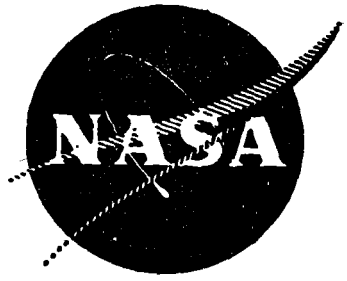

NASA CR 72534

CdS SOLAR CELL DEVELOPMENT

by

F. A. Shirland, W. K. Bower, W. F. Dunn and J. B. Green

CLEVITE CORPORATION

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

CONTRACT NAS 3-9434

L. R. Scudder, Project Manager

NASA CR-72534
Project #303350

FINAL REPORT

CdS SOLAR CELL DEVELOPMENT

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March 14, 1969

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I INTRODUCTION

This report covers a two year development effort on the plastic substrate CdS thin film solar cell under the sponsorship of the Lewis Research Center of NASA on Contract NAS 3-9434. The first year's work was summarized in an Interim Technical Report, "CdS Solar Cell Development" by F. A. Shirland, W. K. Bower and J. B. Green dated February 29, 1968 and issued as NASA Contractor Report 72382.

That report is incorporated into this report by reference and the work reported in it will not be reiterated here. Rather, this report covers the work of the second year of the program and such additions and corrections to the earlier reported work as became subsequently evident.

The major objectives of this second year of the program were to continue the characterization of the stability of the plastic substrate CdS thin film solar cell and to isolate and eliminate the causes of instability whenever possible. Toward that end, a standard process laboratory fabrication line was operated throughout the entire 2 year period to yield a total of 100 acceptable quality cells each month. Of these, 75 cells each month were tested and sent to the Contract Monitor. The remaining 25 cells were retained at Clevite and placed on various dry and wet shelf storage tests, high temperature vacuum storage tests, and various temperature cycling and continuous use tests.

Those cells which showed appreciable loss of output on these various tests were removed and subjected to detailed failure analyses in an effort to determine the causes of failure. Subsequently, various constructional and fabrication process variations were evaluated as possible ways around the cell weaknesses as disclosed by the various tests and analyses.

Many individuals have contributed to the work on this project. Project direction has been provided by F. A. Shirland; W. K. Bower provided the principal investigation into the process engineering and quality control studies; W. F. Dunn provided the principal investigation into the developmental variations and the cell stability characterization and failure analyses; and J. B. Green provided supervision for the cell fabrication efforts. Additional contributions were made by J. E. Hardin, L. R. Shiozawa, R. D. Simonton and J. M. Smith III.

Mr. Larry R. Scudder of the Lewis Research Center, NASA, was Contract Monitor acting under the direction first of Mr. A. F. Forestieri and later Mr. A. Spakowski. Dr. Henry Brandhorst of the Lewis Research Center,

NASA, provided standard cells for regulation of illumination sources and he and his co-workers provided continuing assistance in setting up and maintaining adequately calibrated cell testing facilities.

Acknowledgment is also made to the Clevite Corporation Management who provided the cell fabrication facilities and the extra funding for operation of those facilities at rates well above that covered by the Contract so that cells more representative of a true production process could be obtained for study and characterization.

II CELL FABRICATION

A. Standard Cell Design

The design of the standard CdS thin film solar cell was described in detail in the earlier Interim Technical Report. The design has remained essentially the same over the entire period of this Contract. However, in a few instances minor changes have occurred in some of the cell dimensions. These have occurred more by accident than by choice, though in one or two cases the changes were apparently needed in order to obtain reasonable yields from the cell fabrication line.

One of the changes was in the thickness of the silver Pyre-ML conductive layer on the Kapton substrate. This has gradually increased from the range of 0.25 - 0.30 mils to about 0.35 - 0.40 mils. Another change was in the thickness of the CdS film. Where it had been in the range of 0.8 to 1.0 mils it has recently run as high as 1.3 mils. In both of these cases, it was lack of adequate quality control procedures which allowed the changes to occur.

In a few other cases, it was the capabilities of the vendors of parts going into the cell which caused the changes to occur. The thickness of the positive grid for instance has increased from the earlier 0.45 - 0.50 mil range to about the 0.50 - 0.55 mil range. The thickness of the clear epoxy cement used for cover plastic attachment has had to be increased to correspond. The pattern of the grid itself has remained unchanged, but the width of the grid wires had to be approximately doubled in order to obtain reasonable yields of grids at acceptable prices. This has had the effect of decreasing the light transmission (i.e. open space) of the grid from the earlier 88 - 91% range to the present 82 - 85% range. Of course this has affected the current output and hence the efficiency of the standard cell in direct proportion.

The above changes are relatively minor. Attempts are planned in the future to get back to the earlier dimensions since these clearly are beneficial in yielding a thinner, lighter weight and more efficient cell.

B. Fabrication Process

As in the case of the cell design discussed above, the process for making the cell has also remained substantially the same over the entire period of the Contract. However, here also a careful study of the processing conditions has disclosed a few areas where minor changes have occurred.

One of these is the sintering of the CdS raw material. Where it used to be sintered in vacuum to 850°C and then in argon to 1200°C, it is now sintered in vacuum to 900°C before admitting the argon.

C. Quality Assurance

In the last half of the present Contract period the quality assurance program was operated as outlined in the Quality Assurance Program contained as an appendix to the Interim Technical Report of February 29, 1968. In general, this program was somewhat more ambitious than could be effectively carried out with a single quality control inspector and the part time efforts of a process engineer.

The program was successful however in focusing attention on a number of processing areas where process improvements were needed and in indicating where incoming parts and raw materials were not up to the quality levels that were needed. Some of the processing areas that were most seriously out of control were the substrate preparation area and the CdS film evaporation area. Improvements were effected in these areas, but more are needed and recommendations for these have been made and planned for the follow-on effort.

The quality levels of some of the incoming parts and raw materials have been equally difficult to deal with effectively with a limited quality control organization, and though much progress has been made here, much more is needed. The quality of the gold plated copper metal mesh grids has been one of the problem areas that has absorbed much engineering and inspection time. Another is the adhesive coating of the Kapton cover plastic.

Toward the end of this Contract period an additional quality control inspector was added to the fabrication line. Also, an additional process engineer was added to the engineering staff and arrangements were made to have him concentrate his efforts in the quality assurance area. However, the results of this additional attention to quality control were not fully effective during this Contract period.

D. Yields

In the first 12 months of this Contract a total of 3100 CdS films 3" x 3" in nominal size were started through the vacuum evaporation step for the standard process cell fabrication portion of the contractual effort. These gave 1285 acceptable quality cells for an overall yield of 41%. In the last year (13 months) of the Contract, the standard process cell fabrication efforts were continued. The yields of cells from this effort are summarized in Table I.

It is seen that widely varying yields were experienced at different times. On the whole the yields were lower in the second half of the Contract with a total of 5010 CdS films giving 1299 acceptable quality cells for an overall yield of 26%. However, the results from the latter period are not directly comparable with those from the earlier period. The main reason is that much more restrictive screening practices were put into effect with the advent of the quality assurance program, with the intent to eliminate catastrophic failures on temperature cycling. There was a gradual tightening up of inspection standards throughout the period of the Contract, and particularly so in the second half. Thus, though the yields appeared to have remained about the same or even lower as the work progressed, in reality there was a major improvement in most of the processing areas and this was reflected in the quality of the finished product. This is apparent from the greatly improved performance of the finished cells in vacuum thermal cycling test, and on the improved fill factors and high temperature performance of the cells.

E. Cell Outputs

Over the period of this report no effort was expended on trying to improve the level of the output power of the standard process cell. All efforts rather were put on making the cell as reproducibly as possible, characterizing its stability and determining and eliminating causes of instability.

Over the 13 months of this report period, average cell output levels varied very little. Figure 1 is a histogram giving the distribution of air mass 1 conversion efficiencies measured at 25°C on standard process Kapton covered 3" x 3" size cells fabricated during the 13th through the 25th months of the Contract. Figure 2 is the experience with the open circuit voltage, Figure 3 for the short circuit current, Figure 4 for the voltage at the maximum power point and Figure 5 for the current at the maximum power point for the same cells measured under the same conditions.

TABLE I

YIELDS FROM STANDARD CELL FABRICATION LINE

Month	Total No. of Starts	REJECTS				
		Evap.	Barrier Form.	Grid & Lam.	Final Test	Total
13	310	22	140	3	45	210
14	469	63	156	8	131	358
15	306	3	147	10	46	206
16	432	0	155	15	162	332
17	512	3	145	0	264	412
18	326	9	59	72	86	226
19	360	27	60	5	168	260
20	296	7	59	61	69	196
21	303	36	18	28	121	203
22	219	9	16	60	34	119
23	467	0	87	108	172	367
24	586	0	115	24	347	486
25	424	0	104	5	227	336
Total	5010	179	1261	399	1872	3711

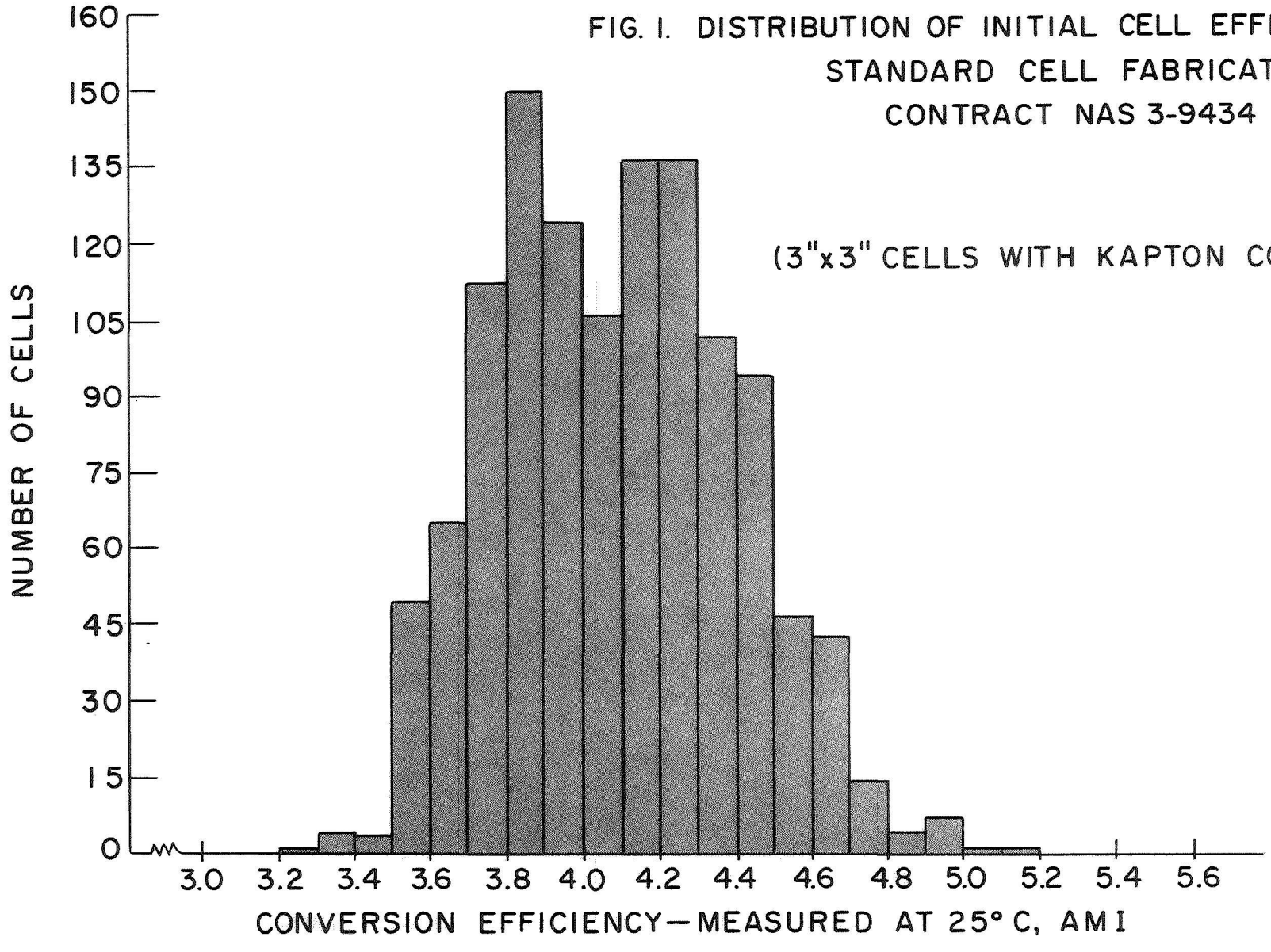
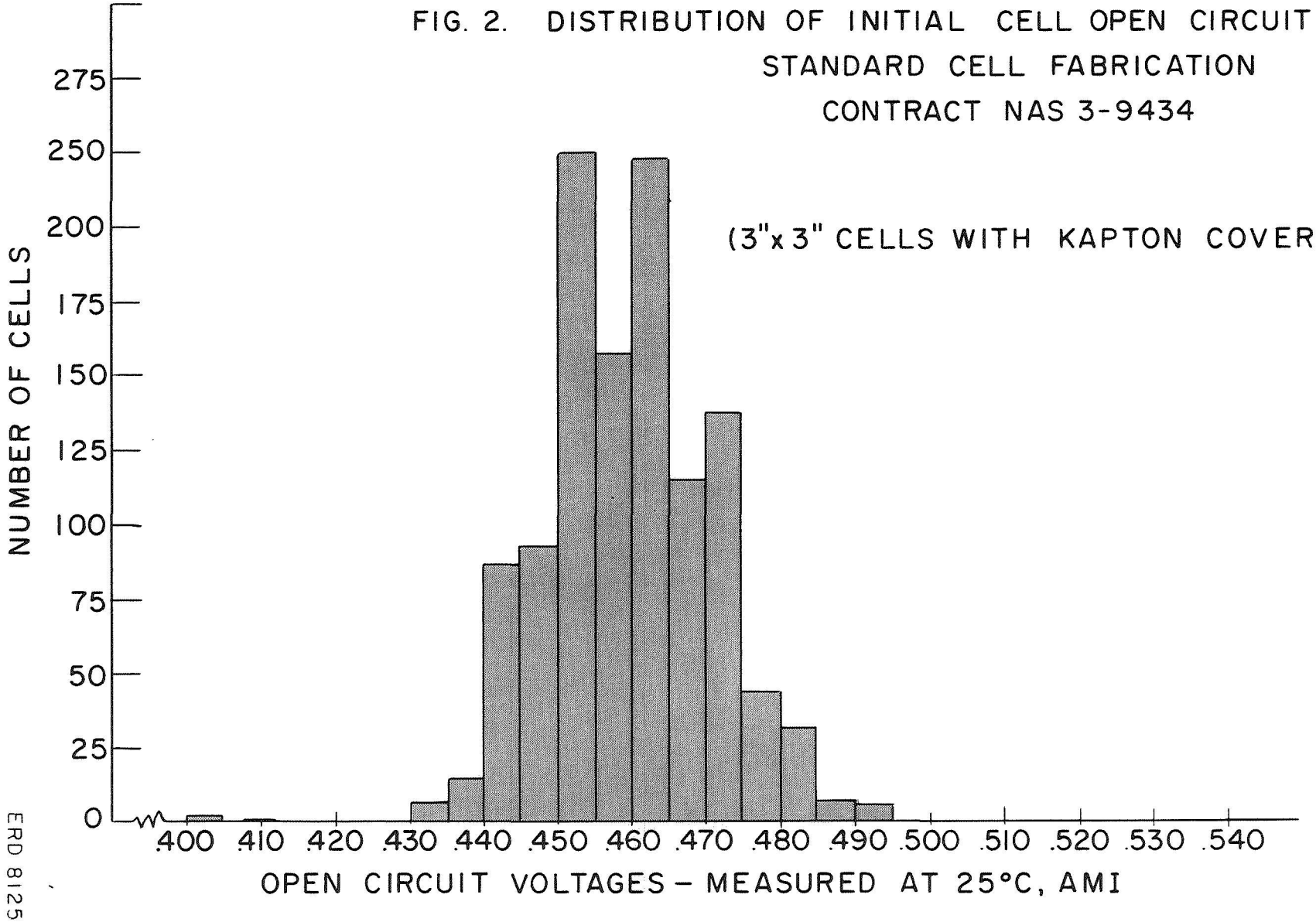


FIG. I. DISTRIBUTION OF INITIAL CELL EFFICIENCIES
STANDARD CELL FABRICATION
CONTRACT NAS 3-9434

(3"x3" CELLS WITH KAPTON COVERS)

FIG. 2. DISTRIBUTION OF INITIAL CELL OPEN CIRCUIT VOLTAGES
STANDARD CELL FABRICATION
CONTRACT NAS 3-9434



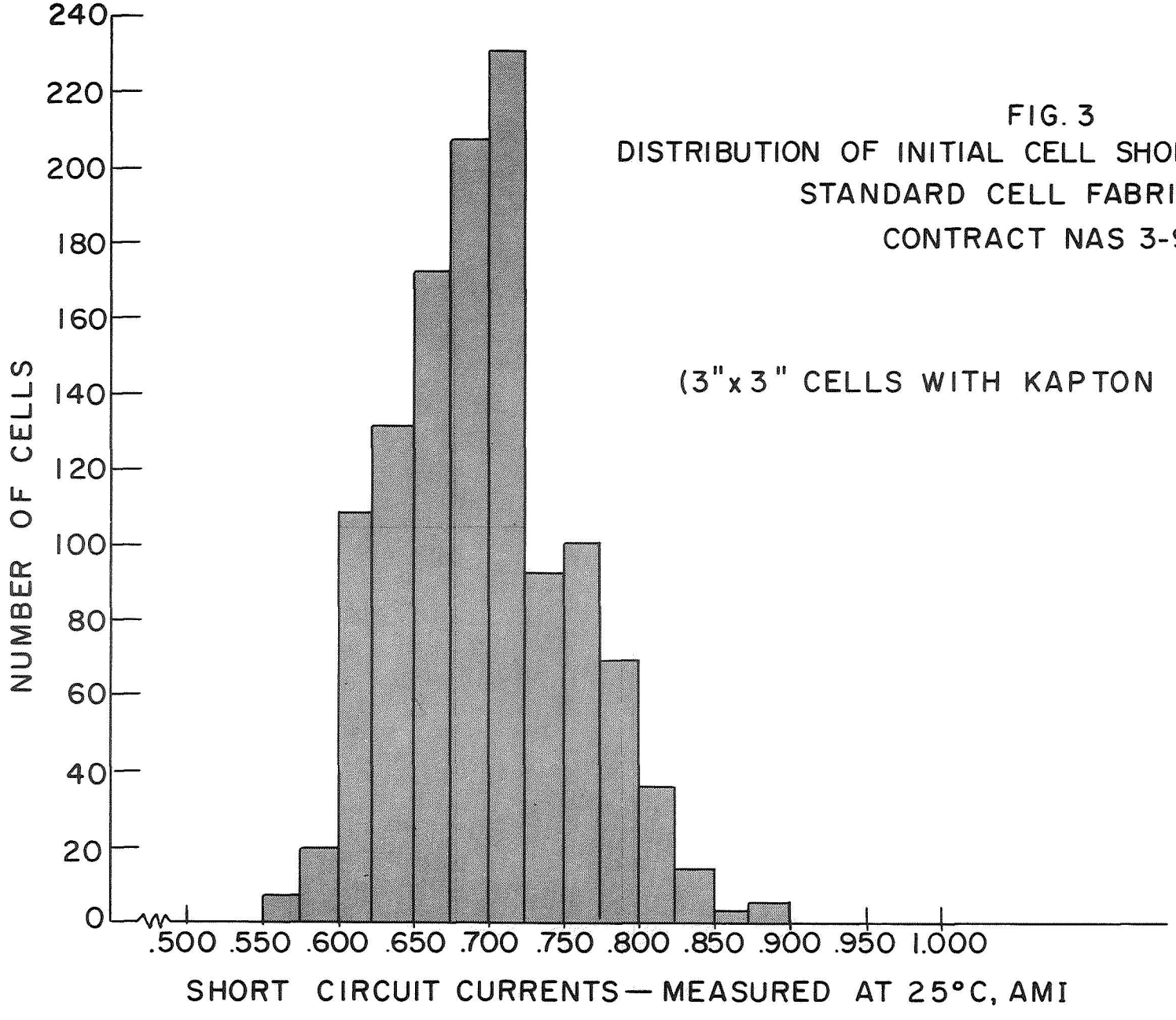


FIG. 3
DISTRIBUTION OF INITIAL CELL SHORT CIRCUIT CURRENTS
STANDARD CELL FABRICATION
CONTRACT NAS 3-9434

(3"x3" CELLS WITH KAPTON COVERS)

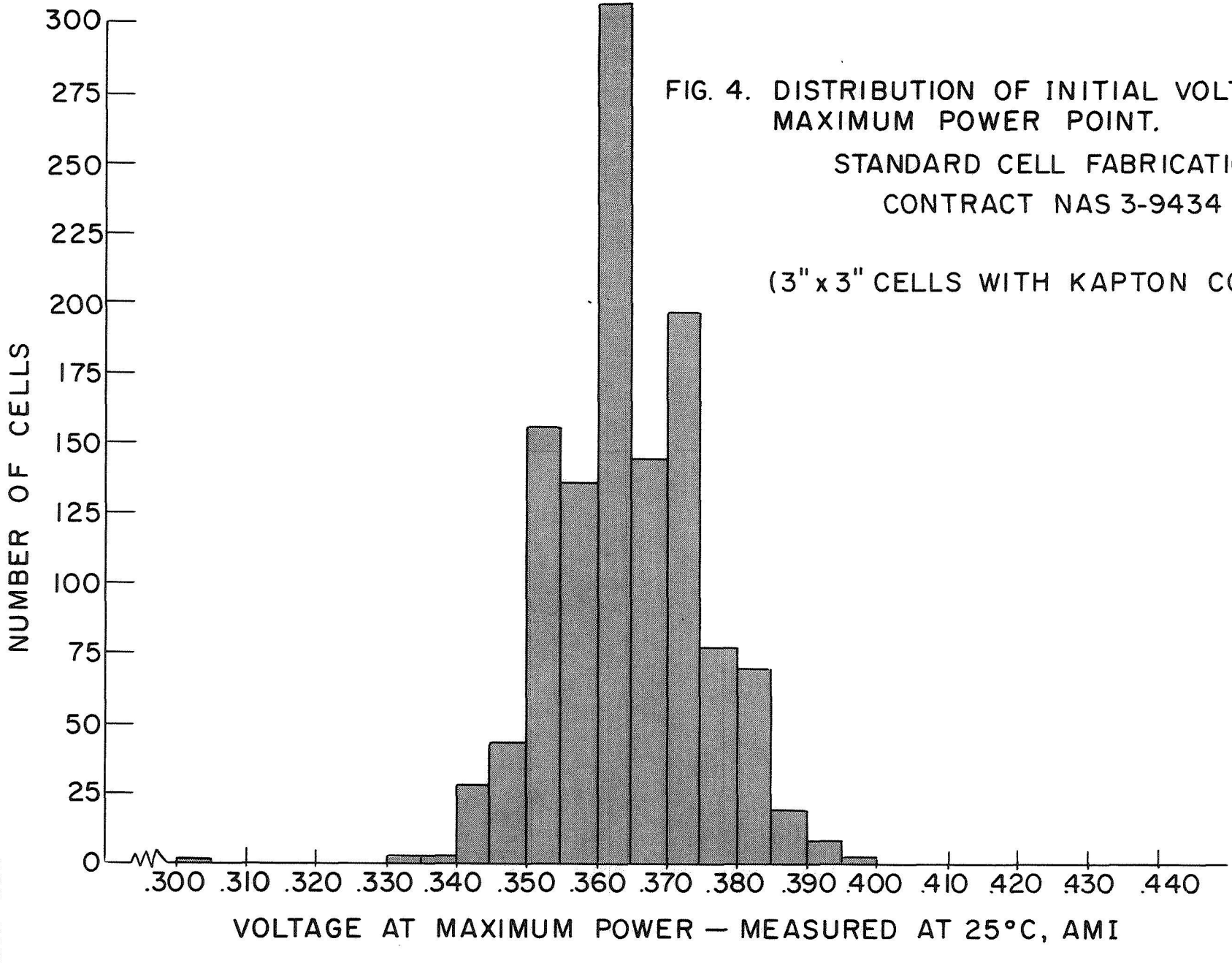


FIG. 4. DISTRIBUTION OF INITIAL VOLTAGE AT MAXIMUM POWER POINT.

STANDARD CELL FABRICATION

CONTRACT NAS 3-9434

(3" x 3" CELLS WITH KAPTON COVERS)

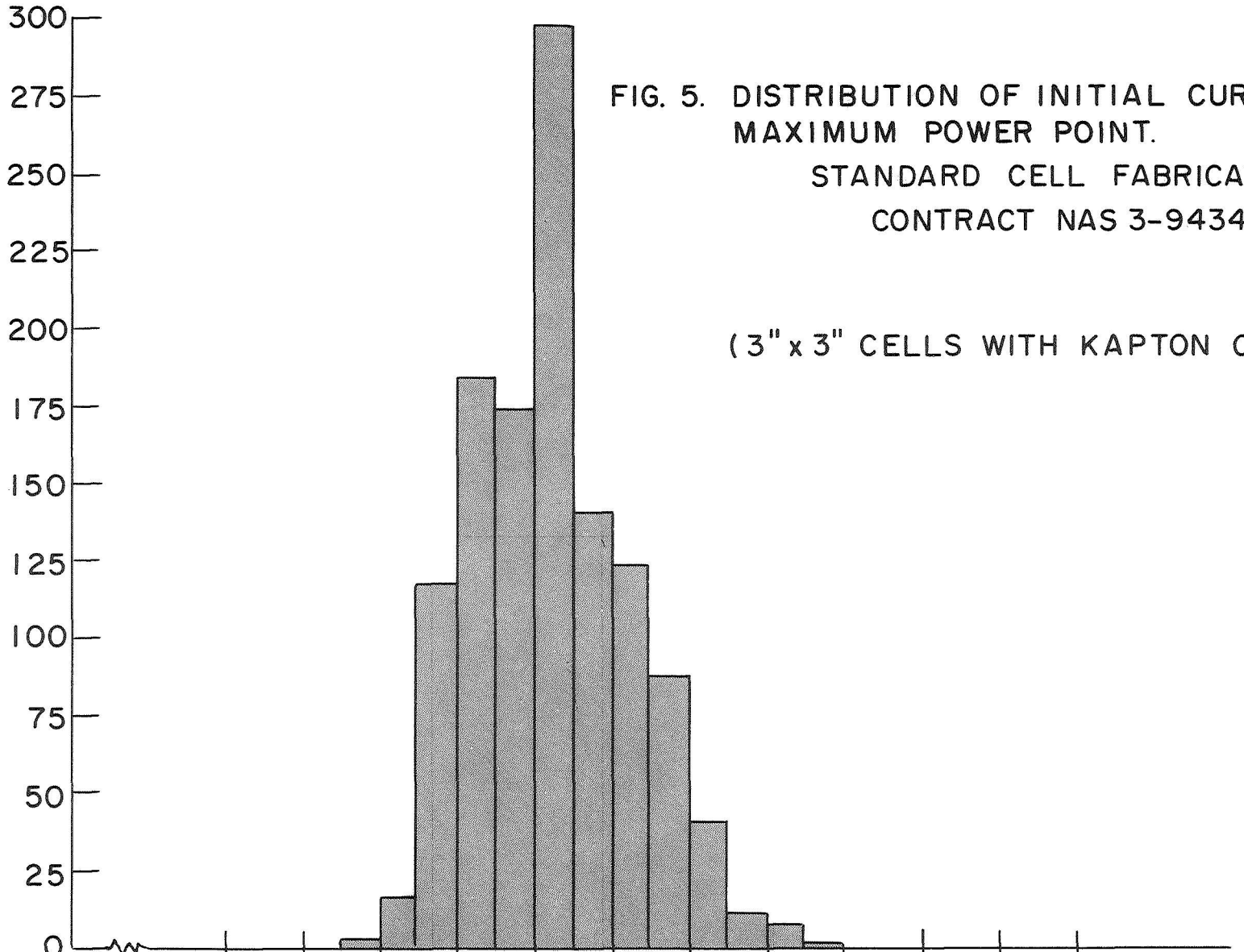


FIG. 5. DISTRIBUTION OF INITIAL CURRENT AT MAXIMUM POWER POINT.
STANDARD CELL FABRICATION
CONTRACT NAS 3-9434

(3" x 3" CELLS WITH KAPTON COVERS)

There is obviously a lot of improvement that can still be made in the performance of these cells. The lack of Gaussian distribution patterns for the attributes in Figures 2 to 5 indicates that the process is not under control.

III STABILITY CHARACTERIZATION

One of the major tasks of this Contract was to characterize the stability of the CdS thin film solar cell under conditions that it would be expected to operate in space. Various shelf and environmental tests were carried out on standard process cells. At intervals, cells showing appreciable amounts of degradation were removed from the test and analysed in an effort to determine the causes for loss of output.

A. Dry Shelf Storage

Every month for about 3 years four standard process cells have been placed in a laboratory desiccator cabinet which is at room temperature. The cells have been removed at regular intervals and their I-V characteristic curves measured under standard conditions of equivalent air mass 1 illumination at 25°C.

In Table II are presented the longer term dry shelf storage test data on cells fabricated in 1966 and early 1967. A total storage time of from 20 to 32 months has been accumulated on these cells. Data for periods of storage up to 19 months on these same cells were presented in the earlier Interim Technical Report. For convenience of interpretation, the earlier reported data are repeated in this Table.

It is difficult to compare the outputs of cells over this long period because of instrumentation problems and difficulties of maintaining the same illumination intensity and spectral quality. The month by month readings show appreciable fluctuation, but over longer periods definite trends appear that are probably reasonably accurate.

There are wide differences between cells on this test, but all cells have shown some loss of output. A few cells dropped as much as 15 to 18%, but most cells lost from about 2% to about 10% of their output over the period of the test - i.e., in 20 to 32 months.

Table III gives the dry shelf storage data on cells made in the latter portion of 1967. These have from 16 to 19 months of exposure. A few of these showed marked loss of output, but on the whole this group behaved better than the older cells of Table II.

TABLE II

DRY SHELF STORAGE - LONG TERM TEST DATA

Cell No.	AM1, 25°C Efficiency after indicated number of months storage:																
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
D289D	4.9			4.9	4.8	4.8	4.9	4.8	4.9	5.0	4.7	4.9	5.0	5.0	4.9	4.7	4.8
D292D	4.7			4.9	4.6	4.6	4.9	4.9	4.8	5.0	4.8	4.9	5.0	5.0	4.8	4.7	4.8
D296B	4.5			4.4	4.3	4.2	4.3	4.3	4.4	4.4	4.4	4.4	4.4	4.4	4.3	4.2	4.3
D304A	4.8			4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.4	4.5	4.2	4.3	4.4	4.2	4.2
D306D	4.9			4.9	4.8	4.8	4.9	4.9	5.0	5.1	5.1	5.1	4.8	5.0	5.0	4.8	5.0
D315A	5.2			5.2	5.0	5.0	5.2	5.3	5.2	5.2	5.1	5.3	5.3	5.2	5.3	5.0	5.2
D336D	4.2		4.1	4.0	4.0	4.1	4.0	4.2	4.4	4.1	4.3	4.3	4.3	4.2	4.2	4.0	4.3
D344C	5.2		4.9	4.8	4.7	4.7	4.7	4.8	4.9	4.7	4.9	4.8	4.8	4.6	4.3	4.0	4.3
D355C	5.7		5.3	5.2	5.3	5.4	5.4	5.5	5.4	5.4	5.8	5.3	5.3	5.2	5.5	-	-
D364F	4.7		4.2	4.1	4.1	4.1	4.0	4.2	4.2	4.2	4.2	4.3	4.3	4.2	4.4	-	-
D375C	4.4	4.3	4.4	4.1	4.4	4.6	4.4	4.4	4.4	4.4	4.4	4.4	4.2	4.3	4.2	4.4	4.0
D381A	5.1	5.1	5.2	5.1	5.1	5.2	5.1	5.1	5.1	5.1	4.8	4.8	4.7	off			
D385B	5.0	5.2	5.1	5.1	5.2	5.0	5.1	5.1	5.1	5.1	5.1	4.9	5.0	4.9	5.1	-	-
D386E	5.1	5.2	5.1	5.2	5.2	5.2	5.2	5.2	5.1	5.2	5.2	5.0	5.0	5.1	5.2	-	5.0
D391B	4.7	5.0	5.2	5.0	5.1	5.1	5.0	5.1	5.1	5.0	5.0	4.9	5.0	4.9	5.0	-	4.8
D395C	4.2	4.2	4.1	4.2	4.2	4.3	4.2	4.3	4.3	4.2	4.2	4.1	4.3	4.2	4.3	-	-
D403B	4.6	4.7	4.8	4.9	4.8	4.7	4.8	4.8	4.7	4.6	4.6	4.6	4.7	4.6	4.8	4.4	-
D410B	4.9	4.8	4.8	4.9	4.9	4.9	4.9	4.9	4.7	4.7	4.6	4.6	4.7	4.7	4.7	4.5	4.5
D507F	5.7	5.3	5.3	5.1	4.9	4.9	4.7	4.7	off								
D513E	5.1	5.0	5.1	5.0	4.8	4.8	4.8	4.6	-	-	4.6	4.6	-	-	4.5	-	-
D521F	4.6	4.4	4.6	4.6	4.4	4.5	4.3	4.3	-	-	4.0	4.3	-	-	4.4	-	-
D522E	4.8	4.7	4.8	4.7	4.5	4.6	4.5	4.4	-	-	4.5	4.4	-	-	4.4	-	-
D551E	4.5	5.0	4.7	4.7	4.6	4.6	4.8	-	4.5	4.5	-	-	4.5	-	-	-	4.5
D563A	4.8	4.9	4.6	4.6	4.5	4.6	4.7	-	4.5	4.5	-	-	4.4	-	-	-	4.4
D579B	5.1	4.9	4.6	4.7	4.5	4.6	4.8	-	4.5	off							
D583C	4.8	5.0	4.7	4.7	4.6	4.6	4.8	-	4.5	4.4	-	-	4.4	-	-	-	4.5
N14B2	5.5	5.2	4.8	4.8	4.7	4.7	-	-	4.6	4.4	-	-	4.4	-	-	-	4.4
N14B5	4.4	4.1	3.8	3.9	3.8	3.8	4.0	off									
N20B1	4.9	5.1	4.8	4.8	4.7	4.9	5.0	-	4.6	4.6	-	-	4.5	-	-	-	4.6
N31BK4	4.1	4.2	4.0	4.1	4.0	4.0	4.2	-	3.7	3.8	-	-	3.8	-	-	-	3.7

TABLE II - continued

DRY SHELF STORAGE - LONG TERM TEST DATA

Cell No.	AM1, 25°C Efficiency after indicated number of months storage:																
	0	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
D289D	4.9	4.7	4.9	5.0	4.6	4.6	-	-	4.6	-	-	-	4.6	-	-	-	4.5
D292D	4.7	4.8	4.8	5.0	4.5	4.6	-	-	4.5	-	-	-	4.6	-	-	-	4.6
D296B	4.5	4.2	4.2	4.5	4.1	4.1	-	-	4.1	-	-	-	4.1	-	-	-	4.1
D304A	4.8	4.2	4.2	4.3	off												
D306D	4.9	4.9	4.9	5.0	4.8	-	-	4.6	-	-	-	4.6	-	-	-	4.6	
D315A	5.2	5.0	5.1	5.2	-	4.9	-	-	4.7	-	-	-	4.7	-	-	-	5.0
D336D	4.2	4.2	4.1	4.2	4.1	-	-	4.2	-	-	-	4.1	-	-	-	3.9	
D344C	5.2	4.0	4.3	4.3	off												
D355C	5.7	5.0	5.2	5.4	5.0	-	-	5.0	-	-	-	5.0	-	-	-	4.9	
D364F	4.7	4.2	4.4	4.5	-	3.8	-	-	-	4.1	-	-	-	4.1			
D375C	4.4	4.0	-	-	4.0	-	-	-	4.0	-	-	-	4.0				
D381A	5.1																
D385B	5.0	4.8	-	-	4.8	-	-	-	4.7	-	-	-	4.7				
D386E	5.1	5.0	-	-	4.8	-	-	-	4.9	-	-	-	4.9				
D391B	4.7	4.8	-	-	4.6	-	-	-	4.6	-	-	-	4.6				
D395C	4.2	4.0	-	-	4.0	-	-	-	4.0	-	-	-	4.0				
D403B	4.6	-	4.3	-	-	-	4.4	-	-	-	4.3						
D410B	4.9	-	-	-	-	-	-	4.3	-	-	-	4.2					
D507F	5.7																
D513E	5.1	-	4.5	-	-	-	4.5										
D521F	4.6	-	4.5	-	-	-	4.2										
D522E	4.8	-	4.4	-	-	-	4.3										
D551E	4.5	-	-	-	4.4												
D563A	4.8	-	-	-	4.2												
D579B	5.1																
D583C	4.8	-	-	-	4.6												
N14B2	5.5	-	-	-	4.5												
N14B5	4.4	-	-	-													
N20B1	4.9	-	-	-	4.6												
N31BK4	4.1	-	-	-	3.6												

TABLE III

DRY SHELF STORAGE - MEDIUM TERM TEST DATA

AM1, 25°C Efficiency after indicated number of months in storage:

Cell No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
D597E	5.0	4.4	4.4	4.3	3.9	4.5	off													
D609B	4.6	4.1	4.1	3.9	4.0	4.2	off													
N35B3	5.0	4.9	5.0	4.9	4.9	5.2	-	4.5	4.6	-	-	4.6	-	-	-	4.9	-	-	-	4.7
N44B3	4.4	4.4	4.4	4.3	4.4	4.4	-	3.7	3.7	-	-	4.0	-	-	-	4.0	-	-	-	3.8
N64BK5	4.0	4.0	4.1	4.1	-	-	4.0	4.0	4.0	4.1	4.0	-	-	-	3.8	-	-	-	3.9	
N65BK5	4.2	4.0	4.2	-	-	4.0	4.0	4.0	4.0	4.0	-	-	-	3.9	-	-	-	3.9		
N71AK2	4.1	3.8	4.0	4.0	-	-	3.9	3.8	3.9	3.8	-	-	-	3.6	-	-	-	3.7		
N78AK5	4.7	3.6	4.2	4.5	-	4.2	4.2	4.2	4.4	4.2	-	-	-	4.0	-	-	-	4.0		
N80AK6	4.2	-	3.8	4.0	-	3.9	4.0	3.8	4.0	3.9	-	-	-	3.6	-	-	-	3.5		
N85BK3	4.4	-	3.9	4.2	-	3.9	3.8	3.9	3.9	-	-	-	3.7	-	-	-	3.8			
N86C5	5.9	4.7	5.4	5.9	-	5.5	5.4	5.1	5.2	-	-	-	5.5	-	-	-	5.3			

The dry shelf storage test data on the cells fabricated in 1968 are summarized in Table IV. Some of these cells are showing no loss of output, and others are showing on the order of 2 to 4%. Of course, the exposure time is much less for this group of cells. However, the general quality of these cells was far superior to the quality of those made earlier. The cells made in 1966 contained many noticeable flaws such as large voids in the epoxy cement, chipped areas in the CdS films, pinholes, poor adhesion of the silver Pyre-ML layer to the Kapton substrate, and poor adhesion of the CdS to the silver Pyre-ML layer. Many of these flaws were eliminated or greatly improved in the cells made in 1967, and further improvements were made in these respects in 1968. Also, as improved processing techniques were employed, more stringent screening practices were put into effect on the finished cells. Hence, the later cells had more rectangular I-V curves as well as fewer constructional shortcomings.

Some of the cells made in 1968 showed little or no loss of output on dry shelf storage. Several years ago, some of the first high efficiency molybdenum and plastic substrate CdS thin film solar cells also showed little or no loss of output over long periods of dry shelf storage. Thus, it is logical to conclude that there is no intrinsic degradation for CdS thin film solar cells on dry shelf storage. However, many cells have shown some loss of output on this test.

A careful analysis of the I-V curves of the cells listed in Tables II, III and IV which showed some loss of output on dry shelf storage, discloses no common pattern of behavior. Most of the cells that degraded lost short circuit current. Some lost open circuit voltage as well. Some lost in fill factor. While it has not been possible to analyze in detail all of the cells which showed a loss of output on this test and to ascribe a definite cause in each case, a cursory examination of the cells and the data sheets leads to the conclusion that a number of different failure mechanisms must have been operating for these cells. For instance, Cell N197AK1 which was made in May 1968 degraded in 28 weeks from 4.0 to 3.7% efficiency or at an annual rate of 14% of its initial value. This cell was heated overnight in a 135°C vacuum oven and recovered to 3.9% efficiency. The sequence is shown in Figure 6. This is what would be expected if the degradation had been caused by moisture. Just how moisture could have been picked up by this cell is a mystery. On the other hand, Cell N86C5 degraded from 5.9 to 5.3% in 16 months. This is an annual degradation

TABLE IV

DRY SHELF STORAGE - SHORT TERM TEST DATA

Cell No.	Month Made 1968	Efficiency AM1, 25°C/after indicated number of weeks: 0	1	2	3	4	8	12	16	20	24	28	32	36	40	44
N116BK9	Jan.	3.8	3.8	3.8	3.7	3.7	3.6	3.7	3.6	3.6				3.6		
N115CK9		3.6	3.5	3.6	3.5	3.5	3.5	3.5	3.5	3.5				3.4		
N115AK2		3.9	3.9	4.0	3.9	3.8	3.8	3.8	3.8	3.8				3.7		
N113CK7		3.9	3.9	3.9	3.8	3.7	4.0	3.8	3.7	3.8		3.6				3.7
N128AK9	Feb.	3.9	3.9	3.8	3.8	3.8	3.8	3.8		3.7		3.6				3.7
N128AK4		4.1	4.1	4.1	4.1	4.1	4.1	4.1				3.9				4.0
N128AK1		4.0	4.0	4.0	4.0	3.9	3.8	3.8	3.8	3.8		3.7				3.8
N127CK3		4.1	4.0		4.0	4.0	4.0	3.9	3.9	3.9		3.8				3.9
N167CK2	March	4.0	4.0	4.0		4.0	3.9	3.8			3.7				3.8	
N163BK9		4.0	4.0			4.0	3.9	4.0	3.9		3.8					3.9
N163BK5		4.2	4.1			4.0	4.0	4.0	4.0		3.9					4.0
N163BK1		4.0	4.0		4.0		4.0	4.0	4.0		3.9					4.0
N186BK7	April	3.8			3.7	3.6	3.6	3.6	3.6	3.6				3.7		
N186BK4		3.7			3.6	3.6	3.6	3.6	3.5	3.6				3.7		
N186AK2		3.7			3.7	3.6	3.6	3.6	3.5	3.6				3.7		
N185BK3		3.7			3.7	3.6	3.6	3.6	3.5	3.6				3.7		
N202BK9	May	4.0	4.0			3.9		3.9	3.9			3.9				
N197AK1		4.0	4.0			3.8		3.7	3.7			3.7				
N196CK4		3.9	3.9			3.8		3.7	3.7			3.7				
N190BK4		4.6	4.3			4.2		4.2	4.2			4.2				
N266AK1	June	3.9	3.9	3.9	3.9	3.9	3.9	3.7	3.7	3.8						
N264BK6		3.7	3.7		3.7	3.7	3.7	3.6	3.6	3.7						
N363CK8		3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.7						
N263AK7		3.5	3.6	3.6	3.6	3.6	3.5	3.5	3.5	3.5						

TABLE IV - continued

DRY SHELF STORAGE - SHORT TERM TEST DATA

Cell No.	Month Made 1968	AM1, 25°C Efficiency after indicated number of weeks: 0	1	2	3	4	8	12	16	20	24	28	32	36	40	44
N280AK8	July	3.8	3.7	3.8	3.7	3.7	3.7	3.7	3.8	3.8	3.8					
N280AK3		3.7	3.7	3.8	3.8	3.6	3.7	3.7	3.8	3.8	3.8					
N280AK1		3.6	3.6	3.7	3.6	3.6	3.6	3.6	3.7	3.7	3.7					
N279BK4		3.8	3.7	3.9	3.8	3.8	3.7	3.8	3.8	3.9	3.8					
N292AK2	Aug.	4.1	4.0	3.9	3.9	3.9	3.9	3.9	4.0	4.0	3.9					
N291BK1		4.1	4.0	4.0	4.0	4.0	4.0	4.0	4.1	4.1	4.0					
N290AK3		4.1	4.0	4.0	4.0	4.0	4.0	4.0	4.1	4.1	4.0					
N289CK6		4.1	4.0	4.0	4.0	4.0	4.0	4.0	4.1	4.1	4.1					
N301BK5	Sept.	3.8	3.8	3.8	3.8	3.8	3.8	3.8	3.8							
N301AK3		3.9	3.8	3.9	4.0	4.0	4.0	4.0	4.0							
N300CK9		3.8	3.8	3.8	3.8	3.8	3.9	3.9	3.9							
N300CK6		3.8	3.8	3.8	3.9	3.9	3.9	3.9	3.9							
N314CK8	Oct.	4.0	3.9	3.9	3.9	3.9	3.9	3.9								
N313AK4		4.0	3.8	3.8	3.8	3.8	3.8	3.8								
N309		3.9	3.8	3.7	3.8	3.8	3.7	3.7								
N308CK9		3.9	3.9	3.8	3.9	3.9	3.8	3.8								
N327CK3	Nov.	4.2	4.2	4.2	4.2	4.2	4.2									
N327BK7		4.2	4.1	4.1	4.1	4.1	4.1									
N326CK5		4.4	4.3	4.3	4.3	4.3	4.3									
N326BK8		4.3	4.2	4.2	4.2	4.2	4.2									
N350BK3	Dec.	4.0	4.0	4.0	4.0	4.0										
N349CK2		4.0	4.0	4.0	4.0	4.0										
N348CK1		4.1	4.1	4.1	4.1	4.1										
N348AK6		3.9	4.0	4.0	4.0	3.9										

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CELL No. N197 AK1
SHEET No. _____ OF _____
AREA= 54.75 cm
AM1 @ 25°C

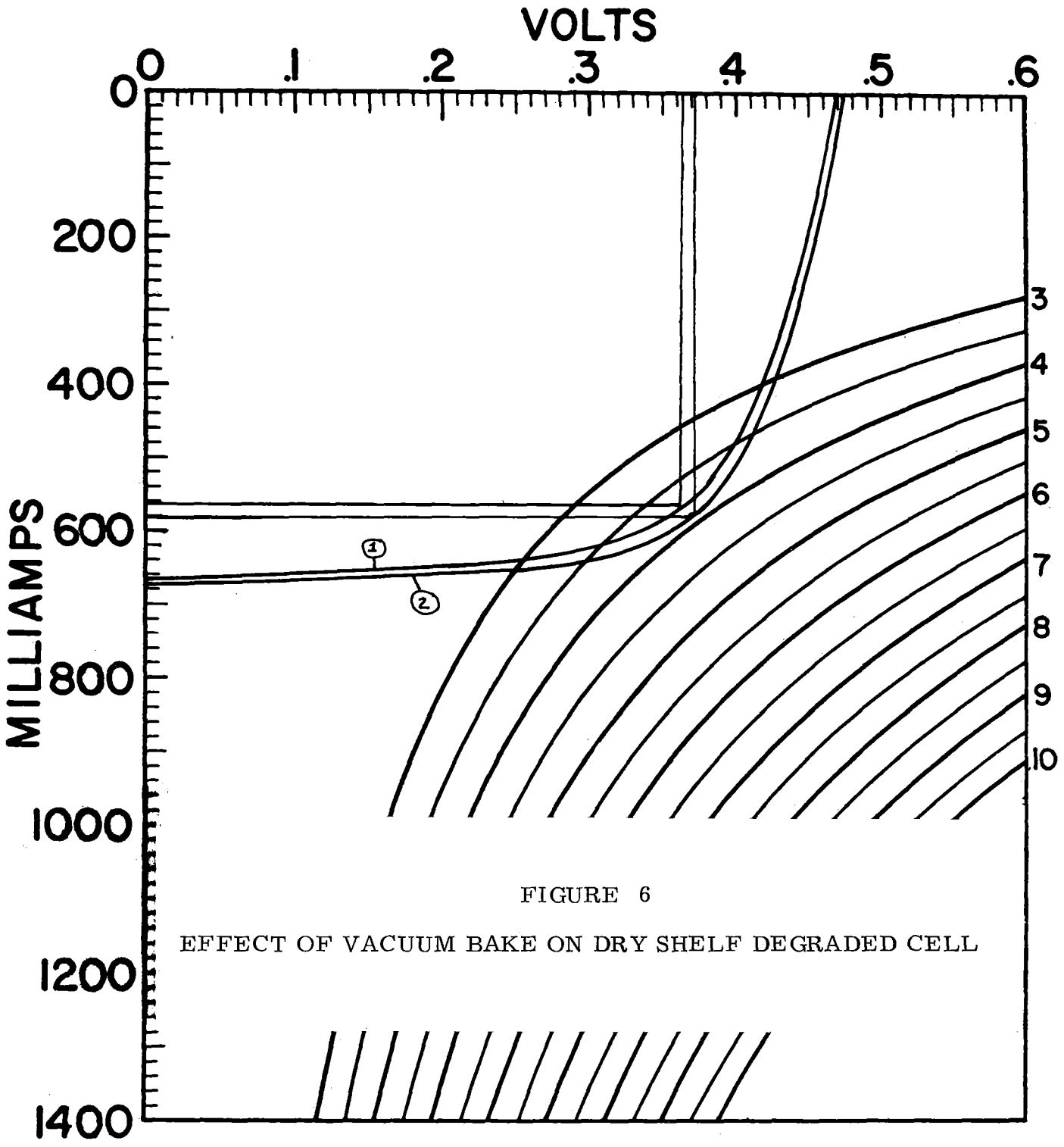

FIGURE 6

EFFECT OF VACUUM BAKE ON DRY SHELF DEGRADED CELL

TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1	2-26-69	.469	.664	.363	.562	.204	65.5	3.7	After 28 wks. Dry Shelf Storage
2	2-27-69	.473	.675	.371	.580	.215	67.4	3.9	After 135°C Vacuum Bake
3									
4									

rate of 7.5% which is still much too high for dry shelf conditions. Heating this cell overnight in a vacuum oven made no change in the power output, as can be seen in Figure 7, though the fill factor did improve slightly at the expense of the short circuit current.

It is tentatively concluded that the loss of cell output exhibited by some cells on dry shelf storage is not an intrinsic characteristic of the CdS thin film solar cell, but rather the result of one or more of a number of different fluctuations in the quality of the parts and materials going into the cells or in the parameters of the various processing steps.

B. Wet Shelf Storage

In the Interim Technical Report of a year ago, a careful analysis was made of cells which had been stored for from 12 to 18 months at 80% relative humidity at room temperature. It was observed that the better cells, which were assumed more likely to exhibit the intrinsic moisture effect, degraded by no more than about 9% per year.

Table V contains the data on those earlier cells and extends the period of time covered from 24 to 35 months. The cells remaining on this test are seen to be holding up at least as well as was estimated a year ago, and in some cases appreciably better. Cell D187B for instance has lost just 11% of its initial power output in 35 months of 80% humidity storage. This is particularly noteworthy because this cell and most of the other cells of this group are of relatively poor quality and would have been rejected during fabrication by the standards of even a year ago.

Table VI presents the wet shelf storage data for the cells made in 1967 with from 19 to 24 months of accumulated exposure. The degradation experienced on these cells was greater than experienced on the cells made in 1966, averaging 14% degradation per year. This higher degradation rate was noted a year ago and was then ascribed to known difficulties in controlling the fabrication process in that period. This is still believed to be the case and it does follow that any structural or other faults that would contribute to cell degradation on dry shelf storage would probably contribute just as much if not more to cell degradation on wet shelf storage.

There is marked improvement in this respect in the stability of the cells made in 1968. Table VII presents the wet shelf storage figures for those cells. Even though these cells have been on test for shorter periods of time, the rate of degradation is lower. Excluding 2 cells with obviously

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SOLAR BATTERY SECTION

CELL No. N86C5
SHEET No. _____ OF _____
AREA= 54.75 cm
AM1 @ 25°C

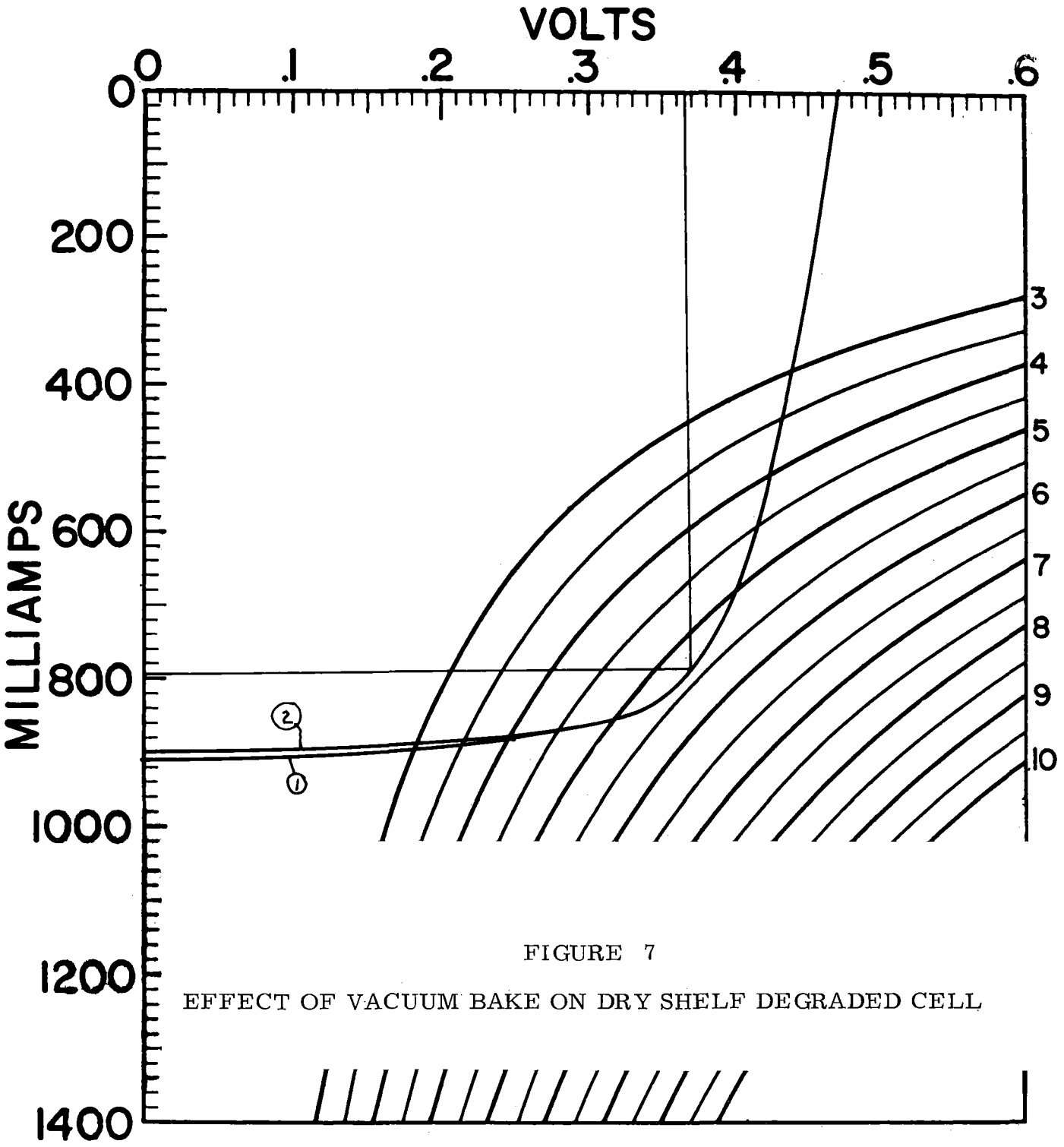


FIGURE 7

EFFECT OF VACUUM BAKE ON DRY SHELF DEGRADED CELL

TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1	2-26-69	.472	.908	.368	.795	.293	68.3	5.4	After 16 mos. Dry Shelf Storage
2	2-27-69	.472	.900	.368	.795	.293	68.9	5.4	After 135°C Vacuum Bake
3									
4									

TABLE V

WET SHELF STORAGE - LONG TERM TEST DATA

Cell No.	AM1, 25°C Efficiency after indicated number of months storage:																		
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
D187B	5.5	-	-	-	-	-	5.5	5.2	5.3	5.3	5.3	5.3	5.4	5.3	5.3	5.3	5.3	5.2	5.1
D291A	4.6	-	4.5	4.6	4.2	4.1	4.2	4.3	4.2	4.2	4.0	4.1	4.1	4.1	4.0	4.1	3.9	off	
D294A	4.3	-	3.4	3.2	3.2	3.2	3.2	3.1	3.2	3.2	3.9	2.8	2.8	2.7	off				
D297C	4.6	-	4.4	4.3	4.0	4.2	4.2	4.2	4.3	4.4	4.2	4.3	4.3	4.3	4.2	4.4	4.2	4.3	4.3
D301A	4.6	-	4.3	4.3	4.0	4.0	4.2	4.2	4.2	4.2	4.1	4.1	4.1	4.1	3.9	4.0	3.7	off	
D313C	4.4	4.1	-	4.1	3.8	4.0	3.8	3.9	4.1	3.9	3.8	3.8	3.8	3.7	3.9	3.7	3.7	off	
D327A	2.8	2.9	-	3.0	2.7	2.7	2.8	2.8	2.7	2.7	2.7	2.6	2.8	2.8	off				
D348C	4.8	-	4.8	4.2	4.3	4.4	4.4	4.5	4.4	4.2	4.5	4.6	4.4	4.4	4.6	4.4	4.4	4.6	4.5
D350F	4.8	-	4.8	4.5	3.8	3.9	4.0	4.2	4.4	3.7	4.3	4.2	4.2	4.2	4.4	4.2	4.3	4.3	4.4
D350C	4.3	4.3	4.4	4.2	4.3	4.4	4.5	4.5	4.2	4.4	4.4	4.2	4.4	4.1	4.2	4.2	4.2	3.7	3.8
D357E	4.4	4.3	4.5	4.4	4.3	4.4	4.4	4.3	4.3	4.3	4.3	4.1	4.3	4.0	4.1	4.0	4.1	4.0	3.7
D372A	4.5	4.3	4.3	4.3	4.3	4.2	4.2	3.9	4.0	4.2	4.2	4.0	4.3	4.0	4.0	4.0	4.1	3.8	3.8
D378B	4.8	4.6	4.6	4.5	4.5	4.4	4.4	4.3	4.3	4.5	4.5	4.0	4.4	4.0	4.1	off	4.2	4.1	-
D385F	5.1	5.2	5.0	5.0	5.1	4.8	4.7	4.8	4.7	4.3	4.6	4.3	4.4	off					
D401B	5.2	5.2	5.0	5.0	5.0	4.8	4.7	4.7	4.8	4.7	5.0	4.6	4.8	4.8	4.7	-			
D405A	4.8	4.5	4.6	4.5	4.5	4.4	4.4	4.4	4.3	4.5	4.3	4.4	4.4	4.4	-	4.1	4.1	-	-
D411F	4.6	4.4	4.4	4.4	4.3	4.3	4.3	4.3	4.2	4.4	4.0	4.3	4.3	4.3	-	3.9	4.0	-	-
D424B	4.5	4.4	4.5	4.3	4.4	4.3	4.3	4.3	4.4	4.1	4.0	4.2	4.2	-	3.7	3.7	-	-	4.1
D424F	5.6	2.8	5.3	5.2	5.3	5.2	5.2	5.1	5.3	5.0	5.0	5.1	5.1	off					
D454A	5.2	4.6	4.6	4.5	4.4	4.4	4.3	4.2	4.0	4.0	3.9	3.9	4.1	-	3.6	-	3.4	-	-

TABLE V - continued

WET SHELF STORAGE - LONG TERM TEST DATA

Cell No.	AM1, 25°C Efficiency after indicated number of months storage: 19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
D187B	5.2	5.1	5.4	-	5.0	5.0	-	-	4.8	-	-	-	5.0	-	-	-	4.9
D291A																	
D294A																	
D297C	-	4.0	4.0	-	-	4.0	-	-	-	3.8	-	-	-	3.8			
D301A																	
D313C																	
D327A																	
D348C	4.1	4.1	-	-	4.0	-	-	-	4.0	-	-	-	4.0				
D350F	4.0	3.8	-	-	3.7	-	-	-	3.7	-	-	-	3.8				
D350C	-	-	3.7	-	-	-	3.7	-	-	-	3.6						
D357E	-	-	3.8	-	-	-	3.8	-	-	-	3.7						
D372A	-	-	3.6	-	-	-	3.7	-	-	-	3.6						
D378B																	
D385F																	
D401B	-	4.0	-	-	-	3.8	-	-	-	3.8							
D405A	4.1	-	-	-	3.9	-	-	-	3.9								
D411F	3.9	-	-	-	3.8	-	-	-	3.7								
D424B	-	-	-	4.1	-	-	-	3.6									
D424F																	
D454A	-	3.4	-	-	-	3.4											

TABLE VI

WET SHELF STORAGE - MEDIUM TERM TEST DATA

Cell No.	AM1, 25°C Efficiency after indicated number of months:																		
	0	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
D436E	5.3	4.3	4.2	4.4	-	4.1	4.1	4.0	4.0	-	4.0	-	-	-	3.7	-	-	-	3.5
D450C	5.3	4.1	3.8	3.8	off														
D454E	5.3	3.5	3.6	3.7	off														
D480B	5.1	4.3	4.1	4.4	-	4.0	4.0	4.0	4.0	-	3.9	-	-	-	3.7	-	-	-	3.6
D495A	5.4	4.5	4.5	4.7	-	4.3	off												
D487C	5.5	4.8	4.7	5.0	-	4.5	4.5	4.5	4.5	-	4.5	-	-	-	4.5	-	-	-	4.3
D476A	5.0	4.5	4.1	4.7	-	4.3	4.3	4.3	4.2	-	4.2	-	-	-	4.1	-	-	-	4.0
D506B	5.7	4.9	-	4.5	4.5	4.5	4.4	4.5	4.3	-	-	-	4.3	-	-	-	4.3		
D509E	5.5	4.4	-	4.0	4.0	3.9	3.8	3.7	3.6	-	-	-	3.7	-	-	-	3.7		
D516A	5.3	4.5	-	4.1	off														
D526C	4.4	4.0	-	4.7	-	-	3.6	3.7	3.6	-	-	-	3.4	-	-	-	3.3		
D554A	5.7	-	4.6	5.2	-	4.6	4.5	4.5	4.5	4.3	-	-	-	4.3	-	-	-	4.3	
D562E	4.7	off																	
N14B8	5.0	-	4.5	5.0	-	4.5	4.5	4.5	4.5	4.4	-	-	-	4.4	-	-	-	4.4	
D580E	5.0	-	3.7	3.6	3.6	3.6	3.6	-	-	-	3.6	-	-	-	3.6				
D585C	5.1	-	4.2	4.1	4.0	4.0	3.8	-	-	-	3.5	-	-	-	3.2				
N17B3	4.8	-	3.6	3.5	3.5	3.4	3.2	-	-	-	3.1	-	-	-	2.8				
D602D	4.6	off																	
D615C	5.3	4.5	4.4	4.3	4.2	4.1	3.8	-	-	4.1	-	-	-	4.1					
N38B7	4.6	4.8	3.6	3.6	3.6	3.6	3.2	-	-	3.1	-	-	-	3.0					
N51B8	5.3	4.2	4.2	4.1	4.0	4.0	3.7	-	-	3.9	-	-	-	3.7					
N52B4	4.9	3.9	3.7	3.7	3.5	3.6	3.3	3.5	3.5	-	-	-	-	3.5					
N59BK7	3.4	3.7	-	3.6	off														

TABLE VII

WET SHELF STORAGE - SHORT TERM TEST DATA

Cell No.	Month Made	AM1, 25°C Efficiency after indicated number of weeks:																
		0	1	2	3	4	8	12	16	20	24	28	32	36	40	44	48	52
N119BK2	Jan.	3.3	3.0	2.9	2.6	2.5	2.4	2.0	off									
N117BK8		4.0	3.9	3.9	3.8	3.8	3.7	3.6		3.6	3.5	3.5	3.5	3.5	3.5	3.5	3.5	
N116CK5		4.0	3.9	3.9	3.8	3.8	3.6		3.5	3.5	3.4	3.3	3.3	3.3	3.3	3.3	3.3	
N115BK8		4.2	4.1	4.1	4.0	4.0	3.9			3.7	3.6	3.5	3.5	3.5	3.6	3.7	3.6	
N127CK4	Feb.	4.3	4.1		4.1	4.1	4.1	4.0		4.0	3.8	3.8	3.8	3.8	3.8	3.8		
N127CK1		4.2	4.0		3.9	3.8	3.8	3.7		3.7	3.6	3.7	3.6	3.6	3.6	3.6		
N127BK6		4.2	4.0		4.0	3.8	3.8	3.8		3.7	3.6	3.7	3.6	3.7	3.7	3.7		
N127BK4		4.1	4.0		3.8	3.8	3.8	3.7		3.7	3.6	3.6	3.6	3.7	3.7	3.7		
N167CK4	March	4.0	4.0			3.8	3.7	3.7	3.7	3.6	3.5	3.5	3.5	3.6	3.5			
N164BK9		3.9	3.8		3.6		3.5	3.5	3.5	3.4	3.4	3.4	3.5	3.5	3.5			
N164BK5		4.0	3.9			3.7	3.7	3.6	3.5	3.5	3.5	3.4	3.5	3.5	3.4			
N161AK1		4.1	3.9			3.3	3.1	3.0	3.0	3.0	3.0	3.0	3.2	3.1	3.1			
N186AK4	April	4.0		3.8		3.8	3.7	3.7	3.6	3.6	3.6	3.7	3.7	3.7				
N185CK8		4.0		3.8		3.7	3.6	3.6	3.5	3.5	3.5	3.6	3.6	3.6				
N185CK4		3.8	3.4			3.5	3.5	3.4	3.4	3.3	3.3	3.4	3.4	3.4				
N172CK4		4.1		4.0		3.9	3.8	3.8	3.7	3.6	3.6	3.6	3.7	3.6				
N199BK4	May	3.9	4.1			3.9		3.8	3.8	3.9	3.9	3.9						
N199AK7		3.8	4.0			3.8	3.7		3.7		3.8		3.7					
N199AK5		3.8	4.1			3.8	3.7		3.7		3.8		3.7					
N198BK2		3.2	3.6			3.3	3.1		3.1		3.1		3.1					
N265CK6	June	4.0	4.0	3.9	3.9	3.9	3.8	3.7	3.7	3.7	3.7							
N265BK7		3.8	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.6	3.6							
N265BK5		4.0	4.1	4.0	3.9	4.0	3.9	3.8	3.8	3.8	3.7							
N265BK4		3.9	3.9	3.7	3.7	3.8	3.6	3.6	3.6	3.6	3.6							
N280AK9	July	3.9	3.8	3.9	3.7	3.8	3.7	3.6	3.7	3.7								
N280AK4		3.7	3.6	3.7	3.6	3.6	3.5	3.5	3.5	3.5								
N280AK2		3.8	3.8	3.8	3.7	3.8	3.7	3.7	3.7	3.7								
N278AK4		3.9	3.8	3.8	3.7	3.8	3.6	3.7	3.7	3.7								

TABLE VII - continued

WET SHELF STORAGE - SHORT TERM TEST DATA

Cell No.	Month Made	AM1, 25°C Efficiency after indicated number of weeks: 0	1	2	3	4	8	12	16	20	24	28	32	36	40	44	48	52
N292AK5	Aug.	4.2	4.0	4.0	4.0	4.0	3.8	3.9	3.9	3.9								
N290BK6		4.2	4.0	4.0	4.0	3.9	3.8	3.9	3.9	3.8								
N290BK3		4.2	4.1	4.2	4.1	4.1	4.0	4.0	4.0	4.0								
N290AK2		4.2	4.0	4.1	4.1	4.0	3.9	4.0	3.9	3.9								
N301CK5	Sept.	3.9	3.7	3.7	3.7	3.7	3.7	3.6										
N301AK9		4.0	3.8	3.8	3.8	3.8	3.8	3.7										
N301AK4		4.0	4.0	4.0	4.0	4.0	4.0	3.9										
N301AK1		4.0	3.8	3.9	3.9	3.9	3.8	3.8										
N314CK1	Oct.	4.0	3.9	3.8	3.8	3.8	3.6											
N313CK9		4.0	4.0	3.9	3.8	3.8	3.7											
N313CK8		4.0	4.0	3.9	3.8	3.8	3.7											
N313BK4		4.0	4.0	3.8	3.8	3.8	3.7											
N329BK9	Nov.	4.2	4.1	4.1	4.0	4.0												
N329BK7		4.3	4.2	4.2	4.2	4.1												
N324BK4		4.4	4.2	4.2	4.2	4.2												
N324AK4		4.5	4.3	4.3	4.3	4.2												
N356CK7	Dec.	4.0	3.8	4.1	4.1	3.6												
N356AK6		4.2	4.2	3.7	3.7	4.1												
N349AK2		4.2	4.1	4.0	4.0	3.8												
N348AK5		4.1	4.0	4.0	4.0	3.8												

maverick behavior, those cells that have been on test for 5 months or more had average annual degradation rates of about 8% and many cells were well under that average.

There appears to be more of a characteristic pattern to the degradation of cells on wet shelf storage than to those on dry shelf storage, though even here there are still many exceptions. In most cases the short circuit current, open circuit voltage and fill factor were all adversely affected. Early experiments with accelerated moisture degradation indicated that true moisture degradation could be completely recovered by a simple vacuum heating as long as secondary structural damage such as a loosened grid contact had not occurred at the same time. Such secondary effects are believed to be unlikely with the present epoxy cemented construction.

It should be possible to determine just how much of the total degradation of each cell that was on this test was due to moisture. In that manner, it should be possible to characterize the intrinsic moisture resistance of the present design cell.

Two cells that had shown appreciable degrees of output loss on wet shelf storage were selected and were baked overnight in a vacuum oven at 135°C and then retested. One of these was Cell D454A which had degraded after 24 months of 80% humidity storage from 5.2 to 3.4% efficiency, and then to 3.3% by the time of the bake out. After the bake out the cell output rose to 3.8%. The before and after I-V curves are presented in Figure 8. It is seen that OCV, SCC and fill all improved with perhaps the OCV showing the most improvement. If the interpretation is correct then, this cell degraded from 5.2% to 3.8% by causes other than the moisture, and from 3.8% to 3.3% by the moisture. Thus the annual rate of moisture degradation was only 4.8%.

The other was Cell N185CK8 which had dropped from 4.0% to 3.6% efficiency in 36 weeks of wet shelf storage, and then to 3.5% by the time of the bake out. After the bake out the cell's efficiency was 3.9%, as shown in Figure 9. Again, OCV and SCC and fill were all affected. The annual rate of moisture degradation for this cell on the same basis would be just over 10%.

There have been recent indications that moisture degradation may not be a uniform effect occurring across the entire area of the cell, but rather that it may be concentrated at the cut edges of the cell where the barrier and CdS and conductive substrate are all exposed. This aspect is discussed in a later section of this report, and some experimental cells with protected edges have been fabricated, and have been placed on wet shelf storage.

CLEVITE CORP.
ELECTRONIC RESEARCH DIVISION
SOLAR BATTERY SECTION

CELL No. D454A
SHEET No. _____ OF _____
AREA= 54.75 cm
AM1 @ 25°C.

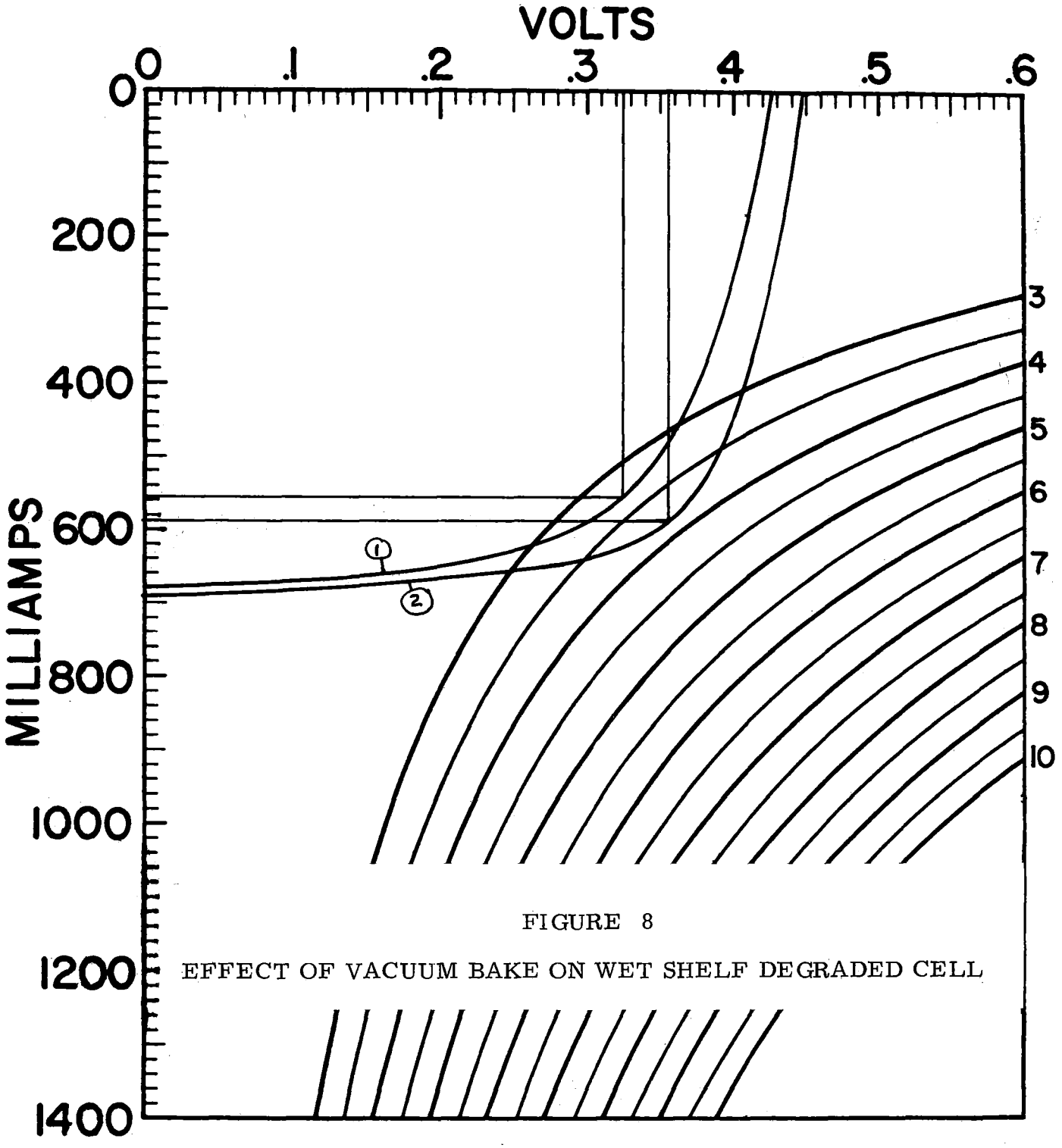


FIGURE 8

EFFECT OF VACUUM BAKE ON WET SHELF DEGRADED CELL

TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1	2-26-69	.427	.680	.324	.557	.180	62.2	3.3	After 24 mos. Wet Shelf Storage
2	2-27-69	.449	.690	.358	.585	.209	67.6	3.8	After 135°C. Vacuum Bake
3									
4									

CLEVITE CORP.
ELECTRONIC RESEARCH DIVISION
SOLAR BATTERY SECTION

CELL No. N185CK8
SHEET No. _____ OF _____
AREA= 54.75 cm
AM 1 @ 25°C.

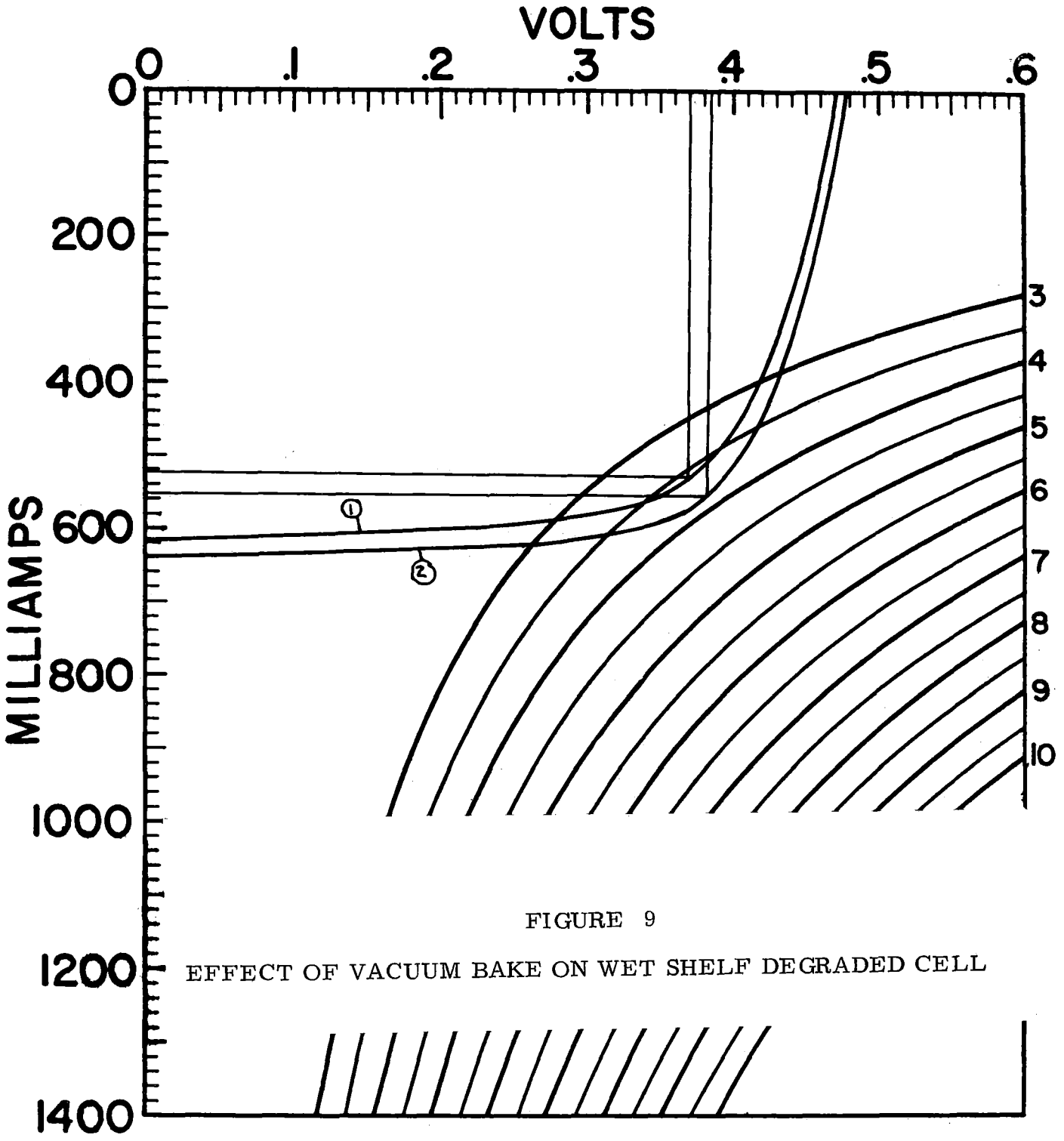


FIGURE 9

EFFECT OF VACUUM BAKE ON WET SHELF DEGRADED CELL

TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1	2-26-69	.470	.618	.370	.520	.193	66.2	3.5	After 36 wks. Wet Shelf Storage
2	2-27-69	.478	.640	.385	.550	.212	69.2	3.9	After 135°C. Vacuum Bake
3									
4									

C. Vacuum Storage at 100°C Temperature

Each month some standard process cells have been selected and placed on storage in a 100°C vacuum oven. The cells have been kept in the dark in the open circuit condition. They have been removed from the oven at regular intervals, tested under standard air mass 1, 25°C test conditions, and then returned to the vacuum oven.

Table VIII contains the longer term test data on cells of 1966 and early 1967 manufacture. Some of the cells from this period failed prematurely from what were believed to be assignable structural causes rather than from the high temperature per se, and these were removed from the test. Of the remaining 15 cells, 4 gave markedly higher degradation rates and thus appear to be atypical. The remaining 11 cells were judged to be representative of the period and their performance is believed to reflect the 100°C vacuum storage condition. The degradation of these 11 cells, calculated on an average basis for the total 18 to 29 month storage period in each case, was 14% per year. This is comparable with the 10% degradation per 8 month period that was calculated for the best 4 cells of this same group a year ago.

If the best 7 cells are selected from Table VIII, the average rate of annual degradation is seen to be just under 10%. Five of the best 7 cells were the latest ones to be made in this group, and this may indicate that the newer cells are of better quality. It may also indicate that the test conditions changed, because in mid-1967 an improved vacuum oven was obtained for this test which permitted a higher vacuum in the 1 to 5 x 10^{-6} Torr range to be achieved in place of the earlier 10^{-4} Torr range.

Table IX presents the 100°C vacuum storage data for cells fabricated in the last year. Excluding 4 cells with unusually high rates of degradation, the remaining 28 cells with 5 months or more of exposure exhibited just 6% average annual degradation on this test. The best 23 cells experienced an average degradation of only 4% per year. This is on a par with the stability of the cells on dry shelf storage at room temperature, and is far better than had been estimated a year ago for 100°C storage. It had earlier been thought that the degradation of cells at 100°C was probably due to diffusion of copper into the CdS thus widening the intrinsic layer and increasing the internal impedance of the cell. This may still be the case but it is evident that it must be a much smaller effect than previously thought. The greater degradations experienced earlier must have been from other causes. Slow oxidation effects from the imperfect vacuum is a likely possibility.

TABLE VIII

100°C VACUUM STORAGE - LONGER TERM TEST DATA

Cell No.	AM1, 25°C Efficiency after indicated number of months storage:																	
	0	10	11	12	13	14	15	16	17	18	19	20	21	22	24	27	28	29
D379E	5.1	4.3	4.3	4.0	3.8	3.7	-	-	3.0	-	-	-	2.6	-	-	-	-	1.4
D388F	4.6	4.2	4.0	3.8	3.9	-	-	3.5	-	-	-	3.3	-	-	-	-	2.9	
D392A	5.0	4.4	4.3	4.1	4.1	-	-	3.6	-	-	-	3.4	-	-	-	-	2.7	
D401F	4.5	3.6	3.5	3.7	4.0	-	-	3.6	-	-	-	3.6	-	-	-	-	2.3	
D407D	4.9	3.7	3.5	3.3	3.5	-	2.7	-	-	-	-	-	-	-	-	2.5		
D438D	5.6	-	4.3	-	-	-	3.9	3.3	3.3	-	-	-	-	-	2.2			
D462E	6.1	-	-	5.1	-	4.5	5.2	4.8	4.7	-	-	-	-	-	4.6			
D504E	5.6	-	-	4.0	4.5	3.9	-	-	-	-	-	-	-	2.5				
D514E	5.3	4.3	3.9	3.4	3.1	3.3	-	-	-	-	-	-	-	1.5				
D554E	5.4	-	4.4	4.5	4.1	4.0	-	-	-	3.7	3.6	3.5						
D579F	5.0	4.3	-	4.2	4.1	4.1	3.8	-	-	-	4.0	4.0	4.0					
H108A4	5.0	-	4.7	5.0	4.7	4.7	-	-	-	4.3	4.4	4.4						
H108A5	5.0	5.0	4.6	4.6	-	-	-	4.3	4.3	4.3								
H108B2	4.9	4.7	4.5	4.5	-	-	-	4.2	4.4	4.3								
H108B5	5.1	5.0	4.8	4.7	-	-	-	4.6	4.7	4.7								

TABLE IX

100°C VACUUM STORAGE - SHORT TERM TEST DATA –

Cell No.	Month Made 1968	AM1, 25°C Efficiency after indicated number of weeks storage: 0	1	2	3	4	8	12	16	20	24	28	32	36	40	44	48	52
N116AK8	Jan.	4.5	4.5	4.6	4.6	4.6	4.6	4.4	4.4	4.5	-	-	4.2	4.2	4.3	4.3	4.4	
N113CK8		4.2	4.2	4.2	4.2	4.2	4.2	4.1	4.1	4.1	-	-	3.7	3.7	3.7	3.6	3.7	
N112AK5		4.2	4.2	4.4	4.3	4.3	4.3	4.2	4.2	4.2	-	-	4.0	4.0	4.0	4.0	4.0	
N111AK2		4.0	4.0	4.0	3.7	3.7	3.7	3.6	3.6	3.3	-	-	2.4	2.4	2.3	2.3	2.5	
N128BK6	Feb.	4.4	4.4	-	4.2	-	4.2	4.1	4.1	4.1	-	-	3.8	3.8	3.8	3.8		
N128BK5		4.8	4.8	-	4.7	-	4.6	4.5	4.5	4.5	-	-	4.0	4.0	3.8	3.8		
N127BK8		4.4	4.1	-	4.5	-	4.5	4.3	4.5	4.5	-	-	4.2	4.3	4.3	4.3		
N127BK2		4.4	4.5	-	4.4	-	4.5	4.2	4.4	4.4	-	-	4.0	4.0	4.0	4.0		
N165BK9	March	3.6	4.2	-	-	4.0	4.0	4.2	-	-	-	4.0	4.1	4.1	4.1			
N164AK2		4.2	4.2	-	-	4.0	4.0	4.1	-	-	-	4.0	4.0	4.0	4.1			
N163BK8		4.1	4.2	-	-	4.0	4.0	4.1	-	-	-	3.9	3.9	3.9	3.9			
N163BK3		4.0	4.1	-	-	3.9	3.8	3.8	-	-	-	3.4	3.4	3.4	3.3			
N187AK5	April	4.2	-	-	4.1	4.1	4.0	-	-	-	4.0	4.0	3.9	3.9				
N186CK5		3.9	-	-	3.8	3.8	4.0	-	-	-	3.7	3.7	3.7	3.7				
N185BK4		4.0	-	-	4.0	4.0	4.0	-	-	-	3.7	3.7	3.5	3.4				
N171BK4		4.0	-	-	3.8	3.8	4.0	-	-	-	3.7	3.6	3.5	3.5				
N202BK6	May	4.1	-	-	-	4.1	-	-	4.0	-	4.0	4.0	4.0					
N200CK9		3.7	-	-	-	3.8	-	-	3.5	-	3.5	3.5	3.5					
N199BK5		4.4	-	-	-	4.5	-	-	4.3	-	4.3	4.3	4.2					
N199AK4		4.1	-	-	-	4.1	-	-	4.0	-	4.0	3.9	3.9					
N265BK1	June	4.0	-	-	-	-	-	4.1	4.1	4.0	4.0							
N264BK7		3.9	-	-	-	-	-	4.0	3.9	3.8	3.8							
N262BK7		4.0	-	-	-	-	-	4.0	4.0	4.0	4.0							
N262BK5		4.0	-	-	-	-	-	4.2	4.0	4.0	3.9							

TABLE IX - continued

100°C VACUUM STORAGE - SHORT TERM TEST DATA

Cell No.	Month Made 1968	AM1, 25°C Efficiency after indicated number of weeks storage: 0	1	2	3	4	8	12	16	20	24	28	32	36	40	44	48	52
N279BK5	July	3.8	-	-	-	-	3.9	3.9	3.8	3.5	3.3							
N278AK7		3.8	-	-	-	-	3.8	3.7	3.7	3.7	3.7							
N278AK5		3.8	-	-	-	-	3.8	3.8	3.8	3.8	3.8							
N278AK1		3.9	-	-	-	-	3.9	3.9	3.8	3.8	3.8							
N290BK7	Aug.	4.3	-	-	-	-	4.3	4.4	4.3	4.3								
N290BK4		4.3	-	-	-	-	4.5	4.5	4.4	4.4								
N290BK1		4.2	-	-	-	-	4.2	4.3	4.1	4.1								
N290AK5		4.3	-	-	-	-	4.5	4.5	4.3	4.3								
N301CK7	Sept.	4.0	4.0	4.0	4.1	4.1	4.0	4.0										
N301CK2		4.1	4.1	4.1	4.2	4.3	4.2	4.2										
N301AK8		4.0	4.0	4.0	4.0	4.0	3.9	3.9										
N330CK2		4.0	4.0	4.0	4.0	4.0	3.9	3.9										
N314CK6	Oct.	4.1	4.2	4.2	4.2	4.2	4.2	4.1										
N314CK5		4.0	4.2	4.1	4.1	4.1	-	4.1										
N313BK7		4.1	4.3	4.3	4.3	4.3	-	4.2										
N309BK5		3.8	3.8	4.2	4.1	4.2	-	4.1										
N330BK7	Nov.	4.5	4.7	4.7	4.7	4.6												
N329BK4		4.4	4.5	4.5	4.5	4.5												
N324CK4		4.3	4.5	4.6	4.5	4.5												
N324BK5		4.3	4.5	4.5	4.4	4.4												
N353AK5	Dec.	4.4	4.5	4.5	4.5	4.4												
N350AK2		4.1	4.2	4.2	4.1	4.2												
N348CK4		4.2	4.3	4.3	4.3	4.3												

D. Thermal Cycling

The inability of the CdS thin film solar cell to hold up under the environmental conditions that would be experienced in a low earth orbit has for several years been the major stumbling block to its acceptance. The early thermal cycling tests of CdS thin film solar cells did not reproduce very well the conditions that would be expected to occur in a low earth orbit. Methods of mounting the thin film cells had to be worked out. Special methods of instrumentation to measure the high currents generated by the large area cells had to be developed. In many cases, it is believed that the test procedures caused stresses to be placed on the cells that would probably not have occurred in actual flight application. At the same time, the early cells were of highly variable quality and most cells tested probably contained one or more weaknesses of construction which caused them to fail prematurely. It was some time before the test procedures evolved to the point where the causes for the erratic cell failures could be established so that corrective actions could be taken.

A year ago, in the Interim Technical Report, the results of a number of different thermal cycling tests by several different organizations were analyzed. It was then concluded that the erratic behavior of CdS thin film solar cells in thermal cycling was probably due to cracks, delaminations, flaws and various nonhomogeneities in cell construction. The mismatch of thermal expansion coefficients of the various layers making up the cell was believed to be the chief contributing factor aggravating the physical faults to the failure point. Much of the basis for that conclusion came from observations of lateral cracks in the CdS layers of degraded cells. These observations were made on micrographs of cross sectioned cells by workers at the Lewis Research Center and the Lincoln Laboratory of MIT, as well as at the Clevite Research Center. It is now clear that those lateral cracks were artifacts of the cross sectioning process and did not exist before the cells were cross sectioned. All parties making the original observations now agree in this respect.

In the last year appreciable improvement has been made in the quality level of the CdS cells, and additional thermal cycling tests have been run under more controlled conditions. A vast improvement in performance of CdS thin film solar cells on these tests has resulted. It is believed also that a better understanding has been achieved of the reasons for the previous erratic behavior.

1. Lincoln Laboratory Test of January 1968 Cells

A group of 4 cells fabricated in January 1968 were tested on the infrared thermograph test and found to be essentially uniform on that test. They were then placed on thermal cycling by the Lincoln Laboratory of MIT. The cycles were of 3 hours duration with 1-1/2 hours at each temperature extreme, and the cells were open circuited when not being measured.

The temperatures ranged from -107°C to -127°C at the cold extreme to between +34°C to +66°C at the hot extreme. One of the cells, due to accidental displacement of a lamp, did not exceed 42°C over the first 80 cycles. It is interesting that this cell showed no degradation of output over the 80 cycles. After this time the position of the lamp was corrected so that the cell temperature reached 51°C, and the cell then started to degrade slightly.

The other cells degraded in output about the same as the December 1967 cells tested earlier. The drop in maximum power for these cells after 87 cycles was respectively to 84%, 72% and 81% of the output obtained during the first cycle.

It was observed during this test that the so-called hysteresis effect that was reported earlier appeared to be an artifact of the measuring technique. The hysteresis effect was noted only when the cells were reverse biased prior to tracing the I-V curve. On later tests the effect was not an artifact and was definitely stronger on degraded cells.

2. Lincoln Laboratory Test of May 1968 Cells

A number of cells that were fabricated in May 1968 were thermally cycled at the Lincoln Laboratory facility with special precautions being taken to keep the cells loaded near the maximum power point between readings. The cells were standard process 3" x 3" size cells with Kapton cover plastic. They had AM1, 25°C efficiencies between 3.3% and 4.3% (or toward the low side of the normal range) and good fill factors between 68 and 71%.

Preliminary data only have been received from Lincoln Laboratory and this is presented in Figure 10. There was a fairly rapid loss of short circuit current over the first 100 cycles and then a much slower loss thereafter. There were 3 cells on this test. Two of the cells showed no loss in open circuit voltage over 700 cycles. These data are comparable with earlier Lewis Research Center and Boeing thermal cycling tests.

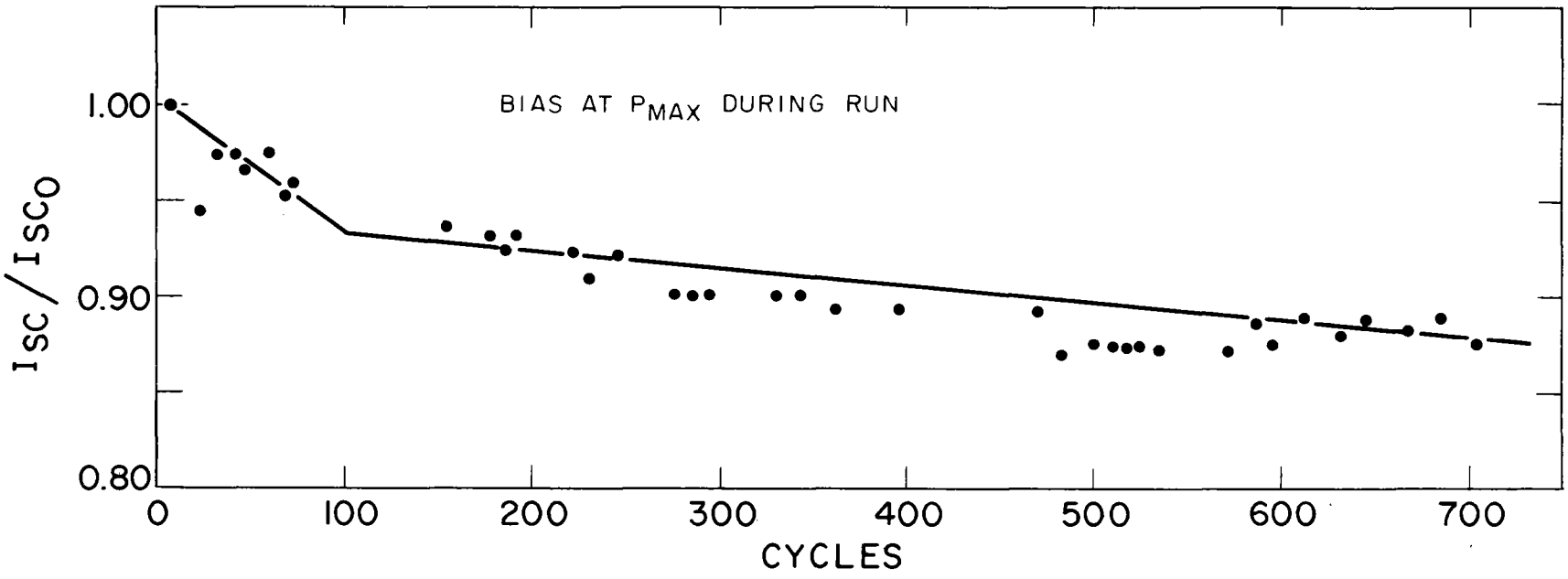


FIG. 10. SHORT CIRCUIT CURRENT DEGRADATION OF LINCOLN LABORATORY THERMALLY CYCLED CELLS.

3. Boeing Company Test of Sept. - Oct. 1967 Cells

For the thermal cycling tests of the Sept.-Oct. 1967 and March 1968 cells, half of the cells were held back as controls and were stored under dry shelf conditions except for periodic measurements. The remainder were mounted in cell holders and placed in a clean vacuum chamber with the pressure below 10^{-6} Torr at all times and with the black walls of the chamber cooled with liquid nitrogen. Each cell was loaded at approximately the maximum power point. A cycle consisted of a 60 minute exposure in simulated air mass 0 light during which period the cell temperatures would rise and level off at about 60 to 70°C, followed by a 30 minute dark period during which the cell temperatures would drop to about -100°C. At selected intervals the resistive load would be removed from each cell and the I-V curve traced and recorded while the cells were at the high end of their temperature excursion.

A group of 7 standard cells fabricated in Sept. and Oct. of 1967 plus 2 copper substrate cells were given a total of 506 cycles on the Boeing facility and then removed from the test and returned to NASA and subsequently to Clevite for analysis. The cells had degraded on this test to between 75 and 88% of their initial power output (except for one of the copper substrate cells which failed catastrophically) as measured by Boeing in situ at temperature during the last cycle. These tests are reported more fully in the Boeing Report dated February 28, 1969 issued as NASA Contractor Report CR-72507. The final test data at Boeing during the last cycle is reproduced in Table X along with the test data on the cells which were returned to Clevite and tested at 25°C after completion of the thermal cycling test.

TABLE X

TEST DATA ON SEPT. - OCT. 1967 CELLS
AFTER BOEING THERMAL CYCLE TEST

Cell No.	Type Cell	Max. Power as % of Initial Power: In Situ at Temp. During Last Cycle	Max. Power as % of Initial Power: At Clevite at 25°C after removal from test
A970B	Copper substrate	77	98
A969D	" "	25	97
NH188AK2	Standard	75	92
NH200AK3	"	88	not available
N89CK7	"	78	71
N90AK5	"	83	83
N90BK4	"	82	91
N90AK1	"	85	not available
N90AK9	"	85	77

It is to be noted that some of the cells when returned to Clevite and tested under standard temperature and illumination conditions were just as low or even lower in output than when tested in situ during the last temperature cycle. This is distinctly different behavior from previous experience on thermally cycled cells showing degradation which cells heretofore had always recovered to within about 2 to 8% of their original power output. The cells that had not recovered their output after this temperature cycling test were carefully examined and in each case a probable cause for this behavior could be assigned. There were several causes found including: short circuited points on the cells, cracked silver Pyre-ML regions which were so severe as to interrupt the current collection by the substrate, and large foreign particles (apparently CdS) trapped under the Kapton cover plastic that might have acted to cause short circuiting. More rigorous inspection and quality control procedures that were installed subsequent to the Sept. - Oct. 1967 period are believed to have eliminated such constructionally flawed cells from being shipped since that time.

4. Boeing Company Test of March 1968 Cells

Starting in March a new screening test for acceptable CdS thin film solar cells was placed into effect. In analyzing the in situ measurements at 60 to 70°C for previous thermal cycling tests, it was noted that some cells gave much poorer performance initially than their 25°C measurements would have led us to expect. It also seemed that these particular cells were among the worst performers as far as stability was concerned. Therefore, starting in March of 1968 all standard cells were tested at both 25°C and 60°C and their I-V curves were compared. It was found that some cells showed a marked drop in fill factor and short circuit current at 60°C compared with the 25°C values, while others had approximately the same fill factor and the same or slightly higher short circuit current. It appeared probable that intrinsically the short circuit current of the CdS solar cell should increase as the temperature is increased from 25°C to 60°C, and that those cells which did not show an increase were faulty in some way. Therefore, starting with the March 1968 cells these were weeded out and rejected. A slight drop in the SCC of up to 20 milliamperes (for a 3" x 3" cell) was permitted, but no more.

Three different groups of cells fabricated in March 1968 were selected and sent to the Boeing Company for thermal cycling. One group had vacuum evaporated gold grids with a standard gold epoxy cemented metal mesh grid overlaid. The second group was fabricated by using a reduced

pressure of 10 psi on the cells during the epoxy setting operations of the gridding and laminating steps. Standard practice uses a 100 psi pressure during these steps. (This group did not meet the new specifications for 60°C vs 25°C current and fill factor levels.) The third group consisted of standard process cells, except that one of the cells had tin plated positive and negative lead tabs in place of the standard gold plating.

In Tables XI and XII are given the 25°C readings taken at AM1 and AMO respectively on the 9 cells which were temperature cycled as measured at Clevite prior to the test. It is interesting to note that cells 1 and 2 with the dual grid system and cells 3, 4 and 5 with low pressure processing all had lower fill factors at AMO than at AM1 while the standard process cells had higher fill factors. At higher light intensity a lower fill factor suggests that the effect of series resistance predominates over the effect of shunt leakage, while a higher fill factor suggests the opposite. The indication is slight in most cases however and these are high quality cells compared with earlier lots. It is also interesting to note that the 3 cells made with lower pressure gridding and laminating gave only 8% more power output at AMO than they did at AM1, whereas the rest of the cells gave from 12 to 18% more power output. The difference was almost entirely due to the relative short circuit current. Why the low pressure gridding and laminating should result in a relative loss of current collection as the light intensity is increased is very puzzling.

At Boeing the cells were given a total of 2031 cycles and then were removed from the test and returned to NASA, Lewis Research Center. The electrical test data taken at Lewis after thermal cycling is given in Table XIII. Comparing these data with those in Table XII it is seen that all of the cells except Cell No. 2 showed a definite loss of efficiency, and all of the cells except Cell No. 2 showed a definite loss in fill factor. All of the cells had higher open circuit voltages after the test than before, and all had lower short circuit currents.

The in situ performance data of these cells are being reported separately by Boeing in much greater detail than is possible here. This group of cells held up better than any other cells which have been tested to date under such rigorous conditions.

No noticeable degradation occurred for about the first couple of hundred cycles, and then a very slight gradual loss of power output was apparent for most of the cells. After about 1000 cycles, Cell No. 1 with

TABLE XI

Air Mass 1, 25°C ELECTRICAL TEST DATA ON MARCH 1968
CELLS PRIOR TO BOEING THERMAL CYCLING

Boeing No.	Clevite Cell No.	Construction	OCV	SCC	Vmp	Imp	M.P.	Fill	Eff.
1	N151CK4	Evap. grid	.464	.662	.370	.595	.220	71.7	4.0
2	N150BK6	" "	.472	.499	.385	.442	.170	72.3	3.1
3	N156AK4	Low pressure	.470	.752	.368	.664	.244	69.1	4.4
4	N156CK2	" "	.477	.684	.377	.600	.226	69.3	4.1
5	N156AK5	" "	.462	.846	.361	.739	.267	68.3	4.9
6	N154BK6	Standard	.460	.758	.360	.670	.241	69.2	4.4
7	N153AK8	"	.459	.765	.359	.671	.241	68.6	4.4
8	N154CK1	"	.465	.699	.370	.581	.215	66.1	3.9
9	N157BK2	Tin plated	.458	.795	.350	.702	.246	67.5	4.5

TABLE XII

Air Mass 0, 25°C ELECTRICAL TEST DATA ON MARCH 1968
CELLS PRIOR TO BOEING THERMAL CYCLING

Boeing No.	Clevite Cell No.	Construction	OCV	SCC	Vmp	Imp	M.P.	Fill	Eff.
1	N151CK4	Evap. grid	.463	.760	.370	.666	.246	70.0	3.2
2	N150BK6	" "	.479	.567	.391	.500	.196	72.0	2.5
3	N156AK4	Low pressure	.473	.815	.374	.707	.264	68.6	3.4
4	N156CK2	" "	.480	.735	.380	.640	.243	68.9	3.2
5	N156AK5	" "	.470	.899	.369	.780	.288	68.1	3.7
6	N154BK6	Standard	.469	.861	.370	.768	.284	70.4	3.7
7	N153AK8	"	.464	.862	.360	.768	.276	69.1	3.6
8	N154CK1	"	.470	.750	.378	.663	.251	71.1	3.3
9	N157BK2	Tin plated	.461	.900	.359	.796	.286	68.9	3.7

TABLE XIII

Air Mass 0, 25°C ELECTRICAL TEST DATA ON MARCH 1968
CELLS AFTER THERMAL CYCLING

Cell No.	Identity	Construction	OCV	SCC	Vmp	Imp	M. P.	Fill	Eff.
1	N151CK4	Evap. grid	.478	.717	.369	.600	.222	64.6	2.9
2	N150BK6	" "	.490	.545	.394	.482	.190	71.1	2.5
3	N156AK4	Low pressure	.487	.762	.370	.660	.244	65.8	3.2
4	N156CK2	" "	.489	.703	.378	.600	.227	66.0	3.0
5	N156AK5	" "	.474	.838	.362	.700	.254	63.8	3.3
6	N154BK6	Standard	.476	.810	.367	.705	.259	67.1	3.4
7	N153AK8	"	.469	.785	.361	.640	.231	63.0	3.0
8	N154CK1	"	.478	.724	.373	.640	.239	69.0	3.1
9	N157BK2	Tin plated tabs	.472	.850	.362	.745	.270	67.2	3.5

Cells tested at NASA, Lewis Research Center.

the dual grid failed catastrophically dropping to about half output and behaving somewhat erratically thereafter. Two of the cells that were processed with the special low pressure conditions became somewhat erratic in output after about 550 cycles and fluctuated as much as ±5% on successive readings.

Cell No. 2 also with the dual grid, held up with almost no loss of output for the entire period. A slight fluctuation from reading to reading is believed to reflect the accuracy of measurement rather than cell fluctuation. All of the rest of the cells showed a very slow gradual drop in output over the period of the test with the final outputs ranging between 83% and 92% of the initial values.

Tables XIV, XV, XVI and XVII present the in situ measurements of the maximum power, open circuit voltage, short circuit current and fill factor respectively of the 9 thermally cycled cells, after various numbers of temperature cycles up to the 1906th cycle. All readings are given as a percentage of the initial reading after correction to correspond to a temperature of 60°C.

After the 1905th cycle, gaseous nitrogen to 1 atmosphere was admitted to the chamber, allowed to stand for 27 hours, and then pumped out. Most of the cells improved slightly after this treatment. The temperature cycling was then resumed, but the test was terminated after 2031 cycles. By the 2031st cycle the cells dropped back to about the same level as on the 1905th cycle - (according to information contained in Boeing Report NASA CR 72507 which was obtained after preparation of this report) or to 49, 96, 86, 90, 84, 87, 84, 92 and 83% of the initial readings respectively.

Closer examination of Tables XIV to XVII shows that the OCV's held up in every case or improved slightly. On the average the OCV was 103% of the initial value, or an average increase of 10 millivolts. The SCC's however decreased on the average to 96% of the initial value, or an average drop of about 30 milliamperes. Greatest change was exhibited in the fill factors. Except for the one experimental cell which failed catastrophically, the fill factors dropped to from 96% to 88% of the initial value, or on the average to 91.5% of the initial fill factor.

As part of this test there were 9 control cells selected at random which were kept on dry shelf storage throughout the period of the thermal cycling test and read periodically. It is interesting that on the average the 9 control cells over the same period of 1906 cycles dropped by nearly 2.5%

Cycle / Cell No.	The maximum powers in this column are given in milliwatts. 0	2	9	16	33	34	44	48	59	62	73	76	77	80	92	95	108	142	143	162
1	190	102	101	103	102	101	99	101	100	98	99	97	101	100	99	100	98	95	100	101
2	156	99	102	103	101	101	99	98	99	102	102	103	103	102	101	101	103	100	102	102
3	206	100	100	100	100	99	99	100	98	100	99	101	100	99	100	99	99	97	99	98
4	198	99	101	101	100	100	100	99	98	99	100	101	101	100	101	101	102	97*	99	99*
5	225	101	100	100	100	98	99	100	99	98	98	97	98	99	96	99	96	96	97	96
6	228	98	102	101	99	97	99	100	99	98	100	98	97	98	96	98	97	95	97	100
7	217	102	100	99	101	101	104	100	101	101	100	100	102	100	101	100	99	97	98	99
8	208	102	101	103	101	103	102	102	102	110	103	102	105	103	102	103	103	101	104	103
9	232	101	100	100	100	101	101	101	100	108	100	100	102	101	100	99	101	99	100	101
Cycle		193	208	209	244	245	320	369	370	433	464	498	499	533	534	553	554	620	652	738
Cell No.																				
1		97	98	97	98	95	97	96	96	96	96	94	93	93	93	93	93	94	91	93
2		101	101	99	99	99	103	102	103	102	100	100	99	103	98	99	97	99	98	98
3		96	96	95	96	93	93	94	92	93	94	93	93	91	92	92	87	92	92	91
4		96	95	97	95	94	94	93	96	89	92	91	94	87	93	90	83	83	94	92
5		97	94	96	95	92	92	92	93	92	92	90	89	89	92	91	93	90	92	87
6		96	97	96	96	93	95	94	94	92	93	93	91	90	93	93	94	91	90	91
7		99	95	97	96	94	94	47	52	78	82	82	81	81	80	84	84	82	82	82
8		101	100	101	100	99	97	98	100	98	97	97	98	97	98	98	97	95	97	97
9		98	97	98	**	102	87	86	88	85	84	85	76	87	87	85	86	86	85	84
Cycle																				
Cell No.		786	887	997	1204	1209	1301	1404	1510	1626	1764	1804	1905	Subtest A	Subtest B	1906				
1		92	90	92	53	62	52	42	54	53	48	53	47	66	76	66				
2		96	98	96	97	92	94	97	96	100	98	95	98	99	101	99				
3		90	92	91	92	89	89	89	88	87	87	85	86	88	90	89				
4		91	93	92	95	93	92	92	92	90	91	87	90	90	92	92				
5		85	86	84	84	84	83	83	82	87	84	82	83	81	83	88				
6		89	86	88	88	86	83	86	85	89	88	85	87	86	85	91				
7		82	85	82	91	85	86	88	87	89	88	84	86	86	85	90				
8		93	93	92	83	92	91	92	91	96	94	90	92	91	94	95				
9		81	81	80	82	80	79	81	83	84	82	78	79	81	85	85				
	* EXHIBITED HYSTERESIS			** NO MEASUREMENT MADE																

TABLE XIV

BOEING THERMAL CYCLING TEST OF MARCH 1968 CELLS - RELATIVE MAX. POWER VS NO. of CYCLES

Cell No. \ Cycle	The open-circuit voltages in this column are given in volts. 0	2	9	16	33	34	44	48	59	62	73	76	77	80	92	95	108	142	143	162
1	.406	100	100	101	101	100	101	101	102	101	102	102	102	102	102	102	102	102	102	103
2	.420	100	100	100	100	100	101	101	101	101	101	102	101	101	101	101	101	102	101	101
3	.413	100	100	100	101	101	101	101	101	101	102	103	102	102	103	102	102	103	102	103
4	.421	100	100	99	99	99	100	99	99	100	100	101	100	101	101	100	101	101*	100	101*
5	.419	100	100	101	101	100	101	101	101	101	101	102	101	102	101	102	101	101	101	102
6	.412	99	99	100	100	101	100	101	101	101	103	102	101	102	101	101	102	102	101	101
7	.416	103	101	101	101	101	104	102	102	102	103	103	103	102	101	103	103	102	102	103
8	.419	101	101	101	100	101	101	101	102	105	102	102	102	102	102	102	103	102	102	102
9	.409	101	100	100	100	101	99	101	101	105	102	102	101	102	103	101	103	102	102	103
Cycle		193	208	209	244	245	320	369	370	433	464	498	499	533	534	553	554	620	652	738
Cell No.																				
1		102	103	102	103	102	102	102	102	103	102	103	103	103	102	102	102	103	103	103
2		101	101	100	100	102	101	101	100	100	100	101	101	103	101	101	101	101	101	102
3		103	103	102	104	101	102	103	100	103	103	104	104	104	103	103	100	104	105	105
4		101	100	100	101	99	101	101	100	100	101	101	102	101	101	101	100	100	102	102
5		104	102	102	102	101	102	102	101	102	101	102	101	102	102	102	102	102	102	103
6		102	103	101	103	101	102	102	101	102	102	103	102	102	101	102	103	102	102	103
7		103	103	10e	104	101	103	90	95	103	103	103	102	103	102	103	103	103	103	104
8		103	102	102	103	101	102	102	102	102	102	103	100	102	103	102	102	102	103	103
9		103	102	101	**	102	100	100	100	100	101	101	93	103	101	101	101	102	102	102
Cycle																				
Cell No.		786	887	997	1204	1209	1301	1404	1510	1626	1764	1804	1905	Subtest A	Subtest B	1906				
1		104	103	103	96	99	93	94	98	98	97	98	98	96	100	100				
2		101	101	101	101	101	101	101	101	101	101	101	101	99	100	102				
3		105	106	105	107	107	108	106	109	104	105	104	105	102	102	107				
4		102	103	102	104	105	105	103	103	100	101	101	103	99	100	102				
5		102	103	103	104	103	104	106	103	104	104	103	104	99	99	104				
6		103	103	103	103	102	102	103	103	103	104	102	104	100	98	103				
7		105	105	104	102	101	103	104	103	103	103	103	104	100	100	103				
8		103	104	103	104	102	103	104	104	104	103	103	104	100	101	103				
9		102	101	102	102	101	102	103	102	103	103	100	102	100	100	102				
	* EXHIBITED HYSTERESIS			** NO MEASUREMENT MADE																

TABLE XV

BOEING THERMAL CYCLING TEST OF MARCH 1963 CELLS

RELATIVE OCV VS NUMBER OF CYCLES

Cycle / Cell No.	The short-circuit currents in this column are given in milliamperes. 0	2	9	16	33	34	44	48	59	62	73	76	77	80	92	95	108	142	143	162
1	727	100	100	100	101	99	99	99	99	99	99	100	99	99	99	99	100	95	100	97
2	549	99	101	101	101	100	99	100	101	101	101	100	99	102	100	101	100	97	101	99
3	773	101	101	101	100	100	99	99	100	99	98	99	99	99	98	99	98	93	99	95
4	726	100	101	102	101	100	100	100	101	102	100	100	100	100	99	103	100	102*	101	101*
5	867	99	100	101	100	99	99	99	99	99	98	98	99	98	98	99	98	94	98	95
6	831	100	100	102	101	100	100	100	101	101	102	101	101	101	99	102	99	95	101	96
7	808	101	99	100	101	99	99	99	100	100	98	98	100	98	101	100	98	94	99	96
8	741	100	98	99	101	100	102	101	101	105	101	101	102	100	101	101	100	96	102	99
9	873	100	100	101	101	101	101	101	101	104	101	101	103	101	100	103	101	96	101	99
Cycle		193	208	209	244	245	320	369	370	433	464	498	499	533	534	553	554	620	652	738
Cell No.																				
1		96	96	98	95	94	99	98	100	97	96	95	96	96	94	95	96	96	94	94
2		99	99	98	98	97	101	102	102	100	100	100	99	99	97	101	99	99	99	98
3		94	95	95	94	96	98	98	99	96	95	95	95	93	93	95	95	94	94	92
4		101	102	103	102	98	98	98	99	98	97	98	97	95	95	96	96	96	96	96
5		94	95	95	94	93	96	95	95	95	94	93	93	92	92	95	95	94	91	89
6		95	96	97	95	96	99	98	99	95	95	95	95	94	96	98	98	97	95	94
7		96	95	94	93	95	94	91	89	87	87	86	87	86	84	87	87	87	87	84
8		98	98	98	97	98	102	98	102	99	96	97	95	95	95	98	97	97	96	94
9		97	96	98	**	98	97	95	98	95	93	95	93	93	95	95	95	95	96	94
Cycle																				
Cell No.		786	887	997	1204	1209	1301	1404	1510	1626	1764	1804	1905	Subtest A	Subtest B	1906				
1		92	93	91	88	89	87	88	89	90	89	88	87	90	93	91				
2		97	99	95	101	97	97	99	100	102	101	99	100	102	105	102				
3		91	92	88	93	92	90	92	92	94	93	93	93	94	98	96				
4		94	95	97	96	94	94	96	94	98	97	96	95	96	98	95				
5		88	89	84	90	90	88	89	89	90	90	89	90	88	91	93				
6		94	90	89	96	94	92	95	94	98	97	96	96	99	101	100				
7		82	87	87	96	94	92	93	92	95	94	92	90	95	96	95				
8		94	93	90	96	95	94	96	94	99	98	96	96	99	101	98				
9		92	93	91	92	93	90	92	90	95	95	91	91	95	97	95				

* EXHIBITED HYSTERESIS ** NO MEASUREMENT MADE

TABLE XVI

BOEING THERMAL CYCLING TEST OF MARCH 1968 CELLS

RELATIVE SCC VS NUMBER OF CYCLES

Cycle / Cell No.	The fill factors in this column are the actual fill factors, in percent, corrected to a temperature of 60°C. 0	2	9	16	38	34	44	48	59	62	73	76	77	80	92	95	108	142	143	162
1	64	102	102	102	102	102	100	102	100	98	98	95	100	98	98	98	97	98	100	102
2	68	100	100	102	100	101	99	97	97	100	100	100	103	97	100	99	101	100	97	101
3	65	99	99	97	99	97	98	98	97	99	99	98	98	98	97	97	97	100	97	100
4	65	99	100	99	100	100	100	100	97	99	100	100	100	98	100	97	100	94*	97	97*
5	62	102	100	99	98	100	100	100	98	99	99	97	98	98	97	98	97	102	98	100
6	67	99	102	99	97	96	97	99	96	96	99	96	94	97	96	94	96	97	94	101
7	65	97	100	105	99	100	100	98	98	99	99	98	98	98	97	97	98	100	97	100
8	67	102	103	103	100	101	100	100	100	99	100	99	101	101	100	100	100	103	101	101
9	65	100	100	100	99	100	100	98	97	99	97	97	97	98	98	95	97	100	97	100
Cycle		193	208	209	244	245	320	369	370	433	464	498	499	533	534	553	554	620	652	738
Cell No.																				
1		100	100	98	102	98	97	97	95	97	98	95	95	94	98	95	95	95	94	97
2		100	100	101	101	100	100	99	100	101	99	99	99	100	99	97	97	97	97	99
3		97	97	97	98	95	92	92	92	94	95	94	94	94	95	92	91	92	92	94
4		94	92	94	92	97	95	94	97	91	94	92	95	91	97	92	86	85	95	94
5		100	97	98	98	98	95	95	97	95	97	95	94	95	97	94	97	94	98	95
6		99	99	97	99	97	94	93	93	94	96	94	93	94	94	93	93	91	93	93
7		98	97	100	98	97	95	66	60	86	91	92	91	91	92	94	94	92	91	94
8		101	100	101	100	99	94	97	96	97	99	97	101	100	100	99	97	96	97	100
9		97	98	98	**	102	89	91	89	89	89	89	88	91	91	89	89	88	86	88
Cycle		786	887	997	1204	1209	1301	1404	1510	1626	1764	1804	1905	[illegible] A	[illegible] B	1906				
Cell No.																				
1		97	94	100	63	70	64	52	63	59	57	63	56	77	83	73				
2		97	99	100	96	94	94	96	96	96	96	94	96	97	97	96				
3		94	94	97	91	91	91	89	88	88	88	85	88	91	89	88				
4		94	95	94	95	95	94	94	94	91	92	89	92	94	95	94				
5		94	94	97	90	90	90	87	89	92	89	89	89	92	92	92				
6		93	93	96	88	88	88	87	88	87	87	85	87	87	85	88				
7		94	94	92	92	89	91	89	91	91	89	89	91	91	88	91				
8		96	96	99	94	94	94	93	93	93	93	91	93	91	93	94				
9		86	86	86	88	86	86	86	89	86	85	86	85	86	88	89				
	* EXHIBITED HYSTERESIS			** NO MEASUREMENT MADE																

TABLE XVII

BOEING THERMAL CYCLING TEST OF MARCH 1968 CELLS

FILL FACTOR VS NUMBER OF CYCLES

in power output. The figures for the control cells are: maximum power 97.6% of initial (range 95 to 99%), OCV to 98.6% (range 97 to 99%), SCC to 99% (range 91 to 101%), and fill factor to 99.4% (98 to 101%).

It is evident that there has been some change in the output of all but one of these cells as a result of the thermal cycling. This change has taken the form of a slight increase in OCV and a slight decrease in SCC and a somewhat greater decrease in the fill factor. This is very reminiscent of the adjustment effect that used to take place on an earlier design cell, prior to the use of epoxy cements, when the pressure grid contact would gradually loosen with time. It is a strong possibility that the present effect is also due to a loosening of the grid contact - though of course to a much lesser extent. It is interesting that Cell No. 2, which had an evaporated gold grid plus a metal mesh overlaid grid, did not show any real change over the 1906 cycles of the test. This would tend to bear out the tentative conclusion that the slight loss of output on thermal cycling of the present cells is due to a very slight loosening of the conductive epoxy cemented grid.

The results of this thermal cycling test are by far the most encouraging obtained to date. The four standard process cells exhibited a 10% loss of output (ranging from 5% to 15%) over the 1900 cycles of this very severe test. The better cells of the type of production that was sampled for this test would probably be satisfactory for many space applications. There is every reason to believe that the establishment of better quality assurance provisions, of the type which are planned for the follow-on effort, will yield an essentially space worthy cell.

E. Constant Illumination at No Load

It had been noted earlier by workers at the Lewis Research Center, and at the Lincoln Laboratory of MIT, that CdS film cells which are illuminated continuously in the open circuit condition undergo a relatively rapid and severe degradation of output. This degradation appears to anneal out if the cells are allowed to rest in the dark and if the degradation has not proceeded too far. However, there are some indications that such recovery may be only temporary and that such cells may be degraded again. At first this effect was considered as merely an interesting but academic phenomenon since the conditions that cause it are not a normal mode of operation for solar cells and since it did appear to anneal out readily. This effect has been studied in the latter portion of this Contract in an effort to understand the mechanism.

The effect was reproduced by mounting the cells on a temperature controlled block (to eliminate complications due to temperature rise) in a vacuum (to eliminate possible complications due to moisture or oxygen) and illuminating them at approximately air mass 1 levels with tungsten iodide lamps. At selected intervals the cells were removed from the chamber and their I-V curves were measured under standard air mass 1, 25°C test conditions.

Several dozen cells have been exposed and tested in this fashion. In most cases severe degradation of power output occurs within a few days. Table XVIII summarizes the experience of a group of 18 cells of different constructions that were exposed to constant illumination at no load for periods of from 29 to 98 hours. The cells were finished to different stages. A total of 12 cells were completely finished and of these 4 had sealed edges. Four cells were gridded but had no cover plastic attached. Two cells were barriered with the subsequent heat treatment but had no grid attached. More detailed electrical test data on the first 4 listed cells of Table VIII are given in Table XIX.

The degradation varied widely from cell to cell, and a few of the cells actually improved slightly. After the test it was noticed that all but one of the degraded cells, and even one of the cells that did not degrade, had small metallic nodules which had grown on the Cu_2S barrier surface. These nodules were about 1 to 2 mils in diameter and about the same height. They were not present prior to the test.

The nodules caused a visible lifting of the cover plastic, and in a few cases of a grid wire. Figure 11 is a photo of the nodules on a part of one cell at two different magnifications. The nodule is the small central portion of the larger circular areas. The light circular region is where the nodule has pushed up the cover plastic causing a void in the package. A nodule grown on a gridded cell that had no cover plastic is shown in Figure 12. Analysis of one of the nodules which was lifted from one of the cells disclosed it to be elemental copper.

Formation of copper nodules on the Cu_2S barrier means that copper must migrate from some other location in the cell. It could come from the copper grid, from excess copper precipitated onto the Cu_2S during barrier formation, or from the Cu_2S lattice. The grid is not in physical contact with the barrier - being separated by the gold epoxy cement and by the gold plating. Thus it seems unlikely that the grid is the source of the copper. It is not known how much copper could be present in the precipitated elemental form, but it

TABLE XVIII

EFFECTS OF CONSTANT ILLUMINATION ON CELLS MOUNTED IN A VACUUM AT 25°C AND MAINTAINED IN THE OCV MODE

Type Cell	Cell No.	Exposure Time (Hrs)	P/Po (%)	Copper Observed	Recovery Attempt	Recovery
Standard	N291CK8	42	112.0	No	None	-
	N292BK4	42	69.4	Yes	None	-
	N293AK1	42	39.0	Yes	None	-
	N294BK5	42	87.5	Yes	None	-
	N314BK4	53	88.4	Yes	None	-
	N314CK2	53	83.2	No	Reverse bias	None
	N314CK4	53	83.4	Yes	Reverse bias	None
	N314CK9	53	94.4	Yes	Reverse bias	None
Sealed edges	N294AK1	29	77.9	Yes	None	-
	N294AK3	29	73.9	Yes	None	-
	N294AK4	29	73.9	Yes	None	-
	N293BK3	29	87.5	Yes	None	-
Partially finished without covers	H742C8	98	58.5	Yes	None	-
	H742C6	98	103.0	Yes	None	-
	H742B9	98	84.5	Yes	None	-
	H743A8	98	116.0	No	None	-
Partially finished without grids and covers	N91C8	98	Not measured	No	-	-
	H273C8	98	Not measured	No	-	-

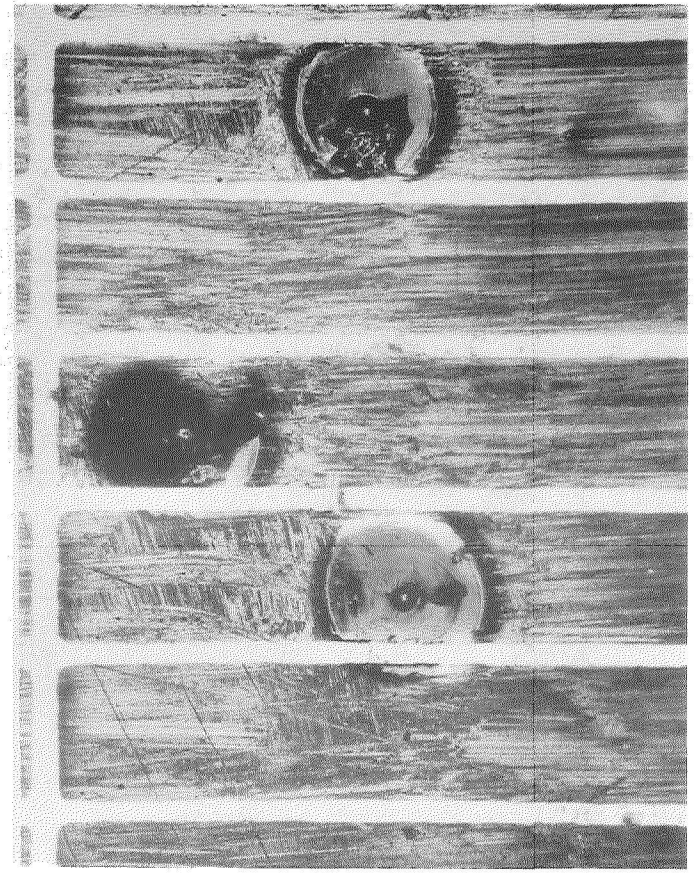
TABLE XIX

CONSTANT ILLUMINATION

STANDARD KAPTON CELLS

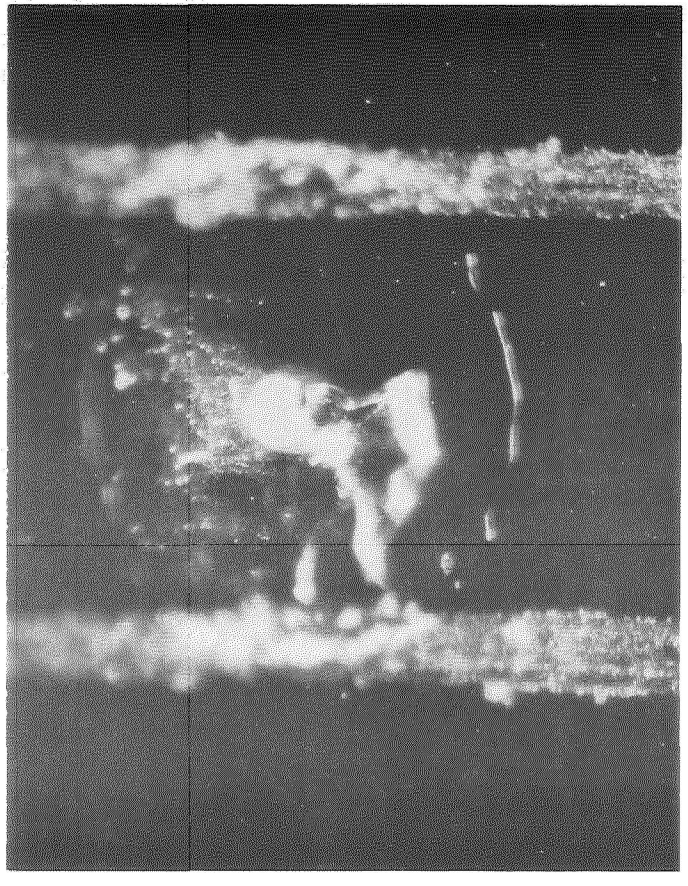
	Original		18 hrs 4 min		42 hrs 40 min	
	Value	Percent	Value	Percent	Value	Percent
N291CK8						
OCV	441	100	439	99.5	445	101
SCC	679	100	700	103.0	739	109
Vmp	340	100	332	97.6	345	101
Imp	585	100	579	99.0	647	110
MaxPwr	199	100	192	96.5	223	112
Fill	66.6	100	62.4	93.5	68.0	102
Eff.	3.6	100	3.5	97.0	4.0	110
N292BK4						
OCV	443	100	438	99.0	423	95.5
SCC	709	100	735	104.0	720	102
Vmp	342	100	336	98.4	322	94.1
Imp	612	100	595	97.3	448	73.4
MaxPwr	209	100	200	95.6	145	69.4
Fill	66.6	100	62.2	93.2	47.5	71.3
Eff.	3.8	100	3.6	95.0	2.6	68.0
N293AK1						
OCV	468	100	450	96.0	395	84.3
SCC	645	100	580	90.0	640	99.3
Vmp	367	100	352	95.8	240	65.4
Imp	554	100	461	83.3	332	60.0
MaxPwr	203	100	162	79.7	79.5	39.0
Fill	67.4	100	62.1	92.2	31.5	46.7
Eff.	3.7	100	2.9	78.5	1.4	38.0

N294BK5	Original		18 hrs 4 min		42 hrs 40 min		After edge trim	
	Value	Percent	Value	Percent	Value	Percent	Value	Percent
OCV	448	100	436	97.3	437	97.5	438	97.9
SCC	799	100	710	89.0	780	97.8	860	107.0
Vmp	348	100	320	92.0	314	90.4	314	90.4
Imp	688	100	501	72.8	542	78.6	667	97.0
MaxPwr	239	100	160	66.9	171	71.5	209	87.5
Fill	66.9	100	51.7	77.4	50.1	74.9	55.5	83.0
Eff.	4.4	100	2.9	66.0	3.1	70.0	3.7	84.0



38X

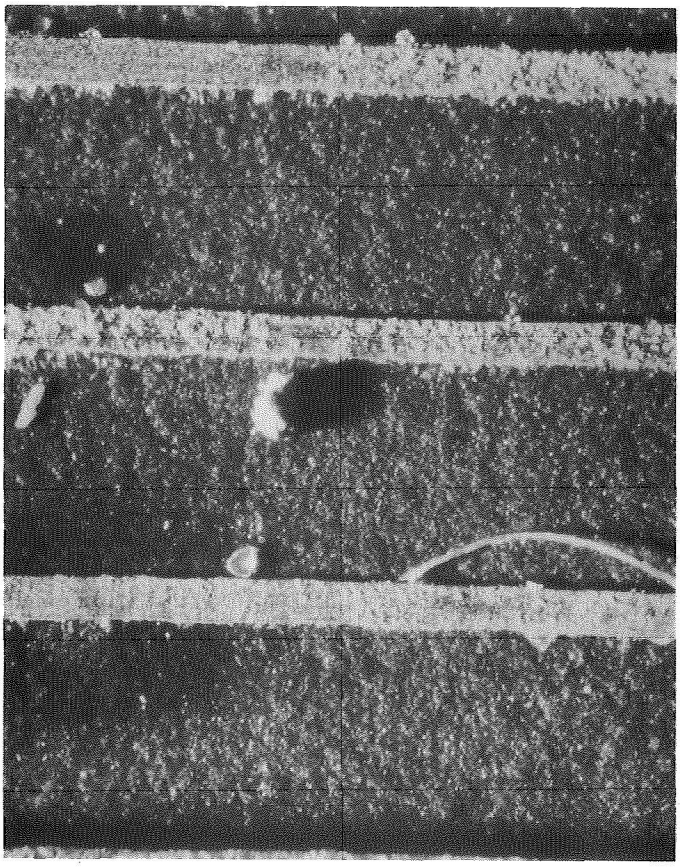
N293AK1



110X

N293AK1

FIGURE 11 Copper Nodules found on the copper sulfide barrier of a standard CdS Solar Cell after Constant Illumination



65X

Cell No. H742B9

FIGURE 12 Copper nodule grown on the copper sulfide barrier of a cell made without cover after constant illumination

seems likely that if there were enough to form the nodules observed that the outputs of the cell would have been very low initially. Therefore, it seems most likely that the copper comes from the Cu_2S lattice.

It is known that Cu_2S has a very strong ionic conductivity at high temperatures. It is presumed that there is some ionic conductivity at room temperature. Copper ions would move in an electric field if that field were above a certain threshold value. The electric field in the Cu_2S barrier region of a cell on open circuit in the light would be such as to move copper ions toward any region that might be even partially shorted to the negative substrate. In the loaded condition the electric field in the cells would be less and the effect would be less and less as the current increased.

It is believed that the very leaky junctions of the present design CdS thin film solar cell are due to numbers of partial short circuits to the substrate, and that these would predispose the cell toward copper plating out of the Cu_2S at such locations if sufficient potential were applied across the cell electrodes. Plating out of copper would decrease the resistance of the short circuit path and the action would continue until the Cu_2S around that locality was essentially depleted of copper. Then the action would probably shift to other localities where partial short circuits existed. The cumulative shunting would result in a lowering of the open circuit voltage, a decrease in fill factor, and eventually a loss of effective cell area. As the degradation of cell output increased, the electric field across the cell would decrease and this would be expected to slow up the rate of degradation.

To verify the tentative conclusion that it is the potential across the cell causing the degradation and not the light, two cells were biased in the dark at 0.45 volts in the forward direction. The I-V curves of these cells were measured at intervals. Both cells degraded rapidly as the test proceeded. The I-V curves for one of these cells at different stages are reproduced in Figure 13. Curve 1 was the I-V curve prior to the test. Curve 2 was taken after 8 hours of forward bias at 0.45 volts in the dark. Curve 3 shows the partial recovery of the cell after resting overnight, and Curve 4 was a retest a few hours later just prior to reverse biasing the cell. Curve 5 was taken after the cell had been reverse biased for 5 hours at 0.465 volts. It is seen that the recovery of the cell was almost complete after reverse biasing. The degradation effect illustrated in Figure 13, and by the data of Table XIX, is clearly that of decreasing shunt resistance.

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SOLAR BATTERY SECTION

CELL No. N301 BK7
SHEET No. _____ OF _____
AREA= 54.75 cm
AM 1 @ 25 °C.

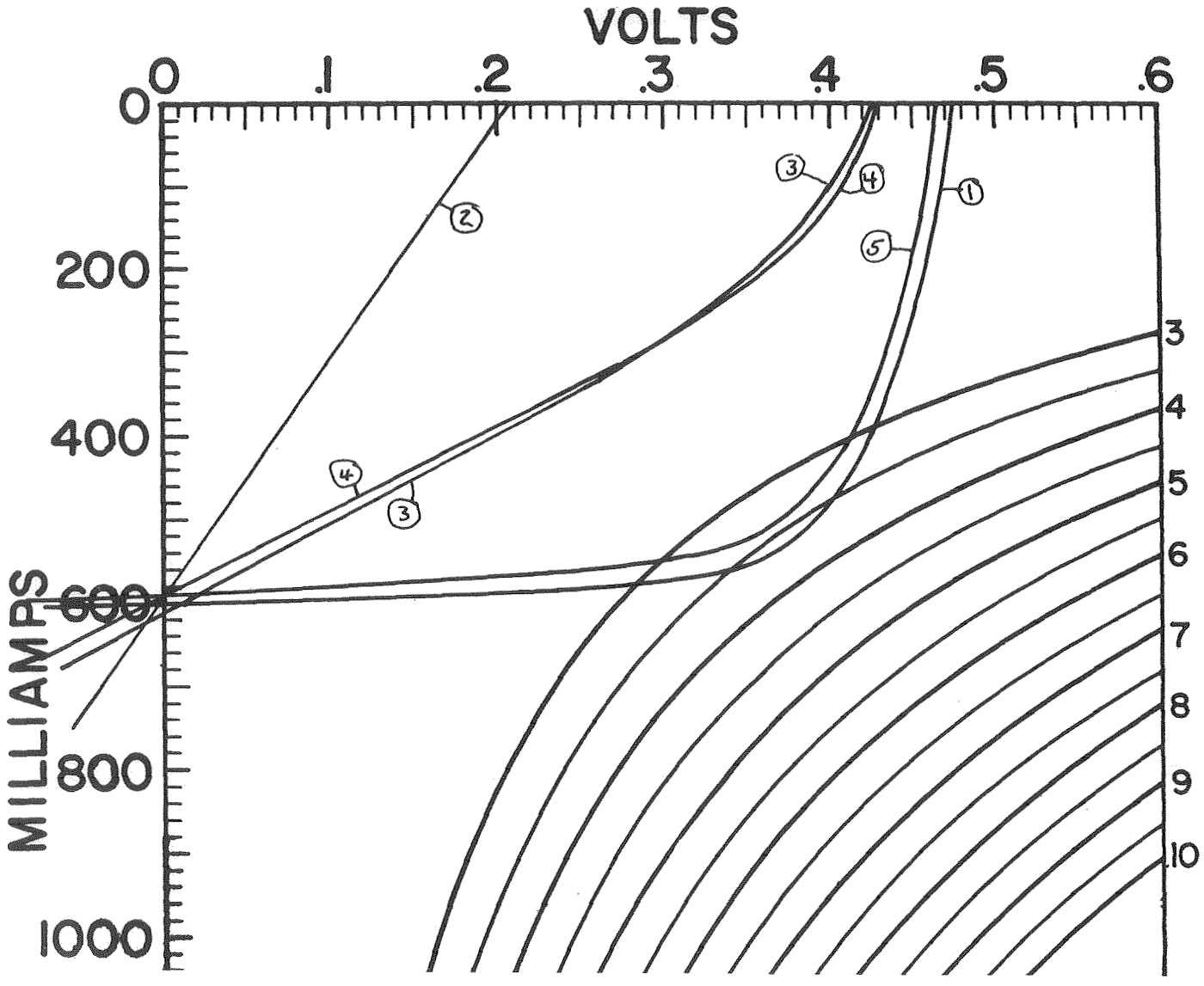

FIGURE 13

EFFECTS OF DRIVING CELL FROM EXTERNAL VOLTAGE SOURCE

TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1	10-22-68	.475	.601	.373	.537	.200	70.2	3.7	PRETEST
2	10-23-68	.209	.590	.100	.311	.031	25.2	0.6	.45 V. FORWARD BIAS - 8 HRS.
3	10-24-68	.423	.600	.269	.311	.084	33.0	1.5	AFTER OVERNIGHT SHELF
4	10-24-68	.430	.600	.318	.234	.074	28.8	1.4	BEFORE REVERSE BIAS
5	10-25-68	.468	.587	.368	.510	.188	68.3	3.4	.465 V REVERSE BIAS - 5 HRS.

It is proposed that the mechanism for the degradation of these cells was the same as for the light degraded cells - even though no copper nodules were observed on these particular cells - and that copper was actually plated out at short circuiting points on these cells. The reverse biasing would effectively back plate the copper and hence remove the degradation.

Since the discovery of these copper nodules during the work of this Contract and the initial investigations of them as described above, more extensive studies have been carried out by H. E. Nastelin and co-workers on Air Force Contract F33615-68-C-1182, by L. R. Shiozawa on Air Force Contract AF33(615)-5224, and by personnel at the Lewis Research Center of NASA. Nastelin has shown that the nodules form whenever a potential on the order of 0.5 or more volts is applied between 2 points of a Cu_2S barrier layer. He has also found that the nodules that occur during actual degradation, when cross sectioned and studied under the microscope, have deep roots that penetrate down open grain boundaries in the CdS layer - in some cases right to the conductive substrate. This has also been demonstrated by Shiozawa by a selective etching technique. Separate more detailed publication of these studies will be made in the reports on the respective Contracts.

Additional studies in conjunction with Lewis Research Center personnel have shown that the nodules cannot usually be made to form by open circuit constant illumination exposure of the better quality cells, but can readily be made to form on poorer quality cells with lower fill factors and poorer shunt leakage characteristics. However, the so-called better quality cells can be made to degrade on open circuit constant illumination exposure.

It is believed that the copper nodule formation is just an extreme manifestation of the degradation of cells on no load constant illumination, and that the cells which do not have visually apparent nodules have probably degraded by the plating of microscopic quantities of copper in smaller grain boundary openings. In the future attempts will be made to secure more physically perfect CdS films and Cu_2S barrier layers to determine if these will indeed be immune to no load constant illumination degradation.

F. Edge Effects

In a group of high efficiency cells which had been kept in a desk for about 6 to 8 months, handled repeatedly, and tested at regular intervals, a few of the cells started losing output and the loss seemed to accelerate with time. The loss was due mostly to deteriorating fill factors, though the

OCV and SCC were also affected slightly. It was puzzling why some of the cells should drop and others hold up when the group of cells appeared at the outset to be very homogeneous with similar electrical characteristics.

One possible explanation for some of the cells losing output might be that moisture or other contamination from the handling was shunting the cells at the cut edges where the Cu_2S barrier layer was exposed. Therefore, a few of the cells which had shown the greatest drop in output were taken and the edges were wiped with an acetone wet tissue. A small but definite improvement in the fill factor and efficiency was noted in every case. Then, the edges of the cells were trimmed with a precision shear so that about 10 to 20 mils were removed from each edge, beyond the margin of the grid. A marked improvement was noted after trimming in each case with the original output being almost completely restored. The sequence is illustrated in the I-V curves of Figure 14.

It is not known whether the degradation at the cut edges of these cells was due to moisture pick-up, contamination (e.g., salt from fingerprints), or oxygen effects, and there was not time for definitive experiments in order to find out. However, the dramatic improvement in cell output from redressing the cell edges has been repeated in a few other instances of cell degradation, and indicates that some form of edge protection is required for individual cells that may be expected to perform on shelf or environmental tests as individual cells. In actual arrays of cells for space flight panels this problem would not exist as the cell edges would undoubtedly be protected by lamination or some other means of mounting into panels.

Two relatively straightforward methods of protecting the cut edges of single cells have been worked out. One of these is to simply cement a narrow "U" - shaped strip of Kapton plastic cover over each edge as illustrated in Figure 15a. The other is to cut the cell to width prior to cover plastic lamination, make the cover plastic slightly wider than normal and fold it over each edge in the lamination step as illustrated in Figure 15b.

Both methods, of course, make the cell somewhat thicker and bulkier, but these techniques would probably not be needed for cells that were going to be used in actual solar panels.

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ELECTRONIC RESEARCH DIVISION
SOLAR BATTERY SECTION

CELL No. H314B4
SHEET No. _____ OF _____
AREA= 54.75 cm
AM1 @ 25°C.

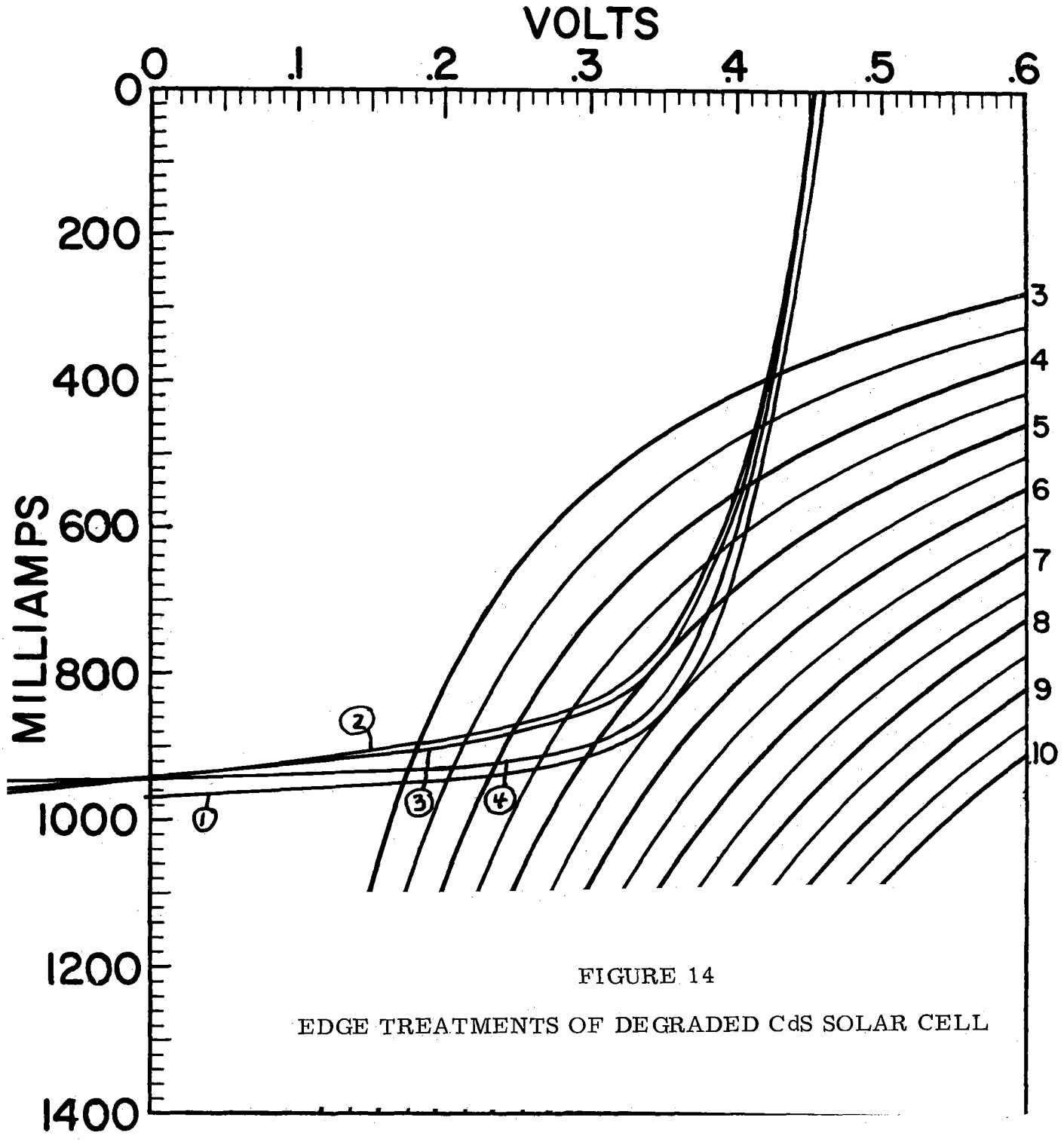
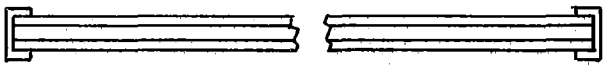


FIGURE 14

EDGE TREATMENTS OF DEGRADED CdS SOLAR CELL

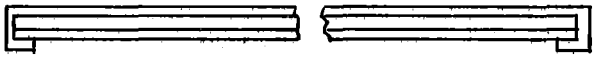
TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1	1-4-68	.461	.964	.351	.848	.298	67.0	5.4	AFTER 2 MOS. LAB. STORAGE
2	7-26-68	.451	.940	.341	.786	.268	63.2	4.9	AFTER 8 MOS. LAB. STORAGE
3	7-26-68	.451	.942	.345	.794	.274	64.5	5.0	AFTER WIPING EDGES
4	7-26-68	.451	.944	.354	.818	.290	68.0	5.3	AFTER TRIMMING EDGES

Fig. 15a



"U" Strip over Cut Edges

Fig. 15b



Cover Plastic folded over edges

FIGURE 15
METHODS OF PROTECTING CUT EDGES OF CELLS

IV CELL DESIGN

A number of changes in the design of the CdS thin film solar cell have been considered, and preliminary studies of some of these have been carried out. A few of these remain as attractive possibilities for yielding a more stable cell, a higher performance level cell and/or a lower cost, more convenient cell to fabricate. However, none of these possible design variations have been carried far enough to warrant their adoption as part of the standard design CdS thin film solar cell. Some of the design variation studies that have been worked on in the present Contract period are discussed in the following sections:

A. Evaporated Grid Contact

The vacuum evaporated grid has the potential advantage of giving an intimately bonded contact to the Cu_2S layer which might be completely free of loosening effects with aging. The vacuum evaporated grid however also has the disadvantage that it cannot be made thick enough to carry the high currents generated in the CdS cell without peeling from the Cu_2S barrier. A combination thin vacuum evaporated grid with a metal mesh overlay as a bus collector grid has the possibility of combining the advantages of the evaporated grid with the low resistance and current carrying capacity of the metal mesh grid.

During this Contract several different lots of cells have been processed with evaporated gold grids, approx. 3000Å thick directly in contact with the Cu_2S barrier layer, plus a standard metal mesh grid cemented on top of the evaporated grid. The first lot consisted of 27 cells, fabricated in March of 1968. Good fill factors of 70% or more were obtained on these cells which is assurance of a good grid contact. However, the current and

power output levels were slightly below normal experience. This was attributed to mis-register of the identical geometry evaporated and metal mesh grid patterns (the metal mesh grid was used as the mask for the resist for the evaporated grid) which resulted in a lower light transmission through the combination grid - and hence lower current and power output.

Four of this first group of cells were sent to the Lewis Research Center of NASA for evaluation on thermal cycling. Detailed data on the performance of these cells have not yet been published, though it is understood that these cells performed as well as any that had been tested to date. Two of the cells were sent to Boeing and were included as Cells 1 and 2 on their thermal cycling tests. As discussed above, Cell No. 1 failed catastrophically, but Cell No. 2 showed essentially no degradation after 1905 cycles. Two of the cells were placed on 150°C vacuum storage test at Clevite. One of these retained full output efficiency for the entire 4 week period of the test - which is the best performance ever obtained in this very severe test - though there was some slight change in the SCC and OCV levels. The other dropped to 72% of its original output after 4 weeks.

Another group of three cells was fabricated later in the Contract period and submitted to NASA for inclusion in the next round of thermal cycling tests. These cells had excellent fill factors but also had lower outputs, due again to the poorer transmission of the dual grid.

The evaporated gold grid-metal mesh overlaid grid combination shows promise of providing the most stable grid contact yet devised. It could yield cells with as much output as the cemented metal mesh grid contact design. However, this process is still far from an acceptable production process and the yields from this method of grid contacting have been very low. There is reason to expect that the techniques for making cells with this dual grid can be improved to the point where yields will be satisfactory and where the costs may approach or even be less than that of the cemented metal mesh grid by itself.

B. Electroplated Grid Contact

Some work has been done with electroplated gold grids using a commercial photo resist mask and state-of-the-art techniques. A number of 3" x 3" size cells were fabricated with these electroplated gold grids but they all had low outputs due to short circuits. The large area cells were subdivided into smaller areas of 1x2cm and a few of these were not shorted.

These were laminated with Mylar cover plastic and positive electrode tabs. However, the best of these was only 4.2% efficient with a fill factor of 62%.

The low outputs appeared to be due to series resistance effects, but this could not have been due to the thickness or current carrying capacity of the electroplated gold grids since these were more than adequate. It seemed more likely at the time that the Cu_2S barrier layer was being damaged by the electroplating process.

It is felt that the electroplated grids have not been given a really satisfactory evaluation, but in view of the initially discouraging results and the lack of resources to expand on this approach, no further work was attempted.

C. Printed Grid Contact

A number of small area cells were fabricated using a printed grid. The ink used was DuPont 7728 conductive epoxy adhesive. It was applied to a thickness of approx. 0.4 mils using a specially prepared stencil. The cells averaged about 3.1% in efficiency with a maximum of 4.0%.

The problem with the printed grid appears to be in securing a fine enough resolution and line spacing to give current collection and light transmission comparable to the metal mesh grid. The method does appear to have some merit, but it seems probable that this grid would be no more stable than the conductive epoxy cemented metal mesh grid.

D. Rhodium Interlayer

Since CdS makes a nonohmic barrier contact to silver, some interlayer between the two has been needed to provide an ohmic contact. Zinc has been used and does provide an excellent low resistance ohmic contact and provides good adhesion of the CdS layer. The zinc does cause problems in processing however. Its vapor pressure is so high that it cannot be used at all when substrate temperatures of 250°C or higher are used, and even at 220°C it causes some difficulty. Further, it alloys with the silver of the conductive substrate to different degrees at different times and probably diffuses into the CdS layer as well to give uncertain properties to the CdS film.

At various times some work has been done to find an alternate material to use as an interlayer between the silver Pyre-ML substrate and the evaporated CdS film. One of the materials that on theoretical grounds should be most attractive is rhodium. Rhodium has been used very

successfully as an ohmic electrode to single crystal CdS, has a very low vapor pressure at temperatures of processing or use of thin film solar cells, and is readily applied by conventional electroplating techniques.

In one group of experiments a total of 18 cells was processed with rhodium interlayers. Plating thickness varied from 500Å to 15,000Å and various plating current densities were used. The electroplated coatings looked very good. However, the outputs of the finished cells were all low with poor fill factors and low open circuit voltages.

In another group of experiments, similar results were obtained. With plating thicknesses of 250 to 1000Å outputs were still low and open circuit voltages were 0.35 to 0.40 volts. When the rhodium thickness was increased to the 1 to 1.5 micron range the results of the cell outputs were even worse. A third lot with thinner coatings were all rejected in processing for zero voltage probes.

Room temperature resistivity measurements were made on a rhodium plated silver Pyre-ML substrate. Resistivity was in the 10^{-5} ohm-cm range, comparable to the standard zinc plated silver Pyre-ML substrate.

Several experiments were conducted to determine if the rhodium interlayer substrate makes an ohmic contact to the CdS film. I-V curves were obtained between an In-Hg amalgam contact on the CdS film and the rhodium plated substrate. The curve, in bright light (about 1 sun) and at low voltages (between -0.1 and +0.1 volt) was linear, indicating an ohmic contact. However, at larger voltages (between -0.4 and +0.4 volts) and in room light, the curve was linear only in a narrow range about the origin (between -0.05 and +0.05 volts) and at larger voltages the curve became nonlinear. The overall curve had the appearance of back-to-back rectifiers. This undoubtedly explains the poor cell performance with the rhodium substrate. Further work with the ohmicity of the rhodium contact is indicated before further cell fabrication experiments.

E. Molybdenum Substrates

The first true thin film flexible solar cells were made on molybdenum metal foil substrates. Molybdenum was chosen at the time because its thermal expansion coefficient closely matched that of CdS. It was believed that this was an essential requirement since fairly thick layers of CdS were needed for successful cells and it was thought that an appreciable mis-match of thermal expansion coefficients would result in poor adhesion.

When techniques were acquired for securing good adhesion of CdS on Kapton plastic substrates, and when cell outputs from such plastic substrates were as good or better than obtained from molybdenum substrate cells, the Kapton substrate was adopted as standard. Weight, flexibility and cost were some of the reasons for choosing the plastic substrate over the metal substrate.

However, it is possible that some of the stability problems with the plastic substrate cell could arise from the considerable strain the CdS film is under with the thermal expansion mis-match between it and the substrate. Therefore, a number of CdS thin film solar cells were fabricated in this Contract period using 1 mil molybdenum substrates and Kapton cover plastic. In Table XX are given the initial outputs of a group that were made which gave results comparable to plastic substrate cells fabricated at the same time.

TABLE XX

OUTPUTS OF MOLYBDENUM SUBSTRATE CELLS

(Tested at 25°C in equivalent AM1 sunlight)

Cell No.	OCV (volts)	SCC (amps)	M. P. (watts)	Fill (%)	Efficiency (%)
N166AK2	.457	.716	.223	68	4.1
N166AK3	.456	.726	.212	64	3.9
N166AK4	.452	.748	.239	71	4.4
N166AK5	.457	.676	.215	70	3.9
N166AK6	.459	.726	.219	66	4.0
N166AK7	.460	.680	.217	70	4.0
N166AK8	.452	.700	.219	69	4.0
N166AK9	.451	.730	.214	65	3.9
N166BK1	.452	.738	.230	69	4.2
N166BK2	.448	.775	.234	67	4.3
N166BK3	.450	.780	.243	69	4.4
N166BK4	.450	.708	.224	70	4.1
N166BK5	.447	.800	.252	70	4.6
N166BK7	.446	.740	.229	69	4.2
N166BK8	.440	.744	.229	70	4.2
N166BK9	.432	.762	.222	67	4.1
N166CK1	.453	.542	.172	70	3.1
N166CK2	.453	.680	.207	67	3.8
Avg.	.451	.721	.221	68	4.0

Ten of the above molybdenum substrate cells were sent to the Lewis Research Center of NASA for evaluation and thermal cycling. Information on the performance of these cells at NASA is not yet available. Two cells were placed on Clevite's high temperature vacuum storage test at 150°C. These gave degradation effects comparable to plastic substrate cells on the same test with the degradation being characterized by loss of fill factor due probably to an increase in series resistance. The remaining cells have been placed on laboratory shelf storage.

F. Tin Plated Electrode Tabs

The gold plated electrode tabs have given good tarnish resistance and make an excellent appearance. They are not completely satisfactory however, especially on the negative electrode tab, since the gold tends to go into solution in the hot melted solder during soldering operations. Also, it is understood that gold can form a crystalline phase layer next to lead-tin solder which under some conditions leads to a greatly weakened bond strength. Thus gold plating is to be avoided where highly reliable solder joints are required.

Therefore, experiments were carried out with a tin-plated electrode in place of the gold. Tin has good tarnish resistance also, and of course is readily soldered. The tin was applied by standard brush plating techniques over a brush plated copper flash coating. There was no difficulty in fabricating cells with the tin plated tabs, nor is any difficulty foreseen in production.

Cell outputs and cell yields do not seem to be affected nor is there any reason that they should be. A total of 27 full size standard cells were fabricated with tin plated negative and positive electrode tabs and submitted to the Lewis Research Center of NASA for evaluation. One of these was included in the Boeing thermal cycling tests described earlier in this report.

From the NASA point of view these cells appeared to be equivalent in all respects to the cells with gold plated tabs, but there appeared to them to be no reason for switching the standard construction to the tin plating at this time.

G. Alternate Pigments in Substrate Conductive Layer

Several alternate pigments have been evaluated in place of silver in the silver Pyre-ML conductive layer on the Kapton substrate. Aluminum was evaluated since it could make an ohmic contact to CdS and

thus eliminate the need for an interlayer, and also would be a good conductor and more economical than silver. Copper was tried also, since solid copper substrates had previously yielded very high efficiency cells. In both cases flake shaped pigment particles were obtained and evaluated.

The copper flake pigment appeared to catalyze the Pyre-ML resin binder and cause it to start curing too soon - even in the spray gun. DuPont confirms that a copper pigment would have this effect and advises that it not be used.

The aluminum flake pigment caused no difficulty with curing of the resin, but unfortunately gave very high resistance coatings. This is due presumably to the oxide coating on the aluminum flake particles making low resistance contacts between particles most difficult. A similar experience was reported by DuPont.

A silver plated copper powder pigment was received from the Burgess Battery Company and evaluated as a possible lower cost pigment for the conductive substrate coating. This powder was not of the flake variety and settled out of the Pyre-ML very quickly, thus complicating the task of spraying the Kapton substrates. However, there was no catalytic action of the silver plated copper powder on the Pyre-ML resin as there was found to be with the unplated copper pigment. Thus, there is some hope that a silver plated copper flake pigment might be suitable.

V FABRICATION PROCESS IMPROVEMENTS

A. Substrate Preparation

1. Spray Process Changes

Infrared thermographs as well as visual observation have disclosed wide variations in the evenness of the silver Pyre-ML layer which forms the conductive substrate. These variations have been well associated with unevenness of application during the spray process. Several changes were introduced, therefore, in the spray process to reduce these effects. A guide was designed and installed in the spray hood to ensure constant distance from the spray nozzle to the substrate and to ensure even traverse of the spray pattern across the substrate. A timer was installed to pace the operator and thus to control the rate of traverse.

These steps have given markedly more uniform substrates and have also resulted in lower sheet resistances without any change in

the composition or thickness of the conductive layer. Sheet resistance of the silver Pyre-ML layer has been decreased to less than 0.01 ohms per square in most cases.

In the regular silver Pyre-ML spray process it has been found that the removal of the D.M.F. solvent prior to curing of the Pyre-ML is very critical. Slight variations in the process frequently can lead to incomplete solvent removal and to poor adherence. The conditions necessary to ensure complete solvent removal are being studied in greater detail.

2. Control of Silver Pigment Quality

Difficulties with pinholes in the silver Pyre-ML conductive layer on the Kapton substrate, and with poor spraying conditions of the thinned mixture, have caused much scrap at various times and poor quality cells. One of the causes of the difficulties has been found to be unusually high levels of iron contamination in the silver flake pigment. Iron particles cause discontinuities in the cured silver Pyre-ML layer and irregularities in the zinc plating.

As a result it has been necessary to remove iron contamination from the silver flake pigment prior to use. This is done by one or more passes through a magnetic separator.

3. Alternate Silver Pyre-ML Material

A preliminary trial has been carried out of DuPont's 449-6291R Silver Pyre-ML conductive varnish as an alternate material for the conductive layer on our substrate. It was applied to Kapton substrates by spraying, using the thinners recommended by the manufacturer.

The coatings had excellent appearance, and resistivities about one third the level obtained with the present standard process silver Pyre-ML coating. These coatings could be soldered readily without the use of additional electroplated coatings as are needed at present. However, the adherence of this coating was not satisfactory. The coatings would not pass the Scotch tape test. This may be due to the thinner used, as similar thinners used with our present standard coating material also yielded poor adhesion. Further consultations with the supplier and additional evaluations of this material are indicated.

4. Roll-Coated Silver Pyre-ML Coatings

Cells have been fabricated from Kapton substrates which were coated with silver Pyre-ML applied by an outside vendor by a

conventional roll coating process in place of the standard process where this coating is applied by spraying. Unfortunately, the resistivities of the roll-coated substrates were very much higher than normally experienced. These ran between 0.05 and 0.06 ohms/square, as compared with about 0.008 ohms/square via the standard process.

The higher resistance resulted partly from a thinner coating and partly from less silver pigment being incorporated in these roll-coated samples, as evidenced by a much lower optical density. It seems probable that much of the silver pigment settled out of the varnish in the vendor's roll coating equipment. However, the samples did exhibit a far more homogeneous and even appearance than any substrates that have been seen in this laboratory so far, and the thin pigment condition can probably be corrected on subsequent trials.

A number of cells that were successfully fabricated gave outputs comparable to the control cells - in spite of the much higher sheet resistance of the roll-coated substrates. The data on these are presented in Table XXI. The fill factors on all of these cells were low. This was probably partly because of the higher resistance of the substrates - but also partly due to copper precipitation during barrier formation (at flaws in the CdS films) that was experienced during this experiment.

From these data there is reason to hope that the roll-coating process can be developed to yield a much more satisfactory substrate than the present spray process.

TABLE XXI

ROLL-COATED VS SPRAYED SILVER PYRE-ML SUBSTRATE CELLS

(Tested at 25°C in equivalent AM1 Sunlight)

Cell No.	Process	OCV	SCC	Vmp	Imp	Max. Pwr.	% Fill	% Eff.
H873B1	roll-coated	.452	.990	.330	.810	.268	59.9	4.9
H873A2	"	.468	1.030	.345	.865	.298	62.0	5.5
H873B2	"	.458	1.020	.333	.858	.286	61.3	5.2
H874B2	"	.458	1.055	.315	.838	.266	55.1	4.9
H873C1	sprayed	.455	.938	.352	.760	.268	63.0	4.9
H873C2	"	.452	.970	.349	.810	.282	64.3	5.2
H873C3	"	.460	.820	.358	.630	.226	59.9	4.1

B. Grid Contacting

1. Grid Quality Problems

The photochemically etched copper metal mesh grid is an essential component of the present high efficiency CdS thin film solar cell. The design of the grid originally was such that the average grid wire width was 0.001" with 60 such wires per inch yielding an overall transmission of 91%. The process for making this grid involves the use of a photo resist which is removed by loosening in a solvent and brushing from the grid wires. In production this has resulted in many broken grid wires which detract from the appearance of the cells.

In order to obtain better yields of usable grids and to keep the cost of these grids from becoming prohibitively expensive, it was necessary to open the specifications of the grid wire width to an average of 0.0020". This had the effect of dropping light transmission to the range of 82 - 85%, with of course a comparable loss of output from the cells.

A number of firms active in the field of photochemical etching were contacted in an effort to obtain a second source of supply for this critical item and in hopes of obtaining a higher quality grid at a more economical price level. Encouraging responses have been obtained in several cases and some evaluations of grids from two additional vendors have been carried out in this period. Initially, the same photographic masters and the same rolled copper foil were supplied to these possible alternate vendors in order to obtain grids that could be directly compared with those from the present vendor.

These evaluations are continuing. In one case, the grids are yielding light transmission of 86 - 87%. In the other case, the transmissions have been running as high as 89%. Since the grids are made from the same photographic master in each case, there must be differences in the etching process for the different manufacturers with more undercutting of the photo resist mask to give higher transmission.

The standard fabrication process uses photochemically etched copper grids obtained from one vendor. These grids are inspected when received for cleanliness, thickness, light transmission, and freedom from broken wires and are then given a cleaning and gold plating in our laboratory. This tends to be a wasteful process because the grids may tarnish or become contaminated by handling, etc. between the time they are etched by the manufacturer and gold plated in our laboratory.

The purpose of the gold plating is as an extra precaution against bare copper coming into contact with the Cu_2S barrier layer if the gold epoxy cement should be thin or locally not present during the gridding step. It was realized that the grids are essentially clean when they are removed from the etching process, and that this would be the ideal time to apply the gold plating before they could become oxidized, stained or otherwise contaminated.

The manufacturer has been willing to do this operation for us, at costs below what could be done here - even without the poorer yields that are obtained by us. Therefore, a quantity of these grids were obtained from the vendor already gold plated by him to the same thickness specifications and done by the same plating conditions, baths, etc. as per our standard practice.

These grids were inspected on receipt and were found to be definitely of better all-round quality than the normal unplated grids. The gold plating probably does protect the grids during shipment, and probably does go on more uniformly on freshly etched grids. Therefore, arrangements have been made to have the gold plating of the grids done by the vendor who fabricates them.

2. Alternate Conductive Cements

In an effort to obtain a more economical, and possibly a higher quality, conductive gold epoxy cement for grid attachment, a number of vendors were solicited and several different cements were obtained for evaluation. DuPont submitted two samples for testing and the results of cells fabricated with these cements are given in Table XXII.

Best results were obtained with DuPont's 7728 adhesive, though an initial test of this cement on a glass slide had appreciably poorer adhesion than the present standard process gold-epoxy cement. The cells listed in Table XXII were all finished with Mylar cover plastics. The cell outputs were all lower than they should have been - including the standard process cells used as controls. Also, the scatter of the data was disappointingly large. However, the DuPont 7728 clearly gave cells with higher open circuit voltages, higher fill factors and higher efficiencies.

TABLE XXII

EVALUATION OF DuPONT GOLD-EPOXY GRID CEMENTS

(Tested at 25°C in equivalent AM1 Sunlight)

Cement	Cell No.	OCV	SCC	Fill	Eff.	Remarks
DuPont 7728	N263A1	.459	.706	70.8	4.2	Grid ok
	N263A2	.450	.740	69.3	4.2	Grid ok
	N267B1	.460	.840	70.1	4.9	Grid ok
	N267B2	.461	.819	68.9	4.7	Grid ok
	N267C1	.440	.738	66.0	3.9	Grid ok
	N267C2	.443	.780	67.5	4.3	Grid ok
	Avg	.452	.770	68.7	4.4	
DuPont 5780	N264B1	.453	.801	70.3	4.7	Gold smeared
	N264B2	.440	.640	71.1	3.7	Gold smeared
	N267A5	.435	.635	70.0	3.5	Gold smeared
	N267B4	.450	.782	70.7	4.5	Gold smeared
	N267B8	.440	.719	66.5	3.8	Gold smeared
	N267C4	.439	.880	67.0	4.7	Gold smeared
	Avg	.443	.743	69.3	4.2	
Standard	N267B5	.441	.835	66.8	4.5	Grid ok
	N267B6	.449	.809	66.2	4.4	Grid ok
	N267B9	.438	.742	65.6	3.9	Grid ok
	N267C3	.458	.780	60.6	4.0	Grid ok
	N267C5	.430	.862	58.0	4.0	Grid ok
	Avg	.443	.806	63.4	4.2	

This cement has a finer sized gold pigment and this may make it less likely to be pressed through the Cu_2S layer during gridding to cause shunting paths - if this is indeed what does occur with the present material. Also, the 7728 cement is quite a lot lower in cost. A larger scale trial of this cement is indicated from these data - particularly at such time as the standard process is yielding what has come to be considered more representative results.

Table XXIII gives the results of two other gold cements that were obtained. Both Epoxy Technology Company's #441 gold epoxy cement and Dynaloy Company's #412 gold epoxy cement gave cells of definitely inferior quality to the present standard process material, though it is not clear that this was the fault of the cements. These materials clearly did give lower output cells, and it is evident that considerable further effort would be required before either of these materials could be used in lieu of the present cement.

TABLE XXIII

EVALUATION OF OTHER CONDUCTIVE EPOXY CEMENTS

(Tested at 25°C in equivalent AM1 Sunlight)

Cement	Cell No.	OCV	SCC	Fill	Eff.	Remarks
Epoxy Tech. #441	N285AK5	.450	.640	66.0	3.5	Voids
	N285BK4	.417	.660	-	3.1	Voids
	N285BK5	.410	.683	65.0	3.3	Voids
	N285CK1	.451	.586	-	3.0	Voids
	N285CK4	.450	.579	-	3.0	Voids
	N286CK2	.454	.646	-	3.2	Voids
	Avg	.439	.632	-	3.2	
Dynaloy #412	N285AK7	.443	.600	68.7	3.3	
	N285AK8	.439	.560	-	3.1	Voids
	N285BK6	.410	.595	-	3.0	
	N285CK5	.440	.598	-	3.2	Voids
	N286CK5	.449	.619	69.0	3.5	
	N286CK7	-	shorted	-	-	Voids
	Avg	.436	.584	-	3.2	
Standard	N285BK7	.427	.712	65.9	3.7	ok
	N285BK8	.420	.783	66.4	4.0	ok
	N286CK1	.456	.674	68.9	3.9	ok
	N285CK2	.450	.681	70.1	3.9	ok
	N285CK6	.458	.661	69.2	3.8	ok
	N286CK8	.443	.701	67.4	3.8	ok
	Avg	.442	.702	68.0	3.8	

3. Fluorescent Dye in Gold Epoxy Cement

More extended trials have been carried out using a fluorescent dye mixed into the gold epoxy cement used as a grid adhesive. The purpose of the dye is to facilitate inspection of the coated grids to ensure complete coverage and a more reliable grid contact.

Though this is a difficult matter to prove, the dye is believed to give better control over the adhesive coating on the grids and has reduced the time required to exercise adequate control over this important step in the fabrication process. There has been no indication of any deleterious effects from the use of the dye.

4. Low Pressure Gridding and Lamination

During the standard process for gridding, the grid with the gold epoxy cement applied to one surface is pressed down against the Cu_2S barrier layer by an aluminum foil diaphragm using tank nitrogen gas at 100 psi

pressure on the top of the diaphragm and evacuating the under side. This pressure had been shown by workers at the Lewis Research Center to cause noticeable distortion of the polycrystalline CdS layer. It has been suspected as a cause of poor shunt characteristics of the finished cells. Similar pressure is applied to the cover plastic during application of the cover plastic and curing of the clear epoxy cement.

Considerable effort therefore was expended in attempting to fabricate cells with greatly reduced pressure during the gridding and laminating steps. A pressure of 10 psi (gauge) was selected as a reasonable pressure that should be adequate to hold the grid (and cover plastic) firmly in place during curing of the cement, and yet might not damage the cells - if indeed the 100 psi pressure was damaging the cells.

It was found that at the lower pressure a large number of voids were obtained in the cover plastic cement. Therefore a much thicker epoxy layer had to be applied to the cover plastic. However, other difficulties were then encountered, and apparently the lower pressure did not yield a low resistance contact between the grid and the Cu_2S layer. Most of the cells fabricated in this manner had short circuit currents, fill factors and efficiencies appreciably below standard practice.

Destructive examination of some of these cells disclosed a layer of insulating epoxy cement between the grids and the conductive gold epoxy cement. It is not known whether this resulted from the 10 psi pressure being inadequate to hold the grid down against the cell thus making it easier for the clear epoxy cement to work in between during the cover plastic lamination step, or whether in trying to eliminate the voids too thick a layer of clear epoxy cement was used. In any case, it is evident that a more extensive period of process parameter optimization would be needed before it could be ascertained whether the low pressure gridding and lamination processes were practical for standard fabrication.

A total of 9 of the better cells processed with the low pressure gridding and laminating steps were forwarded to NASA for evaluation and thermal cycling. As noted earlier, 3 of these were temperature cycled by Boeing and definitely gave results that were inferior to the standard higher pressure gridding and lamination. Additional tests were run at the Lewis Research Center of NASA and these results are in process of publication.

C. Cover Plastic Lamination

1. Adhesive Thickness Control

As became evident during the experiments on low pressure gridding and laminating discussed above, the control of thickness of the clear epoxy cement used for cover plastic attachment can be critical. It has become increasingly evident that this item is one of the most important factors affecting the variability of cell outputs.

The cover plastic normally is coated with the clear epoxy cement by roll-coating by an outside vendor who specializes in this type of work. (The epoxy is in the B-stage form - that is, it dries tack-free and is cured by the use of high temperatures.) After inspection in our plant the coated cover plastic is sent out to another vendor where it is cut into individual pieces of the right size for single cells. The incoming inspection of the adhesive coated Kapton rolls has been confined to the accessible ends.

In view of the critical nature of the adhesive thickness - it is beginning to appear that a variation of not more than ±0.00005" can be tolerated - a much more rigorous sampling and quality control procedure is required. Present practice involves extensive sampling on a destructive basis of the adhesive thickness of small batches of individual cell-sized pieces of cover plastic, combined with 100% inspection where indicated. The control process is further complicated by the fact that the Kapton plastic film thickness itself varies by more than the allowable variation of the adhesive thickness. The present methods leave much to be desired, and better techniques are necessary.

2. Silicone Cover Plastic Adhesive

A one mil thick Kapton tape was secured with a soft flexible silicone adhesive. The adhesive was 3 mils thick. Experiments were carried out in applying this material as the cover plastic of gridded cells. After some trials, methods of applying this tape to cells were evolved which gave good void-free and bubble-free packages. This cover plastic can be applied very readily to CdS cells. However, it does not provide a strongly adherent bond of the cover plastic comparable to what is obtained with the epoxy adhesive.

Cells with this silicone adhesive cover plastic attachment were fabricated for shelf storage, moisture tests and other tests to determine whether the design is promising enough to run thermal cycling

tests, but no data are yet available.

3. Alternate Cover Plastic - Adhesive Combinations

A "Plasticmaster" Roller Laminator was purchased in order to evaluate the possible use of commercial lamination techniques and plastic-adhesive combinations. Several different cover plastic and cover plastic adhesives were evaluated using this equipment. The temperature of the lamination was held at about 200°C in each case. Table XXIV lists the combinations tried.

TABLE XXIV

EVALUATION OF VARIOUS MATERIALS ON ROLLER LAMINATOR

Type of Material	Adherence	Voids
Kapton 7361 Tape with Silicone Adhesive	Good	None
Kapton 7361 Tape with Silicone Adhesive and Primed Surface	Good	None
Mylar with "Permalam" Adhesive	Poor	None
Kapton Film with "B" Staged Epoxy Adhesive	None	Poor

The Kapton Mystic #7361 tape was 1 mil thick Kapton with 1 mil thick silicone resin adhesive. It was 3 inches wide and was tried using various backing sheets for the lamination including Teflon, cardboard, Mylar and Kapton. All of these gave good appearing laminations with little or no evidence of voids. However, the finished structures had little mechanical integrity and the Kapton tape would separate from the cells with a moderate shearing or peeling force in each case. The use of a primer on the gridded cell surface prior to application of the silicone adhesive coated Kapton tape did not improve this. The finished cells curled badly, since the silicone cover plastic adhesive does not exert a force to counterbalance the stresses of the thermal expansion mismatch between the CdS layer and the substrate.

The Mylar plastic with the thermoplastic "Permalam" adhesive gave very poor laminations as the adhesive apparently did not wet the cell surface and hence provided no adhesion. It may be that a different time-temperature combination might be practical with this material, but this did not evolve from the preliminary trials.

The Kapton plastic with the "B" staged epoxy adhesive gave the least acceptable package of all. This is the present material system and it is evident that the present 10 minute dwell time at temperature under pressure is essential to secure adherence. This much time is hardly practical with the roller laminator. When this combination was cured in the

vacuum oven overnight, the adherence of the cover plastic was improved, but of course the voids remained.

The roller laminator is an attractive method for laminating large numbers of cells in production on a continuous basis. It is possible and even probable that different adhesives such as RTV silicones which will harden with time, or more viscous epoxies which will wet the cell surface and hold the package together until curing can be accomplished, will make this a practical production method. However, this appears to require more effort than can be presently spared, and hence further work on this technique is being postponed until a more favorable time.

4. Silicone Cover Plastic

Several samples of optical grade silicone rubbers were obtained from the Dow Corning Company and evaluated as possible cover plastics for CdS thin film solar cells. The samples were: XR-63-489, XR-63-488, XR-61-043-A, and XR-61-049. A primer, XR-63-466, was also obtained. All four rubbers had exceptional optical clarity. They were readily applied with a paint brush; they levelled easily and cured well to an even thickness coating.

Any one of these materials, if successful, would have the advantage of having the cover plastic act as its own adhesive so that only a single material layer would be needed. However, only poor adherence could be obtained from all four samples - even with the use of the primer. Severe cell curling resulted in all cases and it was evident that these silicone rubbers were not practical for this application.

5. Curing of Epoxy Cements

The gridding and laminating steps each consist of a short (10 to 20 minute) heating of the cells in a press to a temperature of 196°C, followed by an overnight (18 hours) annealing in a vacuum oven at 135°C to complete the cure. Difficulties have been experienced at times with overheating of the oven or with leakage of air into the oven. If the temperature does go too high (due to a relay sticking, for instance) then the output of the cells is usually reduced, and if a bad overshoot of temperature occurs, an entire day's production may be lost. Similarly, if the partial pressure of oxygen in the oven rises too high, the cell outputs suffer.

It has not been practical to characterize the effects of too much temperature exposure or of too much oxygen during the overnight anneal, but there is no question that the effects are harmful. In the past year several difficulties with the vacuum ovens used were experienced and these did contribute to the higher scrap rate and to the number of lower output cells. Better equipment and better safeguards against equipment failure have subsequently been set up.

VI CELL TESTING

A. Effect of Series Resistance and Shunt Resistance

In order to facilitate the interpretation of cell degradation and to assign probable causes for such degradation, a number of cells were tested for I-V characteristics with deliberately added amounts of external series resistance and shunt resistance. Figure 16 shows the change in the I-V curve of a 6% cell with 0, 0.02, 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 ohms inserted between the cell and test circuit. It is seen that the open circuit voltage stays fixed. The fill factor suffers with any series resistance and gets progressively worse. The short circuit current is not affected appreciably until the resistance exceeds about 0.2 ohms. The locus of the maximum power points curves in to the voltage axis at half of the open circuit voltage.

Figure 17 is a similar series of curves for various external shunt resistances connected across the cell. The values were 10, 5, 2, 1, 0.5, 0.2 and 0.1 ohms. The short circuit current remained fixed for all values of shunt resistance, and the open circuit voltage was reduced as the shunt path increased. The locus of the maximum power points is a curve as shown which intersects the current axis at half of the short circuit value.

Figure 18 is similar data for a fixed series resistance of 0.2 ohms with a variable amount of shunt resistance. The effect is similar to straight shunting but with the intersection of the short circuit current points displaced in the negative voltage direction.

B. High Temperature Performance of Cells

The I-V characteristics of 4 standard construction cells, including 2 cells that had degraded on temperature cycling and 1 cell that had degraded on high temperature storage, were measured at 10°C intervals from 25°C to 110°C in air and in vacuum. The purpose was to determine if there were differences in high temperature operation between degraded and non-graded cells.

CLEVITE CORP.
ELECTRONIC RESEARCH DIVISION
SOLAR BATTERY SECTION

CELL No. N88A2
SHEET No. _____ OF _____
AREA= 54.75 cm
AM1 @ 25°C.

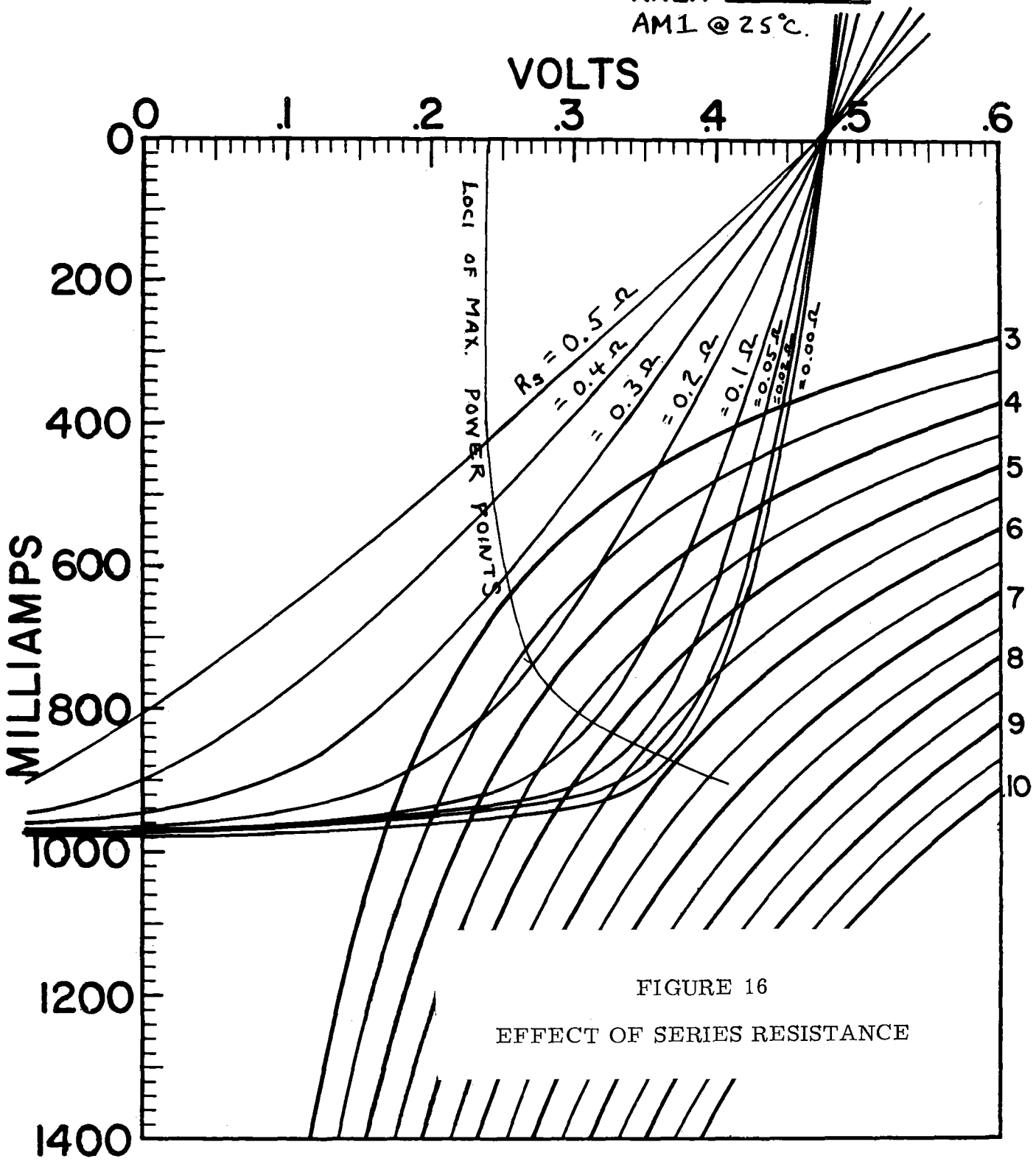


FIGURE 16

EFFECT OF SERIES RESISTANCE

TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1									
2									
3									
4									

CLEVITE CORP.
ELECTRONIC RESEARCH DIVISION
SOLAR BATTERY SECTION

CELL No. N88A2
SHEET No. _____ OF _____
AREA= 54.75 cm

AM 1 @ 25°C.

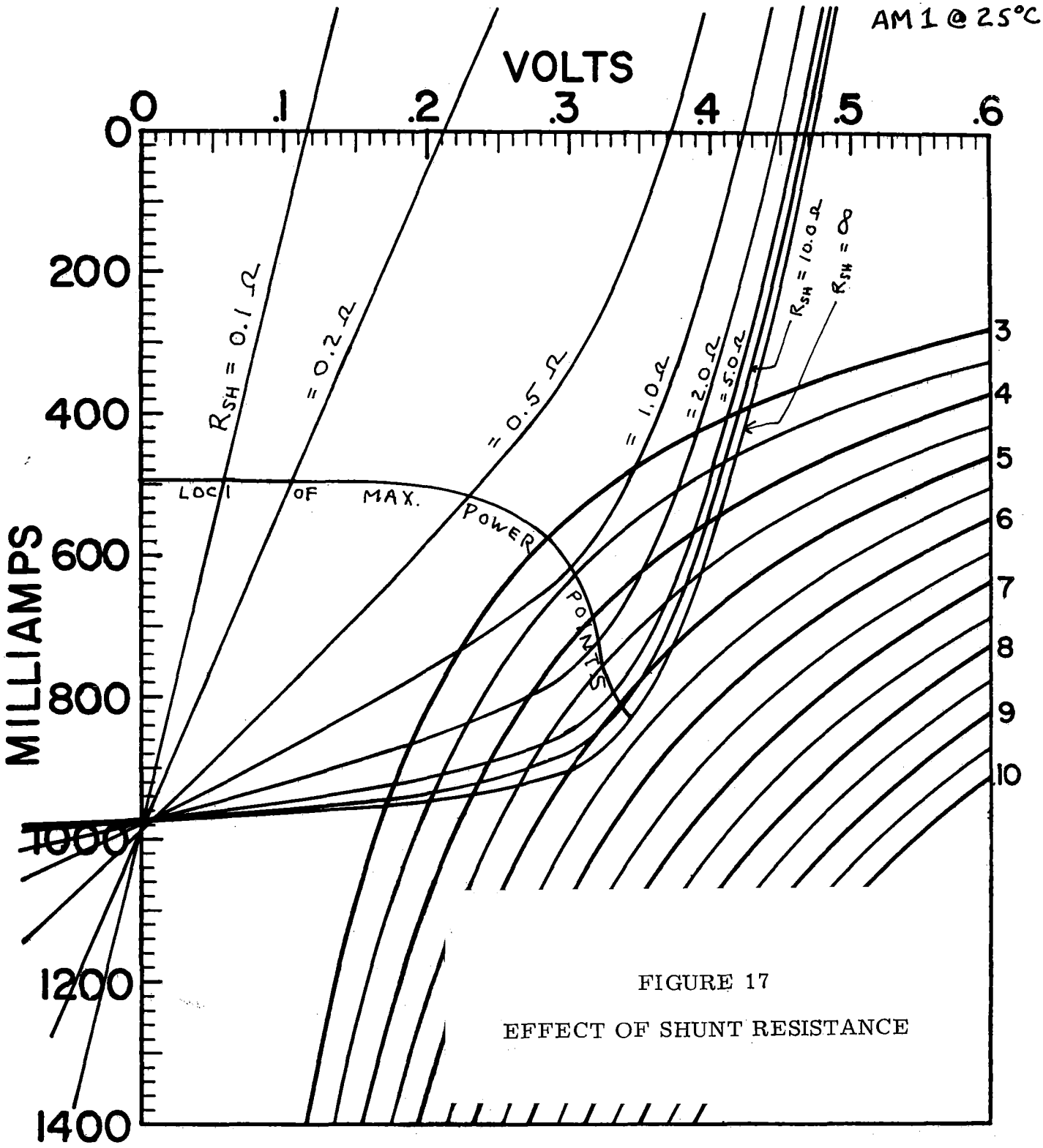


FIGURE 17

EFFECT OF SHUNT RESISTANCE

TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1									
2									
3									
4									

CLEVITE CORP.
ELECTRONIC RESEARCH DIVISION
SOLAR BATTERY SECTION

CELL No. N88A2
SHEET No. _____ OF _____
AREA= 54.75 cm

AM1 @ 25°C.

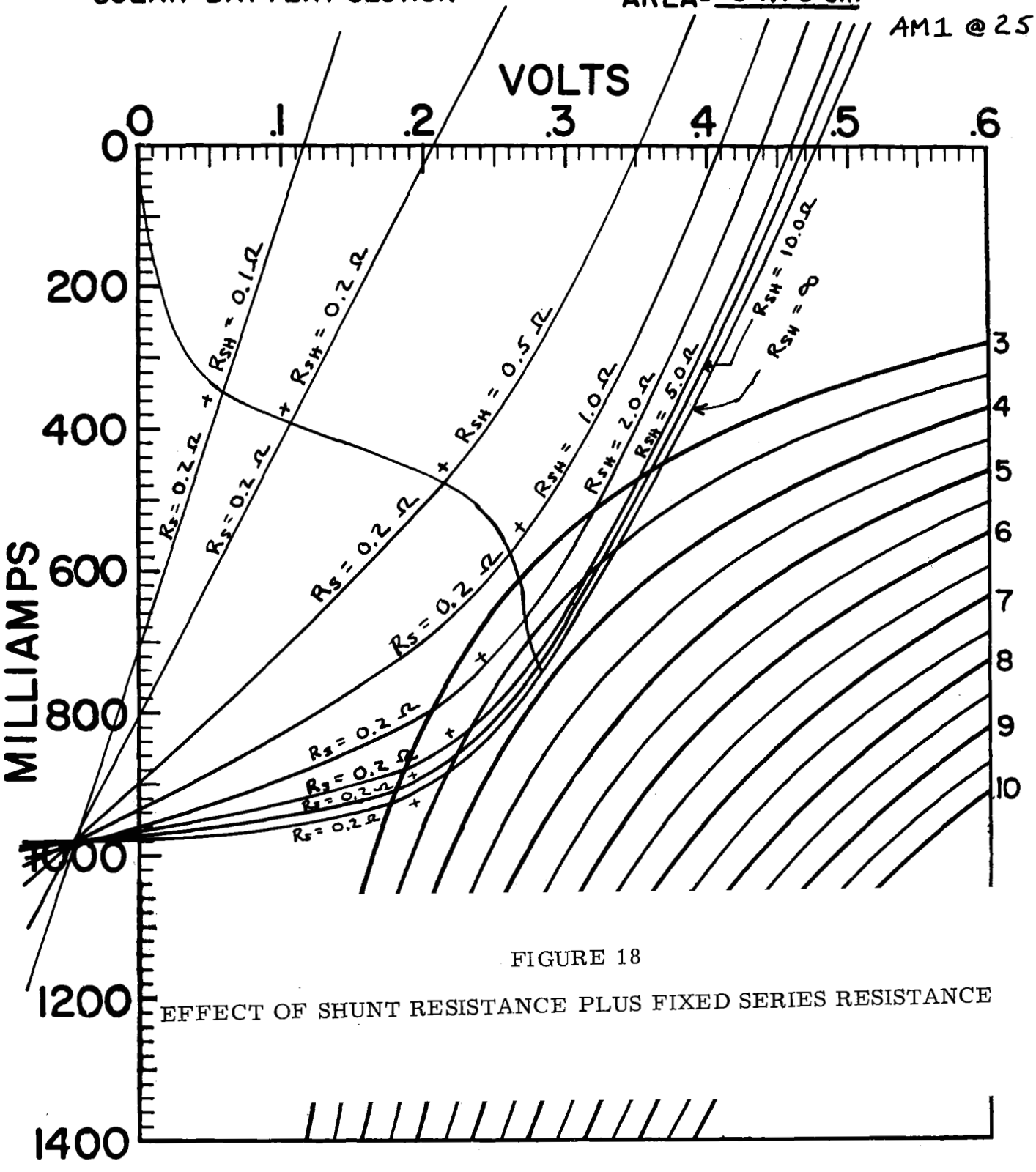


FIGURE 18

EFFECT OF SHUNT RESISTANCE PLUS FIXED SERIES RESISTANCE

TEST NO.	DATE	OCV	SCC	Vmp	Imp	MAX PWR.	% FILL	% EFF.	REMARKS
1									
2									
3									
4									

The fresh nondegraded cell, N110AK4, was a 4.6% efficiency cell. It exhibited very little loss in short circuit current up to 85°C and was down only 6% at 100°C. The open circuit voltage decreased uniformly up to about 85°C, as expected. Above 85°C the rate of decrease began to accelerate slowly. The I-V characteristic showed essentially no loss of squareness to 110°C.

Two temperature cycled cells returned from the Boeing Test were measured. These were cells N99AK5 and H106BK5. For these, the short circuit current decreased as the temperature was increased above 25°C, dropping at an increasing rate above 40°C. The short circuit current dropped by 5% between 85° and 90°C. At 100°C it was down 23% from the 25°C value. The cells showed appreciable loss of squareness of the I-V curve as temperature was increased. The efficiency, which was 4.4% at 25°C, dropped by 2/3 at 100°C.

The fourth cell, No. N84C3, had been stored for 6 weeks at 150°C, and had degraded from 5.0% to 2.5% on that test. Its open circuit voltage dropped with increasing temperature almost identically with the fresh undegraded cell, but its short circuit current began dropping immediately for a loss of 46% at 100°C. The squareness of the I-V curve was poor at 25°C, typical of heat degraded cells, and was virtually lost at 100°C.

Thus, a distinct difference was exhibited in the high temperature output of an undegraded (and presumed good) cell, a heat degraded cell, and two cells which had degraded on temperature cycling and then had recovered to nearly their original output level. The major differences were in the short circuit current and in the fill factors.

In an attempt to determine whether there were differences in the high temperature performance of standard process cells that might indicate major quality differences, a group of 58 standard process cells was measured at a temperature of 60 to 65°C, and the I-V curves compared with the 25°C measurements. In about 15 of the cells there were appreciable drops in the short circuit current and these were accompanied by varying drops in the fill factor with about 5 cells showing severe loss of fill. The current levels of the remaining cells did not change and the fill factors were also relatively unaffected.

Thus, there is some indication that something is wrong with cells which have poor performance characteristics (in short circuit current and fill factor) as the temperature is increased above room temperature.

It is possible that they may contain incipient cracks or other flaws which might not have much effect on cell output initially but which might have such effect as the temperature is increased or as the cells are exposed to various other environmental extremes such as thermal cycling. This characteristic has therefore been used to screen out cells from the standard production line, when those cells might be expected to perform at elevated temperatures or even to be exposed to elevated temperatures prior to use. This practice was put into effect in March of 1968 and is believed to be the main reason for the better performance of cells on temperature cycling, etc., since that time.