GROUP PROJECT

PHOTOVOLTAIC CHARACTERISTICS

By

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2.0 Introduction:

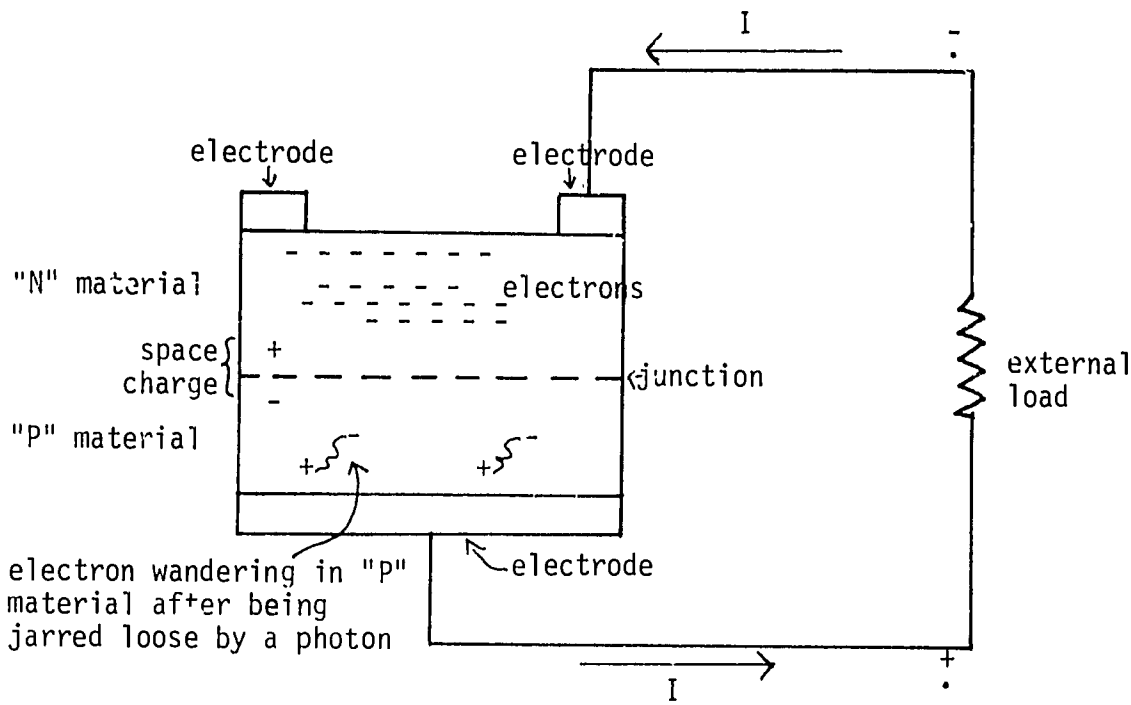
The first observation of the photovoltaic phenomenon was made by a french scientist, Edmund Becquerel, in 1839. Albert Einstein, in 1905, laid the theoretical foundation for understanding the PV effect. The first practical solar cell was fabricated by a group of scientist at the Bell Laboratory in the U.S. in 1954. Improvements since then have led to the present day solar cell devices.

2.1 Solar Cells Operation:

Solar cells convert sunlight directly into electricity by a process called the photovoltaic effect. The most common photovoltaic cells are composed of a thin wafer of single-crystal silicon (about 0.1 cm thick) that is brittle like glass and cracks easily when stressed. The active electricity generating region of a solar cell is only about 0.0001 cm thick; the remaining silicon provides structure.

Silicon solar cells are made by selectively adding minute amounts of impurities to purified silicon. The addition of boron, for example, produces p-type silicon semi-conductor material having an excess of positive charges, while the addition of phosphorous produces n-type silicon with an excess of negative charges. In the fabrication of a solar cell the surface of a p-type silicon wafer is treated with an n-type dopant and followed by a high temperature diffusion process. The result is the formation of a very thin layer of n-type semiconductor material at the surface of the water. Between the n-and p-type material, the "p-n junction," a small region with fixed opposite charges, is formed, creating a potential barrier. Conditions are now right for this compound semiconductor to interact with light. Light can be considered as consisting of tiny "packets" of energy (photons) having mass and travelling

at extremely high speed. Alternatively, light may be described in terms of wave behavior. In this instance wave length is a measure of the energy content; the shorter the wave length the higher the energy content, and vice versa. The solar irradiance received at the earth above the atmosphere is about 1.353 KW/m^2. At the surface of the earth on a clear day with the sun directly overhead, the solar irradiance is about 1 KW/m^2. Photons from the sunlight pass through the upper layer (the "n" material) into the thicker "p" material, striking the atoms, jarring electrons loose. The electrons wander througnout the "p" type material until they are either recaptured by a positively charged ion (an atom that lost an electron) or until they are captured in the "n" type material. The electrostatic charge near the junction between the "n" and "p" material is such that, once in the vicinity of the junction, an electron is drawn across the junction and is held in the "n" material. As a consequence, the "n" material becomes negatively charged and the "p' material, which loses the electrons, becomes positively charged. If the electrons are gathered by the electrodes on the top surface of the cell and connected to an electrode on the bottom surface, the electrons will flow through the external connection, providing electricity through the external circuit. This is shown in Fig. (1) overleaf.



(a) Some are recaptured by the positive charge (hole).

(b) Some wander across the junction and get trapped by the space-charge barrier across the junction.

FIG. 1

The junction in the solar cell is the same as the junction in a diode that might be used to pass electricity in one direction but not in the other. Approximately 0.4 volts is all that is required to drive the electrons from the "n" to the "p" region, across the electrostatic charge at the junction. This internal flow limits the voltage that can be attained with a solar cell. The resistance to electron flow from the "p" to the "n" material is much greater, being on the order of 50 volts. Only because the photons jar the electrons loose is there a flow in this direction under normal solar cell operation.

An equivalent circuit for a solar cell can be devised that incorporates its diode nature (Fig. 2). The photon bombardment acts as a current source, driving the electrical current from the "n" to the "p" material. The diode tends to short this current directly back to the "n" material. An additional shunt resistance characterizing primarily the losses near the edges and corners of the cell, adds to this shunting, although the shunt resistance is usually too small to be considered in most analyses. A series resistor characterizes the resistance of the cell material itself, the electrode resistance, and the constriction resistance encountered when the electrons travel along the sheet of "n" material into the small electrodes on the top surface.

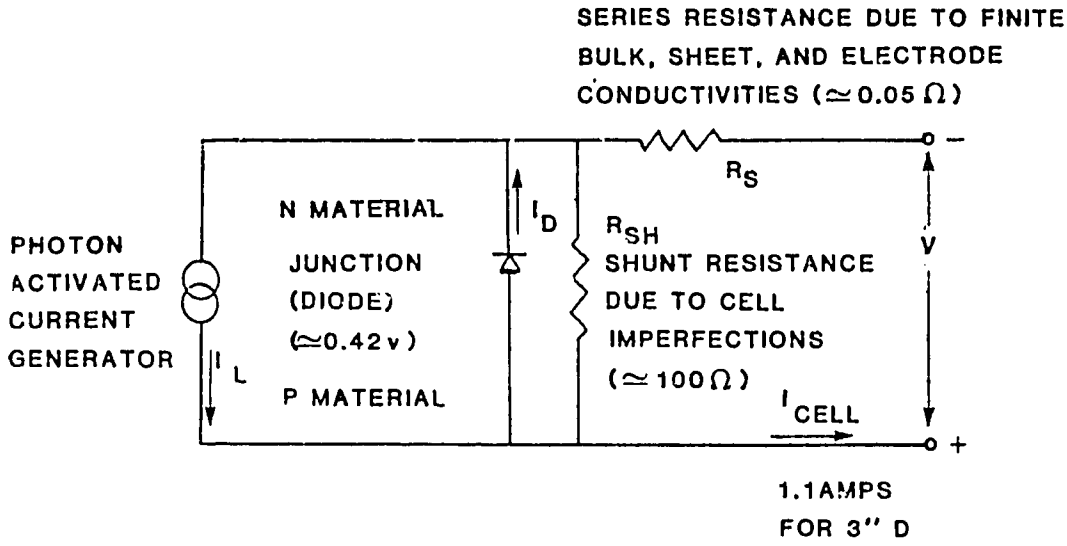


FIG. 2

Current density output of solar cell:

$$I_{Cell}/A = \overbrace{S\,s}^{I_L/A} + \overbrace{K_{dev}\,A_o T^3 e^{-E_{GO}/KT}\left[1 - e^{\frac{q}{KT}(V + R_s I_{Cell})}\right]}^{\text{Diode Current}} - \overbrace{\frac{V + R_S I_{Cell}}{R_{SH}}}^{\text{Shunt Current}}$$

- S — Insolation (kW/m^2)
- s — Current sensitivity (Amps/kW)
- K_{dev} — Device constant (1.55×10^{-39} Amps m^4/carrier^2 for typical cells)
- A_o — Material constant (1.54×10^{45} carriers$^2/m^6/{}^oK^3$ for silicon)
- T — Cell temperature (^oK)
- E_{GO} — Band gap at 0^oK ($E_{GO}/K = 14000^oK$ for silicon)
- K — Boltzman constant
- q — Electronic charge ($q/K = 11600^oK$)

EQUIVALENT CIRCUIT OF A SOLAR CELL

2.2 Efficiency of Photovoltaic Cells

Almost all photons with energy greater than 1.1 electron volts, corresponding to a wave length of 1.15 μm, will be absorbed in the cell and create an electron-hole pair. The excess energy of any photon with energy greater than 1.1 ev is converted to heat in the cell. Calculations indicate that at best a silicon solar cell can convert about 22 percent of terrestrial sunlight into electricity. Present commercial single crystal silicon solar cells for terrestrial use have efficiencies of 11 to 14 percent (at STC). The major causes and energy losses for such cells are displayed in the table below.

LOSS DUE TO	Energy % in sunlight not converted into electricity
Low energy photons not absorbed	23
Excess photon energy not utilized	33
Internal cell functional losses	29
Reflection, series resistance, contacts	1.5
Total	86.5

Project Objectives:

The project objective is to study the photovoltaic cell charateristics and as we have no separate cells we will do that by using photovoltaic modules and arrays and we will study the following:

1. Photovoltaic response to variable insolation.
2. Photovoltaic response to variable temperature.
3. Photovoltaic module and array overall efficiency.

Equipment:

1. Photovoltaic module, polycrystalline type, Solarex panel total area 175 in^2 ($.113m^2$). Peak power 9 watt.
2. Single crystal PV array consists of 7 modules connected in series total area 4000 $.5in^2$ ($2.581m^2$). Peak power 330 watts.
3. Variable low power resistance from 0 to 10,000 Ω .
4. Variable high power resistance from 0 to 200 Ω and open circuit.
5. Heating source and metal plates for heat uniform distribution.

Instruments:

- Epply pyranameter model 8-48, serial No. 20160 and 2053
- Photovoltaic sensor meter pyranameter
- Simpson type AVO - meter
- Digital linear thermocouple indicator.

Conditions:

1. Part of the experiments are out doors in the array and carried out between 9 am and 4 pm.
2. All the module studies were done indoors using two different sources of light.

Experiment (1): Variation of short circuit current (Isc) and open circuit voltage with Insolation.

Using the above specified module an electric circuit was connected as shown below.

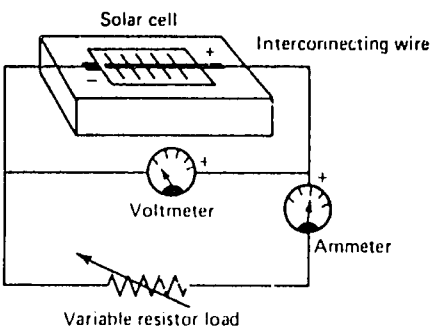


Figure 3 The solar-cell test setup.

In this experiment all factors were constant except for the insolation which was varied from 392 to 834 W/m^2. Both I_{SC} and Voc were recorded at each insolation. Tables No. (1) and (2) were obtained and a graph of I_{SC} and V_{OC} versus insolation was drawn in Fig. 4. The graph shows that the relationship between Isc and insolation is linear and directly proportional. As for V_{OC} it does not change very much with insolation and it maintains itself almost constant for a long period of insolation variation then it suddenly drops down to zero at zero insolation.

Experiment No. (2): Variable Insolation and Variable load.

This experiment was carried out with both array and module with one different condition. In the module case the temperature was held constant by outside means of cooling throughout the array test the experiment was out doors and it was impossible to maintain a constant temperature since it varies with insolation. But the day was relatively cool and the temperature was below 70° F. The array would represent a typical normal condition situation.

Using the same electric circuit in Fig. (3) both module and array experiments were carried out by varying current from open circuit to short circuit for each insolation setting. The insolation range was from 350 to 715 watt/m^2 for the module and from 410 to 962 for the array. The corresponding values of I and V for each load were recorded and tables from 7 to 14 were obtained.

Curves for power versus insolation and IV curves at different insolation were obtained. Fig. 6 to 9 show clearly that I_{SC} changes dramatically with insolation while V_{OC} maintains a constant value and concequently the power is changing being the product of voltage and current. This experiment adds another conclusion to exp. No. 1, that power also changes with insolation. If insolation is increased, power will increase and that the power max. point is variable during the day and tracking should be a design consideration.

Experiment 3 Temperature Effect:

This experiment was intended to show how temperature variation would affect a variable load powered by a photovoltaic. It was very difficult to carry out such an experiment with a wide range of temperature variation. To maintain a constant high or low temperature needs thermal insulation from the surounding which was not available in our situation, so the temperature range was limited to 74° to 125°F.

With the same module and the same circuit, the temperature of the module was set to 74°F, the insolation was set constant at 1024 watt/m^2, the resistance was varied from zero to open circuit and a series of coresponding values of current and voltage were recorded for each load. The same procedure was repeated for each temperature setting.

Tables 3 to 5a were obtained and curves for power versus voltage were drawn. Figs. (10) and (11) from the curves it is apparent that a rise in temperature of a photovaltaic cell causes a big drop in its voltage and a negligible change in current. Consequently output decreases with temperature rise.

It was also noticed that cell temperature is directly porportional to insolation intensity which means, on a very clear summer day the temperature degradation for cell will reach its maximum limit, while sun power is at its best and if the system is located in hot tropical zone where temperature degree may reach 100°F the lost power will reach 20% of the system output.

It was also noticed that there is always a difference between cell temperature and ambient temperature. This difference is due to the cell's dark color and which increases its absorptivity to light.

Efficiency Calculations:

The calculation to obtain efficiency of module and array at different conditions was made:

$$\text{Efficiency} = \frac{\text{Power output}}{\text{Power input}}$$

$$= \frac{\text{Max Power Current x Max Power Voltage}}{\text{Insolation x Array or Module Area}}$$

Also array and module fill factors were obtained.

$$\text{Fill Factor F.F.} = \frac{\text{Max power Current x Max for Voltage}}{\text{Short Circuit Current x Open Circuit Voltage}}$$

Table (3a) shows module efficiency variation with insolation and temperature. Curves produced from these results show that efficiency changes slightly with insolation and this change is directly proportional to insolation intensity. The other curve shows that temperature effects on cell efficiency is greater and the change between them is inversely proportional and is mainly due to voltage variation which came to be 49 mV/$^{\circ}$F/module. A typical coefficient of temperature effect is 2mv/°C/cell for silicon.

Table (4a) shows array efficiency variation with insolation and, as we mentioned before, temperature effect could not be assessed in the array. The resulting curve shows that efficiency variation is very minor with insolation change and that cell efficiency does not change very much with insolation drop, which is very much in favor of solar cell as a device dealing with variable source of energy.

Conclusion:

The maximum efficiency reached by the module which is a polycrystalline type was 4.4% and the condition was 1024 watt/m^2, 74° F (23.2° C) and output power of 5.]3 watt. The conditions are very near to the normal operating conditions (NOC) which is 20° C and 1000 watt/m^2, at which module output should be 9 watts. It is obvious that the efficiency is very low, but that could be justified by the difference in light source spectrum. We know that pv cells are sensitive to certain types of photons, and we are not sure whether the light spectrum of our source is typical or different from sunlight spectrum, but as we have no device to detect that, this remains undeterimed.

As for the array, the maximum efficiency was 9% at 962 watt/m^2 at approximately 70° F (21° C). The array as mentioned before is a single crystal type and that could justify the efficiency difference between array and module.

7% efficiency is a good result for the array under consideration because the electrodes of this array on the top side are suffering from corrosion and had slightly deteriorated.

TABLE 1

* Change of the open circuit voltage with Insolation.

S (W/m^2)	Vo.c (volt)
391.	13.6
428.	13.9
464.	14.1
503.	14.4
542.	14.7
577.	14.9
588.	15.0
607.	15.1
626.	15.2
710.	15.4
834.	15.5

TABLE 2

* Change of the short circuit current with insolation

S (W/m^2)	Is.c (ampere)
350.	0.109
381.	0.119
415.	0.129
443.	0.141
533.	0.158
715.	0.219

MODULE EFFICIENCY TABLE 3a

Insolation Watt/m 2	Power Input watt	Power output-watt	Efficiency %	Fill Factor
	80.79			
715		2-385	2.95	.666
531.35	60.04	1.75	2.91	.667
415.4	46.9	1.38	2.94	.601
350	39.54	1.05	2.65	.657

INSOLATION 1024 Watt/m 2

Temp °F	Power Input watt	Power output-watt	%	Fill Factor
74	115.7	5.13	4.4	.734
94	115.7	4.83	4.17	.747
110	115.7	4.55	3.93	.722
125	115.7	4.12	3.56	.685

TABLE 4

V/I characteristic of the pv module at temp. = 94°F

Temp = 94°F			
R (Ω)	V (volt)	I (Ampere)	P= VxI (watt)
9999	16.0	0.000	0.000
2999	16.0	0.005	0.080
999	16.0	0.016	0.256
699	16.0	0.022	0.352
499	16.0	0.031	0.496
299	15.8	0.053	0.837
99	15.5	0.156	2.418
79	15.2	0.193	2.934
59	14.8	0.250	3.700
39	13.5	0.364	4.914
19	7.5	0.394	2.955
9	3.8	0.399	1.516
0	0.0	0.404	0.000

ARRAY EFFICIENCY (4a)

Insolation Watt/m 2	Power Input watt	Power output-watt	%	F.F.
962	2482.9	224	9	.64
804	2075	185	8.9	.70
678	1749.9	155	8.8	.77
401	1058.2	92	8.78	.74

TABLE 5

V/I characteristic of the pv module at temp. = 110°F

Temp = 110°F			
R (Ω)	V (volt)	I (Ampere)	P= VxI (watt)
9999	15.4	0.000	0.000
2999	15.4	0.005	0.077
999	15.4	0.015	0.231
699	15.4	0.022	0.339
499	15.4	0.030	0.462
299	15.2	0.050	0.760
99	14.8	0.148	2.190
79	14.6	0.184	2.686
59	14.2	0.239	3.394
39	13.5	0.334	4.509
19	7.6	0.396	3.009
9	3.8	0.402	1.528
0	0.0	0.409	0.000

TABLE 7

V/I characteristic of the module at 350 W/m^2

S = 350 W/m^2 = 110.862 $BTU/hr\ ft^2$			
R (Ω)	V (volt)	I (Ampere)	P= VxI (watt)
9999	15.1	0.00	0.00
7999	15.0	0.001	0.015
999	14.8	0.014	0.207
599	14.5	0.024	0.348
399	14.3	0.035	0.501
299	14.0	0.046	0.644
199	13.2	0.066	0.871
99	9.5	0.097	0.922
79	7.8	0.099	0.772
69	6.7	0.100	0.670
59	6.0	0.102	0.612
49	5.0	0.103	0.515
39	4.0	0.103	0.412
29	3.0	0.104	0.312
19	2.0	0.104	0.208
9	1.0	0.105	0.105
8	0.8	0.106	0.085
7	0.7	0.106	0.074
5	0.5	0.106	0.053
4	0.4	0.106	0.042
3	0.3	0.106	0.032
0	0.0	0.106	0.000

TABLE 8

V/I characteristic of the pv module at insolation = 415 W/m^2

S = 415.4 W/m^2 = 131.678 $BTU/hr\ ft^2$			
R (Ω)	V (volt)	I (Ampere)	P= VxI (watt)
9999	15.3	0.00	0.000
999	15.1	0.015	0.227
899	15.0	0.016	0.240
699	14.9	0.021	0.313
399	14.7	0.036	0.529
299	14.5	0.048	0.696
199	14.0	0.070	0.980
99	11.5	0.117	1.346
89	10.7	0.120	1.284
79	9.7	0.124	1.203
69	8.7	0.126	1.096
59	7.5	0.128	0.960
49	6.3	0.129	0.813
39	5.1	0.130	0.663
29	3.8	0.132	0.502
19	2.5	0.134	0.335
9	1.2	0.135	0.162
8	1.1	0.136	0.150
0	0.0	0.136	0.000

TABLE 9

V/I characteristic of the pv module at insolation = 530 W/m^2

S = 531.354 W/m 2 = 168.438 BTU/hr ft 2			
R (Ω)	V (volt)	I (Ampere)	P= VxI (watt)
9999	15.9	0.000	0.000
999	15.6	0.015	0.234
899	15.5	0.017	0.264
699	15.4	0.022	0.339
399	15.2	0.038	0.578
299	15.1	0.050	0.755
199	14.7	0.074	1.088
99	12.9	0.136	1.754
89	12.2	0.138	1.684
79	11.2	0.143	1.602
69	10.2	0.148	1.510
59	9.0	0.153	1.377
49	7.6	0.156	1.186
39	6.1	0.158	0.964
29	4.6	0.160	0.736
19	3.6	0.162	0.583
9	1.5	0.164	0.246
8	1.3	0.164	0.213
0	0.0	0.165	0.000

TABLE 10

V/I characteristic of the pv module at insolation = 715 W/m^2

S = 715 W/m^2 = 226.633 BTU/hr ft^2			
R (Ω)	V (volt)	I (Ampere)	P= VxI (watt)
9999	16.2	0.000	0.000
999	16.0	0.015	0.240
899	15.9	0.018	0.286
699	15.8	0.022	01348
399	15.7	0.039	0.612
299	15.6	0.052	0.811
199	15.4	0.078	1.201
99	14.3	0.147	2.102
89	14.2	0.160	2.272
79	13.6	0.173	2.353
69	12.9	0.187	2,412
59	11.6	0.197	2.285
49	9.9	0.204	2.020
39	8.1	0.210	1.701
29	6.1	0.213	1.299
19	4.1	0.215	0.882
9	2.0	0.219	0.438
8	1.7	0.219	0.372
0	0.0	0.221s	0.000

TABLE 11

V/I characteristic of the pv panel at insolation = 410 W/m^2

S = 410 W/m^2 = 130 BTU/hr ft^2		
V (volt)	I (Ampere)	P= VxI (watt)
122	0.670	81.74
94.5	0.870	82.215
60.5	0.950	57.475
40.0	0.970	38.8
30.5	0.970	29.585
23	0.970	22.31
12	0.970	11.64
4	0.970	3.88
3	0.970	2.91
0	0.970	0.00

TABLE 12

V/I characteristic of the pv panel at insolation = 678 W/m^2

S = 678.239 W/m^2 = 215 $BTU/hr\ ft^2$

V (volt)	I (Ampere)	P= VxI (watt)
133	0.7	93.1
128	0.98	125.44
117	1.30	152.1
102	1.45	147.9
97	1.49	144.53
80	1.51	120.80
64	1.55	99.20
52	1.57	81.64
45	1.57	70.65
35	1.60	56.00
28	1.60	44.80
22	1.60	35.20
13	1.60	20.80
7	1.60	11.20
4	1.60	6.40
0	1.60	0.00

TABLE 13

V/I characteristic of the pv panel at insolation = 804 W/m^2

S = 804.423 W/m^2 = 255 $BTU/hr\ ft^2$

V (volt)	I (Ampere)	P= VxI (watt)
133	0.72	95.76
128	1.20	153.60
117	1.55	181.35
102	1.75	178.50
97	1.80	174.60
80	1.87	149.60
64	1.90	121.60
52	1.90	98.80
45	1.90	85.50
35	1.94	67.90
28	1.95	54.60
22	1.95	42.90
13	1.95	25.35
7	1.95	13.65
4	1.97	7.88
0	1.97	0.00

TABLE 14

V/I characteristic of the pv panel at insolation = 962 W/m^2

S = 962.153 W/m^2 = 305 $BTU/hr\ ft^2$

V (volt)	I (Ampere)	P= VxI (watt)
133	0.74	98.42
128	1.30	166.40
117	1.80	210.60
102	2.20	224.40
97	2.30	223.10
80	2.45	196.00
64	2.50	160.00
52	2.60	135.20
45	2.60	117.00
35	2.60	91.00
28	2.60	72.80
22	2.60	57.20
13	2.60	33.80
7	2.60	18.20
4	2.63	10.52
0	2.64	0.00

Fig "4"

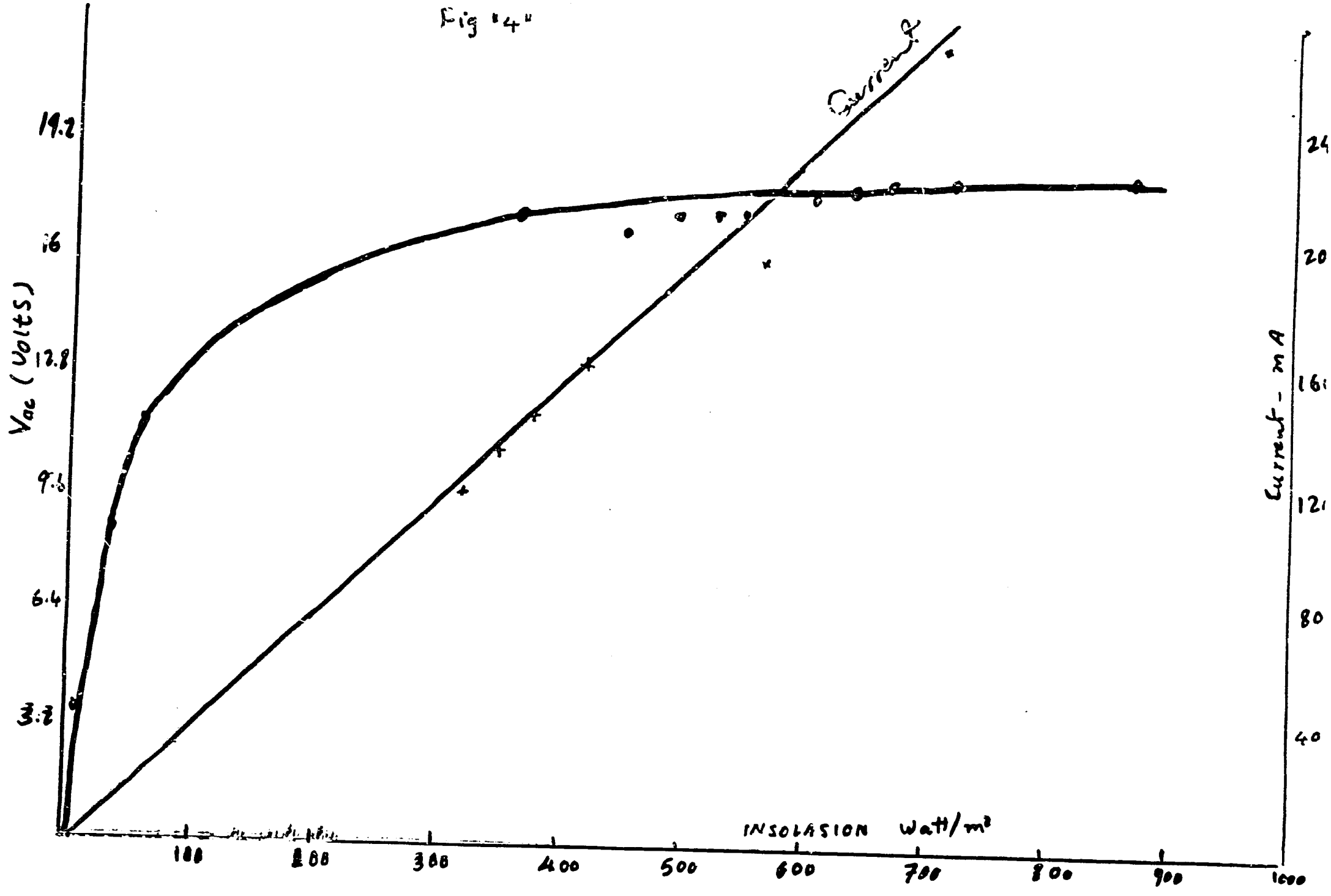

Current
19.2
16
12.8
9.6
6.4
3.2
V_{oc} (Volts)
24
20
16
12
80
40
Current - mA
100
200
300
400
500
600
700
800
900
1000
INSOLASION Watt/m²

Fig "6"

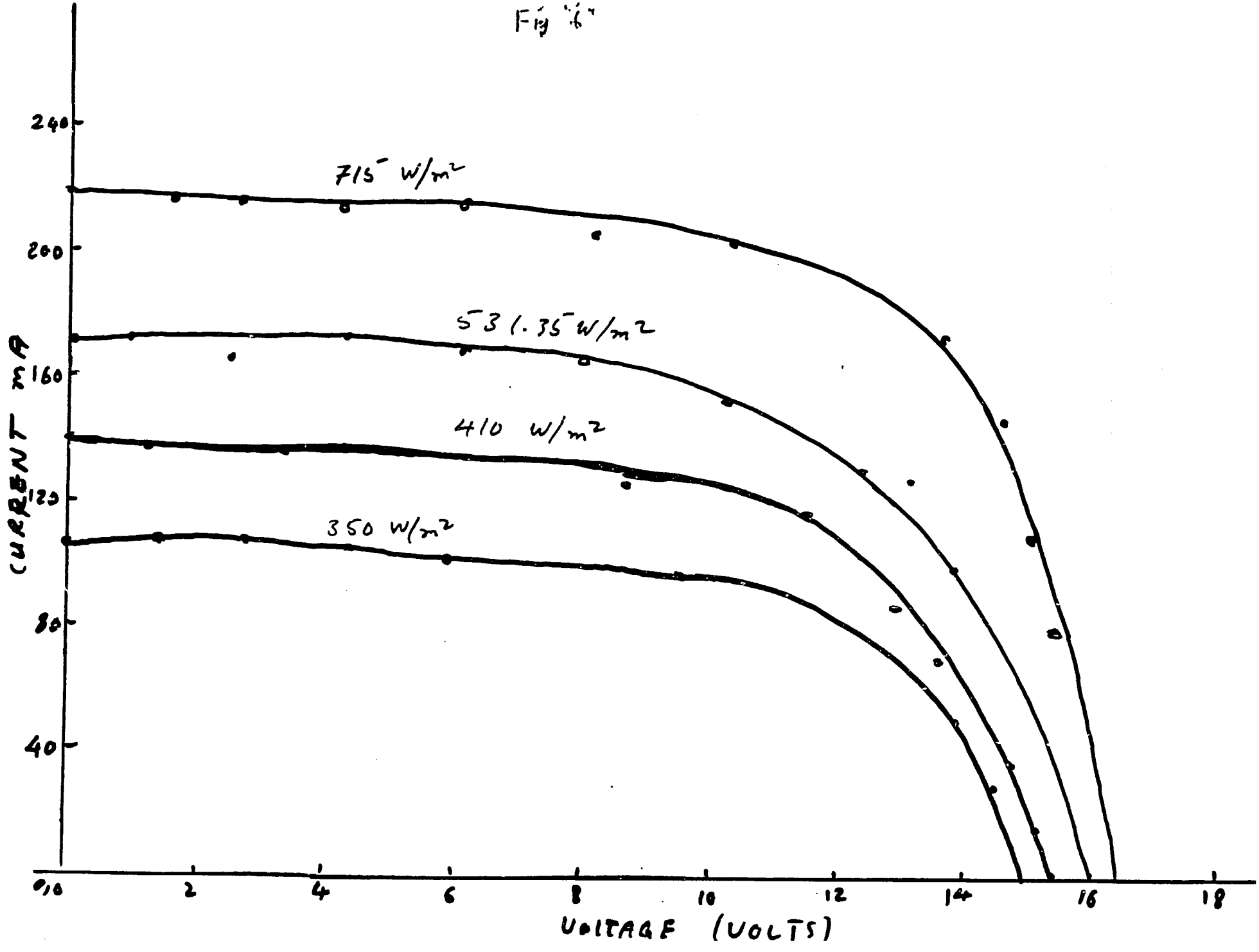

715 W/m²
531.35 W/m²
410 W/m²
350 W/m²
CURRENT mA
240
200
160
120
80
40
0.0
2
4
6
8
10
12
14
16
18
VOLTAGE (VOLTS)

Fig '7'

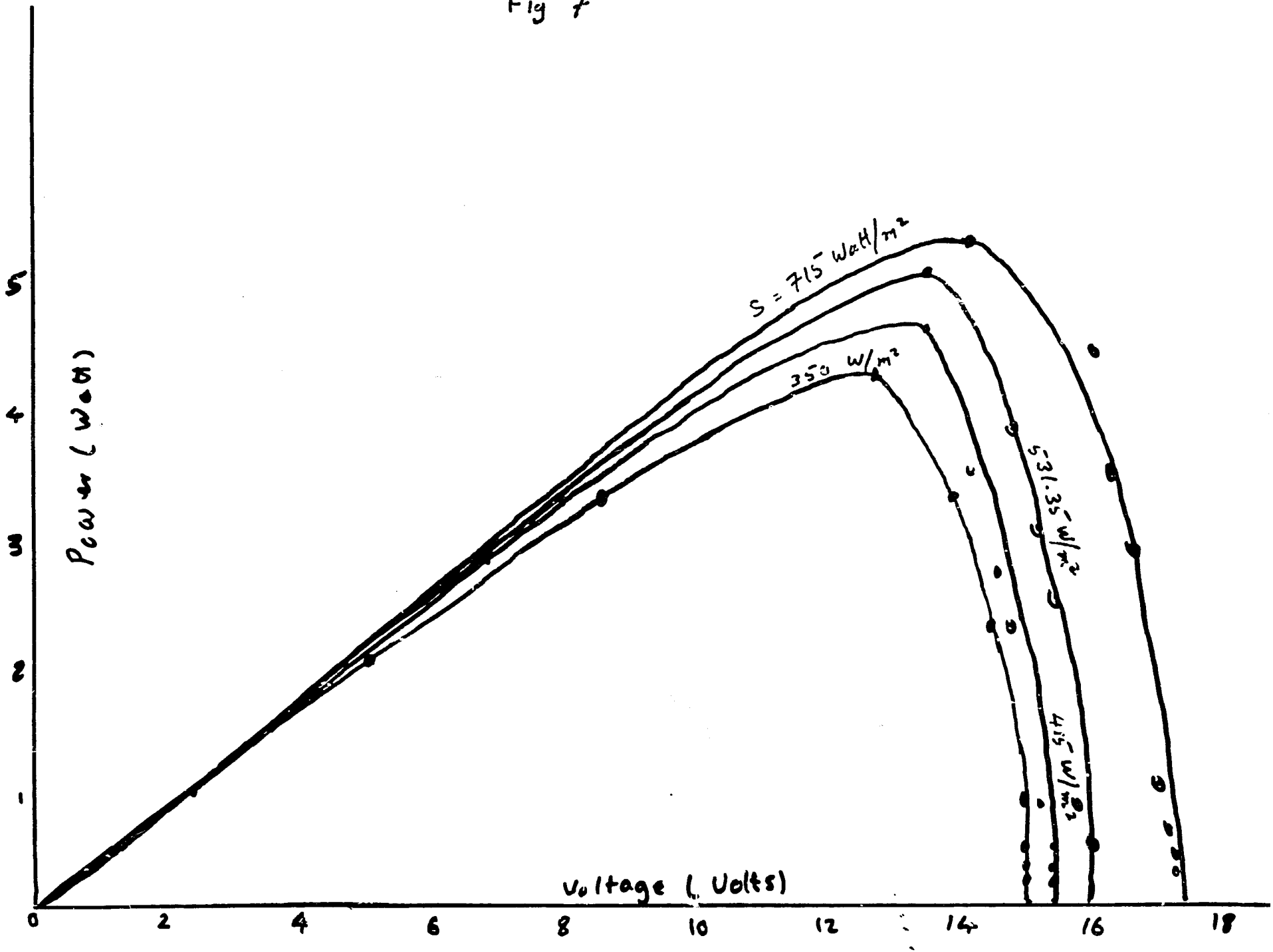
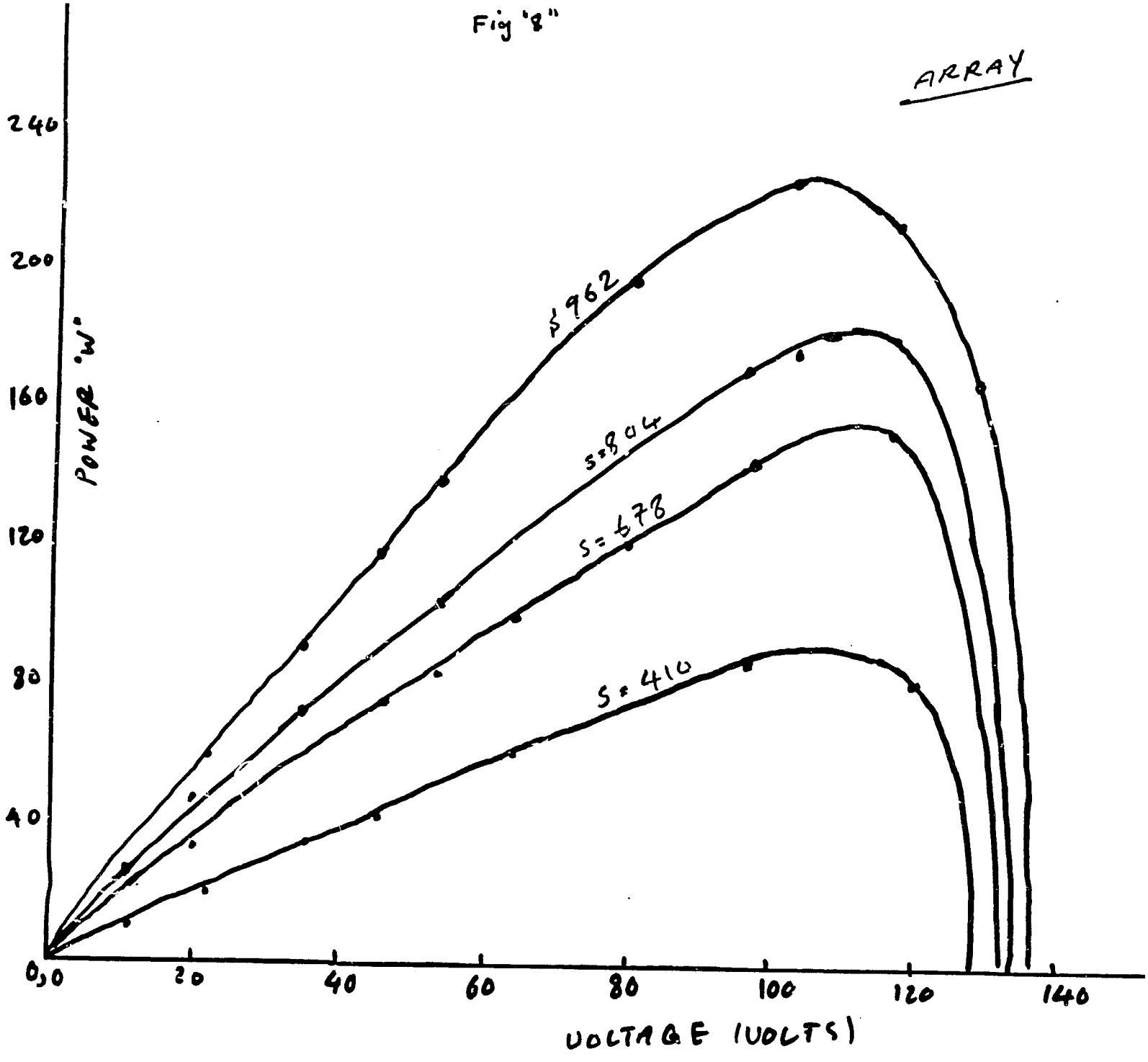

S = 715 watt/m²
531.35 w/m²
415 w/m²
350 w/m²
Power (watt)
Voltage (Volts)
0
2
4
6
8
10
12
14
16
18
1
2
3
4
5

Fig "8"


ARRAY
POWER 'W'
240
200
160
120
80
40
0,0
20
40
60
80
100
120
140
VOLTAGE (VOLTS)
S 962
S=804
S=678
S=410

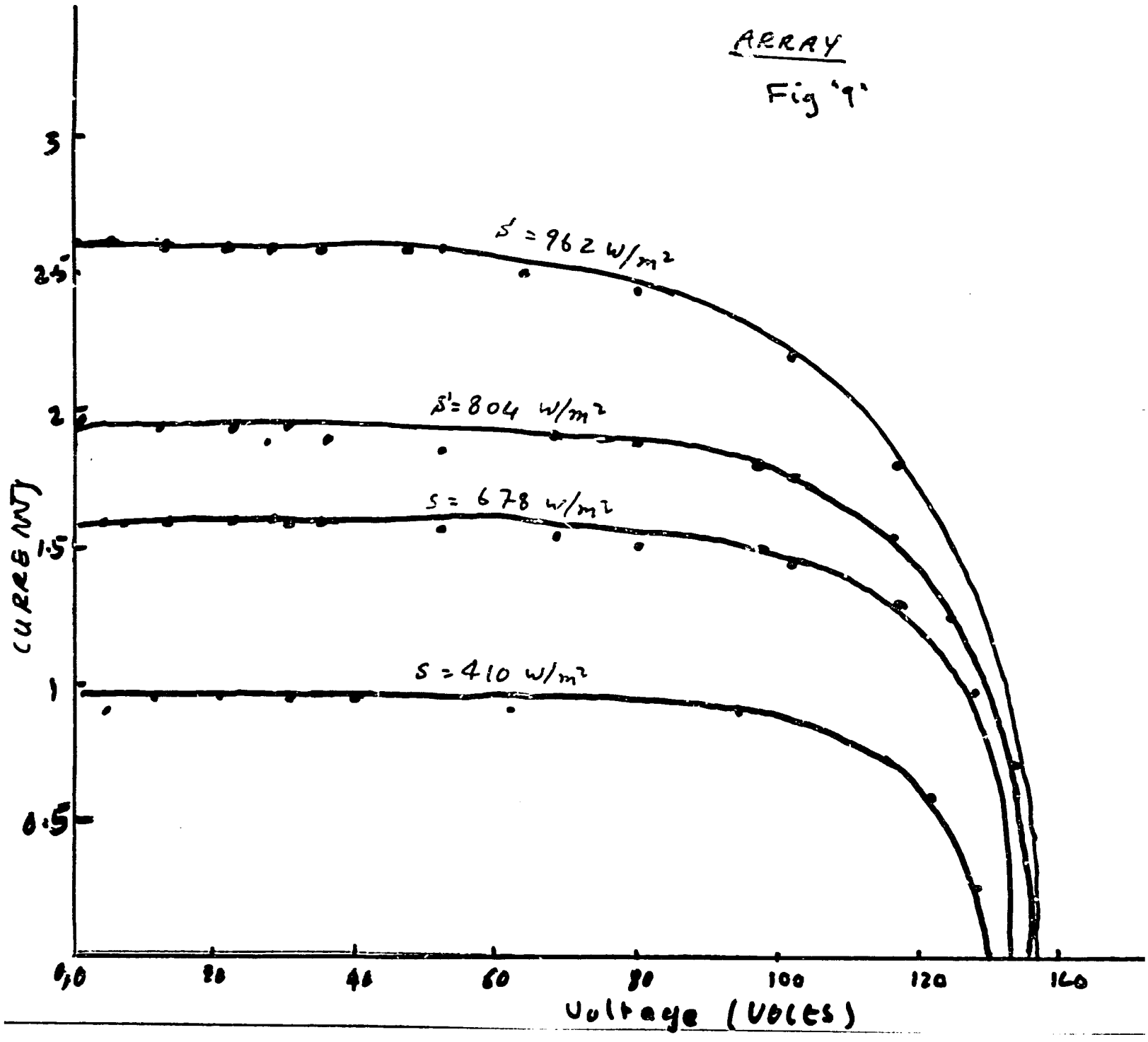

ARRAY
Fig '9'
S = 962 W/m²
S' = 804 W/m²
S = 678 W/m²
S = 410 W/m²
CURRENT
3
2.5
2
1.5
1
0.5
0.0
20
40
60
80
100
120
140
Voltage (Volts)

Fig "10"

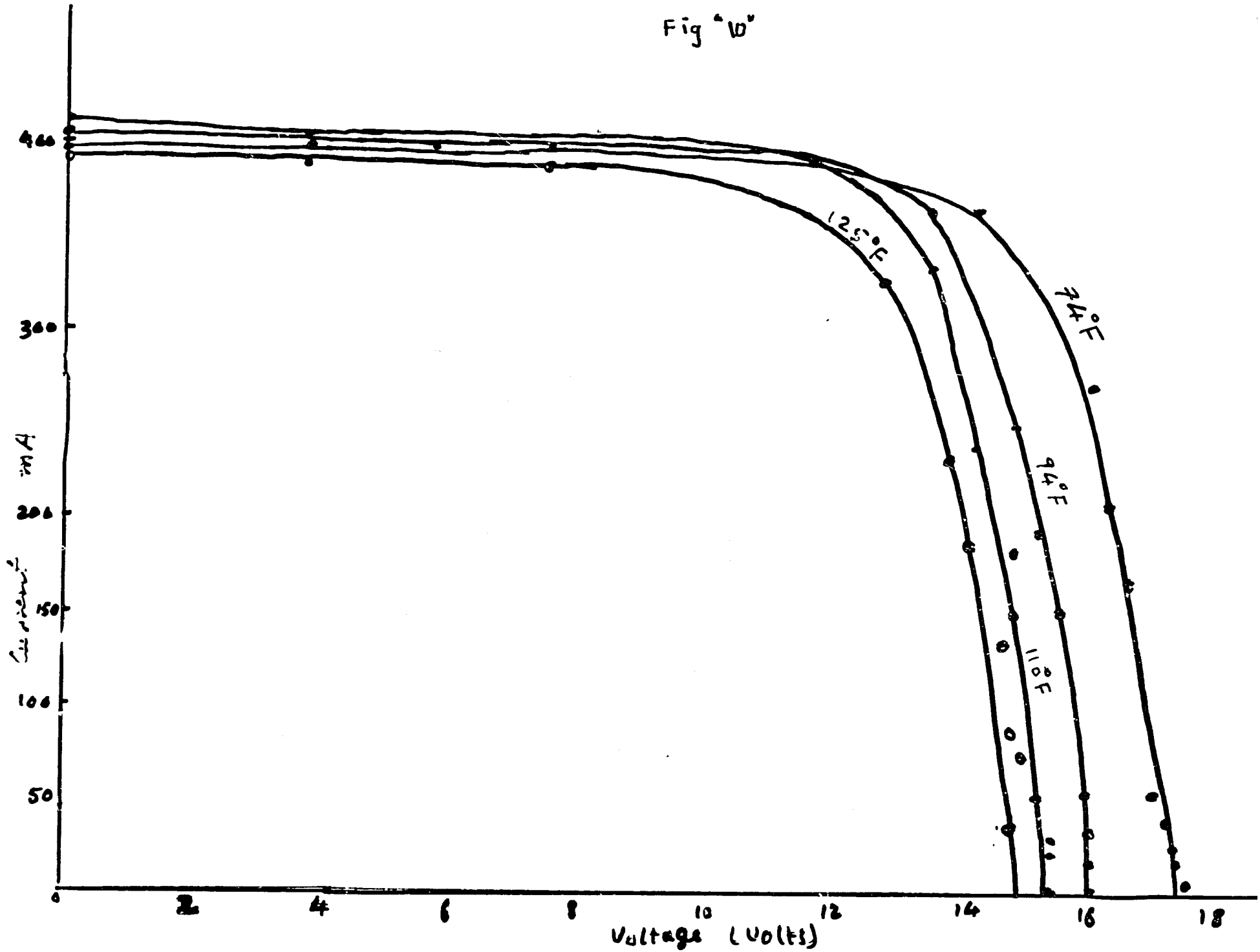
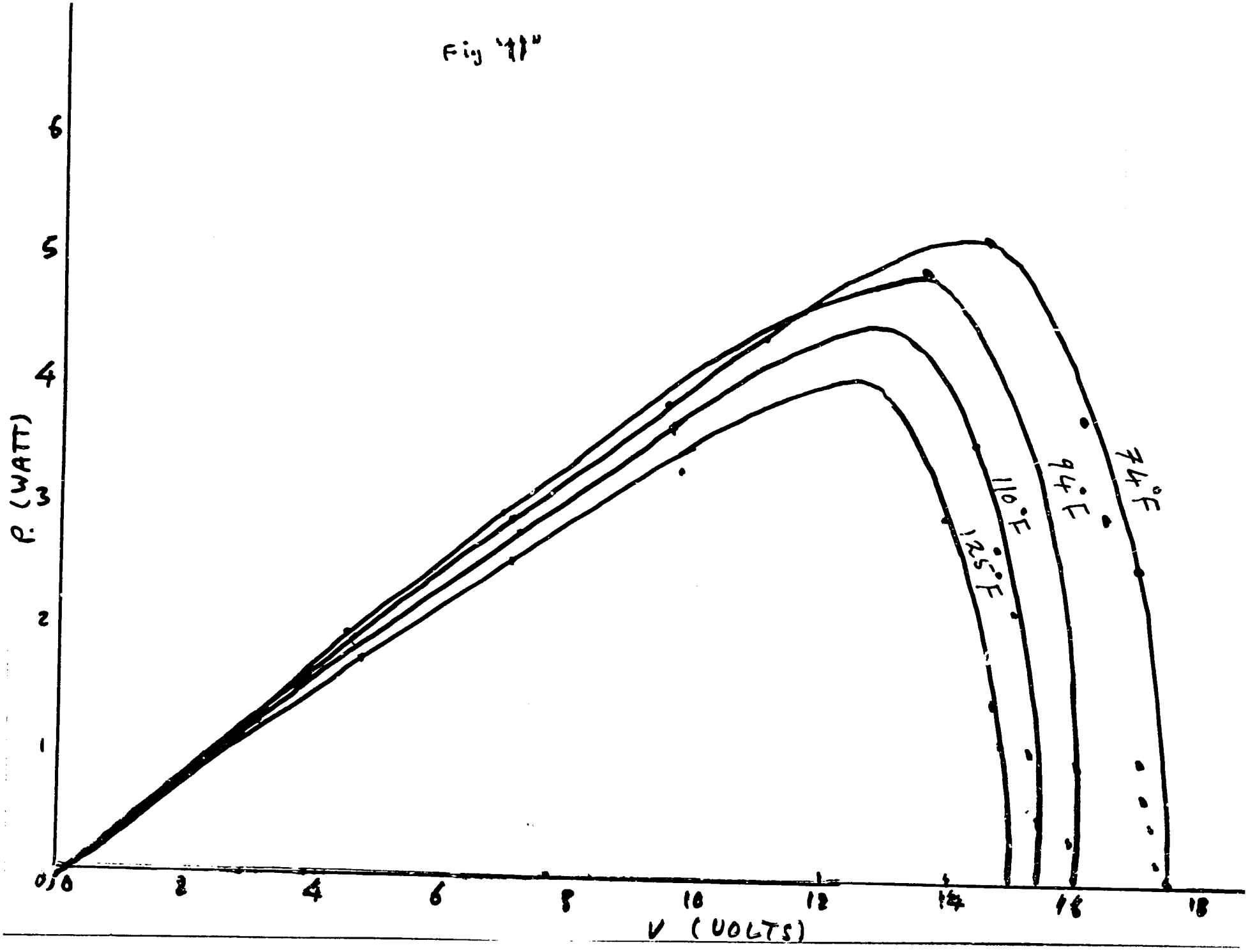
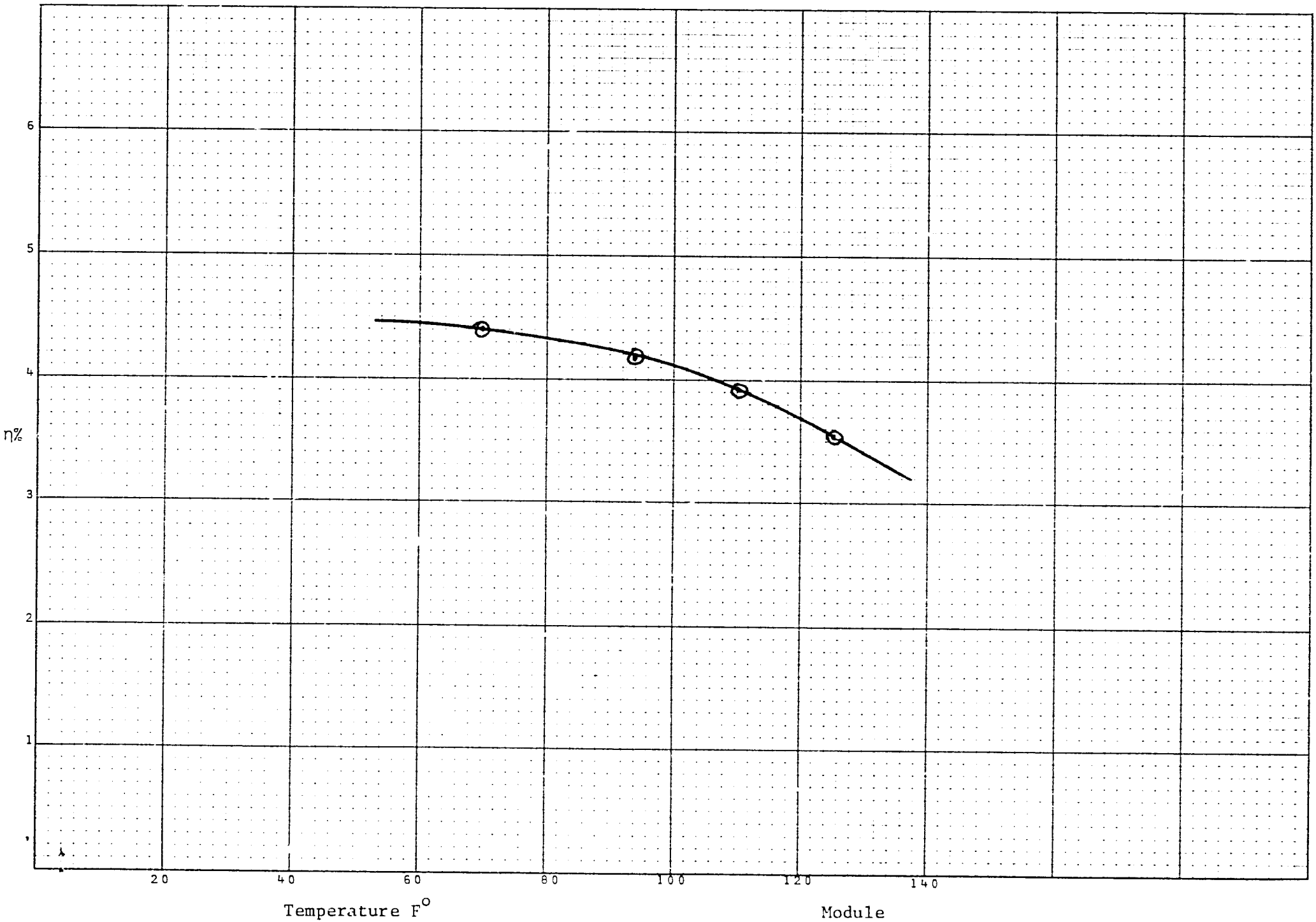
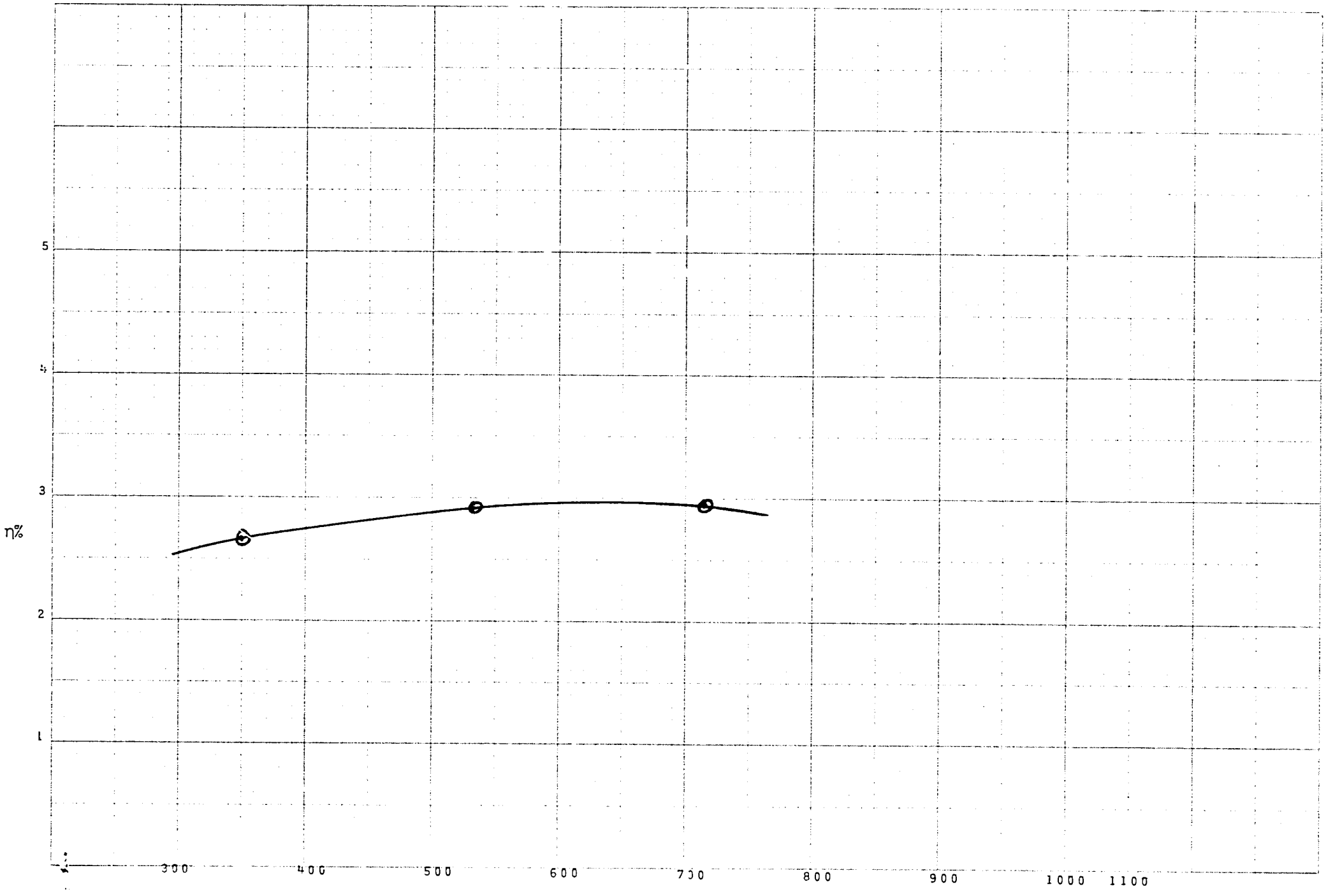

400
300
200
150
100
50
0
2
4
6
8
10
12
14
16
18
Voltage (Volts)
74°F
94°F
110°F
125°F

Fig "1"





CITADEL, NO 642 - CROSS SECTION - 10 SQUARES TO INCH



S in Watt/m²

Module