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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 various experimental test sites, ranging in size from 0.1 to 100 kW of peak power, throughout the United States. These sites contain modules from several manufacturers and serve as test beds for photovoltaic system components. This report, the tenth in a series of similar reports[1-10], summarizes the activities of the Materials, Processes and Testing Laboratory of the Solar Photovoltaic Field Tests and Application Project during the period of March—June 1981.

CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

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Materials, Processes and Testing Laboratory Technical Progress Report March - June 1981

INTRODUCTION

In previous reports (1-10), 45 months of test experience (5/77–2/81) with photovoltaic (PV) modules at various MIT Lincoln Laboratory (MIT LL) experimental test facilities were detailed. In this report, further data are presented for the next four-month period (3/81–6/81). Specific details are presented for site visits where electrically failed modules were found and replaced at Mead, Nebraska, and Bryan, Ohio. Broken interconnects at all MIT LL sites were reported and analyzed. A search for electrically failed modules at the Systems Test Facility (STF) array field was reported and analyzed. Several PV/T modules were analyzed for specific defects.

MIT LL serves as a Field Tests and Applications Center for the U. S. Department of Energy (DOE) to evaluate the energy potential of PV components in various test applications. As part of the DOE Jet Propulsion Laboratory's (JPL) Large-Scale Procurement Program, MIT LL receives PV modules from various manufacturers for use at its experimental test sites. (The names of the module manufacturers are not relevant to this report, and the module types discussed are referrred to as Models A through M.) Each module is inspected visually at the factory of origin and a "road map" outlining its physical appearance and workmanship-related anomalies is completed in the manner discussed previously by one of the authors (12).

Modules are field tested at two types of experimental test facilities. Modules and the many components of a PV system are evaluated at an STF. Four such sites are discussed in this report: a 25-kWp array field at the Mead Field Station of the University of Nebraska; a 15-kWp array field at a radio station in Bryan, Ohio, and a 25-kWp residential STF (RSTF) in Concord, Massachusetts. Modules undergo weathering and soiling in special climates at Environmental Test Sites (urban rooftops in New York City; Cambridge, Mass.; Chicago, and a Mount Washington, New Hampshire, weather station). Data from these sites will be discussed in later reports.

1.0 TRIP REPORT - MEAD, NEBRASKA

During the week of 16 March 1981, members of the MP&TL visited the Mead, Nebraska, test site to search for electrically defective modules. I-V curves were generated for each branch circuit in the array field, failures were located, removed and replaced. The Mead experiment was initiated in July 1977 and this was the thirteenth trip of its type.

The Mead array field consists of 2240 Block II, silicone rubber encapsulated modules: 1512 Model C and 728 Model D. The Model C modules are electrically connected into 42 branch circuits each containing 36 modules wired 4 in parallel by 9 in series. The Model D modules are electrically

Fig. 1. Model D I-V curves for (a) completely open-circuited module (b) partially failed module.

Fig. 2. Model C I-V curves for (a) completely open-circuited module (b) partially failed module.

connected into 35 branch circuits each containing 20 modules wired 2 in parallel by 10 in series. Using the MIT LL curve tracer, 77 I-V curves were generated and stored on tape.

For Model D modules, four new failures were found bringing the total to 39 of 728 or 5.36 percent. As has been shown in a past report (11), a failed module causes a step in the I-V curve (Fig. 1a). In Fig. 1b the failure is evidenced by the diagonally flattened peak power portion of the curve. In the former the module was completely open circuited, whereas in the latter the module short-circuit current was about 25 percent of normal.

For Model C modules, 13 new failures were found, bringing the total to 74 of 1512 modules or 4.89 percent. An example of the effect of an open-circuited module on a branch circuit is shown in Fig. 2a. A partially failed module's effect is shown in Fig. 2b. Failure analysis of the 17 new failures will be completed and documented later.

A summary of the results of each of the 13 visits to Mead is presented in Table I. Clearly, over half of the failures have been found in the past year. This is due to the fact that many of the failures are due to cracked cells caused by a May 1978 hailstorm. Cracked cells can fail at the time of cracking or much later. Site inspections have indicated that more than half of the modules in the array contain at least one cracked cell. The data from Table I has been plotted in Fig. 3 where a parabolic curve follows the data points very closely. Clearly since the hailstorm in May 1978, this curve has been rising at a rapid rate to a cumulative number of failures amounting to 5.04 percent of the total number of modules.

Table I

Module Failures at Mead Test Site (Starting Date: July 1977)

Date of Search	Number of Failures	
	Front Row	Back Row
October 1977	0	1
November	1	1
February 1978	0	3
March	0	0
July	6	3
September	3	1
February 1979	2	0
March 1979	1	2
July	6	7
October	1	10
July 1980	11	7
October	4	26
March 1981	4	13
Totals	39	74

Front row: 728 modules
Back row: 1512 modules

It is likely that more failures were present in the array field, but the cold weather prevented their detection from the I-V curves. The maximum module temperature measured over the three days was 19°C.

There is evidence of several "critters" of various sizes who have taken up residence at the site and module storage area. One box of Model D spare modules contained signs of several small rodents who had nested in the box. They chose to eat the bubble pack rather than the insulation on the wires. There are several 6- to 8-inch-diameter holes in the ground about the array field. These holes appear to house larger critters whose tracks were evident in the mud. Finally, there are several 2- to 3-inch-diameter holes that house a third critter. Fortunately, these critters stayed in their nests during the visit.

2.0 SITE MEASUREMENTS - BRYAN, OHIO

During the period 29 April—1 May 1981, members of the MP&TL visited the photovoltaic test site in Bryan, Ohio, to conduct a search for electrically defective modules. The array field consists of 800 Block III Model D modules, which are silicone rubber encapsulated. These were each washed by a local cleaning company at a cost of $450.00 the day before measurements were made.

The weather on 29 April was abominable—rain and zero (0.00) insolation all day. On 30 April there were about four hours of clear, sunny skies and four more hours of cloudiness with intermittent sunlight.

The array field at WNBO consists of 100 branch circuits. Each branch circuit contains four modules in series paralleled with four more modules in series. The array was turned on in August of 1979 and searches for electrical failures were conducted then and in April 1980. Four nonworking modules were found during the April visit.

During the morning, I-V curves were generated for each branch circuit to screen the curve shapes. There was evidence of 23 open-circuited modules. Each module was subsequently located and labelled as defective in the array field.

Between noon and 1 p.m., branch circuit I-V curves were repeated for all the circuits which had normal curves during the earlier search. A total of 17 more failures were indicated. Location of these failures was not so easy, however, since clouds had moved into the area causing intermittent sunshine.

It is believed that the failure mode on most of the aforementioned 40 failures is at least one pair of broken cell-to-cell interconnects on each module. The 23 modules found during the first search were dead open circuits, i.e., uninfluenced by temperature or insolation fluctuations. The 17 found during the afternoon were operating in an intermittent fashion and open circuiting occurred only when a certain temperature was achieved for each module. Searching for intermittent modules in intermittent sunshine is extremely difficult, however, 16 of the 17 were located while the position of the 17th was narrowed down to one of four.

Four failed modules were removed and replaced. These modules have been shipped to the MP&TL for analysis. A brief inspection of several in-situ modules showed no evidence of hail damage from a hailstorm last August. Replacements for the remaining failures will be removed from the array field at the STF and shipped to Ohio as soon as they can be screened for defective modules.

Fig. 3. In-service performance record for Nebraska photovoltaic modules.

The Block III Model D module is similar to the Block II version used in the front row at Nebraska, where 728 modules have been in service since July 1977. The failure history of these modules is listed in Table II. In 44 months, only 39 modules (5.26%) have failed and less than 10 of these are due to broken interconnects. At Ohio, after 21 months of service, the number of failures is now 44 (5.5%) which is a greater percentage than at Mead. JPL and NASA LeRC have reported similar failures at Mount Laguna (Block III) and Upper Volta and Schuchuli, Arizona (Block II), respectively. The interconnect breakage is a fatigue failure due to diurnal temperature cycling.

Failure analysis at JPL and MIT LL believe that these failures represent the "tip of the iceberg" and that ensuing failures in large numbers will occur. These failures are easily detected and someone at the radio station has been instructed in how to conduct a search at least once a month on a warm, cloudless, sunny day.

There were three different aberrations noticed on the I-V curves depending on the number and location of the failures. These are displayed in Fig. 4. In these curves the insolation,

Fig. 4. Aberrant I-V curves at WBNO (a) one failure, (b) two failures, (c) two failures.

ambient temperature, and cell temperature were not recorded and appear as zeros.

In Fig. 4a, one failure is present and the typical step in the I-V curve occurs. In Fig. 4b, two failures are present in one of the four module strings causing a larger step. In Fig. 4c, two failures are also present, however, there is one in the top four module string and one in the bottom, causing the open-circuit voltage to be reduced by one-fourth of its normal value. As an aside, if the modules were wired two in parallel by four in series, curve 7c would only occur when both modules in a parallel pair were open circuited and not when isolated failures occurred in the top and bottom circuits.

Failures can be located by utilizing the set of 100 switches in the array patch panel. If one observes the operating current at the operating voltage, a failure will be evident by a reduced value of current. Measurements of this type are simple and should be conducted at least once a month.

In summary, 40 failed Block III Model D modules were found at WBNO on 30 April 1981 bringing the total to 44 of 800 after 21 months of operation. This exceeds the number of failures of the Block II version of this module at Nebraska after 44 months of deployment. It is believed that the failure mode at WBNO is at least one pair of broken cell-to-cell interconnects on each open-circuited module. Experience at other sites indicates that occurrence of this type of failure will continue to increase with time.

3.0 BROKEN INTERCONNECTS ON BLOCKS II AND III MODEL D MODULES

A summary of Blocks II and III Model D module failure experiences at all MIT LL test sites is given in Tables II and III. Table II summarizes module deployment at Nebraska, Ohio, and Massachusetts. Since all recent failures have not been examined visually as yet, there may be some with cracked cells, however, there was no evidence of cracks (i.e., burn marks) on either the back or front sides of any of the modules.

Both the Block II and III versions of this module are essentially the same, except the RTV cover is thicker on the Block III version. NASA LeRC and MERADCOM have also deployed these modules and experienced problems which are summarized in Table III. The documentation on the exact number of failures and their causes is sparse and Table III reflects JPL source data.

The interconnects break due to fatigue during diurnal temperature cycling. The glaring questions that come out of Tables II and III are:

a. Why is there such a high percentage of Block II failures at NASA LeRC sites with broken interconnects and so few at Mead?

b. Why are the Block III versions of this module experiencing the broken interconnect mode in large numbers at WBNO?

According to a JPL stress-analysis expert, the key parameter to evaluate is the in-place cell interconnect deflection due to temperature change. This number, coupled with a Manson fatigue analysis, can be used to attempt to predict the number of cycles to failure.

The predicted ΔT (yearly diurnal average) used for Schuchuli was 46°C, which led to a prediction of 50-percent

Table II

MIT LL Model D Module Failures

Site	Start Date	Total Modules	Block	Total Failures	Failures with Broken Interconnect Pairs
Nebraska	7/77	728	II	39	4-7
Ohio	8/79	800	III	44	As many as 41
Roof STF	11/78	74	III	3	3
RES STF	11/78	192	III	13	13

Table III

Other Model D Module Failures

Site	Start Date	Total Modules	Block	Total Failures	Failures with Broken Interconnect Pairs
Schuchuli	11/78	192	II	59	Most
Upper Volta	?	100	II	20	Most
Mount Laguna	Late 1979	756	III	At least 12	Maybe 3 or 4

probability of failure in 1 to 2 years. For Mead and WBNO the measured values of ΔT, averaged over a year, were 33° and 30°C, respectively. Using these values, a 50-percent probability of failure is predicted 3 to 4 years from turn on—which is wrong for both cases.

There are evidently more physical parameters which influence failure. Things such as interconnect misalignment, crimping during installation, the amount and position of solder used, and tool marks also probably come into play to cause increased stresses during fatigue loading. These items are extremely difficult to model.

MIT LL is studying as many interconnects as possible to see any differences that exist between Blocks II and III. JPL is also doing this on Mead and WBNO failures. As soon as any plausible answers arise, they will be publicized. In the meantime, it is expected that the failure mode will persist in Ohio, and eventually cause subsequent failures at Mead.

4.0 SITE MEASUREMENTS—RESIDENTIAL STF

On May 7 and 8, 1981, a search was made in the STF array field at NE RES for electrically failed modules. The results of this search are:

STF-1: At the front of the array field there are 700 Block II Model C modules (silicone encapsulated) arranged into 25 branch circuits. Each circuit contains 28 modules: 4 in parallel by 7 in series. No new failures were found. To date, since November 1978, there have been 13 of 700 failures (2.14%).

STF-II: In the center of the array field there are 192 Block III Model D modules and 288 Block III Model C modules. Both types of modules are silicone encapsulated.

The Model D modules are wired into 18 branch circuits, each containing 8 modules: 4 in series in parallel with 4 in series. Note that 6 circuits (48 modules) have been removed to be used as spares at Bryan. Eight failed modules were found, bringing the total to 13 of 192 (6.77%) since November 1978.

The module terminal boxes on these modules are in disrepair. Many terminal strips have come loose and are simply hanging. Most of the terminal screws are rusted and several bypass diodes are corroded and broken. It is recommended that these modules be rewired 2 in parallel by 4 in series with the use of weatherproof diodes.

The Model C modules are wired 4 in series paralleled 4 times and there are 18 of these branch circuits. No new failures were found. Since November 1978, there have been 8 of 288 failures (2.78%).

STF-III: A series of Block I Model A arrays has been added to the back of the array field. These are wired 9 in parallel by 20 in series and there are three circuits containing 540 modules. No new failures were found. Coupled with the modules on I-roof, there have been 15 of 945 failures (1.6%) since May 1977. In low-voltage situations these modules continue to operate reliably.

TableIV details the PV module failures at MIT LL test sites.

5.0 EXAMINATION OF MODEL L AIR MODULE

In March 1981, one Model L air (cells on glass) module, to be used in advanced PV/T experiments, was electrically and visually inspected in the MP&TL.

The physical characteristics of the module are: the module measures 60 inches long and 31-3/4 inches wide and has a stippled glass front. There are 276 cells with gridded backs arranged in 12 rows of 23 cells each and wired 46 in series with 6 in parallel. The rear side of substrate of the module is made of EVA which has been bonded to the rear side of the cells and the glass.

An I-V curve of the module, using the MIT LL curve tracer, was obtained. At an insolation of 89.8 mw/cm^2, the open-circuit voltage was 25.5 v, the short-circuit current was 6.4 a and the peak power was 111.9 w. The cell and ambient temperatures were also noted and found to be 95^o and 42^{o}F, respectively.

The following is a summary of the conditions found during visual examination of the module:

a. Collector Splash—Particles of the material used in making the collector lines had been spattered onto the active part of all of the 276 cells.

b. Scratches—Scratches were found along and/or in front of the webbed interconnect on all 276 cells.

c. Stains—Brown and/or white stains were found on the majority of the cells. The white stains appeared mostly along the edges of the cells.

d. AR Coating—The antireflective coating on one cell had become quite faded on one-half of the cell.

Table IV

PV Module Failures at MIT LL Test Sites

Data Up To 5/81

Mfg. Start	Neb. (7/77)	RES STF (11/78)	Roof STF (5/77)	UTA (8/78)	Chl. (7/77)	WBNO (8/79)	NBNM (1/80)	Totals
A(I)	-	-	15/945	-	0/288	-	-	15/1233
A(II)	-	-	-	-	-	-	0/720*	0/720
B(II)	-	-	5/64	65/240	-	-	-	70/304
C(II)	74/1512	15/700	0/36	-	-	-	-	89/2248
C(III)	-	8/288	-	7/640+	-	-	-	15/928
D(II)	39/728	-	-	-	-	-	-	39/728
D(III)	-	13/192	1/74	-	-	44/800	-	58/1066
E(III)	-	-	-	-	-	-	1/1740	1/1740
F(III)	-	-	-	-	-	-	34/2064	34/2064
	5.04%	3.05%	1.9%	27% 1.09%	0%	5.5%	0.75%	321/11031 2.9%

* 52 modules have been found with cracked glass cover sheets

\+ Array start date: 4/80

e. Flux—A residue of flux was found under the webbed interconnect on several cells.

f. Bared Copper—Exposed copper was found along the cut edges of the webbed interconnect on a majority of the cells.

g. Grids—The grids on the rear side of the cells were badly tarnished on 179 cells. One cell was found to have this condition on the front side, also.

h. Touching Cells—Two pairs of cells were found, in two different areas of the module, to be touching. Two additional cells were found to be overlapping each other and both of the cells were cracked along the overlapped edges.

i. Cracked Cell—In addition to the cracked cells just cited, one other cell was found which had a crack that started at the edge of the cell, beneath the webbed interconnect, and travelled diagonally up the cell to the opposite edge. However, it does not appear that this cell or either of the above mentioned cells would cause an open circuit in the cell string at this time.

Note: Except for the touching cells, the overall workmanship found in the module was very good. Aesthetically, the module was attractive.

6.0 EXAMINATION OF MODEL J AIR MODULE

During March 1981, one Model J (cells on glass) module, was visually and electrically examined at the MP&TL. This module is to be used in advanced air PV/T experiments.

An I-V curve, using the MIT LL curve tracer, was obtained. At an insolation of 92.6 mw/cm^2, the open-circuit voltage was 20.9 v, the short-circuit current was 3.49 a, and the peak power was 53.05 w. The ambient and cell temperatures were noted to be 48^{o}C and 106^{o}F, respectively.

The following is a summary of the conditions found during the visual examination of the module:

a. Bared Copper—The terminal strips and interconnects of the module were made of a wire mesh material which had obviously been cut from a larger sheet of this material. Areas of bared copper were found along these cut edges on all of the terminal strips and all of the 152 cells.

b. Air Bubbles—Small air bubbles were found on ten cells.

c. Discoloration—The grid lines on 14 cells had changed from white to copper color. Discoloration of the interconnect pads was found on ten cells.

d. Stains—Dark stains were found on the AR coating of 30 cells.

e. Scratches—Three cells were found to have surface scratches.

f. Flux Residue—Forty-eight cells were found which had a residue of flux on the interconnects. A flux residue was also found on some of the interconnect-to-terminal strip junctions.

g. Solder/Collector Splash—Particles of solder, splashed onto the active part of the cell during the soldering process, were found on five cells.

h. Grids—Two cells were found on which some of the grid lines were lifting off the cell surface.

i. Debris—Pieces of debris, such as hair and threads, were found on several of the cells.

j. Delamination—Delamination was found in two areas along the left edge of the modules. One area measured approximately 3-3/4 inches long and penetrated to a depth of 5/16th inch toward the cell area. The Tedlar backing of the module was also delaminated in this area. The second area had delaminated to a depth of 5/32 of an inch and measured approximately 1½ inches long.

k. Thermal Wires—Three pairs of wires protrude from the long sides of the module package which are to be used to assist in the measurement of cell temperatures. These wires were soldered onto the ends of the mesh interconnects that are attached to the rear side of various groups of cells. At the solder junction of the thermal wire and interconnect, it was noted that the wire had not been pre-tinned, leaving exposed copper at the connection and causing the solder to form a poor fillet around the wire, thus giving the appearance of a cold solder joint. This condition was found on all 12 of the solder connections.

Note: Other than the above noted solder defects on the thermal wires, the overall workmanship of the module was very good.

7.0 EXAMINATION OF MODEL M LIQUID PV/T MODULES

During March, 1981, two Model M (roof-integrated) liquid PV/T modules, were examined visually at the MP&TL.

Due to the cumbersome size and weight of these modules, only one was moved outdoors for electrical testing. Using the MIT LL curve tracer, an I-V curve was obtained at an insolation of 87.9 mw/cm^2. The module was found to have an open-circuit voltage of 30.1 v, a short-circuit current of 6.15 a, and a peak power of 135.9 w. The ambient and cell temperatures were noted to be 44^o and 65^{o}F, respectively.

The physical characteristics of the modules are: the module has a wooden frame measuring approximately 77 inches long, 35½ inches wide and 5-5/8 inches deep. The cell area of the module is about 69 inches long and 31-3/4 inches wide. There are 16 rows of 28 rectangular cells (448); divided into four submodules of 112 cells each.

The following is a summary of the conditions found in these modules during visual examination:

a. Stains— Sixty-seven cells of the first module and 105 cells of the second module were found to have light yellow and/or green spots on the AR coating.

Brown stains were found on 97 cells of one module and 46 cells of the other module.

b. AR Coating—Normally, the AR coating on cells is a shade of blue-black. On the first module, the AR coating of 106 cells was a shade of yellowish-green. This condition was found on 100 cells of the second module also.

c. Discolored Grids/Collector Tabs—Grid lines, which had changed from white to a copper color, were found on 52 cells of one module and 36 cells of the other module.

Usually, interconnects are soldered onto collector pads which are located near the edges of the cell. Typically, these collector pads are white in color. These pads were found to have changed to a copper color on 37 cells of the first module. This module also contained one cell on which the tabs had changed to a shade of purple.

d. Scratches—Scratches on the surface of the cell were found on 16 cells of the first module and six cells of the second module.

e. Collector Splash—One module was found on which 124 cells had particles of collector material splashed onto the active part of the cell.

f. Delamination—Slight delamination was found around the periphery of one of the submodules on the first module. The EVA had started to lift along one corner of a second submodule, also. The lifted area measured approximately 0.3 inch in length and 0.2 inch wide.

An area of delamination, 3.9 inches long and 0.25 inch wide, was found along the edge of one of the submodules on the second module.

g. Cracked Cells—Two cracked cells were found on the first module, one of which had an edge-to-edge horizontal crack across the lower third of the cell. The second cell had multiple horizontal and vertical cracks across the lower two-thirds of the cell. Because of the interconnections on these cells, it is difficult to ascertain the effect of either of the cracked cells on the output of their cell strings.

On the second module, one cell was found which had a diagonal, edge-to-edge crack. However, the crack did not appear to be able to cause an open circuit in the cell string.

8.0 EXAMINATION OF MODEL K PV/T MODULES

8.1 Examination of First Module

During March 1981, one Model K PV/T experimental module, was tested electrically and examined visually.

The module is 24 inches long by 12 inches wide and contains 24 cells (3 rows of 8 cells each) which are wired to form a series string. The cells are covered with a layer of clear polyvinyl fluoride (PVF) with a front cover of glass. Beneath the cells are several layers of material consisting of polyvinyl butyrate (PVB), opaque PVF, clear PVF, and a rear side covering of copper mesh which has been bonded to the PVF (Fig. 5).

An I-V curve was made from the module, using the MIT LL curve tracer, at an insolation of 100 mw/cm^2 and an ambient temperature of 15^{o}C. The curve showed the open-circuit voltage to be 13.5 v, the short-circuit current to be 1.51 a with a peak power of 11.61 w. The cell temperature was noted to be 18^{o}C (Fig. 6).

The following is a brief summary of the conditions found in this module during visual examination:

a. Excess Solder—A heavier-than-average layer of solder was found on the main collectors and grid lines of all 24 cells, some of which was splashed onto the active part of several cells.

Solder debris was found along one of the busbars, in a rework area and beside a cell. What appeared to be a piece of the plating from the rear of the cell was found on one interconnect of a cell.

An excessive amount of solder was found which bridged one of the main collectors of a cell to one of the rear side interconnects of the cell. This

Fig. 5. Model K PV/T experimental module.

would constitute a direct short from the negative side to the positive side of the cell and would reduce the open-circuit voltage of the module by approximately 0.5 v.

b. Scratches—Scratches, caused by the use of tools during the assembly process of the vendor, were found on 21 cells.

c. Stains—Random stains were found on 15 cells, as well as four cells which had staining along the main collectors and grid lines.

d. Flux Residue—A residue of flux was found on the interconnect-to-main collector solder connections on 16 cells in the areas where the interconnects are affixed onto the terminal strips.

e. Debris—Small white particles of an unknown substance were found on five cells.

f. Bare Copper—Areas of bare copper were found along the edges of the terminal strips as well as on several interconnects.

g. Corrosion—A green corrosive residue was found in the area of one of the interconnect-to-terminal strip connections. This condition appears to be the result of a reaction of the acid contained in the flux residue, and could have been prevented by performing the proper cleaning techniques during the assembly process at the manufacturer.

h. Interconnects—Creases, of the type found on work-hardened interconnects, were found on three interconnects, one of which was in a repair area.

The above mentioned repair area was found between two cells. It was obvious that a portion of metal had been completely broken out of the center of both interconnects during assembly. As a remedy for this condition, a piece of interconnect material was soldered onto the remaining pieces of act as a "bridge" (Fig. 7). This is <u>not</u> an acceptable practice! It appears that the person performing the work neglected to repair the second broken interconnect (Fig. 8).

Fig. 6. Model K module I-V curve.

The manufacturer was informed that the module had a broken interconnect; he commented that the interconnect must have been broken in shipping. There is no possible way that this interconnect was broken in that manner. If that were the case, the $\frac{1}{4}$-inch-long piece, broken out of the middle of the interconnect, would have been lying there. <u>It wasn't!</u> However, solder debris and bits of metal <u>were found</u> in the adjacent repair area.

Seven cells were found on which 12 of the 14 top side solder connections appeared to have been moved back from their initial solder positions, resulting in cold solder joints (Fig.

Fig. 7. Patched broken interconnect.

9). Three of four of these internects appeared to be "free-floating," but held in contact with the cell surface by the packaging materials of the module. An example of this is seen in Fig. 10.

A condition known as spalling was found around the periphery of 7 of the 12 interconnect solder connections. This is the condition where the collector metallization becomes lifted off the cell and can occur if excessive heat is applied to the area when the interconnect is being soldered onto the cell. Examples of this condition are shown in Figs. 11, 12, and 13.

In addition to the cold solder connections found on the cells, poor solder connections were found in two areas of the interconnect-to-terminal strip junctions. One of these appeared to have been caused by the interconnect not being in contact with the terminal strip when it was soldered.

Fig. 8. Interconnect with $\frac{1}{4}$-in. piece broken out of the middle.

Fig. 9. Interconnect moved back from initial solder position.

Fig. 10. Interconnect appears "free floating." Note lack of solder along right edge of interconnect.

i. Terminal Strip—The smaller terminal strip at the negative end of the module was askew, causing one of the attached interconnects to be doubled back on itself.

j. Copper Mesh—The sheet of copper mesh on the rear side of the module had sharp protruding wires along the cut edges of the mesh.

Note: The workmanship found in this module was very poor and seems to be similar to the quality found on the early Block II Model C modules. The module was returned to the manufac-

Fig. 11. Spalling in front of interconnect solder connection.

Fig. 12. Spalling in front of interconnect and along left side.

Fig. 13. Spalling in front of interconnect and below.

turer because of the defective interconnects.

8.2 Examination of Second Module

During April 1981, one Model K PV/T experimental module, was examined visually and tested electrically. This module was a vendor replacement for the first Model K module which was returned because of defective interconnects. See Figs. 14 and 15 for a front and rear view of the module.

An I-V curve was made of the module, using the MIT LL curve tracer, at an insolation of 103.8 mw/cm^2 and an ambient temperature of $65^{o}F$. The curve showed the open-circuit voltage to be 12.4 v, the short-circuit current to be 1.47 a with a peak power of 11.62 w. The temperature on the rear of the module was noted to be $113^{o}F$ (Fig. 16).

The following is a brief summary of the conditions found in this module during visual examination.

a. Missing Grid Lines—Four cells were found on which some of the grid lines were missing. An example of this can be seen in Fig. 17.

Fig. 14. Model K PV/T, front view.

Fig. 15. Model K PV/T rear view.

b. Spalling of the Grid Lines and Main Collectors—Eight cells were found which had spalling along the main collectors and/or some of the grid lines (Figs. 18, 19). In Fig. 18 the three grid lines on the left do not touch the main collector. In Fig. 19 the interconnect has moved laterally, breaking the solder along the left side.

c. Excess Solder—Splashes of solder were found on the active surface of 15

Fig. 16. Module I-V curve.

Fig. 17. Missing grid lines.

cells. Solder was "globbed" onto the negative wire and terminal strip connection, indicating a possible cold solder joint (Fig. 20).

Excess solder, which bridged both of the front-side main collectors to the rear side interconnects, was found on one cell. This condition was also found on a second cell, but involved only one of the interconnects. These solder bridges constitute a direct

Fig. 18. Spalling of main collector.

Fig. 19. (right) Spalling in front of interconnect junction on main collector.

short from the negative side to the positive side of the cells and each can reduce the open-circuit voltage of the module by approximately 0.5 v (Figs. 21, 22, 23).

d. Scratches—Scratches, caused by the use of tools during the assembly process, were found on 15 cells.

e. Flux Residue—A residue of flux was found on the interconnect-to-main collector solder connections on 13 cells and on several of the interconnect-to-

Fig. 20. Cold solder joint.

terminal strips solder connections. Some of this residue was black, indicating burnt flux and is generally the result of improper cleaning of the solder iron tip before making the solder connection.

f. Stains—Random stains and/or stain-

Figs. 21–23. Examples of solder bridge from top of cell to rear interconnect.

ing along the grid lines were found on 20 cells.

g. Debris—A bristle, of the type found in a paint brush, was found lying on one cell (Fig. 24).

Pieces of thread were found on a second cell and between to other cells.

h. Bare Copper—Areas of bare copper were found along the cut edges of the terminal strips.

i. Misaligned Interconnect—One interconnect was misaligned when soldered onto the terminal strip so that when it was time to affix the interconnect to the main collector on the cell, the interconnect had to be twisted to fit. The adjacent interconnect on this cell was also bent along the area soldered onto the cell (Fig. 25).

Fig. 24. Bristle lying across cell.

Fatigued Interconnects—Two interconnects, connecting a cell to a terminal strip on the positive end of the module, were found which had creases similar to those found on work-hardened interconnects. The fatigue creases were in the area of the interconnect which is soldered onto the cell (Fig. 26). Bare copper was evident along one of these creases, indicating that the interconnect was partially broken through the thickness of the metal as shown in Fig. 27. As this module had never been exposed to the environment to undergo thermal cycling, it is quite obvious that the fatigued interconnects were caused by excessive bending of the interconnect material during the assembly process.

Another interconnect, located between a cell and one of the negative terminal strips, was found to have a metal fatigue crease also.

Fig. 26. Fatigue crease on interconnect.

Fig. 25. Misaligned and bent interconnect.

k. Peeling Grids—Two cells were found on which several of the grids were starting to peel off in the cell. An indication of poor bonding of the metallization to the cell surface is shown in Fig. 28.

l. Delamination—One end of a length of Teflon insulated wire is soldered onto the busbar at the positive and negative ends of the module. These wires then extended outside of the module package to be used in wiring the module externally. Slight delamination was found along the part of the insulation of the wire that is captured by the module package. These areas provide paths for air and/or moisture seepage into the cell area.

Fig. 27. Fatigue crease on interconnect with copper.

Fig. 28. Metallization peeling off cell.

m. Bridged Interconnect—An interconnect, which was affixed to the main collector of a cell, had a second piece of interconnect material acting as a bridge over an area of spalling between the interconnect and the main collector as shown in Fig. 29.

n. Copper Mesh—The sheet of copper mesh on the rear side of the module had sharp protruding wires along the edges of the mesh.

o. Cracked Cell—One cell was found to have a crack running diagonally, from an interconnect, across the corner of the cell. This would not cause an open circuit in the cell as it did not cross either of the main collectors.

Note: The workmanship found in this second module was little improved over the first module. There still exists the problems of damaged or excessively bent interconnect material, spalling of the main collectors and grid lines, poor solder flow along interconnect-to-main collector connections, solder bridges causing the cells to be shorted out of the module string and poor cleaning of the solder joints.

Of the many modules inspected, the two Model K PV/T modules represent two examples of extremely poor workmanship. One of the problems may be that the interconnects extend one-half to two-thirds across the cell, which is quite unnecessary. Because of their length, excessive heat is needed to solder the interconnect to the main collectors. The excessive heat in turn causes spalling of the metallization on the cell.

Fig. 29. Piece of interconnect acting as a bridge over spalled area.

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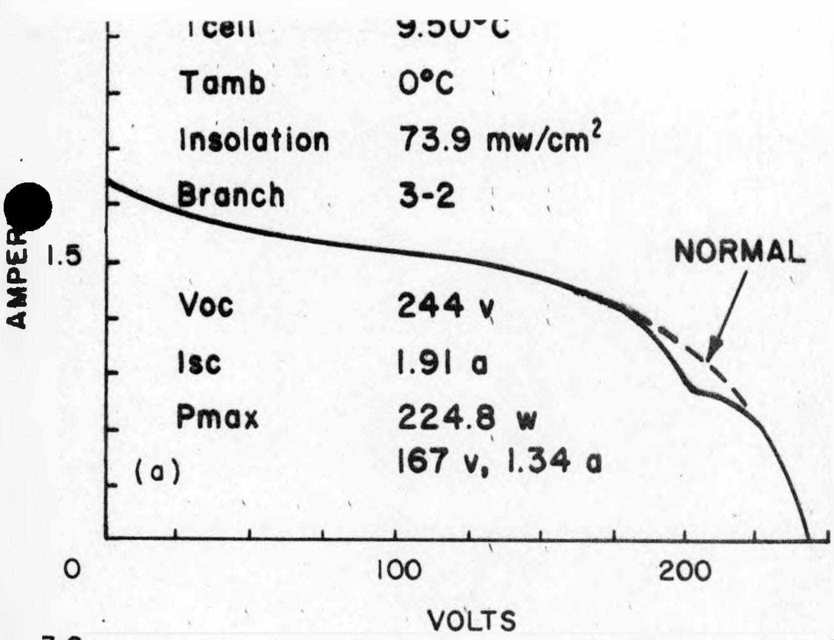
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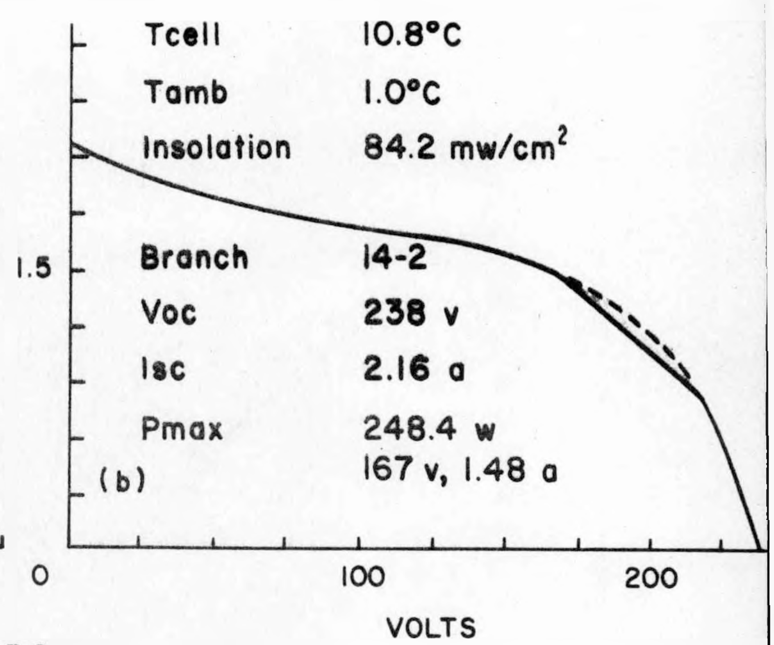
NORMAL
(a)
AMPER
1.5
0
100
200
VOLTS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(b)
1.5
0
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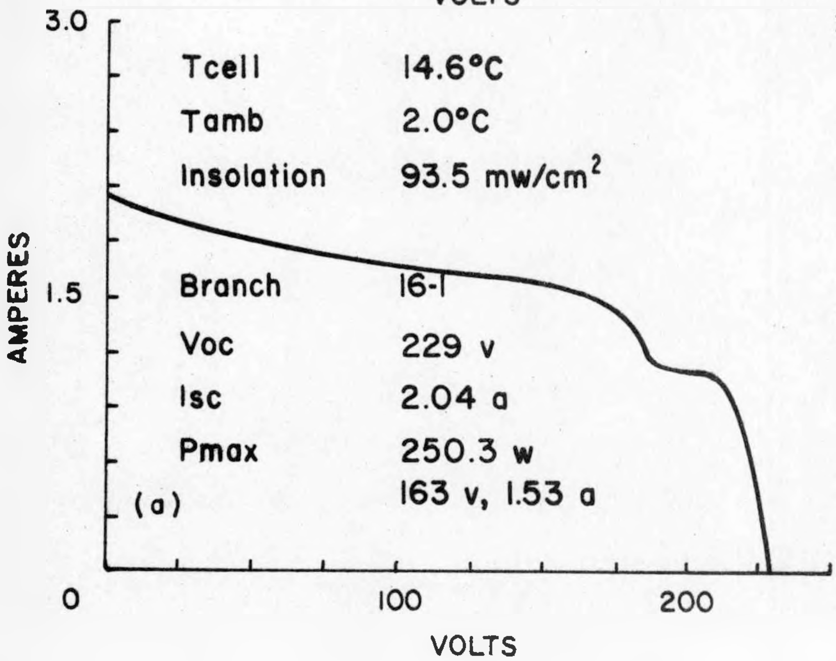
200
VOLTS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AMPERES
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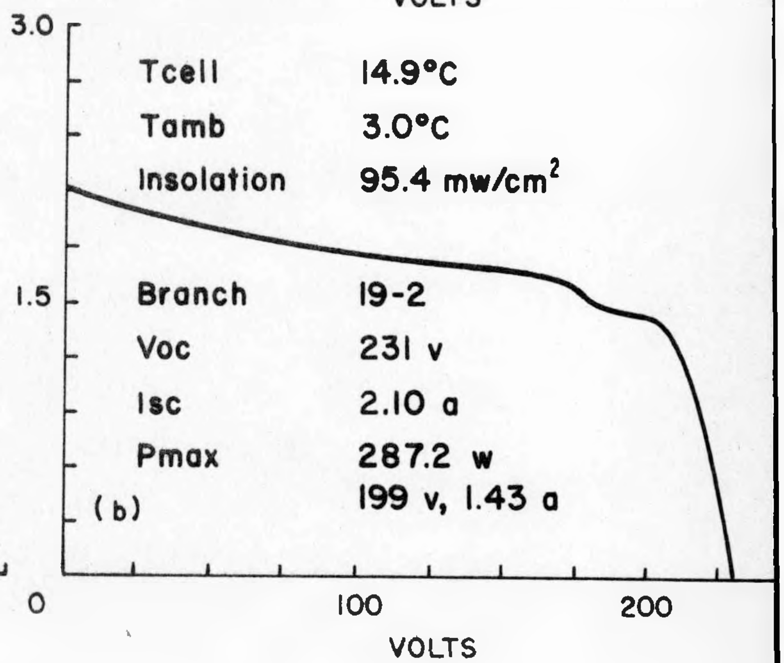
VOLTS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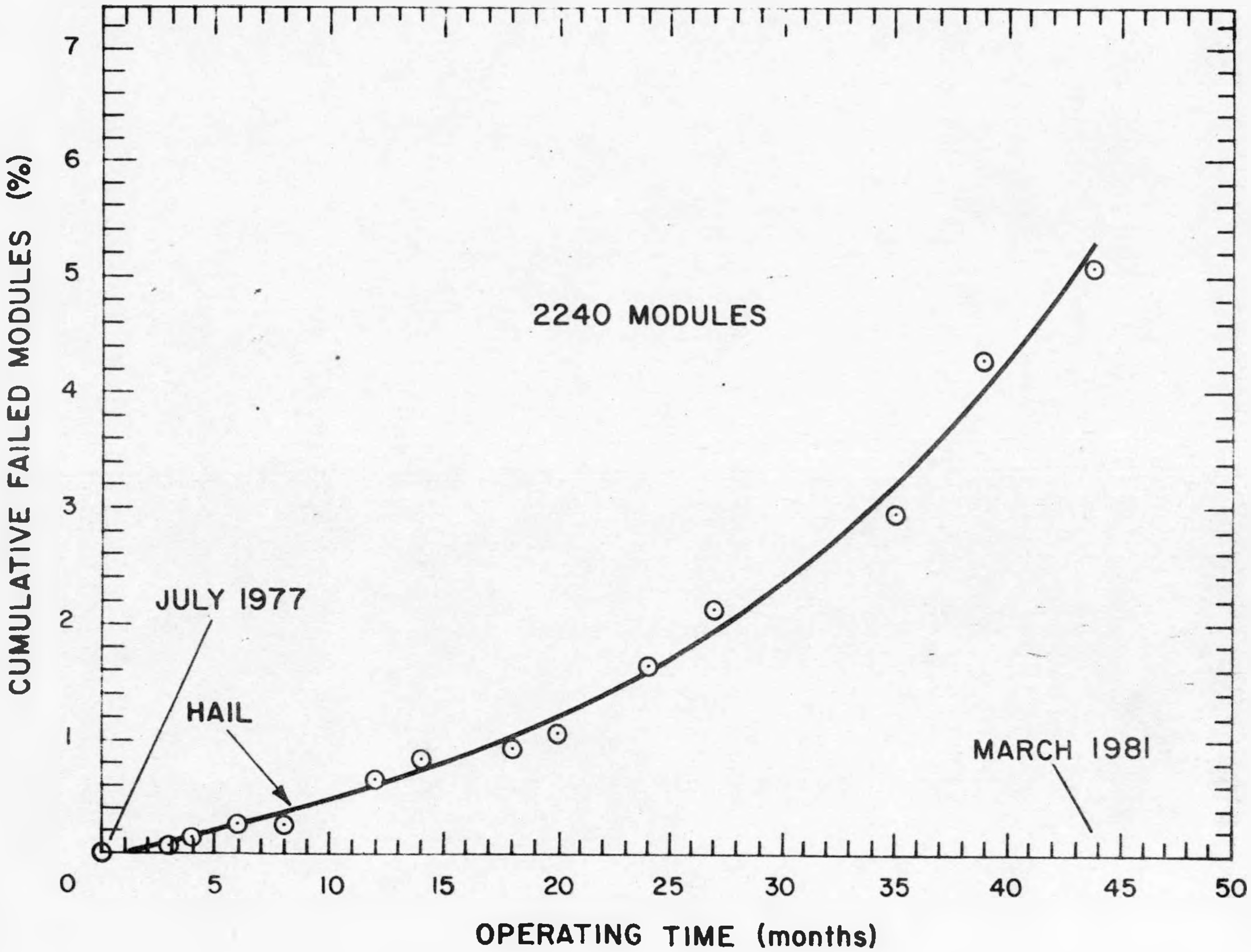
VOLTS



2240 MODULES
JULY 1977
HAIL
MARCH 1981
CUMULATIVE FAILED MODULES (%)
OPERATING TIME (months)
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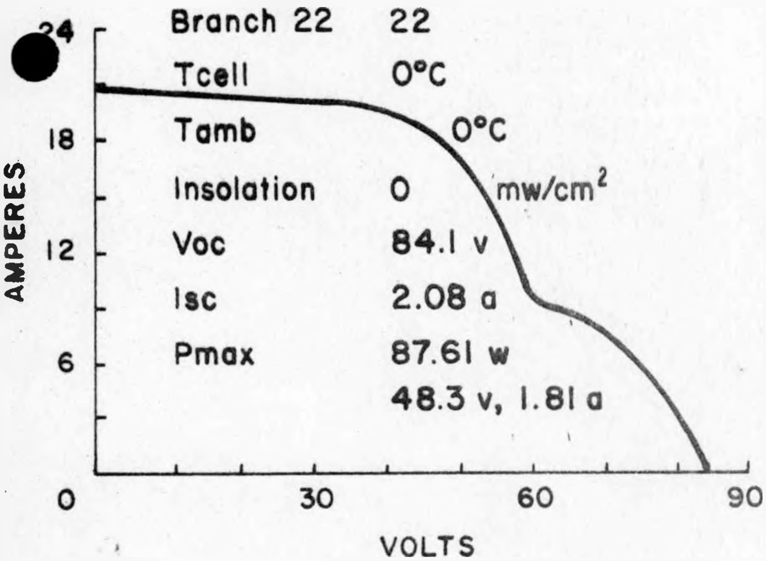
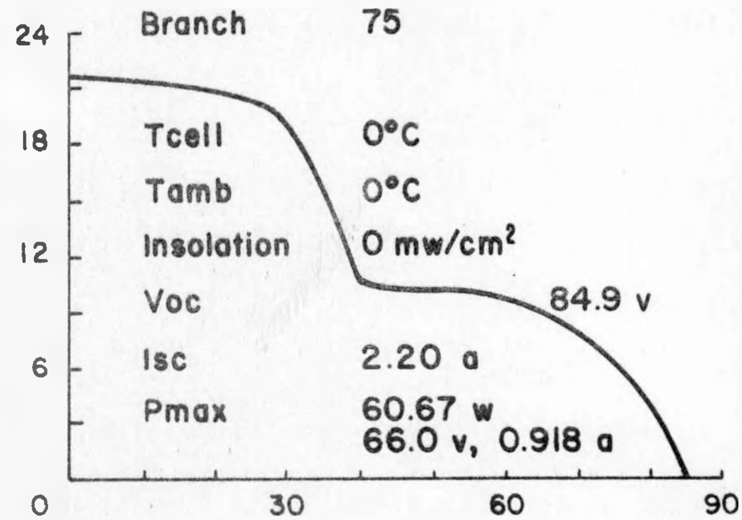
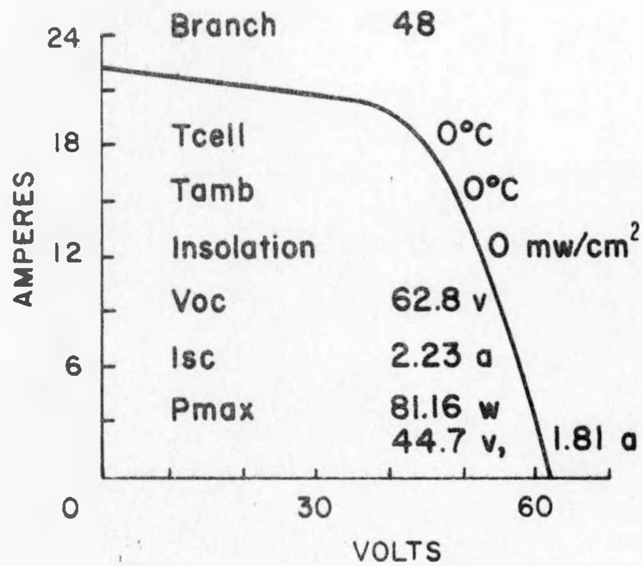
2
3
4
5
6
7
5
10
15
20
25
30
35
40
45
50







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Disc. 9/1981

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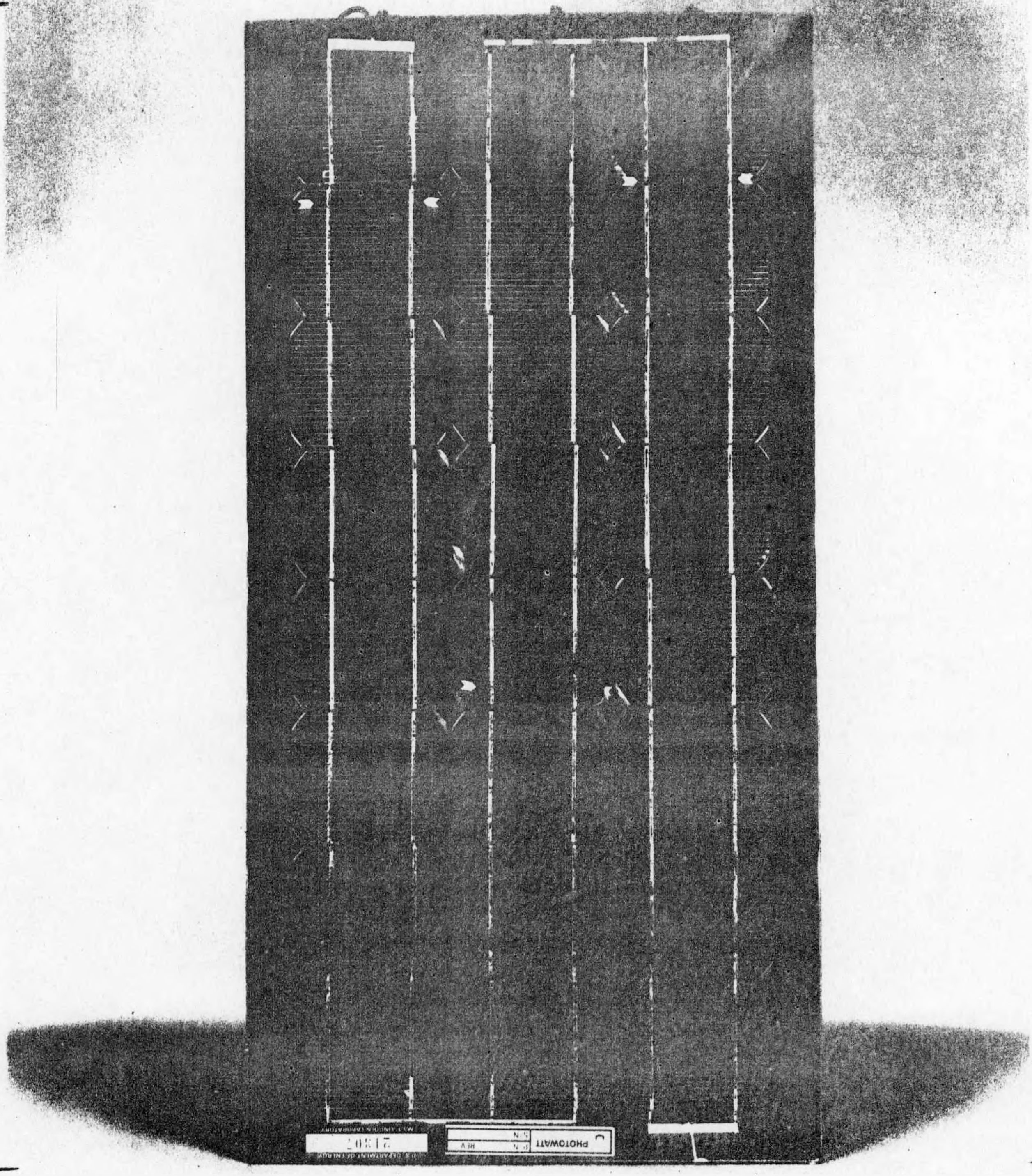
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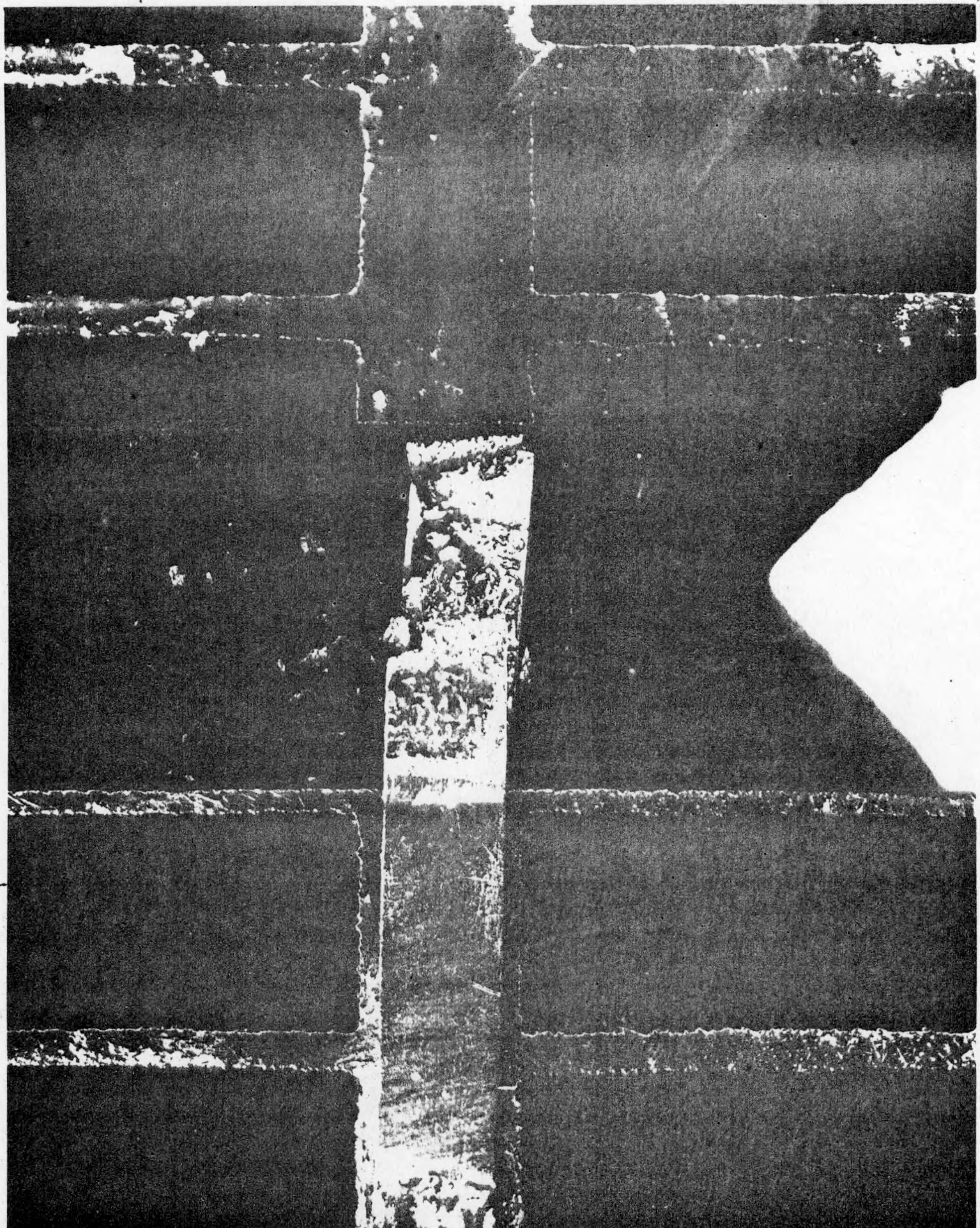

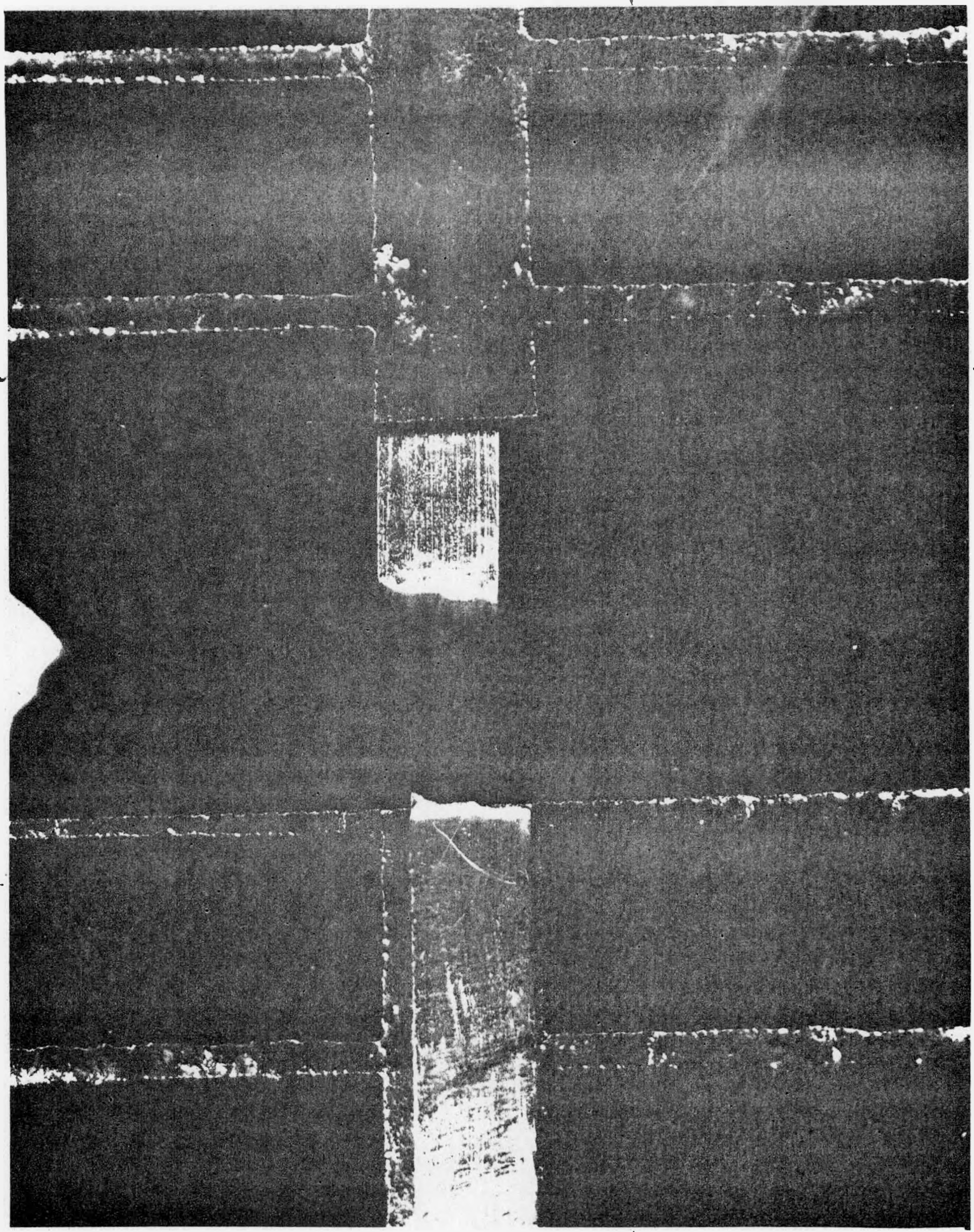

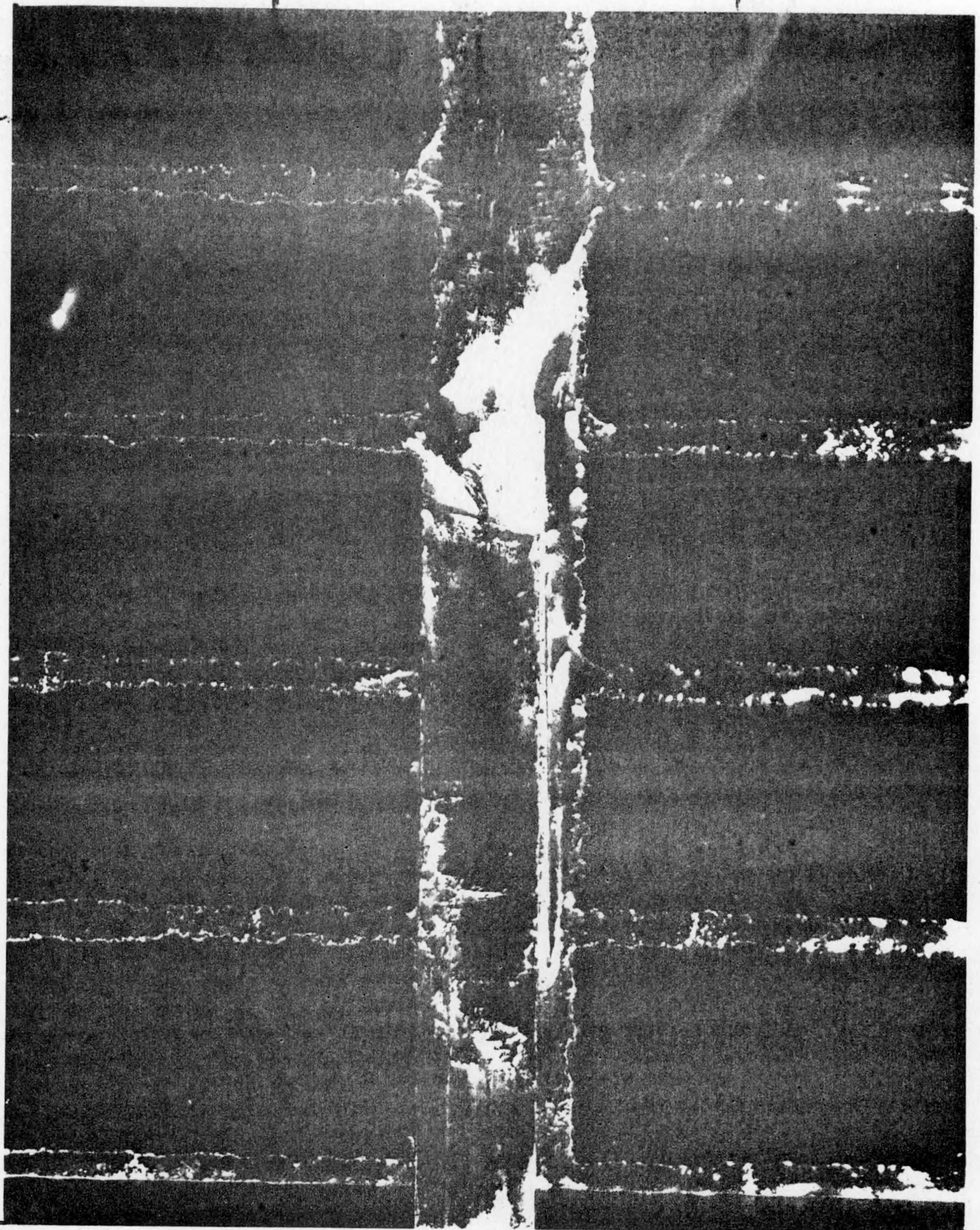

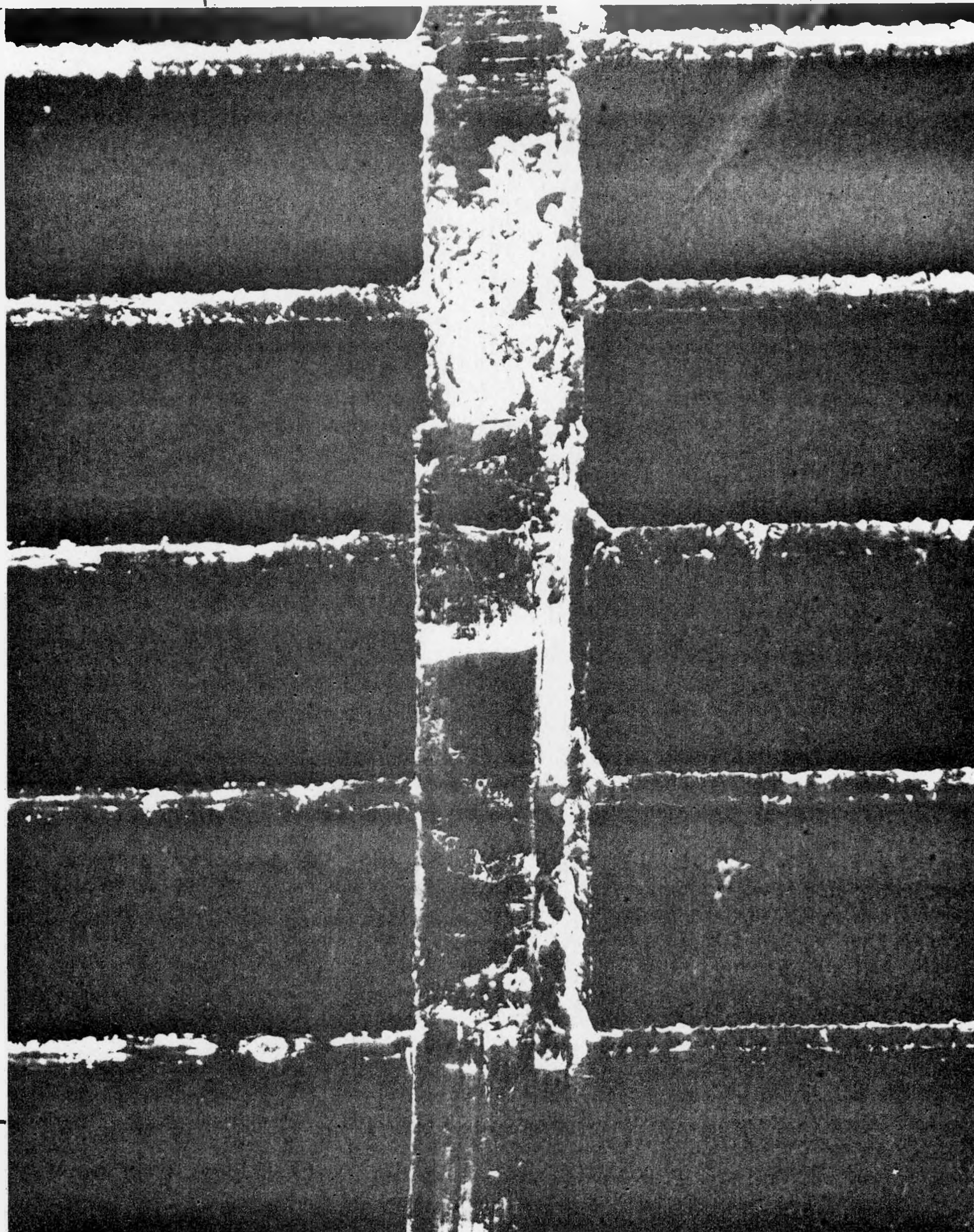

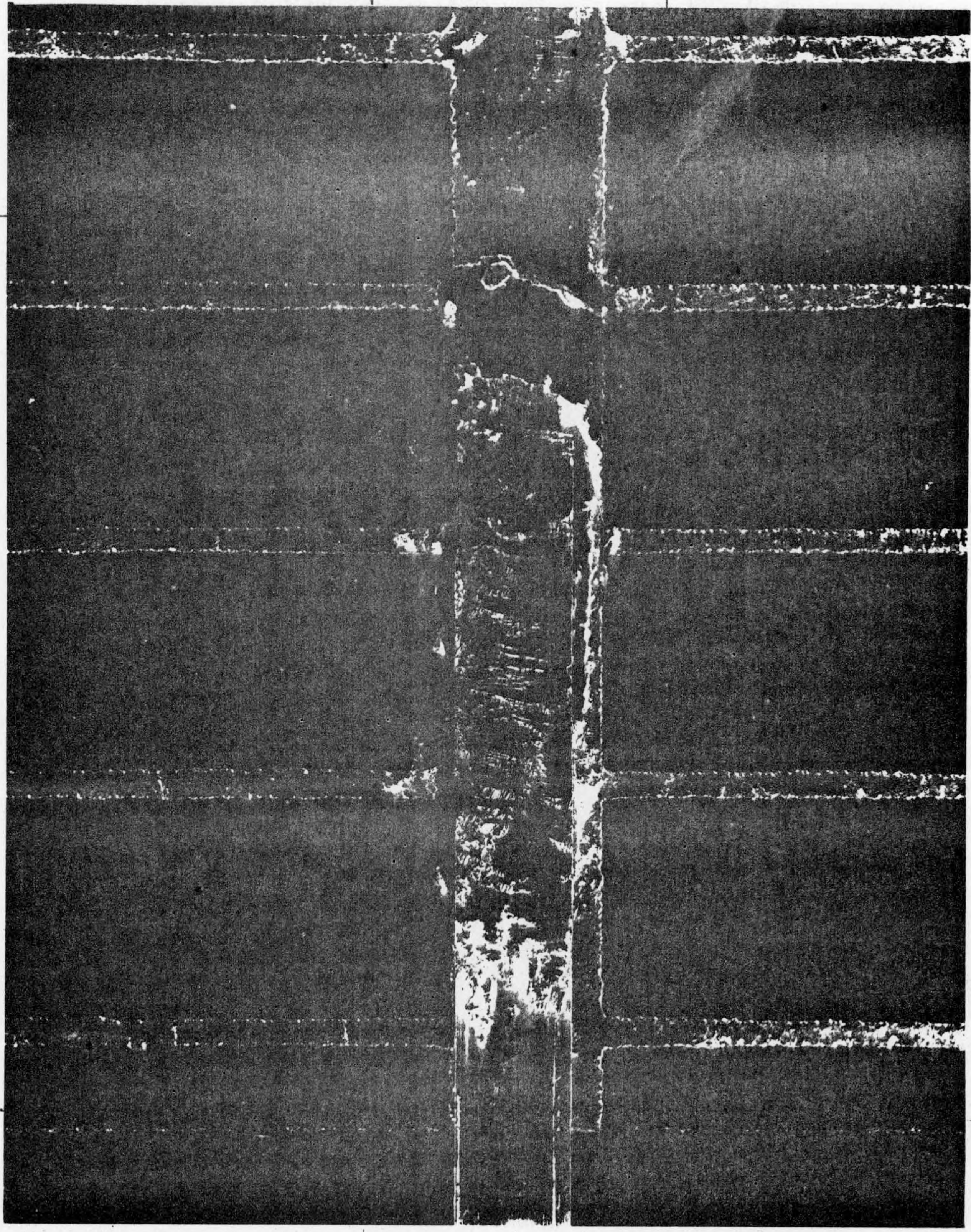

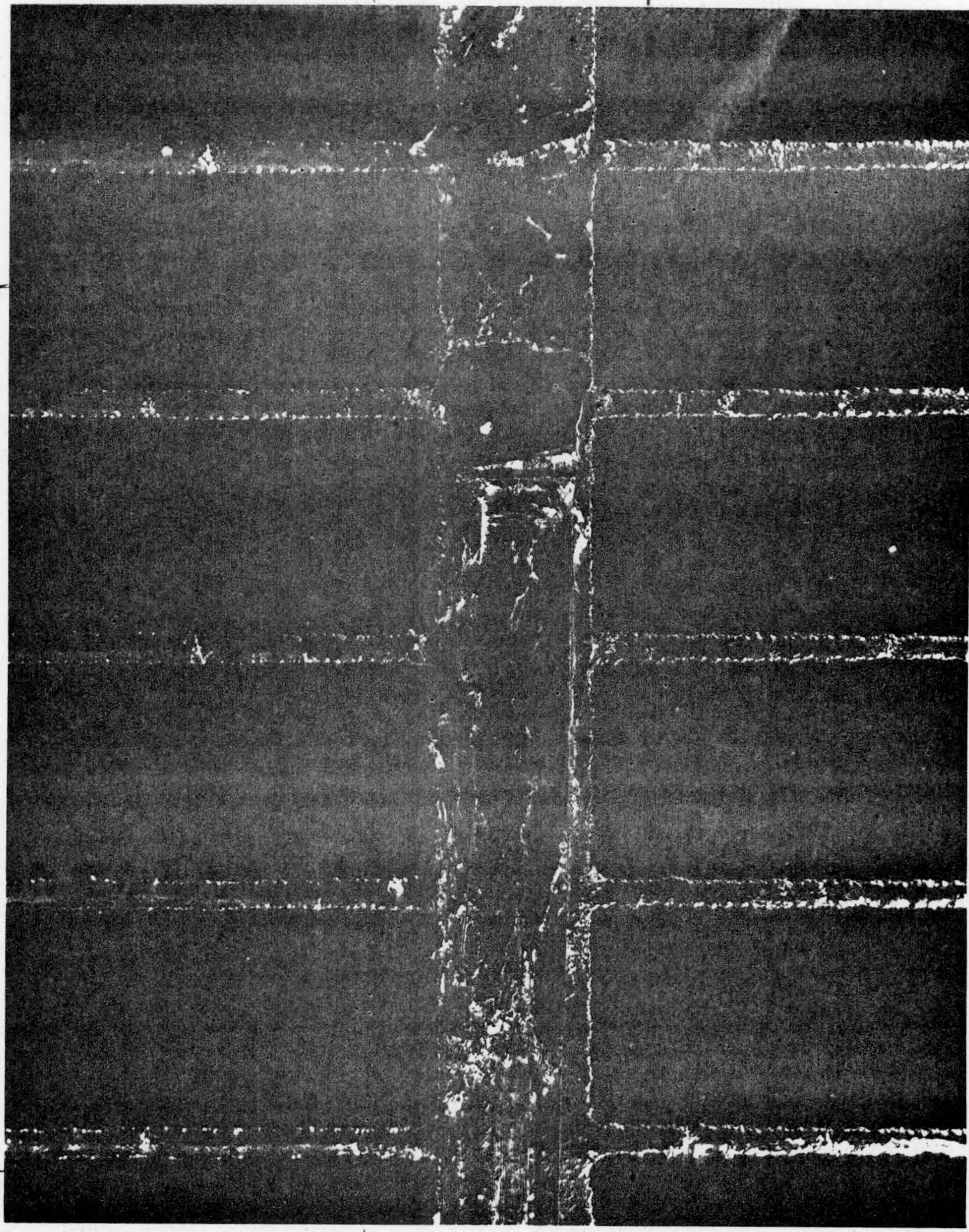

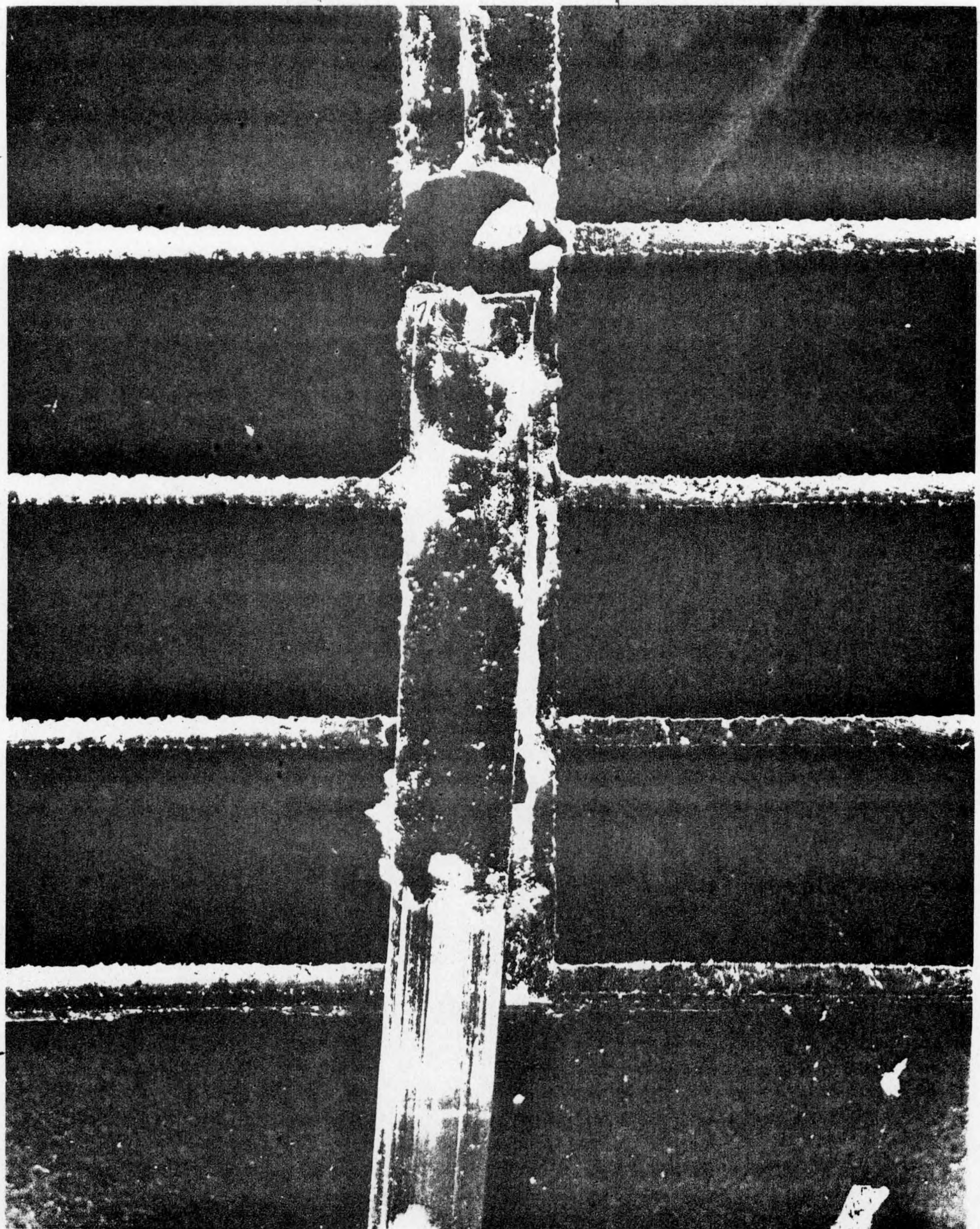

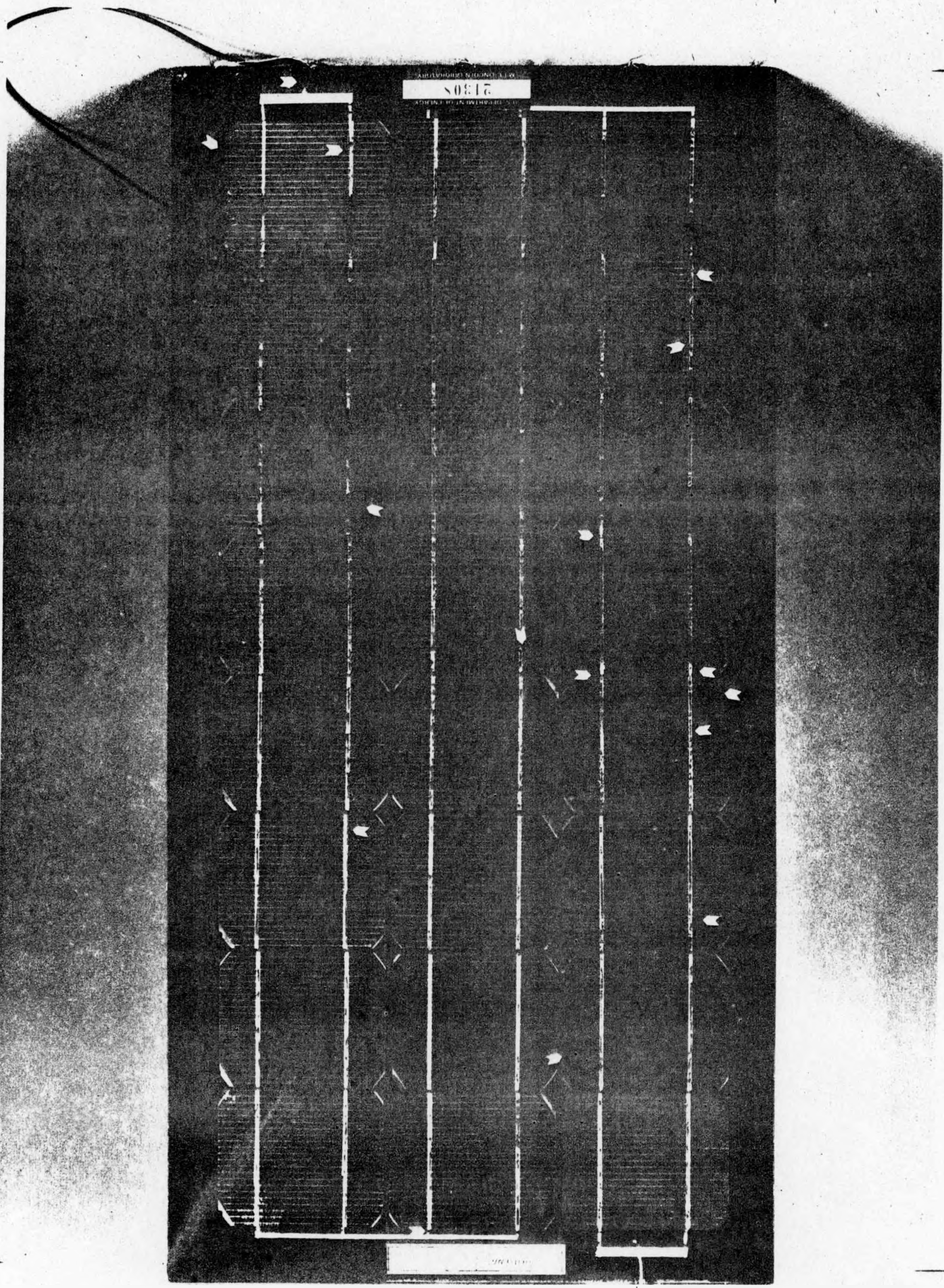

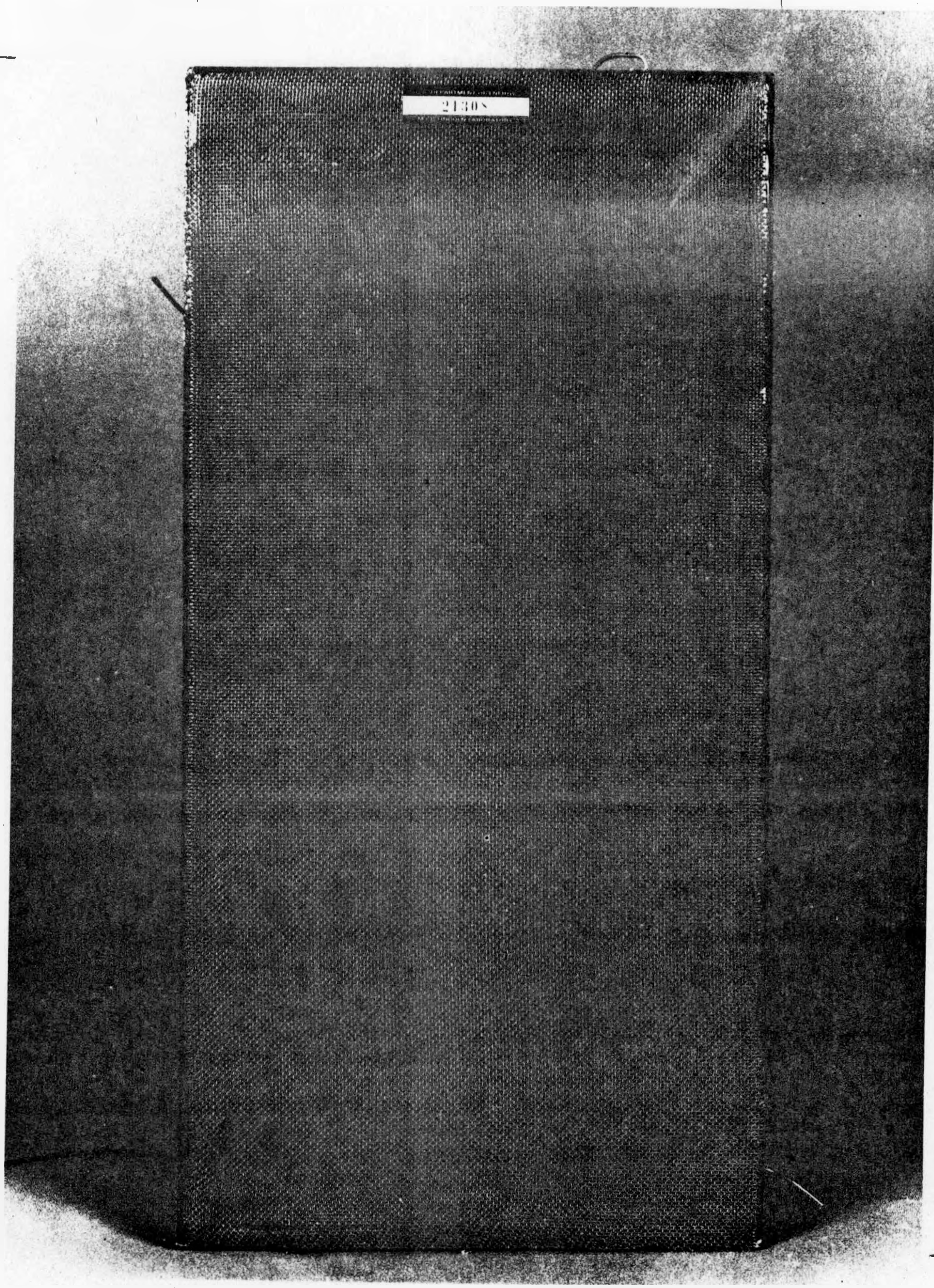
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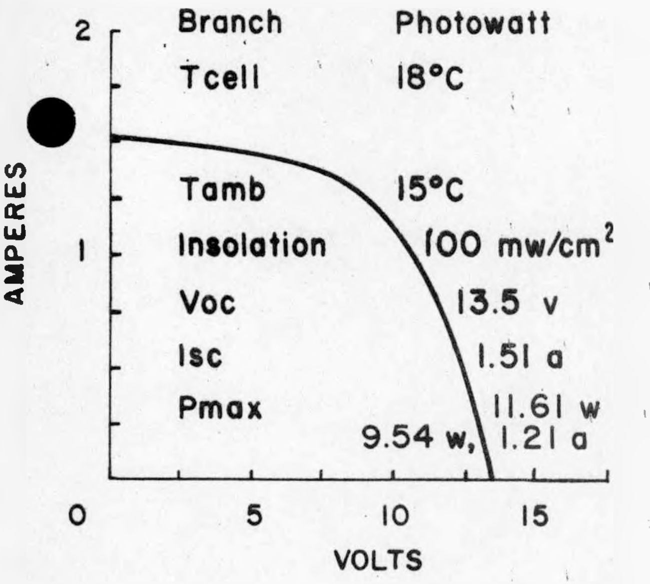
H.F. Canning Dec. 11, 1981



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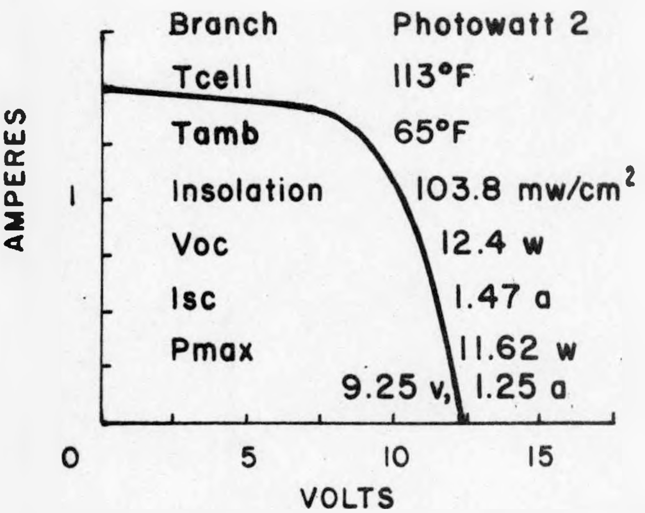

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