JPL PUBLICATION 78-15, VOLUME VIII

Characterization of Solar Cells for Space Applications

Volume VIII. Electrical Characteristics of Spectrolab BSF, BSR, Textured 290-Micron Solar Cells (K7) as a Function of Intensity, Temperature and Irradiation

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September 1, 1979

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ACKNOWLEDGMENT

The authors gratefully acknowledge the invaluable assistance of Lois Fite and James Hix, who wrote the computer programs for performing the data analysis and curve plotting, and Diane Engler, who operates the program and produces the plots.

ABSTRACT

Electrical characteristics of Spectrolab textured, back-surface-field back-surface-reflector, 2 x 4 x 0.029 cm N/P silicon solar cells (K7) are presented in graphical and tabular format as a function of solar illumination intensity, temperature and irradiation.

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SECTION I

INTRODUCTION

A series of reports is being generated to present parametric characterization data on both state-of-the-art and developmental solar cells of interest to the photovoltaic community. These data consist of the electrical characteristics of the candidate solar cell under a wide range of temperature and illumination intensity combinations of the type encountered in typical space applications. This series (JPL Publication 78-15) consists of a number of reports, each report being devoted to a particular type of solar cell and identified by a volume number. Previously published reports with their associated solar cell descriptions are listed in the bibliography. Each report consists primarily of working graphs and tables and does not address itself to interpretive conclusions. The formating of this series of reports is relatively invariant to facilitate comparisons between the characteristics of any of the cell types considered in the series. This report contains a set of parametric data on the Spectrolab textured, back-surface-field, back-surface-reflector solar cell which is a commercially available product.

SECTION II

CELL DESCRIPTION

The cells reported here were manufactured by Spectrolab and are available as off-the-shelf space-qualified solar cells. These cells are fabricated from crucible-grown P-type silicon, boron-doped to a nominal resistivity of 10 ohm-cm. The cell dimensions are 2 x 4 x 0.029 cm (11 mils) thick. A back surface field is added by alloying a layer of evaporated aluminum into the back of the cell. The electrical contact on the top surface consists of solderless Ti-Pd-Ag in a 48-finger grid pattern with a bus bar running the length of the long side. The rear contact is Al-Ti-Pd-Ag. The antireflectance coating is Ta_2O_5. No cover slides were used on this test plate.

SECTION III

TEST PROGRAM

The solar cells were mounted on a copper test plate using RTV 560. The test plate was in turn mounted to a heat sink with provisions for both heating and cooling so that the cells could be maintained at the desired temperature, independent of the solar intensity. All testing was carried out in vacuum at a pressure of less than 1×10^{-6} torr.

The illumination source used was a Spectrolab Model X-25 Mark II Spectrosun filtered solar simulator. This simulator uses an optical integrator lens in the optical system which uniformly distributes a relatively collimated light beam at specific distances from a 2.5-kW short-arc xenon lamp. A system of filters modifies the spectral distribution so that it approximates that of space sunlight. The light beam provides a pattern having a uniformity of ±1% over an area of 225 cm^2 at the test plane. Illumination intensity is varied by position of the simulator in combination with transmission filters. The solar simulator beam is introduced into the vacuum chamber through a window of 7940 fused silica. The solar intensity and spectral integrity of the solar simulator are constantly monitored and maintained using space-calibrated standard cells obtained with the NASA/JPL solar cell balloon flight standardization program. Photographs of the solar cell, the assembled plate, and the experimental characterization test facility are shown in Figs. A-1 through A-4 in the appendix.

The temperature range covered in these measurements was -160 to 140°C, while the solar intensity range covered was 5 to 250 mW/cm^2. The data were taken at each environment point in the matrix in the form of an I-V curve. The appropriate parameters were then read from the I-V curves and punched on cards for the computer analysis and curve plotting functions. The cell temperature was monitored by a thermocouple attached to the surface of a separate cell mounted with the cells under test. Prior, intermediate and post-test ambient measurements were performed daily to insure that the accuracy and stability of the test equipment and the test specimens themselves were maintained within ±2% during the course of the testing program.

After making the solar cell measurements over the above temperature and intensity ranges, the test plate was mounted in the evacuated target chamber of the JPL Dynamitron electron accelerator and irradiated with electron fluences ranging from 5×10^{12} to 2×10^{15} e/cm^2. During the irradiation the cells were maintained at 28°C. I-V curves of the solar cells were measured in situ before and after each irradiation using an Aerospace Controls Model 302 filtered xenon AMO solar simulator. In addition, after the cumulative fluence reached 10^{14} e/cm^2, the solar cells were annealed for approximately 16 hours at 60°C after each irradiation, then remeasured. The results of solar cell electrical characteristics, as a function of electron fluence, are shown in Figures 19 through 23. Annealed cell data is used in the plots.

SECTION IV

DISCUSSION OF RESULTS

A computer program computes statistical averages and standard deviations with respect to the measured cells for each intensity-temperature measurement condition. It then produces summary tables, as shown in Tables 1 to 7, that display averages and standard deviations of the cell characteristics in a two-dimensional array format, one dimension representing cell temperature and the second dimension representing

incoming light intensity (AMO spectrum), The program then produces plots of the various electrical parameters of interest, with either incident intensity or cell temperature as the independent variable, as shown in Figs. 1 to 14. Least square fits to the data points are then made automatically to the measured data points using a second-degree polynominal for most parameters. The curve factors, AMO efficiencies, V_{oc} and V_{mp} data points are not fit but interconnected from point to point. In addition, the program calculates the temperature coefficients of the pertinent cell electrical parameters of interest, using the aforementioned curve fits, and plots these as a function of temperature, with intensity as a parameter, as shown in Figs. 15 through 18.

The figures are intended to be working artifacts; that is, they are formatted in such a way that they can supply information of a general nature or may be used to generate predictions, comparisons, computer input data, etc. To facilitate comparisons and inputting, all units are standardized as follows:

(1) All currents are in units of mA/cm^2.

(2) All voltages are in units of mV.

(3) All power outputs are in units of mW/cm^2.

(4) All curve factors are in dimensionless units.

(5) All efficiencies are in percentages and are based on total cell area.

(6) All temperatures are in ^oC.

(7) All incoming intensities are in units of mW/cm^2 and are representative of an AMO spectrum.

(8) All geometric dimensions are in units of cm or μm (whichever is most convenient conceptually).

The tables included in this report contain complete numerical information with respect to the average values of the following solar cell electrical parameters: I_{sc}, V_{oc}, IP_{max}, P_{max}, CF, and efficiency at each intensity-temperature combination. For each such parameter at each such intensity-temperature combination, the standard deviation is presented to provide estimates of statistical validity. All efficiency, current, and power output data is on the basis of unit area derived by dividing measured output by total cell area.

The Spectrolab K7 type of solar cell is a commercially available cell which is used for space applications. Other space-qualified solar cells in the K series included such features as polished surfaces, back surface reflectors, and other thicknesses. These other types of K cells will be tested and reported in the future.

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Characterization of Solar Cells for Space Applications, JPL Publication 78-15

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Volume II. Electrical Characteristics of Solarex 50 Micron Solar Cells as a Function of Intensity and Temperature, August 1978.

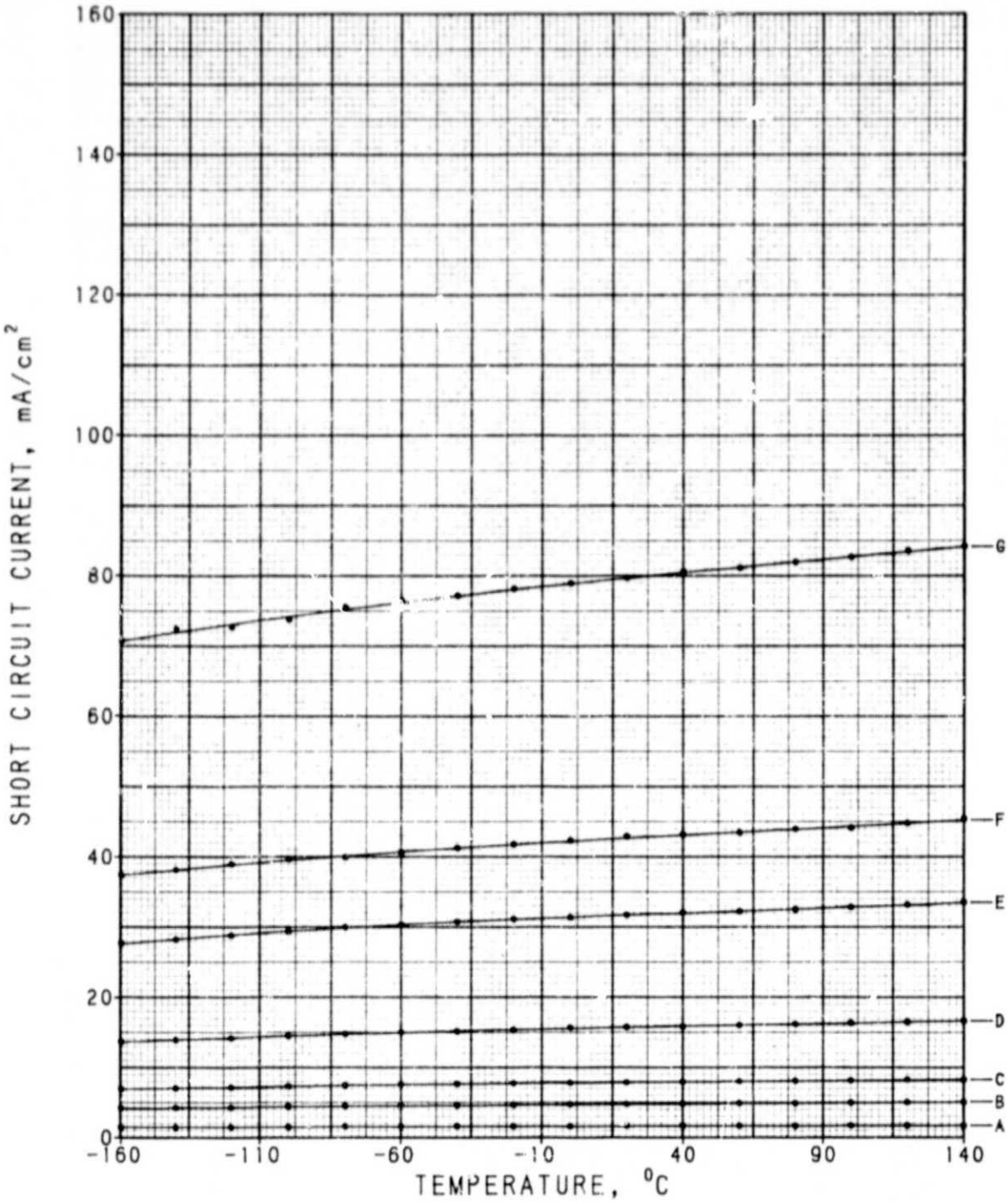
Volume III. Electrical Characteristics of OCLI Hybrid MLAR Solar Cells as a Function of Intensity and Temperature, September 1978.

Volume IV. Electrical Characteristics of Spectrolab 200-Micron Helios Solar Cells as a Function of Intensity and Temperature, November 1, 1978.

Volume V. Electrical Characteristics of OCLI 225-Micron MLAR Wrap-around Solar Cells as a Function of Intensity, Temperature, and Irradiation, April 1979.

Volume VI. Electrical Characteristics of Spectrolab BSF, BSR, Textured, 10Ω-cm 50-Micron Advanced OAST Solar Cells as a Function of Intensity, Temperature and Irradiation, June 1979.

Volume VII. Electrical Characteristics of Spectrolab HEWAC BSF, Textured, 10Ω-cm, 225-Micron Solar Cells as a Function of Intensity and Temperature, June 1979.



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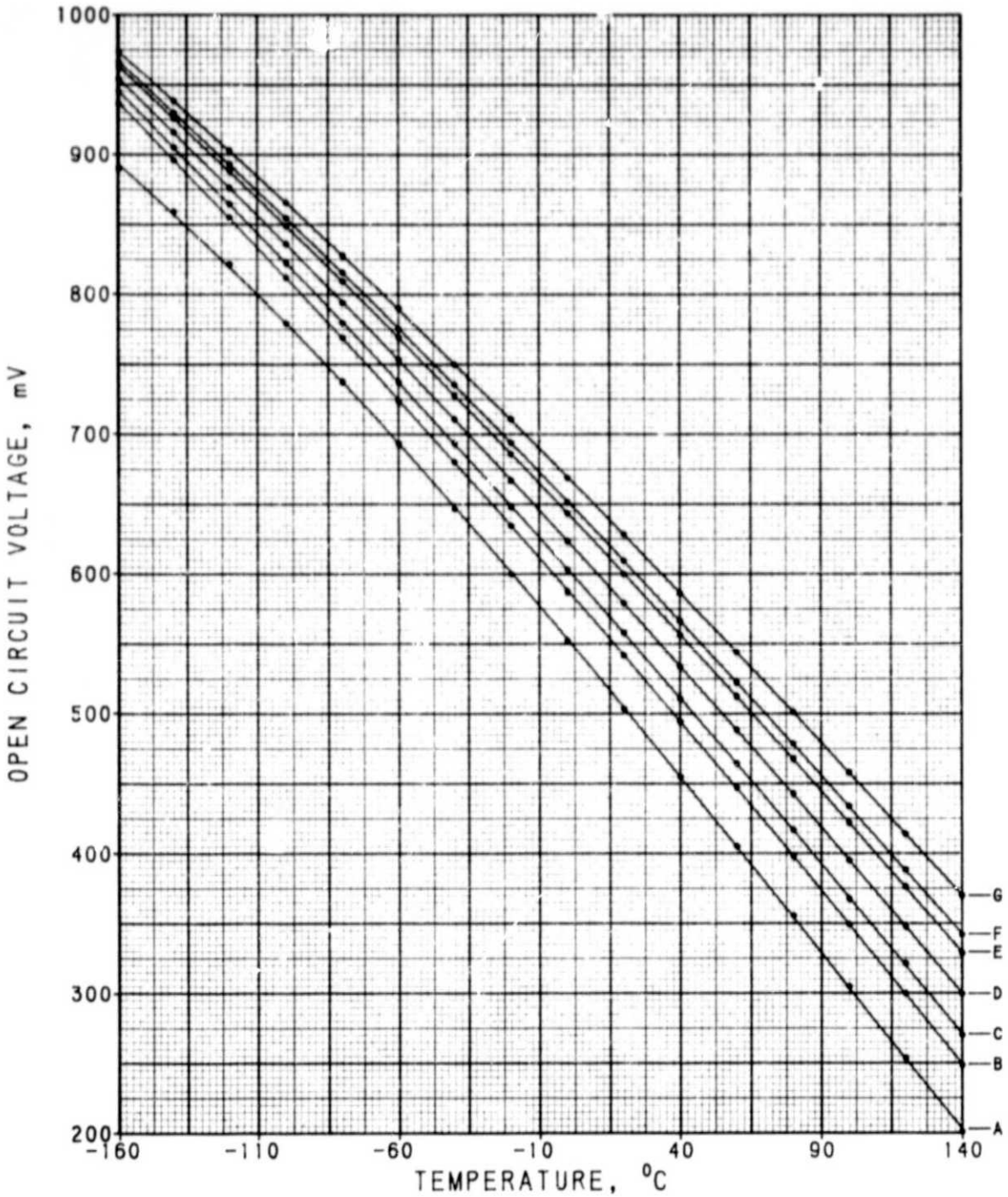
A	5.0
B	15.0
C	25.0
D	50.0
E	100.0
F	135.3
G	250.0

SPECTROLAB TEXTURED, BSF, BSR
N/P 10 OHM-CM CG SILICON
2 X 4 X .029 CM
AL-TI-PD-AG BACK CONTACT
TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8

Figure 1. Average I_{sc}/cm^2 as a Function of Temperature



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B	15.0
C	25.0
D	50.0
E	100.0
F	135.3
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TA2O5 AR COATING
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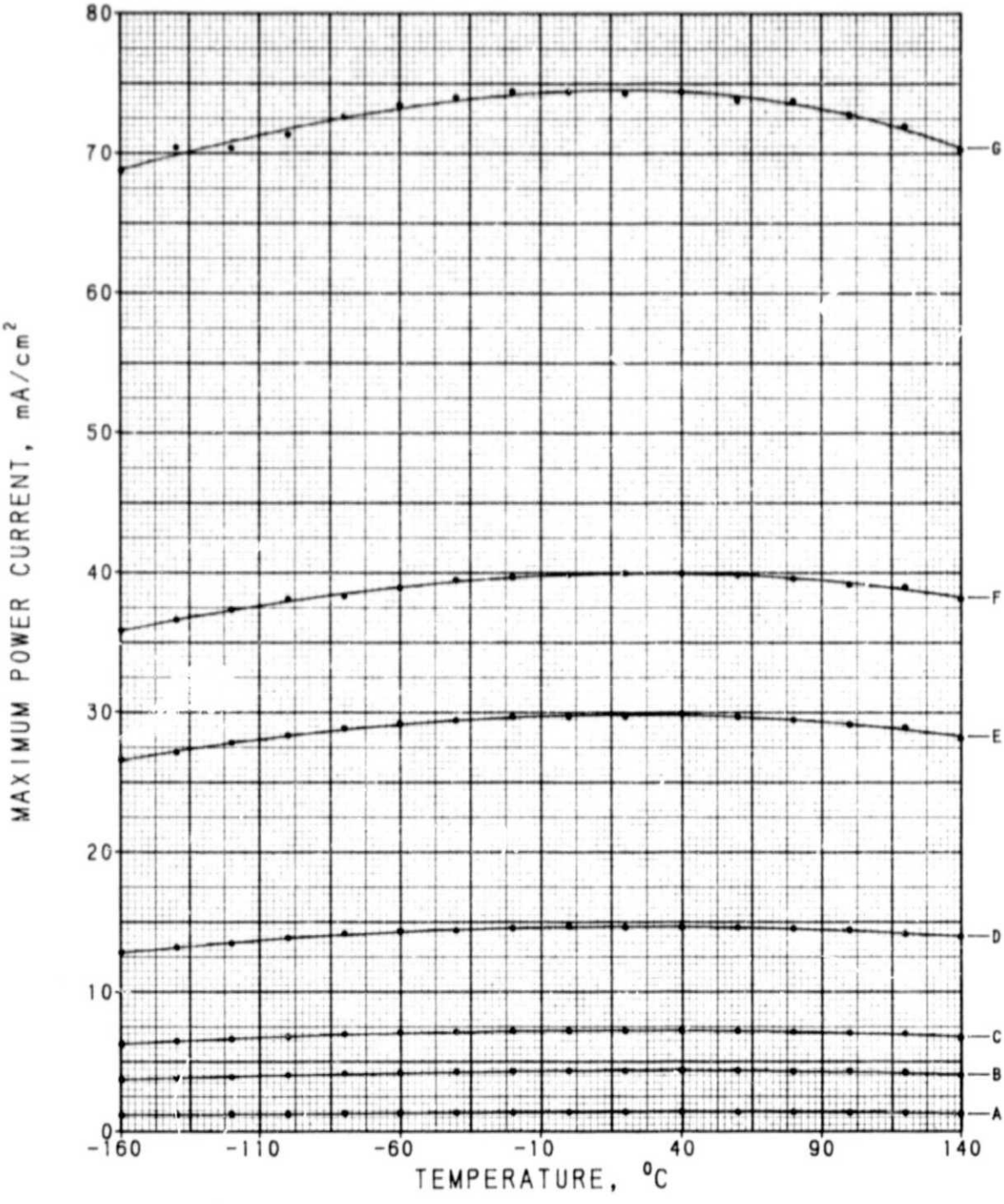
SAMPLE SIZE 8

Figure 2. Average V_{OC} as a Function of Temperature



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C	25.0
D	50.0
E	100.0
F	135.3
G	250.0

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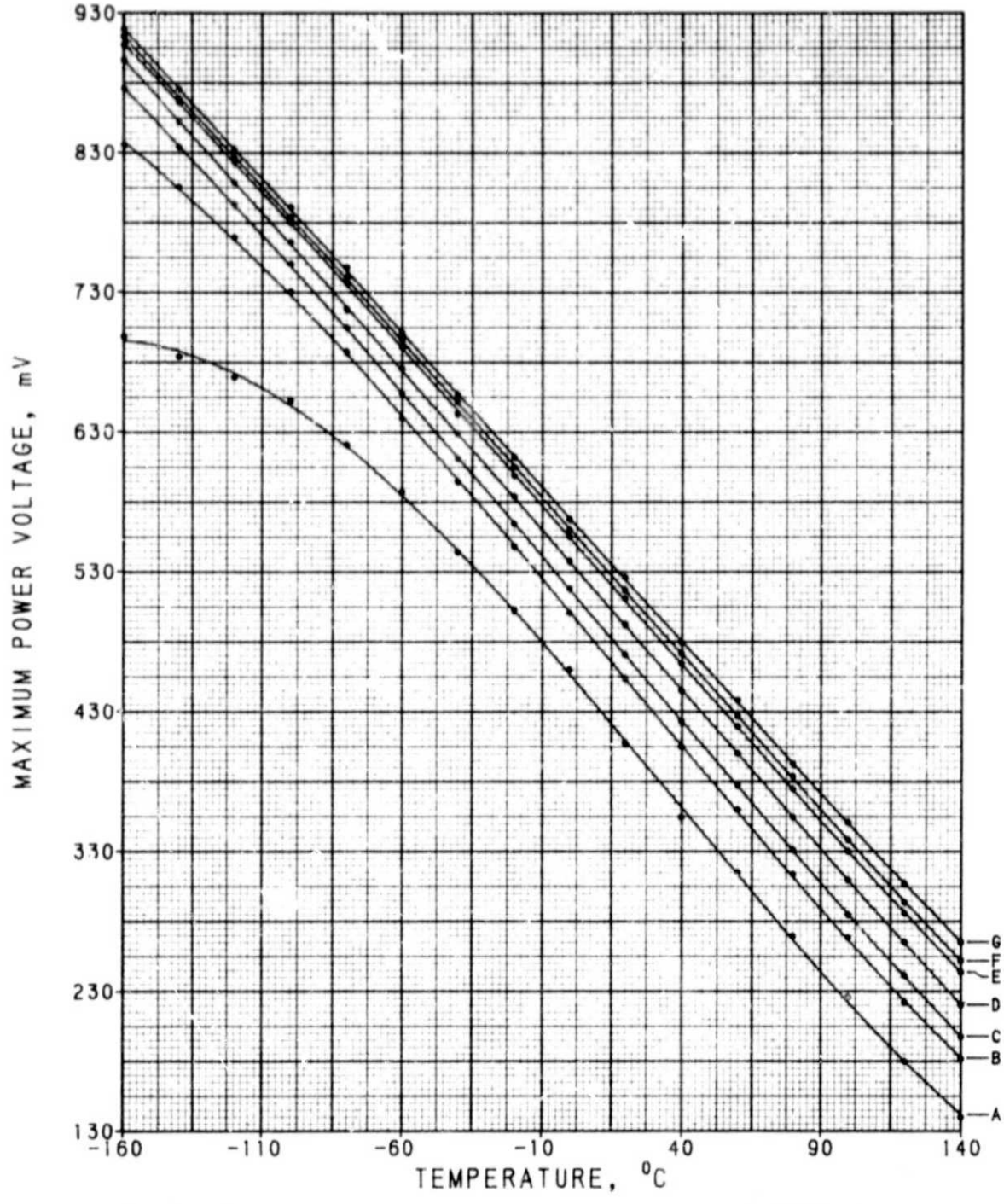
Figure 3. Average I_{mp}/cm^2 as a Function of Temperature



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B	15.0
C	25.0
D	50.0
E	100.0
F	135.3
G	250.0

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TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
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Figure 4. Average V_{mp} as a Function of Temperature

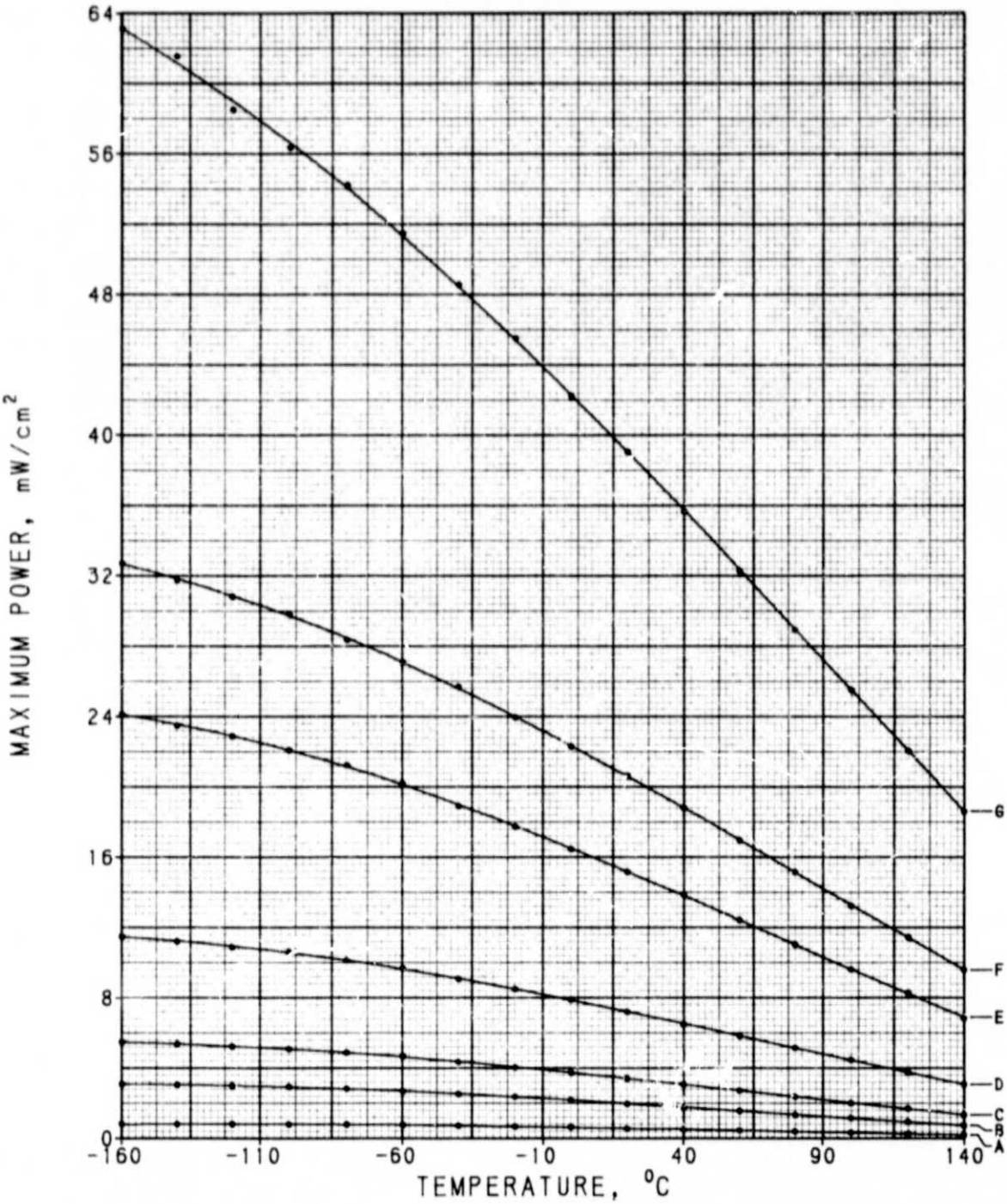


Figure 5. Average P_{max}/cm^2 as a Function of Temperature

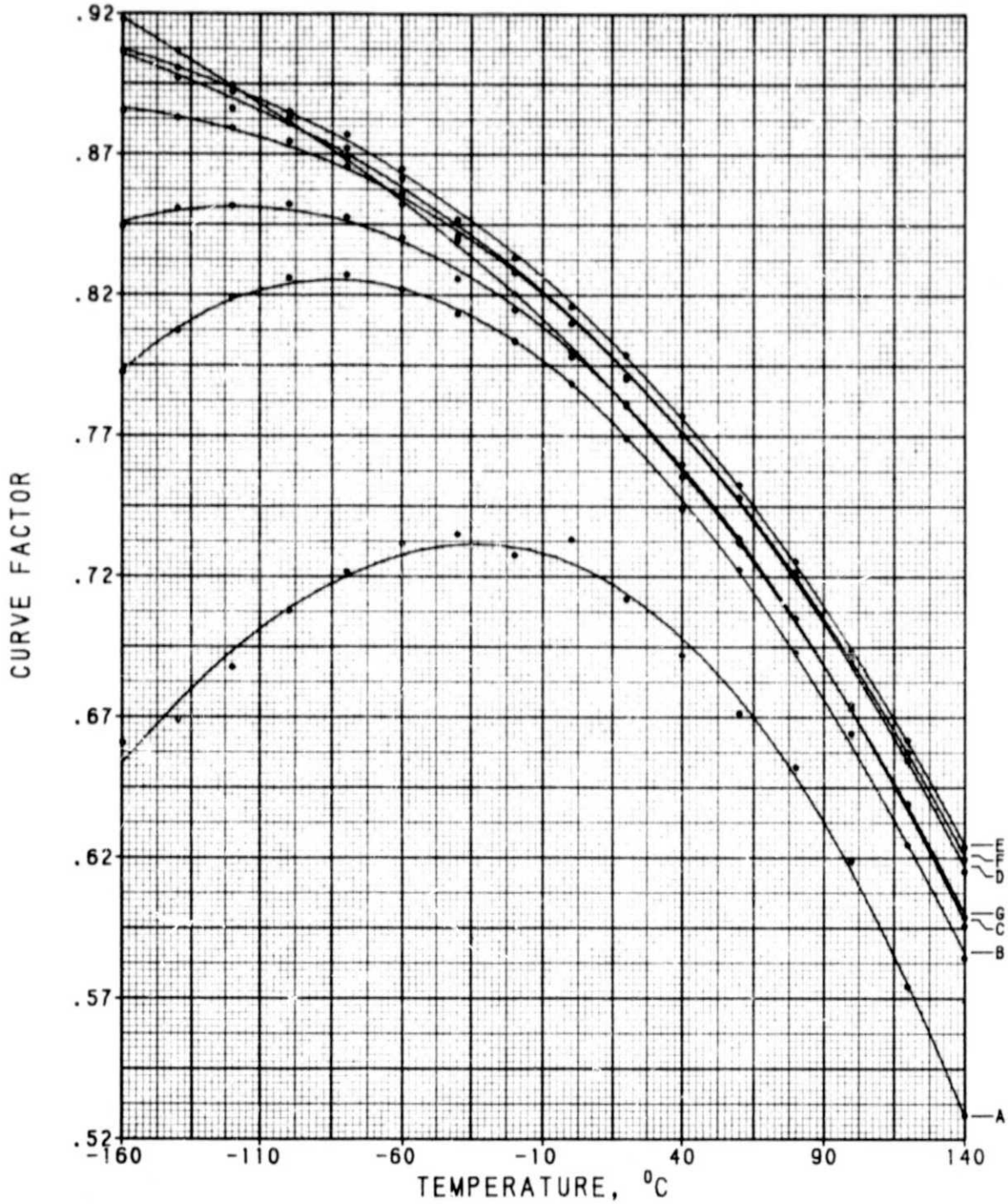
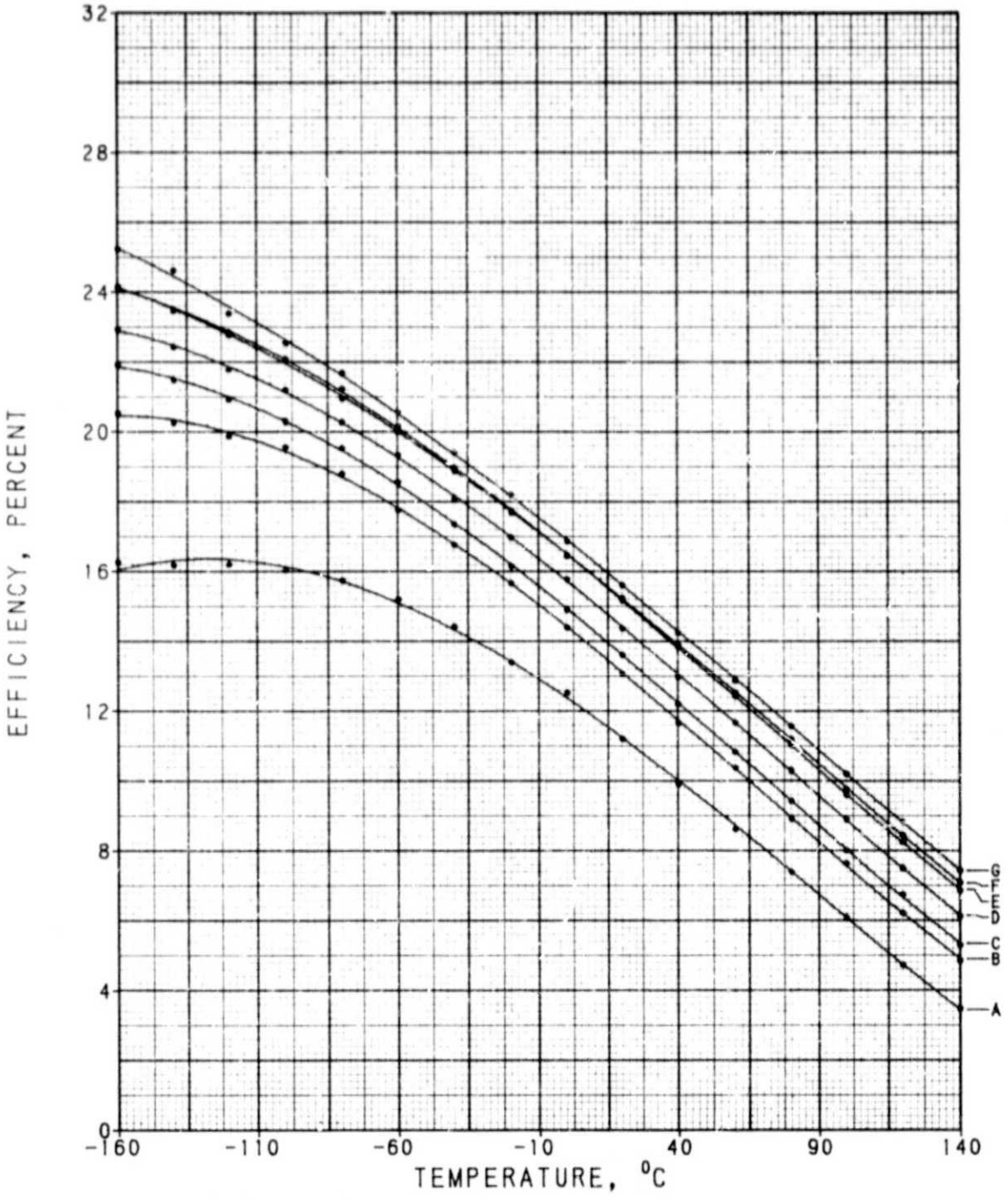


Figure 6. Average Curve Factor as a Function of Temperature



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D	50.0
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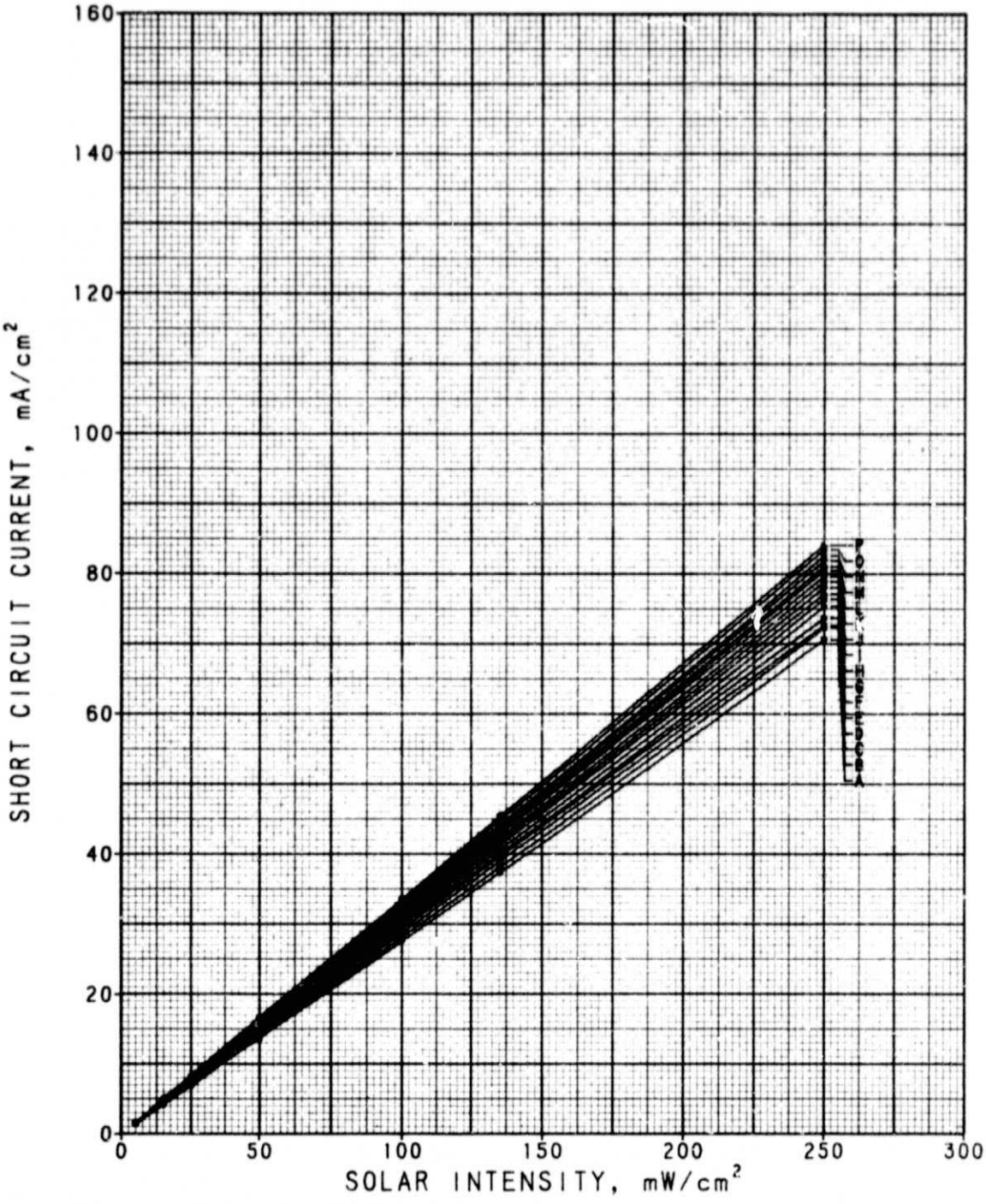
TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8

Figure 7. Average AMO Efficiency as a Function of Temperature



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C	-120.0	K	40.0
D	-100.0	L	60.0
E	-80.0	M	80.0
F	-60.0	N	100.0
G	-40.0	O	120.0
H	-20.0	P	140.0

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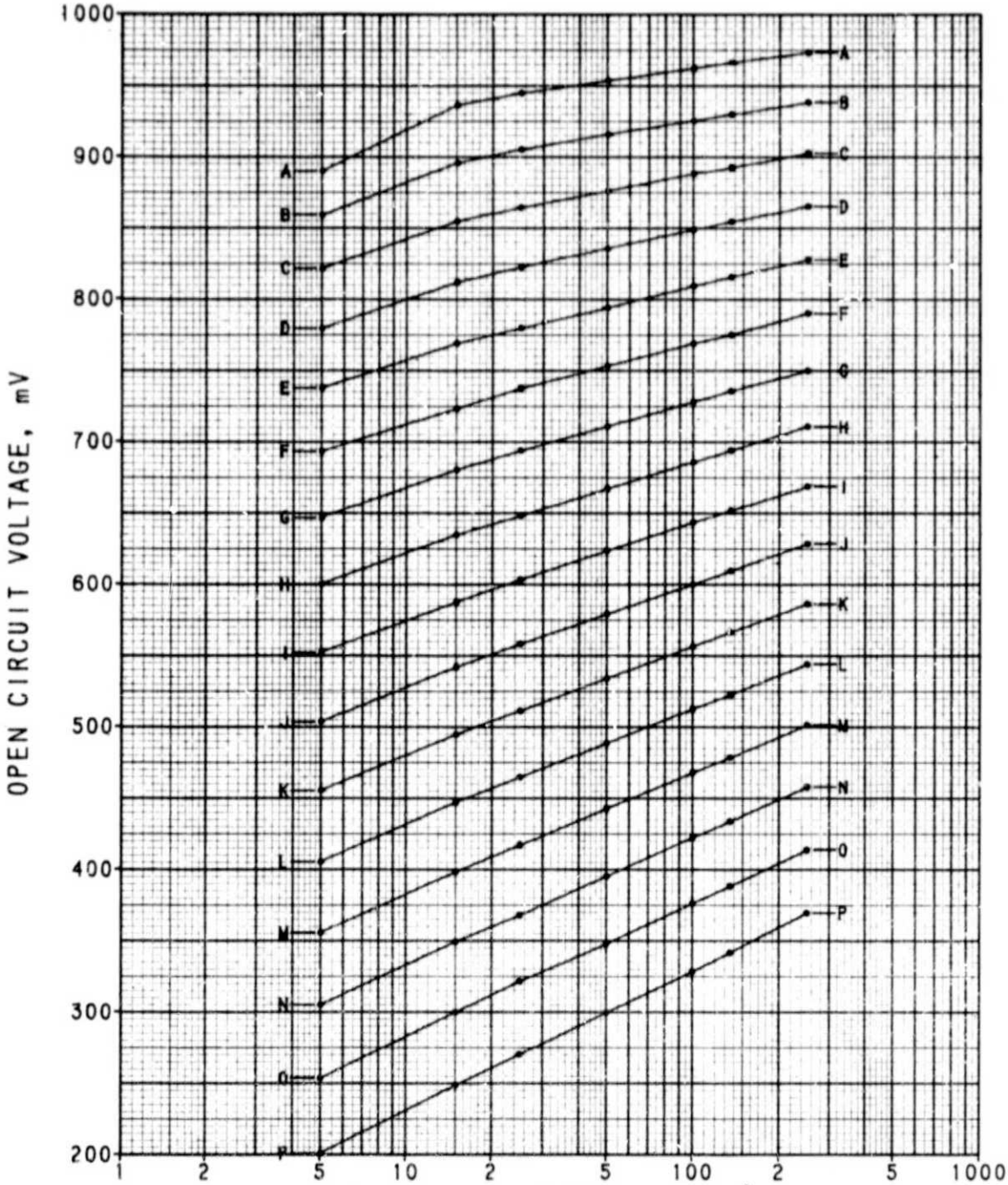
Figure 8. Average I_{sc}/cm^2 as a Function of Intensity



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B	-140.0	J	20.0
C	-120.0	K	40.0
D	-100.0	L	60.0
E	-80.0	M	80.0
F	-60.0	N	100.0
G	-40.0	O	120.0
H	-20.0	P	140.0

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TI-PD-AG FRONT CONTACT
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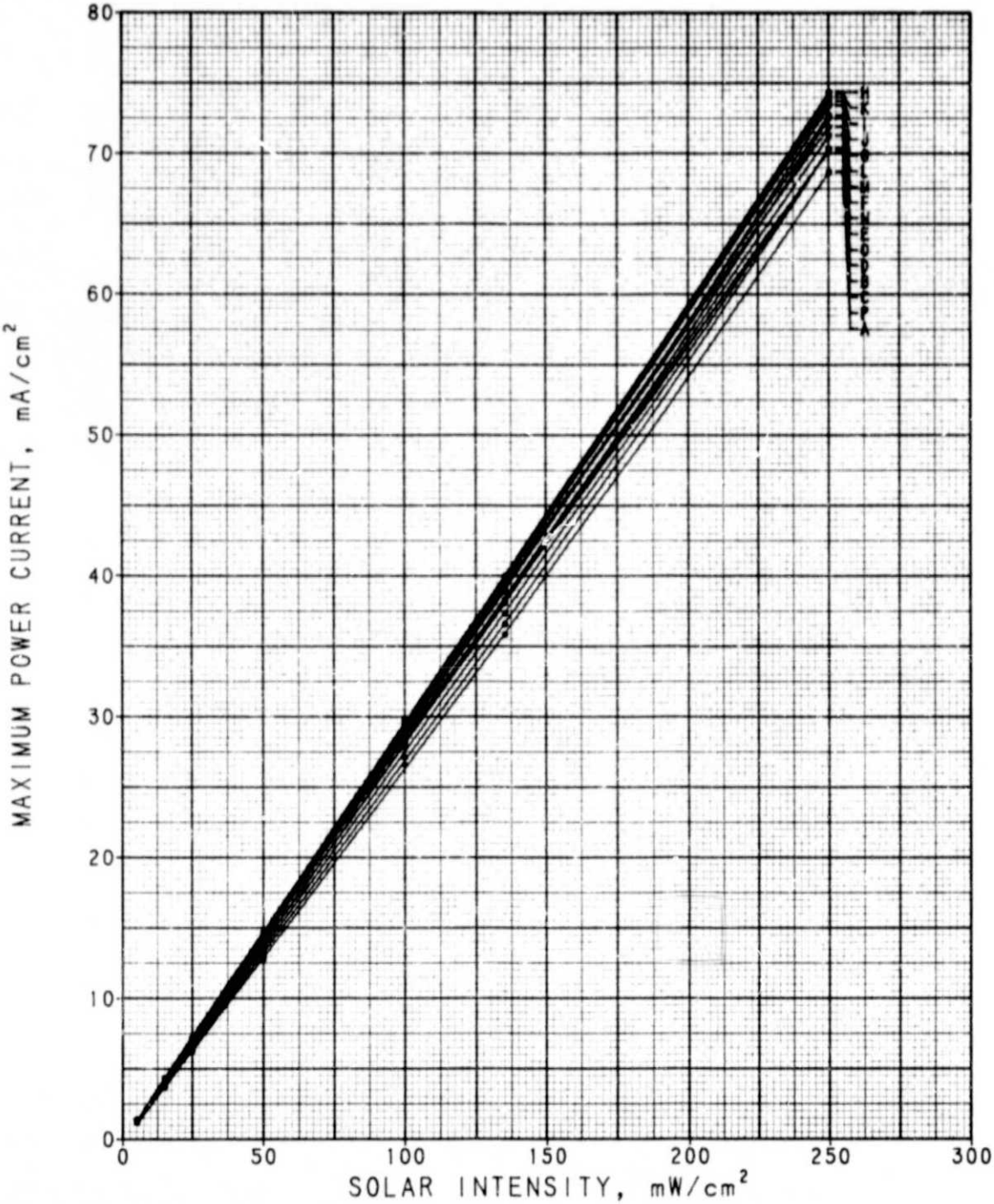
Figure 9. Average V_{oc} as a Function of Intensity



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C	-120.0	K	40.0
D	-100.0	L	60.0
E	-80.0	M	80.0
F	-60.0	N	100.0
G	-40.0	O	120.0
H	-20.0	P	140.0

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NO COVERSLIDE
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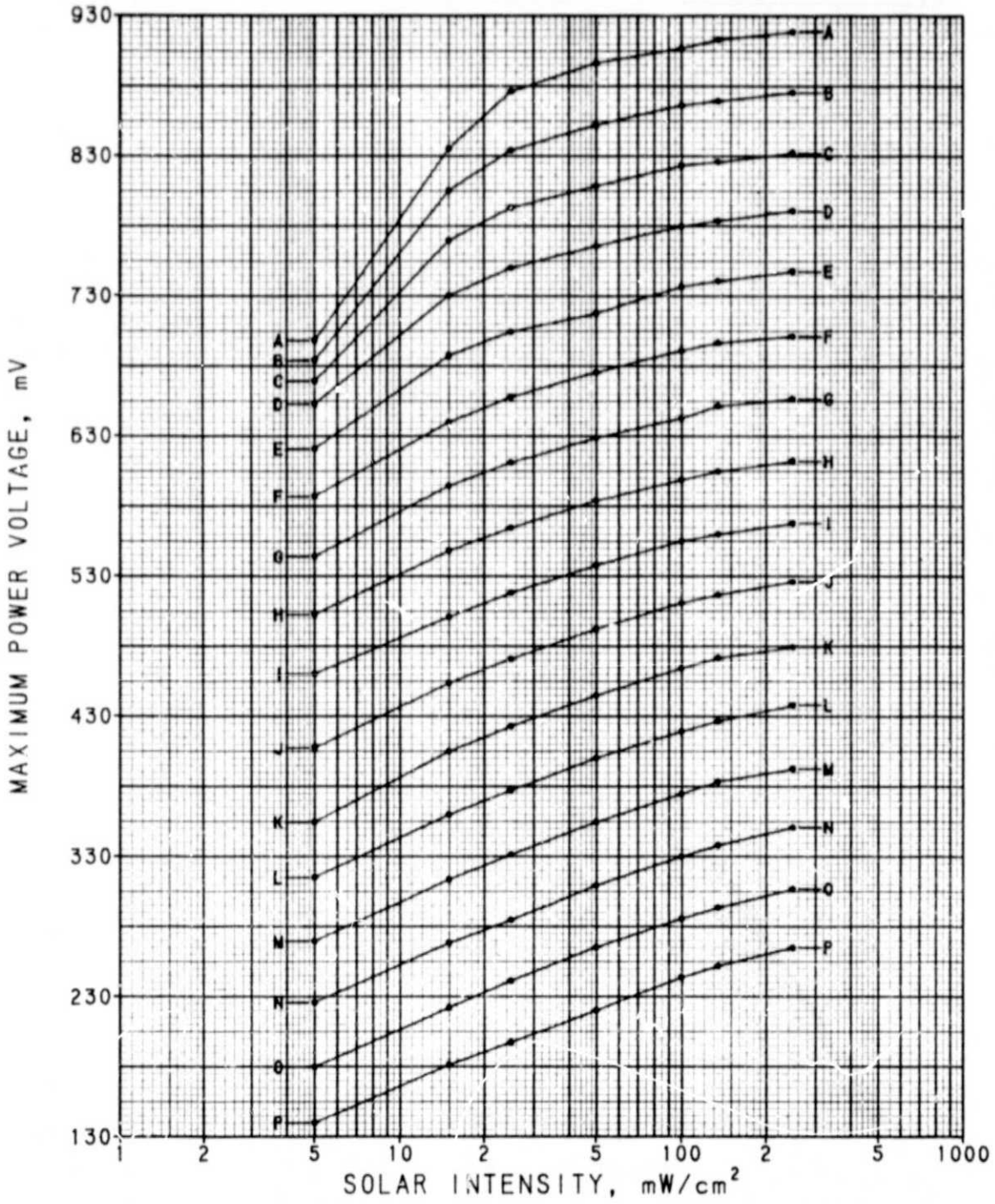
Figure 10. Average I_{mp}/cm^2 as a Function of Intensity



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D	-100.0	L	60.0
E	-80.0	M	80.0
F	-60.0	N	100.0
G	-40.0	O	120.0
H	-20.0	P	140.0

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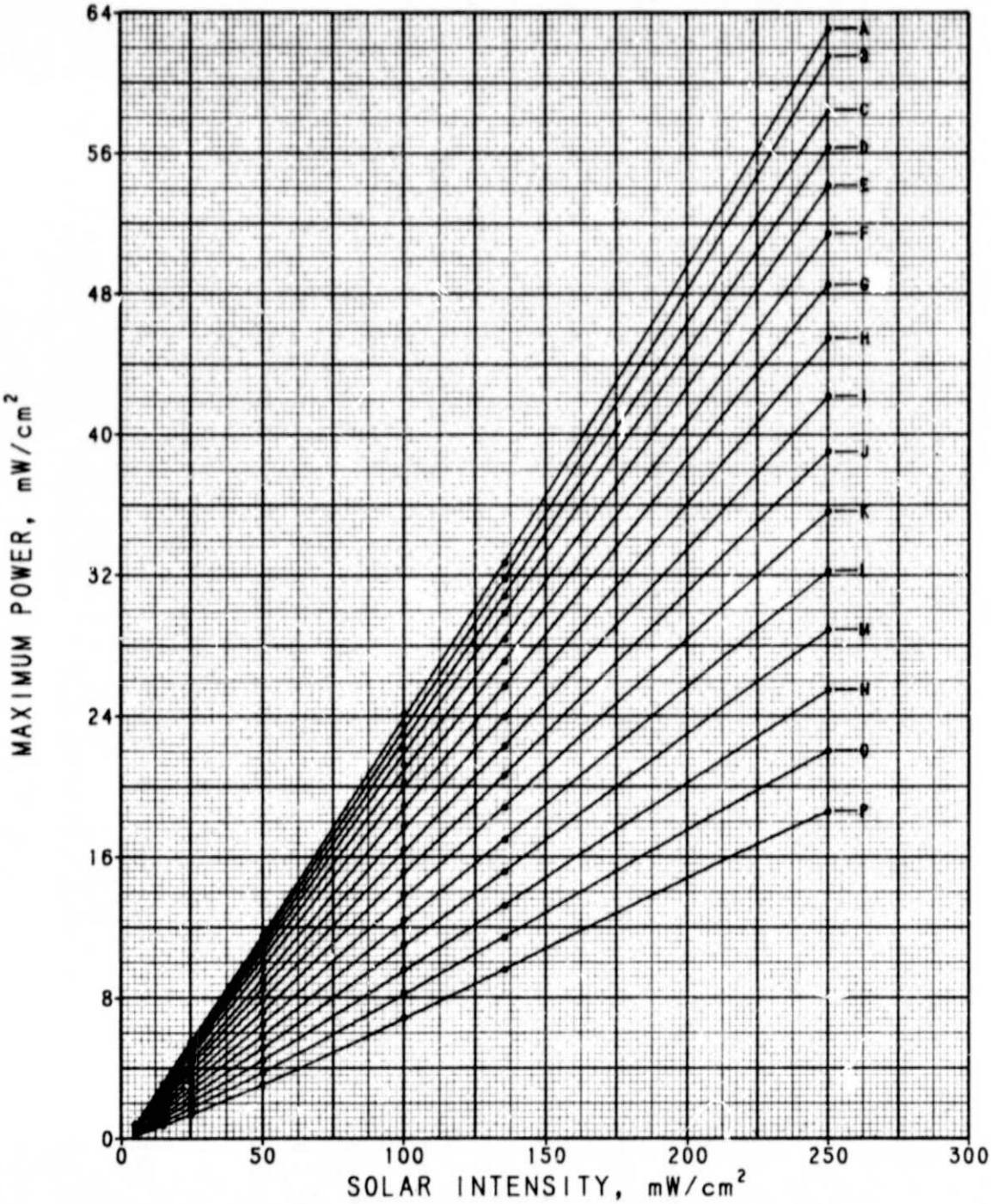
Figure 11. Average V_{mp} as a Function of Intensity



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B	-140.0	J	20.0
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E	-80.0	M	80.0
F	-60.0	N	100.0
G	-40.0	O	120.0
H	-20.0	P	140.0

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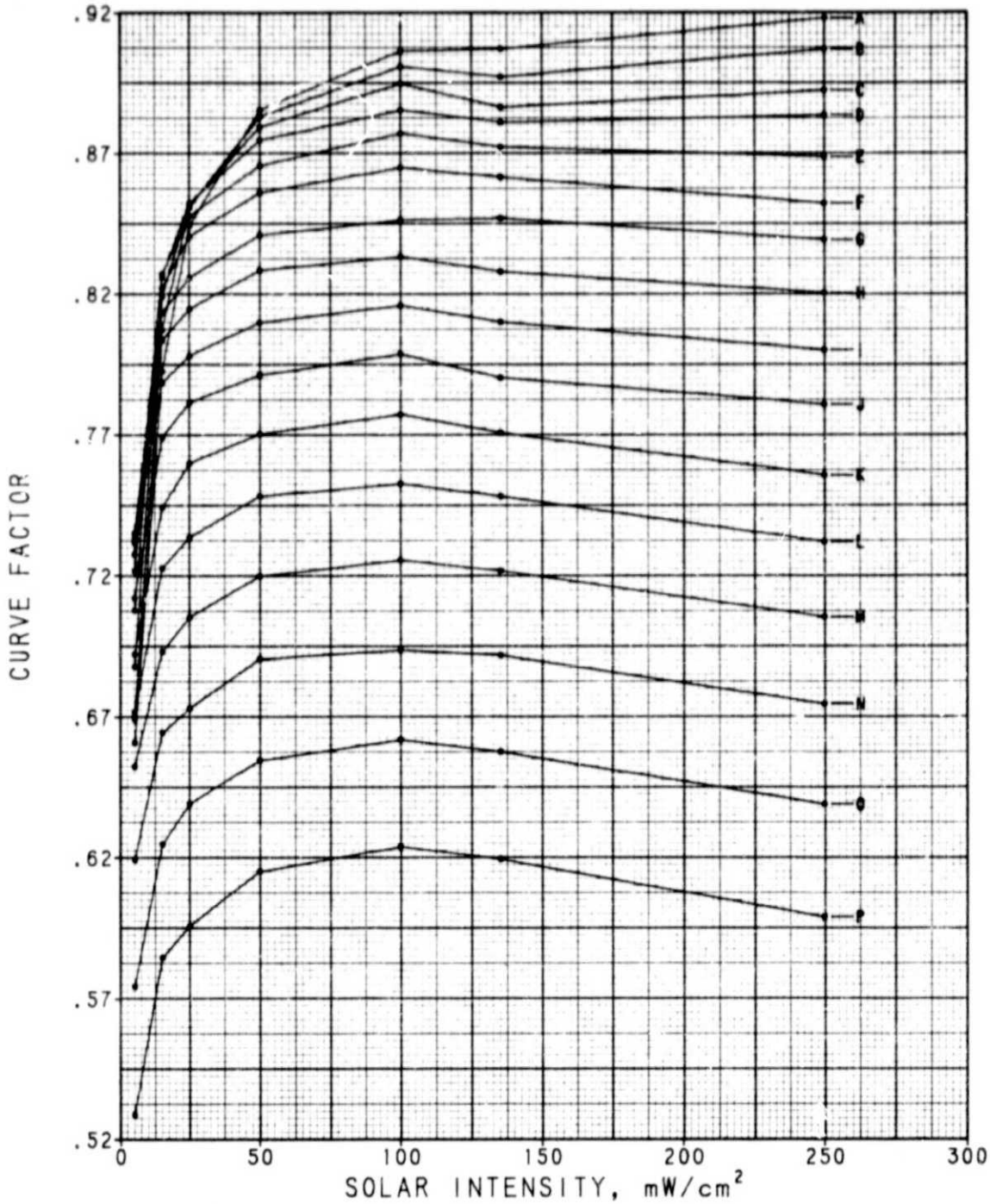
Figure 12. Average P_{max}/cm^2 as a Function of Intensity



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F	-60.0	N	100.0
G	-40.0	O	120.0
H	-20.0	P	140.0

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Figure 13. Average Curve Factor as a Function of Intensity

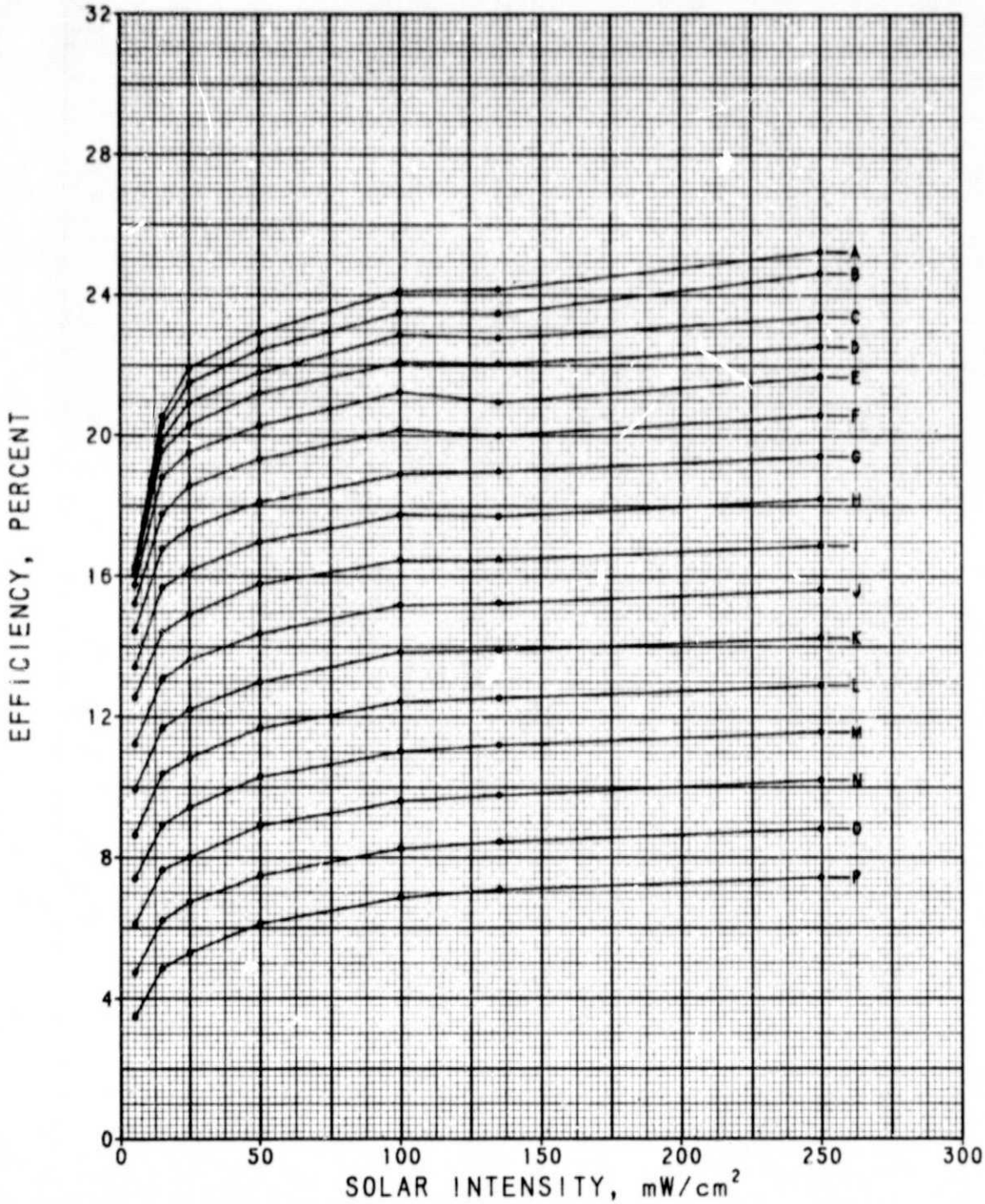

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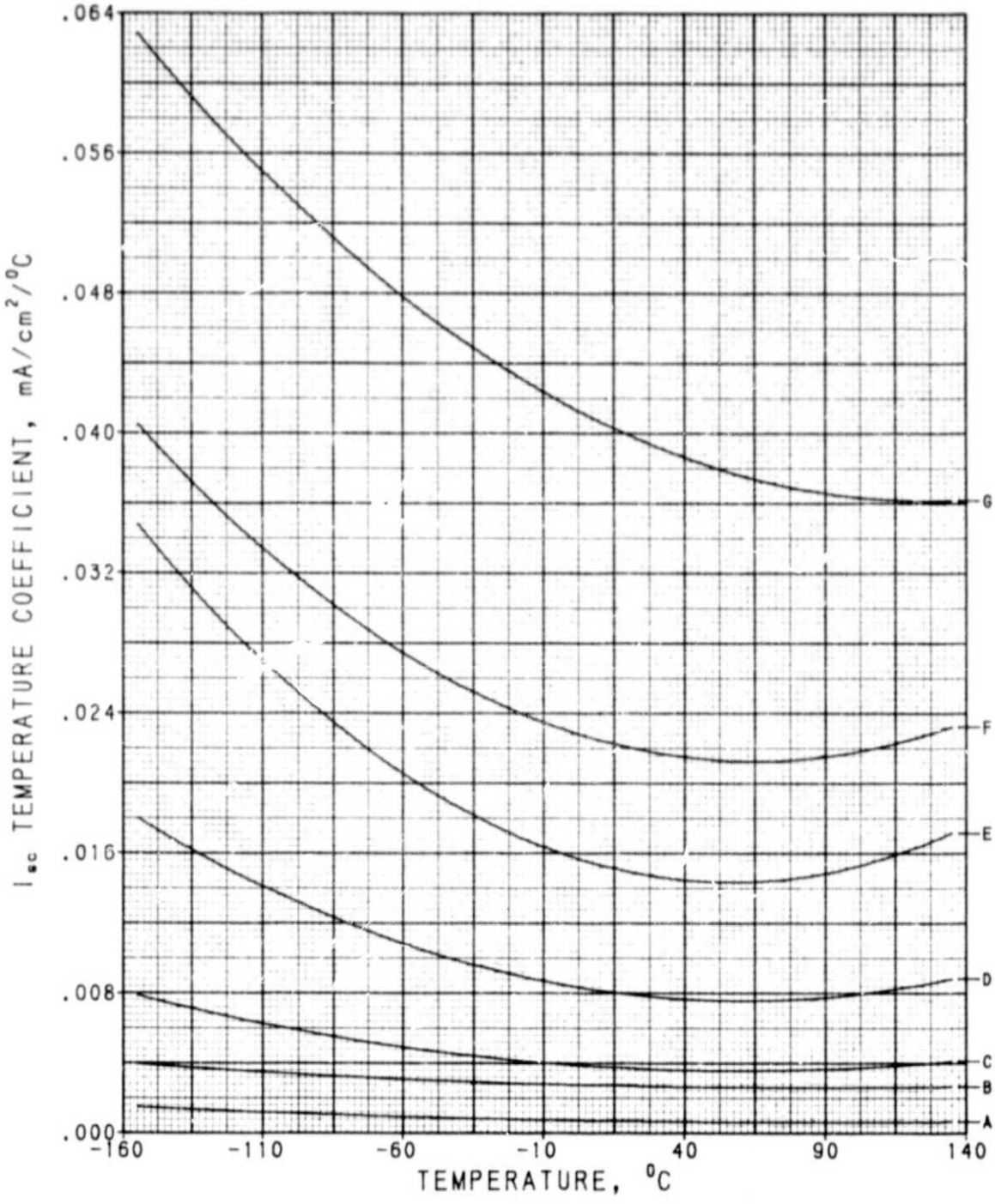
Figure 14. Average AMO Efficiency as a Function of Intensity



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B	15.0
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Figure 15. I_{sc} Temperature Coefficient

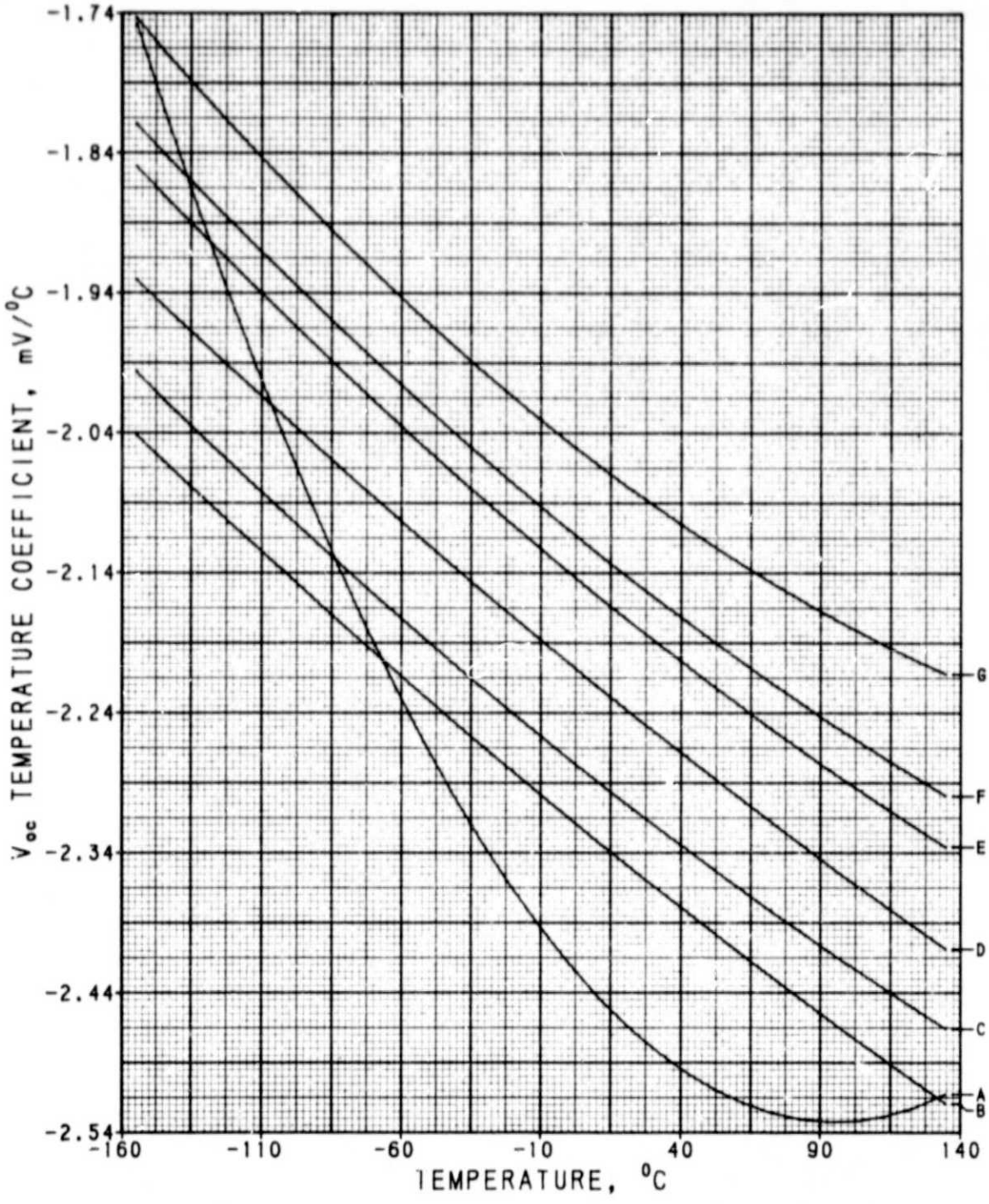

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Figure 16. V_{OC} Temperature Coefficient

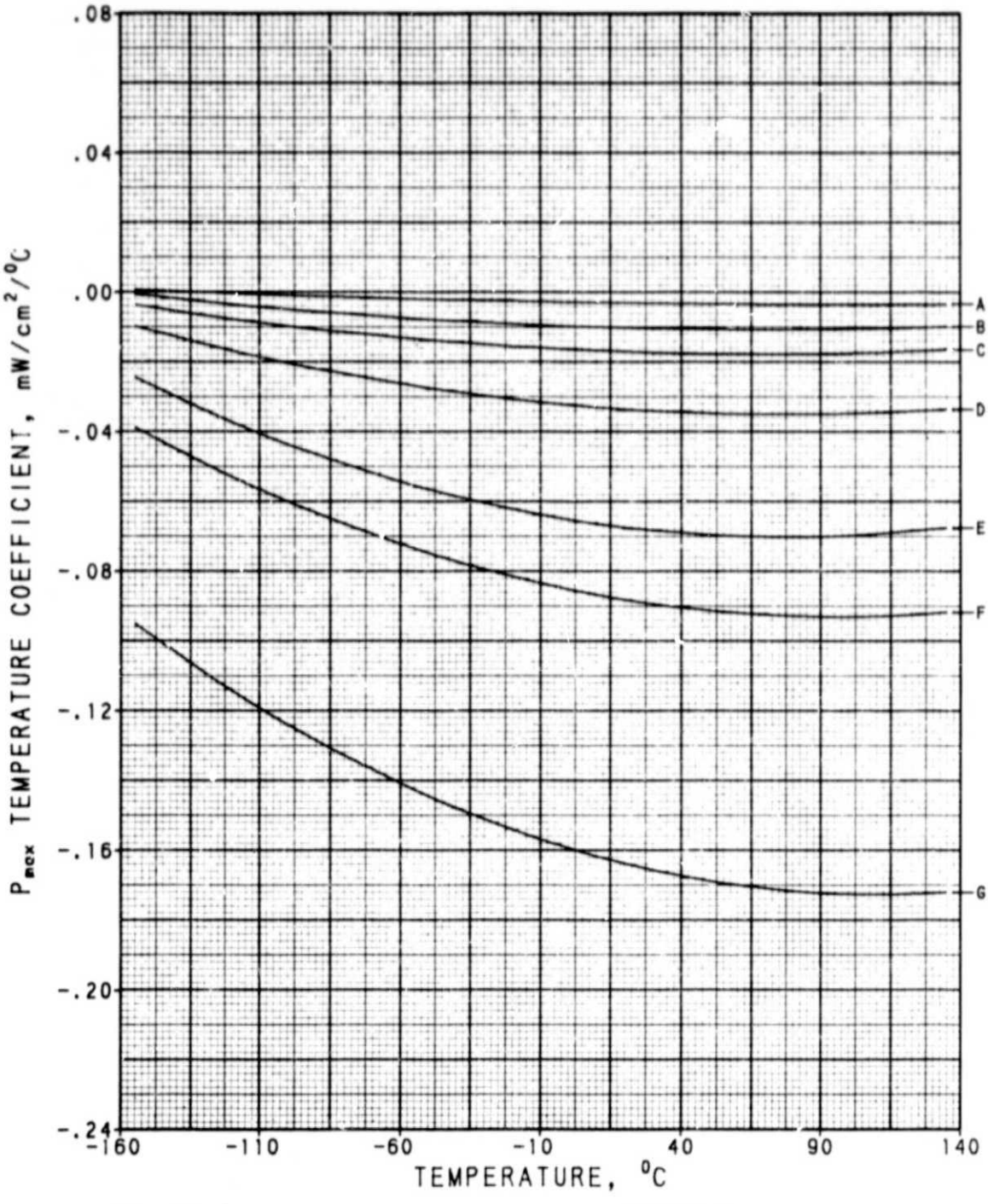

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Figure 17. Absolute P_{max} Temperature Coefficient

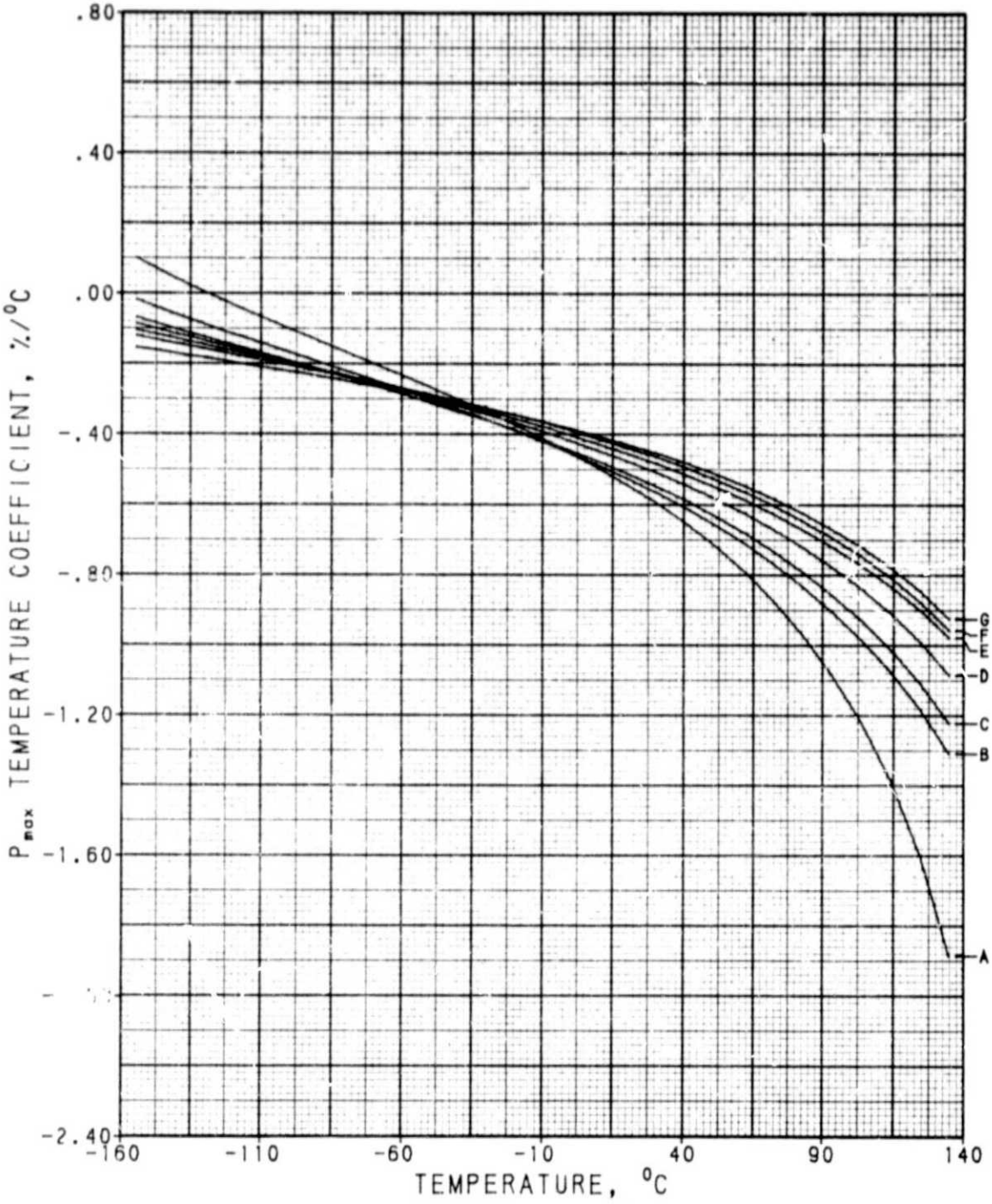

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Figure 18. Percent P_{max} Temperature Coefficient

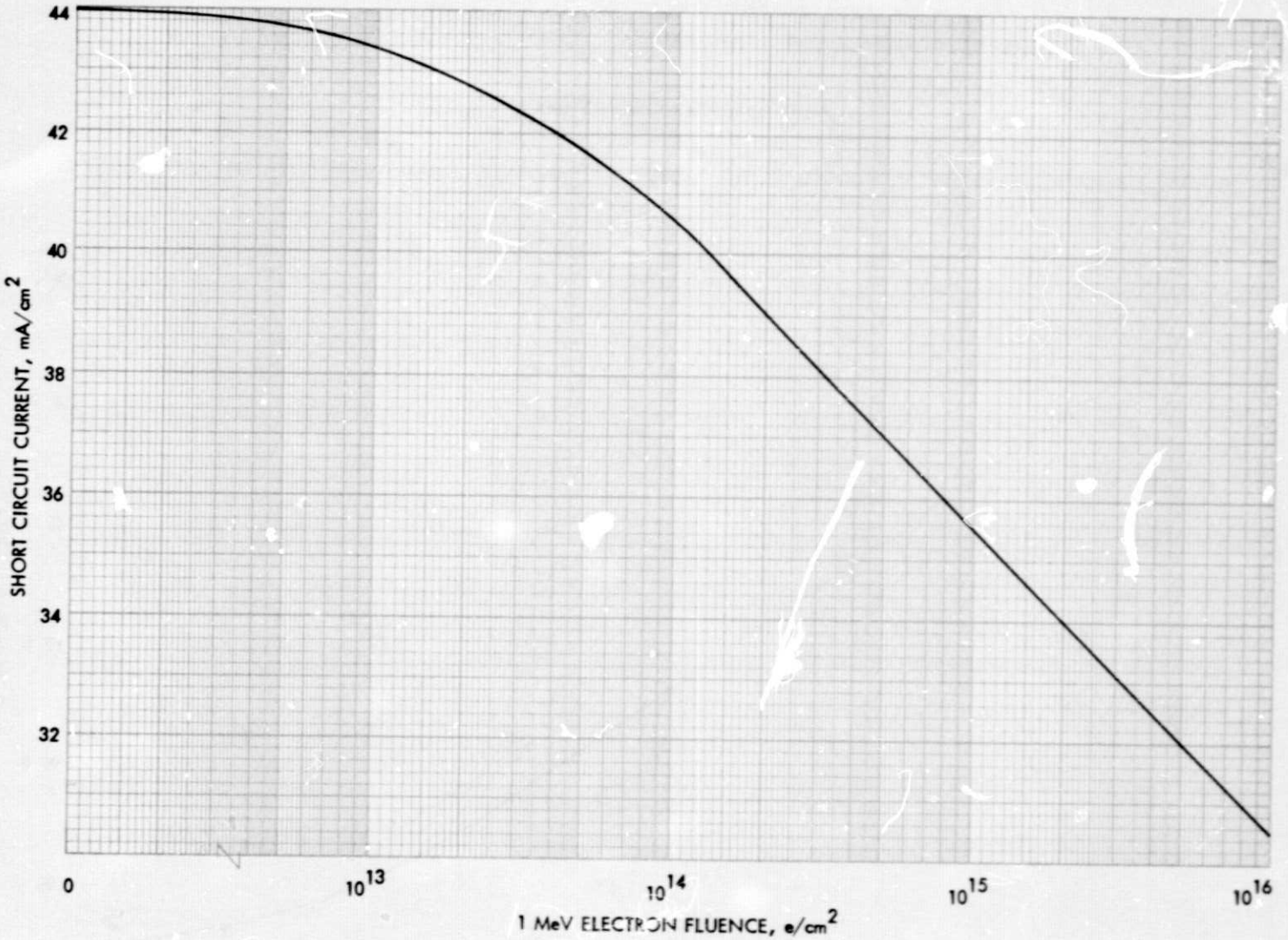

Figure 19. Short Circuit Current Density vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

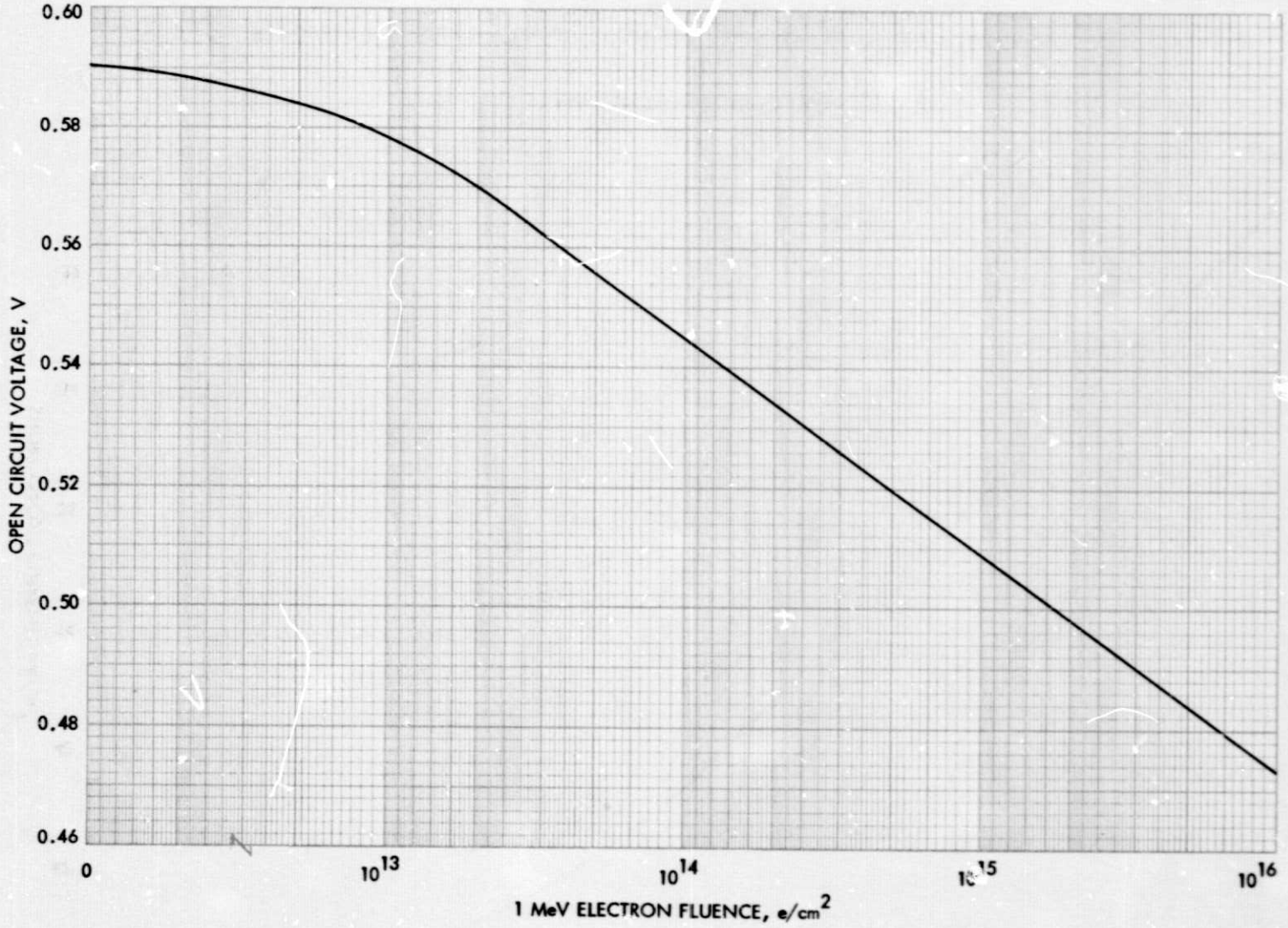

Figure 20. Open Circuit Voltage vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

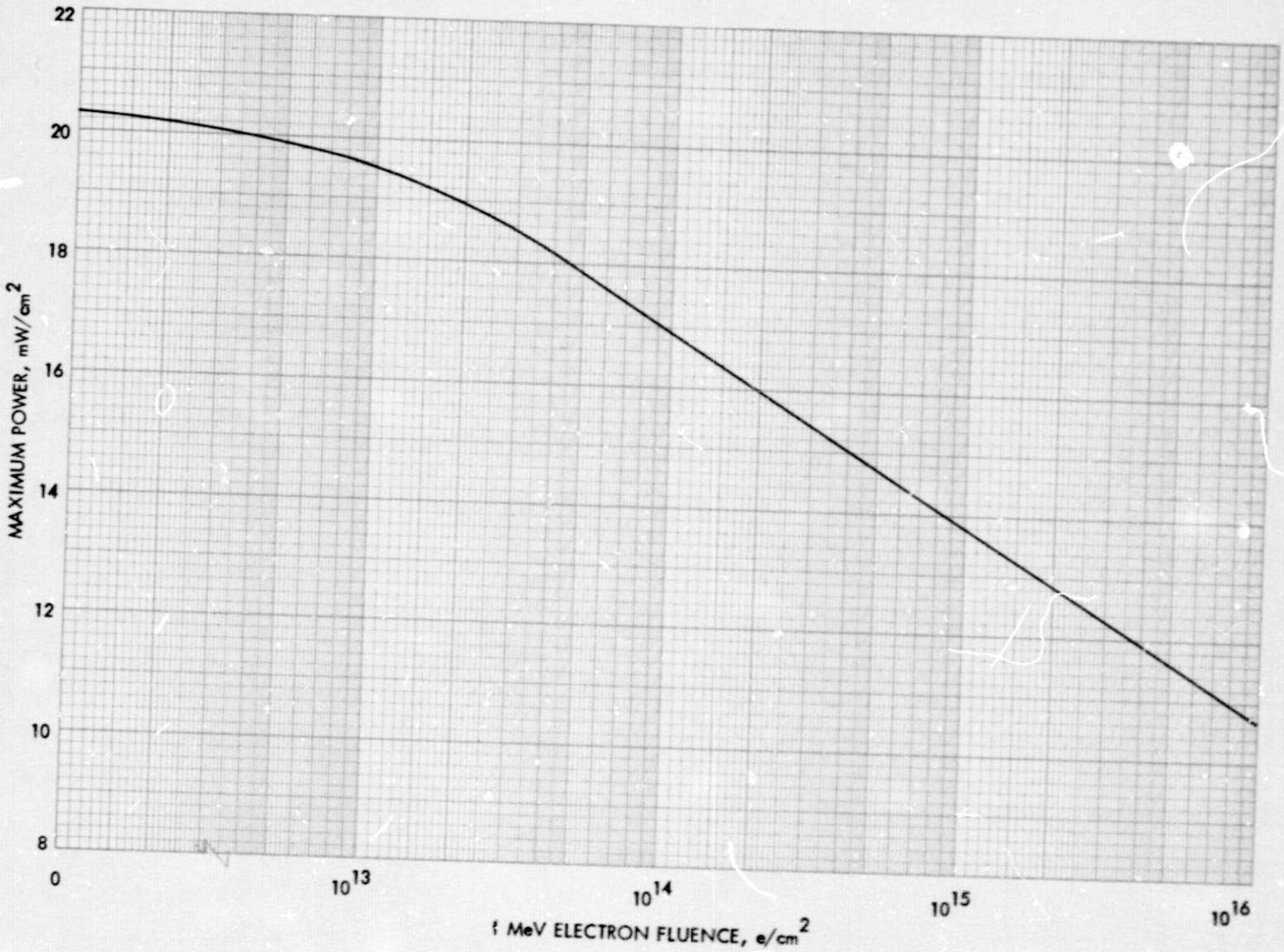

Figure 21. Maximum Power Density vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

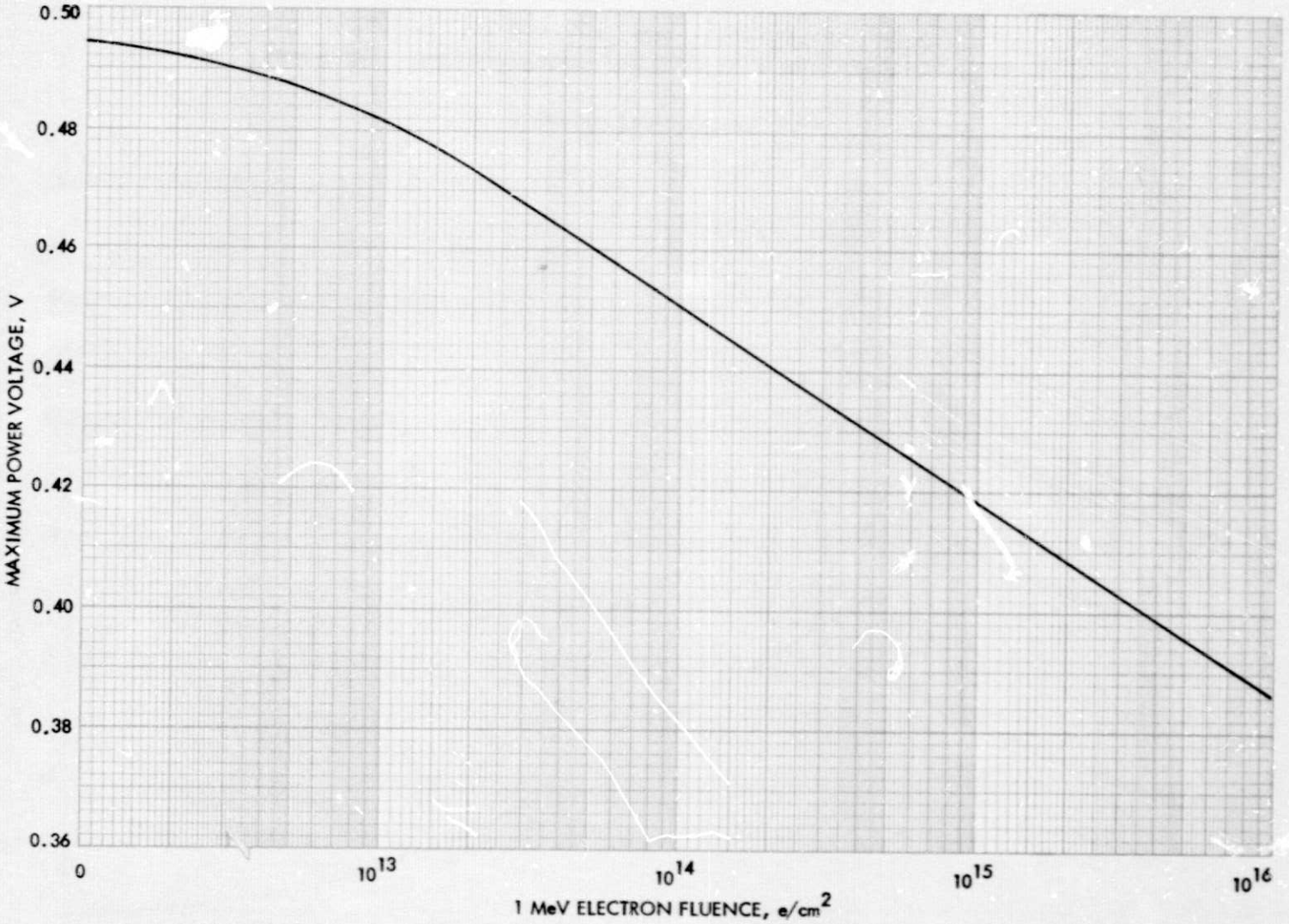

Figure 22. Voltage at Maximum Power vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

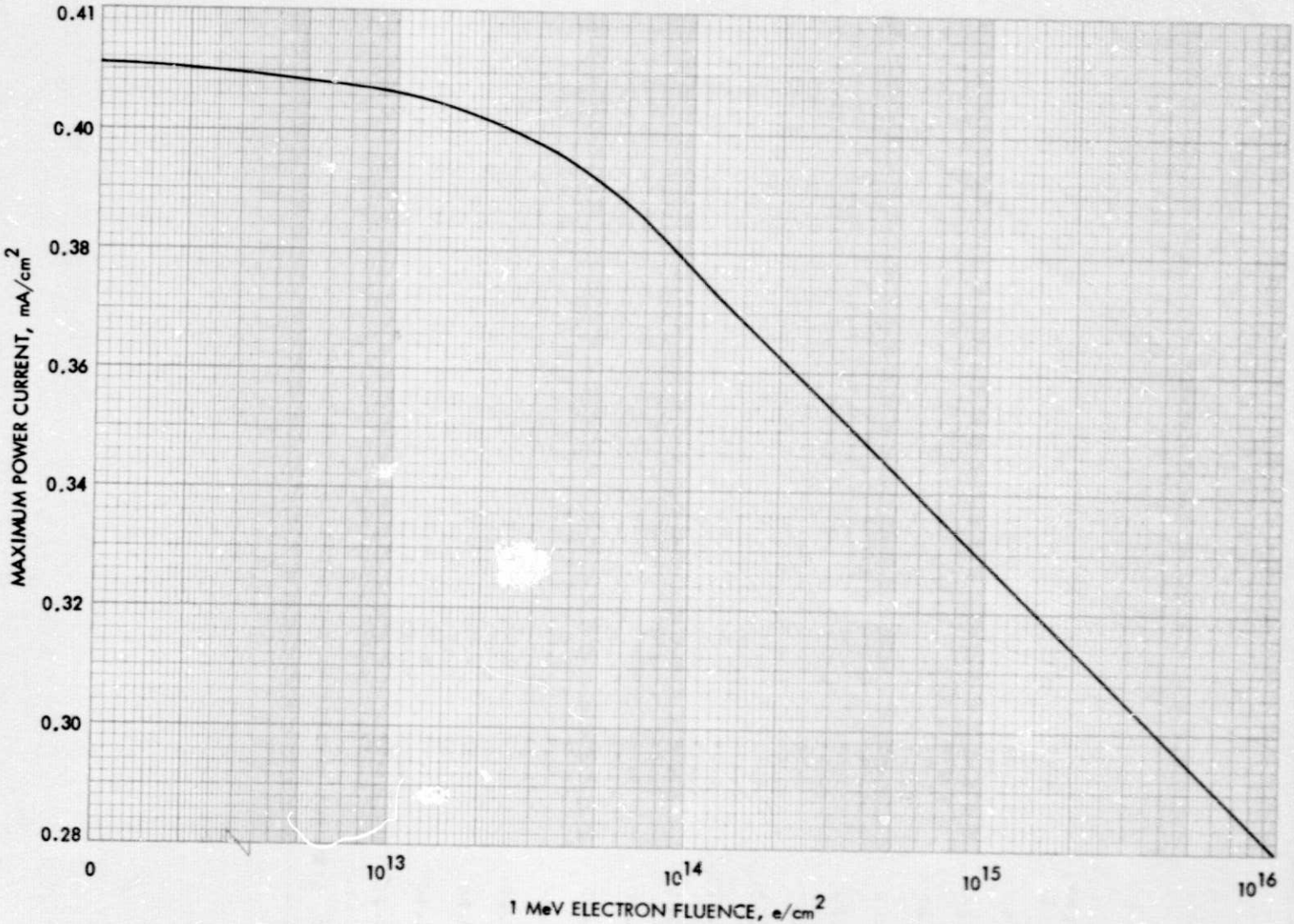

Figure 23. Maximum Power Current Density vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

Table 1. Average Short-Circuit Current, mA/cm^2

SPECTROLAB TEXTURED, BSF, BSR
N/P 10 OHM-CM CG SILICON
2 X 4 X .029 CM
AL-TI-PD-AG BACK CONTACT
TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-44

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 5.00	15.00	25.00	50.00	100.00	135.30	250.00
-160.00	1.38	4.15	6.87	13.58	27.65	37.31	70.65
	(.04)	(.10)	(.18)	(.33)	(.73)	(.83)	(1.66)
-140.00	1.41	4.20	6.98	13.87	28.18	38.08	72.34
	(.04)	(.11)	(.20)	(.40)	(.83)	(.93)	(1.75)
-120.00	1.43	4.26	7.11	14.14	28.78	38.96	72.64
	(.04)	(.11)	(.21)	(.40)	(.83)	(1.01)	(1.75)
-100.00	1.45	4.38	7.24	14.50	29.39	39.62	73.69
	(.04)	(.11)	(.20)	(.38)	(.82)	(.84)	(1.44)
-80.00	1.48	4.44	7.39	14.76	29.92	39.87	75.42
	(.04)	(.10)	(.18)	(.34)	(.73)	(.82)	(1.51)
-60.00	1.50	4.48	7.50	15.00	30.33	40.56	76.45
	(.03)	(.09)	(.17)	(.32)	(.67)	(.82)	(1.41)
-40.00	1.52	4.55	7.58	15.15	30.71	41.26	77.16
	(.03)	(.09)	(.15)	(.29)	(.66)	(.75)	(1.30)
-20.00	1.54	4.61	7.66	15.36	31.09	41.73	78.07
	(.03)	(.09)	(.16)	(.28)	(.66)	(.65)	(1.26)
.00	1.55	4.67	7.75	15.64	31.36	42.27	78.91
	(.03)	(.09)	(.16)	(.28)	(.67)	(.66)	(1.17)
20.00	1.56	4.71	7.81	15.70	31.69	42.84	79.63
	(.03)	(.10)	(.14)	(.27)	(.66)	(.69)	(1.35)
40.00	1.58	4.77	7.86	15.81	32.04	43.13	80.50
	(.03)	(.07)	(.16)	(.28)	(.69)	(.71)	(1.28)
60.00	1.59	4.82	7.96	15.98	32.24	43.43	81.08
	(.03)	(.09)	(.16)	(.27)	(.70)	(.73)	(1.32)
80.00	1.60	4.85	8.03	16.16	32.51	43.91	81.87
	(.03)	(.09)	(.16)	(.28)	(.70)	(.70)	(1.43)
100.00	1.62	4.95	8.09	16.34	32.84	44.12	82.64
	(.03)	(.11)	(.16)	(.27)	(.69)	(.73)	(1.42)
120.00	1.63	4.99	8.21	16.48	33.21	44.81	83.51
	(.03)	(.09)	(.15)	(.28)	(.70)	(.74)	(1.42)
140.00	1.64	5.02	8.25	16.66	33.52	45.37	84.15
	(.03)	(.09)	(.16)	(.29)	(.71)	(.72)	(1.38)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 2. Average Open-Circuit Voltage, mV

SPECTROLAB TEXTURED, BSF, BSR
N/P 10 OHM-CM CZ SILICON
2 X 4 X .029 CM
AL-TI-PD-AG BACK CONTACT
TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-44

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 5.00	15.00	25.00	50.00	100.00	135.30	250.00
-160.00	889.62	936.09	944.47	953.50	962.14	966.09	973.24
	(20.70)	(2.90)	(2.20)	(2.10)	(1.98)	(1.62)	(1.93)
-140.00	858.64	895.66	904.87	915.72	925.49	929.77	938.20
	(13.11)	(4.68)	(3.05)	(2.40)	(2.11)	(1.87)	(1.59)
-120.00	821.30	854.40	864.16	875.91	887.89	892.39	902.45
	(8.94)	(4.39)	(3.96)	(3.12)	(2.19)	(2.28)	(1.66)
-100.00	779.25	811.61	822.19	835.74	848.81	854.29	865.16
	(7.45)	(5.09)	(4.37)	(3.21)	(2.63)	(2.01)	(2.10)
-80.00	737.09	768.79	779.49	793.64	809.22	815.32	827.32
	(6.60)	(4.60)	(4.04)	(3.38)	(2.31)	(2.06)	(2.13)
-60.00	692.99	722.89	736.91	752.95	768.80	774.95	789.85
	(5.81)	(4.36)	(3.71)	(2.81)	(2.35)	(1.97)	(2.17)
-40.00	646.55	680.04	693.35	710.55	727.66	735.21	749.81
	(5.00)	(3.86)	(3.22)	(2.75)	(2.59)	(2.38)	(2.47)
-20.00	599.95	634.39	647.52	666.76	685.34	693.70	710.35
	(5.02)	(3.21)	(4.20)	(3.08)	(2.93)	(2.80)	(2.87)
.00	551.96	587.12	603.01	623.31	643.10	651.24	668.50
	(5.13)	(3.33)	(4.13)	(3.38)	(3.21)	(3.28)	(4.06)
20.00	503.25	541.80	557.75	578.89	599.79	609.30	628.20
	(4.66)	(4.16)	(4.29)	(4.03)	(3.95)	(3.61)	(3.73)
40.00	455.19	494.32	511.00	533.69	556.19	566.10	586.14
	(4.73)	(5.10)	(4.47)	(3.85)	(4.35)	(4.09)	(3.98)
60.00	405.14	447.91	464.43	488.51	512.37	522.34	544.06
	(5.19)	(4.96)	(5.00)	(5.02)	(4.87)	(4.60)	(4.64)
80.00	355.35	398.10	416.64	442.51	467.74	478.45	501.30
	(5.39)	(5.29)	(5.67)	(5.64)	(5.34)	(5.20)	(4.95)
100.00	304.97	349.24	367.81	395.21	422.21	433.66	458.02
	(5.96)	(6.44)	(6.38)	(5.94)	(5.90)	(5.77)	(5.40)
120.00	253.47	299.61	321.20	347.60	376.17	388.31	413.77
	(6.12)	(6.55)	(7.32)	(6.48)	(6.30)	(5.86)	(5.71)
140.00	200.77	248.49	269.84	299.45	328.19	341.61	369.70
	(6.76)	(6.95)	(7.01)	(6.83)	(6.22)	(6.37)	(6.10)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 3. Average Maximum Power Current, mA/cm^2

SPECTROLAB TEXTURED, BSF, BSR
N/P 10 OHM-CM CG SILICON
2 X 4 X .029 CM
AL-TI-PD-AG BACK CONTACT
TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-44

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 5.00	15.00	25.00	50.00	100.00	135.30	250.00
-160.00	1.16	3.68	6.25	12.79	26.59	35.82	68.73
	(.07)	(.23)	(.31)	(.46)	(.79)	(.87)	(1.63)
-140.00	1.18	3.77	6.44	13.17	27.13	36.56	70.37
	(.08)	(.21)	(.29)	(.47)	(.80)	(1.03)	(1.83)
-120.00	1.21	3.88	6.60	13.47	27.79	37.32	70.36
	(.08)	(.20)	(.28)	(.45)	(.96)	(1.06)	(1.84)
-100.00	1.23	4.02	6.77	13.85	28.34	38.09	71.29
	(.08)	(.16)	(.23)	(.40)	(.82)	(.93)	(1.79)
-80.00	1.27	4.11	6.93	14.14	28.83	38.29	72.56
	(.07)	(.15)	(.20)	(.37)	(.74)	(.95)	(1.50)
-60.00	1.30	4.17	7.07	14.32	29.20	38.89	73.42
	(.06)	(.13)	(.21)	(.34)	(.69)	(.82)	(1.49)
-40.00	1.33	4.23	7.11	14.41	29.43	39.45	74.00
	(.05)	(.08)	(.17)	(.32)	(.69)	(.73)	(.99)
-20.00	1.33	4.29	7.16	14.55	29.66	39.65	74.39
	(.05)	(.09)	(.16)	(.32)	(.64)	(.68)	(1.10)
.00	1.36	4.31	7.20	14.69	29.66	39.84	74.37
	(.04)	(.09)	(.15)	(.28)	(.63)	(.72)	(.87)
20.00	1.38	4.33	7.23	14.62	29.74	39.94	74.28
	(.03)	(.09)	(.14)	(.25)	(.68)	(.64)	(1.11)
40.00	1.40	4.33	7.23	14.61	29.86	39.91	74.39
	(.03)	(.09)	(.18)	(.24)	(.69)	(.65)	(.79)
60.00	1.37	4.33	7.19	14.60	29.66	39.79	73.74
	(.03)	(.11)	(.16)	(.30)	(.60)	(.66)	(.91)
80.00	1.37	4.27	7.12	14.52	29.46	39.55	73.73
	(.02)	(.09)	(.15)	(.31)	(.72)	(.52)	(.91)
100.00	1.35	4.28	7.04	14.42	29.15	39.15	72.75
	(.03)	(.12)	(.16)	(.28)	(.56)	(.53)	(.82)
120.00	1.32	4.21	6.99	14.14	28.95	38.98	71.92
	(.04)	(.09)	(.14)	(.29)	(.55)	(.60)	(.76)
140.00	1.25	4.03	6.73	13.95	28.16	38.12	70.25
	(.02)	(.10)	(.14)	(.25)	(.55)	(.38)	(1.04)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 4. Average Maximum Power Voltage, mV

SPECTROLAB TEXTURED, BSF, BSR
N/P 10 OHM-CM CG SILICON
2 X 4 X .029 CM
AL-TI-PD-AG BACK CONTACT
TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-44

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 5.00	15.00	25.00	50.00	100.00	135.30	250.00
-160.00	697.62	834.87	875.75	896.25	906.75	912.87	918.37
	(56.85)	(26.10)	(13.56)	(3.99)	(3.33)	(4.09)	(4.41)
-140.00	683.50	804.87	833.62	852.00	866.00	869.00	874.87
	(45.86)	(20.92)	(9.46)	(7.27)	(4.50)	(4.11)	(5.96)
-120.00	668.75	769.12	792.75	808.25	823.00	825.75	831.62
	(37.89)	(12.89)	(8.33)	(5.60)	(2.45)	(4.17)	(7.15)
-100.00	652.50	730.00	749.62	765.50	779.37	783.12	790.37
	(25.29)	(10.94)	(7.95)	(6.16)	(1.85)	(4.29)	(9.05)
-80.00	620.62	686.87	704.12	717.12	736.50	740.50	747.12
	(17.37)	(7.02)	(6.73)	(4.91)	(3.16)	(3.12)	(8.25)
-60.00	586.75	639.50	657.37	675.12	690.75	696.25	701.00
	(11.40)	(8.54)	(3.34)	(3.64)	(3.41)	(4.27)	(7.13)
-40.00	543.62	594.25	610.75	628.37	642.50	651.12	656.12
	(7.82)	(7.01)	(4.06)	(2.56)	(2.00)	(2.70)	(6.60)
-20.00	502.50	547.62	564.25	583.37	598.50	604.37	611.62
	(6.46)	(6.91)	(4.10)	(4.21)	(1.41)	(3.81)	(8.48)
.00	459.87	500.75	517.75	537.37	554.75	559.75	567.37
	(11.15)	(5.12)	(5.06)	(3.34)	(3.85)	(3.58)	(8.85)
20.00	407.12	453.50	470.75	491.87	510.62	516.37	525.75
	(6.79)	(7.58)	(4.89)	(3.87)	(2.97)	(3.20)	(8.48)
40.00	354.50	404.75	422.75	444.62	463.87	471.37	479.25
	(5.10)	(3.96)	(3.45)	(3.78)	(3.00)	(3.74)	(9.19)
60.00	314.87	359.75	376.87	400.00	419.25	426.50	437.75
	(4.52)	(4.50)	(5.00)	(2.14)	(1.83)	(4.66)	(7.44)
80.00	269.37	313.37	331.25	354.37	374.50	383.37	392.50
	(6.32)	(5.26)	(5.75)	(4.03)	(3.30)	(3.07)	(9.12)
100.00	225.62	268.12	284.50	309.25	329.87	338.00	350.75
	(7.42)	(4.02)	(4.34)	(5.82)	(3.64)	(4.93)	(7.50)
120.00	179.75	221.87	241.12	265.25	285.50	293.50	306.75
	(5.06)	(5.89)	(5.51)	(3.69)	(4.21)	(4.34)	(7.11)
140.00	139.62	181.12	197.12	220.00	243.75	251.75	265.00
	(5.85)	(6.17)	(5.33)	(3.85)	(5.60)	(4.10)	(6.93)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 5. Average Maximum Power, mW/cm^2

SPECTROLAB TEXTURED, BSF, BSR
N/P 10 OHM-CM CZ SILICON
2 X 4 X .029 CM
AL-TI-PD-AG BACK CONTACT
TI-PD-AG FRONT CONTACT
TA205 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-44

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 5.00	15.00	25.00	50.00	100.00	135.30	250.00
-160.00	.81	3.08	5.48	11.47	24.11	32.70	63.12
	(.10)	(.26)	(.34)	(.45)	(.73)	(.88)	(1.34)
-140.00	.81	3.04	5.37	11.22	23.50	31.77	61.56
	(.09)	(.23)	(.29)	(.47)	(.79)	(.97)	(1.36)
-120.00	.81	2.98	5.23	10.89	22.87	30.82	58.5[illegible]
	(.09)	(.19)	(.26)	(.43)	(.82)	(.94)	(1.21)
-100.00	.80	2.93	5.08	10.60	22.09	29.83	56.33
	(.07)	(.15)	(.22)	(.37)	(.66)	(.67)	(.84)
-80.00	.79	2.82	4.88	10.14	21.23	28.35	54.2[illegible]
	(.06)	(.13)	(.17)	(.32)	(.56)	(.65)	(.67)
-60.00	.76	2.66	4.65	9.67	20.17	27.07	51.46
	(.05)	(.10)	(.15)	(.26)	(.47)	(.52)	(.63)
-40.00	.72	2.52	4.34	9.05	18.91	25.69	48.55
	(.04)	(.07)	(.12)	(.22)	(.41)	(.42)	(.44)
-20.00	.67	2.35	4.04	8.49	17.75	23.96	45.49
	(.04)	(.07)	(.12)	(.22)	(.37)	(.31)	(.52)
.00	.63	2.16	3.73	7.90	16.45	22.30	42.19
	(.02)	(.06)	(.11)	(.17)	(.33)	(.32)	(.54)
20.00	.56	1.96	3.40	7.19	15.18	20.63	39.05
	(.02)	(.07)	(.09)	(.17)	(.32)	(.27)	(.40)
40.00	.50	1.75	3.05	6.50	13.85	18.81	35.65
	(.02)	(.05)	(.09)	(.15)	(.35)	(.25)	(.58)
60.00	.43	1.56	2.71	5.84	12.43	16.97	32.28
	(.01)	(.05)	(.09)	(.14)	(.25)	(.19)	(.53)
80.00	.37	1.34	2.36	5.15	11.03	15.16	28.93
	(.01)	(.04)	(.08)	(.14)	(.26)	(.19)	(.60)
100.00	.31	1.15	2.00	4.46	9.62	13.23	25.52
	(.01)	(.05)	(.07)	(.12)	(.23)	(.22)	(.63)
120.00	.24	.93	1.69	3.75	8.27	11.44	22.06
	(.01)	(.04)	(.07)	(.11)	(.22)	(.19)	(.64)
140.00	.17	.73	1.33	3.07	6.86	9.60	18.62
	(.01)	(.04)	(.06)	(.10)	(.21)	(.19)	(.69)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 6. Average Curve Factor

SPECTROLAB TEXTURED, BSF, BSR
N/P 10 OHM-CM CZ SILICON
2 X 4 X .029 CM
AL-TI-PD-AG BACK CONTACT
TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-44

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 5.00	15.00	25.00	50.00	100.00	135.30	250.00
-160.00	.6609 (.0595)	.7925 (.0630)	.8443 (.0476)	.8855 (.0267)	.9065 (.0130)	.9072 (.0117)	.9161 (.0082)
-140.00	.6691 (.0598)	.8073 (.0538)	.8508 (.0362)	.8831 (.0223)	.9009 (.0141)	.8972 (.0086)	.9070 (.0060)
-120.00	.6877 (.0574)	.8191 (.0419)	.8517 (.0277)	.8795 (.0165)	.8948 (.0147)	.8864 (.0084)	.8925 (.0104)
-100.00	.7079 (.0520)	.8261 (.0302)	.8524 (.0206)	.8747 (.0126)	.8854 (.0083)	.8812 (.0062)	.8836 (.0079)
-80.00	.7216 (.0425)	.8271 (.0251)	.8477 (.0159)	.8658 (.0096)	.8771 (.0056)	.8722 (.0056)	.8689 (.0112)
-60.00	.7316 (.0347)	.8221 (.0225)	.8404 (.0136)	.8561 (.0095)	.8649 (.0065)	.8615 (.0051)	.8524 (.0094)
-40.00	.7352 (.0296)	.8133 (.0174)	.8259 (.0123)	.8409 (.0083)	.8462 (.0053)	.8469 (.0065)	.8394 (.0140)
-20.00	.7276 (.0348)	.8036 (.0148)	.8147 (.0106)	.8285 (.0071)	.8332 (.0055)	.8280 (.0056)	.8204 (.0140)
.00	.7331 (.0165)	.7885 (.0119)	.7981 (.0089)	.8100 (.0059)	.8159 (.0068)	.8101 (.0072)	.8001 (.0148)
20.00	.7120 (.0178)	.7691 (.0107)	.7814 (.0092)	.7912 (.0044)	.7988 (.0077)	.7902 (.0069)	.7808 (.0159)
40.00	.6920 (.0130)	.7440 (.0120)	.7600 (.0071)	.7703 (.0055)	.7772 (.0103)	.7707 (.0089)	.7557 (.0194)
60.00	.6715 (.0123)	.7226 (.0098)	.7335 (.0089)	.7482 (.0056)	.7528 (.0086)	.7481 (.0118)	.7320 (.0202)
80.00	.6524 (.0107)	.6932 (.0056)	.7053 (.0052)	.7198 (.0048)	.7256 (.0085)	.7217 (.0139)	.7053 (.0234)
100.00	.6191 (.0090)	.6643 (.0051)	.6730 (.0051)	.6904 (.0057)	.6938 (.0077)	.6917 (.0126)	.6744 (.0236)
120.00	.5742 (.0092)	.6247 (.0059)	.6392 (.0044)	.6546 (.0042)	.6619 (.0077)	.6576 (.0140)	.6389 (.0267)
140.00	.5285 (.0065)	.5844 (.0112)	.5959 (.0030)	.6152 (.0055)	.6240 (.0092)	.6195 (.0154)	.5990 (.0303)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 7. Average AMO Efficiency, Percent

SPECTROLAB TEXTURED, BSF, BSR
N/P 10 OHM-CM CG SILICON
2 X 4 X .029 CM
AL-TI-PD-AG BACK CONTACT
TI-PD-AG FRONT CONTACT
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-44

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 5.00	15.00	25.00	50.00	100.00	135.30	250.00
-160.00	16.26	20.53	21.92	22.94	24.11	24.17	25.25
	(1.96)	(1.76)	(1.37)	(.90)	(.73)	(.65)	(.54)
-140.00	16.19	20.27	21.48	22.44	23.50	23.48	24.62
	(1.87)	(1.51)	(1.14)	(.95)	(.79)	(.72)	(.54)
-120.00	16.22	19.89	20.93	21.79	22.87	22.78	23.40
	(1.74)	(1.29)	(1.03)	(.86)	(.82)	(.70)	(.48)
-100.00	16.04	19.57	20.31	21.21	22.09	22.05	22.53
	(1.50)	(1.00)	(.87)	(.74)	(.66)	(.49)	(.34)
-80.00	15.75	18.82	19.53	20.29	21.23	20.95	21.68
	(1.20)	(.84)	(.69)	(.63)	(.56)	(.48)	(.27)
-60.00	15.21	17.76	18.58	19.34	20.17	20.01	20.58
	(.93)	(.65)	(.60)	(.52)	(.47)	(.38)	(.25)
-40.00	14.44	16.77	17.37	18.10	18.91	18.99	19.42
	(.74)	(.44)	(.49)	(.44)	(.41)	(.31)	(.18)
-20.00	13.41	15.68	16.16	16.97	17.75	17.71	18.20
	(.71)	(.49)	(.46)	(.43)	(.37)	(.23)	(.21)
.00	12.54	14.41	14.92	15.79	16.45	16.48	16.88
	(.36)	(.42)	(.45)	(.34)	(.33)	(.24)	(.22)
20.00	11.21	13.08	13.62	14.38	15.18	15.24	15.62
	(.40)	(.44)	(.37)	(.34)	(.32)	(.20)	(.16)
40.00	9.93	11.69	12.22	13.00	13.85	13.90	14.26
	(.34)	(.34)	(.37)	(.30)	(.35)	(.19)	(.23)
60.00	8.64	10.39	10.85	11.68	12.43	12.54	12.91
	(.28)	(.33)	(.37)	(.28)	(.25)	(.14)	(.21)
80.00	7.41	8.93	9.44	10.30	11.03	11.21	11.57
	(.27)	(.29)	(.32)	(.28)	(.26)	(.14)	(.24)
100.00	6.11	7.66	8.01	8.92	9.62	9.78	10.21
	(.26)	(.31)	(.28)	(.24)	(.23)	(.16)	(.25)
120.00	4.73	6.23	6.75	7.50	8.27	8.45	8.83
	(.22)	(.27)	(.28)	(.23)	(.22)	(.14)	(.26)
140.00	3.49	4.86	5.31	6.14	6.86	7.09	7.45
	(.19)	(.26)	(.24)	(.21)	(.21)	(.14)	(.28)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

APPENDIX

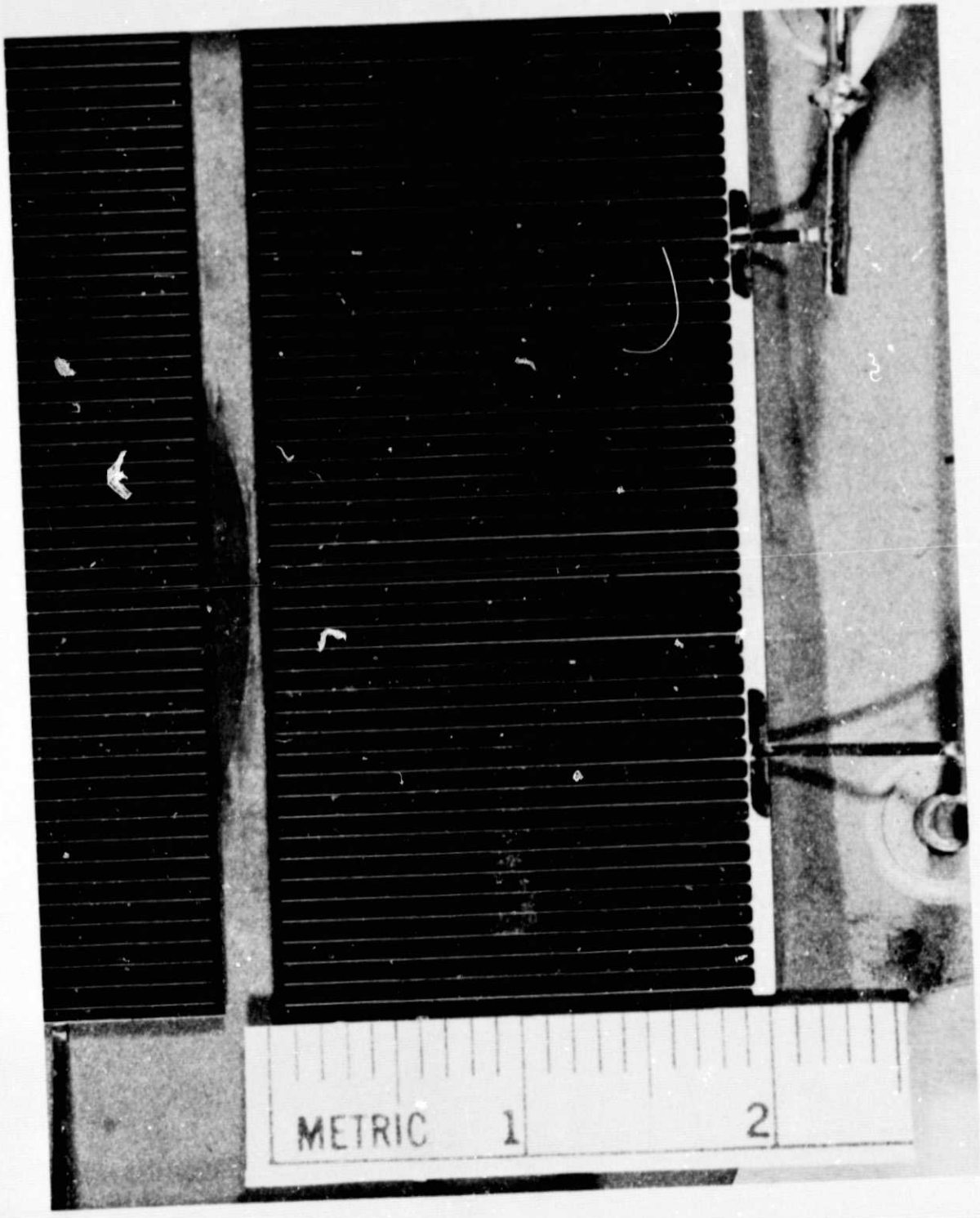

Figure A-1. Solar Cell

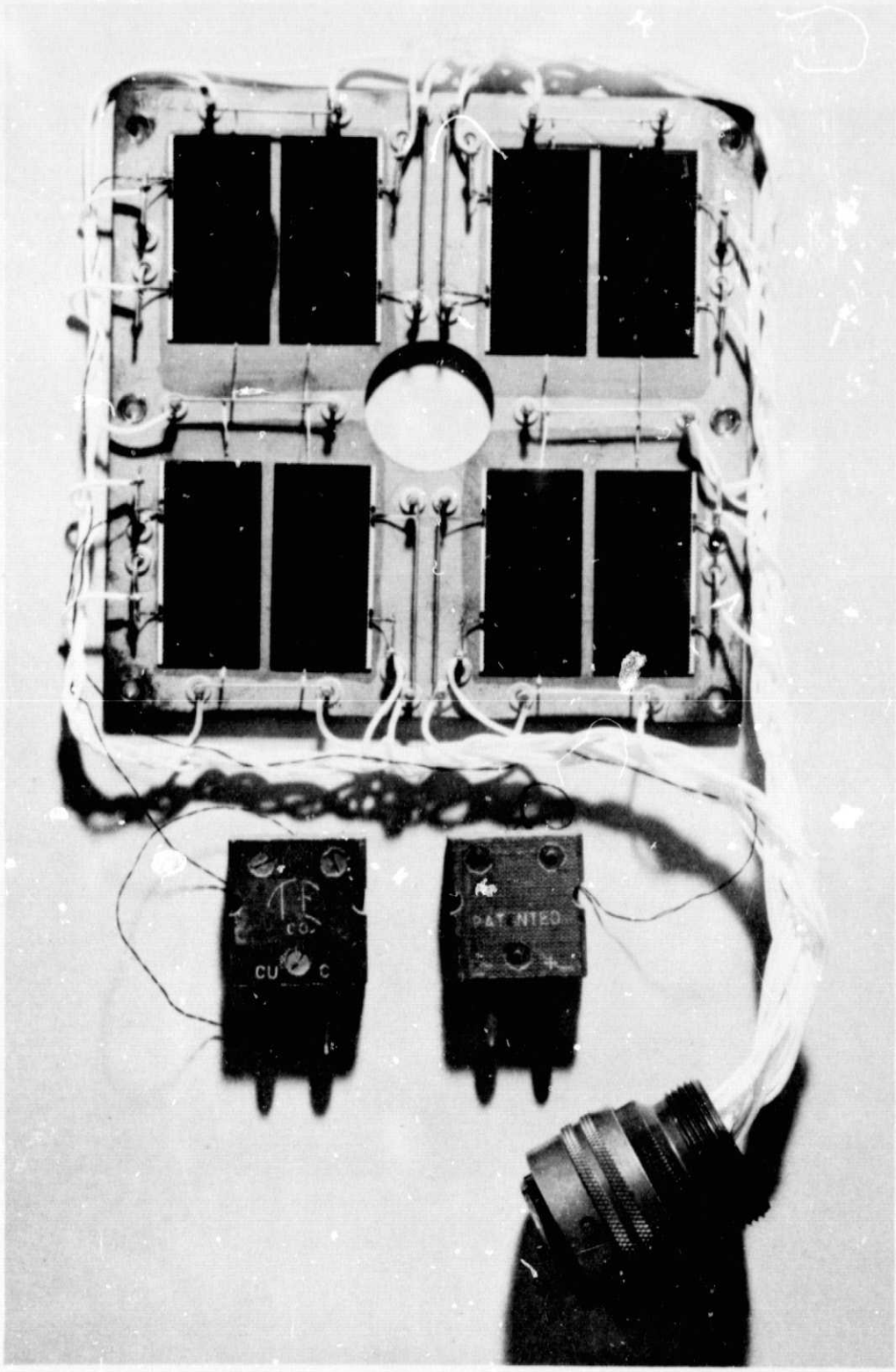

Figure A-2. Test Plate

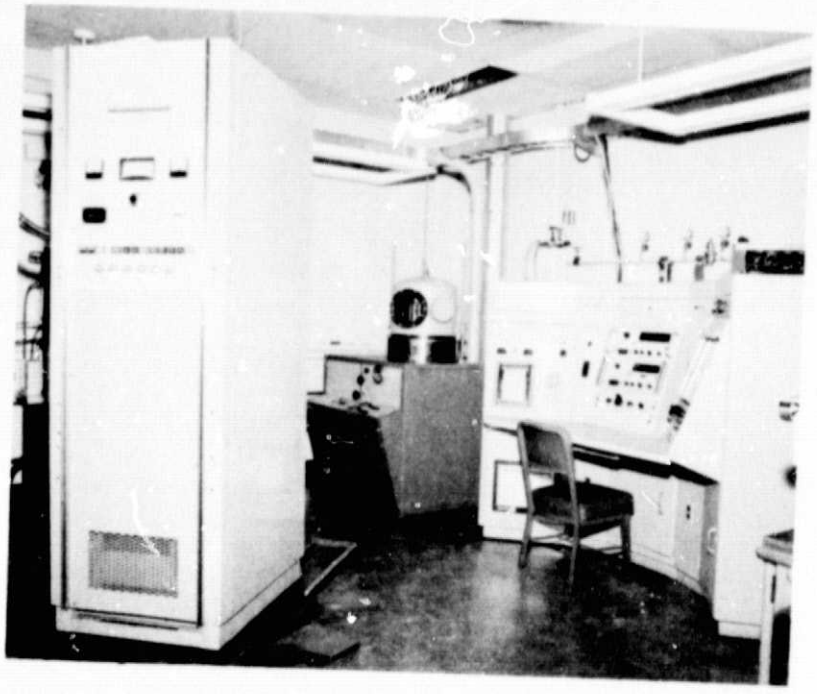

Figure A-3. Solar Cell Characterization Facility

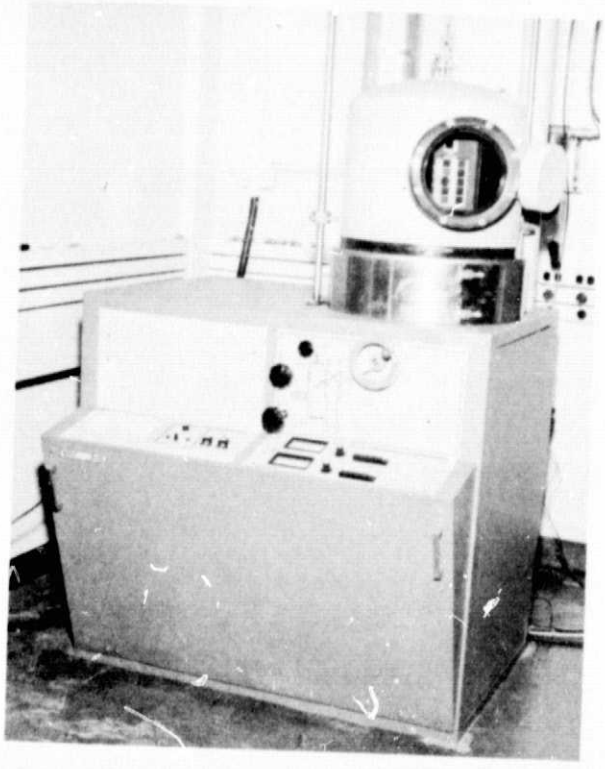

Figure A-4. Solar Cell Environmental Test Chamber

NASA—JPL—Comi., L.A., Calif.