JPL PUBLICATION 78-15, VOLUME XI

Characterization of Solar Cells for Space Applications

Volume XI. Electrical Characteristics of 2 Ohm-cm, 228 Micron Wraparound Solar Cells as a Function of Intensity, Temperature, and Irradiation

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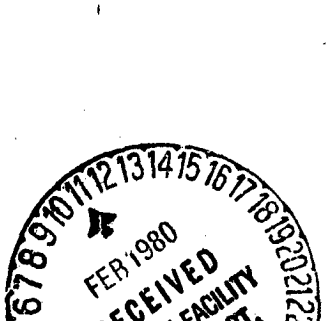

January 15, 1980

National Aeronautics and
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The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract No. NAS7-100.

ACKNOWLEDGEMENT

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 of Diane Eugler who operates the program and produces the plots. Absorptance measurements were performed by Jerry Brown of the TRW Thermophysics Laboratory.

ABSTRACT

Electrical characteristics of Spectrolab 2 ohm-cm, 228-micron wrap-around N/P silicon solar cells are presented in graphical and tabular format as a function of solar illumination intensity, temperature, and 1 MeV electron irradiation.

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Figures

Tables

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 to this document. Each report consists primarily of working graphs and tables and does not address itself to interpretive conclusions. The formatting of this series of reports will be 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 2 x 4 cm, 2 ohm-cm, 228-micron-thick wraparound cell, which was produced in limited quantity as a possible candidate for the Solar Electric Propulsion Mission.

SECTION II

CELL DESCRIPTION

The cells reported here were manufactured by Spectrolab in a limited production run, but they have not undergone a full space qualification program. They are fabricated from crucible-grown, P-type silicon, boron-doped to a resistivity of 1-3 ohm-cm (2 ohm-cm nominal). The cell dimensions are 2 x 4.04 x 0.0228 cm (9 mils) thick. The electrical contacts on both the front and back surfaces are evaporated Cr-Pd-Ag. The contact pattern on the front is a 4-cm-long strip, 0.10 cm wide running down the center of the cell with 30 fingers approximately 0.01 cm wide at right angles. The junction (0.15 microns deep) is wrapped around the cell on the short edges under the ends of the wide contact bar. The contact wraps around the edge also and terminates in 0.38 x 0.49-cm contact pads on the rear surface of the cell. These pads are electrically insulated from the large p contact by a dielectric layer. These cells are not textured and have no back surface fields or back surface reflectors. The antireflection coating is Ta_2O_5.

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 a vacuum at a pressure of less than 1×10^{-6} torr.

After the initial 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 1×10^{16} e/cm^2. During irradiation, the cells were maintained at 28°C. I-V curves of the solar cells are 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, then remeasured. This procedure was used for all fluences higher than 10^{14} e/cm^2. The annealed cell data is used in this report.

Six unirradiated single cells from the same lot of cells were sent to TRW for absorptance measurements. These measurements were made using a Gier Dankle integrating sphere spectrometer. The reflectance is measured over the wavelength range 0.28 to 2.5 micrometers. Absorptance is calculated by weighting the reflectance with the AMO solar spectrum and subtracting from one.

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 2.50-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 Figures 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 with the cells under test. Prior, intermediate, and post-test ambient measurements were performed daily to ensure 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.

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 Figures 1 to 14. Least square fits to the data points are then made automatically to the measured data points using a second-degree polynomial for most parameters. The V_{oc} and V_{mp} data points, curve factors, and AMO efficiencies are not fit but are 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 Figures 15 through 18. The results of the electron irradiation are shown in Figures 19 through 23.

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 <u>total</u> 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}, I_{mp}, V_{mp}, 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 are on the basis of unit area derived by dividing measured output by total cell area.

The absorptance of these solar cells was found to be 0.78 ± 0.01.

The low-temperature, low-intensity I-V curves of these cells varied greatly from cell to cell as can be inferred from the large standard deviations in the tabulated electrical parameters. All cells exhibited the Schottky barrier curve near V_{oc} at low temperatures and most cells suffered from the "broken knee" effect at low temperature. These effects are not attributable to the wraparound configuration since cells of standard design behave the same way. At higher temperature regions of normal spacecraft operation the cells exhibit no anomalous behavior.

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Characterization of Solar Cells for Space Applications, JPL Publication 77-15

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

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Volume V. Electrical Characteristics of OCLI 225-Micron MLAR Wraparound Cells as a Function of Intensity, Temperature, and Irradiation, April 1978.

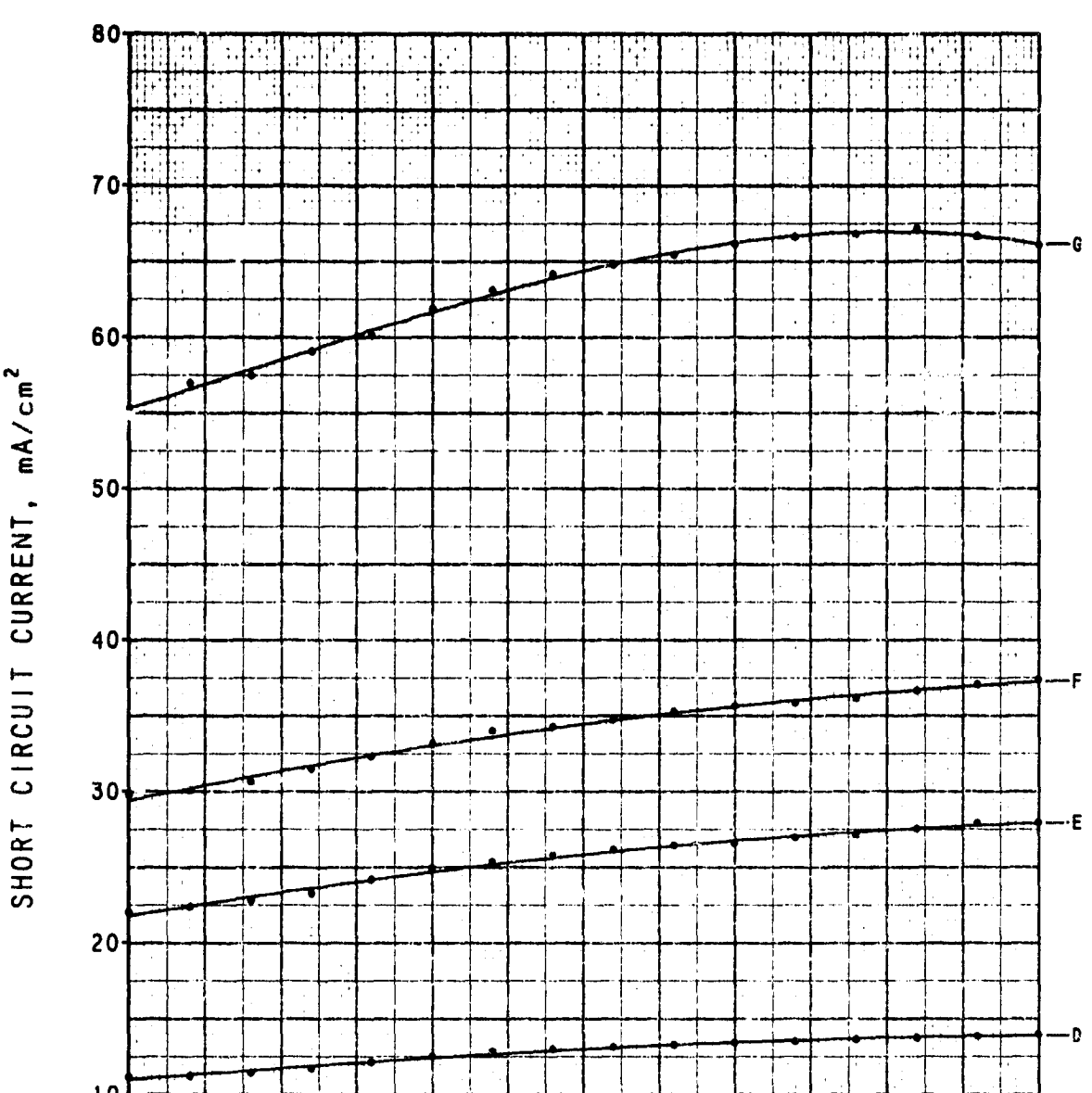
Volume VI. Electrical Characteristics of Spectrolab BSF, BSR, Textured, 10 ohm-cm, 50-Micron Advanced OAST Solar Cells as a Function of Intensity, Temperature, and Irradiation, June 1979.

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

Volume VIII. Electrical Characteristics of Spectrolab BSF, BSR, Textured, 10 Ohm-cm 290-Micron Solar Cells (K7) as a Function of Intensity and Temperature, September 1979.

Volume IX. Electrical Characteristics of Spectrolab BSF, Textured, 10 Ohm-cm 200-Micron Solar Cells as a Function of Intensity, Temperature, and Irradiation, September 1979.

Volume X. Electrical Characteristics of Spectrolab BSF, Textured, 10 Ohm-cm 300-Micron Solar Cells as a Function of Intensity and Temperature, October 1979.



ID	mW/cm²
A	5.0
B	15.0
C	25.0
D	50.0
E	100.0
F	135.3
G	250.0

SPECTROLAB WRAPAROUND
N/P 2 OHM-CM CG SILICON
2 X 4 X .0228 CM
CR-PD-AG CONTACTS
1 X 30 GRID LINES
TA2O5 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-48

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

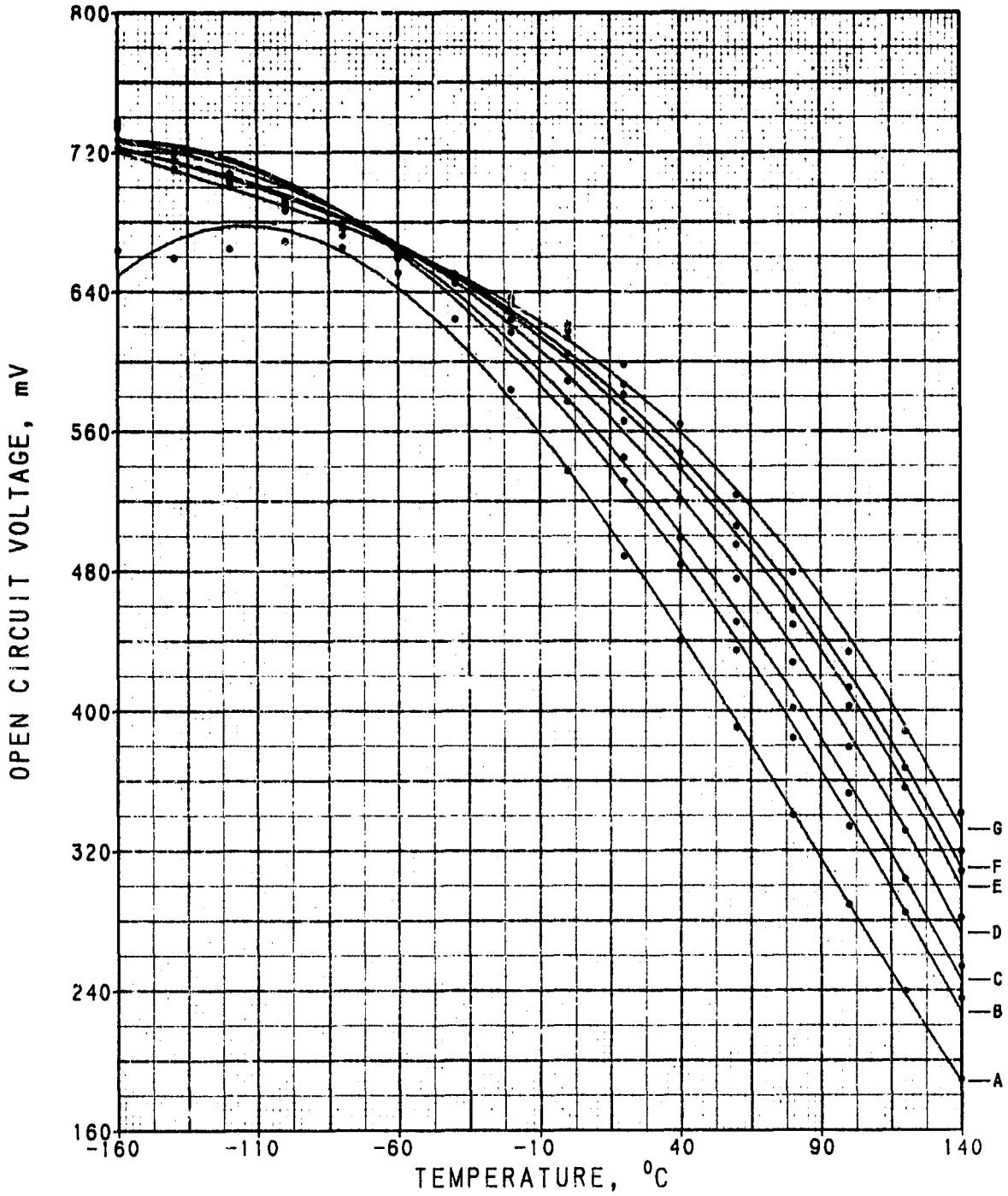


Figure 2. Average V_{oc} as a Function of Temperature

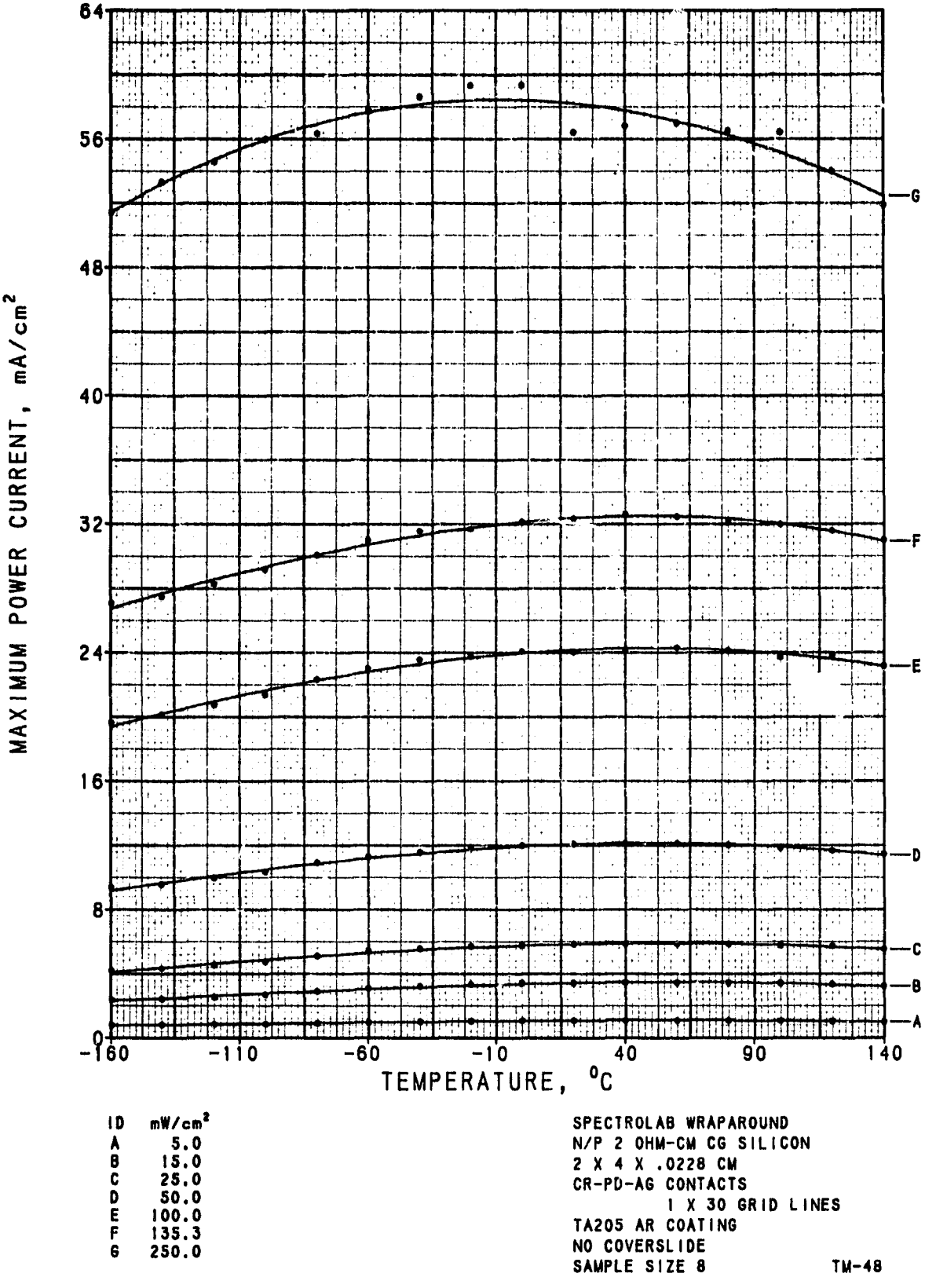


Figure 3. Average I_{mp}/cm^2 as a Function of Temperature

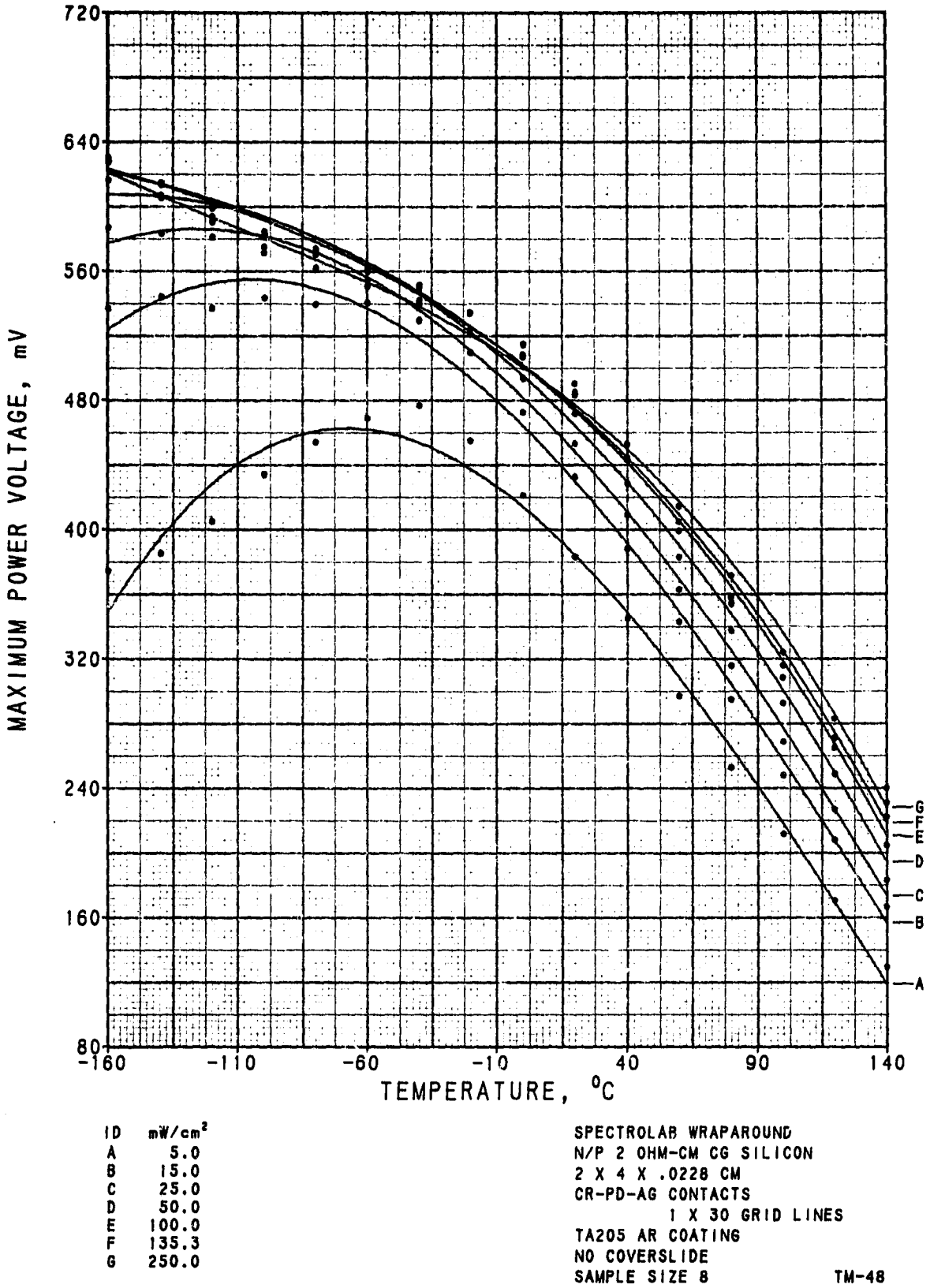
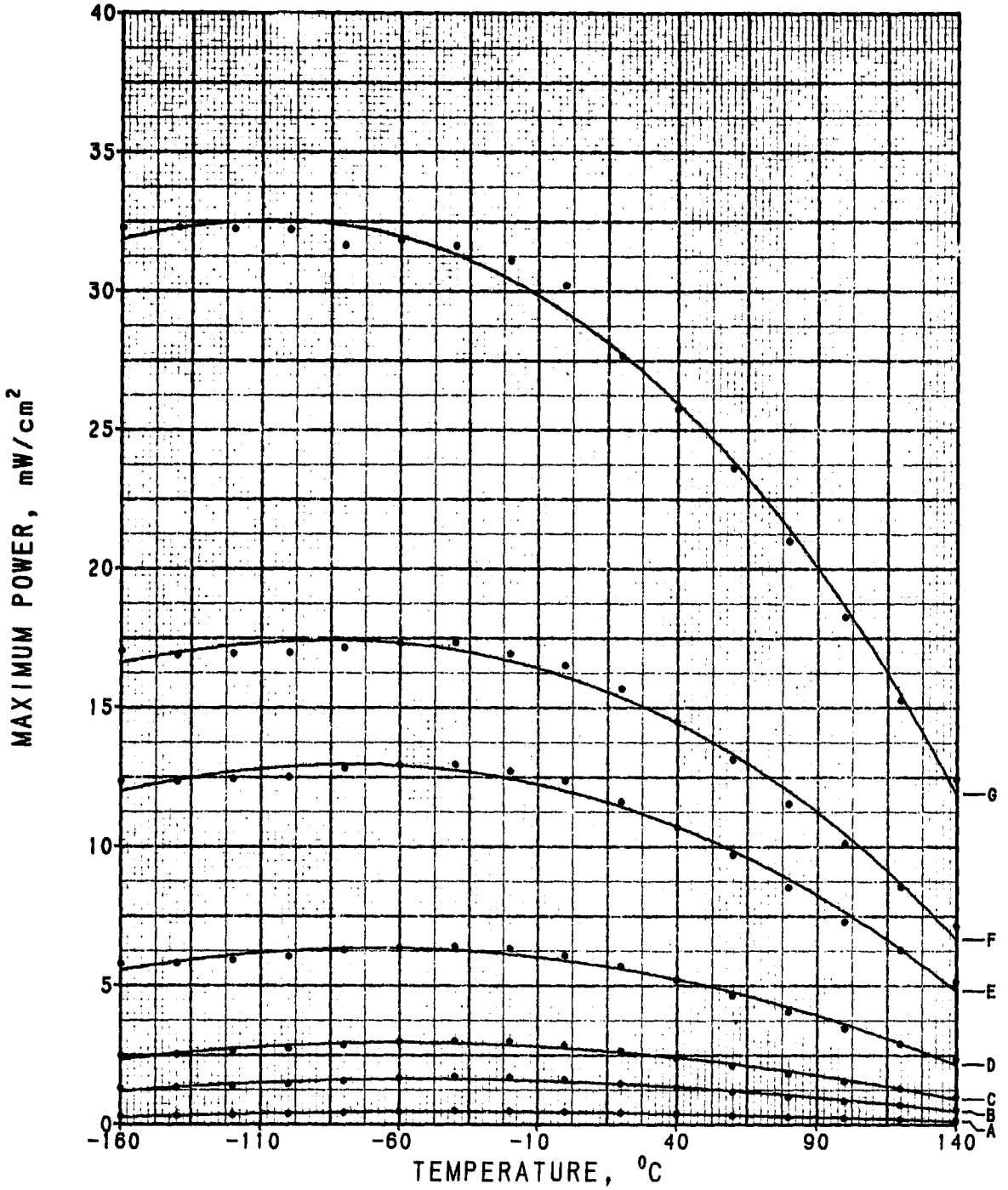


Figure 4. Average V_{mp} as a Function of Temperature



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D	50.0
E	100.0
F	135.3
G	250.0

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

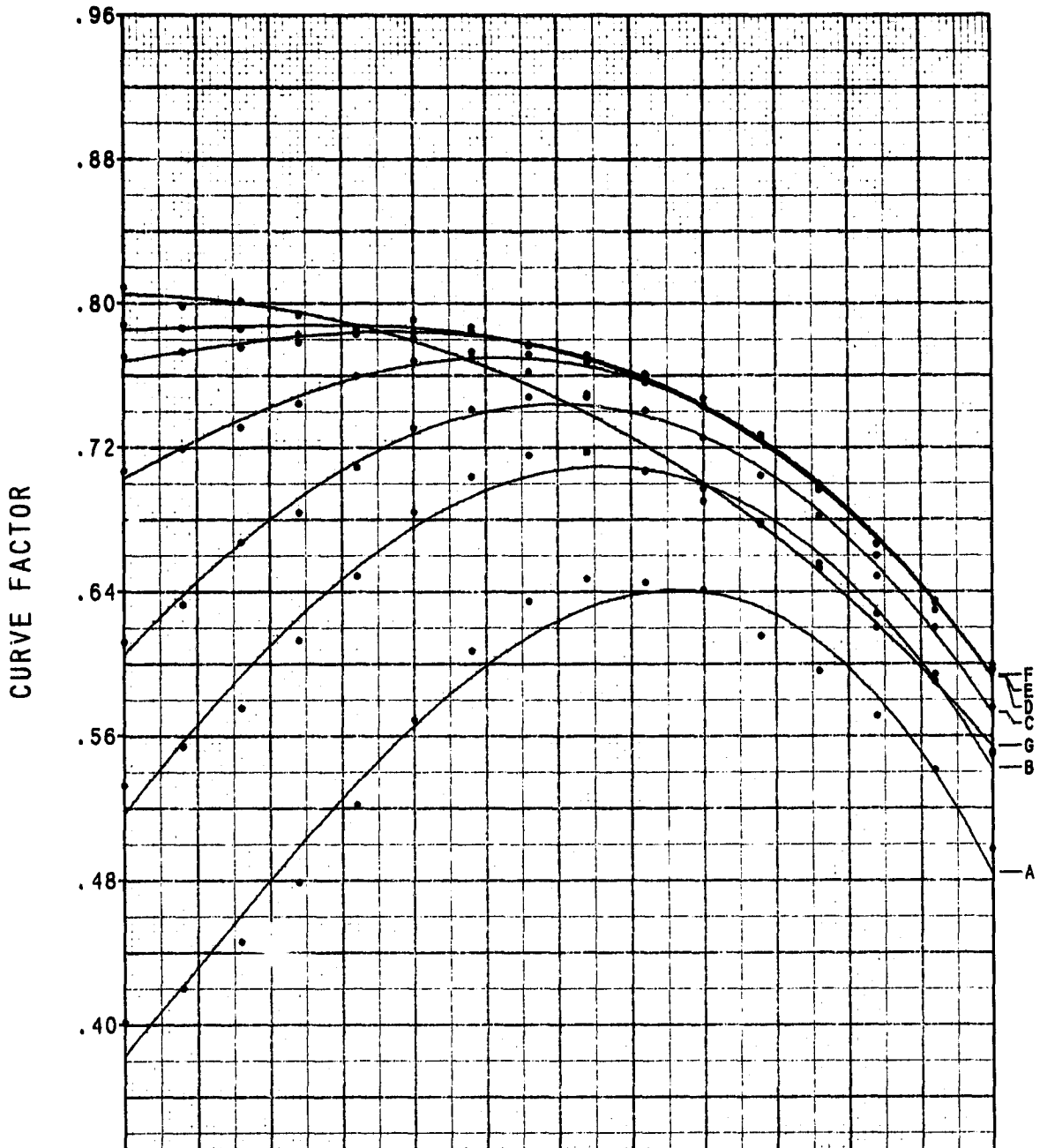

Figure 6. Average Curve Factor as a Function of Temperature

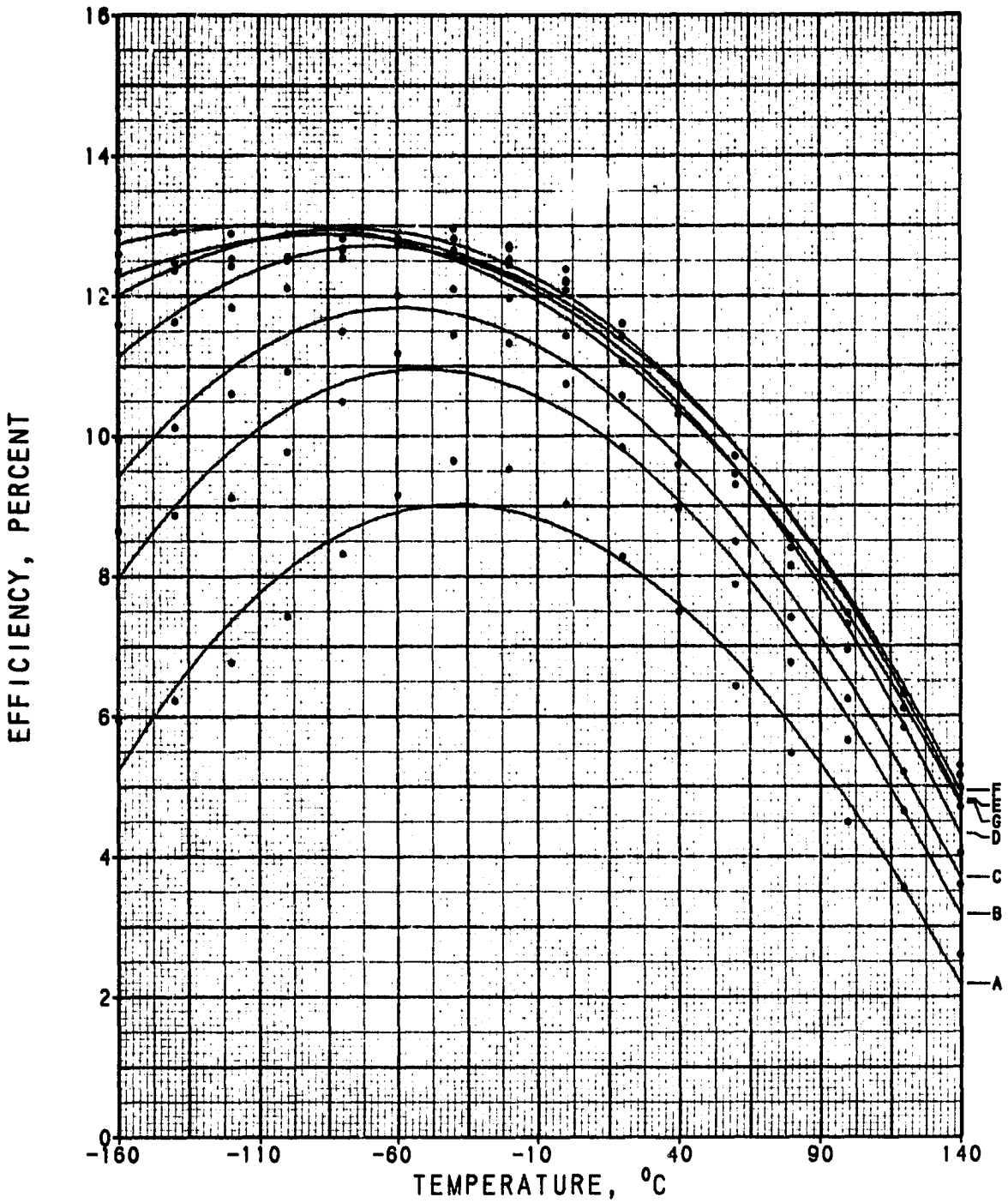

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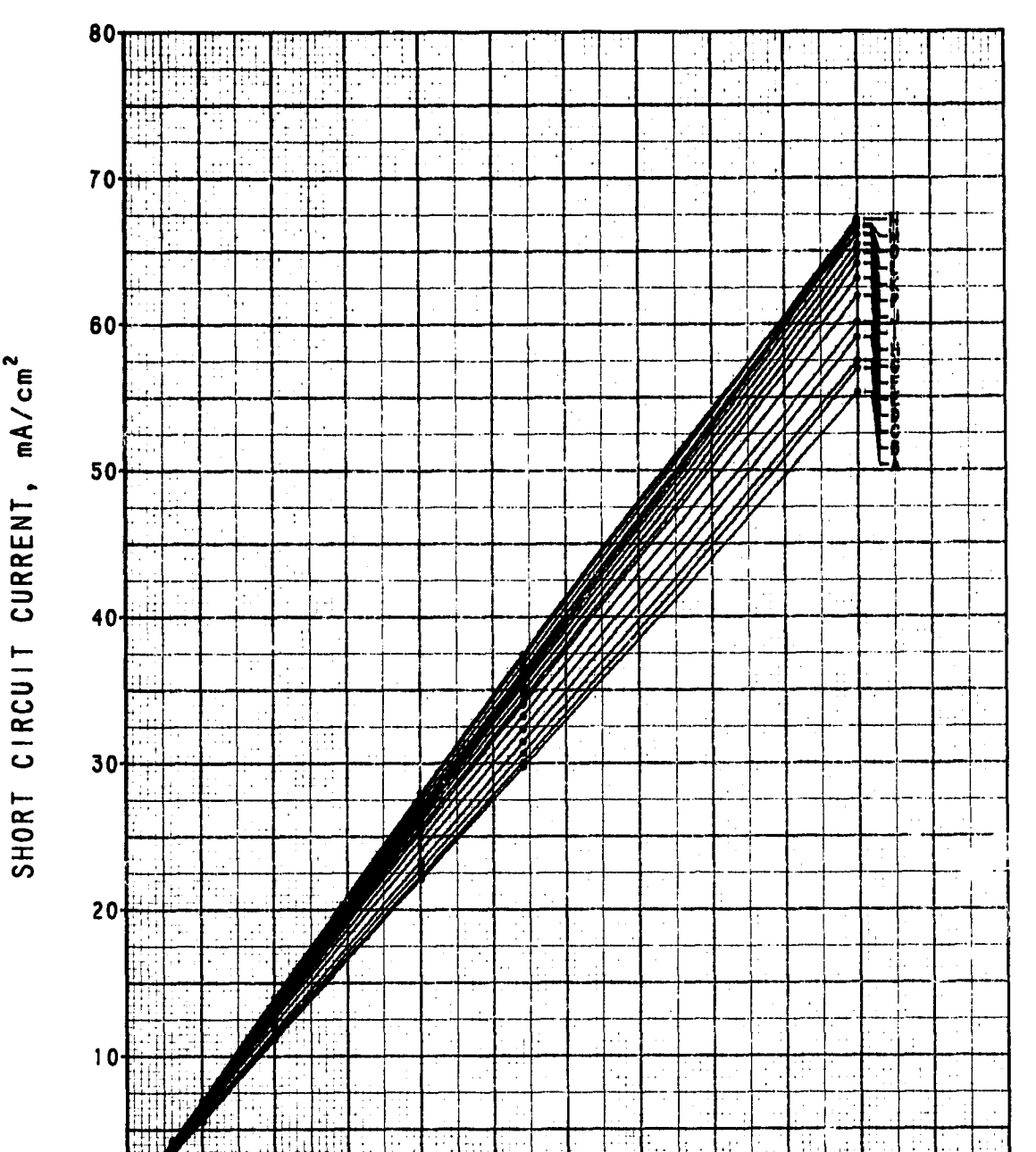
Figure 7. Average AMO Efficiency as a Function of Temperature



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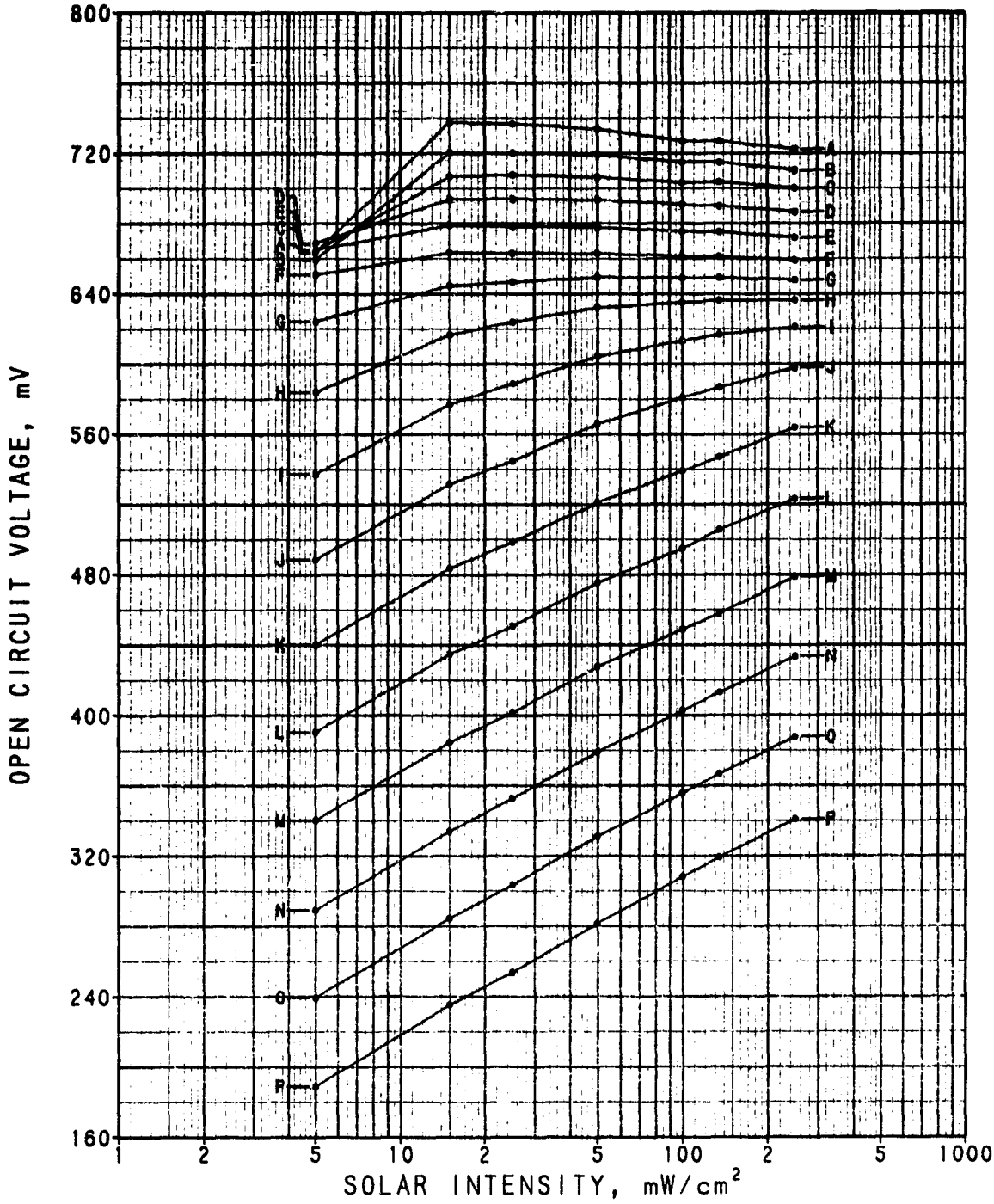
Figure 8. Average I_{sc}/cm^2 as a Function of Intensity



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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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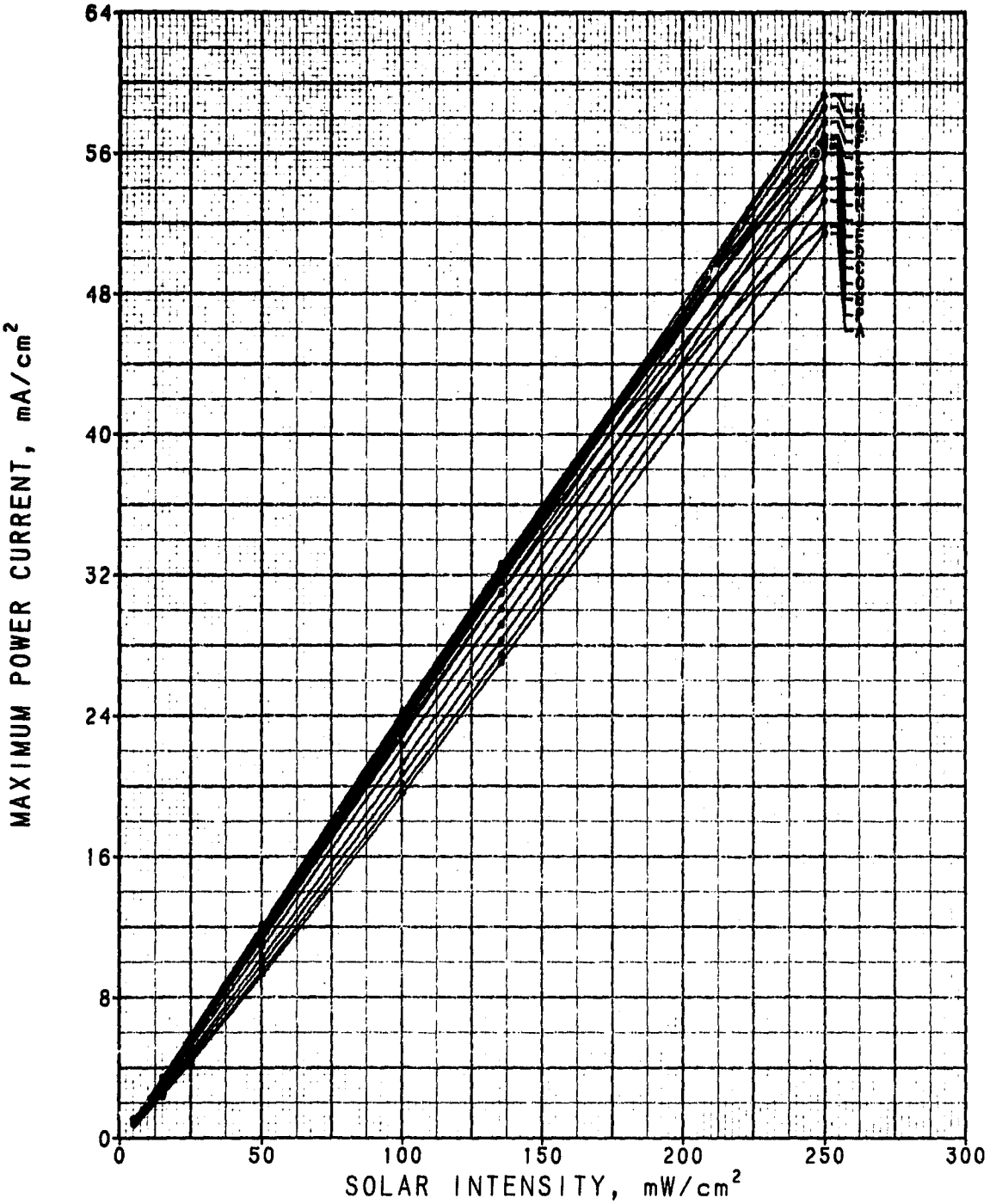
Figure 9. Average V_{oc} as a Function of Intensity



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F	-60.0	N	100.0
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Figure 10. Average I_{mp}/cm^2 as a Function of Intensity

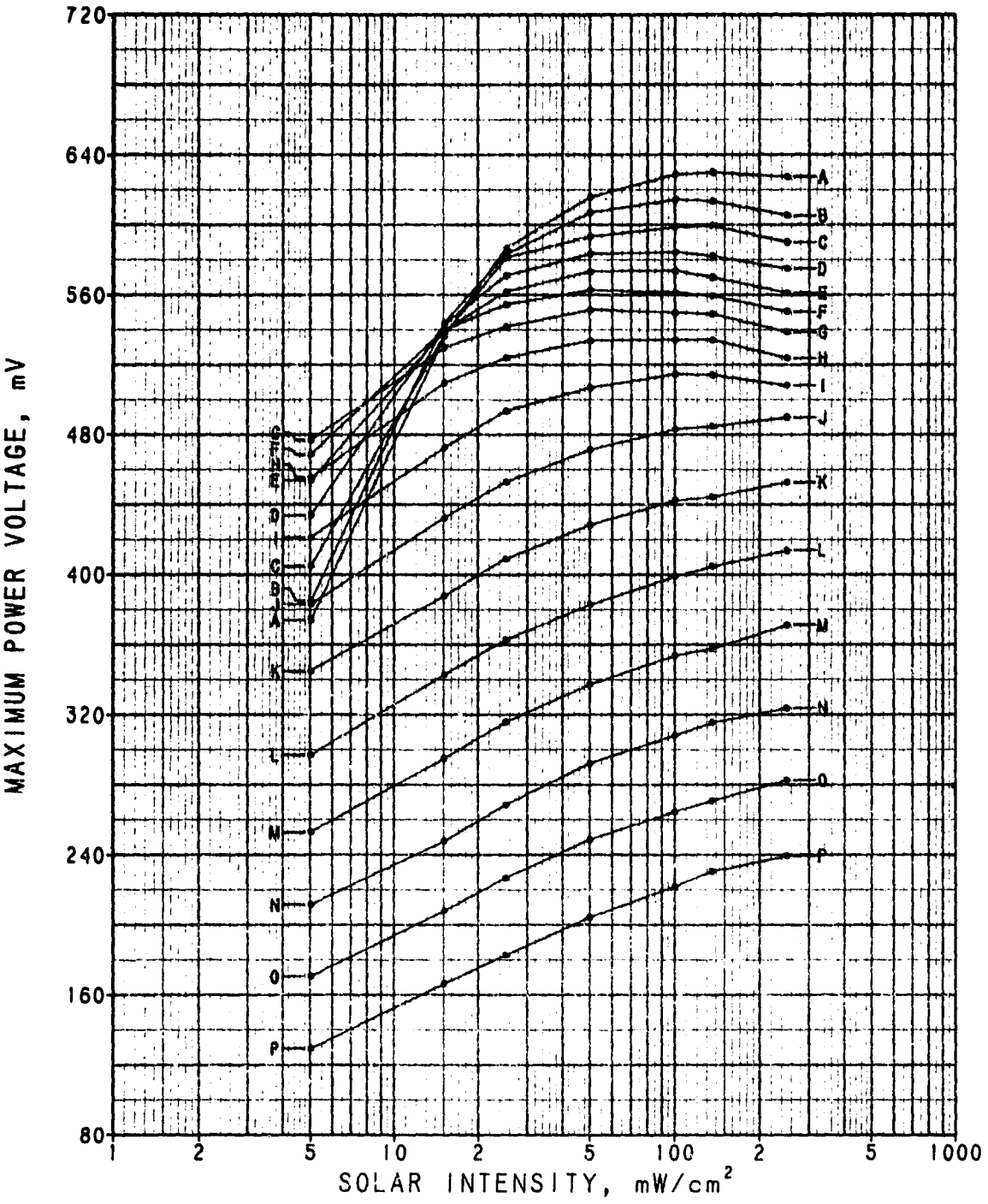

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Figure 11. Average V_{mp} as a Function of Intensity

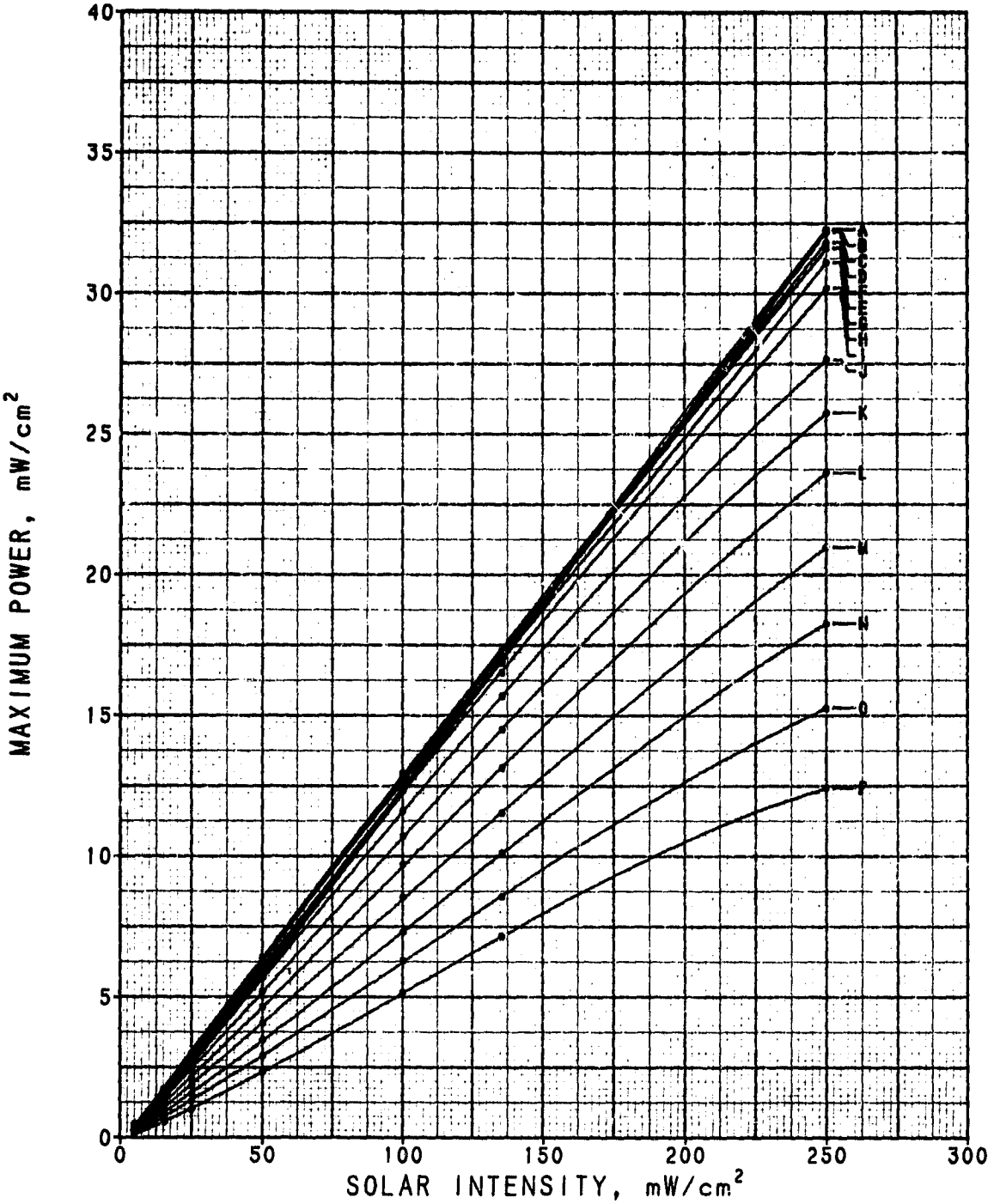

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Figure 12. Average P_{max}/cm^2 as a Function of Intensity

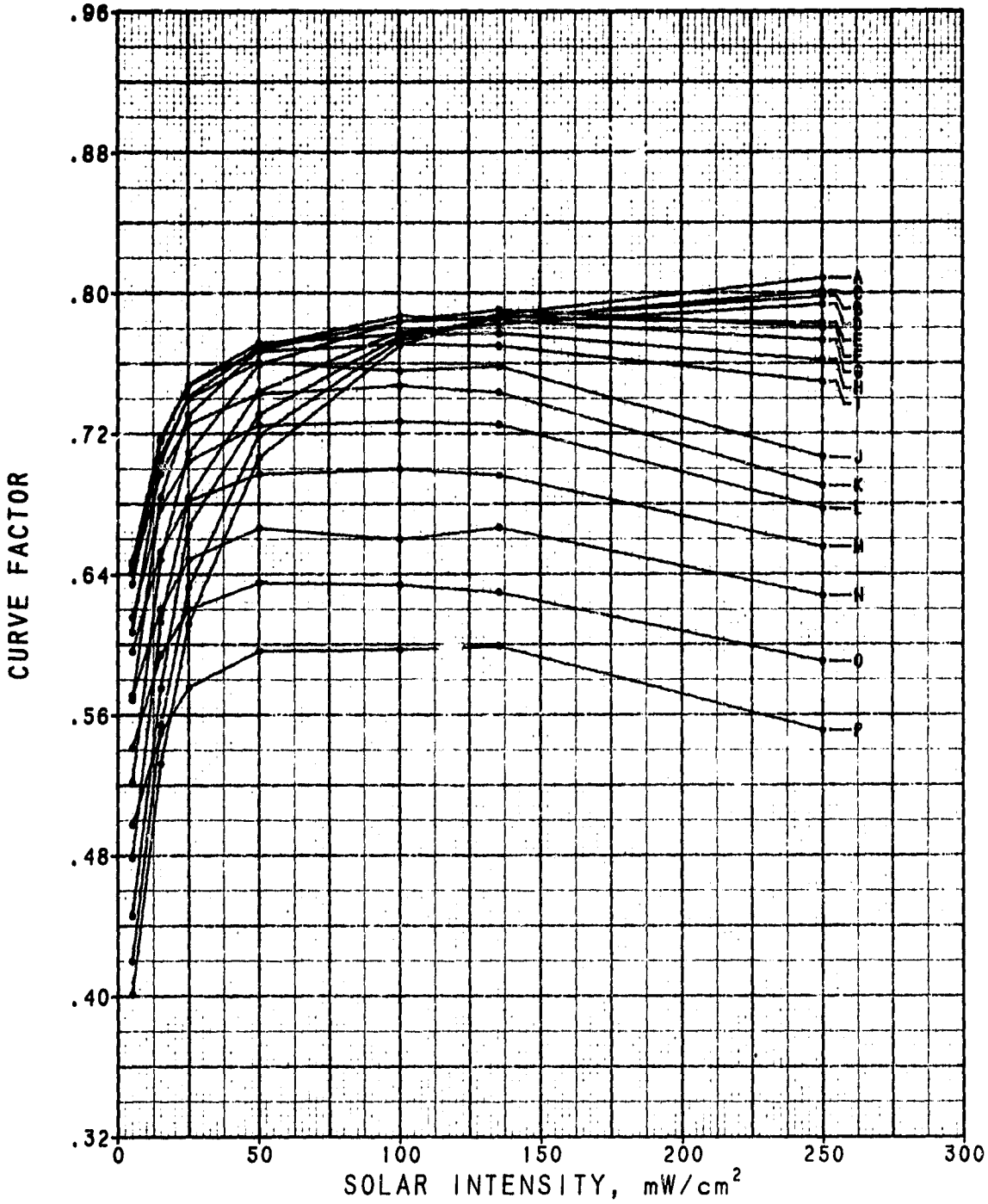

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Figure 13. Average Curve Factor as a Function of Intensity

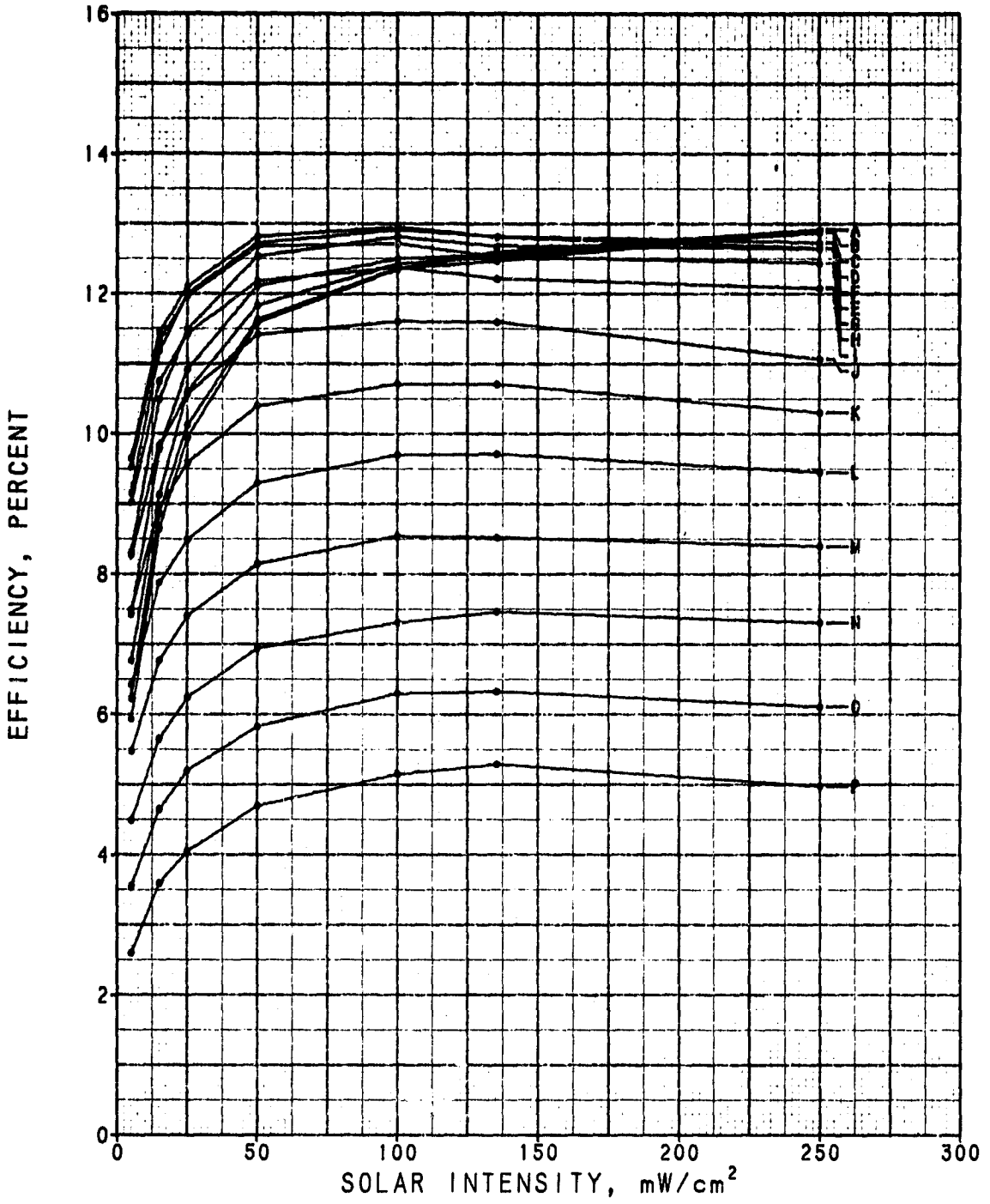

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Figure 14. Average AMO Efficiency as a Function of Intensity

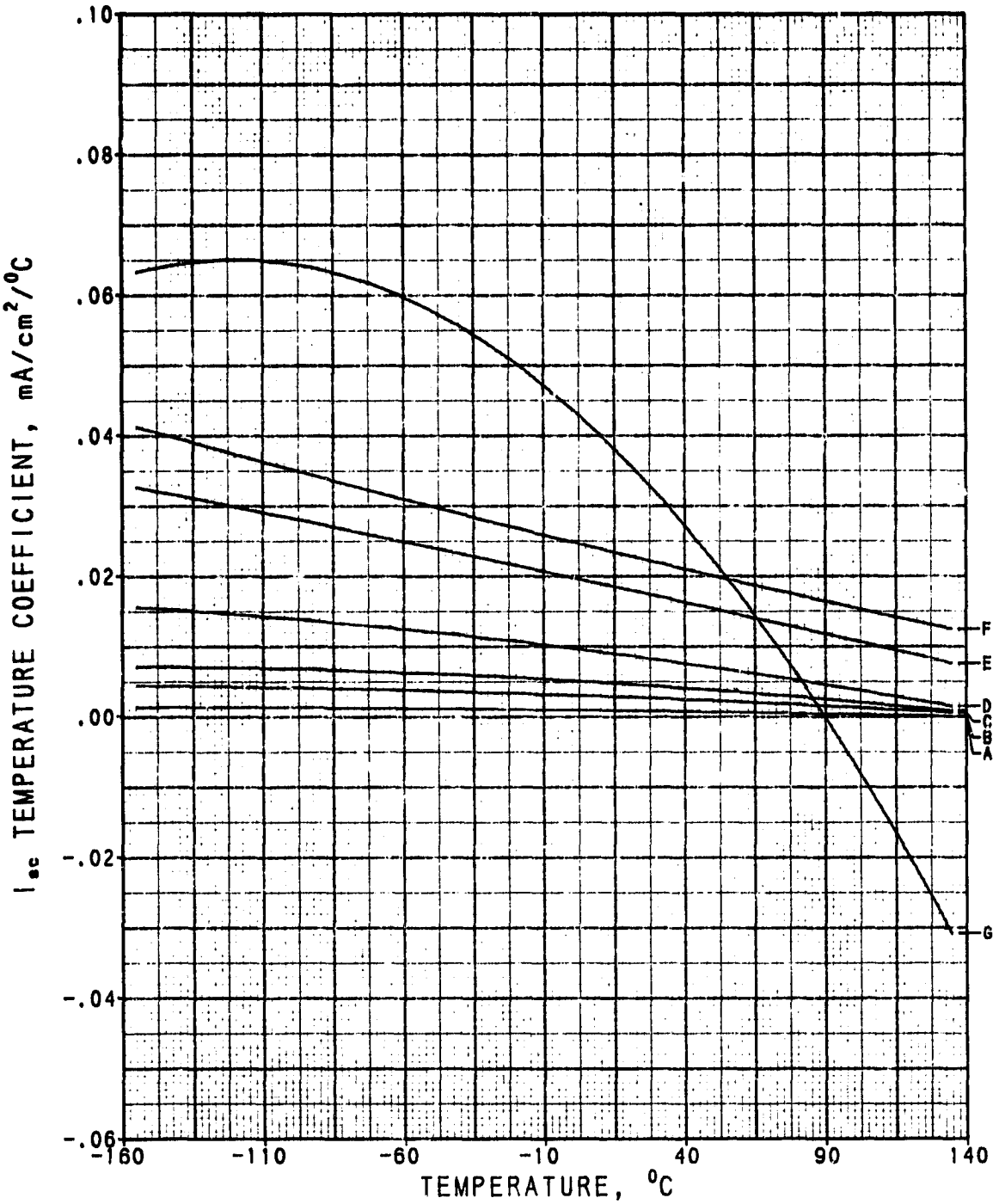

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Figure 15. I_{SC} Temperature Coefficient

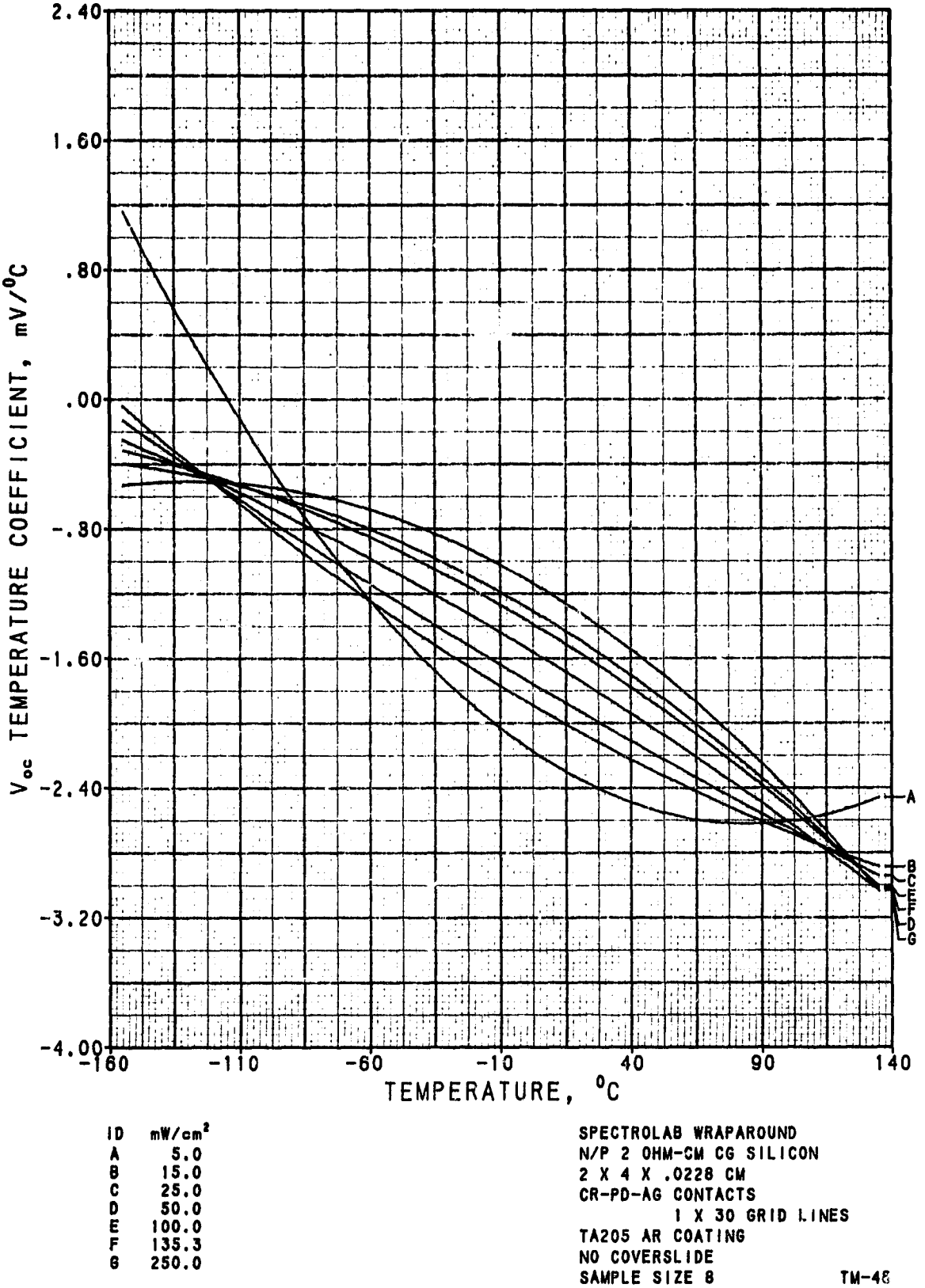

Figure 16. V_{oc} Temperature Coefficient

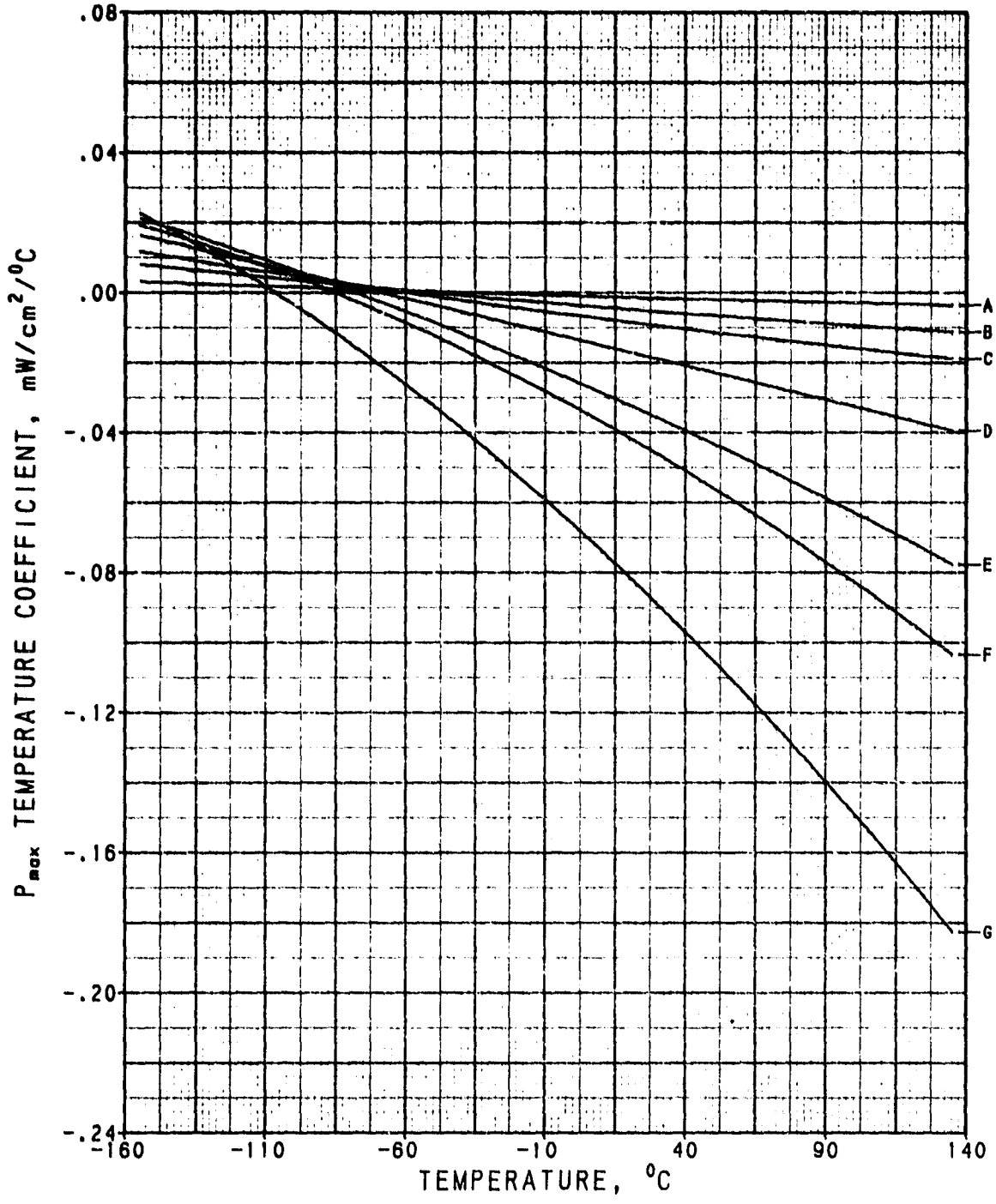

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Figure 17. Absolute P_{max} Temperature Coefficient

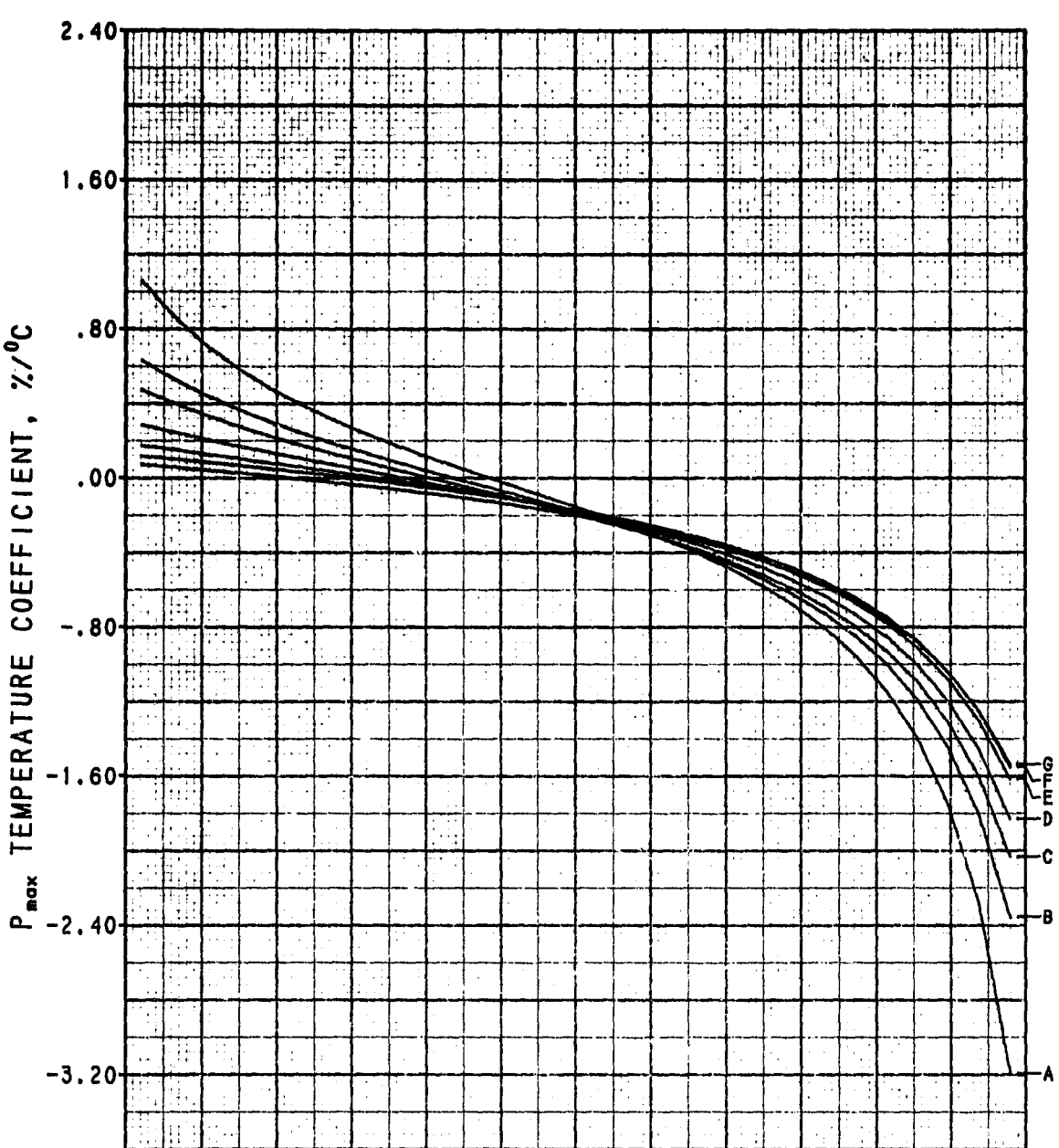

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Figure 18. Percent P_{max} Temperature Coefficient

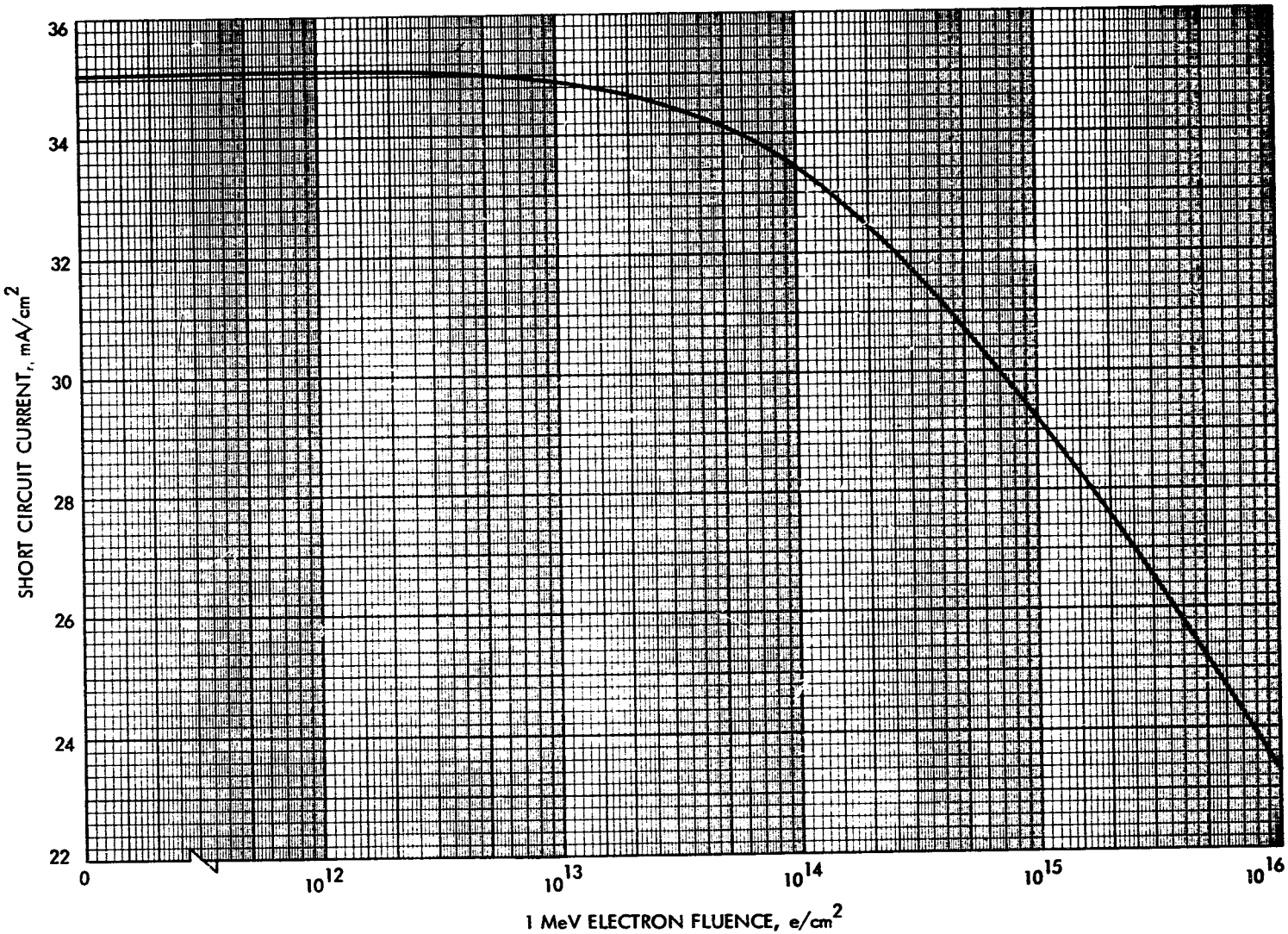

Figure 19. Short Circuit Current Density vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

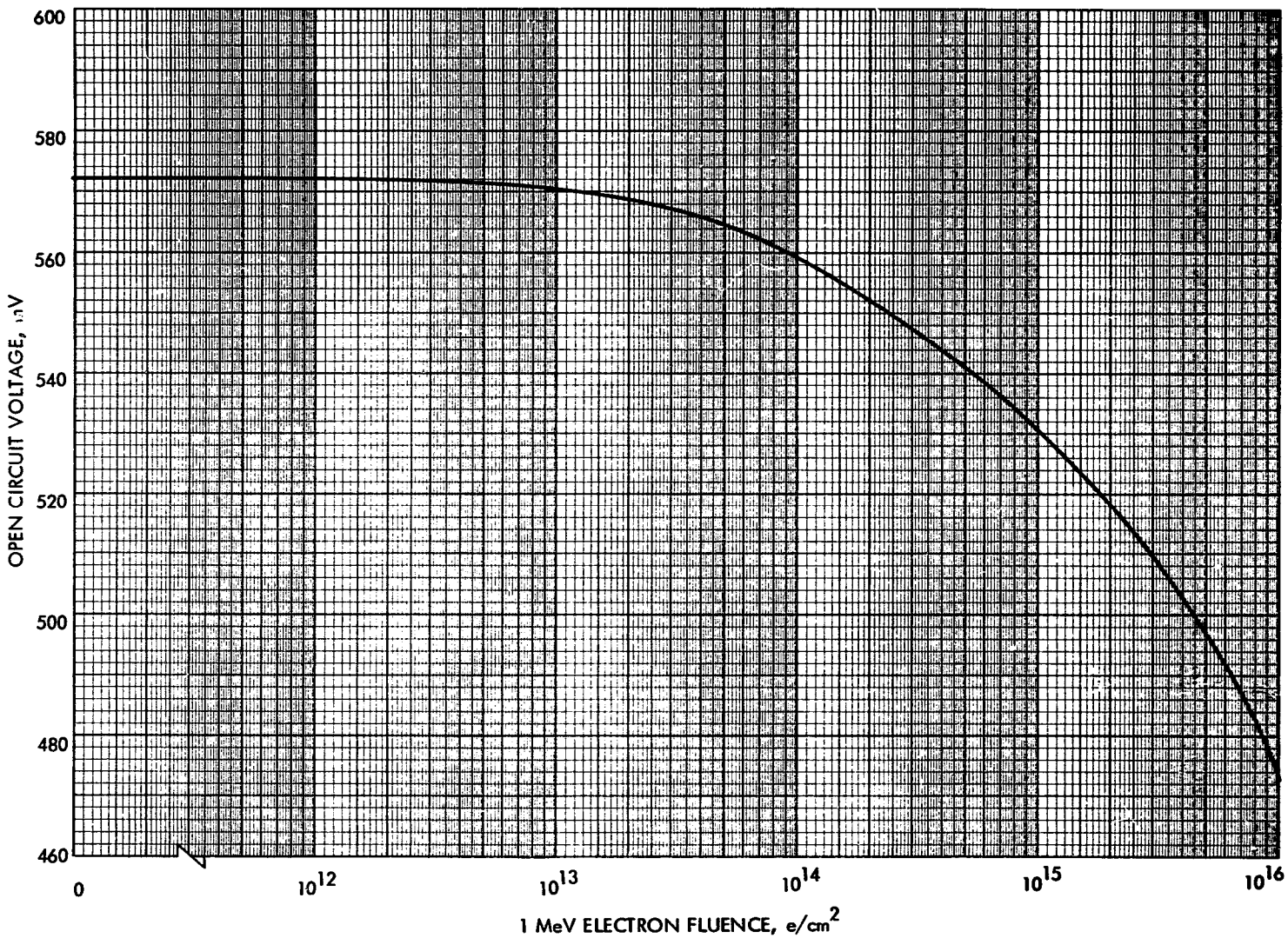

Figure 20. Open Circuit Voltage vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

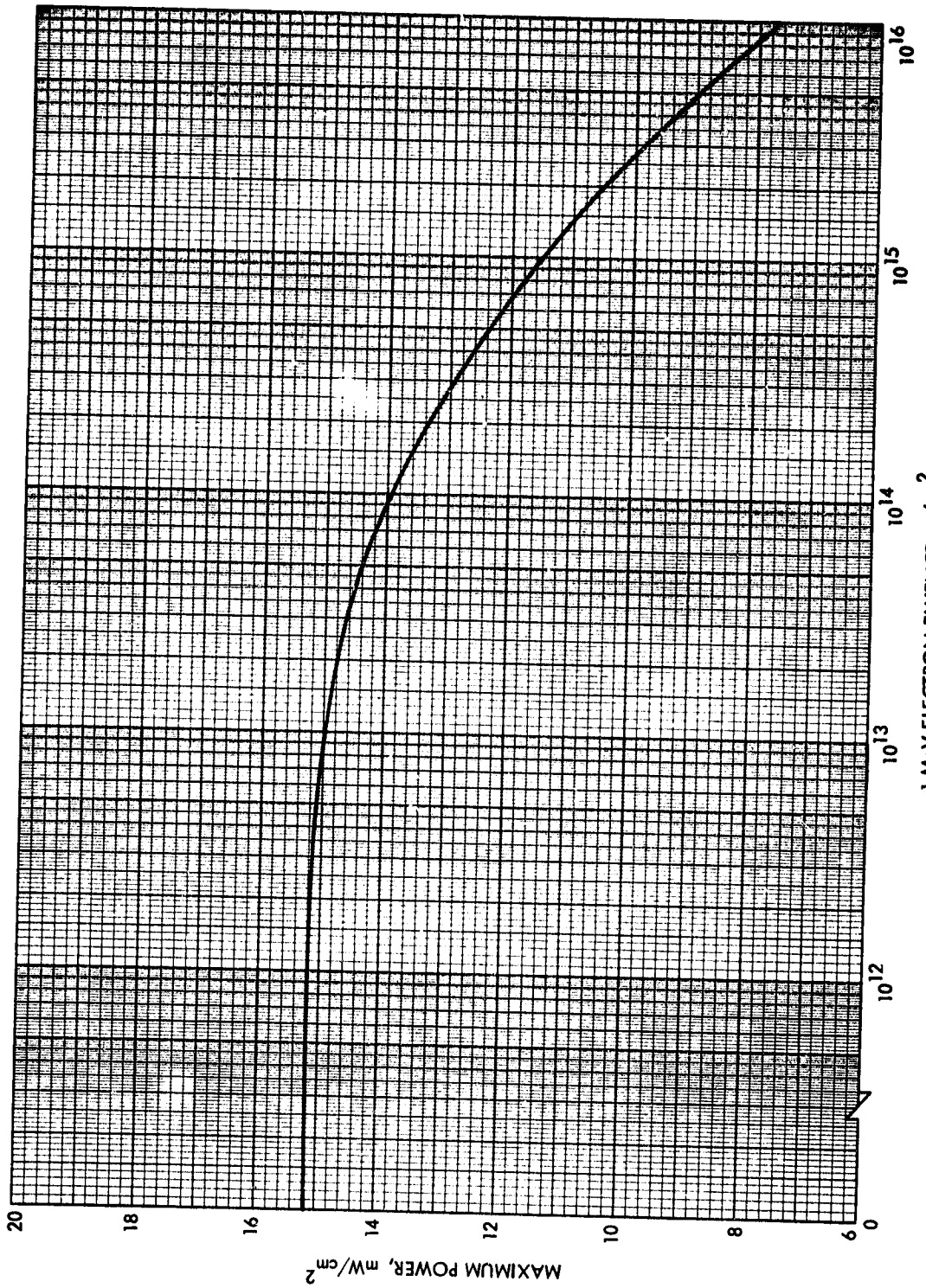

Figure 21. Maximum Power Density vs 1 MeV Electron Fluence at 135.3 mW/cm² AMO Illumination, 28°C

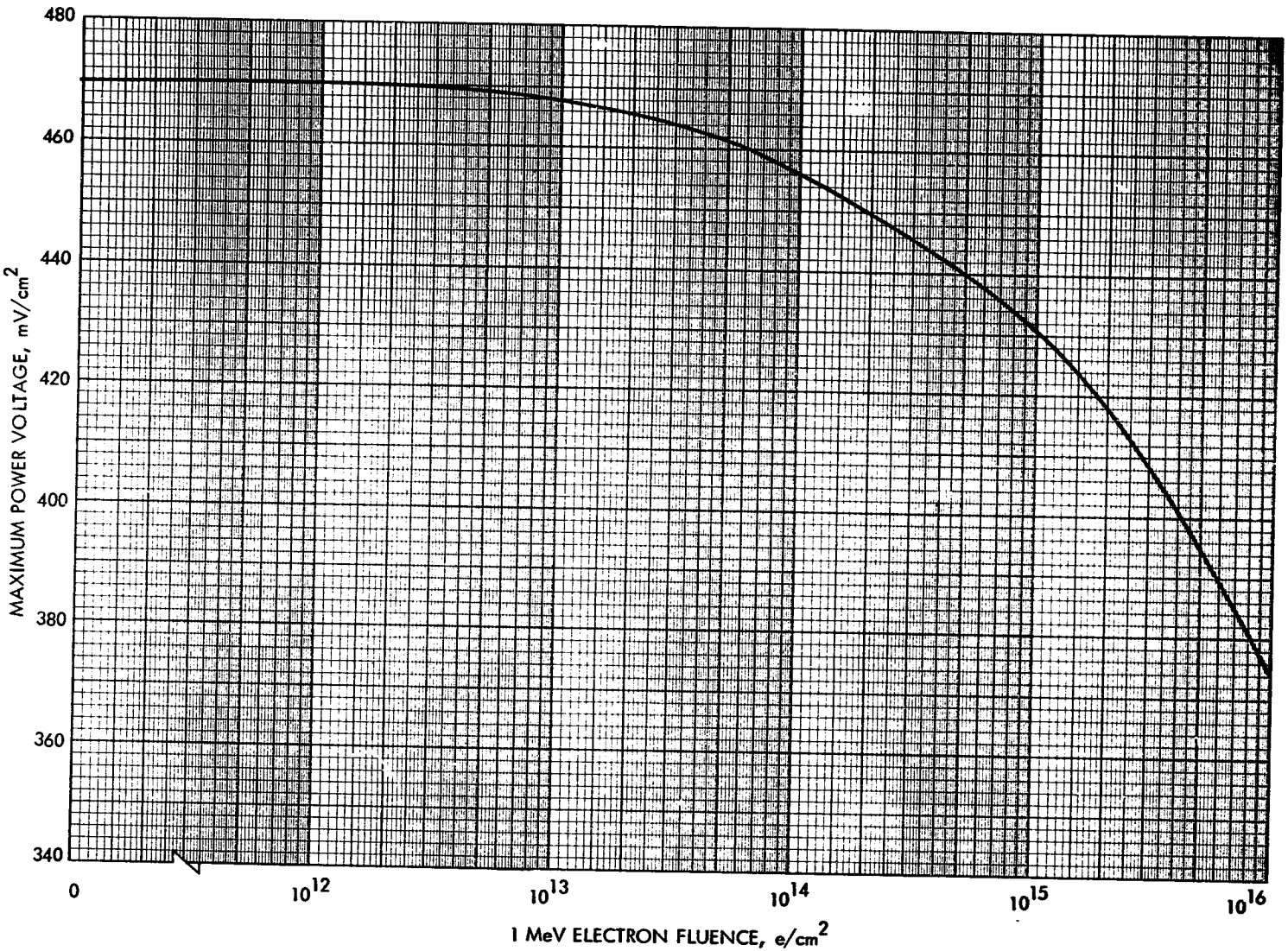

Figure 22. Voltage at Maximum Power vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

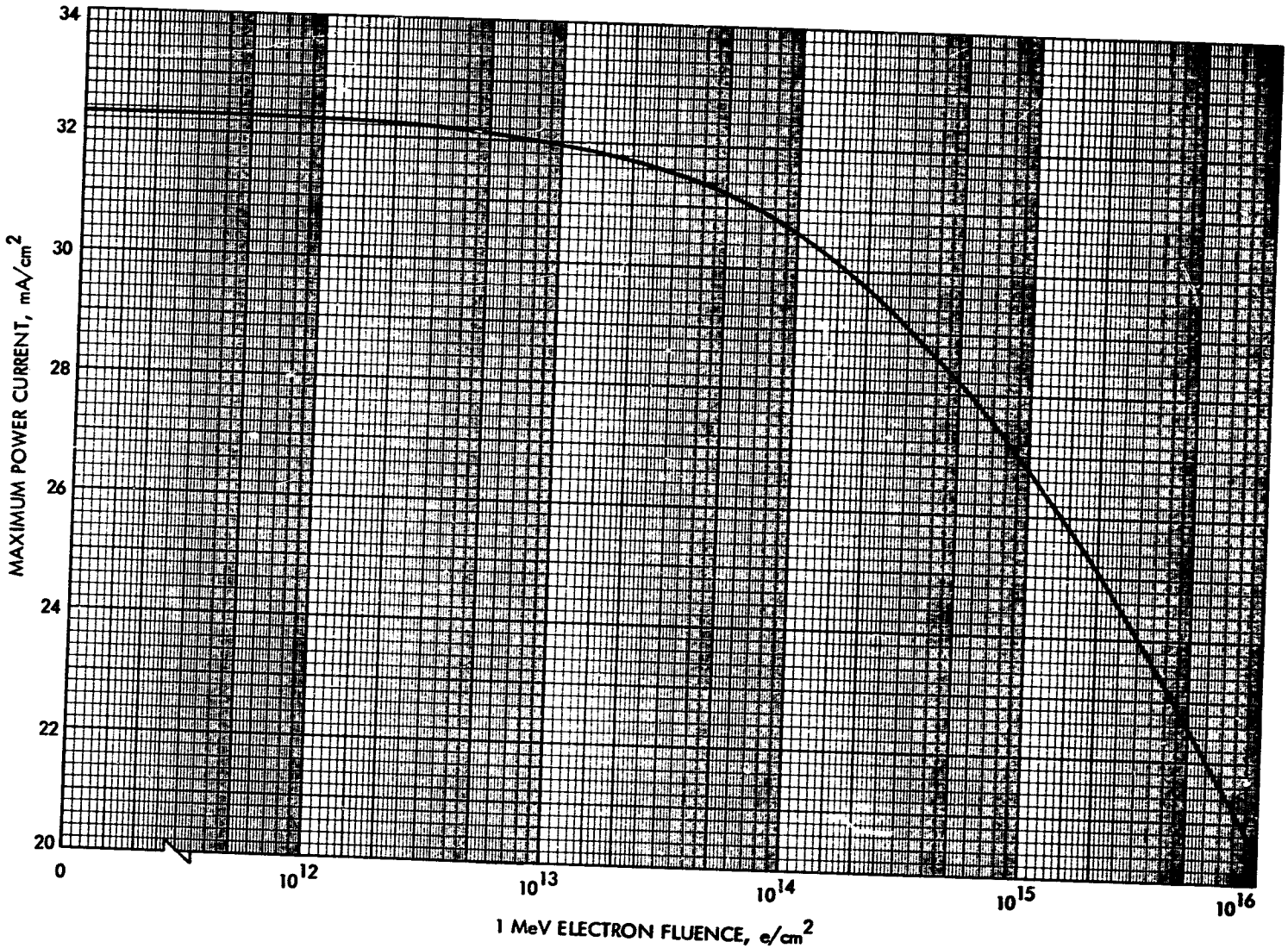

Figure 23. Maximum Power Current Density vs 1 MeV Electron Fluence at 135.3 mW/cm^2 AMO Illumination, 28°C

Table 1. Average Short-Circuit Current

SPECTROLAB WRAPAROUND
N/P 2 OHM-CM CG SILICON
2 X 4 X .0228 CM
CR-PD-AG CONTACTS
1 X 30 GRID LINES
TA205 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-48

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	1.11	3.29	5.51	11.18	22.05	29.74	55.26
	(.02)	(.07)	(.12)	(.17)	(.51)	(.58)	(1.01)
-140.00	1.12	3.33	5.55	11.23	22.36	30.03	56.91
	(.02)	(.06)	(.12)	(.22)	(.47)	(.56)	(1.20)
-120.00	1.13	3.36	5.61	11.45	22.78	30.66	57.43
	(.02)	(.06)	(.10)	(.19)	(.46)	(.63)	(1.17)
-100.00	1.15	3.45	5.75	11.73	23.26	31.45	59.08
	(.02)	(.06)	(.09)	(.18)	(.36)	(.61)	(1.07)
-80.00	1.19	3.57	5.97	12.18	24.19	32.29	60.09
	(.02)	(.04)	(.06)	(.15)	(.29)	(.43)	(.83)
-60.00	1.23	3.70	6.19	12.49	24.91	33.16	61.87
	(.01)	(.04)	(.06)	(.15)	(.25)	(.40)	(1.00)
-40.00	1.27	3.78	6.31	12.82	25.34	34.00	63.09
	(.01)	(.03)	(.07)	(.14)	(.33)	(.39)	(1.09)
-20.00	1.28	3.85	6.41	12.99	25.78	34.24	64.11
	(.01)	(.03)	(.07)	(.19)	(.34)	(.42)	(1.15)
.00	1.30	3.89	6.48	13.13	26.15	34.75	64.79
	(.01)	(.04)	(.08)	(.17)	(.31)	(.41)	(1.14)
20.00	1.31	3.92	6.55	13.26	26.42	35.24	65.41
	(.01)	(.03)	(.09)	(.18)	(.35)	(.50)	(1.06)
40.00	1.33	3.98	6.62	13.43	26.57	35.60	66.13
	(.01)	(.04)	(.08)	(.17)	(.32)	(.52)	(1.04)
60.00	1.34	4.00	6.68	13.49	26.95	35.81	66.63
	(.01)	(.05)	(.08)	(.16)	(.35)	(.45)	(1.07)
80.00	1.35	4.04	6.75	13.65	27.17	36.15	66.80
	(.01)	(.04)	(.08)	(.16)	(.40)	(.36)	(1.06)
100.00	1.36	4.09	6.81	13.74	27.52	36.63	67.13
	(.02)	(.05)	(.10)	(.17)	(.37)	(.47)	(1.13)
120.00	1.37	4.12	6.90	13.84	27.90	37.04	66.66
	(.01)	(.04)	(.09)	(.15)	(.42)	(.50)	(1.09)
140.00	1.38	4.16	6.91	13.97	27.95	37.37	66.10
	(.02)	(.05)	(.09)	(.14)	(.39)	(.44)	(1.06)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 2. Average Open-Circuit Voltage

SPECTROLAB WRAPAROUND
N/P 2 OHM-CM CG SILICON
2 X 4 X .0228 CM
CR-PD-AG CONTACTS
1 X 30 GRID LINES
TA205 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-48

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	663.60	737.91	736.89	733.91	727.19	727.17	722.47
	(99.46)	(19.42)	(15.66)	(18.38)	(19.51)	(19.77)	(21.33)
-140.00	659.44	720.71	720.49	719.61	715.10	715.09	710.49
	(82.75)	(18.44)	(18.44)	(20.65)	(21.78)	(22.43)	(24.30)
-120.00	664.69	706.99	707.92	706.65	703.52	703.87	700.34
	(60.36)	(21.45)	(22.17)	(23.51)	(24.12)	(24.42)	(25.37)
-100.00	668.90	694.12	694.32	693.89	691.24	690.31	686.71
	(41.67)	(23.76)	(24.42)	(25.06)	(25.55)	(25.73)	(26.09)
-80.00	665.26	679.37	678.49	678.10	675.77	675.46	672.39
	(27.91)	(24.57)	(25.15)	(25.34)	(25.38)	(25.50)	(25.27)
-60.00	650.90	663.62	663.20	662.99	661.61	661.27	659.31
	(17.08)	(21.47)	(22.58)	(23.56)	(23.95)	(24.14)	(24.10)
-40.00	624.35	644.90	647.02	649.74	649.41	649.50	648.06
	(9.19)	(14.45)	(16.52)	(19.87)	(21.42)	(21.75)	(22.46)
-20.00	584.02	616.92	624.12	632.39	635.09	636.47	636.81
	(7.53)	(5.54)	(8.09)	(12.66)	(15.77)	(17.51)	(19.20)
.00	537.32	577.20	588.99	604.60	613.61	617.29	621.31
	(7.75)	(2.22)	(2.15)	(4.66)	(7.97)	(9.77)	(12.96)
20.00	488.59	531.55	544.95	565.87	581.06	586.89	598.31
	(7.38)	(3.01)	(2.38)	(1.84)	(2.17)	(3.28)	(5.98)
40.00	440.31	483.51	498.77	521.06	539.17	547.30	564.02
	(7.08)	(3.40)	(2.86)	(2.10)	(1.87)	(1.60)	(1.58)
60.00	390.46	434.82	450.94	475.51	495.05	505.75	523.34
	(6.98)	(3.69)	(3.06)	(2.80)	(3.14)	(2.25)	(1.84)
80.00	340.62	384.55	401.72	427.79	449.19	457.87	479.15
	(6.32)	(3.63)	(3.37)	(3.01)	(2.98)	(2.52)	(2.50)
100.00	289.29	334.15	352.97	379.32	402.72	413.42	433.67
	(6.26)	(3.72)	(3.33)	(3.29)	(2.94)	(3.13)	(2.85)
120.00	239.51	284.52	303.77	331.37	356.02	367.07	387.99
	(5.74)	(3.71)	(3.51)	(3.28)	(3.17)	(3.27)	(2.73)
140.00	189.12	235.29	254.01	281.84	308.44	319.49	341.42
	(5.46)	(3.61)	(3.44)	(2.92)	(3.04)	(3.06)	(3.06)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 3. Average Maximum Power Current

SPECTROLAB WRAPAROUND
N/P 2 OHM-CM CG SILICON
2 X 4 X .0228 CM
CR-PD-AG CONTACTS
1 X 30 GRID LINES
TA205 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-48

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	.79	2.40	4.22	9.40	19.64	27.05	51.44
	(.03)	(.18)	(.44)	(.72)	(.96)	(1.30)	(1.48)
-140.00	.81	2.43	4.33	9.57	20.11	27.50	53.31
	(.03)	(.20)	(.44)	(.68)	(.85)	(1.03)	(1.60)
-120.00	.84	2.54	4.55	9.97	20.75	28.27	54.59
	(.03)	(.23)	(.37)	(.59)	(.73)	(1.03)	(3.00)
-100.00	.85	2.69	4.78	10.38	21.39	29.19	55.98
	(.02)	(.22)	(.35)	(.49)	(.67)	(.91)	(1.99)
-80.00	.91	2.91	5.11	10.93	22.33	30.08	56.34
	(.03)	(.19)	(.28)	(.41)	(.52)	(.65)	(.93)
-60.00	.97	3.10	5.41	11.30	23.00	30.98	57.80
	(.04)	(.17)	(.24)	(.32)	(.31)	(.75)	(.85)
-40.00	1.01	3.24	5.58	11.62	23.55	31.55	58.64
	(.05)	(.14)	(.15)	(.25)	(.36)	(.57)	(.92)
-20.00	1.04	3.33	5.71	11.87	23.80	31.70	59.36
	(.06)	(.11)	(.14)	(.19)	(.38)	(.45)	(.89)
.00	1.07	3.41	5.78	12.01	24.05	32.12	59.36
	(.06)	(.12)	(.14)	(.22)	(.40)	(.45)	(1.05)
20.00	1.08	3.41	5.83	12.11	24.03	32.34	56.42
	(.04)	(.13)	(.13)	(.24)	(.62)	(.50)	(.90)
40.00	1.08	3.46	5.85	12.13	24.20	32.59	56.84
	(.04)	(.08)	(.13)	(.21)	(.40)	(.59)	(1.05)
60.00	1.08	3.44	5.85	12.14	24.30	32.45	57.02
	(.04)	(.08)	(.11)	(.25)	(.39)	(.47)	(.66)
80.00	1.08	3.44	5.86	12.06	24.14	32.20	56.52
	(.04)	(.07)	(.12)	(.24)	(.47)	(.42)	(.95)
100.00	1.06	3.42	5.80	11.87	23.72	31.98	56.42
	(.04)	(.08)	(.14)	(.23)	(.67)	(.41)	(.70)
120.00	1.04	3.35	5.73	11.71	23.77	31.58	54.00
	(.04)	(.08)	(.12)	(.19)	(.43)	(.38)	(1.20)
140.00	1.00	3.23	5.53	11.48	23.17	31.00	51.89
	(.03)	(.08)	(.11)	(.17)	(.37)	(.57)	(1.25)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 4. Average Maximum Power Voltage

SPECTROLAB WRAPAROUND
N/P 2 OHM-CM CG SILICON
2 X 4 X .0228 CM
CR-PD-AG CONTACTS
1 X 30 GRID LINES
TA205 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-48

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	374.25	536.75	586.75	616.12	628.87	630.25	627.62
	(79.54)	(72.88)	(40.27)	(26.39)	(20.90)	(21.66)	(19.94)
-140.00	385.12	543.87	583.37	607.12	614.75	613.75	605.50
	(76.45)	(61.14)	(33.29)	(24.11)	(23.35)	(22.40)	(20.29)
-120.00	405.00	537.12	581.37	593.62	598.87	599.75	590.37
	(74.81)	(46.19)	(29.78)	(22.24)	(20.76)	(21.57)	(21.37)
-100.00	434.12	543.25	571.12	583.62	584.62	582.12	575.12
	(67.28)	(40.79)	(25.27)	(23.97)	(19.86)	(21.83)	(19.97)
-80.00	454.00	539.50	562.00	573.62	573.87	570.25	561.25
	(57.80)	(31.03)	(24.73)	(20.66)	(20.52)	(20.35)	(19.76)
-60.00	468.75	540.37	554.62	562.87	561.62	559.62	550.62
	(43.39)	(26.43)	(22.48)	(22.50)	(18.55)	(20.21)	(19.72)
-40.00	476.87	530.00	541.87	551.50	550.00	549.25	539.00
	(31.36)	(19.46)	(17.83)	(18.57)	(18.38)	(17.45)	(18.78)
-20.00	455.12	509.75	524.12	533.87	534.37	534.37	524.00
	(22.62)	(12.23)	(11.98)	(16.12)	(15.01)	(17.67)	(16.75)
.00	421.25	472.62	493.75	507.00	514.87	514.37	508.37
	(18.64)	(7.27)	(6.80)	(6.87)	(8.06)	(9.90)	(11.96)
20.00	383.12	432.62	452.87	471.62	482.87	485.00	490.12
	(16.87)	(8.30)	(4.09)	(3.78)	(4.70)	(5.68)	(9.64)
40.00	345.12	387.87	409.25	428.50	442.62	444.62	453.00
	(15.64)	(7.51)	(6.16)	(3.89)	(3.46)	(4.10)	(5.53)
60.00	297.25	342.87	362.87	383.00	399.12	404.75	414.25
	(12.56)	(5.64)	(4.70)	(2.62)	(3.04)	(5.15)	(4.65)
80.00	253.12	295.25	315.87	337.62	353.87	358.00	371.25
	(11.36)	(5.28)	(3.83)	(3.62)	(4.61)	(4.14)	(4.71)
100.00	211.75	247.87	268.75	292.62	308.37	315.75	323.87
	(8.65)	(5.36)	(4.17)	(4.31)	(4.03)	(4.37)	(5.38)
120.00	170.75	208.12	226.87	248.87	265.00	271.12	282.87
	(7.76)	(4.79)	(3.52)	(3.76)	(6.37)	(4.55)	(6.60)
140.00	129.50	166.62	182.87	204.62	222.25	230.75	239.75
	(6.99)	(4.47)	(3.64)	(3.50)	(4.40)	(9.62)	(5.97)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 5. Average Maximum Power

SPECTROLAB WRAPAROUND
N/P 2 OHM-CM CG SILICON
2 X 4 X .0228 CM
CR-PD-AG CONTACTS
1 X 30 GRID LINES
TA205 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-48

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	.30	1.30	2.49	5.80	12.35	17.05	32.29
	(.06)	(.25)	(.37)	(.54)	(.78)	(1.02)	(1.52)
-140.00	.31	1.33	2.53	5.81	12.36	16.88	32.28
	(.06)	(.22)	(.33)	(.49)	(.72)	(.92)	(1.55)
-120.00	.34	1.37	2.65	5.92	12.43	16.95	32.22
	(.06)	(.21)	(.30)	(.42)	(.65)	(.85)	(1.89)
-100.00	.37	1.47	2.73	6.06	12.51	16.99	32.20
	(.06)	(.18)	(.24)	(.36)	(.57)	(.78)	(1.63)
-80.00	.42	1.57	2.87	6.27	12.81	17.15	31.6
	(.06)	(.15)	(.20)	(.32)	(.52)	(.73)	(1.33)
-60.00	.46	1.68	3.00	6.36	12.92	17.34	31.83
	(.06)	(.12)	(.18)	(.29)	(.53)	(.73)	(1.33)
-40.00	.48	1.72	3.02	6.41	12.95	17.33	31.62
	(.05)	(.11)	(.16)	(.30)	(.58)	(.71)	(1.47)
-20.00	.48	1.70	2.99	6.34	12.72	16.95	31.11
	(.04)	(.09)	(.12)	(.25)	(.52)	(.72)	(1.37)
.00	.45	1.61	2.86	6.09	12.38	16.53	30.18
	(.04)	(.07)	(.10)	(.18)	(.36)	(.50)	(1.15)
20.00	.41	1.47	2.64	5.71	11.60	15.69	27.65
	(.03)	(.07)	(.08)	(.12)	(.32)	(.35)	(.72)
40.00	.37	1.34	2.40	5.20	10.71	14.49	25.75
	(.03)	(.05)	(.08)	(.11)	(.18)	(.23)	(.48)
60.00	.32	1.18	2.12	4.65	9.70	13.14	23.62
	(.02)	(.04)	(.05)	(.10)	(.12)	(.24)	(.33)
80.00	.27	1.01	1.85	4.07	8.54	11.53	20.98
	(.02)	(.04)	(.05)	(.09)	(.15)	(.18)	(.37)
100.00	.22	.85	1.56	3.47	7.31	10.10	18.27
	(.02)	(.03)	(.05)	(.08)	(.21)	(.21)	(.34)
120.00	.18	.70	1.30	2.91	6.30	8.56	15.27
	(.01)	(.03)	(.04)	(.07)	(.12)	(.17)	(.31)
140.00	.13	.54	1.01	2.35	5.15	7.16	12.44
	(.01)	(.02)	(.03)	(.06)	(.08)	(.38)	(.37)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 6. Average Curve Factor

SPECTROLAB WRAPAROUND
N/P 2 OHM-CM CG SILICON
2 X 4 X .0228 CM
CR-PD-AG CONTACTS
1 X 30 GRID LINES
TA205 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-48

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	.4012	.5324	.6119	.7065	.7704	.7881	.8088
	(.0370)	(.0953)	(.0884)	(.0647)	(.0403)	(.0383)	(.0258)
-140.00	.4201	.5541	.6328	.7194	.7732	.7861	.7984
	(.0383)	(.0893)	(.0821)	(.0586)	(.0362)	(.0316)	(.0187)
-120.00	.4459	.5754	.6673	.7311	.7755	.7857	.8011
	(.0501)	(.0850)	(.0685)	(.0455)	(.0277)	(.0263)	(.0346)
-100.00	.4787	.6129	.6836	.7443	.7781	.7827	.7937
	(.0616)	(.0711)	(.0567)	(.0404)	(.0262)	(.0221)	(.0255)
-80.00	.5217	.6486	.7090	.7596	.7841	.7865	.7828
	(.0688)	(.0585)	(.0458)	(.0324)	(.0208)	(.0168)	(.0123)
-60.00	.5690	.6840	.7305	.7682	.7839	.7907	.7803
	(.0691)	(.0482)	(.0376)	(.0234)	(.0161)	(.0140)	(.0087)
-40.00	.6071	.7038	.7411	.7695	.7870	.7846	.7731
	(.0591)	(.0394)	(.0266)	(.0196)	(.0131)	(.0050)	(.0065)
-20.00	.6345	.7158	.7481	.7718	.7768	.7773	.7619
	(.0550)	(.0338)	(.0244)	(.0147)	(.0116)	(.0098)	(.0078)
.00	.6469	.7176	.7481	.7672	.7714	.7702	.7496
	(.0475)	(.0280)	(.0222)	(.0153)	(.0090)	(.0083)	(.0070)
20.00	.6450	.7072	.7405	.7607	.7560	.7585	.7065
	(.0393)	(.0306)	(.0176)	(.0124)	(.0160)	(.0074)	(.0066)
40.00	.6411	.6975	.7256	.7429	.7476	.7437	.6903
	(.0399)	(.0238)	(.0190)	(.0104)	(.0086)	(.0062)	(.0055)
60.00	.6156	.6781	.7045	.7249	.7269	.7253	.6774
	(.0357)	(.0188)	(.0130)	(.0093)	(.0060)	(.0082)	(.0074)
80.00	.5962	.6529	.6819	.6972	.7000	.6965	.6555
	(.0341)	(.0175)	(.0144)	(.0099)	(.0069)	(.0051)	(.0067)
100.00	.5714	.6202	.6485	.6663	.6600	.6668	.6277
	(.0300)	(.0169)	(.0131)	(.0092)	(.0184)	(.0087)	(.0097)
120.00	.5416	.5944	.6202	.6351	.6340	.6297	.5905
	(.0310)	(.0162)	(.0112)	(.0074)	(.0080)	(.0081)	(.0112)
140.00	.4975	.5500	.5760	.5966	.5973	.5992	.5512
	(.0232)	(.0154)	(.0105)	(.0081)	(.0090)	(.0262)	(.0133)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 7. Average AMO Efficiency (Percent)

SPECTROLAB WRAPAROUND
N/P 2 OHM-CM CG SILICON
2 X 4 X .0228 CM
CR-PD-AG CONTACTS
1 X 30 GRID LINES
TA205 AR COATING
NO COVERSLIDE
SAMPLE SIZE 8 TM-48

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 5.10	15.00	25.00	50.00	100.00	135.30	250.00
-160.00	5.93	8.64	9.94	11.59	12.35	12.60	12.92
	(1.21)	(1.67)	(1.46)	(1.08)	(.78)	(.76)	(.61)
-140.00	6.23	8.87	10.12	11.63	12.36	12.48	12.91
	(1.19)	(1.50)	(1.32)	(.98)	(.72)	(.68)	(.62)
-120.00	6.77	9.12	10.60	11.83	12.43	12.53	12.89
	(1.24)	(1.38)	(1.19)	(.84)	(.65)	(.63)	(.76)
-100.00	7.43	9.77	10.92	12.11	12.51	12.56	12.88
	(1.26)	(1.17)	(.96)	(.73)	(.57)	(.58)	(.65)
-80.00	8.32	10.49	11.49	12.54	12.81	12.68	12.65
	(1.29)	(.98)	(.80)	(.63)	(.52)	(.54)	(.53)
-60.00	9.15	11.18	12.00	12.72	12.92	12.81	12.73
	(1.20)	(.83)	(.71)	(.59)	(.53)	(.54)	(.53)
-40.00	9.64	11.44	12.10	12.82	12.95	12.81	12.65
	(1.03)	(.71)	(.62)	(.60)	(.58)	(.53)	(.59)
-20.00	9.52	11.33	11.97	12.68	12.72	12.52	12.45
	(.90)	(.57)	(.49)	(.50)	(.52)	(.53)	(.55)
.00	9.02	10.75	11.43	12.18	12.38	12.21	12.07
	(.76)	(.49)	(.41)	(.35)	(.36)	(.37)	(.46)
20.00	8.27	9.83	10.57	11.42	11.60	11.59	11.06
	(.61)	(.48)	(.30)	(.23)	(.32)	(.26)	(.29)
40.00	7.49	8.96	9.58	10.40	10.71	10.71	10.30
	(.55)	(.35)	(.31)	(.22)	(.18)	(.17)	(.19)
60.00	6.43	7.87	8.48	9.30	9.70	9.71	9.45
	(.48)	(.28)	(.20)	(.20)	(.12)	(.18)	(.13)
80.00	5.47	6.7[illegible]	7.40	8.15	8.54	8.52	8.39
	(.41)	(.24)	(.22)	(.19)	(.15)	(.14)	(.15)
100.00	4.49	5.65	6.24	6.94	7.31	7.46	7.31
	(.33)	(.23)	(.20)	(.16)	(.21)	(.16)	(.13)
120.00	3.55	4.65	5.20	5.83	6.30	6.33	6.11
	(.29)	(.19)	(.16)	(.13)	(.12)	(.12)	(.13)
140.00	2.60	3.59	4.05	4.70	5.15	5.29	4.98
	(.19)	(.16)	(.13)	(.12)	(.08)	(.28)	(.15)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

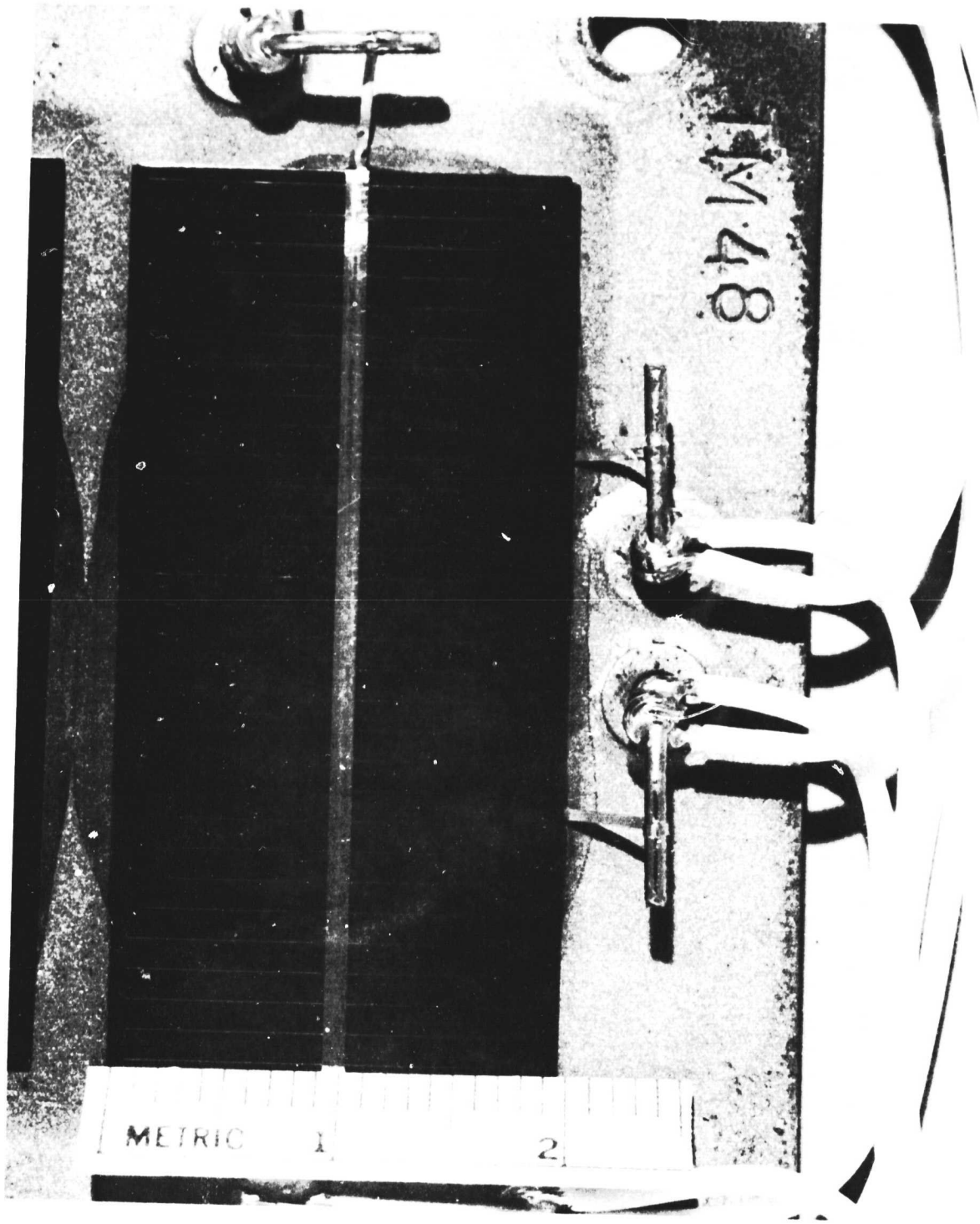

Figure A-1. Solar Cell

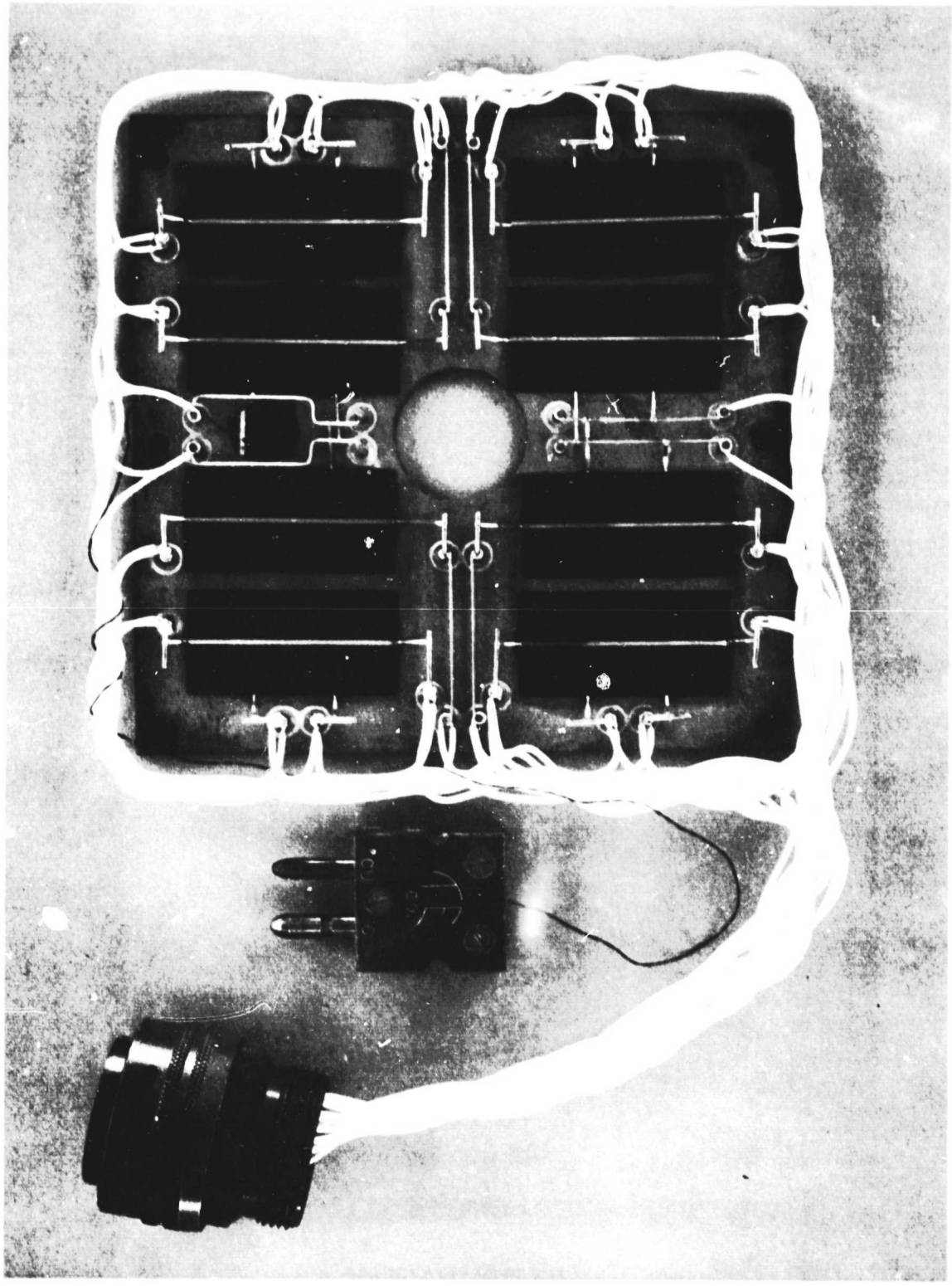

Figure A-2. Test Plate

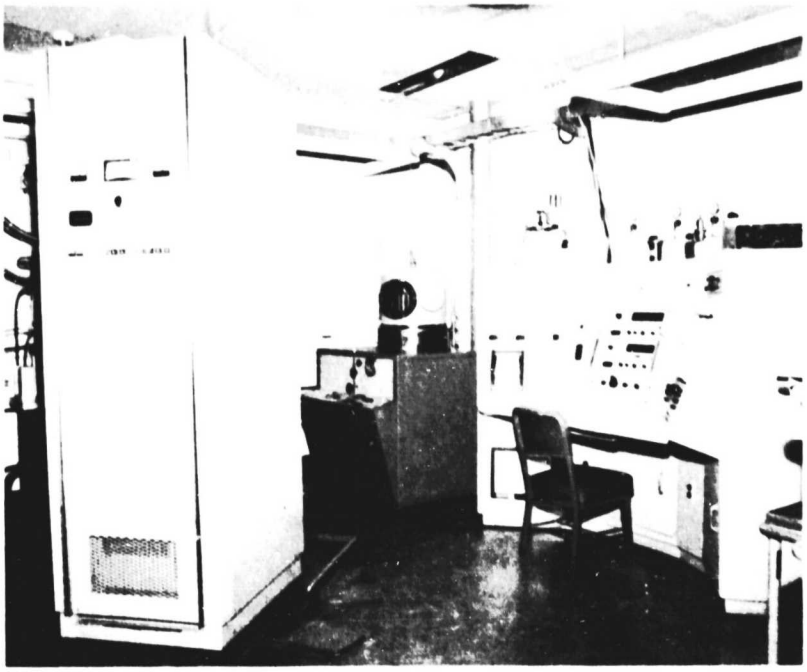

Figure A-3. Solar Cell Characterization Facility

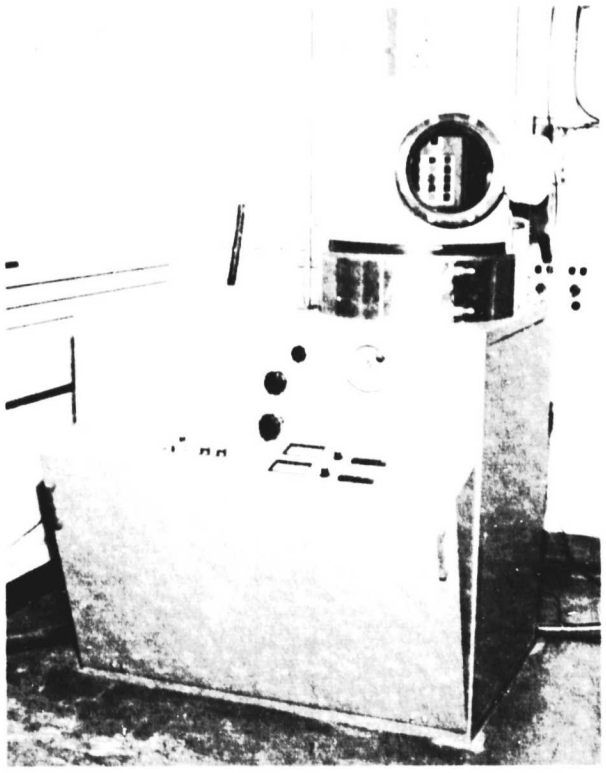

Figure A-4. Solar Cell Environmental Test Chamber