NASA TECHNICAL MEMORANDUM

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CHARACTERIZATION OF THREE TYPES OF SILICON SOLAR CELLS FOR SEPS DEEP SPACE MISSIONS

Volume I. Current-Voltage Characteristics of OCLI BSF/BSR 10 ohm-cm, BSR 10 ohm-cm, and BSR 2 ohm-cm Cells as a Function of Temperature and Intensity

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TABLE OF CONTENTS

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LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

LIST OF TABLES (Concluded)

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CHARACTERIZATION OF THREE TYPES OF SILICON SOLAR CELLS FOR SEPS DEEP SPACE MISSIONS

Volume I. Current-Voltage Characteristics of OCLI BSF/BSR 10 ohm-cm, BSR 10 ohm-cm, and BSR 2 ohm-cm Cells as a Function of Temperature and Intensity

I. INTRODUCTION

This is the first in a series of technical reports on the characterization of high performance solar cells under conditions of low temperatures and low intensities. Today's solar cells have been designed for maximum performance at 1 AU*, AM0, with little regard for the characteristics that would enhance their performance in deep space. In the late 1960's and early 1970's, data were generated on a few solar cells under Jupiter mission conditions; however, little has been produced since that time. The interest in solar cell performance under deep space conditions has been renewed as a result of the SEPS Halley Comet Flyby and Tempel 2 Mission. These data generated in support of the SEPS program are aimed at identifying which of the currently available cells possess the best characteristics for deep space performance. This report contains data on three types of cells taken at 9 intensities and 10 temperatures identified along the SEPS Mission profile. Graphs and tables together with interpretive conclusions are presented for the three types of cells.

II. TEST PROGRAM

A. Solar Cell Descriptions

Three types of cells (BSF/BSR 10 ohm-cm, BSR 10 ohm-cm, and BSR 2 ohm-cm) from Optical Coating Laboratories, Inc. (OCLI), described in Table 1, were selected to compare, under conditions of low temperature and low intensity, the performance of the BSF/BSR configured cells to that of the BSR configured cells and the performance of the 10 ohm-cm base resistivity cells to the 2 ohm-cm base resistivity cells. The silicon utilized in the manufacture of these cells was Czochralski produced (high oxygen content) and boron doped.

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* For this and other acronyms see glossary.

B. Test Profile

The test profile for the evaluation of these cells is shown in Table 2. These temperature/intensity values were selected from the SEPS Halley Comet Flyby-Tempel 2 mission environment. In addition to the I-V data taken at various temperatures and intensities, dark I-V data were taken at nine temperatures.

C. Test Equipment

The cells were mounted to a copper plate using RTV 560. Each test set consisted of 16 cells; one set is shown mounted in Figure 1. The copper plate was then heat sunk to a plate configured for cooling with liquid nitrogen and for heating with hot air. The copper plate and two cells were thermocoupled and temperatures monitored continually. Cell temperatures were maintained independent of the incident solar intensity to within ±0.5°C from 50° to -175°C. The cells were installed in a vacuum system having a 30-cm diameter, 6 mm thick UV grade fused quartz window and tested at a pressure of 1×10^{-4} pascal or less.

The illumination source was a Spectrolab filtered X-75 solar simulator. This system provides a combined beam from three 2.5 kW xenon lamps covering an area of 230 cm^2. Beam intensity was measured at each cell position and was determined to have a uniformity of ±2 percent. The spectral output was modified through the use of a filter system to approximate the solar spectrum. Illumination levels were maintained through the use of a set of neutral density filters and by varying the position of the test chamber. Cell illumination level was monitored through the use of a water-cooled calibrated cell maintained at 28°C ± 0.5°C. One solar constant utilized in the calibration was 135.3 mW/cm^2.

A Spectrolab electronic load model D-1550 provided the variable load for the cells. The cell I-V curves were plotted on an X-Y recorder. Digital voltmeters were used to read the open circuit voltages and short circuit currents. All instruments were calibrated prior to the initiation of these tests. The test setup with associated instrumentation is shown in Figure 2.

The value of the dark current produced through each individual cell by dc forward bias voltage was recorded at each temperature from zero bias to a current of at least 10 mA. These dark I-V curves were analyzed in terms of equivalent circuit models for the solar cells. Preliminary model calculations for selected cells from each set are discussed below. The dark I-V data shown in Table 3 for the best and worst cells of each set have been transcribed from the linear scales of the X-Y recorder to the log I versus linear V scales shown.

III. PRESENTATION OF TEST RESULTS

Current-voltage characteristics for each of three sets of 16 silicon solar cells supplied by OCLI have been measured. The mean values of each set observed at each operating condition (temperature and light intensity), together with observed standard deviations and mean efficiencies, are presented in both tables and graphs. The graphs are plotted from the data presented in the tables. The behavior of the individual best and worst cells of each set, selected on the basis of maximum power output at 0.086 solar constant (SC)/-100°C (where the SEPS will spend considerable time), is described by graphs of their efficiency versus light intensity and temperature and graphs of their dark current versus forward bias (dark I-V) at 25°C and at -150°C. Table 3 presents preliminary model calculations from the dark I-V data for these best and worst cells.

Examples of the dark current versus forward bias for "best" and "worst" cells are presented in Figures 3 and 4, respectively. Current-voltage parameters of the best cell of each set selected on the basis of its maximum power output at 0.086 SC and at -100°C are shown in Table 4. Fill factors which show data scatter within each group are given in Table 5 for three test conditions.

A. General Features

The response of these sets of solar cells to simulated solar illumination and to various temperatures is found to have the following general features:

1) Short circuit current, I_{sc}, is directly proportional to input light intensity. The proportionality constant being nearly independent of temperature is a feature of good cell design.

2) Open circuit voltage, V_{oc}, increases linearly as cell temperature is lowered, with the slope being nearly independent of light flux. The absolute value of V_{oc} drops with increasing light intensity by approximately 50 percent from 0.040 to 1.0 SC.

3) Maximum power, MP, is directly proportional to the incident intensity at each temperature, with a monotonic decrease of the proportionality constant with increasing temperature.

a) Efficiency at maximum power output decreases steadily with increasing temperature, the mean value dropping approximately by a factor of 2 from -150°C to +50°C. This feature is independent of light intensity above 0.08 SC as expected from the close correlation in high performance cells between the maximum power conditions with the open circuit voltage and short circuit current features.

b) Maximum power current, I_{mp}, is directly proportional to light intensity and essentially independent of temperature. This feature is closely related to that of the short circuit current in these high performance cells.

c) Maximum power voltage, V_{mp}, decreases linearly with increasing cell temperature, independent of light intensity above 0.08 SC. This linear decrease feature is closely related to that of the open circuit voltage in these high performance cells.

4) Scatter of measured values within each of the sets of 16 cells is indicated by the standard deviation values in the tables. Another measure of the scatter within each set is given by the fill factors at three test conditions and by discussion of a few individual cells, selected as having the best and the worst maximum power output at 0.086 SC and -100°C.

B. BSF/BSR 10 ohm-cm Silicon Cell

I_{sc}, V_{oc}, I_{mp}, V_{mp}, and MP are plotted as functions of temperature and intensity in Figures 5 through 14. Average values with standard deviations are summarized in Tables 6 through 10. Cell efficiencies are plotted as functions of temperature and intensity in Figures 15 and 16 and summarized in Table 11. To illustrate individual cell performance, the efficiencies of the best and worst cells are plotted in Figures 17 and 18.

Large standard deviations (above 2 percent) begin to appear within this set of 16 cells in their V_{oc} below -50°C and below 0.128 SC. Similarly, large (above 2 percent) standard deviations appear in V_{mp} at and below -50°C and, at and below 0.128 SC. I_{mp} also shows significant (above 10 percent) standard deviations at and below -75°C and at and below 0.128 SC.

C. BSR 10 ohm-cm Silicon Cells

I_{sc}, V_{oc}, I_{mp}, V_{mp}, and MP are plotted as functions of temperature and intensity in Figures 19 through 28. Average values with standard deviations are shown in Tables 12 through 16. Cell efficiencies are listed in Table 17 and plotted as functions of temperature and intensity in Figures 29 and 30. Similarly, the efficiencies of the best and worst cells are shown in Figures 31 and 32.

V_{oc} shows standard deviations as large as 2 percent only at 0.040 SC below -75°C. V_{mp} displays similar large (above 2 percent) standard deviations at and below -50°C and 0.086 SC.

D. BSR 2 ohm-cm Silicon Cells

I_{sc}, V_{oc}, I_{mp}, V_{mp}, and MP are plotted as functions of temperature and intensity in Figures 33 through 42. Average values with standard deviations are summarized in Tables 18 through 22. Cell efficiencies are plotted as functions of temperature and intensity in Figures 43 and 44 and listed in Table 23. In addition, the best and worst cells efficiencies are plotted in Figures 45 and 46.

Large standard deviations begin to appear in V_{mp} at -75°C and 0.063 SC and below. However, all of the standard deviations in the V_{oc} observed for these 16 BSR 2 ohm-cm cells were well below 1 percent.

IV. DISCUSSION OF RESULTS

A. General Features

A number of observations are made concerning the general characteristics of the data. The small standard deviations at and above 0.1 SC and -50°C in the data indicate that the measurements were apparently carried out with sufficient precision to enable discrimination of deviations of a few percent in the output from cell to cell at any given combination of temperature and light intensity. The small standard deviations in current which decrease with decreasing solar intensity are attributable to the beam nonuniformity of ±2 percent. There is some question as to whether a test lot of 16 cells is sufficient to provide reliable quality control statistics for these manufacturer lots at low temperatures and low intensities (LTLI).

Maximum power output was determined to be greatest at 1 SC/+25°C in the BSF/BSR 10 ohm-cm cells and greatest at LTLI in the BSR 2 ohm-cm cells. Large variations in V_{mp} were observed in the BSF/BSR cells under LTLI as a reduction in the curvature of the I-V curve around the maximum power point. This reduction in curvature of the I-V plot is manifested in two forms — one as a softening of the I-V knee only and the other as a gradual decrease in current initiated in the low voltage portion of the curve. This reduction in curvature of the I-V plot results in lowering of the MP of the cell and thereby reduces solar cell efficiency. The magnitude of this occurrence in the three sets of cells tested is seen in the fill factor distributions presented in Table 5. Efficiencies of the best and worst cells selected on the basis of maximum power output at 0.086 SC and -100°C show the extreme values in cell output within each test set. The current-voltage parameters listed for the best cells within each group in Table 4 demonstrate the capabilities of the individual cell type with the BSF/BSR cell have the highest efficiency at almost all test conditions. Mean efficiencies at 1 SC/+25°C were determined to be 14.1 percent for the BSF/BSR 10 ohm-cm cells, 12.1 percent for the BSR 10 ohm-cm cells, and 13.3 percent for the BSR 2 ohm-cm cells.

One of the objectives in this study was to find an observable solar cell feature present at room temperature which would correlate well with cell performance under low temperature and low intensity conditions. While there exists a visual correspondence between the ranking of the cells light I-V curves and their dark I-V curves, no single parameter in the light I-V curves could be determined at room temperature to correlate to the LTLI cell performance. Preliminary conclusions based on the dark current data provided in Table 3 show a correlation as follows: When the junction defects in the cell give a shunt resistance (R_{JD}) below 500 ohms, the MP available at 0.086 SC and -100°C falls off sharply; above that value of R_{JD} the presence of edge channel resistances (R_{CH}) below 1K ohms appears to affect the available power output. Both R_{JD} and R_{CH} are available from the room temperature dark I-V curves as illustrated in Table 3.

B. Comparison of Configurations — BSF/BSR 10 ohm-cm to BSR 10 ohm-cm

The BSF/BSR cells show a greater V_{oc} than the BSR 10 ohm-cm cells at the higher temperatures and intensities — the difference in the average values being 79 mV at 1 SC/+50°C. However, this difference decreased with decreasing temperatures and intensities with a crossover occurring in the mean values at 0.063 SC/-125°C. The BSF/BSR cells show a decreasing change in V_{oc} with temperature at the lower temperatures. Data on the best cells of each group (selected at 0.086 SC/-100°C) indicate a difference in V_{oc} at 1 SC/+50°C of 57 mV with equivalent values at low temperatures and low intensities. No evidence of a Schottky barrier was present in any of the cells tested as would be manifested by a decrease in V_{oc} with increasing solar intensity or by an increase in current near V_{oc}. The application of the BSF to the BSR cell was apparently not successful in increasing the fill factor or V_{oc} at LTLI as had been expected.

Short circuit current is greater in the BSF/BSR cells than in the BSR 10 ohm-cm cells at the higher temperatures and intensities — the difference in average values being 8 mA greater for the BSF/BSR cells at 1 SC/+50°C. This difference decreases with low temperatures and low intensities. The best cells of each set show similar values at LTLI.

Maximum power output at higher temperatures and intensities is greater in the BSF/BSR cells — 69.1 mW at 1 SC/+50°C compared to 55.5 mW for the BSR 10 ohm-cm cells with the difference decreasing with decreasing temperatures and intensities. Maximum power voltage and current show trends similar to V_{oc} and I_{sc} with the BSF/BSR cells having higher values at higher temperatures and intensities. The low shunt resistances evident at LTLI in the BSF/BSR cells reduce V_{mp} and bring about lower efficiencies in three cells.

C. Comparison of Base Resistivity — BSR 10 ohm-cm to BSR 2 ohm-cm

The V_{oc} in the 2 ohm-cm cells was approximately 50 mV higher than that in the 10 ohm-cm cells throughout the test profile. No decrease in V_{oc} with temperature at LTLI was evident in the 2 ohm-cm cells. The large standard deviations (above 2 percent) in the 10 ohm-cm cells at 0.04 SC and at -150°C and below indicate decreases in V_{oc} in some of the 10 ohm-cm cells.

Average values of short circuit current were 3 mA higher in the 10 ohm-cm cells at 1 SC/+25°C. This difference decreased with decreasing temperatures and intensities with a crossover in the data occurring at 0.063 SC/-100°C. The best cells of each group show a similar trend.

The MP produced by the 2 ohm-cm cells is greater than the 10 ohm-cm cells throughout the test profile. The higher values of V_{mp} available in the 2 ohm-cm cells are responsible for the greater MP values and the subsequent higher efficiencies. The trend in I_{mp} in these cells is similar to that of the short circuit current. The 2 ohm-cm cells showed the most consistent cell-to-cell electrical characteristics at both high temperatures and intensities and at low temperatures and intensities.

D. Calculation of Model Parameters from Dark I-V Data

To correlate individual cell performance with one or more of its physical features such as edge channel resistance or shunting junction resistance, the dark I-V curves were analyzed by means of an equivalent circuit for the cell. The principal effects of shunting around the solar cell junction by edge channels and junction defects were represented with the simplified equivalent circuit in Figure 47. By treating the diodes as switches the cell in the dark should show:

1) At low forward bias (< 0.2 V), an equivalent resistance of $R_S + R_{JD}$.

2) At high forward bias (a temperature dependent value > 0.8 V) an equivalent resistance of R_S.

3) At intermediate bias (when the edge channel diode is switched on but the cell junction diode is still off) an equivalent resistance of

$$R_S + \frac{1}{R_{CH}^{-1} + R_{JD}^{-1}} .$$

Values of these three resistances, R_S, R_{JD} and R_{CH}, have been calculated from the dark I-V curves and are listed in Table 3 for the best and worst cells selected from these three test sets.

The general features of the simplified model parameters in Table 3 show that:

1) The effective series resistance, R_S, is consistently low as it should be for high performance cells, with no change from best to worst performance in these three sets of 16. The temperature dependence of R_S may be interpreted as due to the temperature dependence of the carrier concentration in the n and p regions of the silicon wafer.

2) The shunting defects in the cell junction, represented by R_{JD}, seem to be responsible for the reduction in performance from best to worst at room temperature in all three sets with the singular exception of cell 15 in the BSR 2 ohm cm set. Similarly, at -150°C, the worst BSF/BSR cells had their junctions shunted by an effective low resistance; the temperature dependence of R_{JD} in these two cells indicates the type of defect existing within their junction becomes a more effective shunt at low temperature. However, the worst BSR cells at low temperature showed remarkably high values of R_{JD} indicating that the reduction in MP at low temperature is due to some other differences between the cells; the defects in the BSR junctions are of such a type that, in the dark, they require temperature activation to shunt significant currents across the junction.

3) The edge channel resistances, assuming all the edge channels have a diode switching voltage $\lesssim$ 0.2 V, have values near 500 ohms at 25°C and near 1K ohms at -150°C. Therefore the edge channel resistance is the principal shunt resistance during maximum power operation in all of the cells tested, except the two poorest of the BSF/BSR set where junction defects are so bad.

V. SUMMARY

The BSF/BSR 10 ohm-cm cells provided the best performance at 1 SC/+25°C (14.1 percent efficiency) but failed to provide the best performance at LTLI. However, these cells are capable of high performance at LTLI based on the behavior of the best cell in the set. The BSR 2 ohm-cm cells had the highest LTLI performance (22.2 percent efficiency at 0.04 SC/-170°C for the set) and the most consistent cell-to-cell characteristics. The performance observed for the three sets of cells is summarized by the graph of relative maximum power output, P/Po (Po is the power produced at 55°C at 1 AU) versus heliocentric distance in Figure 48. Figure 49 represents the array mission temperatures used in generating the data. The two sets of BSR configured cells produce approximately the same P/Po outputs at large AU's. They give, for example, P/Po 0.150 for the 10 ohm-cm base resistivity cell and 0.148 for the 2 ohm-cm base resistivity cell at 3.4 AU conditions. However, the mean of the 16 BSF/BSR cells produced P/Po of only 0.118 at 3.4 AU conditions.

The observed spread in several of the parameters in these data was well below 1 percent. Therefore, the simulation techniques used to obtain the solar cell performance is capable of making active parameter measurements to better than 2 percent.

Finally, cell characteristics revealed by the dark I-V at room temperature show potential as useful indicators of the cell performance at low temperatures and low intensities.

TABLE 1. TEST CELL DESCRIPTIONS

	Test Group 1	Test Group 2	Test Group 3
Number of Cells	16	16	16
Type	N/P BSF/BSR Silicon	N/P BSR Silicon	N/P BSR Silicon
Size	2 × 2 × 0.025 cm	2 × 2 × 0.025 cm	2 × 2 × 0.025 cm
Base Resistivity	10	10	2
Junction Depth	Shallow (0.2 to 0.25 μm)	Shallow (0.2 to 0.25 μm)	Shallow (0.2 to 0.25 μm)
Contacts	Ti-Pd-Ag	Ti-Pd-Ag	Ti-Pd-Ag
Grids	Fine Line (3/15)	Fine Line (3/15)	Fine Line (3/15)
Cover Glass	FS 0.35 Cut-on (0.3 μm Thick)	FS 0.35 Cut-on (0.3 μm Thick)	FS 0.35 Cut-on (0.3 μm Thick)
Cover Glass Adhesive	93-500	93-500	93-500
Absorptivity	0.74	0.72	0.72
Comments	Production Run	Production Run	Production Run

TABLE 2. TEST PROFILE

Illumination Level (SC)	Temperature (°C)
1.00	0, 25, 50
0.64	-25, 0, 25, 50
0.39	-50, -25, 0, 25, 50
0.25	-75, -50, -25, 0, 25
0.174	-100, -75, -50, -25, 0
0.128	-125, -100, -75, -50, -25
0.086	-150, -125, -100, -75, -50
0.063	-150, -125, -100, -75, -50
0.040	-175, -150, -125, -100, -75
Dark I-V	25, 0, -25, -50, -75, -100, -125, -150, -175

Note: -175°C was not achievable in two of the three test groups.

SC = Solar Constant.

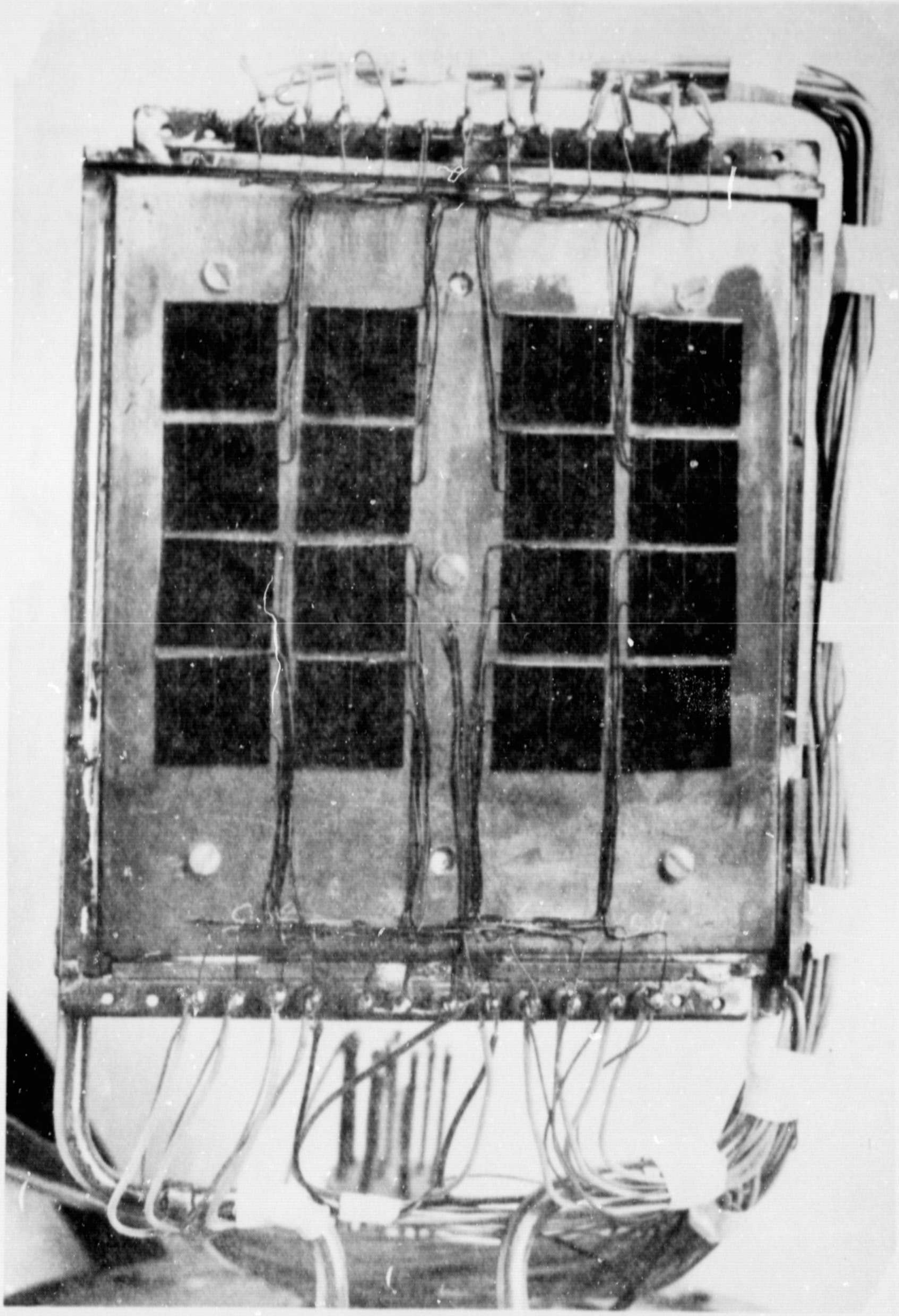


Figure 1. Solar cell test plate.

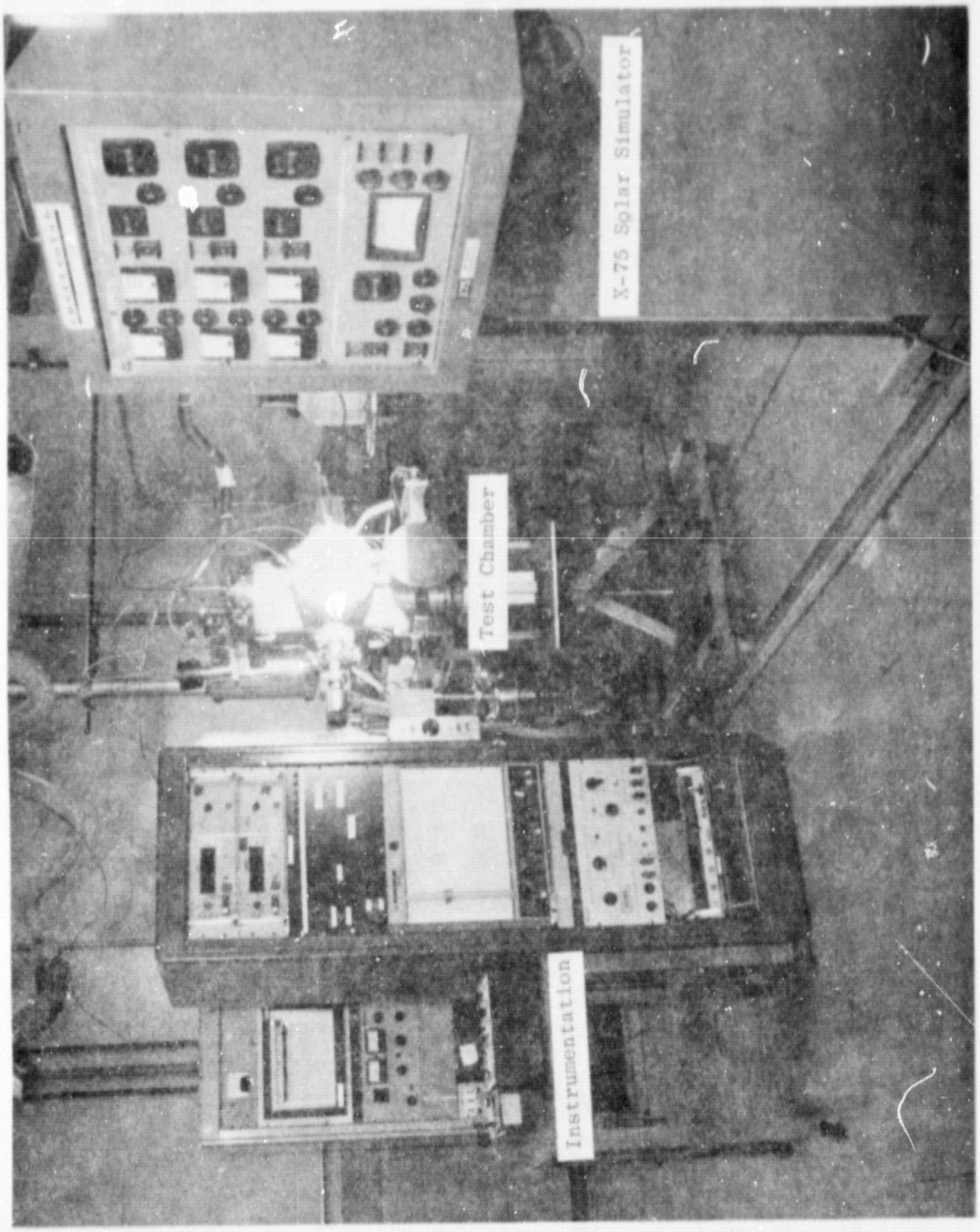


Figure 2. Solar cell characterization equipment and instrumentation.

TABLE 3. EQUIVALENT CIRCUIT RESISTANCES OF SELECTED INDIVIDUAL SILICON SOLAR CELLS

Cells	Max Power (mW)	Resistances (ohms) at 25°C			Resistances (ohms) at −150°C		
		R_s	R_{JD}	R_{CH}	R_s	R_{JD}	R_{CH}
BSF/BSR 10 ohm cm							
B_1	9.6	39	100K	560	68	100^+K	1.2K
B_2	9.4	39	100K	560	65	30K	1.1K
W_1	6.1	38	300	—	62	60	—
W_2	4.0	39	180	—	60	30	—
BSF/BSR 10 ohm cm							
B_1	8.9	35	5K	500	64	>>100K	1.0K
B_2	9.0	35	5K	550	65	7K	1.0K
W_1	6.9	35	500	—	64	>>100K	600
W_2	6.8	35	1.1K	~700	64	100^+K	550
BSR 2 ohm cm							
B_1	9.5	37	20K	600	65	100K	1.1K
B_2	9.4	37	20K	600	65	100K	1.1K
W_1	8.7	37	20K	550	65	100K	1.0K
W_2	8.5	38	4K	550	65	100^+K	800

Note: B = Best, W = Worst, based on max power output at 0.086 SC/−100°C.

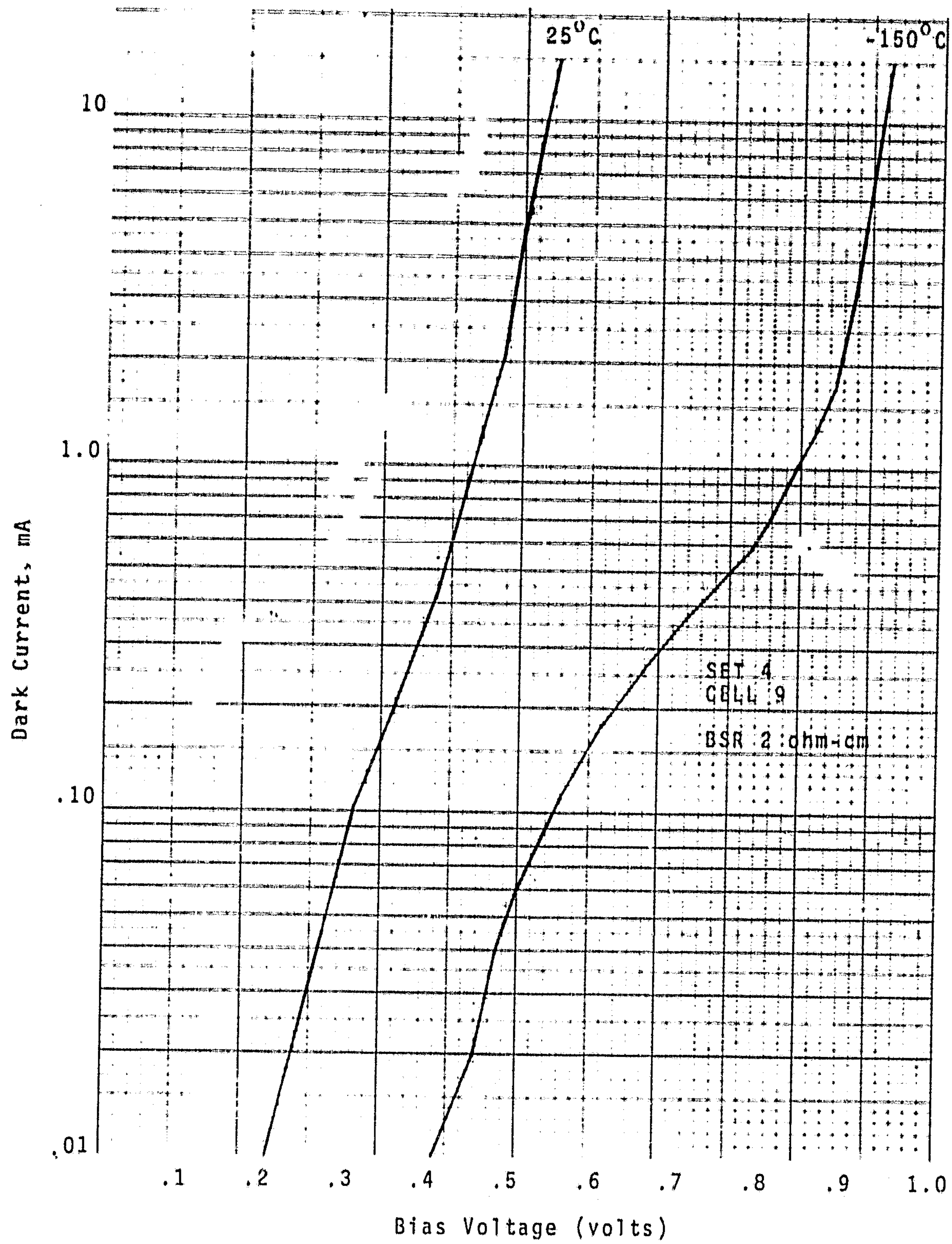


Figure 3. Dark current versus bias voltage for a good cell.

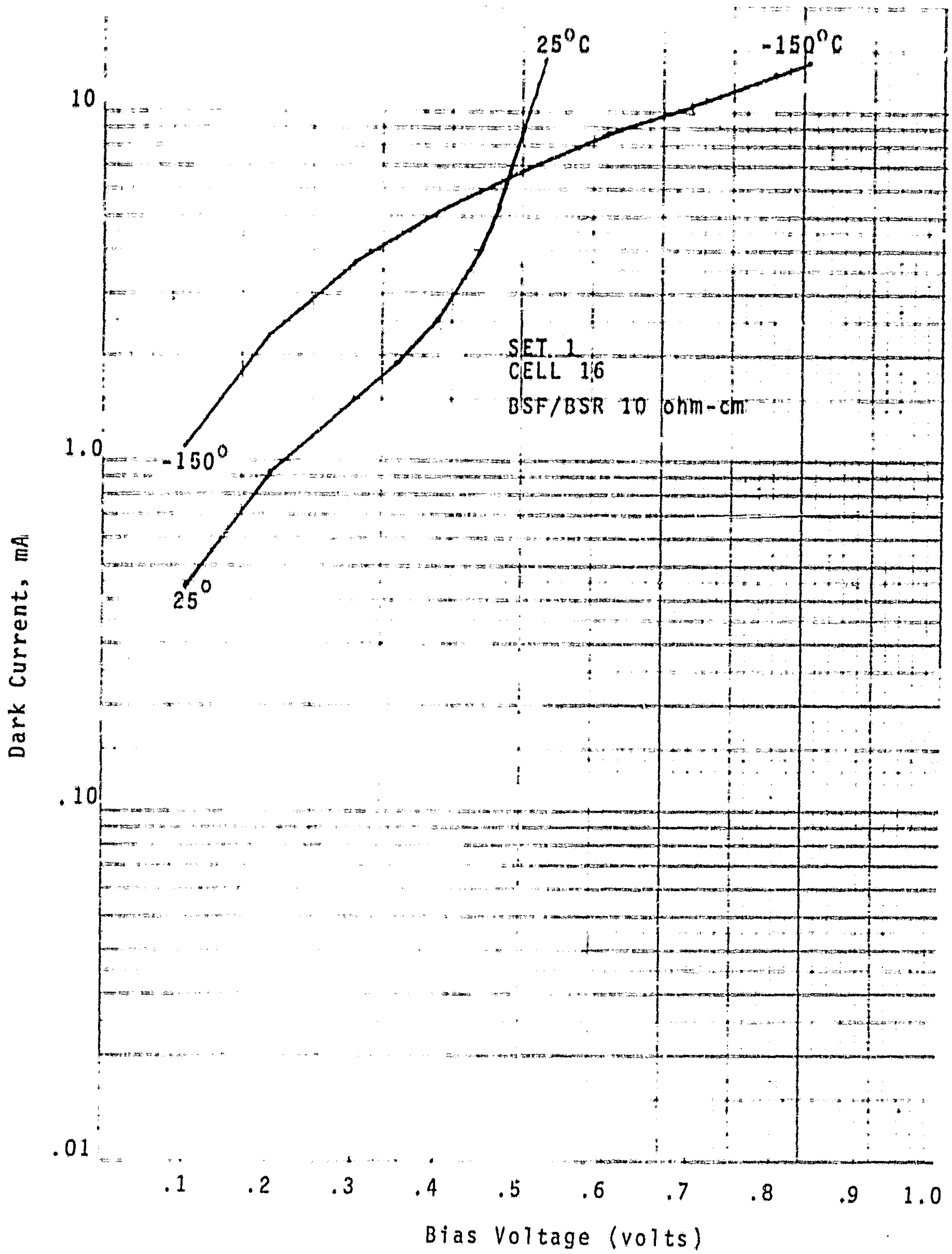


Figure 4. Dark current versus bias voltage for a bad cell.

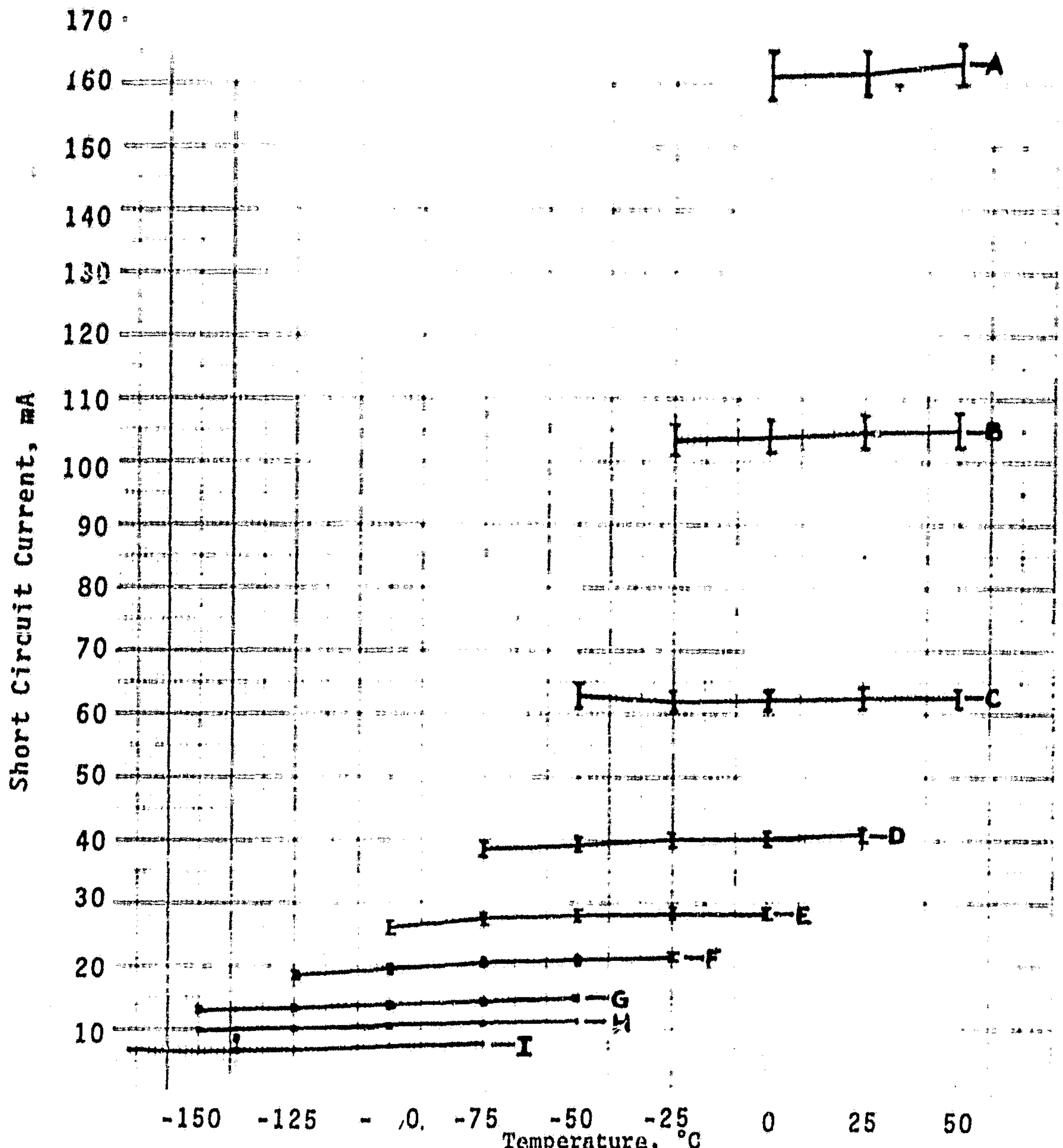
TABLE 4. CURRENT-VOLTAGE PARAMETERS OF THE BEST CELLS

Parameter	Type Silicon Cell: BSF/BSR 10 ohm-cm	BSR 10 ohm-cm	BSR 2 ohm-cm
I_{sc}			
1 SC/25°C	164.0	161	155
0.086 SC/-100°C	13.9	14.0	13.4
0.040 SC/-150°C	6.9	6.8	7.2
V_{oc}			
1 SC/25°C	605	548	598
0.086 SC/-100°C	797	793	822
0.040 SC/-150°C	903	893	908
I_{mp}			
1 SC/25°C	157	152	148
0.086 SC/-100°C	12.8	12.6	12.7
0.040 SC/-150°C	6.4	6.3	6.8
V_{mp}			
1 SC/25°C	485	445	490
0.086 SC/-100°C	750	718	748
0.040 SC/-150°C	828	713	762
MP			
1 SC/25°C	76.1	67.6	72.7
0.086 SC/-100°C	9.6	9.1	9.5
0.040 SC/-150°C	5.3	4.5	5.2
Eff			
1 SC/25°C	14.1	12.5	13.4
0.086 SC/-100°C	20.6	19.5	20.4
0.040 SC/-150°C	24.4	20.8	24.0

Note: Best cells selected for best efficiency at Max Power at 0.086 SC/-100°C.

TABLE 5. FILL FACTORS FOR ALL CELLS

Solar Constant/ Temperature (°C)	Fill Factors (No. of Cells) BSF/BSR 10 ohm-cm	BSR 10 ohm-cm	BSR 2 ohm-cm
1 SC/25°C	0.75 (1)	0.74 (2)	0.78 (6)
	0.76 to 0.77 (14)	0.75 to 0.77 (14)	0.79 (9)
	0.78 (1)		0.80 (1)
0.086 SC/-100°C	0.37 (1)	0.67 to 0.68 (2)	0.78 (1)
	0.53 (1)	0.74 to 0.79 (5)	0.81 to 0.85 (6)
	0.71 to 0.76 (5)	0.81 to 0.86 (9)	0.86 to 0.88 (9)
	0.80 to 0.88 (5)		
0.040 SC/-150°C	0.21 (1)	0.52 to 0.58 (4)	0.61 to 0.68 (5)
	0.36 to 0.41 (3)	0.65 to 0.70 (3)	0.71 to 0.79 (4)
	0.44 to 0.49 (4)	0.73 to 0.77 (6)	0.81 to 0.84 (7)
	0.60 to 0.64 (4)	0.80 to 0.84 (3)	
	0.74 to 0.75 (2)		
	0.84 to 0.85 (2)		



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.040

OCLI
N/P BSF/BSR 10 Ωcm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 5. Average I_{sc} as a function of temperature.

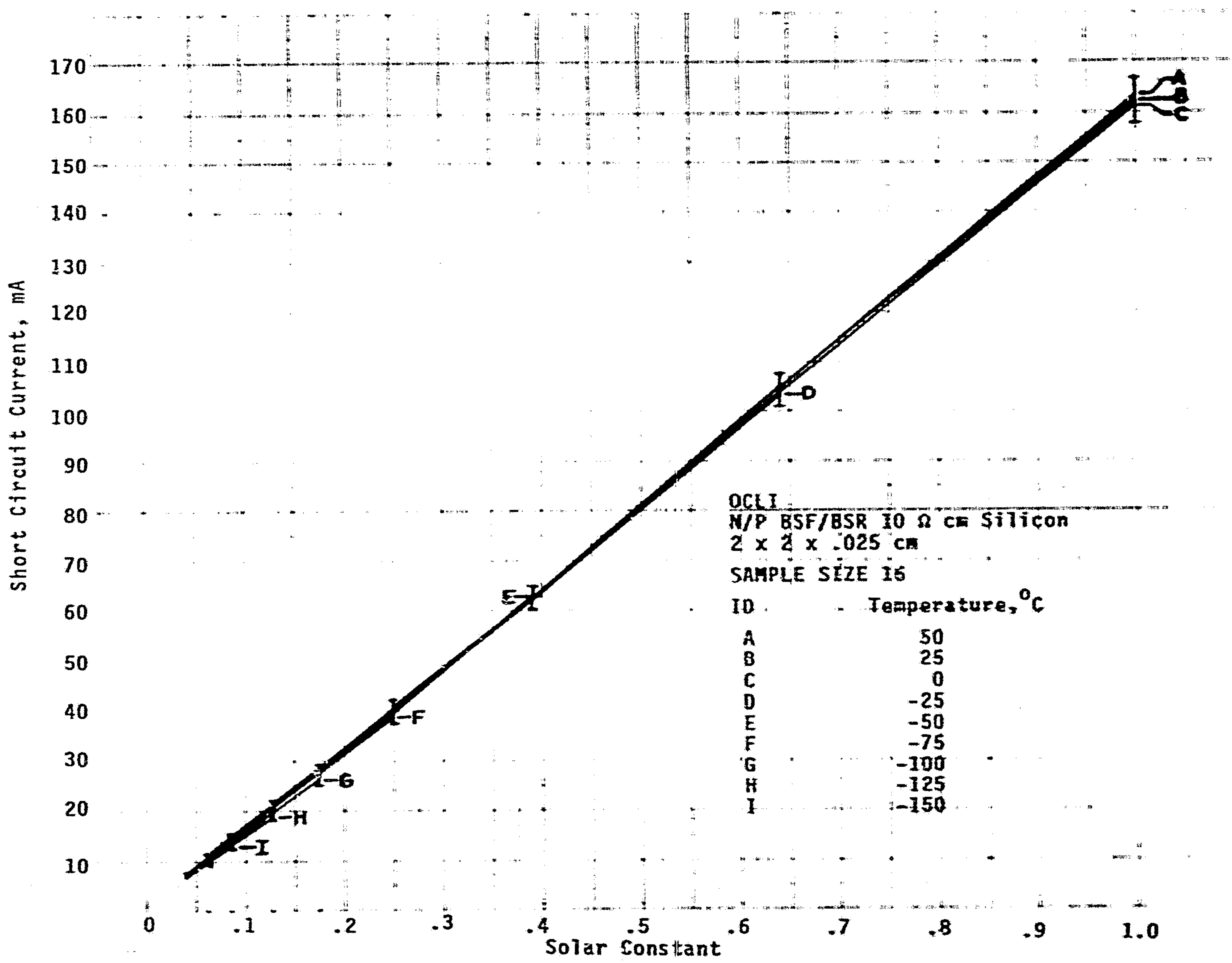
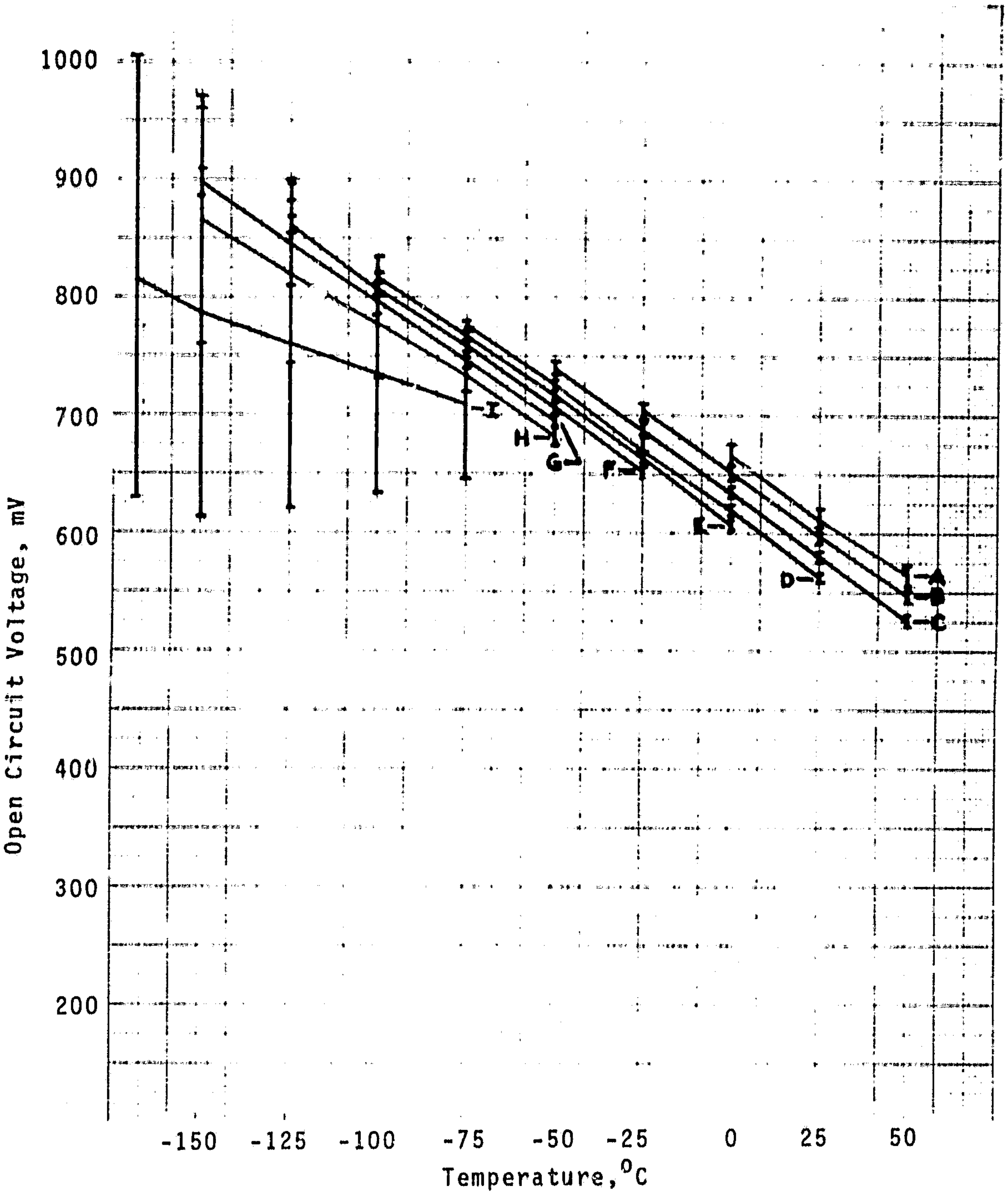


Figure 6. Average I_{sc} as a function of intensity.



ID	Solar Constant
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D	.25
E	.174
F	.128
G	.086
H	.063
I	.040

OCLI
N/P BSF/BSR 10 Ωcm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 7. Average V_{oc} as a function of temperature.

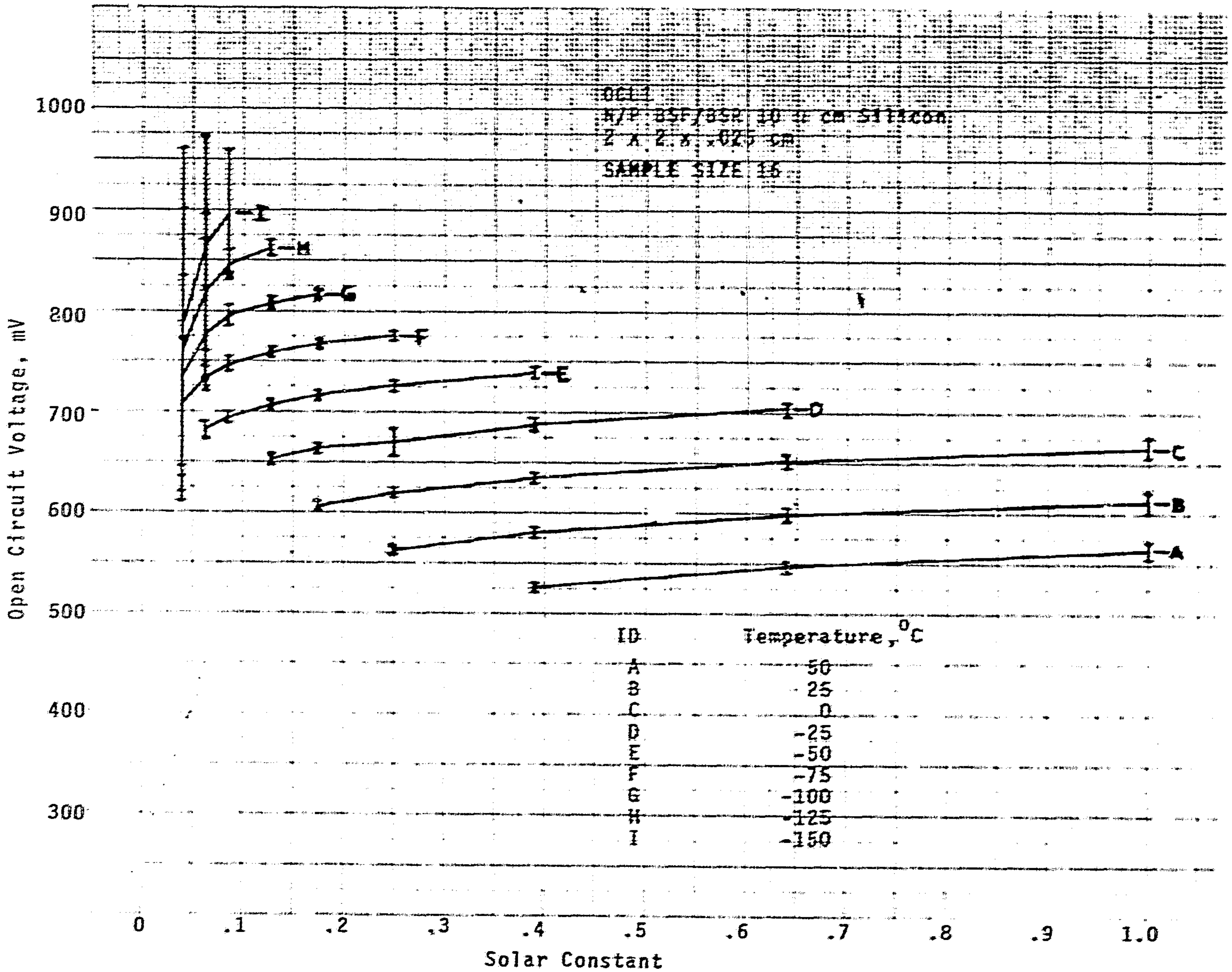
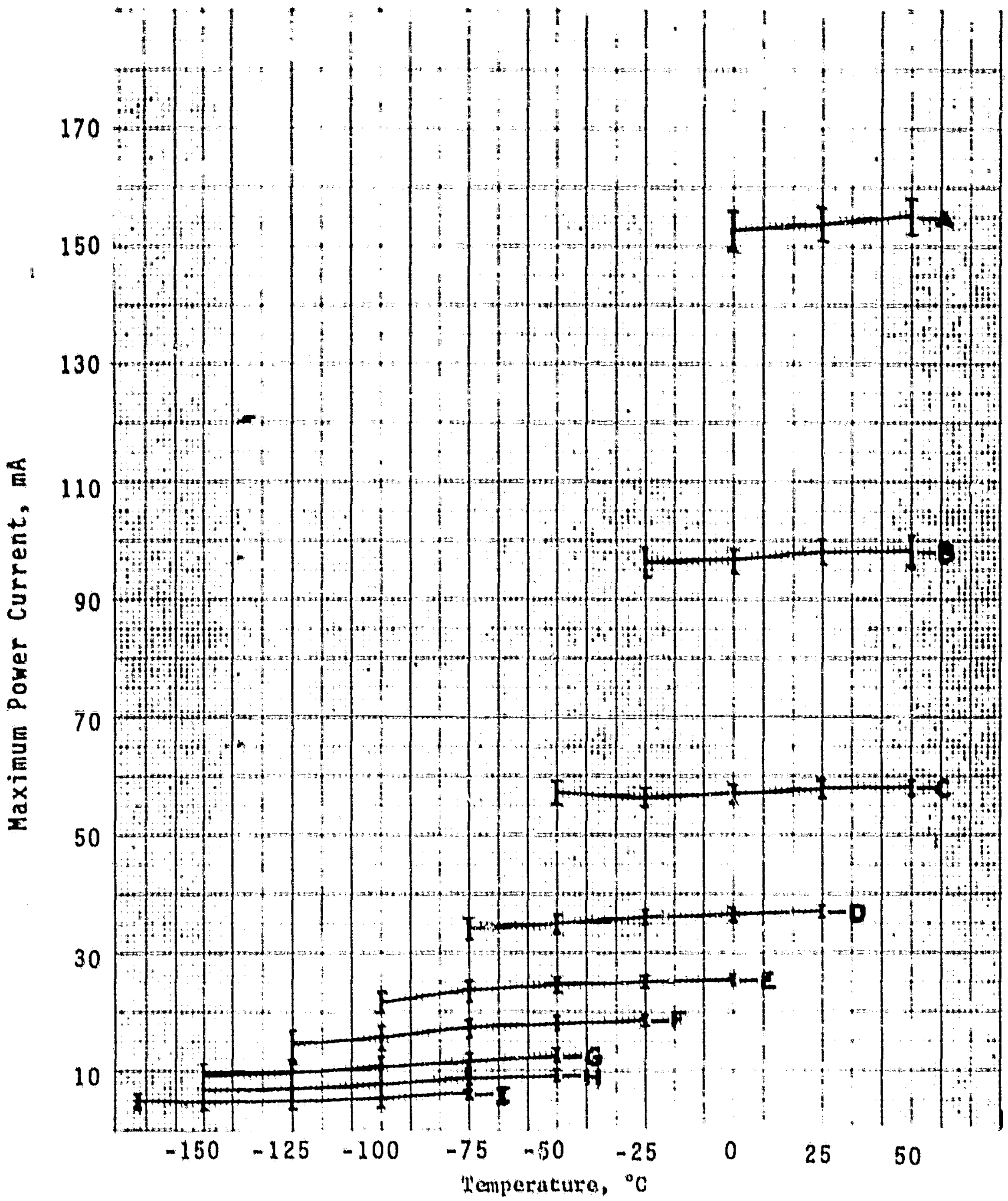


Figure 8. Average V_{oc} as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.040

OCLI
N/P BSF/BSR 10 Ωcm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 9. Average I_{mp} as a function of temperature.

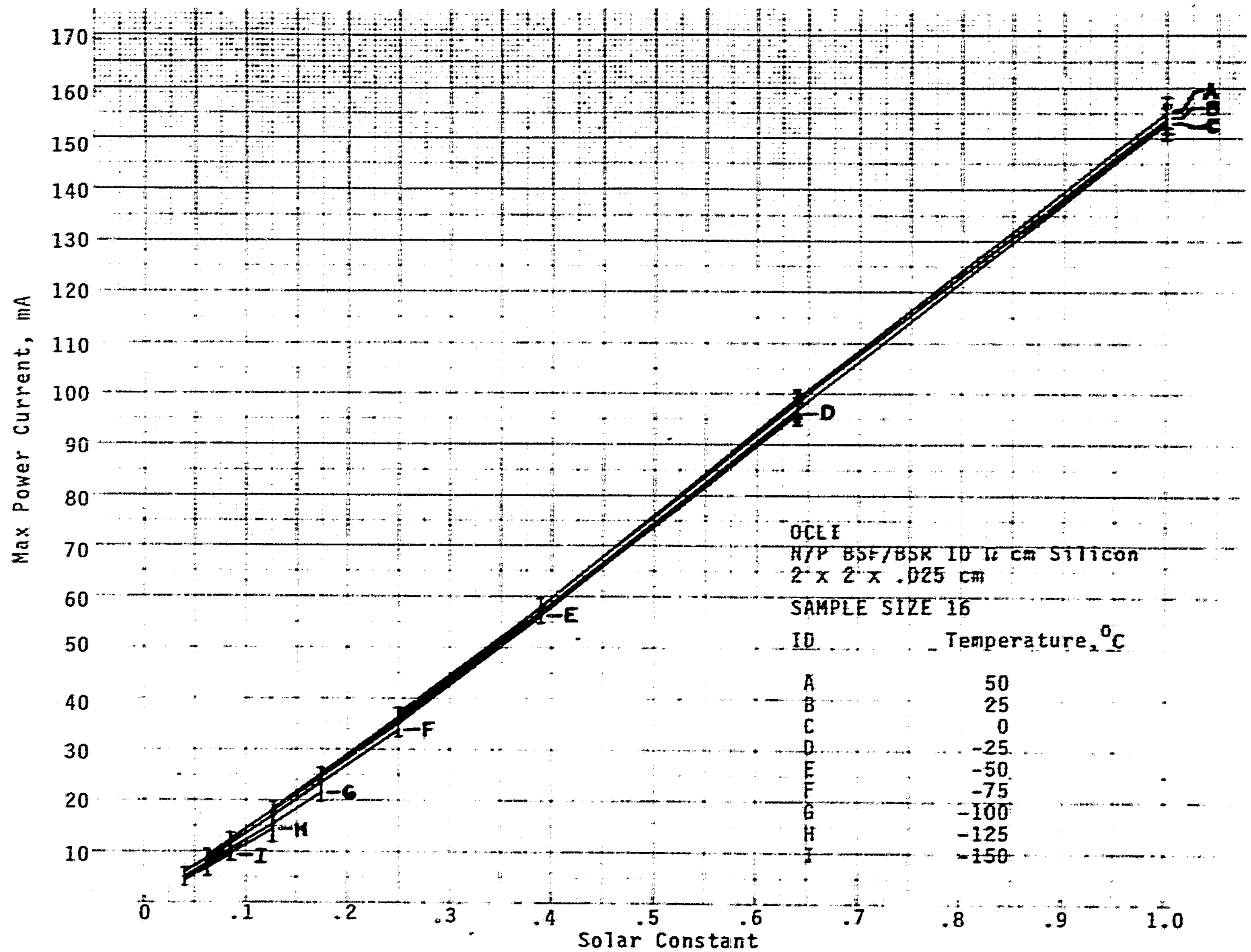
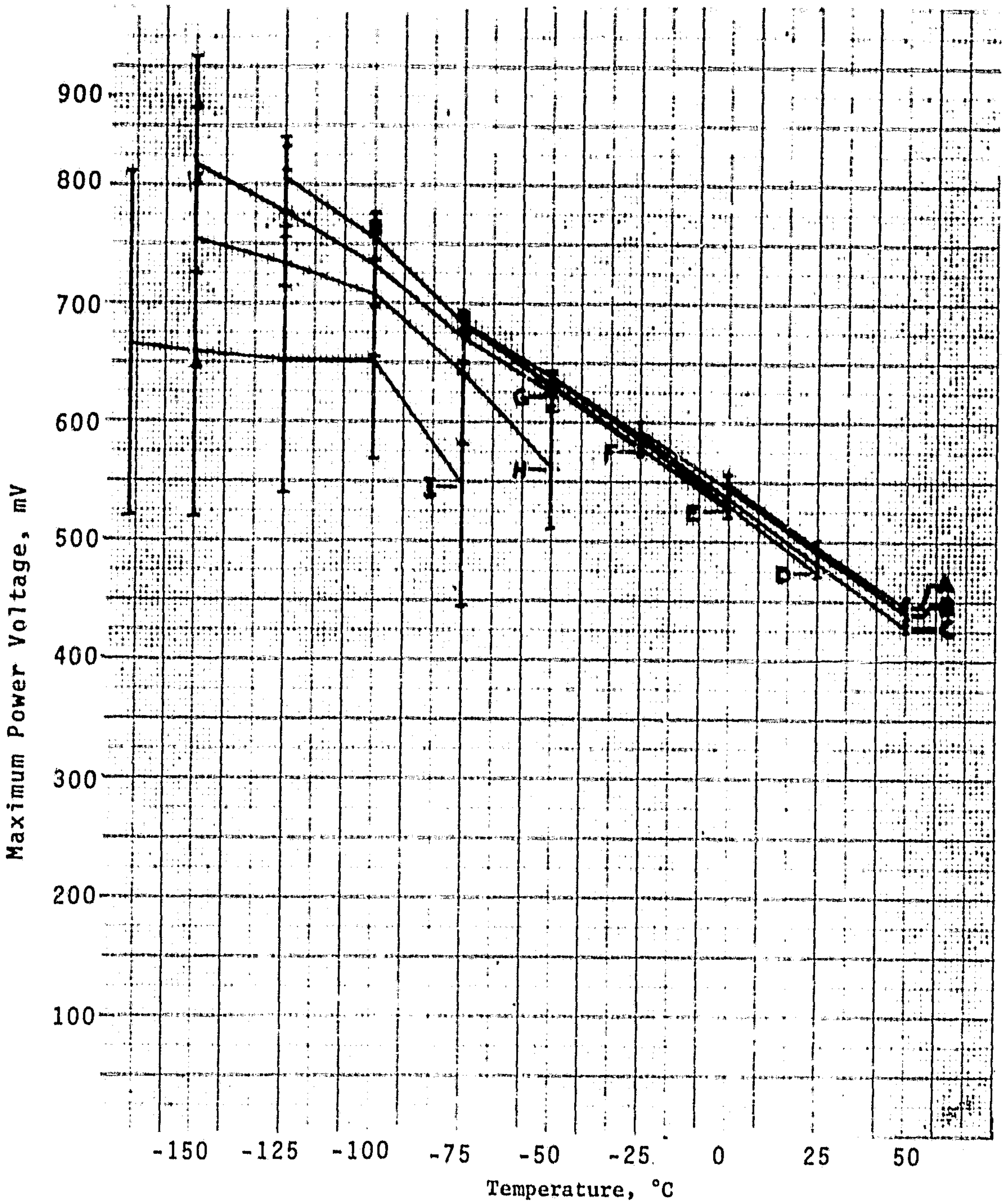


Figure 10. Average I_{mp} as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.040

OCLI
N/P BSF/BSR 10 Ωcm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 11. Average V_{mp} as a function of temperature.

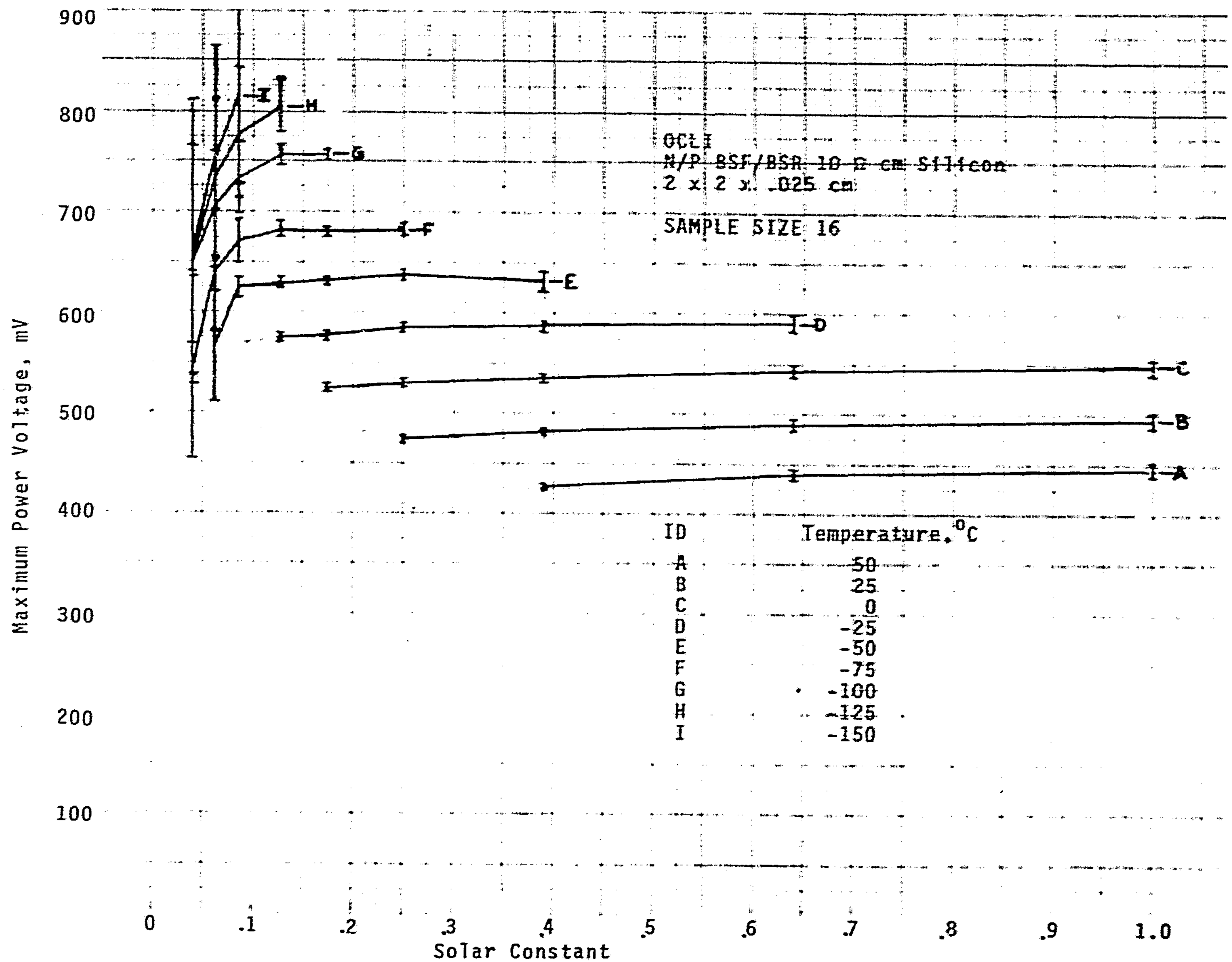
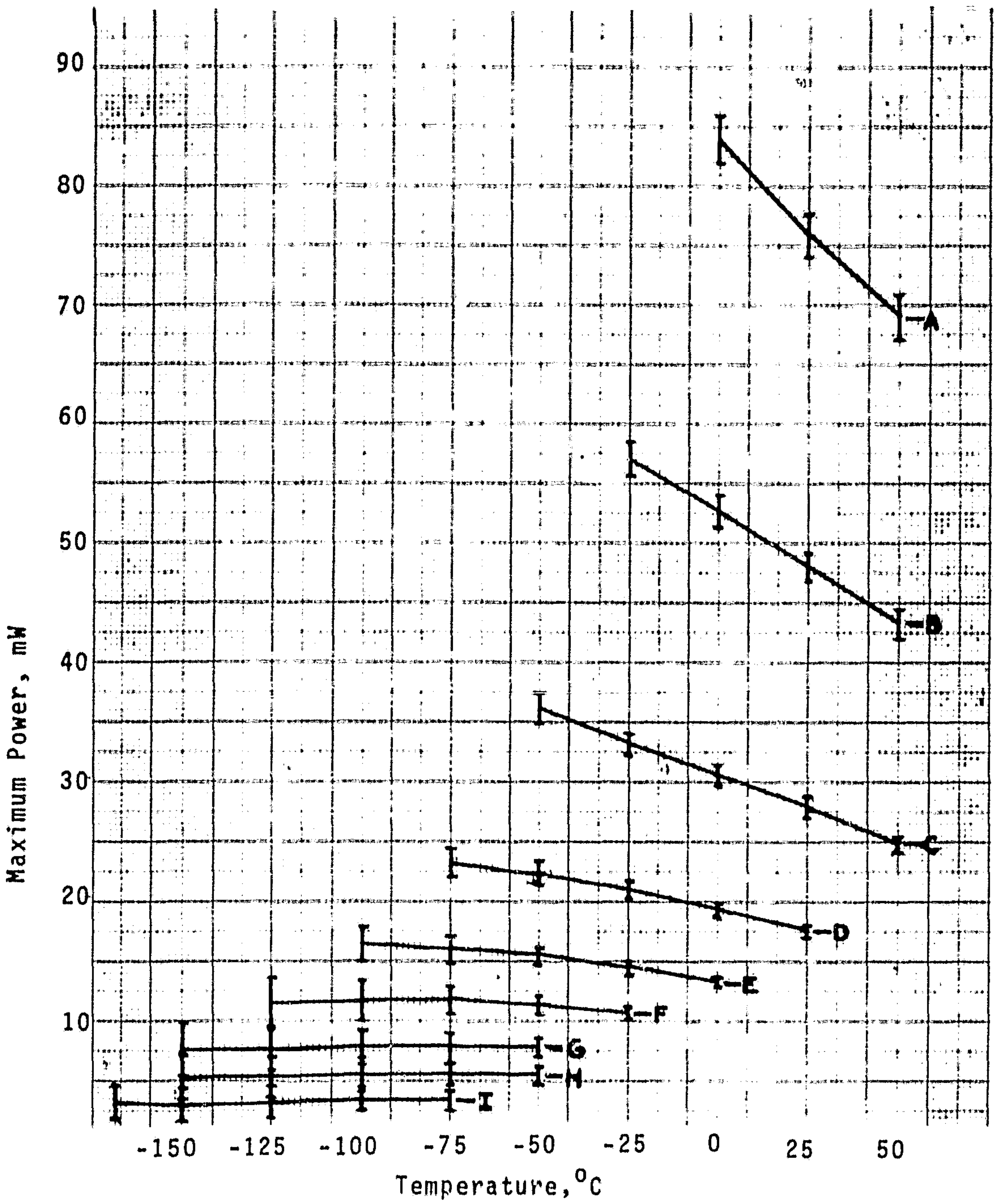


Figure 12. Average V_{mp} as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	,128
G	.086
H	.063
I	.040

OCLI
N/P BSF/BSR 10 Ωcm Silicon
2 x 2 x ,025 cm

SAMPLE SIZE 16

Figure 13. Average MP as a function of temperature.

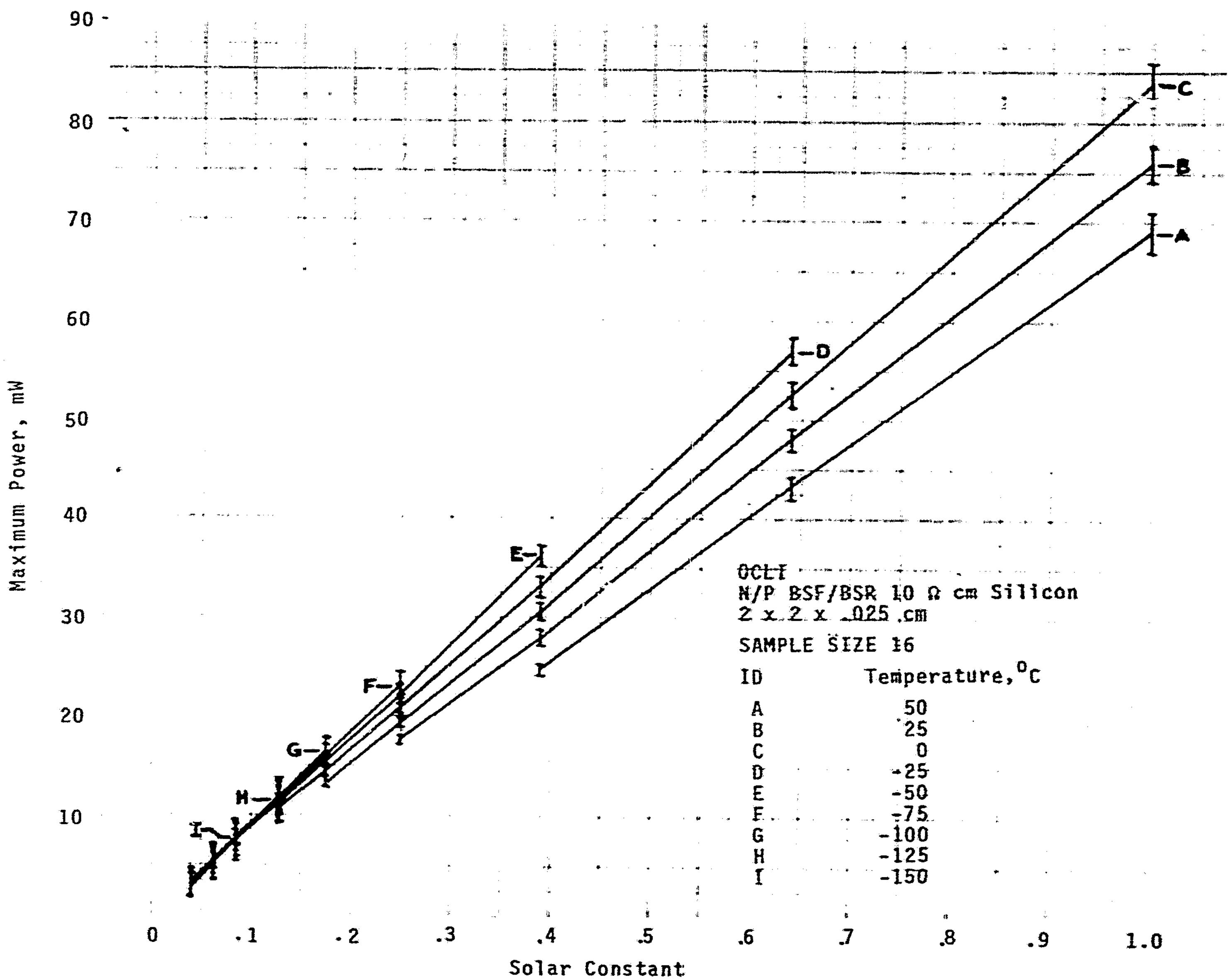
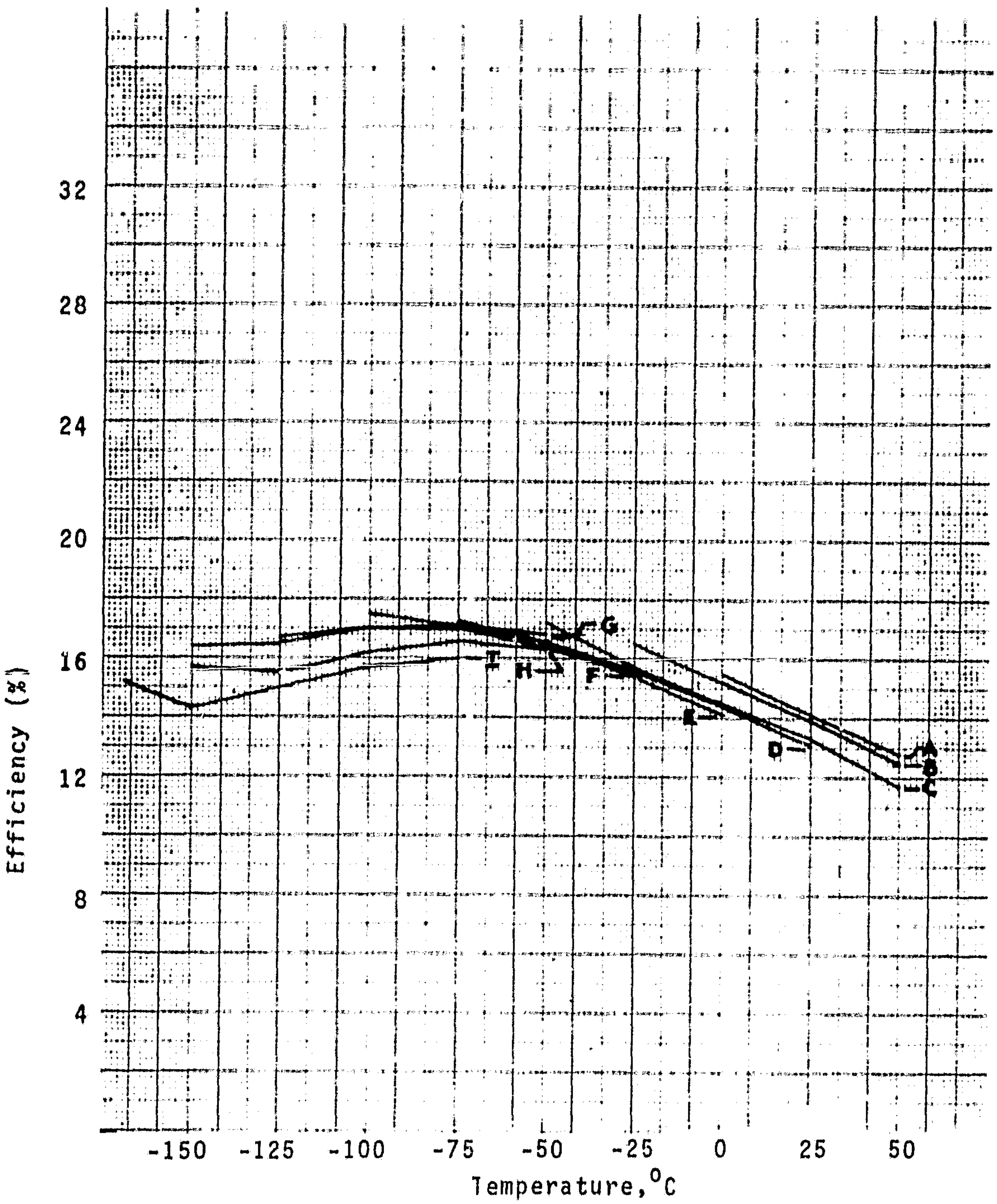


Figure 14. Average MP as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.040

OCLI
N/P BSF/BSR 10 Ωcm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 15. Average efficiency as a function of temperature.

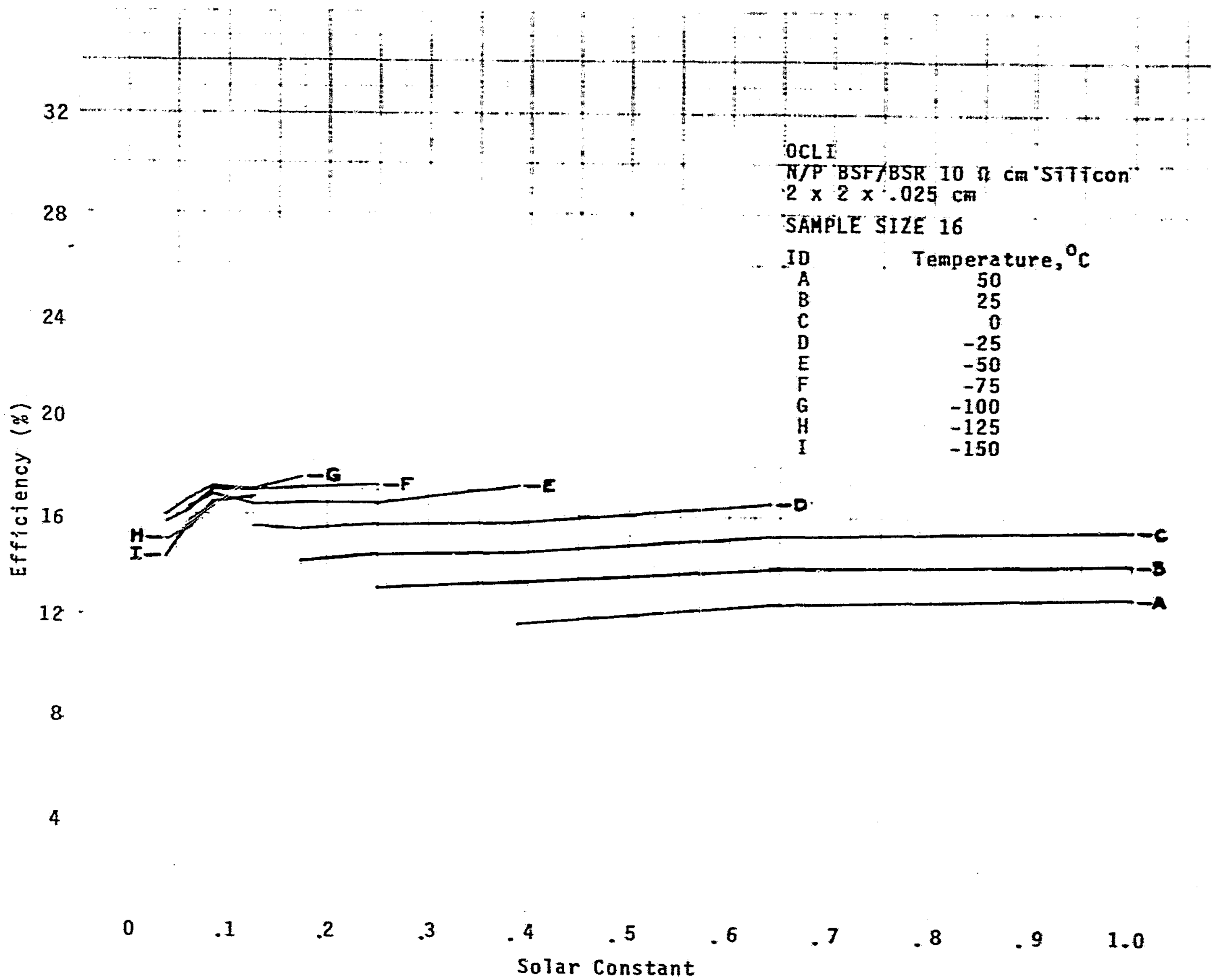
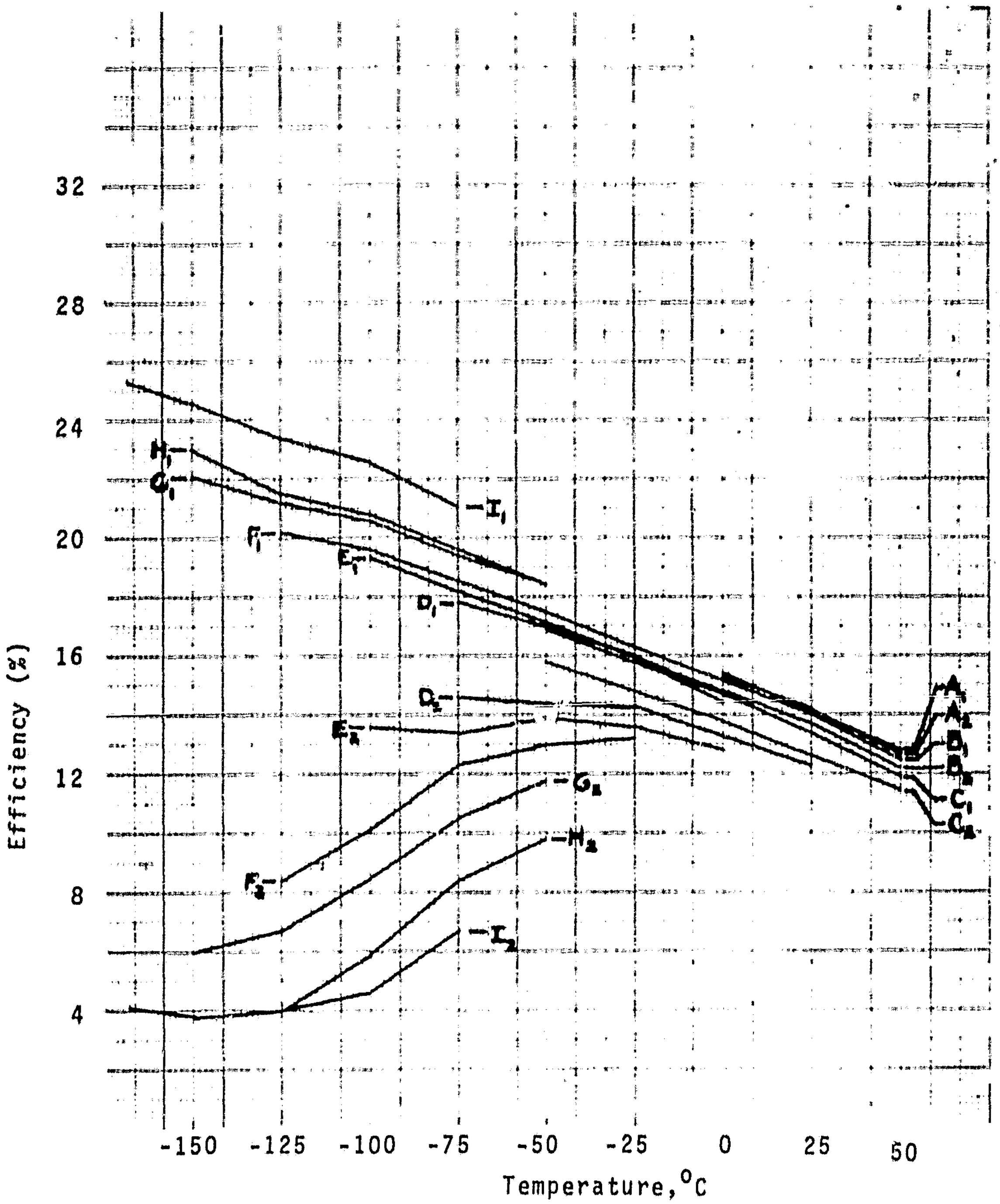


Figure 16. Average efficiency as a function of intensity.



B/W	Solar Constant
A_1/A_2	1.0
B_1/B_2	.64
C_1/C_2	.39
D_1/D_2	.25
E_1/E_2	.174
F_1/F_2	.128
G_1/G_2	.086
H_1/H_2	.063
I_1/I_2	.040

OCLI
N/P BSF/BSR 10 Ωcm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 17. Efficiency of the best/worst cells as a function of temperature.

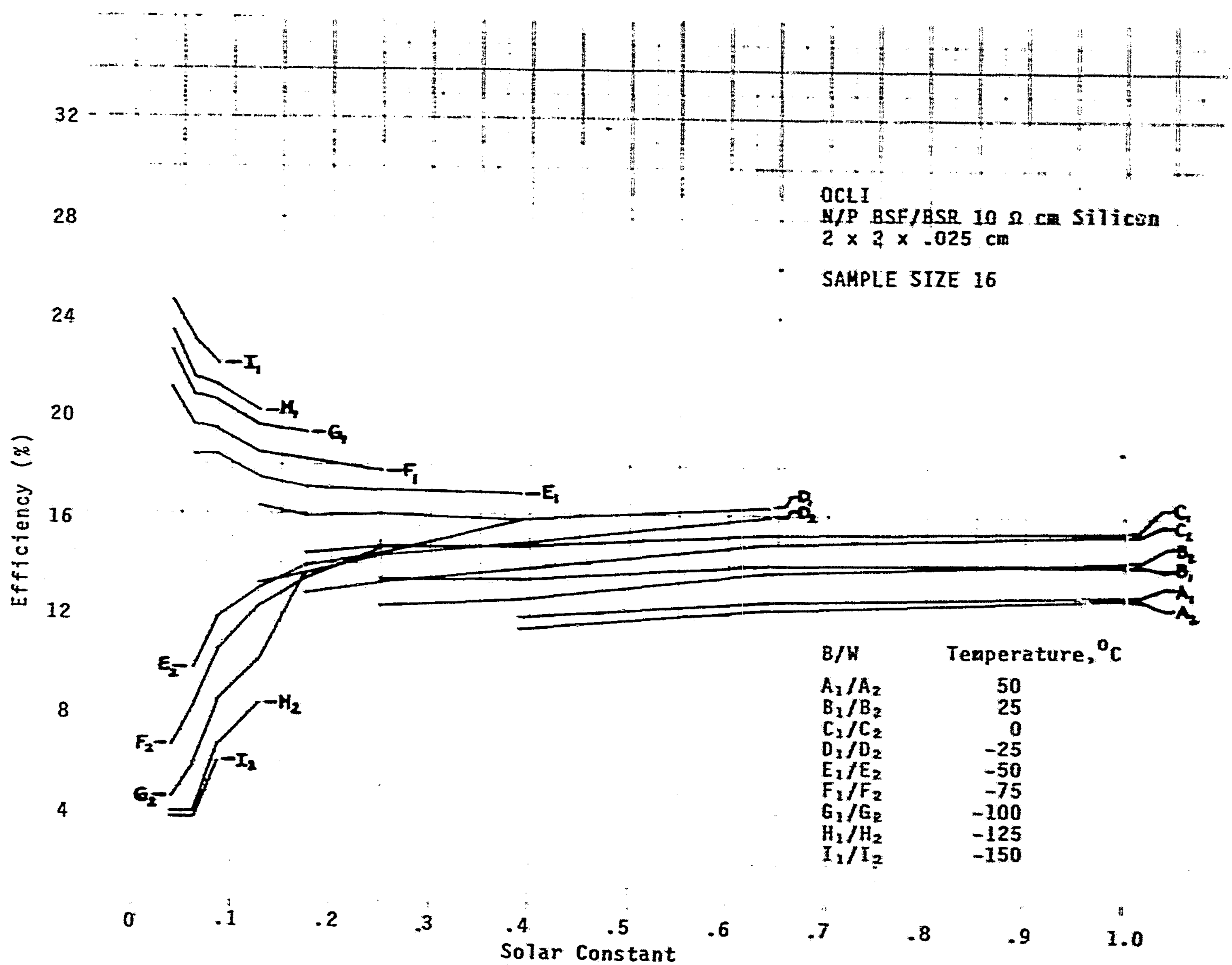


Figure 18. Efficiency of the best/worst cells as a function of intensity.

TABLE 6. AVERAGE I_{sc} (mA)

OCLI
N/P BSF/BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (Blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)
SAMPLE SIZE 16

Temperature	Solar Constants								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50°C	163.3 (3.4)	105.0 (2.8)	62.5 (1.5)						
25°C	161.9 (3.5)	104.8 (2.5)	62.6 (1.7)	41.0 (1.1)					
0°C	161.5 (3.7)	104.0 (2.7)	62.2 (1.6)	40.5 (1.0)	28.5 (.8)				
-25°C		103.5 (2.5)	62.0 (1.6)	40.1 (1.1)	28.5 (.8)	21.5 (.6)			
-50°C			63.0 (2.0)	39.5 (1.1)	28.2 (.8)	21.1 (.6)	15.0 (.4)	11.2 (.3)	
-75°C				38.8 (1.1)	27.6 (.8)	20.7 (.5)	14.6 (.4)	10.9 (.3)	7.4 (.2)
-100°C					26.1 (1.0)	19.6 (.6)	13.9 (.4)	10.4 (.3)	7.2 (.2)
-125°C						18.7 (.5)	13.4 (.4)	10.0 (.3)	6.9 (.1)
-150°C							13.1 (.4)	9.9 (.2)	6.8 (.1)
-168°C									6.9 (.1)

NOTE: Standard Deviations Are Given In Parentheses

TABLE 7. AVERAGE V_{oc} (mV)

OCLI
N/P BSF/BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
$50^{o}C$	564.8 (8.3)	547.3 (5.5)	526.6 (4.3)						
$25^{o}C$	613.7 (8.7)	598.7 (6.3)	580.1 (4.9)	563.3 (4.2)					
$0^{o}C$	666.7 (9.3)	652.3 (6.5)	635.6 (4.9)	620 (4.4)	607.9 (4.1)				
$-25^{o}C$		704.1 (6.8)	688.9 (5.3)	670.9 (13.4)	664.1 (4.3)	653.1 (4.2)			
$-50^{o}C$			739.9 (5.1)	726.4 (4.8)	717.7 (4.2)	707.4 (4.6)	695.1 (5.6)	683.1 (8.6)	
$-75^{o}C$				776.7 (4.4)	768.0 (4.1)	759.2 (4.8)	747.4 (6.8)	734.5 (24.5)	709.9 (63.9)
$-100^{o}C$					817.5 (4.5)	808.9 (5.4)	797.1 (10.5)	777.3 (44.4)	735.1 (100.1)
$-125^{o}C$						862.6 (7.6)	846.9 (36.6)	820.8 (76.4)	761.6 (139.9)
$-150^{o}C$							898.9 (61.8)	866.9 (106.1)	787.5 (174.2)
$-168^{o}C$									817.1 (188.1)

NOTE: Standard Deviations Are Given In Parentheses

TABLE 8. AVERAGE I_{mp} (mA)

OCLI
N/P BSF/BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 µ Cut-on
(.300 µm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50^oC	155.2 (3.1)	98.3 (2.6)	58.0 (1.2)						
25^oC	153.9 (2.8)	98.1 (2.1)	58.0 (1.7)	37.2 (1.0)					
0^oC	152.9 (3.2)	96.9 (2.4)	57.1 (1.5)	36.6 ([illegible]1)	25.4 (.9)				
-25^oC		96.2 (2.4)	56.4 (1.5)	36.0 (1.2)	25.1 (1.0)	18.7 (.9)			
-50^oC			57.1 (2.0)	35.11 (1.5)	24.6 (1.2)	18.1 (1.2)	12.5 (1.1)	9.2 (.9)	
-75^oC				34.1 (1.7)	23.6 (1.7)	17.3 (1.5)	11.8 (1.3)	8.7 (1.0)	6.1 (.7)
-100^oC					21.7 (1.8)	15.5 (2.1)	10.8 (1.7)	7.8 (1.6)	5.1 (1.3)
-125^oC						14.3 (2.5)	9.7 (1.9)	7.0 (1.8)	4.8 (1.4)
-150^oC							9.2 (2.0)	6.9 (1.8)	4.6 (1.3)
-168^oC									4.9 (1.2)

NOTE: Standard Deviations Are Given In Parentheses

TABLE 9. AVERAGE V_{mp} (mV)

OCLI
N/P BSF/BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50°C	445.1 (7.5)	440.4 (4.1)	427.5 (3.6)						
25°C	494.7 (7.8)	490.3 (6.2)	482.5 (3.9)	474.7 (3.2)					
0°C	548.6 (8.9)	544.1 (6.4)	536.3 (4.6)	530.7 (3.9)	525.2 (4.4)				
-25°C		592.5 (8.3)	588.1 (5.3)	585.5 (4.3)	577.2 (4.5)	576.3 (4.2)			
-50°C			633.8 (10.3)	637.2 (5.4)	631.4 (4.6)	629.1 (4.6)	624.9 (10.1)	566.3 (55.2)	
-75°C				683.5 (5.6)	681.1 (4.7)	683.1 (8.0)	671.5 (22.5)	641.9 (59.8)	548.4 (93.0)
-100°C					756.6 (6.1)	756.7 (10.2)	733.8 (35.9)	707.7 (52.8)	652.9 (83.6)
-125°C						806.0 (26.0)	778.5 (63.9)	734.7 (78.3)	652.2 (113.5)
-150°C							818.3 (90.6)	755.5 (110.4)	660.5 (140.8)
-168°C									666.0 (146.6)

NOTE: Standard Deviations Are Given In Parentheses.

TABLE 10. AVERAGE MP (mW)

OCLI
N/P BSF/BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.083	0.04
$50^{o}C$	69.1 (1.9)	43.3 (1.3)	24.8 (.6)						
$25^{o}C$	76.0 (1.9)	48.1 (1.2)	28.0 (.8)	17.7 (.5)					
$0^{o}C$	83.9 (2.0)	52.7 (1.3)	30.6 (.90)	19.4 (.6)	13.3 (.5)				
$-25^{o}C$		57.1 (.14)	33.1 (.9)	21.1 (.7)	14.5 (.6)	10.8 (.6)			
$-50^{o}C$			36.2 (1.2)	22.4 (1.0)	15.5 (.8)	11.4 (.8)	7.8 (.8)	5.6 (.8)	
$-75^{o}C$				23.3 (1.1)	16.1 (1.1)	11.8 (1.1)	7.79 (1.1)	5.7 (1.0)	3.4 (.9)
$-100^{o}C$					16.5 (1.5)	11.8 (1.7)	7.9 (1.5)	5.5 (1.4)	3.4 (1.7)
$-125^{o}C$						11.5 (2.2)	7.7 (1.9)	5.3 (1.7)	3.2 (1.3)
$-150^{o}C$							7.6 (2.2)	5.4 (1.9)	3.1 (1.3)
$-168^{o}C$									3.3 (1.5)

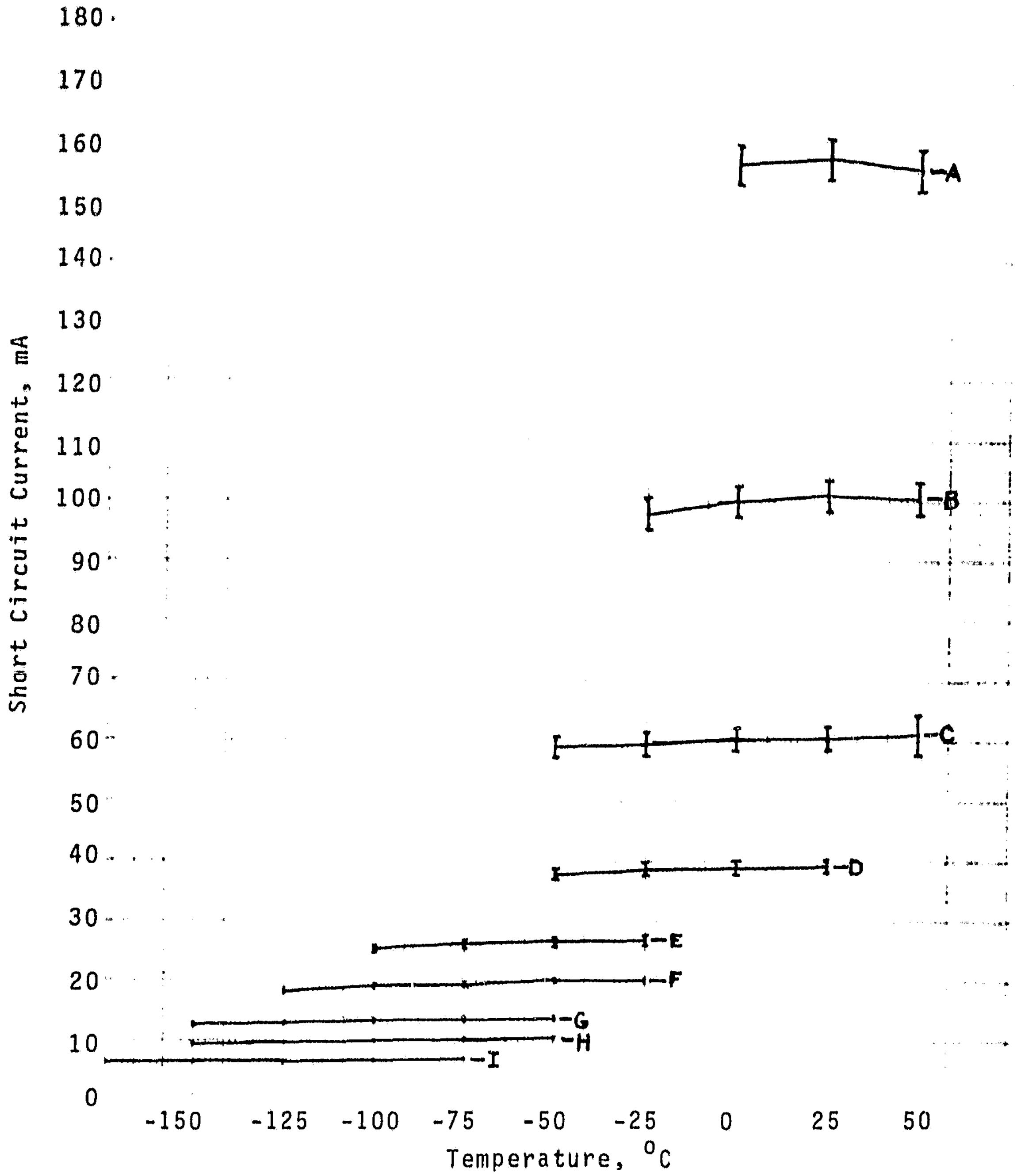
NOTE: Standard Deviations Are Given In Parentheses

TABLE 11. AVERAGE EFFICIENCY (%)

OCLI
N/P BSF/BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50°C	12.8	12.5	11.7						
25°C	14.1	13.9	13.3	13.1					
0°C	15.5	15.2	14.5	14.4	14.1				
-25°C		16.5	15.7	15.6	15.4	15.5			
-50°C			17.2	16.5	16.5	16.4	16.8	16.3	
-75°C				17.2	17.1	17.0	17.1	16.6	16.0
-100°C					17.5	17.0	17.0	16.2	15.7
-125°C						16.7	16.5	15.5	15.0
-150°C							16.4	15.7	14.3
-168°C									15.2



ID	SOLAR CONSTANT
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 10 Ω cm SIlicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 19. Average I_{sc} as a function of temperature.

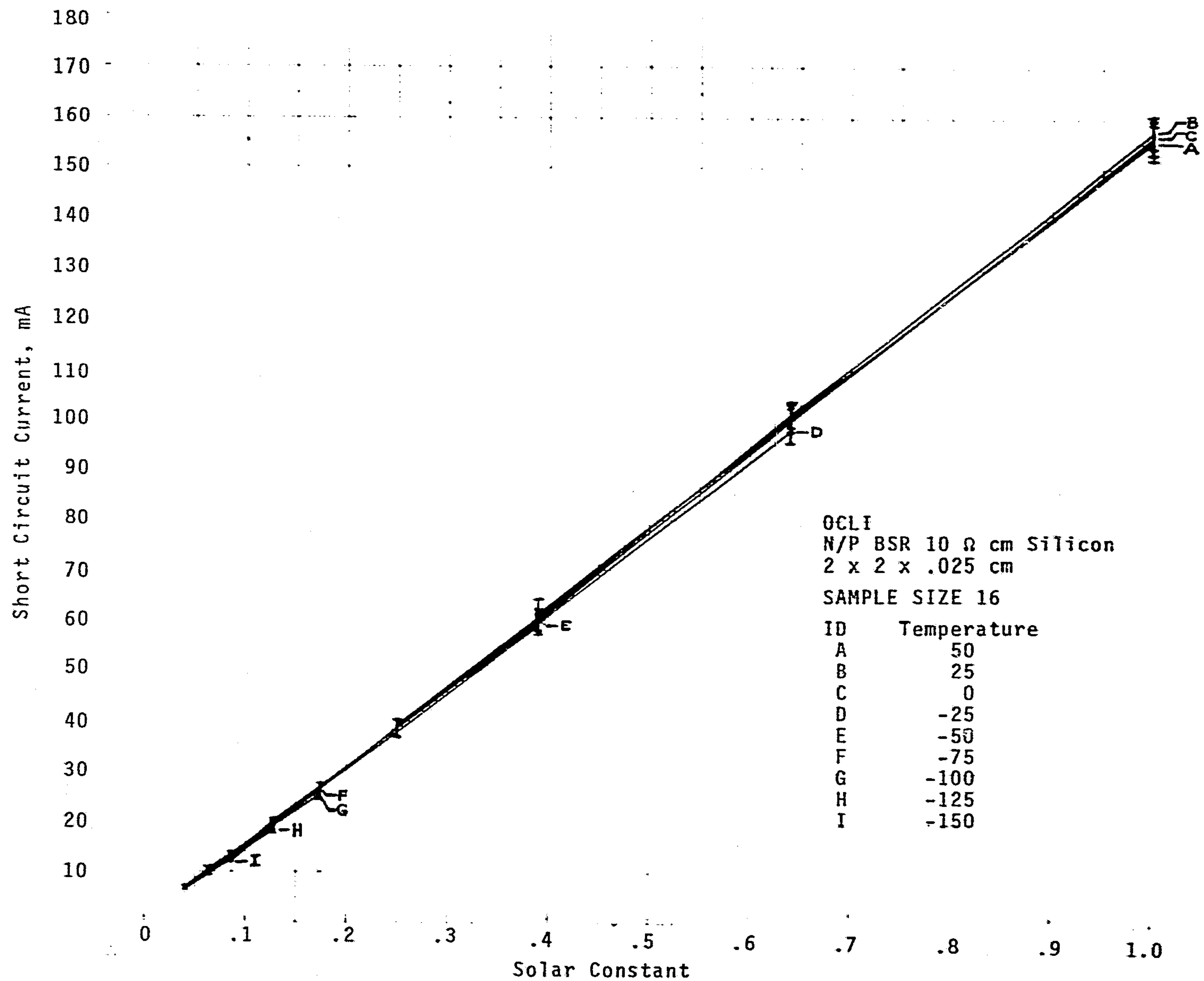
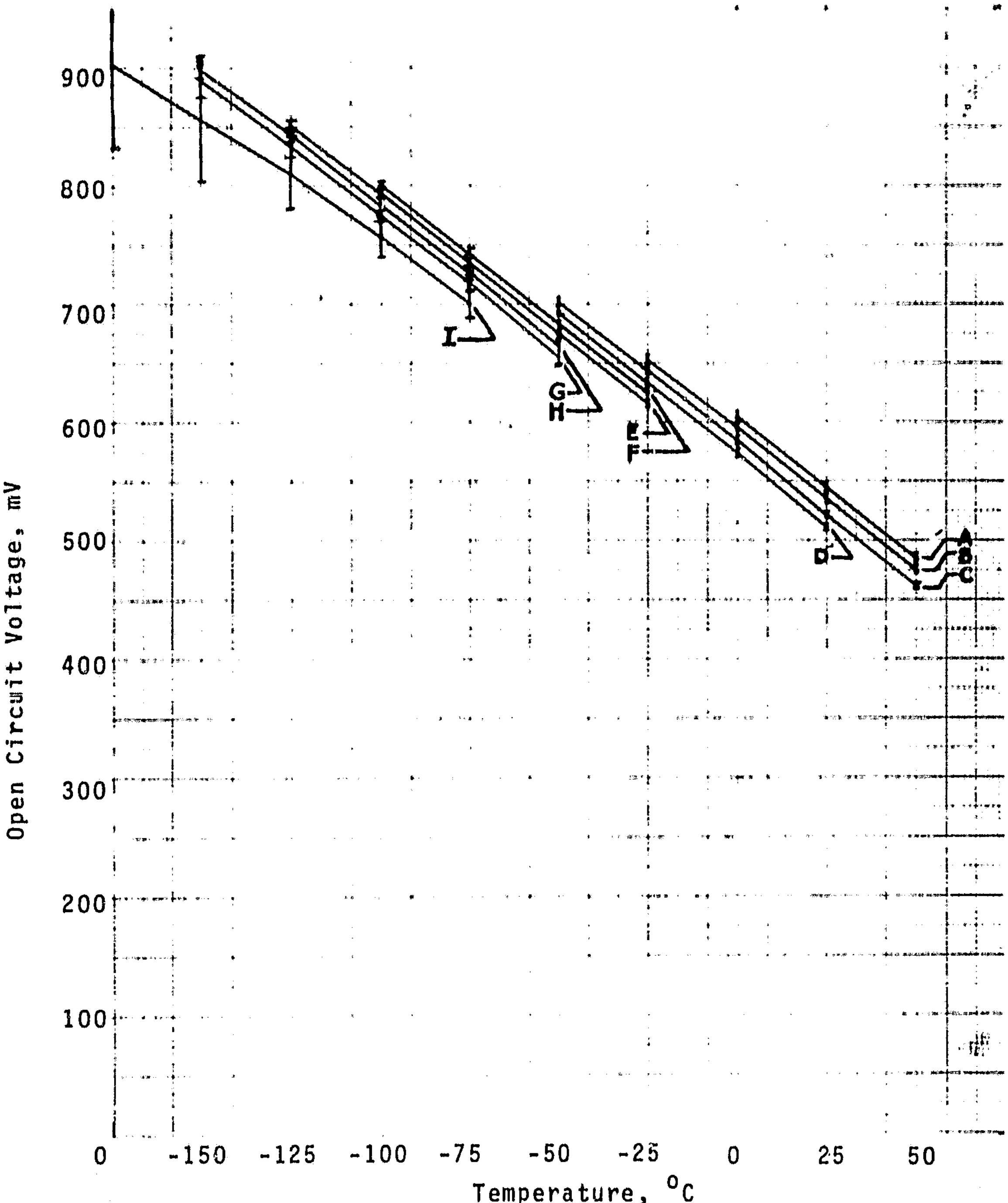


Figure 20. Average I_{sc} as a function of intensity.



ID	SOLAR CONSTANT
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 21. Average V_{oc} as a function of temperature.

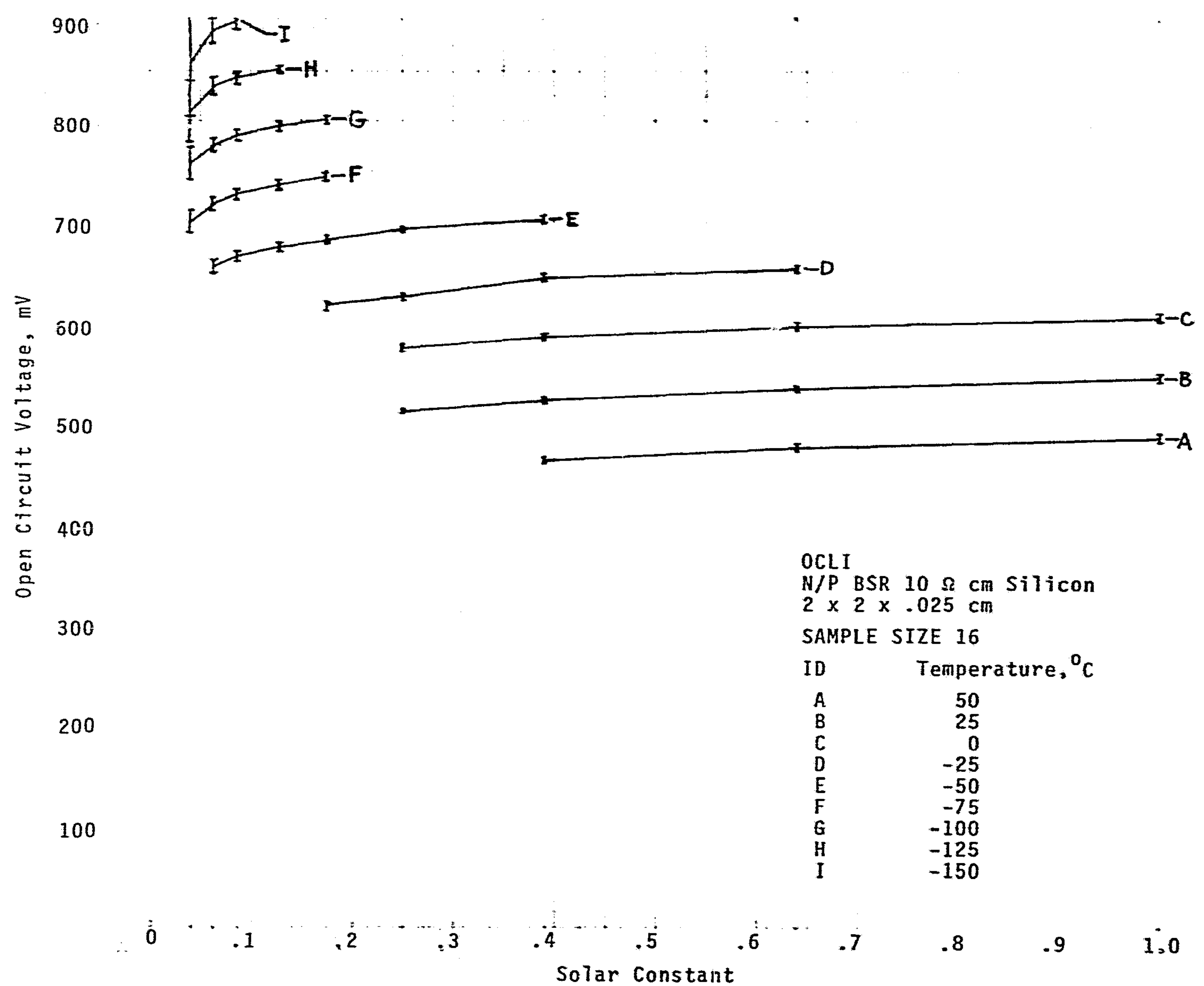
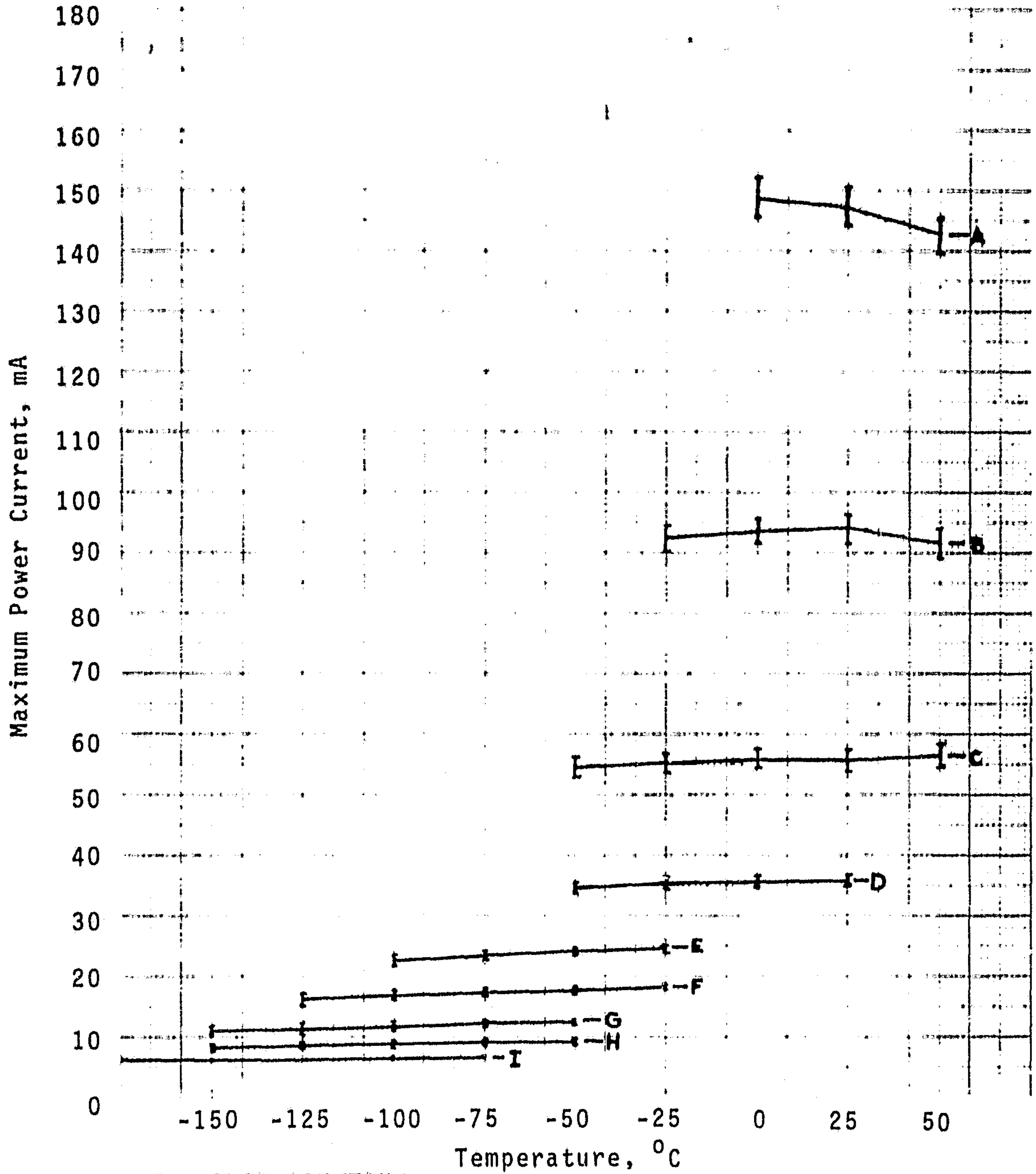


Figure 22. Average V_{oc} as a function of intensity.



ID	SOLAR CONSTANT
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 23. Average I_{mp} as a function of temperature.

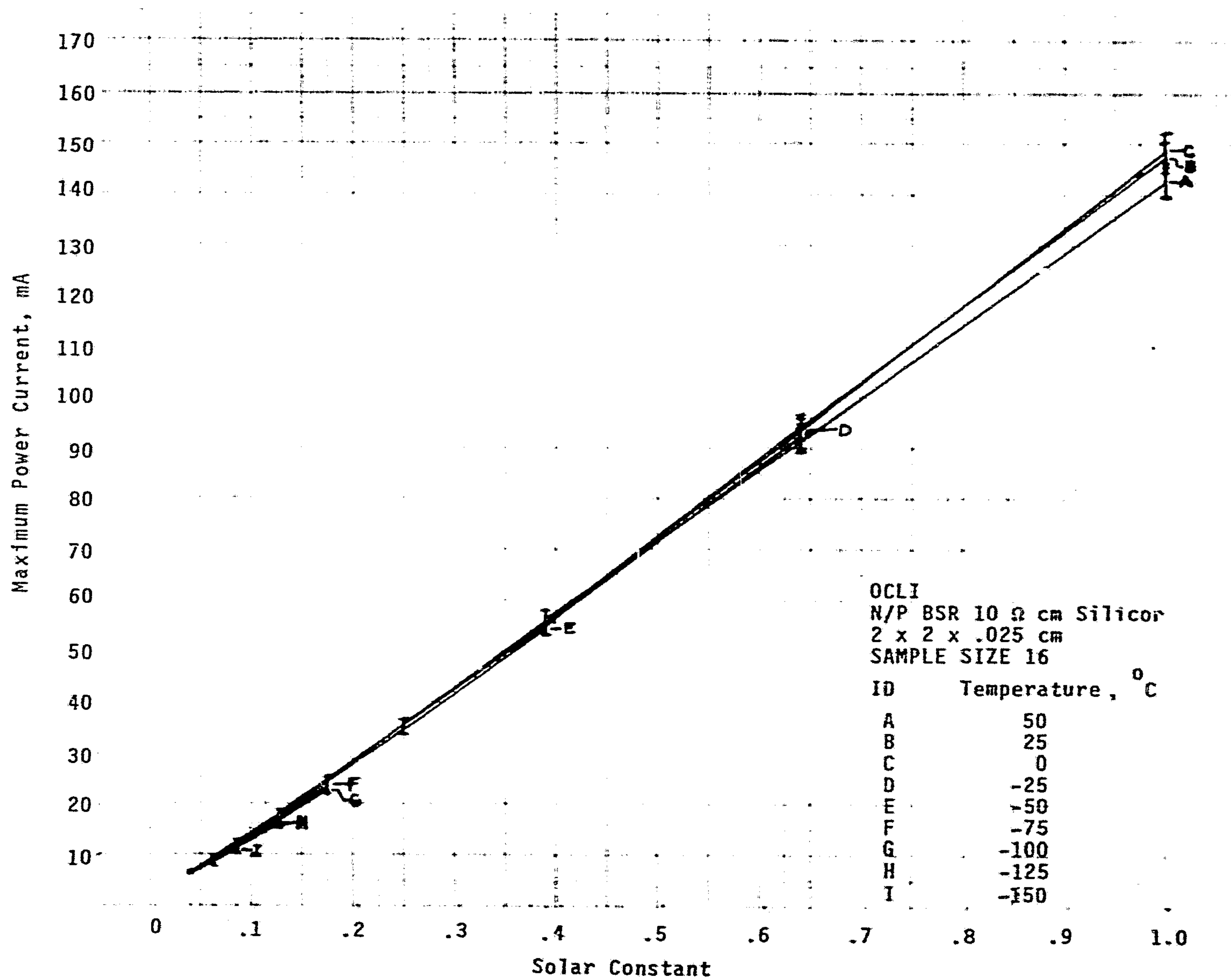
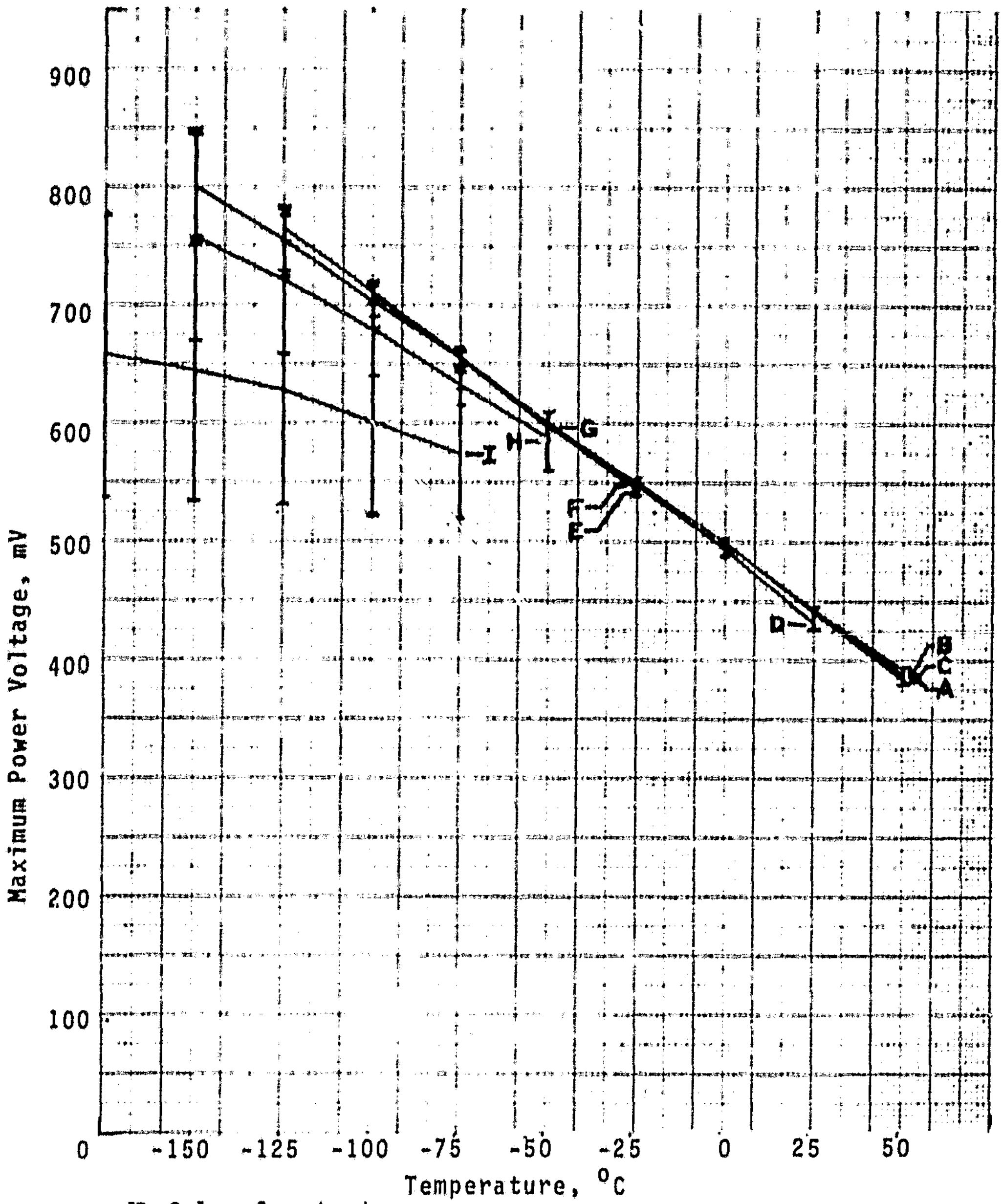


Figure 24. Average I_{mp} as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 25. Average V_{mp} as a function of temperature.

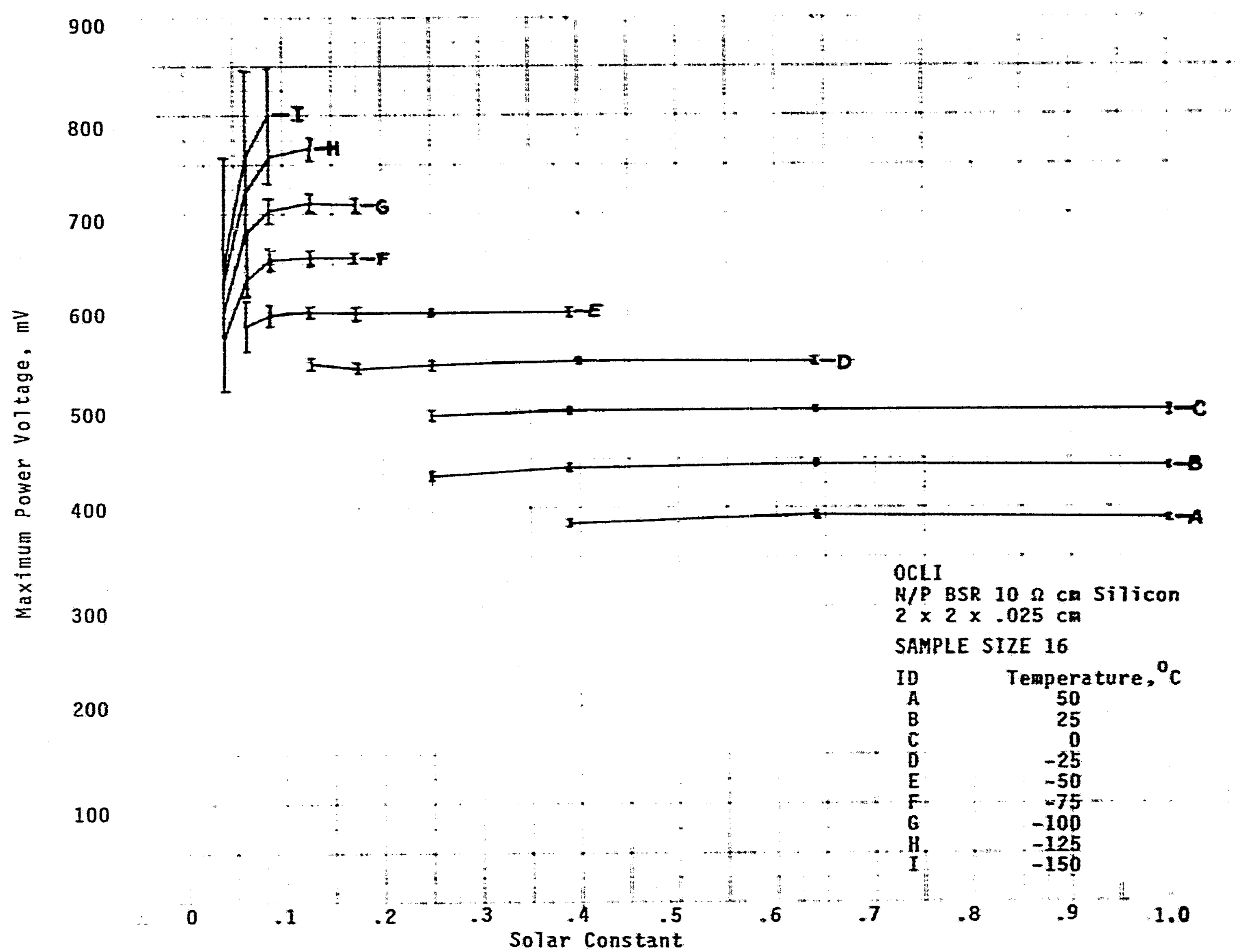
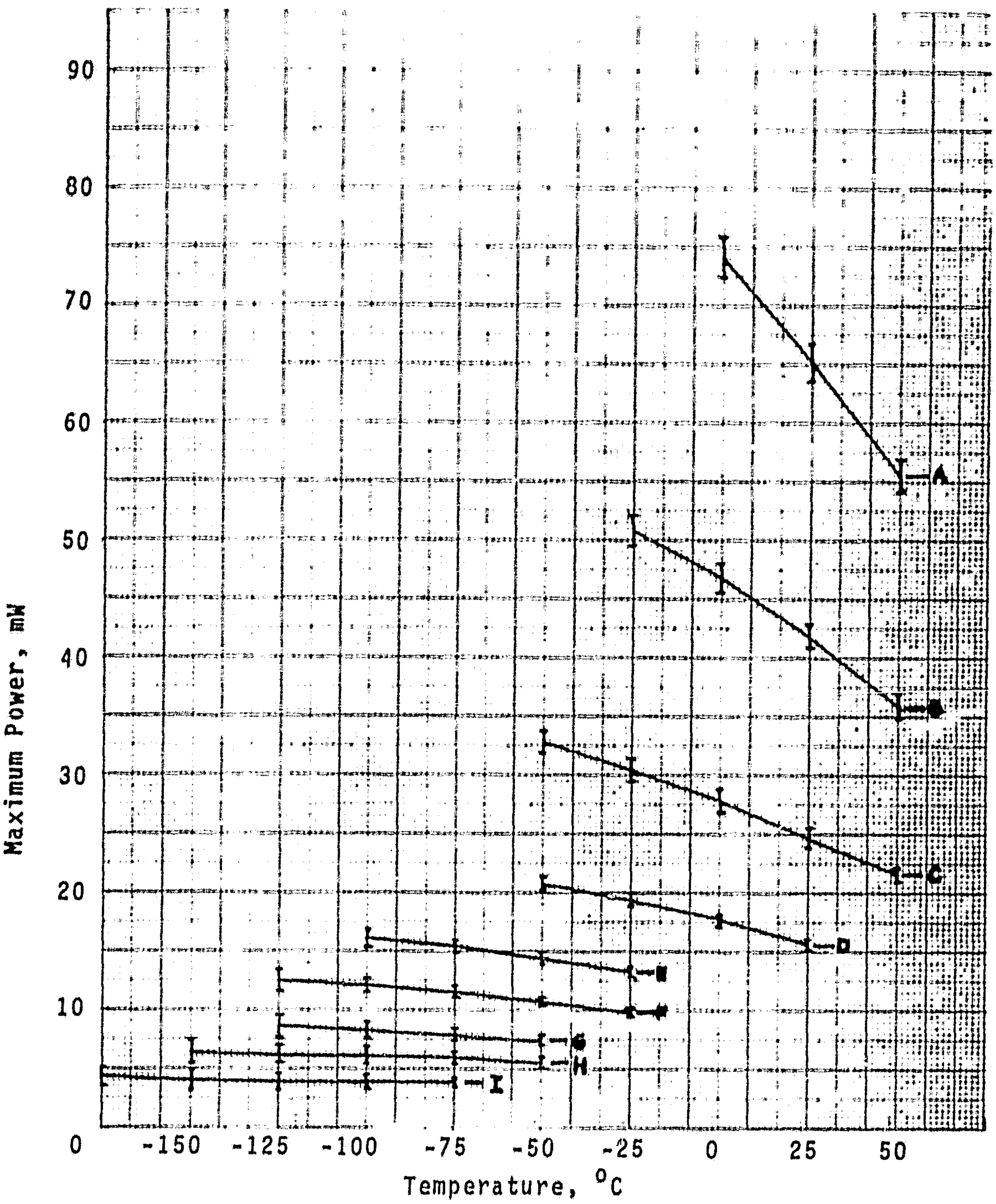


Figure 26. Average V_{mp} as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 27. Average MP as a function of temperature.

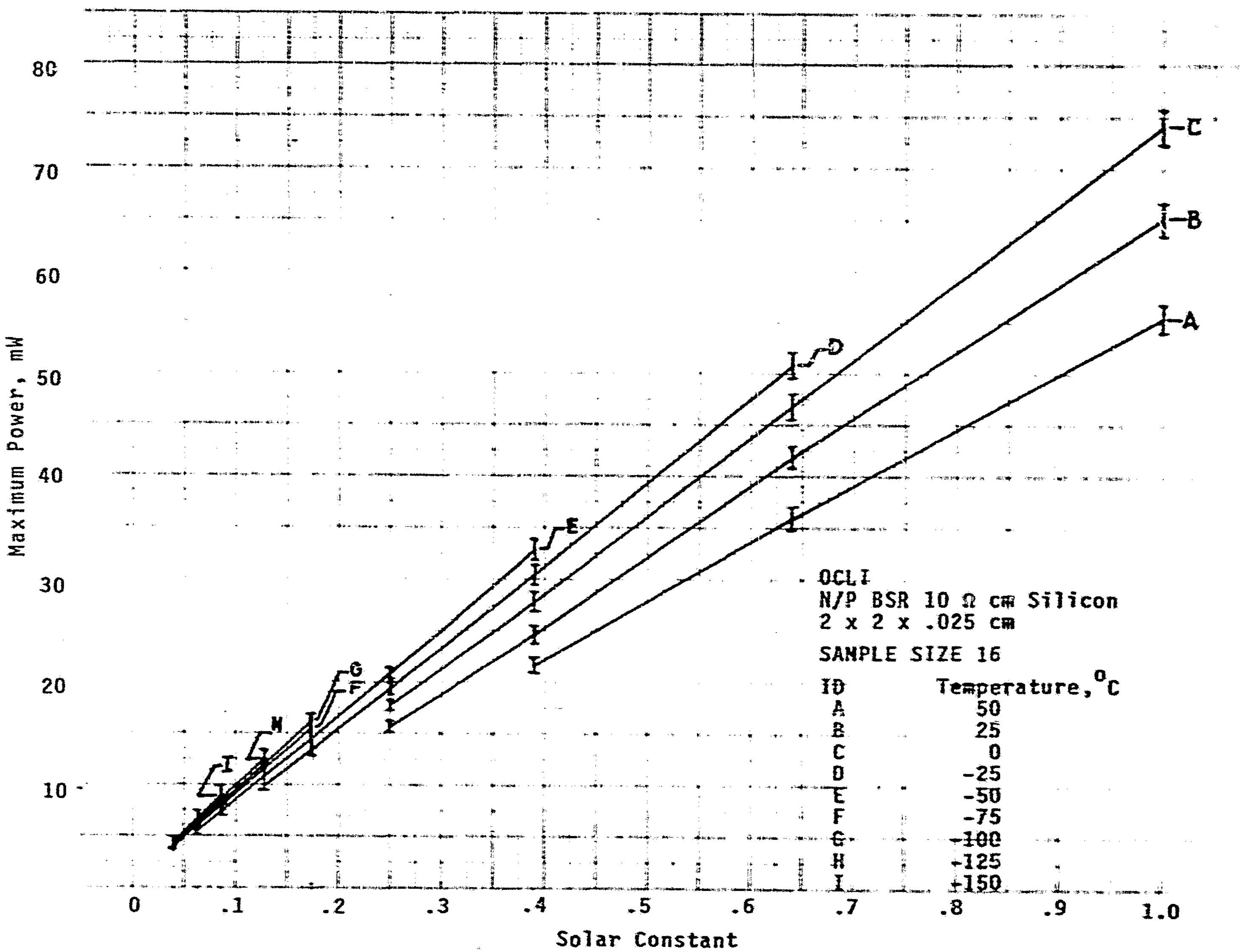
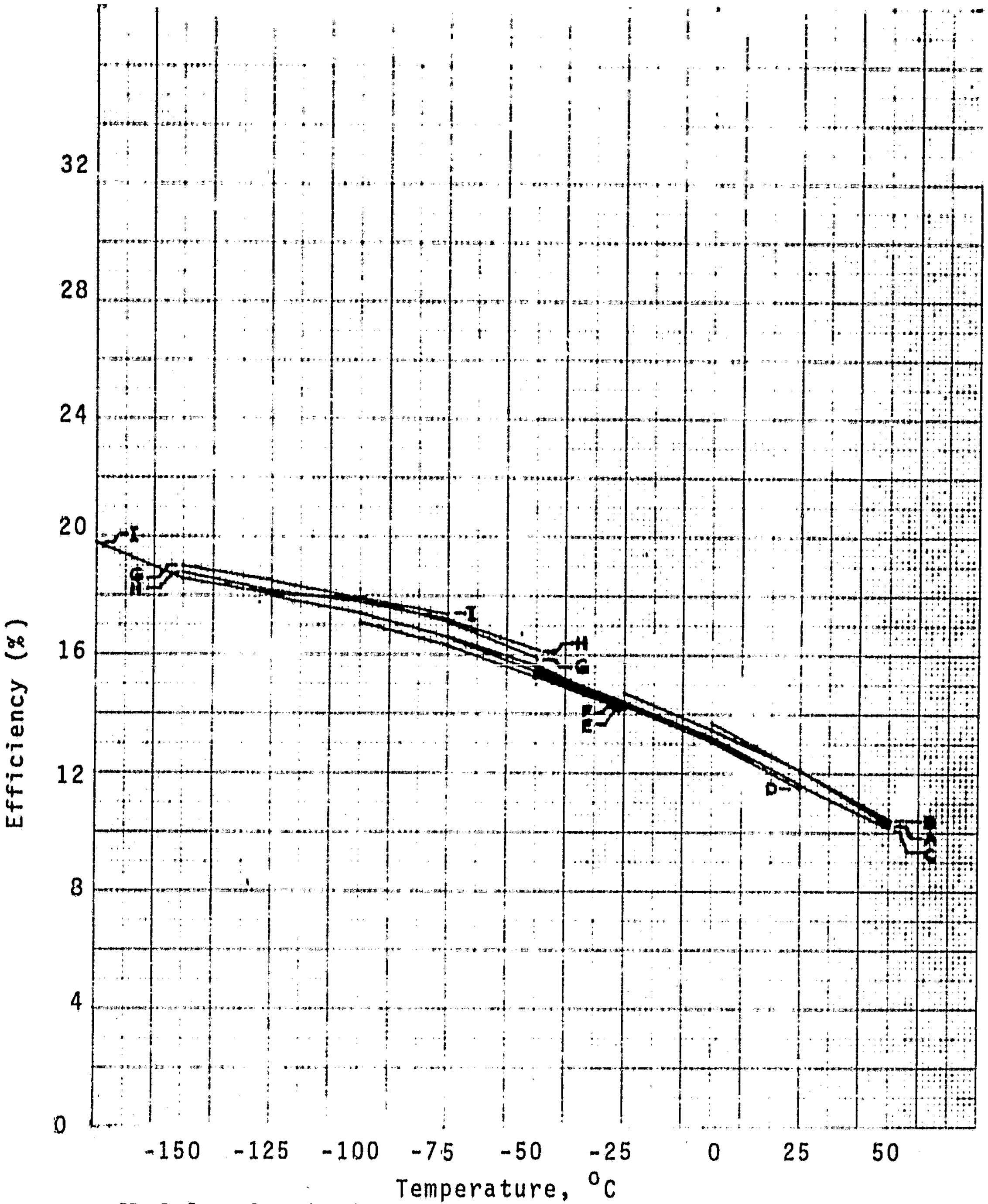


Figure 28. Average MP as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 29. Average efficiency as a function of temperature.

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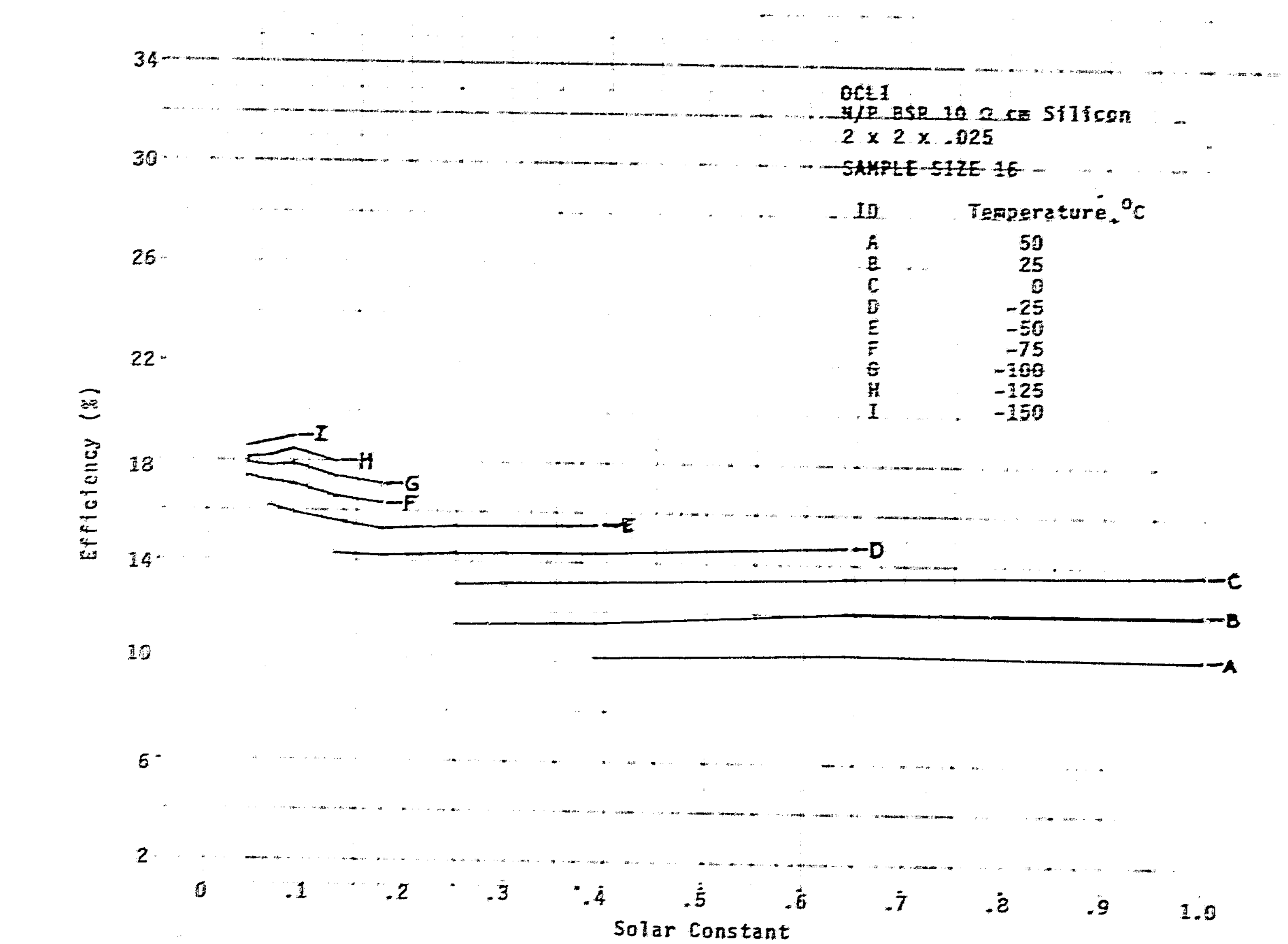
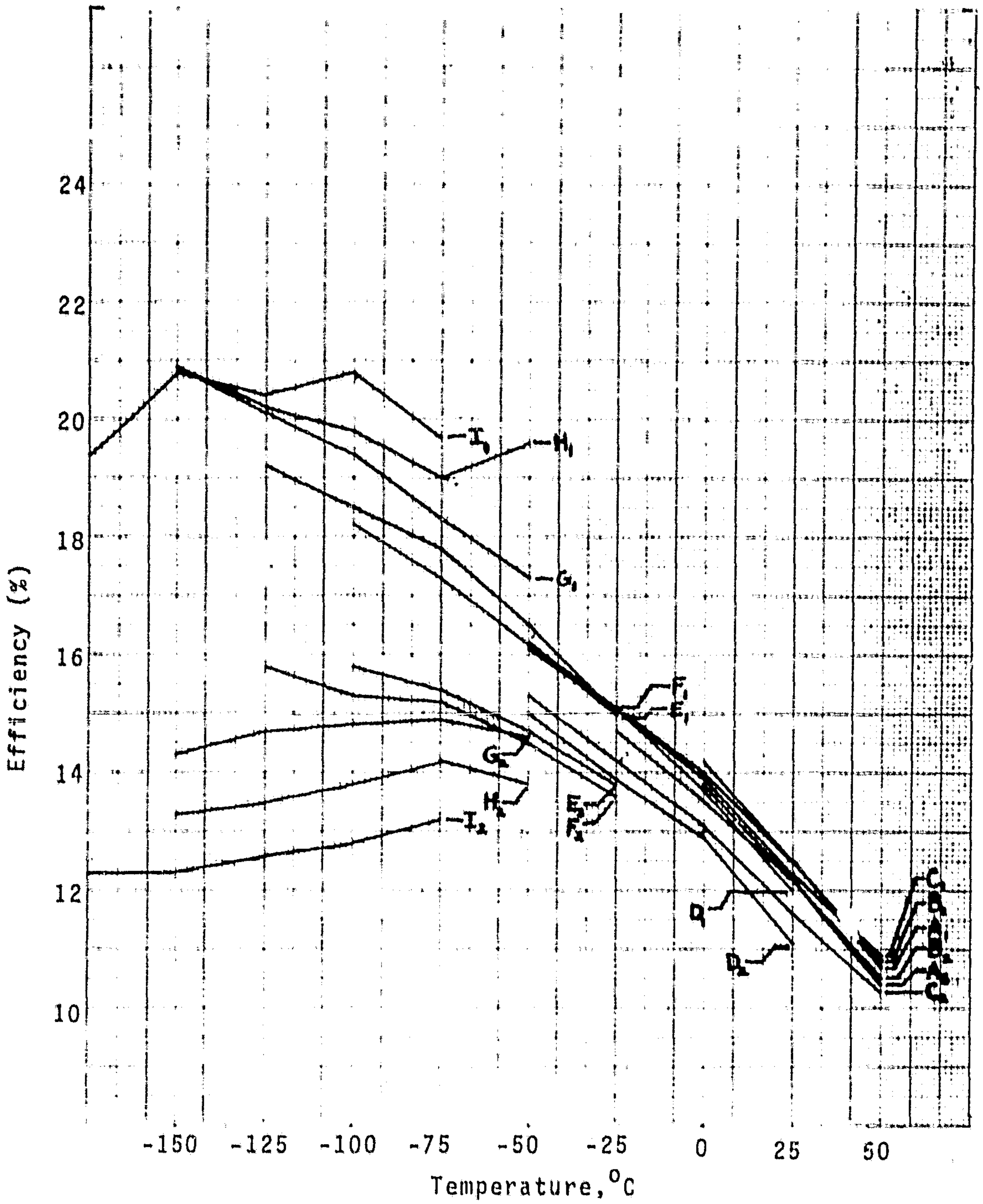


Figure 30. Average efficiency as a function of intensity.



B/W	Solar Constant
A_1/A_2	1.0
B_1/B_2	.64
C_1/C_2	.39
D_1/D_2	.25
E_1/E_2	.174
F_1/F_2	.128
G_1/G_2	.086
H_1/H_2	.063
I_1/I_2	.04

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025

SAMPLE SIZE 16

Figure 31. Efficiency of the best/worst cells as a function of temperature.

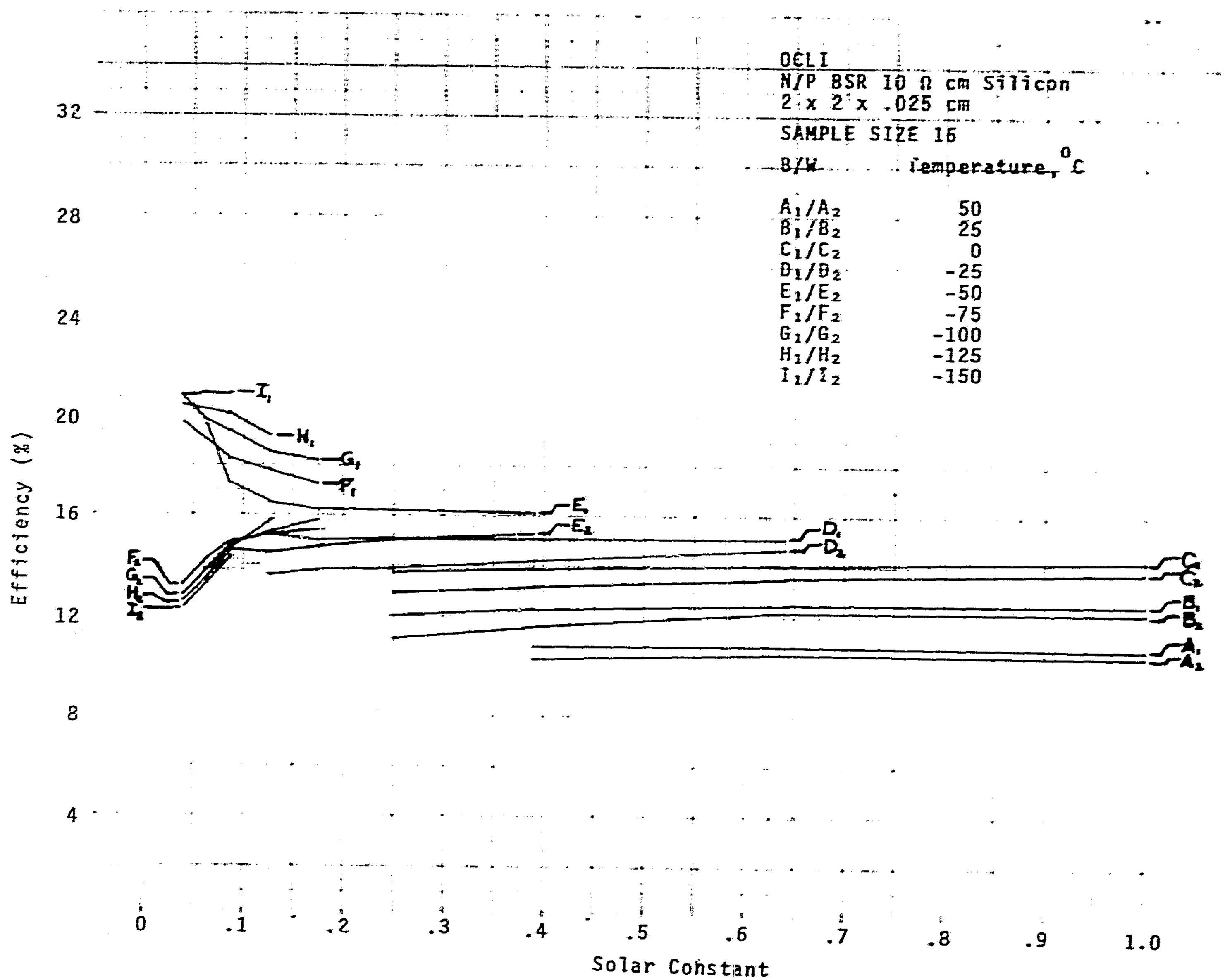


Figure 32. Efficiency of the best/worst cells as a function of intensity.

TABLE 12. AVERAGE I_{sc} (mA)

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50°C	155.4 (3.5)	100.5 (2.6)	61.1 (3.2)						
25°C	157.4 (3.4)	101. (2.6)	60.5 (1.8)	39.2 (1.0)					
0°C	156.3 (3.3)	100 (2.5)	60.3 (1.8)	39.0 (1.1)					
-25°C		97.9 (2.6)	59.5 (1.8)	38.8 (1.1)	26.9 (.9)	20.1 (.5)			
-50°C			59.0 (1.8)	37.9 (.9)	26.5 (.7)	20.1 (.4)	13.9 (.3)	10.6 (.4)	
-75°C					26.1 (.8)	19.5 (.5)	13.7 (.4)	10.4 (.5)	7.0 (.2)
-100°C					25.4 (.6)	19.2 (.5)	13.3 (.5)	10 (0)	6.90 (.2)
-125°C						18.4 (.5)	13.0 (.2)	9.9 (.3)	6.7 (.1)
-150°C							12.8 (.4)	9.8 (.4)	6.7 (.1)
-175°C									6.6 (.2)

NOTE: Standard Deviations Are Given in Parentheses

TABLE 13. AVERAGE V_{oc} (mV)

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50°C	485.6 (4.0)	475.1 (3.2)	462.9 (2.5)						
25°C	545.3 (4.4)	534.8 (3.4)	522.9 (2.8)	511.7 (2.4)					
0°C	605.3 (4.5)	596.3 (3.7)	585.0 (3.0)	574.9 (2.6)					
-25°C		653.7 (3.7)	644.0 (3.4)	634.0 (3.0)	625.2 (3.3)	616.9 (3.8)			
-50°C			702.0 (3.7)	692.1 (3.0)	682.9 (3.7)	675.8 (4.2)	666.3 (5.1)	655.8 (6.5)	
-75°C					743.8 (4.1)	736.9 (4.2)	727.1 (5.4)	717.9 (6.9)	700.8 (11.4)
-100°C					800.8 (3.6)	794.0 (4.5)	784.9 (5.4)	775.8 (7.5)	757.4 (15.8)
-125°C						851.0 (4.0)	843 (5.8)	834.6 (8.9)	810 (31.7)
-150°C							899.8 (7.0)	889.1 (13.6)	857.7 (53.7)
-175°C									903.3 (70.9)

NOTE: Standard Deviations Are Given in Parentheses

TABLE 14. AVERAGE I_{mp} (mA)

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50^oC	142.9 (3.3)	91.5 (2.5)	56.4 (1.8)						
25^oC	147.2 (3.1)	94.1 (2.3)	55.7 (1.8)	35.9 (.9)					
0^oC	148.8 (3.3)	93.7 (2.1)	55.9 (1.6)	35.8 (.9)					
-25^oC		92.3 (2.3)	55.2 (1.7)	35.4 (.9)	24.6 (.6)	18.1 (.6)			
-50^oC			54.6 (1.6)	34.7 (.9)	24.1 (.7)	17.9 (.6)	12.5 (.5)	9.4 (.5)	
-75^oC					23.5 (.7)	17.5 (.6)	12.2 (.6)	9.2 (.5)	6.5 (.3)
-100^oC					22.8 (.9)	16.9 (.8)	11.8 (.8)	8.9 (.6)	6.4 (.2)
-125^oC						16.3 (1.0)	11.4 (.9)	8.6 (.5)	6.2 (.2)
-150^oC							11.0 (.9)	8.4 (.5)	6.2 (.1)
-175^oC									6.2 (.1)

NOTE: Standard Deviations Are Given in Parentheses

TABLE 15. AVERAGE V_{mp} (mV)

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50°C	388.1 (3.0)	392.8 (2.4)	384.0 (3.0)						
25°C	442.1 (3.4)	443.9 (2.3)	441.0 (3.7)	433.5 (4.7)					
0°C	498.2 (4.6)	499.8 (2.5)	498.0 (3.0)	494.6 (3.9)					
-25°C		550.0 (4.3)	550.4 (3.2)	547.3 (3.9)	543.4 (5.8)	548 (6.)			
-50°C			599.6 (5.3)	599.8 (3.5)	598.25 (6.9)	600 (6.)	596.0 (11.2)	586.2 (25.5)	
-75°C					656.0 (6.2)	656 (8)	654 (11.0)	632.0 (16.4)	574.7 (54.6)
-100°C					709.2 (7.7)	711 (9)	703.6 (13.6)	680.1 (39.2)	601.9 (78.3)
-125°C						766 (11)	756.2 (26.2)	722.3 (63.6)	627.9 (97.6)
-150°C							801 (47.0)	758 (87.6)	645 (112.1)
-175°C									658.3 (119.4)

NOTE: Standard Deviations Are Given in Parentheses

TABLE 16. AVERAGE MP (mW)

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50^oC	55.5 (1.4)	35.9 (1.1)	21.6 (.7)						
25^oC	65.1 (1.6)	41.8 (1.1)	24.6 (.9)	15.6 (.5)					
0^oC	74.1 (1.7)	46.8 (1.2)	27.8 (.9)	17.7 (.5)					
-25^oC		50.8 (1.3)	30.4 (1.0)	19.4 (.6)	13.3 (.4)	9.9 (.4)			
-50^oC			32.8 (1.0)	20.8 (.6)	14.4 (.5)	10.8 (.4)	7.4 (.4)	5.5 (.5)	
-75^oC					15.4 (.5)	11.5 (.5)	7.9 (.5)	5.9 (.5)	3.76 (.5)
-100^oC					16.1 (.7)	12.1 (.6)	8.3 (.7)	6.1 (.7)	3.88 (.6)
-125^oC						12.5 (.9)	8.6 (.9)	6.2 (.8)	3.91 (.7)
-150^oC							8.85 (1.1)	6.4 (1.0)	4.03 (.7)
-175^oC									4.3 (.8)

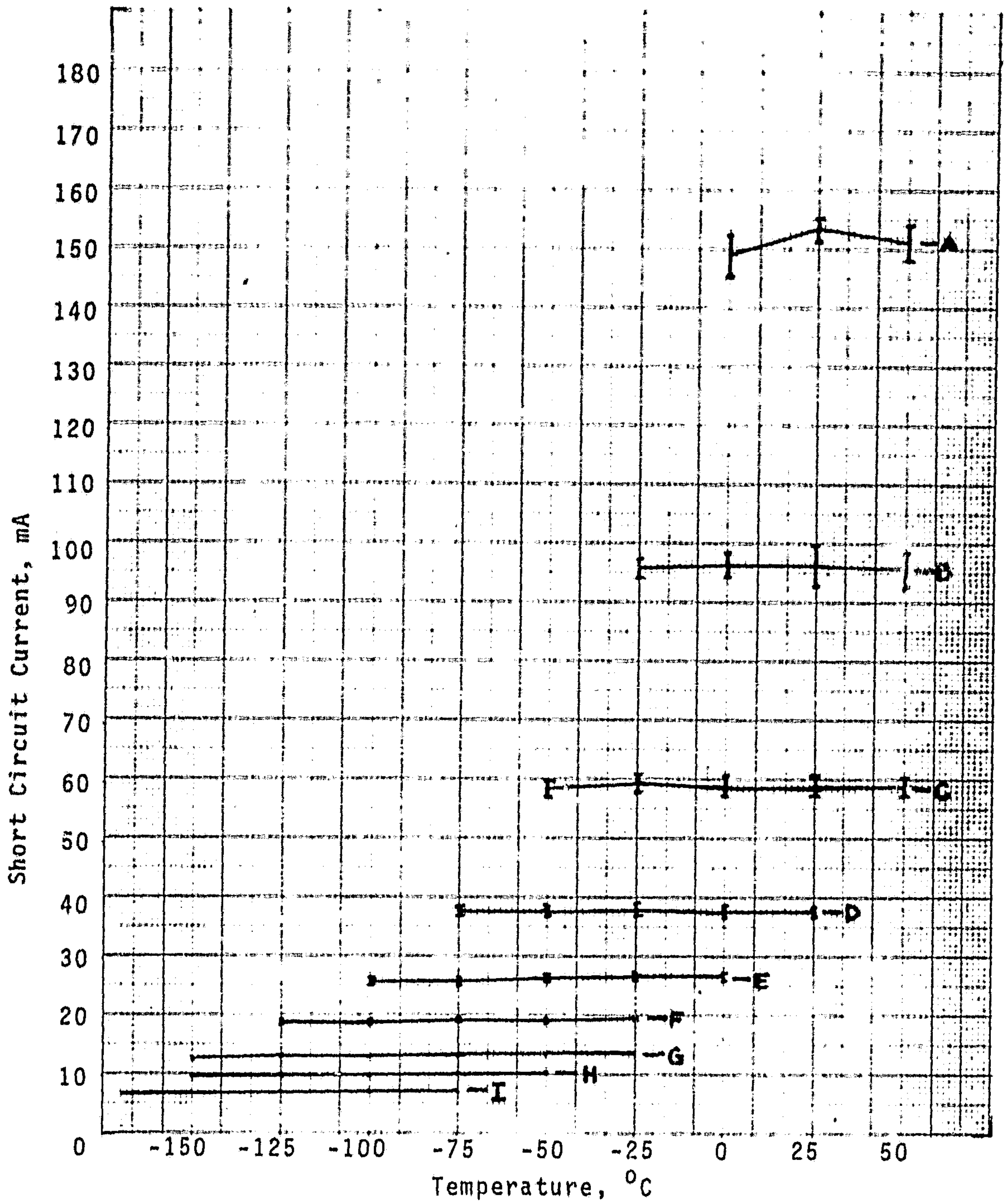
NOTE: Standard Deviations Are Given in Parentheses

TABLE 17. AVERAGE EFFICIENCY (%)

OCLI
N/P BSR 10 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50^oC	10.3	10.4	10.2						
25^oC	12.1	12.1	11.6	11.5					
0^oC	13.7	13.5	13.2	13.1					
-25^oC		14.7	14.4	14.3	14.2	14.3			
-50^oC			15.5	15.4	15.3	15.6	15.9	16.2	
-75^oC					16.3	16.6	17.1	17.2	17.4
-100^oC					17.1	17.4	17.9	17.8	17.9
-125^oC						18.0	18.5	18.2	18.1
-150^oC							19.0	18.8	18.6
-175^oC									19.8



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 33. Average I_{sc} as a function of temperature.

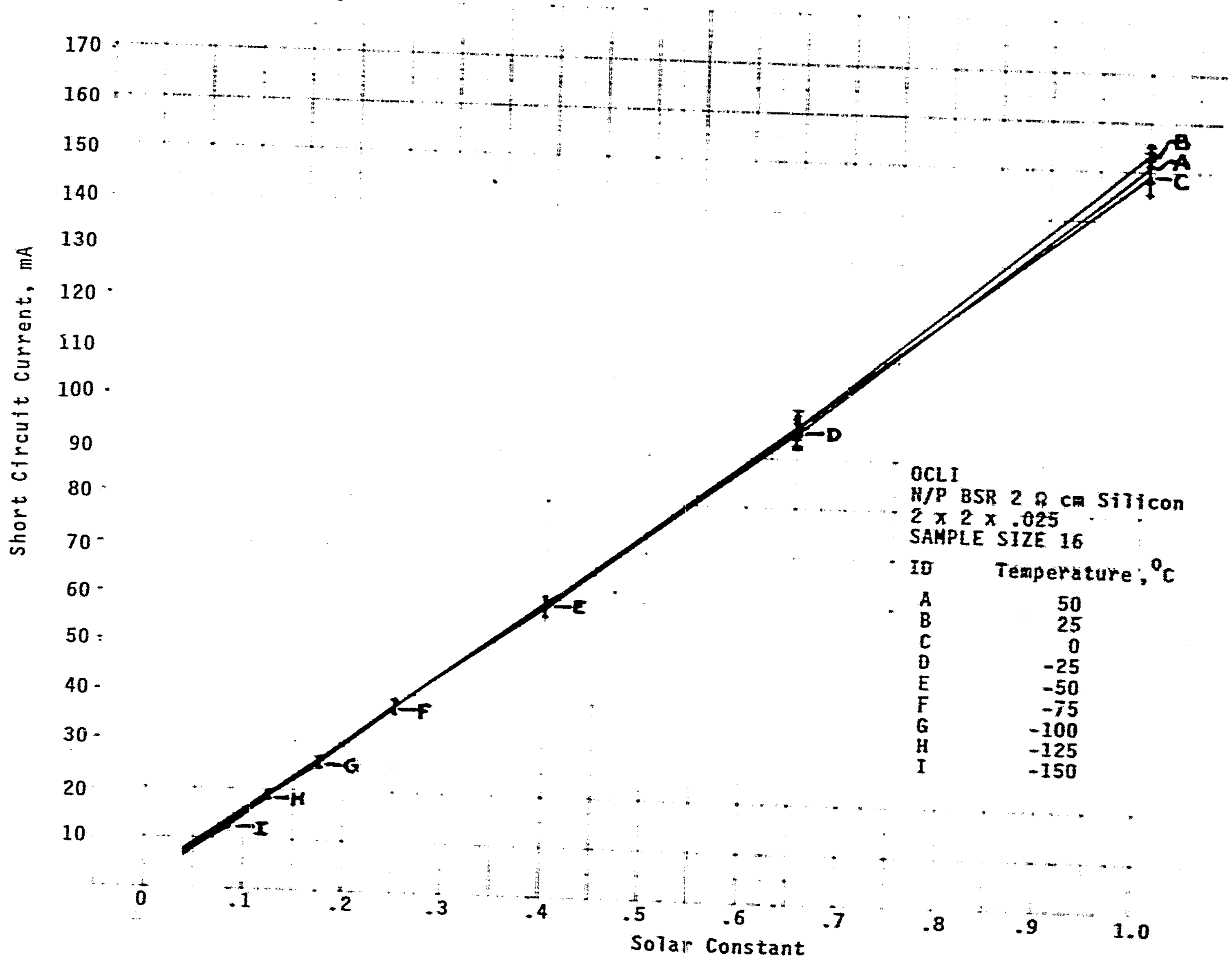
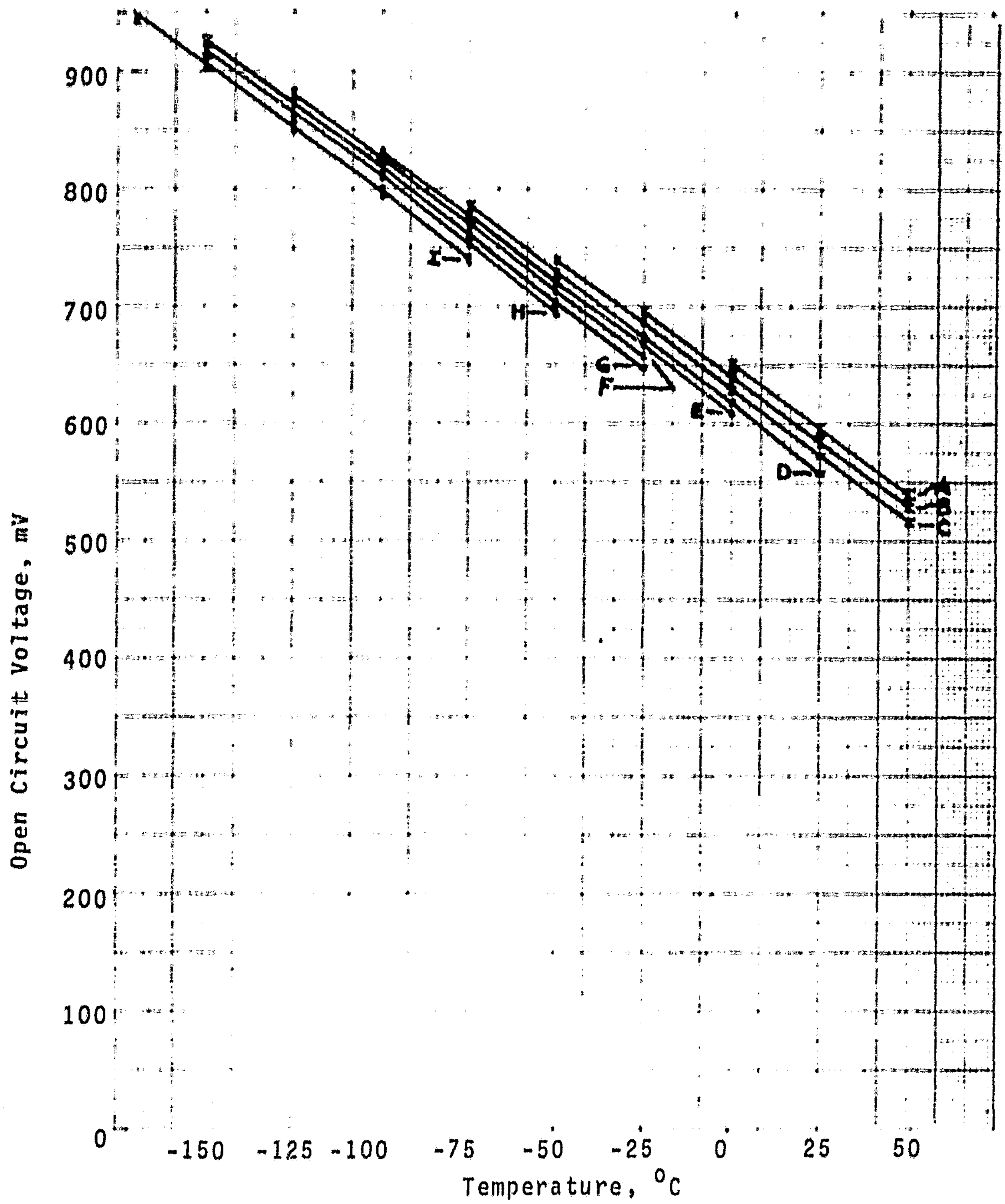


Figure 34. Average I_{sc} as a function of intensity.



ID	SOLAR CONSTANT
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 35. Average V_{oc} as a function of temperature.

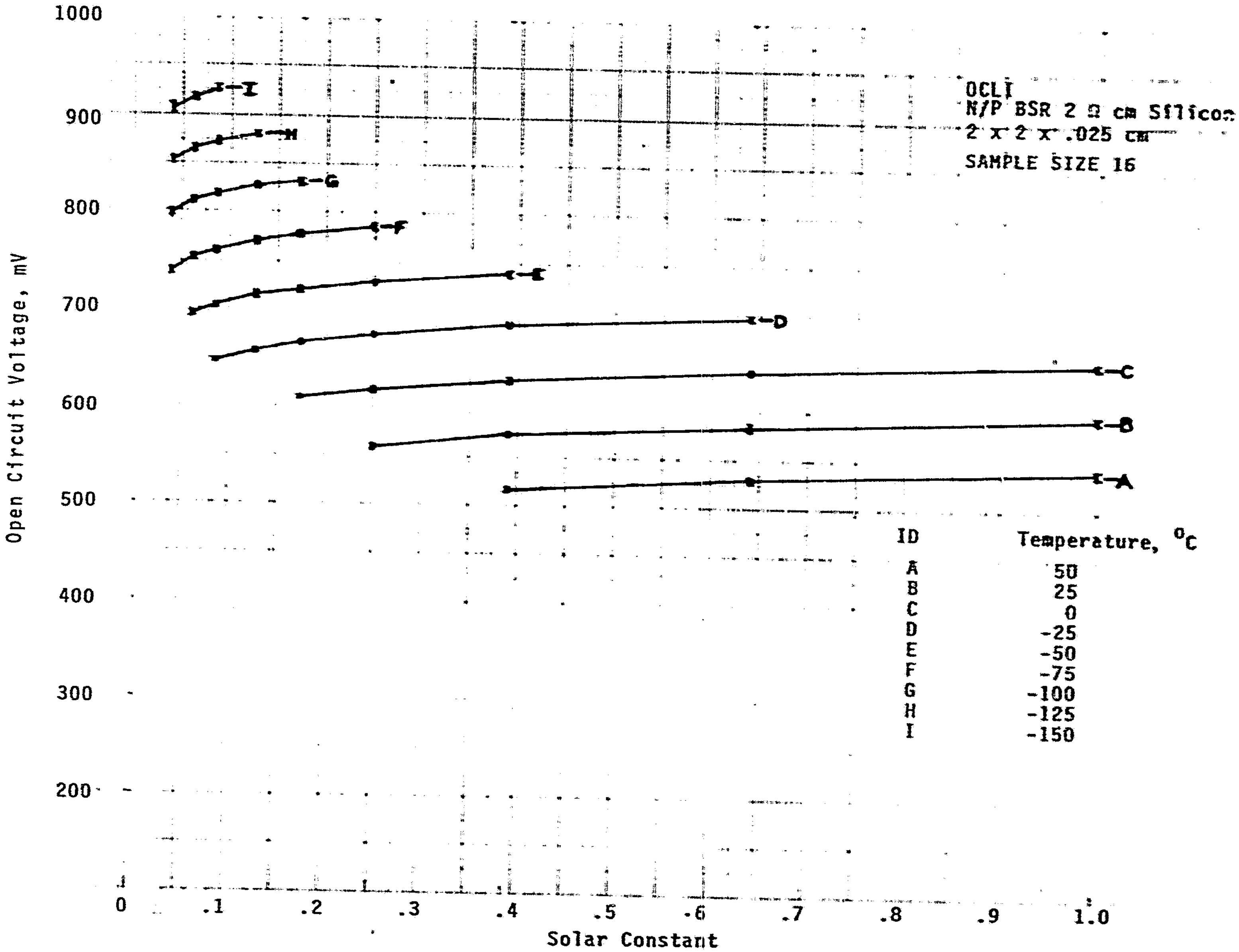
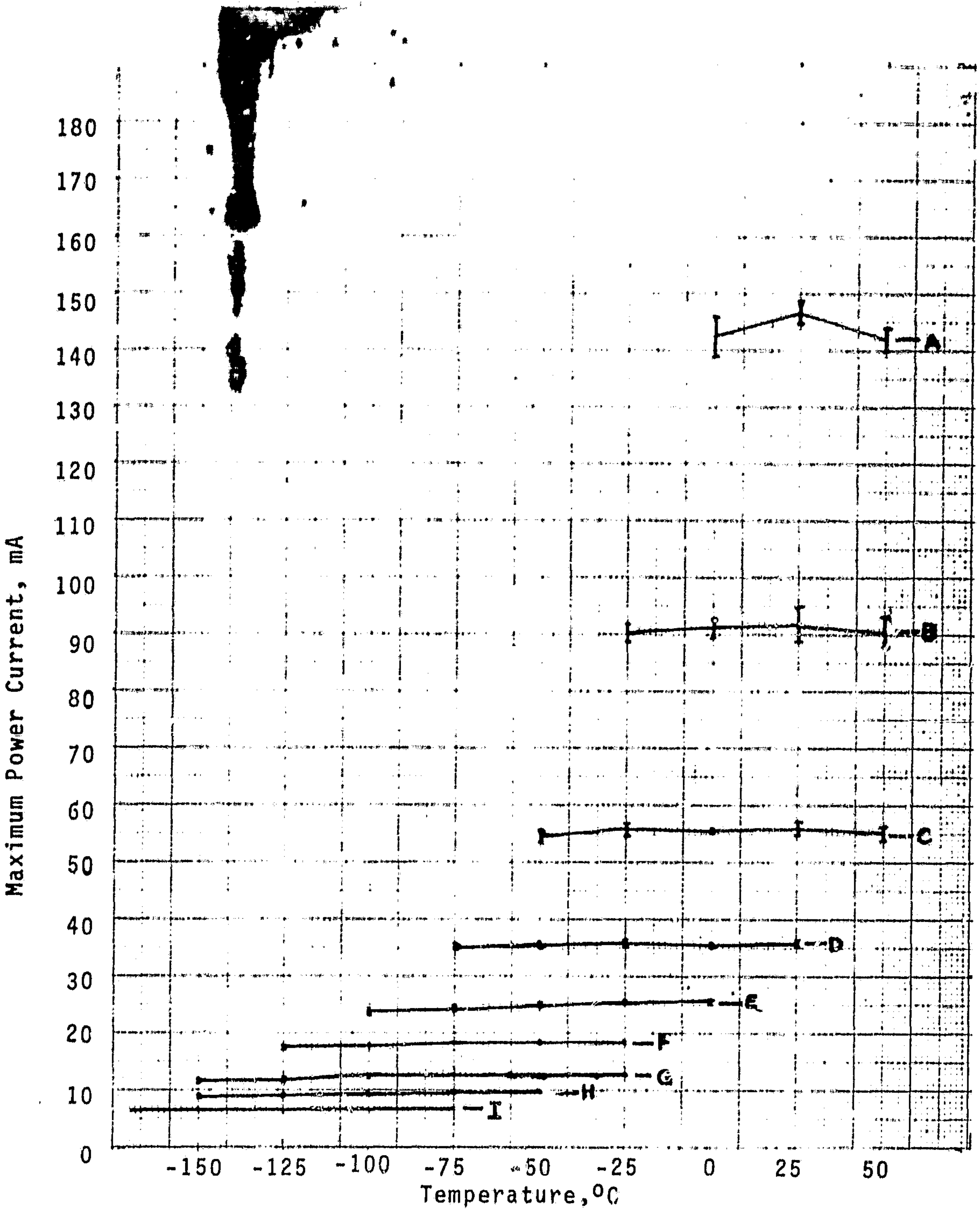


Figure 36. Average V_{oc} as a function of intensity.



ID	SOLAR CONSTANT
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 37. Average I_{mp} as a function of temperature.

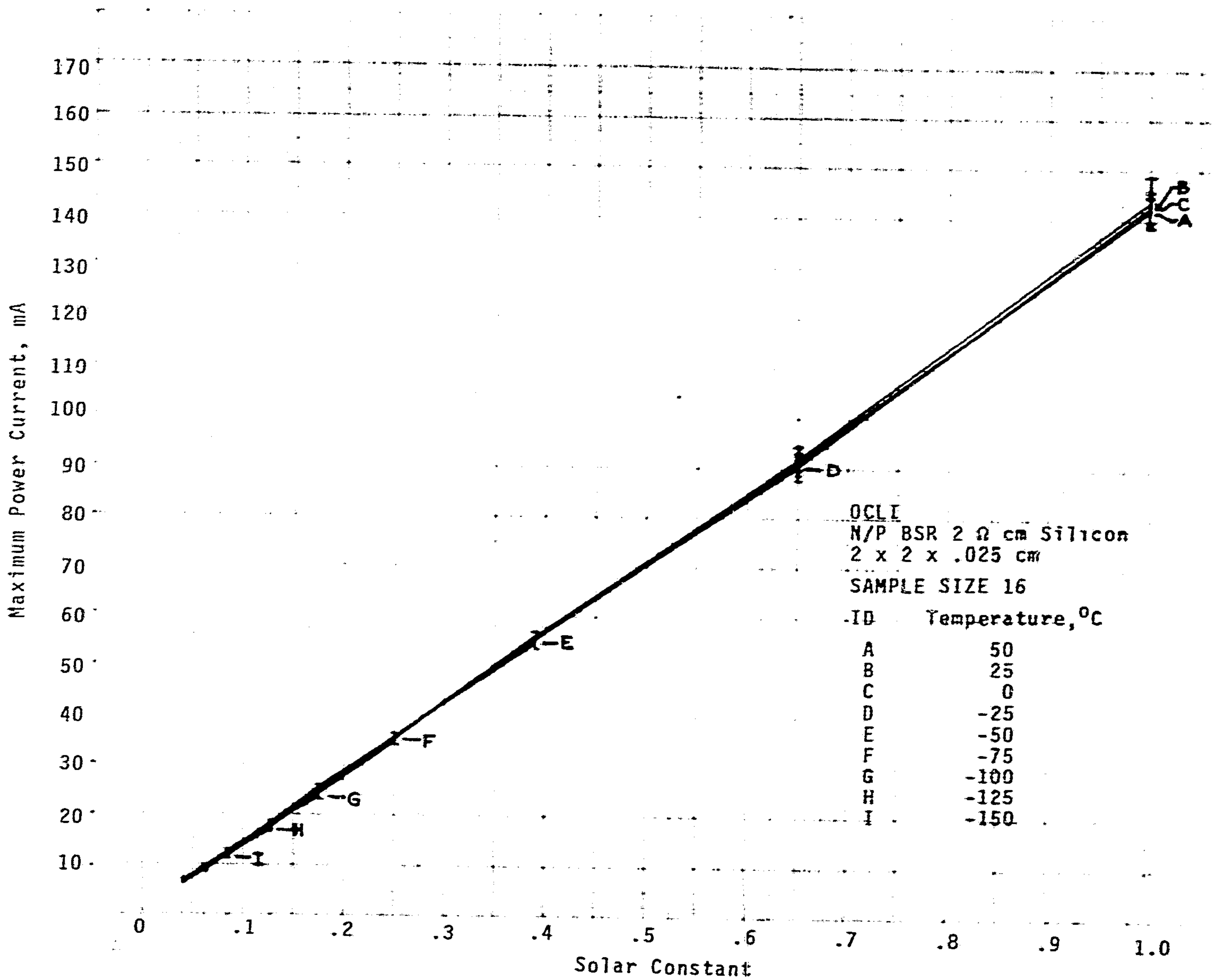
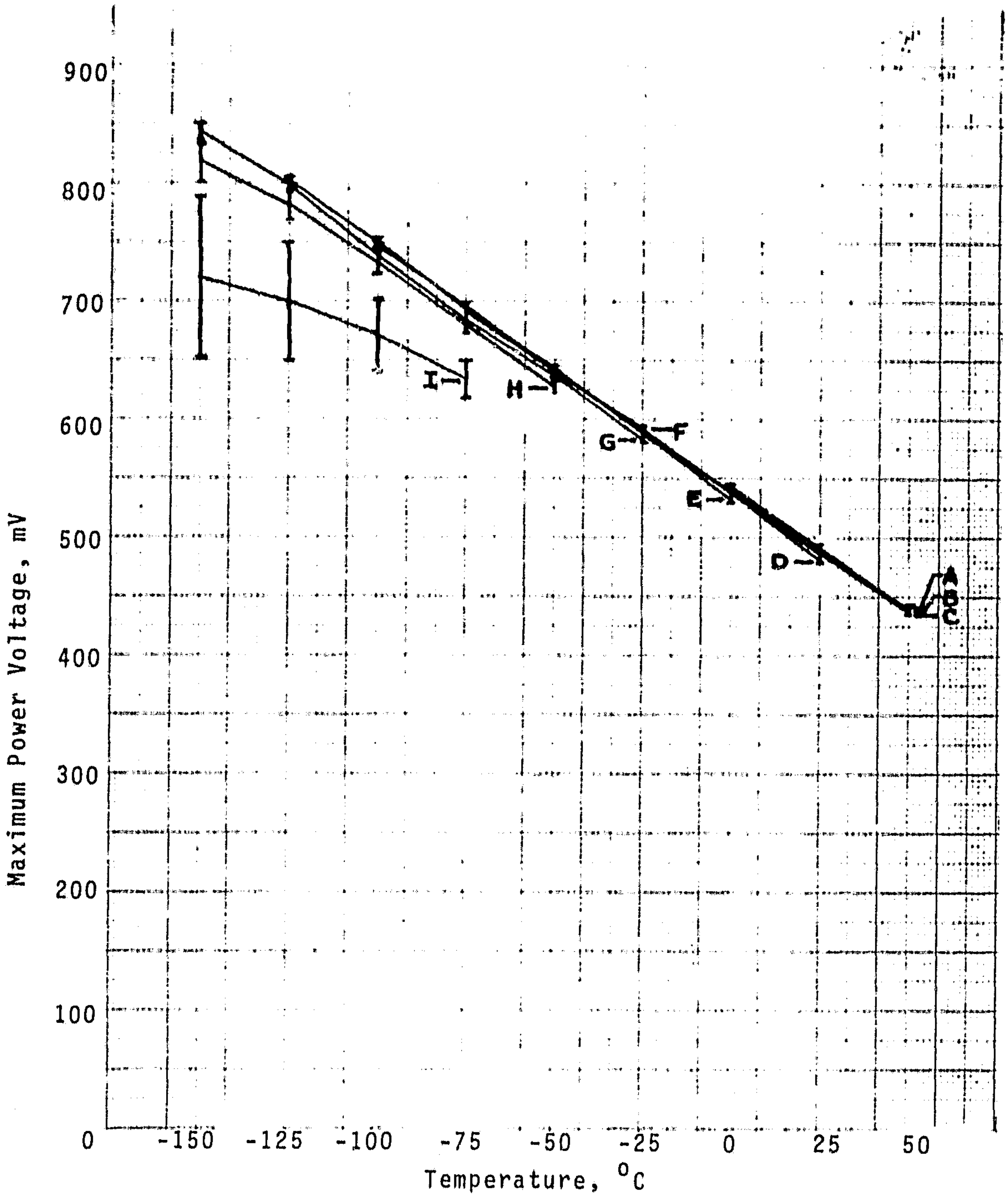


Figure 38. Average I_{mp} as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 2 Ω cm SIlicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 39. Average V_{mp} as a function of temperature.

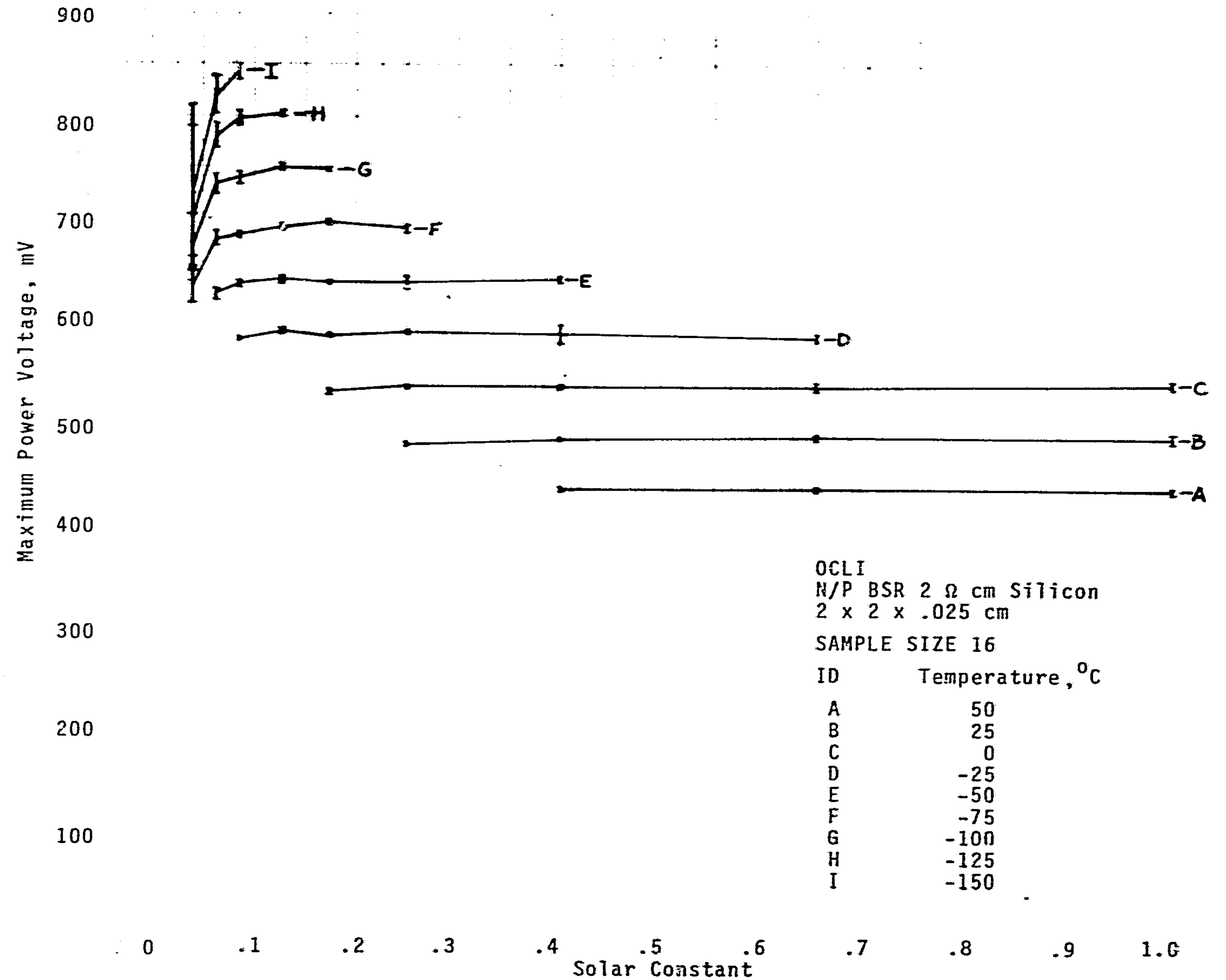
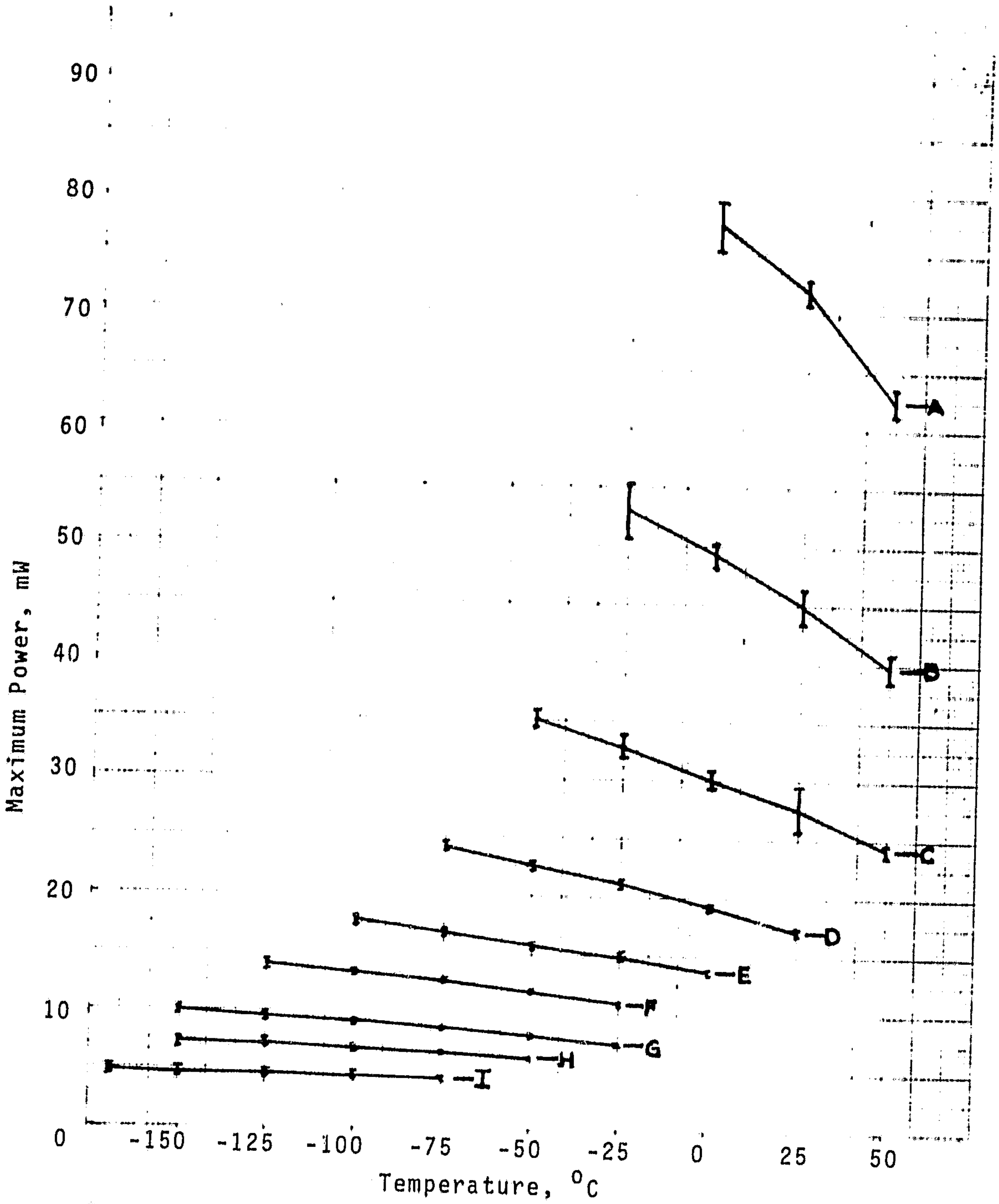


Figure 40. Average V_{mp} as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm
SAMPLE SIZE 16

Figure 41. Average MP as a function of temperature.

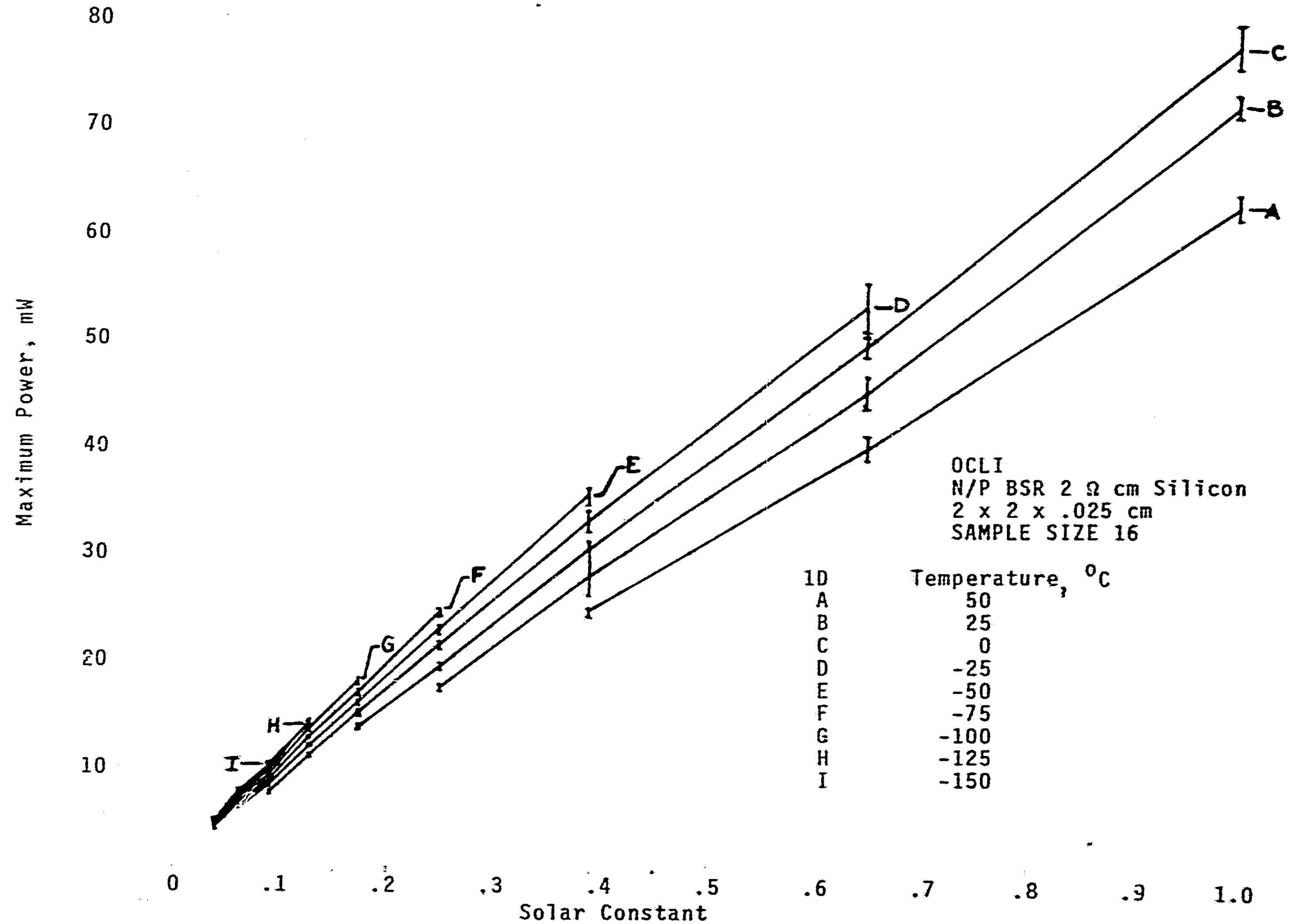
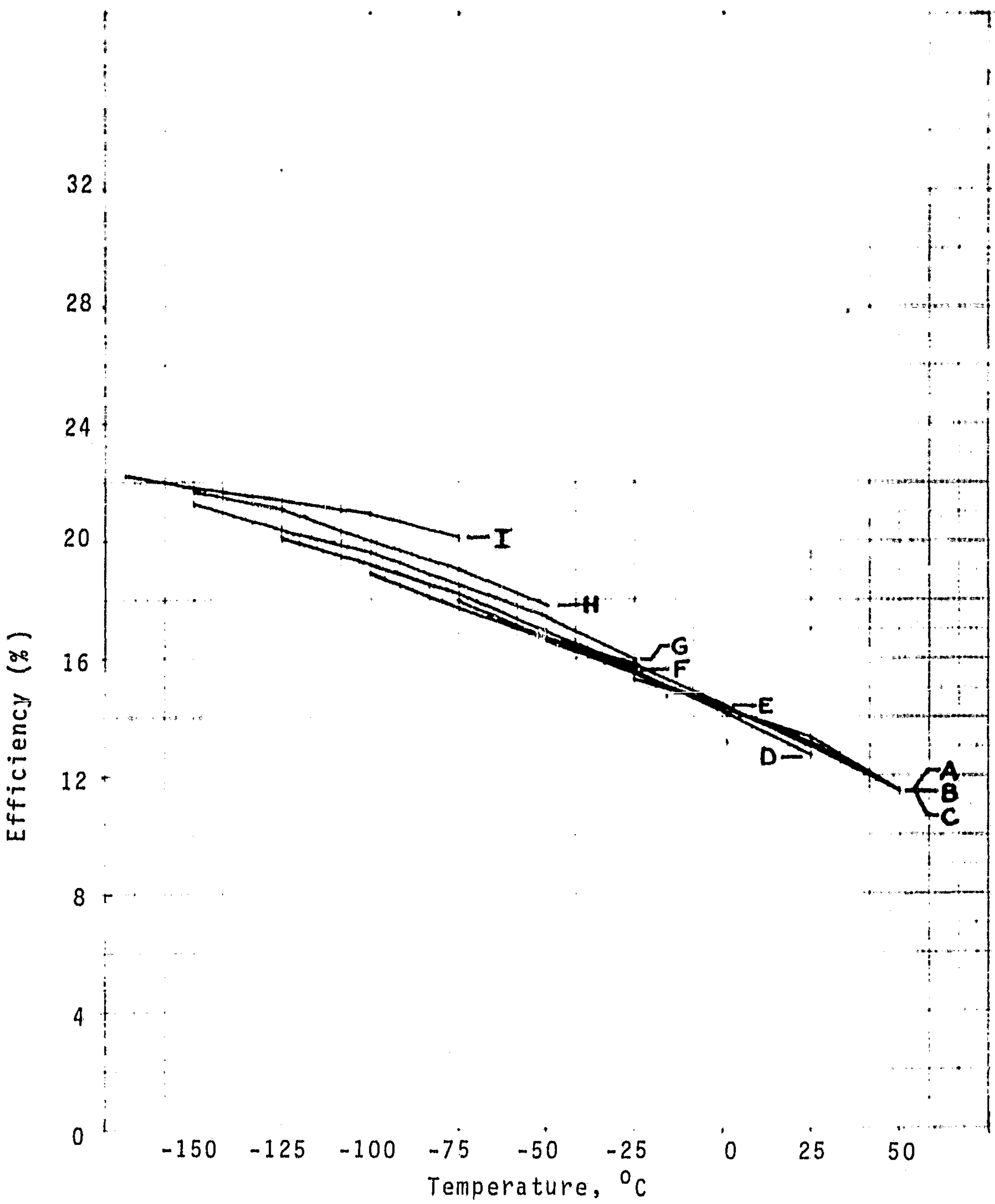


Figure 42. Average MP as a function of intensity.



ID	Solar Constant
A	1.0
B	.64
C	.39
D	.25
E	.174
F	.128
G	.086
H	.063
I	.04

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 43. Average efficiency as a function of temperature.

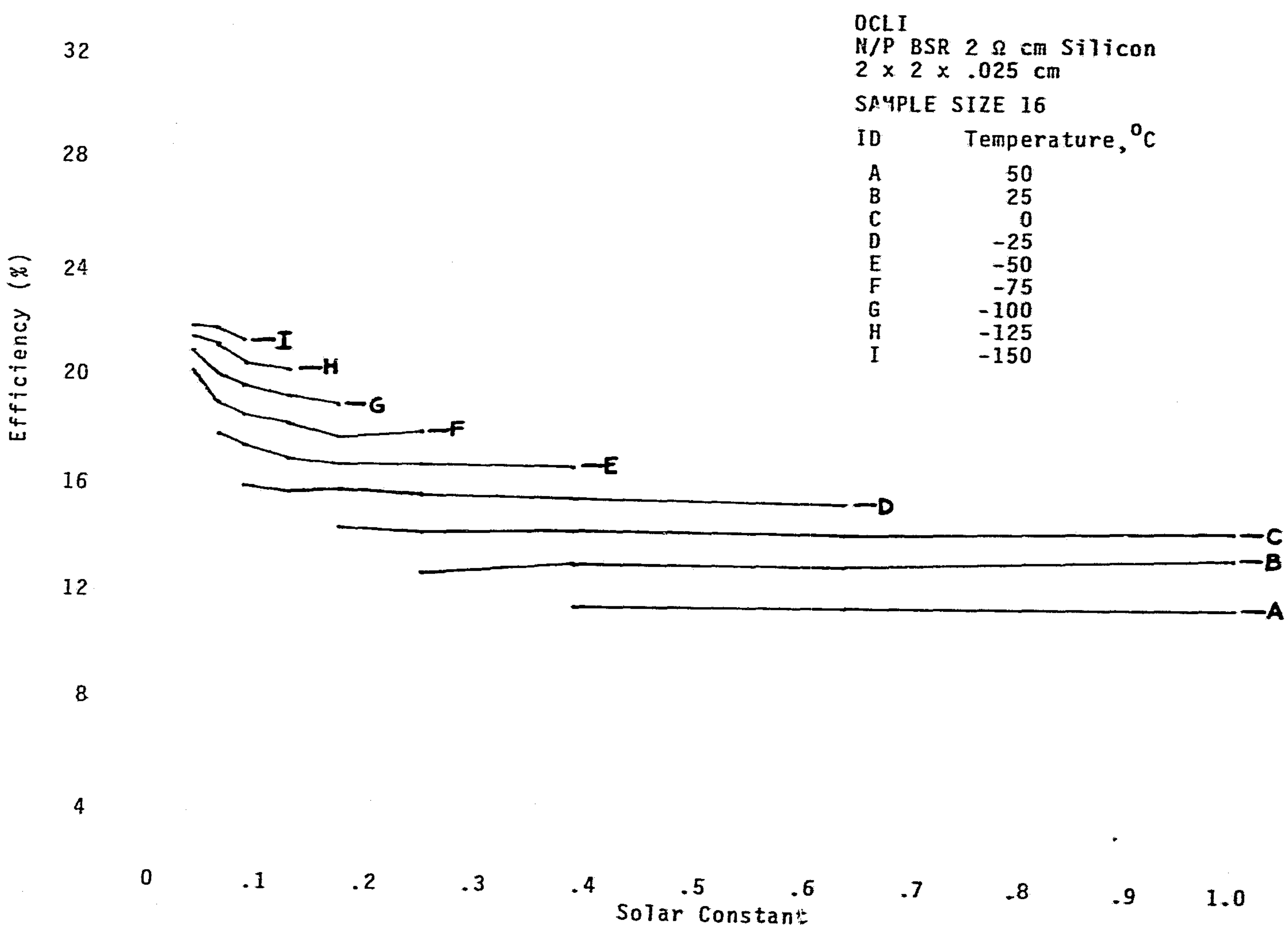
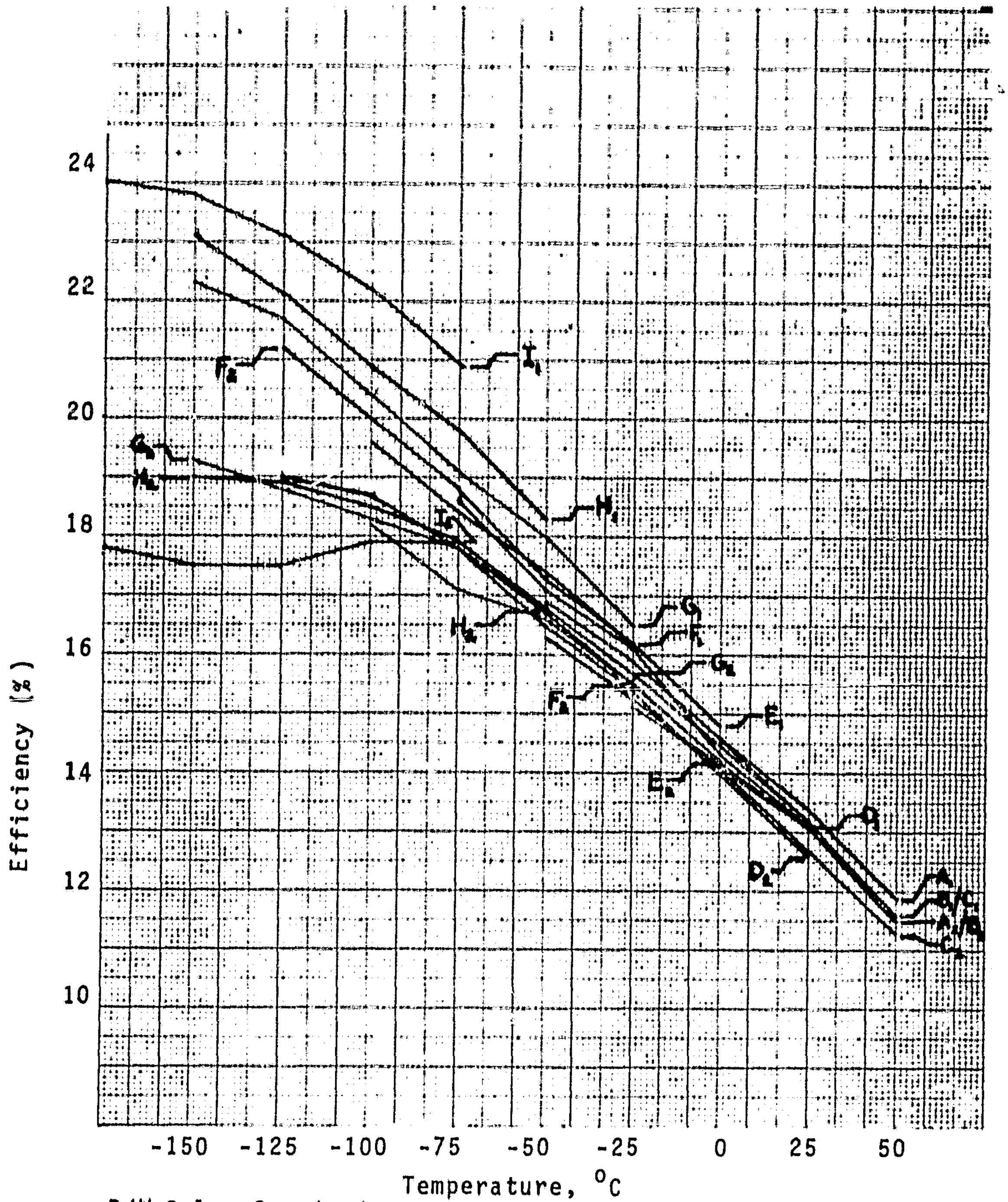


Figure 44. Average efficiency as a function of intensity.



B/W Solar Constant

A_1/A_2	1.0
B_1/B_2	.64
C_1/C_2	.39
D_1/D_2	.25
E_1/E_2	.174
F_1/F_2	.128
G_1/G_2	.086
H_1/H_2	.063
I_1/H_2	.04

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm

SAMPLE SIZE 16

Figure 45. Efficiency of the best/worst cells as a function of temperature.

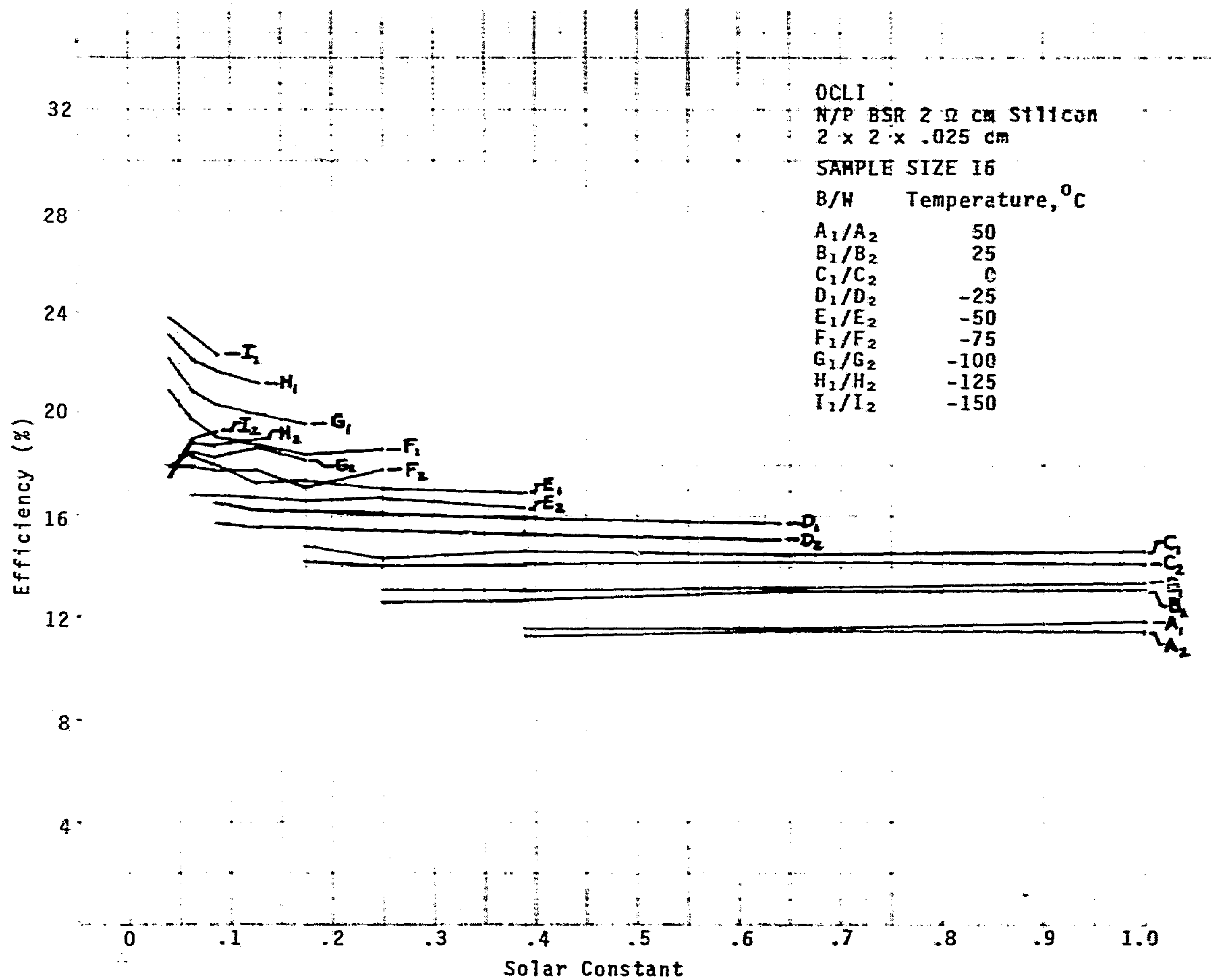


Figure 46. Efficiency of the best/worst cells as a function of intensity.

TABLE 18. AVERAGE I_{sc} (mA)

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50°C	151 (3.0)	95.4 (3.3)	58.3 (1.6)						
25°C	153.3 (2.1)	96.3 (3.8)	58.8 (1.6)	37.5 (.9)					
0°C	149.1 (3.5)	96.3 (2.0)	58.8 (1.6)	37.6 (1.0)	26.5 (.6)				
-25°C		95.7 (1.7)	59.3 (1.5)	37.9 (1.1)	26.5 (.7)	19.2 (.3)	13.7 (.2)		
-50°C			58.3 (1.4)	37.6 (.9)	26.2 (.8)	19.0 (.3)	13.6 (.2)	10.3 (.2)	
-75°C				37.6 (.8)	25.6 (.8)	19.1 (.4)	13.3 (.3)	10.1 (.2)	7.2 (.1)
-100°C					25.7 (.7)	18.8 (.5)	13.1 (.3)	10.0 (.2)	7.2 (.2)
-125°C						18.8 (.5)	12.9 (.3)	9.9 (.3)	7.0 (.2)
-150°C							12.7 (.3)	9.7 (.2)	7.0 (.2)
-170°C									6.8 (.2)

NOTE: Standard Deviations Are Given In Parentheses

TABLE 19. AVERAGE V_{OC} (mV)

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
$50^{o}C$	540.0 (3.7)	529.6 (2.9)	516.1 (2.1)						
$25^{o}C$	595.6 (3.9)	583.9 (3.6)	572.2 (2.1)	558.9 (1.3)					
0^{o}	651.1 (4.1)	641.4 (3.2)	629.7 (2.8)	618.8 (2.3)	609.4 (1.9)				
$-25^{o}C$		696.7 (3.5)	686.1 (2.6)	675.2 (2.5)	666.8 (2.4)	657.6 (1.8)	647.0 (1.5)		
$-50^{o}C$			739.6 (3.1)	729.7 (2.7)	720.8 (3.4)	714.6 (2.6)	704.4 (2.0)	695.9 (1.9)	
$-75^{o}C$				786.0 (3.4)	778.1 (2.7)	771.8 (2.8)	761.9 (2.7)	754.5 (2.1)	740.8 (3.0)
$-100^{o}C$					831.6 (3.1)	826.2 (3.2)	817.0 (3.5)	811.1 (3.2)	797.1 (4.0)
$-125^{o}C$						881.9 (2.7)	874.0 (4.1)	866.6 (3.2)	853.6 (4.8)
$-150^{o}C$							926.3 (3.8)	918.8 (2.9)	907.6 (6.0)
$-170^{o}C$									949.8 (7.5)

NOTE: Standard Deviations Are Given In Parentheses.

TABLE 20. AVERAGE I_{mp} (mA)

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constant								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
50°C	142.1 (2.3)	90.5 (2.7)	55.3 (1.1)						
25°C	146.8 (2.0)	91.8 (2.9)	55.9 (1.2)	35.8 (.6)					
0°C	142.5 (3.6)	91.3 (1.6)	55.9 (1.2)	35.6 (.4)	25.5 (.5)				
-25°C		90.3 (1.7)	55.7 (1.1)	35.8 (.6)	25.4 (.4)	18.3 (.3)	12.7 (.2)		
-50°C			54.6 (1.0)	35.3 (.5)	24.8 (.4)	18.2 (.3)	12.7 (.2)	9.7 (.2)	
-75°C				35.0 (.6)	24.0 (.5)	18.2 (.3)	12.6 (.2)	9.5 (.2)	7.2 (.1)
-100°C					23.8 (.5)	17.7 (.4)	12.3 (.3)	9.3 (.3)	7.2 (.2)
-125°C						17.4 (.5)	11.9 (.5)	9.2 (.4)	7.0 (.2)
-150°C							11.7 (.5)	9.0 (.4)	6.6 (.2)
-170°C									6.5 (.1)

NOTE: Standard Deviations Are Given In Parentheses.

TABLE 21. AVERAGE V_{mp} (mV)

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
$50^{o}C$	439.1 (3.4)	438.8 (1.7)	437.1 (1.7)						
$25^{o}C$	490 (4.6)	489.3 (3.6)	486.4 (1.3)	481.5 (1.8)					
$0^{o}C$	543.3 (4.0)	539.8 (3.6)	538.6 (2.9)	537.9 (1.8)	533.0 (3.0)				
$-25^{o}C$		587.3 (4.8)	589.9 (9.0)	590.7 (2.6)	587.3 (2.1)	591.5 (3.4)	583.3 (2.0)		
$-50^{o}C$			642.6 (3.5)	639.2 (6.7)	639.2 (1.5)	642.1 (3.2)	637.9 (2.6)	627.5 (4.8)	
$-75^{o}C$				691.8 (3.9)	696.9 (2.8)	692.8 (3.3)	684.4 (3.2)	681.9 (7.2)	634.6 (16.8)
$-100^{o}C$					747.4 (2.3)	750.0 (3.9)	739.4 (5.8)	733.3 (10.1)	671.4 (31.6)
$-125^{o}C$						803.3 (3.2)	799.1 (7.1)	782.8 (12.3)	700.62 (50.6)
$-150^{o}C$							843.3 (7.8)	819.8 (18.7)	721.6 (69.0)
$-170^{o}C$									739.2 (72.8)

NOTE: Standard Deviations Are Given In Parentheses

TABLE 22. AVERAGE MP (mW)

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
$50^{o}C$	62.4 (1.2)	39.7 (1.2)	24.2 (.5)						
$25^{o}C$	71.8 (1.1)	44.9 (1.5)	27.6 (1.9)	17.2 (.3)					
$0^{o}C$	77.4 (2.1)	49.3 (1.6)	30.1 (.7)	19.2 (1.3)	13.6 (.2)				
$-25^{o}C$		52.9 (2.4)	32.8 (.9)	21.1 (.4)	14.9 (.3)	10.8 (.2)	7.4 (.1)		
$-50^{o}C$			35.1 (.7)	22.6 (.4)	15.7 (.3)	11.7 (.1)	8.1 (.2)	6.1 (.1)	
$-75^{o}C$				24.2 (.4)	16.7 (.4)	12.6 (.2)	8.6 (.2)	6.5 (.2)	4.3 (.2)
$-100^{o}C$					17.8 (.4)	13.3 (.3)	9.1 (.3)	6.8 (.3)	4.5 (.2)
$-125^{o}C$						13.9 (.4)	9.5 (.4)	7.2 (.4)	4.6 (.4)
$-150^{o}C$							9.9 (.5)	7.4 (.5)	4.7 (.5)
$-170^{o}C$									4.8 (.6)

NOTE: Standard Deviations Are Given in Parentheses.

TABLE 23. AVERAGE EFFICIENCY (%)

OCLI
N/P BSR 2 Ω cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 3/15 Lines
Multilayer (blue) AR Coating
FS Cover 0.35 μ Cut-on
(.300 μm thick)

SAMPLE SIZE 16

Temperature	Solar Constants								
	1	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.04
$50^{o}C$	11.5	11.5	11.5						
$25^{o}C$	13.3	13.0	13.1	12.7					
$0^{o}C$	14.3	14.2	14.3	14.2	14.4				
$-25^{o}C$		15.3	15.5	15.6	15.8	15.7	15.9		
$-50^{o}C$			16.6	16.7	16.7	16.9	17.4	17.8	
$-75^{o}C$				17.9	17.7	18.2	18.5	19.0	20.0
$-100^{o}C$					18.9	19.2	19.6	20.0	20.9
$-125^{o}C$						20.1	20.4	21.1	21.4
$-150^{o}C$							21.3	21.7	21.8
$-170^{o}C$									22.2

Two Terminal Silicon Solar Cell

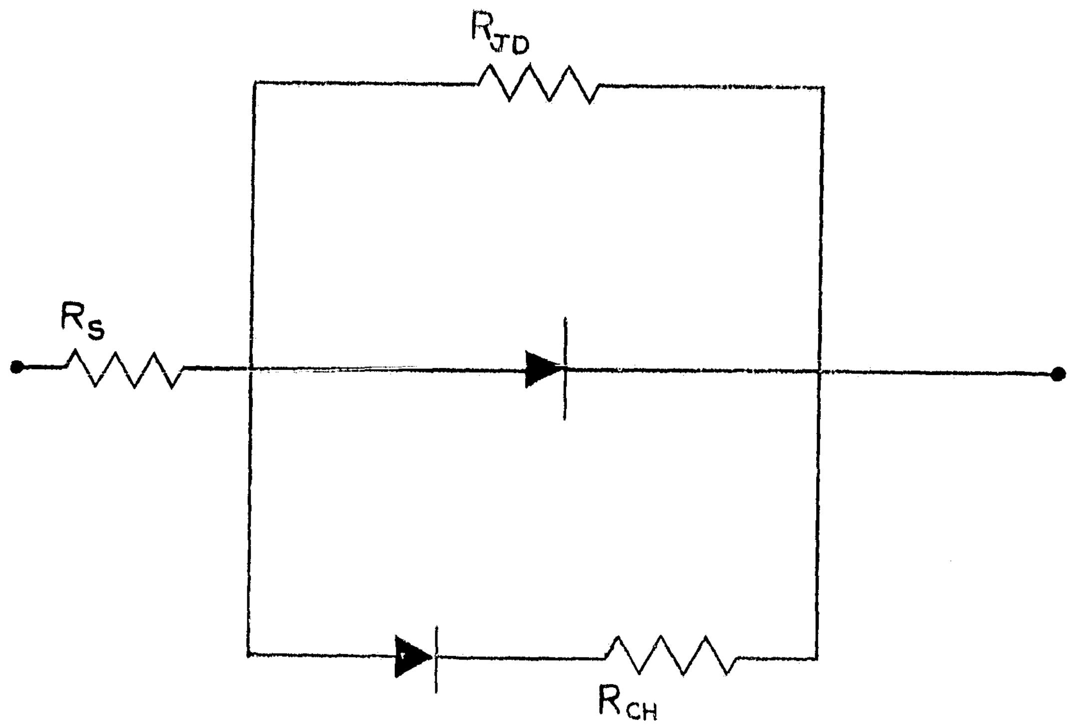


Figure 47. Simplified equivalent circuit of a silicon solar cell.

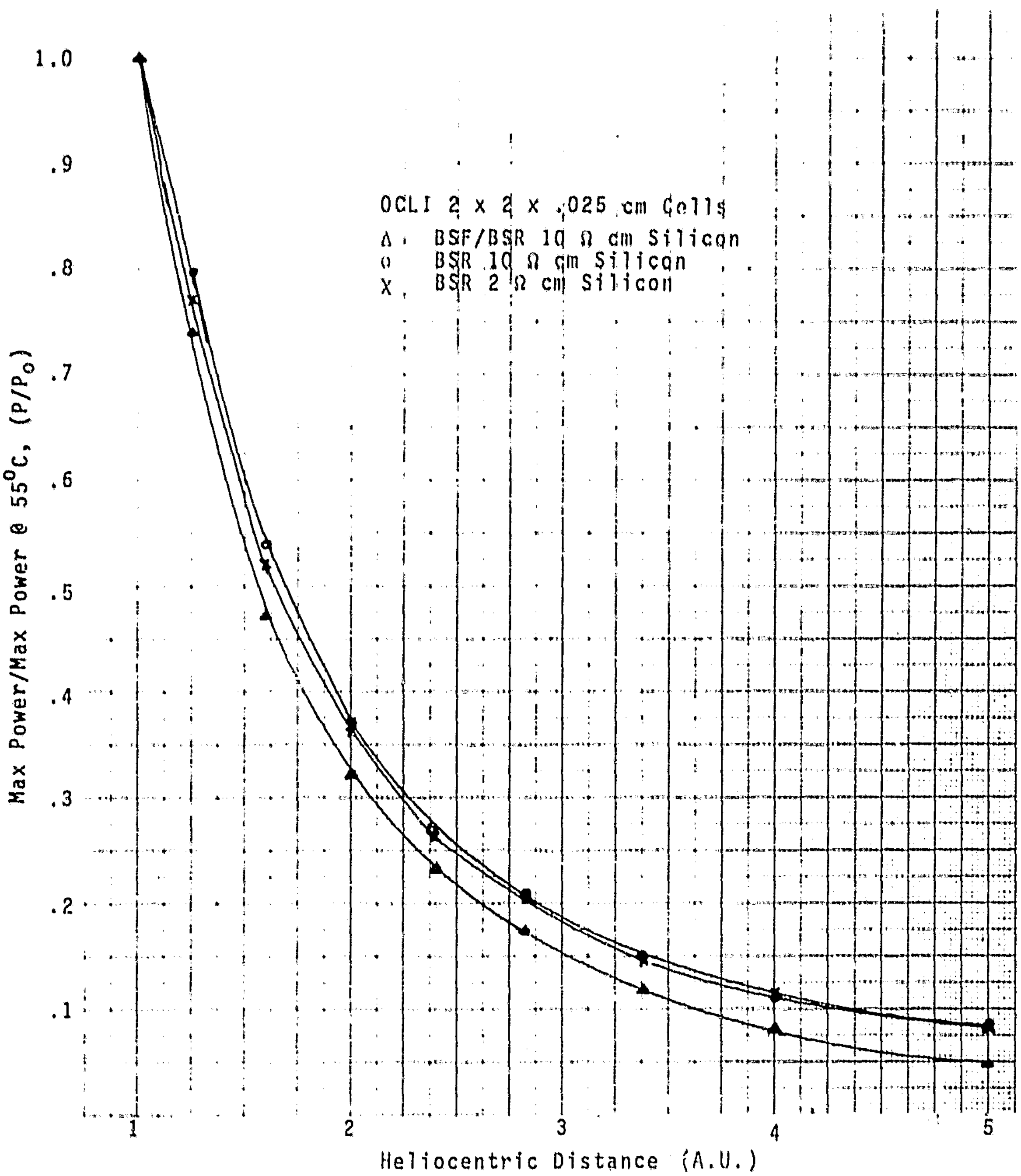


Figure 48. P/P$_o$ as a function of heliocentric distance.

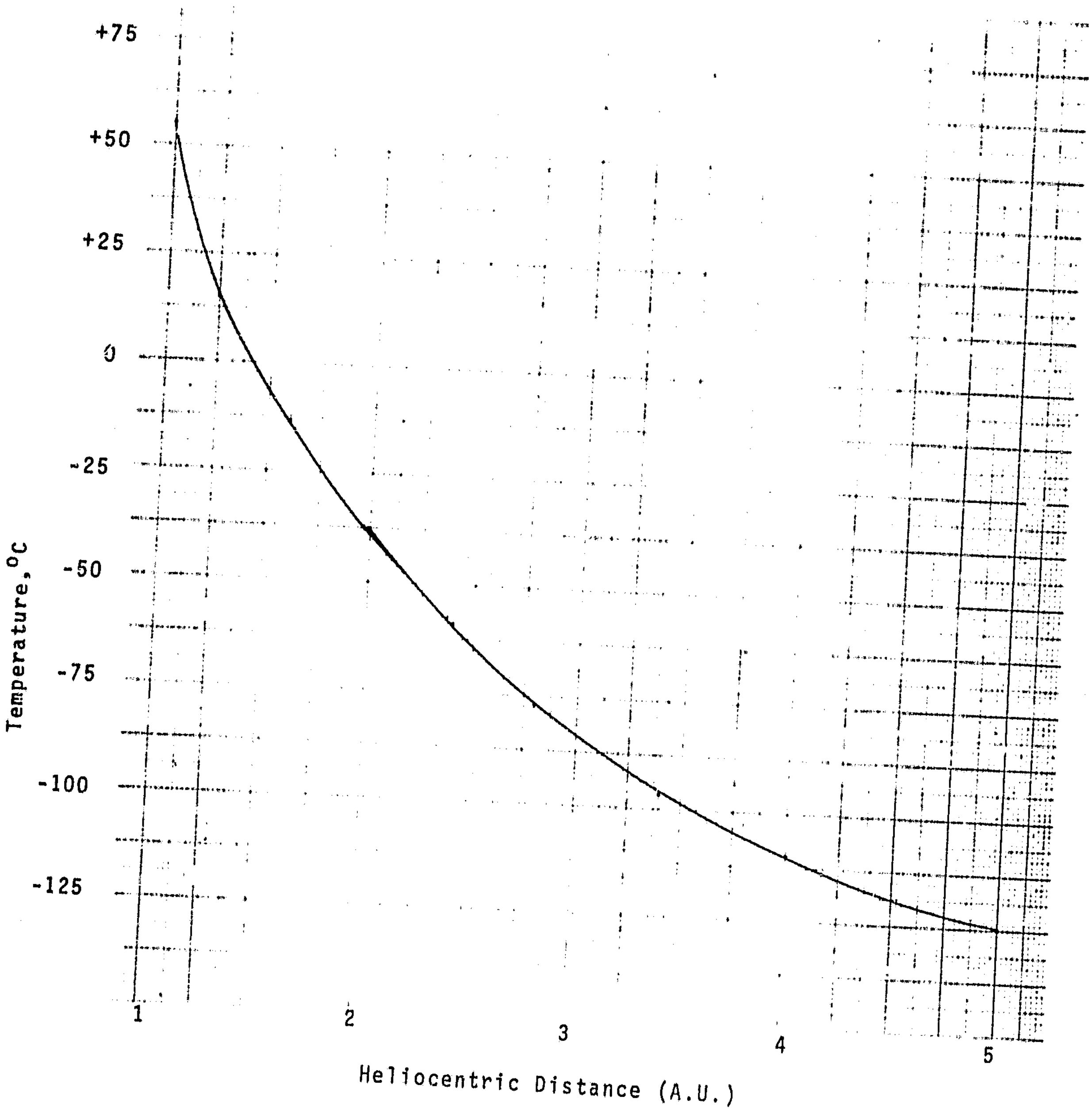


Figure 49. Solar array temperature versus AU.

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GLOSSARY

AU	Astronomical Unit
AM0	Air Mass Zero
BSF	Back Surface Field
BSR	Back Surface Reflector
I_{mp}	Maximum Power Current
I_{sc}	Short Circuit Current
LTLI	Low Temperature and Low Intensity
MP	Maximum Power
P/P_o	Ratio of Maximum Power to Maximum Power at 55°C
R_{CH}	Edge Channel Resistance
R_{JD}	Shunt Resistance
R_S	Series Resistance
SEPS	Solar Electric Propulsion System
SC	Solar Constant
UV	Ultraviolet

APPROVAL

CHARACTERIZATION OF THREE TYPES OF SILICON SOLAR CELLS FOR SEPS DEEP SPACE MISSIONS

Volume I. Current-Voltage Characteristics of OCLI BSF/BSR 10 ohm-cm, BSR 10 ohm-cm, and BSR 2 ohm-cm Cells as a Function of Temperature and Intensity

By A. F. Whitaker, S. A. Little, C. F. Smith Jr., and V. A. Wooden

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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