CONTRACTOR REPORT

SAND82-7134
Unlimited Release
UC-63d

PV Cell Data Reduction Computer Program

T. J. Lambarski
The BDM Corporation
1801 Randolph Rd SE
Albuquerque, NM 87106

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789

Printed November 1981

When printing a copy of any digitized SAND Report, you are required to update the markings to current standards.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.
NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A06
Microfiche copy: A01

SAND82–7134
Unlimited Release
Printed November 1981

Distribution
Category UC–63d

PV Cell Data Reduction Computer Program [redacted]

T. J. Lambarski
The BDM Corporation
1801 Randolph Rd SE
Albuquerque, NM 87106

Abstract

In this document BDM presents the details of a computer program to unfold current versus voltage (IV) data from a photovoltaic cell or module. IV data from both forward and reverse bias is used to calculate parameters such as series resistance, saturation current, shunt resistance, and junction emission constant. Standard deviations of calculated parameters are listed, and a plot of a calculated IV curve overlaying the empirical input data is produced.

FOREWORD

This report, BDM/A-81-549-TR, was prepared by The BDM Corporation, 1801 Randolph Road S.E., Albuquerque, New Mexico 87106, for Sandia Laboratories, Albuquerque, New Mexico under contract number 62-0214.

The Sandia technical project manager was C. B. Rogers. The BDM program manager was T. J. Lambarski, who also performed the PV cell modeling. Computer programming and implementation were accomplished by A. F. Malmberg, W. M. Resnik, R. W. Wolf, and R. Rodriguez. Computer runs were made by D. B. Adamson. This document was written by T. J. Lambarski.

TABLE OF CONTENTS

Chapter		Page
I	INTRODUCTION	I-1
	A. BACKGROUND--PROBLEMS IN DATA REDUCTION	I-1
	B. CODE DEVELOPMENT SUMMARY	I-2
II	PROGRAM FORMULATION	II-1
	A. PV CELL MODEL AND EQUATIONS	II-1
	B. PROGRAM CAPABILITIES AND LIMITATIONS	II-7
	C. DATA REDUCTION INPUT FORMAT	II-10
	D. CAUTIONS	II-13
III	DATA REDUCTION USING PV-TAP	III-1
	A. USER INTERFACE INSTRUCTIONS	III-1
	B. PV-TAP DATA REDUCTION EXAMPLES	III-1
IV	DATA REDUCTION USING PVDR	IV-1
	A. USER INTERFACE INSTRUCTIONS	IV-1
	B. PVDR EXAMPLES	IV-1
V	EXAMPLES OF DATA REDUCTION	V-1
	A. FLAT PLATE CELL AND MODULES	V-1
	1. Cell Data	V-1
	2. Modules	V-21
	B. CONCENTRATOR CELLS AND MODULES	V-32
	1. Cell Data	V-32
	2. Modules	V-32

LIST OF ILLUSTRATIONS

Figure		Page
II-1	PV Cell Model	II-1
II-2	Typical Illuminated Forward I-V Characteristics	II-4
II-3	Typical Dark Reverse I-V Characteristics	II-5
II-4	Typical Dark Forward I-V Characteristics	II-6
II-5	Reverse I-V Curve with Reversing Slope	II-16
II-6	Reverse I-V Curve with Step Increase	II-17
II-7	Dark Forward with No Series Resistance Effect	II-18
II-8	Illuminated I-V Curve with Decreasing Current at Short Circuit	II-20
II-9	Illuminated I-V Curve for Module with Possible Bypass Diode Effect	II-21
III-1	Illuminated Forward Cell I-V Curves	III-3
III-2	Dark Reverse Cell I-V Curve	III-4
III-3	PV-TAP Plot for Illuminated Forward Cell Data Reduction	III-9
III-4	PV-TAP Plot for Dark Reverse Cell Data Reduction	III-11
III-5	Dark Forward Cell I-V Curve	III-12
III-6	PV-TAP Plot for Dark Forward Cell Data Reduction	III-16
III-7	PV-TAP Plot for Illuminated Forward I-V Curves from Dark Forward Data Reduction	III-17
IV-1	PVDR Plot for Dark Reverse Cell Data Reduction	IV-6
IV-2	PVDR Plot for Illuminated Forward Cell Data Reduction	IV-8
IV-3	PVDR Plot for Dark Forward Cell Data Reduction	IV-10
V-1	Illuminated Forward Cell I-V Curves	V-2
V-2	PV-TAP Plot for Illuminated Forward Cell Data Reduction	V-4

LIST OF ILLUSTRATIONS (Continued)

Figure		Page
V-3	Dark Reverse Cell I-V Curve	V-9
V-4	PV-TAP Plot for Dark Reverse Cell Data Reduction	V-10
V-5	Dark Forward Cell I-V Curve	V-16
V-6	PV-TAP Plot for Dark Forward Cell Data Reduction	V-17
V-7	Illuminated Forward Module I-V Curve	V-22
V-8	PV-TAP Plot for Illuminated Forward Module Data Reduction	V-23
V-9	Dark Reverse Module I-V Curve	V-25
V-10	PV-TAP Plot for Dark Reverse Module Data Reduction	V-27
V-11	Dark Forward Module I-V Curve	V-29
V-12	PV-TAP Plot for Dark Forward Module Data Reduction	V-30
V-13	Concentrator Cell I-V Curves	V-33
V-14	PV-TAP Plot for Illuminated Forward Concentrator Cell Data Reduction	V-34
V-15	Concentrator Modules I-V and P-V Curves	V-36
V-16	PV-TAP Plot for Illuminated Forward Concentrator Module Data Reduction	V-37
V-17	Concentrator Module Curves - No. 112	V-41
V-18	Concentrator Module Curves - No. 155	V-42
V-19	Concentrator Module Curves - No. 167	V-43
V-20	Concentrator Module Curves - No. 295	V-44

LIST OF TABLES

Table		Page
II-1	PARAMETERS OBTAINED FROM I-V CURVES	II-7
II-2	DATA REDUCTION CAPABILITIES	II-8
II-3	GENERIC DATA REDUCTION FORMAT	II-11
II-4	DATA REDUCTION INPUT FORMAT EXAMPLE	II-14
III-1	PV CELL DATA REDUCTION IN PV-TAP	III-2
III-2	INPUT LISTING FOR ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION ON PV-TAP WITH RUN TO PRODUCE PLOTS	III-6
III-3	COMPARISON GENERATED BY PV-TAP ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION	III-7
III-4	LISTING OF PARAMETERS BY PV-TAP FOLLOWING ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION	III-8
III-5	INPUT LISTING FOR DARK FORWARD DATA REDUCTION ON PV-TAP WITH RUN TO PRODUCE DARK AND ILLUMINATED PLOTS	III-13
III-6	COMPARISON GENERATED BY PV-TAP DARK FORWARD DATA REDUCTION	III-14
III-7	LISTING OF PARAMETERS BY PV-TAP FOLLOWING DARK FORWARD DATA REDUCTION	III-15
IV-1	PV CELL DATA REDUCTION IN PVDR	IV-2
IV-2	INPUT LISTING FOR ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION ON PVDR	IV-4
IV-3	COMPARISON GENERATED BY PVDR ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION	IV-5
IV-4	LISTING OF PARAMETERS BY PVDR FOLLOWING ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION	IV-6
IV-5	INPUT LISTING FOR DARK FORWARD DATA REDUCTION ON PVDR	IV-9
IV-6	COMPARISON GENERATED BY PVDR DARK FORWARD DATA REDUCTION	IV-9

LIST OF TABLES (Concluded)

Table		Page
IV-7	LISTING OF PARAMETERS BY PVDR FOLLOWING DARK FORWARD DATA REDUCTION	IV-10
V-1	SUMMARY OF ILLUMINATED FORWARD DATA REDUCTION FOR FLAT PLATE CELL	V-5
V-2	SUMMARY OF DARK REVERSE DATA REDUCTION FOR FLAT PLATE CELLS	V-11
V-3	SUMMARY OF DARK FORWARD DATA REDUCTION FOR FLAT PLATE CELLS	V-18
V-4	SUMMARY OF ILLUMINATED FORWARD DATA REDUCTION FOR FLAT PLATE MODULES	V-24
V-5	SUMMARY OF DARK REVERSE DATA REDUCTION FOR FLAT PLATE MODULES	V-28
V-6	SUMMARY OF DARK FORWARD REDUCTION FOR FLAT PLATE MODULES	V-31
V-7	SUMMARY OF CONCENTRATOR CELL ILLUMINATED FORWARD DATA REDUCTION	V-35
V-8	SUMMARY OF CONCENTRATOR MODULE ILLUMINATED FORWARD DATA REDUCTION	V-39

I. INTRODUCTION

A. BACKGROUND--PROBLEMS IN DATA REDUCTION

The BDM Corporation developed the Photovoltaic Transient Analysis Program (PV-TAP), a major revision for PV applications of the NET-2 circuit and network analysis code in contract 07-6941 for Sandia Laboratories (reference 1 and 2). PV-TAP has proven to be useful for a wide variety of PV cell and system applications analyses. The PV cell model used in the program is based on an Ebers-Moll formulation commonly used in circuit design and analysis codes and also in PV cell research.

Procedures for obtaining device parameters for use in the PV cell model in PV-TAP have been discussed in the PV-TAP User's Guide and elsewhere (reference 2 and 3). The method for obtaining parameters from dark forward-bias I-V curves is not particularly difficult because the I-V curve can be divided into three regions which are dominated by different model parameters. Dark I-V curves are not usually available from manufacturers, however, and often prove deceptive for several reasons: 1) the separation of regions is not clearly observable for PV cells with low ohmic losses, 2) the use of an external source to generate current flow does not exactly duplicate photo-induced ionization because different current distributions are produced in the cell, and 3) the PV cell often operates at the transition between the generation-recombination and diffusion current regions making it difficult to observe a single exponential shape.

Since most analyses require good modeling of illuminated behavior, illuminated forward I-V curves are normally used for data reduction. These curves, however, do not lend themselves readily to a separation of regions because the light-generated photocurrent often masks the shunt resistance effect, and the series resistance affects all portions of the curve. The analyst is often faced with the task of solving three iterative equations for three unknowns. In addition, he may be required to obtain parameters for a large number of cells to determine parameter

statistical distributions. For these reasons, it was considered desirable to develop a computer methodology code to facilitate the data reduction process for illuminated as well as dark I-V curves.

B. CODE DEVELOPMENT SUMMARY

The technical activities focused on developing computer coding for reducing dark reverse, dark forward and illuminated forward I-V curves. Illuminated reverse data was not considered since it could be easily reduced to dark data by subtracting the short circuit current from all points on the curve. The data reduction code development was based on the data reduction techniques utilized for zener diodes in PV-TAP, but was tailored to the specific requirements of PV cells.

The data reduction coding was not only implemented as an addition to the PV-TAP program but was also developed into a stand-alone code called PVDR. This code is highly portable and has smaller core requirements than PV-TAP.

Because reverse-biased capacitance data reduction has long been available for diodes and transistors in NET-2 and the procedures did not require modifications for use with PV cells, this capability was implemented for PV cells in PV-TAP. Capacitive data reduction was not considered for PVDR, however, because the parameters can be easily obtained with a hand calculator, and the PVDR code was intended to be as small as possible to provide fast turnaround and be easily implemented on smaller computers.

PV-TAP and PVDR are currently available on both the Sandia and Air Force Weapons Lab (AFWL) computers.

This report contains a description of the PV cell model and equations, a discussion of the capabilities and limitations of the codes, users' interface instructions for both the PVDR code and for data reduction in PV-TAP, and examples of data reduction on cells and modules. For those who possess the PV-TAP manual, the PV-TAP User Interface chapter can also be xeroxed and stapled in for ready reference.

II. PROGRAM FORMULATION

A. PV CELL MODEL AND EQUATIONS

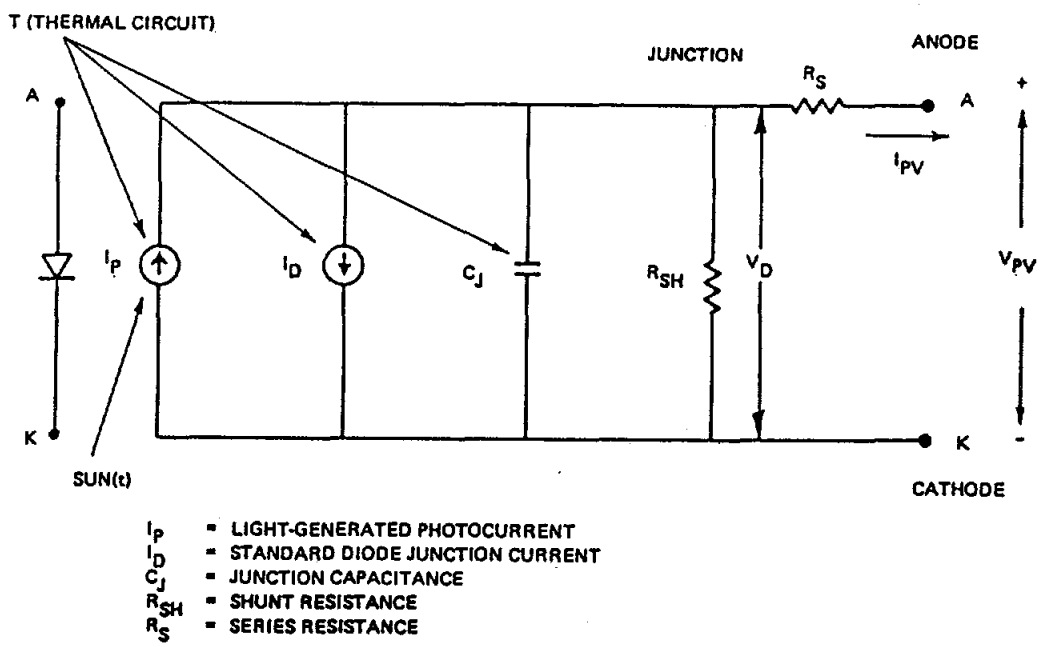


Figure II-1. PV Cell Model

The data reduction coding is designed to provide parameters which describe the PV cell model shown in figure II-1. This is an Ebers-Moll type model which has been used for many years in computer-aided circuit analysis codes such as PV-TAP. The equation which describes the operation of the cell is

$$I_{PV} = I_P - I_D - V_D/R_{SH} - C_J\frac{dV_D}{dt}$$

where

$V_D = V_{PV} + I_{PV}R_S$
I_P = light-generated photocurrent
I_D = junction current
V_D = junction voltage

R_S = series resistance
R_{SH} = shunt resistance
C_J = junction capacitance
I_{PV} = terminal current
V_{PV} = terminal voltage.

The junction current can be further described by the equation

$$I_D = I_{ST}\left[e^{(q/MKT)(V_{PV} + I_{PV}R_S)} - 1\right] - \eta e^{A[V_B - B(V_{PV} + I_{PV}R_S)]}$$

where

I_{ST} = saturation current at temperature T
$= I_S T^P e^{-\alpha/T}$
I_S = temperature independent saturation current
P,α = saturation current temperature parameters
q = electron charge
K = Boltzman's constant
M = junction emission constant
A,B = reverse breakdown constants
V_B = reverse breakdown voltage.
η = breakdown scale factor; normally = 1.0 mA

The junction capacitance describes the transient response of the PV cell and is a combination of reverse-bias and forward-bias terms given by:

$$C_J = C_R + C_F$$

$$= \frac{C_0}{\left(1 - \frac{V_D}{V_Z}\right)^N} + \frac{qI_{ST}\, e^{qV_D/MKT}}{MKT\ \omega}$$

where:

C_0 = depletion capacitance at zero bias

V_Z = contact potential

N = junction grading constant

? = diffusion capacitance constant

≈ inverse of minority carrier lifetime

In normal operation, when the PV cell is illuminated by sunlight, a photocurrent, I_P, is produced across the junction as indicated in figure II-1. This will produce a current in the external load with the positive direction as indicated. If the anode is shorted to the cathode, essentially all the current will flow through the external terminals and the output voltage will be zero. This condition is represented by the short circuit current, I_{SC}, in the typical 1 Sun I-V curve shown in figure II-2. The basic shape of the curve is determined by the diode current, I_D, which is exponential. When a discrete load is placed across the terminals, the voltage developed across this load biases the junction, causing some of the photocurrent to be shunted through the junction. This current, consisting mostly of I_D, subtracts from the photocurrent, reducing the current available at the output.

At the other extreme is the open circuit voltage, V_{OC}, which is obtained when the terminals are disconnected. V_{OC} is determined by the diode equation since essentially all of the photocurrent passes through and forward biases the junction. V_{OC} increases logarithmically with insolation since it is determined by the photocurrent, I_P, being forced through the junction, I_D. Conversely, V_{OC} decreases with temperature since the saturation current, I_{ST}, in the diode equation increases with temperature. This means that the junction is unable to sustain the same voltage at higher temperatures.

The shape of the curve in figure II-2 is also dependent on the values of R_{SH} and R_S. These resistances cause the curve to deviate further from a rectangular shape. Small values of R_{SH} will shunt some of the photocurrent, reducing the current available at the output at all values of voltage. At open circuit, the current in the shunt resistor

"Use or disclosure of proposal data is subject to the restriction on the Title page of this Proposal." (1966 DEC)

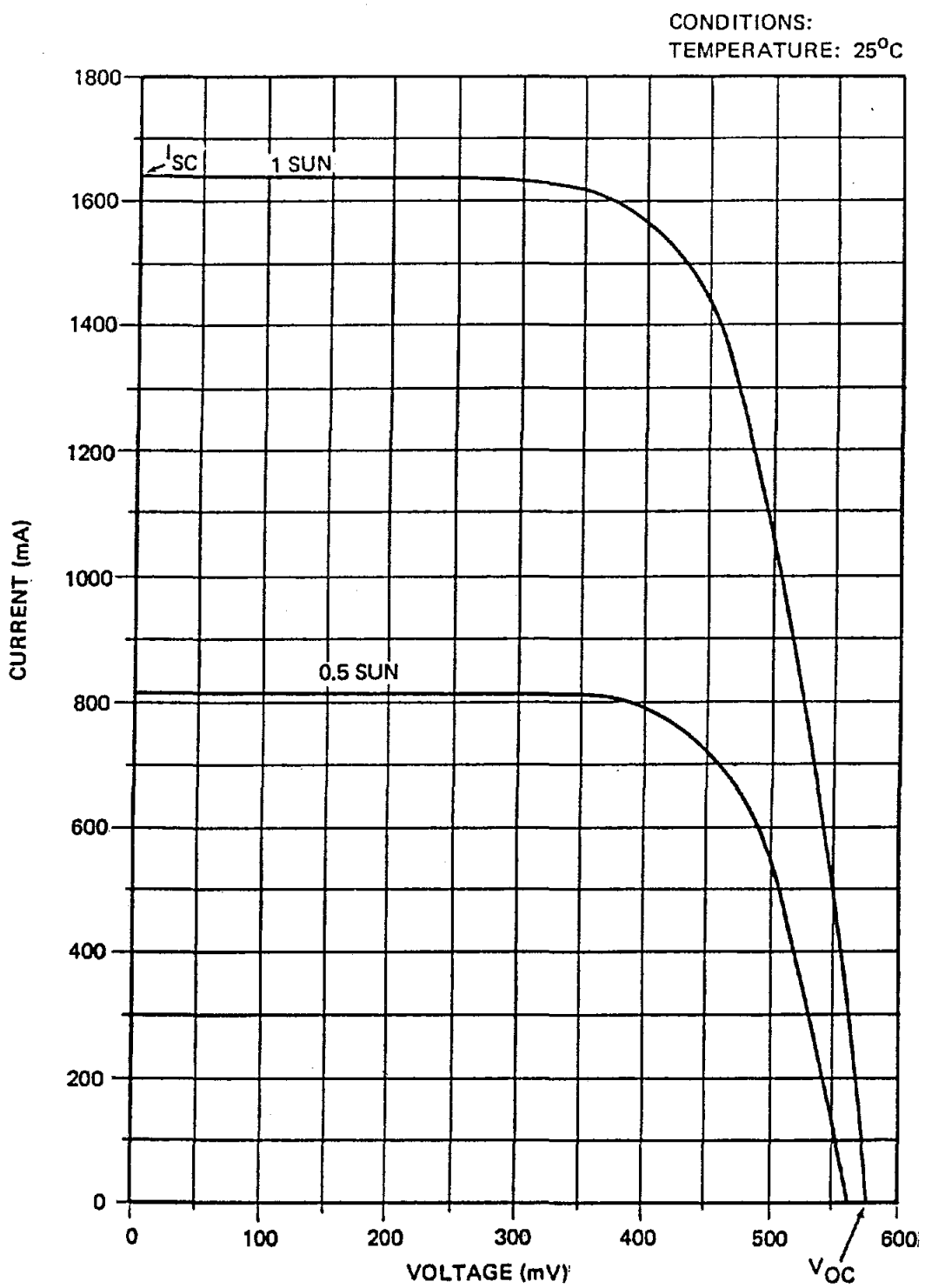


Figure II-2. Typical Illuminated Forward I-V Characteristics

will reduce the current available to the diode equation, reducing V_{OC}. Large values of series resistance will reduce the output voltage at all values of current.

The PV cell can also be operated in reverse bias as indicated by the dark reverse curve shown in figure II-3. This curve is described by the shunt resistance term in the linear region of the curve and by the second term of the diode equation for the breakdown region. V_B is the breakdown voltage, A and B are curve fitting constants, and η is used in PV-TAP to facilitate PV cell aggregation. η is also used to control the units and is normally 1.0 mA. Under partial or full illumination, the curve would simply be displaced upward by the degree of illumination times I_{SC}.

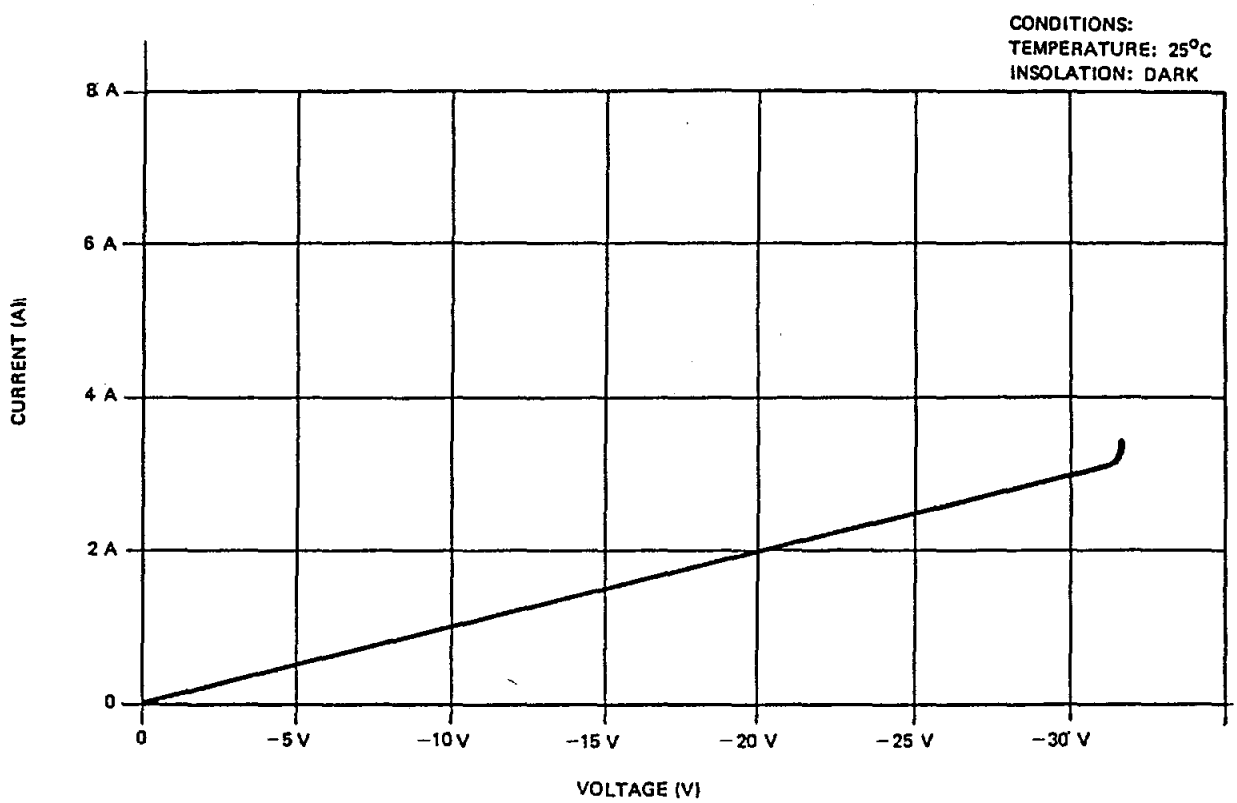


Figure II-3. Typical Dark Reverse I-V Characteristics

The PV cell can also be characterized by the dark forward curve shown in figure II-4. According to PV cell current conventions, this is actually a fourth quadrant curve and represents forward characteristics

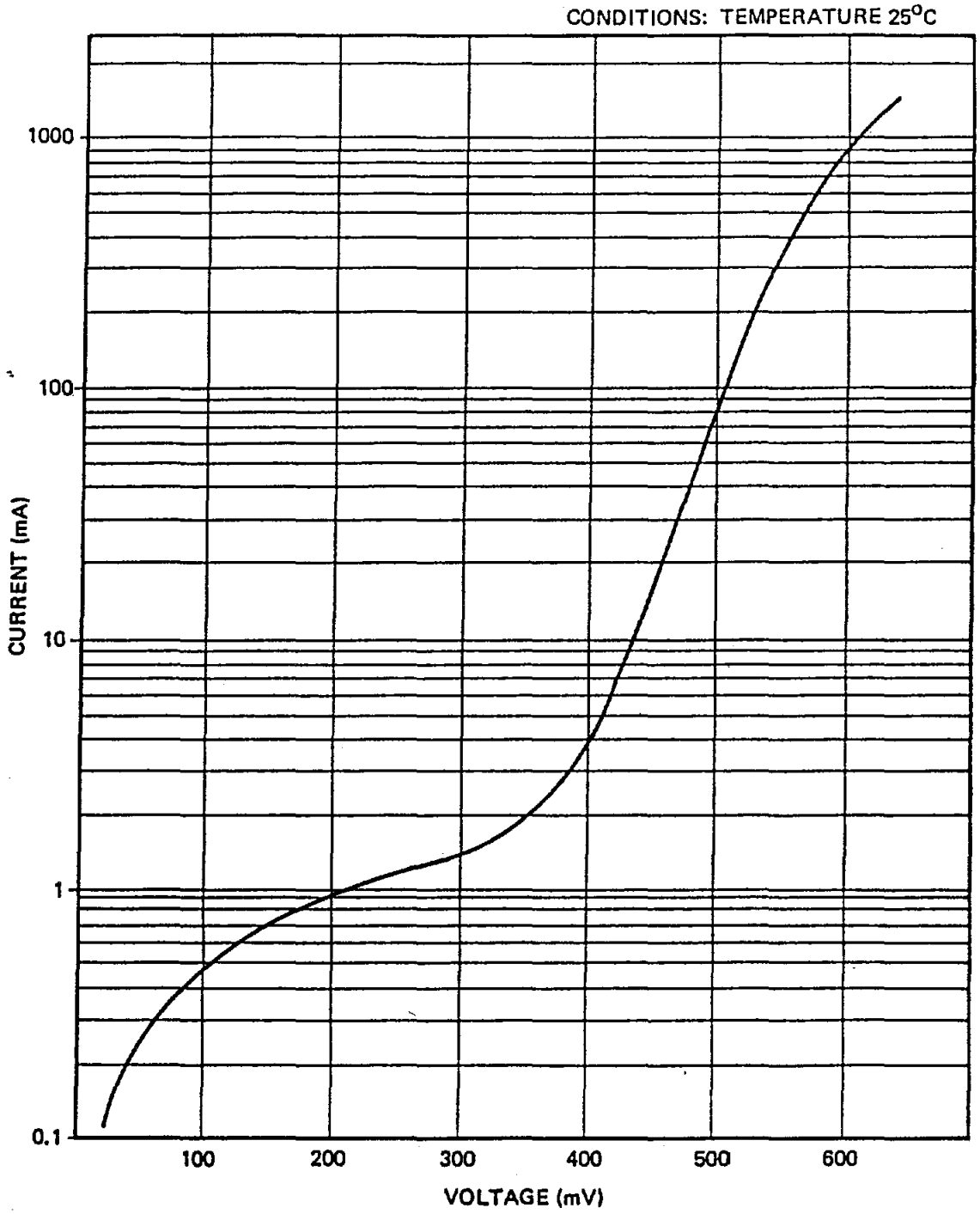


Figure II-4. Typical Dark Forward I-V Characteristics

similar to those in figure II-2 except that 1) the illumination is removed displacing the y-intercept to zero, and 2) the current is produced by an external forward bias and flows into the cell. The curve is plotted on semi-log paper accounting for the different shape. The low voltage region is often dominated by the shunt resistance, the mid-region by the diode equation, and the high voltage region by the series resistance.

All the parameters previously listed can be obtained from these curves except the junction capacitance which is not a steady state term. Table II-1 lists the parameters which can be obtained from each of the curve types. The dark and illuminated forward curves produce similar sets of parameters with the exception of R_{SH} which in the illuminated curve is usually masked by the photocurrent. The breakdown parameters, of course, can only be determined from the reverse curve in the breakdown region.

TABLE II.1. PARAMETERS OBTAINED FROM I-V CURVES

DARK REVERSE —	R_{SH}, A, B, V_B
ILLUMINATED FORWARD —	R_S, M, P, α, I_S
DARK FORWARD —	R_{SH}, R_S, M, P, α, I_S

B. PROGRAM CAPABILITIES AND LIMITATIONS

Both data reduction codes are capable of reducing data from dark and illuminated forward curves and from dark reverse curves. The program can also accept temperature data for calculating temperature dependence. Table II-2 lists the data reduction capabilities, required inputs and program outputs for each. Each type of data reduction can be run separately, or dark reverse and illuminated forward can be run together. With this option, the shunt resistance is calculated from the reverse data and used as an input to the forward data reduction. If illuminated forward data reduction is run alone, the shunt resistance must be supplied by the user. The parameter entry is actually the shunt conductance

TABLE II-2. DATA REDUCTION CAPABILITIES

DR OPTION	INPUTS REQUIRED	OUTPUT
ALL OPTIONS	I-V POINT PAIRS	LIST OF PARAMETERS STANDARD DEVIATIONS ON PARAMETERS TABULATED COMPARISON OF CALCULATED VERSUS EMPIRICAL DATA OVERLAY OF CALCULATED ON EMPIRICAL DATA(1)
REVERSE DARK	5 I-V POINT PAIRS MINIMUM	CALCULATES — RSH, A, B, VB
ILLUMINATED FORWARD	4 I-V POINT PAIRS MINIMUM SHORT CIRCUIT CURRENT (ISC) CELL TEMPERATURE (TEMP) SHUNT CONDUCTANCE (G = 1/RSH)	CALCULATES — RS, M, IS, P, α(2)
OPTIONAL	TEMPERATURE DEPENDENCE (DVDT, DIDT)	
DARK FORWARD	5 I-V POINT PAIRS MINIMUM CELL TEMPERATURE (TEMP)	CALCULATES — RSH,RS, M, IS P, α(2)
OPTIONAL	TEMPERATURE DEPENDENCE (DVDT, DIDT)	
REVERSE DARK FOLLOWED BY ILLUM. FORWARD	5 REVERSE — 4 FORWARD I-V PAIRS MINIMUM SHORT CIRCUIT CURRENT (ISC) CELL TEMPERATURE (TEMP)	CALCULATES — RSH, A, B, VB, RS, M, IS, P, α(2)
OPTIONAL	TEMPERATURE DEPENDENCE (DVDT, DIDT)	
REVERSE CAPACITANCE(3)	4 C-V POINT PAIRS MINIMUM	CALCULATES — CO, N, VZ

NOTES:

(1) OVERLAY IS AUTOMATIC IN PVDR, BUT REQUIRES CIRCUIT RUN IN PV-TAP
(2) α CALCULATED FROM DEFAULT EQUATION IF TEMPERATURE DEPENDENCE IS NOT INPUT
(3) CAPACITANCE DATA REDUCTION CAN ONLY BE PERFORMED IN PV-TAP, NOT IN PVDR

(G = 1/RSH). Illuminated data reduction also requires that the short circuit current and temperature of the cell be input by the user. Dark forward bias data reduction requires only that the temperature of the cell producing the I-V curve be input.

The appropriate parameters for each data reduction type are calculated and listed in the output along with the rest of the parameters which describe the PV cell model. For those parameters not calculated, standard default values are listed unless the user provides specific values for these parameters in the input file. The standard deviations of the calculated parameters are also listed to permit assessment of the goodness of fit to the empirical data. The programs also calculate currents from the generated parameters for each user-provided voltage and tabulate these with the empirical data. The PVDR code also produces a plot overlaying a calculated I-V curve with the empirical data. PV-TAP does not do this automatically, but a circuit run can be made to generate an I-V curve and overlay it with the empirical data.

The temperature parameters, P and α, are calculated for dark and illuminated forward-bias data reduction. P is calculated as 3/M. If no temperature dependence data are provided in the run, α is calculated from the default equation

$$\alpha = E_{GO}/MK$$

where

E_{GO} = the band gap of silicon at 0°K

= 1.21 eV

M = junction emission constant

K = Boltzman's constant

If the rate of change of voltage and current with temperature (DVDT and DIDT) are input, the programs will calculate α based on these parameters from

$$\alpha = \frac{\frac{q}{MK}\left(\frac{V_{OC2}}{T_2} - \frac{V_{OC1}}{T_1}\right) - \ln\left[\left(\frac{I_{SC2}}{I_{SC1}}\right)\left(\frac{T_1}{T_2}\right)^P\right]}{\frac{1}{T_2} - \frac{1}{T_1}}$$

where

$$V_{OC2} = V_{OC1} + (DVDT)(T_2 - T_1)$$
$$I_{SC2} = I_{SC1} + (DIDT)(T_2 - T_1)$$

Capacitive data reduction is performed only in PV-TAP and can be input in the same run with any I-V data reduction option.

Weighting values between 0 and 1.0 may be supplied with each data point-pair. These are used to instruct the program to assign more importance to selected point-pairs when calculating the cell parameters.

All parameters which are normally calculated by a specific data reduction option may instead be assigned a fixed value. Parameters thus specified are called fixedparams and will not then be calculated. The user may also specify parameters as startparams. This specification provides the program with a starting value for that parameter which will be updated by the program to provide the best data fit.

C. DATA REDUCTION INPUT FORMAT

The input format for PVDR was designed to be identical to that for PV-TAP. The basic format for data reduction as shown in table II-3 has an outline format. Subgroups are indented. The user may choose the column number for each indentation level, but once specified, it must be adhered to for the rest of the run.

The first card should be a title card. It must contain an asterisk in column 1. Data reduction in PV-TAP starts with the entry "LIBRARY" in column one. PVDR, however, does not use the library card since it has no meaning for PVDR. The device specification entry is at indentation level one. The term "device" refers to a user-assigned name or serial number for the PV cell. The model number for PV cells in the PV-TAP model library is 11.

TABLE II-3. GENERIC DATA REDUCTION FORMAT

```
*TITLE CARD
LIBRARY(1)

        PV DEVICE 11
            PARAMSPEC
            DATA  DRTYPE  FIXEDPARAMS  /  STARTPARAMS
                DATASET1
                DATASET2
                .
                .
                .
```

WHERE: DEVICE = NAME ASSIGNED TO CELL FROM WHICH DATA WAS OBTAINED

PARAMSPEC = DEVICE PARAMETER SPECIFICATION LINE

DRTYPE = DATA REDUCTION TYPE CODE

FIXEDPARAMS = LIST OF PARAMETER SYMBOLS WHOSE VALUES ARE TO BE FIXED AT PRESCRIBED VALUES

STARTPARAMS = LIST OF PARAMETER SYMBOLS WHOSE PRESCRIBED VALUES ARE TO BE USED AS STARTING VALUES FOR DATA REDUCTION

DATASET1, DATASET2, ETC. = SETS OF NUMERICAL VALUES FOR DATA POINTS

(1) USED ONLY IN PV-TAP

In the "paramspec" entry, values may be assigned to any PV cell model parameter or to essential input parameters such as short circuit current or temperature. Values assigned to parameters which are calculated during data reduction will be replaced by the calculated value unless the parameter is specified in the "fixedparams" field. The paramspecs are entered at indentation level two.

Also at indentation level two, is the "DATA" line which specifies the data reduction type (drtype) and the fixedparams and startparams. For PVDR, the only symbol used for "drtype" is DC indicating steady state I-V data reduction. In PV-TAP, two symbols are allowed for PV cell data reduction, DC and CT, representing I-V curve and transition capacitance data reductions, respectively.

The user may elect to have certain parameter values held constant during the data reduction process (normally these values would be calculated as part of the data reduction). This can be done by including the symbols for these parameters in the optional fixedparams field on the DATA card. Only parameters which are calculated by the specified data reduction type may be included in the fixedparams field. The values of the remaining parameters are calculated so as to be consistent with the fixed parameter values.

The user may also wish to specify a set of starting values to assist the programs in the data reduction process. This can be done by including the symbols for these parameters in the optional startparams field. The startparams field must be prefixed with a slash when it is used. The data reduction process will begin using the specified values for these parameters, but as the data reduction progresses, these values will be modified so as to give an optimal fit to the data points. Only parameters which are calculated by the specified data reduction type may be included in the startparams field.

The term "dataset" refers to the data point-pairs. The point-pairs are entered at indentation level three. The input order for each line is voltage, current (or capacitance), weighting factor. The number of point-pairs must be greater than the number of parameters to be calculated for a given data reduction type. The weighting factors are optional. They instruct the programs to assign more significance to

certain point-pairs to ensure a better match to these points. Values between 0 and 1.0 may be used for weighting factors. If omitted, the programs automatically supply a value of unity.

Table II-4 contains an example of the data reduction input format. The short circuit current entry keys the programs to expect illuminated forward-biased data. The shunt conductance, G, is also required for this type of data reduction. The normal set of units is volts, milliamps, kilohms, millimhos, ^{o}Kelvin, picofarads, nanoseconds. Thus, ISC is in mA and G is in mmhos.

The parameter M which is normally calculated appears in the fixed-params field. It is thereby declared a fixed value parameter with the value 1.5. The parameter RS appears in the startparams field. Thus, the value of 10 mΩ specified in the RS paramspec line will be used as a starting value for RS in the data reduction process.

The data point-pairs must be input in ascending voltage order. The zero voltage point is considered by the programs as a reverse-bias data point and should not be entered with forward data. The programs use ISC as the intercept value for the data. The voltage range in this example is from 0.1 to 0.57 V. The current decreases from 1990 to 0.0 mA. Weighting factors have been assigned to all points with the strongest weights for points near peak power and at open circuit.

D. CAUTIONS

The programs are designed to reduce data which fit the PV cell model equations. Therefore, the program will often reject data which is not well-behaved. In addition, since the programs were intended to reduce data from modules as well as cells, some restrictions which might assist the program in producing meaningful data could not be made. For example, the emission constant, M, for a PV cell is normally in the range of 1.0 to 2.0 with values occasionally between 0.8 and 2.5. However, the value for M for a module of 30 cells might be in the range of 30 to 60. Therefore, restrictions could not easily be placed on the value of M. For this reason, the programs will sometimes produce parameters which are not physically realistic or do not match the curves over the full range of data if the curves are not well-behaved. Examples of such problems are

TABLE II-4. DATA REDUCTION INPUT FORMAT EXAMPLE

```
*ILLUMINATED DATA REDUCTION EXAMPLE
LIBRARY
    PV  CELL12  11
        ISC  2E3
        TEMP  298
        M  1.5
        G  100.
        RS  10E-6
        DATA  DC  M/RS
            0.1     1990    .1
            0.2     1980    .1
            0.3     1965    .1
            0.4     1910    .5
            0.45    1790   1.0
            0.47    1550   1.0
            0.5     1200    .5
            0.55     600    .1
            0.57     0.0   1.0
END
```

included in figures II-5 through II-9 which represent actual data taken on 3-inch flat plate cells (figures II-5 to II-8) and on a concentrator module (figure II-9).

Figure II-5 is a reverse characteristic with a varying slope between the origin and breakdown. The programs expect a linear (or near linear) region from the origin to the onset of breakdown. Since it is not known where breakdown will occur nor how sharp the breakdown will be, the programs look for an increasing slope in the data. The programs will accept some variation in the data, but in this figure, the decreasing slope beyond 10-12 V, which is neither linear nor characteristic of breakdown, was apparently too variant from the model and was rejected by the program.

Figure II-6 exhibits a discontinuity at about -18 V which was probably caused by excess metallization leaking onto the edge of the cell. This results in a partial short across the edge when the voltage becomes high enough to breakdown the air gap. The increased current was interpreted by the program as breakdown of the cell, and all points beyond -18.5 V were rejected as being inconsistent with the model.

In both these cases, the simplest solution would be to draw a straight line from the origin to the onset of breakdown as interpreted by the user. Digitizing from this line would ensure that a clear definition of linear and breakdown regions was obtained. The user might instead attempt to guide the program by placing VB in the fixedparams or startparams field and specifying his choice for VB as a paramspec.

Figure II-7 represents a dark forward curve with no clearly defined series resistance effect. The series resistance would tend to cause a decrease in the slope at high currents. This curve instead exhibits a slight increase in the curve at high current. Data would have to be taken beyond 600 mV to observe the series resistance effect. The series resistance would have to be on the order of at least 20 mΩ to exert appreciable effect on the slope at 500 mA. The upward turn to the curve between 500 and 550 mV may be caused by the transition of the cell from the generation-recombination region to the diffusion region of operation, thus masking the series resistance effect. In cases such as this where no series resistance effect is observable, the programs will supply a default value of RS = 1.0 mΩ .

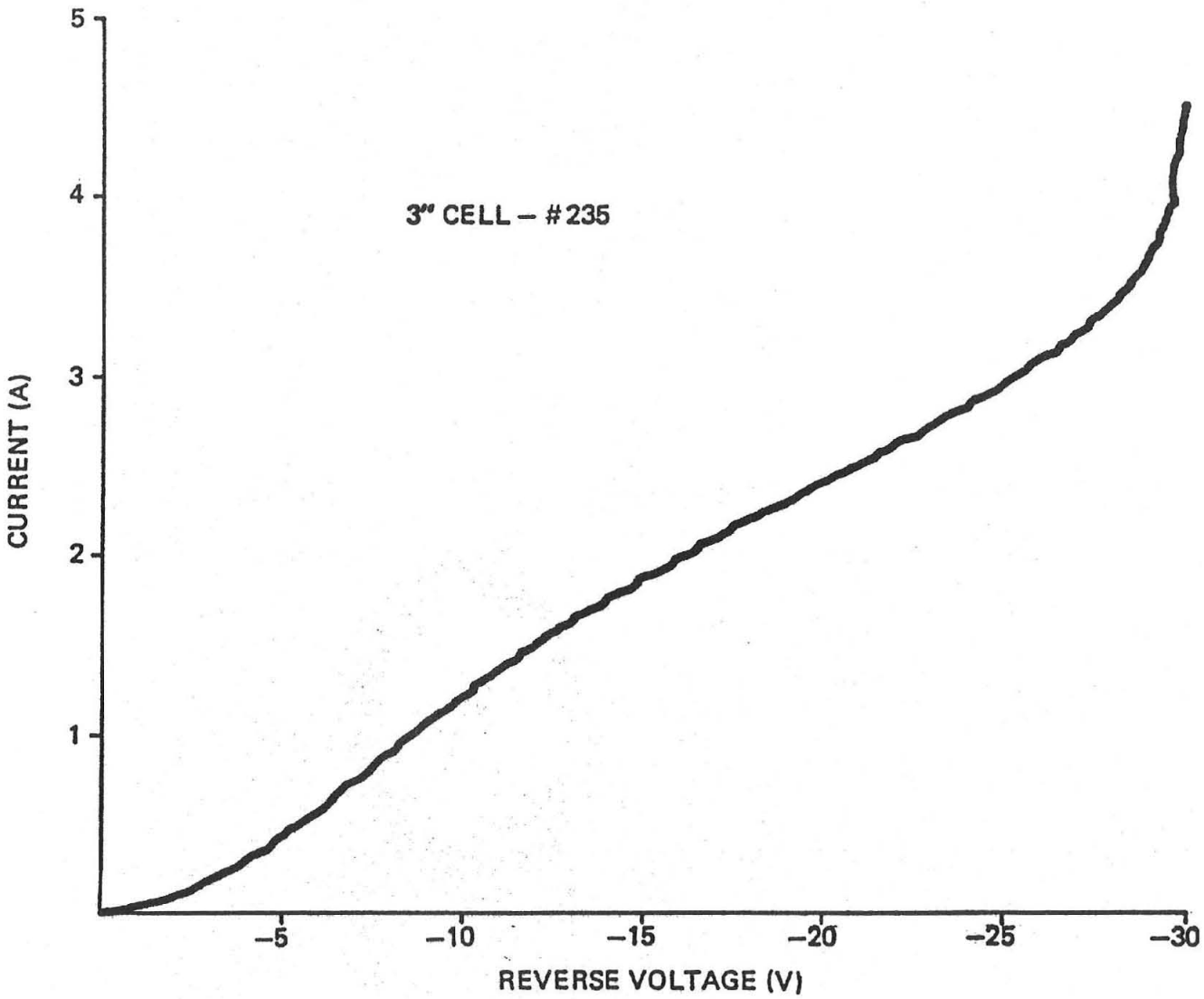


Figure II-5. Reverse I-V Curve with Decreasing Slope

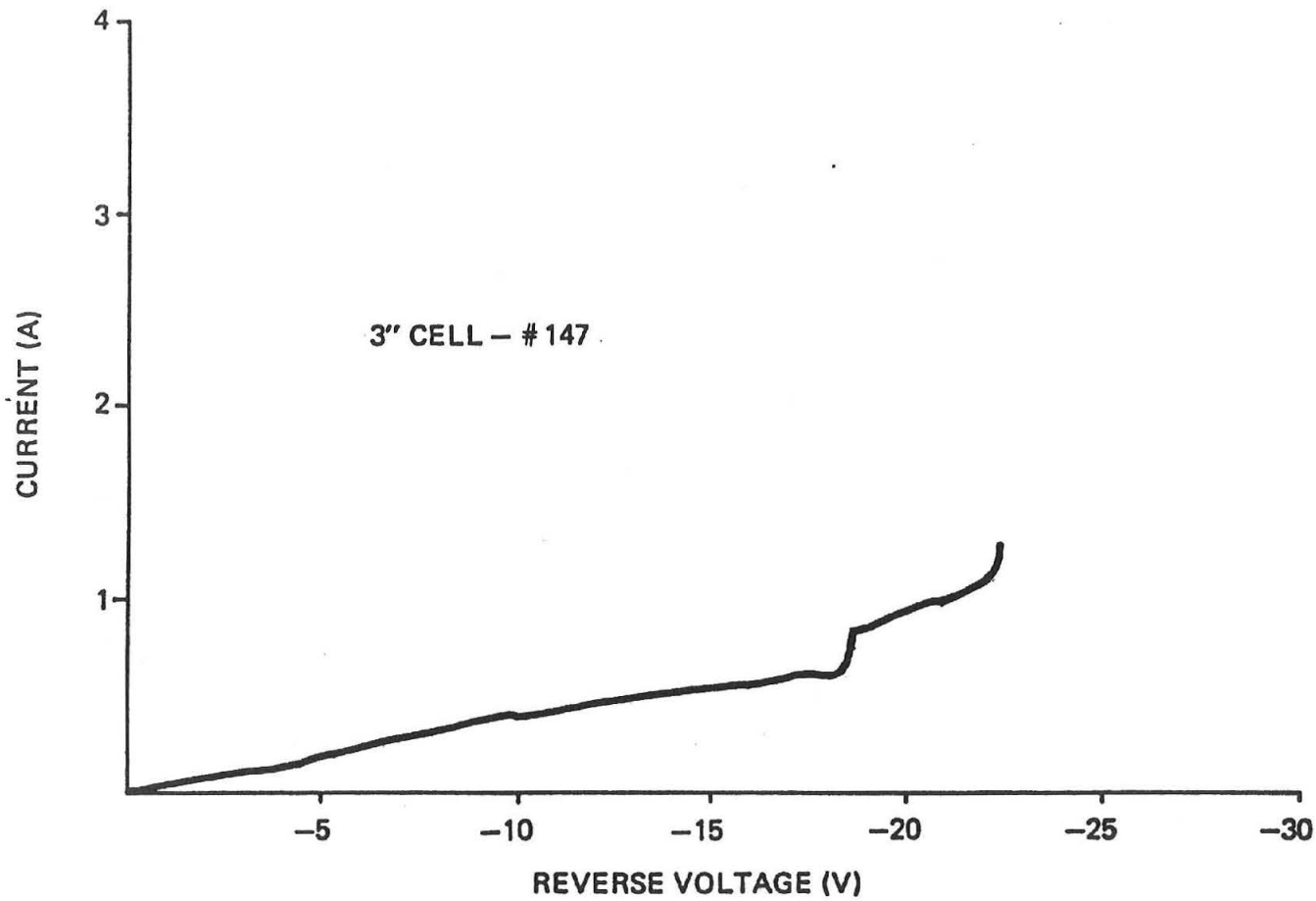


Figure II-6. Reverse I-V Curve with Step Increase

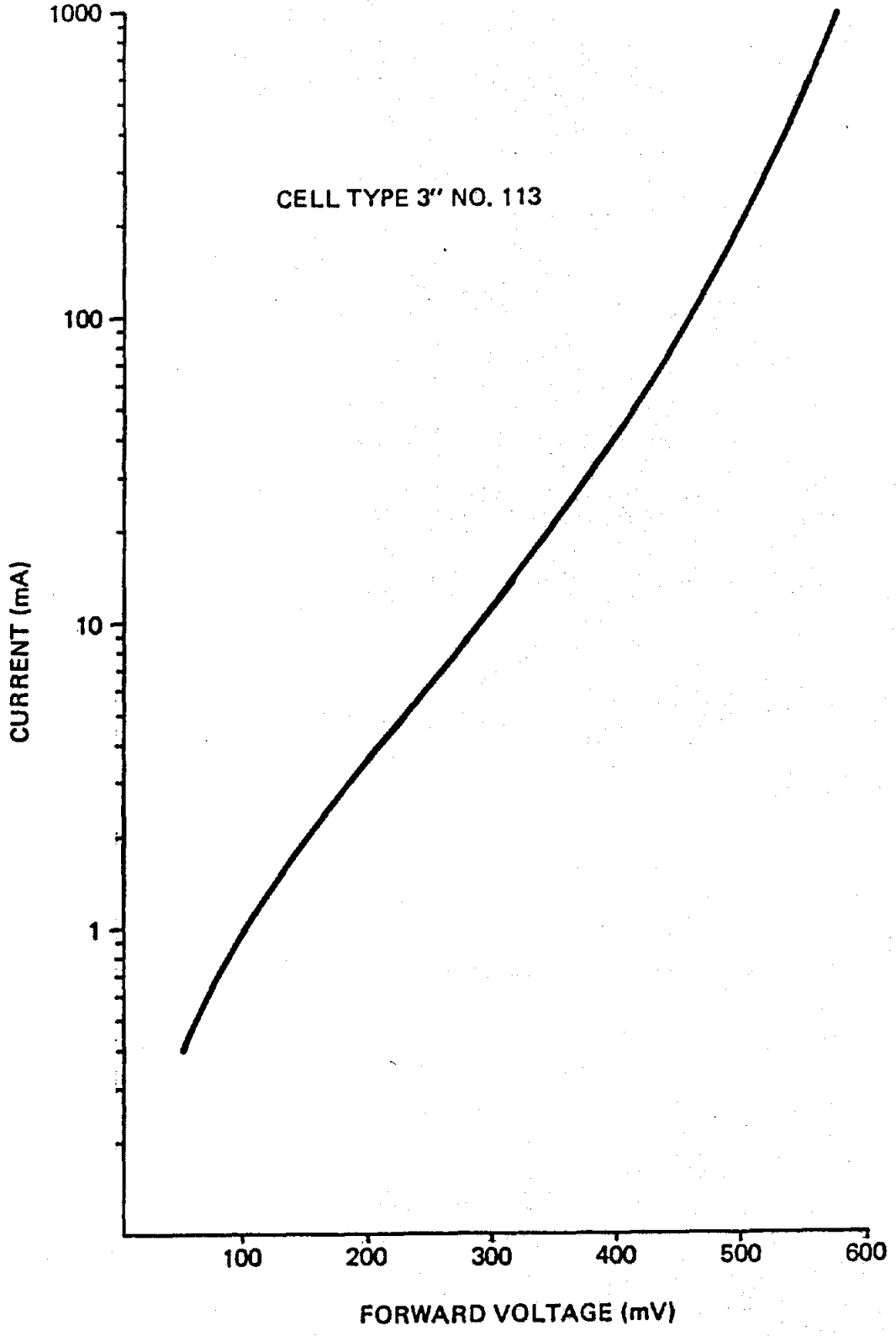


Figure II-7. Dark Forward with No Series Resistance Effect

Figure II-8 represents an illuminated I-V curve with a decreasing current at short circuit. This was probably caused by an error in the experimental procedure since this condition is not consistent with PV cell operation. The programs can not reconcile currents in the forward region which are greater than the short circuit current in the paramspec entry. The best solution is to extrapolate the curve back to a consistent value of ISC which is larger than all other currents in the forward region. Care should be exercised here. If ISC is not significantly larger than the current at the next point, the program may have difficulty reconciling the flat slope with the shunt resistance value which was either input by a paramspec or calculated from reverse data. This could result in an inability to match the data accurately at higher voltages.

Figure II-9 represents data taken on a module on the receiver tube of a linear parabolic trough. Both current and power are plotted versus voltage. The region between the origin and 1.0 V should not be interpreted as data, but is caused by the configuration of the experimental set-up. The plots were made on a mini-computer and required several seconds to sweep the load range. The day was characterized by intermittent high clouds which may be the cause of most of the irregularities in the curve. The step discontinuity at about 14.5 V, however, was probably caused by a bypass diode being activated due to non-uniform illumination along the receiver tube.

To properly model the bypass diode effect in this module, two PV cell models would be required. The user might try inputting the values below 14.5 V on the I-V curve for one data reduction and then subtracting 14.5 V from all voltages above 14.5 V to produce points for a second data reduction.

If the user wishes to model this type of I-V curve with a single PV cell model, he will have to ignore the discontinuity and approximate a single cell curve through the data. The value in using the data reduction codes in this case is that they permit the analyst the luxury of trying several curves through the data. If he had to do the subsequent

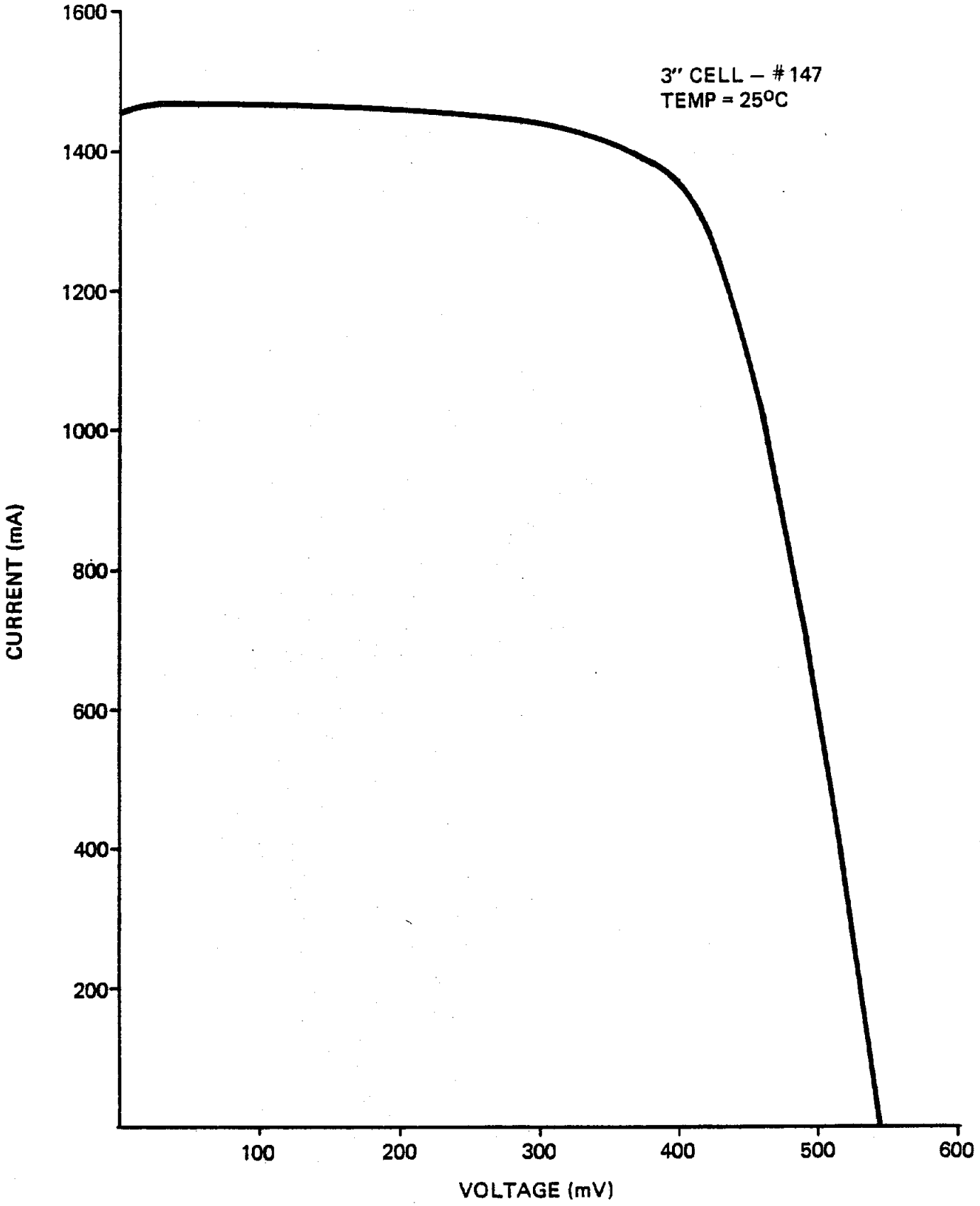


Figure II-8. Illuminated I-V Curve with Decreasing Current at Short Circuit

data reductions by hand, it would probably take many hours, perhaps more than a whole day. It should be noted that parameters generated from this particular curve produced a calculated curve with reasonable match to the data. This curve is shown as an example in chapter V. Other such curves did not produce as good a match to the data. Usually the open circuit voltage was significantly in error.

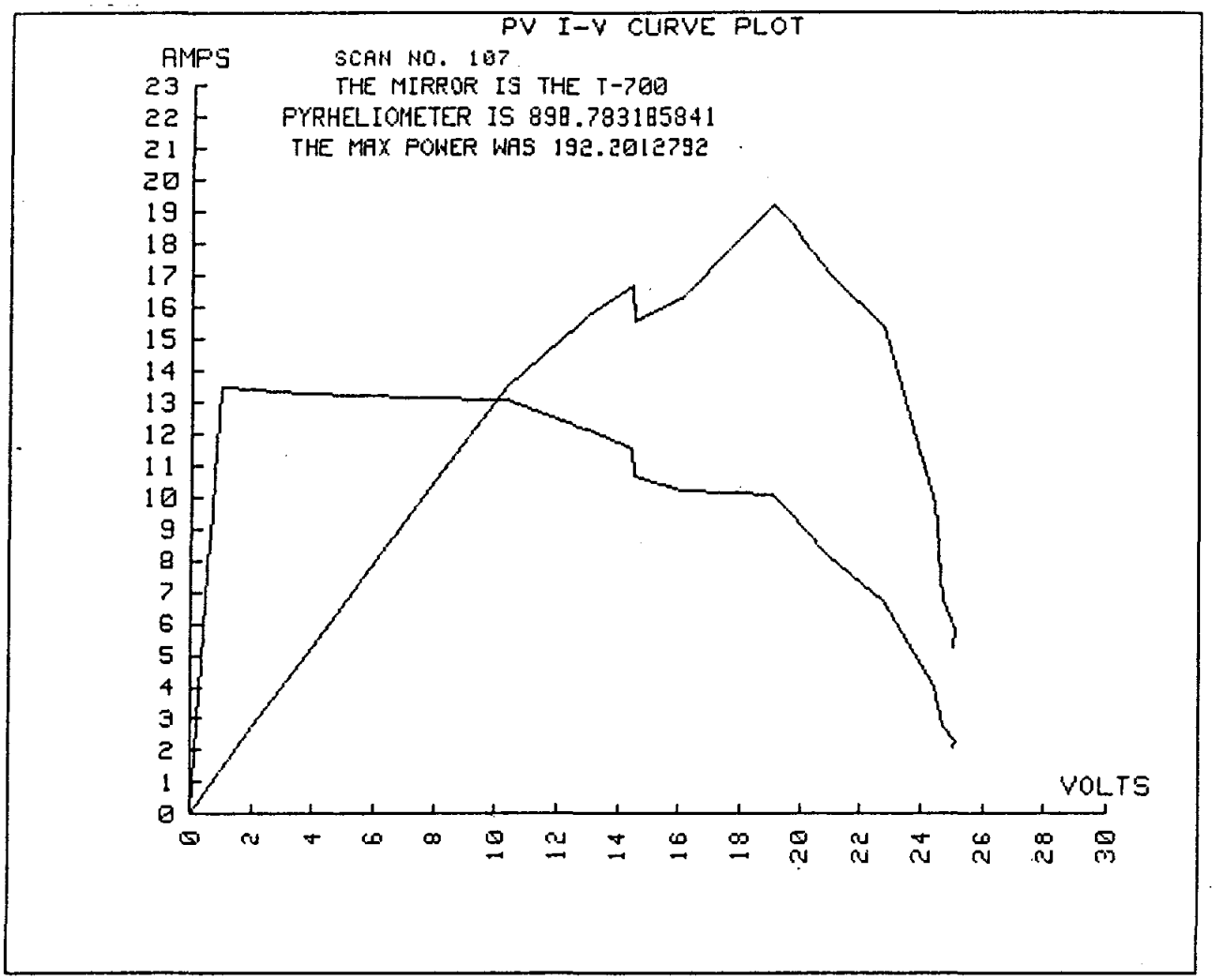


Figure II-9. Illuminated I-V Curve for Module with Possible Bypass Diode Effect

CHAPTER III
DATA REDUCTION USING PV-TAP

A. USER INTERFACE INSTRUCTIONS

General data reduction features are discussed in section II.B and also in the PV-TAP USER'S GUIDE, Vol. III (reference 1). This section presents instructions for using the PV cell data reduction feature in PV-TAP.

All PV-TAP runs start with a title card. This card must contain an asterisk in column 1. All data reduction in PV-TAP is performed under the Library heading. Thus, the second card consists of the word "LIBRARY" starting in column 1. This is followed by the devicespec at indentation level 1 and other cards listed in table II-3. The input requirements and parameters calculated for each type of data reduction in PV-TAP are catalogued in table III-1. The outputs obtained directly from the data reduction consist of a list of all cell parameter values and a tabulated comparison of calculated with experimental currents. Additional outputs such as comparison plots may be obtained from PV-TAP by specifying a state solution run, but this is not part of the data reduction feature. If the user wishes to use only the data reduction feature, the data points are followed by an "END" card starting in column 1. If a state solution run is desired following data reduction, the data points are followed by the circuit topology description and solution control cards. The "END" card is placed at the end of the program. The parameters calculated during data reduction will be used for the state solution run. Additional parameters required will be obtained from the default list unless specific values have been input in a paramspec line.

B. PV-TAP DATA REDUCTION EXAMPLES

Figures III-1 and III-2 are I-V curves taken on a 3-inch diameter single crystal silicon flat plate cell. Figure III-1 contains illuminated forward curves measured at 1 sun and 0.5 suns, both at 25°C. The 1 sun curve was used for this example. Figure III-2 is a dark

TABLE III-1. PV CELL DATA REDUCTION IN PV-TAP

"DRTYPE"	DESCRIPTION	INPUT SEQUENCE	PARAMETERS CALCULATED
DC	DC CHARACTERISTICS		
	DARK REVERSE	V, I, WGT.	G, A, B, VB
	ILLUMINATED FORWARD	ISC, TEMP, G DVDT, DIDT (optional) V, I, WGT	RS, M, IS, P, ALPHA
	DARK FORWARD	TEMP DVDT, DIDT (optional) V, I, WGT.	G, RS, M, IS, P, ALPHA
	DARK REV./ILLUM. FWD.	ISC, TEMP DVDT, DIDT (optional) V, I, WGT.	G, A, B, VB, RS, M, IS, P, ALPHA
CT	CAPACITANCE CURVE	V, C, WGT.	C, VZ, N

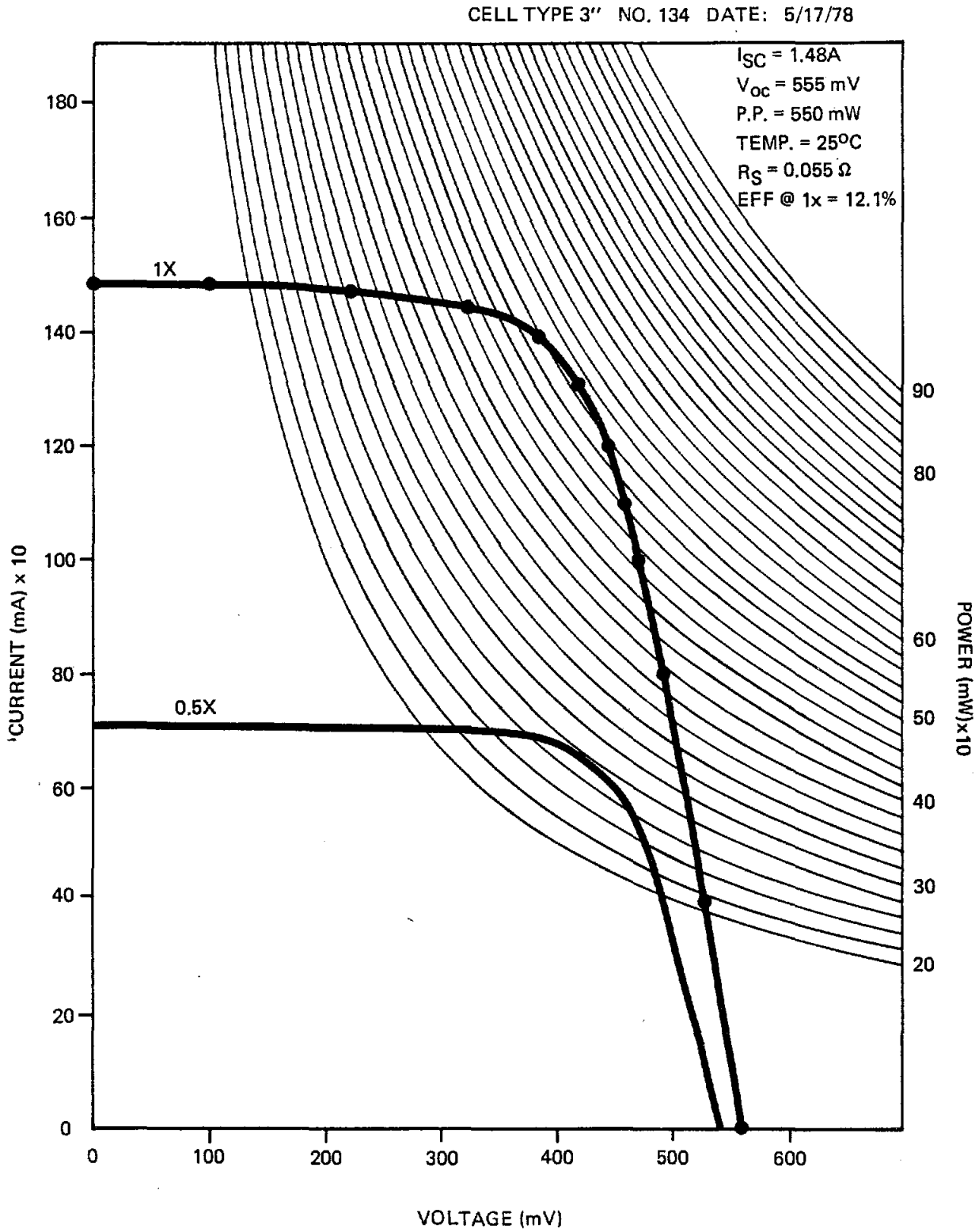


Figure III-1. Illuminated Forward Cell I-V Curves

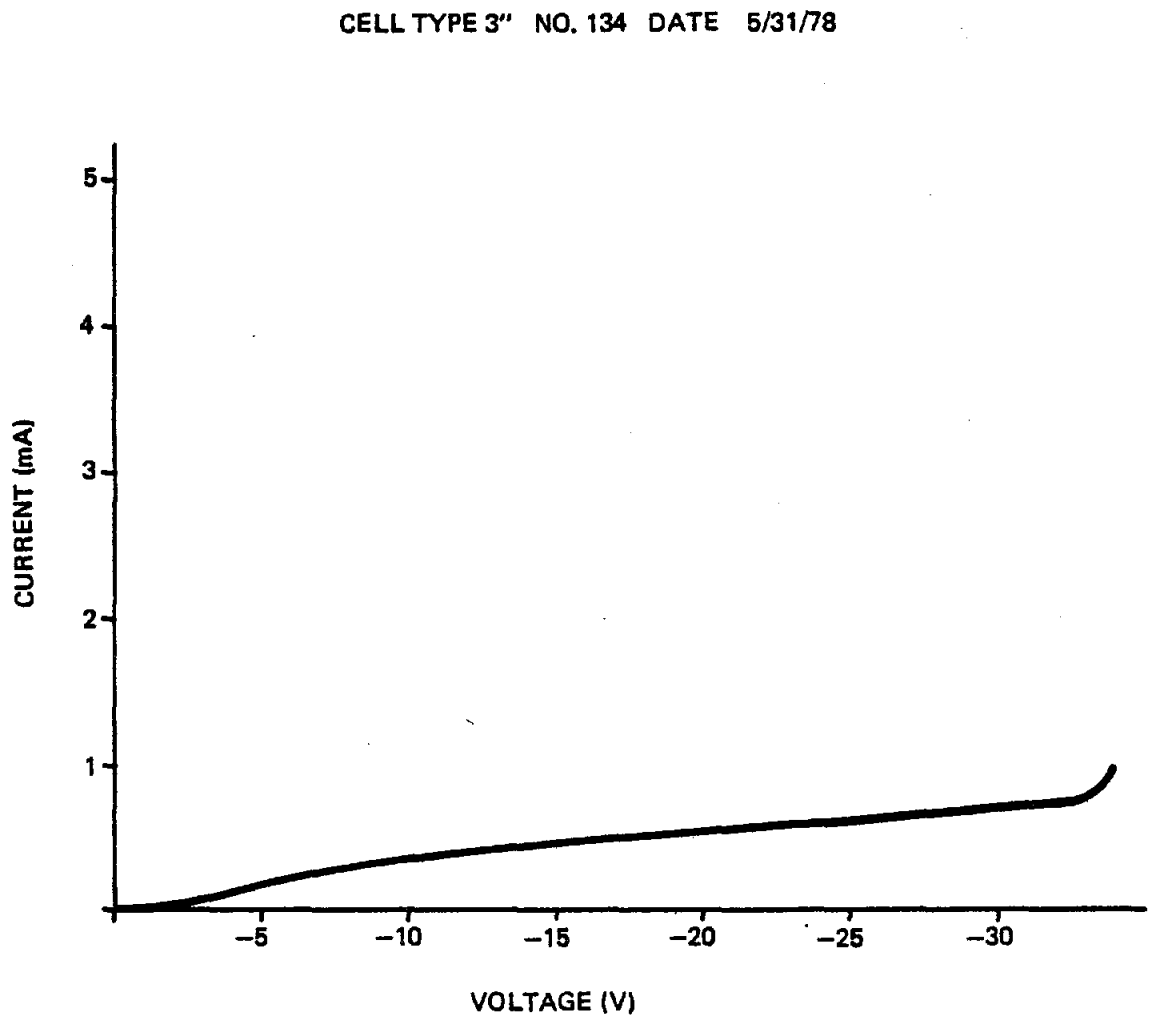


Figure III-2. Dark Reverse Cell I-V Curve

reverse curve measured at 25°C. The input listing used to perform a combined data reduction for these curves and to produce comparison curves is shown in table III-2. The data reduction entries end at line 35. Lines 36 through 40 represent the circuit topology. Lines 41 through 69 define the table used to plot the empirical data. The illuminated state solu- tion controls are contained in lines 70 to 74 while the dark reverse controls are in lines 75 to 80. Note the "END" card in line 81. If lines 36 et. al. were not used, the "END" card would be required following line 35.

In illuminated forward data reduction, the paramspecs ISC and TEMP are required. G (the inverse of shunt resistance) would also be required if dark reverse data reduction were not performed. IP is not required for data reduction, but is required for the illuminated state solution. VB is redundant in this context since the dark reverse data reduction will calculate VB and substitute the calculated value in the device library in place of the specified value. Note that VB has not been placed in a fixedparams or startparams field on the "DATA" card. The use of the DVDT and DIDT paramspec cards instructs the program to calculate ALPHA based on these values.

In the data set cards, the zero voltage point is assumed to correspond to zero current. PV-TAP will ignore the point-pair if the zero voltage point is specified with non-zero current as part of the illuminated data.

If capacitive data reduction is desired, the "DATA CT" and capacitance dataset cards may be placed directly after the I-V dataset cards.

The comparison of calculated to empirical currents performed by the PV-TAP data reduction feature is shown in table III-3. The currents are listed corresponding to each of the input voltages in the dataset cards.

The full list of parameters for device SOLC1 is shown in table III-4. Goodness of fit values for calculated parameters are included in parenthesis. The parameter G is the inverse of the shunt resistance. ALPHA was obtained from the DVDT and DIDT data. Had it been calculated from the default equation, the value would have been 7.054E3°K. Parameters not calculated in data reduction carry standard default values

TABLE III-2. INPUT LISTING FOR ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION ON PV-TAP WITH RUN TO PRODUCE PLOTS

```
        00000000011111111112222222222333333333344444444445555555555666666666677777777778
        12345678901234567890123456789012345678901234567890123456789012345678901234567890
 1      *DATA REDUCTION - 3 INCH CELL, SERIAL NUMBER 134
 2      LIBRARY
 3           PV SOLC1 11
 4                IP 1483
 5                ISC 1483
 6                TEMP 298
 7                VB -33.5
 8                DVDT -2.2E-3
 9                DIDT 0.1
10                DATA DC
11                     -34.0 1000
12                     -33.9 900
13                     -33.5 800
14                     -32.9 754.0
15                     -31.6 744.2
16                     -30.0 713.9
17                     -25.0 631.6
18                     -20.0 552.3
19                     -15.1 473.0
20                     -10.1 369.2
21                     -7.11 283.0
22                     -4.94 184.1
23                     -3.59 104.8
24                     -1.68 26.44
25                     .100 1480
26                     .225 1470
27                     .325 1449
28                     .382 1400
29                     .419 1300
30                     .445 1200
31                     .460 1100
32                     .473 1000
33                     .494 800
34                     .529 400
35                     .556 0.00
36      PV1 I 0 S T P SOLC1
37      I1 0 1 2E3
38      R1 1 0 .3E-3
39      VIS S 0 1
40      VIT T 0 298
41      X1=TABLE1(V(PV1))
42      TABLE1
43           -34.0 1000
44           -33.9 900
45           -33.5 800
46           -32.9 754.0
47           -31.6 744.2
48           -30.0 713.9
49           -25.0 631.6
50           -20.0 552.3
51           -15.1 473.0
52           -10.1 369.2
53           -7.11 283.0
54           -4.94 184.1
55           -3.59 104.8
56           -1.68 26.44
57           .000 .000
58           .001 1483
59           .100 1480
60           .225 1470
61           .325 1449
62           .382 1400
63           .419 1300
64           .445 1200
65           .460 1100
66           .473 1000
67           .494 800
68           .529 400
69           .556 0.00
70      STATE1
71           I1 0.0
72           R1 5E-5 (5) 1E-4 (18) 1E-3 (10) 1E-2
73           PRINT I(PV1) X1 V(PV1)
74           PLOT X1 I(PV1) VS V(PV1)
75      STATE2
76           VIS 0.0
77           R1 100.
78           I1 1E-4 (5) 1E-3 (5) 1E-2 (5) 1E-1 (5) 1E0 (5) 1E1 (5) 1E2 (18) 1E3
79           PRINT X1 I(PV1) V(PV1)
80           PLOT X1 I(PV1) VS V(PV1)
81      END
```

TABLE III-3. COMPARISON GENERATED BY PV-TAP ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION

DATA REDUCTION TYPE DC FOR SOLC1

TERMINAL VOLTAGE	CURRENT EXPERIMENTAL	CURRENT CALCULATED
-.3400E+02	.1000E+04	.9752E+03
-.3390E+02	.9000E+03	.8752E+03
-.3350E+02	.8000E+03	.8300E+03
-.3290E+02	.7540E+03	.8150E+03
-.3160E+02	.7442E+03	.7828E+03
-.3000E+02	.7139E+03	.7432E+03
-.2500E+02	.6316E+03	.6193E+03
-.2000E+02	.5523E+03	.4954E+03
-.1510E+02	.4730E+03	.3740E+03
-.1010E+02	.3692E+03	.2502E+03
-.7110E+01	.2830E+03	.1761E+03
-.4940E+01	.1841E+03	.1224E+03
-.3590E+01	.1048E+03	.8895E+02
-.1680E+01	.2644E+02	.4165E+02
.1000E+00	.1480E+04	.1480E+04
.2250E+00	.1470E+04	.1473E+04
.3250E+00	.1449E+04	.1447E+04
.3820E+00	.1400E+04	.1390E+04
.4190E+00	.1300E+04	.1306E+04
.4450E+00	.1200E+04	.1204E+04
.4600E+00	.1100E+04	.1121E+04
.4730E+00	.1000E+04	.1032E+04
.4940E+00	.8000E+03	.8449E+03
.5290E+00	.4000E+03	.3907E+03
.5560E+00	0.	-.1035E+03

TABLE III-4. LISTING OF PARAMETERS BY PV-TAP FOLLOWING ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION

LIBRARY VALUES AFTER COMPLETION OF DATA REDUCTION

TYPE	PREFIX	MODEL	
SOLC1	PV	11	PHOTOVOLTAIC CELL
G	2.478012+001		(1.80+000)
IS	3.259285+003		(5.27+003)
M	1.991490+000		(1.25-001)
VZ	1.100000+000		
N	5.000000-001		
C	1.500000+006		
W	2.000000-005		
A	1.342989+001		
VB	-3.362021+001		
B	1.000000+000		
RS	1.563399-005		(7.00-006)
IP	1.483000+003		
KSC	4.500000+003		
T	5.000000+004		
CS	0.000000+000		
CST	0.000000+000		
CT	0.000000+000		
CTT	0.000000+000		
P	1.506409+000		(9.48-002)
SR	1.000000+000		
TR	2.980000+002		
ETA	1.000000+000		
QK	1.160000+004		
ALPHA	6.003774+003		(4.04+002)

except for IP which was defined in a paramspec entry. The parameter, QK is the electron charge divided by Boltzman's constant and is given as 1.16E4°K/V. The units for the parameters are KΩ, mmhos, V, mA, pF, ns. If the user wishes to use a different set of units, he must adjust the value of QK to match his set of units.

Figure III-3 contains the comparison plot produced by the illuminated state solution. The x's represent the empirical data as listed in the "TABLE1" entry seen in table III-2. The 1's represent the calculated currents. There is both an x and a 1 for each plotted voltage. Where only 1's are seen at a given voltage this indicates that the currents are too close to be distinguished separately on the plot. Thus the 1 symbol

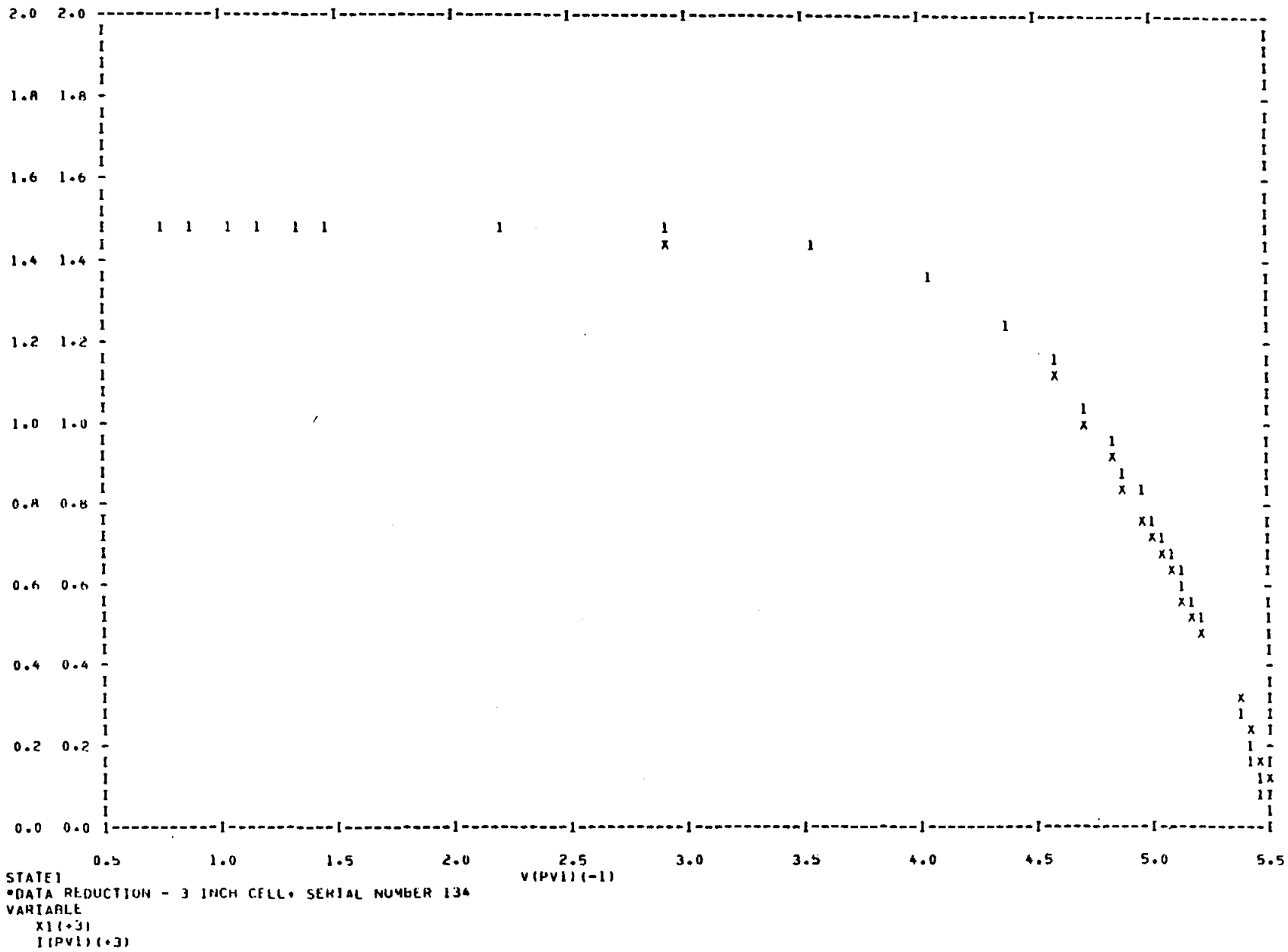


Figure III-3. PV-TAP Plot for Illuminated Forward Cell Data Reduction

is used to represent both calculated and empirical currents. The x-axis is defined as V(PV1)(-1), the voltage across the cell in units of 10^{-1} V. Thus, the values on the x-axis should be multipled by 10^{-1} to obtain the true voltage. The y-axis are defined as X1(+3) and I(PV1)(+3). Thus, the left column from 0.0 to 2.0 represents the empirical data in 10^3 mA, and the right column from 0.0 to 2.0 represents the current out of the cell in 10^3 mA.

Figure III-4 contains the comparison plot produced by the dark reverse state solution. The x's again represent empirical data while the 1's represent calculated currents. The voltage scale is from -36 V to 4.0 V. The current scales are both 0.0 to 1.0 A (or 1.0 x 10^3 mA). The x's indicate that the empirical data is not linear from the origin to breakdown. The 1's plotted in this region represent the best linear approximation (R_{SH} = constant) to the data.

The dark forward I-V curve measured from this same cell is shown in figure III-5. The input listing used to perform the data reduction for this curve and to produce comparison curves is shown in table III-5. In dark forward data reduction, the paramspec TEMP is required. IP is not used for data reduction, but is required if the user wishes to generate an illuminated comparison plot.

Lines 23 through 34 define the table used to plot the empirical dark forward data. Lines 35 through 47 define the table used to plot the empirical illuminated data. The variable X3 in line 48 is used to convert the negative dark currents calculated by PV-TAP into positive quantities so that a semi-log plot can be made.

In STATE1, a semi-log dark forward comparison plot is made. In STATE2, an illuminated I-V curve is generated from the dark parameters and compared with illuminated data.

Table III-6 shows the comparison of calculated to empirical currents produced by the PV-TAP data reduction. The full list of parameters following dark forward data reduction is shown in table III-7. The parameter units are the same as for the previous data reduction example.

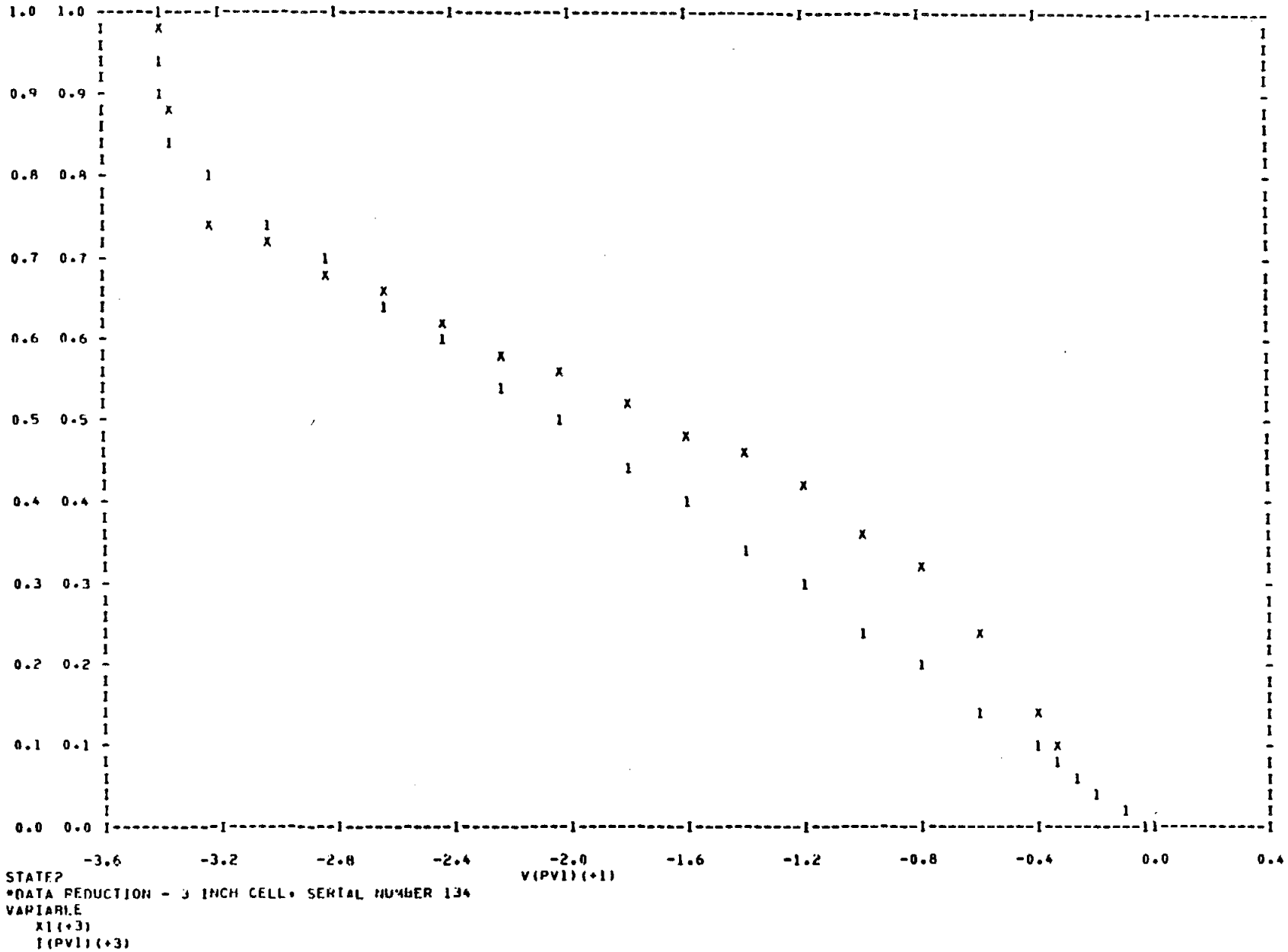


Figure III-4. PV-TAP Plot for Dark Reverse Cell Data Reduction

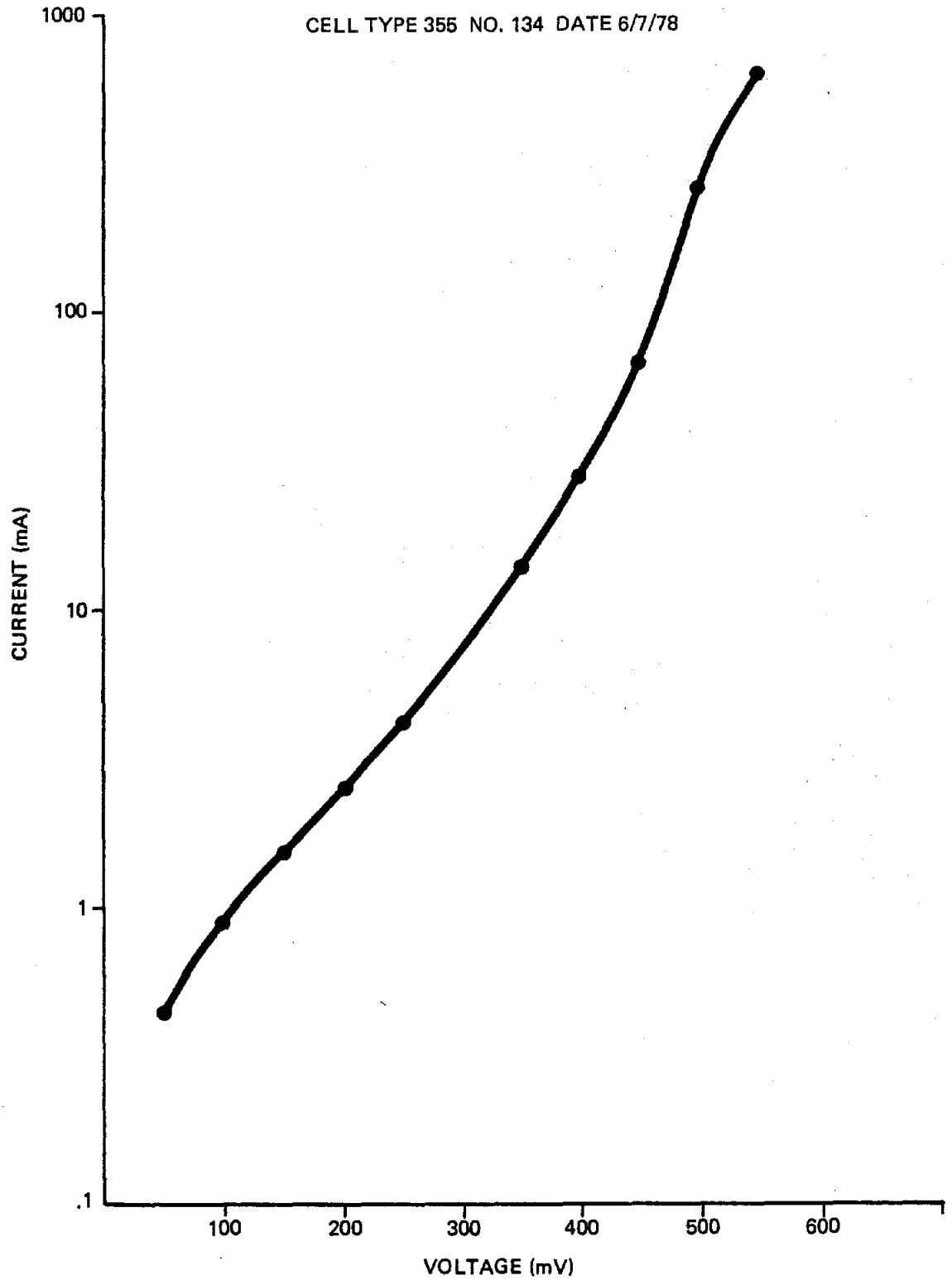


Figure III-5. Dark Forward Cell I-V Curve

TABLE III-5. INPUT LISTING FOR DARK FORWARD DATA REDUCTION ON PV-TAP WITH RUN TO PRODUCE DARK AND ILLUMINATED PLOTS

```
         00000000011111111112222222222333333333344444444445555555555666666666677777777778
         12345678901234567890123456789012345678901234567890123456789012345678901234567890
  1      *DATA REDUCTION - 3 INCH CELL, SERIAL NUMBER 134 - DF
  2      LIBRARY
  3           PV SOLC1 11
  4                IP 1483
  5                TEMP 298
  6                DATA DC
  7                     .100 -.941 .1
  8                     .150 -1.546 .1
  9                     .201 -2.478 .1
 10                     .251 -4.285 .1
 11                     .300 -7.201 .1
 12                     .351 -13.59 .1
 13                     .399 -27.79 .1
 14                     .449 -68.94 1.0
 15                     .498 -271.1 1.0
 16                     .549 -614.7 1.0
 17      PV1 1 0 S T P SOLC1
 18      R1 1 0 .3E-3
 19      V1S S 0 1
 20      V1T T 0 298
 21      V1 2 0 0.6
 22      R2 2 1 .01E-3
 23      X1=TABLE1(V(PV1))
 24      TABLE1
 25           .100 .941
 26           .150 1.546
 27           .201 2.478
 28           .251 4.285
 29           .300 7.201
 30           .351 13.59
 31           .399 27.79
 32           .449 68.94
 33           .498 271.1
 34           .549 614.7
 35      X2 = TABLE2(V(PV1))
 36      TABLE2
 37           .100 1480
 38           .225 1470
 39           .325 1449
 40           .382 1400
 41           .419 1300
 42           .445 1200
 43           .460 1100
 44           .473 1000
 45           .494 800
 46           .529 400
 47           .556 0.00
 48      X3 = -I(PV1)
 49      STATE1
 50           R1 100.
 51           V1S 0.0
 52           V1 0.12 (14) 0.4 (20) 0.6
 53           PRINT I(PV1) V(PV1) X1
 54           PLOT LOGLIN X1 X3 VS V(PV1)
 55      STATE2
 56           R2 100.
 57           V1S 1.0
 58           V1 0.0
 59           R1 5E-5 (5) 1E-4 (18) 1E-3 (10) 1E-2
 60           PRINT I(PV1) V(PV1) X2
 61           PLOT X2 I(PV1) VS V(PV1)
 62      END
```

TABLE III-6. COMPARISON GENERATED BY PV-TAP DARK FORWARD DATA REDUCTION

DATA REDUCTION TYPE JC FOR SOLC1

TERMINAL VOLTAGE	CURRENT EXPERIMENTAL	CURRENT CALCULATED
.1000E+00	-.9410E+00	-.1129E+01
.1500E+00	-.1546E+01	-.1715E+01
.2010E+00	-.2478E+01	-.2385E+01
.2510E+00	-.4285E+01	-.3295E+01
.3000E+00	-.7201E+01	-.5051E+01
.3510E+00	-.1359E+02	-.1012E+02
.3990E+00	-.2779E+02	-.2528E+02
.4490E+00	-.6894E+02	-.7685E+02
.4980E+00	-.2711E+03	-.2309E+03
.5490E+00	-.6147E+03	-.6336E+03

Figure III-6 contains the comparison plot produced by the dark forward state solution. The voltage scale is 0.1 to 0.6 V. The semi-log current scales are each 1.0 mA to 1.0 A. The x's represent the empirical data in variable X1(table III-5, lines 23-34), and the 1's represent the calculated currents from X3 = -I(PV1).

In figure III-7, the illuminated curve (1's) calculated from the parameters generated by the dark forward data reduction are compared to the empirical illuminated data (x's). The curves deviate significantly over the region from peak power to the open circuit. The calculated V_{OC} is 563 mV while the measured V_{OC} is 555 mV. The comparison was made for six other cells and all showed greater deviations up to 688 mV calculated versus 542 mV measured for cell 233. This discrepancy between dark and illuminated curves is also discussed in sections I.A and V.A. Note also the differences in the parameters obtained from each type of data reduction.

TABLE III-7. LISTING OF PARAMETERS BY PV-TAP FOLLOWING DARK FORWARD DATA REDUCTION

LIBRARY VALUES AFTER COMPLETION OF DATA REDUCTION

TYPE	PREFIX	MODEL	
SOLC1	PV	11	PHOTOVOLTAIC CELL
G	1.119509+001		(3.23+000)
IS	2.551340+005		(2.42+006)
M	1.527889+000		(4.19-001)
VZ	1.100000+000		
N	5.000000-001		
C	1.500000+006		
W	2.000000-005		
A	1.500000+001		
VB	-3.500000+001		
B	1.000000+000		
RS	2.679965-005		(4.45-005)
IP	1.483000+003		
KSC	4.500000+003		
T	5.000000+004		
CS	0.000000+000		
CST	0.000000+000		
CT	0.000000+000		
CTT	0.000000+000		
P	1.963494+000		(5.38-001)
SR	1.000000+000		
TR	2.980000+002		
ETA	1.000000+000		
QK	1.160000+004		
ALPHA	9.162971+003		(2.51+003)

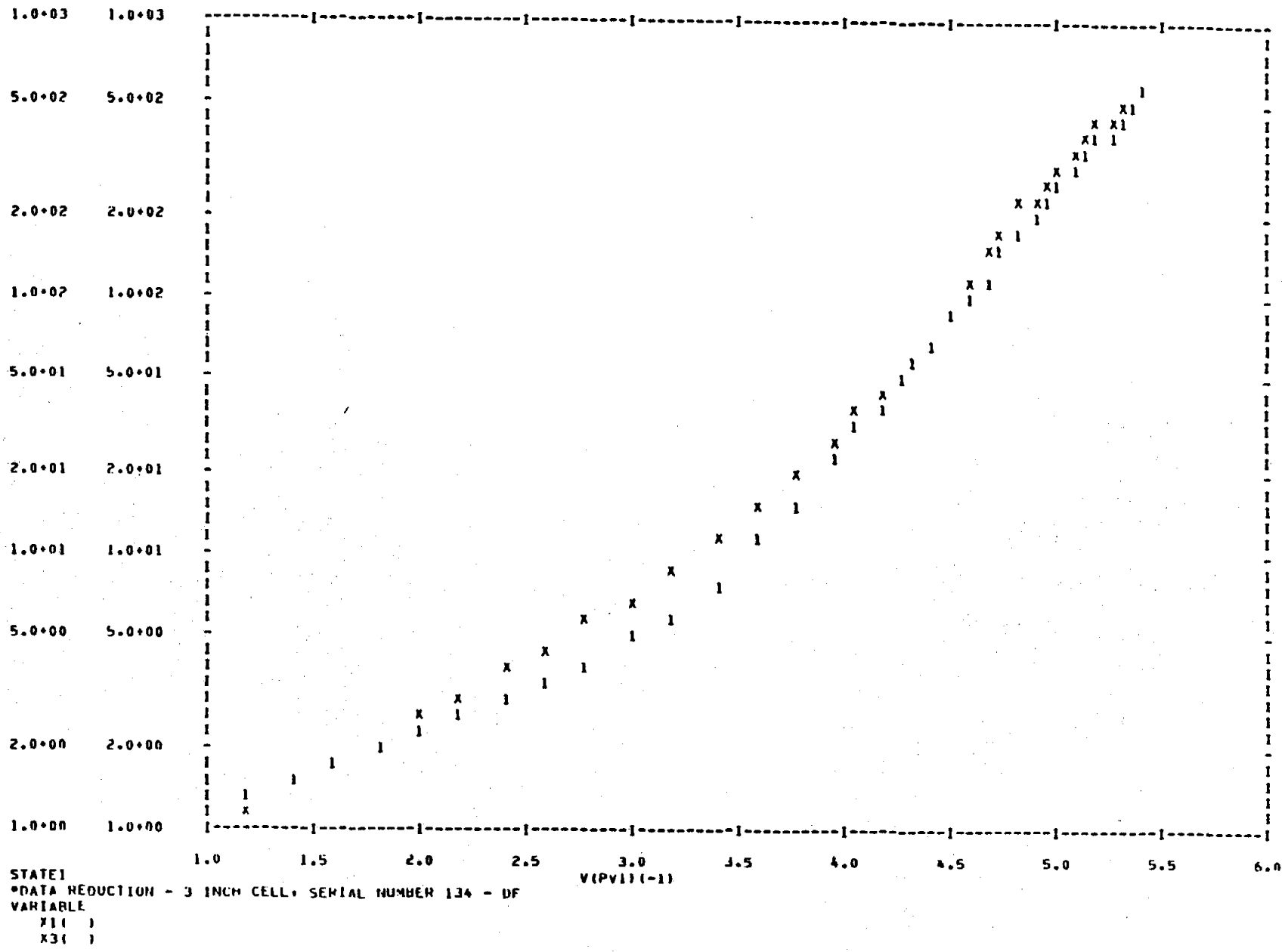


Figure III-6. PV-TAP Plot for Dark Forward Cell Data Reduction

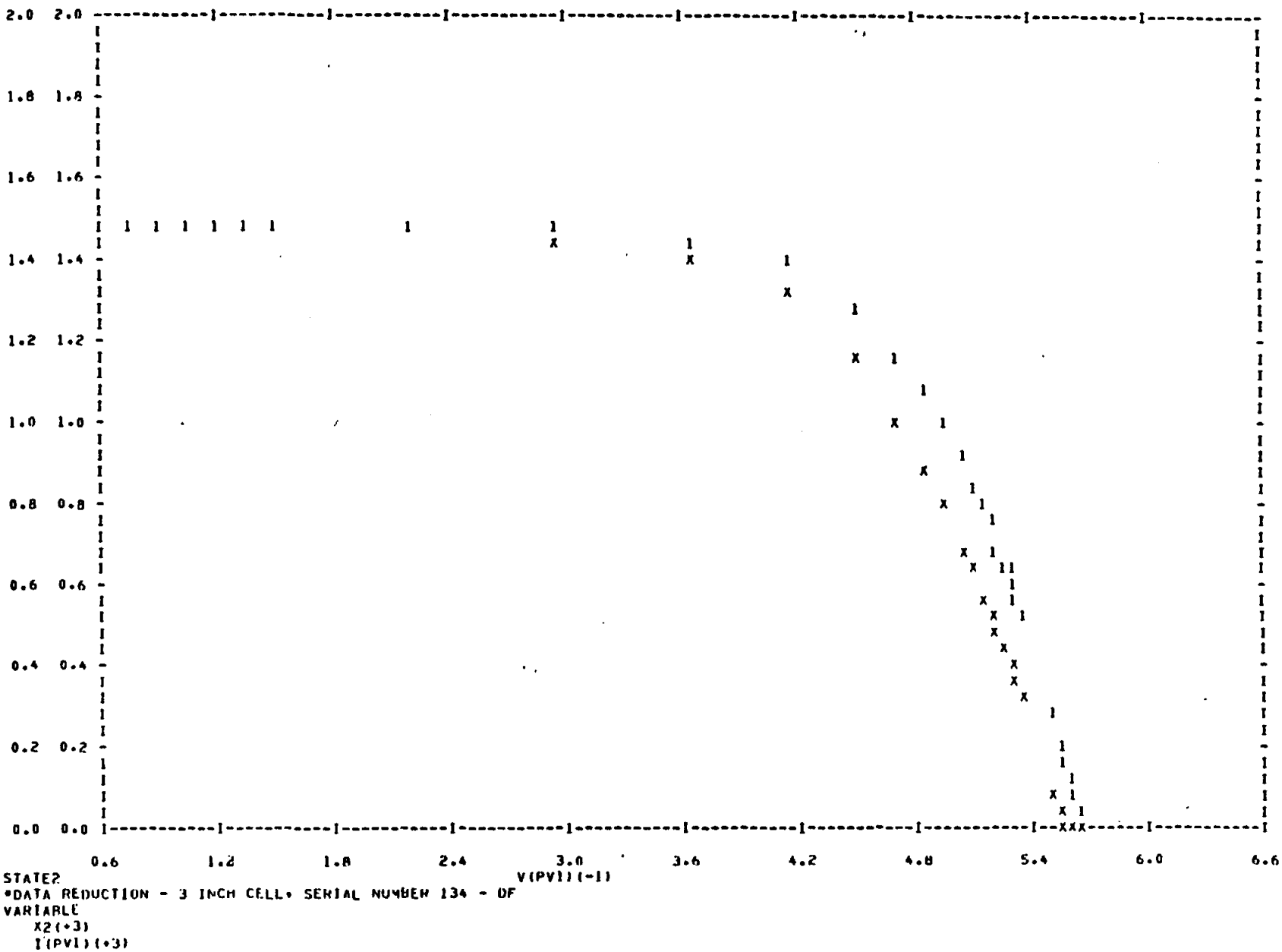


Figure III-7. PV-TAP Plot for Illuminated Forward I-V Curves from Dark Forward Data Reduction

CHAPTER IV
DATA REDUCTION USING PVDR

A. USER INTERFACE INSTRUCTIONS

General data reduction features for PV-TAP and PVDR are discussed in section II.B. This chapter presents user instructions which apply specifically to the PVDR code and examples of the use of PVDR.

All PVDR runs start with a title card. This card must contain an asterisk in column 1. This is followed by the "devicespec" card at indentation level one and other cards listed in table II-3. The input requirements and parameters calculated for each data reduction option in PVDR are catalogued in table IV-1. Three types of output are obtained from PVDR for each run. 1) Currents are calculated from the parameters obtained and tabulated with the experimental currents for each voltage point in the input list. 2) A listing is given of all parameter values used in PVDR to obtain the calculated currents. Included in the listing are the calculated parameters with their standard deviations and other parameters required for I-V calculations. 3) A plot of the currents calculated over the range of input voltages is overlayed with the experimental input data.

The user may obtain additional data reductions in the same run by appending each additional deck behind the last data card of the previous deck. Each additional deck must begin with a title card and contain all required data reduction inputs. At the end of the data reduction run an "END" card is used to signify the end of the run.

B. PVDR EXAMPLES

The same I-V curves used as examples for PV-TAP data reduction in chapter III were repeated on the PVDR code. The parameters obtained using PVDR were the same as those obtained from PV-TAP.

TABLE IV-1. PV CELL DATA REDUCTION IN PVDR

"DRTYPE" = DC

DESCRIPTION	INPUT SEQUENCE	PARAMETERS CALCULATED
DC CHARACTERISTICS		
DARK REVERSE	V, I, WGT.	G, A, B, VB
ILLUMINATED FORWARD	ISC, TEMP, G DVDT, DIDT (optional) V, I, WGT	RS, M, IS, P, ALPHA
DARK FORWARD	TEMP DVDT, DIDT (optional) V, I, WGT.	G, RS, M, IS, P, ALPHA
DARK REV./ILLUM. FWD.	ISC, TEMP DVDT, DIDT (optional) V, I, WGT.	G, A, B, VB, RS, M, IS, P, ALPHA

The experimental data curves were shown previously in figure III-1, III-2, and III-5. The PVDR input listing used for the combined dark reverse and illuminated forward data reduction is shown in table IV-2. The device has been labeled SOLC1 in the "devicespec" line. Note that the LIBRARY card used in PV-TAP is not used with PVDR.

Illuminated forward data reduction requires that values be input in "paramspec" cards for ISC and TEMP. G (the inverse of shunt resistance) would also be required if dark reverse data reduction were not performed. The use of VB in a "paramspec" card is not required unless the user wishes to instruct PVDR not to calculate this parameter by placing VB in the "fixedparams" field. Since the "fixedparams" field is blank, PVDR will calculate VB and substitute the calculated value in the output parameter listing. The use of the DVDT and DIDT "paramspec" cards instructs the program to calculate ALPHA based on these values.

In the "dataset" cards, the zero voltage point is assumed to correspond to zero current and is not required as input. If a non-zero current is input at zero volts corresponding to short circuit current (ISC), PVDR will ignore the point-pair and assume zero.

The comparison of calculated to empirical currents performed by PVDR is shown in table IV-3. The currents are tabulated corresponding to each of the voltages input in the "dataset" cards.

The parameters listed by PVDR are shown in table IV-4. Standard deviations representing goodness-of-fit for most calculated parameters are shown in parantheses. The units for the parameters are KΩ, mmhos, V, mA. The parameter G is the inverse of the shunt resistance. ALPHA was obtained from the DVDT and DIDT data. Had it been calculated from the default equation, the value would have been 7.054E3°K. QK is electron charge divided by Boltzmen's constant = Q/K = 1.16E4°K/V. If the user wishes to change to a different set of units, he must change the value of QK for the new set of units.

Figure IV-1 contains the comparison plot produced by the dark reverse data reduction. The +'s represent the empirical data and the *'s represent calculated values. In cases where an * and a + would be plotted

TABLE IV-2. INPUT LISTING FOR ILLUMINATED FORWARD AND DARK DARK REVERSE DATA REDUCTION ON PVDR

```
*DATA REDUCTION - 3 INCH CELL, SERIAL NUMBER 134
   PV SOLC1 11
     ISC 1483
     TEMP 298
     VB -33.5
     DVDT -2.2E-3
     DIDT 0.1
     DATA DC
       -34.0 1000
       -33.9 900
       -33.5 800
       -32.9 754.0
       -31.6 744.2
       -30.0 713.9
       -25.0 631.6
       -20.0 552.3
       -15.1 473.0
       -10.1 369.2
       -7.11 283.0
       -4.94 184.1
       -3.59 104.8
       -1.68 26.44
       .100  1480
       .225  1470
       .325  1449
       .382  1400
       .419  1300
       .445  1200
       .460  1100
       .473  1000
       .494  800
       .529  400
       .556  0.00
END
```

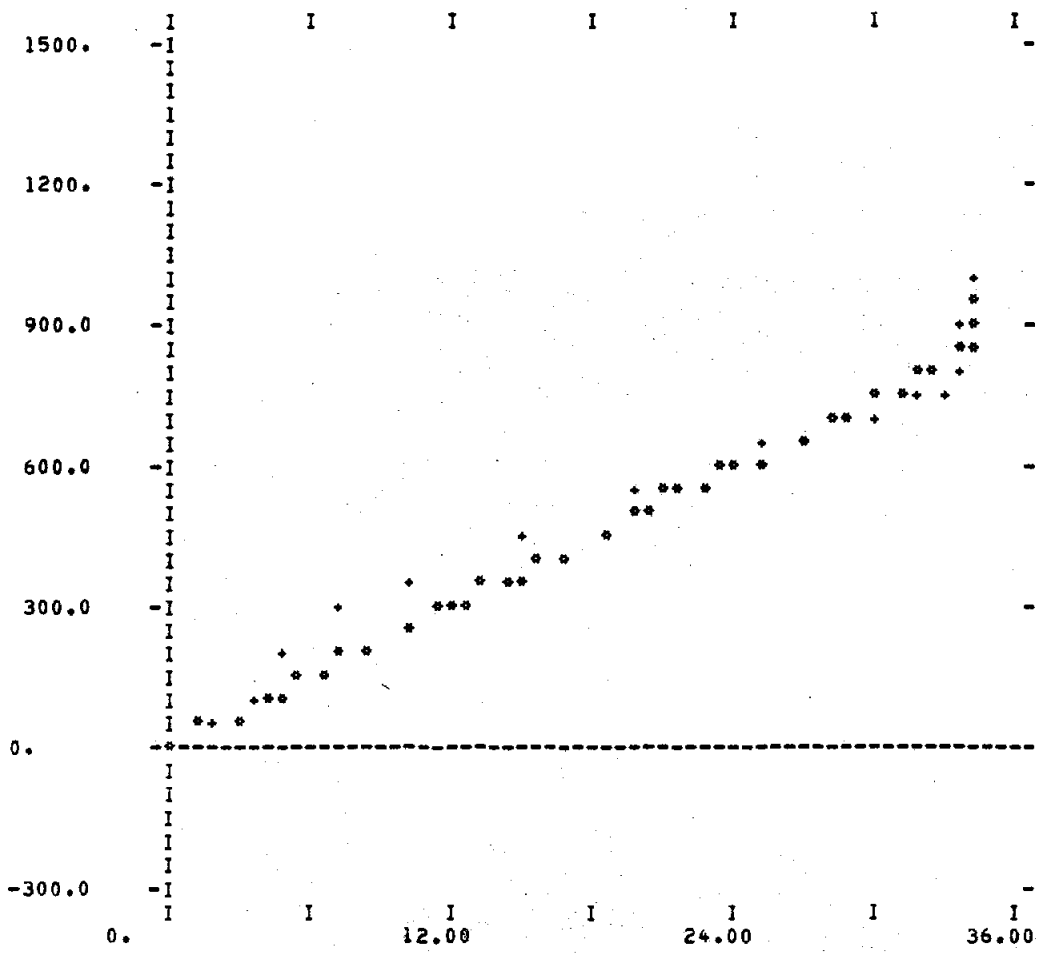
TABLE IV-3. COMPARISON GENERATED BY PVDR ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION

TERMINAL VOLTAGE	CURRENT EXPERIMENTAL	CURRENT CALCULATED
-.3400E+02	.1000E+04	.9752E+03
-.3390E+02	.9000E+03	.8752E+03
-.3350E+02	.8000E+03	.8300E+03
-.3290E+02	.7540E+03	.8150E+03
-.3160E+02	.7442E+03	.7828E+03
-.3000E+02	.7139E+03	.7432E+03
-.2500E+02	.6316E+03	.6193E+03
-.2000E+02	.5523E+03	.4954E+03
-.1510E+02	.4730E+03	.3740E+03
-.1010E+02	.3692E+03	.2502E+03
-.7110E+01	.2830E+03	.1761E+03
-.4940E+01	.1841E+03	.1224E+03
-.3590E+01	.1048E+03	.8895E+02
-.1680E+01	.2644E+02	.4165E+02
.1000E+00	.1480E+04	.1480E+04
.2250E+00	.1470E+04	.1473E+04
.3250E+00	.1449E+04	.1447E+04
.3820E+00	.1400E+04	.1390E+04
.4190E+00	.1300E+04	.1306E+04
.4450E+00	.1200E+04	.1204E+04
.4600E+00	.1100E+04	.1121E+04
.4730E+00	.1000E+04	.1032E+04
.4940E+00	.8000E+03	.8449E+03
.5290E+00	.4000E+03	.3907E+03
.5560E+00	0.	-.1035E+03

TABLE IV-4. LISTING OF PARAMETERS BY PVDR FOLLOWING ILLUMINATED FORWARD AND DARK REVERSE DATA REDUCTION

FINAL PARAMETER VALUES FOR DC DATA REDUCTION

SYMBOL	VALUE	SIGMA
A	.1342989E+02	
ALPHA	.6003774E+04	(.4043E+03)
B	.1000000E+01	
ETA	.1000000E+01	
G	.2478012E+02	(.1795E+01)
IS	.3259285E+04	(.5272E+04)
M	.1991490E+01	(.1253E+00)
P	.1506409E+01	(.9477E-01)
QK	.1160000E+05	
RS	.1563399E-04	(.7001E-05)
VB	-.3362021E+02	



DARK CURRENT VS. REVERSE VOLTAGE
(+ = DATA POINT, * = CALCULATED POINT)

Figure IV-1. PVDR Plots for Dark Reverse Cell Data Reduction

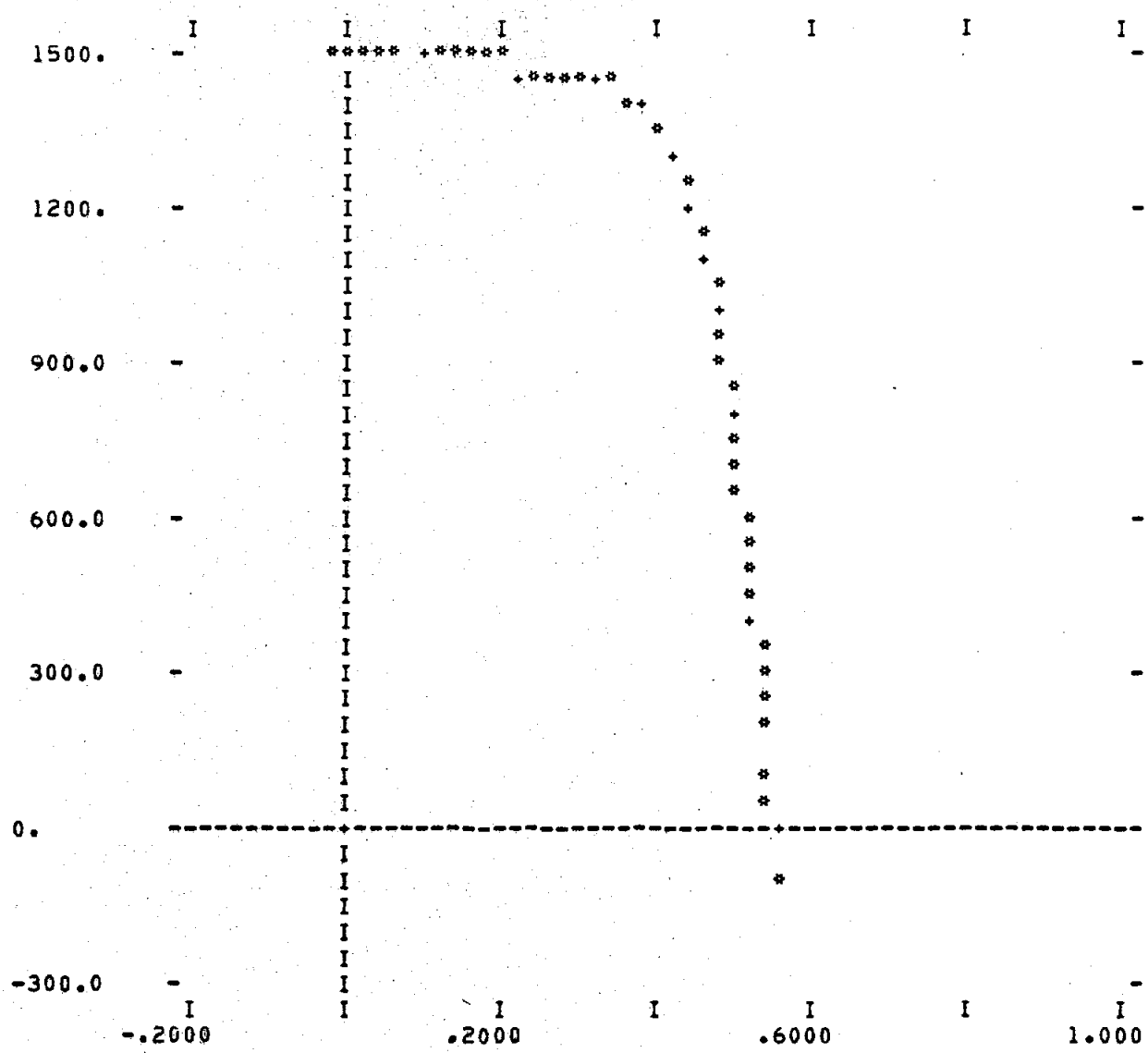
at the same point, the + takes precedence. The units in all plots are mA for the y-axis and volts for the x-axis. For the dark reverse plot, the x-axis is in negative volts; for forward plots, it is in forward volts.

Figure IV-2 contains the comparison plot produced by the illuminated forward data reduction. The +'s are empirical data; the *'s calculated values. Units are mA for the y-axis and volts for the x-axis.

The input listing used for the dark forward data reduction for cell 134 is shown in table IV-5. Dark forward data reduction requires the temperature be input as "paramspec," TEMP. Table IV-6 shows the comparison of calculated to empirical currents performed by PVDR. The currents are tabulated corresponding to each of the voltages input in the "dataset" cards.

Table IV-7 contains the parameter list generated by PVDR. The same parameters are listed from the dark forward as were listed from the illuminated forward and dark reverse data reductions. Since breakdown parameters are not calculated from dark forward data reduction and no values were input as paramspecs, the program supplies default values A=15, B=1, ETA=1, and VB=-35V. The default values are the same as those used in the PV-TAP PV cell model.

Figure IV-3 contains the comparison plot produced by the dark forward data reduction in PVDR. The +'s are empirical data, the *'s calculated values. Units are mA for the y-axis and volts for the x-axis.



ILLUMINATED CURRENT VS. FORWARD VOLTAGE
(+ = DATA POINT, * = CALCULATED POINT)

```
34    END
```

Figure IV-2. PVDR Plot for Illuminated Forward Cell Data Reduction

TABLE IV-5. INPUT LISTING FOR DARK FORWARD DATA REDUCTION ON PVDR

```
*DATA REDUCTION - 3 INCH CELL, SERIAL NUMBER 134 - DF
   PV SOLC1 11
      TEMP 298
      DATA DC
         .100 -.941 .1
         .150 -1.546 .1
         .201 -2.478 .1
         .251 -4.285 .1
         .300 -7.201 .1
         .351 -13.59 .1
         .399 -27.79 .1
         .449 -68.94 1.0
         .498 -271.1 1.0
         .549 -614.7 1.0
END
```

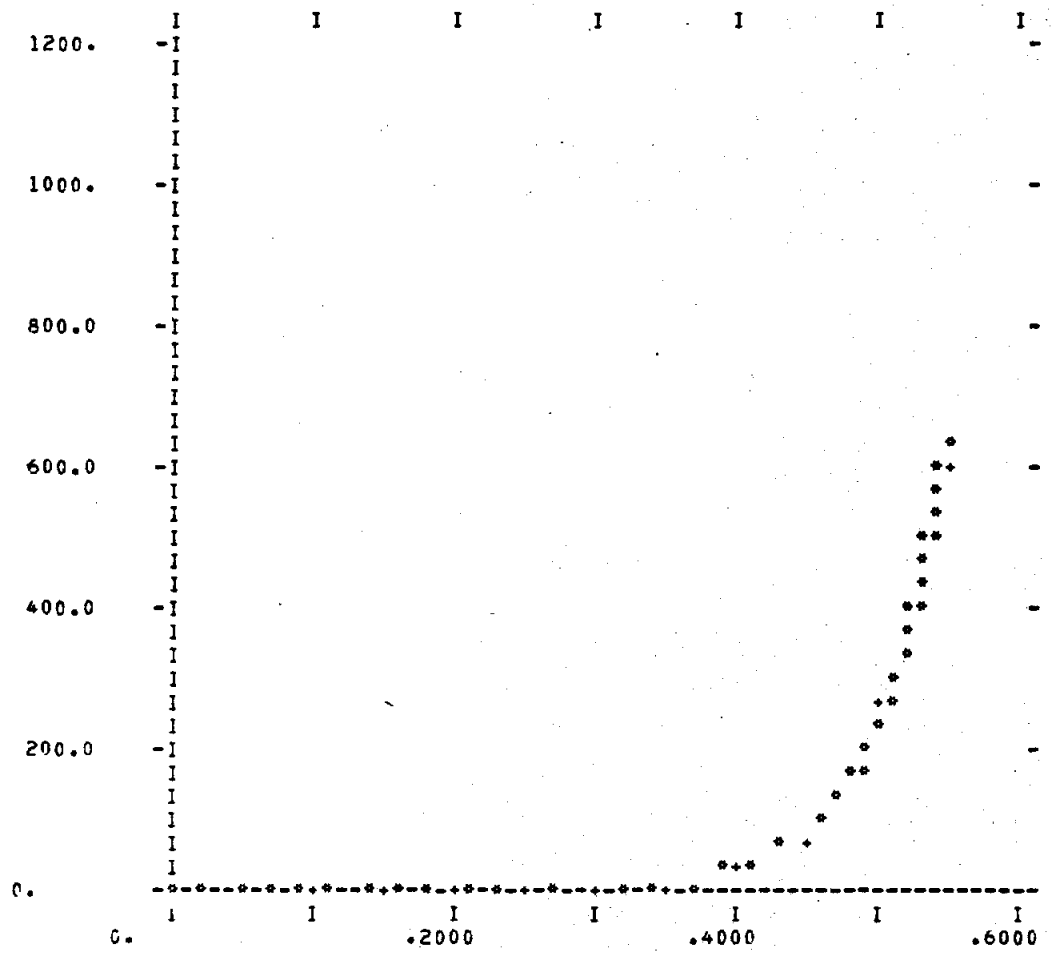
TABLE IV-6. COMPARISON GENERATED BY PVDR DARK FORWARD DATA REDUCTION

TERMINAL VOLTAGE	CURRENT EXPERIMENTAL	CURRENT CALCULATED
.1000E+00	-.9410E+00	-.1129E+01
.1500E+00	-.1546E+01	-.1715E+01
.2010E+00	-.2478E+01	-.2385E+01
.2510E+00	-.4285E+01	-.3295E+01
.3000E+00	-.7201E+01	-.5051E+01
.3510E+00	-.1359E+02	-.1012E+02
.3990E+00	-.2779E+02	-.2528E+02
.4490E+00	-.6894E+02	-.7685E+02
.4980E+00	-.2711E+03	-.2309E+03
.5490E+00	-.6147E+03	-.6336E+03

TABLE IV-7. LISTING OF PARAMETERS BY PVDR FOLLOWING DARK FORWARD DATA REDUCTION

FINAL PARAMETER VALUES FOR DC DATA REDUCTION

SYMBOL	VALUE	SIGMA
A	.1500000E+02	
ALPHA	.9162571E+04	(.2513E+04)
R	.1000000E+01	
ETA	.1000000E+01	
G	.1119509E+02	(.3228E+01)
IS	.2551840E+06	(.2420E+07)
M	.1527989E+01	(.4190E+00)
P	.1963494E+01	(.5384E+00)
QK	.1160000E+05	
PS	.2679965E-04	(.4446E-04)
VP	-.3500000E+02	



DARK CURRENT VS. FORWARD VOLTAGE
(+ = DATA POINT, * = CALCULATED POINT)

Figure IV-3. PVDR Plot for Dark Forward Cell Data Reduction

CHAPTER V
EXAMPLES OF DATA REDUCTION

The following examples of data reduction were performed to provide experience in the use of the codes and to assess problems involved in reducing actual data. They can, thus, serve as a valuable learning tool for the new user.

The results catalogued in the summary should not be viewed as an assessment of the accuracy of the program. Given data which fits the Ebers-Moll model, the program will produce parameters which can be used to match the data. The summaries are meant, instead, to assess the problems associated with reducing real data which contain deviations from the ideal curve shapes, to gauge the tolerance of the program to data anomalies, and to provide practical guidelines for reducing real data.

The data was obtained from BDM files on flat plate cells and modules and concentrating cells and modules. The flat plate data and the concentrating cell data were generated by other organizations. The concentrating module data were generated by BDM.

A. FLAT PLATE CELLS AND MODULES

1. Cell Data

The data reduced consists of dark forward and reverse curves and illuminated forward curves taken on 42 3-inch diameter single-crystal silicon flat plate cells with typical short circuit current of 1.6 A at 100 mW/cm^2 (1 sun) and 25°C.

a. Dark Reverse and Illuminated Forward

Figure V-1 shows typical illuminated forward I-V curves taken at 1 Sun and at 0.5 Suns. The manufacturer's specification of I_{SC}, V_{OC}, and R_S is contained in the upper right corner. The 1 Sun curve was used for data reduction. The shunt resistance required as input to illuminated forward data reduction was obtained from a dark reverse data reduction performed at the same time. This will be shown later.

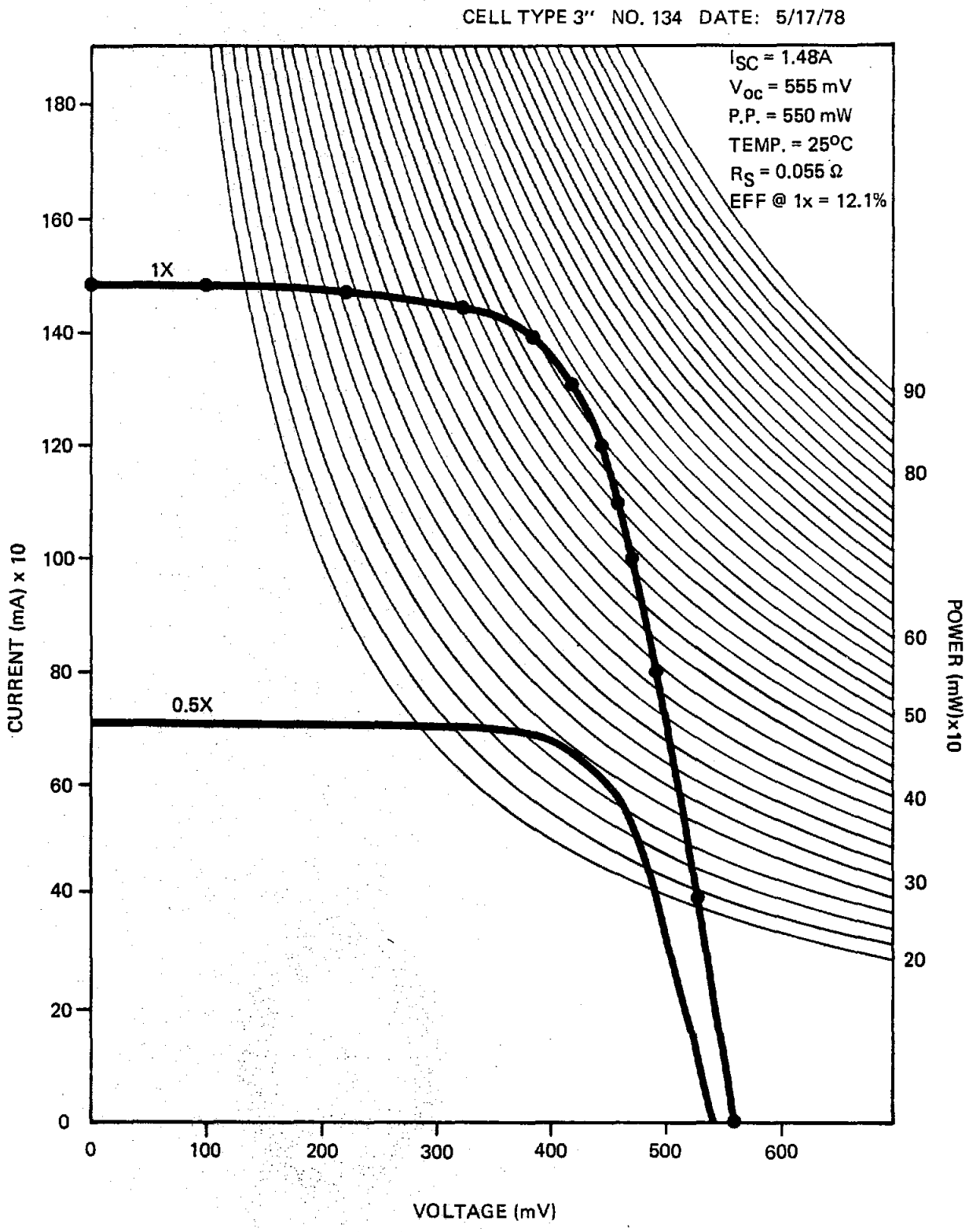


Figure V-1. Illuminated Forward Cell I-V Curves

Figure V-2 contains a plot made by PV-TAP comparing a calculated I-V curve (1's) made from the code-generated parameters with the empirical data (x's). The y-axes are both 2 A full scale and the x-axis is 0.55 V full-scale. In PV-TAP plotting, 1's take precedence over x's so that only 1's are seen at those voltages where the values are nearly identical. The match is good with peak power currents of 1.30 A measured and 1.29 A calculated at 0.42 V, and V_{OC} values of 556 mV measured and 550 mV calculated.

A summary of the illuminated forward data reduction for flat plate cells is contained in table V-1. It contains the key parameters--IS, M, and RS--obtained from data reduction. It also contains comments on the characteristics of the data curves and on the data reduction runs and a comparison of calculated and measured V_{OC}. For 3-inch diameter cells, IS values should normally be in the range of about 1×10^4 to 3×10^6 mA/°K, M values should range from about 1.0 to 3.0, and RS values should be about 20-60 mΩ. Values obtained beyond these ranges and deviations from measured V_{OC} can be caused either by anomalies in the forward or reverse data or by non-optimum selection of input parameters.

In general, points were input evenly from all portions of the curves. It appears more prudent, however, to input more points from peak power to open circuit portions than from the short circuit and low voltage portions since the most important cell characteristics are open circuit voltage (V_{OC}), peak power current (I_{pp}) and voltage (V_{pp}), and short circuit current (I_{SC}). Since I_{SC} is input as a "paramspec", this point is matched exactly, but I_{pp}, V_{pp}, and V_{OC} are matched through the calculated parameters. Therefore, more emphasis should be placed on these data points either by preferential selection of data points input or by the use of weighting factors.

In many cases, irregularities in the data required correcting approximations to obtain results. A positive slope in the data near short circuit in an illuminated forward curve will cause a fatal error in the program. Irregularities in reverse data will either cause errors in forward data reduction since shunt resistance is obtained from reverse data reduction or will result in fatal errors or convergence problems.

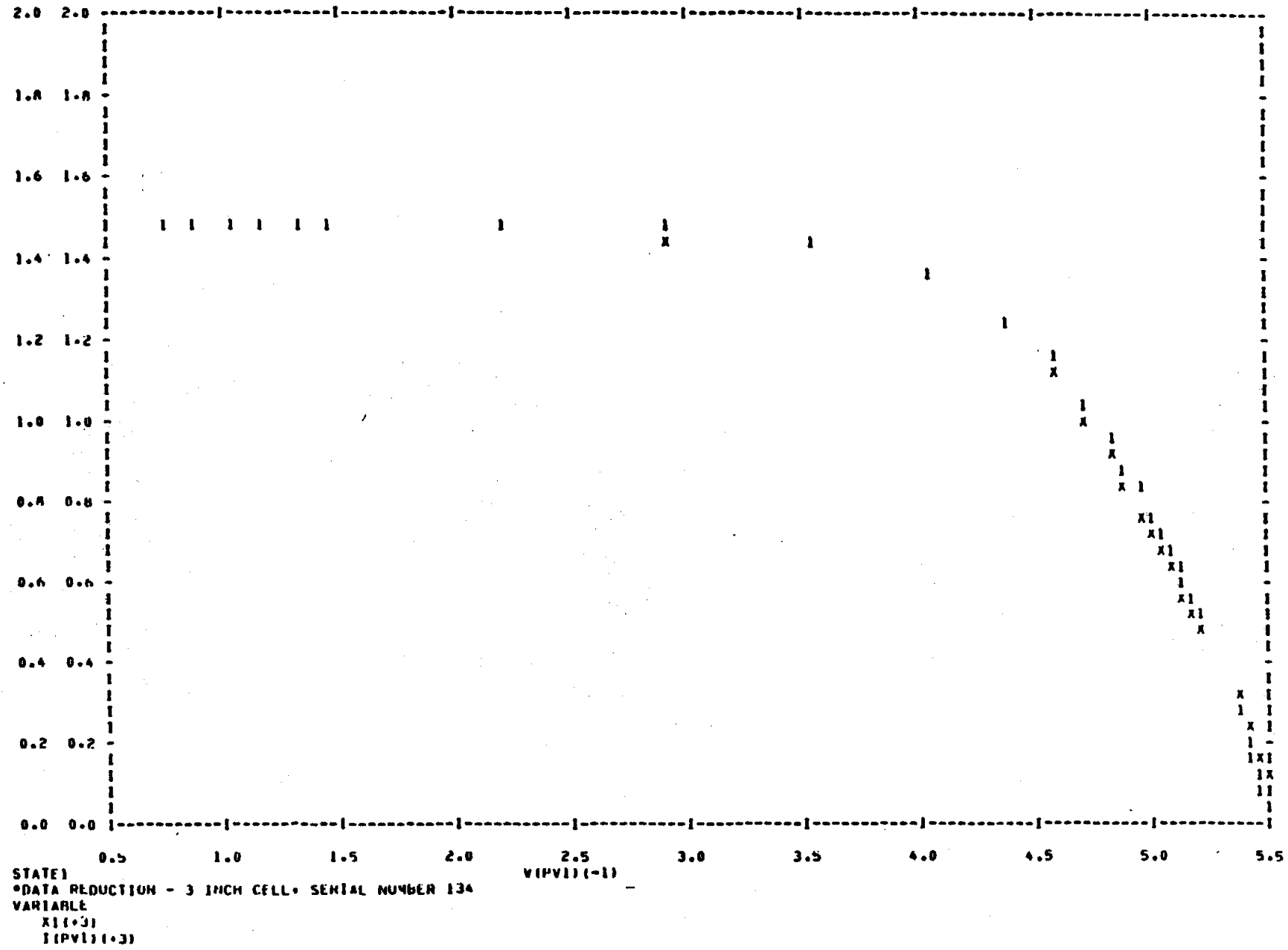


Figure V-2. PV-TAP Plot for Illuminated Forward Cell Data Reduction

TABLE V-1. SUMMARY OF ILLUMINATED FORWARD DATA REDUCTION FOR FLAT PLATE CELL

CELL NR	COMMENTS RE DATA	IS(mA/°K)	M	RS (mΩ)	V_{OC}(mV) DATA	V_{OC}(mV) CALC.	COMMENTS RE DATA REDUCTION
113		9.98E3	3.17	1.0	567	608	Large slope at ISC compared with reverse data causes error at V_{OC}
116		3.55E5	1.48	13.5	565	560	Irregularities in reverse data required correction
118		1.17E5	1.93	1.0	548	551	
120	Curve has inflection at 120 mV	2.18E6	1.25	39.8	534	534	Irregularities in reverse data required correction
134		1.02E5	1.99	15.6	556	550	
136	Curve has inflection at 100 mV	6.17E4	2.20	5.43	558	553	
138		6.25E5	1.28	59.9	543	565	
141		8.75E4	2.05	12.6	552	553	
143	Current at 100 mV > ISC	1.01E6	1.43	1.75	543	526	Slope required correction
147	Current at 100 mV > ISC	1.12E6	1.35	31.8	538	537	Slope required correction
185	Current at 100 mV > ISC	2.68E6	1.24	6.73	544	527	Slope required correction
196		1.88E4	3.03	1.0	544	568	
201		1.55E5	1.87	16.5	542	545	
203	Current at 125 mV = ISC	1.35E6	1.24	48.7	548	551	Slope required correction Irregularities in reverse data corrected

TABLE V-1. SUMMARY OF ILLUMINATED FORWARD DATA REDUCTION FOR FLAT PLATE CELLS (Continued)

CELL NR	COMMENTS RE DATA	IS(mA/°K)	M	RS (mΩ)	V_{OC}(mV) DATA	V_{OC}(mV) CALC.	COMMENTS RE DATA REDUCTION
210		3.79E4	2.55	7.95	549	553	
211		2.99E5	1.68	24.0	534	539	
222	Curve has inflection near peak power	2.56E5	1.69	36.3	541	540	Irregularities in reverse data required correction
226	Curve has inflections between 100 and 250 mV	1.96E4	3.24	1.0	539	550	
227		1.41E4	3.20	1.0	547	575	
228	Curve has inflection at 220 mV	1.28E5	1.98	30.5	545	541	
229	Curve has inflections at 430 and 490 mV	9.83E4	1.82	11.5	577	565	Irregularities in reverse data required correction
230		3.19E4	2.63	1.0	533	555	
231		5.27E4	2.09	31.2	575	575	
232		1.12E5	1.97	1.0	547	546	
233		6.90E4	2.25	1.0	527	540	
234	Curve has inflection near open circuit	8.75E4	1.80	49.5	559	579	Irregularities in reverse data required correction
235	Curve has inflection at 400 mV	1.28E5	1.76	42.3	561	562	Irregularities in reverse data required correction
236	Curve has many inflections	4.43E10	4.24	1.0	573	580	Errors due to inconsistency between high reverse leakage and slope near ISC

TABLE V-1. SUMMARY OF ILLUMINATED FORWARD DATA REDUCTION FOR FLAT PLATE CELLS (Concluded)

CELL NR	COMMENTS RE DATA	IS(mA/°K)	M	RS (mΩ)	V_{OC}(mV) DATA	V_{OC}(mV) CALC.	COMMENTS RE DATA REDUCTION
237	Current at 150 mV = ISC	3.88E4	2.44	1.0	559	561	Slope required correction
238	Curve has inflection near 250 mV	1.68E5	1.81	9.09	561	544	Irregularities in reverse data required correction
239		4.07E4	2.26	20.0	571	571	Irregularities in reverse data required correction
240		1.89E5	1.82	22.2	542	541	
261		2.03E4	2.72	1.0	559	576	
262	Curve has inflections near peak power	1.41E4	3.21	1.0	551	576	
263		8.05E3	2.82	1.0	580	640	Errors due to inconsistency between high reverse leakage and slope near ISC
264		7.14E5	1.30	45.0	547	560	Irregularities in reverse data required correction
265	Current at 250 mV = ISC	3.22E5	1.49	20.4	562	559	Slope required correction
266		7.89E4	1.88	15.0	572	573	Irregularities in reverse data required correction
268		1.56E4	3.07	1.0	547	575	
269	Curve has inflection at 240 and 475 mV	5.19E4	2.55	1.0	530	534	Irregularities in reverse data required correction
273		5.27E4	2.36	1.0	538	550	
275		5.47E5	1.42	27.6	550	551	Irregularities in reverse data required correction

In general, data inflections with negative slopes will not halt the data reduction program, but may produce errors in parameters obtained.

Figure V-3 shows a typical dark reverse I-V curve. Data was taken to breakdown or to about -34 V if breakdown did not occur. The cell shown (134) did not breakdown in the actual measurement, but breakdown data was artificially created in this case to provide a good breakdown example. Most of the cells, which did enter into breakdown, exhibited very sharp "knees" at breakdown and could not be taken more than 0.1 to 0.2 V beyond breakdown.

Note the nonlinear shape of the curve from the origin to about -12 V. This is also evident in the PV-TAP comparison plot in figure V-4. The x's represent empirical data; the 1's are calculated values. This type of irregularity will often halt the data reduction program and require approximating a straight line through the input data to obtain results. This is indicated in some of the data reduction comments in the dark reverse data reduction summary chart in table V-2. In some cases, superlinear and sublinear regions could be handled by the program. This depends on the degree of nonlinearity. If a line drawn from the origin to the onset of breakdown, reasonably bisects the data, results can usually be obtained from the original data. If the data is mostly above the line (sublinear curve), the program may not accept the data. If the data is mostly below the line (superlinear curve), the program may postulate a low breakdown voltage with a mild breakdown slope and reject the real breakdown data.

Shunt resistances for flat plate cells vary over a wide range from occasionally less than 10 Ω to over 1000 Ω. The 3-inch diameter flat plate cells in this sample should have shunt resistances from about 10 Ω to 200 Ω. The range of values in the chart is consistent with this range; however, individual values may be incorrect due to misinterpretation of data anomalies by the program. This, in turn, can affect the accuracy of the forward data reduction since shunt resistance is a required input for illuminated forward data reduction.

In some cases, A, B, and VB were input as "fixedparams" because the shape of the curve in breakdown was non-monotonic causing the

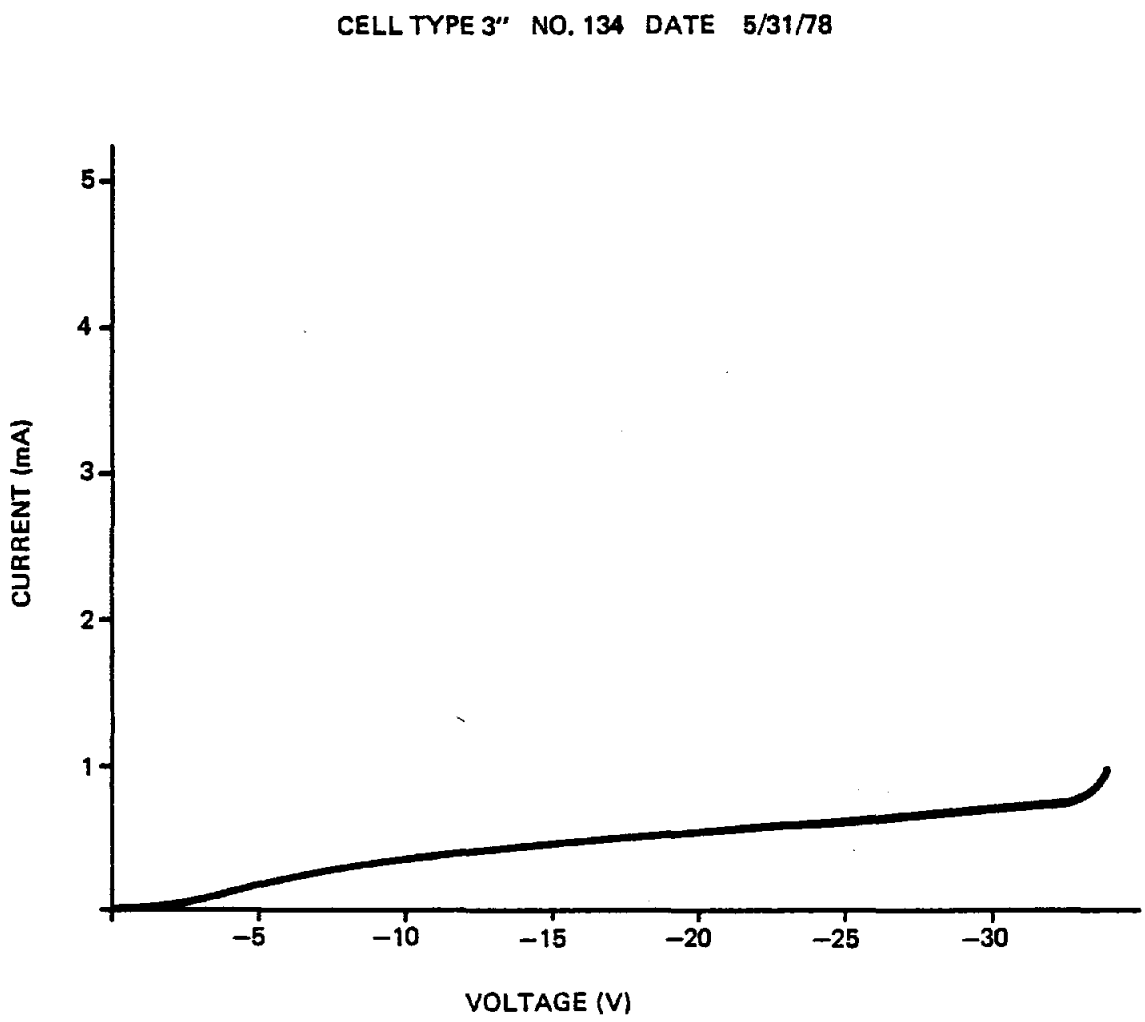


Figure V-3. Dark Reverse Cell I-V Curve

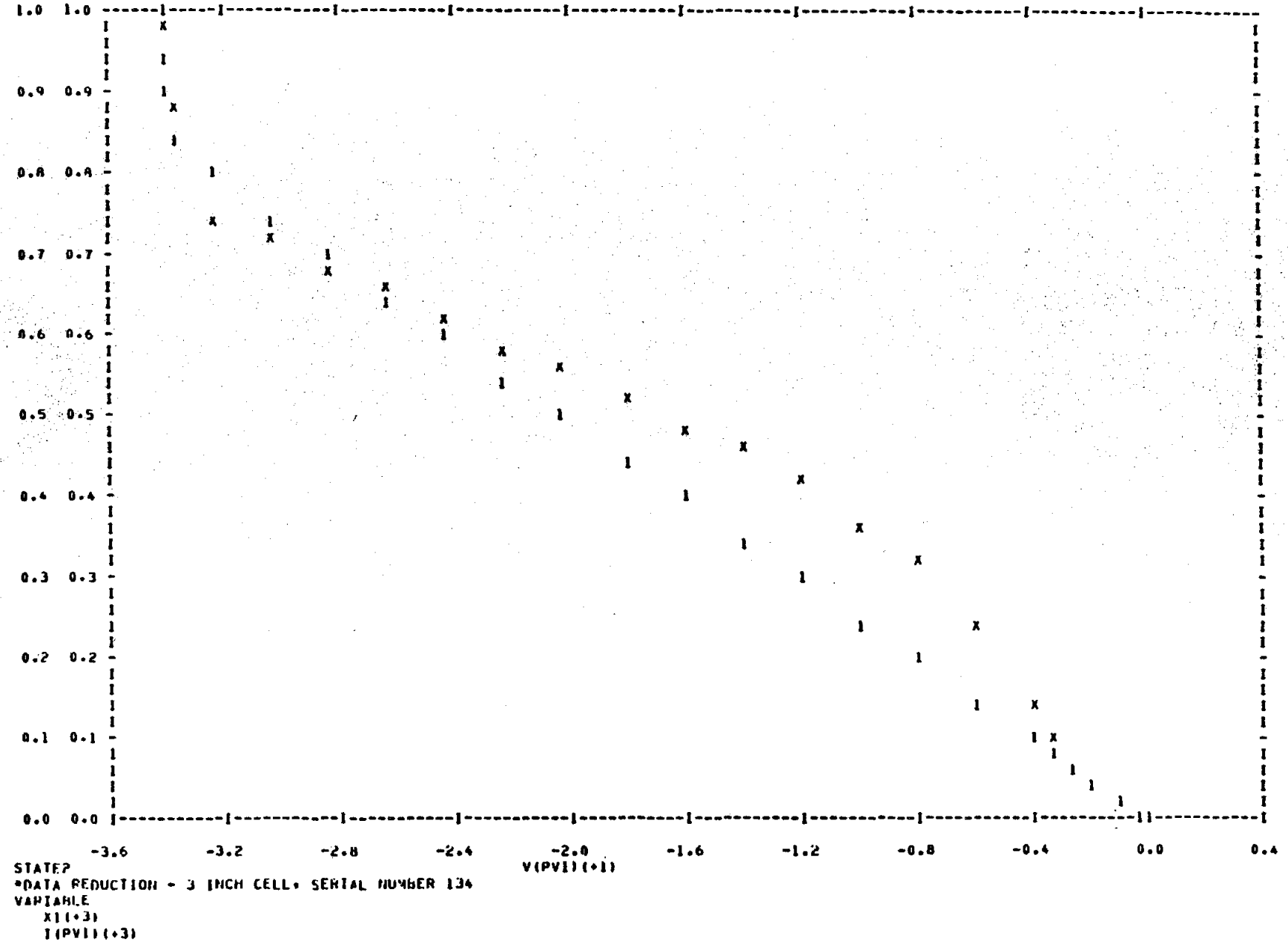


Figure V-4. PV-TAP Plot for Dark Reverse Cell Data Reduction

TABLE V-2. SUMMARY OF DARK REVERSE DATA REDUCTION FOR FLAT PLATE CELLS

CELL NR	COMMENTS RE DATA	RSH(Ω)	A	B	VB(-V) DATA	VB(-V) CALC.	COMMENTS RE DATA REDUCTION
113	No breakdown at -33 V	51.3			NA		
116	Sublinear beyond -15 V Vertical slope in breakdown	19.5	15.0	1.0	32.7	32.7	A, B, VB input as "fixed-params" to circumvent breakdown irregularities
118	No breakdown at -32 V	30.6			NA		
120	Superlinear beyond -20 V	28.5	10.1	1.0	28.5	28.0	Straight line approximation required
134	No breakdown at -33 V Sublinear beyond ~ -8 V	40.4	13.4	1.0	NA	33.6	Breakdown data artificially created to provide good example run
136	No breakdown at -33 V Sublinear beyond ~ -8 V	54.2			NA		
138	No breakdown at -33 V	139.			NA		
141	No breakdown at -33 V Sublinear beyond ~ -7 V	52.5			NA		
143	Superlinear beyond -14 V	60.0	0.40	1.0	25.3	13.2	Low calculated VB due to superlinearity
147	Sublinear beyond -10 V Stop discontinuity at -18.2 V	27.2	1.06	1.0	~24	18.5	
185		67.9	0.52	1.0	~25	14.3	Low calculated VB due to slight superlinearity and soft breakdown
196	No breakdown at -34 V	489.			NA		
201	No breakdown at -34 V	129.			NA		

TABLE V-2. SUMMARY OF DARK REVERSE DATA REDUCTION FOR FLAT PLATE CELLS (Continued)

CELL NR	COMMENTS RE DATA	RSH(Ω)	A	B	VB(-V) DATA	VB(-V) CALC.	COMMENTS RE DATA REDUCTION
203	Sublinear beyond -15 V	18.0	13.5	1.0	~30	30.1	Straight line approximation required
210	Sublinear beyond -14 V	34.4	3.58	1.0	25.2	24.5	
211	Superlinear beyond -22V	43.2	0.34	1.0	34	16.5	Low calculated VB due to superlinearity
222	Sublinear beyond -15 V	12.9	4.06	1.0	32.5	31.5	Straight line approximation required
226	No breakdown at -34 V	111.			NA		
227	No breakdown at -34 V	48.0			NA		
228		25.5	1.22	1.0	25.5	22.2	
229	Highly superlinear curve	17.2	0.34	1.0	~31	10.8	Low calculated VB due to superlinearity Straight line approximation required
230		101.	0.87	1.0	~33	28.1	
231		25.2	1.49	1.0	~29	25.9	
232	Superlinear beyond -19 V	59.8	0.51	1.0	~25	13.8	Low calculated VB due to superlinearity
233	Superlinear beyond -20 V	69.0	0.62	1.0	~25	16.7	Low calcuated VB due to superlinearity
234	Sublinear beyond -12 V	14.2	2.26	1.0	~23	21.2	Straight line approximation required
235	Superlinear below -8 V Sublinear beyond -8 V	8.28	1.22	1.0	~27-29	24.3	Straight line approximation required

TABLE V-2. SUMMARY OF DARK REVERSE DATA REDUCTION FOR FLAT PLATE CELLS (Continued)

CELL NR	COMMENTS RE DATA	RSH(Ω)	A	B	VB(-V) DATA	VB(-V) CALC.	COMMENTS RE DATA REDUCTION
236	No breakdown at -10.5 V High leakage (5 A at -9 V)	1.83			NA		
237	No breakdown at -34 V	31.2			NA		
238	Sublinear beyond -15 V	15.3	2.57	1.0	26	24.6	Straight line approximation required
239	Highly superlinear curve	23.8	0.26	1.0	~27-34	7.6	Straight line approximation required Low calculated VB due to superlinearity
240	Superlinear beyond -20 V Step discontinuity at -28 V	22.1	0.30	1.0	~30	7.8	Low calculated VB due to superlinearity
261	No breakdown at -34 V	146	0.21	1.0	NA	11.1	Slight superlinearity interpreted as mild breakdown
262	No breakdown at -34 V	116	0.16	1.0	NA	1.3	Slight superlinearity interpreted as mild breakdown
263	No breakdown at -20.5 V Superlinear; High leakage	3.55			NA		
264	No breakdown at -34 V Sublinear beyond -20 V	23.1			NA		Straight line approximation required
265	Superlinear beyond -29 V	38.4	0.53	1.0	32.7	22.8	
266	Superlinear below -15 V Sublinear beyond -15 V Negative slope in breakdown	12.1	15.0	1.0	27.2	27.2	A, B, VB input as "fixed-params" to circumvent data irregularities

TABLE V-2. SUMMARY OF DARK REVERSE DATA REDUCTION FOR FLAT PLATE CELLS (Concluded)

CELL NR	COMMENTS RE DATA	RSH(Ω)	A	B	VB(-V) DATA	VB(-V) CALC.	COMMENTS RE DATA REDUCTION
268	Soft breakdown	38.1	1.13	1.0	~27-29	24.7	
269	Negative slope in breakdown	46.5			16.	16.	A, B, VB input as "fixed-params" to circumvent breakdown irregularities
273	No breakdown at -34 V Step discontinuity at -30 V	176	0.17	1.0	NA	5.2	Slight superlinearity interpreted as mild breakdown.
275	Superlinear below ~ -17 V Sublinear beyond ~ -17 V	19.1	2.29	1.0	32	30.4	Straight line approximation required

program either to reject the data and supply default parameters, to produce unacceptable values or to halt completely. In some cases the data appeared to exhibit two soft knees and in others the breakdown region exhibited a vertical or negative slope.

b. Dark Forward

Figure V-5 contains a typical dark forward I-V curve for 3-inch diameter flat plate cells. The data was taken at 25°C. The comparison plot generated by PV-TAP for this cell is shown in figure V-6. The semi-log plot has logarithmic y-axes scales, each from 1.0 mA to 1000 mA. The linear x-axis goes from 0.1 to 0.6 V. The results exhibit a good match for this cell because the cell data itself exhibited a distinct RS effect at the top of the curve and because the data was input with increased weighting on the upper three points of figure V-5. However, the resultant parameters, as discussed previously in sections I-A and III-B, do not produce an illuminated I-V curve with a good match to the illuminated data.

In the dark forward data reduction summary chart in table V-3, the comments indicate most of the problems encountered in the runs. The measurements were made only out to 0.55 V for most cells. Since the current direction is into the cells in dark forward measurements, the voltage at the junction is lower than the terminal voltage as opposed to the illuminated case in which the junction voltage is higher than the terminal voltage. Therefore, higher terminal voltages must be employed to obtain the same current through the junction. In most cases, the maximum currents produced were less than 1.0 A. Thus, most curves exhibited little or no RS effect. This results in the program assigning the minimum allowable value of 1.0 mΩ. This was done to prevent generation of negative values. Since PV cells are operated at low current densities compared to semiconductor devices, they can be safely measured at much higher forward currents and should have been taken to 2.0 A.

The points shown on the curve of figure V-5 indicate that six of the ten points input were taken below 0.4 V. Since only RSH is obtained from this region, more points should be input from the region

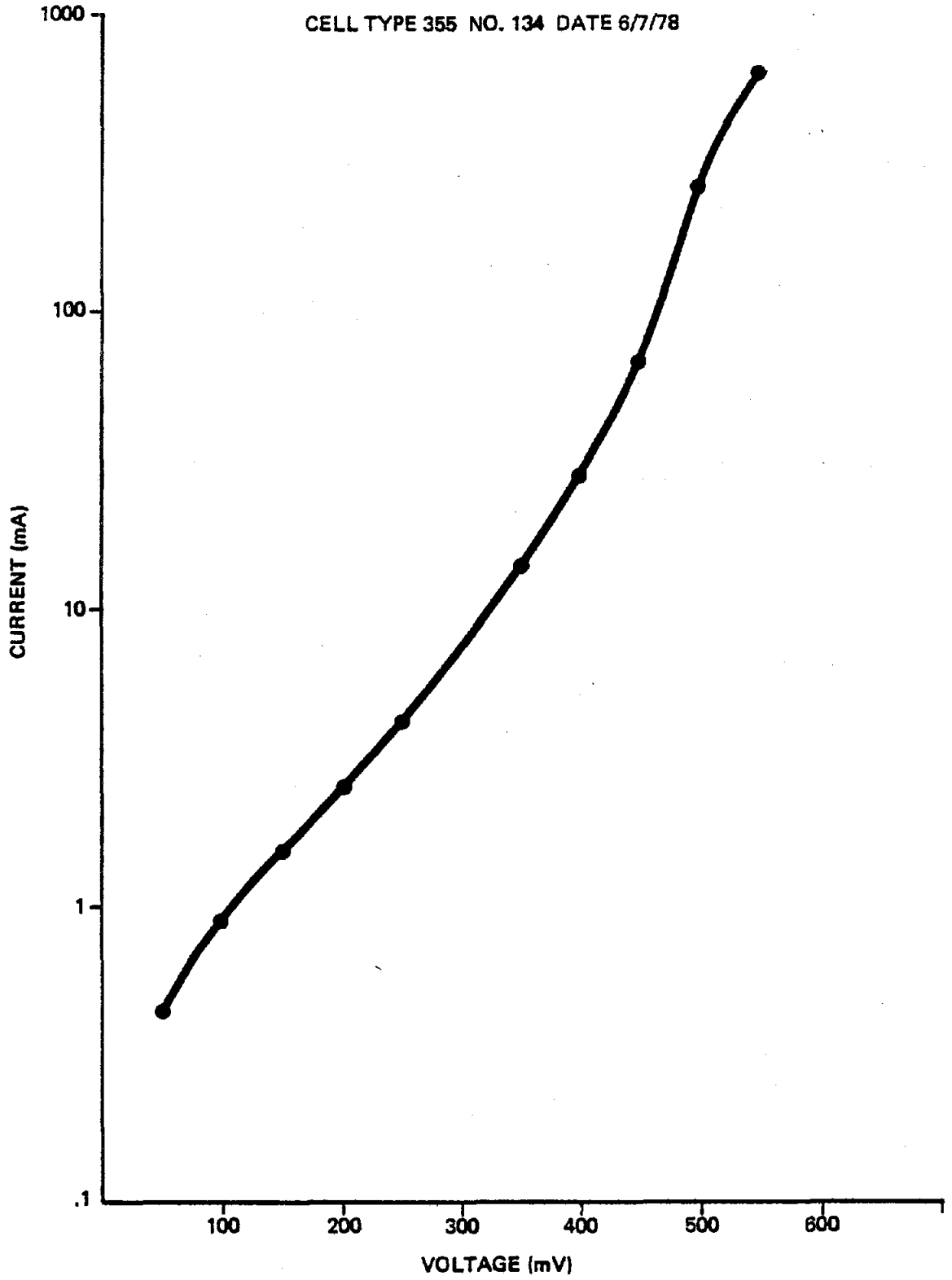


Figure V-5 . Dark Forward Cell I-V Curve

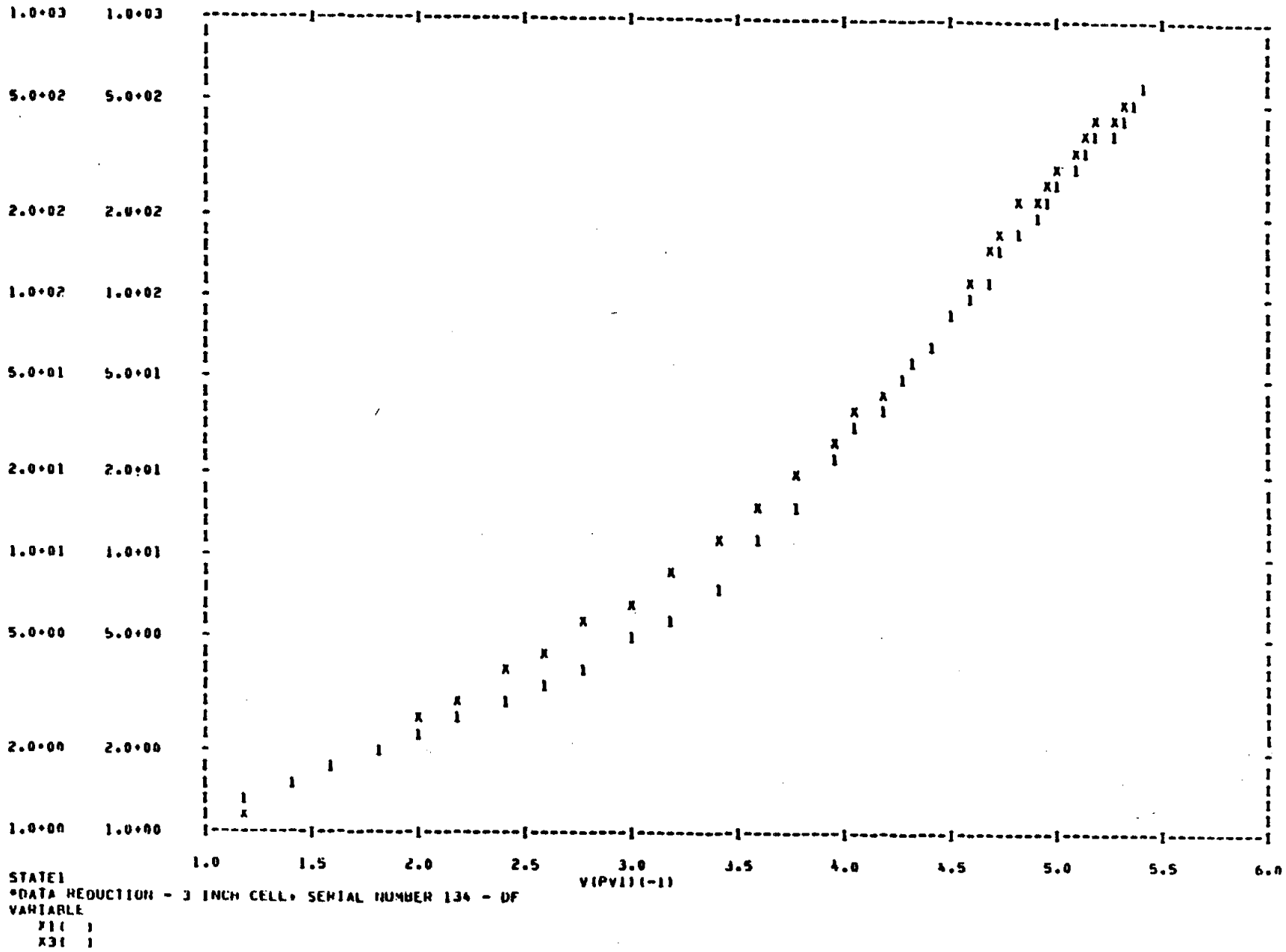


Figure V-6. PV-TAP Plot for Dark Forward Cell Data Reduction

TABLE V-3. SUMMARY OF DARK FORWARD DATA REDUCTION FOR FLAT PLATE CELLS

CELL NR	COMMENTS RE DATA	RSH (Ω)	IS(mA/°K)	M	RS (mΩ)	COMMENTS RE DATA REDUCTION
113	No RS effect	221	5.60E3	2.96	1.0	Lack of RS effect in data results in default value of 1.0 mΩ and tends to produce errors in other parameters. Data should have been taken at higher currents, and less low current points should have been input in data reduction
116	No RS effect	87.6	1.35E3	3.97	1.0	
118	No RS effect	229	3.09E3	3.05	1.0	
120	Slight RS effect	71.5	1.24E3	3.83	1.0	
134		89.3	2.55E5	1.53	26.8	Weighting factors used to improve results at high currents
136	Slight RS effect	165	3.43E3	2.88	1.0	
138	Slight RS effect	658	8.35E3	2.39	1.0	
141	No RS effect	153	6.87E3	2.83	1.0	
143	Slight RS effect	301	6.81E3	2.66	1.0	
147		28.3	7.01E4	1.86	7.89	
185		148	4.98E3	2.65	1.0	
196	Slight RS effect	5140.	1.88E4	2.15	1.0	
201	Slight RS effect	773	2.98E4	2.11	1.0	
203	No RS effect	119	1.19E3	4.06	1.0	
210	No RS effect	79.6	9.80E2	4.24	1.0	
211	No RS effect	109	2.35E3	3.46	1.0	
222	No RS effect	112	1.05E3	4.44	1.0	

TABLE V-3. SUMMARY OF DARK FORWARD DATA REDUCTION FOR FLAT PLATE CELLS (Continued)

CELL NR	COMMENTS RE DATA	RSH (Ω)	IS(mA/°K)	M	RS (mΩ)	COMMENTS RE DATA REDUCTION
226	No RS effect	213	1.85E4	2.52	1.0	
227	No RS effect	247	7.64E3	2.90	1.0	
228	No RS effect	156	1.65E3	3.74	1.0	
229	No RS effect	51.0	1.08E4	2.60	1.0	
230	Slight RS effect	274	5.77E3	2.60	1.0	
231	Slight RS effect	56.3	8.88E3	2.72	1.0	
232	No RS effect	144	2.46E3	3.13	1.0	
233	Slight RS effect	129	3.72E3	3.05	1.0	
234	No RS effect	61.3	9.67E2	5.06	1.0	
235	No RS effect	35.5	1.34E4	2.89	1.0	
236	No RS effect	38.1	1.29E3	6.41	1.0	
237	No RS effect	329	3.11E3	3.39	1.0	
238	No RS effect	94.8	1.92E3	3.92	1.0	
239	No RS effect; Very low leakage	-176	2.62E3	3.52	1.0	Very low leakage interpreted as negative RSH
240	No RS effect	132	1.32E3	4.01	1.0	
261	No RS effect	501	1.38E4	2.51	1.0	
262	No RS effect	319	1.01E4	2.75	1.0	
263	No RS effect	26.6	3.82E3	3.44	1.0	

TABLE V-3. SUMMARY OF DARK FORWARD DATA REDUCTION FOR FLAT PLATE CELLS (Concluded)

CELL NR	COMMENTS RE DATA	RSH (Ω)	IS(mA/°K)	M	RS (mΩ)	COMMENTS RE DATA REDUCTION
264	No RS effect	133	1.22E3	3.63	1.0	
265	No RS effect	141	3.29E3	3.09	1.0	
266		21.7	1.39E5	1.88	27.2	
268	No RS effect	132	4.26E3	3.15	1.0	
269	No RS effect	159	8.79E3	3.02	1.0	
273	No RS effect	251	1.57E4	2.28	1.0	Weighting factors used to improve results at high currents
275	No RS effect	96.9	2.14E3	3.50	1.0	

above 0.4 V, or weighting factors should be used to place more emphasis on the higher voltage points. This was done for cells 134 and 273. The results were good for cell 134 whose data exhibited a RS effect, but the improvement was not quite as satisfactory for cell 273 whose data exhibited no RS effect. The M of 2.28 is better than the other cells which showed no RS effect, but RS is still 1.0 mΩ.

2. Modules

The flat plate modules consist of 42 series-connected cells. The cells are of the type reduced in the previous section. The data consists of dark forward and reverse curves and illuminated forward curves taken on six modules at 25°C.

a. Dark Reverse and Illuminated Forward

Figure V-7 contains a typical illuminated forward module I-V curve taken at 1 sun and 25°C. The PV-TAP comparison plot is shown in figure V-8. The match is good with identical V_{OC}'s of 22.8 V and currents at 16.4 V of 1.52 A measured and 1.51 A calculated.

The summary chart for all six modules is shown in table V-4. Initial runs were made with 10 to 11 data points spaced as shown in figure V-7. The results were not satisfactory, producing significant discrepancies at open circuit and very high saturation currents. Reverse curves calculated from the parameters exhibited currents which were higher then the reverse data because the saturation current was higher then the current through the shunt resistance. The results shown in table V-4 were obtained by eliminating all illuminated input points below 15 V. This resulted in lower IS and better V_{OC} matching.

The problem appears to have been caused by larger slopes in the data near short circuit than should have been obtained considering the low reverse currents. By eliminating these data points from the input data, the program was better able to match the remaining data.

Figure V-9 shows a typical dark reverse module curve. The measurements were taken only out to -10 V because it was feared that most of the voltage could be impressed across a single cell which could become permanently damaged. Several cells had been destroyed during dark

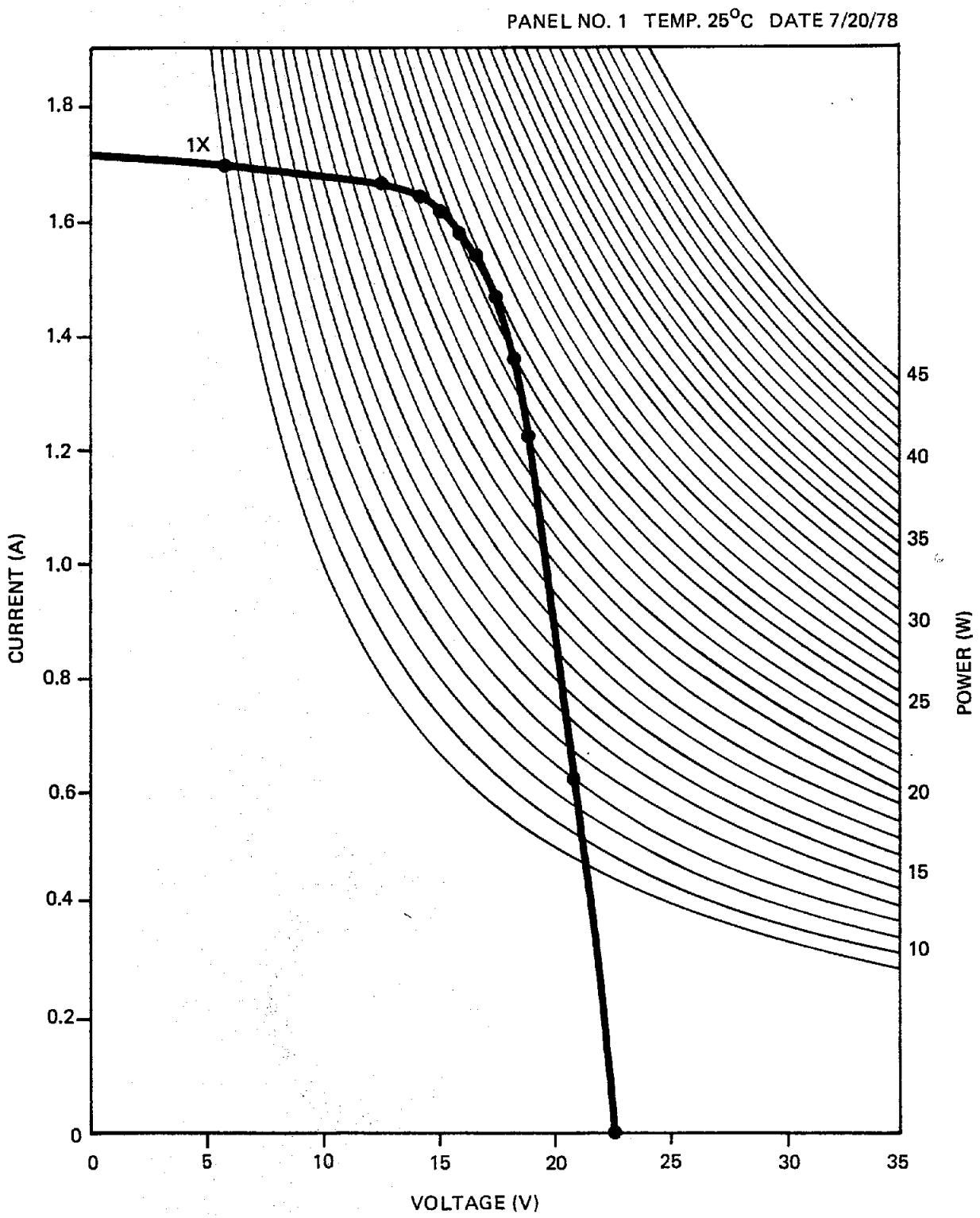


Figure V-7. Illuminated Forward Module I-V Curve

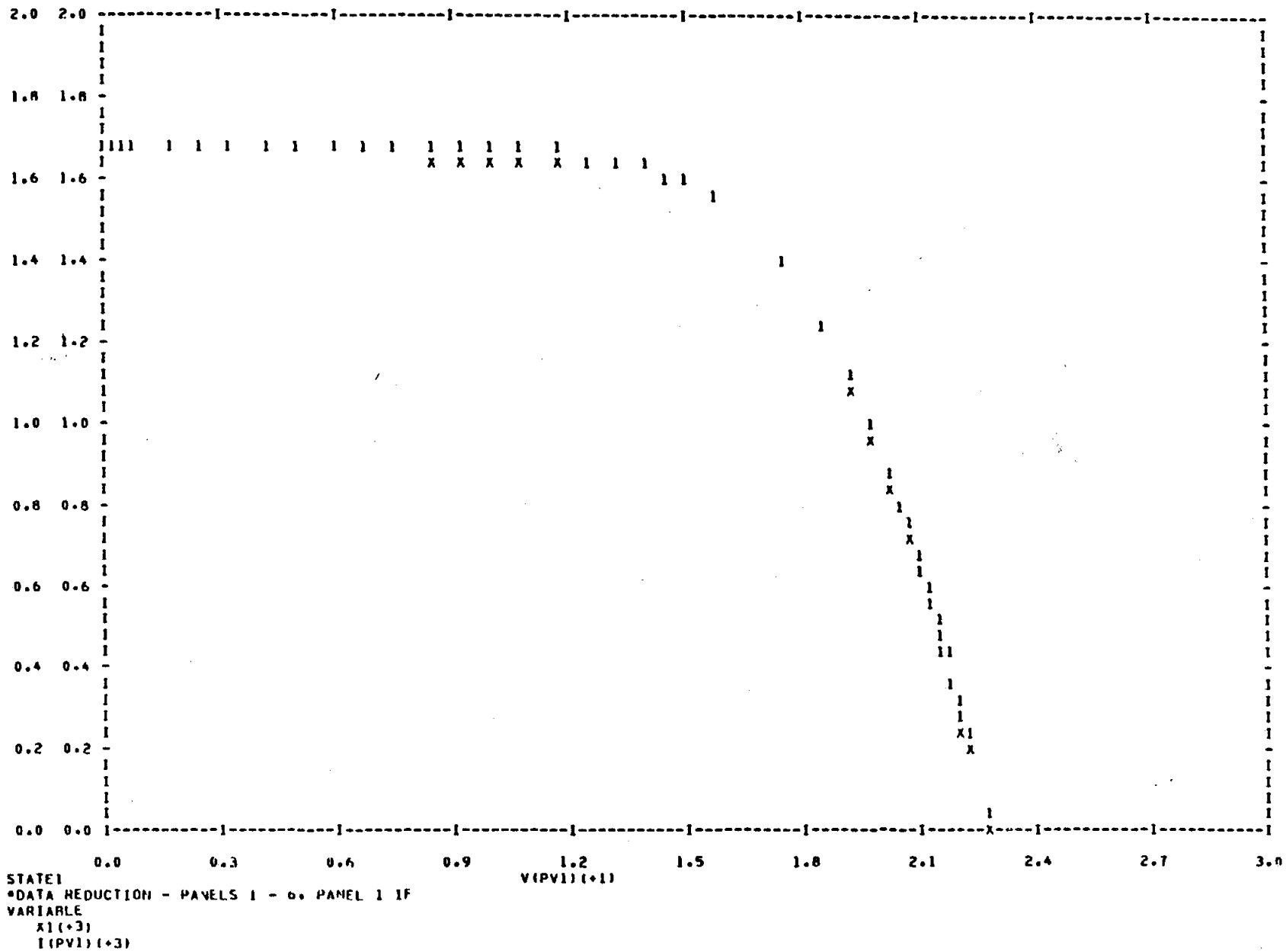


Figure V-8. PV-TAP Plot for Illuminated Forward Module Data Reduction

TABLE V-4. SUMMARY OF ILLUMINATED FORWARD DATA REDUCTION FOR FLAT PLATE MODULES

MODULE NR	COMMENTS RE DATA	IS(mA/°K)	M	RS (Ω)	V_{OC}(V) DATA	V_{OC}(V) CALC.	COMMENTS RE DATA REDUCTION
1	All illuminated forward module curves appeared well-behaved	2.03E-2	75.7	1.28	22.8	22.8	Illuminated data below ~15 V was eliminated from input for all runs to produce parameters with good match from peak power to open circuit. Based on cell data, M and RS for modules should be about 60-100 and 1.0-2.4 Ω, respectively.
2		1.09E-3	59.7	1.45	22.6	22.6	
3		9.07E-2	86.1	1.10	22.5	22.4	
4		2.44E-2	76.1	1.33	22.5	22.5	
5		5.28E-3	67.7	1.44	22.8	22.7	
6		1.57E-2	73.9	1.14	22.7	22.7	

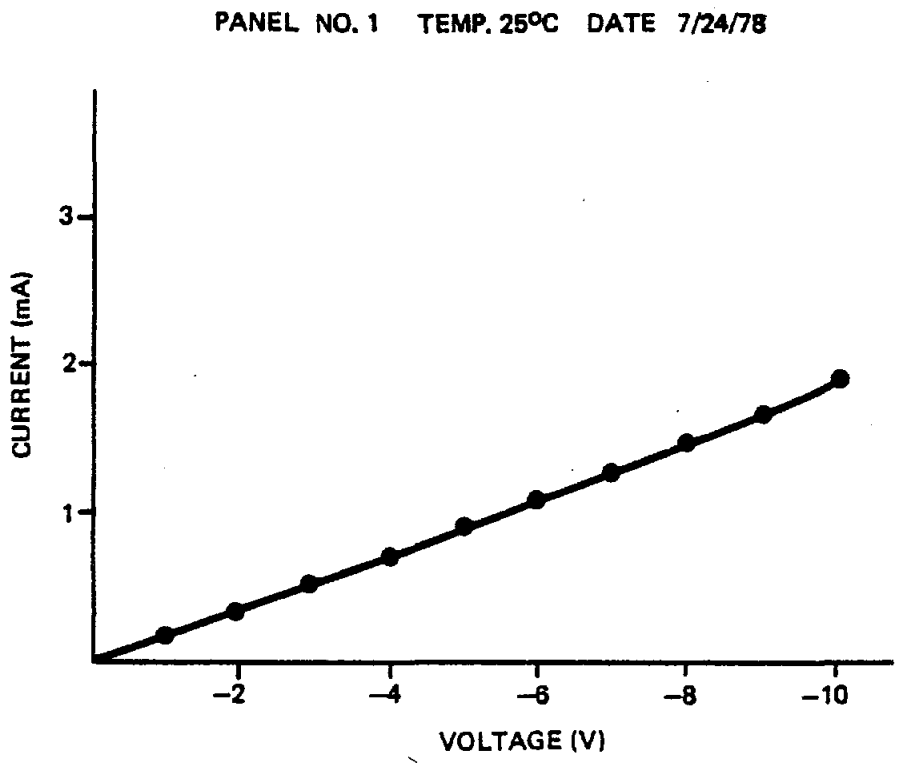


Figure V-9. Dark Reverse Module I-V Curve

reverse cell testing and were discarded. A cell failure in a module would have been more disastrous; therefore, high reverse voltages were avoided.

All the reverse module I-V curves exhibit a light super-linear behavior as shown in figure V-9 and by the x's of the comparison plot (figure V-10). The slope continues to increase from 0 out to -10 V as illustrated by the increasing separation between the x's and the l's which are linear. The two x's on the upper left of figure V-10 are not part of the data. The table which was used to plot the data ended at -10 V. Since the voltages in the PV-TAP plot went beyond -10V, PV-TAP supplied the end value for all voltages beyond -10 V.

In order to prevent the data reduction routine from interpreting the increasing slope as a breakdown curve, the parameters--A, B, and VB--were specified as "fixed params" in all runs as noted in table V-5. Thus, PV-TAP supplied the default values of A = 15 V, B = 1 V, and VB = -35 V for all runs making these parameters strictly user input and not calculated.

b. Dark Forward

Figure V-11 contains a typical dark forward module I-V curve. The PV-TAP comparison plot is shown in figure V-12. The data exhibits a slight RS effect; however, it is rather small for the magnitude of the voltages in the data. As can be seen from the comparison plots, the program did not match the data well at high voltages. The l's fall below the x's in this region. The comments in the summary chart (table V-6) indicate that this was true for all six modules. Fewer low voltage points should have been input and the measurements should have been taken at higher voltages so that a significant RS effect could have been seen.

In the comparison plot of figure V-12, it should be noted that the last two x's at the lower left are not real data since the data only starts at -2 V. This is the same phenomenon as previously described in section 2.a above.

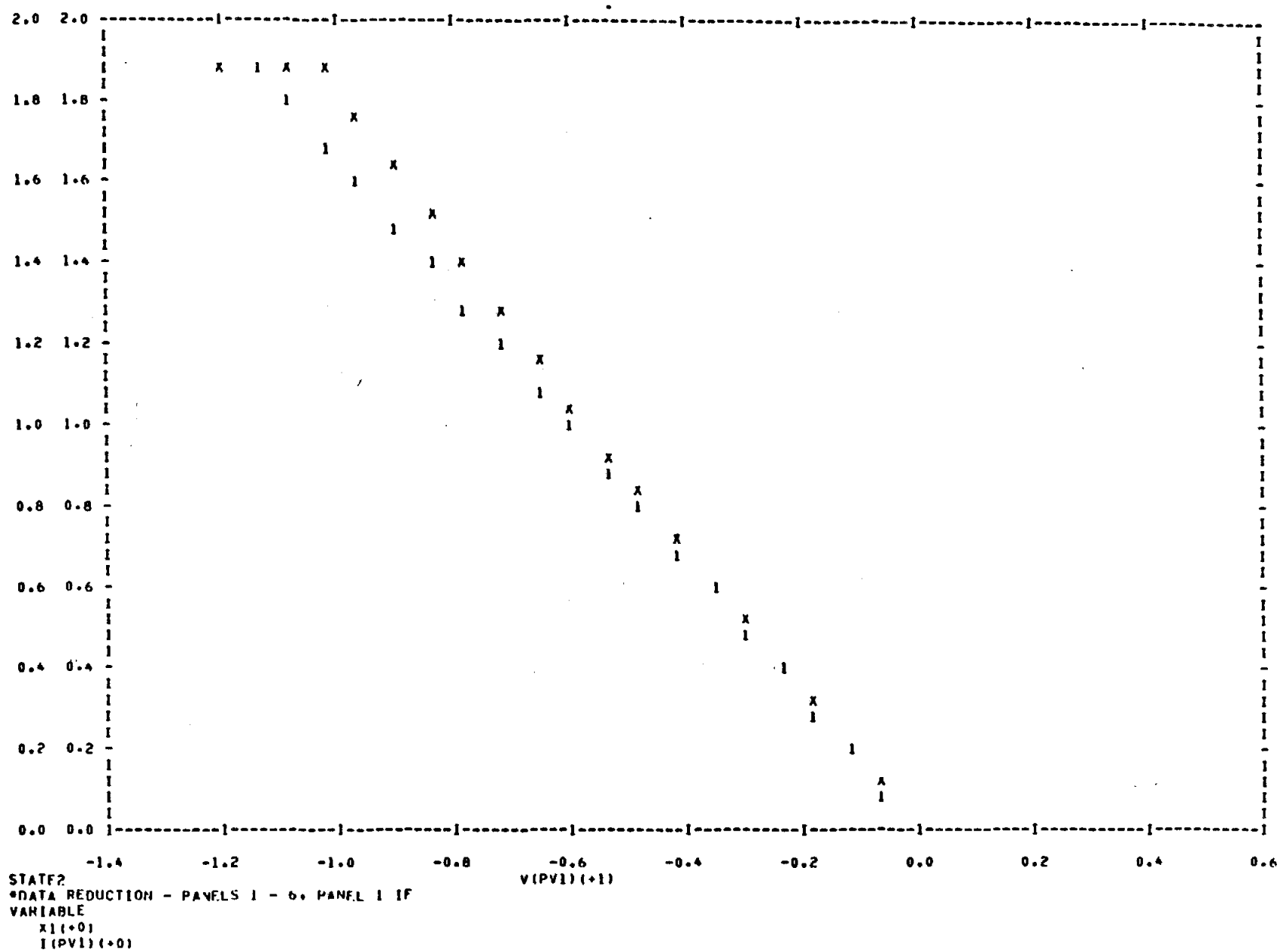


Figure V-10. PV-TAP Plot for Dark Reverse Module Data Reduction

TABLE V-5. SUMMARY OF DARK REVERSE DATA REDUCTION FOR FLAT PLATE MODULES

MODULE NR	COMMENTS RE DATA	RSH(Ω)	A	B	VB(-V) DATA	VB(-V) CALC.	COMMENTS RE DATA REDUCTION
1	All module data curves are superlinear. Module reverse data was taken only to -10 V.	6084	15.0	1.0	NA	35.0	A, B, VB were specified as "fixedparams" in all runs to inhibit calculation to breakdown parameters.
2		8255	15.0	1.0	NA	35.0	
3		6045	15.0	1.0	NA	35.0	
4		5417	15.0	1.0	NA	35.0	
5		5408	15.0	1.0	NA	35.0	
6		5016	15.0	1.0	NA	35.0	

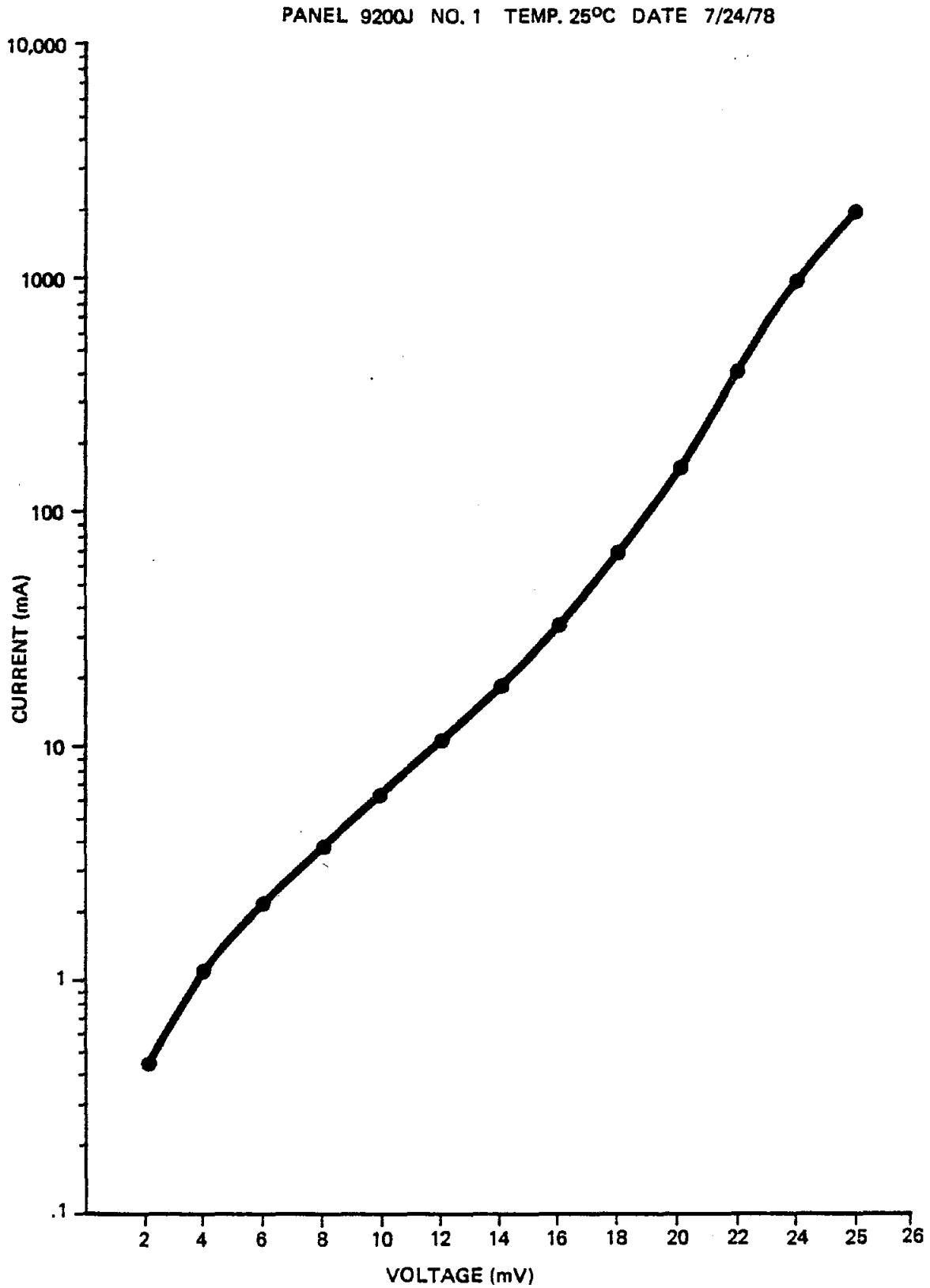


Figure V-11. Dark Forward Module I-V Curve

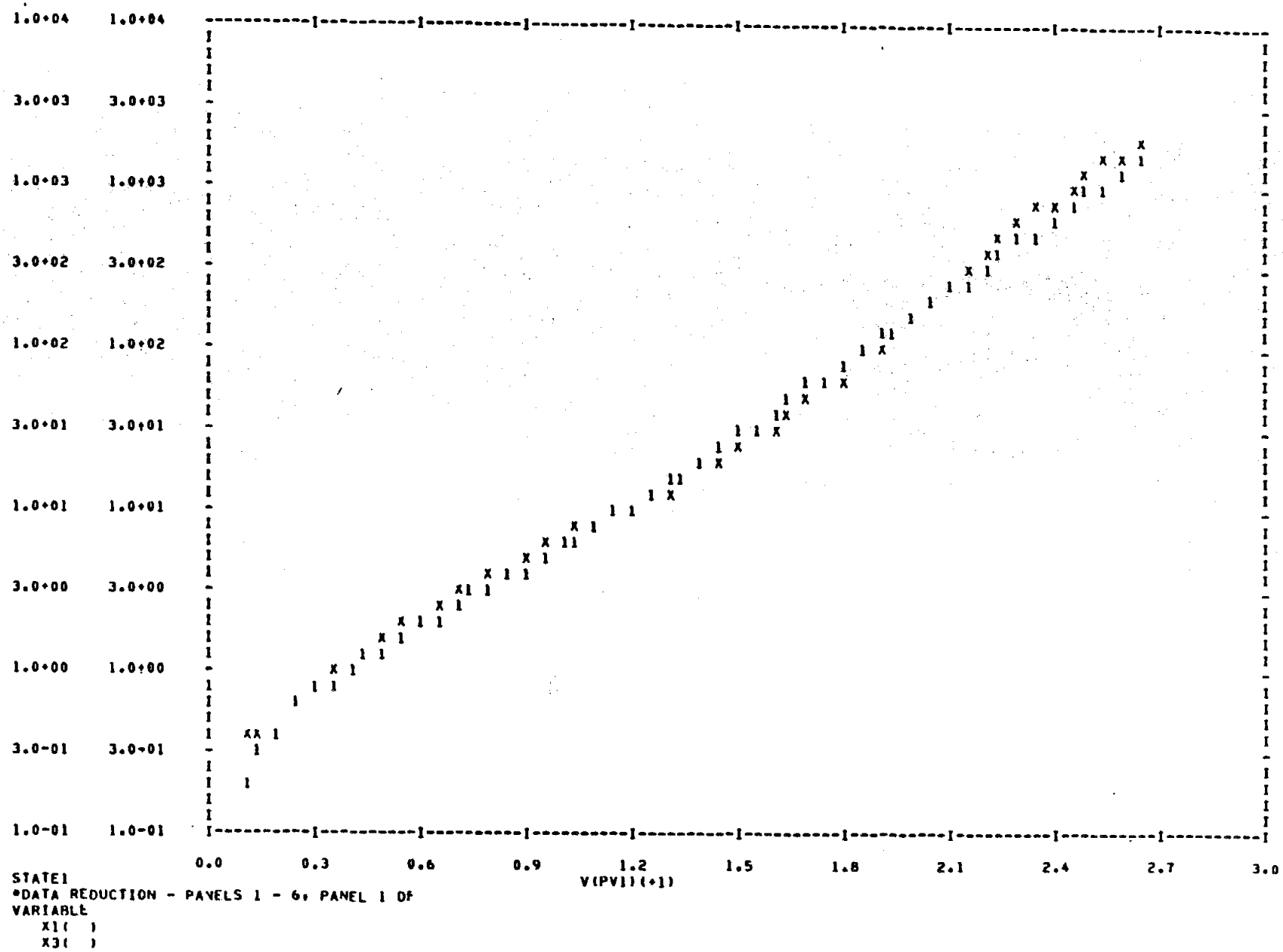


Figure V-12. PV-TAP Plot for Dark Forward Module Data Reduction

TABLE V-6. SUMMARY OF DARK FORWARD REDUCTION FOR FLAT PLATE MODULES

MODULE NR	COMMENTS RE DATA	RSH (Ω)	IS(mA/°K)	M	RS (mΩ)	COMMENTS RE DATA REDUCTION
1	All modules exhibit only slight RS effect	6285	1.58E-1	108	1.0	Lack of significant RS effect in data results in default value of 1.0 mΩ and tends to produce errors in other parameters compared to values obtained from illuminated data reduction. Data should have been taken at higher currents and fewer low-current points should have been input to data reduction.
2		6098	1.38E-1	105	1.0	
3		11286	6.25E-1	141	1.0	
4		6107	2.45E-1	112	1.0	
5		5134	3.29E-1	125	1.0	
6		5691	2.15E-1	116	1.0	

B. CONCENTRATOR CELLS AND MODULES

1. Cell Data

The data reduced consists of illuminated forward I-V curves of a single concentrator cell at seven concentration ratios. The cell is approximately 3/4 inch by 2.5 inches, single crystal silicon for use in a linear parabolic trough at concentrations of about 20X. The I-V curves taken by the manufacturer are shown in figure V-13. A comparison plot made for the 50X curve is shown in figure V-14. Since reverse data was not available a typical shunt resistance of 100 was input as a "paramspec" to the data reduction. As can be seen from the summary in table V-7, reasonable parameters and good V_{OC} match were obtained for all curves even though the higher concentration curves exhibit significant noise. The match at peak power for the 50X curve is 17.20 A calculated versus 17.19 A measured at 0.482 V. The good match can be attributed largely to the fact that no data below about 0.35 V for the higher concentration curves and about 0.45 V for the lower ones were input to the data reduction.

2. Modules

The module data consists of illuminated forward I-V curves of series-connected cells on the receiver tube of a linear parabolic trough. The modules consist of 44 series-connected cells of the type reduced in the previous section. A typical module I-V curve is shown in figure V-15. The data was taken at the BDM Solar Test Facility. Both I-V and power curves were made. The data was taken outdoors with north-south oriented troughs. The linear portion of the I-V curve from the origin to 1 V is not real data, but is related to the start-up of the plotting routine. The irregularities and steps in the curve are due to 1) the activation of bypass diodes as a result of non-uniform illumination along the length of the receiver tube and 2) fluctuations in incident illumination due to large intermittent clouds present on that day. The purpose of using data from this day in place of much smoother data which was available was to gauge the program tolerance to severe irregularities in the data.

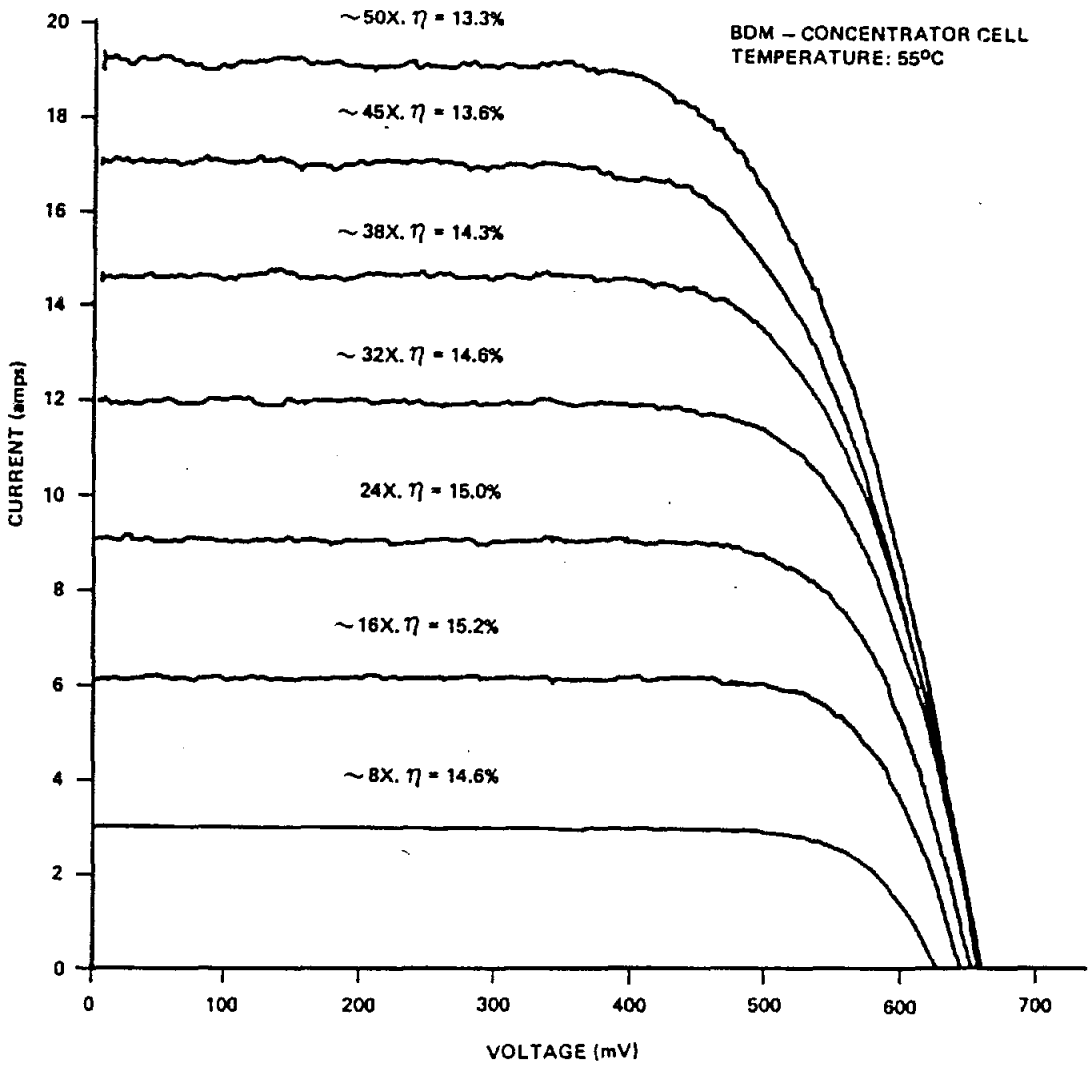


Figure V-13. Concentrator Cell I-V Curves

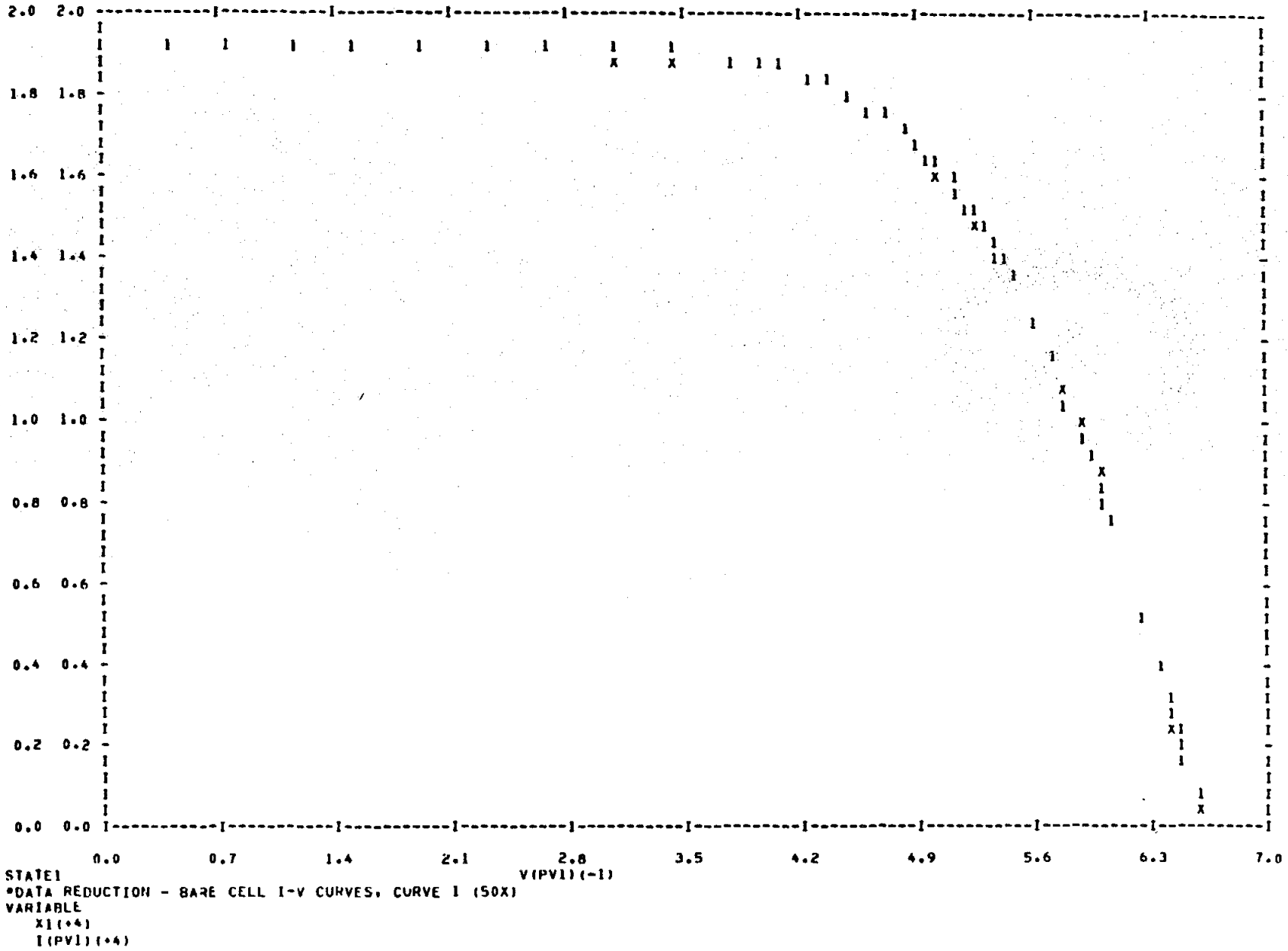


Figure V-14. PV-TAP Plot for Illuminated Forward Concentrator Cell Data Reduction

TABLE V-7. SUMMARY OF CONCENTRATOR CELL ILLUMINATED FORWARD DATA REDUCTION

CONCEN-TRATION	COMMENTS RE DATA	IS(mA/°K)	M	RS (mΩ)	V_{OC}(mV) DATA	V_{OC}(mV) CALC.	COMMENTS RE DATA REDUCTION
8x	Noise on curves increases with concentration ratio.	4.86E5	1.07	9.15	624	628	Typical RSH of 100Ω was assumed for data reduction for all cases.
16x		1.27E5	1.63	1.15	643	642	
24x		2.34E5	1.37	4.43	652	653	
32x		1.09E5	1.97	1.53	658	656	
38x		2.59E5	1.41	5.19	660	664	
45x		1.84E5	1.75	4.38	659	661	
50x		1.59E5	1.97	3.84	660	661	

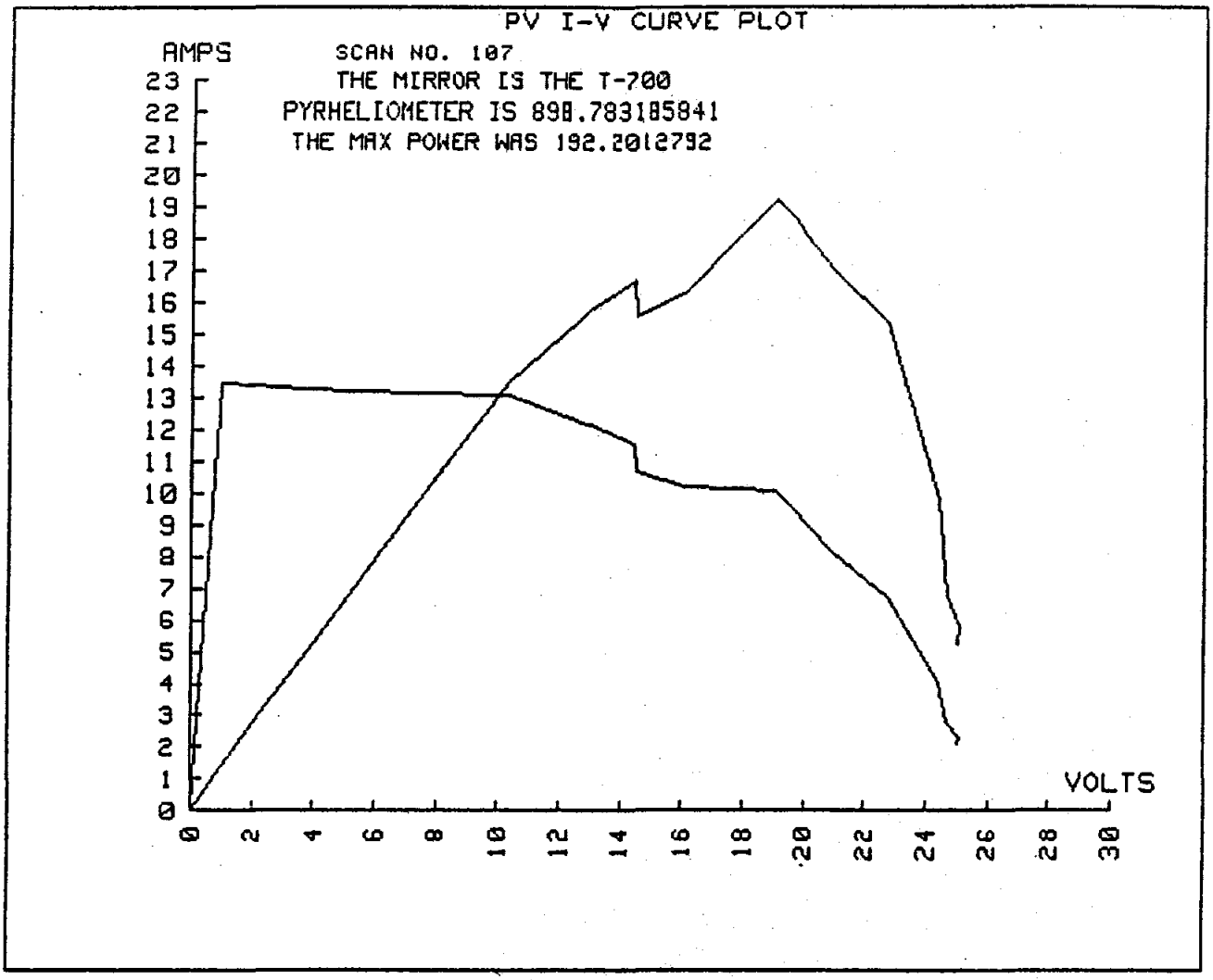


Figure V-15. Concentrator Module I-V and P-V Curves - No. 107

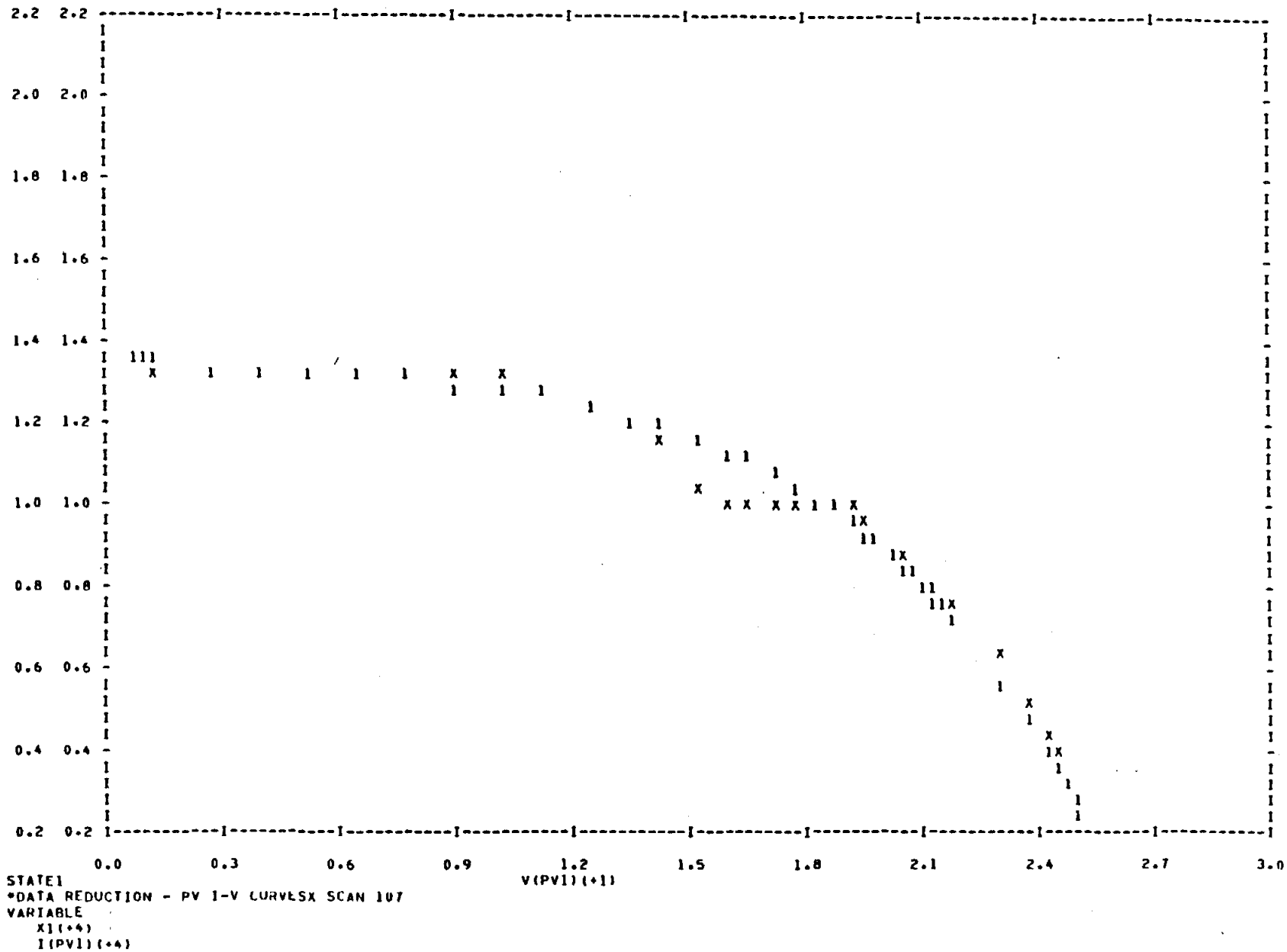


Figure V-16. PV-TAP Plot for Illuminated Forward Concentrator Module Data Reduction

The program handled this particular curve very well as can be seen from the comparison plot in figure V-16 and the test 107 line in the summary table V-8. The values for M and IS deviate somewhat from expected values based on cell parameters; RS is consistent and V_{OC} shows a good match. The current at the peak power voltage of 19.1 V was 9.57 A calculated versus 9.92 A measured. The comparison of V_{OC} was not made at zero current but rather at the last point available from the input data. The V_{OC} of the module is actually larger than 25.2 V.

It can be seen that the calculated curve in figure V-16 has a smooth shape compared with the original data. This is consistent with the modeling in which all 44 cells are represented by the single cell model which has a single exponential. If the user wishes to model the bypass diode step effect, he must model the module as individual cells. This can be done by scaling the parameters by 44, and providing a different illumination for each cell to simulate the real environment.

The data reduction summary for 20 tests is shown in table V-8. Comments concerning the shape of the data are included plus comments on the data reduction as appropriate. Data curves for four more of the tests have been included in figures V-17 through V-20 to provide further insight into the irregularities encountered.

Perusing the summary, it can be seen that half of the data reduction resulted in default values of 1.0 m for RS. This may have been due in part to the irregularities in the curves and in part because a full range of data was input starting with 1.0 V. Only test 167 would not produce results from the original input data. This run was finally accomplished by deleting much of the data and inputting only four points near peak power and open circuit. Why this curve, which is no more irregular than most, was the only one which required this smooth curve approximation is not clear, but may result from the long ramp followed by the short bypass ramp which may have been interpreted as the termination of the peak power region. In any case, the good results obtained in half the tests and the ease of convergence for all but one case illustrates the value of using the program for reducing irregular data which could be extremely time-consuming to accomplish by hand.

TABLE V-8. SUMMARY OF CONCENTRATOR MODULE ILLUMINATED FORWARD DATA REDUCTION

TEST NR	COMMENTS RE DATA	IS(mA/°K)	M	RS (mΩ)	V_{OC}(V) DATA	V_{OC}(V) CALC.	COMMENTS RE DATA REDUCTION
106	Ramp from 13-16 V	3.01E1	172	340	25.6	26.4	Based on cell data, M and RS for modules should be in the ranges 60-80 and 100-300 mΩ, respectively.
107	Step at 14 V	5.62E1	183	143	25.2	25.2	
108	Ramp from 13-14 V	4.98E1	179	134	25.2	25.4	
109	Ramp from 13-15 V	5.25E1	181	164	25.2	25.6	
110	Ramp from 10-18 V	1.15E2	214	148	25.1	25.9	
111	Ramp from 14-20 V	9.25E1	197	50.2	25.1	25.1	
112	Step at 9 V Ramp from 12.5-14 V	1.09E2	202	14.8	25.1	24.9	
155	Ramp from 6-13V Ramp from 13-14 V	4.61E2	304	1.0	24.8	27.3	Ramps and steps are inconsistent with single exponential model resulting in inability to match curve over full range and generate reasonable parameters as indicated by high M and low RS.
156	Ramp from 5-10 V Steep ramp from 13-15 V	6.54E2	327	1.0	24.7	26.2	
157	Ramp from 10-16 V	4.99E2	284	3.96	24.7	24.7	
167	Ramp from 4-12 V Step at 14 V	5.89E2	312	4.28	24.6	26.0	Smooth Curve approximation required to obtain results
180	Ramp from 2-10 V Ramps from 13-16 V	4.03E2	290	205	24.6	26.2	Same comment as #155
228	Steps at 13 V and 21 V Ramp from 13-16 V	5.43E2	312	1.0	25.2	26.0	Same comment as #155
295	Steep ramp from 10-12 V Ramp 15-17 V, Step 21 V	1.06E3	381	1.0	25.2	25.5	Same comment as #155

TABLE V-8. SUMMARY OF CONCENTRATOR MODULE ILLUMINATED FORWARD DATA REDUCTION (Concluded)

TEST NR	COMMENTS RE DATA	IS(mA/°K)	M	RS (mΩ)	V_{OC}(V) DATA	V_{OC}(V) CALC.	COMMENTS RE DATA REDUCTION
324	Ramps from 8-10 V and 10-18 V Step at 21 V	7.63E2	345	1.0	25.5	26.0	Same comments as #155
325	Ramps from 10-12 V, 13-15 V and 20-21 V	8.68E2	364	1.0	25.4	26.5	Same comment as #155
326	Ramp 1-13 V Steep ramp 13-15 V	5.69E2	318	1.0	25.5	26.5	Same comment as #155
327	Steep ramp 12-15 V	4.74E2	25	1.0	25.6	25.8	Same comment as #155
328	Ramp 11-15 V	3.44E2	268	1.0	25.5	25.7	Same comment as #155
329	Ramps from 7-8 V, 12-14 V and 19-20 V	2.50E2	241	1.0	25.6	25.2	Same comment as #155

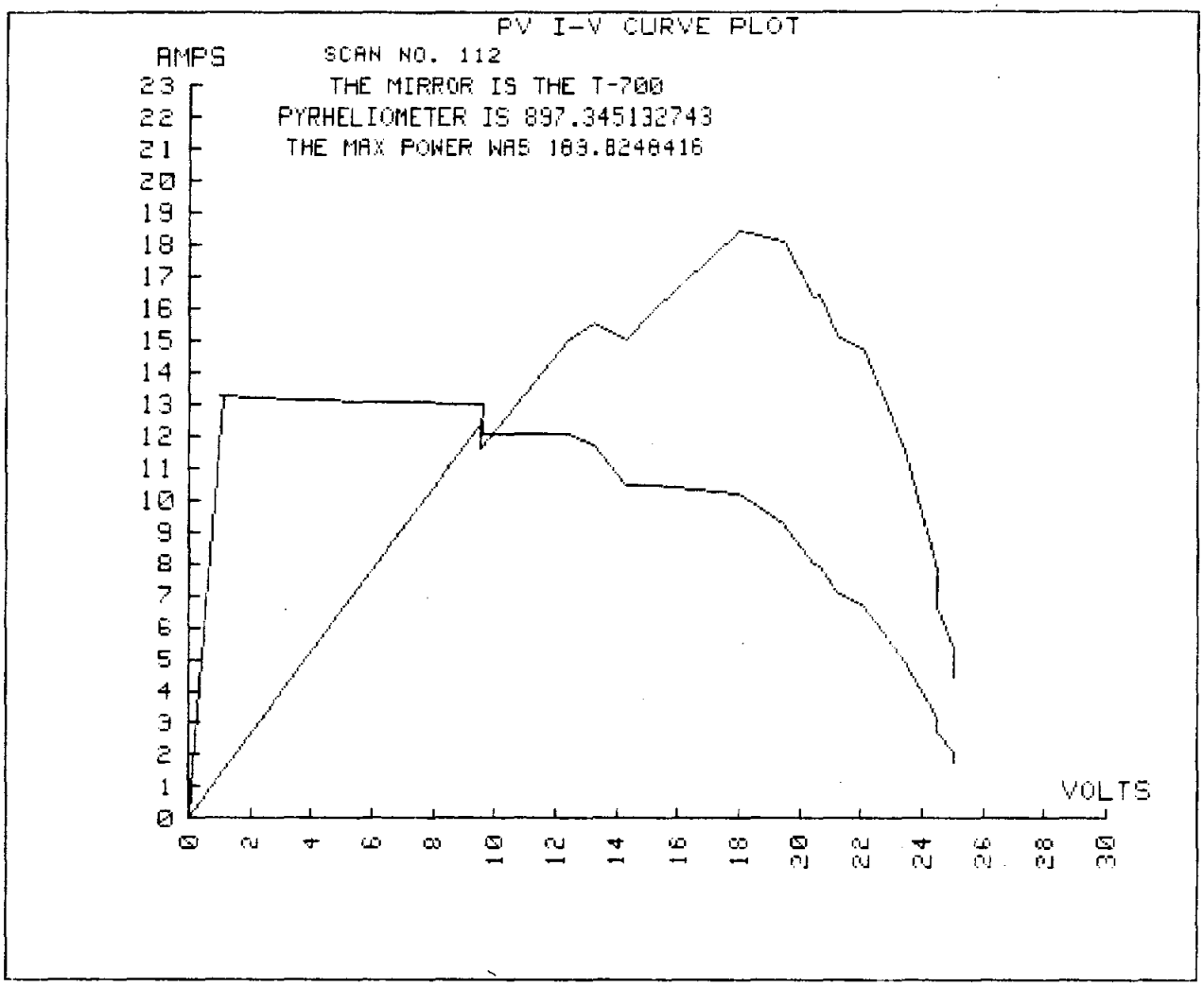


Figure V-17. Concentrator Module Curves - No. 112

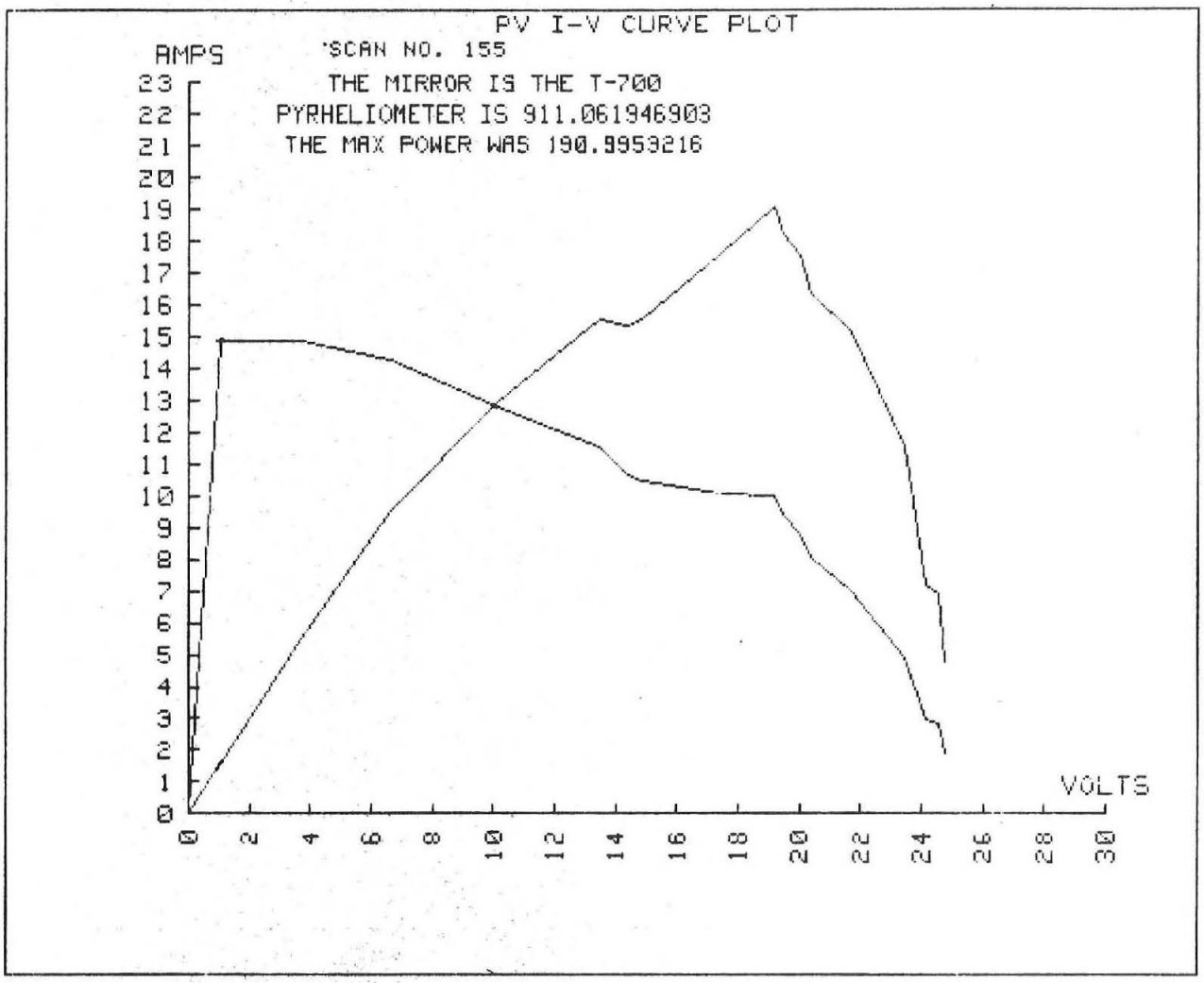


Figure V-18. Concentrator Module Curves - No. 155

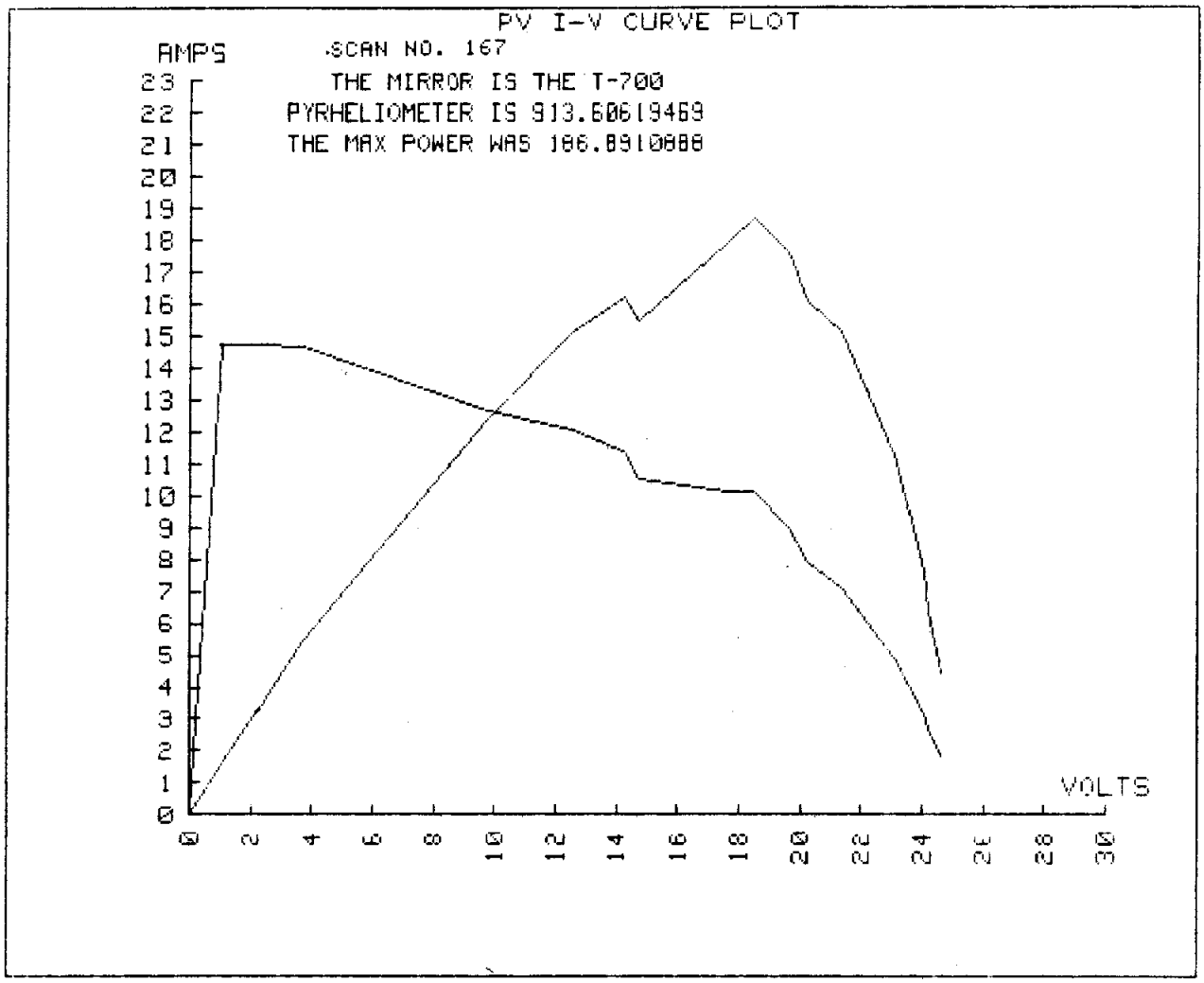


Figure V-19. Concentrator Module Curves - No. 167

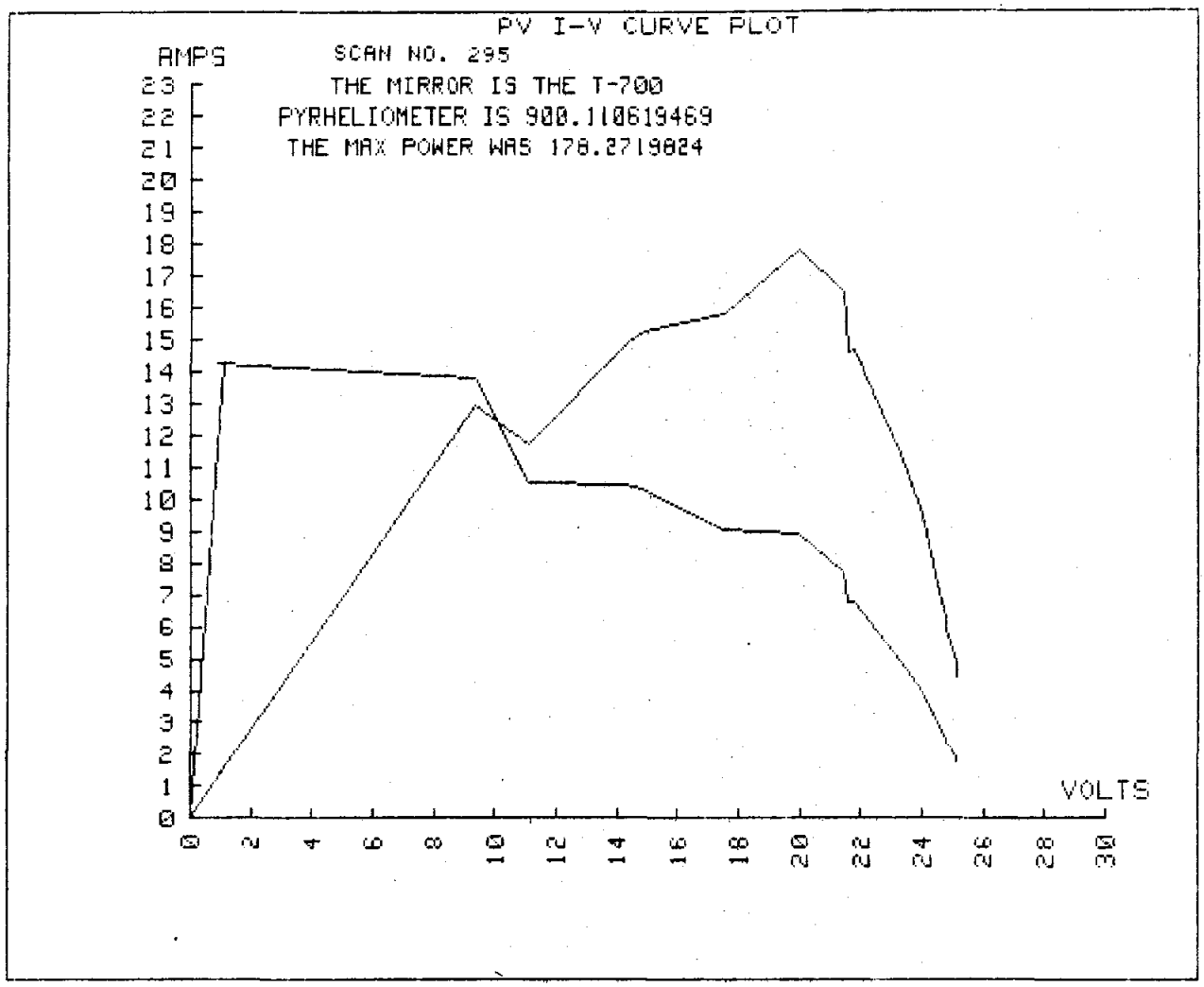


Figure V-20. Concentrator Module Curves - No. 295

REFERENCES

1. Lambarski, T. J., et. al., "PV-TAP-A Program For Performing Electrical and Thermal Analyses on Photovoltaic Elements," 14th IEEE PV Specialists Conference, January 1980, pgs. 1272-1276.

2. Lambarski, T. J., et. al., PHOTOVOLTAIC TRANSIENT ANALYSIS PROGRAM USER'S GUIDE. The BDM Corporation for Sandia Corporation, SAND 78-7038, October 1978.

3. Bowers, J. C. and S. R. Sedore, SCEPTRE: A COMPUTER PROGRAM FOR CIRCUIT AND SYSTEMS ANALYSIS, Prentice-Hall, Inc., 1971.

Distribution:

Program"

Acurex Corporation
Aerotherm Group
Attn: Dariush Rafinejad
485 Clyde Avenue
Mountain View, CA 94042

The Aerospace Corporation
Attn: E. J. Simburger
P. O. Box 92957
Los Angeles, CA 90009

Albuquerque Operations Office
U.S. Department of Energy
Attn: J. A. Morley
Albuquerque, NM 87115

Applied Solar Energy Corp.
Attn: K. Ling
15251 East Don Julian Rd.
City of Industry, CA 91749

Arizona Public Service Co.
Attn: Joe McGuirk
411 North Central Avenue
Phoenix, AZ 85036

Arizona State University
Attn: Don L. Evans
Department of M.E. and Energy
Tempe, AZ 85281

Battelle Columbus Laboratories
Attn: D. C. Carmichael
505 King Avenue
Columbus, OH 43201

BDM Corporation
Technology Applications Center
Attn: W. R. Kauffman
1801 Randolph Rd., SE
Albuquerque, NM 87106

Clemson University
Attn: Dr. J. W. Lathrop
College of Engineering
Clemson, SC 29631

U.S. Department of Energy
Division of Photovoltaic
Energy Systems
Forrestal Building
1000 Independence Ave. SW
Washington, DC 20585
Attn: A. L. Barrett, Jr.
A. D. Krantz
M. B. Prince

E-Systems, Inc.
Energy Technology Center
Attn: Mark J. O'Neill
P. O. Box 226118
Dallas, TX 75222

General Electric Company
Attn: E. M. Mehalick
P. O. Box 8661
Philadelphia, PA 19101

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91103
Attn: R. Forney
J. A. Evans
R. Ross

Lee County Electric Cooperative
P. O. Drawer 1447
Attn: Pete Felfe
Lovington, NM 88260

Mission Research Corporation
Attn: R. L. Pease
1400 San Mateo Blvd. SE
Suite A
Albuquerque, NM 87108

New Mexico Energy Institute
Attn: H. S. Zwibel
Box 3S0L
Las Cruces, NM 88003

Oak Ridge National Laboratory
Attn: Steve Kaplan
P. O. Box X
Oak Ridge, TN 37830

Science Applications, Inc.
Attn: Dr. Yudi Gupta
8400 Westpark Drive
McLean, VA 22102

Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401
Attn: Gary Nuss
Library (2)
Amy Pinkerton

Solar Power Corporation
Attn: R. R. Addiss, Jr.
20 Cabot Road
Woburn, MA 01801

Spectrolab
Attn: J. A. Castle
12500 Gladstone Ave.
Sylmar, CA 91342

Westinghouse Electric Corp.
Attn: P. F. Pittman
1310 Beulah Road
Pittsburgh, PA 15235

9700 E. H. Beckner
9720 D. G. Schueler
9721 H. J. Gerwin
9723 H. H. Baxter
9723 K. L. Biringer
9723 E. L. Burgess
9723 T. D. Harrison
9723 C. B. Rogers (25)
9724 E. C. Boes
9724 D. L. King
5133 R. J. Chaffin
3141 L. J. Erikson (5)
3151 W. L. Garner (3)
3154-3 C. H. Dalin (25)
for DOE/TIC Unlimited Distribution
8214 M. A. Pound