N71-25534

# NASA TECHNICAL MEMORANDUM

NASA TM X-2292

NASA TM X-2292



# EFFECT OF CELL VINTAGE AND CERTAIN TESTING PROCEDURES ON DEGRADATION OF CADMIUM SULFIDE THIN-FILM SOLAR CELLS

*by Thomas M. Klucher and Anthony F. Ratajczak*

*Lewis Research Center*

*Cleveland, Ohio 44135*



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1971

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| NASA TM X-2292 | | |
| 4. Title and Subtitle EFFECT OF CELL VINTAGE AND CERTAIN TESTING PROCEDURES ON DEGRADATION OF CADMIUM SULFIDE THIN-FILM SOLAR CELLS | | 5. Report Date May 1971 |
| | | 6. Performing Organization Code |
| 7. Author(s) Thomas M. Klucher and Anthony F. Ratajczak | | 8. Performing Organization Report No. E-6041 |
| | | 10. Work Unit No. 120-33 |
| 9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135 | | 11. Contract or Grant No. |
| | | 13. Type of Report and Period Covered Technical Memorandum |
| 12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546 | | 14. Sponsoring Agency Code |
| 15. Supplementary Notes | | |

16. Abstract

Vacuum thermal cycling tests, simulating an earth orbit environment, were performed on 23 cadmium sulfide thin-film solar cells to determine the effect of four factors on cell performance. The factors under study were: test facility, cell vintage, cell electrical interconnection, and cell load and measurement procedure. A multiple linear regression analysis indicated that differences in open-circuit voltage results between different test facilities were significant. Based upon the t statistics calculated from the regression analysis, the probability that the open-circuit voltage and test facility are independent was found to be 0.3 percent. Other performance-factor relations studied were less significant. However, considerable scatter in the data due to unknown variables may have introduced spurious effects on the results.

| 17. Key Words (Suggested by Author(s)) | 18. Distribution Statement |
|---|---|
| Solar cell<br>Cadmium sulfide<br>Environmental testing | Unclassified - unlimited |

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price* |
|---|---|---|---|
| Unclassified | Unclassified | 15 | $3.00 |

*For sale by the National Technical Information Service, Springfield, Virginia 22151

# EFFECT OF CELL VINTAGE AND CERTAIN TESTING PROCEDURES ON DEGRADATION OF CADMIUM SULFIDE THIN-FILM SOLAR CELLS

by Thomas M. Klucher and Anthony F. Ratajczak

Lewis Research Center

## SUMMARY

Vacuum thermal cycling tests, simulating an earth orbit environment, were performed on 23 cadmium sulfide thin-film solar cells to determine the effect of four factors on cell performance. The factors under study were: test facility, month of cell manufacture, cell electrical arrangement, and cell loading and measurement procedure. Accordingly, cells manufactured in two separate months were studied in each of two different test facilities. In each facility were single cells and cells connected in series strings. Further, some series strings and single cells were maintained at constant maximum power load throughout the test while others were unloaded briefly every 100 cycles to perform I-V characteristic measurements.

After 1000 vacuum thermal cycles, each cycle consisting of 1 hour of simulated sunlight and 1/2 hour of darkness, a statistical analysis of the results indicated that only the open-circuit voltage results between test facilities were significant. In one facility, the average performance results after 1000 cycles were -2.8 percent change in maximum power, -2.5 percent change in short-circuit current, -1.8 percent change in fill factor, and 1.7 percent change in open-circuit voltage. In the other facility, the results were -4.9 percent change in maximum power, -2.8 percent change in short-circuit current, -2.6 percent change in fill factor, and 0.6 percent change in open-circuit voltage.

## INTRODUCTION

Vacuum thermal cycling tests on cadmium sulfide (CdS) thin-film solar cells have been performed in simulated space environments to estimate the cell performance in an actual space environment. During these tests the cells have been observed to degrade in performance with increase of cycling time. For example, one recent report on a group of seven cells tested for 2000 cycles stated that the average loss per cell amounted to

12 percent in maximum power output, 7 percent in short-circuit current, and 9 percent in fill factor, which is defined as the maximum power divided by the product of open-circuit voltage and short-circuit current. The cells also showed an average gain of 3.4 percent in open-circuit voltage (ref. 1).

Recently a new testing facility at Lewis Research Center was established to test the effects of vacuum thermal cycling on CdS cells. In the first test using this facility, nine CdS cells were connected in a series string arrangement and were vacuum thermally cycled for 905 cycles. The average maximum power output from these cells was found to degrade 1.9 percent. Other performance changes were: a 3.4 percent loss for short-circuit current, a 2.4 percent loss for fill factor, and a 3.6 percent gain for open-circuit voltage.

Since the degradation in maximum power output for the series string was only one-third the degradation measured at 900 cycles in reference 1, a number of questions arose as to the possible causes for the difference. Consideration of potential causes for these differences in results led to four possibilities: (1) differences in facilities, (2) month of manufacture of the cells, (3) cell electrical arrangement, and (4) cell loading condition and measurement procedure.

In order to determine which of these factors, if any, may be influencing the performance during cycling, a fractional factorial experiment was performed, using two different vacuum thermal cycling facilities at Lewis Research Center. In each test facility, cells manufactured in two different months were subjected to vacuum thermal cycling. Some cells from each month were treated as individuals while others were combined into series string arrangements. Finally, some cells were maintained under constant resistance load throughout the test, while others were unloaded periodically in order to make current-voltage (I-V) characteristic measurements.

Nine CdS cells in one vacuum chamber and 14 CdS cells in another vacuum chamber were subjected to thermal cycling during this test. The cells in the first chamber were subjected to 1020 cycles, while the cells in the second chamber were subjected to only 962 cycles due to a malfunction of the facility. The cycle period for each chamber was the same, 1.5 hours, during which the cells were illuminated by simulated sunlight for 1 hour and 1/2 hour during which the cells were in the dark. The equilibrium temperatures were about $60^{\circ}$ C in sunlight and $-120^{\circ}$ C in the dark. The cells which were maintained at constant load were measured by an I-V curve only on the first cycle and the last cycle; the cells for which I-V curves were taken were measured every 100 cycles. Cell performance measurements were made before and after vacuum thermal cycling to determine the amount of cell change. Based upon these measurements, a statistical analysis was performed to analyze the effects on cell performance due to the four variables (test facility, month of cell manufacture, type of cell electrical arrangement, and load condition on cell during test).

## TEST EQUIPMENT

The test equipment used in this experiment has been reported elsewhere (ref. 2). Therefore, only short descriptions of the equipment and the differences between facilities will be pointed out here.

Ambient test apparatus. - The ambient test apparatus was used to measure CdS cell current-voltage characteristics prior to and following vacuum thermal cycling. The apparatus consists of a temperature control block, filtered tungsten iodide source, an electronic load to take the I-V curve, and an x-y plotter which records the I-V curve. The standard deviations of electrical performance parameters obtained using this apparatus are 1.3 millivolts for open-circuit voltage, 2.1 milliamperes for short-circuit current, and 2.8 milliwatts for maximum power (ref. 3).

Test facility A(1). Test facility A(1) includes a vacuum chamber, solar simulator, and electronic load. The solar simulator consists of a 4.2-kilowatt xenon lamp and filtered optical components and approximates air mass zero sunlight, which is defined as the spectral distribution and intensity of sunlight in near-earth space without atmospheric attenuation. The uniformity of intensity over the test area inside the chamber was measured to be ±3 percent of one solar constant.

The 0.61-meter-diameter by 1.22-meter-long (2- by 4-ft) vacuum chamber utilizes a titanium sublimation and ion pumping system to maintain a vacuum of $10^{-7}$ to $10^{-8}$ torr. A liquid nitrogen cooled shroud also provides cryopumping and space temperature simulation. The solar cells are mounted in the chamber to a glass epoxy board frame by strips of Kapton tape. Two silicon cells are also mounted on the epoxy board to monitor the light intensity during testing. A 30-gage (0.010-in. or 10-mil) welded copper-constantan thermocouple was attached to each CdS cell by a 1-square-centimeter piece of thermoadhesive Kapton tape and cell temperatures were recorded on a multipoint temperature recorder. The CdS cells mounted on the epoxy board are shown in figure 1.

Cell performance during testing was recorded by measuring cell maximum power voltage with a digital voltmeter or by taking I-V curves using the electronic load located on the ambient test apparatus.

Test facility A(2). - Test facility A(2) also includes a vacuum chamber, solar simulator, and electronic load. All of these components differ from the components in A(1). The solar simulator in A(2) consists of a 4.2-kilowatt xenon lamp but does not include filters. Therefore, the spectral output of the simulator does not approximate air mass zero sunlight, but is the unfiltered illumination of the xenon lamp. The uniformity of intensity over the test area inside the chamber was also measured to be ±3 percent of one solar constant.

The 0.76-meter-diameter by 1.43-meter-long (2.5- by 4.7-ft) vacuum chamber uses an oil diffusion pump system to maintain a vacuum of $10^{-7}$ torr. As with the chamber A(1), a liquid nitrogen cooled shroud also provides cryopumping and space temperature simulation. The solar cells in chamber A(2) are mounted between glass epoxy board slats on a glass epoxy board frame. A 33-gage (0.007-in. or 7-mil) Chromel-Alumel welded thermocouple was attached to the back of each cell by masking tape. Temperatures were measured using a 338 K reference junction, a digital voltmeter, and a scanner and printer. Four silicon solar cells mounted on the epoxy board were used to monitor the light intensity in the chamber. The CdS cells mounted on the epoxy board are shown in figure 2.

Cell performance during testing was measured as in test facility A(1). The electronic load used in this facility differs somewhat from the electronic load used in facility A(1). The electronic load in facility A(2) draws a small amount of control current through the cell voltage leads during I-V measurement, whereas the electronic load in facility A(1) draws no current through its voltage leads.

Infrared viewing device. - This instrument consists of an infrared camera and display unit and is used to view temperature changes on the cell surface. Further information on the operation and properties of the device is given in reference 4.

## TEST PROCEDURE

Twenty-three CdS cells selected for testing in the 1/2 replicate of a $2^4$ experiment were obtained from production line cells delivered to Lewis Research Center in January 1969 and June 1969. The cells to be tested were selected according to their efficiencies as measured and reported by the manufacturer. These efficiencies were approximately equal to the efficiencies of the cells tested in the nine cell series string of reference 2. As in that test, the cells were first scanned with the infrared viewing device to determine their thermal uniformity profile under application of the dark forward bias technique described in reference 5. Cells which showed nonuniform thermal patterns at dark forward bias currents of 0.5 ampere were considered unacceptable for the factorial study. All of the cells selected were found to exhibit uniform thermal patterns before testing.

Current-voltage characteristics of the cells were measured on the ambient test apparatus at temperatures of $25^{\circ}$, $40^{\circ}$, $50^{\circ}$, and $60^{\circ}$ C. The I-V characteristics of the cells tested were the basic measure of the cell performance parameters prior to vacuum thermal cycling. The I-V characteristic of each cell was also measured after vacuum thermal cycling. Comparisons of postcycling I-V characteristics with precycling characteristics were made to determine cell performance changes due to thermal cycling. These results were used in the statistical analysis to study which variables had effects upon cell performance.

After precycling ambient test measurements, the 23 cells were divided so that vacuum chamber A(1) contained four cells delivered in January and five cells delivered in June; chamber A(2) contained seven cells from each month. The cells were assigned to the vacuum chambers in a random manner. Two series strings, one string composed of three January cells and another of three June cells, were included in each vacuum chamber; the remaining cells in each chamber were tested as single cells. Finally, some cells and series strings were designated for testing under constant load, while others were designated for periodic I-V characteristic measurements while under test. A schematic of the cells undergoing each treatment is presented in figure 3.

The CdS cells and series strings were mounted on the epoxy mounting boards as shown in figures 1 and 2. Electrical leads and thermocouples were applied to all cells so that the I-V characteristic of any cell could be measured. The cells were placed in the vacuum chambers and thermal cycling tests were started. During the first hour of the test, the I-V characteristic of each cell or series string was measured in order to find the maximum power point at which to load the cells. Thereafter, the cells were maintained at that load throughout the test. The cells marked for I-V measurement during the test were unloaded very briefly to perform this measurement, which occurred approximately every 100 cycles.

The cells in vacuum chamber A(1) were vacuum thermally cycled for 1020 cycles. The cells in vacuum chamber A(2) were tested until cycle 962, at which time vacuum chamber difficulties forced an end to the test. The cells were measured on the ambient test apparatus as explained previously.

## RESULTS AND DISCUSSION

The effect of vacuum thermal cycling on the individual cells is shown in tables I and II. The values in table I are absolute values of the performance parameters based upon ambient test apparatus measurements at $50^{\circ}$ C before and after cycling. The values in table II are percentage changes based upon the results listed in table I. The results listed in tables I and II have been adjusted for a possible bias in either the before or after measurement. This bias was noticed when comparisons of four untested control cells showed small but consistent losses in short-circuit current, maximum power, and fill factor. The four control cells showed a loss of 1.3 percent in short-circuit current, 1.9 percent in maximum power, and 0.7 percent in fill factor when the cells in chamber A(1) were measured. When the cells in chamber A(2) were measured, the same four cells showed a loss of 1.5 percent in short-circuit current, 1.4 percent in maximum power, and 0 percent in fill factor. All values stated hereinafter include corrections for the bias.

After 1020 cycles, the cells in vacuum chamber A(1) had an average loss of 2.9 percent in maximum power, an average loss of 2.6 percent in short-circuit current, and an average loss of 1.8 percent in fill factor. The open-circuit voltage increased an average of 1.7 percent for each cell. Under the assumption that cell performance at 1000 cycles can be obtained by linear interpolation, the cells would have the following average changes after 1000 cycles; a maximum power loss of 2.8 percent, a short-circuit current loss of 2.5 percent, a fill factor loss of 1.8 percent, and an open-circuit voltage gain at 1.7 percent. One cell in this group, cell 5, had an edge delamination with an area loss of about 1.5 percent.

The results for cells in chamber A(2) after 962 cycles of testing were a 4.7 percent average loss of maximum power, a 2.7 percent average loss of short-circuit current, a 2.5 percent average loss in fill factor, and a 0.6 percent average increase in open-circuit voltage. Under the assumption that all performance changes would have continued at the same rate to 1000 cycles, the cells would have the following average changes after 1000 cycles: a maximum power loss of 4.9 percent, a short-circuit current loss of 2.8 percent, a fill factor loss of 2.6 percent, and an open-circuit voltage increase of 0.6 percent. Three cells in this group also delaminated along the edges. Cell 2 had an area loss of 5.2 percent, cell 7 had an area loss of 0.6 percent, and cell 11 had an area loss of 3.7 percent.

A fractional factorial statistical analysis was performed to determine which factors had significant effects on changes in maximum power, short-circuit current, open-circuit voltage, and fill factor. Using a multiple linear regression program (ref. 6), $t$ statistics and their associated probabilities for each factor and performance parameter were calculated from the data in table II and are presented in table III. In addition, the standard error of estimate $\epsilon$, and coefficient of determination $R^2$, for each regression are also presented in table III. The values surrounded by parentheses in the table are the statistical results based upon cell performance with corrections for delaminated area losses. The statistics without parentheses do not include corrections for delamination losses. All results stated in table III include corrections for difference in number of cycles between facilities.

Based upon $\epsilon$ and $R^2$ values listed in table III, the analysis indicates that, in general, the observed performance results of this test are not accounted for only by the differences between test facilities, cell vintage, cell load and measurement procedure, and cell electrical interconnection. Both $\epsilon$ and $R^2$ are measures of how closely the regression equation accounts for the experimental data. The relatively large values of $\epsilon$ demonstrate the large scatter observed in the data even within a given factor group. Similarly, the small $R^2$ values imply that factors other than the four tested have apparently caused most of the differences observed in performance. For example, only 15 to 24 percent of the maximum power change is accountable by the four factors studied; the inference is that 76 to 85 percent of the change remains to be accounted for by still undetermined variables. The performance parameter which was explained best by the regression equation was the open-circuit voltage; its $\epsilon$ value was 0.7 percent and its $R^2$ value was 42 percent.

The $t$ statistics in table III demonstrate a significant performance parameter-factor relation between open-circuit voltage and test facility. The probability of observing a t statistic larger than that shown in table III, if there were in fact no difference in open-circuit voltage due to change in test facility, is 0.3 percent. Therefore, the conclusion is that there is a real dependence of open-circuit voltage on test facility. Other performance parameter-factor relations show smaller t values and therefore their associated probabilities in table III are greater than for the open-circuit voltage-test facility relation. However, the considerable scatter existing in the data due to unknown variables may be introducing spurious effects on the tested relations; so, it must be concluded that the statistical results do not rule out all of the performance parameter-factor effects tested here.

## SUMMARY OF RESULTS

The results of vacuum thermal cycling tests on 23 cadmium sulfide solar cells indicate the following after 1000 cycles:

1. The average loss in maximum power for nine cells tested in chamber A(1) was 2.8 percent. The average short-circuit current loss was 2.5 percent, and the average fill factor loss was 1.8 percent. The average open-circuit voltage gain was 1.7 percent. Cell 5 delaminated with an estimated area loss of 1.5 percent.

2. The average loss in maximum power for 14 cells tested in chamber A(2) was 4.9 percent. The average short-circuit current loss was 2.8 percent, and the average fill factor loss was 2.6 percent. The average open-circuit voltage gain was 0.6 percent. Cells 2, 7, and 11 delaminated with area losses of 5.2, 0.6, and 3.7 percent, respectively.

3. A 1/2 replicate of a $2^4$ experiment, analyzed by means of a multiple linear regression equation, demonstrated that the open-circuit voltage results between different facilities were significantly different. Based upon the t statistic calculated from the regression analysis, the probability that open-circuit voltage and test facility are independent was found to be 0.3 percent. Other performance parameter-factor relations were less significant than the relation between open-circuit voltage and test facility. In general, however, the regression accounted for less than 42 percent of the observed data. Thus, the considerable scatter existing in the data due to unknown variables may have introduced spurious effects in the results.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 8, 1971,
120-33.

## REFERENCES


1. Kennerud, K. L.: Simulated Space Environmental Tests on Cadmium Sulfide Solar Cells. Rep. D2-121002-1, Boeing Co. (NASA CR-72507), Feb. 28, 1969.
2. Klucher, T. M.; and Ratajczak, A. F.: Test of Cadmium Sulfide Solar Cells in a Series String. NASA TM X-2231, 1971.
3. Spakowski, A. E.; and Forestieri, A. F.: Observations on CdS Solar Cell Stability. Presented at the IEEE Photovoltaic Specialists Conference, Pasadena, Calif., Nov. 19-21, 1968.
4. Borg, Sven-Bertil: Thermal Imaging with Real Time Picture Presentation. Appl. Opt., vol. 7, no. 9, Sept. 1968, p. 1697.
5. Scudder, Larry R.; Godlewski, Michael P.; and Klucher, Thomas M.: Observations of Degraded CdS Solar Cells. NASA TM X-52668, 1969.
6. Sidik, Steven M.; and Henry, Bert: Rapier - A Fortran IV Program For Multiple Linear Regression Analysis Providing Internally Evaluated Remodeling. NASA TN D-5656, 1970.

TABLE I. - ABSOLUTE VALUES OF CELL PERFORMANCE CHARACTERISTICS BEFORE AND AFTER VACUUM THERMAL CYCLING (ROUNDED TO THREE PLACES)

| Cell | Maximum power, $P_{max}$, mV | | Short-circuit current, $I_{sc}$, mA | | Open-circuit voltage, $V_{oc}$, mV | | Fill factor, FF | | Treatment |
|---|---|---|---|---|---|---|---|---|---|
| | Before | After | Before | After | Before | After | Before | After | |
| Vacuum chamber A(1) - 1020 cycles | | | | | | | | | |
| 1 | 219 | 214 | 720 | 703 | 430 | 436 | 706 | 698 | January, series, I-V curves |
| 2 | 214 | 212 | 711 | 693 | 430 | 437 | 700 | 701 | |
| 3 | 222 | 218 | 732 | 712 | 436 | 444 | 697 | 692 | |
| 4 | 205 | 204 | 702 | 689 | 426 | 438 | 685 | 678 | June, series, constant load |
| 5 | 198 | 199 | 675 | 660 | 426 | 434 | 689 | 695 | |
| 6 | 201 | 179 | 678 | 649 | 440 | 446 | 673 | 618 | |
| 7 | 212 | 202 | 707 | 676 | 433 | 437 | 692 | 685 | June, individual, I-V curves |
| 8 | 204 | 202 | 704 | 699 | 425 | 433 | 681 | 665 | |
| 9 | 209 | 200 | 727 | 707 | 425 | 432 | 675 | 655 | January, individual, constant load |
| Vacuum chamber A(2) - 962 cycles | | | | | | | | | |
| 1 | 202 | 189 | 680 | 656 | 431 | 437 | 689 | 659 | June, individual, constant load |
| 2 | 199 | 183 | 700 | 652 | 418 | 424 | 680 | 662 | |
| 3 | 197 | 191 | 675 | 656 | 433 | 433 | 675 | 673 | |
| 4 | 203 | 196 | 708 | 689 | 429 | 430 | 668 | 661 | |
| 5 | 229 | 213 | 780 | 758 | 430 | 430 | 683 | 655 | January, series, constant load |
| 6 | 222 | 212 | 800 | 789 | 409 | 409 | 678 | 657 | |
| 7 | 224 | 213 | 773 | 751 | 420 | 420 | 691 | 686 | |
| 8 | 217 | 208 | 714 | 688 | 447 | 449 | 682 | 673 | January, individual, I-V curves |
| 9 | 203 | 197 | 760 | 767 | 421 | 430 | 635 | 595 | |
| 10 | 223 | 216 | 735 | 713 | 437 | 437 | 693 | 692 | |
| 11 | 222 | 211 | 812 | 771 | 411 | 415 | 666 | 660 | |
| 12 | 211 | 200 | 742 | 731 | 417 | 421 | 683 | 653 | June, series, I-V curves |
| 13 | 219 | 211 | 771 | 755 | 437 | 442 | 649 | 633 | |
| 14 | 209 | 201 | 746 | 741 | 418 | 418 | 670 | 647 | |

TABLE II. - PERCENTAGE CHANGES IN CELL PERFORMANCE CHARACTERISTICS AFTER VACUUM THERMAL CYCLING

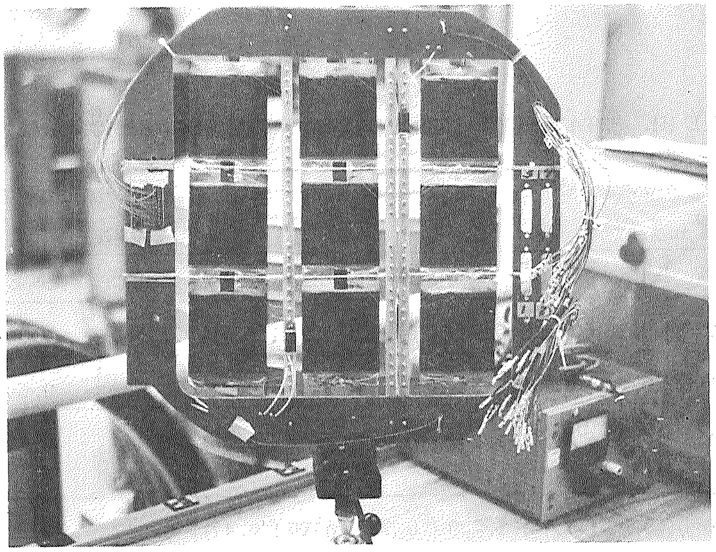
| Cell | Change in maximum power, $\Delta P_{max}$, percent | Change in short-circuit current, $\Delta I_{sc}$, percent | Change in open-circuit voltage, $\Delta V_{oc}$, percent | Change in fill factor, $\Delta FF$, percent | Treatment |
|---|---|---|---|---|---|
| Vacuum chamber A(1) - 1020 cycles | | | | | |
| 1 | -2.3 | -2.3 | 1.3 | -1.1 | January, series, I-V curves |
| 2 | -.9 | -2.5 | 1.6 | .2 | |
| 3 | -1.8 | -2.7 | 1.8 | -.7 | |
| 4 | -.5 | -1.9 | 2.7 | -1.1 | June, series, constant load |
| 5 | .5 ([a]2.0) | -2.2 ([a]-0.7) | 2.0 | .9 | |
| 6 | -10.9 | -4.3 | 1.2 | -8.2 | |
| 7 | -4.6 | -4.3 | 0.9 | -1.0 | June, individual, I-V curves |
| 8 | -1.2 | -.7 | 1.9 | -2.3 | |
| 9 | -4.3 | -2.8 | 1.6 | -3.0 | January, individual, constant load |
| Average | -2.9 | -2.6 | 1.7 | -1.8 | ------------------------------ |
| Vacuum chamber A(2) - 962 cycles | | | | | |
| 1 | -6.5 | -3.5 | 1.3 | -4.3 | June, individual constant load |
| 2 | -8.2 ([a]-3.0) | -6.9 ([a]-1.7) | 1.3 | -2.6 | |
| 3 | -3.2 | -2.8 | 0 | -.3 | |
| 4 | -3.5 | -2.7 | .2 | -1.0 | |
| 5 | -6.9 | -2.8 | 0 | -4.1 | January, series, constant load |
| 6 | -4.4 | -1.4 | 0 | -3.1 | |
| 7 | -4.9 ([a]-4.3) | -2.8 ([a]-2.2) | 0 | -.7 | |
| 8 | -4.3 | -3.6 | 0.6 | -1.3 | January, individual, I-V curves |
| 9 | -3.0 | .9 | 2.2 | -6.3 | |
| 10 | -3.1 | -3.0 | 0 | -.1 | |
| 11 | -4.9 ([a]-1.2) | -5.0 ([a]-1.3) | .9 | -.9 | |
| 12 | -5.0 | -1.5 | 0.9 | -4.4 | June, series, I-V curves |
| 13 | -3.6 | -2.1 | 1.0 | -2.5 | |
| 14 | -4.0 | -.6 | 0 | -3.4 | |
| Average | -4.7 | -2.7 | 0.6 | -2.5 | ------------------------------ |

[a]Estimated changes after adjustment for delaminated area loss.

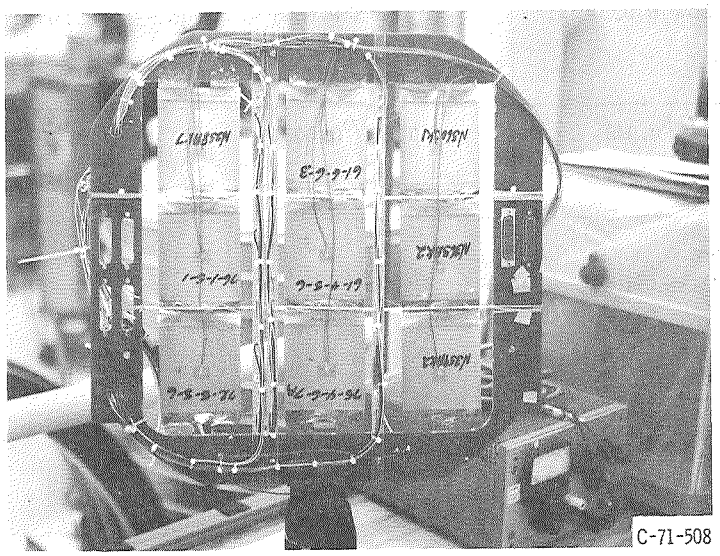
TABLE III. - STATISTICS CALCULATED FROM REGRESSION ANALYSIS

| | Maximum power, $P_{max}$ | | Short-circuit current, $I_{sc}$ | | Open-circuit voltage, $V_{oc}$ | | Fill factor, FF | |
|---|---|---|---|---|---|---|---|---|
| | t(df)[a] | Probability | t(df)[a] | Probability | t(df)[a] | Probability | t(df)[a] | Probability |
| Test facility | 1.599 ([b]1.270) | 0.13 ([b]0.22) | 0.044 ([b]0.680) | 0.97 ([b]0.51) | 3.540 | 0.003 | 0.873 | 0.40 |
| Cell vintage | 0.235 ([b]0.158) | 0.82 ([b]0.88) | 0.244 ([b]0.179) | 0.81 ([b]0.86) | 0.634 | 0.54 | 0.576 | 0.57 |
| Cell load and measurement | 1.246 ([b]0.934) | 0.23 ([b]0.37) | 1.208 ([b]0.951) | 0.25 ([b]0.36) | 0.440 | 0.67 | 0.284 | 0.78 |
| Cell inter-connection | 0.182 ([b]0.284) | 0.86 ([b]0.78) | 1.730 ([b]0.735) | 0.10 ([b]0.47) | 0.667 | 0.52 | 0.432 | 0.67 |
| Standard error of estimate, $\epsilon$ | 0.025 ([b]0.026) | | 0.015 ([b]0.013) | | 0.007 | | 0.024 | |
| Coefficient of determination $R^2$ | 0.24 ([b]0.15) | | 0.21 ([b]0.09) | | 0.42 | | 0.07 | |

[a]df ≡ 15 degrees of freedom.
[b]Include corrections for delaminated area loss.

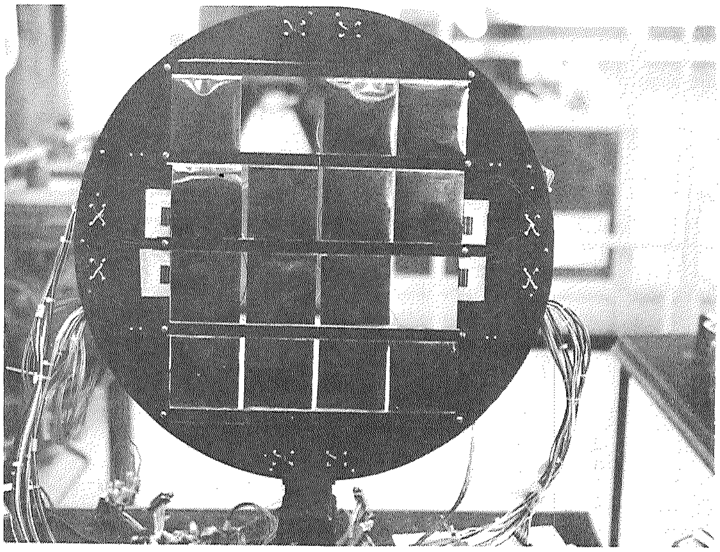


(a) Front view.

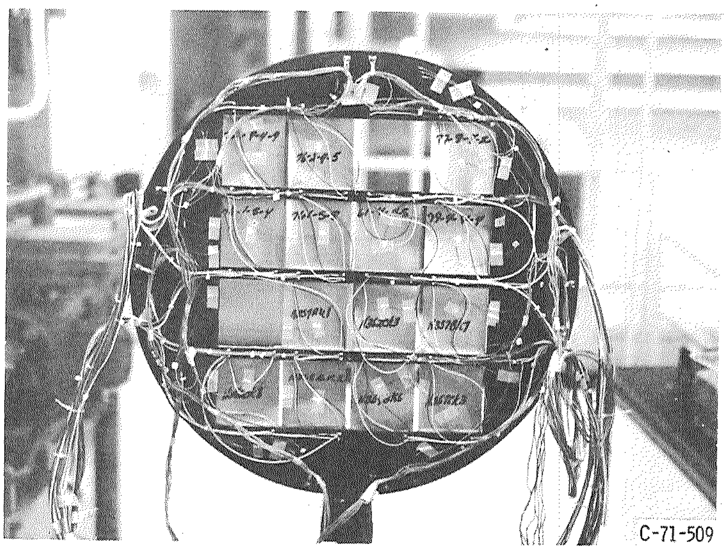



(b) Back view.

Figure 1. - Cadmium sulfide solar cells mounted on vacuum thermal cycling mounting board of chamber A(1).



(a) Front view.




(b) Back view.

Figure 2. - Cadmium sulfide solar cells mounted on vacuum thermal cycling mounting board of chamber A(2).

| | | Chamber A(1) | | Chamber A(2) | |
|---|---|---|---|---|---|
| | | I-V | No I-V | I-V | No I-V |
| Month: June | Individual | Cells 7, 8 | | | Cells 1, 2, 3, 4 |
| | Series | | Cells 4, 5, 6 | Cells 12, 13, 14 | |
| Month: January | Individual | | Cell 9 | Cells 8, 9, 10, 11 | |
| | Series | Cells 1, 2, 3 | | | Cells 5, 6, 7 |

Figure 3. - Block schematic of 1/2 replicate of $2^4$ experiment.



NASA-Langley, 1971 —— 3 E-6041

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

**FIRST CLASS MAIL**

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

*"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."*

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

# NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

*Details on the availability of these publications may be obtained from:*

**SCIENTIFIC AND TECHNICAL INFORMATION OFFICE**

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**
**Washington, D.C. 20546**