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Manufacturer of Space Age Solid State Devices

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HIGH EFFICIENCY SILICON SOLAR CELLS

REPORT NUMBER I

FIRST QUARTERLY PROGRESS REPORT

REPORT DATE: October 15, 1962

PERIOD: June 15, 1962 to September 15, 1962

CONTRACT NO. DA 36-039-SC-90777

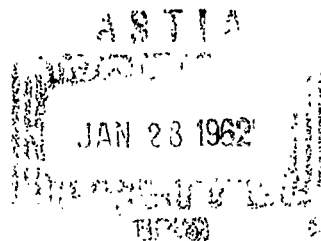
ORDER NO. 1091-PM-62-93-93(4213)

PROJECT NO. 3A99-09-002

PLACED BY: U.S. ARMY
ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY,
FORT MONMOUTH, NEW JERSEY

HELIOTEK
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HIGH EFFICIENCY SILICON SOLAR CELLS

Report Number I

Contract No. DA36-039-SC-90777

Order No. 1091-PM-62-93-93(4213)

Project No. 3A99-09-002

First Quarterly Progress Report

Covering Period from June 15, 1962 to September 15, 1962

OBJECTIVE: INVESTIGATION FOR THE IMPROVEMENT OF
HIGH EFFICIENCY SILICON SOLAR CELLS
FOR TERRESTRIAL APPLICATIONS

Report Prepared by: Paul A. Berman
Roland J. Handy
G. Perry Rolik

Approved by: Eugene L. Ralph

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Sylmar, California

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PURPOSE

The purpose of this contract is the development of high efficiency, low cost silicon solar cells. The objective is high yields, in the order of seventy (70) percent of the cells having efficiencies in the range of twelve to fourteen percent leading to a cell cost of \$2.00 to \$3.00 for a cell having dimensions of 1 cm by 2 cm. Both N^+ on P and P^+ on N cell structures are to be studied and the cells optimized for use in terrestrial environment with and without utilization of solar concentrator\$.

ABSTRACT

Preliminary experiments have been performed on N/P and P/N cells having various junction depths to determine the effects of light intensity on cell performance for these various cell configurations. Preliminary results seem to show that cells diffused twice as long as standard production-type cells operate more efficiently at the higher solar intensities. The shallow diffused cells, however, had higher short circuit currents indicating higher potential efficiencies with the use of optimized grid designs to further reduce series resistance.

Theoretical calculations have been carried through in order to determine the optimum grid configuration for shallow-diffused cells. It has been found that according to the equations used, the optimum grid spacing is very insensitive to changes in light level if all other variables are held constant. The grid spacing does, however, change significantly with various A-factor values, and it is possibly through this mechanism that the optimized grid spacing changes as a function of light level.

A detailed solar cell equivalent series resistance circuit is presented and studies in order to determine where the cell series resistance is located and to determine which locations are more important with respect to the reduction of the total series resistance.

Characteristics of solar cells fabricated from polycrystalline base material are discussed

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Preliminary experiments have been performed on N/P and P/N cells having various junction depths to determine the effects of light intensity on cell performance for these various cell configurations. Preliminary results seem to show that cells diffused twice as long as standard production-type cells operate more efficiently at the higher solar intensities. The shallow diffused cells, however, had higher short circuit currents indicating higher potential efficiencies with the use of optimized grid designs to further reduce series resistance.

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Characteristics of solar cells fabricated from polycrystalline base material are discussed

CONFERENCES

On 6 July 1962 a conference was held between Messers. M. Wolf, E. Ralph and P. Berman of Heliotek and Messers. A. Daniels, E. Kittl, G. Hunrath, and Lt. Clemons of the USA Electronics Research and Development Laboratory. During this conference the scope of the contract, areas of investigation, and methods of approach were discussed.

Heliotek proposed the following lines of investigation which meet with the Laboratory's approval.

PROGRAM PLAN FOR USAERDL CONTRACT NO. DA 36-039 SC-90777

APPROACH A. Terrestrial Cell - Type A (P/N)

Design Study Phase: Phase I

1. Performance vs Spectral Response (at $m=1$, $m=2$, etc.
2. Series Resistance vs concentration
 - a. Grid Design
 - b. Junction Depth
 - c. Contact Resistance (alloyed-fired)
 - d. Cell Size
 - e. Temperature effect
 - f. Dark cell effect
 - g. Bulk resistivity

Fabrication and Evaluation Phase: Phase II

1. Experimental cell fabrication
2. Experimental cell measurements
3. Evaluation of results

Pilot Line Demonstration (500 cells): Phase III

APPROACH B. Space Cell - Type B (N/P) (possibly terrestrial)

Design Study Phase: Phase I

1. Verify concentration theory as in A above for N/P cells.
 - a. Determine best junction depth for space operation.
 - b. Redesign series resistance for new junction depth.
 - c. Optimization of anti-reflectance coating

Fabrication and Evaluation Phase: Phase II

1. Experimental cell fabrication
2. Experimental cell measurement
3. Evaluation of results

Pilot Line Demonstration (250 cells): Phase III

APPROACH C. Space Cell - Type C (N/P)

Design Study Phase: Phase I

1. Surface preparation effects
2. Reflection loss study
3. Junction depth optimization
4. Contact improvement

FACTUAL DATA

1.0 INTRODUCTION AND SUMMARY

The purpose of this contract is the development of low cost silicon photovoltaic converters for terrestrial use, with and without the utilization of solar concentrators. Many solar cell parameters are inversely related to others so that one must obtain optimized values by trading-off one desirable characteristic to obtain another. Thus, for example, the series resistance can be lowered by depositing more grid lines on the surface of the solar cell; however, this results in a decrease of active area and consequently of short circuit current. Therefore, an optimum must be reached between series resistance reduction and active area reduction. This optimum will not necessarily be the same for all light levels; in fact, it most probably will not. Therefore, solar cells must be designed specifically for their particular purpose and optimized accordingly. Furthermore, the limits over which this optimization is valid must be determined as well.

Terrestrial-type cells are to be optimized for earth environment at normal solar intensities of about $80 - 110 \text{ MW/CM}^2$ and at concentrated solar intensities of about 350 MW/CM^2 . Two cell designs must be developed, one for each of the intensity ranges. A secondary study is also to be performed on space-type cells at solar intensities of about 140 MW/CM^2 and at concentrated intensities of approximately 420 MW/CM^2 . The spectral distribution in space is significantly different than the spectral distribution at the earth's surface due to wavelength-selective atmospheric absorption. Hence, the spectral response of the solar cells must be optimized separately for these two cell types. One cannot, however, vary spectral response independently without also affecting other parameters. For example, spectral response can be varied

significantly by varying junction depth. However, this change in junction depth will also affect parameters such as sheet resistance and possibly open circuit voltage. (If the junction is very thin the open circuit voltage has been found to decrease.)

Consequently, some preliminary experiments have been performed during this report period on N^+/P and P^+/N cell configurations to determine the effects of higher intensity solar illumination on these cell types. A solar concentrator having three plane mirrors was utilized to concentrate sunlight at approximately sea level onto cells having the typical shallow diffused layer and other cells having deeper diffused layer thicknesses, to determine their behavior under this concentrated illumination. It was found that there was excessive series resistance present (about 0.5Ω) in the circuitry external to the cell during these tests, so that the results do not give all the information that was expected. However, it was observed that the cells which were diffused for twice the length of time as standard commercial cells had higher efficiencies at approximately $300 \text{ MW}/\text{CM}^2$ than the other cells tested. This was primarily due to the preserved rectangularity of the current-voltage characteristic over the range of solar intensities studied. If the advantage of the longer diffusion time is primarily a lowering of the sheet resistance, the standard, shallow diffusion should still be more advantageous with the proper grid configuration since the shallow-diffused cells have higher short circuit currents than the deeper-diffused cells. (This is not surprising since the spectral response of the former cell type had an additional response in the blue region of the spectrum.) However, if the advantage of the longer diffusion time is connected with a lower A-factor, it may be necessary to utilize the deeper junction to obtain a wider space-charge region. Further experiments will be performed to supply additional information along this line of reasoning.

Another objective of this contract is the fabrication of low-cost solar cells. Since single crystal silicon is normally used in the fabrication of cells the cost is inherently high. The utilization of polycrystalline silicon as the base material in cell fabrication would reduce the material costs considerably. Consequently, experimental cells made from such material have been fabricated. The cells were measured under tungsten light having a color temperature of 2800°K and an equivalent solar intensity of approximately $100 \text{ MW}/\text{CM}^2$. The cells were maintained at a temperature of $28^{\circ}\text{C} \pm 2^{\circ}\text{C}$. Efficiencies as high as 8% have been observed to date with most of the cells falling between 6-8% in efficiency. Open circuit voltages range between .45 and .50 volts and the short circuit currents range between 43 - 48 mA. These polycrystalline cells will begin to look very promising if the efficiencies can be increased to 10-12% efficiency.

The various effects of series resistance on the behavior of silicon solar cells under normal and concentrated solar intensities have been discussed. It is theoretically predicted that series resistance is extremely detrimental to solar cell behavior especially at concentrated light intensities. The components which make the largest contribution to the total cell resistance have been experimentally determined and are found to be the resistance in the diffused layer, and the resistance of the silicon in the base region. It is also possible that the contact resistance of the metal-to-semiconductor interface at the back electrode could be appreciable if the proper fabrication techniques are not utilized.

Using theoretical equations for optimization of grid spacing, optimum grid spacings have been calculated as a function of incoming solar intensity. It is found that for constant values of the A-factor, which occurs in the exponential term of the diode equation

$$I = I_0 \left(\exp \frac{qV}{AKT} - 1 \right)$$

and which represents a departure of the diode from the ideal case, the grid spacing is surprisingly insensitive to change of light level. The grid spacing is somewhat sensitive to the sheet resistance of the diffused region, and quite sensitive indeed to changes in A-factor. The equivalent A-factor has been found to be a function of voltage. If there is any series resistance there will be a change in the voltage at which maximum power occurs as a function of light intensity. The consequent change in A-factor with voltage appears that it might be the predominant mechanism which determines the grid spacing as a function of light intensity if one is considering grid optimization for maximum power voltage. It is calculated that for an A-factor of 2 the optimum grid spacing for N/P cells is about .186 CM at 100 MW/CM^2 solar intensity and about .184 CM at 300 MW/CM^2 solar intensity. For P/N cells the grid spacings are calculated to be .219 CM and .216 CM respectively. For an A-factor of unity, the grid spacings for N/P and P/N cells (other values remaining the same as the A=2 calculations) are calculated to be .381 CM and .402 CM respectively at approximately 100 MW/CM^2 solar intensity. These values were calculated using pessimistic values of sheet resistance. Using more representative sheet resistance values give grid spacing of .482 CM and .512 CM for N/P and P/N cells respectively (with an A-factor of unity).

A more complete equivalent resistance model of the solar cell, which takes into account all the component resistances in the cell, has been developed. It is hoped that by analyzing this model a more complete understanding of solar cell design with respect to series resistance will be attained. The equivalent circuit is presented and its total equivalent resistance in terms of the component resistances has been solved. This solution must be further reduced into the basic physical

quantities represented by the resistances, and this reduced equivalent resistance must be utilized in the solar cell equation to provide the optimum grid configuration.

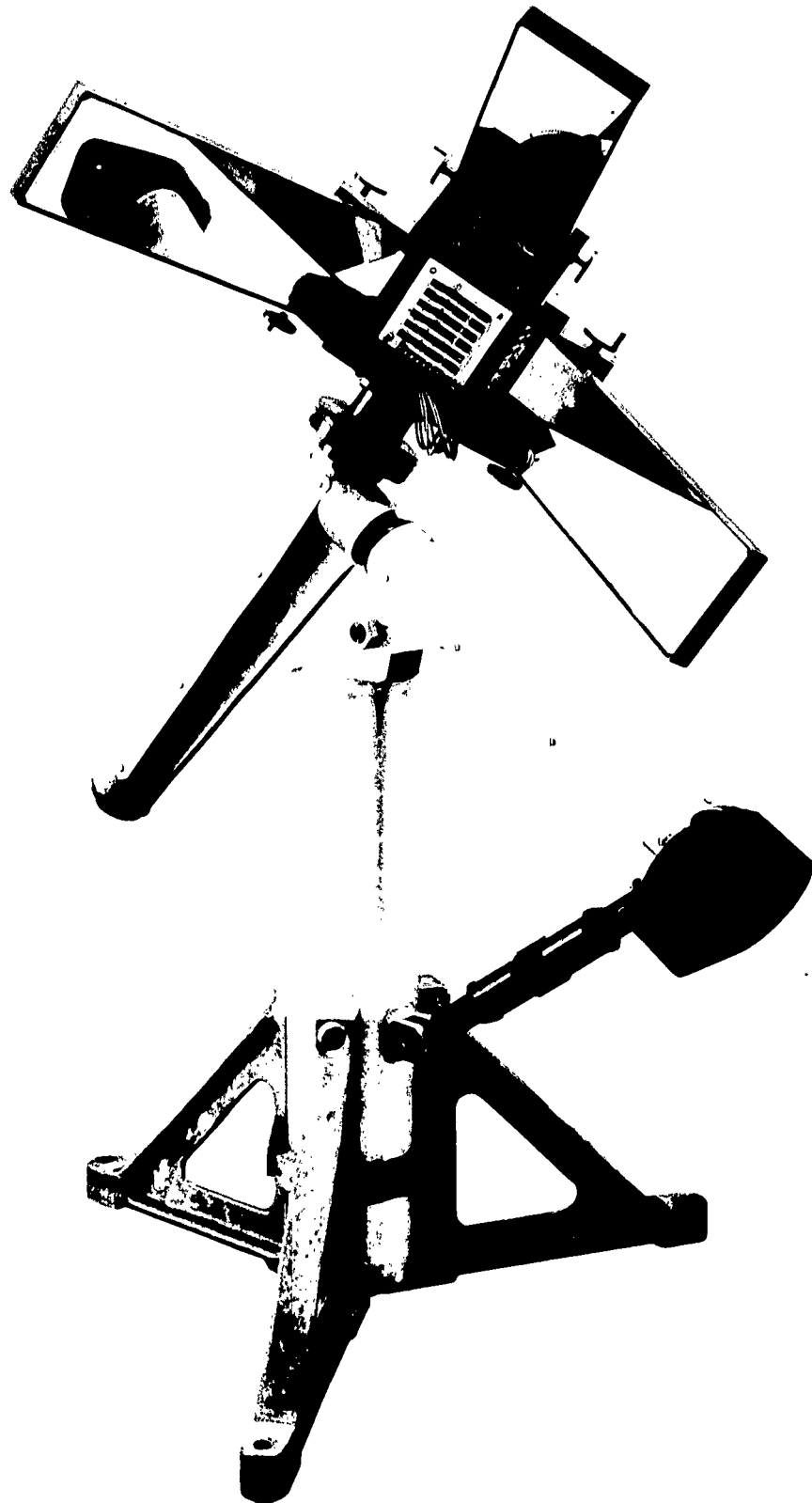
2.0 CONCENTRATED SUNLIGHT MEASUREMENTS

Preliminary concentrator measurements have been made in order to obtain information on the behavior of typical N^+ on P and P^+ on N solar cells with respect to one another under concentrated solar illumination. Preliminary measurements have also been made on N^+ on P and P^+ on N cells having deeper junction depths to provide some indication of the effect of junction depth variation on the efficiency of solar cells under increasing intensities of solar illumination. The shallow (typical) diffused and deeper diffused cells of each type were fabricated from the same silicon ingot to form a basis of comparison.

At this point a discussion of the concentrator would be appropriate. A photograph of the concentrator is presented in Fig. 1. It consists basically of a mount with sun tracking mechanism upon which is mounted a concentrator system consisting of three 6" x 20" aluminum evaporated, front surfaced, adjustable plane mirrors. In order to fully evaluate the capabilities of this test equipment a series of experiments were performed.

The short circuit currents of several solar cells mounted in the test position of the concentrator were utilized to monitor the solar intensity. When the mirrors were rotated into position they uniformly illuminated an area of 5" x 5". The cells were soldered to a metallic base plate which was in turn mounted on a water cooled plate inside the concentrator. Thus, good thermal conduction was achieved, the temperature of the cells being held constant for all measurements at $25^\circ\text{C} \pm 2^\circ\text{C}$.

For the first test of the concentrator performance, all three mirrors were adjusted to provide maximum intensity (over the 5" x 5" area) and then each mirror in turn was rotated so that it no longer reflected light onto the cell area. The change in I_{sc} upon removal



HELIOTEK SOLAR CONCENTRATOR

FIGURE 1

of any one of the mirrors was independent of the individual mirror removed to within 1 mA out of about 50 mA, indicating that each mirror has essentially the same dimensions and optical properties as the other. The removal of any mirror on this particular day gave an I_{sc} decrease of about 22%.

The second test was quite similar to the first. In this test the mirrors were positioned so that they did not reflect light onto the target area (the 5" x 5" area on which cells are mounted). Each mirror in turn was then rotated into position of maximum concentration, the cell I_{sc} measured, and the mirror returned to its non-contributing position. Once **again** the short circuit current increase was independent of the individual mirror utilized except for a 1 mA variation.

The third test consisted of rotating the mirrors into position in various sequences to provide increasing concentrations. For this particular day the concentration ratios were about 1.63 for one mirror, 2.29 for two mirrors, and 2.93 for three mirrors, using the I_{sc} obtained without concentration as the normalization factor. These tests were made in Sylmar, California. At a later test made at Table Mountain, California, the concentration ratios were found to be about 3% greater for each of the mirror combinations (1, 2, and 3 mirrors).

The mirrors, when rotated into position, shadow the cells from some of the sky radiation. A short circuit current gain due to additional direct sunlight reflected onto the cells is observed when a mirror is rotated into concentrating position, but this gain can appear to be somewhat reduced because of a decrease in the sky radiation impinging on the cells due to shadowing by the mirror. Since there is a larger amount of sky radiation present near sea level than at Table Mountain, the shadowing effect will be more

pronounced in the former case, and this would account for the 3% increase in concentration ratio in going to Table Mountain as opposed to those obtained in Sylmar.

As the magnitude of the sky-radiation shadowing effect of the mirrors can be expected to vary from day to day, it will be necessary to monitor the concentration ratio for each series of tests. The ratio can be determined by utilizing the short circuit current of one or more of the cells being measured, provided that the combined effect of the solar cell series resistance and solar concentration are not so great as to affect the relationship between I_{sc} and light intensity and cause a deviation from linearity. It has been found that for Heliotek cells fabricated in the normal manner this would not be expected to occur until a solar intensity greater than 400 mw/cm^2 is attained. The incident solar intensities of this series of tests were of the order of 300 mw/cm^2 so that no difficulty in utilizing short circuit current to determine concentration ratio has been encountered, as verified by the E - I curve which is approximately perpendicular to the current axis at short circuit current. In order to measure the magnitude of the incident solar intensity as the mirrors are added, it is necessary to utilize a standard solar cell which has been calibrated against a pyrheliometer.

In the first set of preliminary measurements to determine the operating conditions of the concentrator, eight cells were mounted in the concentrator and the complete current-voltage curves were measured utilizing reflection from 0 mirror, 1 mirror, 2 mirrors and 3 mirrors. The eight cells measured were comprised of the following cell types:

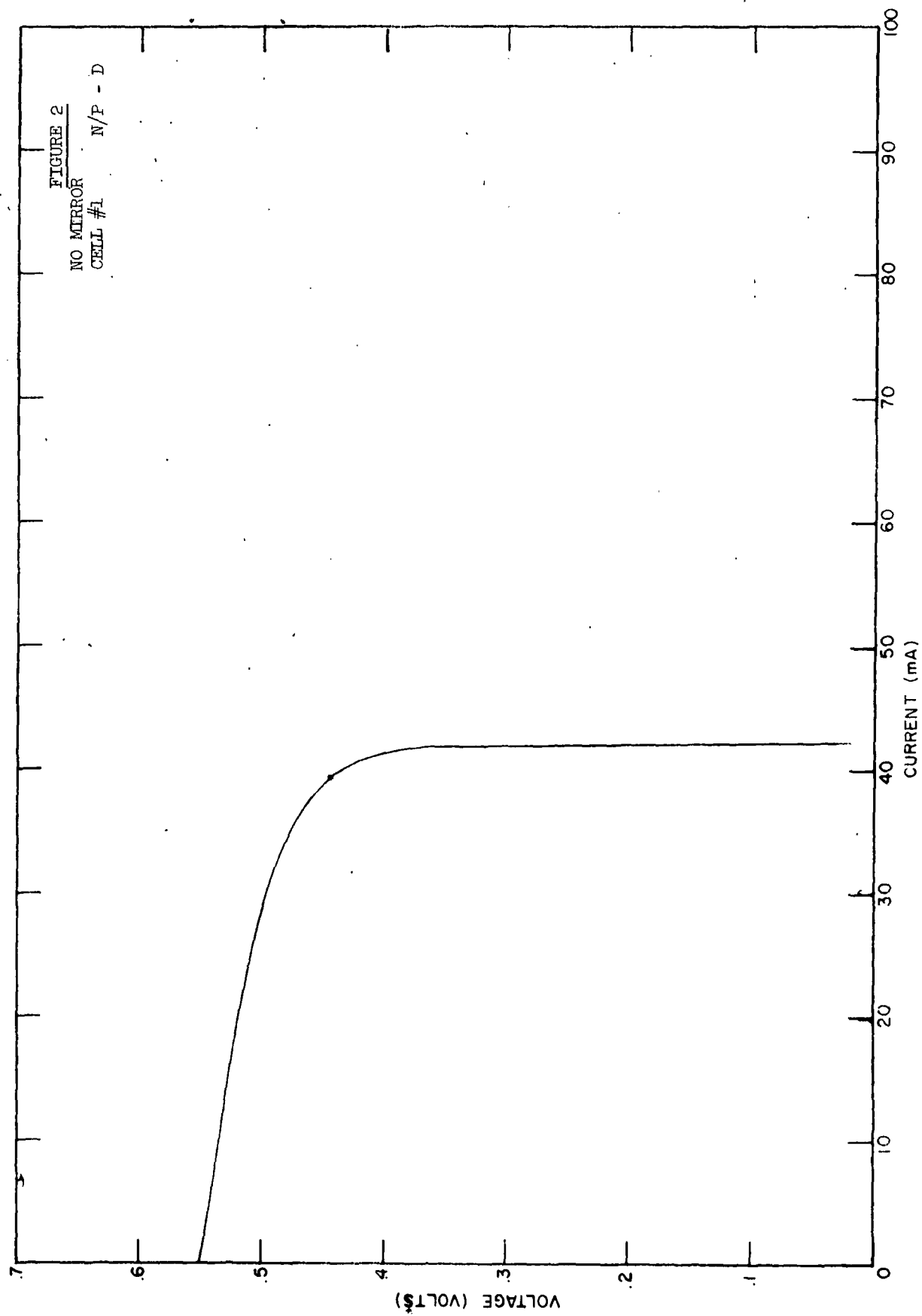
Cell No.	Cell Type	Diffusion Time
1	N/P - D*	480 Minutes
2	N/P - D*	480 Minutes
3	N/P - S*	20 Minutes
4	N/P - S*	20 Minutes
5	P/N - D*	40 Minutes
6	P/N - D*	40 Minutes
7	P/N - S*	10 Minutes
8	P/N - S*	10 Minutes

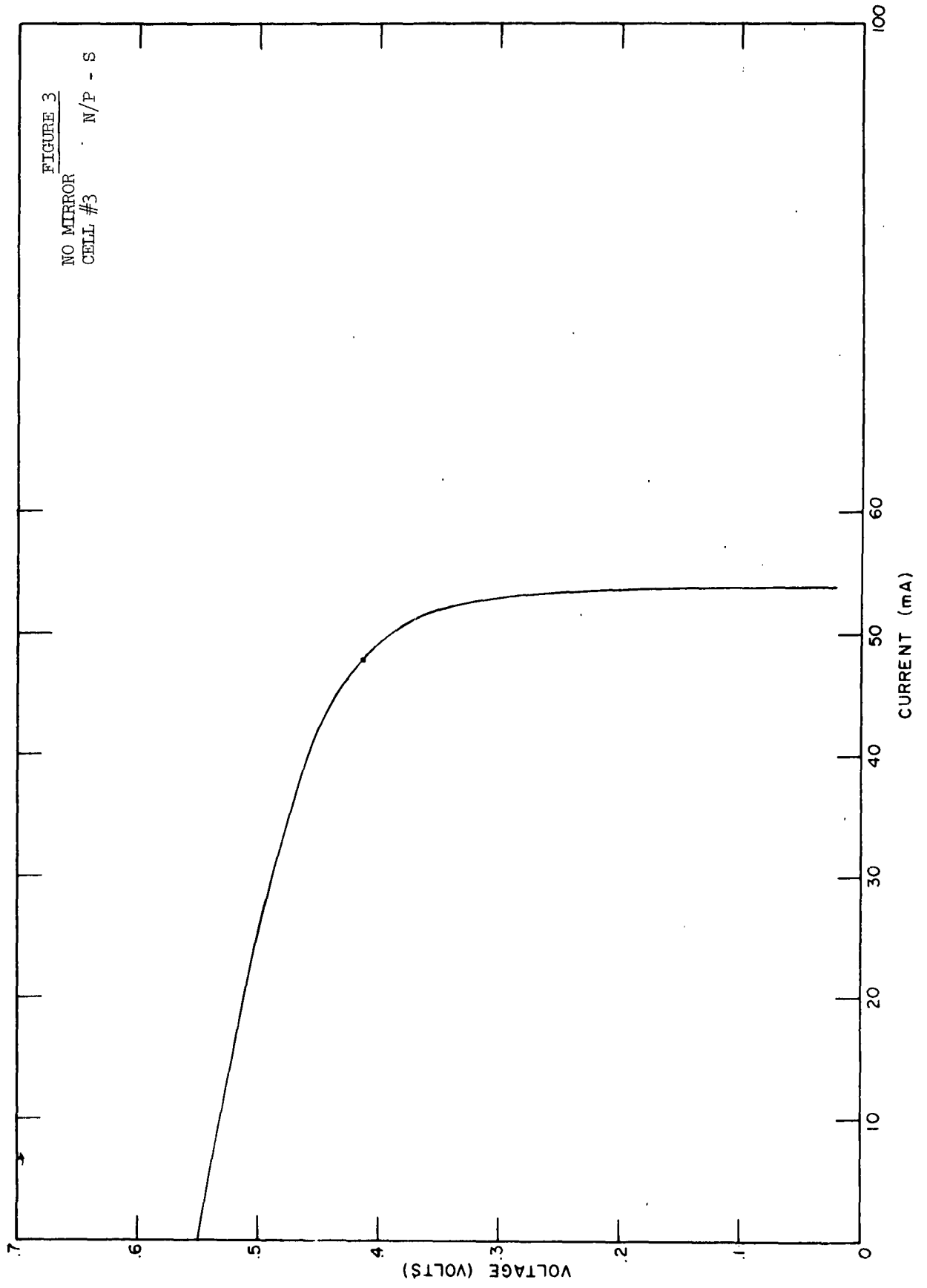
* "D" and "S" refer to deep and shallow diffused respectively.

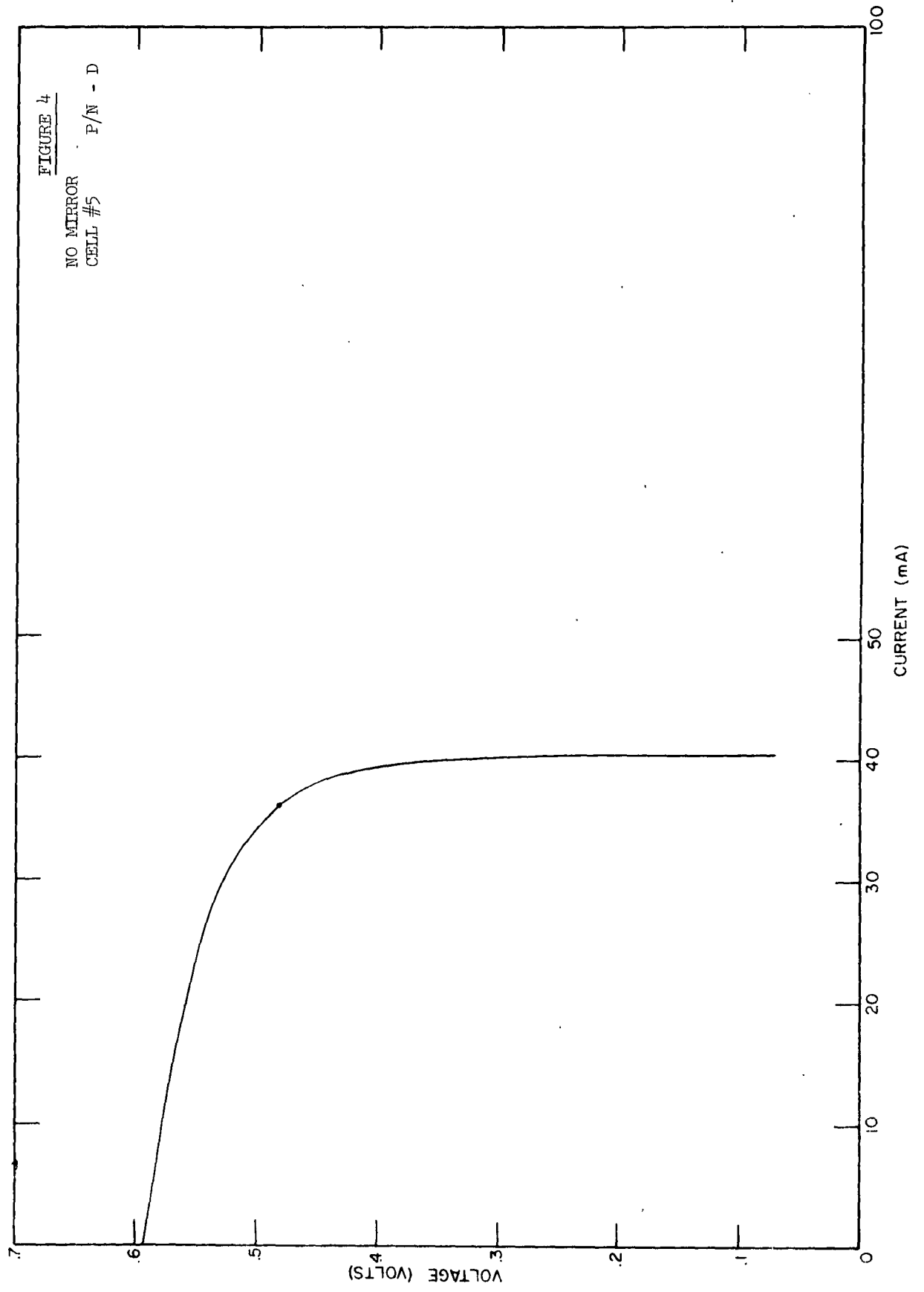
The object of the experiment was to determine the relative behavior of N^+ on P and P^+ on N cells representative of standard production cells under concentrated solar illumination and to study the relative behavior under concentrated and normal solar illumination of both cell types having both a normal shallow and a substantially increased junction depth. The diffusion temperature was held constant for each cell type (P/N and N/P respectively) for the above experiment.

During these tests, a collimated standard cell was mounted outside the concentrator to determine the actual solar intensity exclusive of sky radiation while the short circuit currents of the cells being measured were utilized to determine the relative concentration ratio.

The necessity of obtaining complete current voltage curves becomes obvious if one examines the current-voltage characteristics obtained. The no mirror and 3 mirror runs are presented in Figures 2 to 9 (note the scale change on the current axis). Since the 1 and 2 mirror curves simply gave intermediate shape changes, they are not presented. The difference in the I - V characteristic between the standard diffused cells of either polarity and the deeper diffused cells is somewhat startling, especially in the N^+ on P cells. These cells have higher base resistances because 5-10 μ -cm starting material







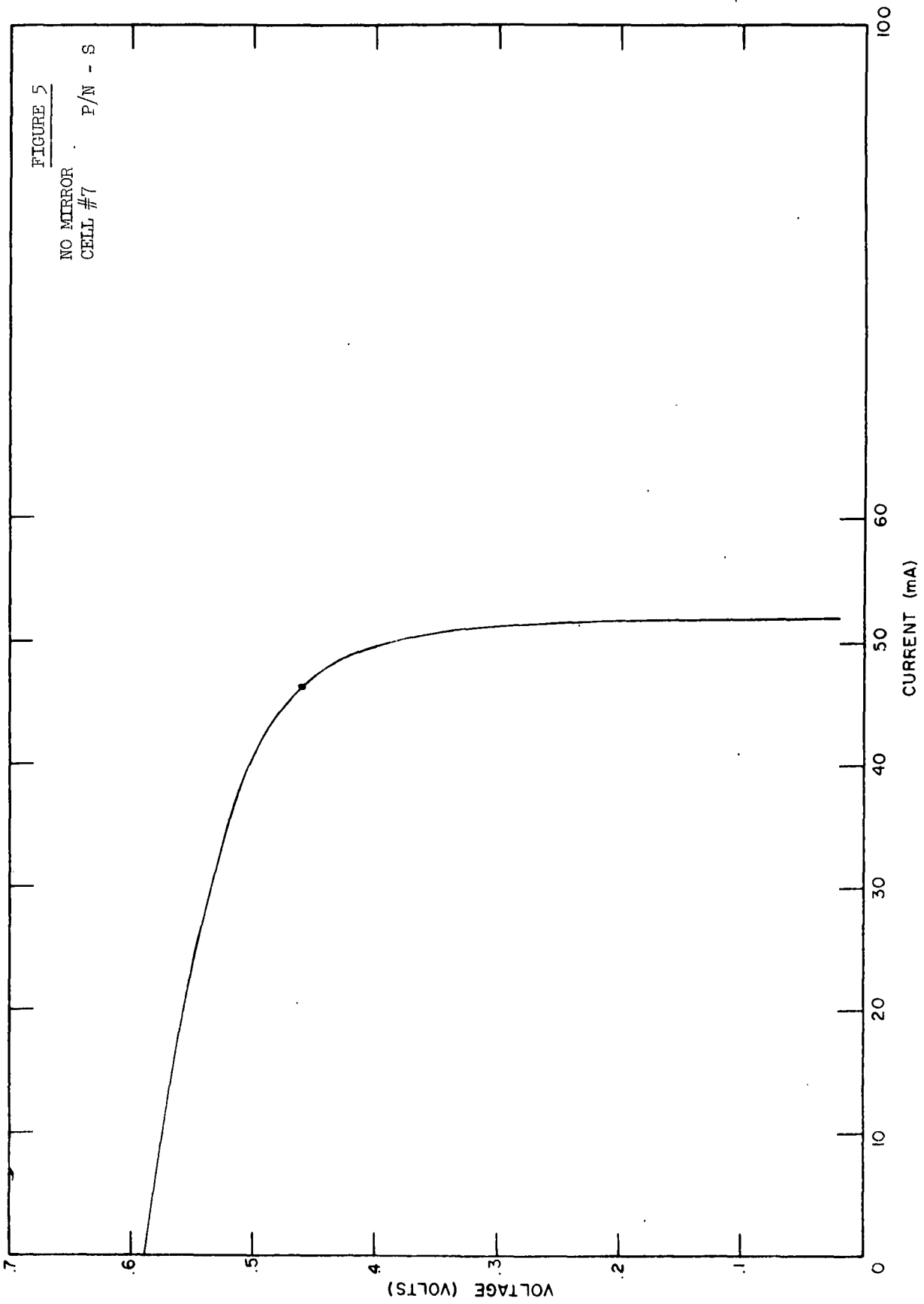
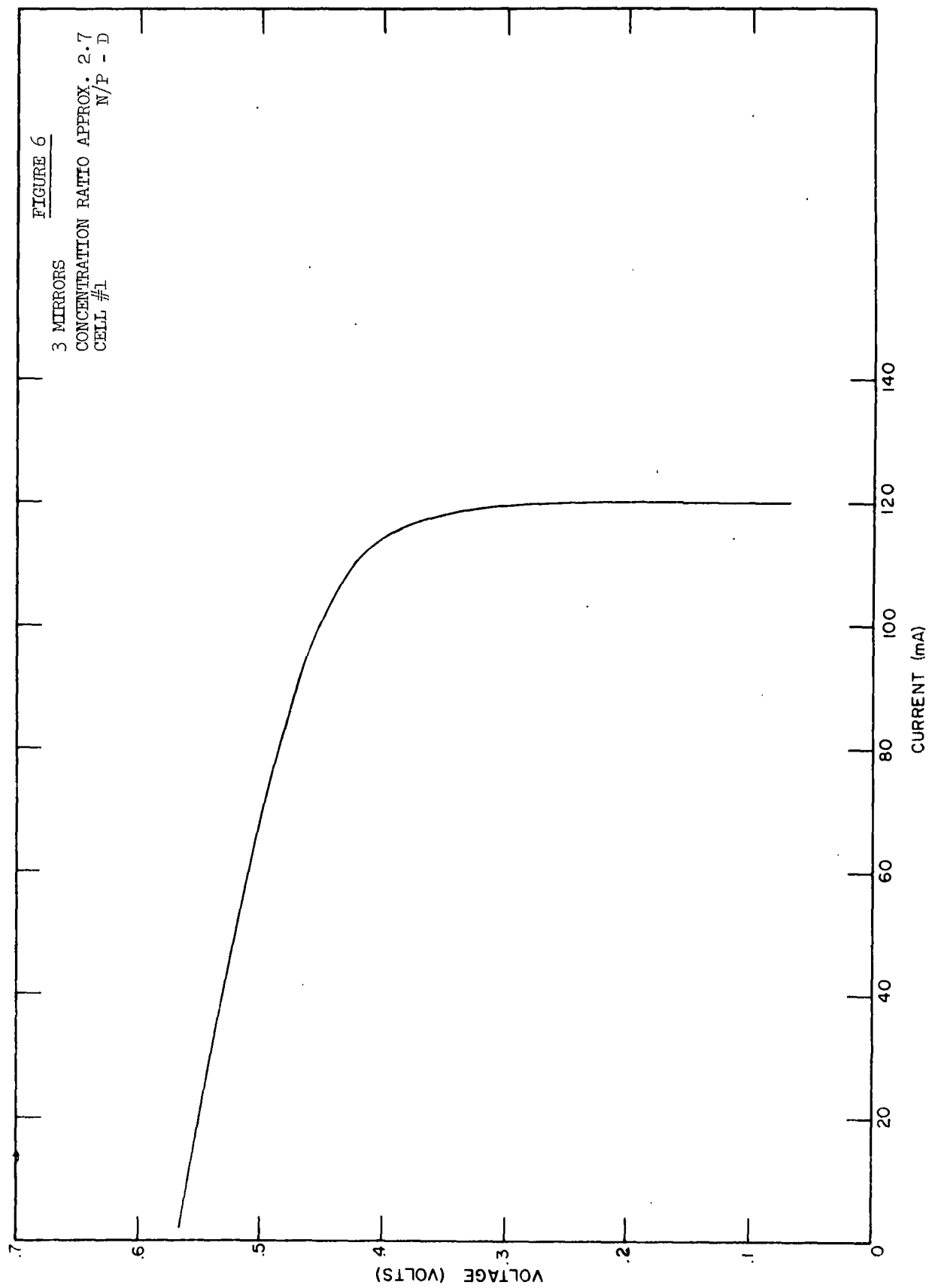


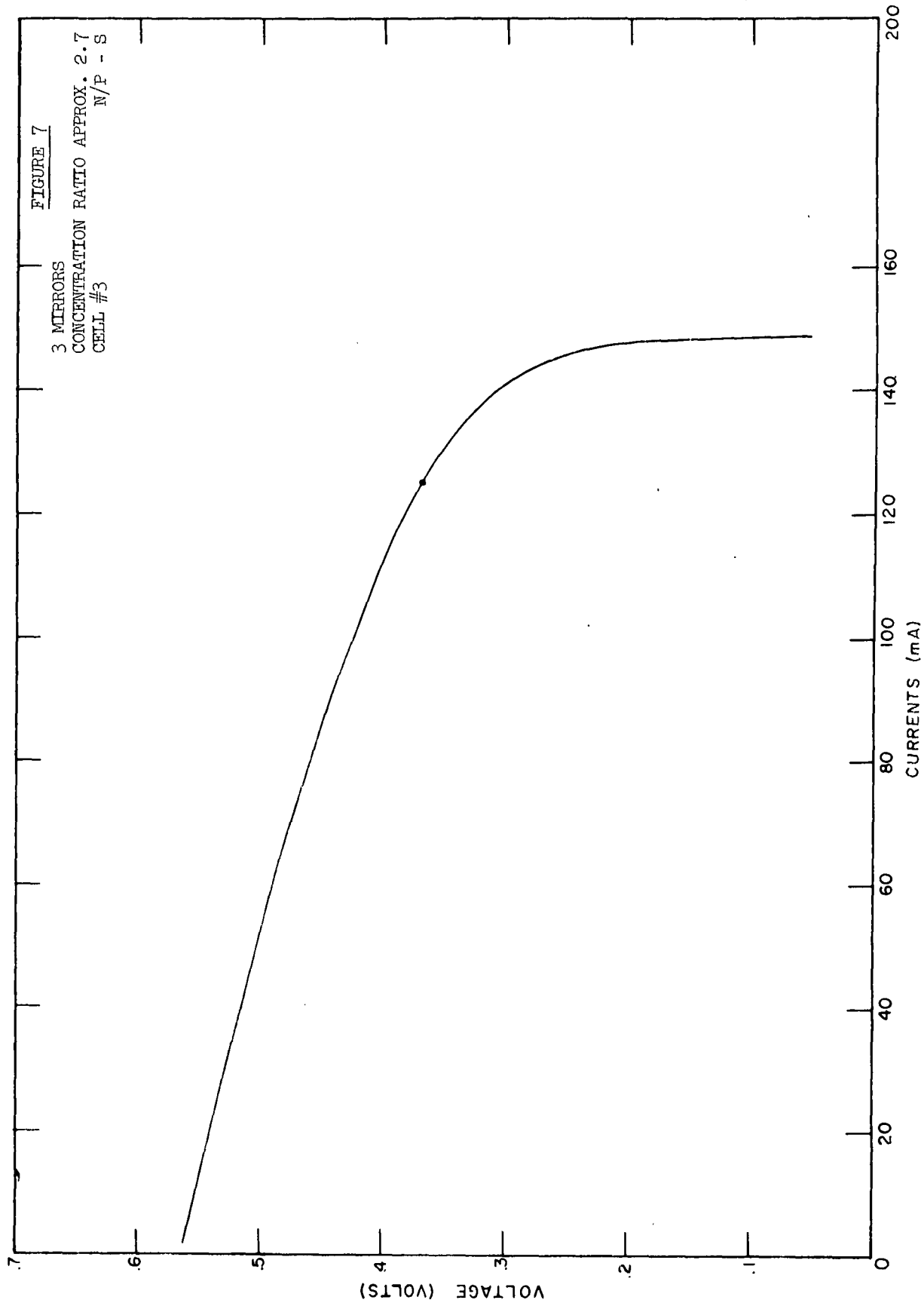
FIGURE 6

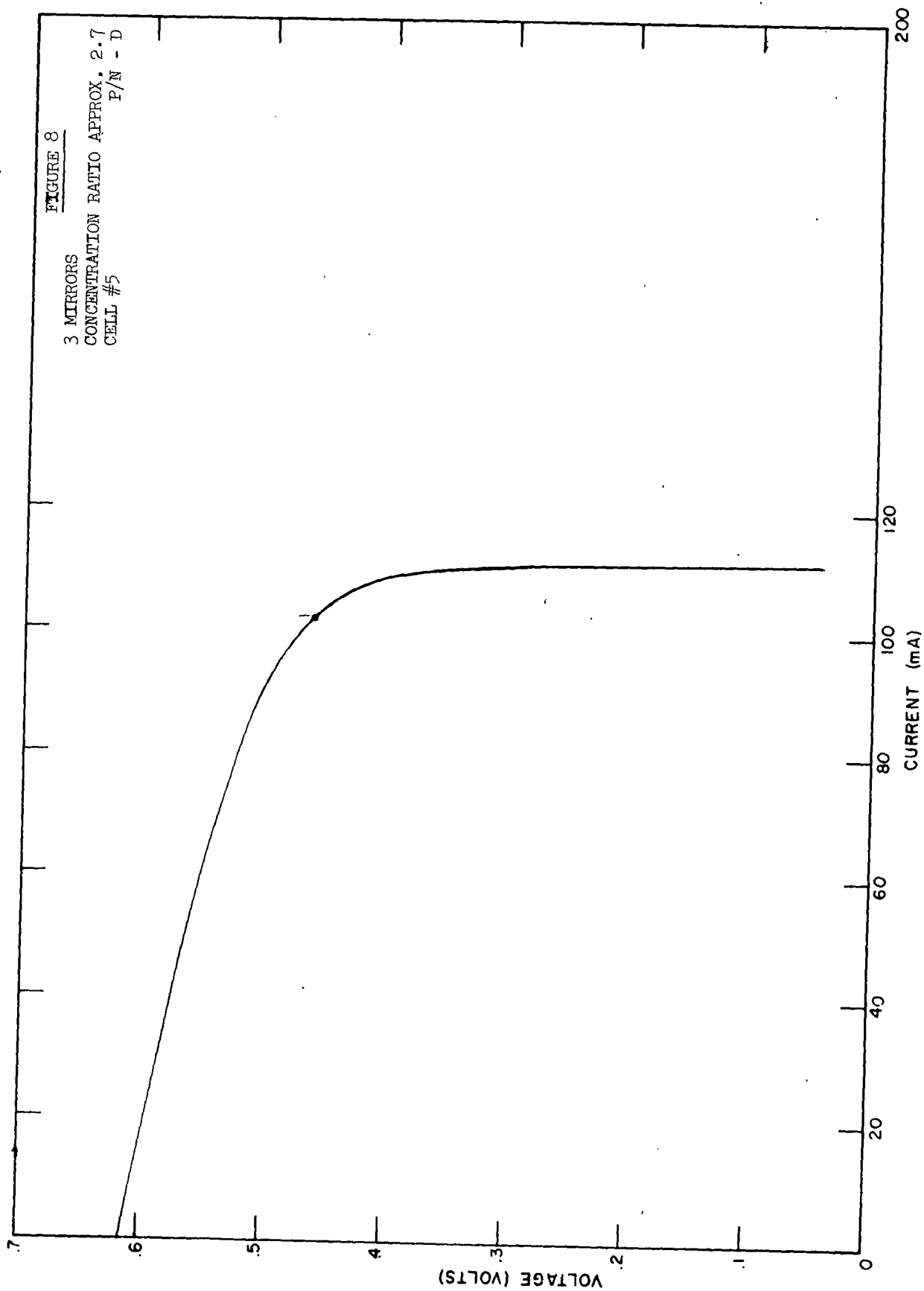
3 MIRRORS

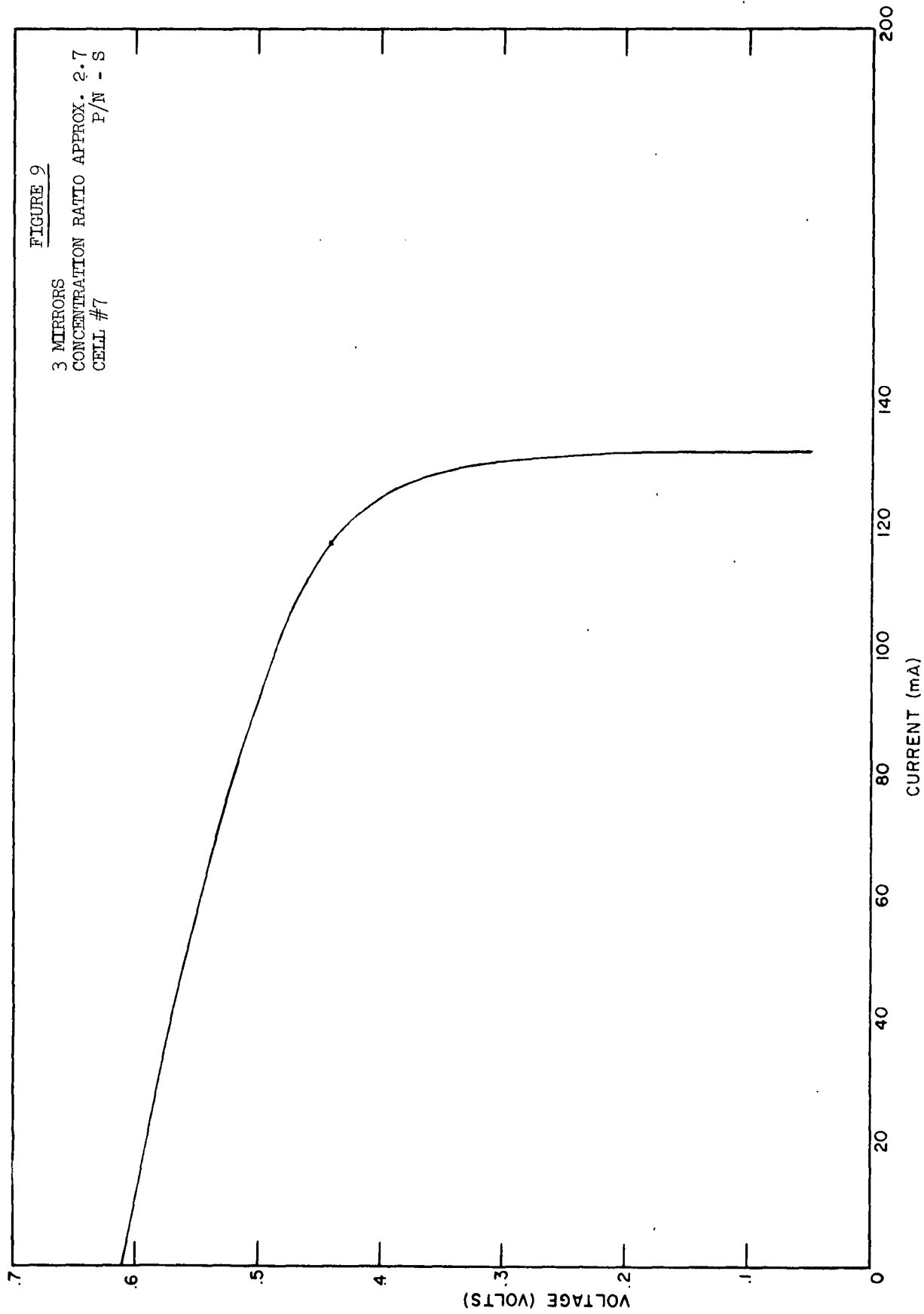
CONCENTRATION RATIO APPROX. 2.7

CELL #1 N/P - D









was used, resulting in a higher total series resistance (R_s of the order .7 ohm). The preliminary results seem to show an actual curve-shape change in the area of the knee, the knee becoming more rounded for the cells having higher series resistance (shallower diffusion depths). There were also indications that additional series resistance may have been contributed by the wiring to the cells which would influence the characteristics. Therefore, the conclusions that can be drawn on the basis of these preliminary tests is limited and it should be pointed out that these tests were made primarily to provide indications as to what one might expect in utilizing concentrated sunlight to illuminate solar cells of various configurations, and to provide experience in conducting concentrator measurements with this particular equipment. Some of the results of the experiments will be discussed below as a matter of interest, and are only qualitative in nature.

The rounding out of the knee with increased illumination is especially noticeable in Figures 3 and 7 which depict the shallow (standard) diffused N/P cells at 0 and 3 mirror concentrations respectively. The deeper diffused cells preserve their curve shape throughout the range of incident intensities. The maximum power point is shown for each of the curves.

From the curves obtained in this series of experiments (eight of which are shown in this report) the maximum power voltage was plotted as a function of the concentration ratio (obtained by normalizing each cell short circuit current to the short circuit current obtained at 0 mirror condition) and this is depicted in Figure 10. Hence, while the ordinate is absolute, the abscissa is relative to each curve, because the incoming solar intensity was not the same for each of the cells in the unconcentrated condition, and therefore each curve is normalized to an initial intensity which may vary slightly from one curve to another. However, the solar intensity did not vary

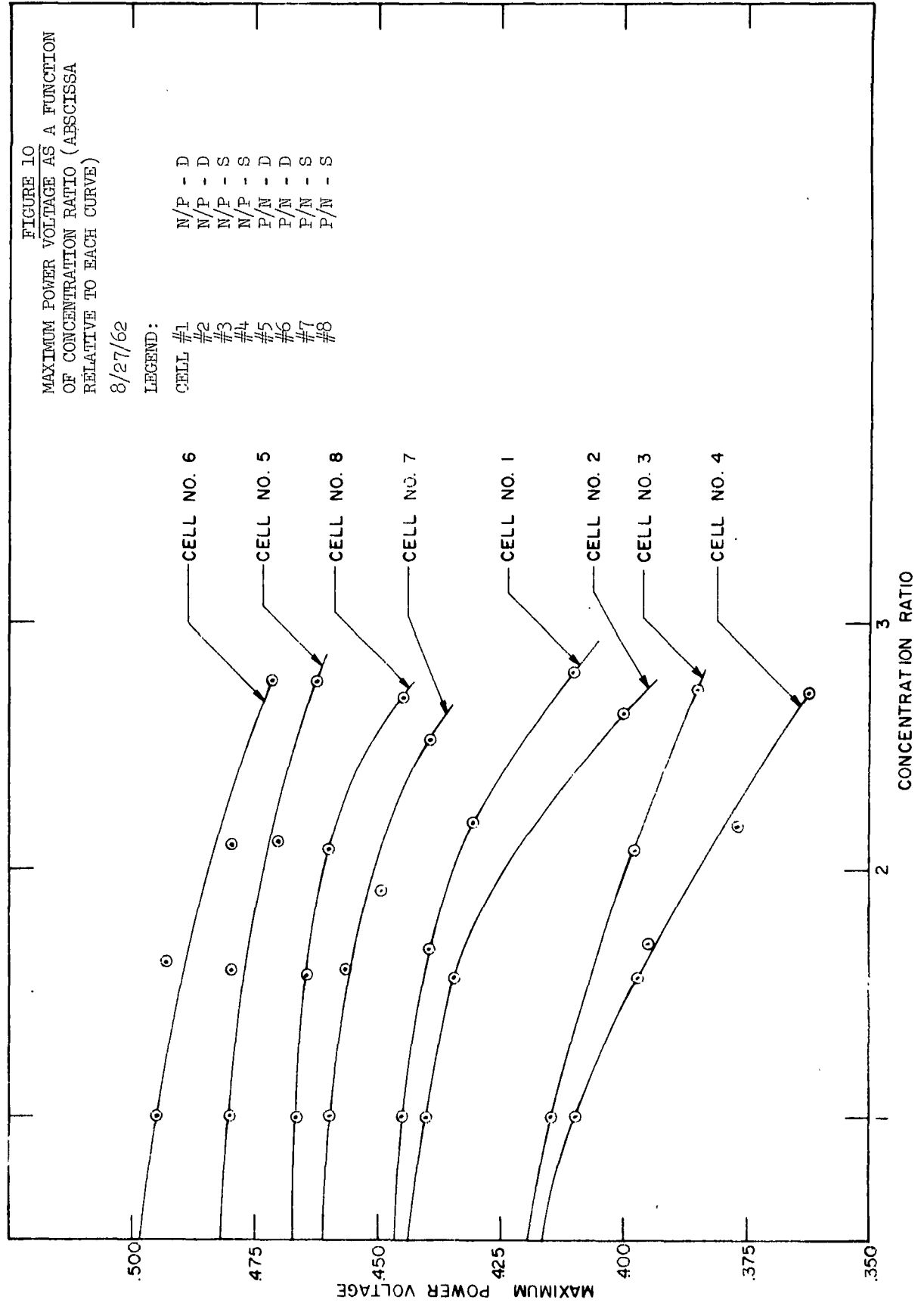
FIGURE 10
MAXIMUM POWER VOLTAGE AS A FUNCTION
OF CONCENTRATION RATIO (ABSCISSA
RELATIVE TO EACH CURVE)

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LEGEND:

CELL #1
#2
#3
#4
#5
#6
#7
#8

N/P - D
N/P - S
N/P - S
N/P - S
P/N - D
P/N - D
P/N - S
P/N - S

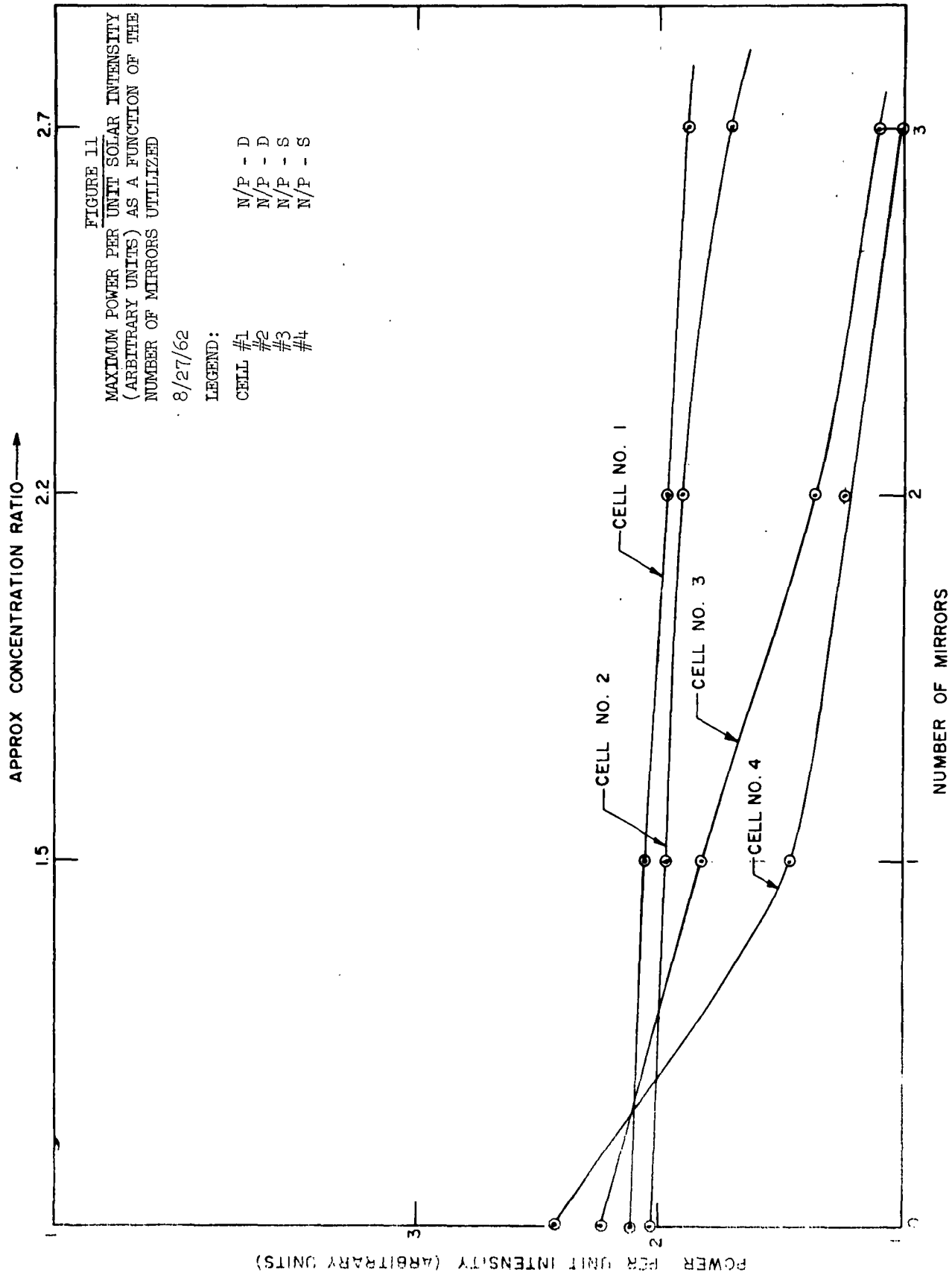


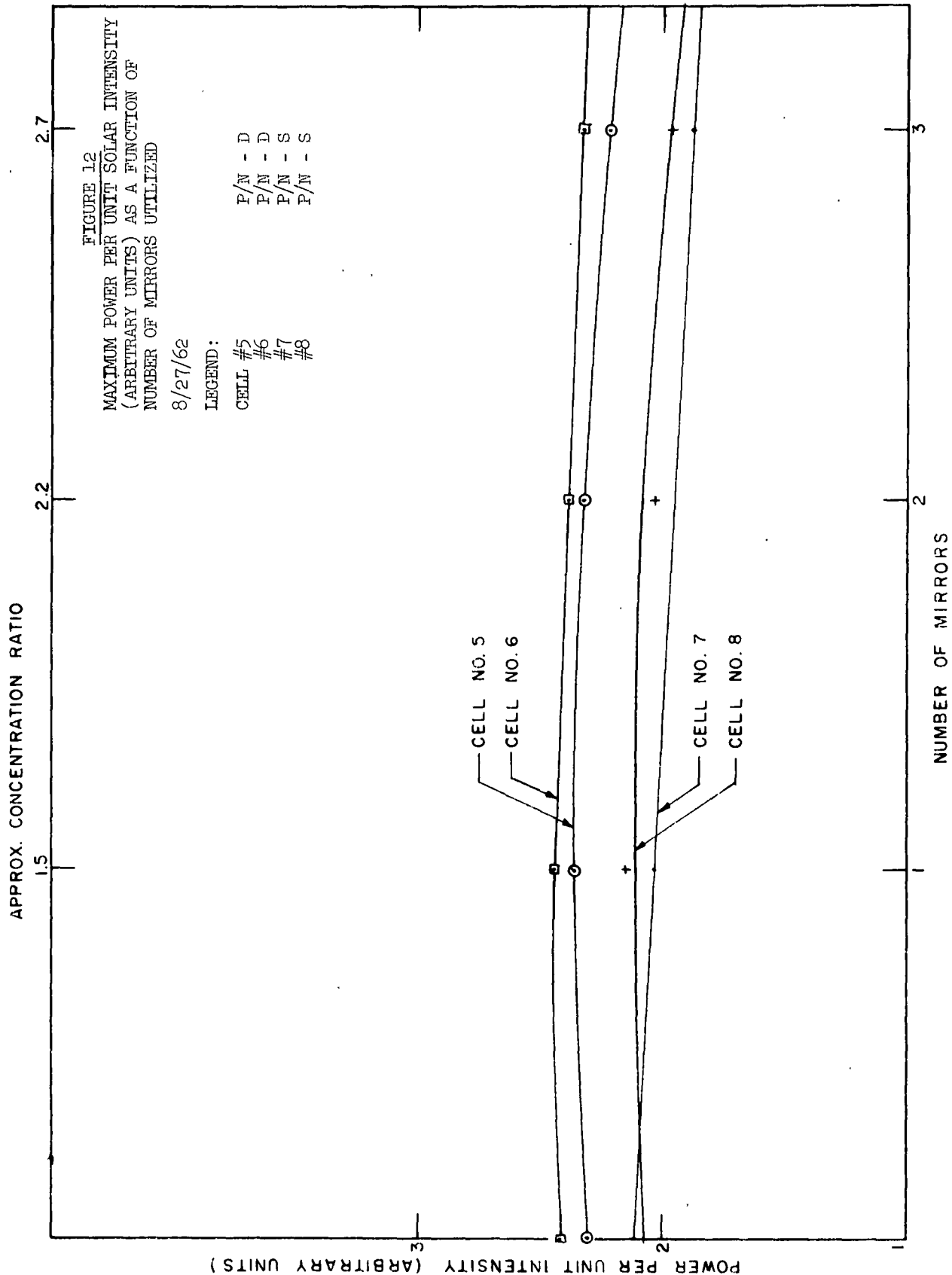
more than 10% during the test so that a fairly good basis for comparison still exists. It can be seen from this figure that the highest maximum power voltages occur for the deep diffused P/N cells and the lowest maximum power voltages occur for the shallow diffused N/P cells. The greatest relative decreases in maximum power voltage with increasing irradiance ratio occur in the N/P cells. These cells are known to have a series resistance of about 0.3Ω higher than the comparable P/N cells, due simply to the higher resistivity base material utilized in the fabrication of the cells.

It can also be seen that the deeper diffused cells maintained higher absolute values of maximum power voltages than the shallow diffused cell of the same polarity.

From the data, it was also possible to obtain the maximum power per unit solar intensity (where the unit is arbitrary) as a function of the number of mirrors utilized to concentrate the sunlight. These curves are shown in Figures 11 and 12. The maximum power per unit solar intensity was determined by dividing the maximum power obtained from each curve by the short circuit current of that curve, which has been assumed proportional to the solar intensity. Therefore, since each cell was used as its own "standard" and since the constant of proportionality between short circuit current and incoming solar intensity is not necessarily the same for each cell, the arbitrary intensity unit is different for each curve, though it is consistent throughout a specific curve. Thus, the ordinate is relative to each curve rather than absolute. On the upper abscissa of the graph the approximate concentration ratios are presented which correspond to the number of mirrors as shown on the lower abscissa.

It seems that the deep diffused N/P cells and both the deep and shallow diffused P/N cells preserve their power per unit solar intensity fairly well, over the concentration range considered, while the

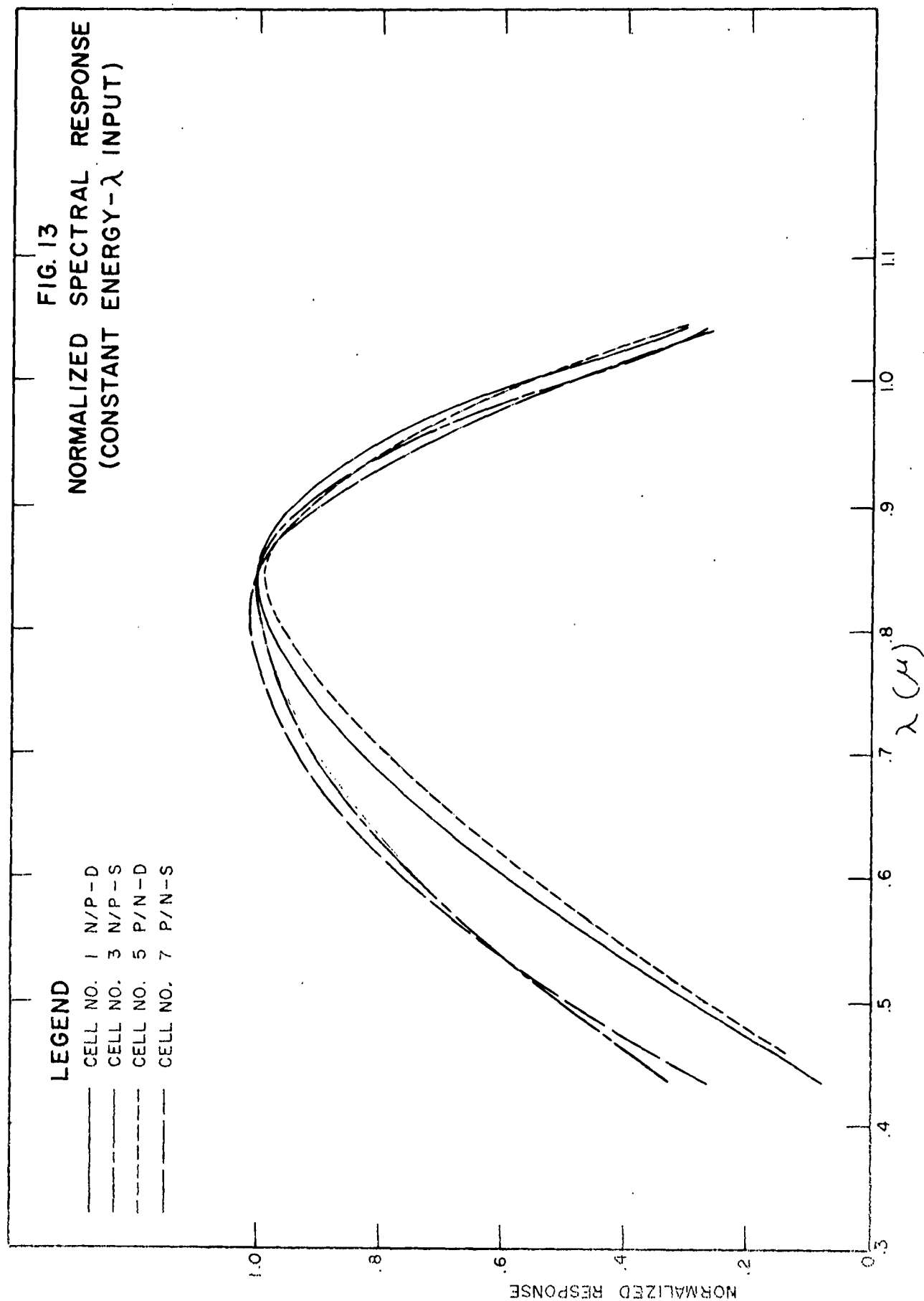


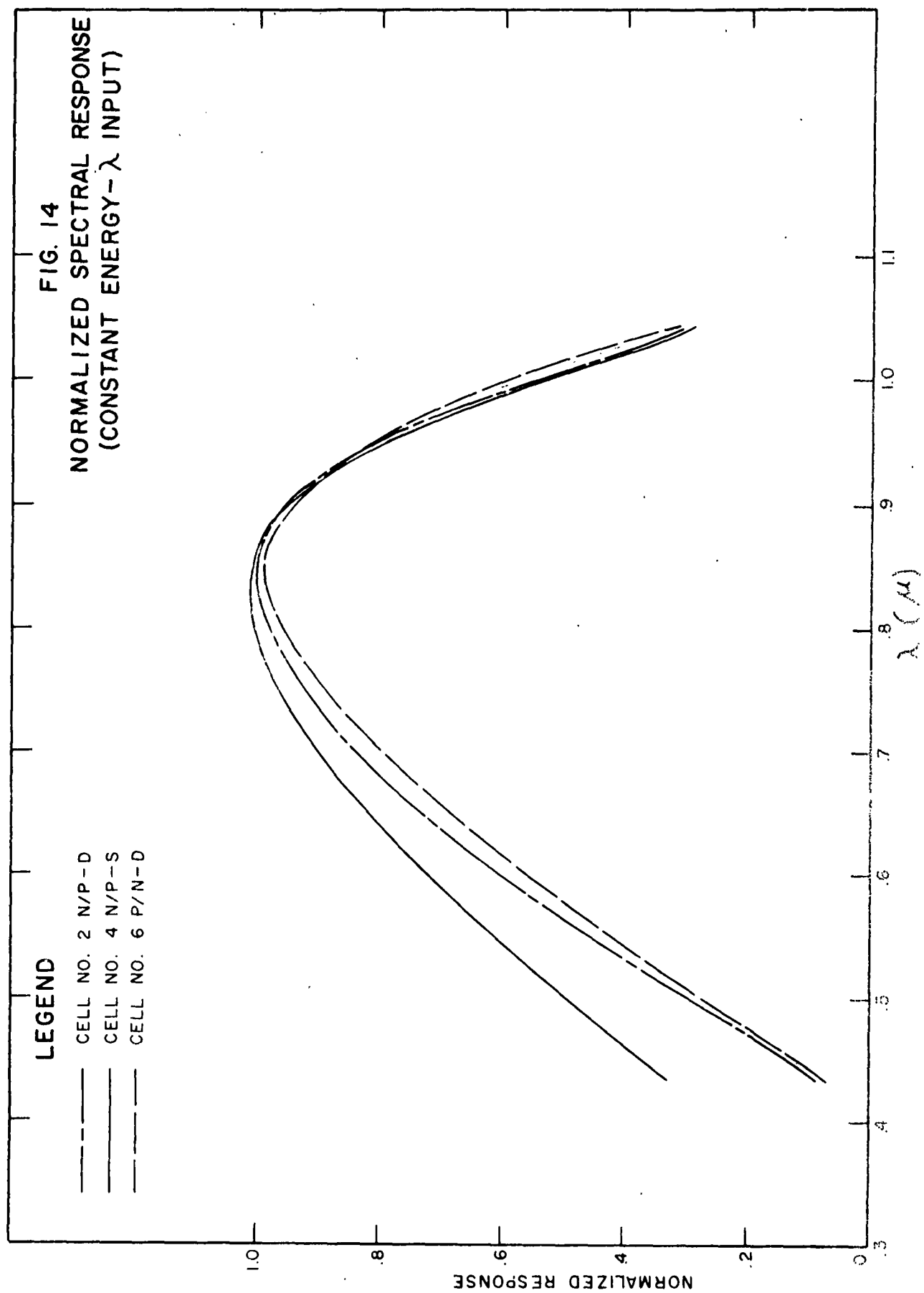


shallow diffused N/P cells decrease considerably in power per unit solar intensity.

It is believed that significant electrical resistance occurred in the jiggling set-up utilized in this experiment, thus affecting the total series resistances measured. The following method was used to determine the approximate series resistance encountered. The current voltage curves of the cell to be measured are obtained under several different light intensities. A point is marked on each curve a fixed ΔI from the short circuit current of that curve (in this case $\Delta I = 15$ mA was used.) It should then be possible to connect the marked points of all curves with a straight line. If there were no series resistance present, the line would be parallel to the current axis. If the line is not parallel to the current axis a change in voltage has occurred which is proportional to the IR drop caused by the series resistance in the cell itself and/or in the external circuitry up to the point where the voltmeter is connected to the current carrying portion of the circuit. In this experiment difficulty was experienced in the circuit resistance so that the total series resistance was about 1 ohm compared to 0.5 ohms for a typical solar cell.

Spectral response curves at a constant energy wavelength input for the cells tested above are presented in Figures 13 and 14. The responses were obtained with the Heliotech Filter-Wheel Monochromator. The shallower diffused cells show the improved response to light of wavelengths between .4 and .8 μ . The shallow diffused cells also were found to have the expected higher I_{sc} in sunlight, as can be seen from the current-voltage curves in Figs. 2-9. Thus, in designing a solar cell with lower series resistance for high light intensity applications, changes of the spectral response must be taken into consideration, especially if performance in sunlight is anticipated, if the lowering of the series resistance is attempted by variation of the junction depth.





The information thus far obtained from the above tests seems to indicate that the deeper diffused cells still show better utilization of concentrated sunlight, primarily due to the sharper break in the current voltage characteristic curve. It should be pointed out though that the shallow diffused cell can still be improved with more efficient gridding techniques, and in the case of N/P cells, utilization of base material having lower resistivity, as well. Experiments to show these effects have not been concluded as yet. If, on the other hand, the shape of the knee of the curve is a controlling factor as a result of the A-factor in the exponential term of the diode equation:

$$I = I_0 (e^{qV/AkT} - 1) \quad (\text{Eq. 2 - 1})$$

it may again be desirable to use deeper junction depths since the A-factor is thought to occur because of generation and recombination of carriers in the space-charge region and/or due to tunneling through the space-charge region. Either of these two mechanisms would be adversely affected by the formation of a junction near the surface of the material due to recombination centers introduced into the space-charge region through disturbances at or near the surface, and due to the decrease of the thickness of the space-charge when it is nearer to the surface.

It is quite possible that both the knee-shape and the series resistance of the cell strongly affect cell behavior under concentrated illumination so that it will be necessary to optimize both these cell parameters through development of the appropriate cell configuration.

3.0 SERIES RESISTANCE EFFECTS AND GRID OPTIMIZATION

3.1 SERIES RESISTANCE MODEL

In considering the behavior of a solar cell, a number of simplifying assumptions can be used over certain limits. For low light levels of about 30 mw/cm^2 the representative current-voltage relationship can be expressed as:

$$I = I_0 (e^{BV} - 1) - I_L$$

For higher light levels, between about 50 to 400 mw the effects of series resistance must be considered and the following equation is applicable:

$$I = I_0 (e^{B(V-IR_s)} - 1) - I_L$$

where I_s is a lumped series resistance approximation of the internal resistance of the cell.

For still higher light levels, probably above 400 mw/cm^2 , the distributed nature of the sheet resistance must be taken into account. The following equation is then applicable

$$I = I_0 \left\{ \exp \left[\frac{q}{AkT} (V - IR_{s2}) \right] - 1 \right\} + I_0 \left\{ \exp \left[\frac{q}{AkT} \left[V - IR_{s2} - \left(I - \frac{1}{2} I_L + I_{D2} \right) R_{s1} \right] \right] - 1 \right\} - I_L$$

where: $I_{D2} = I_0 \left\{ \exp \left[\frac{q}{AkT} (V - IR_{s2}) \right] - 1 \right\}$

In this equation two equivalent resistances are considered, one corresponding to the bulk resistance, the contact resistance, and a portion of the sheet resistance near the conducting electrode, while the other resistance corresponds to the remainder of the sheet resistance.

It should be strongly emphasized that the approximate limits over which these equations are valid are dependent upon the value of the IR_s products. As either the value of the series resistance or of load current I increases, the more complicated equations must be used. This can occur even at the somewhat lower light levels, if the values of series resistance are large.

The above equations neglect the effect of shunt resistance which is usually negligible for normal high efficiency cells, and especially at high light levels.

The effects of series resistance and the conditions under which the distributed nature of the resistance of the diffused sheet must be taken into consideration are discussed below.

The series resistance of a solar cell is an important parameter in solar cell operation and one which becomes increasingly more detrimental when the cell is operated under conditions of increased illumination. Increasing series resistance causes the maximum power point to shift to lower cell voltages. Though the experiments described in the "Concentrator" section of this report were preliminary, and the effects of individual parameters were not isolated, the indication was that the shallow diffused N+/P cells showed the worst efficiency degradation of all the cells tested under concentrated solar illumination. This was due to the higher series resistances which these cells exhibited.

In speaking of "series resistance" one must bear in mind that there are two distinct types of series resistance present in a solar cell, namely a resistance of the diffused sheet, which is a distributed resistance acting on a non-uniform current distribution and other resistances which can be "lumped" since they are uniformly traversed by the current flowing through the cell. The resistance of the diffused sheet cannot readily be lumped, since the current carriers are injected into this diffused sheet in an essentially uniform distribution with respect to planes parallel to the surface of the cell. Hence the length l , that the carrier traverses through the diffused sheet, essentially in a direction parallel to the junction plane, in order to reach a highly conducting grid or contact strip, is especially dependent on the location where the carrier enters the diffused region. From the relationship between resistance and length:

$$R = \frac{\rho l}{A} \quad (\text{Eq. 3-1})$$

where ρ is the resistivity of the material and A is the cross-sectional area, it is obvious that no single path length or associated resistance value can be ascribed to all carriers in the diffused sheet, and that

when one refers to a particular value of "resistance" in this region one refers to some sort of average or equivalent resistance, mostly based on the assumption that carriers are generated uniformly in a plane parallel to the junction plane. A model for the solar cell, which takes into account the distribution of parameters, has been proposed by Wysocki (1) and is represented by a number of infinitely small generator-diode-resistance circuits connected in parallel. From a more complete model, a simplified version of a solar cell equivalent circuit was evolved by M. Wolf and H. Rauschenbach (2) which is more amenable for analytical evaluation. In this model, two generator-diode-resistance circuits in parallel are utilized, one of these circuits including the bulk resistance, contact resistance, and a portion of the equivalent resistance of the diffused sheet near the terminal, and the other circuit including the remaining portion of the equivalent resistance of the diffused sheet. The resistance of the base region of the solar cell can be considered a "lumped" resistance because in a reasonable model, the current flow is uniform and perpendicular to the junction plane and hence most majority carriers see the same length l , namely the "thickness" of this region. Also, the contact resistances which occur at the metal-semiconductor interface of the contacts, and the resistance of the contacts themselves can be considered "lumped" resistances. Therefore it is possible to accurately represent the "lumped" resistances by a single resistance in series with the cell. It has been shown originally by Prince (3) and also in the two papers mentioned above, that the effect of adding such resistance to the cell is extremely detrimental to the shape of the current-voltage curve. At more concentrated solar intensities, another effect makes itself felt due to the distributed resistance in the diffused layer. Wysocki (1) has shown that for cells having high sheet resistance at normal light intensities the surface of the cell

- (1) The Effect of Series Resistance on Photovoltaic Solar Energy Conversion by J. J. Wysocki, RCA Review, Vol. XXII, No. 1, March 1961.
- (2) Series Resistance Effects on Solar Cell Measurements by M. Wolf and H. Rauschenbach, Pacific General Meeting of the AIEE, Salt Lake City, Utah, August 23 - 25, 1961.
- (3) Silicon Solar Energy Converters, by M. B. Prince, J.A.P., Vol. 26 No. 5, May 1955.

is no longer an equipotential surface except at values of load resistance approaching open circuit condition. (The lower the load resistance, the greater the departure of the surface from equipotentiality.) This is due to the distributed nature of the resistance such that the resistance which a majority carrier in the diffused layer sees is dependent upon its distance from a conducting contact. Thus, the potential across the diffused sheet of a solar cell will vary with distance from the conducting contacts when a current is flowing, due to the additive IR drop produced by the carriers as a function of their distribution over the surface. The potential variation will then increase with increasing sheet resistance. Due to the fact that there is a varying potential across the surface, there is a varying forward bias on the junction as a function of distance from the contact, the magnitude of the bias becoming greatest at the extremities of the cell. In general, a varying forward bias implies a varying amount of current flowing through the junction, which means, in this case, that the current flow through the junction becomes a function of distance from the contact. The potential variation along the diffused region for a current flow and sheet resistance becomes greater with an increase in light level because the increase of current flowing augments the differential IR potential drops. By creating a sufficiently high current level in the diffused region through increased illumination the condition can be reached where the potential difference across the surface of the cell is so great that part of the cell is forward biased to the extent that all the current generated in this portion flows back through the junction and this portion of the cell attains an open circuit condition by not contributing to the load current. The generation level at which such a condition would prevail is inversely related to the sheet resistance of the cell. The effect of the potential variance across the diffused sheet has been observed, manifesting itself in the departure of the proportionality of the short circuit current to the light generated current at high illumination levels (Fig. 15) (approximately 400 mw/cm^2 solar intensity for standard cells). The potential variance across the diffused sheet is

MILLI AMP
200

FIG. 15

↑ SHORT CIRCUIT CURRENT

175

150

125

100

75

50

25

0

$R = 0.38 \Omega$
CELL A-N-12

$R_s = 3.5 \Omega$
CELL A-N-16

SHORT CIRCUIT CURRENT
VERSUS SOLAR IRRADIANCE
AT DIFFERENT INTERNAL
SERIES RESISTANCE VALUES

100

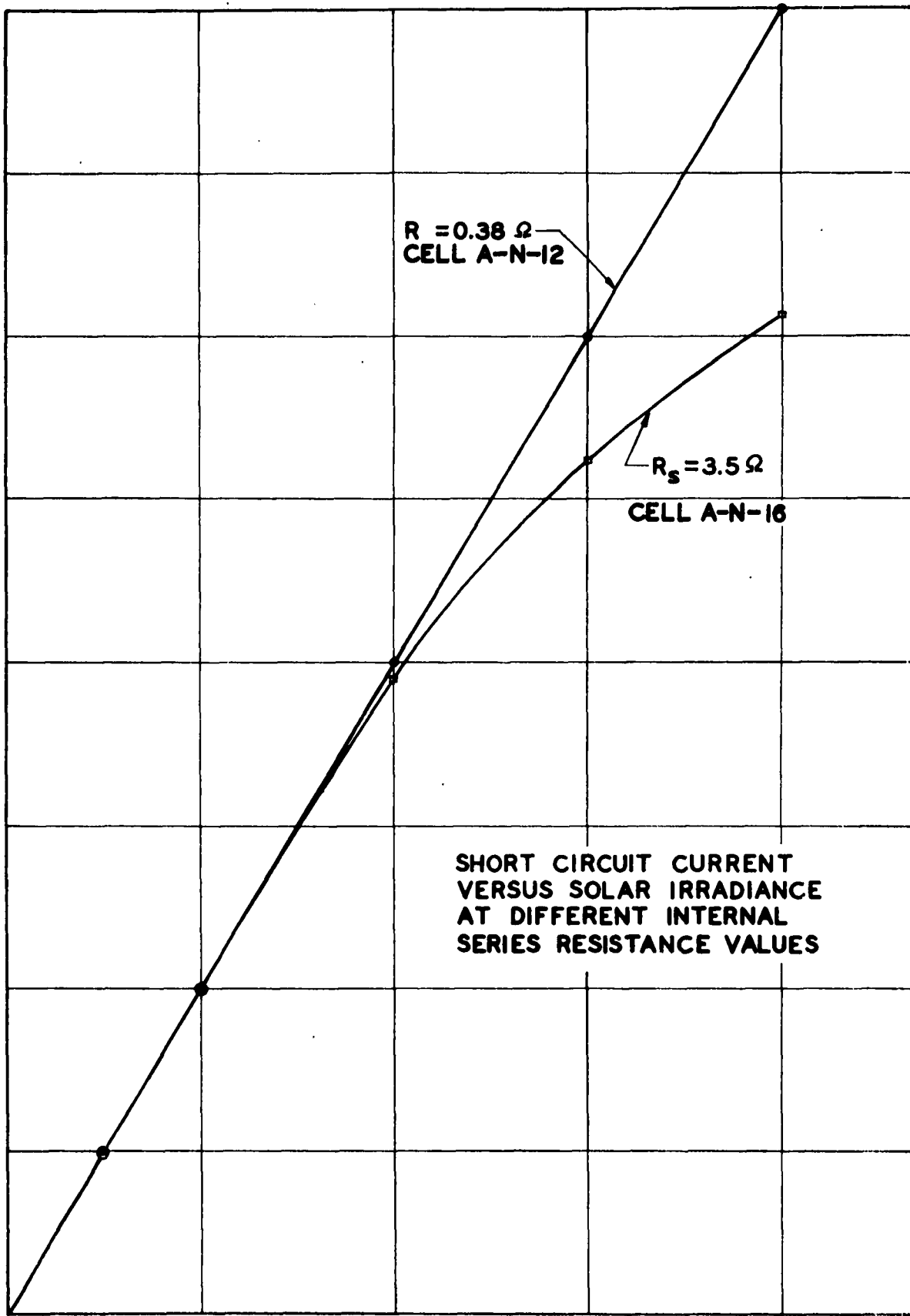
200

300

400

m^2

→ SOLAR IRRADIANCE MW CM



directly related to the amount of current flowing in the sheet. This will show up as increasing voltage losses with increased currents so that maximum power will consequently decrease.

Considering the experimental results discussed in the previous section in respect to the above discussion, it is proposed that the severe effect of higher illumination levels on the standard-diffused N⁺/P cells of the experiment was due, in part, to the higher resistivity material used to fabricate the cell. This resulted in a base resistance approximately in order of magnitude greater than that of the P⁺/N cells (10 ohm cm material compared to 1 ohm cm material). This alone would not account for all the degradations of curve shape observed, however, since the deeper-diffused N⁺/P cells which were fabricated from the same ingot, and which had approximately the same base resistivity, showed considerably less degradation. The answer obviously lies, in part, in the consideration of the sheet resistance and its distributed nature.

3.2 CALCULATION OF OPTIMUM GRID SPACING

Wolf (4) has obtained theoretical expressions for optimizing the grid thickness and spacing as follows:

$$T = 2^{5/4} \frac{\rho_T^{3/4}}{\rho_P^{1/2}} (BCj_0 e^{BV})^{1/4} W^{3/2} \quad (\text{Eq. 3-2})$$

$$S \approx \sqrt[3]{\frac{2T}{BC\rho_T j_0 e^{BV}}} - \frac{2T}{3} \quad (\text{Eq. 3-3})$$

-
- (4) Limitations and Possibilities for Improvement of Photovoltaic Solar Energy Converters, Considerations For Earth's Surface Operation, by M. Wolf, Proc. IRE, July 1964.

$$C \equiv 1 - \frac{I_0}{I_L} (e^{BV} - 1) = - \frac{I}{I_L} \quad (\text{Eq. 3-4})$$

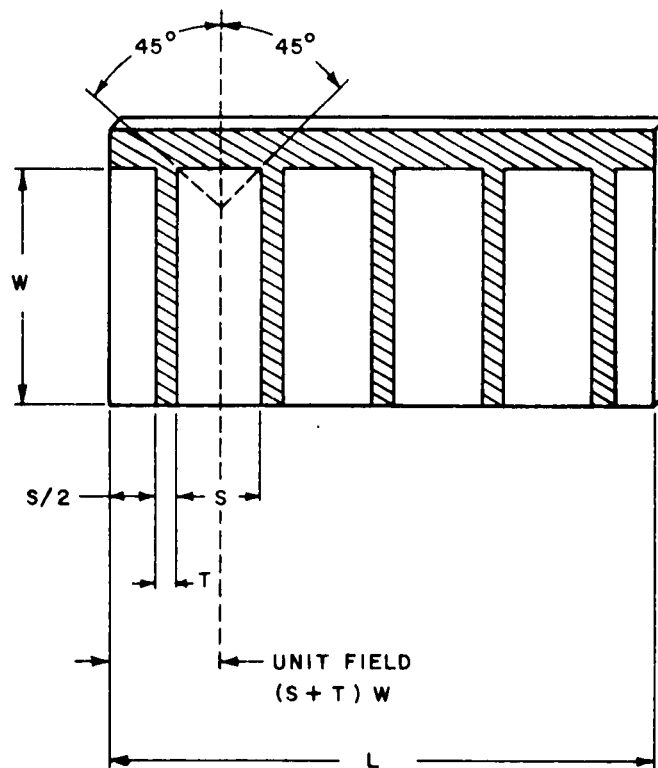
Where the following symbols are used (see Fig. 16)

- I_0, j_0 = Saturation current, total and density, respectively;
- I_L, j_L = Light generated current, total and density, respectively;
- I, I_R = Terminal current without and with series resistance respectively;
- V = Terminal voltage;
- V_0 = Open circuit voltage;
- ρ_p = Diffused layer resistance per unit thickness;
- ρ_T = Contact strip resistance per unit thickness
- T = The width of the grid strip
- $B = \frac{q}{AkT}$;
- q = Electronic charge;
- A = "A factor" which represents departure from ideal diode curve;
- k = Boltzman's constant;
- T' = Temperature in °K;
- W = Width of cell measured from the inside edge of contact strip to opposite edge of cell;
- S = Distance between grid strips measured from the inside edge of one strip to the edge of the next in a direction parallel to the contact strip.

These equations were used to calculate the optimum grid width and grid spacing on typical solar cells in the following manner:

For N/P cells the value of I_L for the entire cell has been measured at about 60 mA at a solar intensity of 100 mw/cm², while the corresponding V_0 is about .55 volts. An A factor of 2 is assumed (values of 1 to 3 are observed depending on voltage), giving a value of $B = 20$, then using the solar cell equation:

$$I = I_0 (e^{B(V-IR_s)} - 1) - I_L \quad (\text{Eq. 3-5})$$



DEFINITION OF TERMS USED IN
GRID OPTIMIZATION CALCULATIONS

FIGURE 16

in the open circuit condition we obtain:

$$I_o = \frac{I_L}{(e^{BV} - 1)} = \frac{.06}{e^{11} - 1} = 1.00 \times 10^{-6} \text{ amps.} \quad (\text{Eq. 3-6})$$

Since the typical solar cell area is approximately 2 cm^2

$$j_o = 5 \times 10^{-7} \text{ amps cm}^{-2} \quad (\text{Eq. 3-7})$$

It has been found statistically that the maximum power occurs for a standard N/P cell at a voltage of .42 volts. Using this voltage point in Equation 3-4 we obtain:

$$C_{n/p} = 1 - \frac{I_o}{I_L} (e^{BV} - 1) = 1 - \frac{4.45 \times 10^{-3}}{I_L} \quad (\text{Eq. 3-8})$$

This then gives us the quantity C as a function of I_L and the only variation of the quantities T and S with light level are seen through the quantity "C". The cell width, W, is assumed constant at 1 cm for this study.

For the P/N cells typical values of I_L and V_{oc} are .055 amps and .59 volts respectively giving rise to a j_o value of $1.88 \times 10^{-7} \text{ amps/cm}^2$. The maximum power for these cells normally occurs at a voltage of .48 volts so that C as a function of I_L , in this case, is given by:

$$C_{p/n} = 1 - \frac{5.56 \times 10^{-3}}{I_L} \quad (\text{Eq. 3-9})$$

For specific values of I_L Equations 3-8 and 3-9 can then be used in Equation 3-2 to determine the optimum grid width. The resistivity of 60/40 tin/lead solder is used in the value for ρ_T for both N/P and P/N cells. However, the sheet resistances of the two cell types are different

so that values of 60 ohms/sq and 40 ohms/sq were used for N/P and P/N cell types respectively. The width of the cell, W, is taken as 1 cm in both cases, while the values for V were .042A and .048A for the N/P and P/N cells respectively. Using these values, the following relationships between grid width, T, and the quantity C were found:

For N/P cells

$$T_{n/p} = 3.73 \times 10^{-3} C^{1/4} \quad (\text{Eq. 3-10})$$

For P/N cells

$$T_{p/n} = 4.85 \times 10^{-3} C^{1/4} \quad (\text{Eq. 3-11})$$

The values of C obtained for different I_L were then substituted into Equations 3-10 and 3-11 to give T as a function of I_L . The values of T for the various I_L and the corresponding values for C were then substituted into Equation 3-3 to determine the grid spacing, S, as a function of I_L .

Since the optimum grid thickness, T, is too narrow to be amenable to low cost production, the convenient grid width of 12×10^{-3} cm was also substituted into Equation 3-3 for all values of I_L (which varies S through the quantity C) to obtain the optimum grid spacing for this particular grid width as a function of I_L . It should be stated here that the values of sheet resistance, ρ_p , which were used in the equations were pessimistic, and hence give rise to a worse-case condition. However, this resistance enters into the calculation as a cube root so that the spacing between the grids is not quite so sensitive to changes in ρ_p , as one might expect.

The results of all these calculations are tabulated in Table I where the quantities C, T, S, and S with a value of T constant at .005" for N/P and P/N cells are shown for each value of I_L . It is again surprising

TABLE I

OPTIMIZATION OF GRID SPACING (A-FACTOR = 2)

PARAMETERS →	N ⁺ /P CELLS			S for T=.005"	P ⁺ /N CELLS			S for T=.005"
	C	T (cm)	S (cm)		C	T (cm)	S (cm)	
GENERATED CURRENT I _L (MA) ↓								
60(≈100 mw/cm ²)	0.926	3.66x10 ⁻³	0.142	0.186	0.907	4.71x10 ⁻³	0.164	0.219
80	0.944	3.68x10 ⁻³	0.141	0.185	0.930	4.75x10 ⁻³	0.163	0.217
90	0.951	3.68x10 ⁻³	0.141	0.185	0.938	4.77x10 ⁻³	0.163	0.217
100	0.956	3.69x10 ⁻³	0.141	0.185	0.944	4.77x10 ⁻³	0.162	0.216
120(≈200 mw/cm ²)	0.963	3.70x10 ⁻³	0.141	0.185	0.954	4.78x10 ⁻³	0.162	0.216
150	0.970	3.70x10 ⁻³	0.140	0.184	0.963	4.79x10 ⁻³	0.162	0.216
180(≈300 mw/cm ²)	0.975	3.71x10 ⁻³	0.140	0.184	0.969	4.80x10 ⁻³	0.162	0.216
200	0.978	3.71x10 ⁻³	0.140	0.184	0.972	4.82x10 ⁻³	0.162	0.216

to note that the parameters T and S are quite insensitive to changes in I_L over the range of values studied.

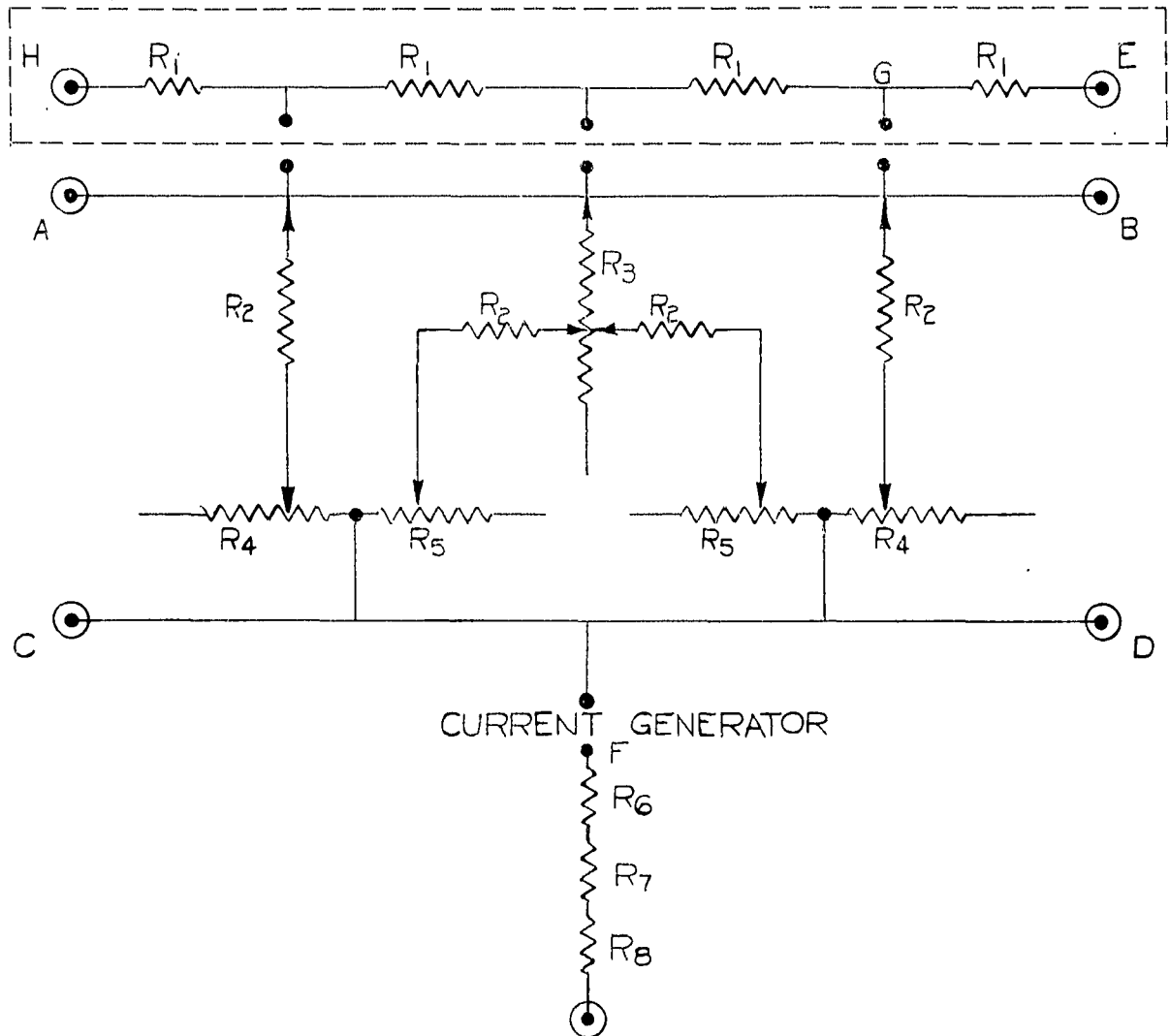
Since it has been observed that solar cells can have A-factors with values as large as 3, this value was used in the calculation for the optimum grid spacing of a P/N cell at an I_L of 60 ma. With a value of A of 3, B has a value of 13 volts⁻¹, I_0 a value of 2.6×10^{-5} amps and j_0 a value of 1.3×10^{-5} amps cm⁻². Using these values to calculate C and substituting this value for C into Equation 3-3, a value of S of .202 cm is obtained for a grid width of 12×10^{-3} cm. This compares with an S value of 0.219 for an A-factor of 2. As was noted before, the optimum grid spacing, S, is surprisingly insensitive to changes in light level. However, the grid spacing is quite sensitive to the value of the A-factor. Let us consider, for example, a value for the A-factor of unity. For a typical N⁺/P cell, this gives rise to a value of I_0 of approximately 2×10^{-12} amps by Equation 3-6. Utilizing Equation 3-3 with a grid width of .005" and a sheet resistance of 40 Ω /sq we obtain a value of S of .402 cm for an I_L of 60 ma, as compared with an S-spacing of .186 cm obtained with an A-factor of 2. This shows that the A-factor has a very strong effect on the grid spacing according to these equations. It has been shown by Wolf and Rauschenbach (2) that the A-factor is a function of voltage and varies for typical P⁺/N cells, from a value of 2.86 at voltages below about .4V to a value of 1 near and above voltages of about .6V. There is a transition region between .4 volts and .6 volts. Therefore if the maximum power voltage drops as the light level is increased, and one wishes to always operate the cell at maximum power voltage, the grid spacing should be selected accordingly. The grid spacing for an A-factor of unity was also calculated for several sheet resistances such as: .512 cm for $\rho_p = 20 \Omega$ /sq, and .645 cm for $\rho_p = 10 \Omega$ /sq.

For N⁺/P cells, an A-factor of 1 gives rise to an I_0 of 1.7×10^{-11} amps. For sheet resistances of 60, 30, and 15 Ω /sq this gives S spacings of .381, .482 and .611 cm respectively.

In order to derive his equations for minimization of S and T , Wolf (4) considered only the resistances present in the diffused layer and the conducting metallic grids. He implicitly assumed the other series resistance elements of the cell to be negligible compared to the resistance of the diffused layers. Wolf further assumed that all current flow from the diffused layer takes place to the grid lines only, and he neglected any direct flow to the major contact strip in order to obtain an analytically simpler expression. The latter assumption may lead to errors in some special cases. For instance, the effect of placing the contact strip down the middle of the cell rather than along one edge may not be entirely predicted because of this assumption. The advantage of this placement is that with the same active area, the average path length to the major contact strip is cut in half for the carriers in the diffused region. This comes about because the conducting strip would then be collecting from both sides rather than only one. Of course, even greater advantage could be realized if the conducting strip could then be made narrower (yet wide enough to efficiently carry all the current generated in the diffused region) since the active area would be increased. The contact strip will preferentially collect carriers which are closer to it than to a grid strip, and such carriers are contained in an area determined by a line drawn bisecting the right angle formed by the intersection of the grid strip and the contact strip (see Fig. 16). If the width of the cell is smaller than half the distance between the grids, the contact strip will actually collect more carriers from the diffused sheet than will the grid strip. When this condition is reached, there is no advantage in using grids.

A more detailed equivalent resistance circuit which is useful for studies at high light intensities is presented in Fig. 17. This configuration takes into account current collection by the contact strip and the resistance in the base region of the cell, R_6 as well as contact resistances to the grids and contacts R_2 , R_7 respectively. The concept

EQUIVALENT RESISTANCE OF A SOLAR CELL UNIT FIELD



- $4R_1$ = Resistance of contact strip
- R_2 = Contact resistance between diffused region and electrodes
- R_3 = Resistance of grid strip
- R_4 = Resistance of diffused region for carriers flowing to contact strip
- R_5 = Resistance of diffused region for carriers flowing to grid strip
- R_6 = Resistance of bulk region
- R_7 = Contact resistance of bulk region to bottom electrode
- R_8 = Resistance of bottom electrode

Figure 17

of the "unit field" cell as defined by Wolf has been adopted here. In utilizing such a model, the cell is broken down into the smallest system which will allow the generation of the entire cell by addition of the appropriate number of such systems. Variable resistance symbols are used in places where the resistance value is likely to be varied in this study, however, for a specific solar cell these resistances have specific values.

Fig. 17, exclusive of the portion within the dotted rectangle, depicts the case where the cell is used in a shingle configuration. The line AB represents the contact strip which presents no resistance to the current flow in this configuration. Additional fields are added by connecting the B contact with the A contact of the next field, and the point D of the circuit to the point C of the next field. The resistances in the base are common to all the fields, and are connected in series to the equivalent resistance of all the fields comprising the cell. That is, all the diffused layer fields are connected at F.

For the case where the cell is to be used in a shingle configuration the equivalent resistance of one solar cell unit field is given by:

$$R_{Ts} = \frac{R_2 + R_4}{2 + \frac{R_2 + R_4}{R_3 + \frac{1}{2}(R_2 + R_5)}} + R_6 + R_7 + R_8 \quad (\text{Eq. 3-12})$$

If the cell is not operated in a shingle array, however, and a lead is attached at point A, the proper representation of the conduction strip is given by the line HE as shown in the dotted rectangle. This would replace contact line AB of the shingled-cell model. This says that carriers which have been collected by the grid, and consequently have passed through a resistance R_3 , must pass through an additional resistance $2R_1$. Carriers created in the sheet to the left of the grid strip which are collected by the contact strip will see an average resistance of approximately R_1 . It is assumed here that the contact strip is almost an

equipotential and that the current distribution is fairly uniform along its length. Similarly, carriers collected by the contact strip to the right of the grid strip see a resistance of $3R_1$ in the contact. The equivalent resistance of one field when the lead connection is made at point H (and assuming area contact made to base) is given by:

$$R_T = R_1 + \frac{\left\{ 1 + \frac{R_1}{R_3 + \frac{1}{2}(R_2 + R_5)} + \frac{R_1}{R_1 + R_2 + R_4} \right\} (R_2 + R_4)}{2 + \frac{R_1 + R_2 + R_4}{R_3 + \frac{1}{2}(R_2 + R_5)}} + R_6 + R_7 + R_8 \quad (\text{Eq. 3-13})$$

The R_1 between points E and G enters into the picture only when another field is connected to the right (i.e. to points E and H). In this case, current would also flow through this R_1 which is then in series between the two parallel connected diffused layer fields.

By utilizing these equations it should then be possible to optimize the grid spacing to obtain the most advantageous configuration. Unfortunately, it will not be enough to simply minimize R_{Ts} as this would undoubtedly result in a cell which had 100% of its surface covered with contacts. An optimum trade-off between minimum resistance and maximum current generation must be calculated. This can be done by obtaining the resistance R_{Ts} as a function of the spacing, S , between the grids and substituting this into the following equation:

$$I = I_0 \left[(e^{B(V - IR_{Ts}(S))})_1 \right] - I_L \quad (\text{Eq. 3-14})$$

Then by setting the derivative of I with respect to S equal to zero, the optimum S can be found for specific values of all other parameters.

It should be noted here that because we are optimizing the grid spacing

to provide low series resistance under the light intensities at which the cells are to be used, the diffused region should be approximately equipotential across its entire area. In this case it would then be possible to consider the resistance in the diffused sheet as an average lumped resistance. That is, it should not be necessary to consider a distributed resistance model in this case. If, however, the resistance is high enough to require a distributed resistance model for the diffused layer, the equations would be extremely difficult to solve.

The component resistances which are shown in Fig. 17 can be isolated and theoretically or experimentally determined. The conducting electrodes are assumed to have essentially, the resistivity of 60/40, lead/tin solder. Using the definition $R \equiv \frac{\rho L}{A}$, the resistance can be calculated by simply measuring the thickness, length and width of the electrode (or grid strip). The resistance of the silicon in the base region can be found by utilizing the 4-point probe method to determine the resistivity and the measured dimensions to determine the resistance. The sheet resistance of the diffused layer can also be obtained by means of 4-point probe measurements and the appropriate mathematical correction factors. The contact resistance to the base region can be found by simply depositing metal contacts uniformly over both sides of a silicon wafer whose resistance is known (using the relationship $R = \frac{\rho l}{A}$), subtracting the resistance of the silicon from the total measured resistance of the wafer, and dividing by 2 (since contacts were applied to 2 surfaces). The contact resistance to the diffused layer can be obtained by diffusing the impurity normally used in the fabrication of the cell being studied into a silicon wafer of known resistance and of the same type as the diffusant impurity. (i.e. diffuse P type dopant into known resistivity P-type material.) The contact resistance to the diffused layer can then be obtained by depositing the contacts uniformly over both surfaces, measuring the total resistance, subtracting the resistance of the silicon wafer and dividing by 2.

Experiments of this type have been done and qualitative results are presented below'. Work is still being done to obtain accurate quantitative values for each of these resistances.

The larger and consequently the most important resistances observed in typical solar cells were R_4 , the resistance of the diffused region for carriers flowing to the contact strip, R_5 , the resistance of the diffused region for carriers flowing to the grid strip (these two resistances are equal only for specific cases), and R_6 , the resistance of the bulk region. The contact resistance of the bulk region to the bottom electrode, R_7 , can be appreciable if high resistivity (of the order of $20 \Omega \text{ cm}$) material is used in the base region. The resistances of the contact strip, R_1 , of the grid strip (providing the strip has a width greater than .002"), R_3 , of the contact between the diffused region and the metallic conducting electrodes, R_2 , and of the bottom electrode, R_8 , are all small and can usually be neglected.

Experiments to obtain numerical values for the component series resistances will be performed in the next period to verify the previous work and to provide additional information with regard to N/P cells.

4.0 COST FACTORS

One of the prime considerations of this contract is solar cell cost. If the yield of high efficiency solar cells could be increased with little or no additional fabrication expense, the cost per cell would, of course, be reduced. Such would be the case for example, if it were found that cells having greater junction depths were comparable to shallow-diffused cells at concentrated solar intensities at the earth's surface. Because of the greater depth the junction would most likely be less vulnerable to damage and to detrimental surface effects encountered during fabrication.

Another cost-factor in the fabrication of silicon solar cells is the cost of the single crystal silicon utilized in the fabrication of such cells. Consequently, cells were fabricated from lower cost polycrystalline material to determine the applicability of this type of material to the fabrication of solar cells.

The polycrystalline material utilized in these experiments was cut from reactor grown ingots which are formed in the purification of the raw material. The polycrystalline silicon is in the form of cast rod and is highly densified. The single crystalline grain diameters are about 2 - 3 millimeters for the most part.

At first it was thought that it would be necessary to eliminate the grain boundary effects by gridding the active surface of the cells with conducting strips about 2 mm apart in the vertical and horizontal directions to effectively connect all the single crystal grains in parallel with one another. By gradually increasing the grid spacing, however, it was found that the efficiency actually improved due to the increased active area of the cell surface, until finally, the standard 5-line grid was utilized. The highest efficiency cells were

obtained with this grid configuration. Efficiencies of N/P solar cells as high as 8% at intensities of 100 mw/cm² have been obtained, with most of the cell efficiencies falling between 6 - 8%. The short circuit currents range between 43 and 48 milliamps, and the open circuit voltages are between 0.45 and 0.50 volts.

These cells look promising for lower efficiency, low-cost applications and might very well be utilized in terrestrial applications.

CONCLUSIONS

On the basis of the preliminary experiments thus far performed the cells diffused deeper than standard shallow-diffused commercial cells have higher efficiencies under solar intensities of about 300 mw/cm^2 . Whether this is due to a series resistance effect or an A-factor effect has not been determined. If this effect is due primarily to lower resistance in the diffused region, the standard, shallow-diffused cells should have the greatest potential under concentrated solar intensities with proper gridding since these cells had the highest short circuit currents.

If, on the other hand, the superiority of the slightly deeper diffused cells is due to a lower A-factor at maximum power voltage, it may be more desirable to diffuse deeper, obtain the lower A-factor and sacrifice some short circuit current. Cost-wise there should also be an advantage to fabricating deeper-diffused cells since a higher yield can be expected. (The junction would not be so vulnerable to damage).

It has been found through utilization of theoretical equations that the optimum grid spacing is most sensitive to the value of A-factor used, and quite insensitive to light level values if all other parameters are kept constant.

Fabrication of solar cells from polycrystalline base-material has shown promising results giving rise to solar cells having efficiencies in the 6 - 8% range.

PROGRAM FOR NEXT INTERVAL

Concentrator experiments will be continued in order to determine the effects of concentrated solar illumination on N/P and P/N cells of various configurations. Series resistance in the measuring circuit will be further reduced so that measurements of cell characteristics are attributable only to the cell itself. A calibrated standard cell will be utilized in order to determine the actual light intensity impinging on the cells in the concentrators. This will provide absolute comparative values as opposed to the relative values obtained in the first experiments. Evaluation of solar cell performance under concentrated solar illumination as a function of junction thickness will be continued in order to accumulate statistical data.

Theoretical studies of series resistance effects will be continued and an attempt will be made to carry through a more complete analysis of the solar cell equivalent resistance circuit which will lead to a more thorough understanding of the effects of the component resistances. From this study it should be possible to verify the results obtained to date or obtain more accurate relationships that will result in a more effective grid configuration. The optimum grid configuration for approximately 250 mW solar intensity as calculated and presented in this report will be evaluated experimentally by comparing cells having this configuration to cells having the standard five-line grid configuration (but otherwise processed in exactly the same manner) under concentrated solar illumination.

A polyvariable statistical experiment will be performed in which the two variables, junction depth and grid spacing, will be studied and analyzed in order to determine a trend leading to mutual optimization of those variables.

Work will be done to improve efficiencies and yields by investigating processing techniques and making such changes that give added control and decrease distribution spread. These studies will also consider changes in processes that will decrease cell manufacturing costs.

IDENTIFICATION OF KEY TECHNICAL PERSONNEL

The following engineering hours of work were performed during this reporting period:

M. Wolf	13 hours
E. Ralph	12 hours
P. Berman	391 hours
R. Handy	88 hours
P. Rolik	112 hours
S. von Szeremy	96 hours

There were also 985.5 hours of work performed by various other Heliotek personnel, such as Engineering Aides and Technicians, in collecting and presenting the data contained in this report.

Brief resumes of the background of key personnel involved in this work are shown in the following pages.

Martin Wolf, General Manager

Martin Wolf was born in Wuppertal, West Germany, on August 2, 1922. He received the Vordiplom Physiker degree (equivalent to B.S. Physics) in 1948, and the Diplom Physiker degree (equivalent to M. S. Physics) in 1952, both from the Georg August University in Goettingen, West Germany.

From 1943 to 1945, he designed power distribution systems for the Allgemeine Elektrizitaets Gesellschaft, Duesseldorf, Germany. From 1950 to 1952, he developed microwave measuring equipment at the Georg August University and carried out research concerning the input impedances of different antenna configurations in the microwave region. In 1952, he joined the Admiral Corporation in Chicago, Illinois, where, as Project Engineer, he was in charge of the development of UHF television tuners and transmitters. From 1955 to 1961, Mr. Wolf was associated with the Semiconductor Division of Hoffman Electronics Corporation in Evanston, Illinois and later in El Monte, California. He carried out research and development work on various silicon diffused junction devices and on general semiconductor problems. As Manager of the Special Projects Section from 1958 to 1961, he was responsible for all research and development activities of that company in the field of photovoltaic devices. Since 1961, Mr. Wolf has been General Manager in charge of Heliotek, Division of Textron Electronics, Inc., in Sylmar, California.

Mr. Wolf is a member of the American Physical Society, the Association for Applied Solar Energy, the American Rocket Society, the Electrochemical Society, and senior member of the Institute of Radio Engineers. He is co-recipient of the Marconi-Award for 1958 of the British IRE for a paper on "New Developments in Photovoltaic Devices".

Publications

"Design of Silicon Photovoltaic Cells for Special Applications".

AIEE-IRE Semiconductor Devices Research Conference in

Boulder, Colorado, July 15-17, 1957

Contributed paper. Not printed.

"New Developments in Silicon Photovoltaic Devices and Their Applications To Electronics".

M. Wolf and M. B. Prince

Congress for Solid State Physics and its Applications in Electronics and Communications in Brussels, Belgium, June 2-7, 1958

Contributed paper; Academic Press, Inc., New York, N.Y. 1960. Vol. 2

"New Developments in Silicon Photovoltaic Devices"

M. B. Prince and M. Wolf

Invited paper; Jour. Brit. IRE, Vol. 18, pp. 583-595; october 1958.

"Solar Energy".

Fall Symposium of the North Carolina Section of the IRE in Winston-Salem, N. C., October 17-18, 1958. Invited Paper. Not printed.

"New Developments in Solar Batteries".

AIEE - Winter General Meeting in New York, N.Y., February 3, 1959

Invited paper. Not printed.

"New Developments in Photovoltaic Solar Energy Conversion".

Colloquium of the National Research Council of Canada in Ottawa, Canada, May 1, 1959.

Invited paper. Not printed.

"The Present State of Photovoltaic Solar Energy Converters and Possibilities for Their Improvement".

National Electronics Conference in Chicago, Ill., October 12-14, 1959.

Invited paper. Proceedings of the National Electronics Conference, Vol. 15, pp. 226-240.

"Limitations and Possibilities for Improvement of Photovoltaic Solar Energy Converters. Part 1: Considerations for Earth's Surface Operation".

Contributed paper. Proc. IRE, vol. 48, May 1960 (to be published).

"Photovoltaic Solar Energy Converters and Their Technology".

Colloquium of the Electrical Engineering Dept., University of Wisconsin, Madison, Wisconsin, March 24, 1960.

Invited paper. Not printed.

"Photovoltaic Solar Energy Converters".

Los Angeles Section of the Institute for Environmental Sciences, April 4, 1960.

Invited paper. Not printed.

"Recent Advancements in Solar Cell Technology".

1960 American Society of Mechanical Engineers, Semi Annual Meeting and Aviation Conference in Dallas, Texas, June 5-9, 1960.

Invited Paper.

"Advances in Silicon Solar Cell Development".

The Space Power Symposium of the American Rocket Society, Santa Monica, California, September 27-30, 1960.

Invited Paper. To be published as paper #1289-60 in Vol. #3 of the ARS Progress Series., Academic Press, New York

"Reliability Aspects of Secondary Power Supplies for Space Vehicles

"Using Photovoltaic Energy Converters".

Seminar on Reliability in Space Vehicles, Los Angeles, California December 5, 1960.

Invited paper. Not printed.

"The Present State-of-The-Art of Photovoltaic Solar Energy Conversion".

1960 Winter Convention on Military Electronics, February 1-3, 1961, Los Angeles, California. Invited paper.

Published in Solar Energy, Vol. V, #3, July-September, 1961.

"Developments in Photovoltaic Solar Energy Conversion for Earth Surface Applications".

United Nations Conference on New Sources of Energy, Rome, Italy, August 21-31, 1961.

Contributed paper. Preprints available.

"Series Resistance Effects on Solar Cell Measurements".

M. Wolf and H. Rauschenbach

Presented at the 1961 Pacific General Meeting of the AIEE at
Salt Lake City, Utah, August 23-25, 1961.

Invited paper. Not printed.

Eugene L. Ralph, Manager Device Development

Mr. Ralph was born in Mineral Point, Wisconsin, where he completed grade and high school. He attended Platteville State College, Wisconsin, for one year and studied chemistry and mathematics. He received a BS degree in Chemical Engineering at the University of Wisconsin in 1953 and in 1959 took one year of graduate work in Business Management at the University of Chicago.

From June, 1953, to January, 1954, he was a Chemical Engineer for Phillips Chemical Company in Pasadena, Texas, where he did plant layout, piping design and structural design for a new plant installation.

He was a Lieutenant in the U. S. Air Force from January, 1954, to January, 1956, and did vacuum tube research at the Air Force Cambridge Research Center. This work involved design of special vacuum tubes and studies of grid emission properties of various metals and investigations of ceramic type cathodes made from sintered titanium dioxide. A special design cathode ray vacuum tube for airplane flight pattern control was designed and built. Material studies for vacuum tube components were also made.

From January, 1956, to February, 1961, he was in the Research Department of Hoffman Electronics Corporation's Semiconductor Division. Much of his time was devoted to the development of new and improved methods and techniques for fabricating of semiconductor devices. Plating techniques for making good ohmic contacts to silicon were investigated. For two years he was directly associated with solar cell development. Diffusion processes and fabrication techniques were studied in order to promote the solar cell state-of-the-art and significant improvements were obtained. Studies of low light level solar cells and photodiodes were also studied. Processes for making a large area solar cell from spheres of silicon were developed. He was Project Supervisor for a Signal Corps contract which sponsored this

work and was also Project Supervisor for an Air Force contract to develop a pilot line for making 12% efficiency solar cells with a 70% yield. This involved spectral response measurements and testing correlations in order to determine the cell output in space. Solar cell reflection and absorption studies were studied in the course of this contract

He has filed six patent disclosures with one patent issued, and has made numerous other patent disclosures.

As Manager of Device Development of Heliotek, Mr. Ralph is in charge of development of new solar cell designs and process improvement. This involves a study of the effects of radiation on conventional solar cells and cells made by using new methods. Studies of other semiconductor devices are also being made.

Professional affiliations are the American Chemical Society, The American Rocket Society and the Electrochemical Society. In 1958 he was the co-author of a paper published in The Journal of Applied Physics entitled, "Ohmic Aluminum-n-type Silicon Contact". He also co-authored a paper given at the Columbus, Ohio, Electrochemical Society Meeting in 1959 entitled, "A Low Resistance Ohmic Contact For Silicon Semiconductor Devices". This paper was published in The Solid-State Electronics in 1961.

Paul Berman, Senior Engineer, Device Development

Mr. Berman attended Brandeis University in Waltham, Massachusetts where he majored in Physics, receiving his B.A. degree in 1958. He did graduate work with emphasis on solid state physics, at Tufts University in Medford, Massachusetts during 1959 and 1960, receiving his M.S. degree in Physics. During this period he served as a laboratory instructor and research assistant at Tufts University. In the summer of 1959 he was employed as a physicist at the High Temperature Branch of the Watertown Arsenal in Watertown, Massachusetts, where he did research work on high temperature refractory materials. In May of 1960 he joined the research department of Transition Electronic Corporation where he did work on high efficiency solar cells, and radiation damage effects in solar cells. He developed and put into pilot line production radiation resistant n on p cells, eventually becoming solar cell project leader.

On October 20, 1960, he presented an invited paper entitled "Radiation Damage in Silicon Solar Cells Using 750 Kev and 2 Mev Electrons" at a meeting on "Radiation Damage to Semiconductors by High Energy Protons" in Washington, D. C., sponsored by the National Aeronautics and Space Administration. He also presented an invited paper entitled "Recent Advances in n on p Solar Cells" at the 15th Annual Power Sources Conference in Atlantic City, New Jersey.

At the present time he is employed at Heliotek as Senior Engineer in the Device Development Department, as Project Engineer on this contract.

He is a member of Sigma Xi and the American Rocket Society.

Roland J. Handy, Sr. Engineer, Device Development

Mr. Handy attended the University of California at Los Angeles, receiving a B. S. degree in Physics in 1958. He did graduate work during 1959 and 1960 receiving his M. S. degree in Applied Physics in the field of acoustics.

During the years 1953 to 1956 he taught electronics at Fort Bliss, Texas Army Electronics School. During the summer of 1958 he was employed by the Bendix Computer Division where he developed the Computer Logic for the Bendix G-15 PR Reader Input System. In 1960 he was employed by the Bendix Pacific Corporation in the A.S.W. Branch where he did theoretical, research and development work on the Acoustical properties of Piezoelectric materials as used in transducers for under water acoustics. Here he developed a method of utilizing the Smith Chart in the development of piezoelectric longitudinal vibrators. He also wrote a paper on the "Theoretical Analysis of Piezoelectric Bimorph Transducers" which is to be published.

He also is a member of the Physics Staff at Los Angeles Valley College, in the capacity of an instructor of Physics.

He is a member of Sigma Pi Sigma and the American Physical Society.

Presently he is employed at Heliotek and is working toward his Ph.D. in Applied Math at the University of California at Los Angeles.

Geza P. Rolik, Jr., Engineering, Device Development

Mr. Rolik was born in Chicago, Illinois where he completed grade and high school and later attended Wright Junior College and De Paul University School of Liberal Arts for two years. He received a B. Mus. degree in music theory and musicalogy from Chicago Conservatory of Music in 1956 and an M. Mus degree (Magna Cum Laude) from the same institution in 1957. Mr. Rolik has also done work in Mathematics and Physics at Illinois Institute of Technology and the University of Southern California.

From July 1951 to July 1954 he was a Sergeant in the U. S. Army Signal Corps and attended the Signal School at Ft. Monmouth, New Jersey, taking courses in field radio repair and fixed station operation and maintenance. He served with the Eighth Army in Korea from May 1952 to October 1953 as a UHF Fixed Station operator.

In January of 1956 Mr. Rolik joined the Research and Development Department of Hoffman Semiconductor Division, where he did original work on Zener Regulators and Zener Diodes and on high voltage transistors. Upon transfer of the Division to El Monte, California, he joined the Transistor Development group and aided in the development of a high frequency mesa transistor.

In April of 1960 he joined Giannini Controls Corporation Research Labs where he did developmental work on piezorestivity of silicon and compound semiconductors, plus basic research on the properties of Cadmium Sulfide. He submitted several patent disclosures, two of which are being applied for at the present time.

Mr. Rolik is presently employed as Engineer in Device Development with Heliotek and does development work on semiconductor devices and processes.

Sigmund von Szeremy, Jr. Engineer, Research and Development

Born in Hamburg, Germany, he attended grade school there and (due to evacuation of children during World War II) in Budapest, Hungary. He matured at Budapest 6th District Gymnasium and went on to the University of Heavy Industry, Miskolc, Hungary. Political events in that country led to his expulsion from the University and imprisonment.

Upon entering the United States in 1957, he received a Rockefeller Foundation Grant for language studies, which were completed at St. Michael's College, Winooski, Vermont. Another scholarship sent him to Luther College, Decorah, Iowa, where he spent one year.

Hired by Yale University Medical School, he designed and worked on electronic training and research equipment. After hours interests brought him into close working relationship with the R and D Department of Bradley Semiconductor Corporation, New Haven, Connecticut. He joined that company in 1959, where he took part in the development of Bradley silicon diodes.

Presently at Heliotek, Mr. von Szeremy is working on process and methods development.

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