SOLAR CELL PERFORMANCE AT HIGH TEMPERATURES

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Various space missions can be envisioned which would subject the solar cells of a space vehicle to temperatures higher than 75° C. Questions arise as to what performance to expect of silicon solar cells, and what, if any, substitute cells can be used to better advantage at these high temperatures.

In this paper, the temperature behavior of various resistivity, unbombarded and bombarded silicon cells and unbombarded and bombarded GaAs cells will be discussed and compared. The characteristics to be discussed are: the open circuit voltage, the maximum power output, and the curve power factor, which is defined as the maximum power output divided by the product of the short-circuit current and open-circuit voltage.

$$\text{CPF percent} = \frac{P_O}{V_{OC} \times I_{SC}} \times 100$$

Table I shows typical outer space characteristics of unbombarded cells at 25° C. These are the values that can be achieved at the present time

TABLE I. - EQUIVALENT OUTER SPACE CHARACTERISTICS

	V_{OC}, V	R_C, Ohms	I_{SC}/cm^2, ma/cm^2	P_O/cm^2, MW/cm^2	V_{MP}, V	CPF, percent	Efficiency, 1 cm × 2 cm, percent
GaAs	0.9	0.3	11	7.2	0.7	73	5.1
GaAs	.9	.3	16	10.0	.7	70	[a]7.1
Si:							
1 Ohm cm	.57	.3	32	12.6	.43	69	9.0
10 Ohm cm	.54	.3	36	14.0	.44	72	10.0
50 Ohm cm	.49	.4	36	11.5	.42	65	8.2
100 Ohm cm	.43	.7	36	8.5	.3	55	6.0

[a]Manufacturer's quoted sunlight efficiency, 10.5 percent.

[redacted]

for various resistivity n on p silicon solar cells. In going from 1-, to 10-, to 50-, to 100-ohm-cm cells, the open-circuit voltage decreases. The small increase in short-circuit current for 10-ohm-cm cells occurs because of the longer diffusion lengths in 10-ohm-cm cells. The short-circuit current remains at this value for the higher resistivity cells since the processing reduces the diffusion lengths to approximately equal values.

The curve power factors of the 10-ohm-cm cells are better than the 1-ohm-cm cells because junctions with better characteristics can be made in 10-ohm-cm material. However, as the resistivity increases, the maximum power output decreases due to both the lower open-circuit voltage and the increasing bulk parasitic resistance. Maximum efficiencies are achieved for 10-ohm-cms cells.

Considering the two categories of GaAs cells (Table I), the 5 percent cells were procured commercially, and the 7 percent cells were obtained through the courtesy of the U.S. Air Force, Wright Development Center. The efficiencies quoted are based on airplane measurements that agree with Lewis simulator measurements.

Figure 1 shows the change in open circuit voltage as a function of temperature for various resistivity silicon solar cells. There is a 0.2 mv/°C difference between the coefficients for 1- and 10-ohm-cm cells; a negligible difference between 10- and 20-Ω-cm cells and a significant difference of 0.6 mv/°C between the coefficients of 1- and 80-ohm-cm cells. Similar temperature coefficients of open-circuit voltage were obtained for solar cells doped to equivalent resistivities with either aluminum, gallium, indium, or gadolinium

Another important factor in the temperature degradation of solar cells is the change of curve power factor with temperature as shown in Figure 2. The curve power factor of 10-ohm-cm cells degrades faster than that of 1-ohm-cm cells, and that of 80-ohm-cm cells degrades most rapidly with increasing temperature. This decrease of curve power factor occurs because junction losses increase with increasing temperature.

The degradation of open circuit voltage and of curve power factor leads to degradation of maximum power output as shown in Figure 3. For these measurements the short-circuit current was maintained constant for all temperatures at a value equivalent to 25° C outer space current. A measure of the power degradation is indicated by the temperature at which the power has fallen to half that at 25° C and is given by the coefficient expressed as percent-power-lost per °C. As the resistivity of the base material is increased, the half-power point occurs at lower temperatures. For 1-ohm-cm cells, the half-power point occurs at about 135° C; for 10-ohm-cm cells it is about 20° lower; and for 80 ohm-cm cells, it occurs below 100° C. The same values of half-power point have been found for silicon doped with materials other than boron.

From the above considerations it is apparent that the 1-ohm-cm cell would be the most useful for high temperature applications.

One- and 10-ohm-cm silicon cells were subjected to an electron bombardment of 1.5×10^{16} - 1 Mev electrons per cm^2. The open circuit voltages were measured at various temperatures below 100° C with the illumination level such that the short-circuit currents were equivalent to those the cells would have in outer space. There is no observable change in the temperature coefficient of open-circuit voltage after this level of bombardment. The same is true for proton-bombarded cells, bombarded to a dose of 3.9×10^{12}-10 Mev protons per cm^2, which is equivalent in damage production to approximately 1×10^{16} 1 Mev electrons per cm^2.

Figure 4 is a plot of curve power factor versus temperature for 1- and 10-ohm-cm, unbombarded and bombarded cells. Since the plots are straight lines in this temperature range, a coefficient can be determined. There is a significant change in the temperature rate of decrease for the curve power factor, increasing with bombardment dose. The same behavior is also found for proton-bombarded cells. The change in power output degradation of bombarded cells also depends upon the variation of short-circuit current with temperature. Bell Laboratories reports (private communication) that the short-circuit current increases with temperature at a rate of 0.2 percent per °C for heavily bombarded cells. Based on our measurements and calculations, the half-power point and temperature coefficient of power output for bombarded cells will be similar to those of unbombarded cells.

The power supplies of satellites are usually designed for constant-voltage operation. Therefore, bombarded solar cell power output was studied as a function of temperature for various constant-voltage conditions. Figure 5 shows the power output for 1- and 10-ohm-cm electron-bombarded cells. For maximum power output at 55° C, the voltage for constant-voltage operation should be 0.3 V for 1-ohm-cm and 0.25 V for 10-ohm-cm cells. For operation at 75° C, the voltages are 0.25 V for 1-ohm-cm cells and 0.2 V for 10-ohm-cm cells. Between 75° C and 100° C maximum power output under constant-voltage operating conditions is attained by operating 10-ohm-cm cells at 0.15 V. The power output of 10-ohm-cm cells is still higher than that available from 1-ohm-cm cells operated at 0.2 V. The optimum voltages for maximizing power output in the constant-voltage condition depends on the operating temperature and the bombardmemt dose. In all cases, 10-ohm-cm cells maintain considerably higher power output than do 1-ohm-cm cells, as shown in Figure 5.

For temperatures above 150° C, the 1-ohm-cm cell is preferable to the 10-ohm-cm cell. GaAs solar cells have also been proposed for operation between 150° to 200° C. Figure 6 compares the open-circuit voltage degradation with temperature for typical GaAs cells and 1-ohm-cm silicon solar cells. GaAs cells have a temperature coefficient of 2.5 mv/°C as compared to 2.1 mv/°C for 1-ohm-cm silicon cells. However, because of the initially higher open-circuit voltage of the GaAs cell, its open-circuit voltage at 200° C is 0.43 V as compared to 0.22 V for the silicon cell. It should be realized that the ultimate limitation in the use of cells made from high-energy-gap semiconductor materials is the temperature at which the open-circuit voltage approaches zero. If the curve for GaAs cells is extrapolated, the voltage will fall to zero at a temperature of about 375° C. This should be contrasted with reported open-circuit voltages for GaP experimental cells of 0.4 V at 350° C.

Figure 7 is a plot of curve power factor for 1-ohm-cm silicon cells and for GaAs cells. In general, the curve power factor of silicon cells decreases more rapidly than that of GaAs cells, the decrease becoming more rapid at temperatures above 125° C.

The variation of maximum power output with temperature is shown in Figure 8 for both high and low efficiency GaAs cells and for 1-ohm-cm silicon cells. The half-power point occurs at about 165° C for GaAs cells as compared to 135° C for silicon cells. This is reflected in the lower degradation factor for GaAs, 0.35%/°C, as compared to 0.46%/°C for silicon. However, since the silicon cell has twice the short-circuit current under outer space illumination as does the high-efficiency GaAs cell both cells have the same power output at 175° C. At 200° C there is a 2-milliwatt difference in power output. However, the power output of the 1-ohm-cm silicon cell equals that of the commercially available, lower efficiency, GaAs cell at 200° C. The choice of either silicon or GaAs cells for 200° C operation depends on the factors of reliability, availability, cost, and minimum power output requirements. Based on these considerations, the present commercial 1-ohm-cm silicon cells are not surpassed for operation at 200° C by any other type of commercial cell presently available.

Figure 9 is a plot of the product of open-circuit voltage and short-circuit current versus temperature for high efficiency GaAs cells and 1-ohm-cm silicon cells. The significance of this plot is that, if the curve power factor of the 1-ohm-cm silicon cell can be raised sufficiently at room temperature, then its power output will be greater than that of the high-efficiency GaAs cell for all temperatures up to and including 200° C. Recent information on the effects of impurities indicates that this improvement may now be possible.

Just as in the case of silicon solar cells, GaAs cells bombarded to a dose of 3.9×10^{12} - 10 Mev protons/cm^2 show no change in the temperature coefficient of open-circuit voltage. Curve power degradation increases after bombardment in a manner similar to the silicon case. A degradation coefficient of 0.12%/°C in the temperature range from 50° to 100° C is found for bombarded cells as compared to 0.10%/°C in the same temperature range for unbombarded cells.

At present, the performance of any available solar cell is marginal at 200° C. GaP is therefore being considered for use in the range above 200° C.

The current status of GaP solar cells has been mentioned in a previous paper; however, it should be pointed out that, if the anticipated open-circuit voltage of 1.5 V can be achieved, then operation of these cells to temperatures of 500° C would be possible. The low short-circuit currents of GaP cells would not necessarily eliminate them from consideration since these cells would be expected to operate where solar intensities are many times those in earth space.

V_{OC} VS TEMPERATURE FOR VARIOUS RESISTIVITIES

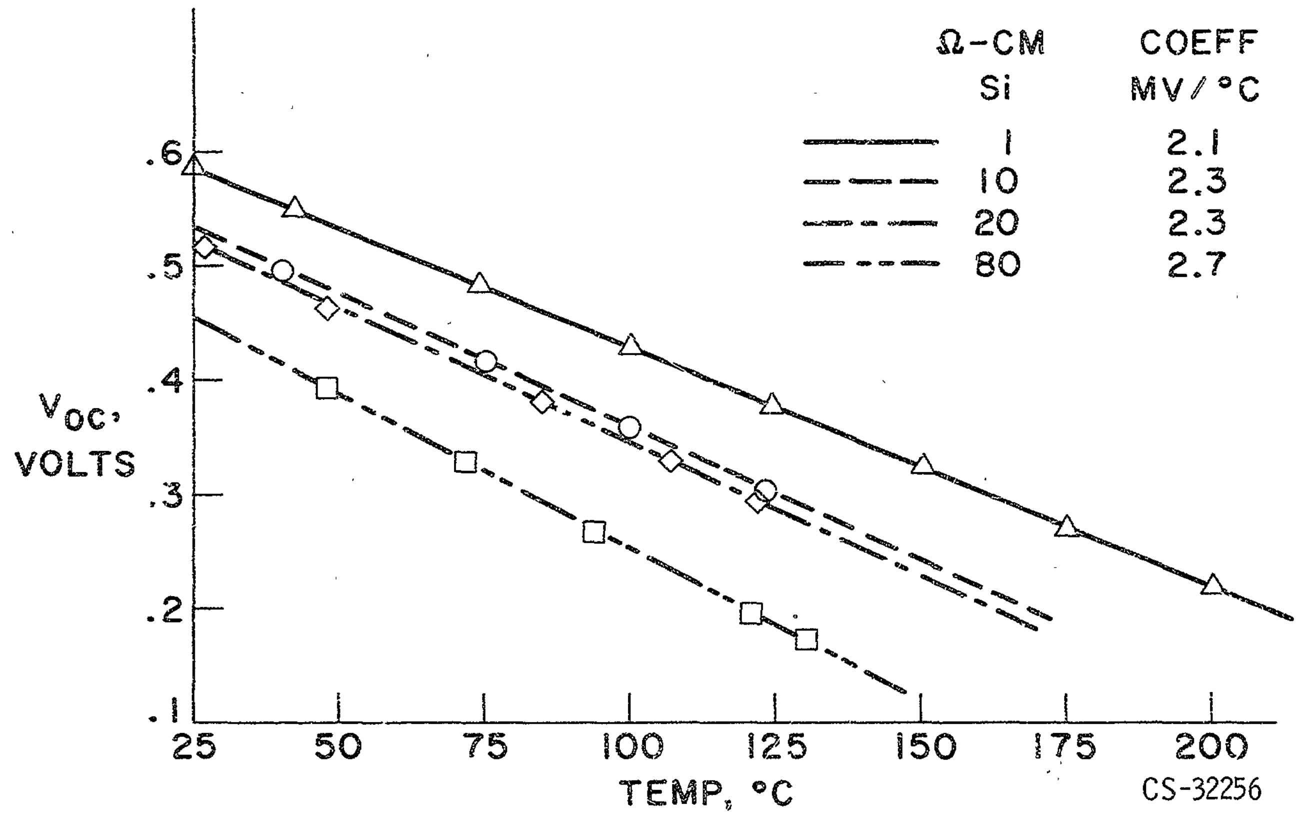


Figure 1.

CURVE POWER FACTOR VS TEMPERATURE

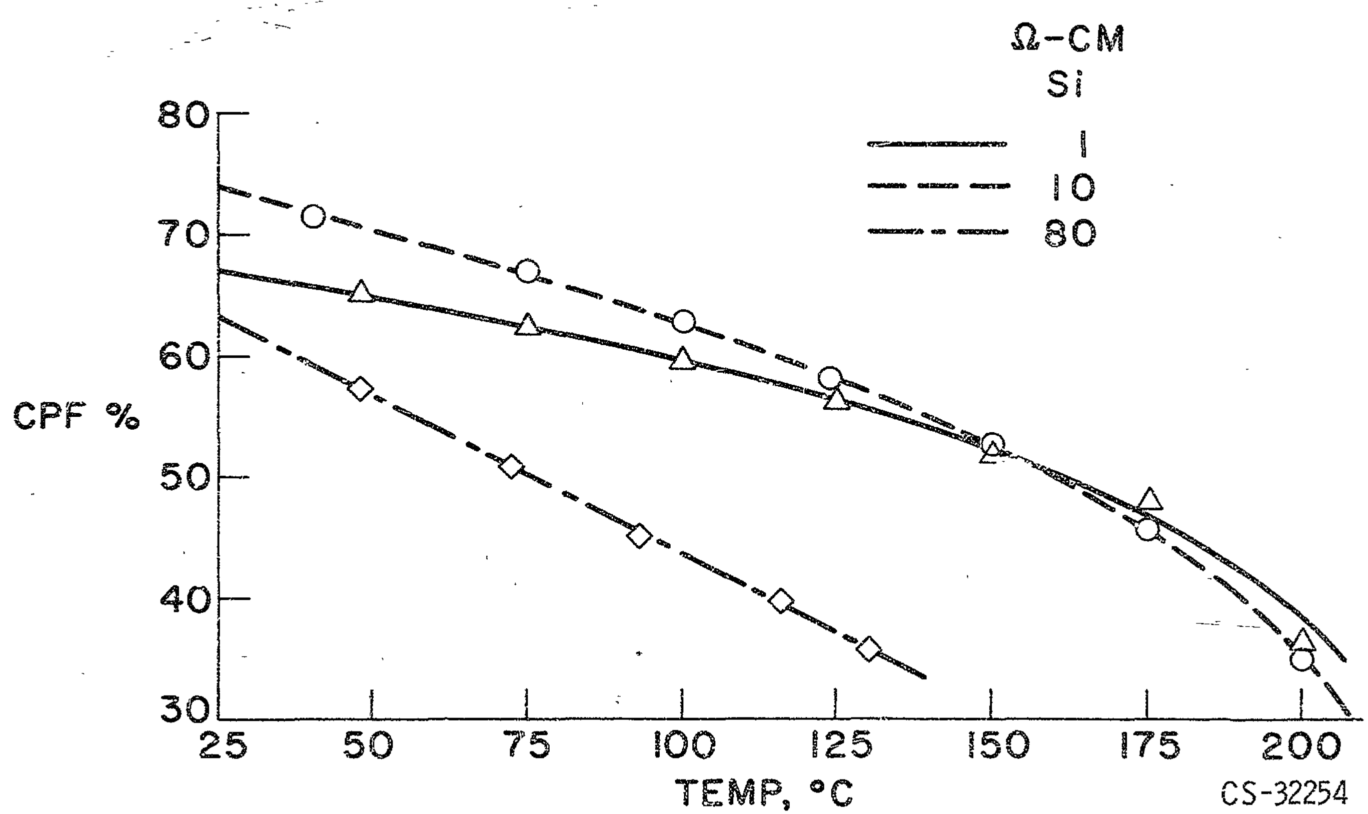


Figure 2.

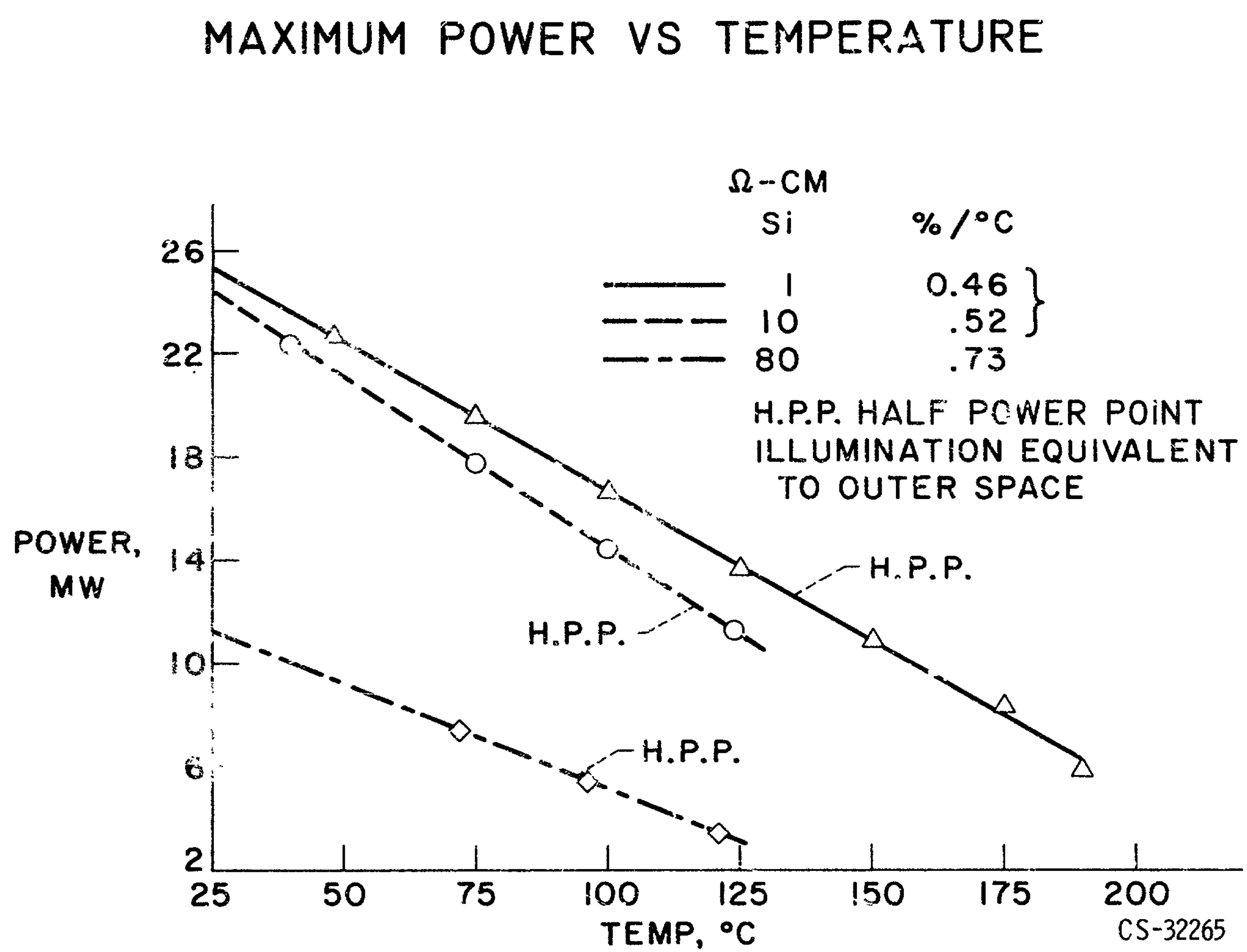

MAXIMUM POWER VS TEMPERATURE
Ω-CM
Si
%/°C
1
0.46
10
.52
80
.73
H.P.P. HALF POWER POINT
ILLUMINATION EQUIVALENT
TO OUTER SPACE
H.P.P.
H.P.P.
H.P.P.
POWER,
MW
26
22
18
14
10
6
2
25
50
75
100
125
150
175
200
TEMP, °C
CS-32265

Figure 3.

CURVE POWER FACTOR VS TEMPERATURE

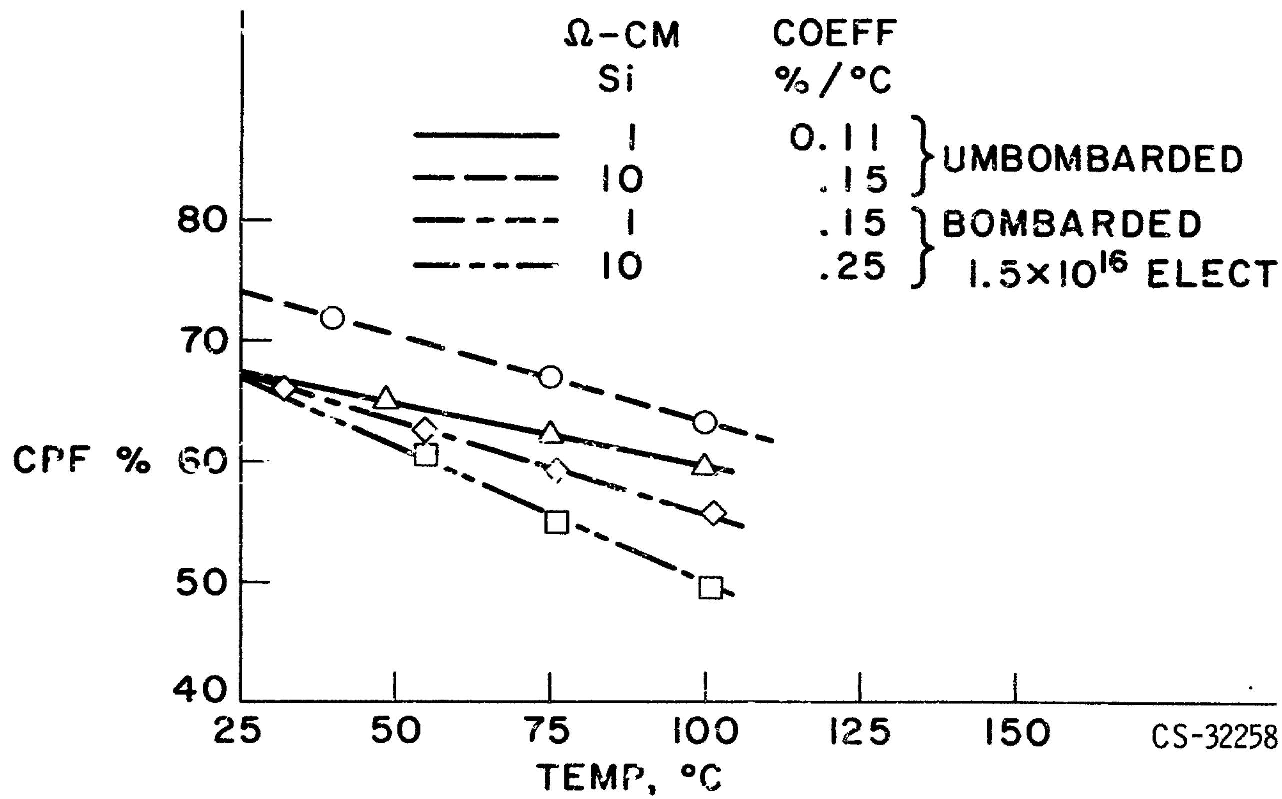


Figure 4.

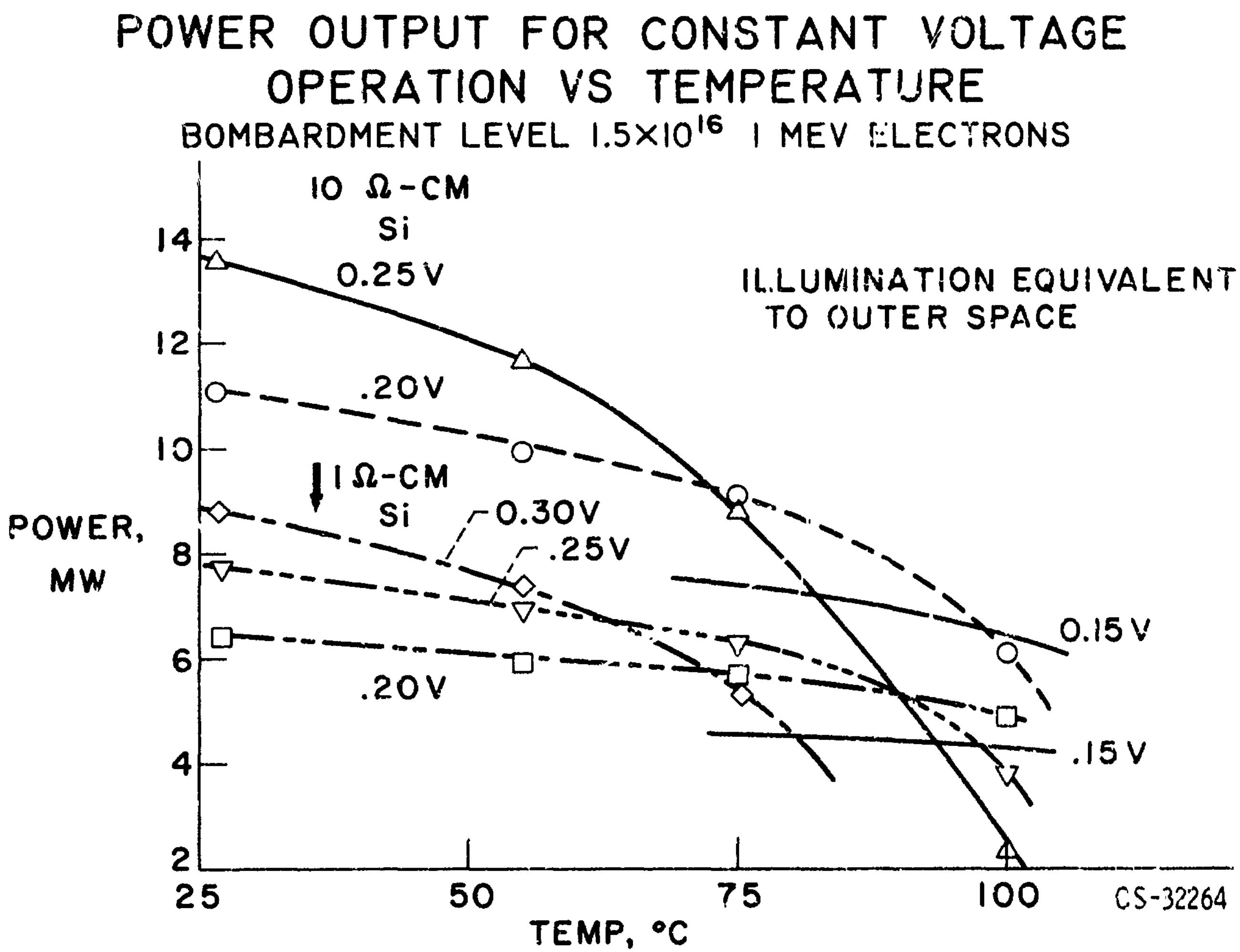
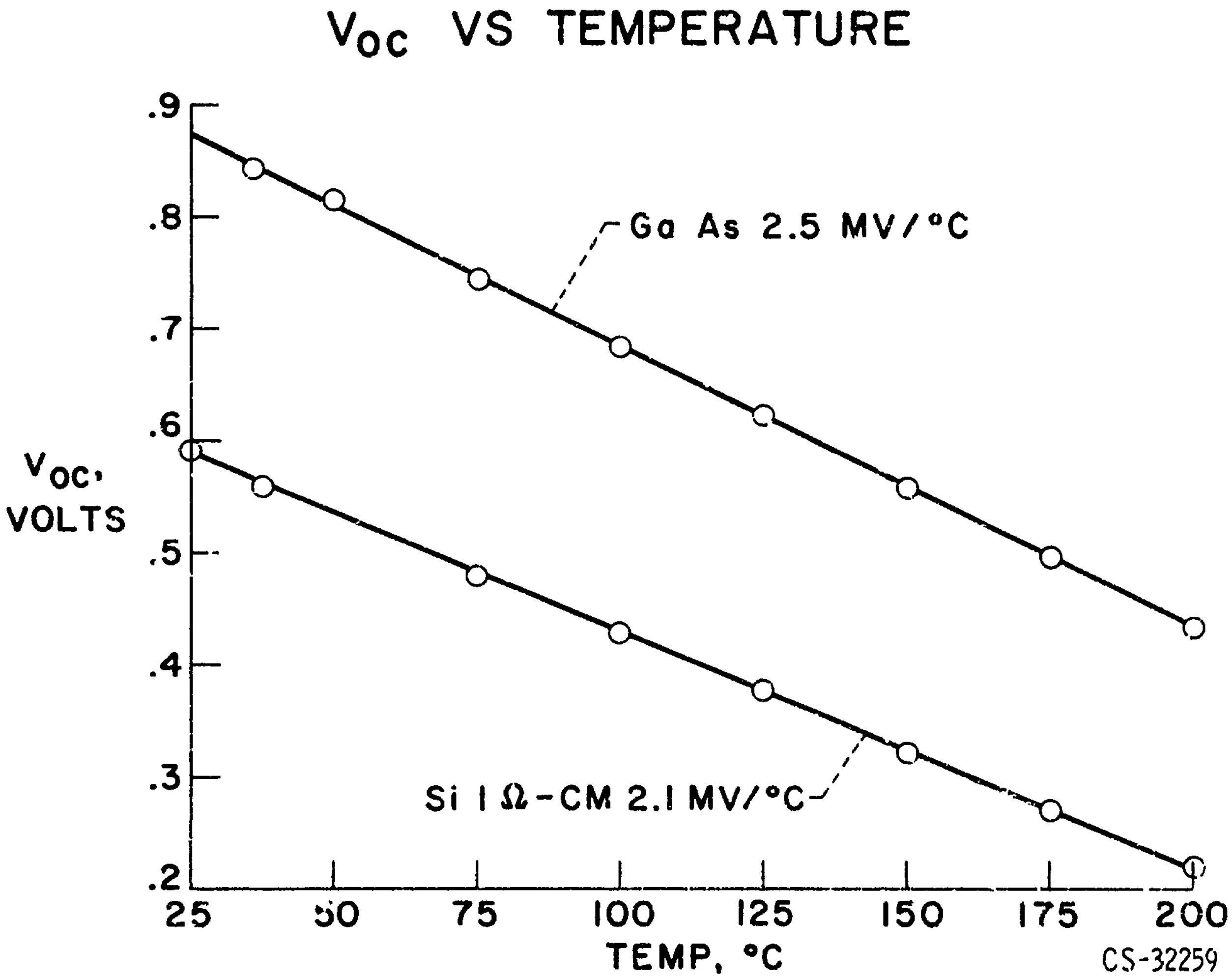

POWER OUTPUT FOR CONSTANT VOLTAGE OPERATION VS TEMPERATURE
BOMBARDMENT LEVEL 1.5×10^16 1 MEV ELECTRONS
10 Ω-CM
Si
0.25 V
.20 V
1 Ω-CM
Si
0.30 V
.25 V
.20 V
ILLUMINATION EQUIVALENT
TO OUTER SPACE
0.15 V
.15 V
POWER,
MW
14
12
10
8
6
4
2
25
50
75
100
TEMP, °C
CS-32264

Figure 5.



Voc VS TEMPERATURE
.9
.8
.7
.6
.5
.4
.3
.2
Voc, VOLTS
Ga As 2.5 MV/°C
Si 1 Ω-CM 2.1 MV/°C
25
50
75
100
125
150
175
200
TEMP, °C
CS-32259

Figure 6.

CURVE POWER FACTOR VS TEMPERATURE

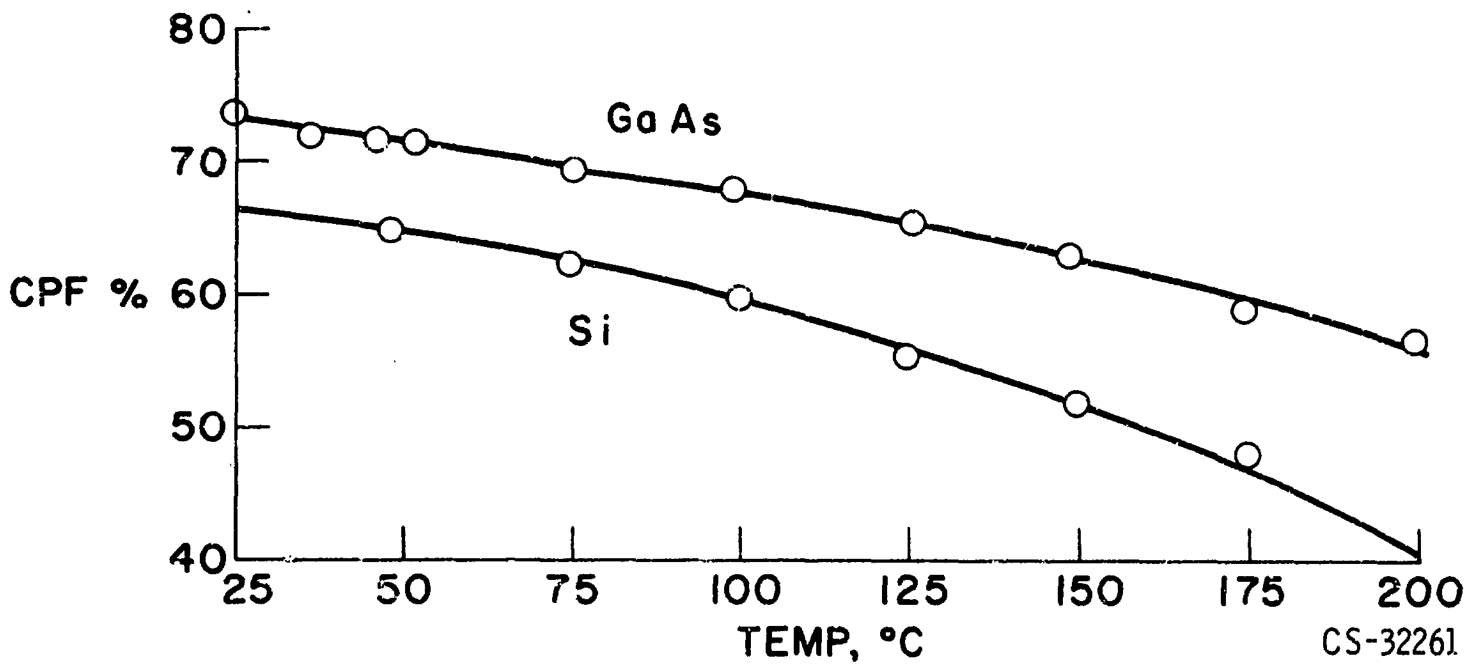


Figure 7.

MAXIMUM POWER VS TEMPERATURE

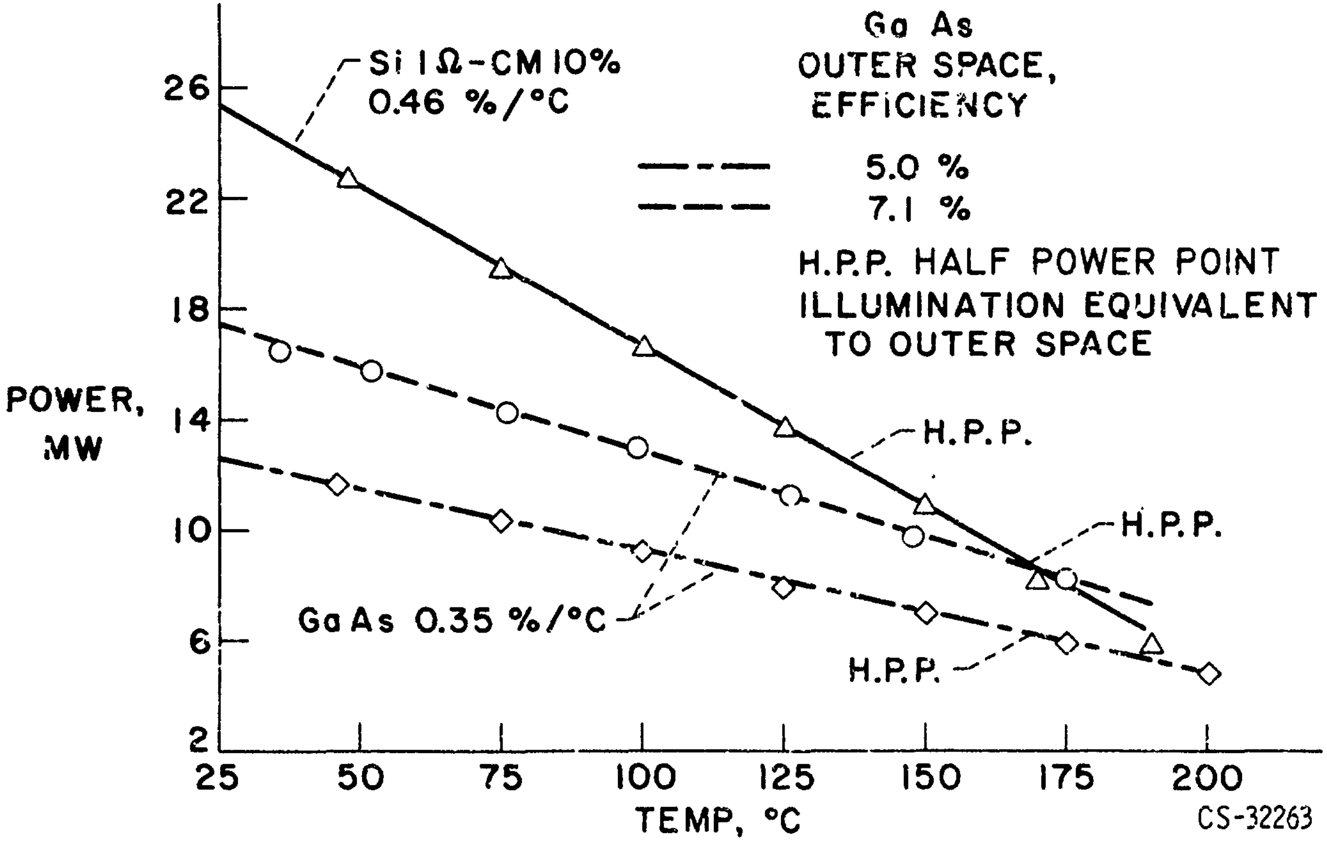
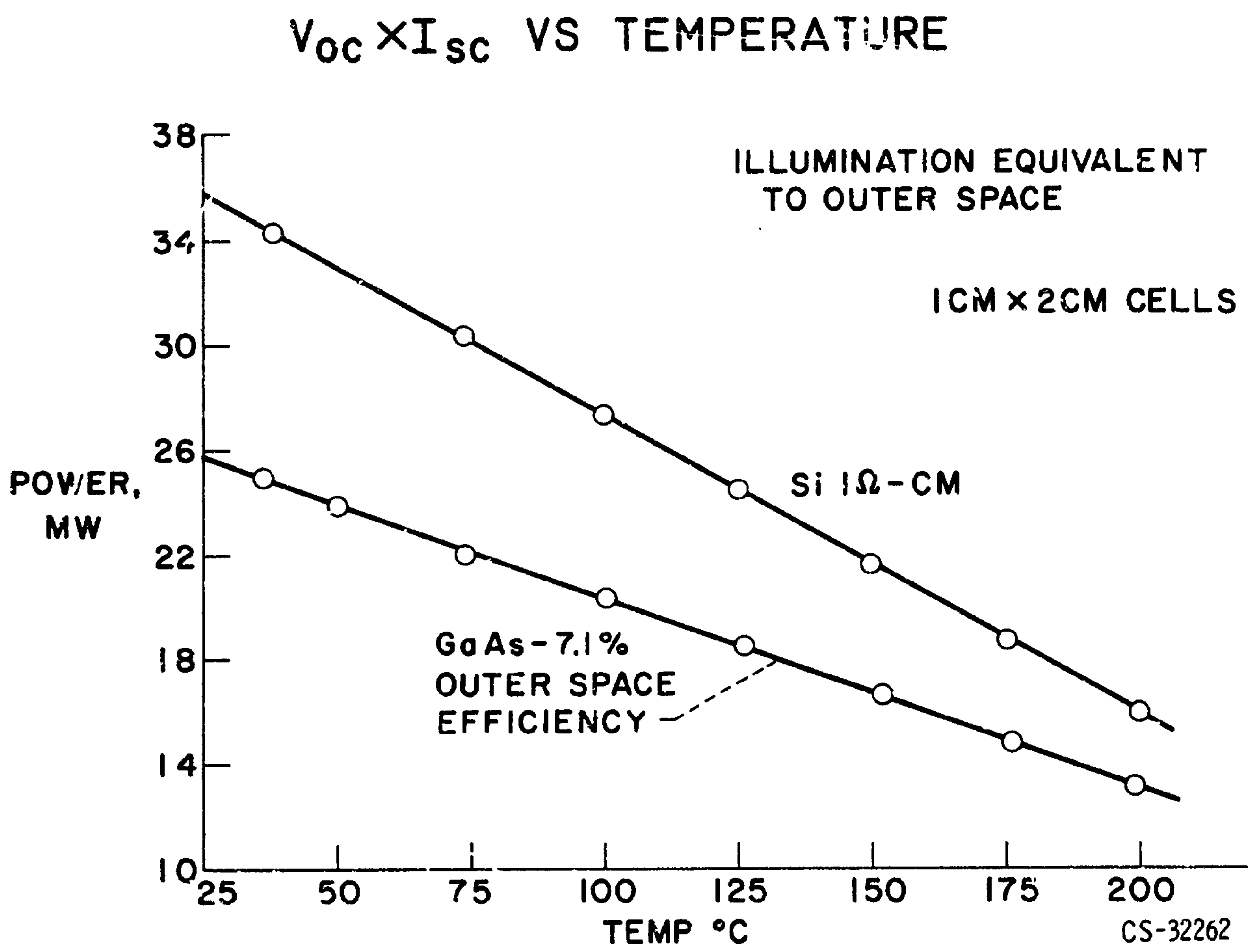


Figure 8.



$V_{OC} \times I_{SC}$ VS TEMPERATURE
ILLUMINATION EQUIVALENT TO OUTER SPACE
1CM × 2CM CELLS
POWER, MW
38
34
30
26
22
18
14
10
25
50
75
100
125
150
175
200
TEMP °C
Si 1Ω-CM
GaAs-7.1% OUTER SPACE EFFICIENCY
CS-32262

Figure 9.