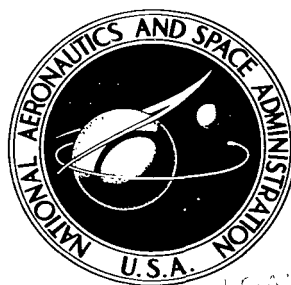


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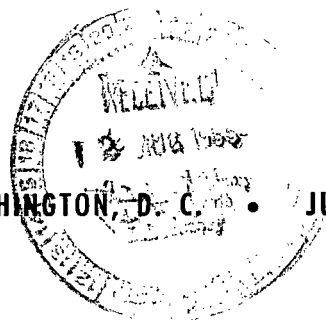
# RADIATION DAMAGE TO CADMIUM SULFIDE SOLAR CELLS

*by Henry W. Brandhorst, Jr., and Russell E. Hart, Jr.*

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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# RADIATION DAMAGE TO CADMIUM SULFIDE SOLAR CELLS

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## SUMMARY

Cadmium sulfide thin-film solar cells were irradiated in vacuum with 2.5-, 1.0-, and 0.6-million-electron-volt electrons and 10-, 7-, 5-, and 2-million-electron-volt protons. Doses ranged from  $10^{15}$  to  $10^{17}$  electrons per square centimeter and from  $10^{12}$  to  $3.6 \times 10^{14}$  protons per square centimeter. Three types of plastic encapsulant, polyethylene terephthalate, polyvinyl fluoride, and polyimide, were also evaluated. The performance of the cells was measured before and after irradiation with a carbon-arc solar simulator. Cell dimensions were 1 by 2 centimeters, and efficiencies ranged from 1.3 to 2.5 percent and averaged 1.7 percent. Spectral responses of the cells were determined with a series of 18 monochromatic interference filters covering the range from 0.35 to 1.20 microns. Additional parameters measured under tungsten illumination included series resistance, dark and light shunt resistances, and the junction parameters  $A$  and  $I_0$ .

The results showed that, under electron irradiation, the cells encapsulated in polyethylene terephthalate and polyimide films were undamaged electrically up to the highest dose ( $10^{17}$  electrons/sq cm) even though the former film had become very brittle. There appeared to be no dependence on electron energy. Cells covered with polyvinyl fluoride failed rapidly in the test because of darkening and ultimate rupture of the film itself. An anomalous behavior was observed for all cells irradiated at high doses of electrons ( $\geq 4 \times 10^{16}$  electrons/sq cm). The cells appeared to be badly damaged immediately after irradiation, but they recovered their original characteristics after an overnight exposure to weak illumination. The cells experienced some slight damage under proton irradiation. At  $3.6 \times 10^{14}$  protons per square centimeter, the short-circuit current was 92 percent of its original value, and the maximum power was 87 percent of its original value. At all levels of irradiation, all parameters measured confirmed the resistance of cells encapsulated in polyethylene terephthalate and polyimide to these types of irradiation.

## INTRODUCTION

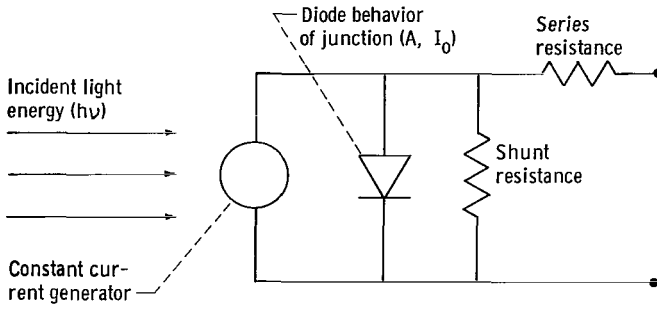


Figure 1. - Equivalent circuit of solar cell.

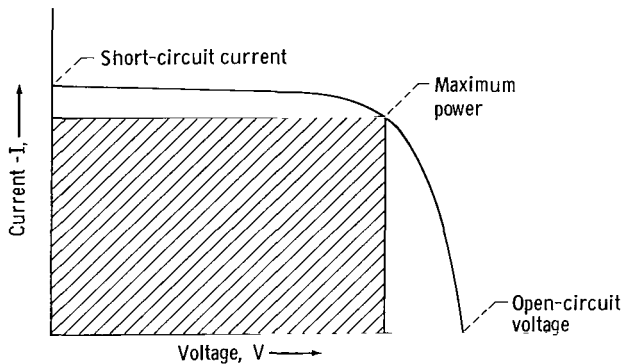


Figure 2. - Electrical output of solar cell.

Solar cells are semiconductor devices that convert light energy into electrical energy. An equivalent circuit for a solar cell is shown in figure 1. Basically, a solar cell can be represented as a current generator activated by light and controlled by the diode behavior of the junction. Certain losses are encountered in getting the current out of the device. The first loss is the shunt resistance  $R_{sh}$  that allows some current leakage around the diode, while a second loss is the series resistance  $R_s$  that impedes the current flow to the collector. The shape and magnitude of the electrical output characteristic of this device depend on the diode behavior of the junction, the

series and shunt resistances, and the total radiant energy converted into electrical energy. Mathematically, the output of a solar cell is given by the equation (ref. 1)

$$I = I_0 \left\{ \exp \left[ \frac{q}{AkT} (V - IR_s) \right] - 1 \right\} - I_\ell + \frac{V}{R_{sh}} - \frac{IR_s}{R_{sh}} \quad (1)$$

where

- A constant
- I output current
- $I_\ell$  light-generated current
- $I_0$  reverse saturation current of diode
- k Boltzmann constant
- q electronic charge
- $R_s$  series resistance
- $R_{sh}$  shunt resistance
- T absolute temperature
- V output voltage

A typical output characteristic derived from this equation is shown in figure 2. The short-circuit current  $I_{sc}$  is reached when the voltage drop across the cell is zero. Likewise, the open-circuit voltage  $V_{oc}$  is obtained when an infinite load is placed across the cell so that no current flows. The output power of the device depends on the load placed across the cell. In order to obtain maximum power  $P_{max}$ , a load resistance is chosen to make the product  $I \times V$  a maximum (shaded area in fig. 2).

Exposure of silicon solar cells to the electron and proton radiation in the van Allen Belts seriously degrades their output. The primary factors in equation (1) that are affected by radiation are  $I$  and  $R_s$ , while  $A$  and  $I_o$  are affected to a lesser degree. Doses of about  $10^{12}$  protons per square centimeter and  $10^{15}$  electrons per square centimeter are sufficient to degrade n/p solar cells to 75 percent of their original output. Early experiments on cadmium sulfide thin-film solar cells indicated an outstanding resistance to electron irradiation. After a dose of  $10^{16}$  electrons per square centimeter, the short-circuit current had degraded by about 10 percent. It was of considerable interest, therefore, to extend these studies to higher doses of electrons and to begin extensive studies of proton damage.

## PROCEDURE AND APPARATUS

Irradiations of 70 cadmium sulfide thin-film solar cells were conducted as follows: Groups of 10 cells each were exposed to doses of electrons of 2.5, 1.0, and 0.6 million electron volts (MeV), respectively. Total accumulated doses progressed from  $10^{15}$  to  $10^{17}$  electrons per square centimeter in decade steps. Similarly, four other groups of cells were exposed to 10-, 7-, 5-, and 2-MeV protons. Accumulated doses were to range in decade steps from  $10^{12}$  to  $10^{14}$  protons per square centimeter.

The cells within each group were further subdivided according to type of plastic encapsulant. Three different plastics were used: polyethylene terephthalate (film M), polyvinyl fluoride (film T), and polyimide (film H). These three materials have shown promise for space applications on the basis of preliminary tests. Cell dimensions were 1 by 2 centimeters, and efficiencies, as measured on the solar simulator, ranged from 1.3 to 2.5 percent and averaged 1.7 percent.

To assess the performance of the cells accurately, several measurements were made on each cell after irradiation. First, a family of current-voltage curves was measured under several levels of tungsten illumination. These data were used to obtain the cell series resistance, dark and light shunt resistances, and various junction parameters. Secondly, the spectral response was measured with a series of monochromatic interference filters. Finally, the short-circuit current, maximum power, and open-circuit voltages of the cells were measured with a carbon-arc solar simulator. The third set of

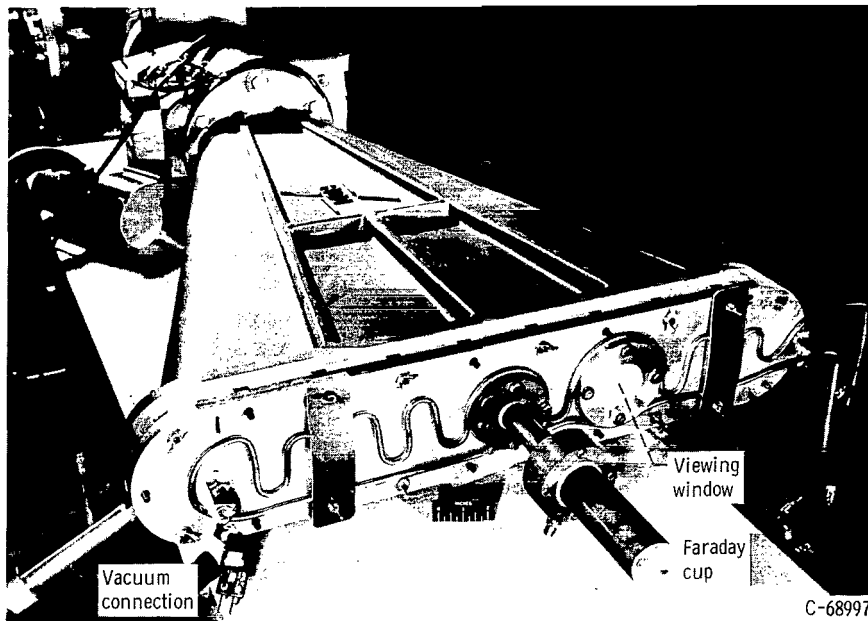


Figure 3. - Sample holder attached to electron accelerator.

measurements was used to determine the performance degradation experienced by the cells, while the two former measurements were designed to show what part of the cell was being degraded.

### Irradiation Apparatus

The Lewis Research Center 3.0-MeV Cockcroft-Walton accelerator was used for the electron irradiations. The holder for these irradiations is

shown in figure 3. The cells were mounted on the water-cooled end plate, and the defocused beam swept across them in the horizontal plane. The dose was measured with a Faraday cup mounted in the center and exposed through a 1- by 2-centimeter opening. A vacuum connection is shown on the lower left side. During a run, the vacuum was maintained at about 1 micron. A front view of this mounting plate can be seen in figure 4. Thermocouples were placed at each end of the row of cells to ensure full horizontal beam coverage. A large viewing window was placed toward one end to monitor the vertical coverage of the beam.

Temperatures were measured with a thermocouple imbedded in a typical cell that was permanently mounted on the plate. Sample temperatures did not exceed 60<sup>0</sup> C. A secondary confirmation of the dose received by the cells was obtained by mounting a typical silicon cell on the plate. The dose was computed by measuring the diffusion length of the test cell and comparing it with values derived empirically from almost identical silicon cells. Doses computed this way averaged about 50 percent higher than those indicated by

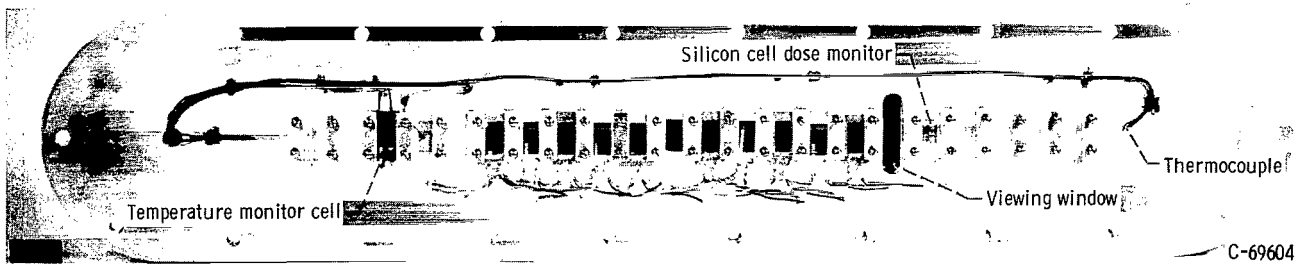


Figure 4. - Sample holder for electron-damage studies.

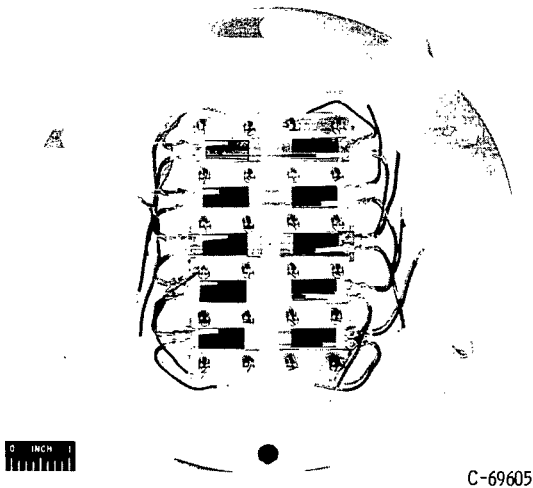


Figure 5. - Sample holder for proton-damage studies.

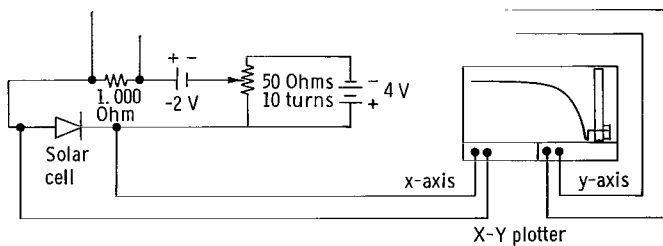


Figure 6. - Circuit diagram of current-voltage curve plotter.

the Faraday cup. No better accuracy was anticipated, and this measurement served as a secondary monitor to ensure against gross errors.

For proton irradiations, the Lewis Research Center 60-inch cyclotron with a maximum proton energy of 10 MeV was used. The mounting plate for these irradiations (fig. 5) was attached to a large beam duct that was maintained at the same vacuum as the cyclotron. The cyclotron beam was diffused to approximately 4 inches in diameter to irradiate all samples uniformly. For bombardments in excess of  $10^{12}$  protons per square centimeter, the dose was determined by measuring the amount of activation of a 0.0005-inch-thick permalloy foil (80 percent Ni, 15 percent Fe, 5 percent Co) placed individually over the cells. The iron present in the foil was activated, and the radioactivity of the foil was measured 1 week later after short-lived isotopes had decayed. For irradiations at  $10^{12}$  protons per square centimeter and at all doses of 2-MeV protons, activation analysis was not used. For these studies, irradiations were made in air with a rotating wheel and a solid-state detector to determine the dose. This apparatus was also used to calibrate the permalloy foil. The different energies were obtained by using aluminum absorbing foils and/or stacking the cells. The temperature of the cells was not measured because no significant heating was expected at these low doses; however, cooling air was blown over the sample plate during the runs as an added precaution. A check of the sample-holder temperature immediately after a run showed no significant change over ambient temperatures.

## Current-Voltage Apparatus

A circuit diagram of the measurement apparatus is shown in figure 6. Current-voltage curves were obtained by varying a bias voltage across the sample from -2 to 2

volts. A negative 2-volt bias was bucked with a positive 4-volt bias through a potentiometer thus giving the desired range. The current was measured by determining the voltage drop across a 1-ohm resistor, while the voltage applied to the cell by the bucking circuit was measured directly. These voltages were then displayed on an X-Y plotter for analysis.

The light source used for routine measurements was a 1000-watt tungsten-iodine lamp filtered through 2 inches of water. Samples were attached next to a permanently mounted silicon solar cell on a temperature-controlled block. The silicon cell was used as an intensity monitor.

Light intensity was set to "100 milliwatts per square centimeter sunlight equivalent" by using a calibrated silicon solar cell. Reproducibility of this setting during the test was ensured with the permanent intensity monitor cell. Because the effective intensity of a tungsten light source is dependent on the spectral response of the cell being measured, a check of the intensity was made with cadmium sulfide thin-film cells. Forty cells, the efficiencies of which had been determined in sunlight, were measured under the tungsten source, and their maximum power output was determined. Comparison with the results of the sunlight measurements showed that the effective intensity of the tungsten light for cadmium sulfide cells was  $105 \pm 5$  milliwatts per square centimeter. This is in substantial agreement with the primary calibration as determined by the reference silicon solar

cells. Intensity was adjusted by varying the height of the light source above the cells. The lamp was cooled by a stream of air to ensure a long life, and a constant voltage power supply was used with the light to gain additional stability.

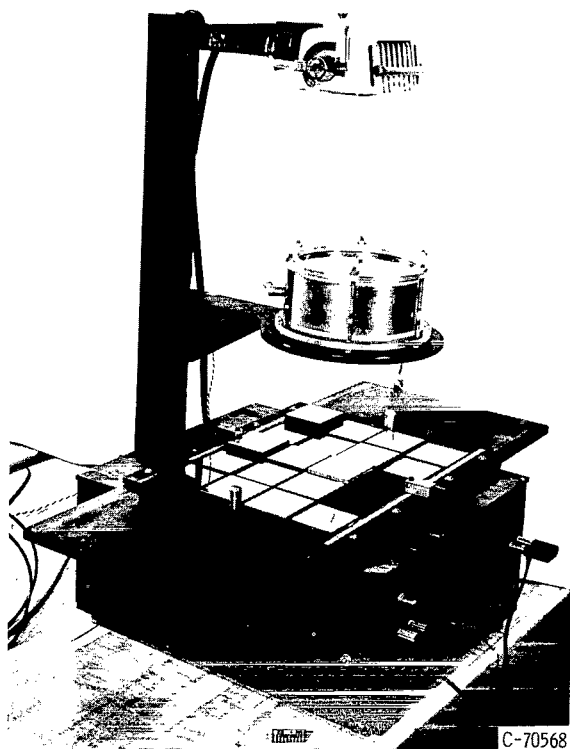


Figure 7. - Apparatus for measuring spectral response.

## Spectral Response Apparatus

Spectral responses were measured on the apparatus shown in figure 7. Eighteen monochromatic interference filters were used to cover the region from 0.35 to 1.20 microns in 0.05-micron intervals. In addition, one space provided full illumination, while another provided darkness. Thus, all measurements on the cell could be made in one location without remounting the cell. The table top can be moved in the horizontal plane and has



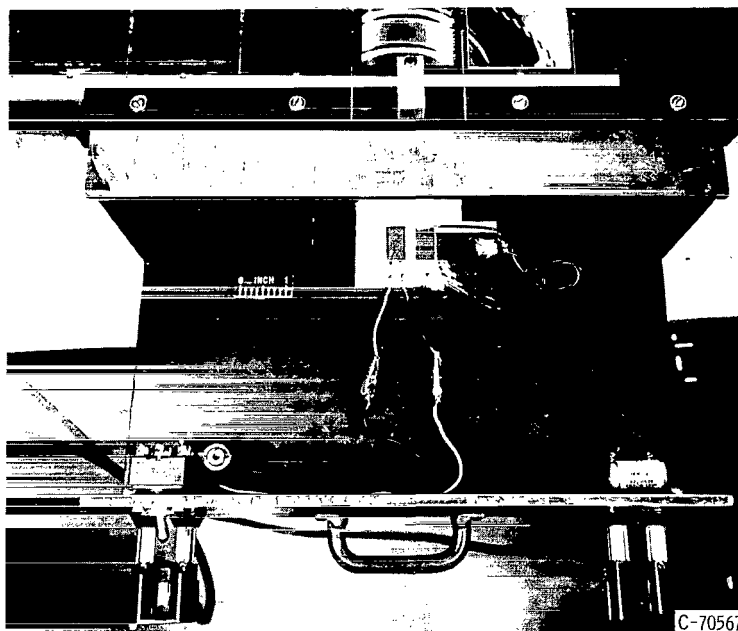


Figure 8. - Detail of sample mounting in spectral-response apparatus.

spring-loaded balls for indexing purposes. Position reproducibility of each filter is within  $1/32$  inch. Details of the sample mounting are shown in figure 8. The silicon standard cell is permanently affixed to the plate, while the test cells are held down by double-sided masking tape. The area of uniform illumination is approximately 3 by 3 centimeters. Tempered water flows through the underside of the mounting table for temperature control. Mounted inside the box are four 6-volt lamps that provide white-light bias when spectral responses are being measured. This white-light bias was necessary when measuring cadmium sulfide cells, because the readings in the infrared region exhibited a considerable decay without the bias. This decay is probably caused by electron traps in the cadmium sulfide. At the low-light levels used in this study, these traps can capture a significant fraction of the total current produced thus giving erroneously low results. By maintaining a light bias of about 0.3 milliamperes on the cell this difficulty could be largely eliminated.

When a spectral response was measured, the current output of the cells was obtained by switching a precision 1-ohm resistor across the cell. This resistor was not part of the current-voltage curve plotter and was removed when a current-voltage curve was to be measured. The voltage across the 1-ohm resistor was monitored with a millimicrovoltmeter. The output from this voltmeter was displayed on a digital voltmeter for recording purposes. When white-light bias was used, the portion of the signal caused by this source was balanced out with the millimicrovoltmeter. In this way, monochromatic responses as low as 1 microvolt could be measured.

With the light set to "100 milliwatts per square centimeter sunlight equivalent," the maximum intensity through the interference filters was about 1.5 milliwatts per square centimeter and was observed at 0.85 micron. Minimum intensity was approximately 0.012 milliwatt per square centimeter at 0.35 micron. Maximum silicon-cell output was 140 microamperes. These intensities were determined with an eight-junction bismuth-silver normal-incidence thermopile. Periodic measurements confirmed the calibration and intensity distribution.

During a typical run, (1) the current-voltage curves were taken under the standard illumination with the precision resistor removed, (2) the dark characteristics were measured, and (3) the 1-ohm resistor was switched across the cell, the bias lights were turned on, and the spectral response was determined. Initially, the intensity of the light was set with the internal silicon cell; however, in the dark, and while the spectral response is being measured, no such internal calibration is possible. Therefore, a second monitor cell was mounted on the underside of the water filter off to one side where it did not affect the internal distribution. In this way, constant intensity could be assured during the run.

### Carbon-Arc Solar-Simulator Measurements

The amount of degradation suffered by the cells was measured on a carbon-arc solar simulator. Because of the basically unstable nature of this arc over a long period of time, the intensity was continuously monitored with a silicon standard cell. This standard cell had been calibrated both by Earth-bound techniques and by an airborne technique with excellent agreement between the two. This cell was used as a reference so that all measurements were relative to a common base and could be compared directly. The output of the cadmium sulfide cells was plotted on the current-voltage curve tracer, while the short-circuit current of the standard cell was measured with a precision milliammeter that has a load resistance of less than 1 ohm. Both cells were positioned together in the center of the beam to be in a uniform area. The total diameter of the beam was about 12 inches, while the cells were within a 2-inch-diameter circle. During the measurement of the current-voltage curve of the test cell, the short-circuit current of the standard cell was continuously monitored and usually changed less than  $\pm 1$  percent. The mounting plate was cooled by tap water and was maintained at about 15<sup>o</sup> C. After the run, the short-circuit current and the maximum power of the cadmium sulfide cell were normalized to 139.6 milliwatts per square centimeter using the short-circuit current of the calibrated silicon cell.

## Calculations

To obtain the series resistance, dark and light shunt resistances, and the junction parameters  $A$  and  $I_0$ , several calculations must be performed on the empirical data. The shunt resistances were determined directly from the slope of the current-voltage curve in the reverse direction (negative voltage) and are detailed in figure 9. It can be seen from equation (1) that if the voltage  $V$  becomes negative, the quantity within the braces approaches  $-1$  very quickly. The reverse saturation current of the diode  $I_0$  is very small, and the last term is small compared with  $V/R_{sh}$ . The light generated current  $I_l$  is a constant, hence, the slope of a plot of  $I$  against  $V$  is  $R_{sh}$ . No difference should be noted between light- and dark-shunt-resistance measurements because  $I_l$  does not affect the slope. In cadmium sulfide cells, however, the light shunt resistance is about 60 percent of the dark value. This is probably caused by the high photoconductivity of cadmium sulfide. The light shunt resistance was measured under the "100 milliwatts per square centimeter sunlight equivalent" tungsten illumination described previously.

The series resistance was calculated according to a technique outlined by Wolf and Rauschenbach (ref. 2). Two current-voltage curves are taken under different intensities of illumination, and an arbitrary point close to the maximum power point on the highest curve is selected (fig. 9). This point has the coordinates  $(I_1, V_1)$ . The difference between  $I_1$  and  $I_{sc, 1}$  is  $\Delta X$ . The point  $I_2$ , which equals  $I_{sc, 2} - \Delta X$ , is located. The intersection of  $I_2$  with the lower current-voltage curve yields the point  $(I_2, V_2)$ . The

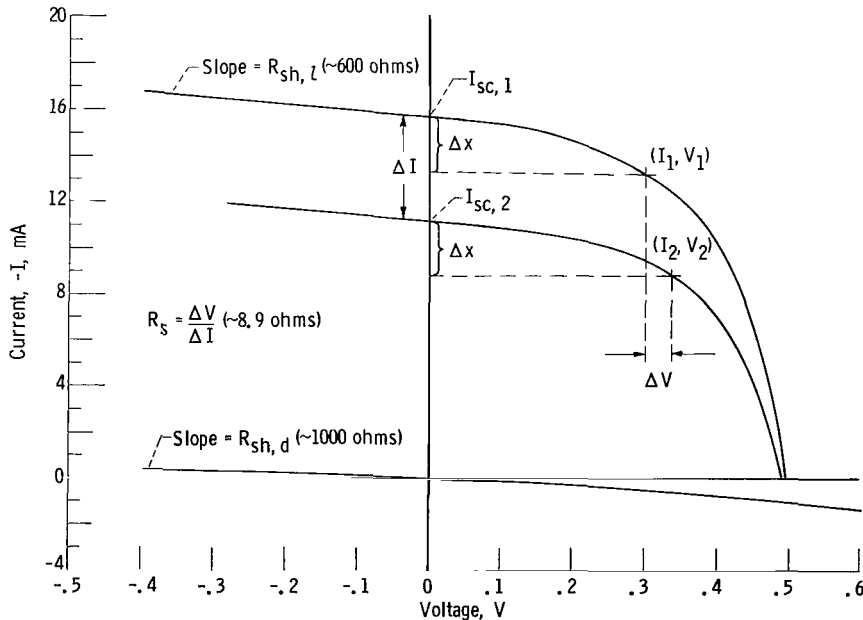


Figure 9. - Calculation of dark and light shunt resistance and series resistance.

series resistance is then defined as

$$R_s = \frac{V_2 - V_1}{I_{sc,1} - I_{sc,2}} = \frac{\Delta V}{\Delta I} \quad (2)$$

Note that  $\Delta X$ , which was arbitrary, no longer enters into the equation.

The junction parameters  $A$  and  $I_0$  were also determined by a technique outlined by Wolf and Rauschenbach (ref. 2). In this technique, the cell is illuminated at a number of different intensities. The intensity was changed with a series of calibrated screens. For each curve, the light-generated current  $I_\ell$  and the open-circuit voltage  $V_{oc}$  are determined. For cells with low series resistance,  $I_\ell$  equals the short-circuit current. For each curve, values of  $I_\ell$  and  $V_{oc}$  are obtained that are then plotted as a single point on a curve of the natural logarithm of the current against voltage. The equation that governs this characteristic is

$$I_\ell = I_0 \left[ \exp\left(\frac{q}{AkT} V_{oc}\right) - 1 \right] \quad (3)$$

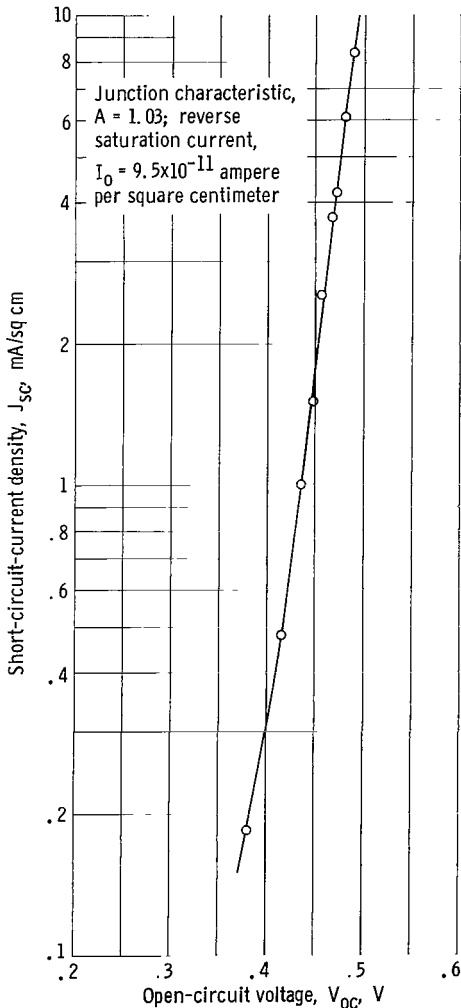


Figure 10. - Determination of junction parameters  $A$  and  $I_0$  of cadmium sulfide thin-film solar cell.

This is derived from the general equation for the photovoltaic output of a solar cell (eq. (1)) by setting  $I = 0$ ,  $V = V_{oc}$ , and assuming that  $R_{sh}$  is high. A typical example of such a plot is shown in figure 10. From inspection of the equation, it can be seen that, from a plot of the natural logarithm of  $I_\ell$  against  $V$ , the slope is  $q/AkT$  and the intercept is the natural logarithm of  $I_0$ . In practice, however, two points on a straight line are determined, and the resulting simultaneous equations are solved for  $A$  and  $I_0$ .

## RESULTS

The degradation of the short-circuit current of cadmium sulfide solar cells after electron irradiation is shown in figure 11. These data were measured on a carbon-arc solar simulator. Although the damage appears to be independent of electron energy over this range, there is a decided dependence on the type of plastic encapsulant. All the cells encapsulated in films

M and H (9 and 12 cells, respectively) reached a dose of  $10^{17}$  electrons per square centimeter with no apparent degradation of electrical characteristics. Some unusual behavior was noted at doses above  $10^{16}$  electrons per square centimeter and will be discussed later. The cells covered with film M had become very brittle at a dose of  $10^{17}$  electrons per square centimeter, while the cells encapsulated with film H were apparently unharmed.

Cells covered with film T, on the other hand, failed rapidly in this test. At a dose of  $10^{15}$  electrons per square centimeter, the film T cells were slightly darkened by the radiation, but this had nearly annealed away in a few hours. After a dose of  $10^{16}$  electrons per square centimeter, the film T cells had deteriorated badly because (1) the plastic had darkened with only slight annealing and (2) delamination of the cells caused the grid electrode to pull away from the cell thus degrading the output. Four cells were completely lost as a result of delamination; hence, the performance is tabulated for the five remaining cells.

Five high-efficiency cadmium sulfide cells (average efficiency, 4.2 percent) were

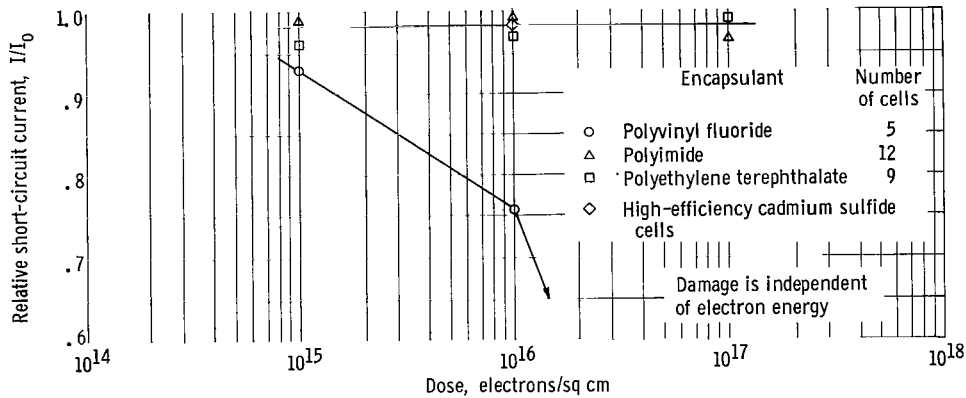


Figure 11. - Degradation of short-circuit current by 2.5-, 1.0-, and 0.6-million-electron-volt electrons.

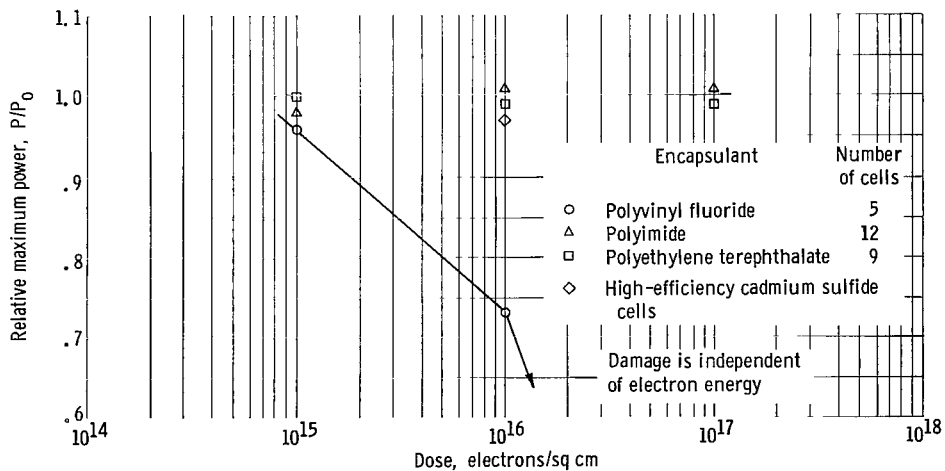


Figure 12. - Degradation of maximum power by 2.5-, 1.0-, and 0.6-million-electron-volt electrons.

also irradiated to  $1 \times 10^{16}$  electrons per square centimeter. Essentially no degradation of the short-circuit current was observed, as shown in figure 11.

The variation of the maximum power of the cells is illustrated in figure 12. The deterioration here is practically the same as that shown for the short-circuit current (fig. 11). In both figures, the failure of the cells encapsulated in film T shortly after  $10^{16}$  electrons per square centimeter was due to complete rupture of the plastic covering the cell. This failure stripped the front grid electrode completely from the cell. Also included in figure 12 are the data for the high-efficiency cadmium sulfide cells.

At doses above  $10^{16}$  electrons per square centimeter, the cells behaved rather strangely, as shown in figure 13. The uppermost curve was measured prior to irradiation, and the lower curve was obtained immediately after irradiation. If the cell in this degraded condition was simply left exposed to a weak light overnight, it would recover its original characteristics. If the cell was exposed only to ambient room light with no load applied, the annealing took several days, but the recovery was complete. If, however, the cell was short-circuited or loaded at its maximum power point, only very slight annealing took place regardless of ambient illumination. A scan of the spectral response immediately after irradiation showed that the response in the blue region had been adversely affected as shown in figure 14. Data were not obtained beyond 0.7 micron because of experimental difficulties. The short-circuit current of the cell in this example had degraded about 50 percent. After exposure to an illumination of 40 milliwatts per

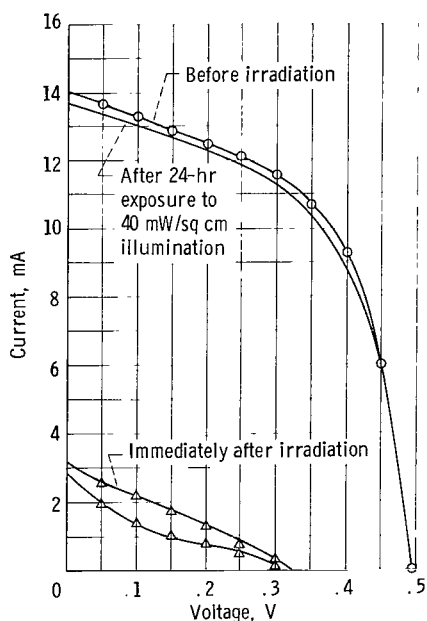


Figure 13. - Effect of high-electron doses on cadmium sulfide cells.

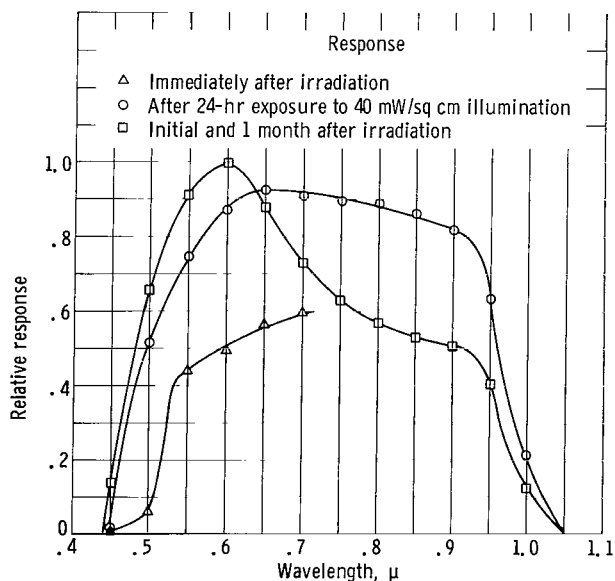


Figure 14. - Spectral responses during annealing.

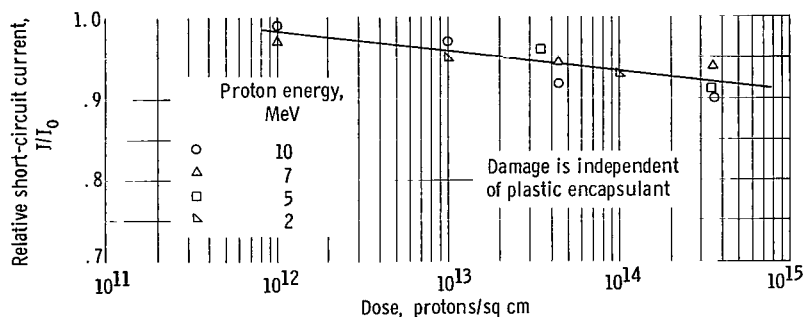


Figure 15. - Degradation of short-circuit current by 10-, 7-, 5-, and 2-million-electron-volt protons.

square centimeter, the spectral response had greatly increased in the red region. A 10-percent increase in the short-circuit current above the prebombardment level was observed that qualitatively agrees with the increased response. After the cell had rested for about 1 month under ambient conditions, the spectral response was again at the original level. No attempt was made to observe the response of this cell during this 1-month period; hence, the recovery time is not known. The 21 cells that were exposed to this dose showed degradations ranging from 50 to 90 percent immediately after irradiation, and all recovered their initial performance.

The origin of this effect is not clear at the present time, although it is apparent that the cells have been adversely affected by the radiation for a short time at least. The effect was observed at doses in excess of  $4 \times 10^{16}$  electrons per square centimeter, independent of electron energy. The dose rate ( $3 \times 10^{16}$  electrons/sq cm in 8 hr) used for the electron irradiations was not excessively high. This same rate was used at all levels of irradiation, and hence it should not be a contributing factor.

The results of electron irradiation show less cell degradation than reported by Schaefer (ref. 3) possibly because of individual cell variations or other influences. In this work, moisture was rigidly excluded from the cells because it had been observed that a 10-percent degradation of cell output took place in about 3 weeks under normal room humidity. Desiccation of the samples prevented this degradation.

Figure 15 shows the degradation of the short-circuit current of cadmium sulfide cells exposed to 10-, 7-, 5-, and 2-MeV protons as measured with the solar simulator. In this case, the damage appeared to be independent of the plastic encapsulant. The cells received a maximum dose of  $3.6 \times 10^{14}$  protons per square centimeter. A variation of about  $\pm 10$  percent in dose was observed from cell to cell, but this difference was not considered significant. The degradation of the short-circuit current is very slight: at the maximum dose, the cells still have 92 percent of their original output.

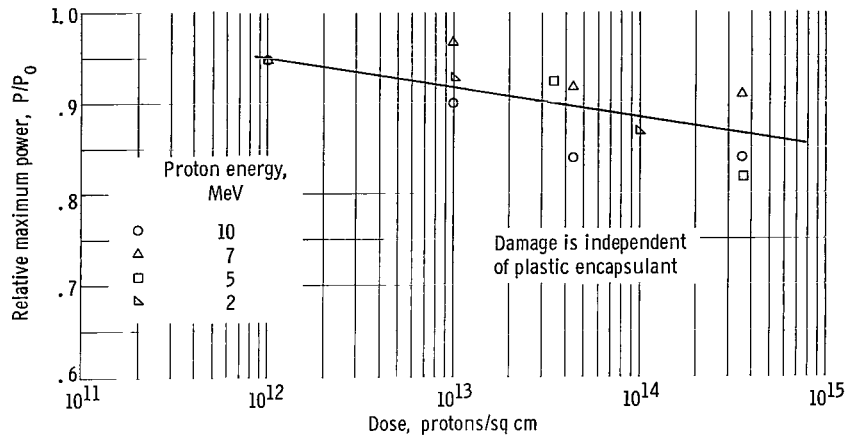


Figure 16. - Degradation of maximum power by 10-, 7-, 5-, and 2-million-electron-volt protons.

The variation of the maximum power of the cells with proton dose is shown in figure 16. Only slightly more degradation is observed here compared with the short-circuit current. At  $3.6 \times 10^{14}$  protons per square centimeter, the maximum power is 87 percent of its original value. The higher degradation rate is probably caused by the increase in series resistance. This factor has also contributed to the increased scatter of the data.

All the measured parameters confirmed the lack of damage to these cells. Typical examples of the series resistance, dark and light shunt resistances, and the junction parameters  $A$  and  $I_0$  are presented in table I. These values are averages of tests on 18 cells. Some indication of the range of values encountered is also shown in the table. The cells are uniformly characterized by high series resistance, low shunt resistances, and low  $A$  and  $I_0$  values. The series resistance,  $A$ , and  $I_0$  values increased with irradiation, while the shunt resistances decreased. The changes in these parameters are not great and reinforce the solar-simulator measurements. No significant changes were observed in the spectral-response measurements. Contrary to silicon solar cells, the decrease in response was general over the entire curve with no region showing excessive degradation.

TABLE I. - CELL PARAMETERS AS FUNCTION OF PROTON DOSE<sup>a</sup>

Proton dose	Series resistance, $R_s$ , ohms	Light shunt resistance, $R_{sh, \ell}$ , ohms	Dark shunt resistance, $R_{sh, d}$ , ohms	Junction characteristic, $A$	Reverse saturation current, $I_0$ , A/sq cm
Unbombarded	$10.8 \pm 0.5$	$438 \pm 54$	718	1.21	$5 \times 10^{-10}$
$10^{13}$ protons per square centimeter	$13.1 \pm 0.5$	$427 \pm 63$	662	1.30	$2 \times 10^{-9}$
High	17.4	1000	5000	1.70	$8 \times 10^{-8}$
Low	6.6	46	65	.95	$7 \times 10^{-11}$

<sup>a</sup>Values are averages of tests on 18 cells at 10 and 7 MeV.



Subsequent to the experimental portion of this investigation, additional data were presented by Schaefer (ref. 3) on the effects of 1.8- and 3.0-MeV protons on cadmium sulfide thin-film cells. With 1.8-MeV protons, a decrease of 4 percent in cell short-circuit current was observed at a dose of  $3 \times 10^{12}$  protons per square centimeter. The use of 3.0-MeV protons had decreased the short-circuit current 2 percent at the same dose. The data presented in this paper show a 3-percent decrease at that dose with no energy dependence, which is in substantial agreement with the results of reference 4.

## CONCLUSIONS

Under electron irradiation, the cells encapsulated in polyethylene terephthalate and polyimide films were undamaged electrically at the highest dose ( $10^{17}$  electrons/sq cm) although the former film had become very brittle. There appeared to be no dependence on electron energy at these doses and energies. The cells covered with polyvinyl fluoride failed rapidly in the test because of darkening and ultimate rupture of the film itself. Therefore, it can be concluded that polyvinyl fluoride is not a suitable encapsulant for these cells in a high-radiation environment. Anomalous behavior of the cells covered with polyethylene terephthalate and polyimide was observed at high doses of electrons ( $\geq 4 \times 10^{16}$  electrons/sq cm). The cells appeared to be badly damaged immediately after irradiation but recovered their original characteristics after an overnight exposure to weak illumination. Unusual behavior of the spectral response was also observed during the annealing process. High efficiency (4.2 percent) cadmium sulfide cells were also irradiated and were undamaged at doses of  $10^{16}$  electrons per square centimeter.

Slight damage to the cells was observed under proton irradiation. At  $3.6 \times 10^{14}$  protons per square centimeter, the short-circuit current was 92 percent of its original value and the maximum power was 87 percent. The slight difference was probably caused by an increase in series resistance. At all levels of irradiation, all parameters measured confirmed the lack of great damage to the cells.

In view of the present experiments, it appears that the cadmium sulfide thin-film cell encapsulated in polyethylene terephthalate or polyimide film is extremely resistant to electron and proton radiation and should be capable of operating for extended periods of time in the space environment without suffering serious radiation damage.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, May 4, 1965.

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