JPL PUBLICATION 84-96

Characterization of Terrestrial Solar Cells for Space Applications

Electrical Characteristics of Thin Westinghouse Dendritic Web Cells as a Function of Solar Intensity, Temperature, and Incidence Angle

P.M. Stella
B.E. Anspaugh

January 15, 1985

NASA
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Jet Propulsion Laboratory
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ACKNOWLEDGEMENT

The authors gratefully acknowledge the invaluable assistance of James Hix, who wrote the computer programs for performing the data analysis and curve plotting, and of Tetsuo Miyahira and Robert Weiss, who carried out the cell measurements presented here.

ABSTRACT

Electrical characteristics of thin (100- and 140-micron) Westinghouse dendritic-web N/P silicon solar cells are presented in graphical and tabular format as a function of solar illumination intensity and temperature. Performance is also shown as a function of solar illumination angle of incidence for AMO.

CONTENTS

Tables

100-μm-Thick Cells

140-μm-Thick Cells

SECTION I

INTRODUCTION

The JPL Publication 78-15 series presents parametric characterization data on state-of-the-art and developmental solar cells of interest to the space photovoltaic community. These cells have all been developed specifically for use in the space environment. The reports in this series consist primarily of working graphs and tables that allow convenient descriptions of the cells' behavior as a function of temperature and illumination intensity variations.

In recent years, JPL has examined the possibility of using some of the results of the terrestrial photovoltaic energy development programs for space applications (Ref. 1). An example is the use of low-cost technology for a very large power system, such as that required for a space station. As part of those studies, low-cost terrestrial cells were evaluated for their performance under various space-type tests such as power output, temperature cycling, and radiation.

Based on these test results, one of the more promising cell types for space use was the dendritic-web cell (Ref. 2). In view of this, it was felt that a temperature-intensity performance characterization would be useful for those who wished to do a more complete analysis of the cell's performance under space array operating conditions. In addition, the determination of cell output as a function of illumination incident angle was made to establish whether or not anomalous behavior would result from the unique AR coating method employed in fabrication of the dendritic-web cell (see Section II).

Since the web cells are grown directly to a final thickness, eliminating the costly material removal steps required for conventional space cell fabrication, and since there is a trend toward thinner space cells for reasons of mass reduction and improved radiation behavior, it was decided to examine web cells thinner than those normally used in terrestrial work. Although a nominal thickness of 0.005 cm was desired, it was necessary to use somewhat thicker samples to avoid any additional process development.

SECTION II

CELL DESCRIPTION

The cells reported here were manufactured by Westinghouse Electric Corporation as part of their low-cost terrestrial array development program. These cells are fabricated from dendritic-web, P-type silicon, boron-doped to a nominal resistivity of 4 ohm-cm. The cell dimensions are 2 × 2.5 cm, and were divided into two thickness groups of six cells each, one nominally 0.010 cm and the other 0.014 cm, to determine any thickness-dependent behavior. A conventional gaseous phosphorous diffusion is used to form the junction, and a back surface field is formed by diffusion from a surface layer of "baked-on" boron dopant from a liquid source. The top surface electrical contact consists of Ti-Pd-Cu in a fan-shaped grid pattern with interconnecting pads at 1.2-cm intervals spaced along the length of

one side. The rear has a full-coverage contact of the same material. The cell AR coating is formed by heating after immersion in a liquid source. Since the basic cell size fabricated by Westinghouse is approximately 2.5 × 9.8 cm, the long strips were diced by Westinghouse to the smaller 2- × 2.5-cm size required for the JPL test fixture.

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.

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 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 the 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 -70 to 75°C while the solar intensity range covered was 10 to 135.2 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 posttest 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.

Angle-of-incidence measurements were obtained using a Spectrolab large-area pulsed xenon simulator under ambient conditions, with correction to AMO, 28°C conditions, through use of an appropriate space-calibrated standard cell. The test-plate-to-simulator distance was sufficient for an intensity variation of less than ±1% from front to rear of the test plate at maximum rotation. Averaging of cell data further eliminated any significant source of discrepancy.

SECTION IV

DISCUSSION OF RESULTS

A computer program calculated statistical averages and standard deviations with respect to the measured cells for each intensity-temperature measurement condition. It then produced summary tables: Tables 1 through 7 for nominal 100-μm-thick cells and Tables 8 through 14 for nominal 140-μm-thick cells. These tables display averages and standard deviations of the cell characteristics in a two-dimensional array format, one dimension representing cell temperature and the other representing incoming light intensity (AMO spectrum). The program then produced plots of the various electrical parameters of interest, with either incident intensity or cell temperature as the independent variable, as shown in Figures 1 through 18 for the thinner cells and Figures 19 through 36 for the thicker. Least square fits to the data points were then made automatically to the measured data points using a second-degree polynomial for most parameters. The V_{oc} and V_{mp} data points were fit with a linear equation. The curve factors and AMO efficiencies were not fit but were interconnected from point to point. In addition, the program calculated the temperature coefficients of the pertinent cell electrical parameters of interest, using the aforementioned curve fits, and plotted these as a function of temperature, with intensity as a parameter, as shown in Figures 15 through 18 and Figures 33 through 36 for thinner and thicker cell sizes, respectively.

The figures are intended to be working artifacts; that is, they are formatted to supply information of a general nature or to generate such working tools as predictions, comparisons, and computer input data. 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 °C.

(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 more 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 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.

Review of the cell data shows the thinner cell group to have higher performance than the thicker. This is not felt to be a true characteristic of the web-grown cell, but rather an artifact — the result of the limited sample sizes and the still evolving terrestrial cell production process. Error limits for the data partially reflect this condition, and are, in general, greater than those normally obtained for the cells characterized and described in the JPL 78-15 series. There is certainly a greater nonuniformity from cell to cell than normally observed, and, in some cases, it can be traceable in part to such observable cell characteristics as grid line discontinuities and edge chipping. These discrepancies, although understandable in terms of the low-cost processing approach development, would require additional limits before the application to space could be considered viable.

The output as a function of illumination angle of incidence is shown in Figure 37 for both maximum power and short-circuit current. The data are presented as the average of all thicknesses, since thickness was not considered an influence on this behavior. An analysis of a single thick and a single thin cell selected at random from the group displayed the same angular relationships, verifying the use of the overall average. The data are quite consistent with a number of prior evaluations on conventional cells, indicating that the use of the dip AR coating does not introduce any anomalous behavior in this respect.

Although not intended to satisfy all concerns regarding the space applicability of the terrestrial dendritic-web solar cell, the performance data presented here indicate a level of process maturity that should encourage consideration and analysis of such cells for space applications that could benefit from any significant cost reductions ultimately derived from a successful terrestrial cell process development.

REFERENCES

1. J. Scott-Monck, P. Stella, and P. Berman, "The Applicability of DOE Solar Cell and Array Technology to Space Power," in Proceedings of the 15th IECEC, Seattle, Washington, August 1980.

2. P. Stella, "Preliminary Evaluation of Advanced Silicon Material for Space," Proceedings of the 14th IEEE Photovoltaic Specialists Conference, San Diego, California, January 1980.

100-μm-THICK CELLS

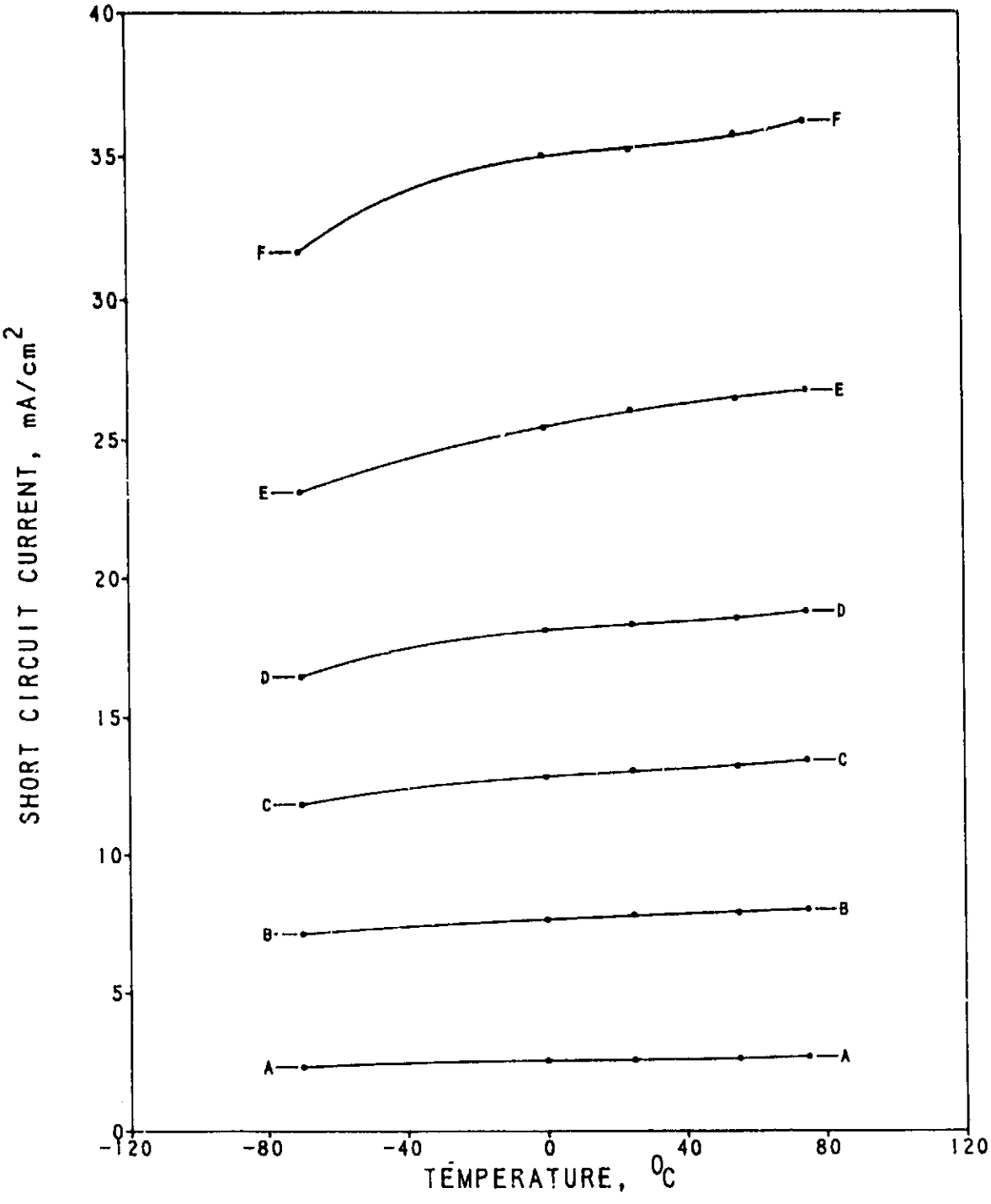


Figure 1. Average I_{sc}/cm^2 as a Function of Temperature

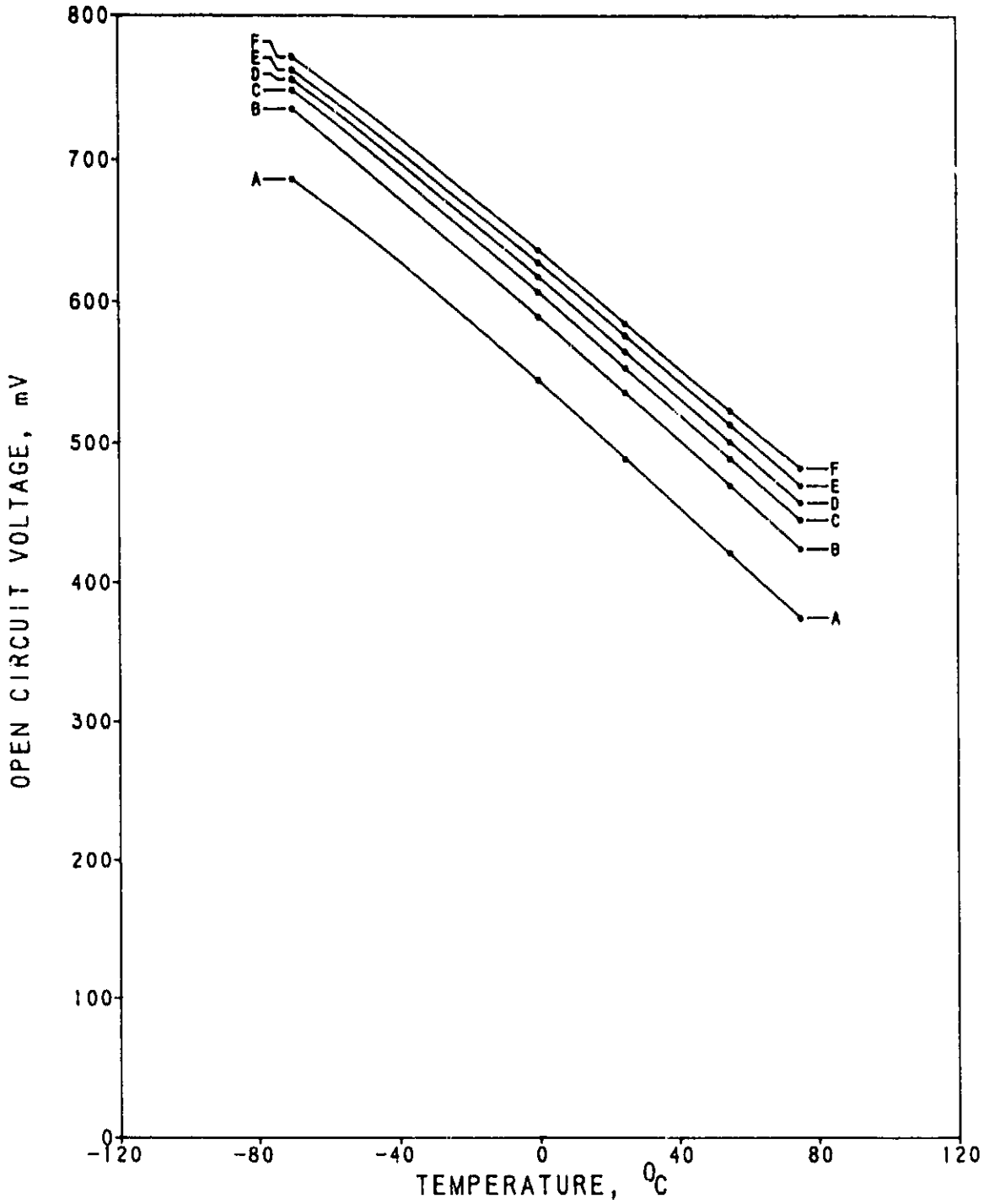


Figure 2. Average V_{oc} as a Function of Temperature

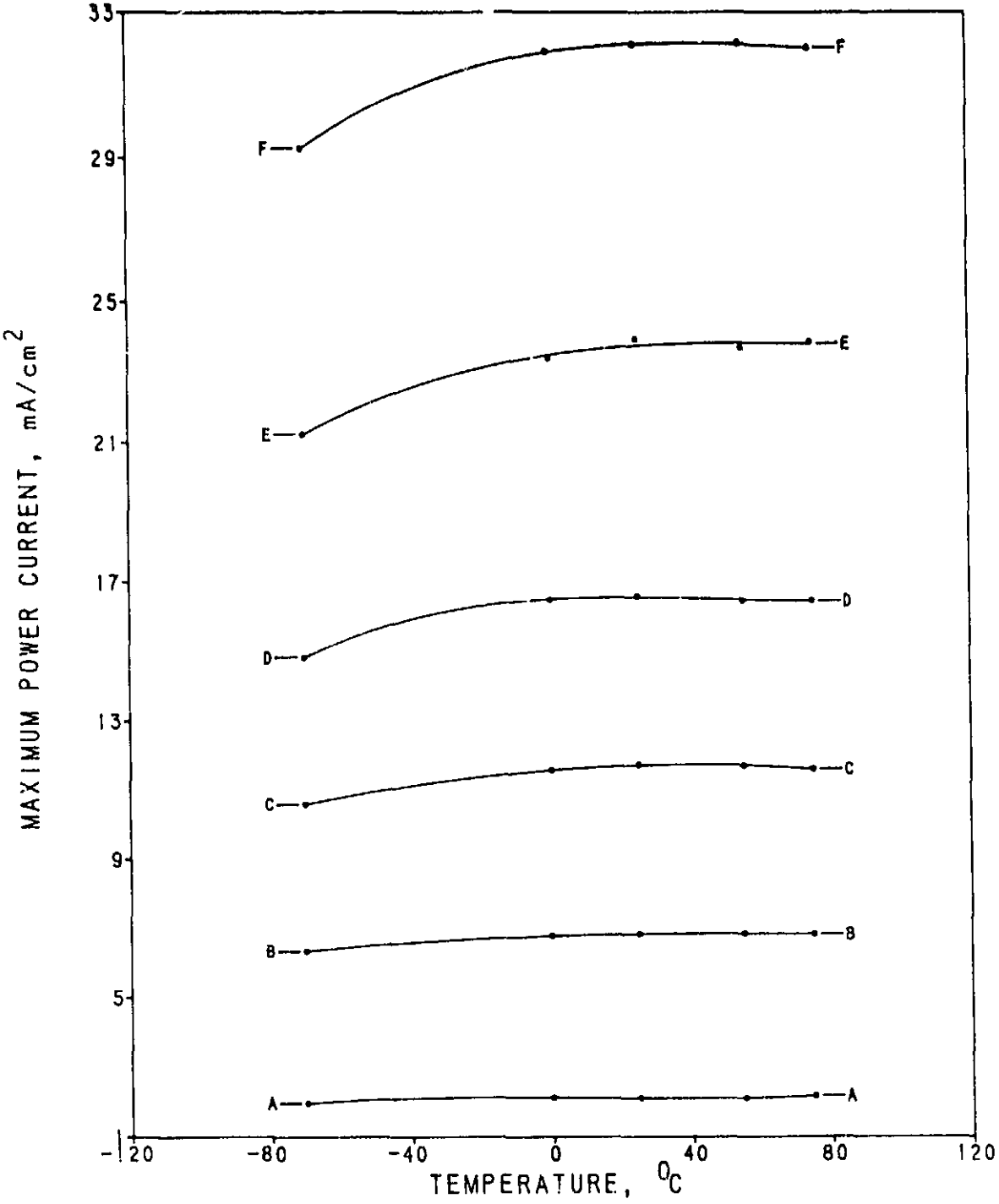


Figure 3. Average I_{mp}/cm^2 as a Function of Temperature

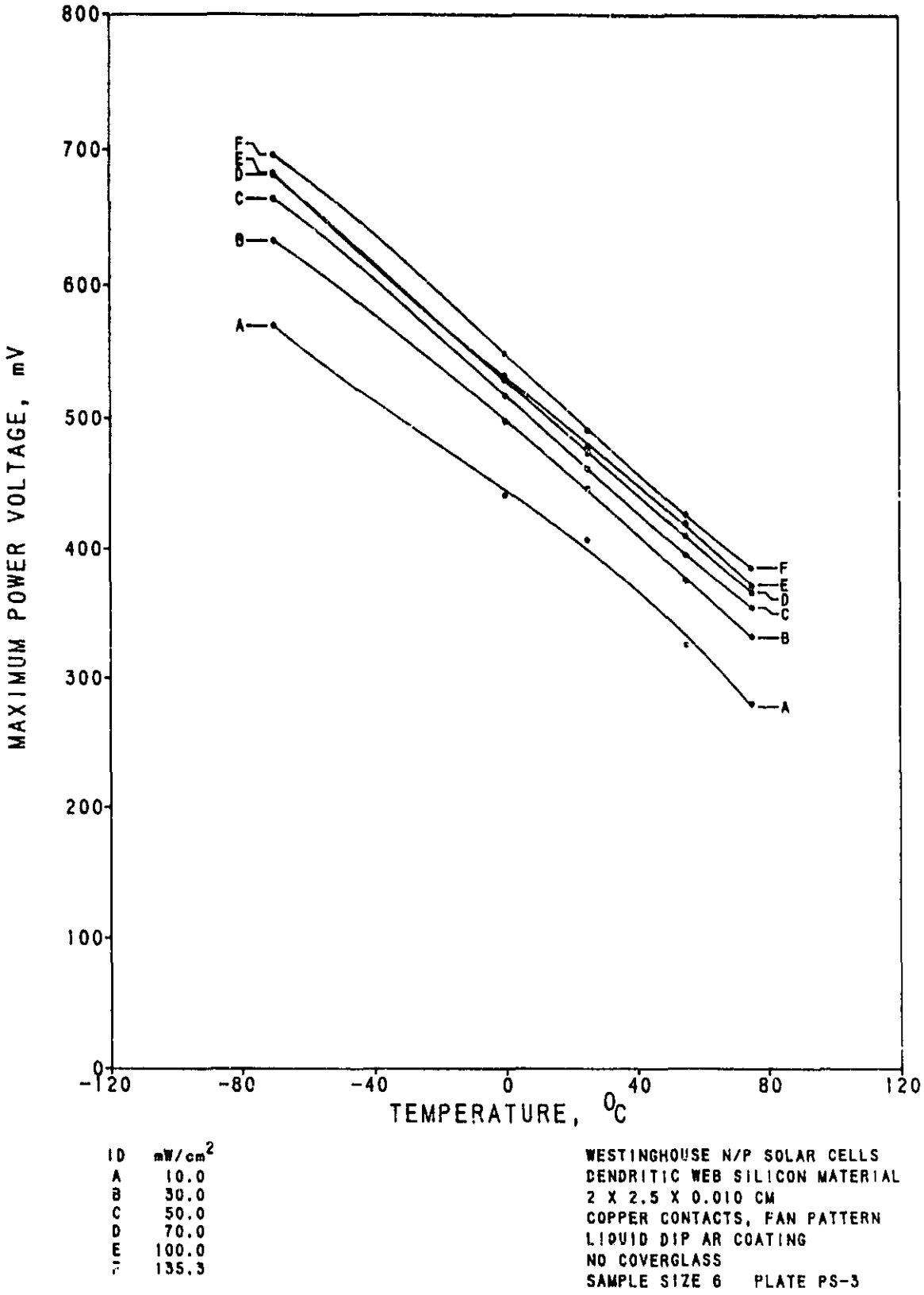


Figure 4. Average V_{mp} as a Function of Temperature

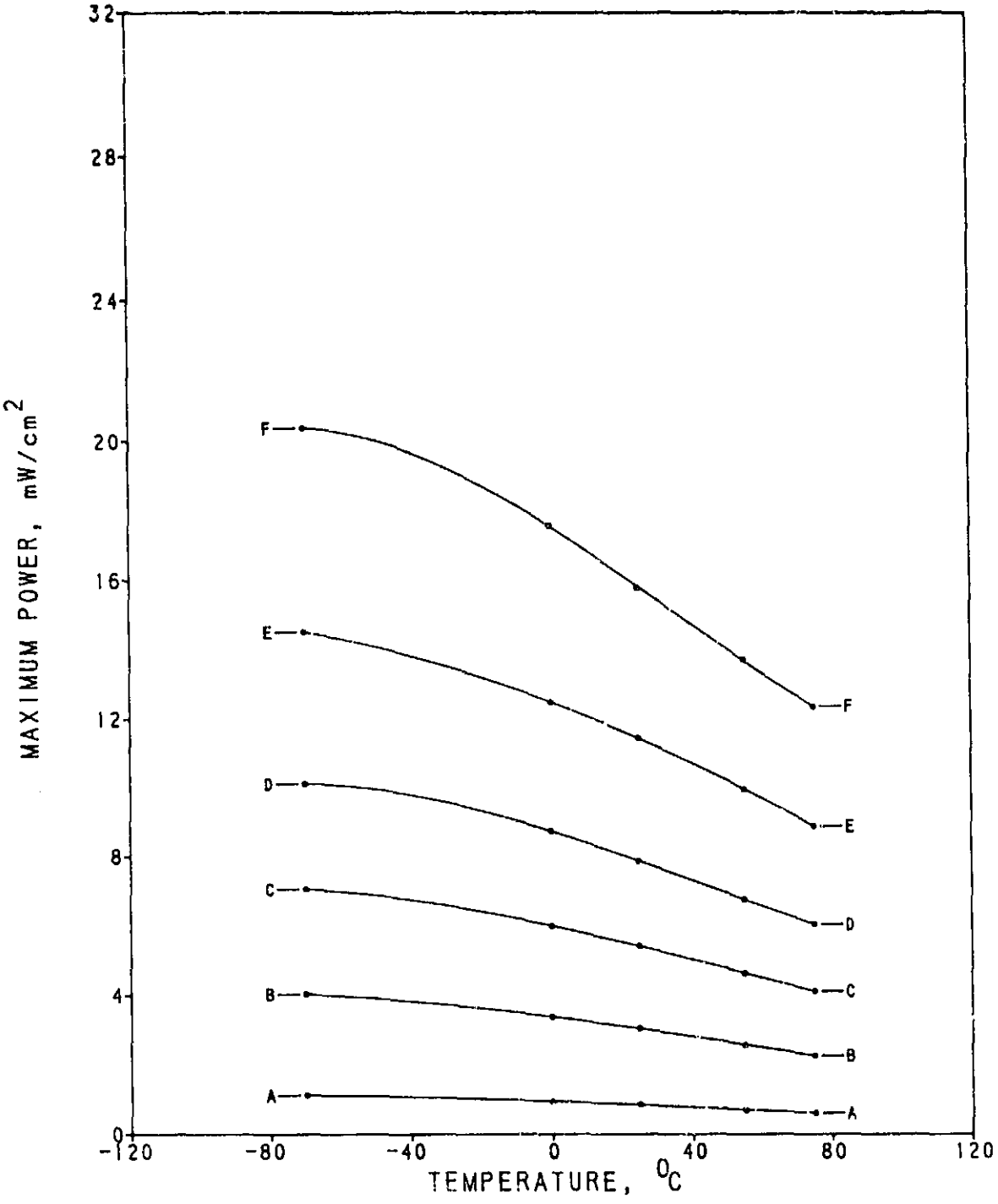


Figure 5. Average P_{max}/cm^2 as a Function of Temperature

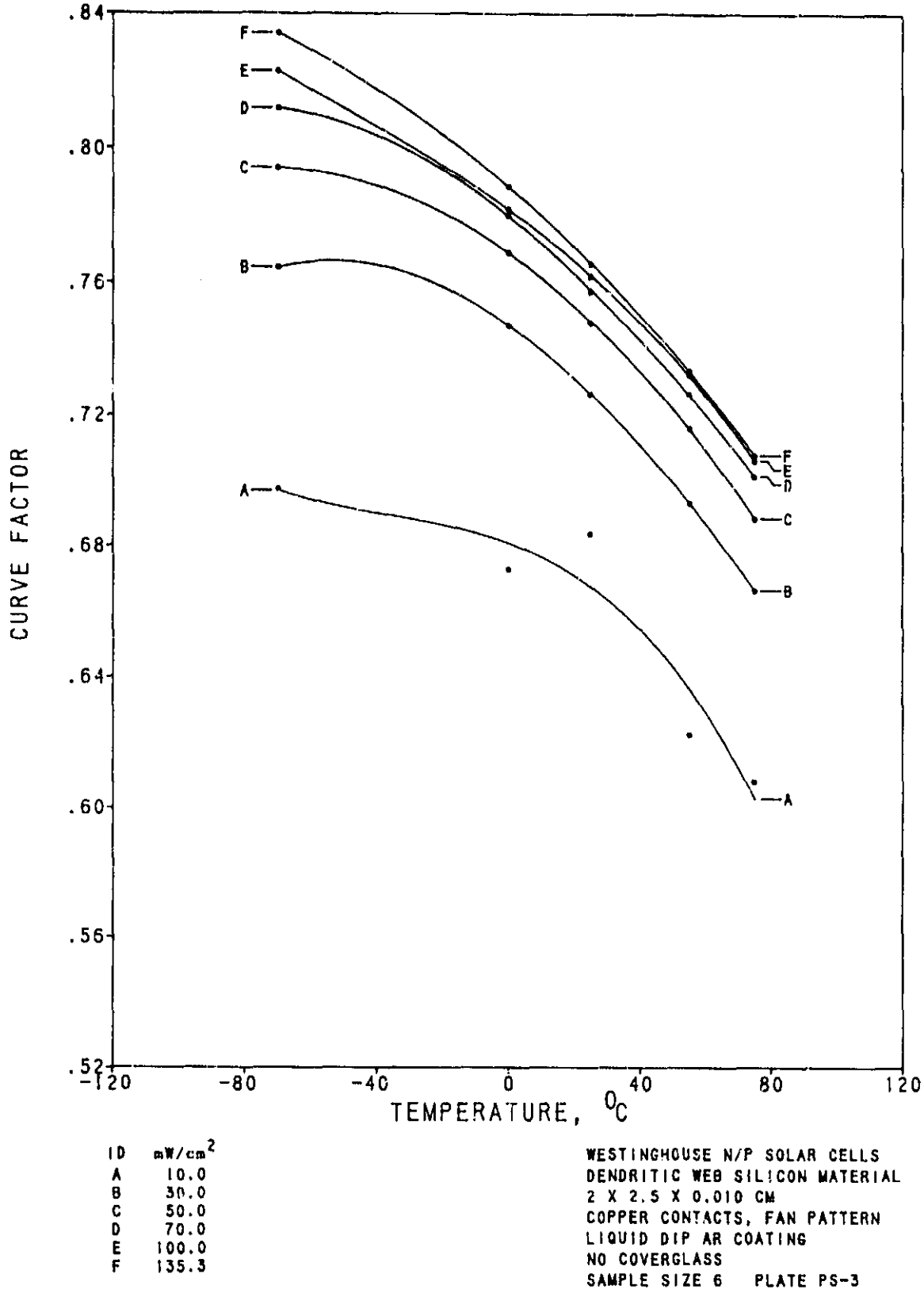


Figure 6. Average Curve Factor as a Function of Temperature

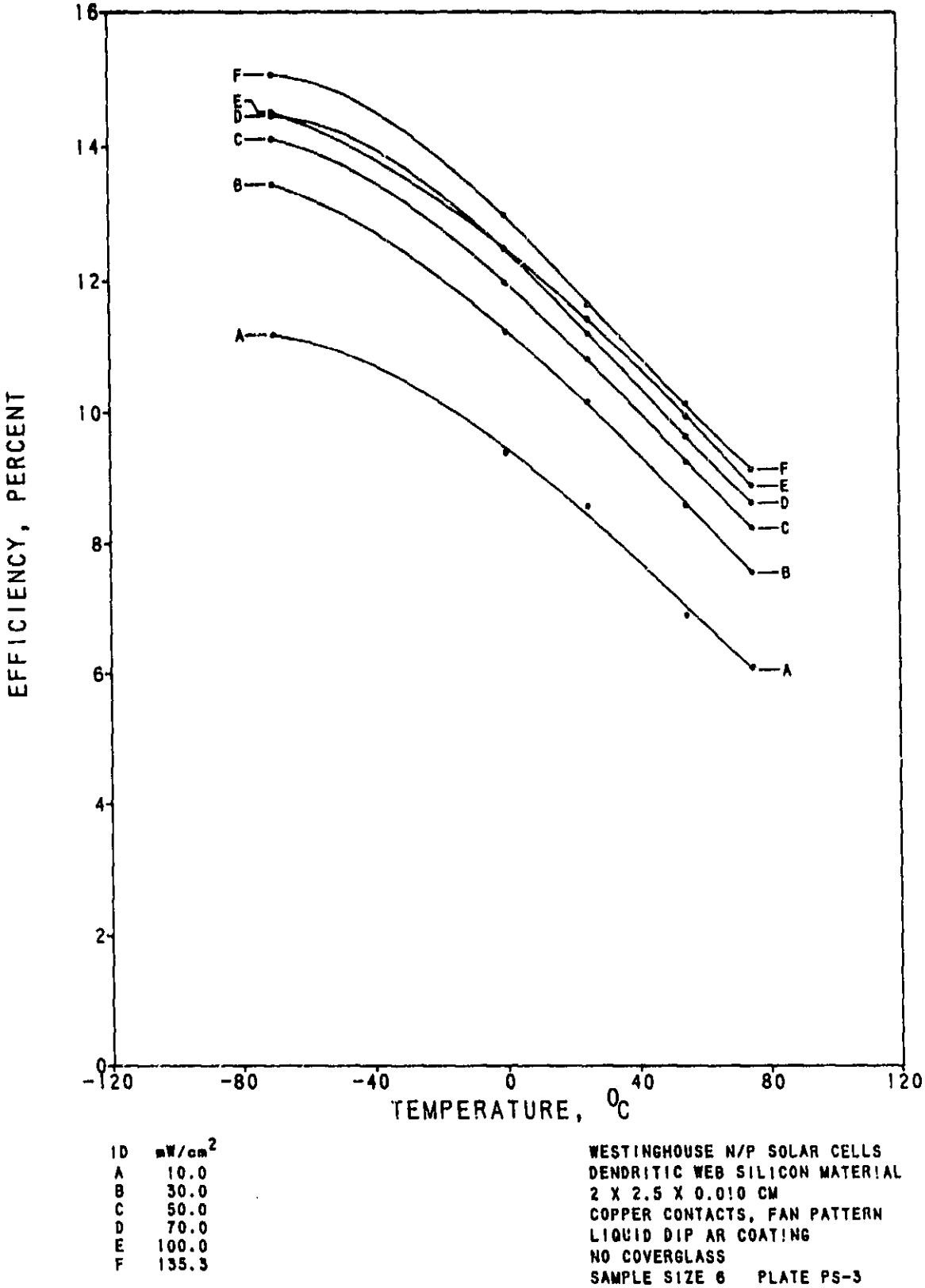


Figure 7. Average AMO Efficiency as a Function of Temperature

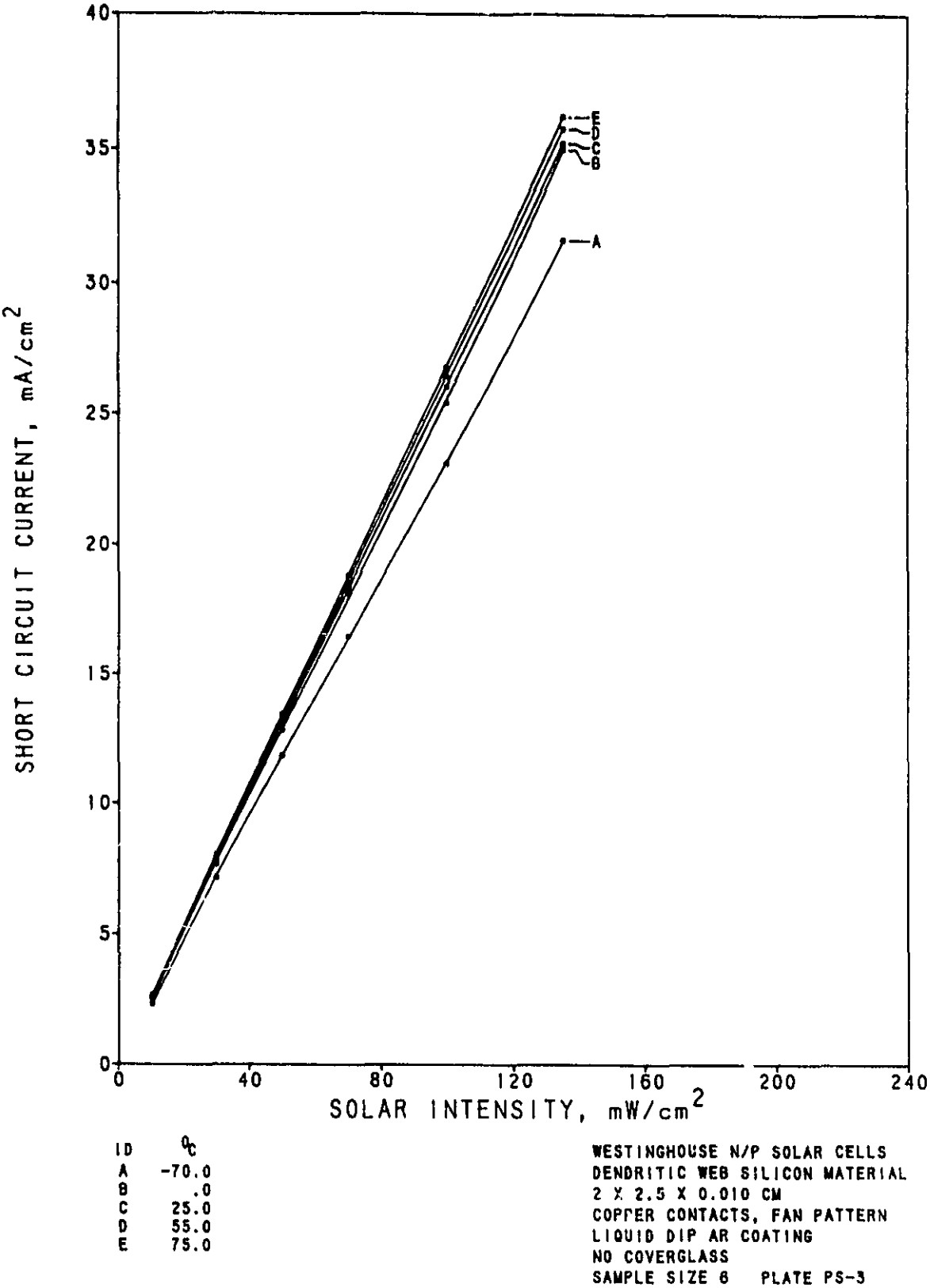


Figure 8. Average I_{sc}/cm^2 as a Function of Intensity

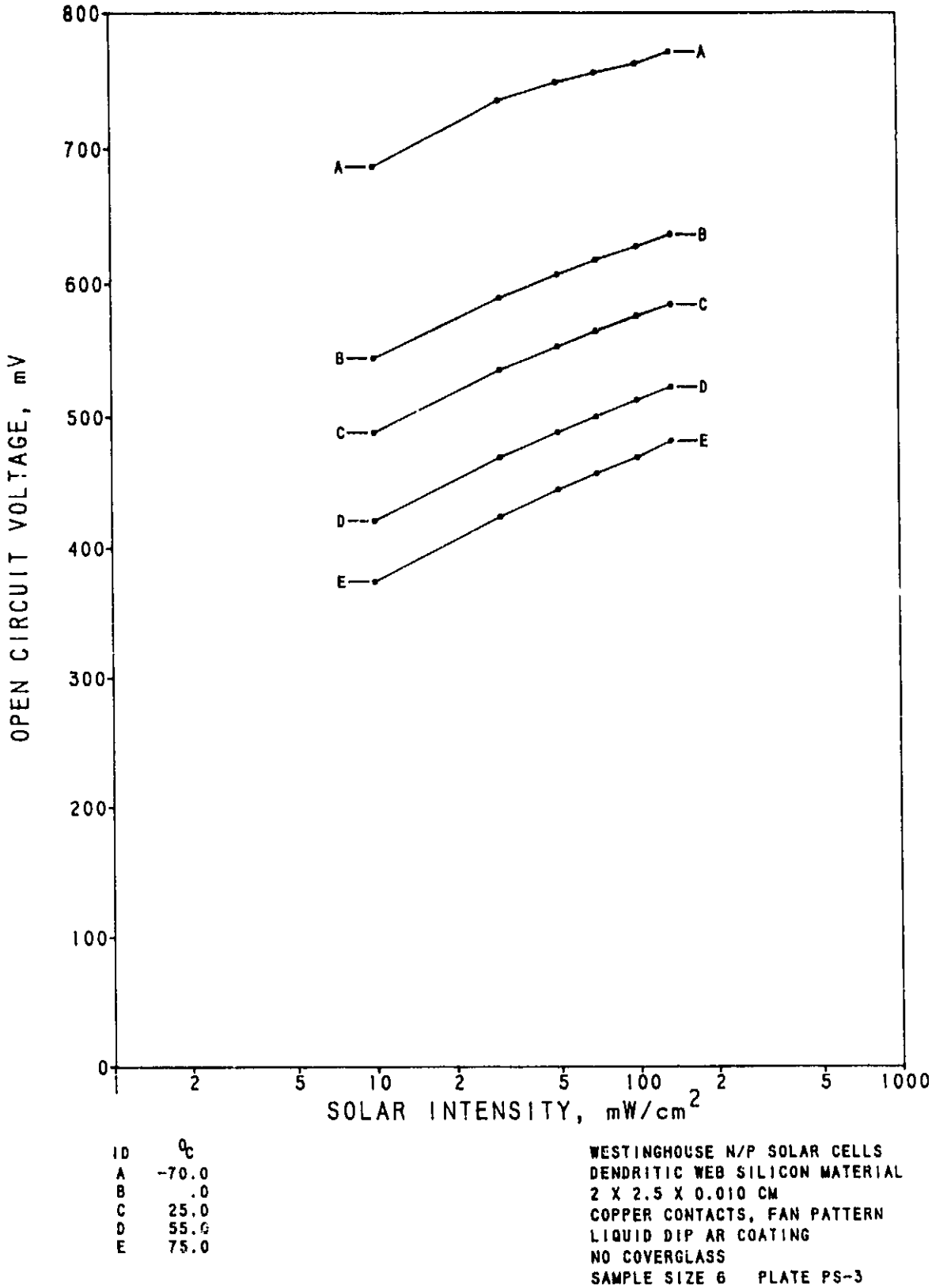


Figure 9. Average V_{oc} as a Function of Intensity

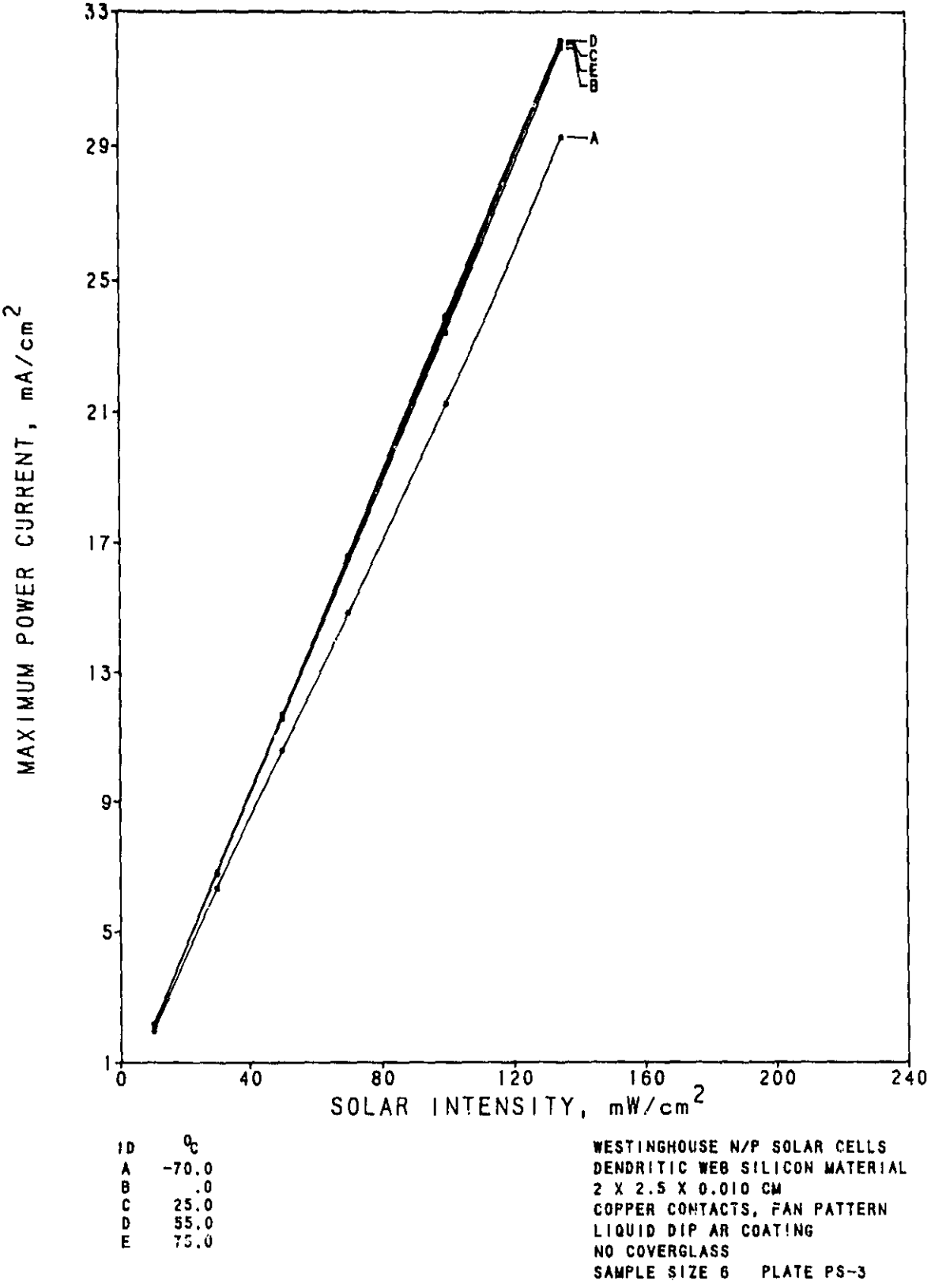


Figure 10. Average I_{mp}/cm^2 as a Function of Intensity

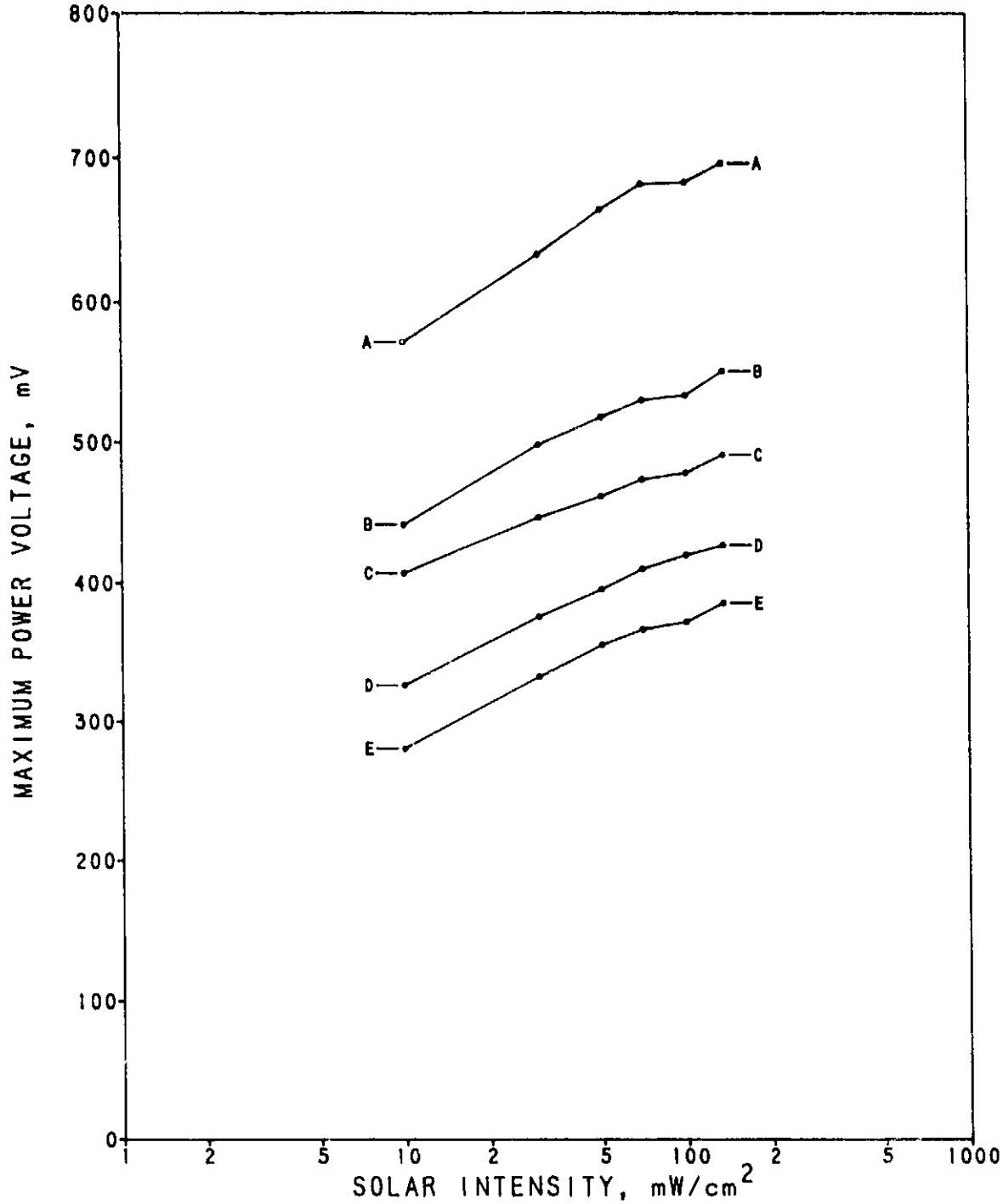


Figure 11. Average V_{mp} as a Function of Intensity

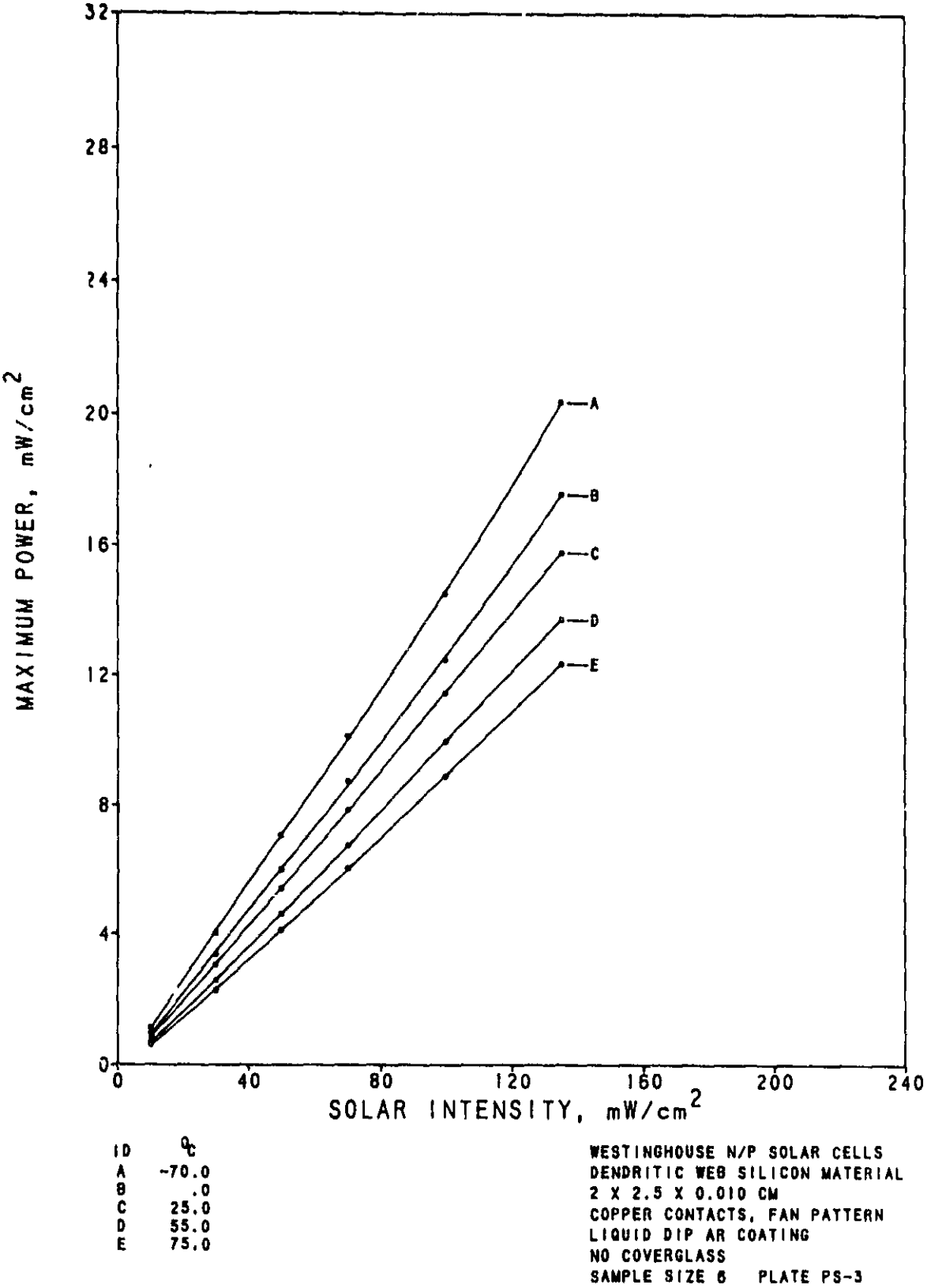


Figure 12. Average P_{max}/cm^2 as a Function of Intensity

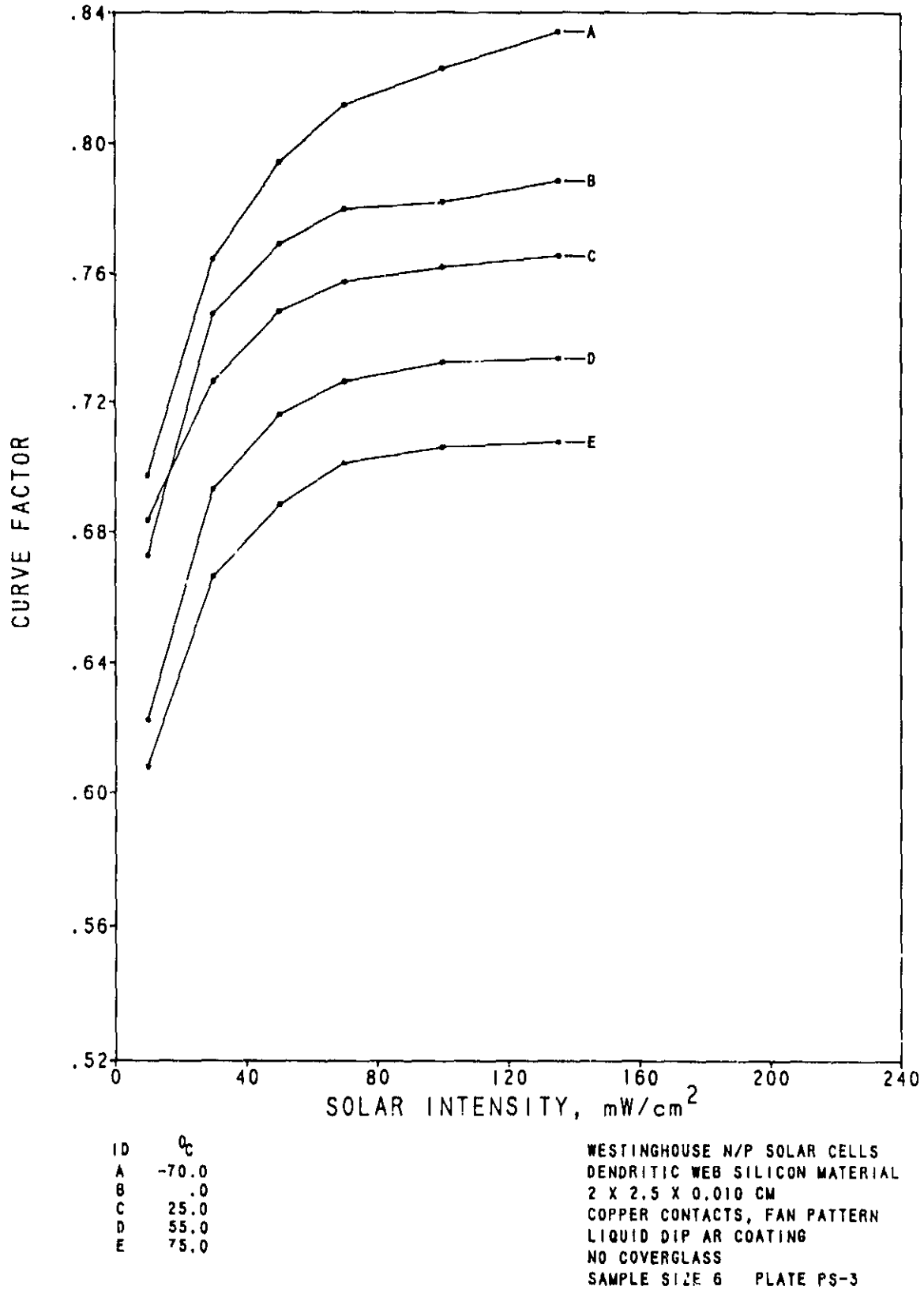


Figure 13. Average Curve Factor as a Function of Intensity

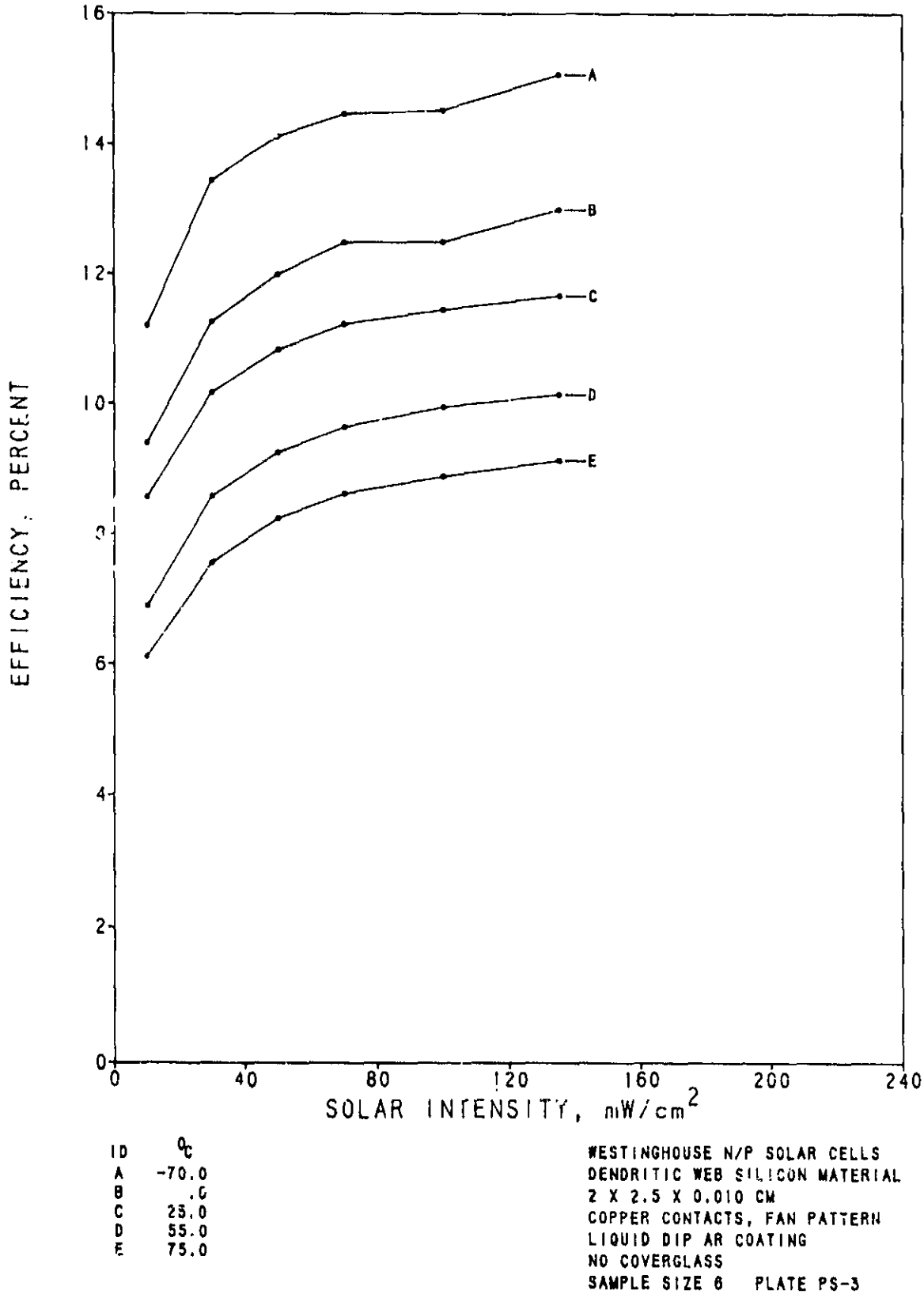


Figure 14. Average AMO Efficiency as a Function of Intensity

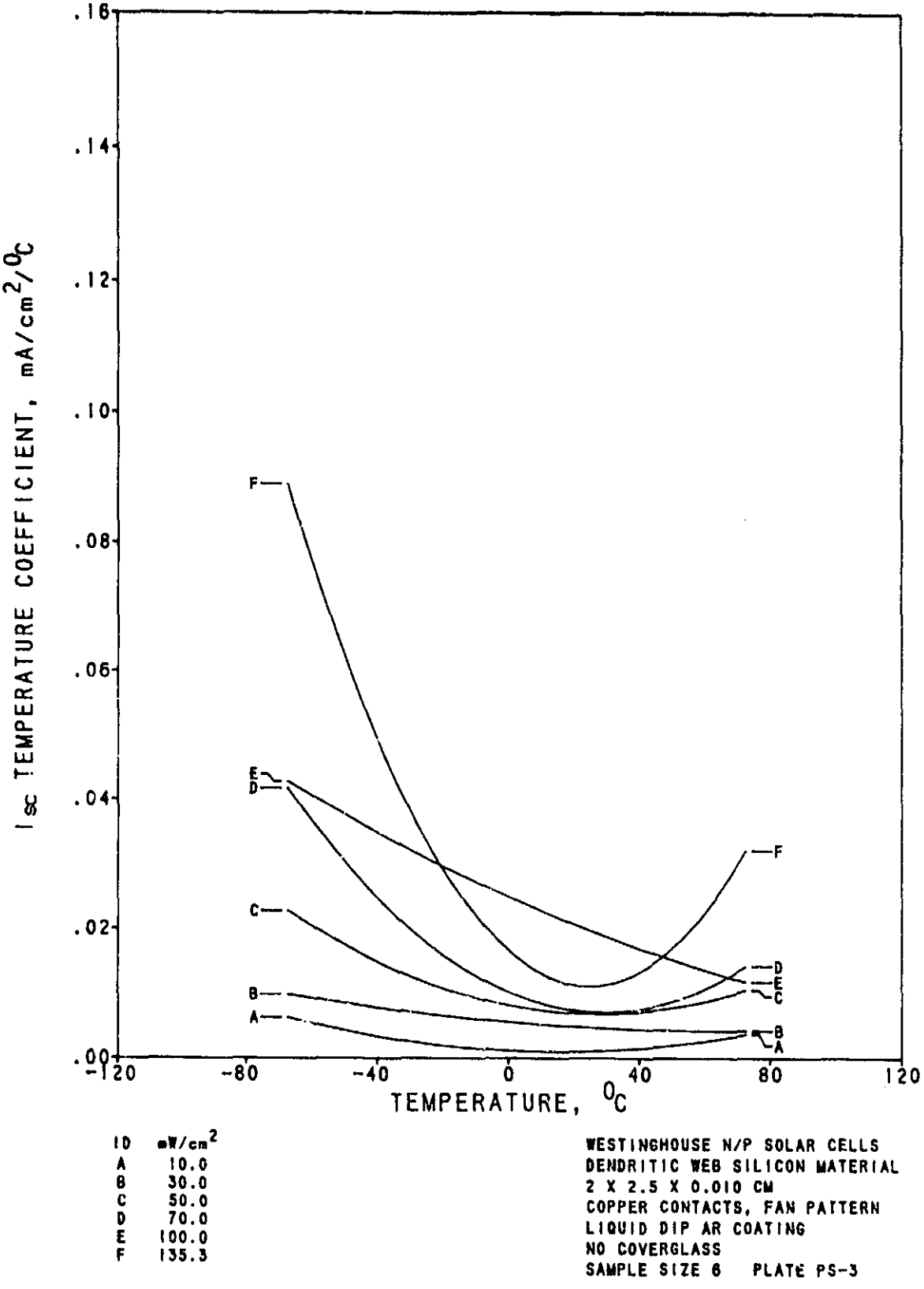
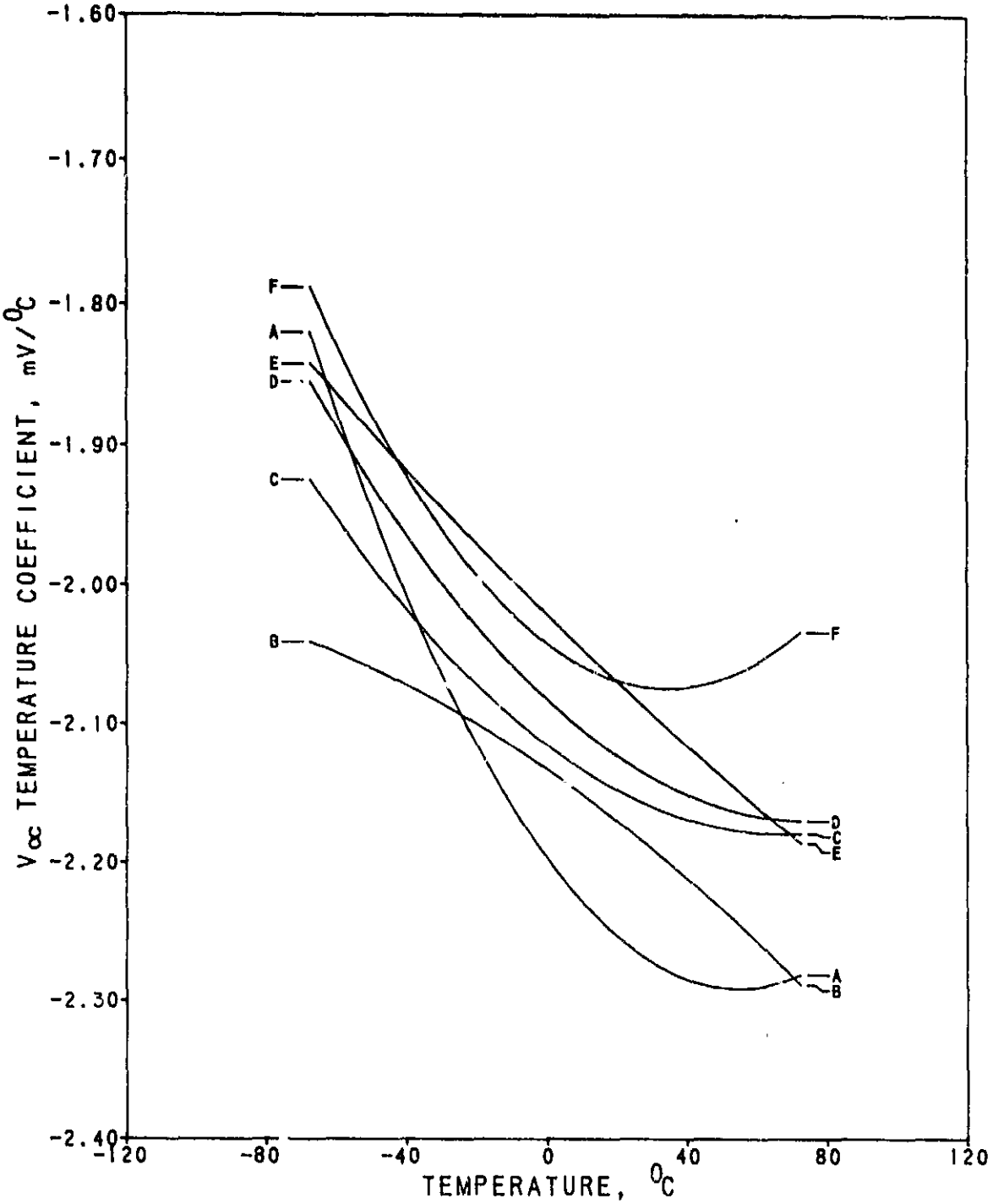


Figure 15. I_{sc} Temperature Coefficient



ID	mW/cm^2
A	10.0
B	30.0
C	50.0
D	70.0
E	100.0
F	135.3

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIF AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS-3

Figure 16. V_{oc} Temperature Coefficient

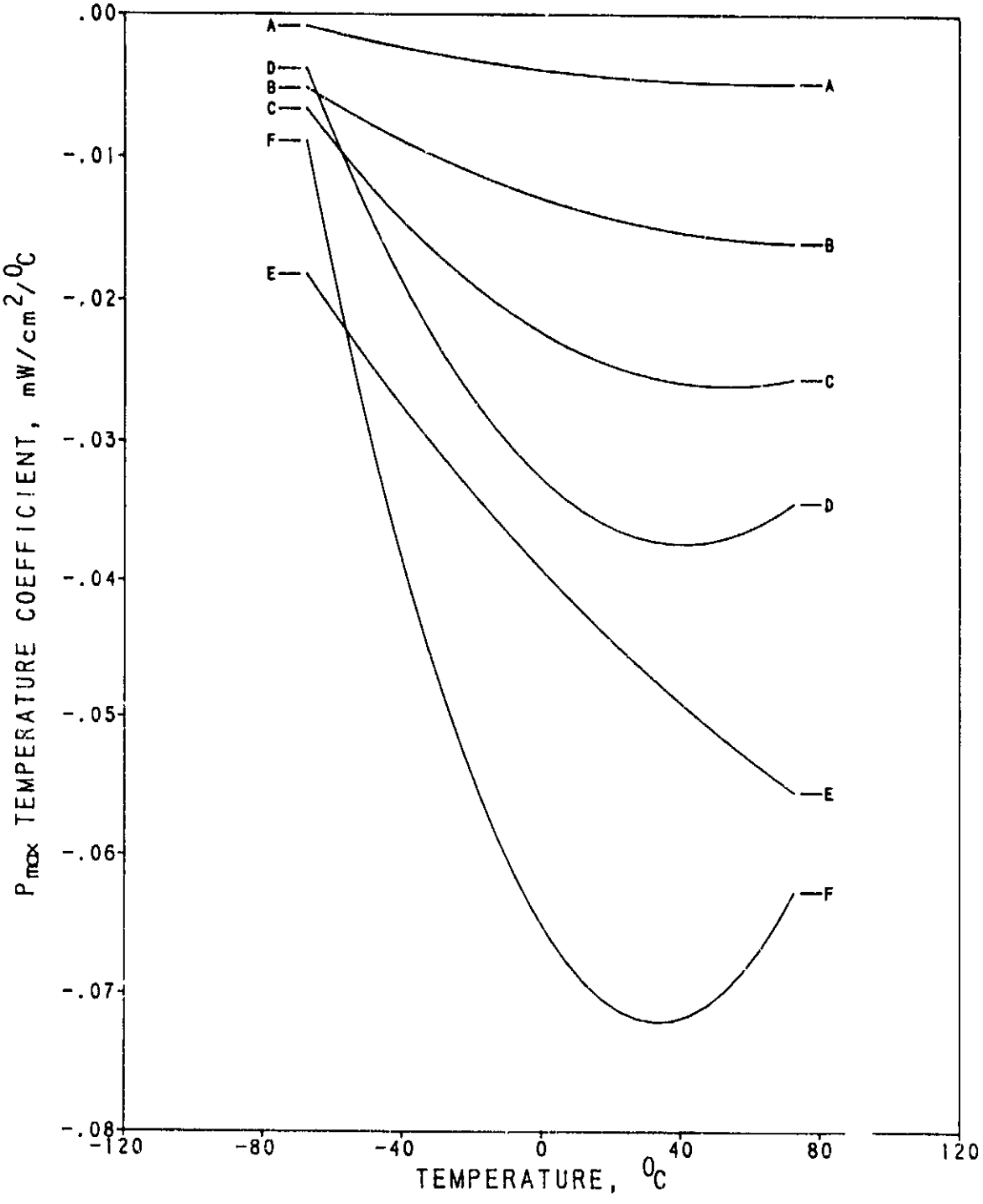
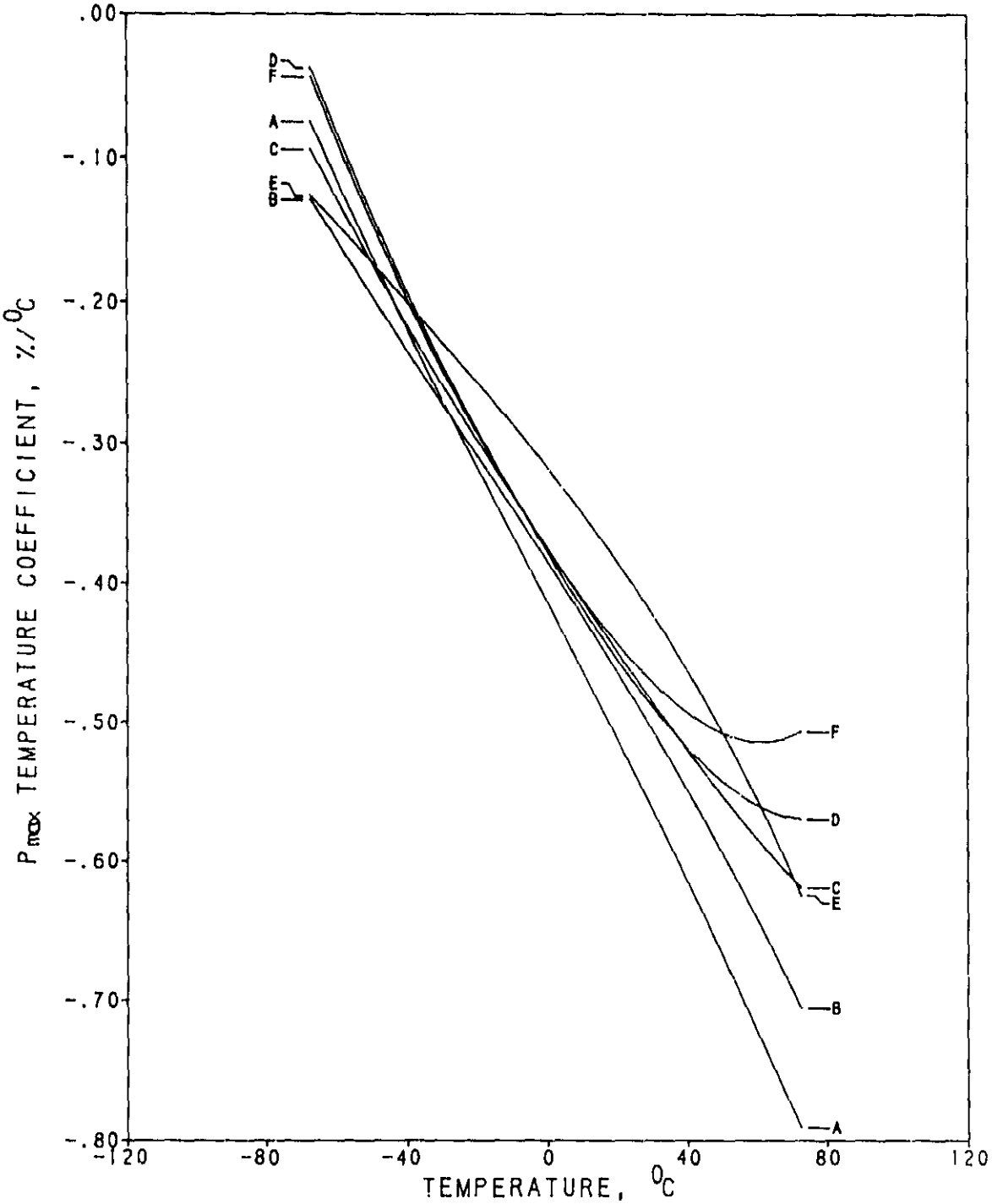


Figure 17. Absolute P_{max} Temperature Coefficient



ID	mW/cm^2
A	10.0
B	30.0
C	50.0
D	70.0
E	100.0
F	135.3

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS-3

Figure 18. Percent P_{max} Temperature Coefficient

Table 1. Average Short-Circuit Current

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS=3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	2.32	7.14	11.84	16.46	23.10	31.64
	(.05)	(.18)	(.28)	(.43)	(.53)	(.69)
.00	2.55	7.65	12.83	18.12	25.43	34.99
	(.09)	(.27)	(.32)	(.30)	(.56)	(.74)
25.00	2.57	7.82	13.06	18.34	26.06	35.22
	(.08)	(.30)	(.33)	(.30)	(.63)	(.80)
55.00	2.62	7.90	13.22	18.56	26.47	35.75
	(.08)	(.28)	(.37)	(.25)	(.61)	(.79)
75.00	2.68	8.02	13.44	18.81	26.79	36.20
	(.08)	(.27)	(.34)	(.31)	(.58)	(.81)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 2. Average Open-Circuit Voltage

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	686.38	735.37	748.75	756.10	762.75	771.62
	(48.38)	(11.27)	(8.82)	(8.31)	(8.02)	(7.71)
.00	545.03	589.63	604.75	617.65	627.67	636.50
	(15.27)	(9.48)	(7.66)	(6.85)	(6.25)	(7.34)
25.00	486.08	535.88	553.67	565.25	576.23	584.83
	(14.22)	(9.42)	(7.80)	(7.09)	(6.55)	(5.42)
55.00	420.97	469.33	486.22	500.33	512.92	522.87
	(13.33)	(9.16)	(8.44)	(7.40)	(7.10)	(6.38)
75.00	374.35	424.05	444.90	457.23	469.40	481.80
	(12.50)	(9.62)	(8.39)	(7.13)	(7.38)	(6.81)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 3. Average Maximum Power Current

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS=3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	1.96	6.33	10.59	14.82	21.23	29.26
	(.20)	(.51)	(.89)	(1.25)	(1.45)	(1.70)
.00	2.12	6.77	11.57	16.49	23.42	31.93
	(.17)	(.44)	(.58)	(.63)	(.83)	(.92)
25.00	2.10	6.82	11.72	16.58	23.94	32.12
	(.13)	(.44)	(.54)	(.49)	(.94)	(.93)
55.00	2.11	6.84	11.69	16.45	23.69	32.14
	(.11)	(.32)	(.47)	(.44)	(.79)	(.96)
75.00	2.17	6.82	11.60	16.46	23.88	32.03
	(.13)	(.29)	(.48)	(.42)	(.57)	(.54)

NOTE; STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 4. Average Maximum Power Voltage

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS=3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	571.07	633.37	664.42	682.15	683.22	696.55
	(86.68)	(56.11)	(25.57)	(11.10)	(9.73)	(8.19)
.00	441.58	498.13	517.78	529.77	533.22	550.27
	(33.35)	(15.17)	(10.01)	(9.09)	(13.42)	(13.56)
25.00	407.17	446.60	461.88	473.70	478.15	491.00
	(42.55)	(10.13)	(6.59)	(9.99)	(11.21)	(12.17)
55.00	326.17	375.92	395.38	410.13	419.83	426.77
	(17.07)	(12.62)	(8.58)	(10.24)	(12.70)	(13.31)
75.00	280.45	332.30	355.20	366.62	371.97	385.58
	(16.01)	(12.63)	(9.21)	(11.36)	(13.06)	(17.70)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 5. Average Maximum Power

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE P8-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	1.12	4.03	7.06	10.12	14.51	20.38
	(.22)	(.62)	(.82)	(.96)	(1.11)	(1.29)
.00	.94	3.38	5.99	8.74	12.49	17.57
	(.14)	(.32)	(.39)	(.42)	(.59)	(.80)
25.00	.86	3.05	5.41	7.86	11.45	15.78
	(.09)	(.26)	(.32)	(.35)	(.57)	(.81)
55.00	.69	2.57	4.62	6.75	9.95	13.73
	(.07)	(.20)	(.27)	(.28)	(.54)	(.79)
75.00	.61	2.27	4.12	6.03	8.89	12.36
	(.07)	(.18)	(.25)	(.26)	(.49)	(.72)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 6. Average Curve Factor

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2,5 X 0,010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS=3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10,00	30,00	50,00	70,00	100,00	135,30
-70,00	,6974	,7646	,7942	,8118	,8227	,8341
	(,0989)	(,0928)	(,0732)	(,0591)	(,0488)	(,0337)
,00	,6728	,7474	,7691	,7800	,7819	,7867
	(,0669)	(,0412)	(,0277)	(,0193)	(,0143)	(,0150)
25,00	,6837	,7265	,7481	,7576	,7619	,7656
	(,0703)	(,0289)	(,0188)	(,0150)	(,0126)	(,0180)
55,00	,6224	,6932	,7161	,7265	,7323	,7337
	(,0332)	(,0208)	(,0144)	(,0123)	(,0163)	(,0209)
75,00	,6080	,6664	,6884	,7014	,7062	,7078
	(,0425)	(,0191)	(,0141)	(,0118)	(,0153)	(,0203)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 7. Average AMO Efficiency

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.010 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	11.20	13.44	14.11	14.46	14.51	15.07
	(2.18)	(2.05)	(1.65)	(1.36)	(1.11)	(.96)
.00	9.39	11.26	11.99	12.48	12.49	12.99
	(1.38)	(1.06)	(.79)	(.61)	(.59)	(.59)
25.00	8.56	10.17	10.83	11.22	11.45	11.66
	(.95)	(.87)	(.63)	(.50)	(.57)	(.60)
55.00	6.89	8.58	9.25	9.64	9.95	10.14
	(.70)	(.67)	(.55)	(.39)	(.54)	(.56)
75.00	6.11	7.56	8.24	8.62	8.89	9.13
	(.68)	(.60)	(.51)	(.38)	(.49)	(.53)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

140-μm-THICK CELLS

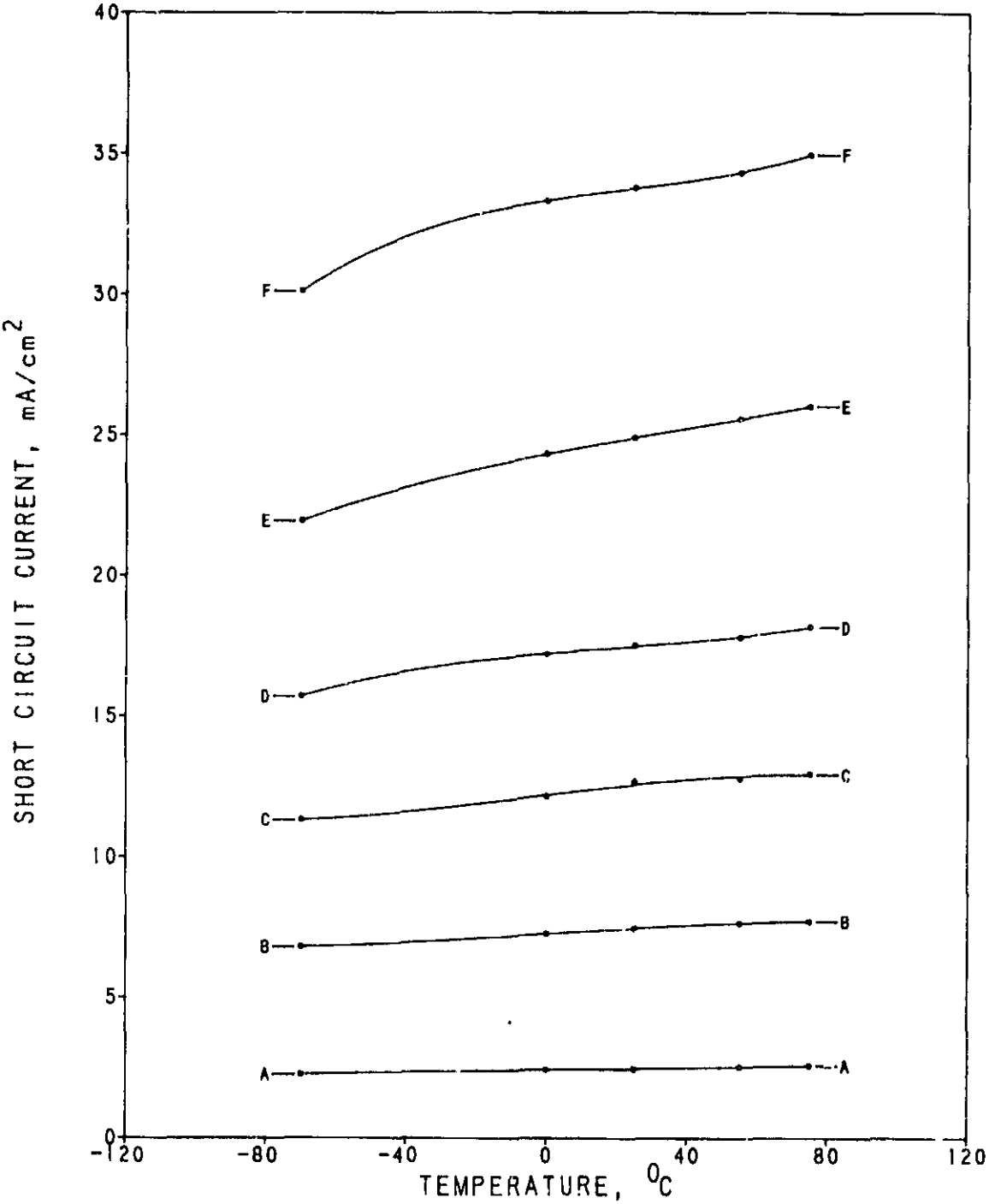


Figure 19. Average I_{sc}/cm^2 as a Function of Temperature

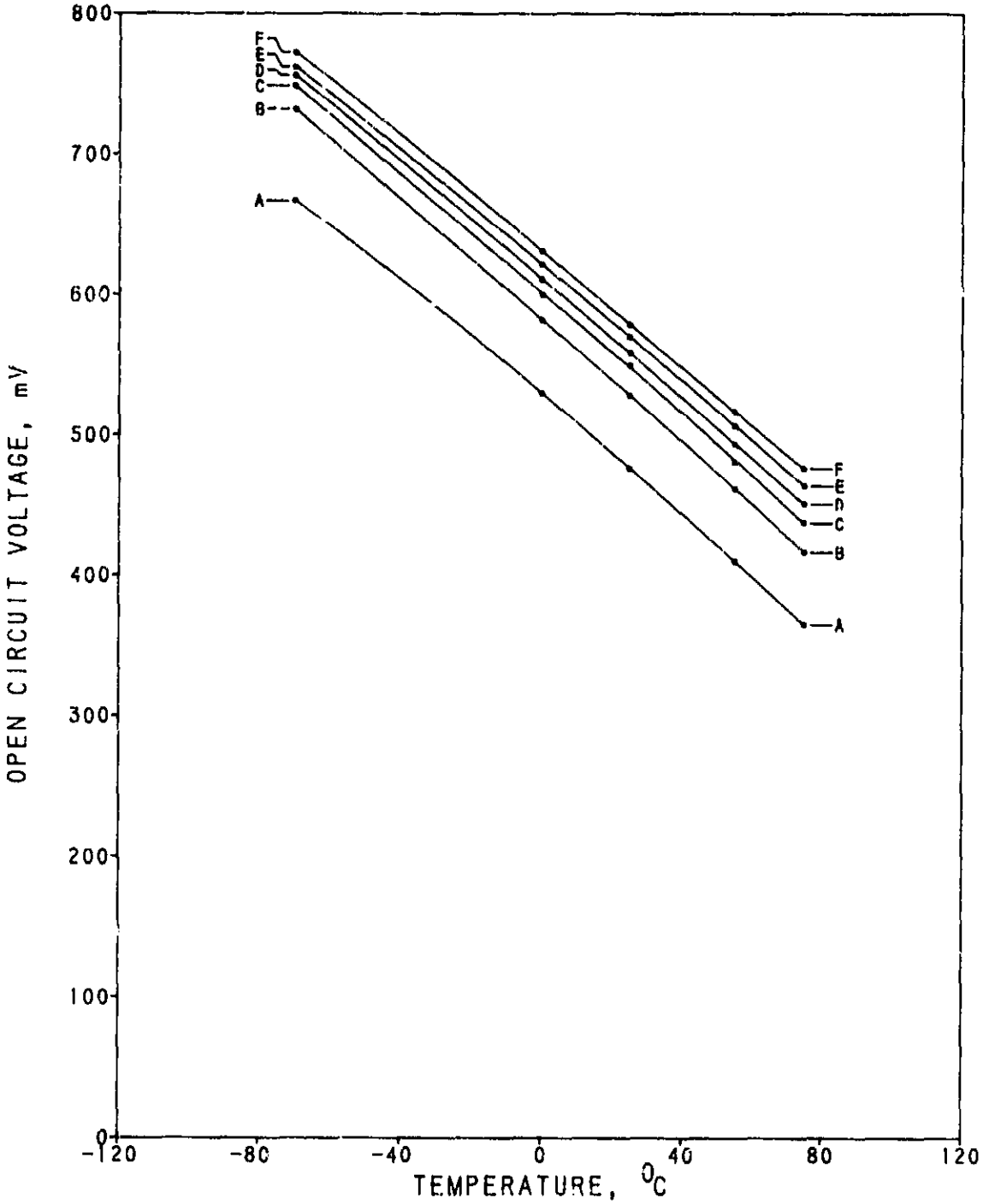


Figure 20. Average V_{oc} as a Function of Temperature

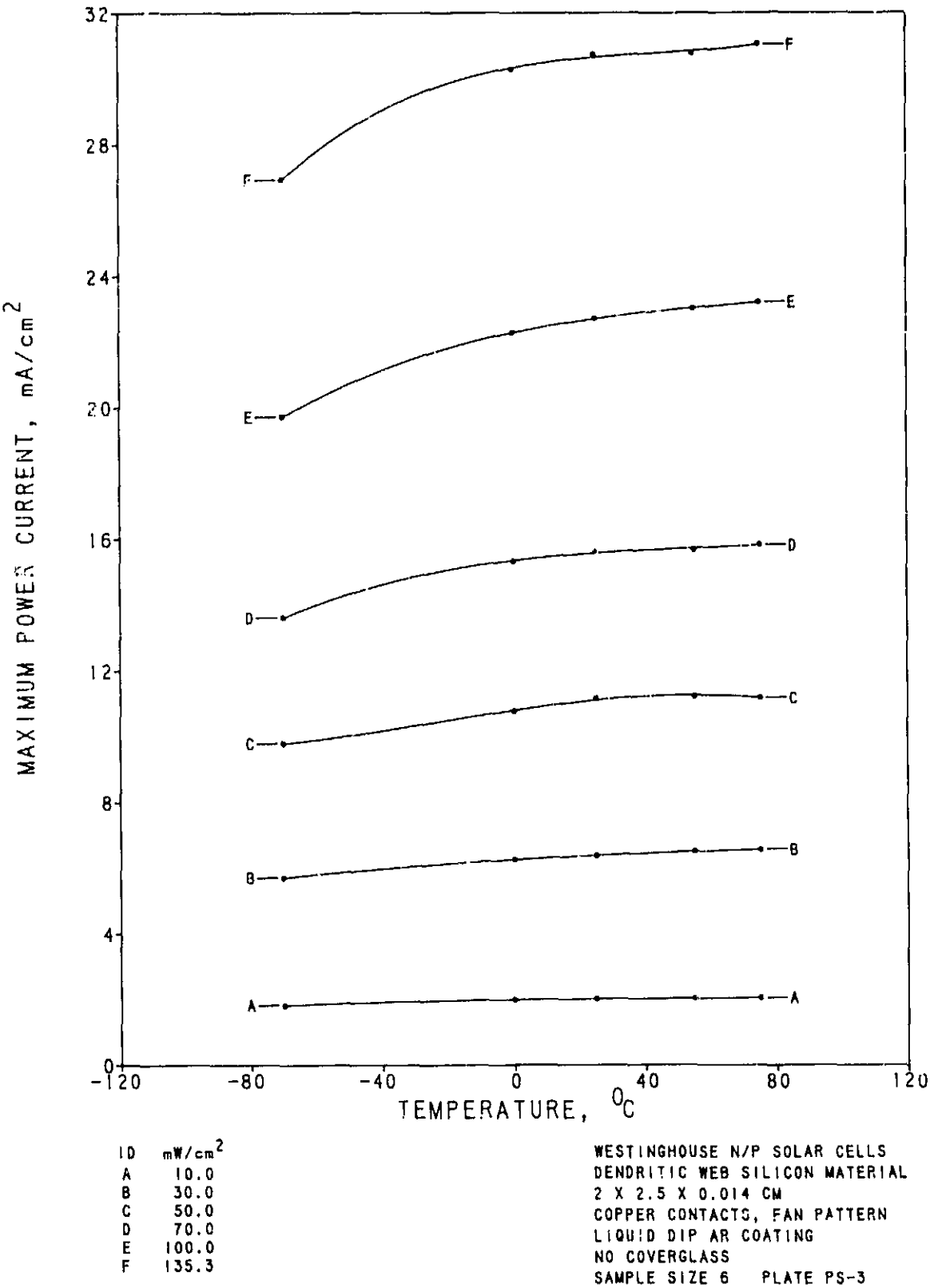


Figure 21. Average I_{mp}/cm^2 as a Function of Temperature

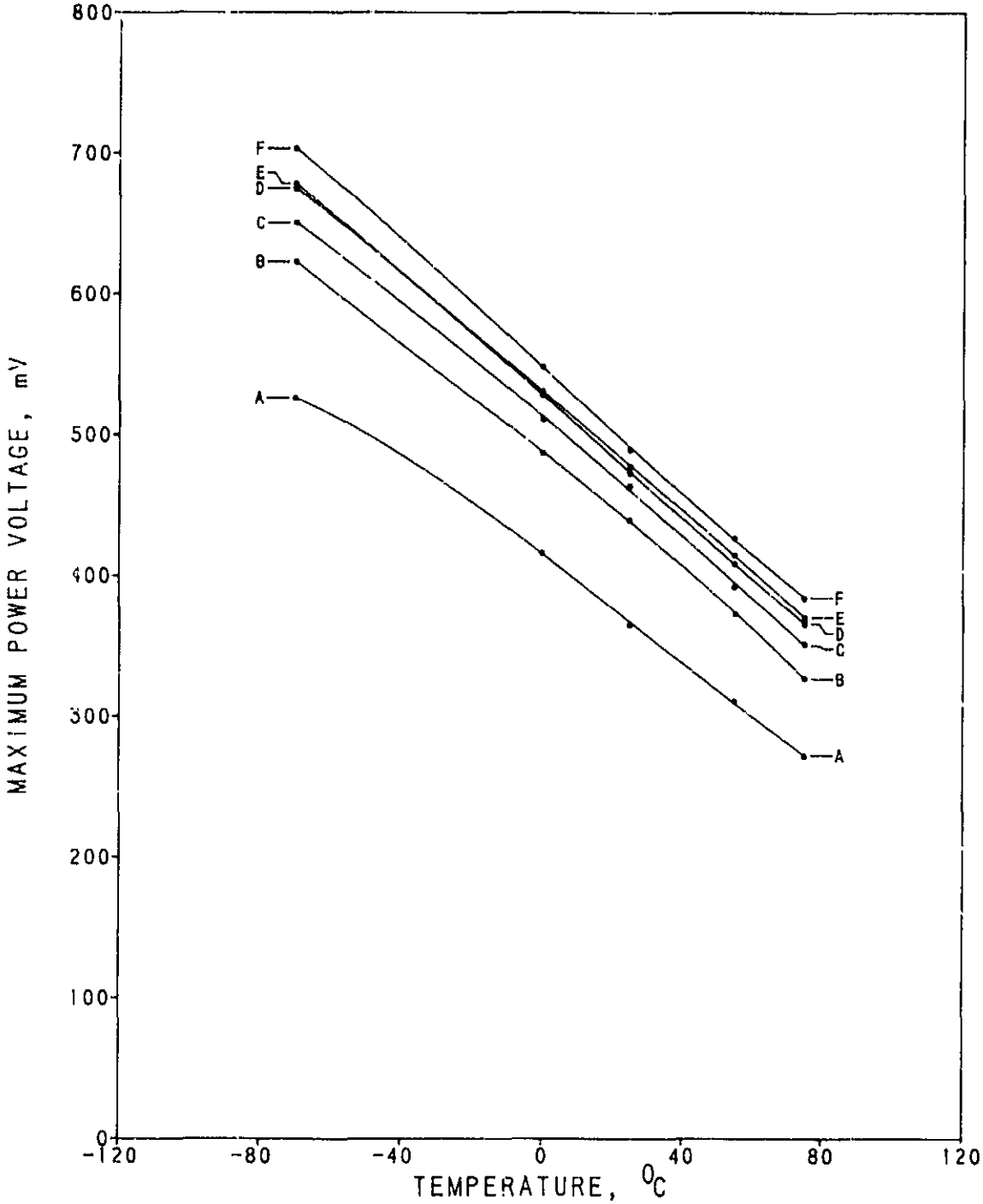


Figure 22. Average V_{mp} as a Function of Temperature

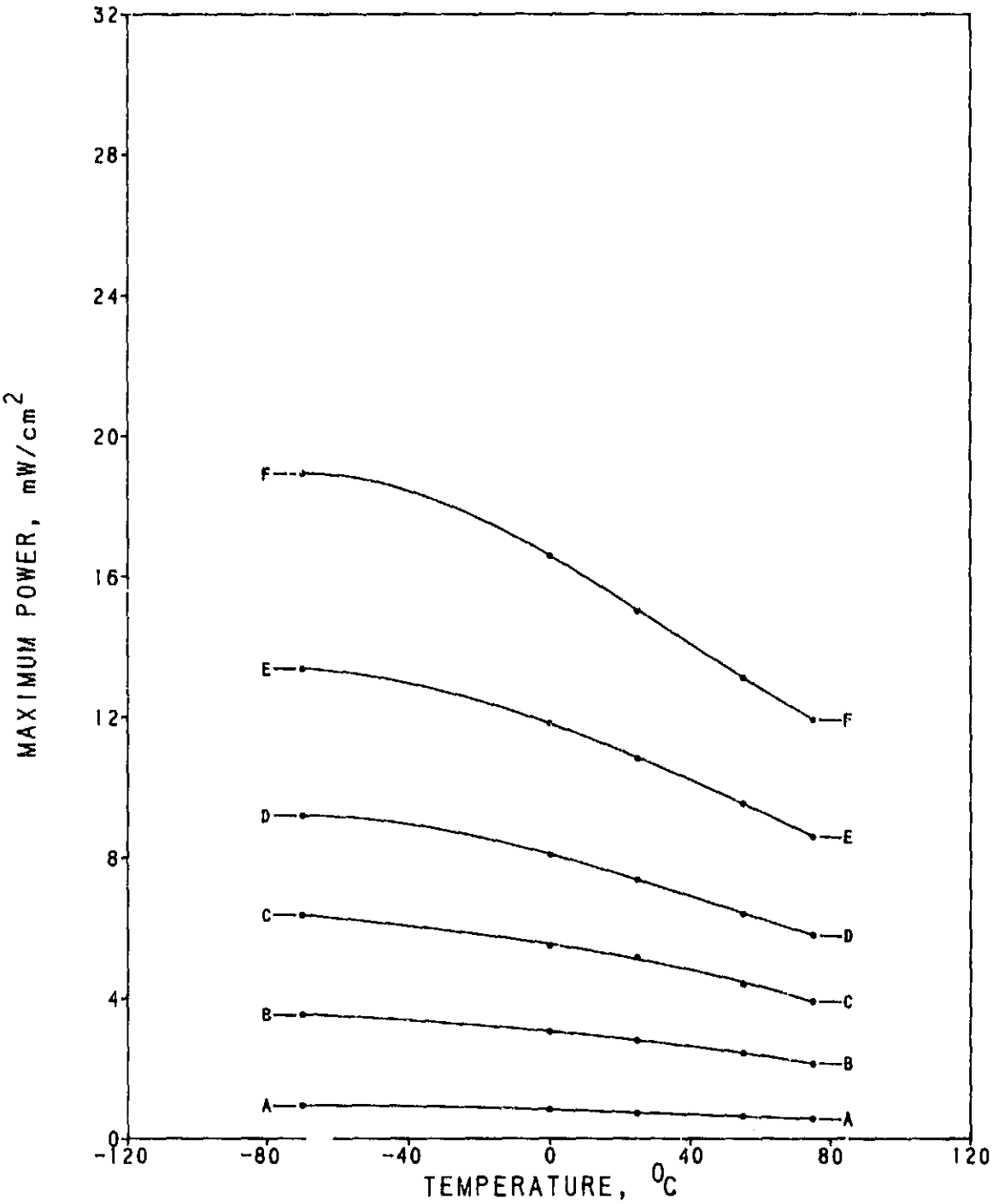


Figure 23. Average P_{max}/cm^2 as a Function of Temperature

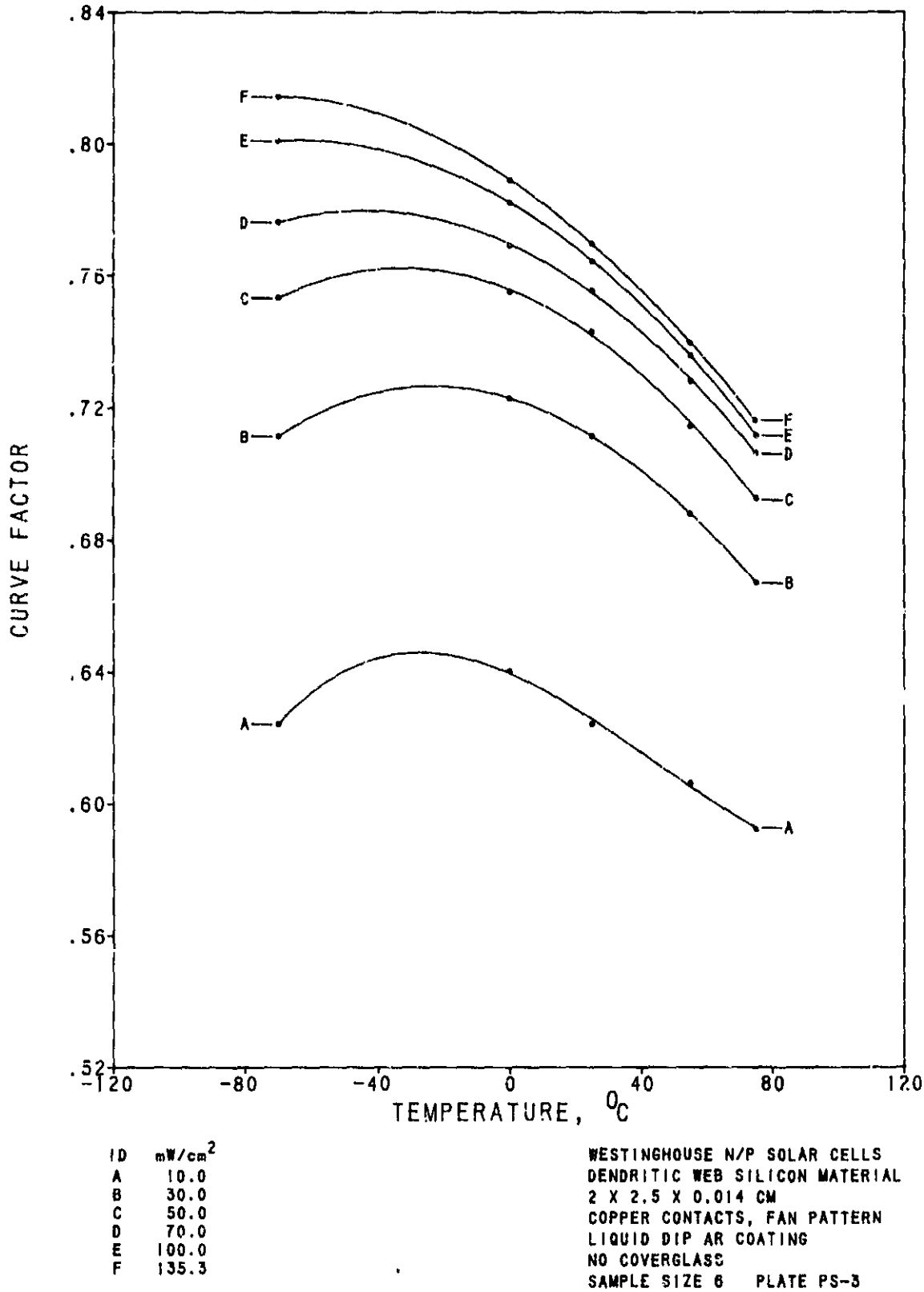


Figure 24. Average Curve Factor as a Function of Temperature

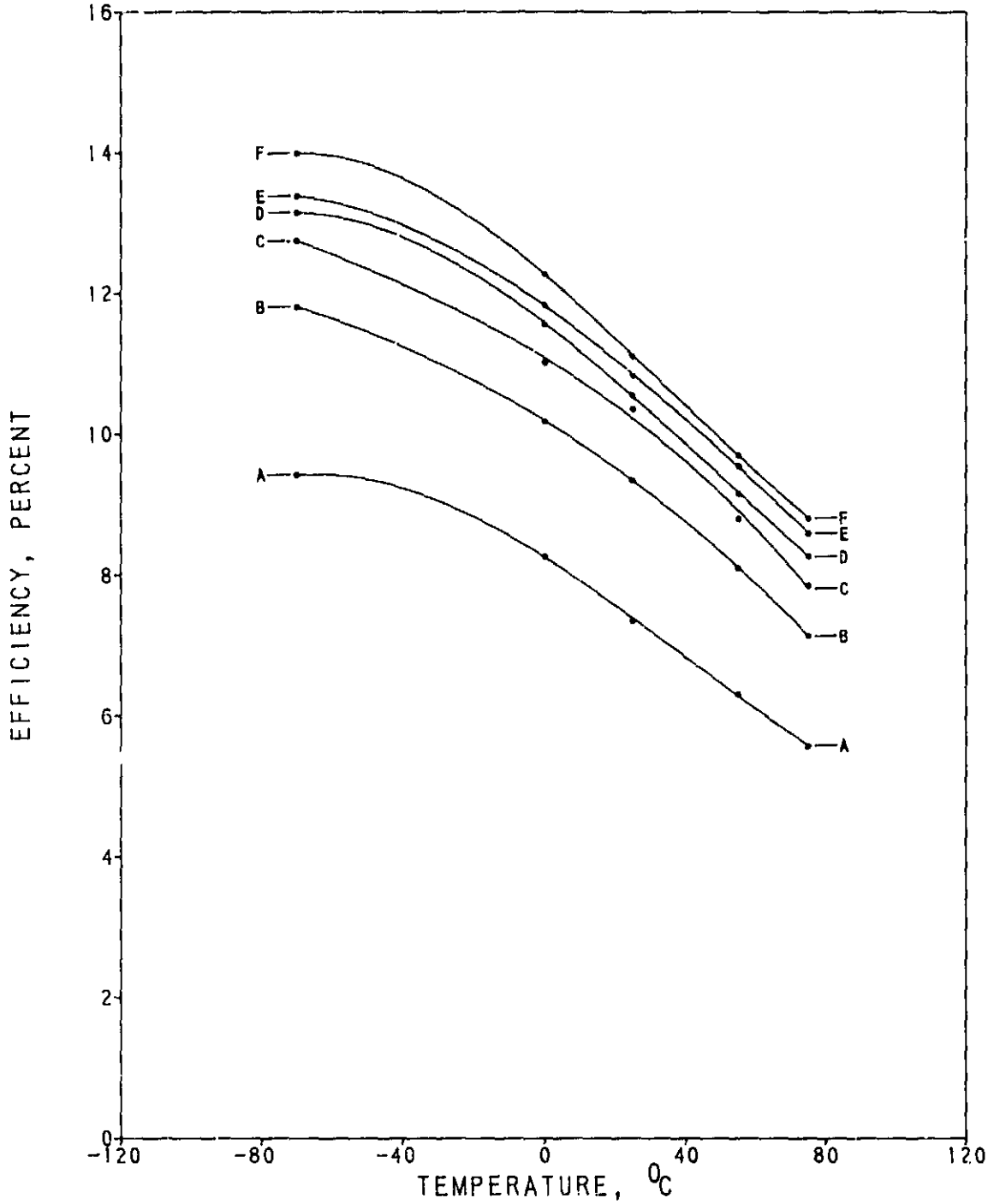


Figure 25. Average AMO Efficiency as a Function of Temperature

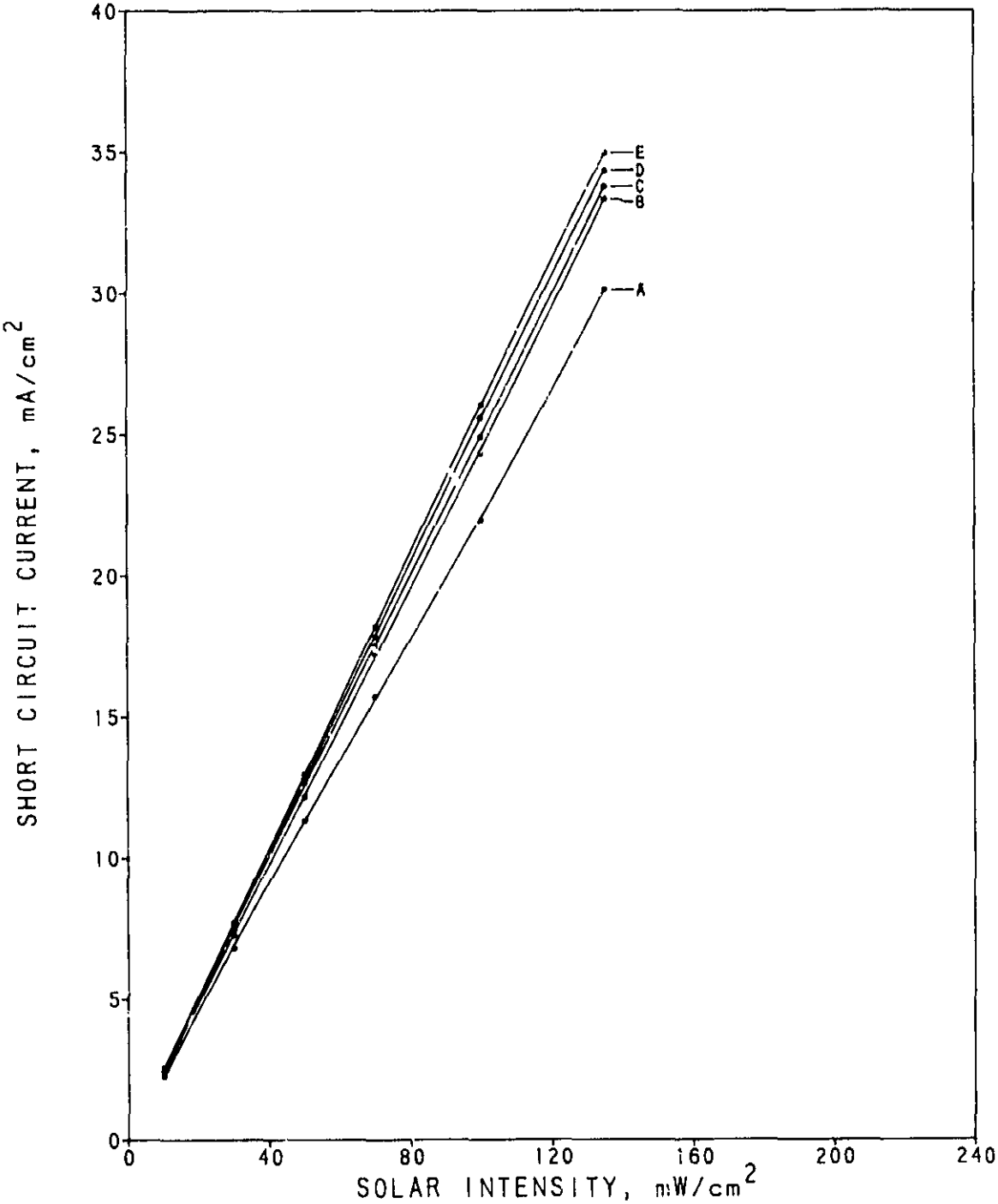


Figure 26. Average I_{sc}/cm^2 as a Function of Intensity

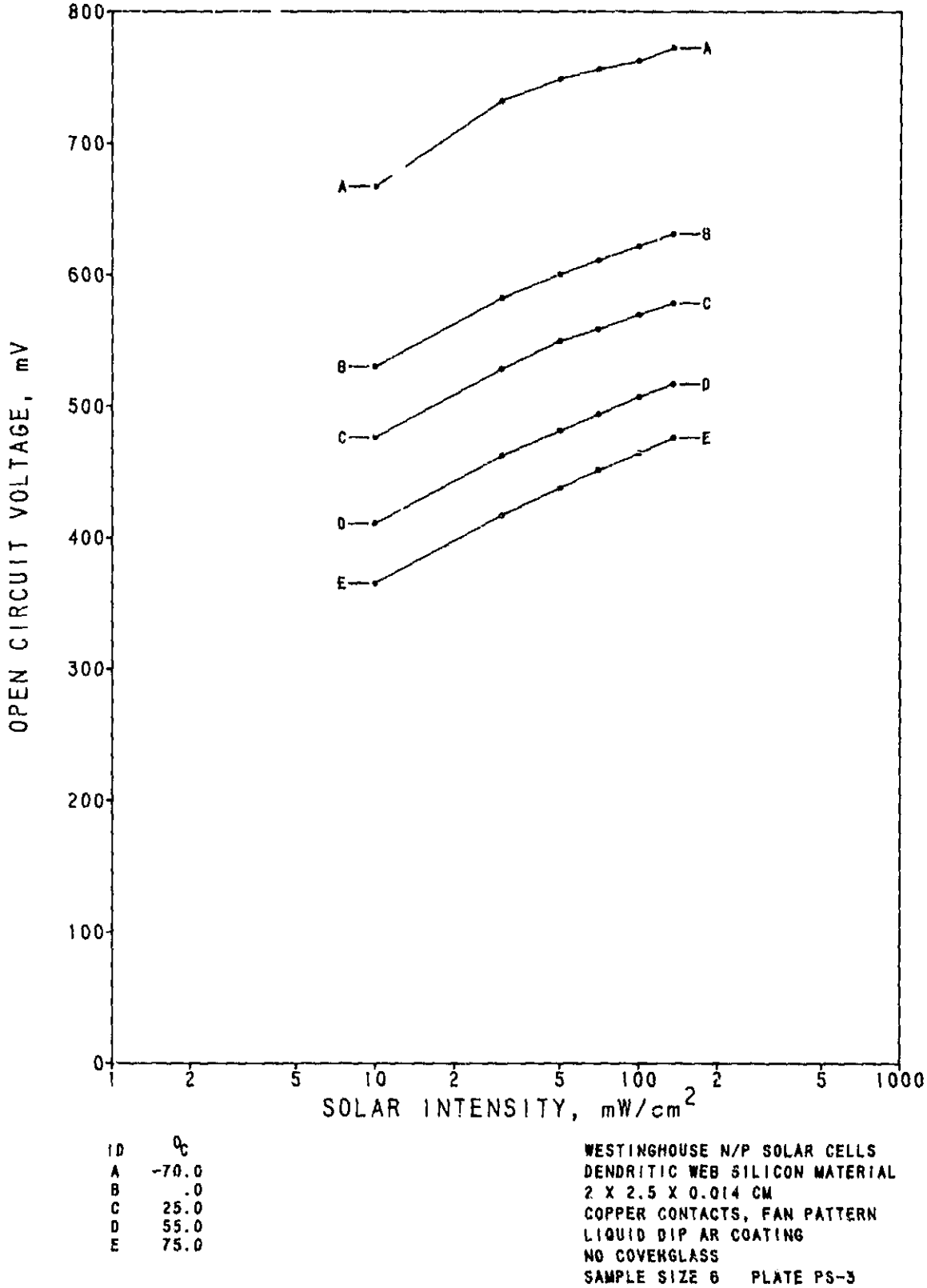


Figure 27. Average V_{oc} as a Function of Intensity

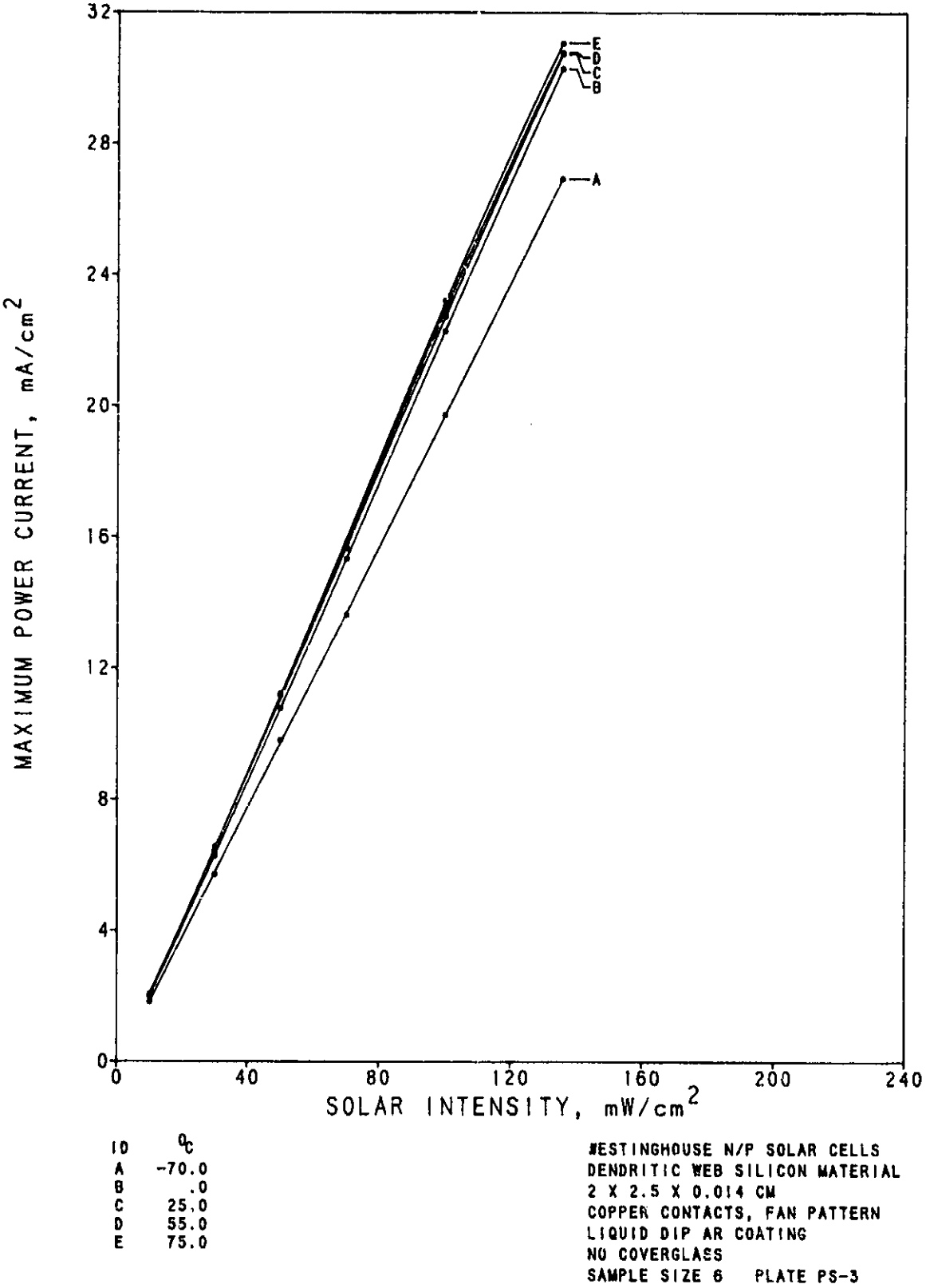


Figure 28. Average I_{mp}/cm^2 as a Function of Intensity

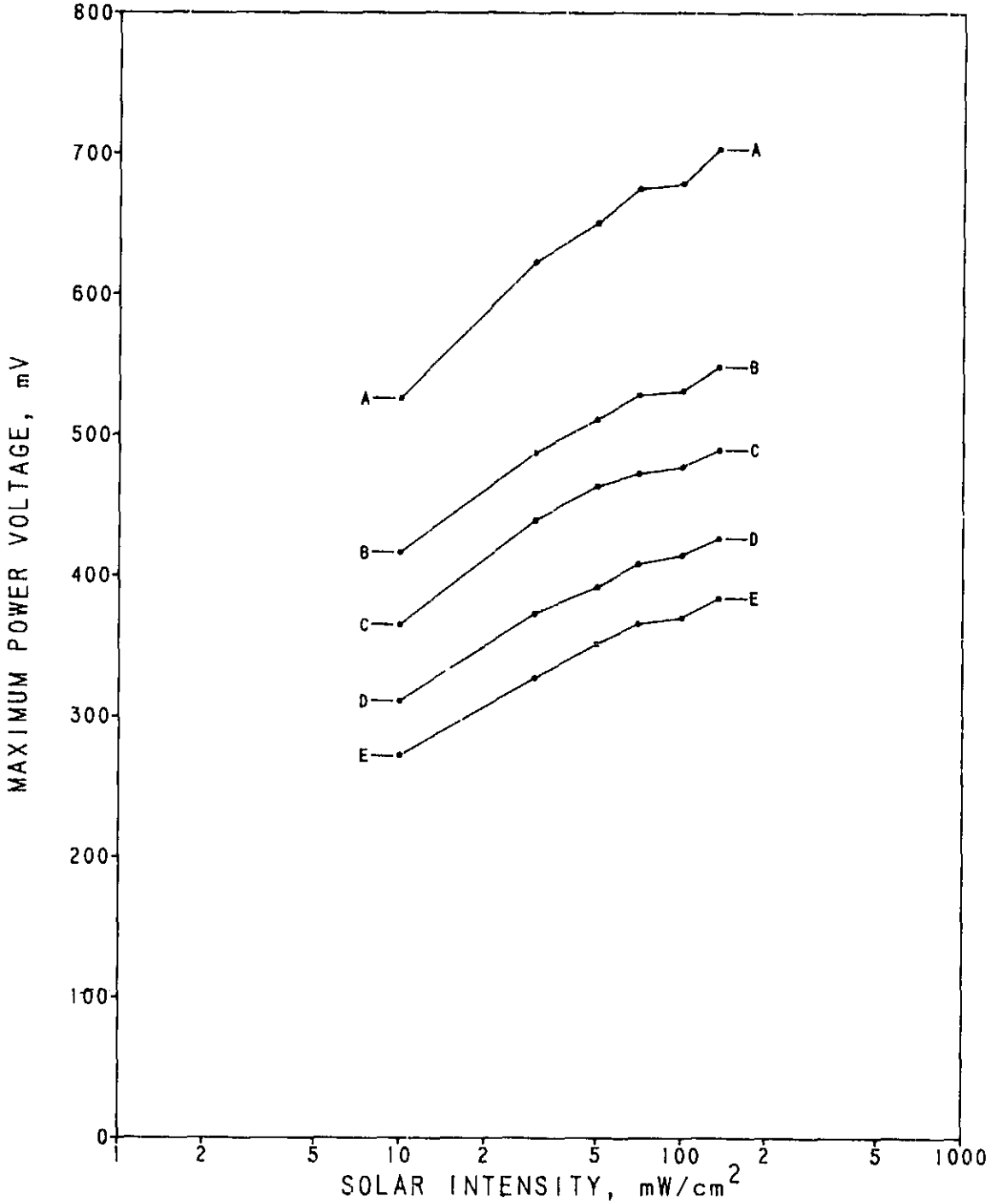


Figure 29. Average V_{mp} as a Function of Intensity

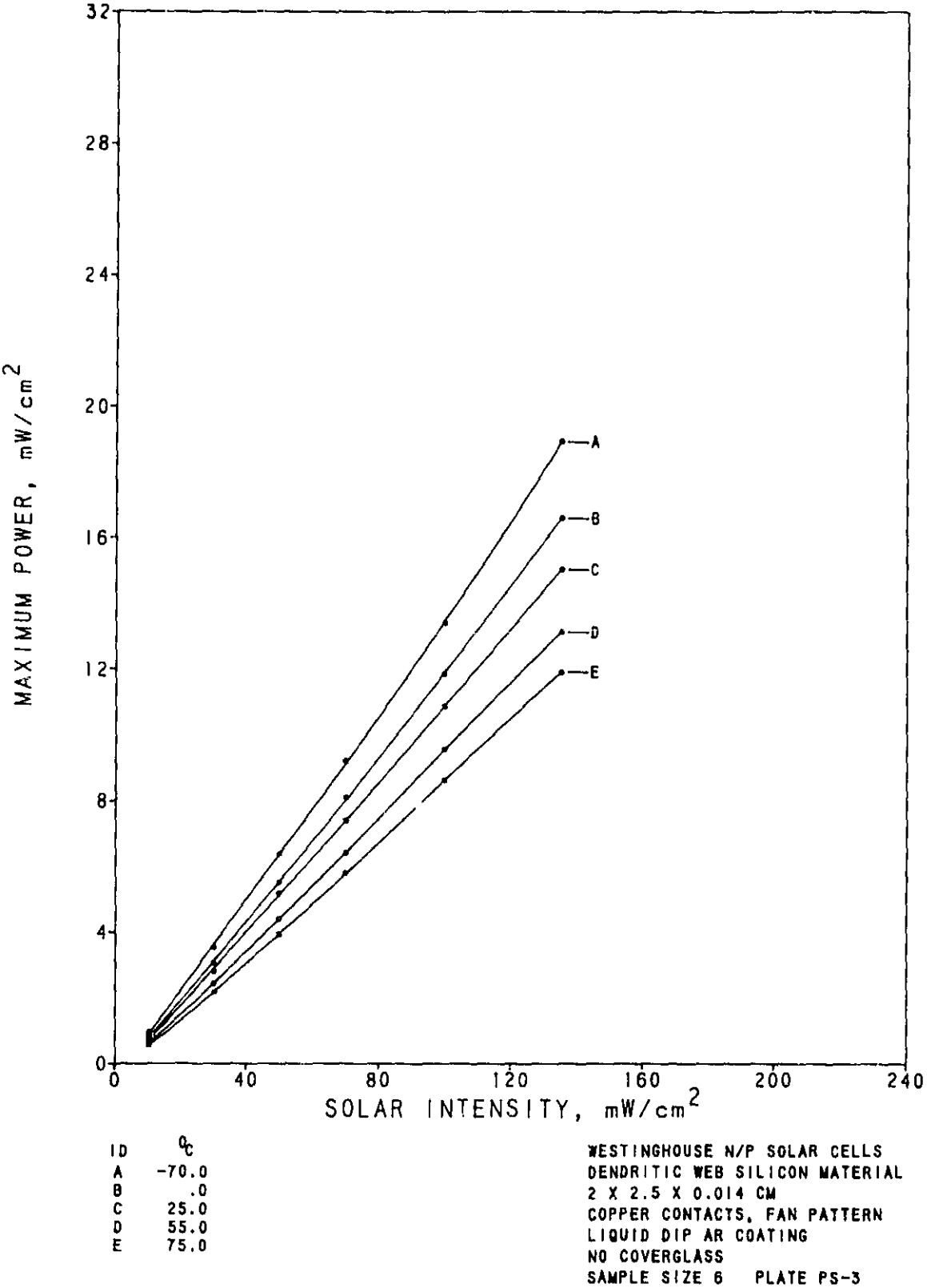


Figure 30. Average P_{max}/cm^2 as a Function of Intensity

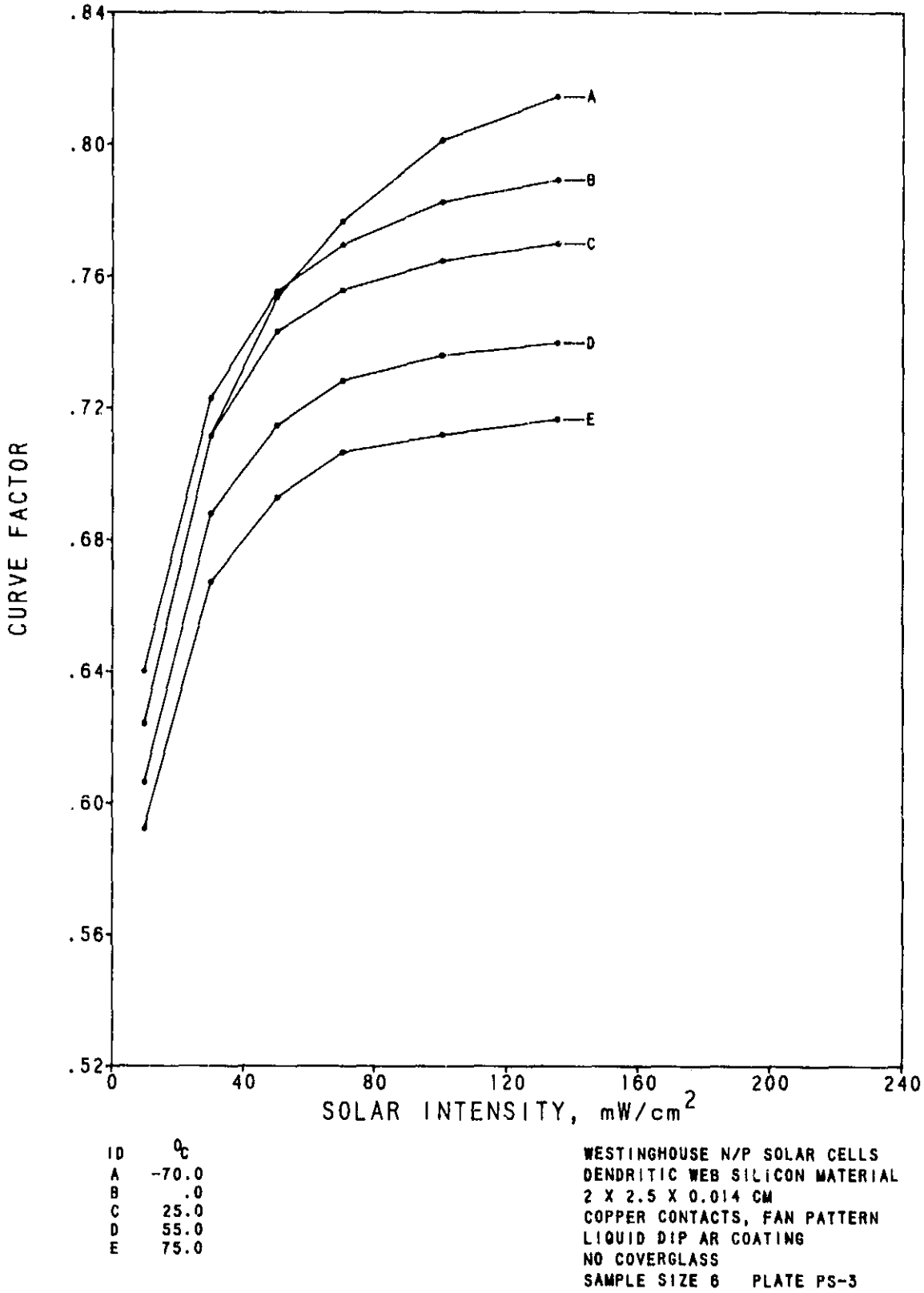


Figure 31. Average Curve Factor as a Function of Intensity

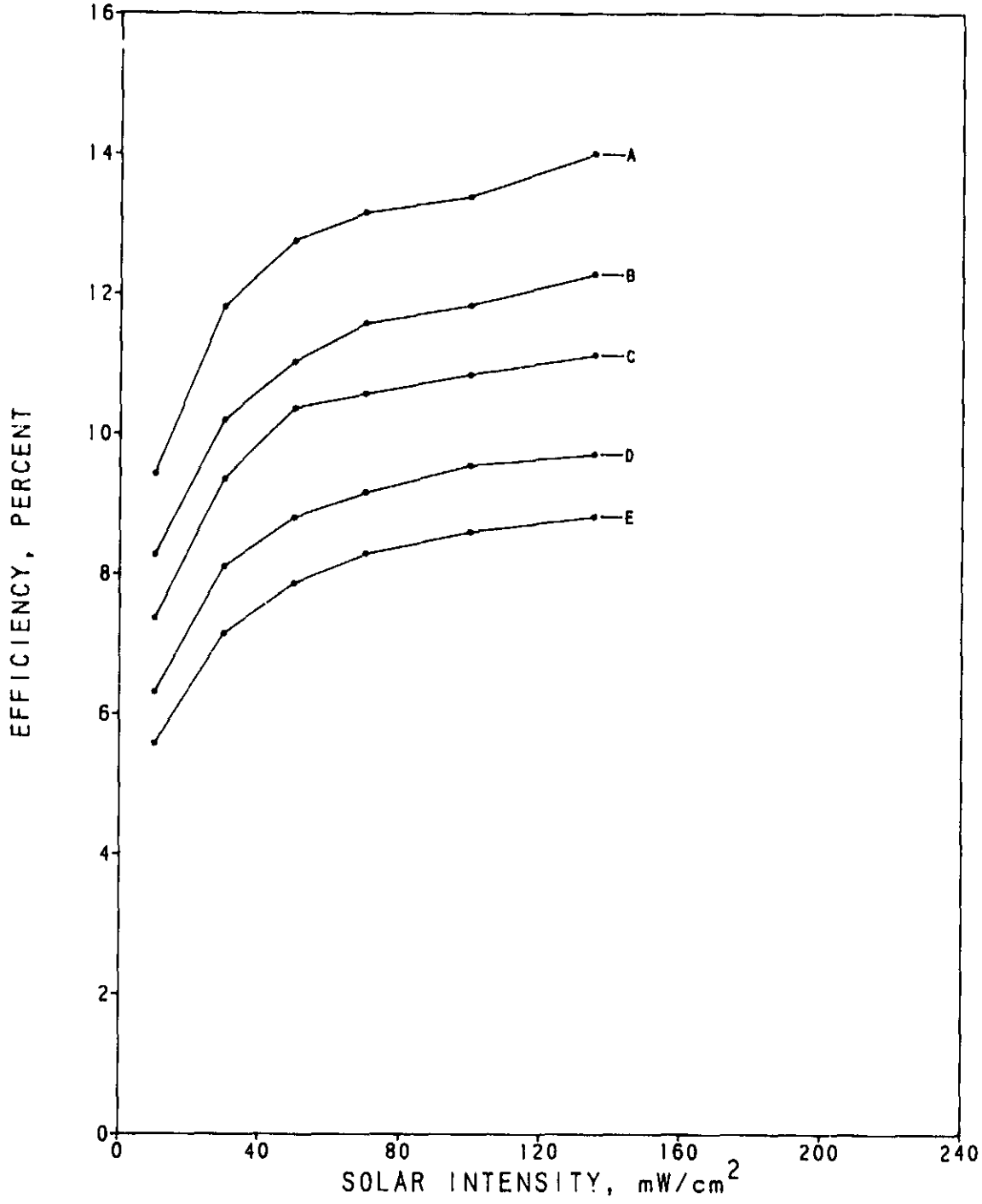


Figure 32. Average AMO Efficiency as a Function of Intensity

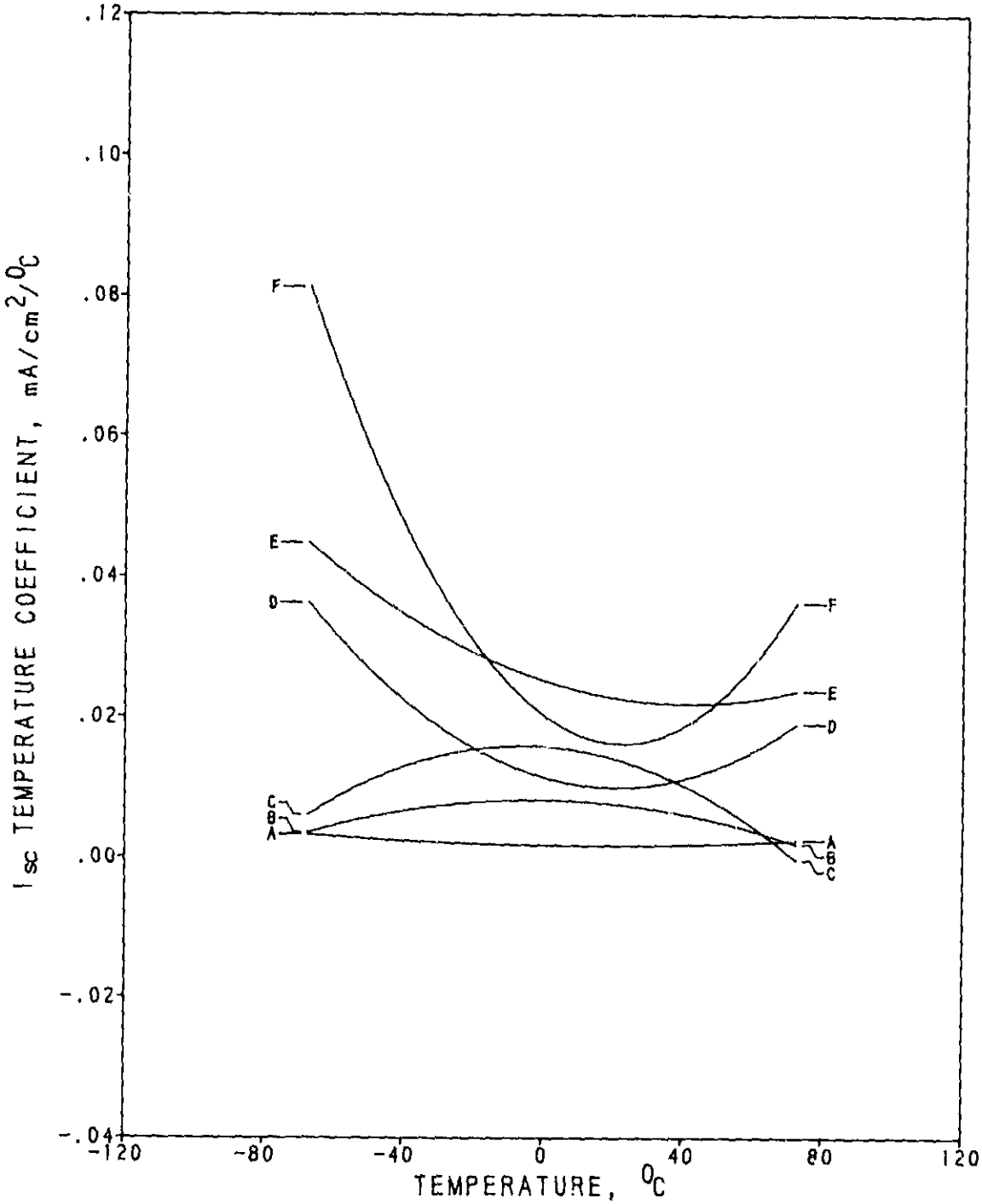
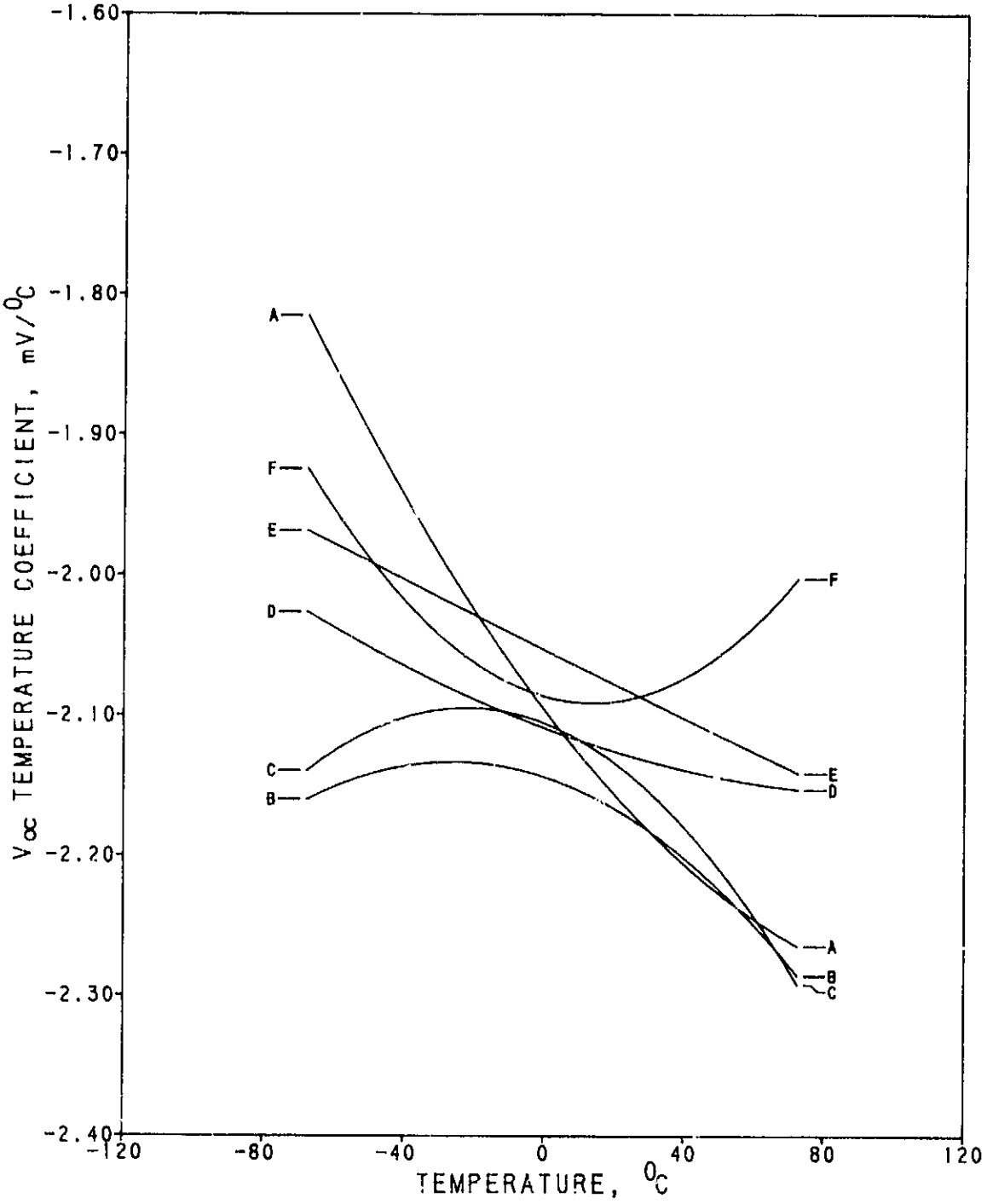


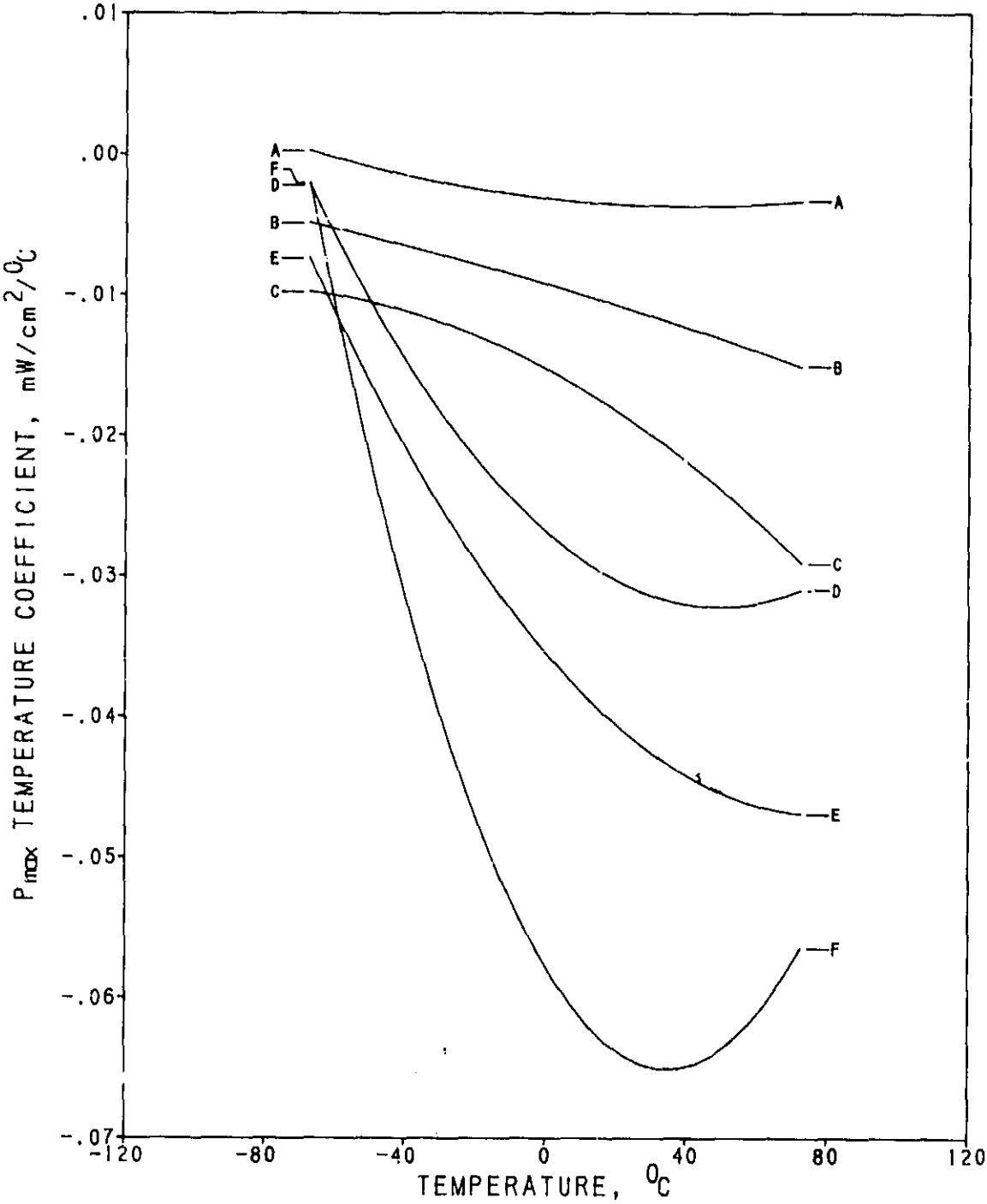
Figure 33. I_{sc} Temperature Coefficient



ID	mW/cm^2
A	10.0
B	30.0
C	50.0
D	70.0
E	100.0
F	135.3

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS-3

Figure 34. V_{oc} Temperature Coefficient



ID	mW/cm^2
A	10.0
B	30.0
C	50.0
D	70.0
E	100.0
F	135.3

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS-3

Figure 35. Absolute P_{max} Temperature Coefficient

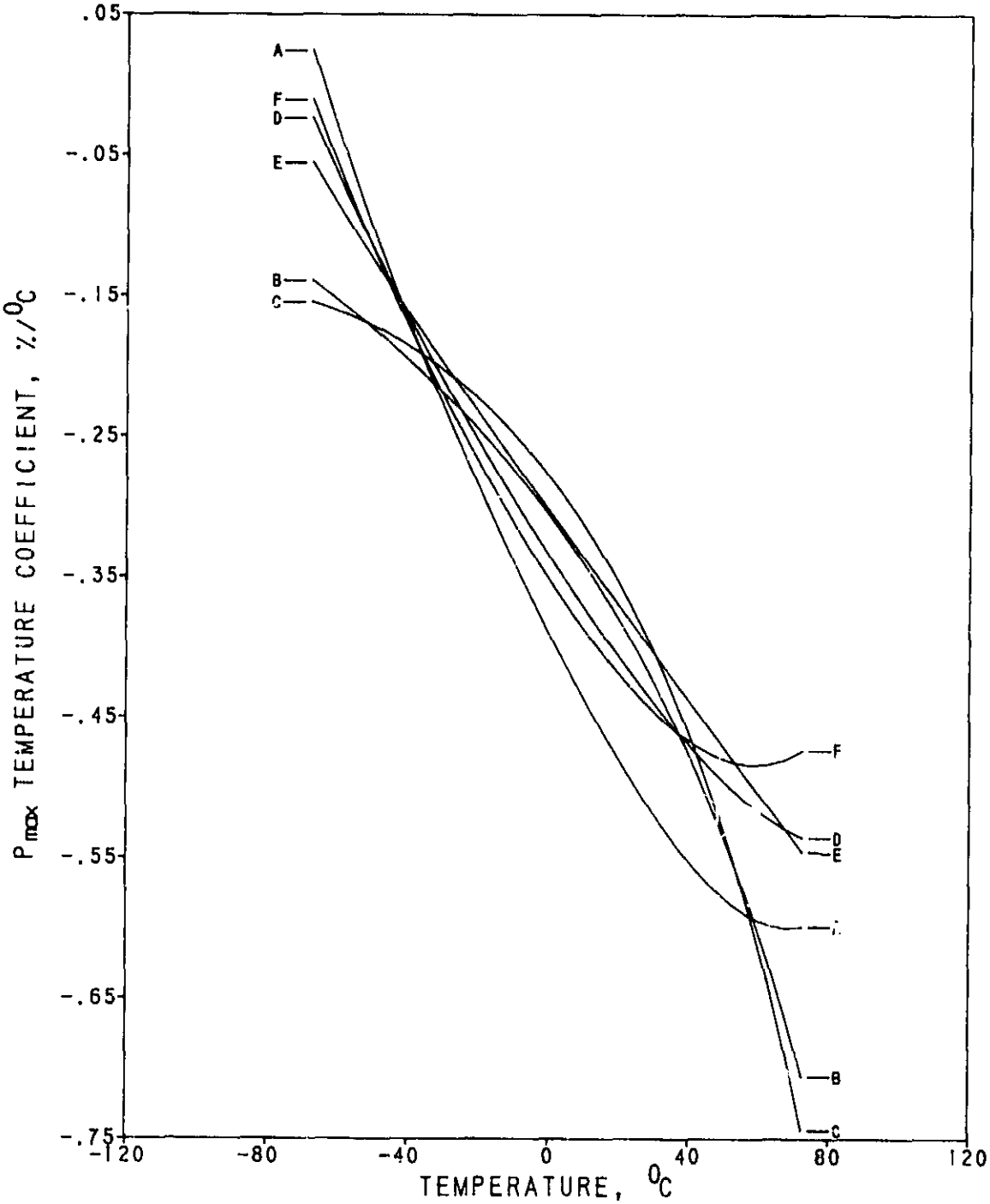


Figure 36. Percent P_{max} Temperature Coefficient

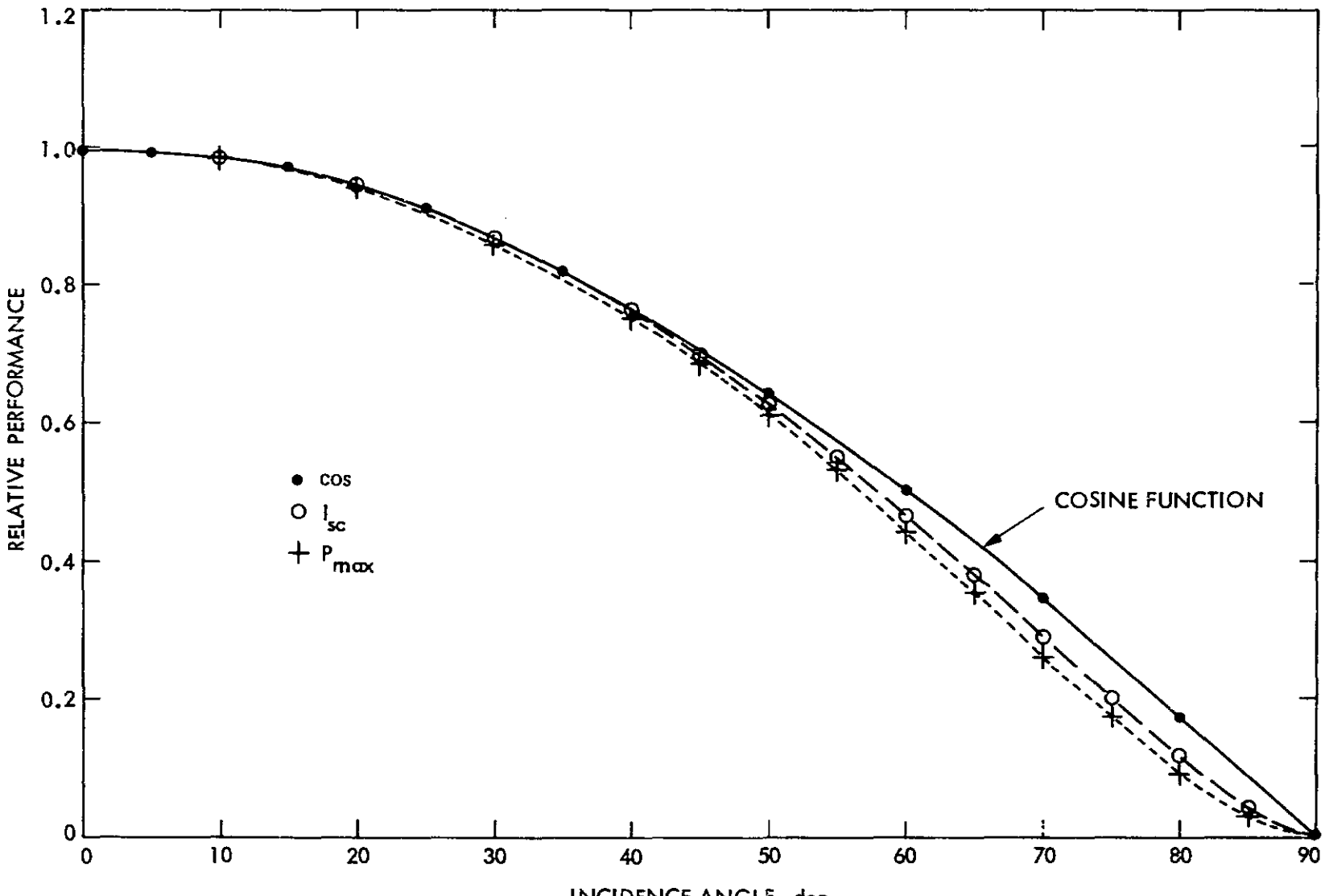


Figure 37. P_{max} and I_{sc} as a Function of Illumination Incidence Angle

Table 8. Average Short-Circuit Current

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE P8-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	2.27	6.81	11.32	15.71	21.95	30.12
	(.08)	(.14)	(.22)	(.41)	(.46)	(.60)
.00	2.43	7.26	12.15	17.22	24.33	33.33
	(.06)	(.23)	(.29)	(.57)	(.68)	(.88)
25.00	2.47	7.47	12.67	17.51	24.89	33.78
	(.06)	(.23)	(.36)	(.61)	(1.00)	(1.00)
55.00	2.53	7.64	12.79	17.81	25.58	34.34
	(.07)	(.24)	(.34)	(.60)	(.91)	(1.03)
75.00	2.57	7.71	12.96	18.17	26.02	34.97
	(.06)	(.24)	(.36)	(.56)	(.92)	(1.04)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 9. Average Open-Circuit Voltage

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	667.00 (67.81)	731.97 (16.44)	748.58 (11.34)	756.06 (11.81)	762.27 (11.73)	772.48 (12.94)
.00	529.93 (24.68)	582.18 (12.85)	600.27 (12.79)	611.02 (12.48)	621.72 (12.20)	631.15 (11.52)
25.00	476.17 (19.89)	528.05 (13.07)	549.55 (11.43)	558.62 (12.19)	569.63 (11.12)	578.48 (10.45)
55.00	410.52 (17.38)	462.22 (12.77)	481.18 (11.69)	493.72 (11.12)	507.02 (10.08)	516.87 (8.79)
75.00	365.13 (16.04)	416.78 (12.64)	437.80 (11.08)	451.18 (10.26)	464.08 (9.45)	476.06 (7.80)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 10. Average Maximum Power Current

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE P8-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	1.81	5.70	9.79	13.61	19.71	26.92
	(.21)	(.40)	(.47)	(.79)	(1.26)	(1.69)
.00	1.98	6.26	10.77	15.33	22.28	30.28
	(.12)	(.42)	(.71)	(1.15)	(1.25)	(1.60)
25.00	2.01	6.38	11.17	15.64	22.72	30.74
	(.13)	(.45)	(.77)	(.95)	(1.26)	(1.26)
55.00	2.02	6.51	11.22	15.68	23.03	30.77
	(.15)	(.39)	(.57)	(.79)	(1.04)	(1.03)
75.00	2.04	6.55	11.18	15.63	23.21	31.06
	(.13)	(.31)	(.46)	(.67)	(.80)	(1.13)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 11. Average Maximum Power Voltage

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	525.97	622.93	650.65	674.92	678.47	703.23
	(97.01)	(82.96)	(64.55)	(39.25)	(16.29)	(9.74)
.00	416.37	487.22	511.13	528.40	531.17	548.57
	(54.00)	(25.64)	(13.41)	(12.82)	(10.55)	(13.36)
25.00	365.05	439.23	463.63	472.58	477.35	489.43
	(37.84)	(15.07)	(13.18)	(11.31)	(16.03)	(10.27)
55.00	310.72	373.07	391.93	408.48	414.68	426.63
	(26.16)	(14.07)	(13.10)	(13.21)	(15.62)	(9.96)
75.00	271.98	327.15	351.52	365.88	370.27	384.13
	(20.22)	(14.76)	(12.54)	(11.35)	(11.50)	(11.74)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 12. Average Maximum Power

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE P8-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	.94	3.54	6.38	9.21	13.39	18.93
	(.15)	(.48)	(.77)	(.96)	(1.08)	(1.35)
.00	.83	3.06	5.51	8.10	11.83	16.61
	(.13)	(.32)	(.47)	(.63)	(.71)	(.83)
25.00	.74	2.81	5.18	7.39	10.84	15.04
	(.10)	(.26)	(.41)	(.51)	(.62)	(.68)
55.00	.63	2.43	4.40	6.41	9.55	13.13
	(.09)	(.19)	(.28)	(.40)	(.51)	(.56)
75.00	.56	2.14	3.93	5.79	8.60	11.93
	(.07)	(.16)	(.23)	(.34)	(.45)	(.50)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 13. Average Curve Factor

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE P8-3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	.6243	.7114	.7534	.7764	.8011	.8144
	(.0784)	(.0954)	(.0972)	(.0884)	(.0723)	(.0643)
.00	.6402	.7229	.7552	.7693	.7823	.7892
	(.0751)	(.0690)	(.0551)	(.0445)	(.0326)	(.0249)
25.00	.6240	.7114	.7432	.7556	.7645	.7698
	(.0629)	(.0565)	(.0410)	(.0313)	(.0224)	(.0187)
55.00	.6063	.6878	.7145	.7281	.7359	.7397
	(.0573)	(.0404)	(.0277)	(.0226)	(.0174)	(.0144)
75.00	.5922	.6670	.6926	.7064	.7117	.7165
	(.0504)	(.0303)	(.0215)	(.0162)	(.0132)	(.0149)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

Table 14. Average AMO Efficiency

WESTINGHOUSE N/P SOLAR CELLS
DENDRITIC WEB SILICON MATERIAL
2 X 2.5 X 0.014 CM
COPPER CONTACTS, FAN PATTERN
LIQUID DIP AR COATING
NO COVERGLASS
SAMPLE SIZE 6 PLATE PS=3

CELL TEMP. (DEG. C)	SOLAR INTENSITY (MW/CM**2) 10.00	30.00	50.00	70.00	100.00	135.30
-70.00	9.42	11.81	12.75	13.15	13.39	13.99
	(1.49)	(1.59)	(1.54)	(1.37)	(1.08)	(.99)
.00	8.27	10.19	11.02	11.57	11.83	12.27
	(1.32)	(1.08)	(.93)	(.89)	(.71)	(.61)
25.00	7.36	9.35	10.36	10.56	10.84	11.12
	(1.04)	(.88)	(.82)	(.73)	(.62)	(.50)
55.00	6.31	8.10	8.80	9.15	9.55	9.70
	(.88)	(.65)	(.57)	(.57)	(.51)	(.41)
75.00	5.57	7.15	7.86	8.28	8.60	8.82
	(.71)	(.52)	(.45)	(.48)	(.45)	(.37)

NOTE: STANDARD DEVIATIONS ARE GIVEN IN PARENTHESES.

APPENDIX

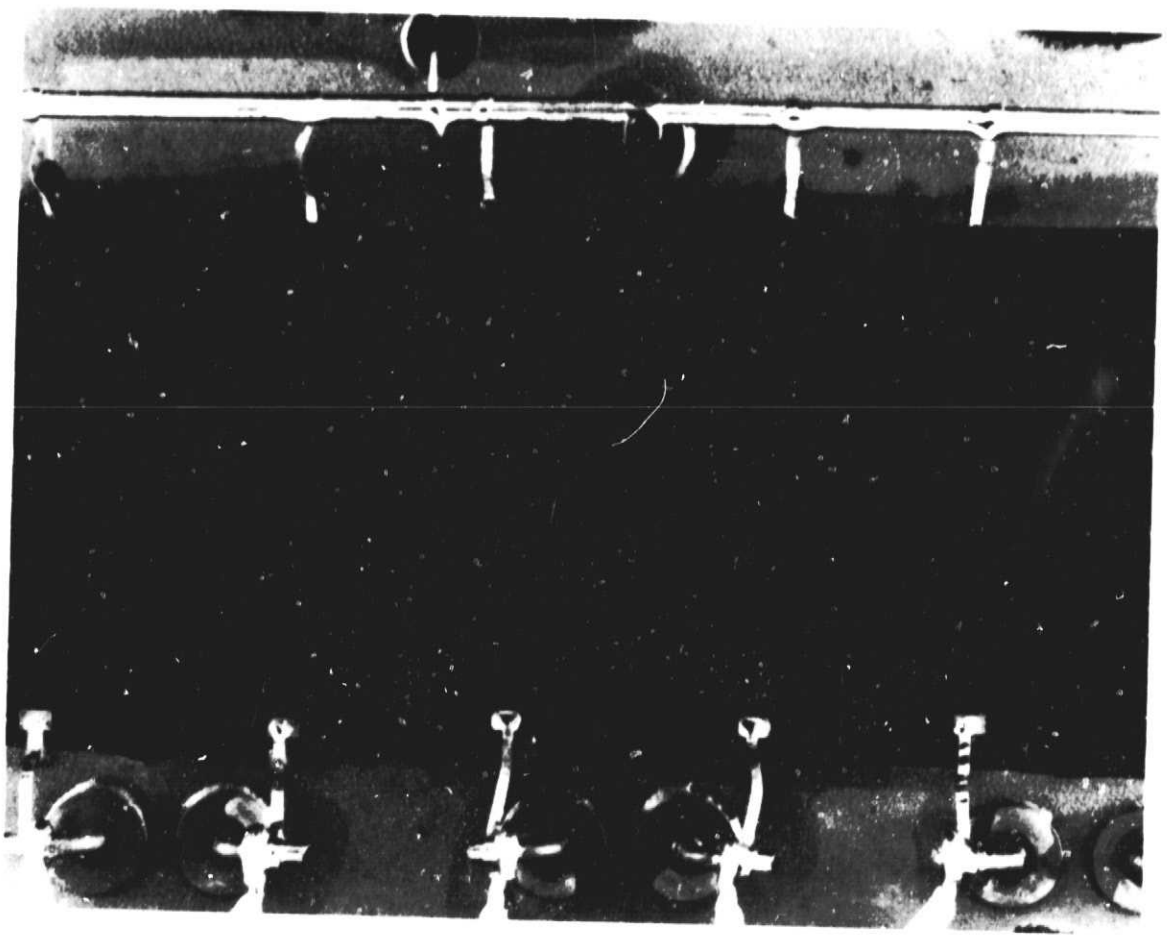


Figure A-1. Solar Cell

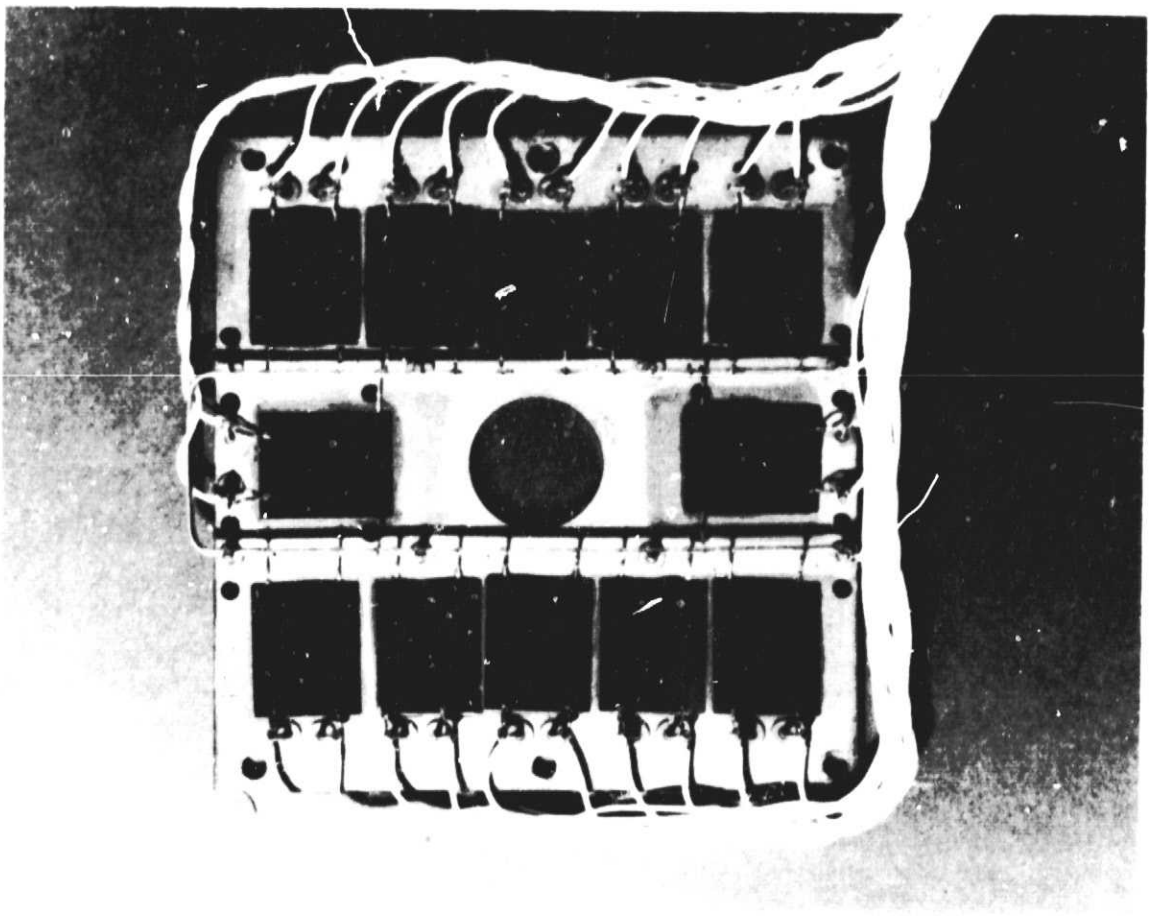


Figure A-2. Test Plate

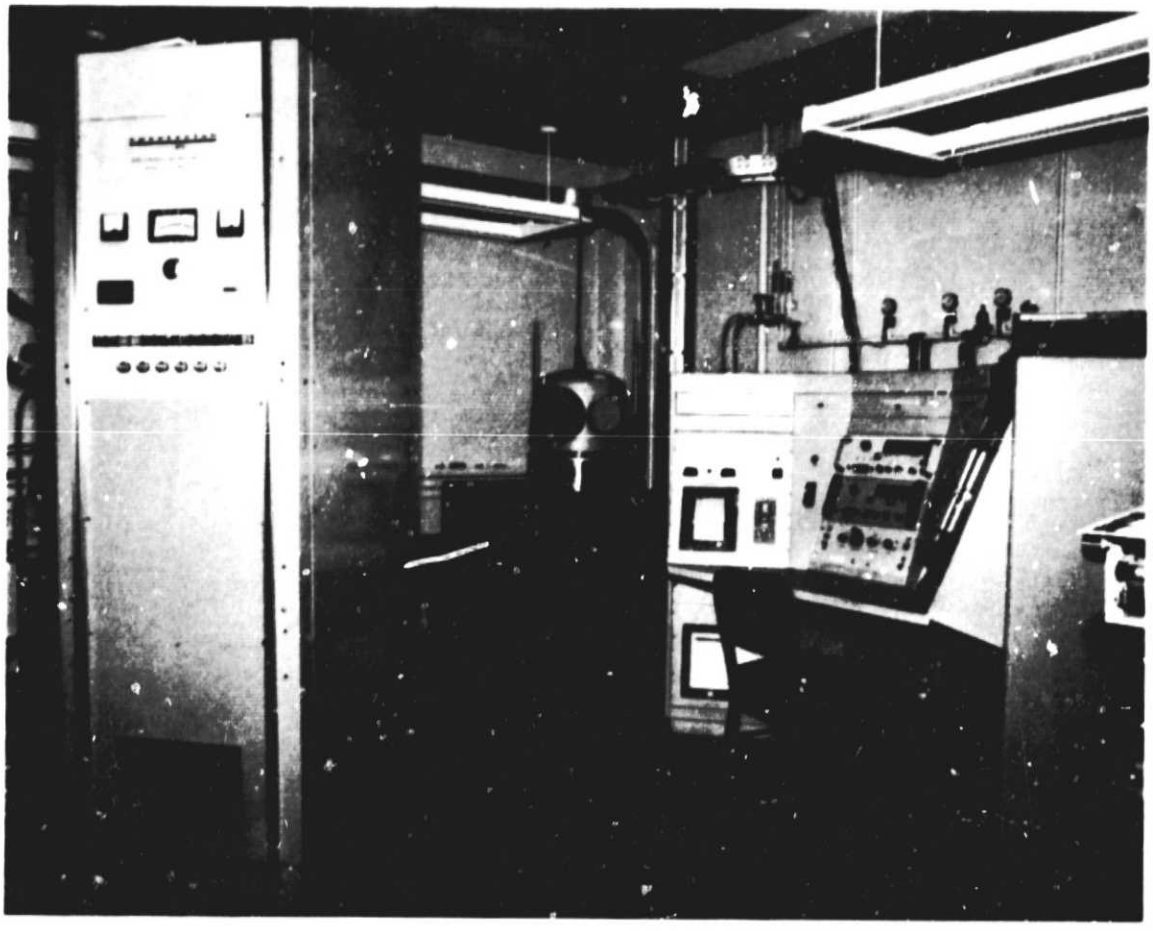


Figure A-3. Solar Cell Characterization Facility

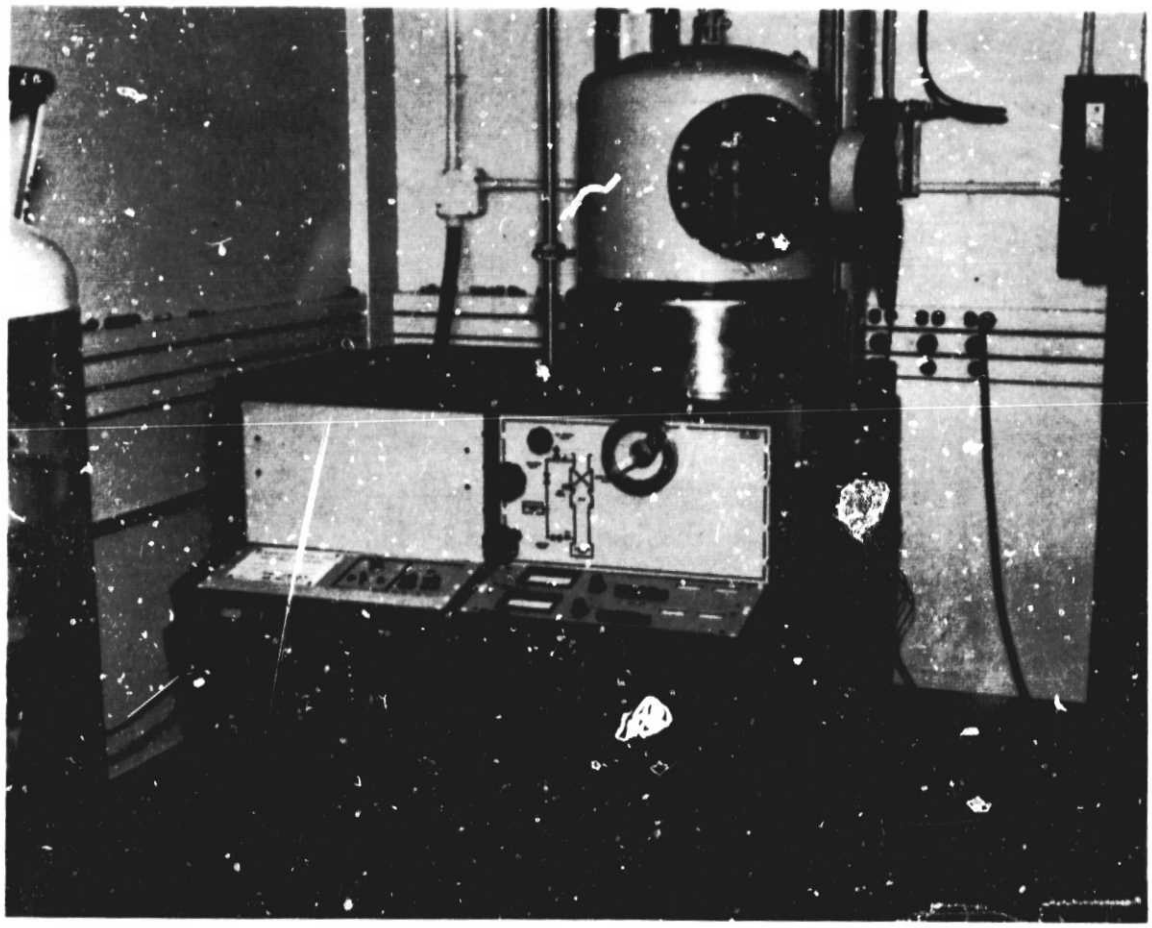


Figure A-4. Solar Cell Environmental Test Chamber

NASA—JPL—Coml., L.A., Calif.