NASA TECHNICAL NOTE

NASA TN D-3038

NASA TN D-3038

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1965

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SUMMARY

Heat damage and thermal cycling tests were performed on thin-film cadmium sulfide solar cells to determine the suitability of these cells for operation in a space environment. The temperature range was 80° to 200° C for heat damage studies and -90° to 62° C for thermal cycling tests. Test durations for heat damage and thermal cycling studies were 586 hours and 1600 cycles, respectively.

Mechanical and physical weaknesses in the cell design were uncovered during heat damage tests. These weaknesses, which consisted of faulty cell contacts and delamination of plastic encapsulant, were overcome by soldering the contacts to the cell structure and by using a high-temperature encapsulant. Degradation of cell output at elevated temperatures was evident at 200° C for the heat damage tests; the cell output, however, stabilized after the temperature was reduced below 200° C, which indicated that no damage to the cell junction had occurred.

Thermal cycling tests revealed several cell problem areas, which included loss of cell contact between gold grid and silver collecting straps, failure of cell encapsulant, and short circuiting of the cell caused by the type of grid used. These problems were solved by the use of a high-temperature encapsulant. With electroformed grids instead of the earlier wire-mesh grids, the solar cells were able to withstand wide temperature excursions without short circuiting. Improved solar cells, designed to eliminate these types of failure, were successfully run up to 1495 thermal cycles without any apparent cell degradation.

INTRODUCTION

For solar cells to be successful sources of power in space, they must be capable of operating in a hostile space environment for extended periods of time. In order to evaluate new cell designs, particularly thin-film cadmium sulfide cells, a program was undertaken at the Lewis Research Center in which the function of such cells in the vacuum and thermal environment of space was tested.

In the vacuum of space, cell temperatures are determined by radiation balance; as a result, high operating temperatures occur. The normal operating temperature of thin-film cadmium sulfide solar cells in space sunlight has been estimated at 50° to 70° C depending on the orbit. It is possible that several years exposure to this temperature could degrade the cell output significantly. To explore this possibility, cells were operated at elevated temperatures ranging from 80° to 200° C in vacuum.

Orbiting through the shadow of the Earth also imposes severe thermal stresses on the cells. The thermal effects of such orbits were evaluated by subjecting the cells to alternate periods of simulated sunlight and darkness in a vacuum chamber with liquid-nitrogen cooled walls. Failures observed in these tests were analyzed and have provided cell designs capable of withstanding long-term cycling.

DESCRIPTION OF APPARATUS

The space simulator, shown in figure 1, has a 10-inch-diameter, 26-inch-long chamber that can accommodate four 3- by 3-inch cells. For thermal cycling studies, this chamber is cooled by a pressure-fed liquid-nitrogen system which consists of two separate cooling shrouds, as shown in figure 2. The outer shroud is made of 3/8-inch-diameter stainless steel tubing which is coiled along the entire chamber length. The inner cooling shroud, also of 3/8-inch-diameter stainless steel tubing, is geometrically the frustum of a cone, and it is in this area that the four cadmium sulfide cells being tested are located. Both shrouds were blackened by a sodium dichromate treatment so that the cells would be in a blackbody environment. The purpose of the outer shroud is to bring inside chamber temperature down to approximately -90° C, and the inner shroud ensures that the cells will reach the -90° C equilibrium temperature quickly.

Initially, the space simulator chamber used for heat damage and thermal cycling tests was a 12-inch-long chamber with liquid-nitrogen cooling coils inside. The first test in this space chamber, using thin-film solar cells with temperature thermistors attached, showed that the chamber did not provide adequate cooling. With a constant flow of liquid nitrogen through the cooling-coil shrouds and with no light irradiation upon the cells, the minimum dark-cell temperature attainable was -17° C, and with light irradiation the cell temperature was approximately 110° C. It is estimated that a thin-film cadmium sulfide solar cell should have a dark temperature of -90° C and an illuminated temperature of approximately 62° C based on a 90-minute orbit.

A 1/4-inch-diameter, blackened aluminum ball with an iron-constantan thermocouple embedded within was mounted in the test plane of the chamber. After the test ball was irradiated for 1/2 hour with a tungsten light source, the temperature of this ball was 121° C. With no irradiation, the test ball had a dark temperature of -15° C after 3/4 hour. The evaluation of these data disclosed that the chamber test plane was receiving significant thermal radiation from the outside surroundings. The chamber length, therefore, was increased to 26 inches, and additional liquid-nitrogen cooling coils were added.

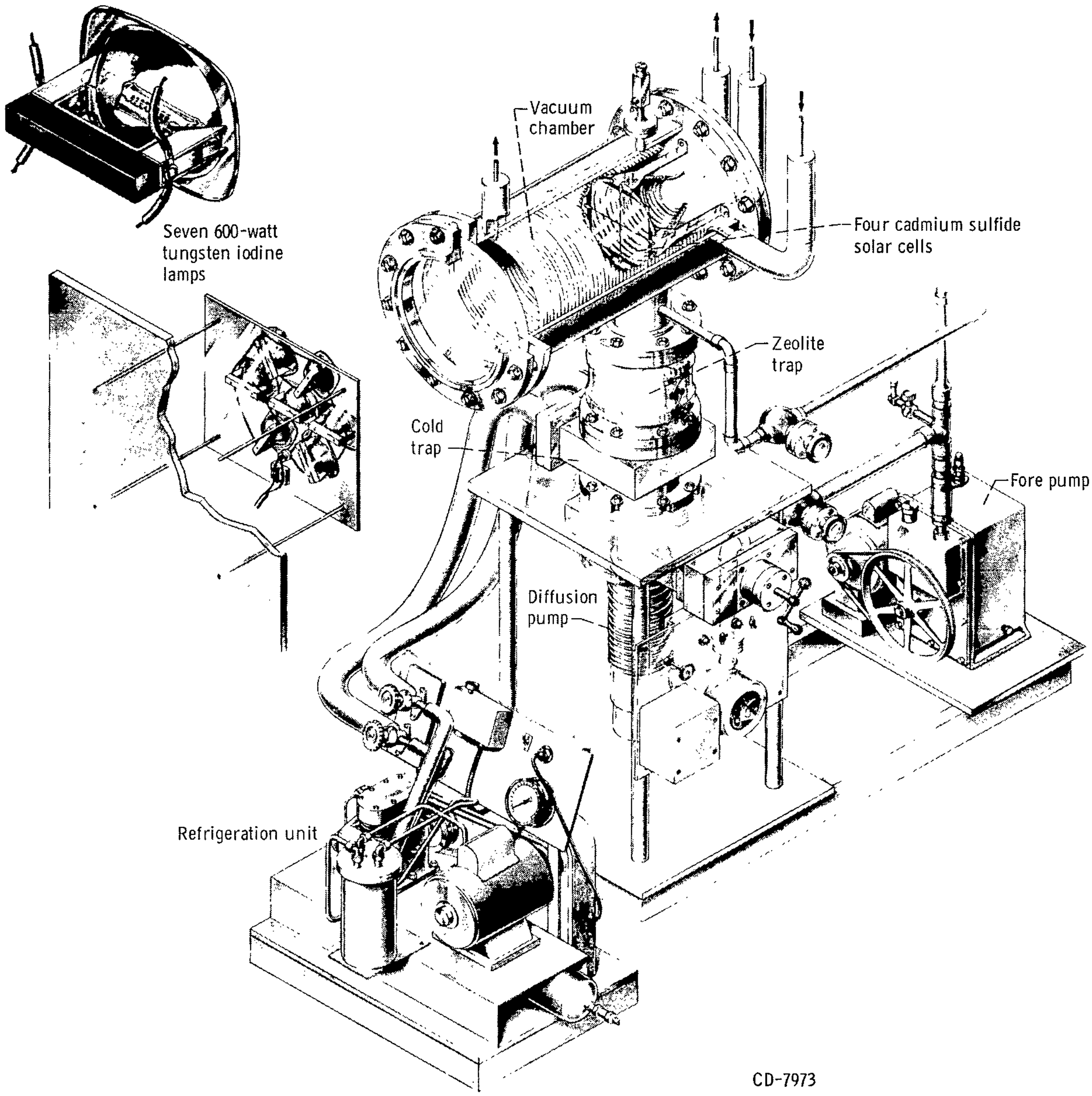


Figure 1. - Layout of space simulator test apparatus.

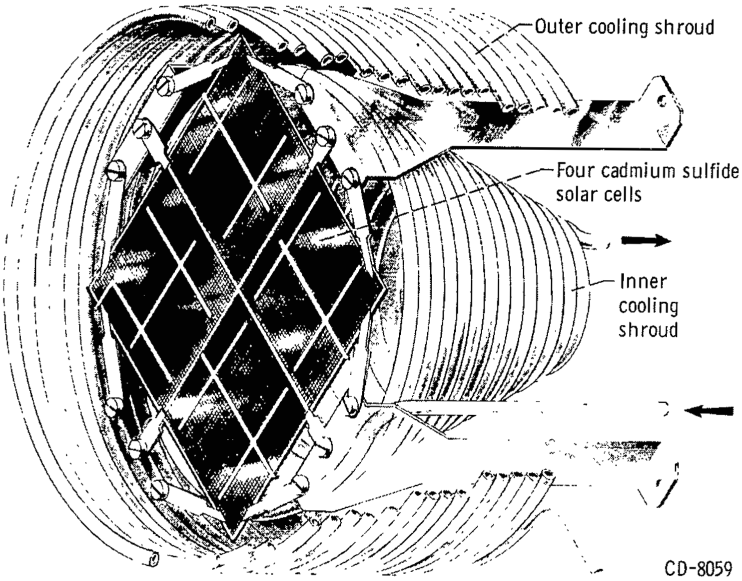


Figure 2. - Inner and outer cooling shrouds and location of cadmium sulfide solar cells.

The chamber used for the present investigation comes to an equilibrium dark temperature of -90° C in approximately 7 minutes; and, with tungsten irradiation, the cell temperatures stabilize after 7 to 8 minutes at 62° C. For heat damage studies, the liquid-nitrogen cooling coils were modified to accept water, so that the chamber could be operated at elevated temperatures.

The vacuum equipment associated with the chamber includes a roughing pump, a diffusion pump, and a refrigerated cold trap system (see fig. 1, p. 3). The light source consists of seven 600-watt tungsten iodine lamps with individual reflectors located approximately 4 feet from the test plane. The chamber window is 1-inch-thick fused quartz.

Figures 3 and 4 are electrical diagrams showing the power, control, measuring, and recording systems. The power system utilizes a variac to control input to the tungsten lamp source. Control of the tungsten light source on-off cycle is attained by means of a tandem timer that is preset to the desired duty cycle. The automatic data-recording system is built around a modified standard 24-point 10-millivolt recorder. A synchronized rotary switch, installed inside the recorder, switches the positive side of each cell to the next respective cell, while the negative side of each cell is tied to a common ground. Under normal operation, data are recorded for cell open-circuit voltage and for load voltages of 3, 1, 0.5, and 0.1 ohm. The load resistors used are precision wire-wound resistors that have an accuracy of ±0.1 percent. When the last reading (0.1-ohm load) is taken for a particular solar cell, a cam-operated microswitch, mechanically linked to the recorder drive, switches to the next solar cell. The open-circuit and load-voltage sequences are then repeated for this cell.

Data for all cells were taken when cell temperatures stabilized. The equilibrium temperature was usually attained after approximately 8 minutes of light irradiation. However, for cycles with lights on for 60 minutes and off

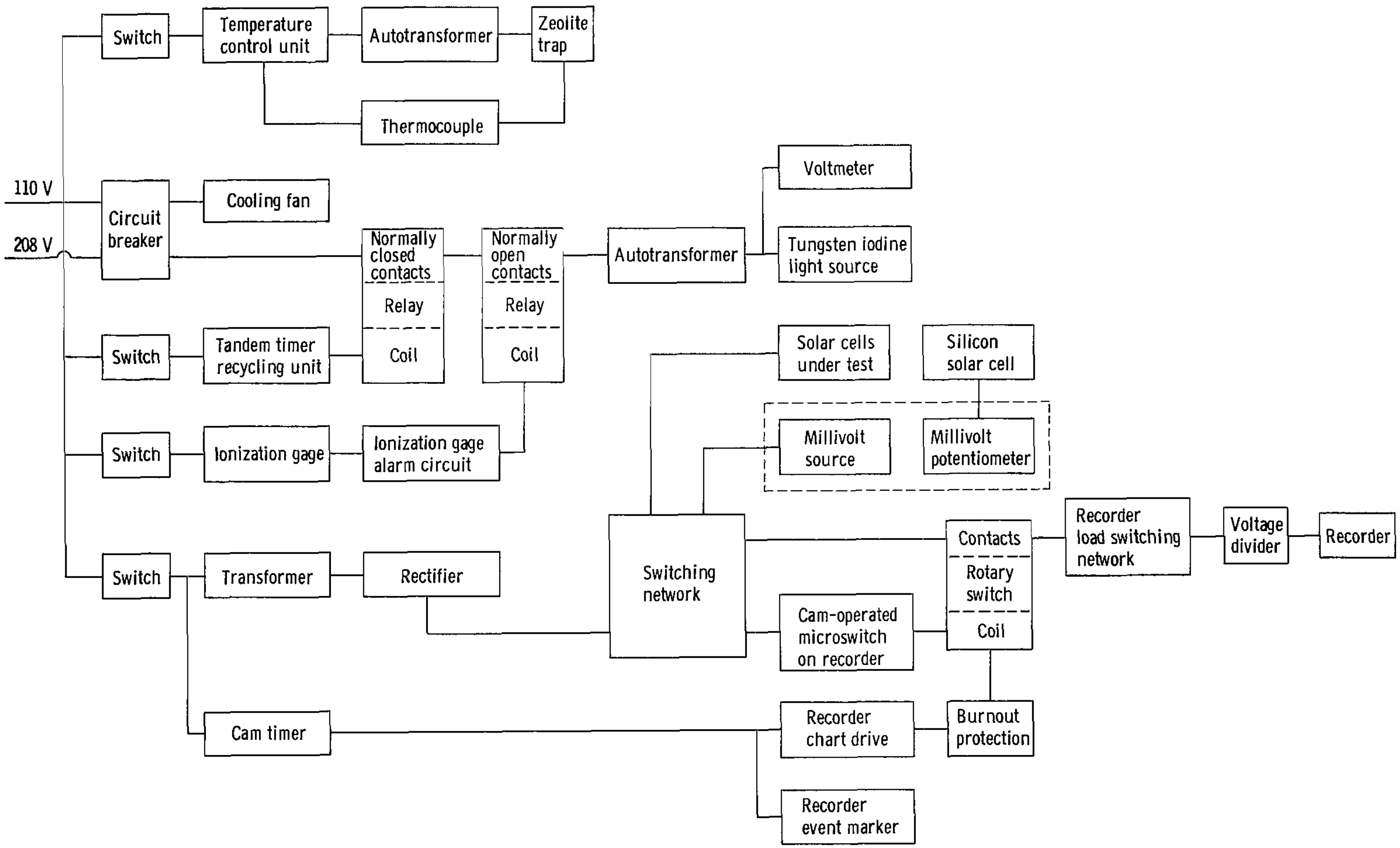


Figure 3. - Electrical schematic of instrumentation.

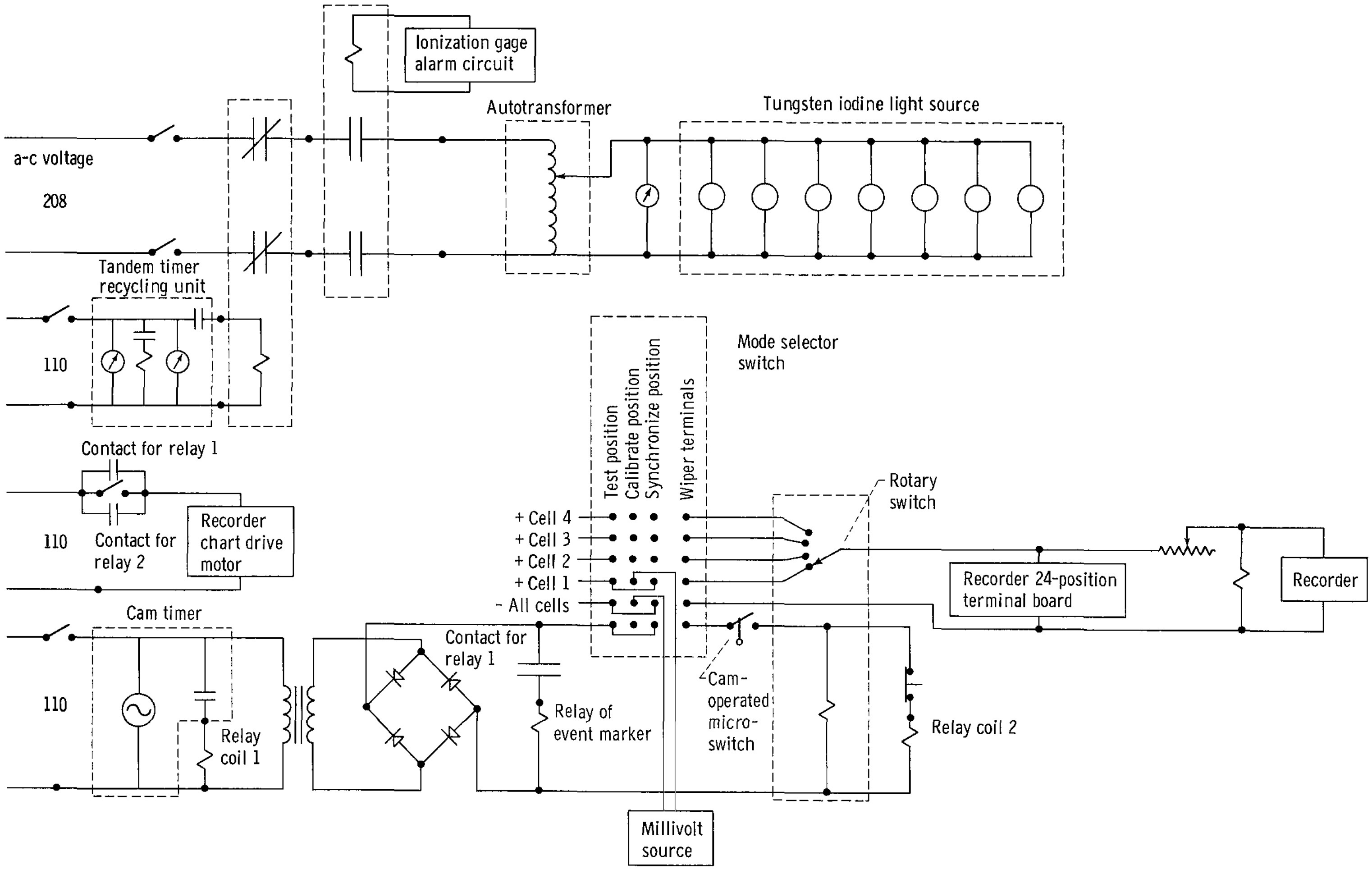


Figure 4. - Wiring diagram for instrumentation.

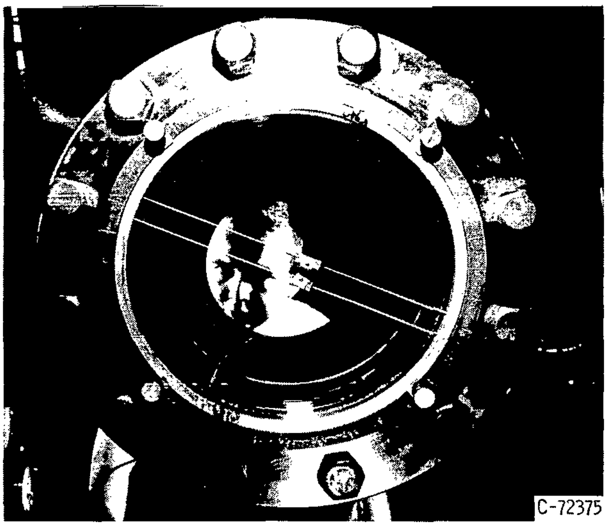


Figure 5. - Flux monitor, mounted on front flange of vacuum chamber.

for 30 minutes, measurements were taken 30 minutes after the lights were turned on. This was done to ensure that all cells were under equilibrium conditions, and that cell output data were taken at the same time for every thermal cycle. Before the data from each respective cell were recorded, a voltage divider network dropped the cell voltages for open circuit and loads, in order to accommodate the 10-millivolt recorder range.

Provisions have been made in this system for recorder calibration and cell synchronization, as shown in figure 4. The calibration source provides a variable full-scale span from 0 to 1100 millivolts. In the synchronization, test, cell position, cell number, cell load number, and recorder print number are all coordinated with each other. To ensure trouble-free operation during thermal cycling tests, the recorder calibration and cell synchronization are checked weekly. Provisions have also been incorporated for a manual readout of the system when required. This procedure utilizes a digital voltmeter in conjunction with a manually operated load-selector switch.

In order to provide a light intensity equivalent to an average solar constant, the voltage of the tungsten source was varied until the total intensity, as measured with a 180° pyranometer without regard to matching the solar spectrum, was 140 milliwatts per square centimeter. Cell temperatures (measured with thermistors) were approximately 62° C during cycling tests at the same lamp power and distance.

To ensure constant radiation intensity on the cells, a light source monitor using a silicon solar cell was employed. Solar cell short-circuit current was measured radially in the correct light plane once a week, and light input was corrected when required. It has been found that, as the tungsten iodine lamps age, their spectrum shifts, and this results in decreased solar cell outputs. Compensation of light input to the solar cells or installation of new lamps alleviated this change. Figure 5 shows the flux monitor and its placement in the system. The monitor, mounted on the front of the chamber, consisted of two concentric rings, the inner ring being movable. The silicon monitor cell assembly moved on two wire guides that were mounted on a diameter of the inner ring. With this monitor cell it was possible to obtain a flux profile of the tungsten light source.

DESCRIPTION OF SOLAR CELL

The thin-film cadmium sulfide solar cell, shown in figures 6 and 7, is composed of a molybdenum foil substrate upon which a thin film (2 mils) of

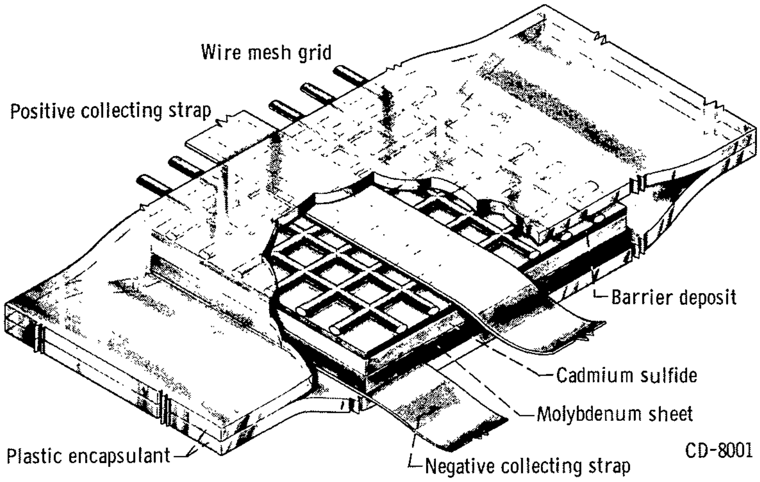


Figure 6. - Sectional view of cadmium sulfide solar cell (not to scale).

cadmium sulfide is applied by vacuum evaporation (ref. 1). A barrier deposit is formed on the cadmium sulfide and is contacted by a gold mesh current collector grid. The appropriate negative and positive collecting straps are positioned, and the cell is completed by lamination between layers of sheet plastic encapsulant. The plastic encapsulant is required for this type of solar cell in order to keep the cadmium sulfide from absorbing moisture and also to ensure cell component integrity.

The earlier cadmium sulfide solar cells used gold wire mesh as the current collector. This wire grid was laid on the barrier surface and held in place by plastic encapsulant. The later cells were fabricated with electroformed grids of gold which were plated from a chemical bath as the current collector. These cells were an improvement over the earlier cells because the new grids adhered well to the barrier layer without being dependent on the plastic encapsulant.

Two barrier deposit methods, electroplating and chemiplating, were used for thin-film cadmium sulfide solar cells. The electroplated barrier was formed by electrically plating cuprous sulfide onto the cadmium sulfide substrate from a buffered cuprous chloride solution, and the chemiplated barrier was the result of the chemical reaction of cadmium sulfide and cuprous chloride in solution to form a barrier layer of cuprous sulfide. In practice, the cadmium sulfide film is dipped in the cuprous chloride solution for approximately 1 second. After removal from the solution, it is annealed at an elevated temperature. The chemiplated carrier is similar in appearance to the electroplated barrier, but has a slightly gray cast.

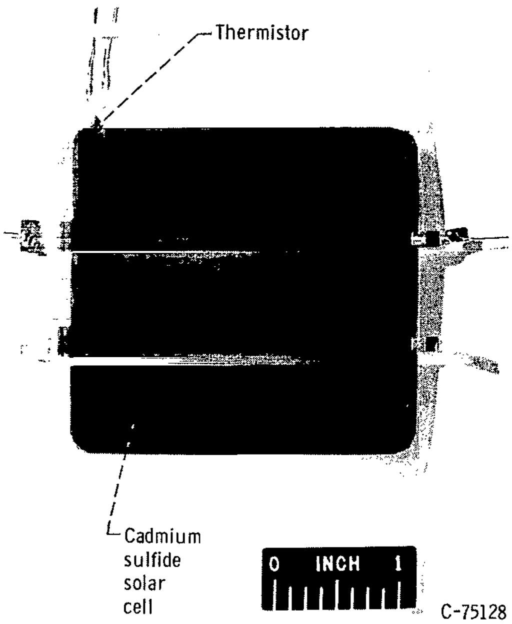


Figure 7. - Cadmium sulfide solar cell with thermistor attached.

PROCEDURE

Heat Damage Tests

Prior to use in heat damage tests, cadmium sulfide solar cells were stored in either a desiccator or a vacuum chamber. The solar cells were prepared for testing by mounting a small bead thermistor (nominal resistance, 2000 ohms) to the front of each cell with epoxy cement (fig. 7). Cells were then mounted on a blackened stainless steel plate with epoxy cement, to ensure cell temperature stabilization during heat damage runs. The liquid-nitrogen cooling coils were connected to a water supply so that cell temperatures could be controlled by varying the coolant flow as well as the tungsten light intensity. For the heat damage series of tests, the chamber vacuum attained was 2×10^{-5} torr. In heat damage test 1 cadmium sulfide solar cells were run continuously at cell temperatures of 80°, 100°, and 120° C. In heat damage test 2 cells were run at temperatures of 100°, 130°, and 180° C, and in test 3 cells were run at temperatures of 150° and 200° C. In test 2 cell temperatures were cycled, whereas in test 3 the cell temperatures were not cycled. A heat damage cycle in test 2 consisted of 1 hour of light illumination at a predetermined cell temperature and 1/2 hour of dark time. It was thought that this type of cyclic test would tend to accelerate damage or degradation of the cells; it did not, however, greatly influence either. In heat damage test 3, therefore, solar cells were illuminated continuously at a given temperature. Data from the three heat damage tests of thin-film cadmium sulfide solar cells were taken manually every 4 hours.

Thermal Cycling Tests

The cells used in thermal cycling tests were mounted to the back flange assembly by means of clamping devices, which minimized heat conduction paths between the cells and the cooling cone. The chamber with mounted cells was evacuated, and the zeolite trap was baked out. After a vacuum of 1×10^{-6} torr was attained, the liquid-nitrogen flow was started through both shrouds. At this time, the recorder calibration and cell synchronization were checked. When cell temperatures reached approximately -90° C with a stable chamber vacuum of about 2×10^{-7} torr, the thermal cycling test was started. For the light portion of the initial thermal cycle, the tungsten iodine lamps were turned on and lamp voltage was adjusted to give the required stabilized cell temperature of 62° C. Data for each individual cell consisted of open-circuit voltage and load voltage measurements for 3.0, 1.0, 0.5, and 0.1 ohm. Cell temperatures were taken manually once a day.

DISCUSSION

Heat Damage Tests

Heat damage test 1 was conducted on three 1- by 3-inch cadmium sulfide solar cells in the space simulator. The cells were tested at temperatures of 80°, 100°, and 120° C for various periods of time. Not only did the cells fail at high temperatures, but there were large fluctuations and a steady decline in open-circuit voltage and load voltages. In all cases, cell outputs became very intermittent, and in one case the plastic encapsulant discolored. Inspection of cells revealed the two probable causes to be poor contact between the silver collecting strap and the gold grid (fig. 6, p. 8), and plastic encapsulant delamination from the cell structure. One cell was modified by applying silver-filled conducting epoxy under the silver collecting straps. After 150 hours of constant light irradiation at 120° C, the cell output began to fluctuate rapidly and continued to fluctuate for the remainder of the test.

Results from heat damage test 1 showed that the silver collecting straps were not making pressure contacts with the gold grid or the molybdenum substrate. The following improvements were made in the contacts:

(1) The molybdenum substrate was extended and used as a negative terminal.

(2) A copper strip was spot-welded to the molybdenum substrate extension.

(3) The silver collecting straps were soldered to the gold grid with soft gold-base solder or silver-filled conducting epoxy.

The problems of discoloration and delamination of plastic encapsulants might be solved by the use of a higher temperature encapsulating film rather than the present film; the delamination problem might also be solved by closer control of the encapsulation procedure.

A total of 586 hours of heat damage studies were made at temperatures of 100°, 130°, 150°, 180°, and 200° C with cells improved by the methods just listed. Three cadmium sulfide solar cells were run at test temperatures of 100°, 130°, and 180° C, and four other cells were run at 150° and 200° C.

TABLE I. - EFFECT OF TEMPERATURE ON OUTPUT OF CADMIUM SULFIDE SOLAR CELLS

Cell temperature, °C	Heat damage test (a)	Run time, hr	Change in open-circuit voltage, percent	Change in 1.0-ohm load voltage, percent
100	2	144	-3	+4
130	2	52	-2	-1
150	3	120	-1	-9
180	2	56	+5	-7
200	3	214	-22	-47

[a]In heat damage test 2, three cells were tested; in heat damage test 3, four cells were tested.

Table I shows the average percentage change in open-circuit voltage and short-circuit current for increasing cell temperatures in these tests. These data show a small average percentage change in open-circuit voltage and short-circuit current for cells over a temperature range of 100° to 180° C. Although the average deviation in this temperature range varied between 5 and -9 percent, deviations of this order cannot be considered significant because of other random errors present. However, the average percentage change of -22 to -47 percent for the 200° C temperature is significant, as are the wide fluctuations in output for these cells at 200° C. The outputs were so low, random, and fluctuating that it was first thought that the cells had completely failed or had been destroyed; however, the cells were subsequently operated successfully at 150° C for 120 hours. With the cells operating at 200° C continuously, it would be possible for cell delamination to occur, which would cause a loss of pressure contact between silver collecting straps and cell grid.

Because the average cell performance with the improved contacts remained essentially constant between 100° and 180° C, it was concluded that some of the failures noted earlier were due to faulty cell contacts and delamination of plastic encapsulants. The results also indicated that the junctions of these cells were apparently not damaged by operation at elevated temperatures (up to 180° C).

It is of interest to note that for the 150° and 200° C heat damage tests, the 200° C portion of the test was run first for a total of 214 hours. The observed outputs for the 150° C heat damage tests were fairly uniform and steady for a further 120 hours of tests. These data support the conclusion that cell junctions were not damaged by operation at elevated temperatures.

Thermal Cycling Tests

In thermal cycling under vacuum conditions, the solar cells were subjected to alternate periods of light and dark to simulate a near Earth orbit. During the light-on period, cell temperature, open-circuit voltage, and voltage across various loads were recorded. Five series of thermal cycling tests conducted on thin-film cadmium sulfide solar cells are presented in table II with the mechanical and electrical characteristics.

For thermal cycling test 1, all cells were constructed with an electroplated barrier and a gold wire mesh grid. The film encapsulants used in the cells were polyethylene terephthalate, polyvinyl fluoride, and polyimide type H, which will be referred to hereafter as materials M, T, and H, respectively. Film H is a highly durable plastic and is ideally suited for the temperature range of a thin-film cadmium sulfide solar cell. For this test, cells initially had a nominal open-circuit voltage of 375 millivolts, and all cell outputs tended to drop quickly and fluctuate over a wide range. The output for two of the four cells dropped to 50 percent of the original values. After 390 cycles, the test was terminated. It was found, upon inspection, that the mechanically fastened terminal posts were loose on all cells, which could account for the wide fluctuations and reduced outputs. It was concluded that positive contact between the cell and the terminal strip had to be maintained. This could be accomplished either by welding or by soldering the terminals to the cell. The cells had also delaminated at the silver collecting straps (see fig. 6, p. 8), and the resulting intermittent contact with the gold grid contributed to the variations in the outputs. It was decided that the use of the plastic encapsulant to hold the silver collecting straps in contact with the grid by pressure alone was undesirable. One solution proposed was to electroplate a strap onto the grid so that the grid and the collecting strap would become one integral unit.

TABLE II. - CHARACTERISTICS OF CADMIUM SULFIDE SOLAR CELLS SUBJECTED TO THERMAL CYCLING

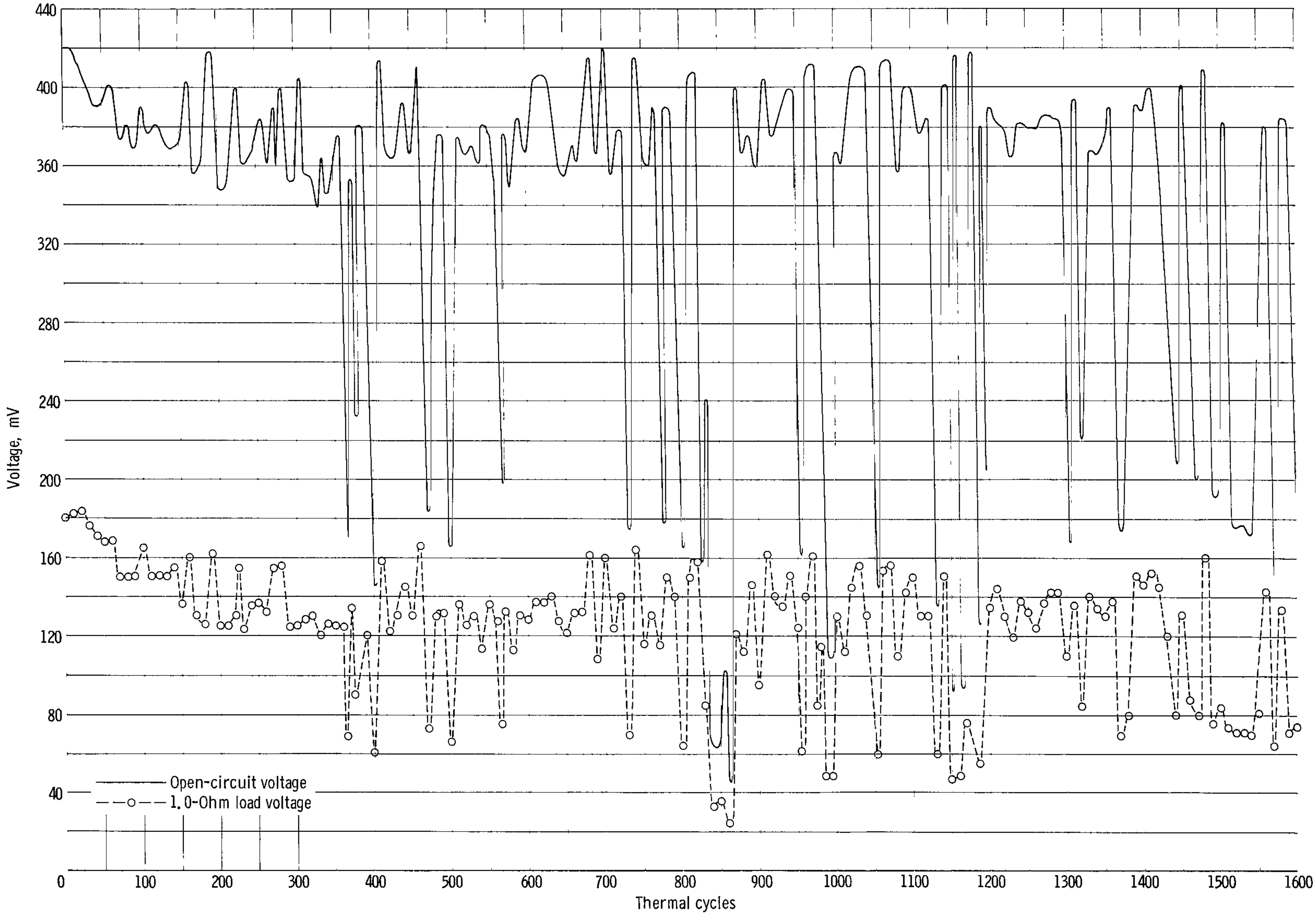
Test	Solar cell	Encapsulant		Type of barrier	Type of gold grid	Open-circuit voltage, E_{oc}, mV (c)	Short-circuit current, I_{sc}, mA (c)	Gridded area, cm^2 (c)	Power, mV (c)	Efficiency, percent (c)	Number of cycles to -		Total cycles
		Thickness, mils	Material (b)								Unstable output	Reduced output	
1	A1	1.0	M	Electro-plated	Wire mesh	480	470	44.5	109	2.5	40	300	390
	A2	1.0	H			480	440		105	2.4	75	200	
	A3	2.0	T			460	450		130	2.9	---	135	
	A4	.5	H			475	455		126	2.8	200	385	
2	B1	1.0	M	Electro-plated	Wire mesh	470	450	44.5	116	2.6	---	---	80
	B2	1.0	H			460	390		105	2.4	8	72	
	B3	.5	H			460	390		108	2.4	24	30	
	B4	.5	H			460	390		108	2.4	14	58	
3	C1	1.0	H	Electro-plated	Wire mesh	460	440	44.5	123	2.8	---	---	1600
	C2	.5				470	380	44.5	104	2.3	365	---	
	C3	[d]1.0				440	380	49.0	90	1.8	800	---	
	C4	[d]1.0				440	420	48.0	102	2.1	1100	---	
4	D1	[d]1.0	H	Chemi-plated	Electro-formed	400	480	51.0	92	1.8	----	---	1495
	D2		H	Chemi-plated	Electro-formed	400	460	51.5	91	1.8	----	---	
	D3		M	Electro-plated	Wire mesh	450	385	31.3	103	3.3	250	---	
	D4		H	Electro-plated	Electro-formed	400	265	47.0	76	1.6	---	---	
5	E1	1.0	H	Electro-plated	Electro-formed	440	380	45.0	91	2.0	---	---	1350
	E2					420	310		69	1.5	---	---	
	E3					440	360		96	2.1	---	---	
	E4					370	105		25	0.6	---	---	

[a]All cells were plastic encapsulated front and back unless otherwise noted.
[b]Material H, polyimide film type H; material M, polyethylene terephthalate; material T, polyvinyl fluoride.
[c]Manufacturer's results taken with 100 mW/cm^2 tungsten light source in open air.
[d]Plastic on front side of cell only.

All the collecting straps which had lost their pressure contact with the gold grid were repaired by being cemented with a silver-filled conducting epoxy. Although these cells operated satisfactorily under atmospheric conditions with a tungsten light source, it was felt that in the space chamber they might not produce reliable data because they had been substantially degraded in the previous failures. It was decided, therefore, to incorporate the results into cell designs for thermal cycling test 2 instead.

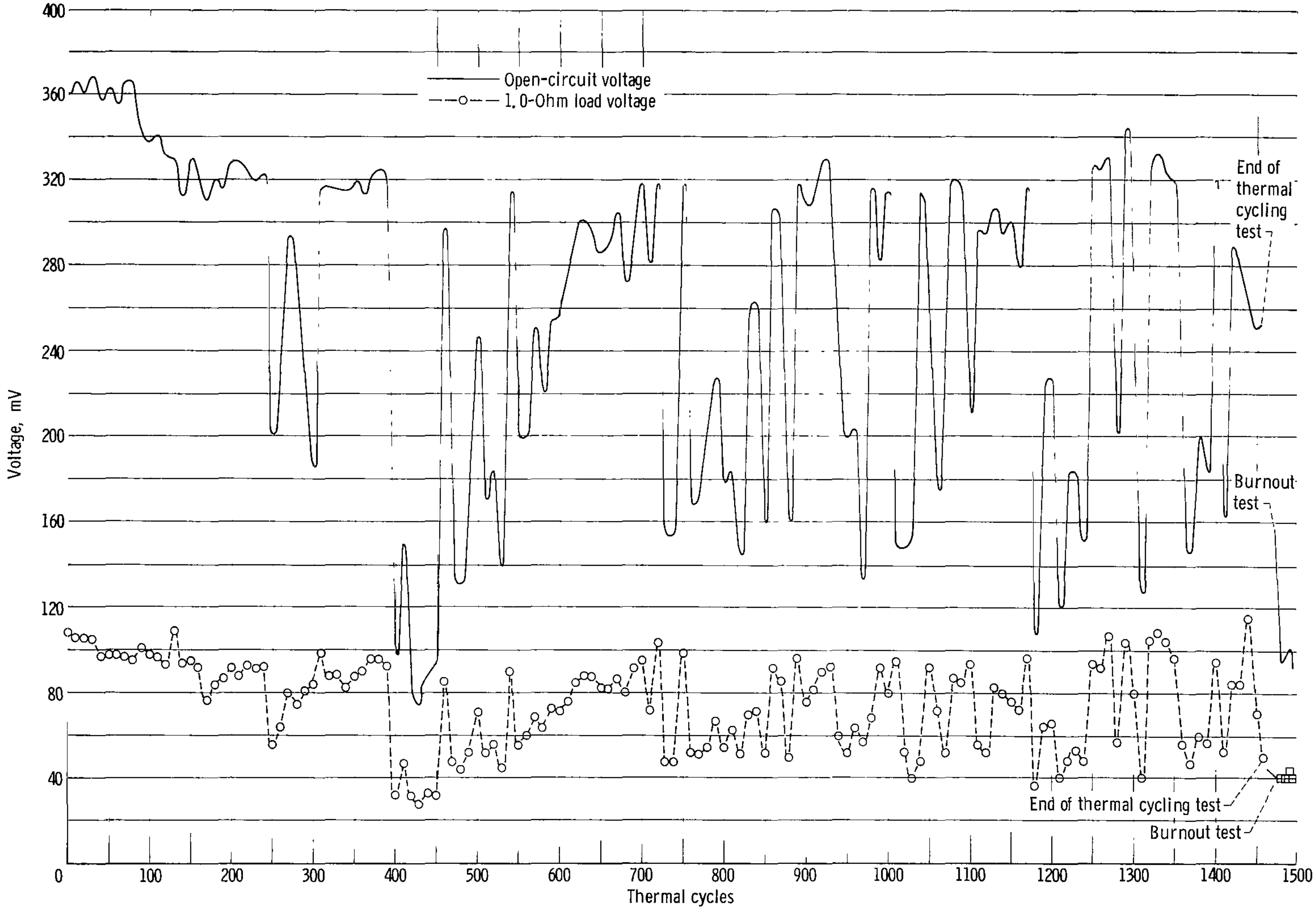
Thermal cycling test 2 was started on four modified cadmium sulfide cells. Three cells (B2, B3, and B4) were encapsulated in H film, and the fourth cell (B1) was encapsulated in M film material. The barriers and grids were the same as those used for thermal cycling test 1. The cell terminal connections were improved by being mechanically fastened and soldered, and the encapsulation procedures were conducted carefully on these cells so that the aforementioned delamination problems were minimized. Wide fluctuations were observed for three cells after 25 thermal cycles, and typical variations in open-circuit voltages were from 375 to 100 millivolts. Thermal cycling test 2 was terminated after 80 thermal cycles. Inspection of the cells showed diagonal cracks running from the corners on cell B1. These cracks might have been caused by the pressure restrictions imposed by the M film encapsulant. The cells which were encapsulated with H film, B2, B3, and B4, were short circuited. Cell B1 was the only cell that had stable outputs throughout thermal cycling test 2. No conclusions were reached regarding the failures experienced with H film encapsulated cells. Because thermal cycling test 2 was inconclusive in this respect, cell modifications for two cells were repeated and the validity of thermal cycling test 2 was checked in the next thermal cycling test.

In thermal cycling test 3, all cells were encapsulated with H film, and all had wire mesh grids and electroplated barriers. Two cells (C1 and C2) were similar to the cells used in thermal cycling test 2, while cells C3 and C4 were further modified by plastic film encapsulants on the front sides only. The back plastic encapsulant was removed for several reasons, which included weight reduction, decreased thickness, and better thermal control of the back side of the cell. Open-circuit voltages of cells C2, C3, and C4 started to fluctuate rapidly at approximately 365, 800, and 1100 thermal cycles, respectively. When the tests were terminated at 1600 cycles, cells C2, C3, and C4 were found to be short-circuited, while cell C1 had a fairly uniform output throughout the test. Figure 8(a) shows the wide fluctuations of the open-circuit voltage and voltage across a 1-ohm load during thermal cycling for cell C2. These fluctuations were also typical for cells C3 and C4. Delamination of cell encapsulant was not evident for this test, nor did any of the silver collecting straps lose their pressure contacts with the cell gold grid. Therefore, the problems of cell delamination and pressure contacts experienced in thermal cycling tests 1 and 2 were solved, and it appeared that the H film encapsulation was an improvement for a thin-film cadmium sulfide solar cell. Thermal cycling test 3 did, however, uncover a new problem for thin-film cadmium sulfide solar cells - cell short circuits. It was concluded that the source of the problem could be the gold grid. Because the various components of cadmium sulfide cells have different coefficients of thermal expansion, movement between various parts of the cell could take place during thermal cycling, and it is reasonable to assume that the gold wire grid could move back and forth on the cell barrier (see fig. 6, p. 8) and eventually break through the barrier and establish a localized



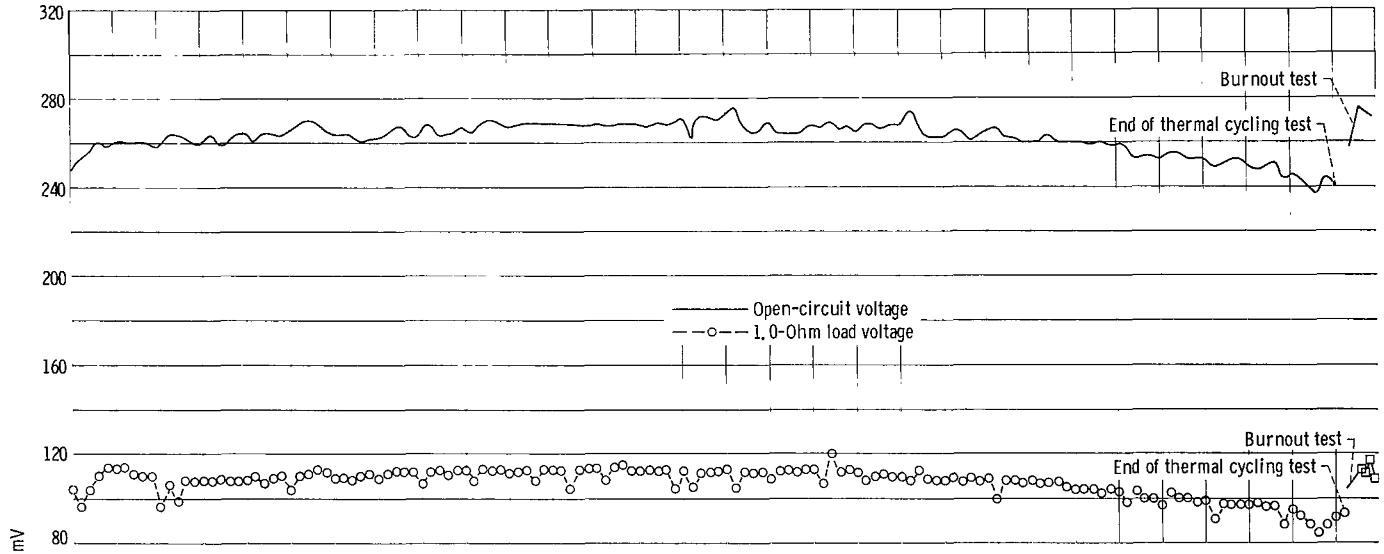
(a) Cell C2; thermal cycling test.

Figure 8. - Output of cadmium sulfide solar cells during thermal cycling and burnout tests.

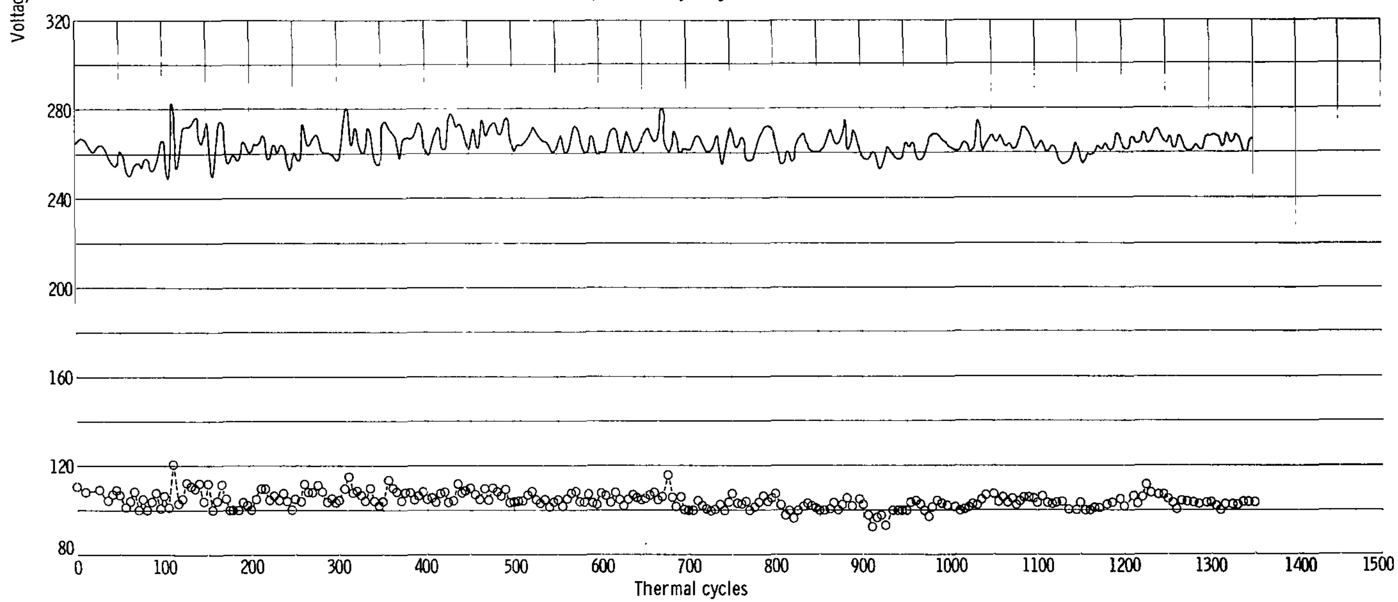


(b) Cell D3; thermal cycling and burnout tests.

Figure 8. - Continued.



(c) Cell D4; thermal cycling and burnout tests.



(d) Cell E1; thermal cycling test.

Figure 8. - Concluded.

short circuit. The fluctuations recorded may be due to the making and breaking of this localized short circuit with the temperature cycling. A possible solution for this short circuiting would be an electroformed grid rather than a gold wire mesh on the barrier layer.

This theory was tested in thermal cycling test 4. Three improved solar cells (D1, D2, and D4) had electroformed grids, while the fourth cell (D3) had a gold wire mesh grid. Cells D1, D2, and D4 were encapsulated with H film, while D3 was M film encapsulated, and all cells had plastic film encapsulant on the front side only for the reasons mentioned on page 13. Two of the cells (D1 and D2) had chemiplated barriers, and the other two (D3 and D4) had electroplated barriers. It was thought that a substantial increase in cell efficiency might result from the use of a chemiplated barrier rather than the standard type of electroplated barrier for a cadmium sulfide solar cell. As can be seen in table II (p. 12), there was no evident increase in cell efficiencies due to using the chemiplated cells, D1 and D2, rather than the standard electroplated barriers.

Since cells D1 and D2 had been fabricated, it was decided to include them in thermal cycling test 4. This test was run with a 30-minute on-off cycle in order to accelerate the testing. Data from the cells were taken 7 minutes after the light was turned on. Solar cell D3 fluctuated after 250 cycles and was found to be short circuited, while all other cells had stable and uniform outputs. This was expected since cell D3 had the wire grid which had earlier proven to be a source of failure. Thermal cycling test 4 was terminated after 1495 thermal cycles, and it was concluded from this test that electroformed grids were a definite improvement over the gold wire mesh grids. Another thermal cycling test was run to verify these results.

While on the dark part of the cycle in the space chamber, an attempt was made to burn out the short circuit of cell D3 (fig. 8(b)) at 1475 thermal cycles. An unregulated direct-current power supply was connected to the cell so that current was passed through the cell in the reverse direction. An oscilloscope was connected across the output terminals of the solar cell in order to measure the voltage output which, for a short-circuited cell, was very low. Current to the cell was slowly increased until the oscilloscope indicated a substantial increase in the cell voltage output. Thermal cycling tests were then continued with the indication that cell D3 had improved; that is, fluctuations in voltage output were not present. It was noted, however, that the outputs were much lower than they had been before burnout. Inadvertently, cell D4 was also given the burnout treatment. The current that was passed in the reverse direction through this cell was very low. As can be seen in figure 8(c), cell D4 did improve substantially. Unfortunately, this test was terminated 20 cycles after burnout was applied to the cells; thus, it is not known whether or not outputs for both cells so treated would have returned to their original values if thermal cycling had been continued.

Cells in thermal cycling test 5 had electroformed grids and electroplated barriers and were H film encapsulated. Figure 8(d) shows the typical results obtained. All cells had fairly uniform outputs throughout the test with little or no fluctuation, and this result verifies the data from test 4. Test 5 was terminated after 1350 thermal cycles, and it was concluded that the cells with electroformed grids had greatly improved stability compared to the cells with regular mesh grids. The improvement attained by the use of H film encapsulation is indicated by two effects: first, no contact failures were noted because cell terminals were fastened mechanically and soldered; and second, delamination of the cells, which would cause a loss of pressure contact between silver collecting straps and grid, was not evident at the conclusion of thermal cycling test 5.

CONCLUDING REMARKS

Three series of heat damage tests were run on thin-film cadmium sulfide cells. At temperatures between 80° and 200° C, deficiencies in cell design were uncovered. These deficiencies (cell delamination and faulty contacts) were remedied by the use of a high-temperature encapsulant (film H) and by soldering the contacts to the cell. In addition to this, the molybdenum substrate was extended and used for the negative current collector. With the improved designs, there was no appreciable degradation of cell output with time for temperatures between 80° and 180° C, although severe degradation was observed at 200° C. This degradation was not permanent, however, because stable performance was achieved simply by lowering the temperature, which indicated that the cell junction was undamaged.

The five series of thermal cycling tests proved that the electroformed grids on thin-film cadmium sulfide solar cells are an improvement over the wire mesh type of grid. Thermal cycling tests 4 and 5, with electroformed grids, showed that cells have the ability to withstand wide temperature excursions without failure due to short circuits. It also was found that dependence on the plastic encapsulant is no longer required to ensure cell continuity by pressure contact, if current collecting straps are physically attached to the cell structure. Mechanical weaknesses in the contact terminal were corrected by using cells with welded or electroplated contacts.

Thin-film cadmium sulfide solar cells incorporating these advanced designs have successfully undergone 1495 thermal cycles with no apparent cell degradation. This cycling would correspond to operation for 98 days in a 90-minute Earth orbit.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 1, 1965.

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