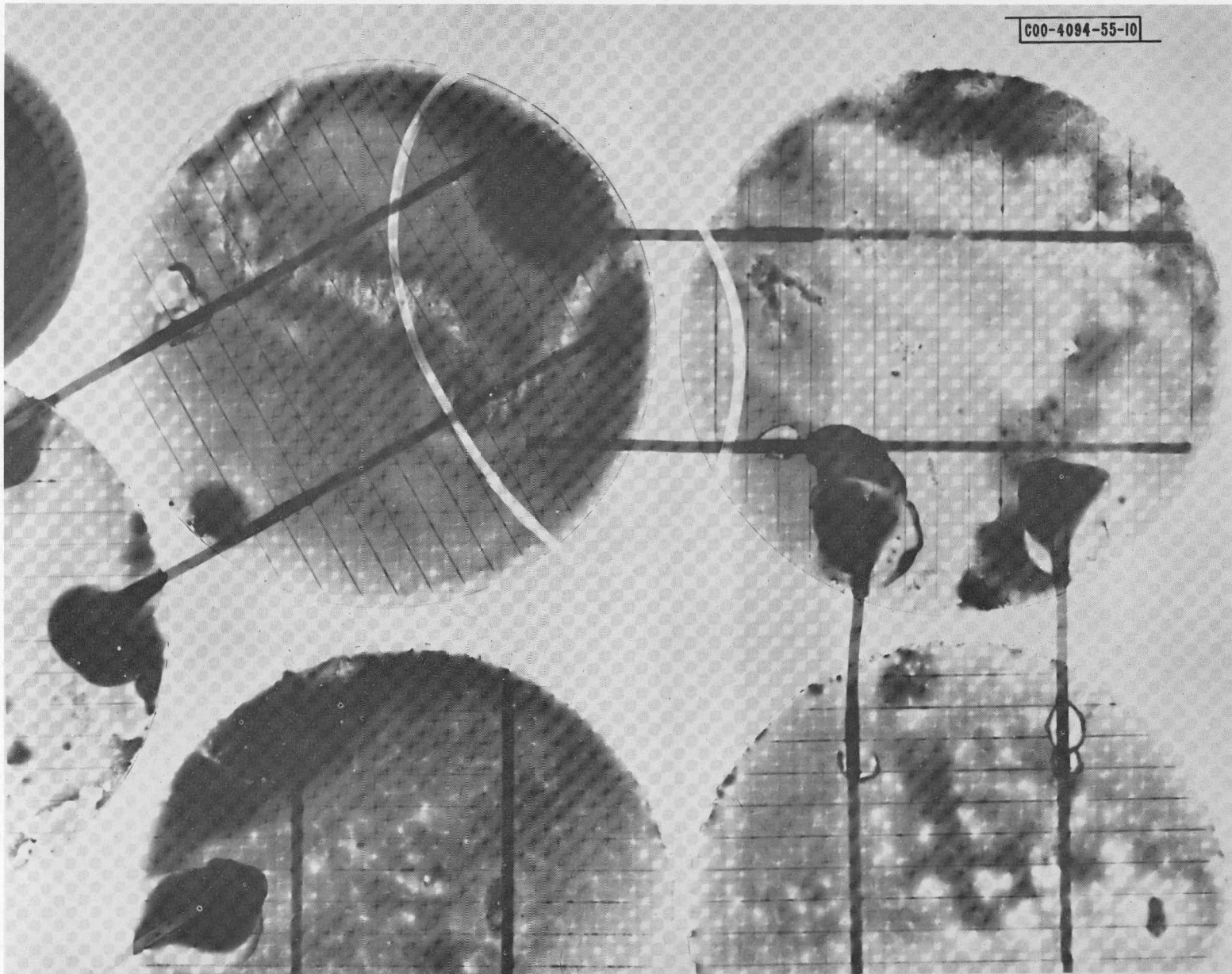


Figure 10. X-ray of unsoldered interconnect.

REFERENCES

1. Forman, S. E., "Summary of Field Experience of Photovoltaic Modules at Various MIT/LL Test Sites," MIT/LL C00-4094-8, 22 March 1978.
2. Forman, S. E., "Endurance and Soil Accumulation Testing of Photovoltaic Modules at Various MIT/LL Test Sites," MIT/LL C00-4094-23, 28 September 1978.
3. Forman, S. E., and Themelis, M. P., "Quarterly Report for 10/1/78 to 12/31/78 on Photovoltaic Module Performance at Mead, Nebraska Test Site," MIT/LL C00-4094-40, 1 April 1979.
4. Forman, S. E., "Visual Defects in Terrestrial Photovoltaic Modules," MIT/LL C00-4094-6, 21 March 1978.
5. Millner, A. R., "Solar Module Curve Tracer," MIT/LL C00-4094-36, 7 February 1979.