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SOLAR-CELL PERFORMANCE AT LOW TEMPERATURES AND SIMULATED SOLAR INTENSITIES

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SUMMARY

The photovoltaic properties of two commercial CdS thin-film solar cells and 14 silicon solar cells were measured at low temperatures and solar intensities to simulate Jupiter conditions. Also included are measurements at other conditions. All the silicon cells showed acceptable efficiencies ranging from 10 to 11 percent at Earth condition air mass zero, but there were large differences of efficiency at Jupiter conditions. The efficiencies of the best silicon cells and CdS cells at Jupiter conditions were 1.4 and 1.1 times greater, respectively, than near Earth. The efficiencies of the poorer-performing silicon cells ranged from about 1 to 11 percent at Jupiter conditions. At room temperature, the percent change of fill factor with intensity between 136 and 6 milliwatts per square centimeter increased as the efficiency at Jupiter decreased. This suggests that fill-factor monitoring can be useful for sorting out the better-performing cells at Jupiter conditions without resorting to low-temperature tests.

INTRODUCTION

Solar cells are being considered as power sources for Jupiter probe missions. Near Jupiter, they could be required to operate at temperatures as low as 140 K and at solar intensities of 5 to 6 milliwatts per square centimeter.

Previous works on solar-cell performance at temperatures and/or light intensities other than near-Earth conditions include measurements at simulated near-Venus and near-Mars conditions (refs. 1 to 3). Data at Jupiter conditions for several 1- by 2-centimeter silicon cells are reported in reference 4, and for a single CdS cell in reference 5.

Reported herein are the results of an experimental study made on 14 flight-type, 2- by 2-centimeter, 1- and 10-ohm-centimeter silicon solar cells and two commercial cadmium sulfide thin-film solar cells at near-Earth to near-Jupiter conditions. Values of illumination intensity and temperature used were 136 milliwatts per square centimeter and 300 K at Earth and 6 milliwatts per square centimeter and 140 K at Jupiter. Illuminated electrical characteristics of all the cells are given for the two planet conditions and for selected cells as a continuous function of temperature at three intensities, 136, 14.6, and 6 milliwatts per square centimeter. Based on the experimental results, a method for preselecting the best-performing silicon cells for Jupiter conditions is presented.

EXPERIMENT

Solar-cell mounting and instrumentation are described in appendix A. A filtered xenon light source was used to simulate sunlight. Current-voltage (I-V) curves were obtained with an electronic load and an X-Y plotter. The solar flux incident upon solar cells and their resulting equilibrium temperatures at Earth and Jupiter conditions are estimated in appendix B to be 136 milliwatts per square centimeter and 300 K and 6 milliwatts per square centimeter and 140 K, respectively. Solar-cell performance was measured over this entire range of conditions. Measurements were made at three intensities, 136, 14.6, and 6 milliwatts per square centimeter. At each intensity, 9 to 12 equilibrium temperatures were selected over the temperature range of 330 to 140 K, and I-V curves were drawn at these conditions. Electrical parameters of the cells were taken from the I-V curves. Currents and voltages were plotted against temperature, and smooth curves were drawn through the data. The curves and the data points always corresponded within ±2 percent. These plots and other parameters derived therefrom, such as efficiency, maximum power, and fill factor, are presented in table and graph form.

The 2- by 2-centimeter silicon cells selected from three manufacturers were designated as groups I, II, and III and were numbered from 1 to 14. There were six cells in group I and four cells in each of the other two groups. The cells in groups I and II had a nominal base resistivity of 10 ohm-centimeter. The base resistivity of the group III cells was 1 ohm-centimeter. The thickness of the cells was 0.036 centimeter (0.014 in.). In addition, typical Kapton encapsulated cadmium sulfide thin-film cells were tested. The area of the cadmium sulfide cells was 54.75 square centimeters. A description of the cadmium sulfide cells (October, 1967), is given in reference 6.

The techniques outlined in reference 7 were used to obtain silicon-cell dark series resistance (includes sheet, bulk, and contact resistance) and reverse current for 0.6-volt reverse bias. Analysis of the experimental error associated with these tests is presented in appendix C.

RESULTS AND DISCUSSION

Photovoltaic Properties Near Earth and Jupiter

The photovoltaic properties of silicon and cadmium sulfide cells were studied at several intensities and over a range of temperatures. Because they are of principal

TABLE I. - PHOTOVOLTAIC PROPERTIES OF SILICON AND CdS CELLS AT EARTH CONDITIONS

[Solar intensity, 136 mW/cm^2; equilibrium temperature, 300 K.]

Cell		Total area, cm^2	Short-circuit current density, mA/cm^2	Open-circuit voltage, mV	Current density at maximum power, mA/cm^2	Current density at maximum power divided by intensity, mA/mW	Voltage at maximum power, mV	Efficiency, percent	Maximum power density, mW/cm^2	Fill factor
Group	Number									
Group I: Si base resistivity, 10 ohm-cm	1	4.01	34.4	550	32.2	0.237	450	10.7	14.5	0.77
	2	↓	34.4	550	32.5	.239	435	10.4	14.1	.75
	3		35.7	550	33.2	.244	435	10.6	14.4	.74
	4		34.6	555	32.0	.235	472	11.1	15.1	.79
	5		35.3	550	31.0	.228	440	10.0	13.6	.70
	6		35.2	550	31.0	.228	440	10.0	13.6	.70
Group II: Si base resistivity, 10 ohm-cm	7	3.93	35.5	550	32.0	0.235	470	11.0	15.0	0.77
	8	3.93	36.3	552	33.2	.244	450	11.0	14.9	.74
	9	3.92	35.2	540	33.2	.244	420	10.2	13.9	.73
	10	3.92	35.2	540	33.2	.244	420	10.2	13.9	.73
Group III: Si base resistivity, 1 ohm-cm	11	3.93	34.6	580	31.3	0.230	470	10.8	14.7	0.73
	12	↓	34.1	589	30.6	.225	479	10.8	14.7	.73
	13		34.1	590	31.8	.234	480	11.2	15.3	.76
	14		35.2	589	31.5	.232	485	11.2	15.3	.74
CdS cells	15	54.75	14.2	475	13.0	0.0956	350	3.3	4.6	0.68
	16	54.75	13.4	475	12.2	.0897	370	3.3	4.5	.71
Average of Si 1, 2, 3, 7		-----	35.0	550	32.5	0.239	448	10.7	14.6	0.76
Average of CdS 15, 16		-----	13.8	475	12.6	0.0926	360	3.3	4.5	0.69

TABLE II. - PHOTOVOLTAIC PROPERTIES OF SILICON AND CdS CELLS AT JUPITER CONDITIONS

[Solar intensity, 6 mW/cm^2; equilibrium temperature, 140 K.]

Cell		Total area, cm^2	Short-circuit current density, mA/cm^2	Open-circuit voltage, mV	Current density at maximum power, mA/cm^2	Current density at maximum power divided by intensity, mA/mW	Voltage at maximum power, mV	Efficiency, percent	Maximum power density, mW/cm^2	Fill factor
Group	Number									
Group I: Si base resistivity, 10 ohm-cm	1	4.01	1.28	900	1.09	0.182	820	14.9	0.894	0.78
	2	↓	1.25	900	1.10	.183	820	15.0	.902	.80
	3	↓	1.34	900	1.14	.190	770	14.6	.878	.73
	4	↓	1.18	860	.883	.147	720	10.6	.636	.63
	5	↓	1.27	450	1.04	.173	305	5.28	.317	.55
	6	↓	1.21	190	.61	.102	100	1.02	.061	.27
Group II: Si base resistivity, 10 ohm-cm	7	3.93	1.35	800	1.26	0.210	670	14.1	0.844	0.78
	8	3.93	1.27	780	1.08	.180	630	11.3	.680	.69
	9	3.92	1.26	715	1.07	.178	470	8.4	.503	.56
	10	3.92	1.33	480	.80	.133	230	3.1	.184	.29
Group III: Si base resistivity, 1 ohm-cm	11	3.93	1.27	815	0.93	0.155	610	9.5	0.567	0.55
	12	↓	1.28	740	1.04	.173	510	8.8	.530	.56
	13	↓	1.15	820	.79	.132	600	7.9	.474	.50
	14	↓	1.15	750	.84	.140	410	5.7	.344	.40
CdS cells	15	54.75	0.56	580	0.46	0.0767	455	3.5	0.209	0.64
	16	54.75	.46	600	.43	.0717	500	3.6	.215	.78
Average of Si 1, 2, 3, 7		-----	1.30	875	1.15	0.192	770	14.6	0.880	0.77
Average of CdS 15, 16		-----	0.51	590	0.44	0.0742	478	3.5	0.210	0.70

interest, the results obtained for Jupiter conditions are discussed first. The results are compared with those obtained for near-Earth conditions.

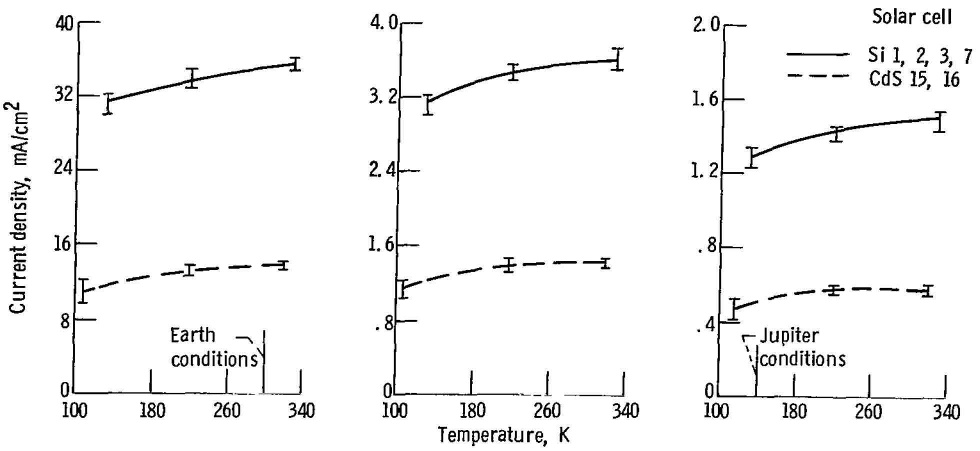
The primary result of these experiments was that although all the silicon cells showed acceptable performance at near-Earth conditions, large differences in efficiency were noted at Jupiter conditions. This is shown in tables I and II. These tables list the electrical characteristics of the 14 silicon cells. In each group, the silicon cells are numbered such that increasing cell number corresponds to decreasing efficiency at Jupiter conditions (table II). The efficiency of the silicon cells shown in table I is representative of modern, flight-type cells; efficiencies ranged from 10 to 11.2 percent at air mass zero and 300 K. In contrast, table II shows differences in silicon-cell efficiency of 1 to 15 percent near Jupiter. The average efficiency of the best silicon cells (Si 1, 2, 3, and 7) and the CdS cells was about 1.4 and 1.1 times greater near Jupiter than near Earth, respectively. This greater efficiency results from the larger voltage at maximum power achieved at the Jupiter conditions; that is, for the silicon cells, the ratio of current density at maximum power to intensity is about 20 percent less at Jupiter than at Earth. However, the voltage at maximum power is about 72 percent higher near Jupiter. The fill factors (maximum power/short-circuit current × open-circuit voltage) for these cells remained high at the Jupiter conditions; the average for the cells was about 0.77.

At Jupiter the sunlight intensity is about one twenty-seventh of that at Earth. Thus, if the silicon-cell efficiency were the same at Earth and Jupiter conditions, about 27 times as many cells would be needed at Jupiter to achieve the same power density at Earth. But the average efficiency of the best cells is greater at Jupiter. Therefore, comparison of the average maximum power densities at Earth and Jupiter conditions given in tables I and II shows that only about 17 times as many cells would be needed.

Performance of Best Silicon Cells and Cadmium Sulfide Cells with Temperature and Intensity

Figures 1 to 4 present, for the four best silicon cells and for the two cadmium sulfide cells, the dependence of average short-circuit current density, open-circuit voltage, and efficiency with temperature and intensity. The bars shown in figures 1, 3, and 4 at the selected measurement temperatures represent the range of the measured solar-cell property.

Short-circuit current density. - The average short-circuit current density against temperature for three values of intensity is shown in figure 1. For silicon, the extreme values vary from the average by about 10 percent; and at all given intensities, the de-



(a) Spectral intensity, 136 milliwatts per square centimeter.

(b) Spectral intensity, 14.6 milliwatts per square centimeter.

(c) Spectral intensity, 6 milliwatts per square centimeter.

Figure 1. - Variation of average short-circuit current density with temperature at given intensities of CdS cells and best silicon cells.

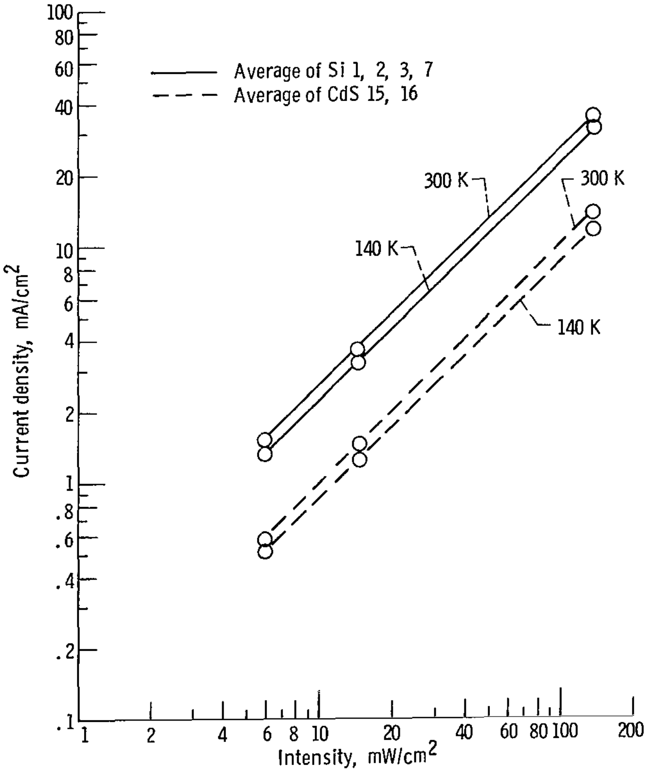
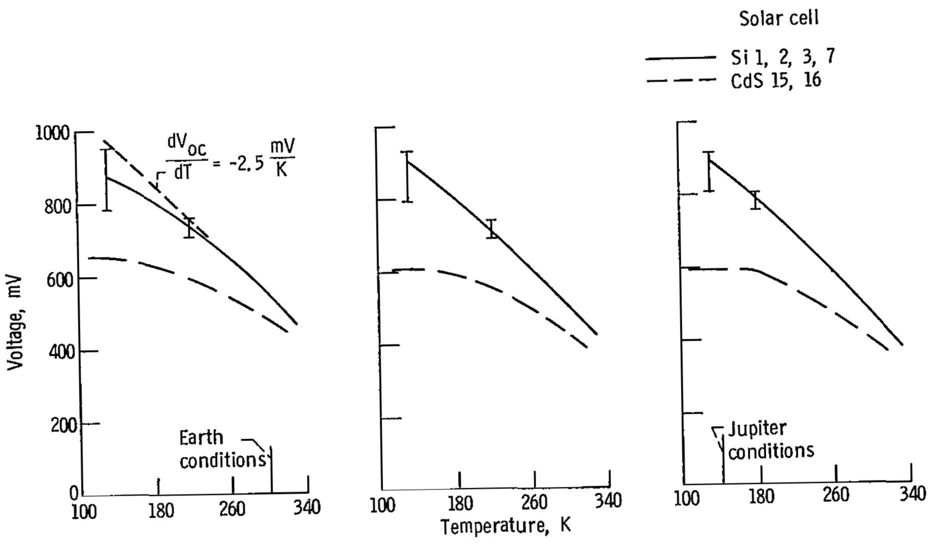


Figure 2. - Average short-circuit current density against intensity of CdS cells and best silicon cells.

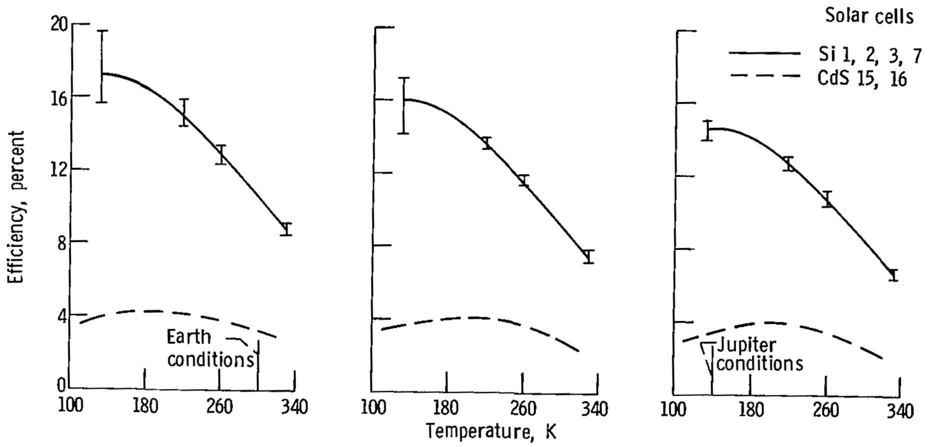


(a) Spectral intensity, 136 milliwatts per square centimeter.

(b) Spectral intensity, 14.6 milliwatts per square centimeter.

(c) Spectral intensity, 6 milliwatts per square centimeter.

Figure 3. - Variation of average open-circuit voltage with temperature at given intensity of CdS cells and best silicon cells.



(a) Spectral intensity, 136 milliwatts per square centimeter.

(b) Spectral intensity, 14.6 milliwatts per square centimeter.

(c) Spectral intensity, 6 milliwatts per square centimeter.

Figure 4. - Variation of average efficiency with temperature at given intensity of CdS cells and best silicon cells.

crease of short-circuit current density from 300 to 140 K is less than 12 percent. Reference 8 attributes decreases of silicon-cell short-circuit current with decreasing temperature to "lifetime and series resistance changes."

The change of the average short-circuit current density with intensity at 300 and 140 K is presented in figure 2. Over the range of intensities of 136 to 6 milliwatts per square centimeter, the ratio of current density to intensity is constant at a given temperature. For silicon, this ratio (0.26 and 0.22 mA/mW) decreased about 15 percent as the temperature changed from 300 to 140 K.

The changes of cadmium-sulfide-cell short-circuit current densities with temperature and intensity were similar to those observed with the silicon cells. The ratio of current density to intensity (0.094 and 0.082 mA/mW) decreased about 13 percent as the temperature changed from 300 to 140 K.

Open-circuit voltage. - A plot of the variation of average open-circuit voltage with temperature and at the three intensities is presented in figure 3. At each intensity, the silicon cells exhibited a temperature coefficient of voltage dV_{oc}/dT of about minus 2.5 millivolts per K. These coefficients are somewhat smaller than those found in reference 8 (-2.9 mV/K at $W \approx 100$ mW/cm^2). The rise of silicon-cell average open-circuit voltage with temperature from 300 to 140 K is about 56 to 84 percent.

At the higher temperatures, the average silicon-cell voltage decreased with decreasing intensity. At 300 K, the voltage decreased 15 percent as the intensity was reduced from 136 to 6 milliwatts per square centimeter. However, at 140 K this decrease was negligible. The voltage of the cadmium sulfide cells also increased as temperature was reduced, but more slowly than for the silicon cells. There was little change in voltage below 180 K. As temperature rose, these voltages approached those of the better silicon cells.

At given temperatures, the open-circuit voltages of the silicon and cadmium sulfide cells changed linearly with the logarithm of the intensity. This relation was also found in references 3 and 8.

Efficiency. - Figure 4 presents the change of average efficiency with temperature at various intensities. The average efficiency for silicon increases as temperature decreases, rising to 17 percent at 140 K and 136 milliwatts per square centimeter. The efficiency drops as intensity drops, and at 6 milliwatts per square centimeter and 140 K the average efficiency is 15 percent.

The variations of the current and voltage at maximum power with temperature and intensity were similar to those presented in figures 1 to 3. Thus, the higher Jupiter efficiency arises because the increase in cell voltage with decreasing temperature more than compensates for the decrease in voltage with lowered intensity and the decrease in current with lowered temperature.

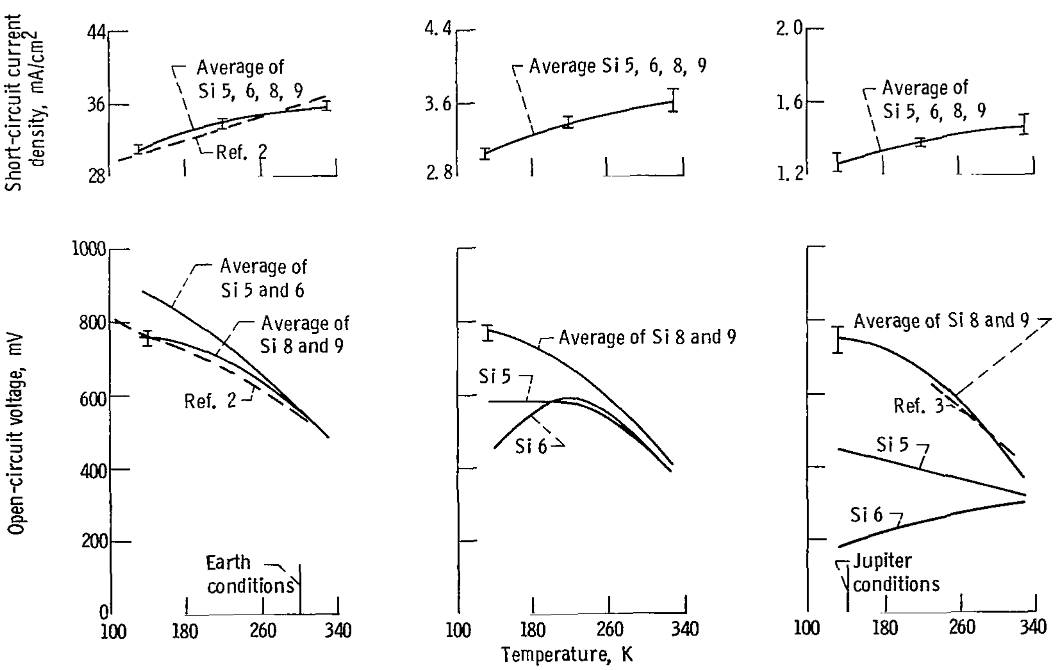
Performance of Poorer Silicon Cells with Temperature and Intensity

Figure 5 presents the short-circuit current and open-circuit voltage for Si cells 5, 6, 8, and 9, typical poor cells. In general, the values of short-circuit current density at any temperature and intensity varied little from those observed with the better-performing cells (fig. 1). As observed with the best cells (fig. 2), the short-circuit current density of all the cells was linear with intensity at all given temperatures. However, it can be seen in tables I and II that the current at maximum power dropped faster than the intensity.

At 136 milliwatts per square centimeter, the voltages compared closely with those of the better cells (fig. 3). At the lower intensities, the voltages for all these cells were lower than those for the better cells, and the variation among the poor cells was wide.

At 136 milliwatts per square centimeter, the efficiencies were lower than those of the best cells. The efficiency of the cells deteriorated rapidly as temperature and intensity were reduced.

Literature values of short-circuit current density and open-circuit voltage are also presented in figure 5. These values compare well with the data presented in figures 1 and 3 for the best-performing cells.



(a) Spectral intensity, 136 milliwatts per square centimeter.

(b) Spectral intensity, 14.6 milliwatts per square centimeter.

(c) Spectral intensity, 6 milliwatts per square centimeter.

Figure 5. - Variation of short-circuit current and open-circuit voltage of poorer-performing cells with temperature at given intensities.

Possible Contributions to Deterioration of Silicon-Cell Performance at Low Temperatures and Intensities

The theory of an illuminated n-p junction based on a simple equivalent circuit indicates that excessive series resistance and reverse current can drastically lower cell performance. The practice is to measure the room-temperature dark values of these properties and use these values to predict the quality of a cell while illuminated. It is of interest, therefore, to investigate the dark properties of cells and compare them with the illuminated cell properties taken from the I-V curves.

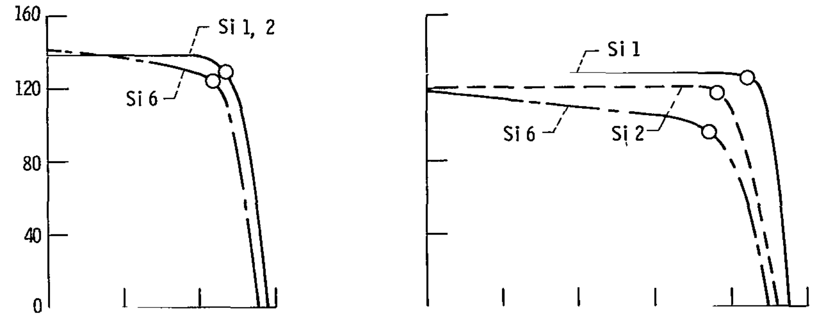
The methods described in reference 7 were used to obtain the dark series resistance and the reverse current of all the silicon cells as a function of temperature. The dark series resistance of the cells measured was 0.20 to 0.30 ohm at room temperature and increased with decreasing temperature. On many of the cells, resistance was not obtained at temperatures below 200 K because the current-voltage relation was nonlinear.

Values of room-temperature dark reverse current were obtained that extended over three orders of magnitude. Cells with Jupiter efficiency of 8 percent or more produced currents of less than 110 microamperes. The average reverse current of cells 1, 2, 3, and 7 was 18 microamperes. The currents of the other cells ranged from about 200 to 11 000 microamperes. The poorest-performing cell (cell 6) had the highest dark reverse current.

As temperature was reduced from 300 to 140 K, the dark reverse currents of the best cells decreased, but the reverse current of cell 6 increased slightly. In figure 6, comparison of the shapes of the I-V curves of cells 1 and 2 with cell 6 indicates that excessive reverse current is affecting the performance of cell 6 at approximately room temperature and at 140 K. Thus, observations of dark reverse currents and the shape of I-V curves indicates that poor performance may be related to high reverse currents.

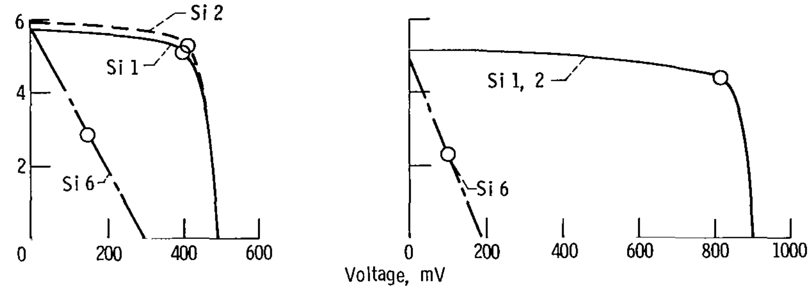
To check this observation, the room-temperature reverse current of cell 6 was reduced from about 11 000 to 250 microamperes by edge etching. Although the Earth efficiency was thereby reduced to 8 percent and room-temperature series resistance increased from 0.26 to 0.37 ohm, the Jupiter efficiency was raised from 1 to 10 percent.

These experiments suggest that good Jupiter efficiencies can be obtained only on cells which show very low values of room-temperature dark series resistance ($<0.25\ \Omega$) and reverse current ($<18\ \mu A$).



(a) Near-Earth conditions: spectral intensity, 136 milliwatts per square centimeter; equilibrium temperature: 294 K for Si 1 and 2; 300 K for Si 6.

(b) Spectral intensity, 136 milliwatts per square centimeter; equilibrium temperature, 138 K.



(c) Spectral intensity, 6 milliwatts per square centimeter; equilibrium temperature: 294 K for Si 1 and 2; 300 K for Si 6.

(d) Near-Jupiter conditions: spectral intensity, 6 milliwatts per square centimeter; equilibrium temperature, 138 K.

Figure 6. - Current-voltage characteristics of silicon solar cells Si 1, 2, and 6.

Method for Selecting Best Silicon Cells for Jupiter Conditions

The data for the silicon cells was examined to see whether there was a screening method using room-temperature measurements that would be useful for selecting cells for operation at Jupiter conditions. It was apparent that screening on the basis of dark series resistance or dark reverse current alone was not sufficient. It was noted, however, that fill factor was highly sensitive to intensity for the poor cells. Figure 7 presents the percent decrease of fill factor at 300 K from intensities of 136 to 6 milliwatts per square centimeter against Jupiter efficiency for all the cells investigated.

Cells with less than 9 percent change in fill factor had efficiencies at Jupiter greater than 11 percent; those with less than 4 percent change had efficiencies near 15 percent. These data indicate that a determination of the fill factor can be useful for selecting better-performing silicon cells at Jupiter conditions. Monitoring at room temperature is convenient because no sophisticated mounting techniques are required.

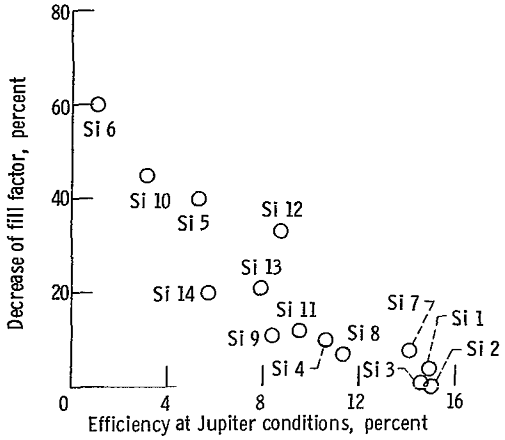


Figure 7. - Silicon-cell percent decrease of fill factor at 300 K from intensities of 136 to 6 milliwatts per square centimeter, against Jupiter efficiency.

SUMMARY OF RESULTS

The photovoltaic properties of silicon and cadmium sulfide solar cells were investigated at simulated solar intensities of 136, 14.6, and 6 milliwatts per square centimeter and at temperatures from about 340 to 140 K.

All the silicon cells showed acceptable efficiencies ranging from 10 to 11 percent at Earth conditions, but large differences in efficiency, ranging from about 1 to 15 percent, were noted at Jupiter conditions.

The efficiency of the best-performing cells at Jupiter conditons was about 1.4 times that achieved at Earth conditions. This efficiency is higher than those presented in the literature. The efficiency of the cadmium sulfide cells at Jupiter was about 1.1 times higher than at Earth.

At room temperature, the percent change of fill factor with intensity between 136 and 6 milliwatts per square centimeter increased as the efficiency at Jupiter decreased. This suggests that observation of the fill factor as the intensity is varied can be useful for sorting out the better-performing cells at Jupiter conditions without resorting to low-temperature tests.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 28, 1969,
120-33.

APPENDIX A

SOLAR-CELL MOUNTING AND INSTRUMENTATION

The cadmium sulfide cells were easily glued to the brass substrates. However, several methods of mounting the silicon cells were tried before good results were obtained. Gluing the silicon cells to the substrate gave poor bonds at low temperatures and made removal difficult. Soldering of the cells to the substrate made them crack at low temperatures and deteriorate, and also made them hard to remove.

These problems were overcome by using the silicon cell holder shown in figure 8. The holder was made from brass and was bolted to a cooled block set in a vacuum chamber having a quartz window. The holders were electrically insulated from the block. Less than 1 percent of the cell active area was covered by holddown devices, and the cell area was corrected to include this effect.

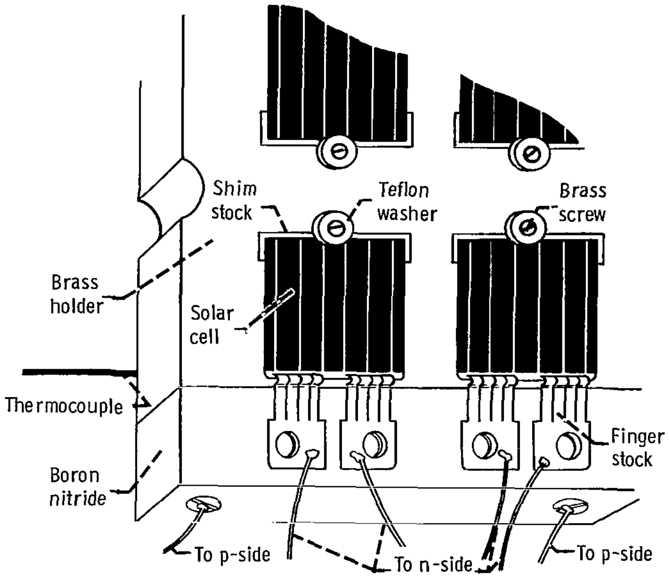


Figure 8. - Mounting of n-p silicon solar cells to holder.

Two copper-constantan thermocouples were inserted in the holder at a distance of 0.16 centimeter (1/16 in.) below the top surface and under the cells. On one edge of the n-p cell, 0.008-centimeter- (0.003-in.-) thick brass shim stock cut about to the width of the cell was placed between the holder and the rear contact. This guaranteed electrical contact. Brass screws and nylon washers held the cell and shim to the holder with only the washer in contact with the cell. Because the cell backs were generally rough and uneven, heat-sink compound was placed on the remainder of the rear contact which was not in contact with the shim, thus ensuring good thermal contact. The other edge of the cell was held to the holder with finger stock in electrical contact to the n-side. The n-side was electrically isolated from the brass holder by attaching the finger stock to strips of boron nitride mounted on the brass holder.

A four-wire system and a modified three-wire system were used to connect the CdS and silicon cells, respectively, to the electronic load. A curve tracer was used to determine the dark parameters of the silicon cells.

APPENDIX B

SOLAR INTENSITY AND EQUILIBRIUM TEMPERATURES NEAR EARTH AND JUPITER

The solar constant of the Earth is about 136 milliwatts per square centimeter (ref. 9). The solar flux at Jupiter has been estimated as 5 to 6 milliwatts per square centimeter.

The equilibrium temperature is difficult to predict because it is dependent on solar array configurations, solar flux, optical properties of the cells, and, when the cells are operating close to the planet surface, planet albedo and radiant flux. However, sunlit equilibrium temperatures of thin-film CdS cells in an Earth orbit and at various distances from the Earth's surface have been calculated as ranging from 310 to 360 K when in sunlight (ref. 10). Solar simulator measurements with CdS cells (ref. 5) indicate an equilibrium temperature of 325 K when no planet albedo and radiant flux are present. Temperatures of illuminated silicon-cell arrays in an Earth orbit have been measured as about 320 K (ref. 11).

Experiments in a simulated Jupiter orbit with no incident planet radiation or albedo indicate that the temperature of thin-film CdS cells is about 180 K (ref. 5). The temperature of a silicon cell at this orbit was calculated herein as 148 K from the measured normal spectral emittance of a typical cell given in figure 9. The procedures are described in reference 10; the following expressions were used:

$$\alpha_S = \frac{b_1 T_S}{\sigma} \int_0^\infty \epsilon_\lambda \frac{W_{\lambda T, S}}{W_{\lambda m T, S}} \, d\lambda \tag{B1}$$

$$\epsilon_{T,N} = \frac{b_1 T_C}{\sigma} \int_0^\infty \epsilon_\lambda \frac{W_{\lambda T, C}}{W_{\lambda m T, C}} \, d\lambda \tag{B2}$$

where

α_S	total normal solar absorptance
b_1	constant, 1.2864×10^{-15} W/(cm^2)(μm)(K^5)
T_S	temperature of Sun, 5800 K
σ	Stefan-Boltzmann constant, 5.669×10^{-12} W/(cm^2)(K^4)

ϵ_λ	normal spectral emittance
$W_{\lambda T}$	spectral intensity of blackbody at temperature T
$W_{\lambda m T}$	maximum spectral radiant intensity of blackbody at temperature T
λ	wavelength, μm
$\epsilon_{T,N}$	total normal emittance
T_C	temperature of solar-cell surface, 148 K

It was assumed that the back of the cell was black and that the temperatures were equal throughout the cell. The equations for relating $\epsilon_{T,N}$ to the total hemispherical emittance were taken from reference 12.

Based on these considerations, values of equilibrium temperature were chosen as 300 K at 136 milliwatts per square centimeter and 140 K at 6 milliwatts per square centimeter for the Earth and Jupiter conditions, respectively.

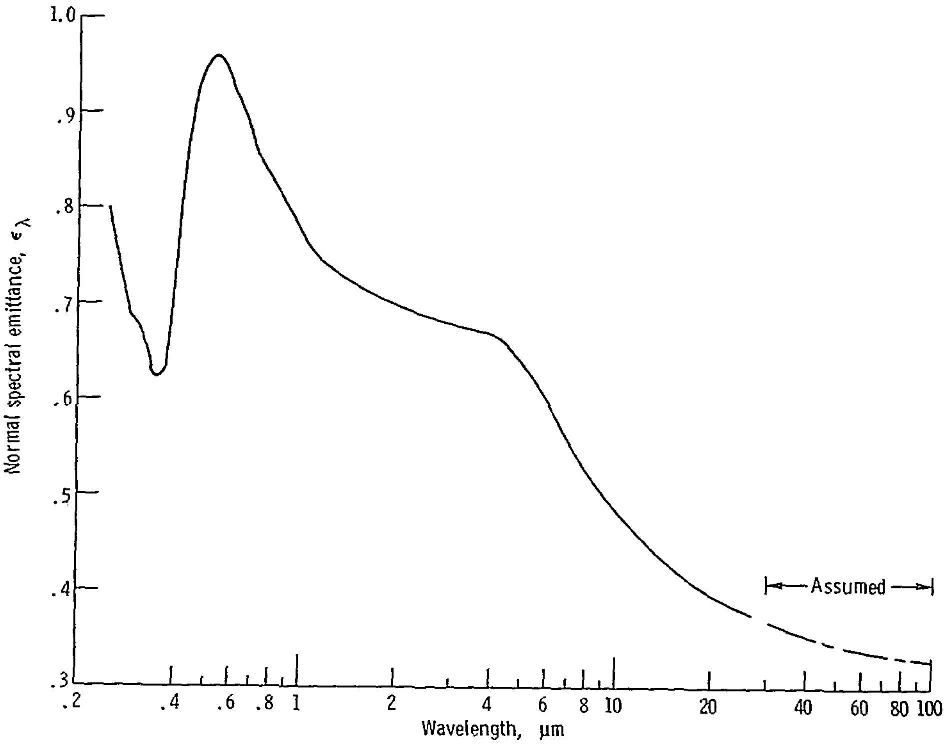


Figure 9. - Room-temperature spectral emittance of coated silicon cell.

APPENDIX C

EXPERIMENTAL ERROR

Uncertainty in Solar Intensity Measurements

Prior to testing, the spectral distribution of the filtered xenon light source was evaluated and was found to be within the specifications given by the manufacturer. These specifications show that at wavelengths of 0.35 to 1.20 microns, approximately the wavelength region within which the cells convert sunlight to electricity, the percent deviation of the intensity of the source from the Johnson data is generally ±5 percent. The intensity was set at air mass zero conditions at the test plane with a standard silicon cell calibrated for outer-space conditions using high-altitude aircraft (ref. 9). Fluctuations of intensity caused the currents and voltages to vary not more than ±1 percent. The uniformity of the intensity at the test plane was measured with the standard silicon cell and was found to be uniform within ±1 percent.

Screens were used to lower the intensity from 136 milliwatts per square centimeter ±1 percent, to 14.6 and 6 milliwatts per square centimeter ±2 percent. The short-circuit current of the standard cell is a linear function of intensity and therefore was used to establish the values of these lower intensities. The transmission of the screens was checked in spectrophotometers between 0.25 and 15 microns and was invariant with wavelength. The values of intensities were also crosschecked with a total radiation bolometer.

Uncertainty in Electrical and Temperature Measurements

Cadmium sulfide solar cells. - The voltages and currents as obtained with an X-Y plotter and an electronic load were accurate to within ±1 percent. The thermocouples, mounted in the cell holders, were checked at boiling-water and liquid-nitrogen temperatures. Accuracy was within 1 percent.

The thermocouples were located under the adhesive and beneath the back of the cell. Because the cell is very thin and the thickness of the glue is less than 0.0025 centimeter (0.001 in.), calculations show that cell and thermocouple temperature will be within 1 K. Thus, the maximum error of voltages, currents, and efficiencies at given temperature are believed to be ±2, ±2, and ±5 percent, respectively.

Precision: The performance of one cadmium sulfide cell was investigated four times over the range of conditions incurred in these experiments. Percent maximum repeatability of results was identical with percent maximum accuracy.

Mounting: Before the cadmium sulfide cells were glued to a substrate, I-V curves at an intensity of 136 milliwatts per square centimeter and at room temperature were obtained with a separate device which used filtered sungun lamps and a vacuum holddown. Also, after the low-temperature intensity tests were concluded, the cell was removed from the substrate and measured again in the separate testing device. The currents and voltages obtained with the separate device corresponded within ±2 percent, and the efficiency to within ±5 percent, of the values found at comparable temperature and intensity conditions during the tests. Thus, it was concluded that within these limits the performance of the cadmium sulfide cells was not altered by these mounting procedures.

Silicon solar cells. - The accuracy of the electronic equipment and thermocouples just discussed applies here as well.

The thermocouples used for recording the silicon-cell temperatures were not attached directly to the cell because all attempts (soldering, peening, etc.) caused cell deterioration. Calculations indicate that there will be some difference between the temperature of the cell holder recorded herein and the actual cell temperature. A separate experiment was made to determine the extent of this difference. Two cells were mounted as shown in figure 8, but copper-constantan thermocouples were also soldered to the backs of the cells. At all intensities and in the temperature range of 330 to 160 K, the cell and holder temperatures were within ±1 K. In the range of 160 to 145 K and at all intensities, the temperatures were within ±4 K. However, at an intensity of 136 milliwatts per square centimeter and 140 K, the cell temperatures were about 10 K higher than the holder temperature. The accuracy of the voltage-temperature and efficiency-temperature plots presented herein could be affected by about 4 and 7 percent, respectively, if cell and holder temperatures differ by 10 K.

In general, then, the accuracy of the data is thought to be less than ±3 percent for voltages and currents and ±4 percent for efficiencies. At the highest intensities and lowest temperatures only, the accuracy of the currents is within about ±3 percent, voltages about ±4 percent, and efficiencies ±7 percent.

Precision: Experiments over the range of temperature and intensity used in these experiments were repeated once on cells 1, 7, 8, and 13 mounted as shown in figure 8. Also, a cell with a reasonably smooth back contact was mounted on the holder without use of the shim and heat-sink compound. The performance of this cell using both mounting techniques was recorded. In all cases, maximum percent repeatability of results was identical with maximum percent accuracy. This latter test indicates that, within these limits, use of the shim and heat-sink compound did not affect cell performance.

Mounting: To ensure that there was good electrical contact between cell and holder, measurements of dark series resistance and reverse current were made at room temperature on all the silicon cells before and after mounting and also while they were mounted. Agreement was within ±6 percent.

Following the procedure used with the cadmium sulfide cells, I-V curves of several silicon cells were taken at room temperature before and after the low-temperature tests had been completed. Agreement of current densities, voltages, and efficiencies was found to be within ±2, ±3, and ±5 percent, respectively, of the values found at comparable temperature and intensity conditions during the tests. Thus, it is concluded that within these limits no silicon-cell deterioration had occurred as a result of mounting procedures.

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