NASA TECHNICAL MEMORANDUM

NASA TM-78305

(NASA-TM-78305) CHARACTERIZATION OF THREE TYPES OF SILICON SOLAR CELLS FOR SEPS DEEP SPACE MISSION. VOLUME 3: CURRENT-VOLTAGE CHARACTERISTICS OF SPECTROLAB SCULPTURED BSR/P+ (K7), BSR/P+ (K6.5) AND BSR (K4.5) N80-33863

Unclas
G3/44 28981

CHARACTERIZATION OF THREE TYPES OF SILICON SOLAR CELLS FOR SEPS DEEP SPACE MISSIONS, Volume III: Current-Voltage Characteristics of Spectrolab Sculptured BSR/P^+ (K7), BSR/P^+ (K6.5) and BSR (K4.5) Cells as a Function of Temperature and Intensity

By A. F. Whitaker, S. A. Little, V. A. Wooden, D. E. Carter, B. E. Cothren, and C. A. Torstenson
Materials and Processes Laboratory, Science and Engineering Directorate

August 1980

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
NASA TM-78305		

4. TITLE AND SUBTITLE

Characterization of Three Types of Silicon Solar Cells for SEPS Deep Space Missions*

5. REPORT DATE

August 1980

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S) A. F. Whitaker, S. A. Little, V. A. Wooden, D. E. Carter, B. E. Cothren, and C. A. Torstenson

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS

George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

13. TYPE OF REPORT & PERIOD COVERED

Technical Memorandum

12. SPONSORING AGENCY NAME AND ADDRESS

National Aeronautics and Space Administration
Washington, DC 20546

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Materials and Processes Laboratory, Science and Engineering

16. ABSTRACT

Three types of high performance silicon solar cells, sculptured BSR/P$^+$ (K7), BSR/P$^+$ (K6.5) and BSR (K4.5) manufactured by Spectrolab have been evaluated for their low temperature and low intensity performance. Sixteen cells of each type were subjected to 11 temperatures and 9 intensities. The sculptured BSR/P$^+$ (K7) cells provided the greatest maximum power output both at 1 AU and at LTLI conditions. The average efficiencies of this cell were 14.4% at 1 SC/+25°C and 18.5% at 0.086 SC/-100°C.

* Volume III. Current-Voltage Characteristics of Spectrolab Sculptured BSR/P$^+$ (K7), BSR/P$^+$ (K6.5) and BSR (K4.5) Cells as a Function of Temperature and Intensity

Volume II of this series was published as NASA TM-78272, March 1980.

17. KEY WORDS

18. DISTRIBUTION STATEMENT

Unclassified-Unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	91	NTIS

MSFC - Form 3292 (Rev. December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

ACKNOWLEDGMENTS

The authors wish to thank Messrs. John Owens and Charles Smith for assistance in setting up the test equipment, Bob Ives for plotter programming, and Mrs. Barbara Simms for typing the manuscript.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Concluded)

LIST OF TABLES

LIST OF TABLES (Concluded)

TECHNICAL MEMORANDUM

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

Volume III. Current-Voltage Characteristics of Spectrolab Sculptured BSR/P^+ (K7), BSR/P^+ (K6.5) and BSR (K4.5) Cells as a Function of Temperature and Intensity

I. INTRODUCTION

This is the third in a series of technical reports on the characterization of high performance solar cells under conditions of low temperatures and low intensities. Today's solar cells have been designed for maximum performance at 1 AU*, AM0, with little regard for the characteristics that would enhance their performance in deep space. In the late 1960's and early 1970's, data were generated on a few solar cells under Jupiter mission conditions; however, little has been produced since that time. The interest in solar cell performance under deep space conditions has been renewed as a result of the proposed SEPS Comet Missions. These data generated in support of the SEPS program are aimed at identifying which of the currently available cells possess the best characteristics for deep space performance. This report contains data on three types of cells taken at 9 intensities and 11 temperatures identified along the SEPS Mission profile. Graphs and tables together with interpretive conclusions are presented for the three types of cells.

II. TEST PROGRAM

A. Solar Cell Descriptions

Three types of cells, sculptured BSR/P^+ (K7), BSR/P^+ (K6.5) and BSR (K4.5) from Spectrolab, described in Table 1, were selected to compare under conditions of low temperature and low intensity, the performance of the sculptured BSR/P^+ cell to the BSR/P^+ cell and the performance of the BSR/P^+ cell to the BSR cell. All the cells tested were n on p with Al P^+ and had a 10 ohm-cm base resistivity.

---

* For this and other acronyms see glossary.

B. Test Profile

The test profile for the evaluation of these cells is shown in Table 2. These temperature/intensity values were selected from the SEPS Halley Comet Flyby and Tempel 2 Mission environment. In addition to the I-V (current-voltage) data taken at various temperatures and intensities, dark I-V data were taken at 10 temperatures. The dark I-V data analysis will be the subject of a separate report.

C. Test Equipment

The cells were mounted to a copper plate using RTV 560. Each test set consisted of 16 cells; one set is shown mounted in Figure 1. The copper plate was then heat sunk to a plate configured for cooling with liquid nitrogen and for heating with hot air. The copper plate and two cells were thermocoupled and temperatures monitored continually. Cell temperatures were maintained independent of the incident solar intensity to within $\pm 0.5^{\circ}C$ from 65° to $-175^{\circ}C$. The cells were installed in a vacuum system having a 30-cm diameter, 6 mm thick UV grade fused quartz window and tested at a pressure of 1×10^{-4} pascal or less.

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

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

III. PRESENTATION OF TEST RESULTS

Current-voltage characteristics for each of three sets of 16 silicon solar cells supplied by Spectrolab have been measured. The mean values of each set observed at each operating condition (temperature and light intensity), together with observed standard deviations and mean efficiencies, are presented in both tables and graphs.

The graphs are plotted from the data presented in the tables. The behavior of the individual best and worst cells of each set, selected on the basis of maximum power output at 0.086 solar constant, -100°C (where the SEPS will spend considerable time), is described by graphs of their efficiency versus light intensity and temperature. Current-voltage parameters of the best cell of each set selected on the basis of its maximum power output at 0.086 SC/-100°C are shown in Table 3. Fill factors which show data scatter within each group are given in Table 4 for three test conditions. Current-voltage curves for three cells are shown in Figure 3. The distribution of the maximum power output for the three types of cells is shown at 4 test conditions in Figures 4, 5 and 6.

A. General Features

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

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

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

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

a. Efficiency at maximum power output decreases steadily with increasing temperature, the mean value dropping approximately by a factor of 2 from -150°C to 165°C. This feature is independent of light intensity above 0.08 SC as expected from the close correlation in high performance cells between the maximum power conditions with the open circuit voltage and short circuit current features.

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

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

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

B. Sculptured BSR/P$^+$ (K7) Cell

I_{sc}, V_{oc}, I_{mp}, V_{mp}, and MP are plotted as functions of temperature and intensity in Figures 9 through 18. Average values with standard deviations are summarized in Tables 5 through 9. Cell efficiencies are plotted as functions of temperature and intensity in Figures 19 and 20 and summarized in Table 10. To illustrate the spread in individual cell performance, the efficiencies of the best and worst cells are plotted in Figures 21 and 22.

Large standard deviations (above 2 percent) begin to appear within this set of 16 cells in their V_{oc} below -125°C and below 0.063 SC. Similarly, large (above 2 percent) standard deviations appear in V_{mp} at and below -75°C and, at and below 0.128 SC. I_{mp} at 1 AU shows a reduction in mean value as the temperature is increased from +25°C to +65°C.

C. BSR/P$^+$ (K6.5) Cell

I_{sc}, V_{oc}, I_{mp}, V_{mp}, and MP are plotted as functions of temperature and intensity in Figures 23 through 32. Average values with standard deviations are shown in Tables 11 through 15. Cell efficiencies are listed in Table 16 and plotted as functions of temperature and intensity in Figures 33 and 34. Similarly, the efficiencies of the best and worst cells are shown in Figures 35 and 36.

V_{oc} shows standard deviations as large as 2 percent at and below -100°C and at and below 0.063 SC. V_{mp} displays similar large (above 2 percent) standard deviations at and below -50°C and 0.174 SC.

D. BSR (K4.5) Cell

I_{sc}, V_{oc}, I_{mp}, V_{mp}, and MP are plotted as functions of temperature and intensity in Figures 37 through 46. Average values with standard deviations are summarized in Tables 17 through 21. Cell efficiencies are plotted as functions of temperature and intensity in Figures 47 and 48 and listed in Table 22. In addition, the best and worst cells efficiencies are plotted in Figures 49 and 50.

Large standard deviations (above 2 percent) begin to appear in V_{oc} at and below -100°C and 0.063 SC. Similarly, large standard deviations appear in V_{mp} at and below -50°C and at and below 0.174 SC.

IV. DISCUSSION OF RESULTS

A. General Features

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

Maximum power output was determined to be greatest both at 1 SC/+25°C and at LTLI for the K7 cells. The K4.5 cells provided the lowest maximum power output at these conditions. Large variations in V_{mp} were observed for the three types of cells under LTLI conditions primarily as a sharp break in the I-V curve around the knee of the curve (broken knee). Several of the BSR/P^+ cells displayed a gradual decrease in current initiated in the low voltage portion of the curve. These behaviors are indicative of shunting impedance problems thought to arise from the cell fabrication processes. I-V curves indicating these problems are shown in Figure 3 along with the I-V curve for a high performing cell. These reductions in curvature of the I-V plot result in lowering of the MP of the cell and thereby reduces solar cell efficiency. The relative magnitude of this occurrence in the three sets of cells tested is seen in the fill factor distributions presented in Table 4. Efficiencies of the best and worst cells selected on the basis of maximum power output at 0.086 SC and -100°C show the extreme values in cell output within each test set. The current-voltage parameters listed for the best cell within each group in Table 3 demonstrate the capabilities of the individual cell type with the K7 cell having the highest efficiency at all test conditions. In constructing Table 3, incident intensities were normalized in order to provide an accurate comparison of best cell within each test group. In all three types of cells the best cell at LTLI was not the best cell under 1 AU conditions. Mean efficiencies at 1 SC/+25°C were determined to be 14.4 percent for the K7 cells, 13.2 percent for the K6.5 cells and 12.3 percent for the K4.5 cells.

B. Comparison of Sculptured BSR/P^+ (K7) to BSR/P^+ (K6.5)

The sculptured surface provides a larger effective surface area to incident photons thereby resulting in greater current output of the cell. In addition, the sculptured cell would, in the absence of active thermal control, operate at a higher temperature than the planar cell under the same incident intensity conditions. However, since the temperature of these cells was actively controlled the latter feature was not examined.

I_{sc} values at 1 AU were about 8 percent greater in the sculptured cells than in the planar cells. Similarly, I_{mp} values at 1 AU were greater in the sculptured cells by about 7 to 9 percent. Average values of I_{mp} for sculptured cells show at 1 SC similar values or slight decreases as the temperature was increased from +25°C to +65°C. Average V_{oc} of the sculptured cells is about 1 percent or less than the planar cell throughout the test profile. Average V_{mp} values in the sculptured cells were 1 to 2 percent greater than in the planar cells at 1 AU but similar values were obtained at 0.040 SC/-125°C conditions. The large deviations in V_{mp} for both types of cells are responsible for their reduced efficiencies at LTLI. The high efficiency of the sculptured BSR/P^+ cell at higher intensities is attributed to its large output current.

C. Comparison of BSR/P^+ (K6.5) to BSR (K4.5)

The average values of I_{sc} and I_{mp} were greater in the K6.5 cells than in the K4.5 cells by about 2 to 6 percent through the test profile. Included in the average current values of the BSR cells were three cells whose currents were low initially. Average values of V_{oc} and V_{mp} were from 2 to 6 percent greater in the K6.5 cells than in the K4.5 cells. Large variations in V_{mp} were evident at LTLI in both groups of cells. The greater efficiency of the K6.5 at 1 AU conditions is attributed primarily to the greater output voltage of the cell.

V. SUMMARY

The sculptured BSR/P^+ (K7) cells provided the best performance at both 1 AU conditions and at LTLI conditions. Mean efficiencies at 1 SC/+25°C were determined to be 14.4 percent for the K7 cells, 13.2 percent for the K6.5 cells and 12.3 percent for the K4.5 cells. All three types of cells showed evidence of variations in shunting impedance at LTLI by sharp breaks in their I-V curves around the maximum power point and/or a gradual reduction in current initiated in the low voltage portion of the curve. These undesirable shunting impedance variations are attributed to techniques utilized in processing of the cells. The performance observed for the three sets of cells is summarized by the graph of relative maximum power output, P/P_o (P_o is the power produced at 55°C at 1 AU) versus heliocentric distance in Figure 7. Figure 8 represents the array mission temperatures used in generating the P/P_o data. The values of P/P_o were largest for the BSR (K4.5) cells throughout the region from 1.25 to 5 AU.

The reader is reminded that the ultimate response of the solar cell to the space environment would be influenced not only by temperature and incident intensity but also by particulate and electromagnetic radiation.

TABLE 1. TEST CELL DESCRIPTIONS

	Test Group 1	Test Group 2	Test Group 3
Number of Cells	16	16	16
Type	N/P Sculptured, BSR/P^+	N/P BSR/P^+	N/P BSR
Manufacturer's Designation	K7	K6.5	K4.5
Silicon	Boron-Doped, Czochralski P-Type	Boron-Doped, Czochralski P-Type	Boron-Doped, Czochralski P-Type
Size	2 x 2 x .025 cm	2 x 2 x .025 cm	2 x 2 x .025 cm
Base Resistivity	10 ohm-cm	10 ohm-cm	10 ohm-cm
Junction Depth	Shallow Diffused	Shallow Diffused	Shallow Diffused
Contacts	Ti-Pd-Ag	Ti-Pd-Ag	Ti-Pd-Ag
Grids	Fine Line (24)	Fine Line (24)	Fine Line (24)
Cover Glass	Ceria-Doped Microsheet	Ceria-Doped Microsheet	Ceria-Doped Microsheet
Cover Glass Adhesive	DC 93-500	DC 93-500	DC 93-500
Antireflective Coating (Cover/Cell)	MgF_2/Ta_2O_5	MgF_2/Ta_2O_5	MgF_2/Ta_2O_5
Comments	Production Run	Production Run	Production Run

TABLE 2. TEST PROFILE

Illumination Level (SC)	Temperature (°C)
1.00	0, 25, 55, 65
0.64	-25, 0, 25, 55
0.39	-50, -25, 0, 25, 55
0.25	-75, -50, -25, 0, 25
0.174	-100, -75, -50, -25, 0
0.128	-125, -100, -75, -50, -25
0.086	-150, -125, -100, -75, -50
0.063	-150, -125, -100, -75, -50
0.040	-175, -150, -125, -100, -75
Dark I-V	50, 25, 0, -25, -50, -75, -100, -125, -150, -175

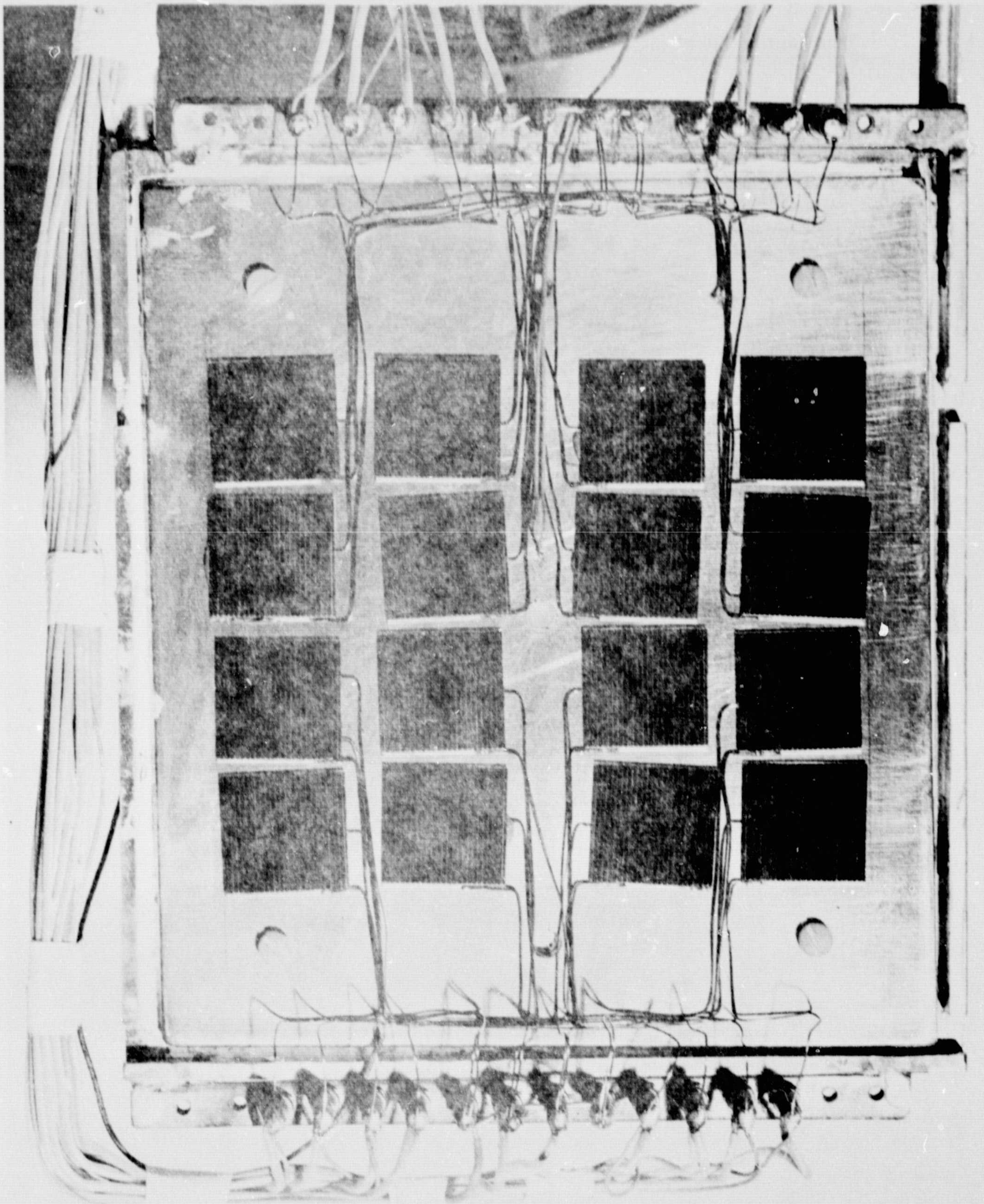

Figure 1. Solar Cell Test Plate

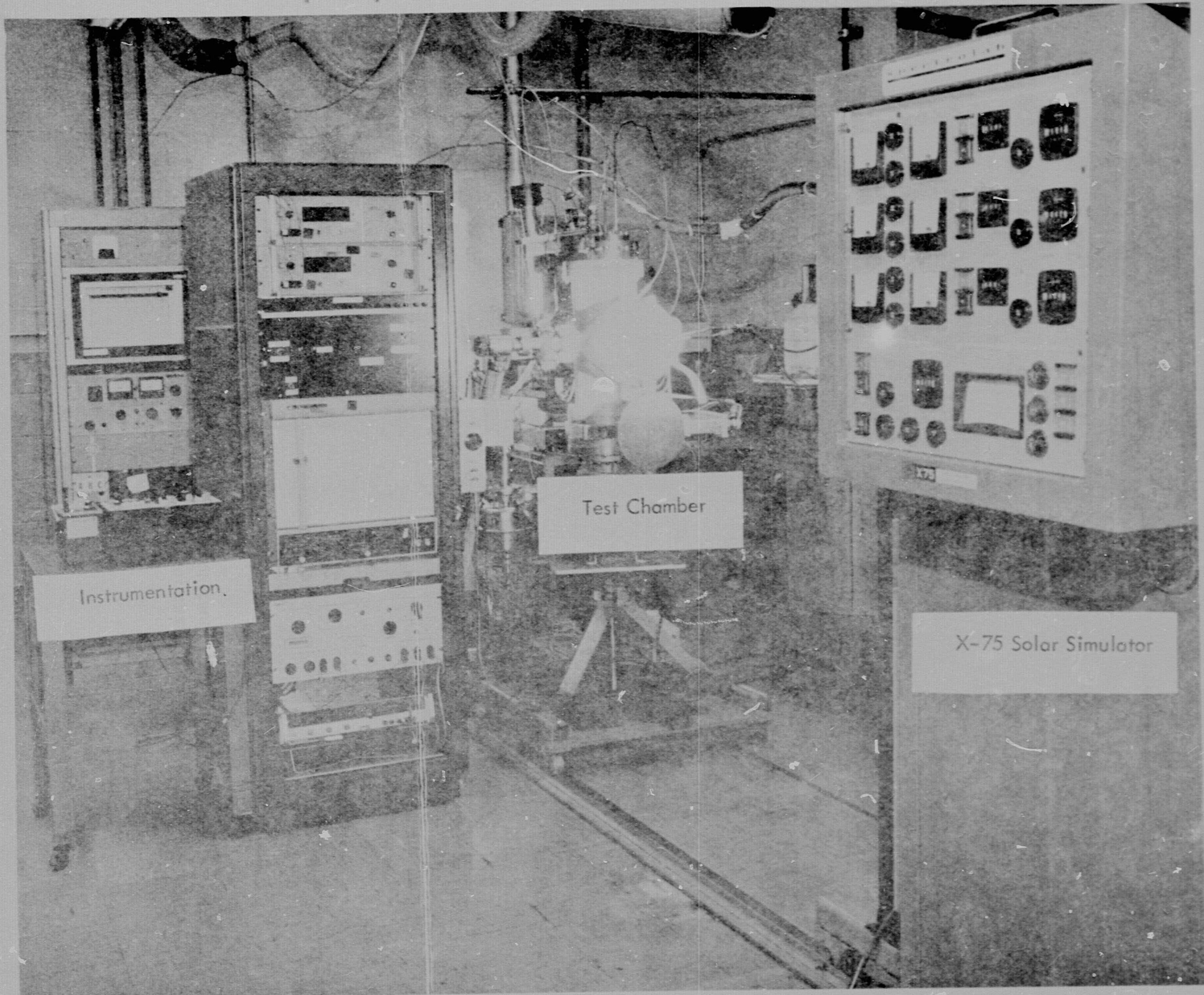

Figure 2. Solar Cell Characterization Equipment and Instrumentation

3. CURRENT-VOLTAGE PARAMETERS OF THE BEST CELLS

Parameter	TYPE SILICON CELL K7	K6.5	K4.5
I_{sc}			
1.0 SC/55°C	179.8	165.5	158.8
1.0 SC/25°C	177.8	162.4	156.8
0.086 SC/-100°C	14.0	12.8	12.4
0.040 SC/-150°C	6.3	5.7	5.8
V_{oc}			
1.0 SC/55°C	536	530	488
1.0 SC/25°C	599	593	556
0.086 SC/-100°C	813	806	806
0.040 SC/-150°C	908	903	913
I_{mp}			
1.0 SC/55°C	163.3	150.0	143.1
1.0 SC/25°C	162.1	150.8	144.3
0.086 SC/-100°C	12.8	12.2	11.6
0.040 SC/-150°C	5.7	5.4	5.0
V_{mp}			
1.0 SC/55°C	424	416	390
1.0 SC/25°C	488	483	462
0.086 SC/-100°C	752	723	743
0.040 SC/-150°C	830	813	835
MP			
1.0 SC/55°C	69.3	62.5	55.8
1.0 SC/25°C	79.1	72.8	66.7
0.086 SC/-100°C	9.6	8.8	8.6
0.040 SC/-150°C	4.8	4.4	4.1
Eff			
1.0 SC/55°C	12.8	11.5	10.3
1.0 SC/25°C	14.6	13.5	12.3
0.086 SC/-100°C	20.6	18.9	18.5
0.040 SC/-150°C	22.2	20.3	18.9

NOTE: Best Cells selected for highest maximum power output at 0.086 SC/-100°C. Incident intensity normalized for uniform intensity.

TABLE 4. FILL FACTORS FOR SPECTROLAB CELLS AT 3 TEST CONDITIONS

Solar Constant/ Temperature (°C)	FILL FACTORS (NO. OF CELLS) K7	K6.5	K4.5
1.0 SC/25°C	.72 to .73 (2) .74 (10) .75 (3) .76 (1)	.73 (6) .74 (9) .76 (1)	.73 (1) .74 (3) .75 (4) .76 (7) .77 (1)
0.086 SC/-100°C	.69 (1) .71 to .73 (6) .76 (2) .79 to .84 (7)	.57 (1) .59 to .60 (3) .69 (1) .72 (1) .77 to .79 (5) .81 to .82 (4) .85 (1)	.61 (1) .66 (1) .72 to .74 (3) .77 to .80 (6) .85 (4) .86 (1)
0.040 SC/-150°C	.58 to .63 (9) .69 (1) .73 (2) .76 (2) .79 (1) .83 (1)	.48 (1) .51 to .55 (3) .59 (2) .67 to .71 (4) .73 to .76 (4) .78 (1) .87 (1)	.50 (2) .52 to .54 (3) .56 to .57 (2) .61 to .62 (2) .65 to .69 (2) .72 to .74 (2) .77 (2) .83 (1)

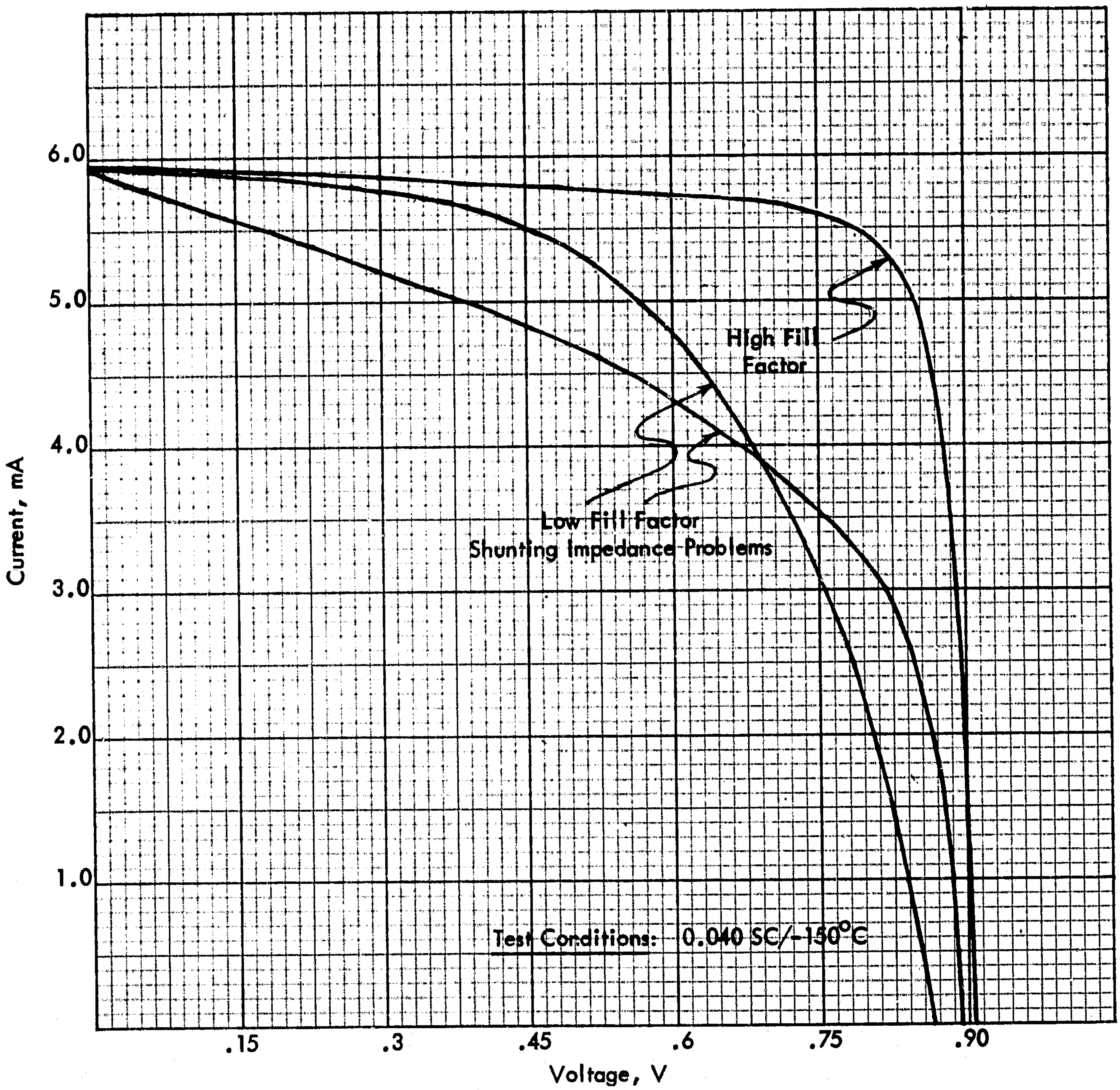

Figure 3. Current-Voltage Curves for Three BSR/P+ (K6.5) Cells at 0.040 SC/-150°C

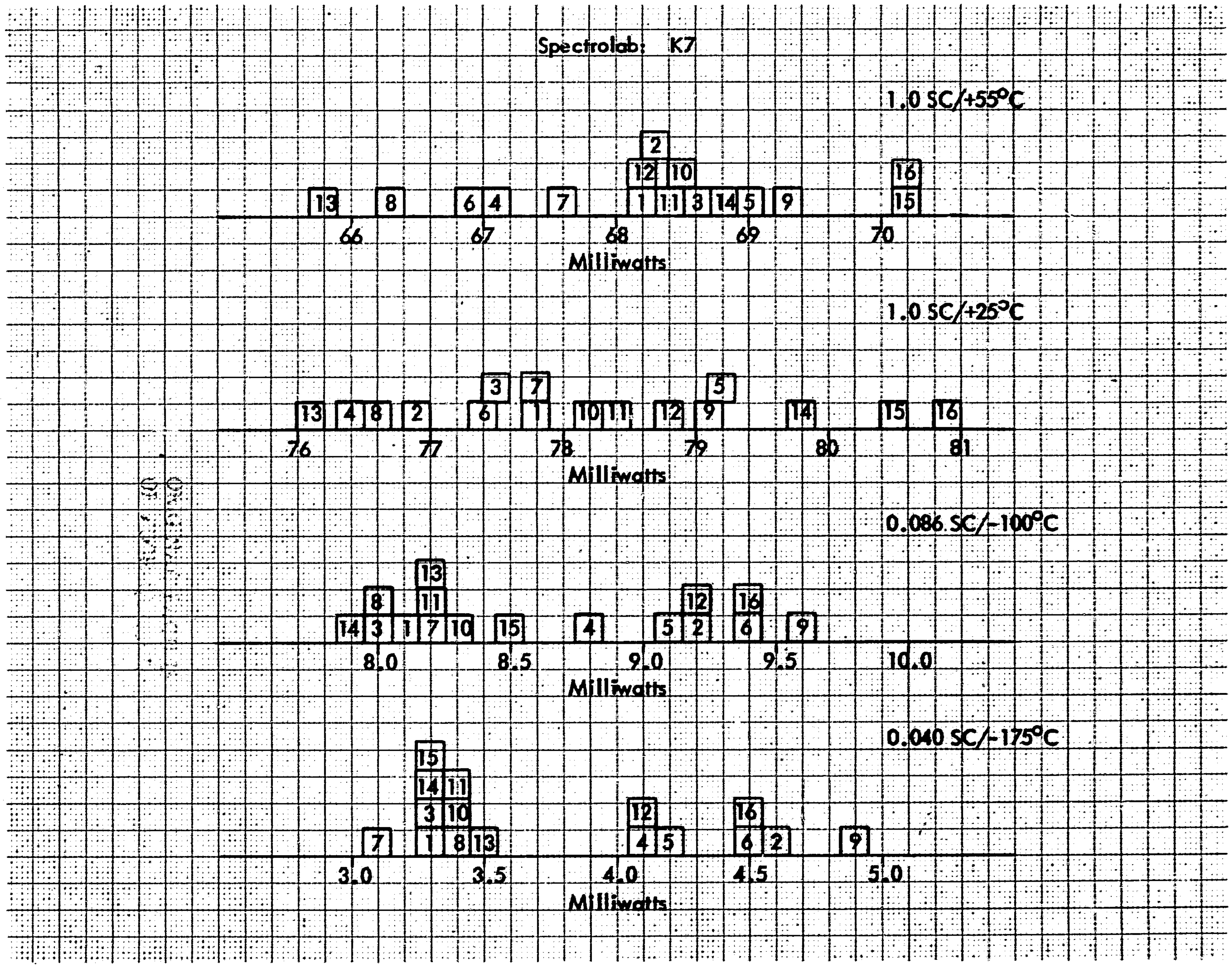

Figure 4. Distribution of K7 Cells at 4 Test Conditions as a Function of Maximum Power Output

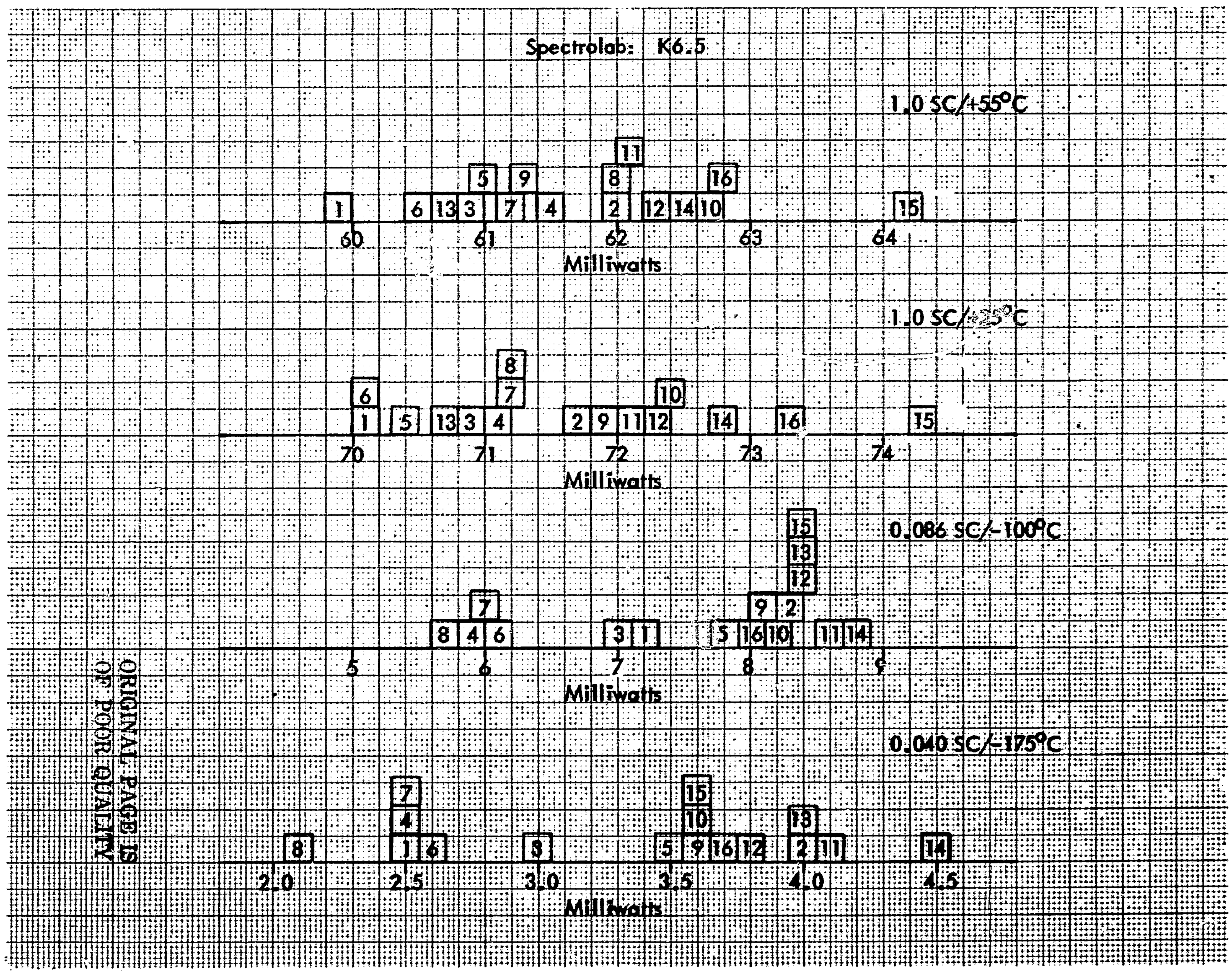

Figure 5. Distribution of K6.5 Cells at 4 Test Conditions as a Function of Maximum Power Output

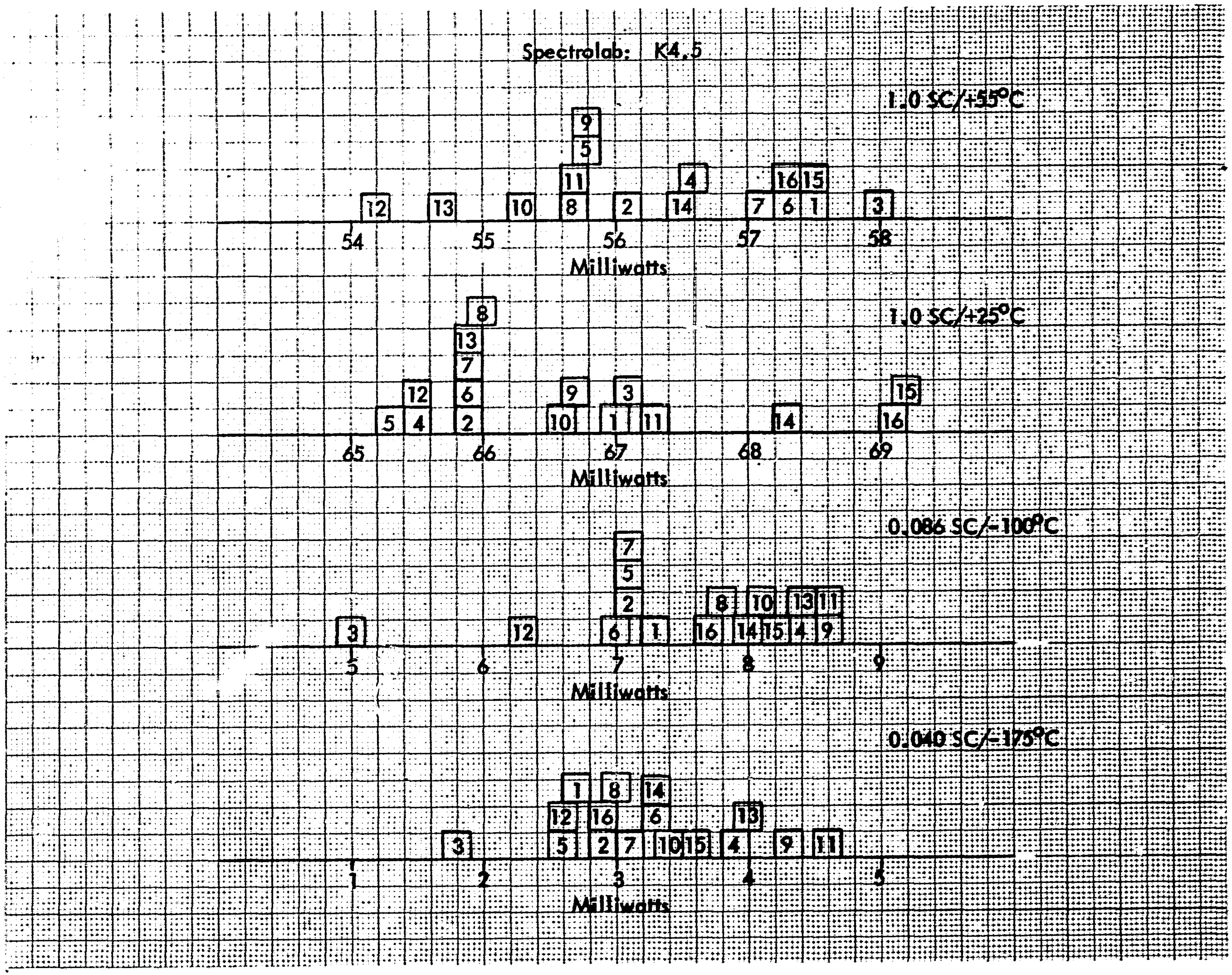

Figure 6. Distribution of K4.5 Cells at 4 Test Conditions as a Function of Maximum Power Output

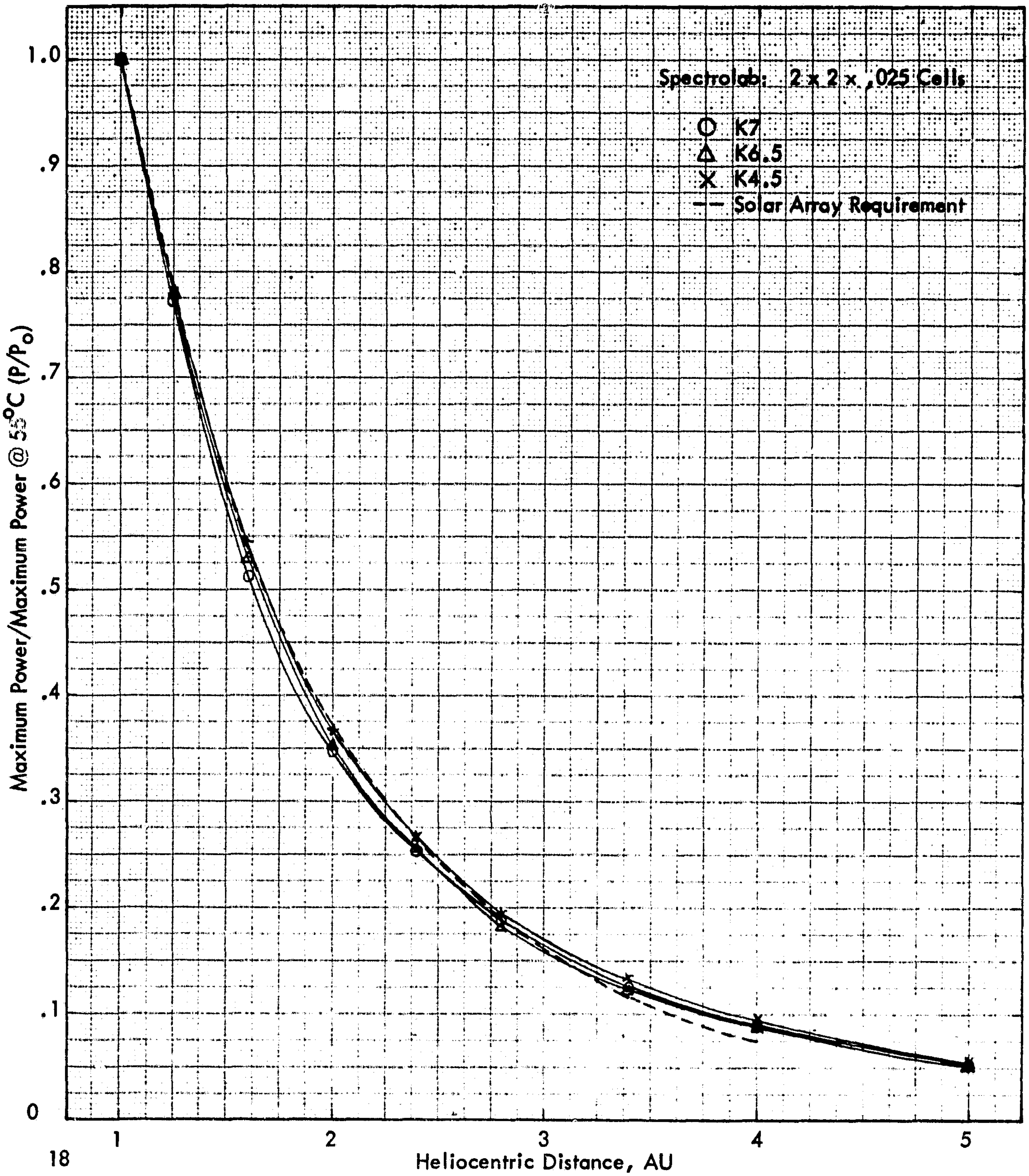

Figure 7. P/P_o as a Function of Heliocentric Distance

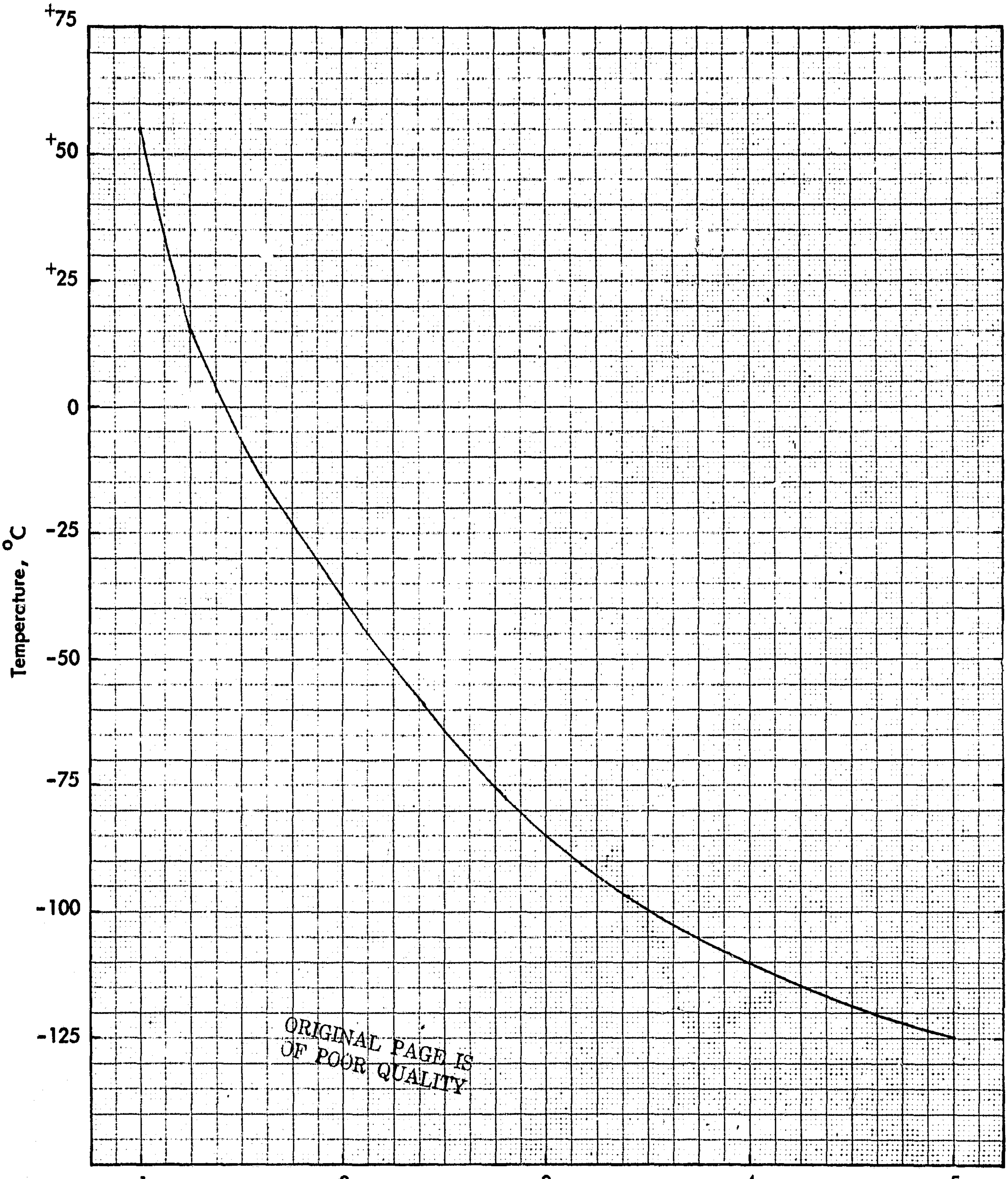

Figure 8. Solar Array Temperature Versus AU

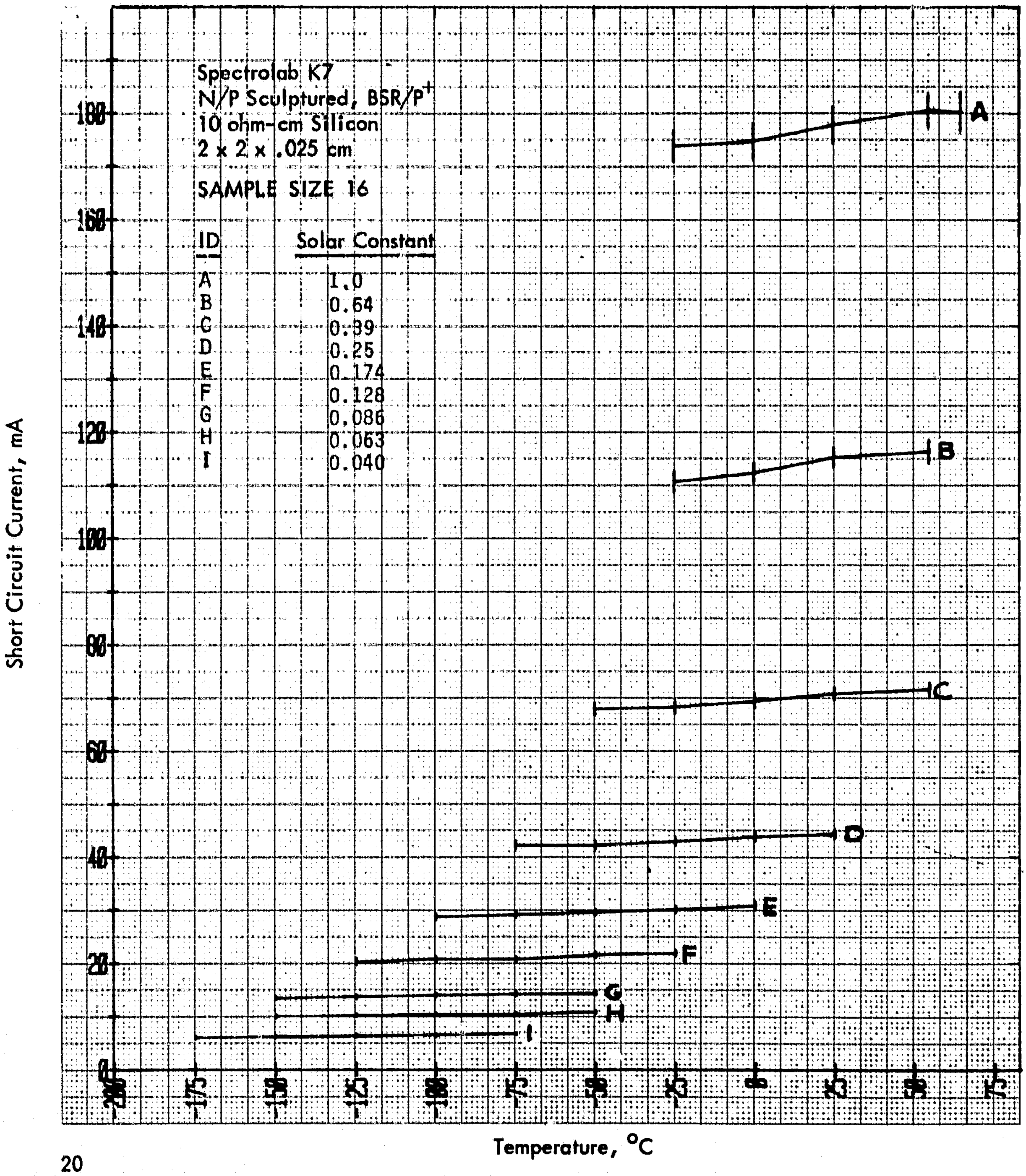

Figure 9. Average I_{sc} as a Function of Temperature

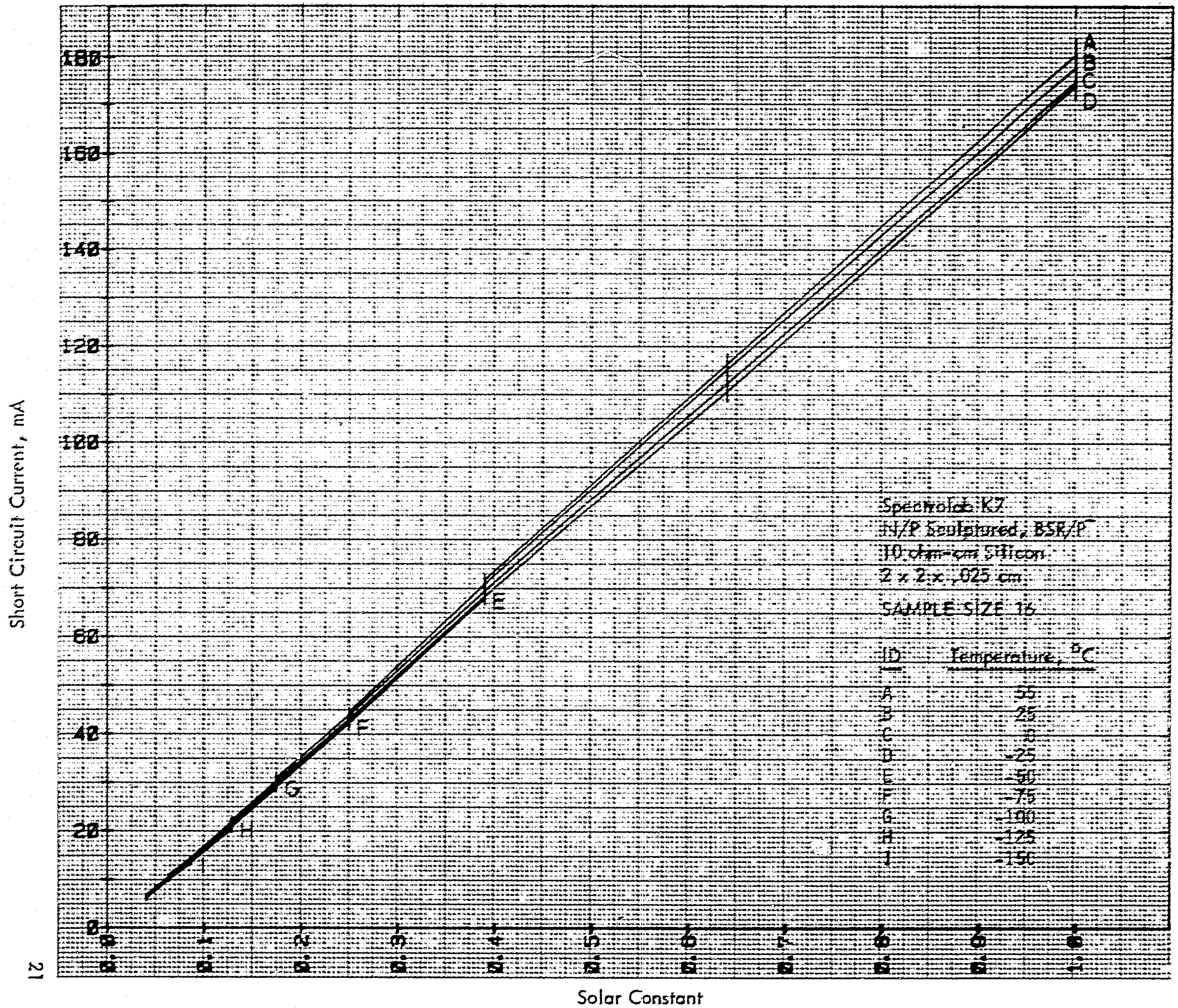

Figure 10. Average I_{sc} as a Function of Intensity

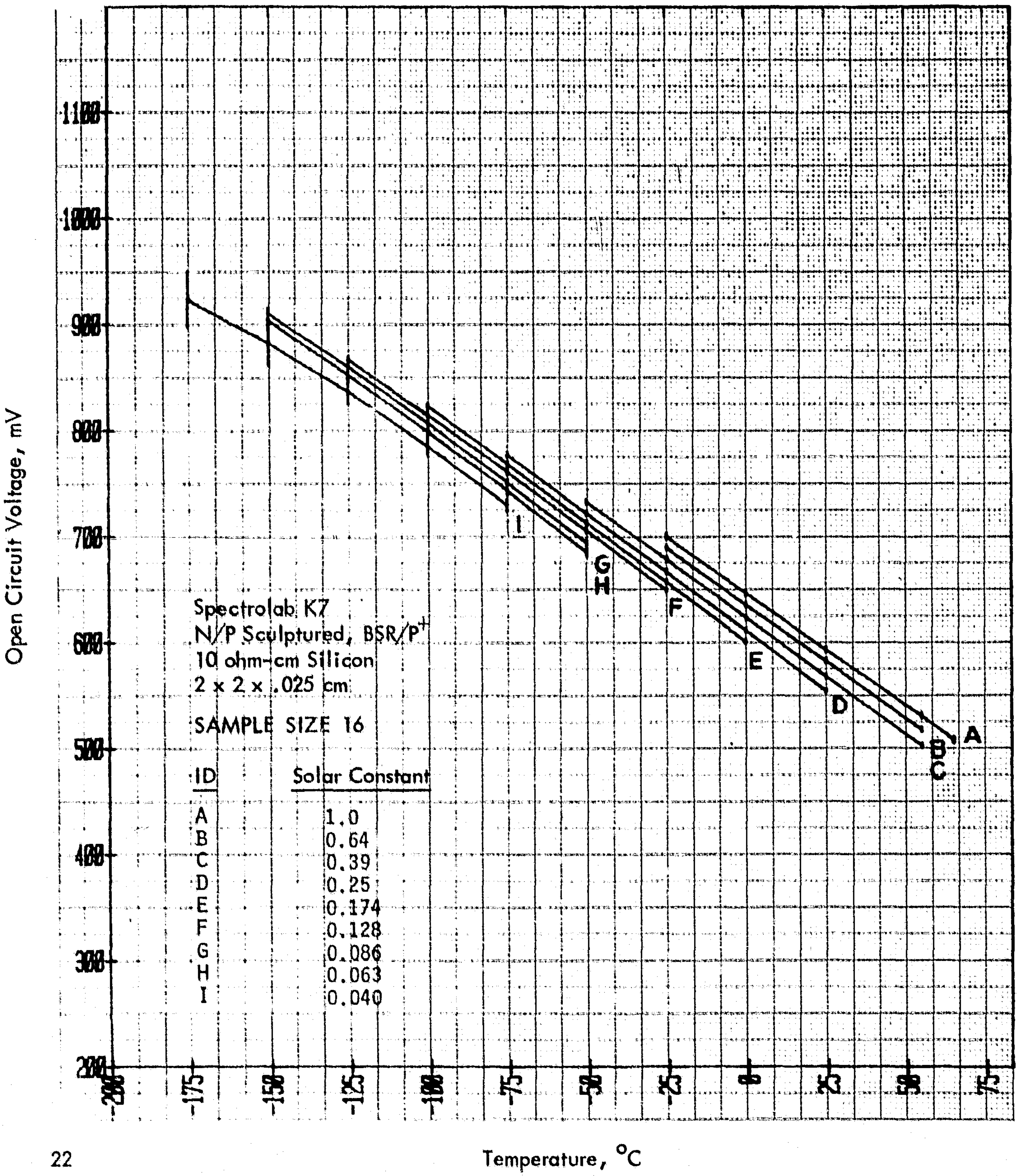

Figure 11. Average V_{oc} as a Function of Temperature

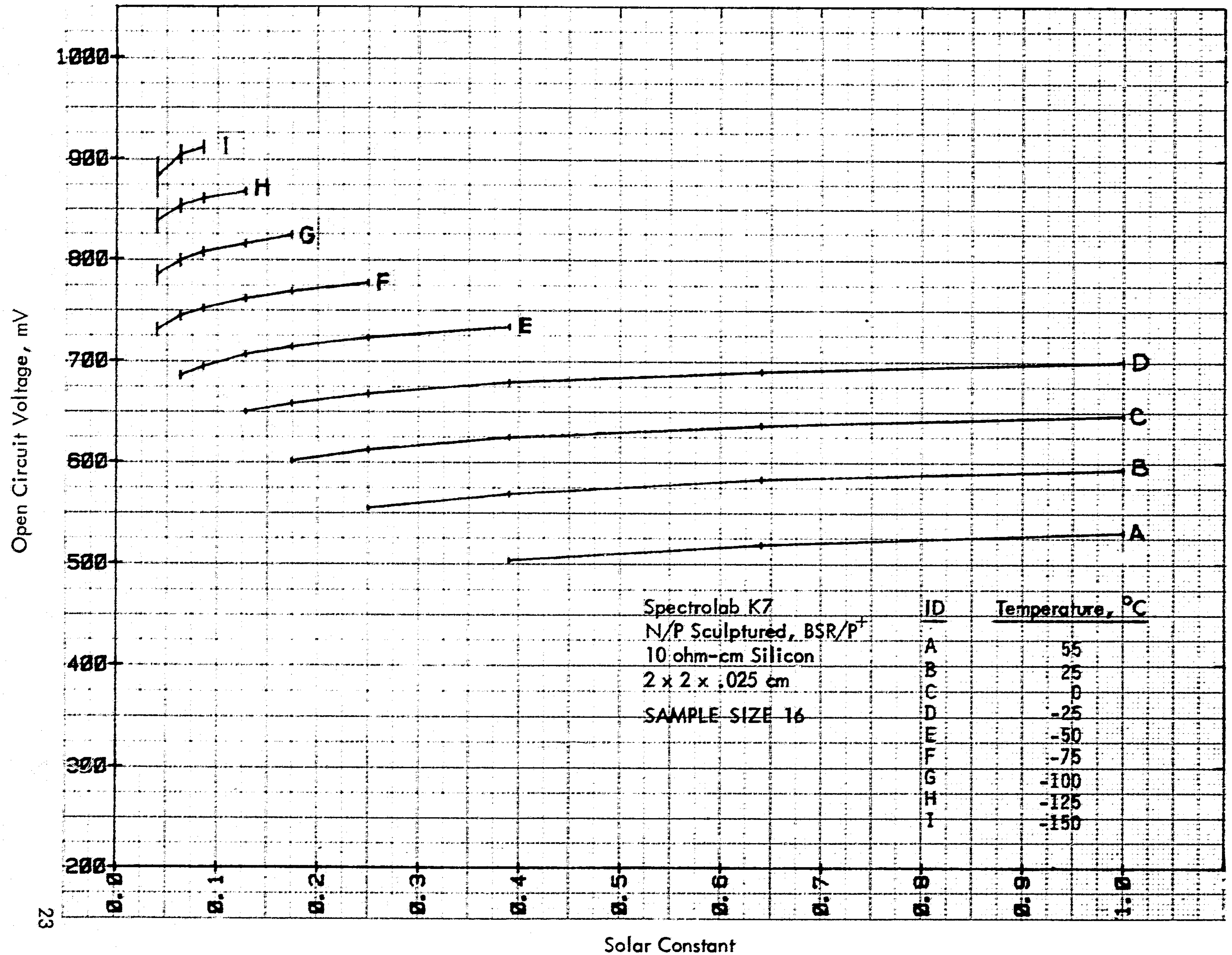

Figure 12. Average V_{oc} as a Function of Intensity

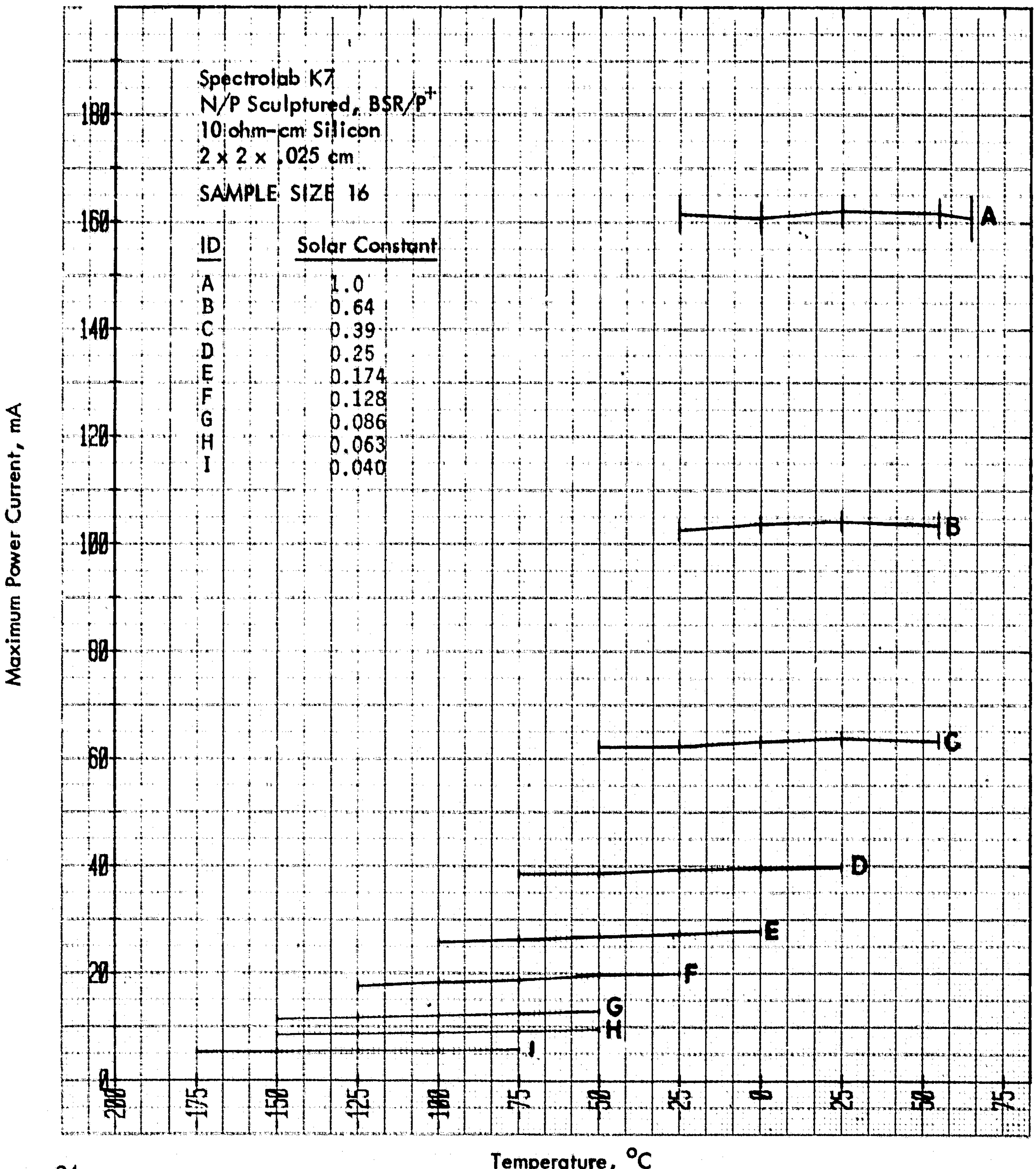

Figure 13. Average I_{mp} as a Function of Temperature

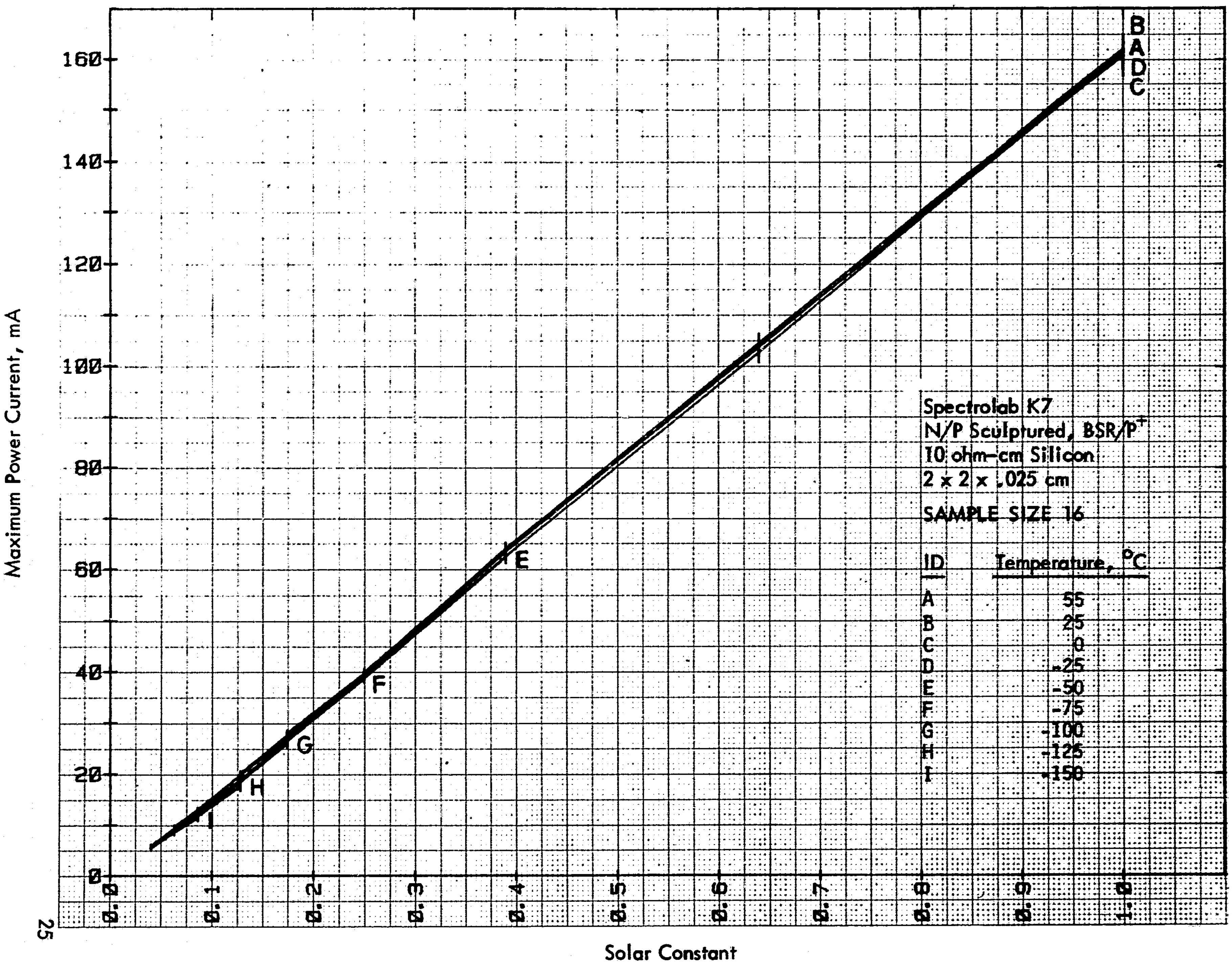

Figure 14. Average I_{mp} as a Function of Intensity

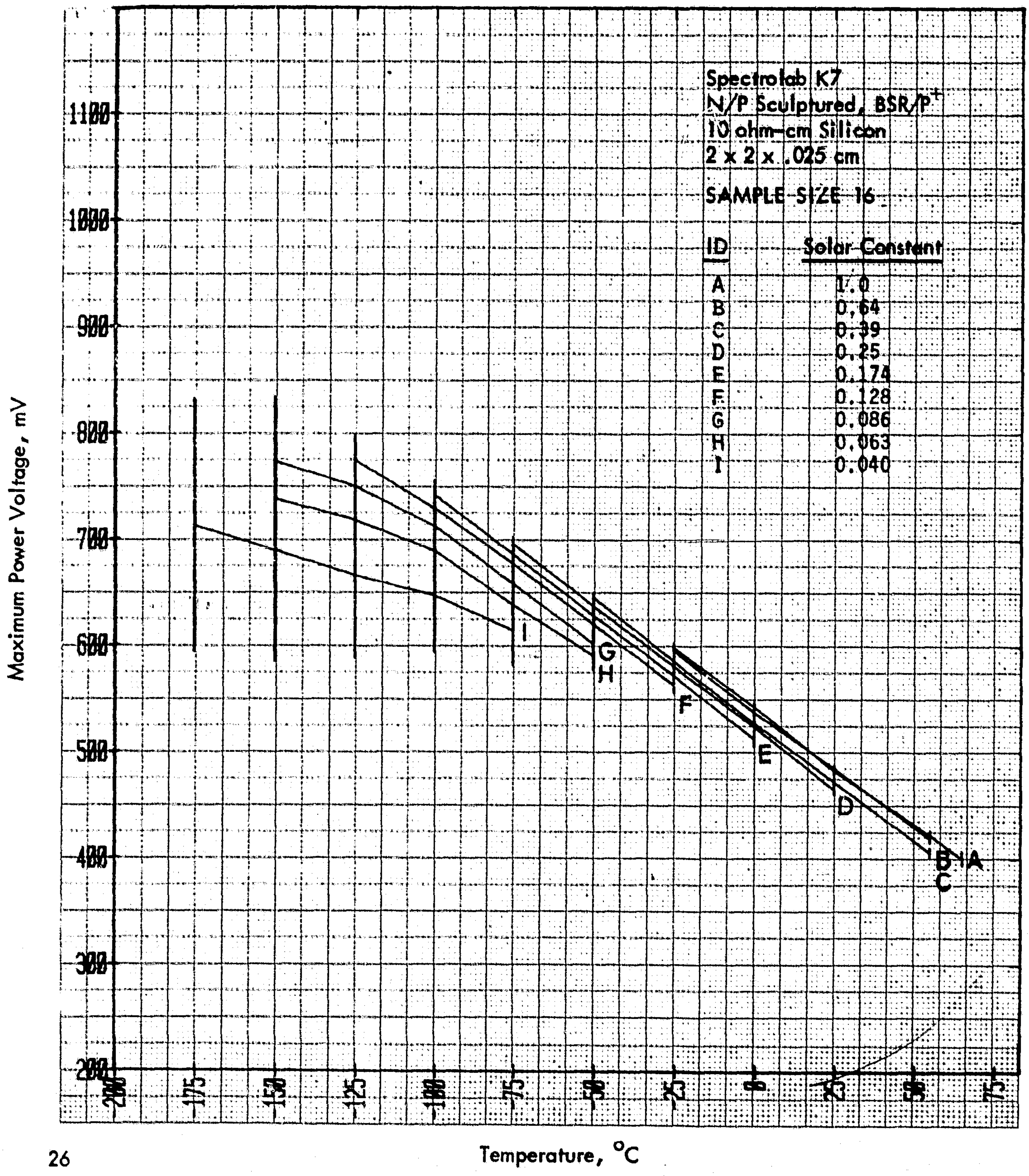

Figure 15. Average V_{mp} as a Function of Temperature

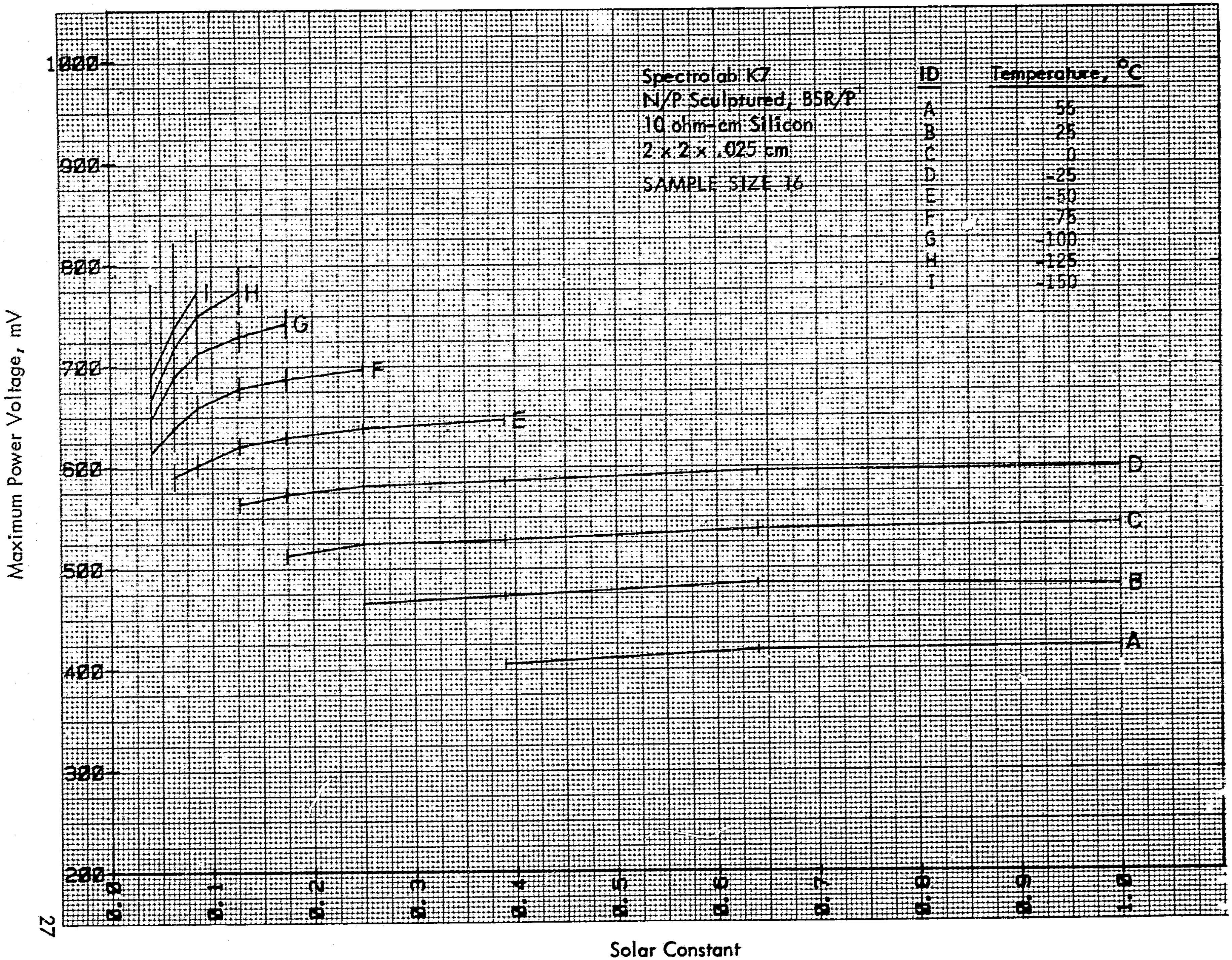

Figure 16. Average V_{mp} as a Function of Intensity

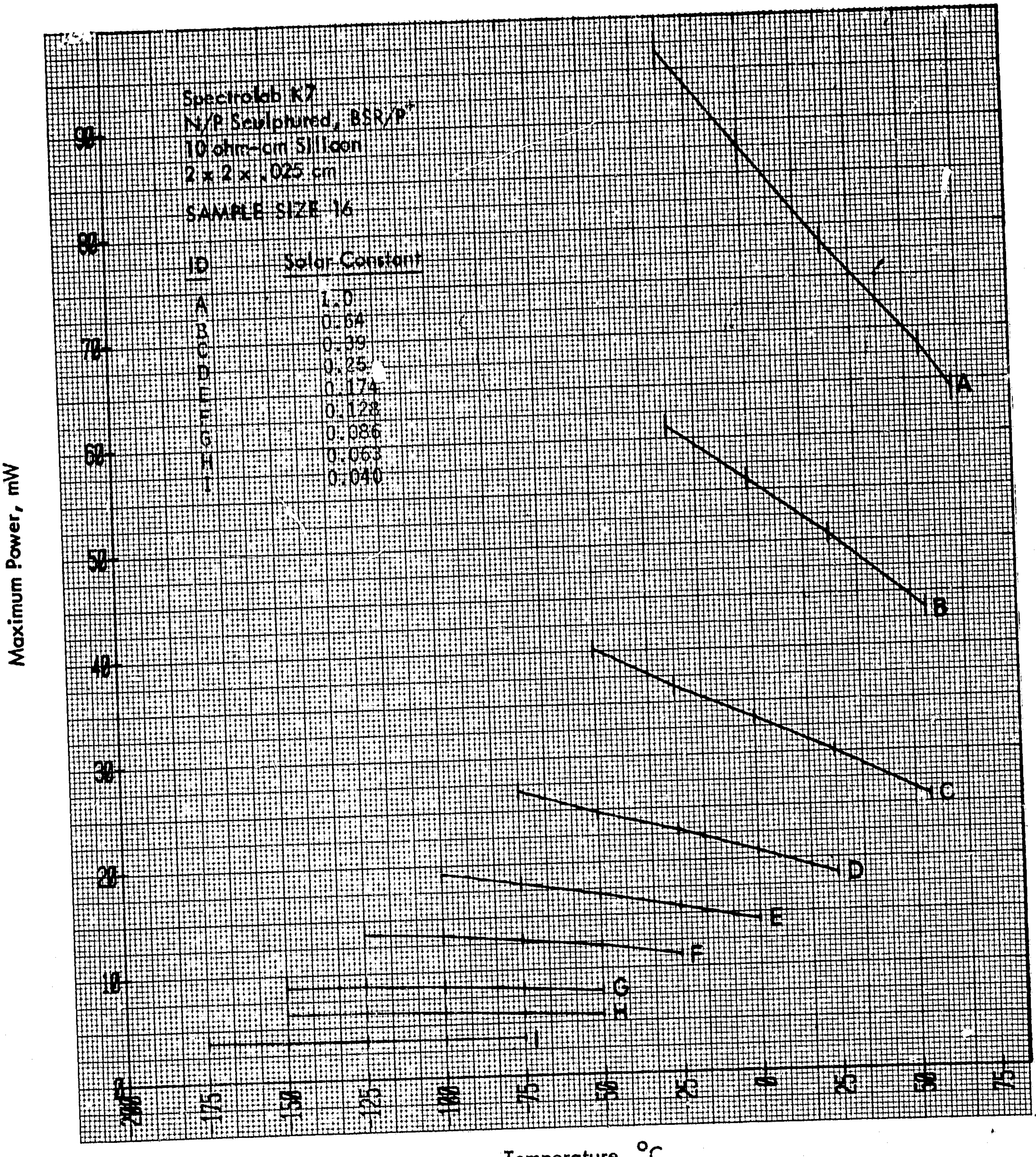

Figure 17. Average MP as a Function of Temperature

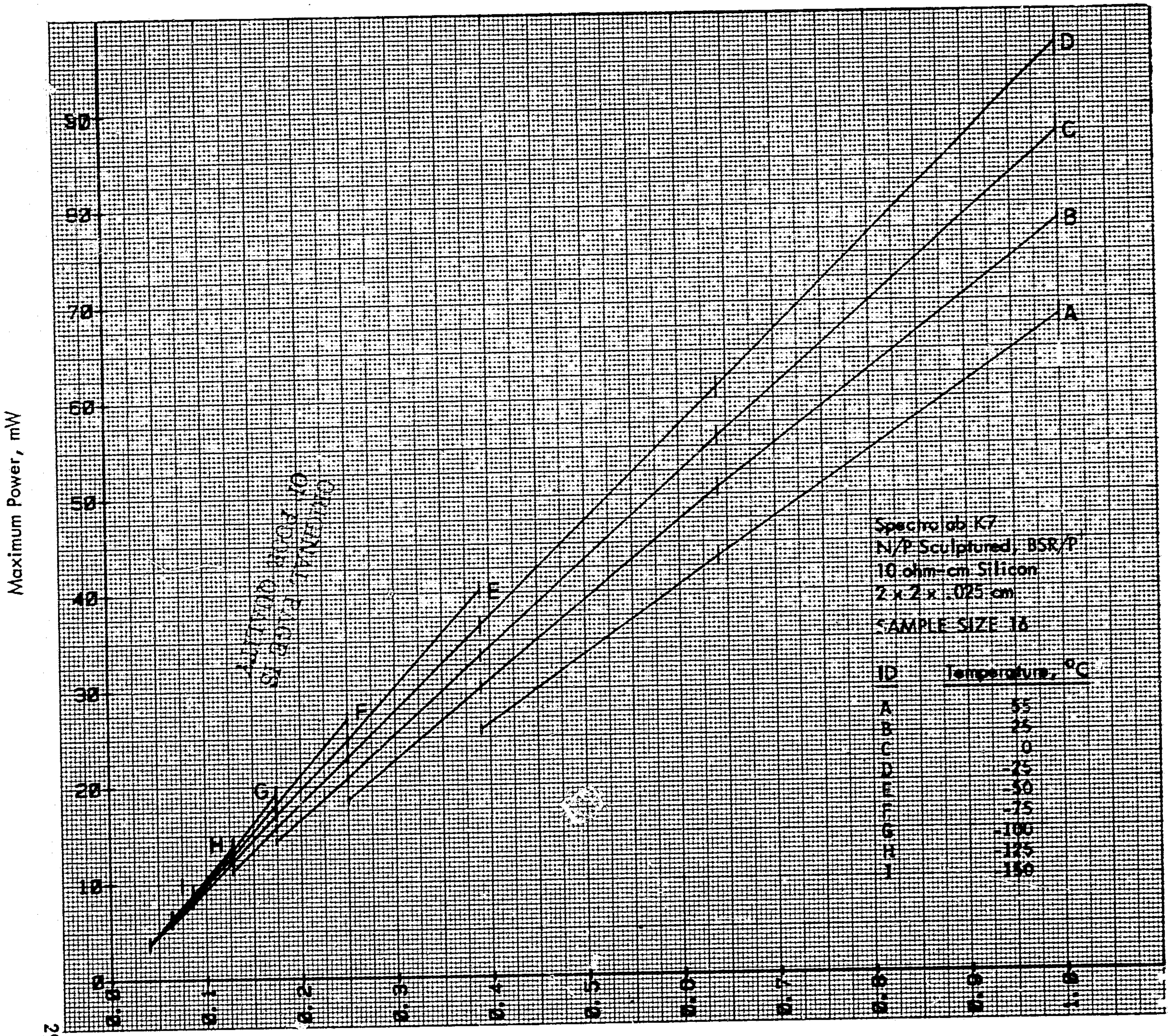

Figure 18. Average MP as a Function of Intensity

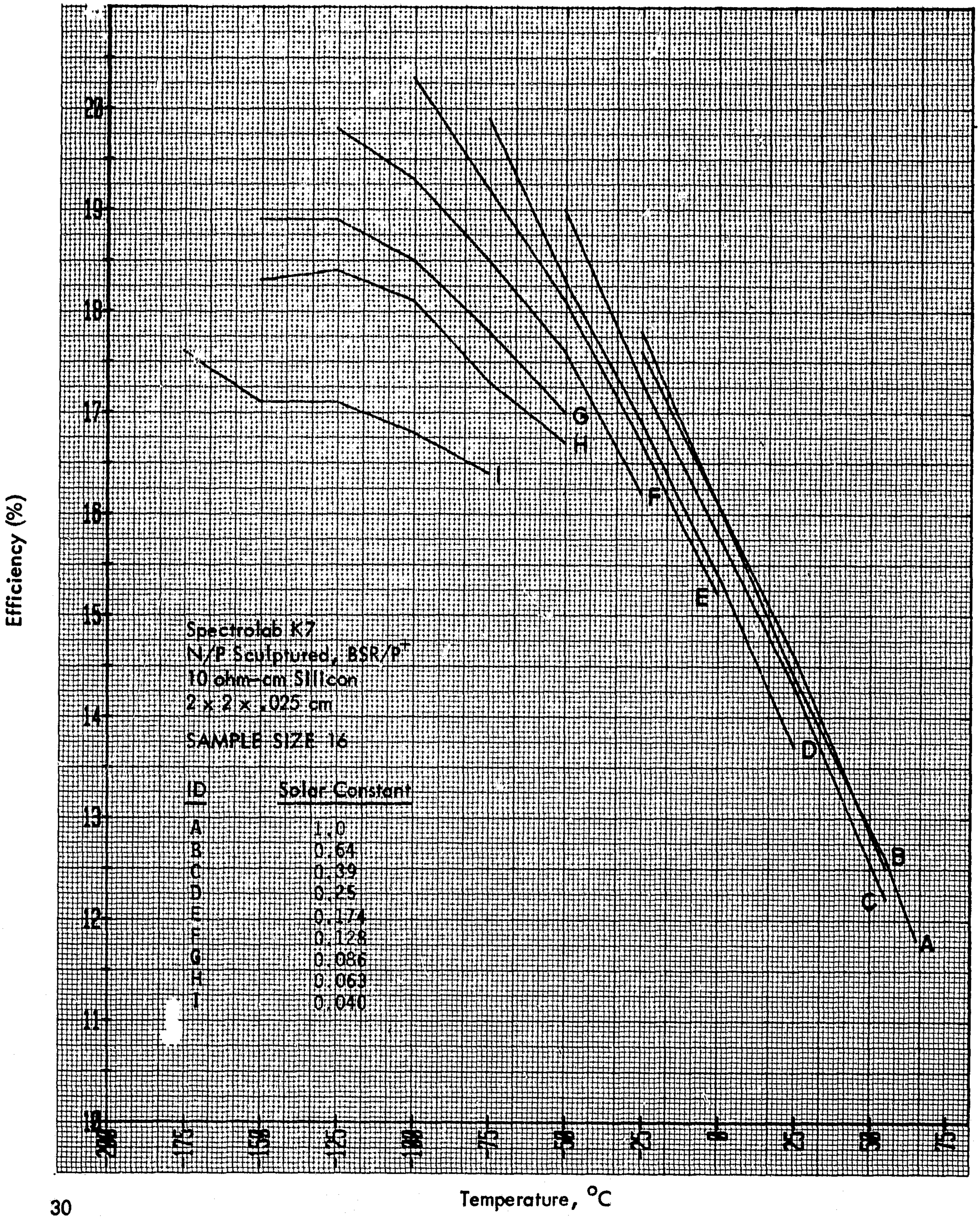

Figure 19. Average Efficiency as a Function of Temperature

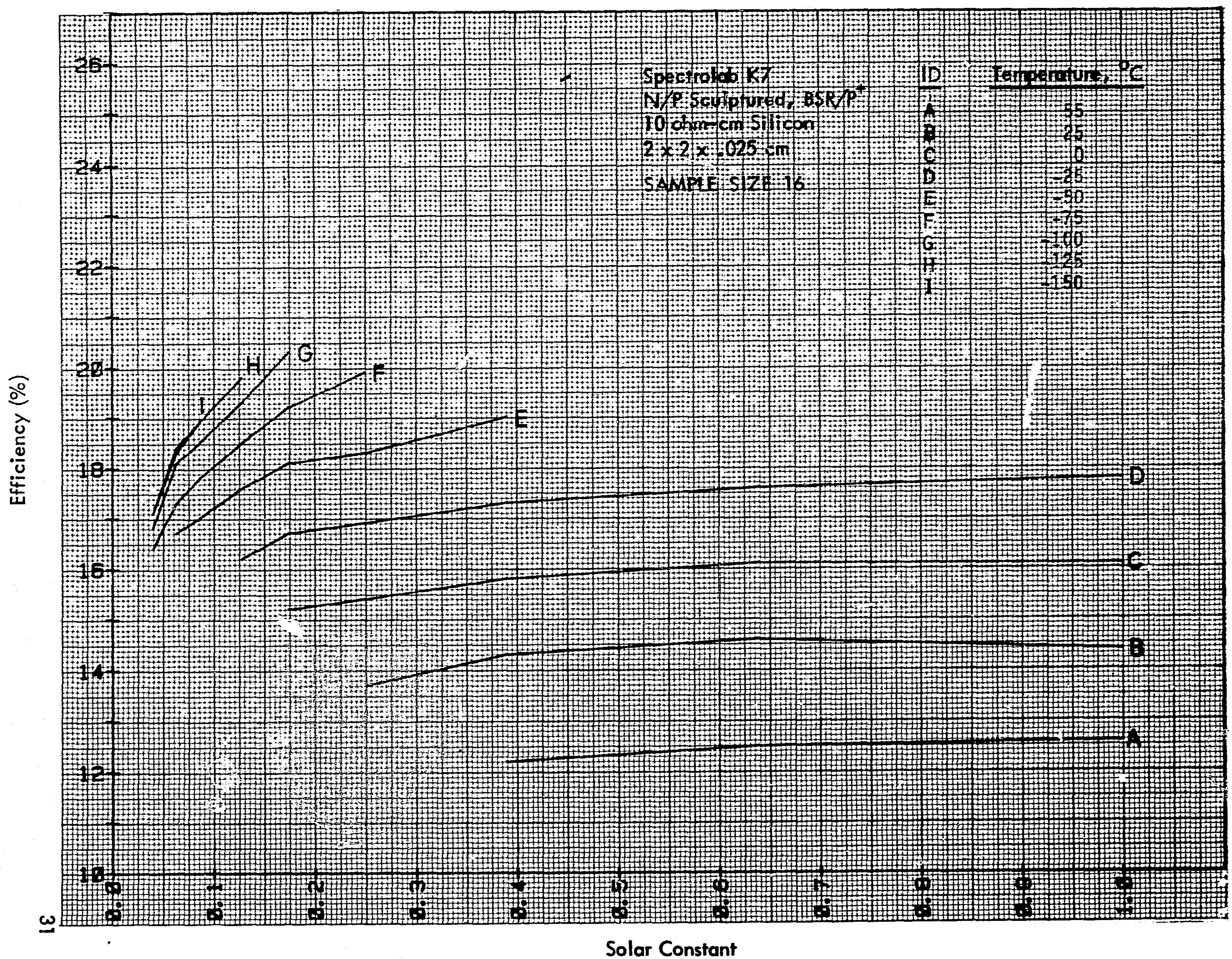

Figure 20. Average Efficiency as a Function of Intensity

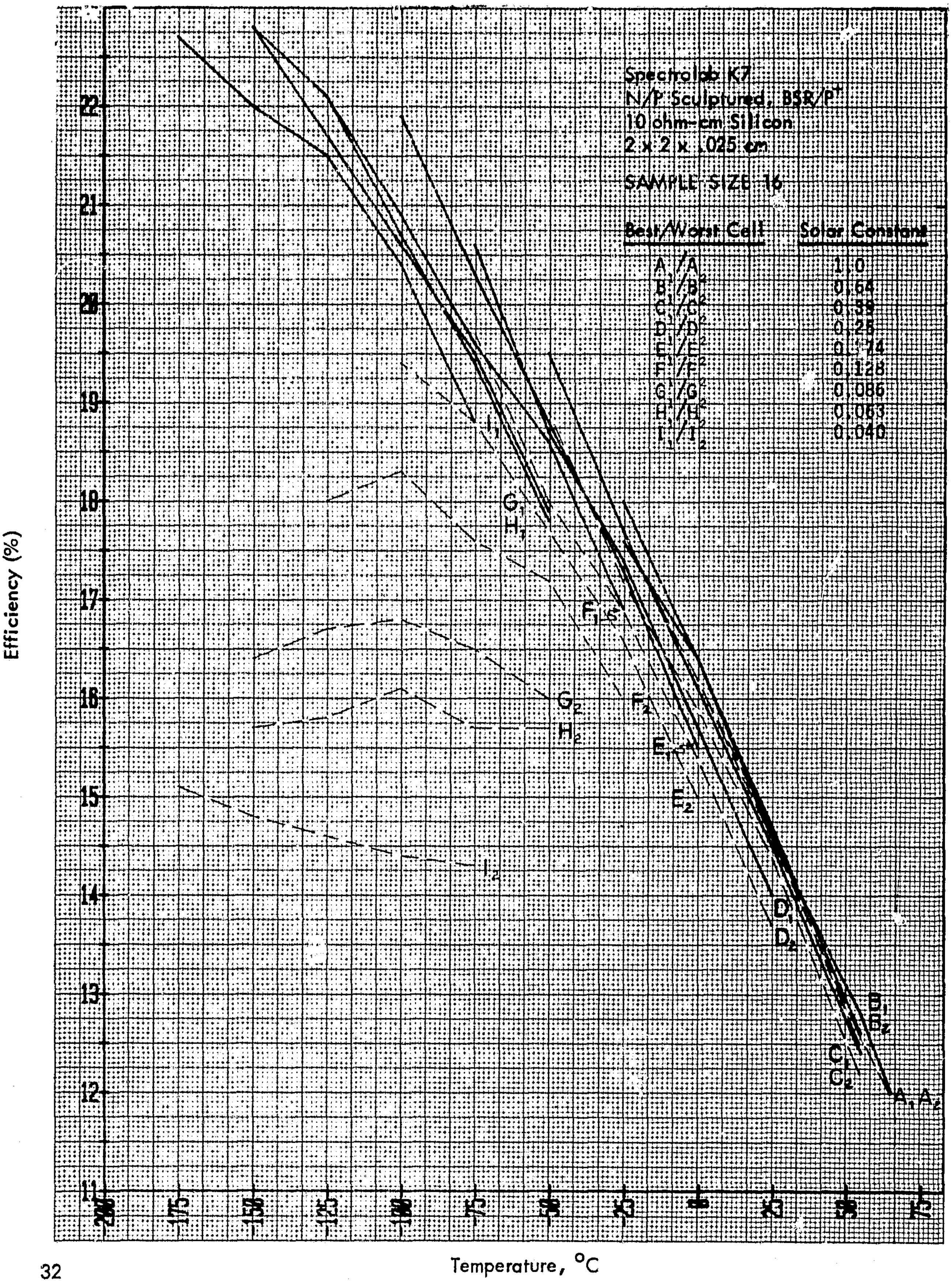

Figure 21. Efficiency of the Best/Worst Cells as a Function of Temperature

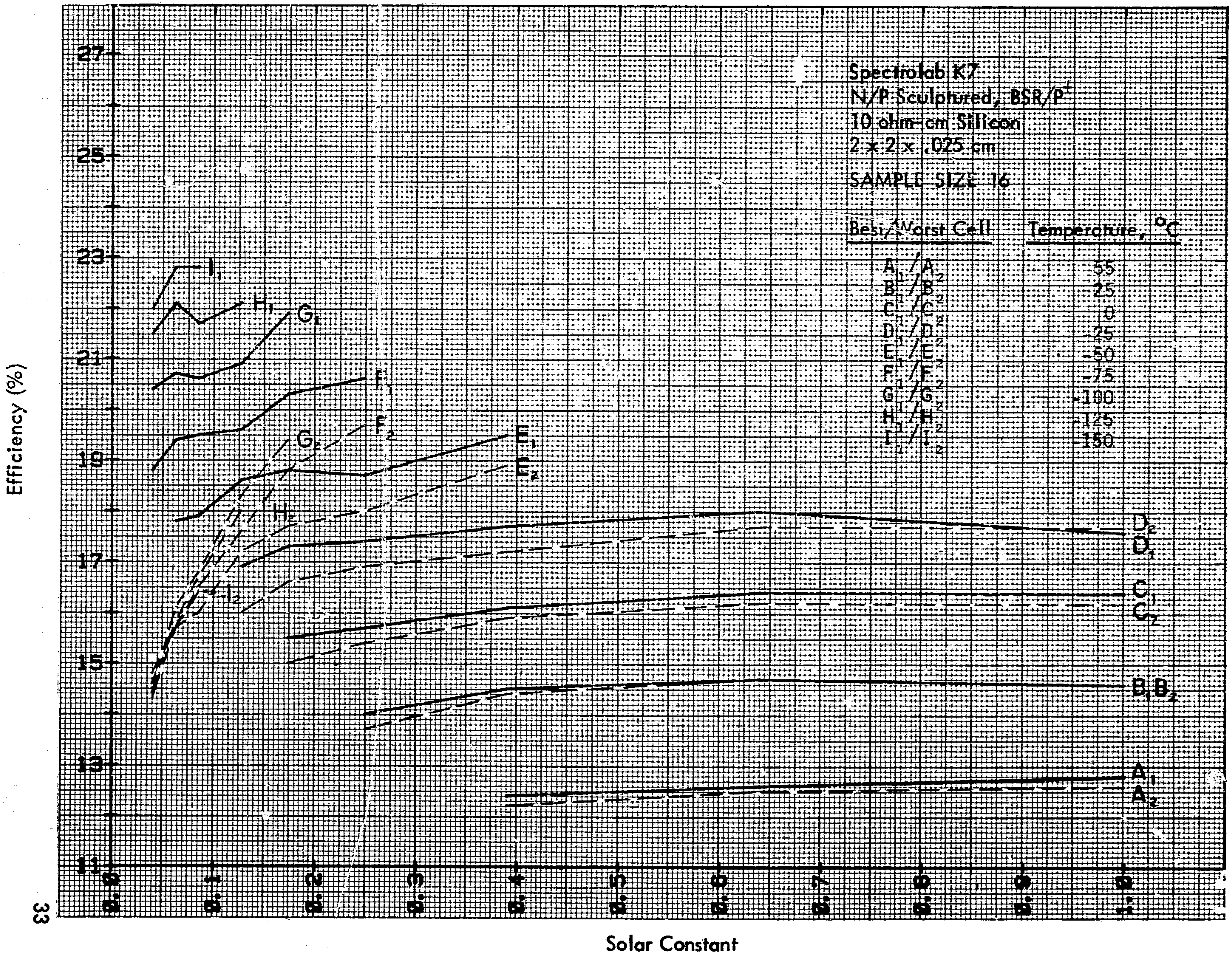

Figure 22. Efficiency of the Best/Worst Cells as a Function of Intensity

TABLE 5. AVERAGE I_{sc} (mA)

Spectrolab K7
N/P Sculptured, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity 1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	180.3 (3.6)								
55°C	180.6 (3.1)	116.3 (2.1)	71.6 (1.2)						
25°C	177.8 (3.4)	115.2 (1.8)	70.8 (1.1)	44.4 (0.9)					
0°C	174.7 (3.3)	112.3 (1.8)	69.4 (1.3)	43.8 (0.8)	30.8 (0.7)				
-25°C	173.8 (2.8)	110.6 (2.0)	68.3 (1.2)	42.9 (0.7)	30.1 (0.6)	21.9 (0.5)			
-50°C			67.9 (1.1)	42.2 (0.8)	29.6 (0.5)	21.6 (0.5)	14.4 (0.3)	10.8 (0.2)	
-75°C				42.2 (0.8)	29.1 (0.5)	20.8 (0.4)	14.2 (0.3)	10.4 (0.2)	6.7 (0.1)
-100°C					28.7 (0.6)	20.8 (0.4)	14.0 (0.3)	10.4 (0.2)	6.5 (0.1)
-125°C						20.3 (0.6)	13.7 (0.3)	10.2 (0.2)	6.4 (0.2)
-150°C							13.4 (0.2)	10.0 (0.3)	6.2 (0.2)
-175°C									6.0 (0.2)

ORIGINAL PAGE IS
OF POOR QUALITY

NOTE: Standard Deviations are given in parentheses.

TABLE 6. AVERAGE V_{oc} (mV)

Spectrolab K7
N/P Sculptured, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	508.4 (2.9)								
55°C	531.2 (2.7)	518.1 (2.1)	502.8 (2.0)						
25°C	593.6 (2.4)	583.1 (2.4)	568.4 (2.1)	554.4 (1.9)					
0°C	647.1 (2.6)	635.8 (2.2)	624.1 (2.1)	611.9 (2.1)	600.8 (2.0)				
-25°C	700.1 (2.9)	689.6 (2.1)	679.0 (2.3)	667.3 (2.4)	657.4 (2.1)	649.5 (2.0)			
-50°C			732.8 (2.1)	722.0 (2.2)	713.3 (2.1)	705.8 (2.5)	694.1 (2.9)	685.4 (3.6)	
-75°C				777.3 (2.4)	768.6 (2.5)	761.2 (3.1)	751.2 (3.0)	743.8 (4.5)	729.8 (6.0)
-100°C					822.9 (2.6)	814.5 (3.1)	806.9 (3.9)	798.9 (5.3)	785.0 (8.3)
-125°C						867.1 (3.3)	860.2 (4.6)	852.6 (6.6)	836.8 (12.2)
-150°C							910.5 (5.6)	903.6 (8.2)	882.6 (20.9)
-175°C									923.9 (26.4)

NOTE: Standard Deviations are given in parentheses.

TABLE 7. AVERAGE I_{mp} (mA)

Spectrolab K7
N/P Sculptured, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	160.8 (4.1)								
55°C	161.7 (2.6)	103.6 (2.3)	63.4 (1.3)						
25°C	162.1 (3.0)	104.4 (1.9)	63.9 (1.3)	39.8 (0.8)					
0°C	160.8 (2.9)	103.8 (1.6)	63.3 (1.2)	39.6 (0.7)	27.9 (0.6)				
-25°C	161.5 (3.4)	102.6 (2.0)	62.4 (1.2)	39.4 (0.7)	27.5 (0.6)	20.0 (0.5)			
-50°C			62.3 (1.2)	38.7 (0.9)	27.0 (0.6)	19.7 (0.5)	13.0 (0.4)	9.6 (0.3)	
-75°C				38.6 (0.8)	26.4 (0.7)	18.8 (0.6)	12.6 (0.5)	9.3 (0.4)	5.8 (0.3)
-100°C					25.9 (0.8)	18.4 (0.7)	12.1 (0.5)	8.9 (0.4)	5.6 (0.3)
-125°C						17.6 (0.9)	11.7 (0.7)	8.7 (0.5)	5.6 (0.3)
-150°C							11.4 (0.6)	8.5 (0.5)	5.4 (0.4)
-175°C									5.4 (0.4)

NOTE: Standard Deviations are given in parentheses.

TABLE 8. AVERAGE V_{mp} (mV)

Spectrolab K7
N/P Sculptured, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	399.8 (6.4)								
55°C	421.8 (4.0)	418.5 (3.9)	405.1 (3.7)						
25°C	482.6 (4.1)	484.7 (2.6)	471.9 (3.7)	464.6 (4.4)					
0°C	542.9 (4.3)	537.6 (5.9)	527.2 (4.8)	523.9 (4.4)	512.3 (6.8)				
-25°C	598.3 (4.0)	595.4 (4.5)	585.4 (3.5)	580.6 (6.0)	571.9 (6.4)	562.8 (6.8)			
-50°C			645.6 (4.6)	637.4 (4.7)	628.7 (5.8)	620.4 (7.3)	601.7 (10.1)	590.6 (13.2)	
-75°C				696.1 (6.3)	686.3 (10.2)	677.5 (11.0)	658.5 (12.6)	638.6 (21.5)	614.3 (32.6)
-100°C					741.8 (13.6)	729.4 (13.8)	712.8 (24.7)	689.5 (33.0)	647.3 (53.6)
-125°C						774.4 (22.8)	749.9 (37.7)	718.1 (58.5)	666.1 (78.0)
-150°C							773.1 (60.5)	738.1 (83.5)	689.6 (104.3)
-175°C									713.1 (119.0)

NOTE: Standard Deviations are given in parentheses.

TABLE 9. AVERAGE MP (mW)

Spectrolab K7
N/P Sculptured, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	64.1 (1.2)								
55°C	68.3 (1.1)	43.4 (0.9)	25.7 (0.5)						
25°C	78.2 (1.1)	50.6 (0.9)	30.1 (0.6)	18.5 (0.4)					
0°C	87.4 (1.5)	55.9 (0.9)	33.4 (0.6)	20.8 (0.4)	14.3 (0.3)				
-25°C	96.6 (1.7)	61.1 (1.0)	36.5 (0.8)	22.9 (0.5)	15.7 (0.4)	11.2 (0.3)			
-50°C			40.2 (0.8)	24.7 (0.6)	17.0 (0.5)	12.2 (0.4)	7.9 (0.4)	5.7 (0.3)	
-75°C				26.9 (0.7)	18.1 (0.6)	12.8 (0.5)	8.3 (0.5)	5.9 (0.4)	3.6 (0.3)
-100°C					19.2 (0.8)	13.4 (0.7)	8.6 (0.6)	6.2 (0.6)	3.6 (0.4)
-125°C						13.7 (1.0)	8.8 (0.8)	6.3 (0.7)	3.7 (0.5)
-150°C							8.8 (1.1)	6.3 (0.9)	3.7 (0.6)
-175°C									3.8 (0.6)

NOTE: Standard Deviations are given in parentheses.

TABLE 10. AVERAGE EFFICIENCY (%)

Spectrolab K7
N/P Sculptured, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	11.8								
55°C	12.6	12.5	12.2						
25°C	14.4	14.6	14.3	13.7					
0°C	16.1	16.1	15.8	15.4	15.2				
-25°C	17.8	17.6	17.3	16.9	16.7	16.2			
-50°C			19.0	18.3	18.1	17.6	17.0	16.7	
-75°C				19.9	19.2	18.5	17.8	17.3	16.4
-100°C					20.3	19.3	18.5	18.1	16.8
-125°C						19.8	18.9	18.4	17.1
-150°C							18.9	18.3	17.1
-175°C									17.6

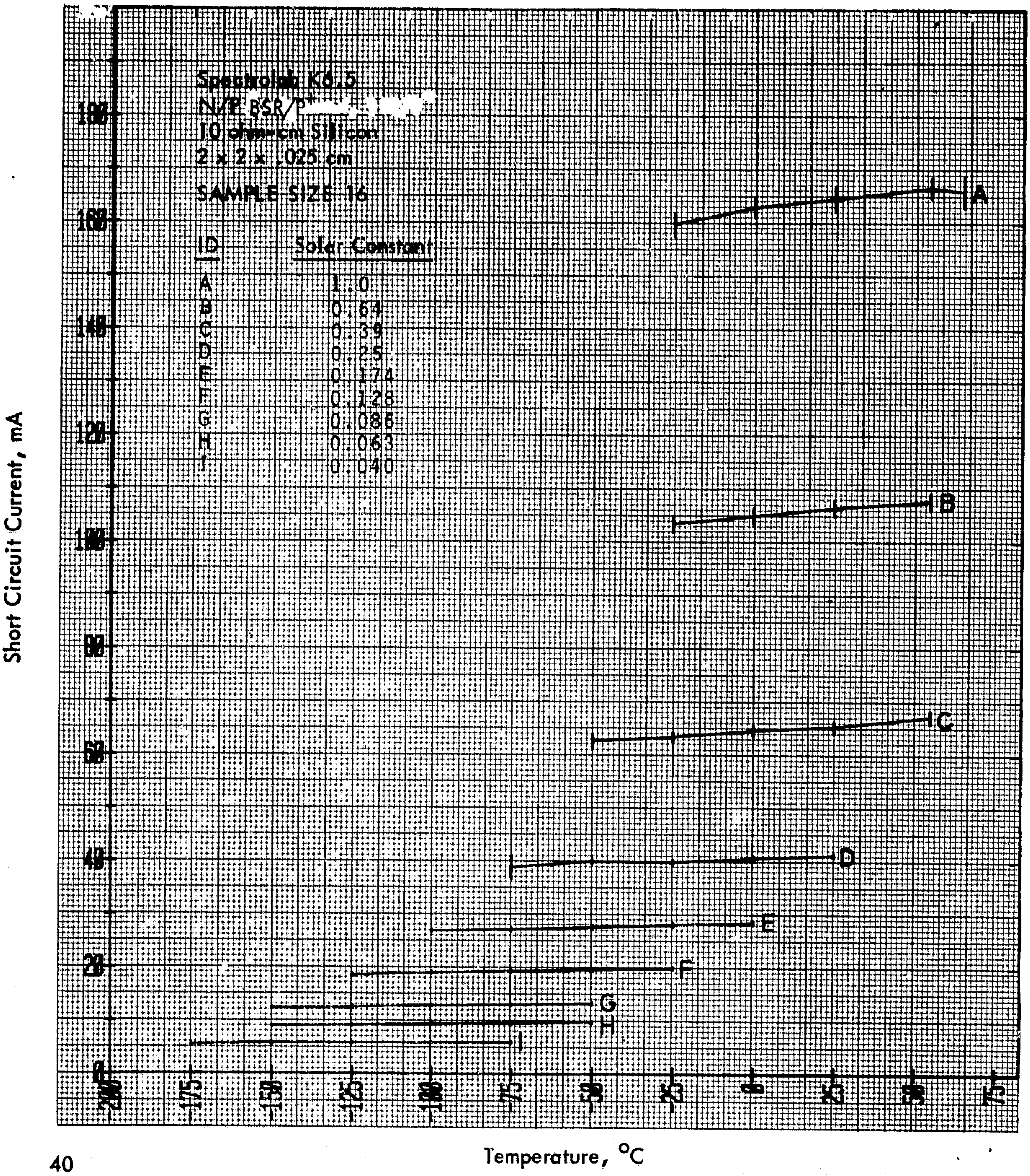

Figure 23. Average I_{sc} as a Function of Temperature

ORIGINAL PAGE IS
OF POOR QUALITY

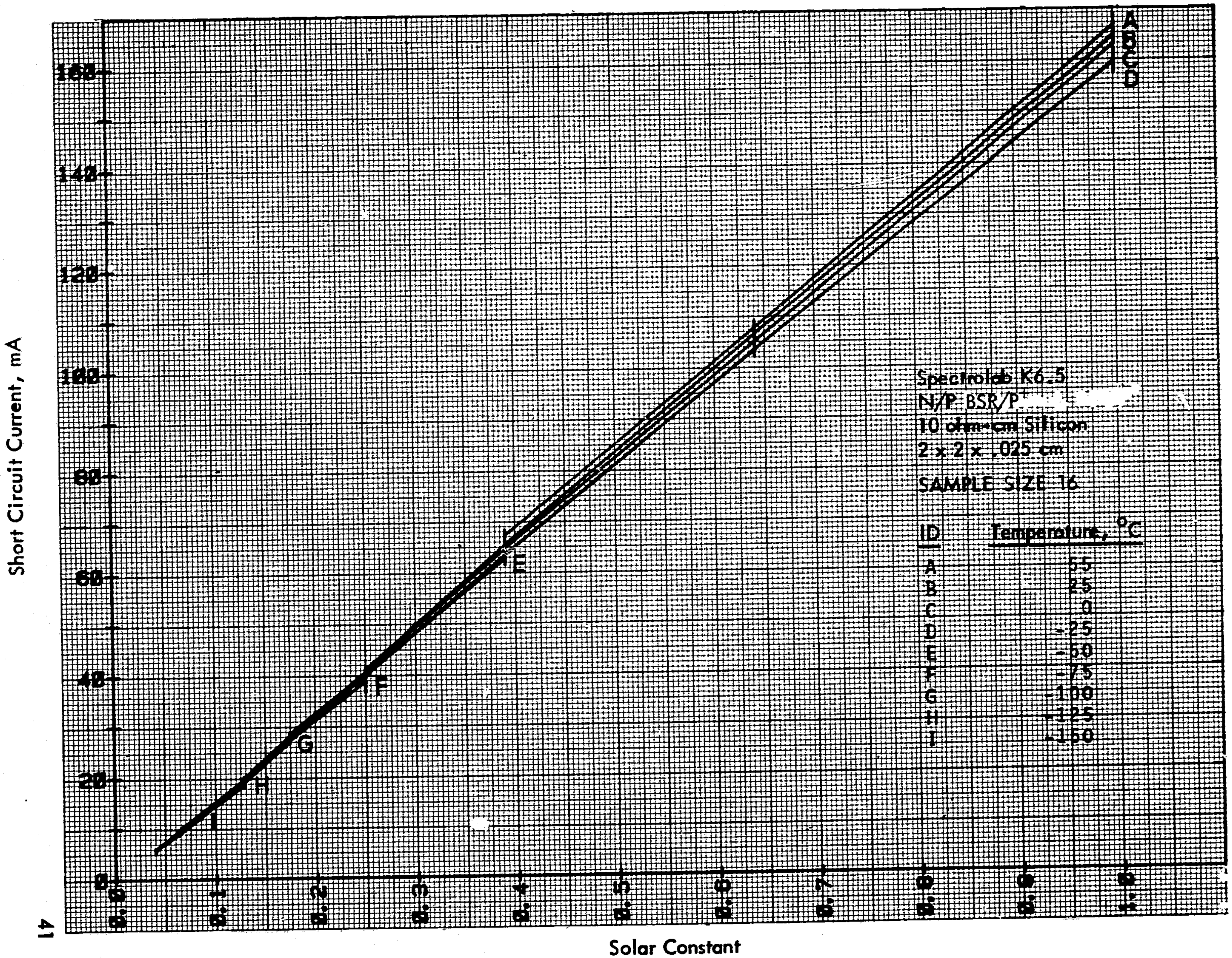

Figure 24. Average I_{sc} as a Function of Intensity

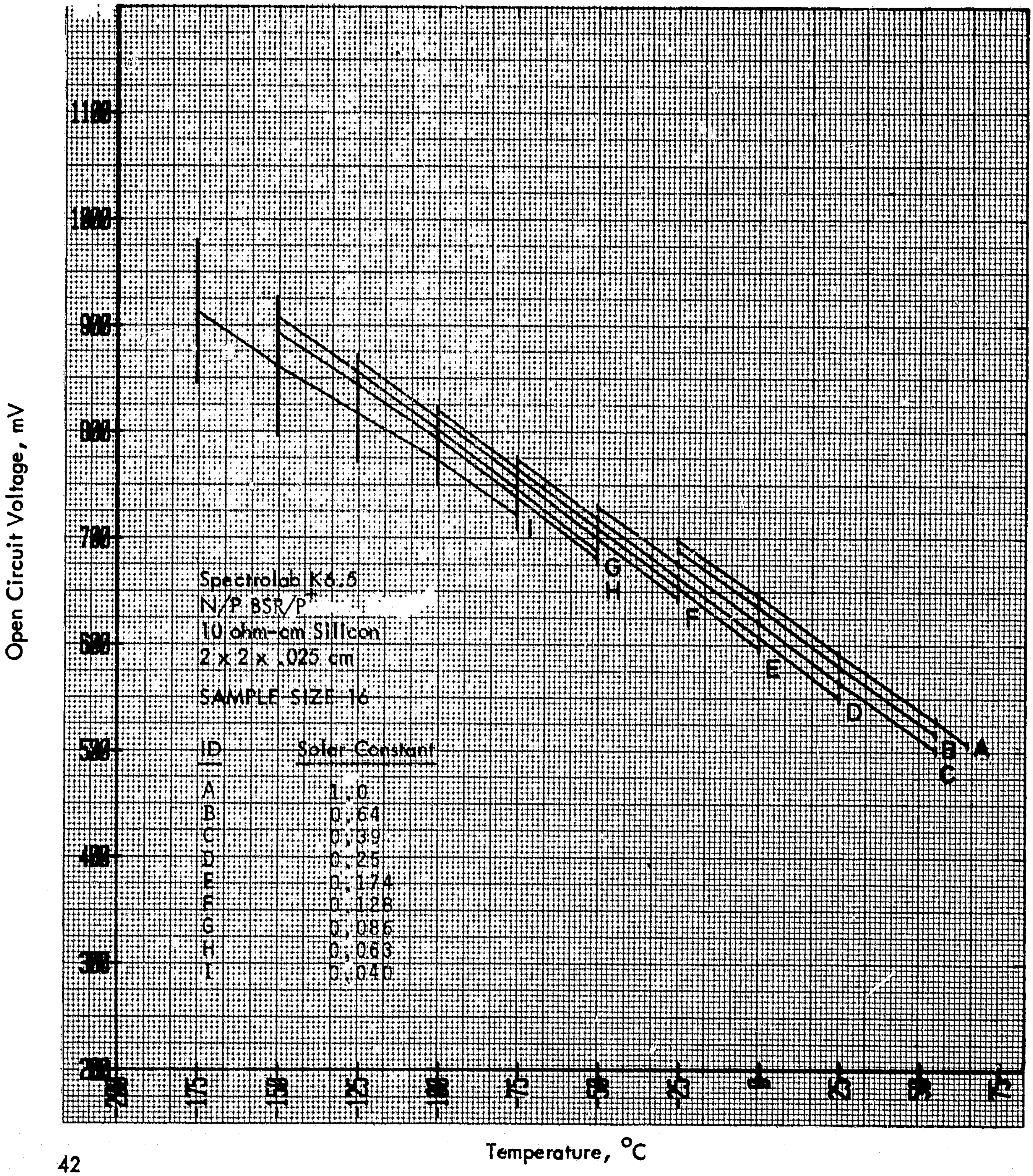

Figure 25. Average V_{oc} as a Function of Temperature

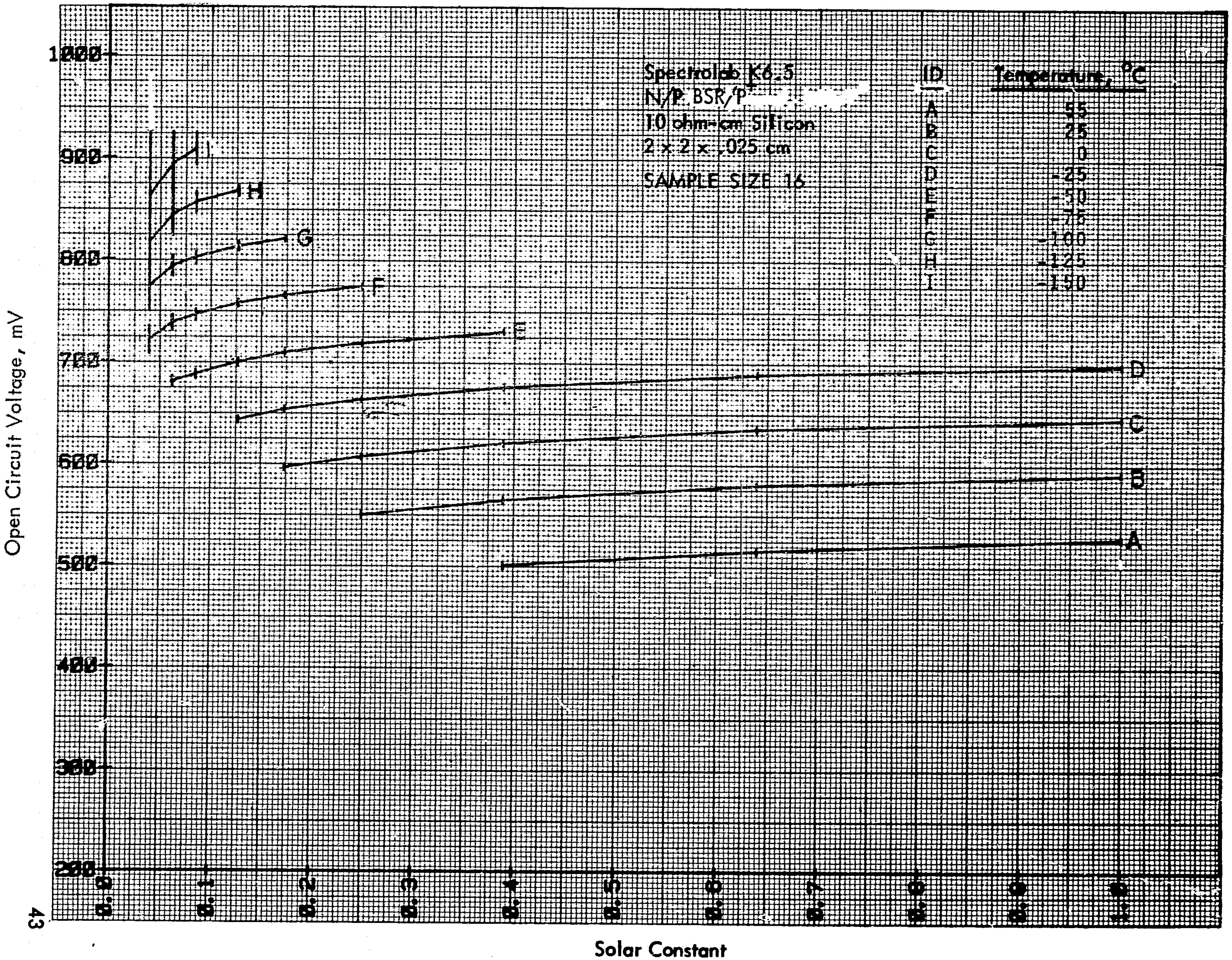

Figure 26. Average V_{oc} as a Function of Intensity

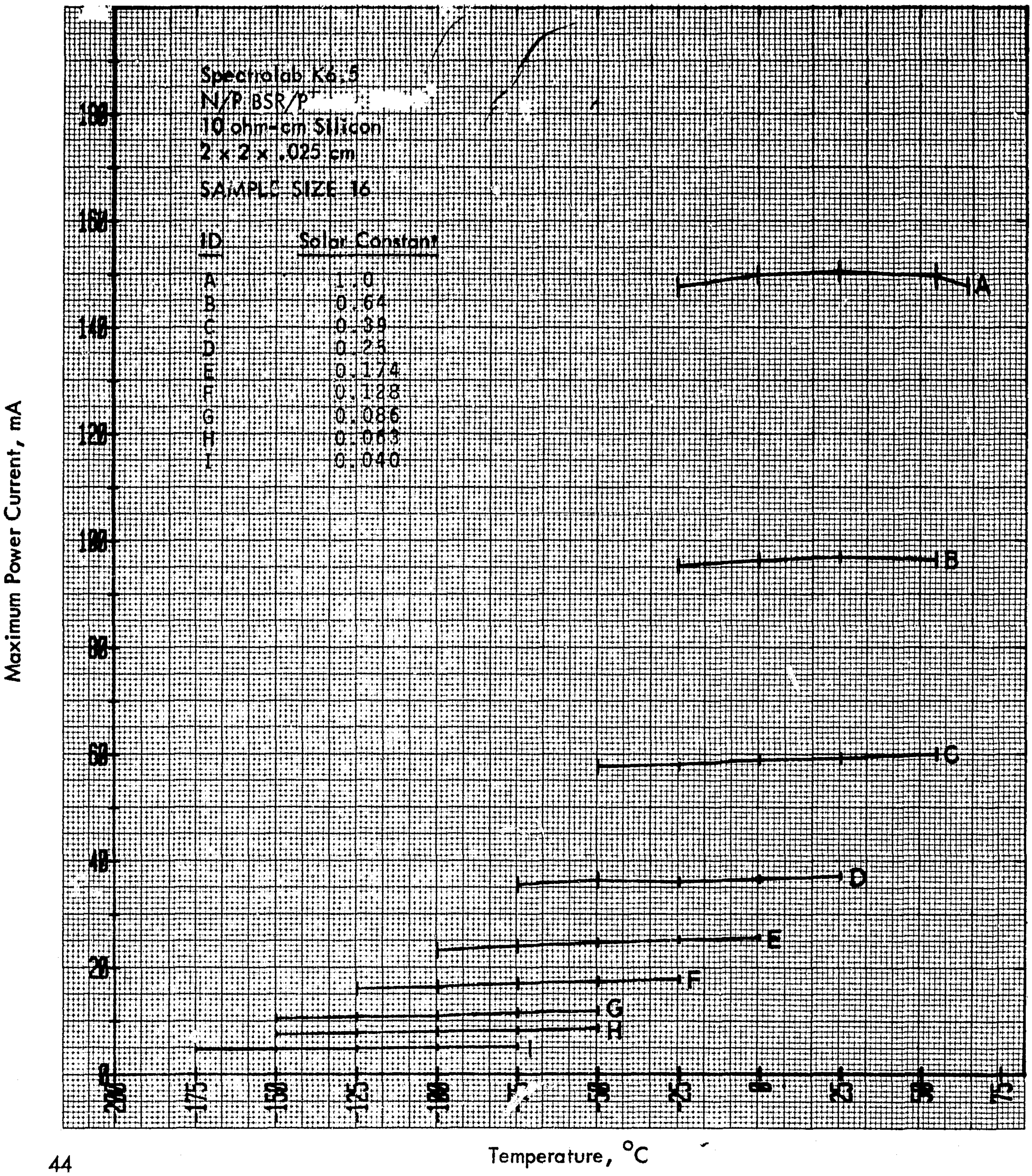

Figure 27. Average I_{mp} as a Function of Temperature

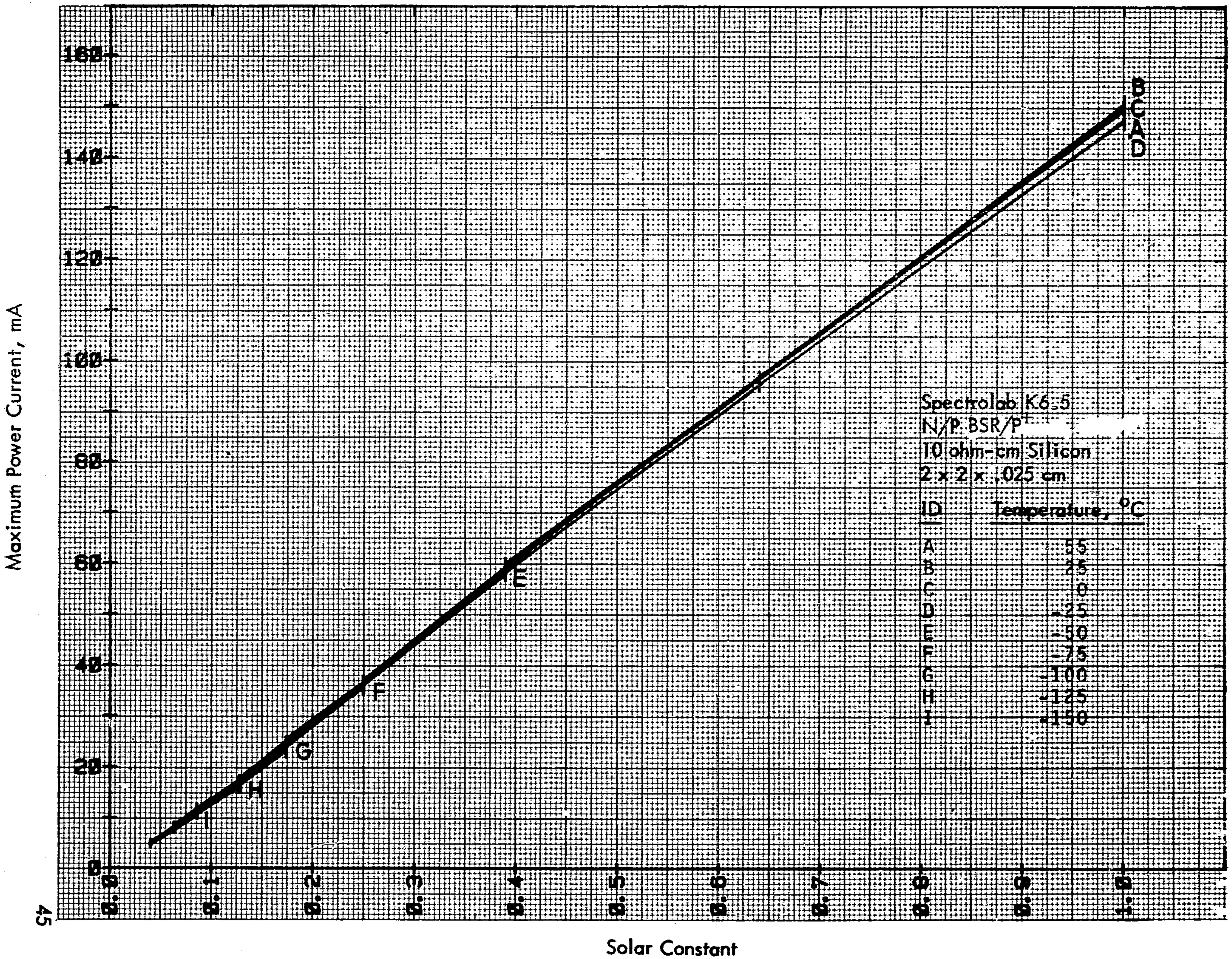

Figure 28. Average I_{mp} as a Function of Intensity

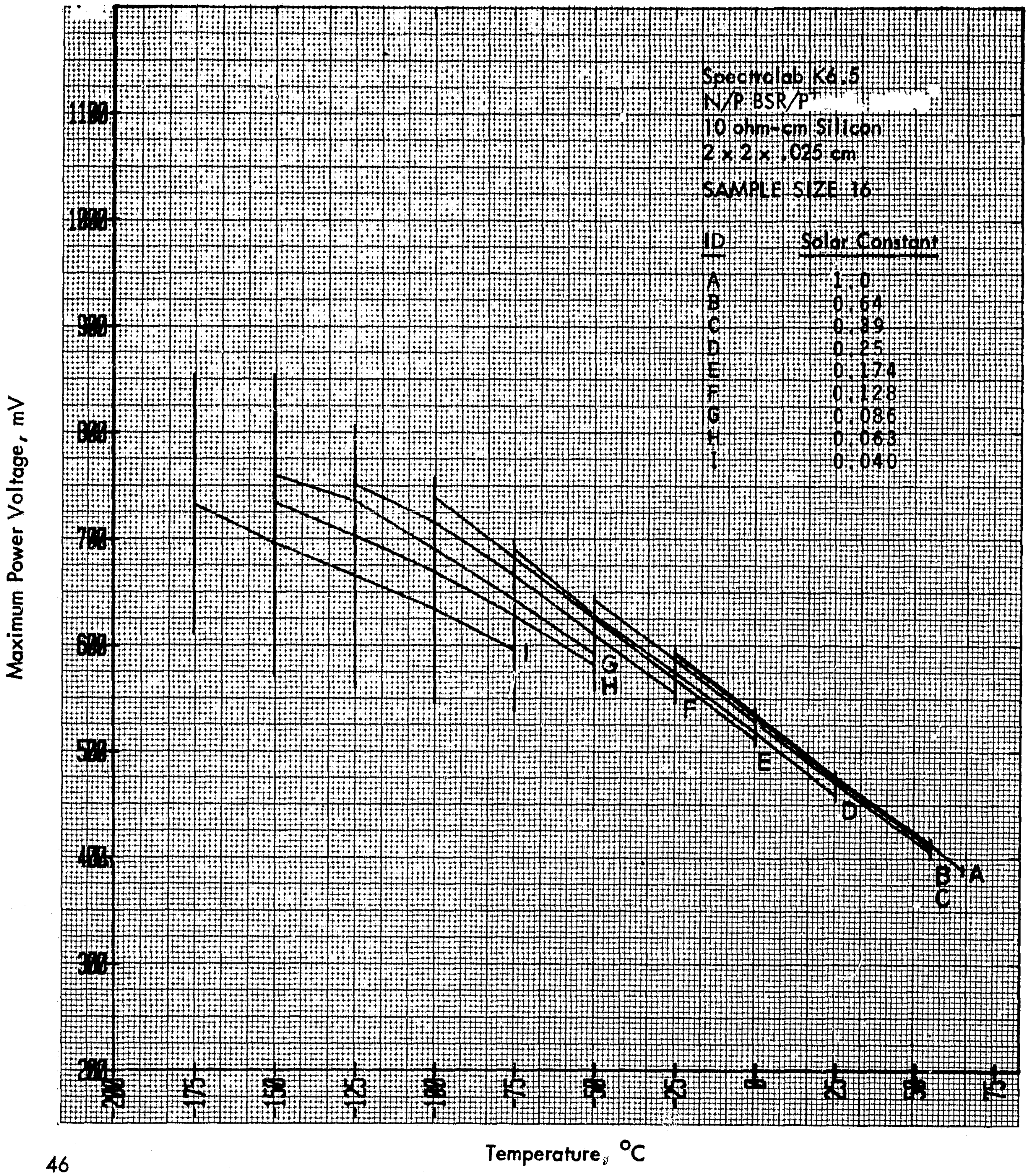

Figure 29. Average V_{mp} as a Function of Temperature

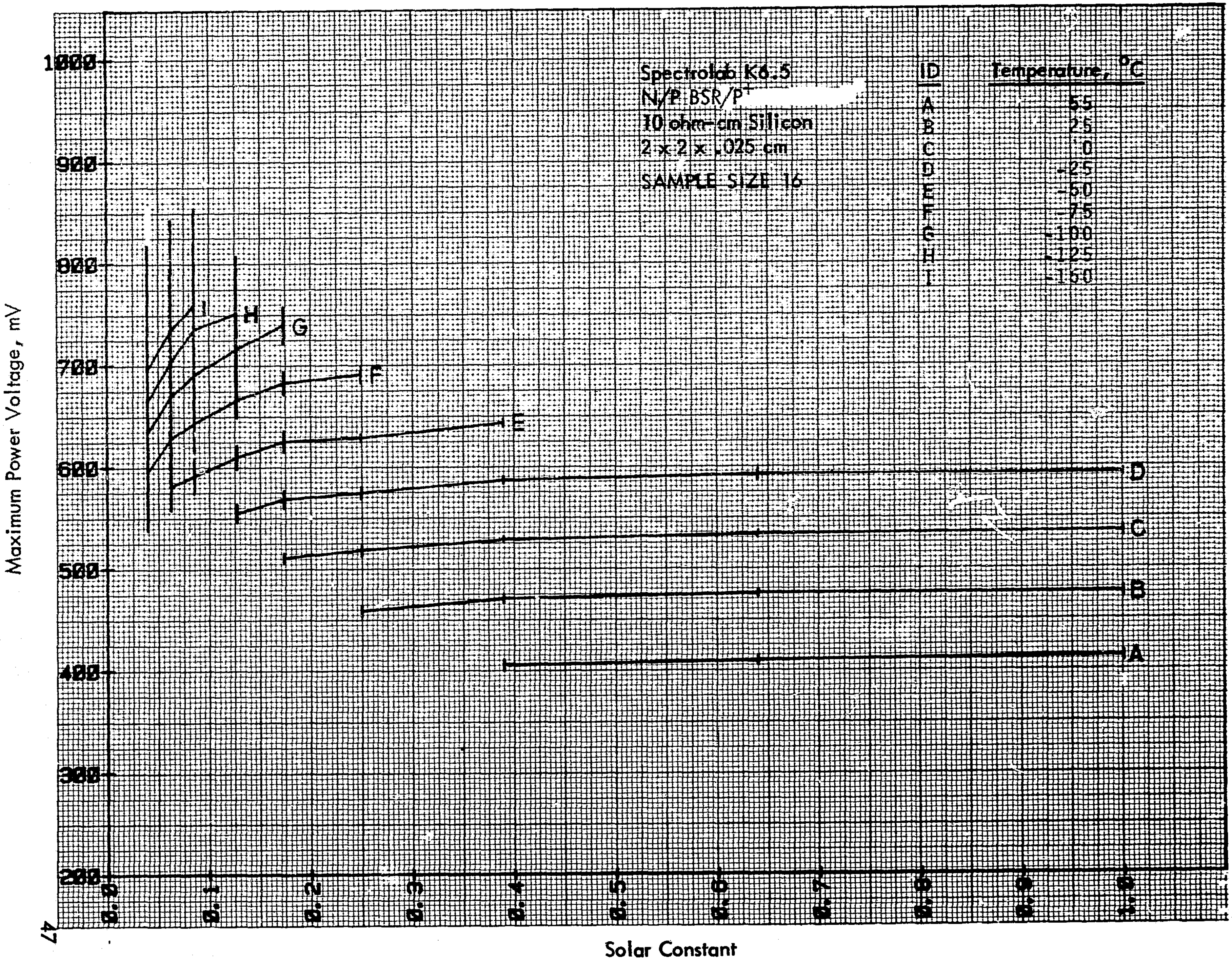

Figure 30. Average V_{mp} as a Function of Intensity

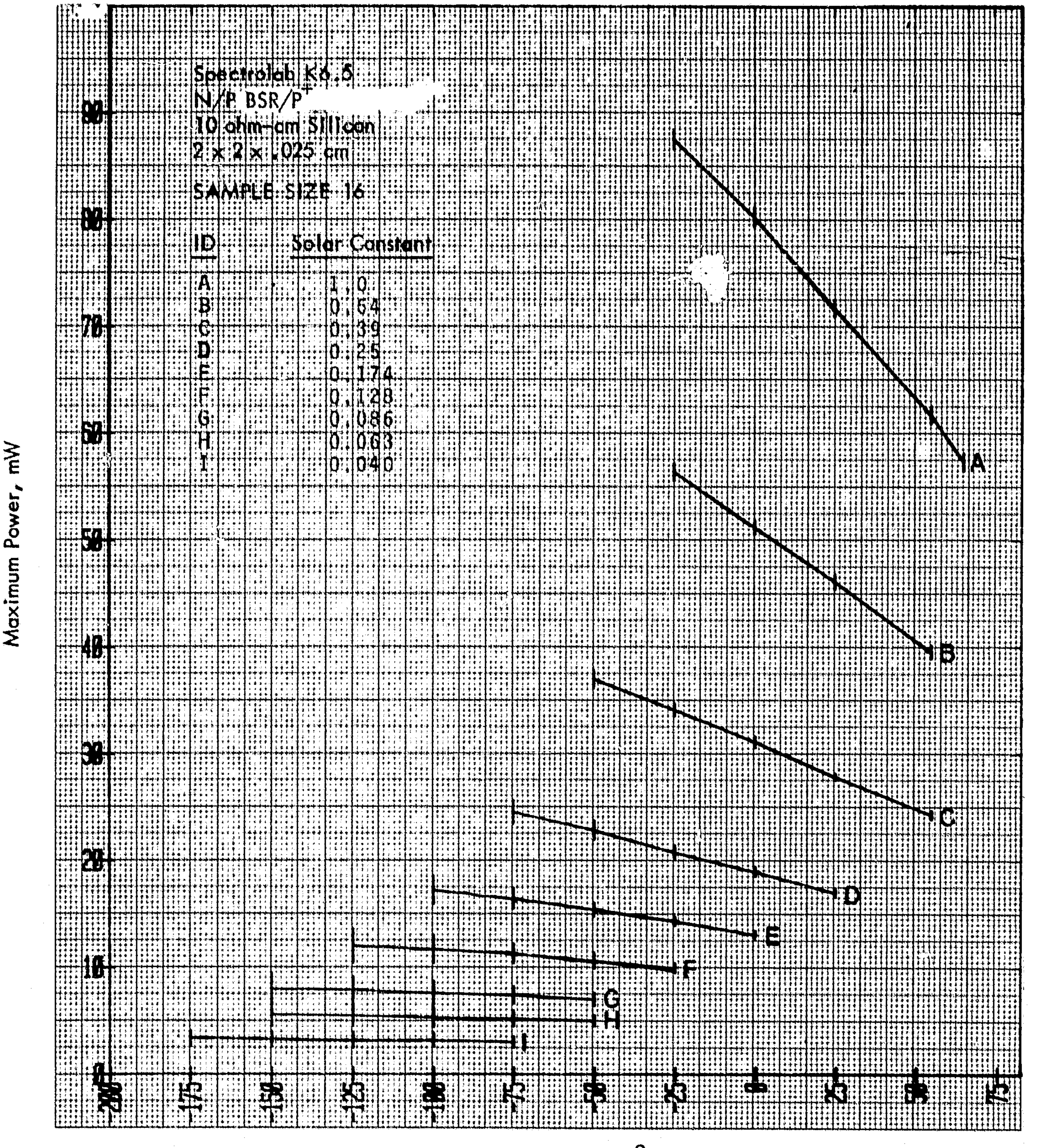

Figure 31. Average MP as a Function of Temperature

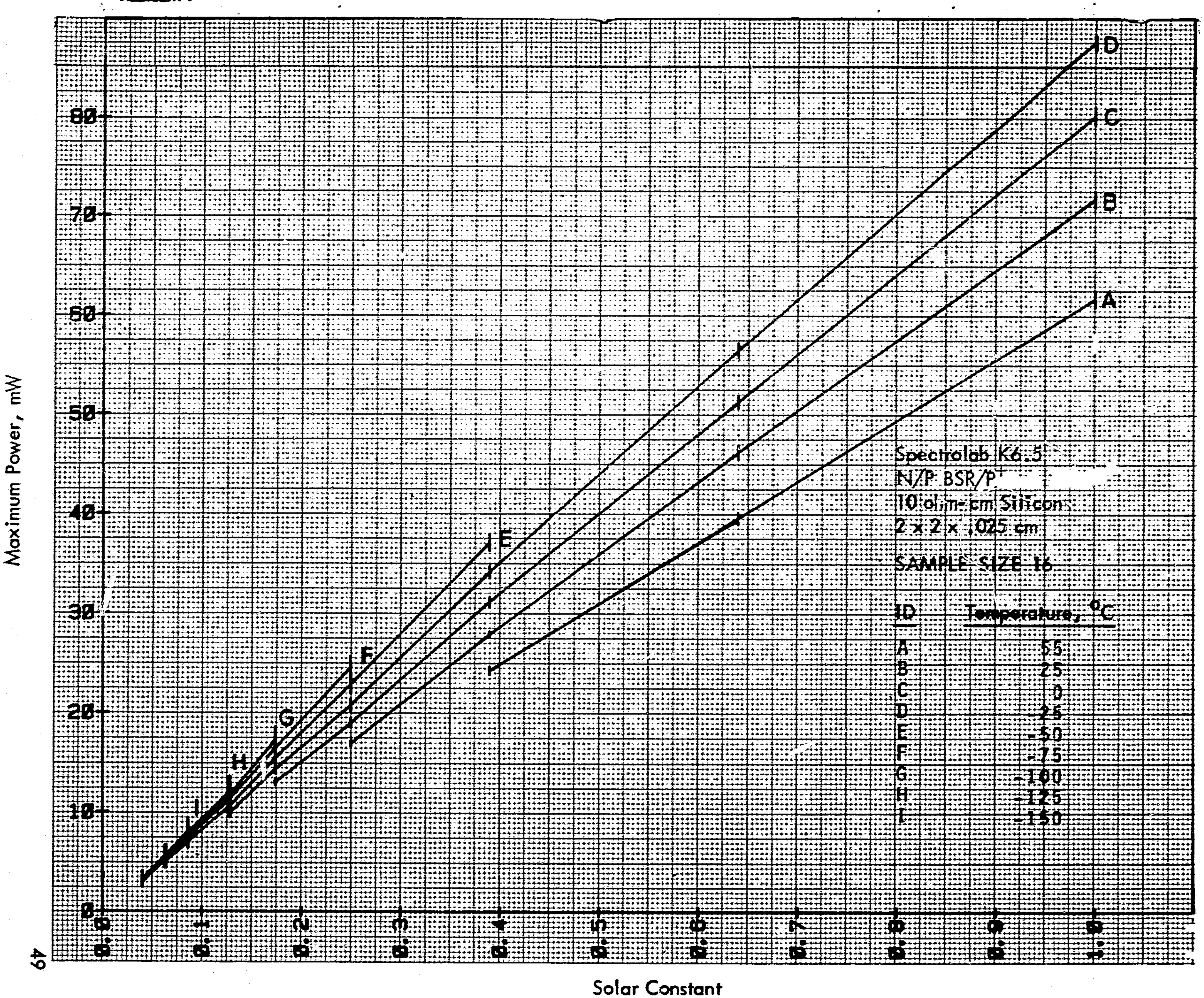

Figure 32. Average MP as a Function of Intensity

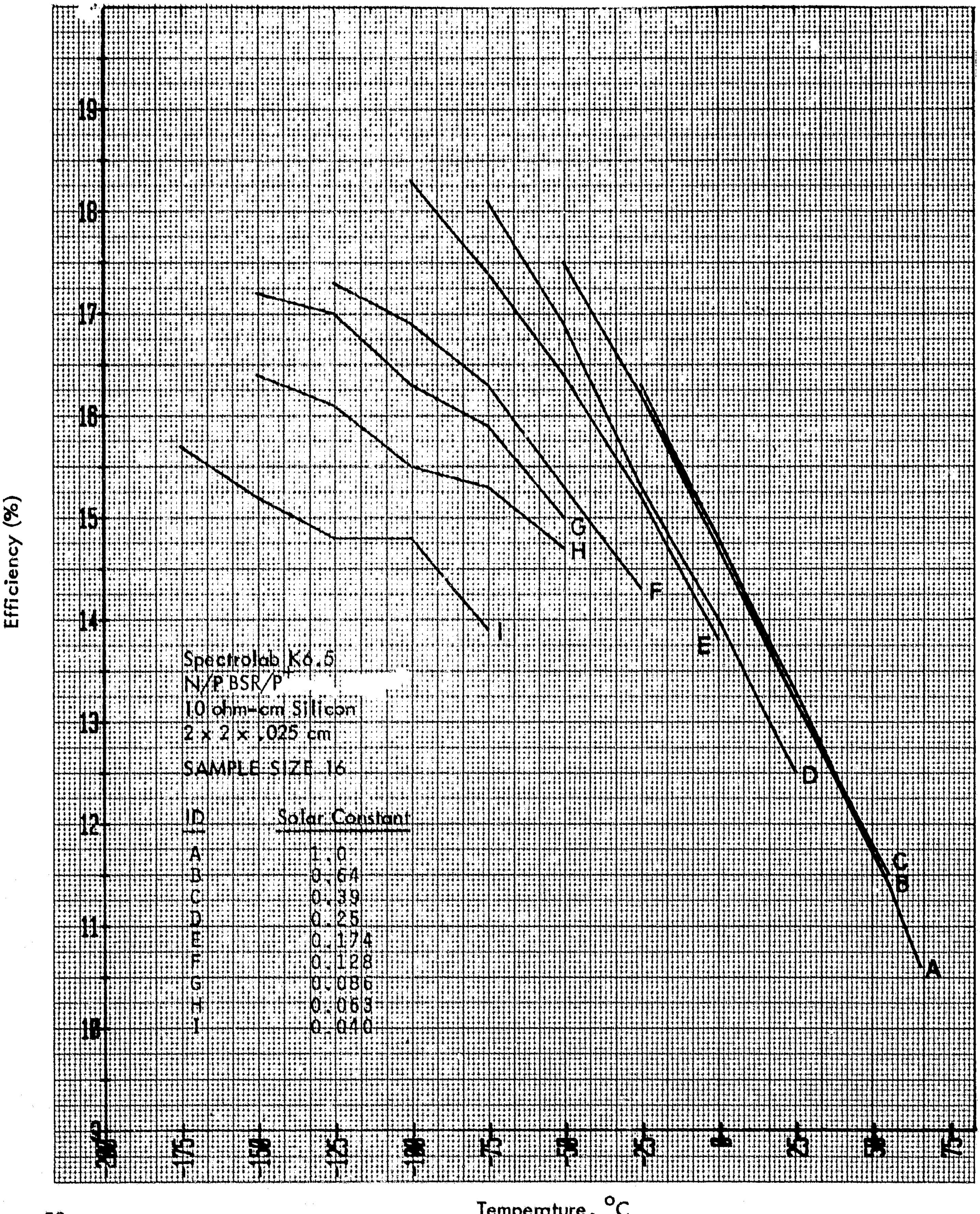

Figure 33. Average Efficiency as a Function of Temperature

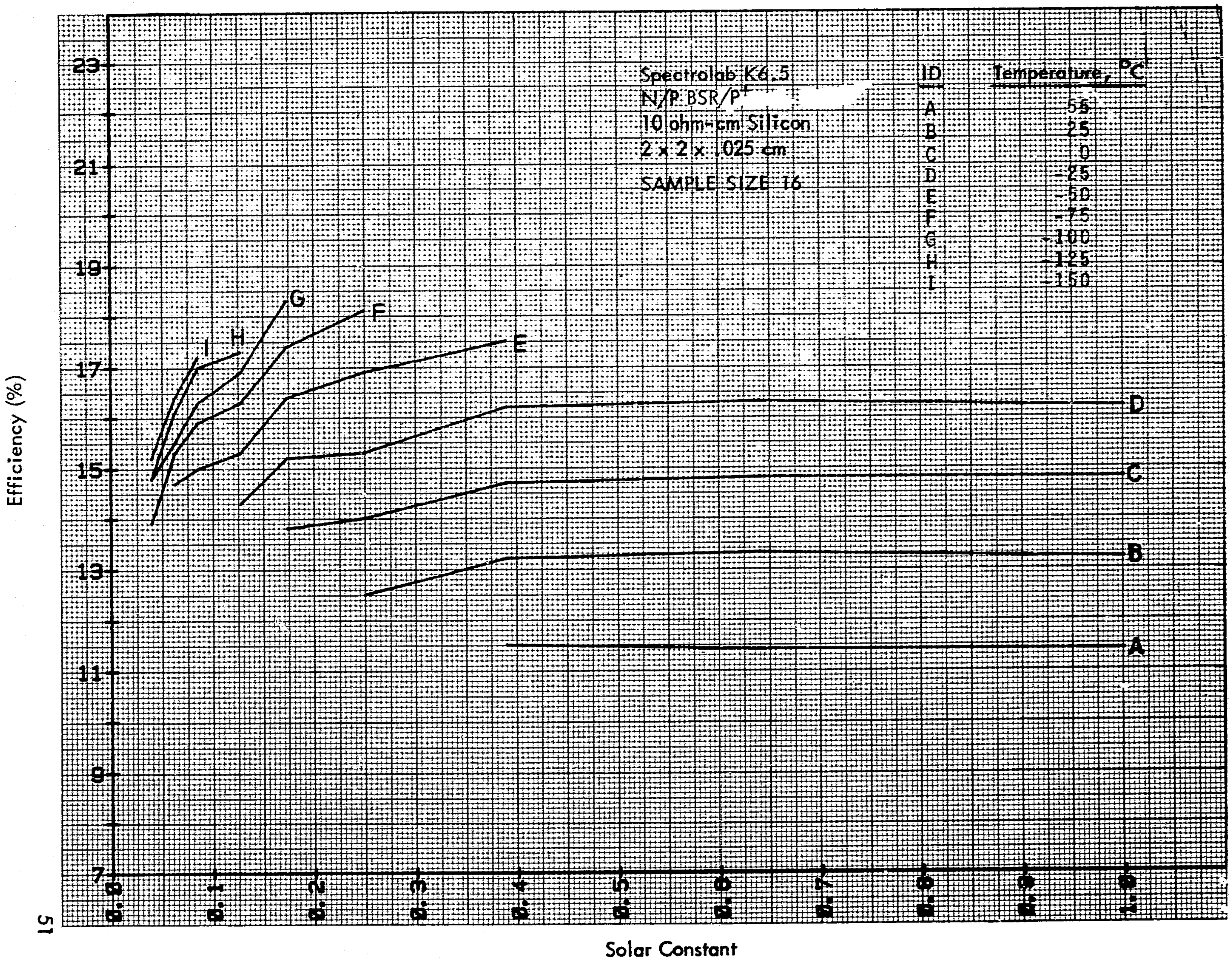

Figure 34. Average Efficiency as a Function of Intensity

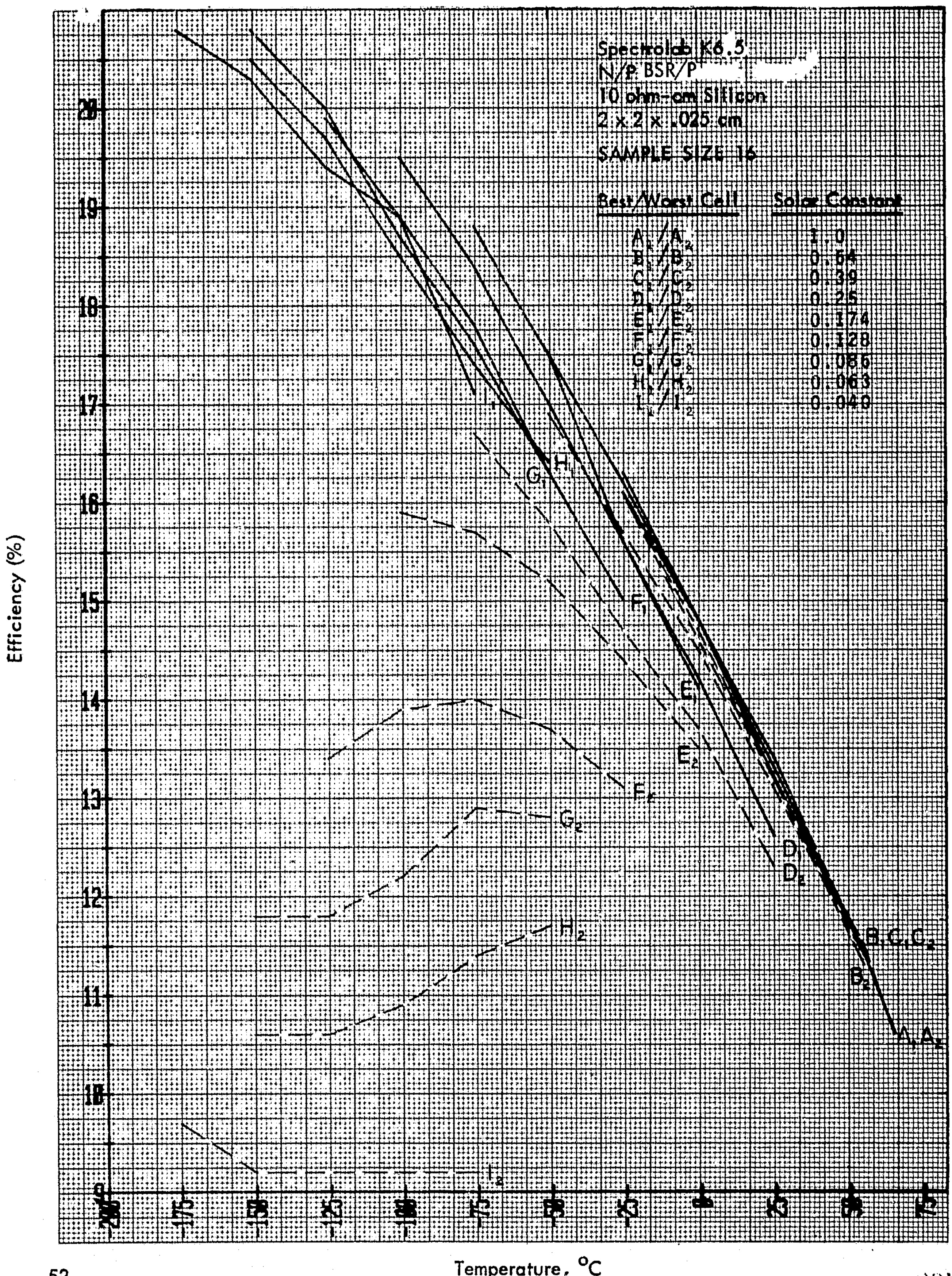

Figure 35. Efficiency of the Best/Worst Cells as a Function of Temperature

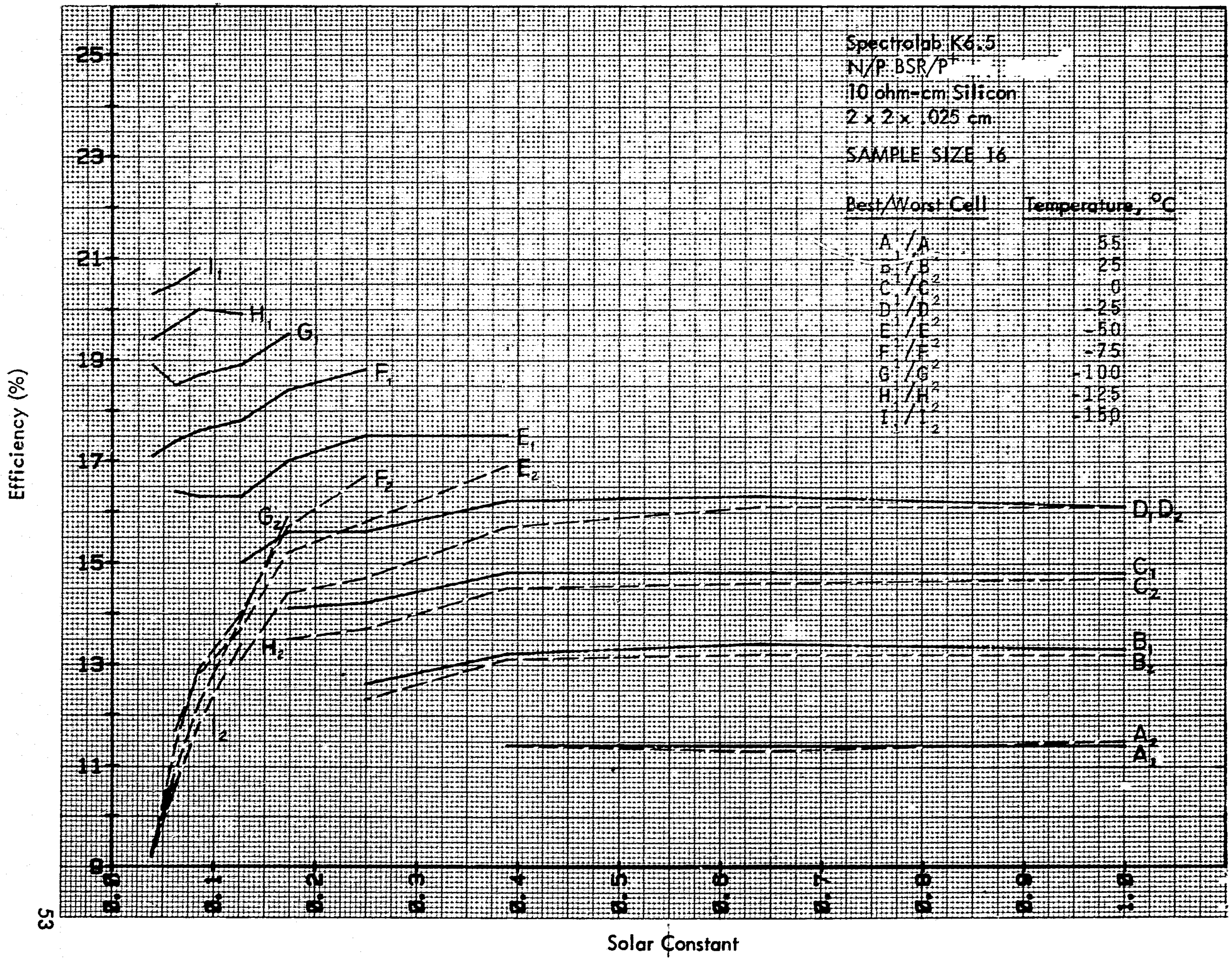

Figure 36. Efficiency of the Best/Worst Cells as a Function of Intensity

TABLE 11. AVERAGE I_{sc} (mA)

Spectrolab K6.5
N/P, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.085	0.063	0.040
65°C	165.8 (2.9)								
55°C	166.5 (1.9)	107.6 (1.5)	67.1 (1.2)						
25°C	164.4 (2.2)	106.4 (1.5)	65.3 (1.0)	41.0 (0.4)					
0°C	162.8 (1.8)	104.9 (1.6)	64.6 (1.0)	40.5 (0.4)	28.4 (0.3)				
-25°C	159.6 (2.2)	103.4 (1.5)	63.4 (0.9)	39.8 (0.5)	28.0 (0.4)	19.9 (0.2)			
-50°C			62.6 (1.2)	39.9 (0.5)	27.5 (0.4)	19.6 (0.3)	13.2 (0.2)	9.7 (0.1)	
-75°C				38.8 (2.2)	27.1 (0.3)	19.3 (0.2)	13.0 (0.1)	9.5 (0.1)	5.9 (0.1)
-100°C					26.8 (0.3)	19.0 (0.2)	12.8 (0.1)	9.4 (0.2)	5.9 (0.1)
-125°C						18.5 (0.2)	12.5 (0.2)	9.1 (0.1)	5.8 (0.1)
-150°C							12.3 (0.2)	8.9 (0.1)	5.7 (0.1)
-175°C									5.5 (0.1)

NOTE: Standard Deviations are given in parentheses.

TABLE 12. AVERAGE V_{oc} (mV)

Spectrolab K6.5
N/P, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity 1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	505.6 (3.3)								
55°C	527.9 (3.4)	515.1 (3.4)	500.4 (3.5)						
25°C	590.5 (3.2)	579.3 (3.2)	564.2 (3.3)	549.3 (3.5)					
0°C	645.3 (3.0)	634.7 (2.7)	620.4 (2.9)	606.9 (3.1)	596.2 (3.4)				
-25°C	697.9 (2.6)	688.4 (2.4)	675.6 (2.7)	662.8 (2.7)	653.2 (3.1)	643.1 (3.5)			
-50°C			729.7 (2.2)	718.4 (2.7)	709.4 (2.9)	699.7 (3.7)	687.8 (4.4)	680.8 (5.3)	
-75°C				774.1 (2.6)	765.3 (3.1)	757.4 (3.6)	746.2 (5.4)	738.4 (7.2)	721.4 (13.2)
-100°C					820.7 (2.9)	813.3 (4.4)	802.3 (6.7)	793.7 (10.3)	773.8 (24.1)
-125°C						867.6 (5.5)	856.4 (10.0)	844.2 (20.6)	817.3 (45.5)
-150°C							908.9 (16.4)	893.9 (31.8)	862.2 (65.4)
-175°C									913.8 (67.3)

NOTE: *Standard Deviations are given in parentheses.*

TABLE 13. AVERAGE I_{mp} (mA)

Spectrolab K6.5
N/P, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	147.7 (1.5)								
55°C	149.6 (2.2)	96.4 (1.4)	59.9 (1.1)						
25°C	150.5 (1.8)	96.9 (1.0)	59.2 (0.9)	37.0 (0.5)					
0°C	149.8 (1.6)	96.3 (1.3)	58.9 (0.8)	36.5 (0.6)	25.5 (0.4)				
-25°C	147.6 (1.7)	95.3 (1.2)	58.1 (1.0)	36.0 (0.7)	25.1 (0.5)	17.7 (0.6)			
-50°C			57.7 (1.2)	36.3 (1.3)	24.6 (0.7)	17.4 (0.8)	11.8 (0.7)	8.5 (0.6)	
-75°C				35.5 (1.3)	24.0 (1.1)	17.0 (1.0)	11.5 (0.8)	8.2 (0.6)	5.1 (0.4)
-100°C					23.2 (1.3)	16.4 (1.1)	10.9 (0.8)	8.0 (0.7)	5.0 (0.4)
-125°C						16.0 (1.1)	10.7 (0.7)	7.7 (0.6)	4.8 (0.4)
-150°C							10.5 (0.7)	7.5 (0.5)	4.7 (0.4)
-175°C									4.6 (0.4)

NOTE: Standard Deviations are given in parentheses.

TABLE 14. AVERAGE V_{mp} (mV)

Spectrolab K6.5
N/P, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	388.1 (4.4)								
55°C	412.6 (4.7)	409.2 (4.8)	404.7 (5.5)						
25°C	476.3 (4.9)	475.0 (3.4)	470.3 (4.2)	458.4 (5.1)					
0°C	535.5 (5.2)	532.7 (3.2)	527.9 (2.8)	518.2 (5.5)	510.9 (4.7)				
-25°C	593.1 (3.2)	591.9 (5.2)	586.7 (3.3)	574.6 (5.8)	568.3 (8.6)	554.6 (8.8)			
-50°C			642.9 (3.9)	628.5 (3.7)	625.4 (10.4)	610.0 (11.5)	591.6 (17.3)	581.1 (23.5)	
-75°C				690.6 (8.3)	682.4 (10.6)	666.2 (16.9)	643.4 (27.9)	628.3 (42.7)	595.7 (57.5)
-100°C					739.6 (18.2)	715.9 (31.2)	690.6 (50.0)	669.5 (62.9)	634.3 (88.6)
-125°C						751.3 (55.4)	735.8 (66.2)	703.1 (91.1)	665.7 (105.8)
-150°C							759.9 (94.7)	734.6 (108.4)	696.2 (123.6)
-175°C									732.8 (121.8)

NOTE: Standard Deviations are given in parentheses.

TABLE 15. AVERAGE MP (mW)

Spectrolab K6.5
N/P, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	57.3 (0.8)								
55°C	61.7 (0.8)	39.5 (0.6)	24.2 (0.4)						
25°C	71.7 (0.8)	46.1 (0.7)	27.8 (0.3)	16.9 (0.3)					
0°C	80.2 (0.9)	51.2 (0.6)	31.1 (0.5)	18.9 (0.4)	13.0 (0.3)				
-25°C	87.5 (0.9)	56.4 (0.8)	34.1 (0.6)	20.7 (0.6)	14.3 (0.4)	9.9 (0.4)			
-50°C			37.0 (0.8)	22.8 (0.9)	15.4 (0.6)	10.6 (0.7)	7.0 (0.6)	5.0 (0.5)	
-75°C				24.5 (1.1)	16.4 (0.9)	11.3 (0.9)	7.4 (0.8)	5.2 (0.7)	3.0 (0.5)
-100°C					17.2 (1.3)	11.7 (1.3)	7.6 (1.1)	5.3 (0.9)	3.2 (0.6)
-125°C						12.0 (1.6)	7.9 (1.2)	5.5 (1.0)	3.2 (0.7)
-150°C							8.0 (1.4)	5.6 (1.1)	3.3 (0.7)
-175°C									3.4 (0.7)

NOTE: Standard Deviations are given in parentheses.

TABLE 16. AVERAGE EFFICIENCY (%)

Spectrolab K6.5
N/P, BSR/P^+ 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	10.6								
55°C	11.4	11.4	11.5						
25°C	13.2	13.3	13.2	12.5					
0°C	14.8	14.8	14.7	14.0	13.8				
-25°C	16.2	16.3	16.2	15.3	15.2	14.3			
-50°C			17.5	16.9	16.4	15.3	15.0	14.7	
-75°C				18.1	17.4	16.3	15.9	15.3	13.9
-100°C					18.3	16.9	16.3	15.5	14.8
-125°C						17.3	17.0	16.1	14.8
-150°C							17.2	16.4	15.2
-175°C									15.7

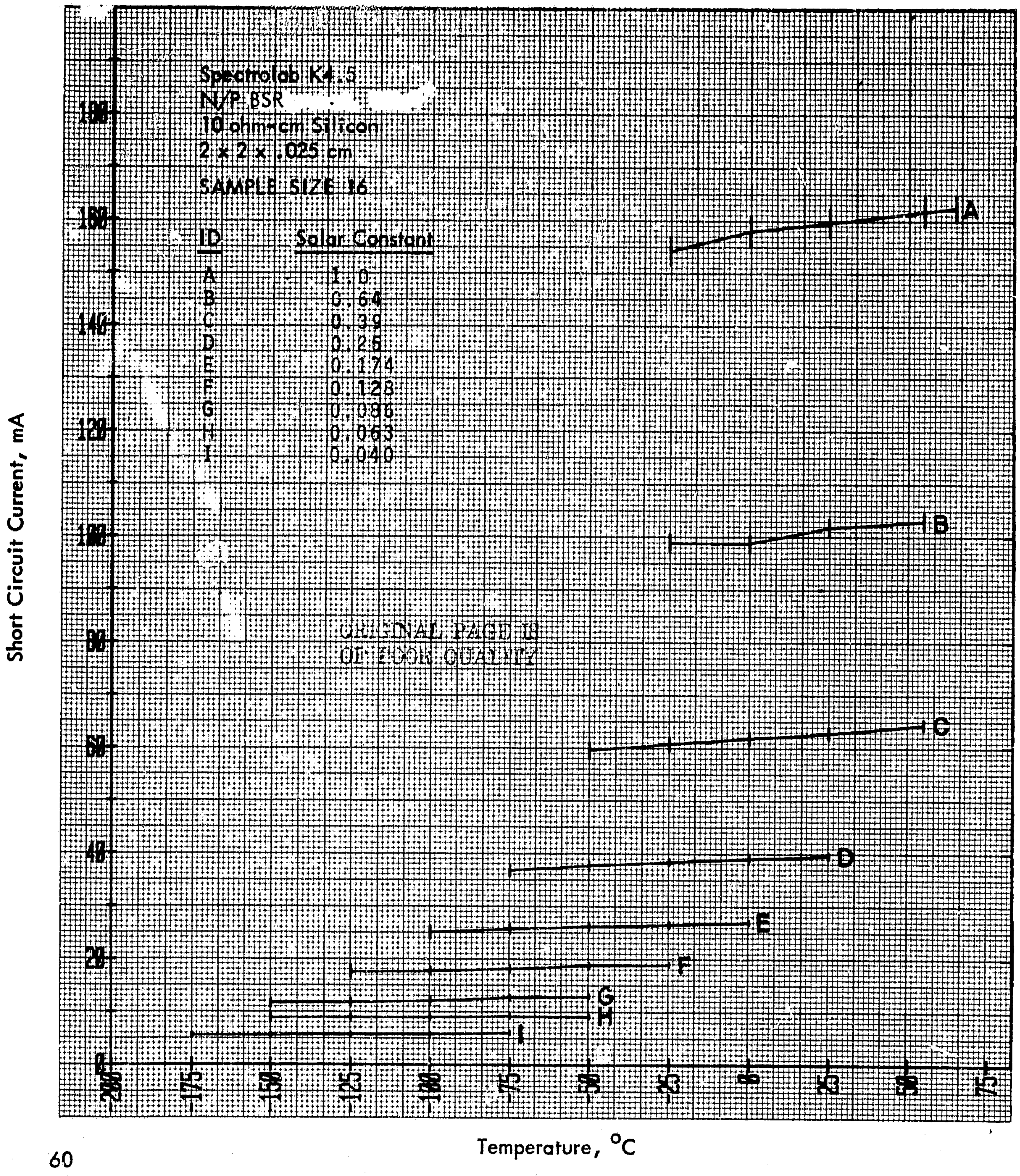

Figure 37. Average I_{sc} as a Function of Temperature

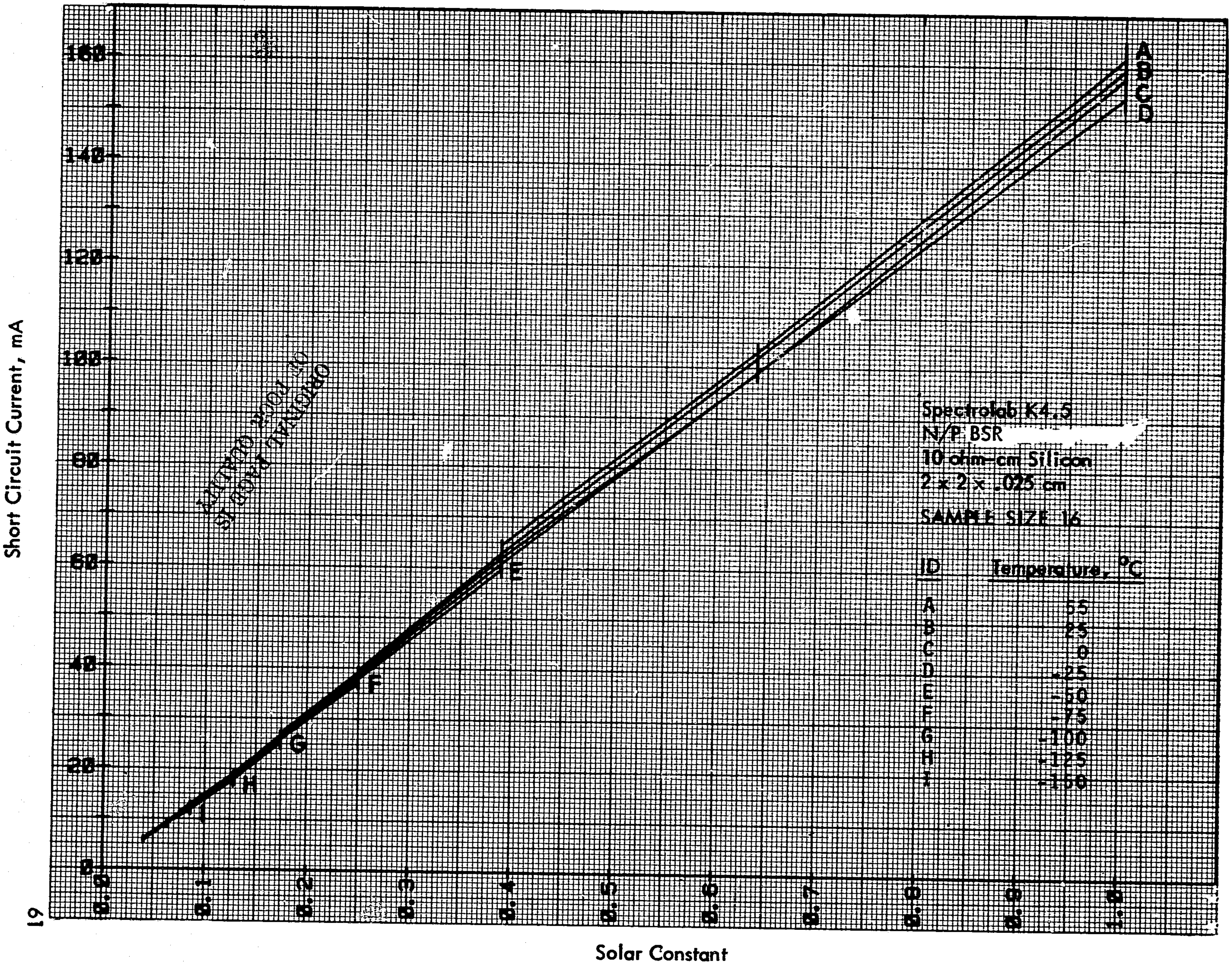

Figure 38. Average I_{sc} as a Function of Intensity

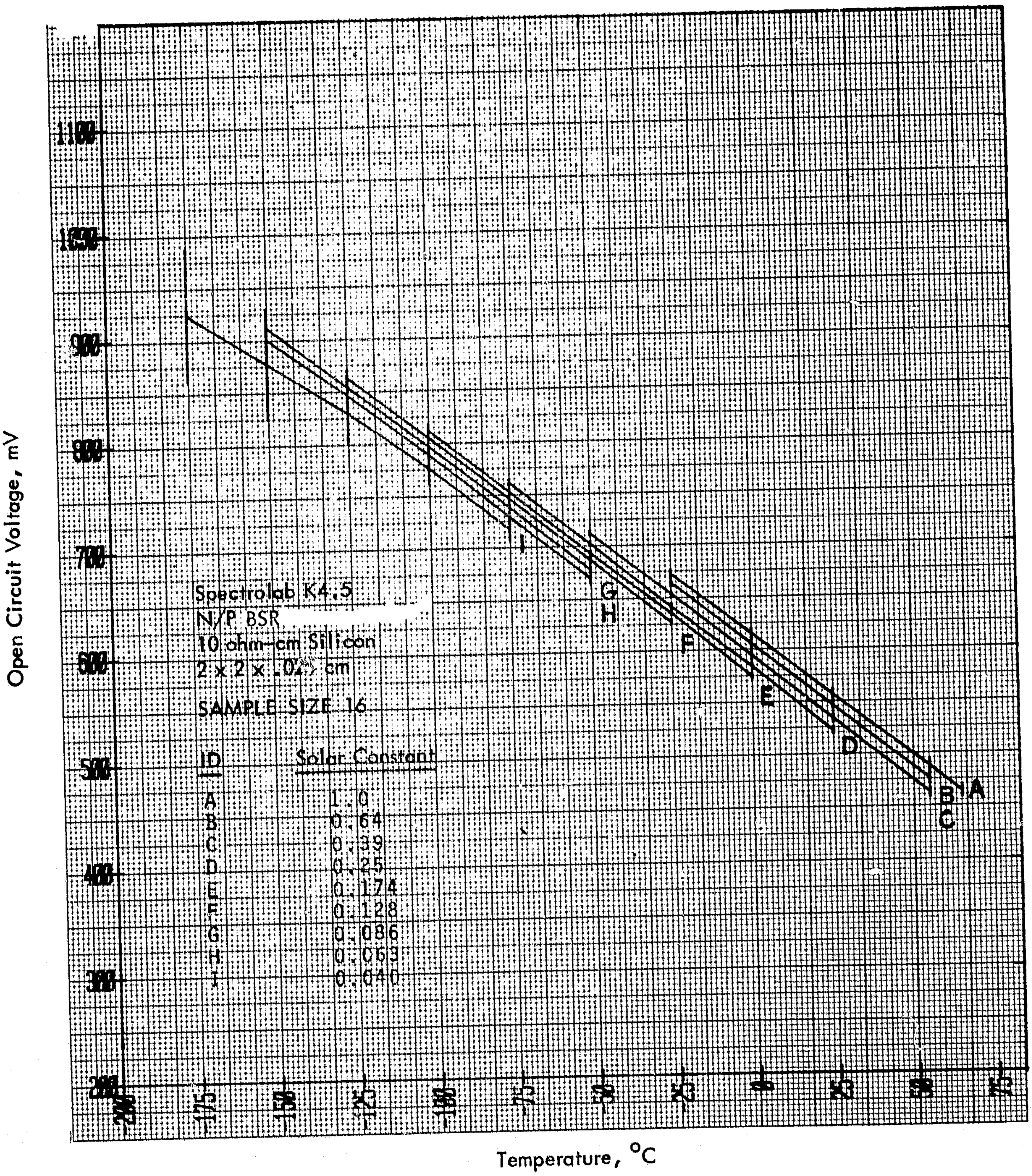

Figure 39. Average V_{oc} as a Function of Temperature

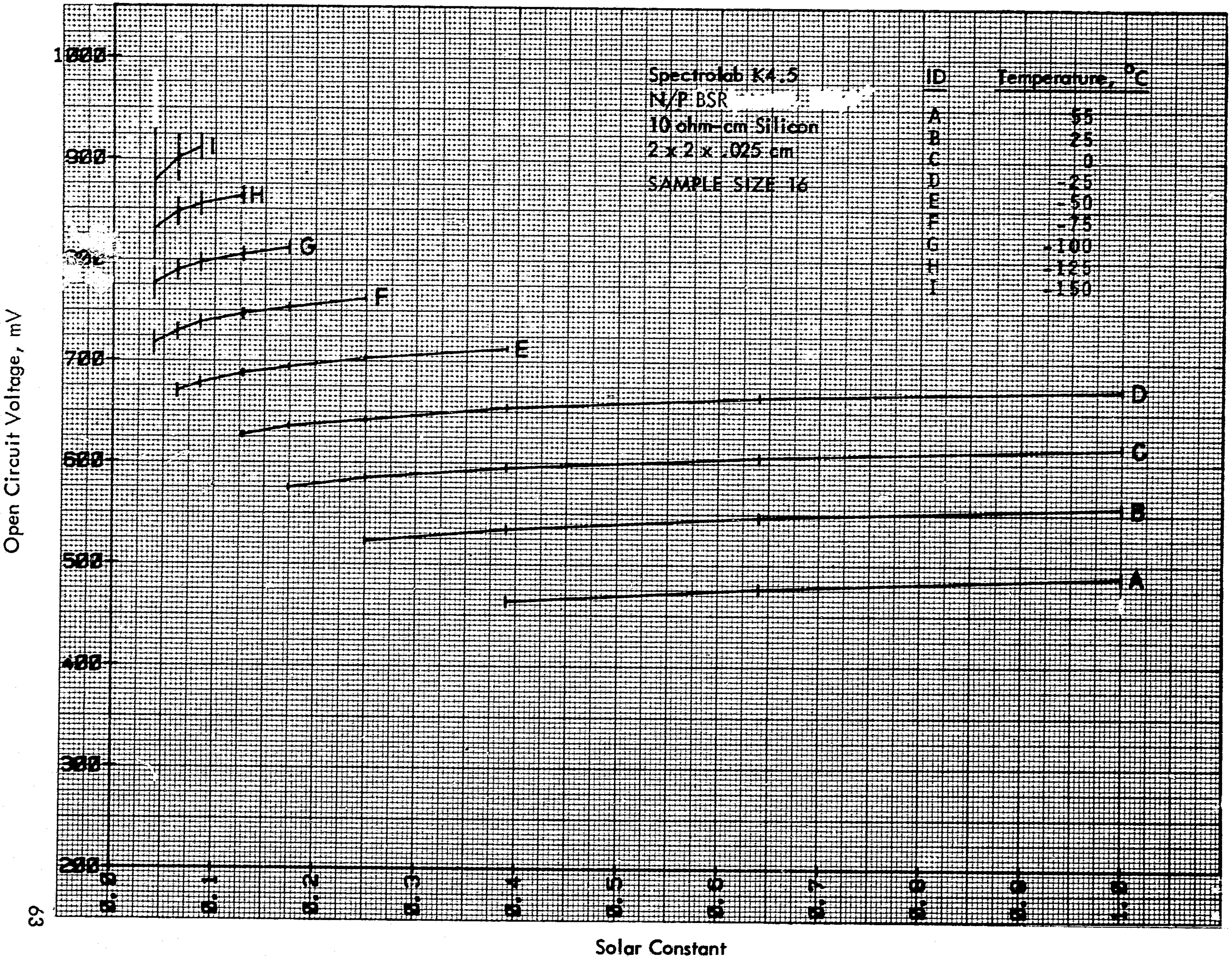

Figure 40. Average V_{oc} as a Function of Intensity

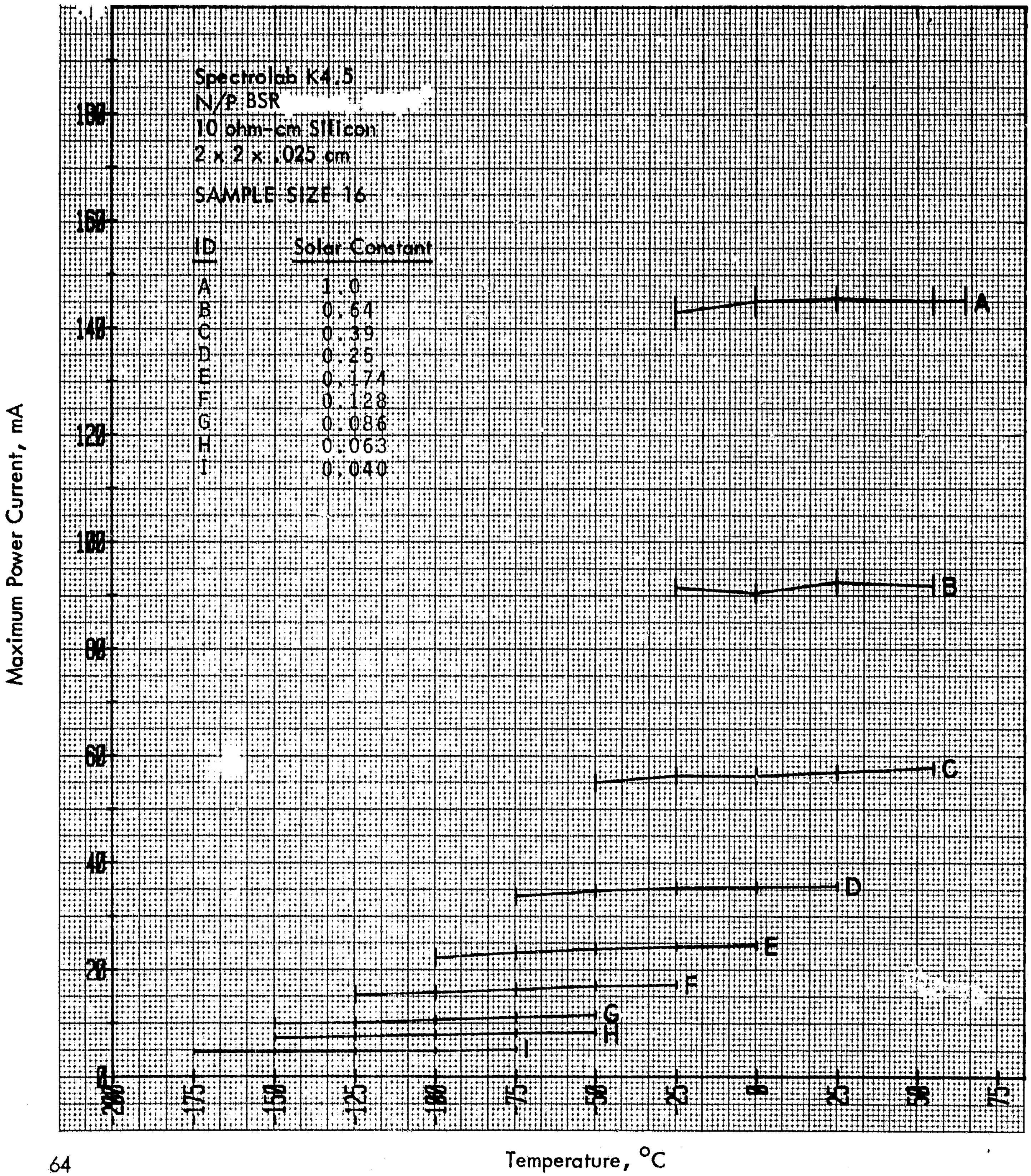

Figure 41. Average I_{mp} as a Function of Temperature

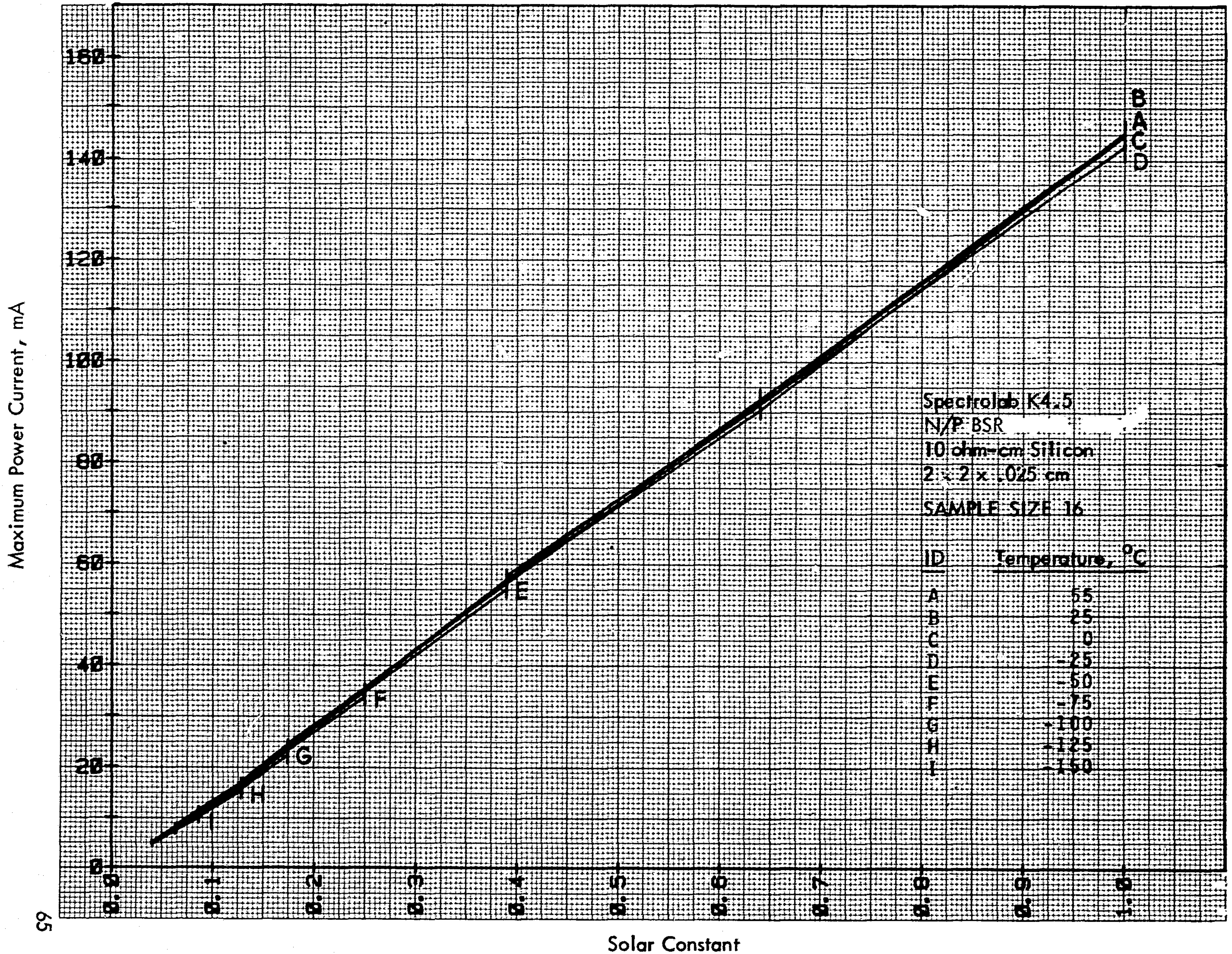

Figure 42. Average I_{mp} as a Function of Intensity

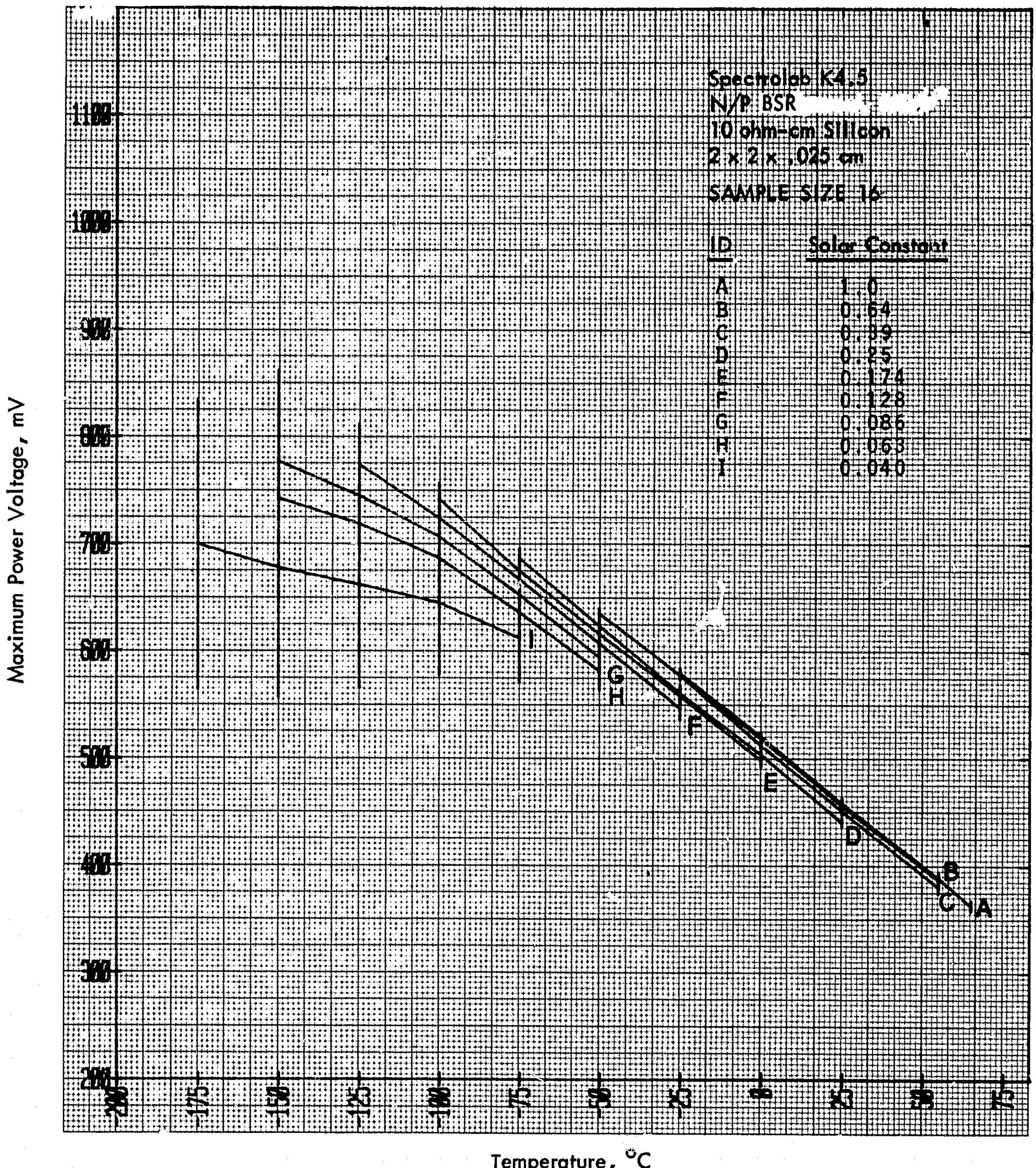

Figure 43. Average V_{mp} as a Function of Temperature

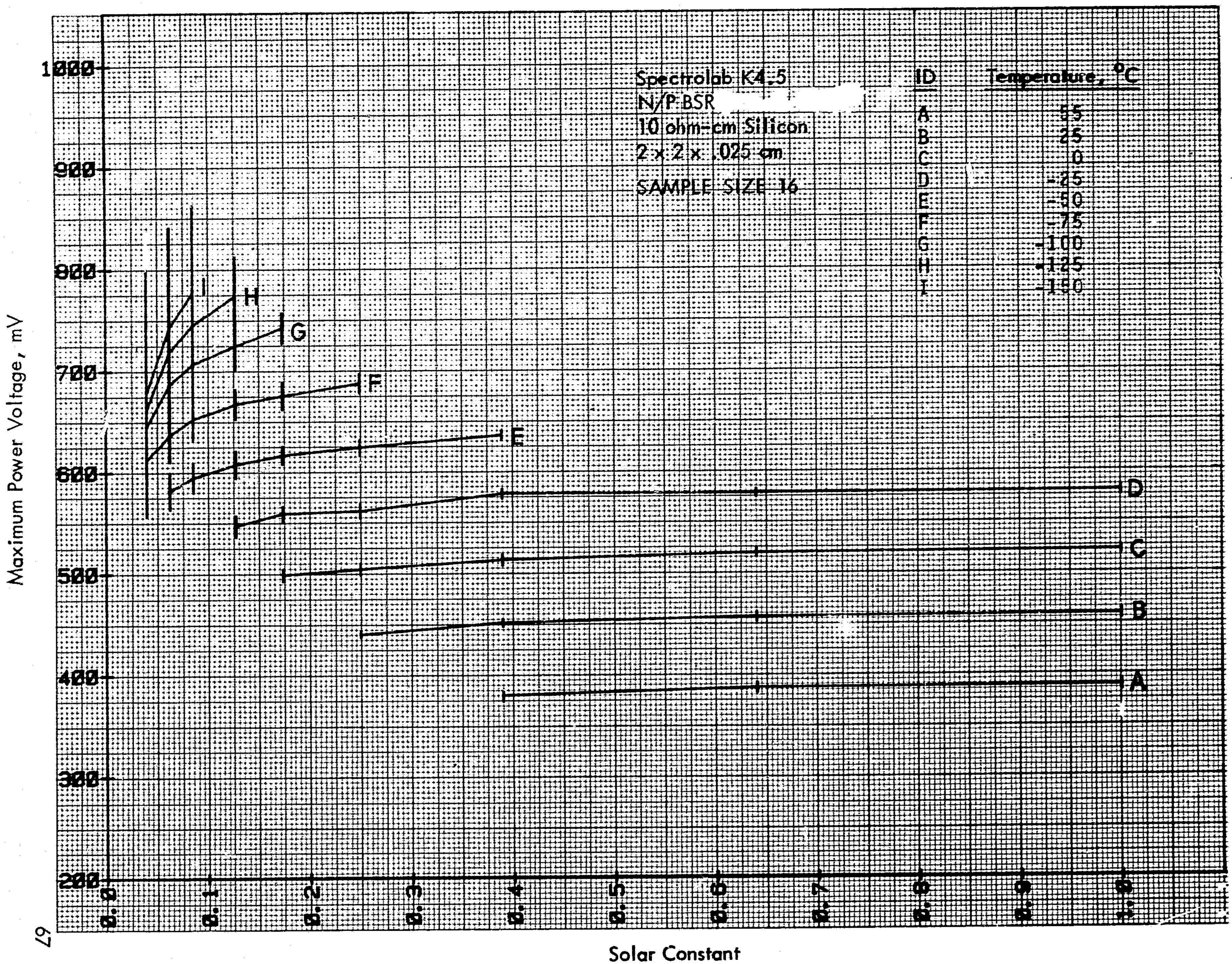

Figure 44. Average V_{mp} as a Function of Intensity

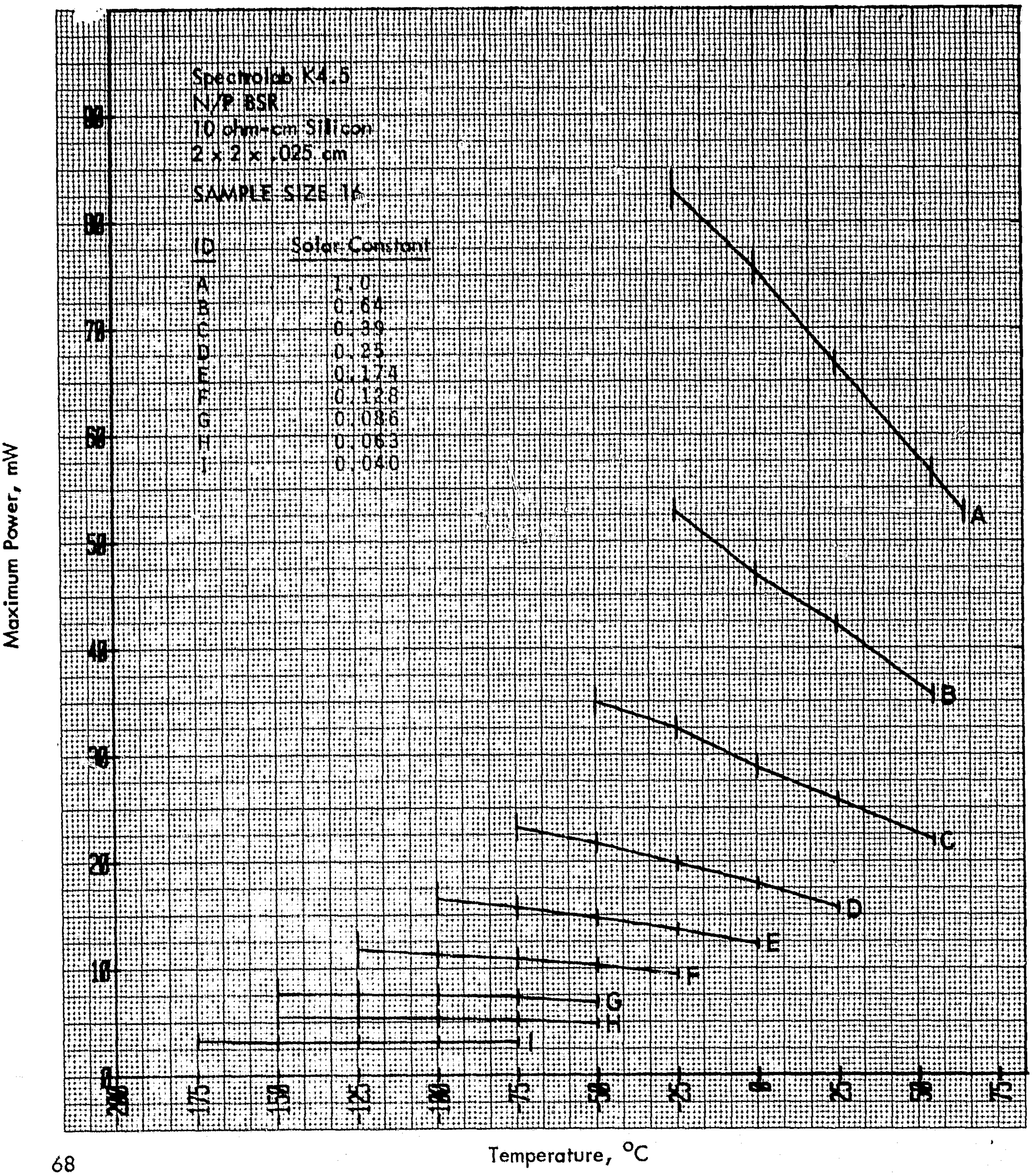

Figure 45. Average MP as a Function of Temperature

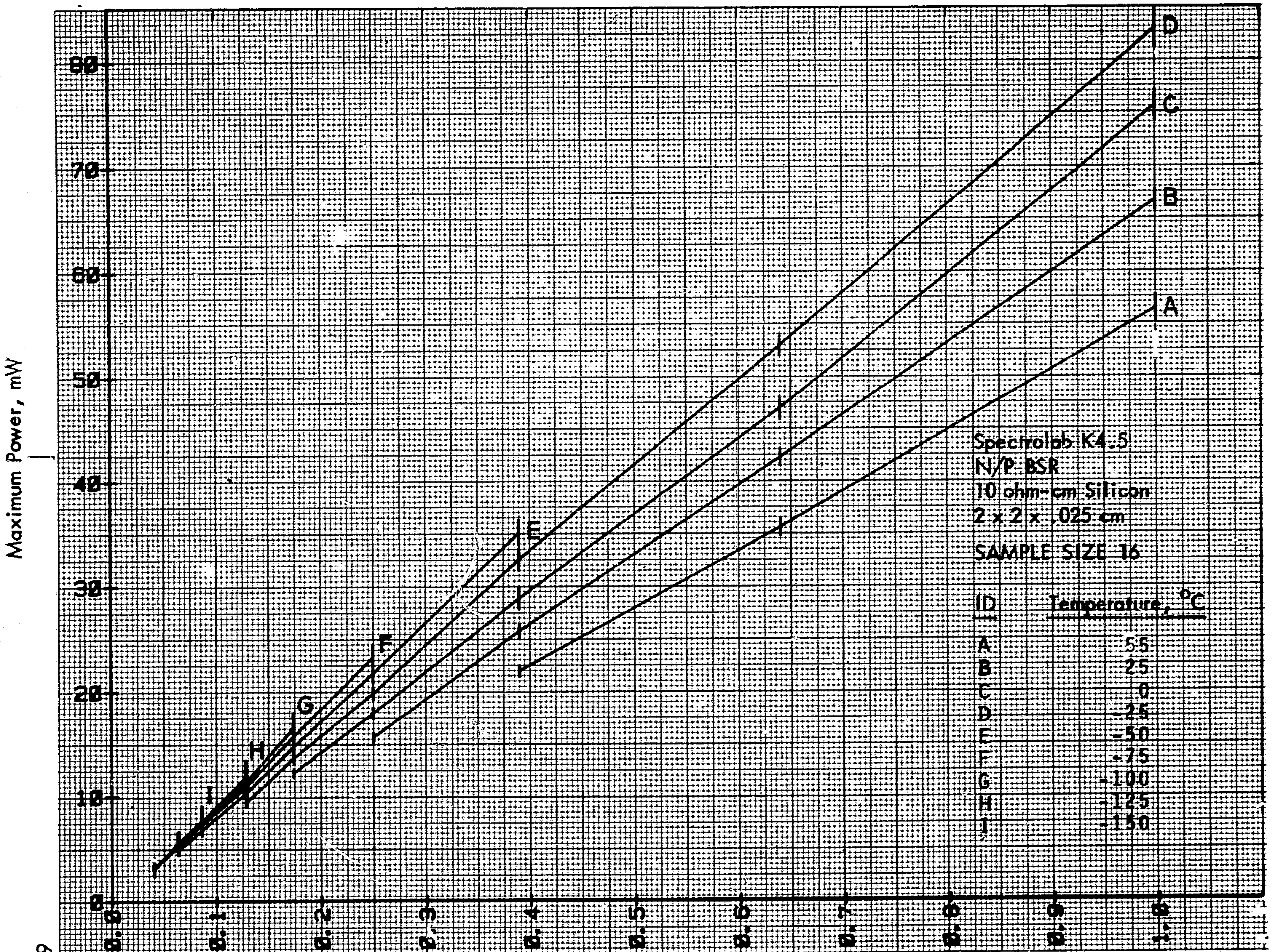

Figure 46. Average MP as a Function of Intensity

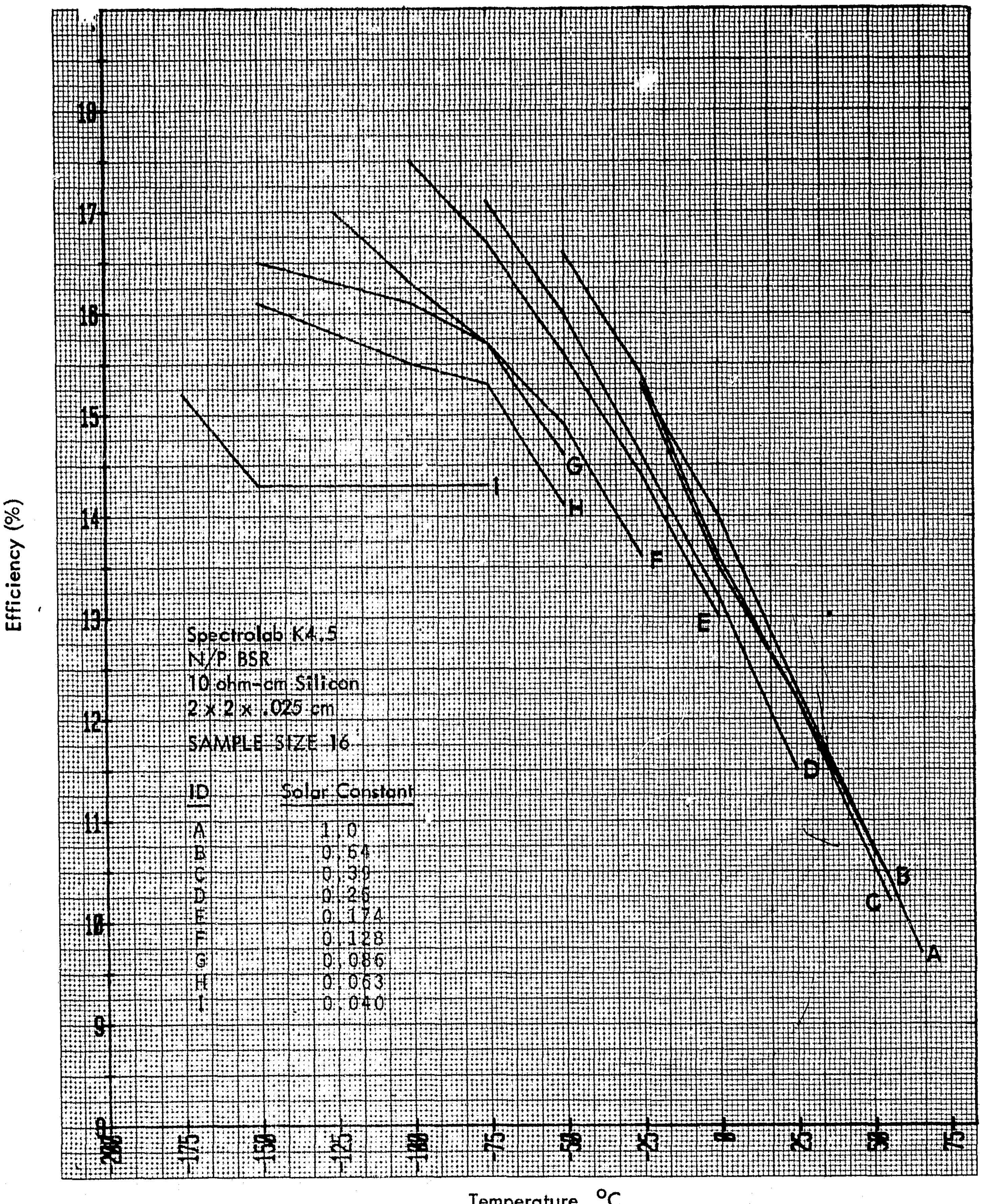

Figure 47. Average Efficiency as a Function of Temperature

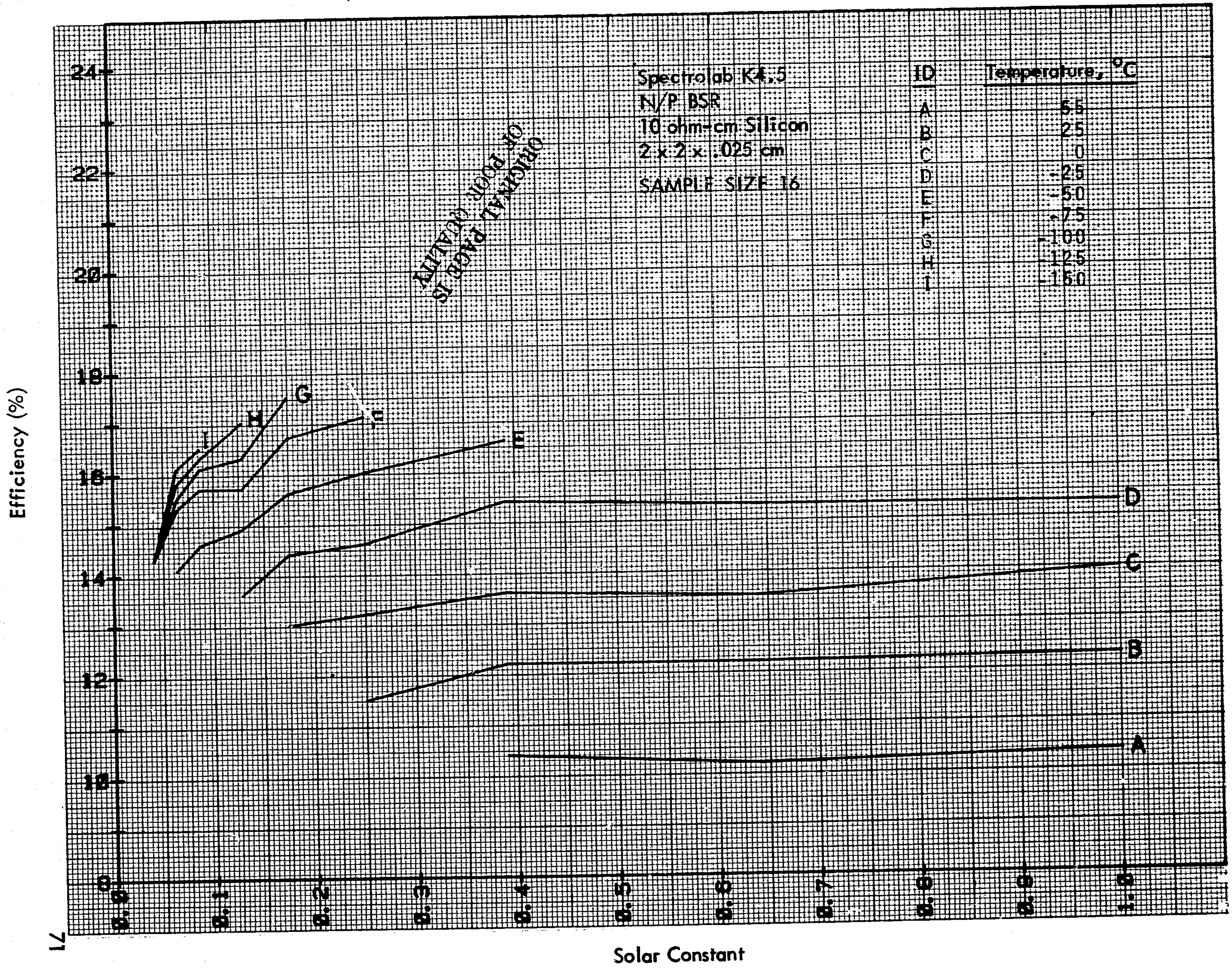

Figure 48. Average Efficiency as a Function of Intensity

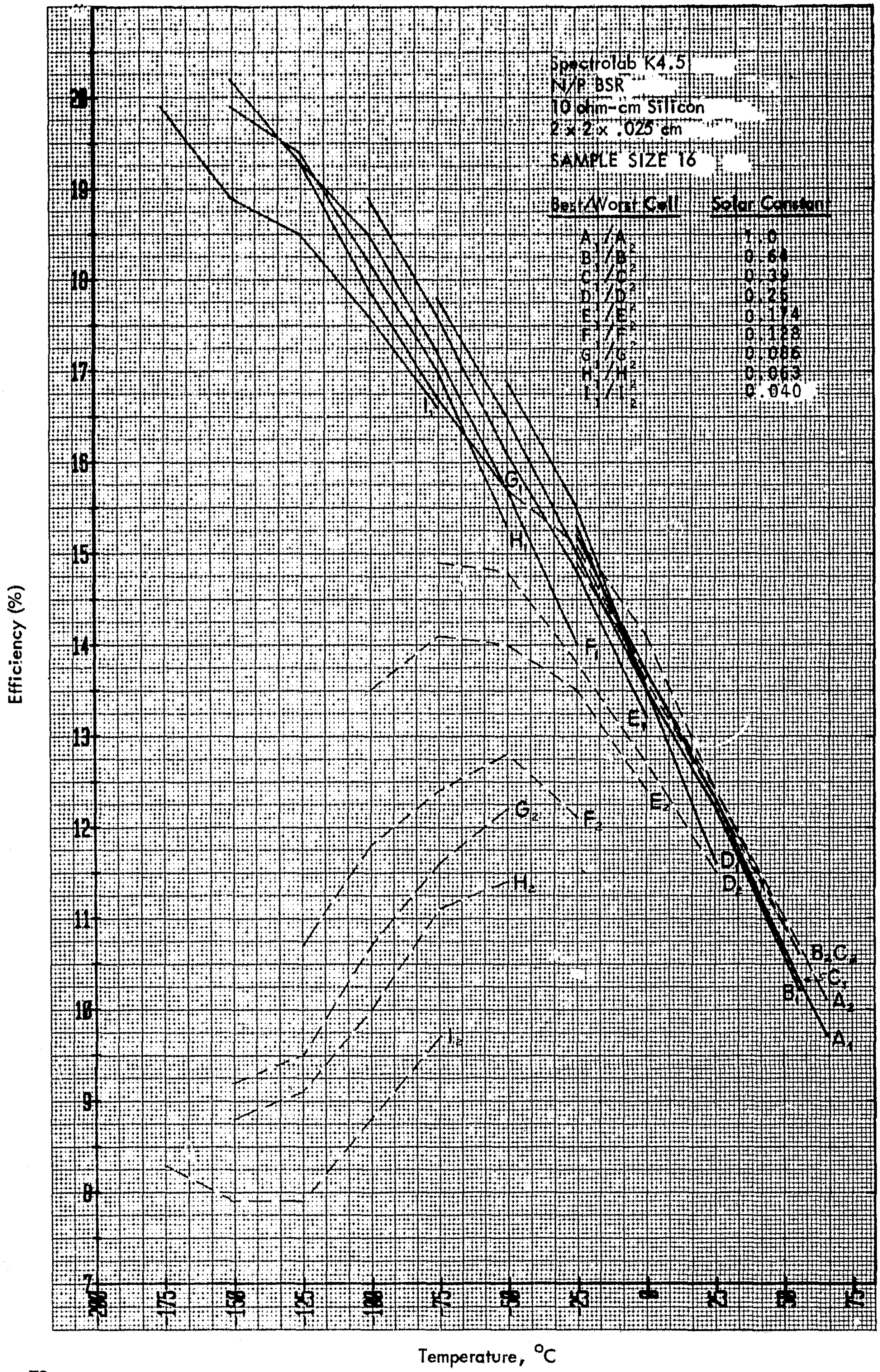

Figure 49. Efficiency of the Best/Worst Cells as a Function of Temperature

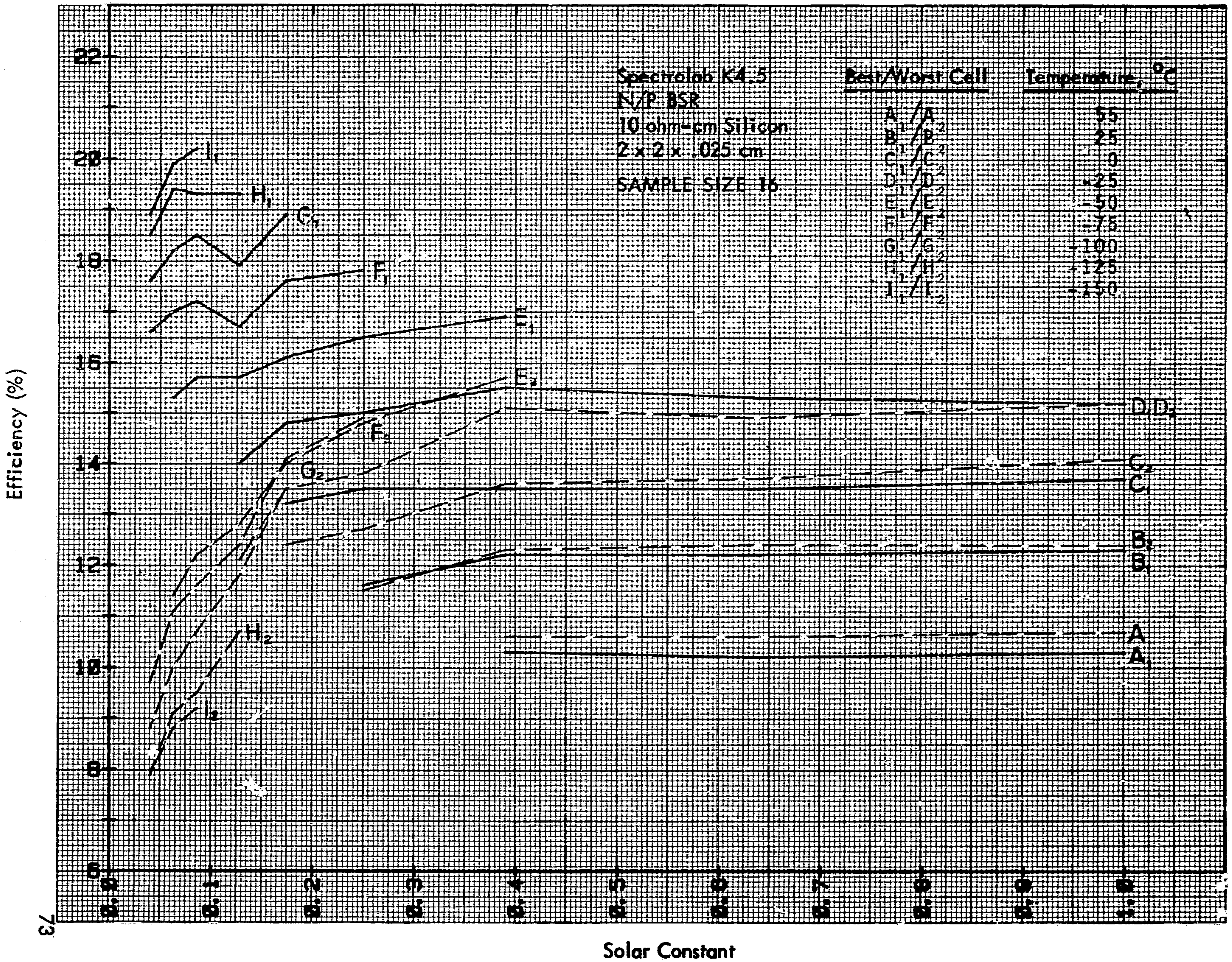

Figure 50. Efficiency of the Best/Worst Cells as a Function of Intensity

TABLE 17. AVERAGE I_{sc} (mA)

Spectrolab K4.5
N/P BSR 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity 1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	162.4 (2.3)								
55°C	161.7 (2.8)	103.0 (1.6)	64.4 (1.0)						
25°C	159.5 (2.6)	101.8 (1.6)	62.8 (1.1)	39.5 (0.6)					
0°C	157.9 (2.8)	98.8 (1.6)	61.9 (1.2)	39.0 (0.6)	26.9 (0.4)				
-25°C	154.1 (2.6)	98.9 (1.6)	60.8 (1.3)	38.4 (0.6)	26.5 (0.6)	18.9 (0.4)			
-50°C			59.6 (1.5)	37.7 (0.9)	26.2 (0.7)	18.8 (0.5)	12.9 (0.4)	9.1 (0.3)	
-75°C				36.8 (1.1)	25.7 (0.9)	18.2 (0.7)	12.7 (0.5)	9.2 (0.4)	6.0 (0.3)
-100°C					25.1 (1.2)	17.7 (0.9)	12.1 (0.7)	9.0 (0.5)	5.8 (0.3)
-125°C						17.6 (1.2)	11.8 (0.8)	9.0 (0.6)	5.7 (0.4)
-150°C							11.7 (0.9)	8.9 (0.7)	5.6 (0.4)
-175°C									5.6 (0.4)

NOTE: Standard Deviations are given in parentheses.

TABLE 18. AVERAGE V_{oc} (mV)

Spectrolab K4.5
N/P BSR 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity 1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	464.1 (5.8)								
55°C	488.2 (5.6)	475.8 (5.1)	462.8 (4.8)						
25°C	556.7 (4.9)	546.3 (4.5)	534.0 (4.0)	522.0 (3.3)					
0°C	615.3 (4.4)	605.4 (4.0)	594.5 (3.4)	584.3 (2.8)	574.6 (2.3)				
-25°C	672.5 (3.9)	664.3 (3.3)	653.8 (2.7)	641.4 (2.2)	635.3 (2.0)	626.5 (2.5)			
-50°C			712.1 (2.2)	702.5 (2.3)	693.5 (2.3)	687.1 (3.4)	677.6 (4.7)	669.6 (6.3)	
-75°C				761.4 (2.9)	752.8 (3.6)	746.4 (4.8)	738.2 (6.5)	729.1 (7.5)	717.3 (11.0)
-100°C					811.8 (5.6)	805.1 (6.6)	796.8 (8.5)	789.0 (9.5)	776.0 (15.6)
-125°C						862.7 (8.3)	854.3 (10.9)	846.2 (13.2)	829.3 (29.7)
-150°C							911.5 (12.4)	900.2 (23.3)	877.0 (52.3)
-175°C									924.1 (62.9)

NOTE: Standard Deviations are given in parentheses.

TABLE 19. AVERAGE I_{mp} (mA)

Spectrolab K4.5
N/P BSR 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	145.2 (2.5)								
55°C	145.1 (2.5)	91.8 (1.8)	57.7 (1.2)						
25°C	145.5 (2.2)	92.5 (2.1)	56.9 (1.3)	35.5 (0.7)					
0°C	145.0 (2.7)	90.4 (1.7)	56.2 (1.5)	35.4 (0.9)	24.5 (0.7)				
-25°C	142.9 (3.0)	91.5 (1.6)	56.3 (1.5)	35.3 (1.0)	24.3 (0.7)	17.1 (0.6)			
-50°C			55.0 (1.6)	34.7 (1.1)	23.8 (0.9)	16.9 (0.7)	11.5 (0.6)	8.3 (0.5)	
-75°C				33.7 (1.5)	23.2 (1.2)	16.3 (1.1)	11.1 (0.8)	8.1 (0.6)	5.0 (0.4)
-100°C					22.2 (1.6)	15.7 (1.2)	10.6 (0.8)	7.8 (0.7)	4.8 (0.4)
-125°C						15.3 (1.5)	10.1 (0.9)	7.5 (0.7)	4.7 (0.4)
-150°C							9.9 (0.9)	7.3 (0.6)	4.6 (0.4)
-175°C									4.6 (0.4)

NOTE: Standard Deviations are given in parentheses.

TABLE 20. AVERAGE V_{mp} (mV)

Spectrolab K4.5
N/P BSR 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity 1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	362.7 (4.9)								
55°C	388.4 (5.0)	386.4 (4.9)	379.6 (5.5)						
25°C	458.5 (4.8)	456.2 (4.6)	451.1 (3.7)	440.1 (3.0)					
0°C	521.0 (4.0)	518.8 (4.0)	512.8 (5.3)	504.1 (5.8)	498.6 (5.9)				
-25°C	580.0 (4.6)	578.0 (3.8)	578.2 (4.8)	567.1 (7.2)	558.8 (7.2)	546.8 (10.4)			
-50°C			635.6 (4.9)	624.1 (7.4)	616.6 (8.8)	607.8 (13.3)	594.9 (14.7)	581.9 (18.3)	
-75°C				687.1 (9.5)	675.4 (13.2)	667.4 (14.6)	653.0 (21.1)	636.6 (26.2)	612.2 (41.5)
-100°C					742.2 (15.1)	724.6 (23.7)	706.9 (39.5)	686.9 (42.5)	645.3 (67.9)
-125°C						774.2 (38.0)	745.4 (62.1)	719.2 (71.4)	662.3 (96.4)
-150°C							777.4 (85.1)	743.1 (98.0)	678.0 (121.0)
-175°C									699.9 (135.7)

NOTE: Standard Deviations are given in parentheses.

TABLE 21. AVERAGE MP (mW)

Spectrolab K4.5
N/P BSR 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	52.7 (1.0)								
55°C	56.4 (1.3)	35.5 (0.8)	21.9 (0.5)						
25°C	66.7 (1.0)	42.2 (0.8)	25.7 (0.6)	15.6 (0.4)					
0°C	75.6 (1.5)	46.9 (1.1)	28.8 (1.0)	17.9 (0.5)	12.2 (0.4)				
-25°C	82.9 (1.8)	52.9 (1.0)	32.5 (1.0)	19.8 (0.6)	13.6 (0.5)	9.4 (0.4)			
-50°C			35.0 (1.2)	21.7 (0.9)	14.7 (0.7)	10.3 (0.6)	6.8 (0.5)	4.8 (0.4)	
-75°C				23.2 (1.2)	15.7 (1.0)	10.9 (0.9)	7.3 (0.7)	5.2 (0.6)	3.1 (0.4)
-100°C					16.5 (1.4)	11.3 (1.2)	7.5 (0.9)	5.3 (0.8)	3.1 (0.5)
-125°C						11.8 (1.6)	7.6 (1.2)	5.4 (0.9)	3.1 (0.6)
-150°C							7.7 (1.4)	5.5 (1.1)	3.1 (0.7)
-175°C									3.3 (0.7)

NOTE: Standard Deviations are given in parentheses.

TABLE 22. AVERAGE EFFICIENCY (%)

Spectrolab K4.5
N/P BSR 10 ohm-cm Silicon
2 x 2 x .025 cm
Ti-Pd-Ag Contacts 24 Lines
Tantalum Oxide AR Coating
Ceria-Doped Microsheet Filter

SAMPLE SIZE 16

Temperature	Intensity								
	1.0	0.64	0.39	0.25	0.174	0.128	0.086	0.063	0.040
65°C	9.7								
55°C	10.4	10.2	10.4						
25°C	12.3	12.2	12.2	11.5					
0°C	14.0	13.5	13.6	13.2	13.0				
-25°C	15.3	15.3	15.4	14.6	14.4	13.6			
-50°C			16.6	16.0	15.6	14.9	14.6	14.1	
-75°C				17.1	16.7	15.7	15.7	15.3	14.3
-100°C					17.5	16.3	16.1	15.5	14.3
-125°C						17.0	16.3	15.8	14.3
-150°C							16.5	16.1	14.3
-175°C									15.2

REFERENCES

1. Payne, P.: Research and Development of Silicon Solar Cells for Low Solar Intensity and Low Temperature Applications. Final Report NAS2-5519, 1970.

2. Brandhorst, H., Jr., and Hart, R., Jr.: Effects of Decreasing Temperature and Illumination Intensity on Solar Cell Performance. NASA TMX-52756, 1970.

3. Downing, R. and Weiss, R.: Characterization of Solar Cells for Space Applications. JPL Publication 78-15, Vol. II, 1978.

4. Bartels, F., Ho, J., and Kirkpatrick, A.: Silicon Solar Cell Development for Low Temperature and Low Illumination Intensity Operation. Vol. I, Analysis Report, NAS2-5516, 1970.

5. Whitaker, A. F., Little, S. A., Smith, C. F., Jr., and Wooden, V. A.: Characterization of Three Types of Silicon Solar Cells for SEPS Deep Space Missions. Vol. I, NASA TM-78253, 1979.

6. Brandhorst, Henry W., Jr.: Introduction to Basic Solar Cell Measurements. Technical Report III-1, NASA CP-2010, ERDA/NASA 1022/76/8.

7. Whitaker, A. F., Little, S. A., and Wooden, V. A.: Characterization of Three Types of Silicon Solar Cells for SEPS Deep Space Missions. Vol. II, NASA TM-78272.

GLOSSARY

AU	Astronomical Unit
AM0	Air Mass Zero
BSR	Back Surface Reflector
I-V	Current-Voltage
I_{mp}	Maximum Power Current
I_{sc}	Short Circuit Current
K4.5	Refers to Spectrolab Designation for Their BSR 10 ohm-cm Cell
K6.5	Refers to Spectrolab Designation for Their BSR/P^+ 10 ohm-cm Cell
K7	Refers to Spectrolab Designation for Their Sculptured BSR/P^+ 10 ohm-cm Cell
LTLI	Low Temperature and Low Intensity
MP	Maximum Power
P^+	Back Surface Field
P/P_o	Ratio of Maximum Power to Maximum Power at 55°C
SEPS	Solar Electric Propulsion System
SC	Solar Constant
Sculptured	Refers to a Rough Silicon Front Surface which Provides a Lower Reflectance for the Cell
UV	Ultraviolet
V_{mp}	Maximum Power Voltage
V_{oc}	Open Circuit Voltage

APPROVAL

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

Volume III. Current-Voltage Characteristics of Spectrolab Sculptured BSR/P^+ (K7), BSR/P^+ (K6.5) and BSR (K4.5) Cells as a Function of Temperature and Intensity

By A. F. Whitaker, S. A. Little, V. A. Wooden,
D. E. Carter, B. E. Cothren, and C. A. Torstenson

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

R. J. Schwinghamer

R. J. SCHWINGHAMER
Director, Materials and Processes Laboratory

PRECEDING PAGE BLANK NOT FILMED