NASA TECHNICAL NOTE

NASA TN D-6612

c. 1

NASA TN D-6612

EFFECT OF LOAD VOLTAGE ON THIN-FILM CUPROUS SULFIDE - CADMIUM SULFIDE SOLAR CELLS THERMALLY CYCLED IN A SIMULATED SPACE ENVIRONMENT

by John J. Smithrick and Ralph D. Thomas

Lewis Research Center

Cleveland, Ohio 44135

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

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TN D-6612		
4. Title and Subtitle EFFECT OF LOAD VOLTAGE ON THIN-FILM CUPROUS SULFIDE - CADMIUM SULFIDE SOLAR CELLS THERMALLY CYCLED IN A SIMULATED SPACE ENVIRONMENT		5. Report Date December 1971
		6. Performing Organization Code
7. Author(s) John J. Smithrick and Ralph D. Thomas		8. Performing Organization Report No. E-6419
		10. Work Unit No. 113-33
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 Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Thin-film Cu_2S-CdS solar cells, loaded at various fixed values of load resistance, were thermally cycled for 1429 cycles in a simulated space environment. Cell performance was measured under controlled conditions in air before and after thermal cycling. These data were used to determine the effect of load voltage on cell performance. The performance of the cells was relatively independent of load voltage up to about 0.39 volt. This appears to be a threshold voltage, beyond which there was a significant loss in cell performance. Fortunately, this threshold voltage appears to be sufficiently higher than the maximum power voltage of 0.33 volt so that it can be avoided in most applications.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Solar cells Energy conversion Thermal cycling Cadmium sulfide	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	12	$3.00

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

EFFECT OF LOAD VOLTAGE ON THIN-FILM CUPROUS SULFIDE - CADMIUM SULFIDE SOLAR CELLS THERMALLY CYCLED IN A SIMULATED SPACE ENVIRONMENT

by John J. Smithrick and Ralph D. Thomas

Lewis Research Center

SUMMARY

Thin-film cuprous sulfide - cadmium sulfide (Cu_2S-CdS) solar cells, loaded at various fixed values of load resistance, were thermally cycled in a simulated space environment for 1429 cycles. A thermal cycle consisted of illuminating the cells for 1 hour with a xenon-arc solar simulator lamp (initial cell equilibrium temperature, $\sim$323 K (50° C)) and then interrupting the lamp beam, allowing the cells to cool in the dark for one-half hour (cell temperature, 163 K (-110° C)). Cell performance was measured under controlled conditions in air prior to and after the test. These data were used to determine the effect of load voltage on the loss in cell performance due to thermal cycling.

The performance data showed that there was a load voltage effect. The degradation of the cells was relatively independent of load voltage up to about 0.39 volt. This appears to be a threshold voltage beyond which there was a significant degradation of cell output.

INTRODUCTION

As part of a continuing evaluation program of thin-film cuprous sulfide - cadmium sulfide (Cu_2S-CdS) solar cells, simulated space environmental tests and ambient tests are being conducted (refs. 1 to 5).

Ambient tests conducted at Lewis Research Center (ref. 5) on Cu_2S-CdS solar cells showed that cells loaded at open-circuit voltage degraded significantly more rapidly than those loaded at short-circuit current. In these ambient tests, the cells were constantly illuminated in air with a tungsten-iodine light source. A constant cell temperature of 298±1 K (25°±1° C) was maintained with a thermal control block during illumination.

The purpose of the present investigation is to determine the load voltage effect (the loss in performance as a function of load voltage) on Cu_2S-CdS solar cells thermally cycled in a simulated space environment.

The Cu_2S cells tested were 7.62 by 7.62 centimeters (3 by 3 in.) cells and were manufactured in October 1968. They were the same design as those described in reference 6. Fifteen cells were tested by loading them at various fixed values of load resistance. The load voltages ranged from 0.235 to 0.426 volt. The cells were thermally cycled for 1429 cycles in a vacuum chamber at about 10^{-6} torr. A thermal cycle consisted of illuminating the cells for 1 hour with a xenon-arc solar simulator and then interrupting the lamp beam and allowing the cells to cool in the dark for one-half hour. During illumination the cells reached an equilibrium temperature of 323 K (50° C) and in the dark reached a temperature of 163 K (-110° C). Cell performance was measured under controlled conditions in air before and after vacuum thermal cycling. These data were used to determine the load effect.

TEST EQUIPMENT

Photovoltaic Measurement Apparatus

The light source used to measure ambient current-voltage (I-V) characteristics on each cell consisted of four 650-watt tungsten-iodine lamps. The light was filtered through 5.08 centimeters (2 in.) of 1 percent copper sulfate - water solution to reduce the infrared portion of the light spectrum. The four lights were positioned such that the uniformity over a 10.16 square centimeter (4 $in.^2$) area was ±2 percent when measured by a 2 square centimeter Cu_2S-CdS standard cell. Intensity at the test plane was adjusted to air mass zero (AM0) by the standard Cu_2S-CdS cell calibrated as described in reference 7. The intensity is reproducible to ±0.3 percent of one solar constant. The standard deviations of open-circuit voltage, short-circuit current, and maximum power are ±1.3 millivolts, ±2.1 milliamperes, and ±2.8 milliwatts, respectively (ref. 8).

A constant cell temperature was maintained during the I-V curve measurements by placing the cells on a water-cooled thermal control block regulated to ±1 K. Good thermal contact was achieved by means of a vacuum holdown. Electrical contact to the cells was made by means of two current and two voltage leads. The I-V curves were measured using an electronic load, and the output of the cells was plotted on an X-Y recorder.

Infrared Viewing Device

The infrared viewing device consisted of an infrared camera and a display unit. The field of view of the camera was 5° by 5° and the display unit frame size was 42 by 54 millimeters. Spatial resolution of the display was 0.5 millimeter and the thermal resolution was about 0.2 K (ref. 9). A photograph of the display, called a thermogram, was obtained using a photographic camera for a permanent record of the image.

Space Environmental Chamber and Light Source

The vacuum chamber was 76 centimeters (30 in.) in diameter and 101 centimeters (42 in.) long, and its longitudinal axis was horizontal. The chamber was fabricated of 7.95 mm (5/16 in.) type 309 stainless steel. The ends of the vacuum chamber were hemispherical, and one end was removable. Feedthroughs were provided for power and vacuum facilities. A 31 centimeters (12 in.) diameter ground quartz plate (ultraviolet grade) window 2.54 centimeters (1 in.) thick, located in the fixed end of the chamber, permitted use of an external light source.

The operating vacuum of the system for tests was about 10^{-6} torr. Two 25.4 centimeter (10 in.) oil diffusion pumps with liquid nitrogen baffles and suitable forepumps were used. Two instruments were installed in the tank to measure pressures: (1) a naked ionization gage of the Bayard-Alpert type, and (2) a pirani gage between the forepump and the diffusion pumps. The walls of the vacuum chamber were cooled with liquid nitrogen and painted black to simulate a space heat sink. An unfiltered xenon-arc solar simulator was used during the environmental test.

PROCEDURE

Cell Mounting

The cells were mounted in a 3.17 millimeter (1/8 in.) glass-epoxy mounting frame located on the rear bulkhead of the vacuum chamber as shown in figure 1. The cells were attached to horizontal bars in the mounting frame by their negative electrodes using double-backed masking tape. The positive electrodes of the cells hung freely in slots. Although 16 Cu_2S-CdS thin-film cells are shown in figure 1, test results on one of them are not reported because the method of taking data on this cell was different. The two circular cells mounted on the sides of the tank are not thin-film cells and the data on

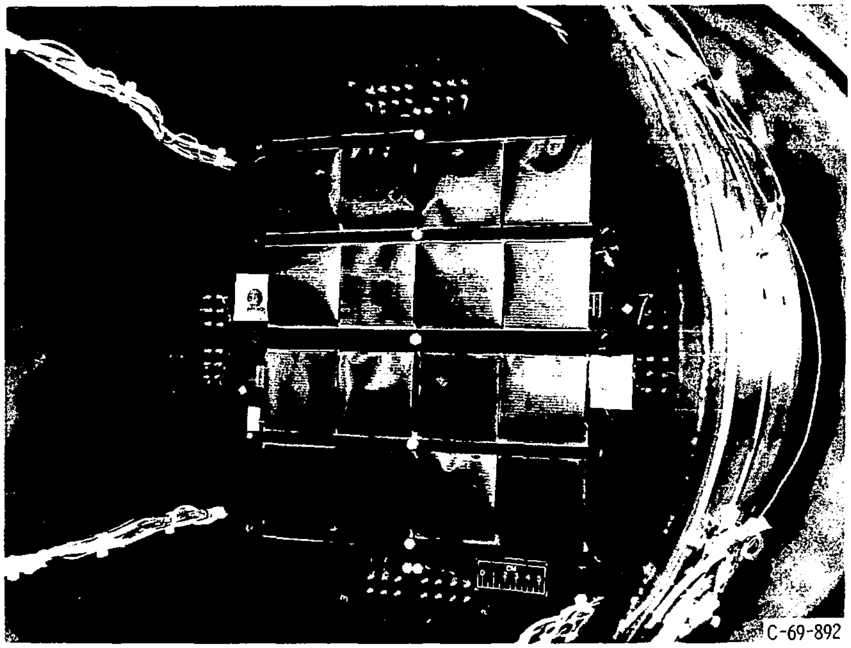

Figure 1. - Cuprous sulphide - cadmium sulphide solar cells mounted on vacuum thermal cycling frame in rear bulkhead of vacuum chamber.

them are not reported. The remaining two cells are silicon solar cells used to monitor the light intensity in the chamber.

Measurements

Before and after thermal cycling, two thermograms of each cell were taken. One was taken with no current to establish a background reference, and the other was taken with a forward bias current of 0.3 ampere, provided by a power supply. The purpose of the thermograms was to detect possible "hot spots" in the cells. Also, before and after thermal cycling, I-V characteristics of the Cu_2S-CdS cells were measured under controlled conditions in air using the photovoltaic measurement apparatus. Before thermal cycling, the I-V curves were traced with the cells under AM0 intensity at 298±1 K ($25^{\circ}\pm1^{\circ}$ C) and at 323±1 K ($50^{\circ}\pm1^{\circ}$ C); after thermal cycling the I-V curves were traced at 298±1 K ($25^{\circ}\pm1^{\circ}$ C), AM0.

A thermal cycle in the vacuum chamber consisted of illuminating the cells for 1 hour with the xenon-arc solar simulator lamp and then interrupting the beam and allowing the cells to cool in the dark for 30 minutes. After 15 minutes of illumination, the cells reached an equilibrium temperature of 323 K (50° C). After 30 minutes in the dark, the cells reached a temperature of 162 K (-110° C). The temperatures of the cells were measured using Chromel-Alumel thermocouples which were coated with a silicone heat-sink compound and attached to the substrate side of each cell with masking tape.

An I-V curve for each cell was traced at cycle 1. These data were used to load the cells at various values of fixed resistance. The load voltages ranged from 0.235 to 0.426 volt. Ten cells were loaded above 0.33 volt (maximum power voltage at 323 K (50° C)), and five were loaded below 0.33 volt. The load voltage and currents were monitored throughout the tests. During the remainder of the test no additional I-V curves were traced.

Voltage Error and Method of Correction

An apparent four-wire system was used to make performance measurements on the cells during thermal cycling. Two pieces of number 16 single-strand wire were soldered to the lead tab of each cell. One set of wires was used to measure cell voltage, and the other set was used to complete the load circuit across each cell. The current through each cell was computed from the voltage drop measured across a precision resistor included in the load circuit.

The negative voltage leads between cells and the negative leads completing the load circuits were made common due to circuit switching restrictions. This method of wiring cells allowed stray currents to flow in the voltage leads, thus causing a voltage error that was proportional to the load current.

Because of the error in the electrical circuit, correction of the load voltage during the in situ test was necessary. The technique used to find the corrected load voltages involved the assumption that the cell performance at cycle 1 was no different than at the ambient measurement. The load voltages were then corrected as follows:

First, any difference in intensity between ambient and in situ measurements were noted. A comparison of the short-circuit current for ambient and cycle 1 I-V curves was used in this case since short-circuit current is unaffected by the error in the electrical circuit. Next, the load current was measured; this likewise was unaffected by the circuit error. Finally, after adjusting the ambient I-V curve to cycle 1 intensity conditions as described in reference 10, the corrected load voltage was taken as the voltage on the reconstructed ambient I-V curve corresponding to the load current measured at cycle 1. For all but two cells the corrected load voltage was higher than the uncorrected load voltage (table I). For one of these two cells the corrected voltage was 0.005 volt lower and for the other cell, the corrected voltage was 0.008 volt lower.

TABLE I. - ABSOLUTE VALUES OF INDIVIDUAL CUPROUS

SULFIDE - CADMIUM SULFIDE CELL DATA

Cell	Load resistance, R_L, ohms	Uncorrected load voltage, $V_{L,1}$, V	Corrected load voltage, $V_{LC,1}$, V	Corrected load voltage cycle 1429, V_{LC}, V
1	0.43	0.265	0.314	0.301
2	.42	.249	.310	.298
3	.48	.273	.340	.322
4	.67	.327	.375	.368
5	.93	.385	.392	.394
6	1.38	.408	.403	.400
7	4.85	.434	.426	.419
8	.32	.211	.235	.222
9	.62	.335	.361	.357
10	.50	.229	.316	.298
11	.53	.276	.347	.327
12	.59	.318	.357	.351
13	.43	.269	.311	.289
14	.64	.328	.374	.352
15	.64	.328	.362	.354

RESULTS AND DISCUSSION

The performance measurements taken after the cells were exposed to 1429 thermal cycles showed that most of them degraded. The performance degradation was generally characterized by a decrease in maximum power, a decrease in short-circuit current, and an increase in open-circuit voltage. The maximum power output ranged between 81 and 100 percent of their precycling values. Others (ref. 1) have observed this same type of degradation. Visual inspection revealed four of the fifteen cells delaminated slightly along the edges.

A thermogram of the cell loaded at the highest voltage value indicates a hot spot after thermal cycling which was not present prior to cycling. Hot spots are believed to be caused by high currents passing through short circuits in the cell (ref. 8). A thermogram of the cell is presented in figure 2. The thermogram on the left of this figure was taken with no apparent current passing through the cell (background). The reason for the light region on the thermogram is not known. The thermogram on the right of this figure was taken with current (0.3 A) passing through it and showed a hot spot. The location of the hot spot is the same as the light region in the background. To ensure that

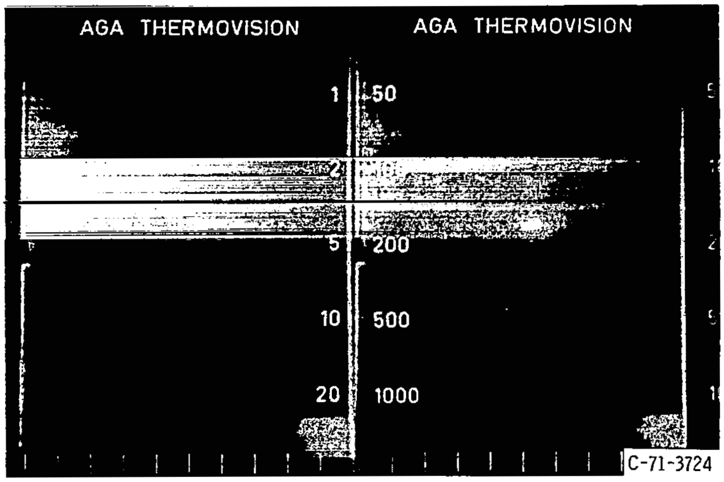

Figure 2. - Thermograms of cuprous sulphide - cadmium sulphide solar cell which degraded the most.

this was not a spurious observation, current through the cell was varied. The diameter and intensity of this hot spot was varied with the amount of current passing through the cell. The gray scale at the bottom of the picture represents a temperature scale, in this case, a 5 K range.

Individual relative cell data are presented in table II. The parameters $P_m/(P_m)_O$, $V_{oc}/(V_{oc})_O$, and $I_{sc}/(I_{sc})_O$ are the relative maximum power, open-circuit voltage, and short-circuit current, respectively (post-cycling relative to precycling). These relative parameters were obtained from the I-V curves traced at 298 K (25° C). The parameter A/A_O is the relative active (nondelaminated) cell area. The relative maximum power and relative short-circuit current values shown were corrected for the loss of active cell area by a simple ratio of areas.

The load resistance R_L, cycle 1 uncorrected load voltage $V_{L,1}$, cycle 1 corrected load voltage $V_{LC,1}$, and cycle 1429 (end of test) corrected load voltage V_{LC} are presented in table I. The corrected load voltage changed between cycle 1 and cycle 1429. However, this change in load voltage was small for cells 5, 6, and 7, which were loaded at the highest initial load voltage values. For cells 5, 6, and 7 the change in load voltage was 0.002, 0.003, and 0.007 volt, respectively.

From the data in tables I and II, a curve of $P_m/(P_m)_O$ as a function of the cycle 1 corrected load voltage is shown in figure 3. These data show the presence of a load voltage effect. The degradation of the cells was relatively independent of their load voltage up to about 0.39 volt, which appears to be a threshold voltage beyond which there was a significant loss in performance of the cells.

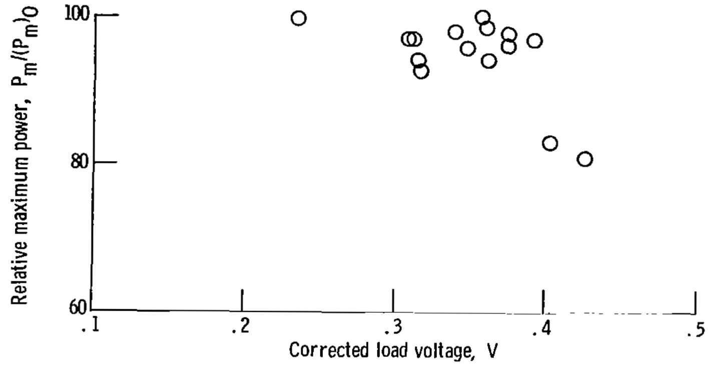

Figure 3. - Effect of load voltage on maximum power of cuprous sulfide - cadmium sulfide solar cells which were thermal cycled for 1429 cycles.

TABLE II. - RELATIVE VALUES OF INDIVIDUAL CUPROUS SULFIDE - CADMIUM SULFIDE CELL DATA

Cell	Post-cycling to precycling			
	Maximum power,[a] $\frac{P_m}{(P_m)_O}$	Open-circuit voltage,[a] $\frac{V_{oc}}{(V_{oc})_O}$	Short-circuit current,[a] $\frac{I_{sc}}{(I_{sc})_O}$	Active area, $\frac{A}{A_O}$
1	0.14	1.02	0.96	1.00
2	.97	1.02	.97	1.00
3	.98	1.02	.98	1.00
4	.98	1.01	.97	1.00
5	.97[b]	1.02	.97[b]	.96
6	.83	.99	.88	1.00
7	.81	1.00	.90	1.00
8	1.00	1.03	.97	1.00
9	.99[b]	1.03	.99[b]	.92
10	.93[b]	1.01	.96[b]	.98
11	.96	1.00	.99	1.00
12	1.00	1.02	.99	1.00
13	.97	1.02	.97	1.00
14	.96	1.00	.99	1.00
15	.94[b]	1.01	.99[b]	.97

[a]Data taken in air at 298±1 K (25°±1° C) and simulated air mass zero (AM0) sunlight.

[b]Corrected for loss in active area.

The correction made to the measured load voltages had no effect on the indicated value of the threshold voltage. Figure 4 shows $P_m/(P_m)_o$ as a function of the uncorrected load voltage. The lower voltage points have moved to somewhat higher voltages, but the higher voltage points are essentially unchanged, and the threshold voltage appears to be about 0.39 volt as shown in either figure 3 or 4.

The threshold voltage of about 0.39 volt is in agreement with the voltage of 0.386 volt (ref. 11) necessary to decompose Cu_2S into metallic copper and cupric sulfide (barier layer of CdS cell is composed of Cu_2S (ref. 12)). This decomposition voltage was

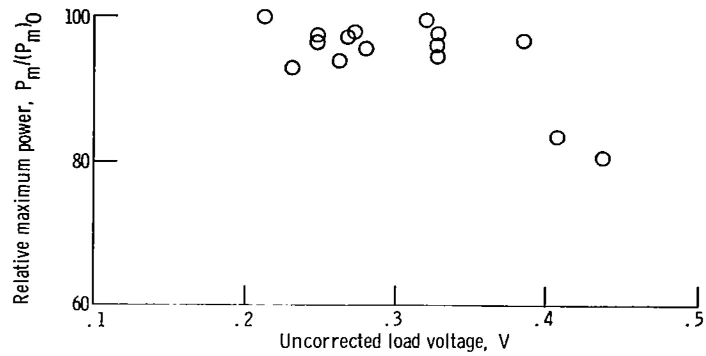

Figure 4. - Effect of uncorrected load voltage on maximum power of cuprous sulfide - cadmium sulfide solar cells which were thermal cycled for 1429 cycles.

calculated at 298 K (25° C); however, the cells in situ operated at about 323 K (50° C).

The decomposition of Cu_2S may be the primary cause of CdS cell degradation. The observations that (1) the cells which degraded the most in maximum power were loaded at voltages higher than the decomposition voltage, and (2) the cell loaded at the highest voltage developed a hot spot are what one would expect when Cu_2S was being decomposed. Others (ref. 7) observed copper nodules on some degraded cells. However, microscopic inspection (X80) of the hot-spot region developed on the cell, in this test, showed no copper nodules.

CONCLUSIONS

The effect of load voltage on thin-film Cu_2S-CdS solar cells thermally cycled for 1429 cycles in a simulated space environment was investigated. Cell performance was measured under controlled conditions in air before and after vacuum thermal cycling.

There was a load voltage effect. The degradation of the Cu_2S-CdS solar cells was relatively independent of load voltage up to about 0.39 volt, which appears to be a threshold voltage. Beyond this voltage the cells degraded rapidly. The cell which was loaded at the highest voltage value developed a hot spot. Fortunately, the threshold voltage appears to be sufficiently higher than the maximum power voltage of 0.33 volt, so that it can be avoided in most space applications.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 7, 1971,
113-33.

REFERENCES

1. Kennerud, K. L.: Simulated Space Environmental Tests on Cadmium Sulfide Solar Cells. Rep. D2-121002-1, The Boeing Co. (NACA CR-72507), Feb. 28, 1969.
2. Smithrick, John J.: Effects of Thermal-Shock Cycling on Thin-Film Cadmium Sulfide Solar Cells. NASA TM-X-1819, 1969.
3. Ratajczak, Anthony F.; Klucher, Thomas M.; and Swartz, Clifford K.: Effects of Simulated Space Environment on Full-, Half-, and Quarter-Size Cadmium Sulfide Thin-Film Solar Cells. NASA TM X-1884, 1969.
4. Scudder, Larry R.; Godlewski, Michael P.; and Klucher, Thomas M.: Observations on Degraded CdS Solar Cells. NASA TM X-52668, 1969.
5. 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.
6. Shirland, F. A.; and Heitenan, J. R.: The Thin Film CdS Solar Cell. Thin Film Solar Cells and Radiation Damage. Vol. II of the Proceedings of the Fifth Photovoltaic Specialists Conference. Rep. Pic-Sol-209/6.1, Pennsylvania Univ. (NASA CR-70169), Jan. 1966.
7. Brandhorst, Henry W., Jr.: Calibration of Solar Cells Using High-Altitude Aircraft. Solar Power Systems Considerations. Vol. III of the Proceedings of the Fifth Photovoltaic Specialists Conference. Rep. Pic-Sol-209/6.2, Pennsylvania Univ. (NASA CR-70170), Jan. 1966.
8. Scudder, Larry R.; Godlewski, Michael P.; Bozek, John M.; and Klucher, Thomas M.: Shorting Path Mode of Degradation in Copper Sulfide-Cadmium Sulfide Thin-Film Solar Cells. NASA TN D-6362, 1971.

9. Borg, Sven-Bertil: Thermal Imaging with Real Time Picture Presentation. Appl. Opt., vol. 7, no. 9, Sept. 1968, p. 1697.

10. Wolf, Martin; and Rauschenbach, Hans: Series Resistance Effects on Solar Cell Measurements. Advanced Energy Conversion, vol. 3, no. 2, Apr.-June 1963, pp. 455-479.

11. Bernatowicz, Daniel T.; and Brandhorst, Henry W., Jr.: The Degradation of Cu_2S-CdS Thin-Film Solar Cells Under Simulated Orbital Conditions. Conference Record of the Eighth Photovoltaic Specialists Conference. IEEE, 1970, pp. 24-29.

12. Brandhorst, Henry W., Jr.: Impurity Profile and Energy Band Diagram for Cu_2S-CdS Heterojunction. Presented at the IEEE Photovoltaic Specialists Conference, Pasadena, Calif., Nov. 19-21, 1968.