**MASTER DO NOT MICROFILM
COVER**

THEORETICAL MODELS OF EFFICIENCY FOR POLYCRYSTALLINE THIN FILM
SOLAR CELLS

DE-AC-1-79ET-23107

September 1, 1979 - January 31, 1981

Final Report

February 1981

INSTITUTE OF ENERGY CONVERSION
University of Delaware
Newark, Delaware 19711

Supported by the Department of Energy, Report No. DE-AC01-79ET-23107-03

DISCLAIMER

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, 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 or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MASTER

NOTICE
PORTIONS OF THIS REPORT ARE ILLUMINABLE
It has been reproduced from the best available copy to permit the broadest possible availability.

**THEORETICAL MODELS OF EFFICIENCY FOR POLYCRYSTALLINE THIN FILM
SOLAR CELLS**

DE-AC-1-79ET-23107

September 1, 1979 - January 31, 1981

Final Report

February 1981

INSTITUTE OF ENERGY CONVERSION
University of Delaware
Newark, Delaware 19711

Supported by the Department of Energy, Report No. DE-AC01-79ET-23107-03

TABLE OF CONTENTS

<u>Title</u>	<u>Page</u>
I. Introduction	1
II. Homojunctions	2
1. Short Circuit Current and V_{oc}	2
2. Fill Factor and Efficiency	3
III. Heterojunctions	4
1. Short Circuit Current and Open Circuit Voltage	4
2. Fill Factor and Efficiency	6
IV. Conclusions	8
References	10
Acknowledgments	10
Figures	11 - 20
Appendix A	21
Appendix B	24
V. Distribution List	

DISCLAIMER

This book 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, 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 or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

I. INTRODUCTION

The main tasks of this program were to: (1) critically evaluate the mechanisms which have been proposed to explain Schottky and MIS solar cell behavior in order to identify mechanisms applicable to Zn_3P_2 solar cells; and (2) analyze the data from the experimental cell development program under Contract # DE-AC-1-79ET-23107 and perform a parametric analysis of the device in order to determine upper limits of efficiency.

In relation to the first task, the literature on Schottky and MIS diodes was thoroughly reviewed.⁽¹⁾ Underlying the accepted theoretical models for MIS devices we have identified a major weakness in the handling of current flow through the insulating layer. An alternative model based on pinholes in the insulating layer was proposed.⁽¹⁾

In task II parametric analysis of Zn_3P_2 homojunctions and $\text{ZnO}/\text{Zn}_3\text{P}_2$ heterojunctions was done and limits of efficiency were calculated (see Sections II and III).

II. HOMOJUNCTIONS

INTRODUCTION:

Estimates for the open circuit voltage (V_{oc}), short circuit current (J_{sc}), spectral response, fill factor (FF) and efficiency (η) of Zn_3P_2 shallow p-n homojunctions were found.

The calculations were done through a computer program based on a model that assumes a shallow, abrupt p-n homojunction.⁽¹⁾

Computations were made for AM1.5 illumination. A detailed printout of the program can be found in Appendix A-1.

1. Short Circuit Current and V_{oc}

V_{oc} decreases uniformly with the width of the n-layer.⁽¹⁾ For a concentration of donors (N_D) of 10^{17} cm^{-3} and a concentration of acceptors (N_A) of $5 \times 10^{16} \text{ cm}^{-3}$, the maximum value for V_{oc} is 0.87 V. Although the shape of the curve V_{oc} vs width of the n-layer is parallel to the experimental data,⁽²⁾ the actual predicted value is much higher than the experimental one (0.58 V).⁽²⁾ To explain this discrepancy, some parameters should be measured more precisely such as the lifetimes in the depletion region. Also the n-type conductivity has not been measured directly so some modifications to allow for a deeper donor level could be introduced in the model.

The short circuit current compares well with the experimental data.

2. Fill Factor and Efficiency

The fill factor was computed as a linear approximation (valid when $R_S \ll \frac{V_{OC}}{I_{SC}}$) of the series resistance (R_S). This gives a lower limit for N_A (acceptor concentration) of $2 \times 10^{15} \text{ cm}^{-3}$ (see Section III.2).

The contribution of the n-layer to R_S was neglected because that layer is very thin and the electron concentration high.

For a donor concentration of 10^{17} cm^{-3} and an acceptor concentration of $5 \times 10^{16} \text{ cm}^{-3}$, the efficiency is about 17% in the range (0.1 μm - 0.3 μm) for the width of the n-layer (see Fig. 2).

III. HETEROJUNCTIONS

INTRODUCTION:

A computer program to estimate J_{sc} , V_{oc} and FF for n-window, p-base solar cells, operating in backwall mode, was developed and applied to the particular case of ZnO/Zn_3P_2 heterojunctions.

The computations were performed for AM1.5 illumination.

The energy gaps in both materials (E_{G1} and E_{G2}) the difference in electron affinities ($\Delta\chi$), the absorption coefficient of the p-region (α) and the thickness of the p-layer were held as fixed parameters. The carrier concentrations (N_A and N_D), the minority carrier diffusion lengths (L_n and L_p) and the interface recombination velocity (S_i) were taken as variable parameters and their influence on the final efficiency of the device was studied.

A detailed printout of the program can be found in Appendix A-2.

1. Short Circuit Current and Open Circuit Voltage

The short circuit current (J_{sc}) was computed, assuming a backwall mode of operation of the cell. The contributions of the bulk p-region and of the p-side of the space charge region were considered.

The open circuit voltage (V_{oc}) was computed as a function of the short circuit current and of the dark saturation current (J_0).

In the computation of the dark saturation current three different mechanisms were considered; interface recombination (J_{s_i}), space charge region recombination (J_{orec}) and minority carriers diffusion (J_{od}).

Each of these mechanisms would lead to the following current-voltage relations:

$$J = J_{ox} e^{\frac{qV}{A_x kT}}$$

where J_{ox} is the saturation current and A_x is the correspondent diode factor.

For minority carrier diffusion, the diode factor is:

$$A_d = 1$$

For space charge region recombination:

$$A_{rec} = 2$$

For interface recombination instead:

$$A_i = \frac{N_A + N_D}{N_D} \quad \text{if} \quad N_D > N_A$$

In all the cases considered,

$$N_D \geq 10 N_A, \text{ so that}$$

$$A_1 \leq \frac{N_A + 10 N_A}{10 N_A} \leq 1.1$$

So we shall take $A_1 = 1$ in order to obtain a solvable quadratic equation for V_{oc} .

This is:

$$V_{oc} = \frac{2kT}{q} \ln \left\{ \left[\left(\frac{J_{orec}}{2(J_{od} + J_{S1})} \right)^2 + \frac{J_{sc}}{(J_{od} + J_{S1})} \right]^{1/2} + \frac{J_{orec}}{2(J_{od} + J_{S1})} \right\}$$

2. Fill Factor and Efficiency

The fill factor was computed using a linear approximation in the series resistance, valid when $R_S \ll \frac{V_{oc}}{I_{sc}}$.

Assuming only bulk contributions to R_S , this is the same as:

$$\rho_s t \ll \frac{V_{oc}}{J_{sc}} \quad (\text{where } t \text{ is the thickness of the p-layer})$$

In our case, ρ_s was estimated as the resistivity of the p-layer.

$$\rho_s = \frac{1}{q \cdot N_A \cdot \mu_p}$$

where: q (electron charge)

N_A (carrier concentration)

μ_p (mobility)

The condition implies then: $N_A \geq 2 \times 10^{15} \text{ cm}^{-3}$ using $\mu_p = \frac{25 \text{ cm}^2}{\text{V} \cdot \text{sec}}$

The contact effects were not included in the estimate for R_S . This will give an upper limit for the efficiency.

In this way the fill factor results:

$$FF = FF_0 - \frac{J_{sc} R_S A C}{V_{oc}} \quad (\text{where } A \text{ is the area of the cell})$$

Where FF_0 and C are functions of V_{oc} obtained as solutions of the implicit equation that results from the maximum power point (see Fig. 1).

The efficiency (η) is:

$$\eta = \frac{FF V_{oc} J_{sc}}{P_{in}}$$

Where P_{in} is the incident power taken to be equivalent to
 $AM1.5 = 71.39 \text{ mW/cm}^2$

IV. CONCLUSIONS

The short circuit current and V_{oc} are slightly dependent on the doping concentration (see Figs. 3, 4, 5 and 6).

The efficiency increases rapidly from 4% to 6.9% in the range $(2 \times 10^{15} - 2 \times 10^{16} \text{ cm}^{-3})$ (see Fig. 7).

Both V_{oc} and η are strongly dependent on the interface recombination velocity. In the limit where minority carrier diffusion is the dominant transport mechanism ($S_1 \rightarrow 0$), V_{oc} is as high as 0.8 V and η reaches 16% (see Figs. 3 and 10).

When only bulk effects contribute to the series resistance (R_s), even at high values of S_1 , an efficiency higher than 5.5% is achievable. If good contacts can be obtained, the heterojunction looks promising.

From the intercept of the V_{oc} vs T curve (Fig. 8) one can get another measure of $\Delta\chi$.

$$V_{oc}(T) = \frac{kT}{q} \ln \left(\frac{J_{sc}}{J_{oc} + J_{S_1}} \right)$$

Therefore,

$$V_{oc}(0) = E_{G2} - \Delta\chi = V_D + \delta_1 + \delta_2$$

when interface recombination is the dominant mechanism.

While if minority carrier diffusion is the main transport mechanism,

$$V_{oc}(0) = E_{G2} - \delta_1 - \delta_2$$

where δ_1 and δ_2 are the distance of the Fermi level to the valence band and to the conduction band in the p and n materials respectively.

In the Zn_3P_2/ZnO case we have:

$$\Delta\chi = \chi_n - \chi_p = 4.2 - 3.8 = 0.4 \text{ eV}$$

While:

$$\delta_1 + \delta_2 = 0.14 \text{ eV}$$

The value of the intercept can be used to determine the dominant current transport mechanism. Comparison with experimental data⁽³⁾ shows that $V_{oc}(0)$ runs from 0.76 eV to 0.82 eV, suggesting that interface recombination is dominant. The values of V_{oc} at higher temperatures also support this hypothesis.

REFERENCES

1. "Theoretical Models of Efficiency for Polycrystalline Thin Film Solar Cells." Quarterly Progress Report #3 - DE-AC-1-79ET-23107.
2. "Zn₃P₂ as an Improved Semiconductor for Photovoltaic Solar Cells." Quarterly Report #8 - DOE/IEC Subcontract # XR-9-8062-1.
3. "ZnO/Zn₃P₂ Heterojunction Solar Cells." P. S. Nayar and A. Catalano, to be submitted to Applied Phys. Letters.

ACKNOWLEDGMENTS

The list of contributors are: Dr. Allen Rothwarf, Dr. John D. Meakin, Dr. Ines Pereyra and Mr. John Felton.

We would also like to thank Dr. K. Mitchell and Dr. R. Nottenburg of SERI for their assistance.

FIGURE 1

IEC81026

Calculated efficiency under
AM1.5 for Zn₃P₂ solar cell.
as a function of n-layer
thickness using calculated
fill factor

FIGURE 2

IEC81030

Calculated short circuit current under AM1.5 for n/Zno/P/Zn₃P₂ solar cell as a function of p-layer carrier density

FIGURE 3

IEC81024

Calculated short circuit current under AM1.5 for n/ZnO/p/Zn₃P₂ solar cell as a function of p-layer carrier density

IEC81025

FIGURE 4

Calculated open circuit voltage under AM1.5 for n/ZnO/p/Zn₃P₂ solar cell as a function of p-layer carrier density

FIGURE 5

IEC81031

Calculated open circuit voltage under AM1.5 for n/ZnO/p/Zn₃P₂ solar cell as a function of p-layer carrier density

FIGURE 6

IEC81020

Calculated efficiency of
n/ZnO/p/Zn₃P₂ solar cell
under AM1.5 as a function
of p-layer carrier density

IEC81019

FIGURE 7

Calculated V_{oc} vs temperature for
 n/ZnO/p/Zn₃P₂ solar cell under
 AM1.5

FIGURE 8

IEC81022

FIGURE 9

IEC81028

Calculated open circuit
 voltage of n/ZnO/p/Zn₃P₂
 solar cell as a function
 of interface recombination
 velocity under AM1.5
 illumination

FIGURE 10.

IEC81029

PROGRAM CALCULATES JSC,VOC,POWER,AND EFFICIENCY
 VS THE WIDTH OF THE N LAYER. TO CHANGE FROM ONE TO THE OTHER:
 FIRST, SET RANGE(I)=0 FOR ALL I. SECOND, CHANGE THE VARIABLES
 IN ARRAY ITITLE TO CONSTRUCT SUITABLE AXES TITLES.
 THIRD, INSERT THE SUITABLE ARRAY NAMES INTO THE 'CALL USFLT'
 STATEMENT AND RUN PROGRAM USING COMMAND:
 EX SR82.FOR,REL:IMSL.REL/LIB

KP = SURFACE RECOMBINATION VELOCITY (CM/SEC)
 LAMBDA = WAVELENGTH (NM)
 LN = DIFFUSION LENGTH FOR ELECTRONS (CM)
 LP = DIFFUSION LENGTH FOR HOLES (CM)
 JODIF = MINORITY CARRIERS DIFFUSION DARK SATURATION
 CURRENT (MA/CM2)
 JOREC = SPACE CHARGE RECOMBINATION DARK SATURATION
 CURRENT (MA/CM2)
 JSC = SHORT CIRCUIT CURRENT (MA/CM2)
 NA = ACCEPTOR CONCENTRATION (CM-3)
 ND = DONAR CONCENTRATION (CM-3)
 NI = INTRINSIC CARRIER CONCENTRATION (CM-3)
 PIN = INCIDENT POWER AM 1.5 (MW/CM2)
 QUE = ELECTRONS CHARGE (COULOMBS)
 T = TEMPERATURE (DEGREES K)
 VOC = OPEN CIRCUIT VOLTAGE (VOLTS)
 WIDTHIN = WIDTH OF N LAYER (CM)
 INITIALIZATION
 DIMENSION AN(75),AP(75),CE(75,100),ICHAR(10),IMAG4(5151),
 1 ITITLE(144),RANGE(4),FLUX(75),WIDTHN(100),
 2 VOC(100,10),FF00(14),CO(14),POWER(100,10),EFF(100,10)
 REAL LAMDA0,LN,LP,F,LAMBDA(75),JOREC(100),JODIF(100),
 1 NA,ND,NI,JSC(100,10),NAN(10)
 DATA(ITITLE(N),N=1,72)/21*' ','E','F','F','I','C',
 1 'I','E','N','C','Y',
 2 ' ','V','S',' ','W','I','D','T','H',
 3 'O','F',' ','N',' ','L','A','Y','E',
 4 'R',21*' '//
 DATA(ITITLE(N),N=73,108)/10*' ','W','I','D','T','H',
 1 'O','F',' ','N',' ','L','A','Y','E','R',10*' '//
 DATA(ITITLE(N),N=109,144)/12*' ','E','F','F','I','C',
 1 'I','E','N','C','Y',14*' '//
 DATA(RANGE(I),I=1,4)/4*0/
 DATA(RANGE(I),I=1,4)/0,3.2E-6,.19,.215/
 DATA(ICHAR(N),N=1,10)/'1','2','3','4','5','6','7','8','9','0'/
 DATA NPTS/61/,Y/.05/,LP/2E-4/,LN/2E-4/,
 1 LAMDA0/600/,INCR/50/,KP/1E8/,DN/.5/,T/300/,
 2 NI/3E6/,ND/1E18/,QUE/1.609E-19/,PIN/71.39132/
 DATA(NAN(I),I=1,10)/5E16,5E12,1E13,5E13,1E14,5E14,1E15,
 1 5E15,1E16,5E16/
 DATA(FLUX(I),I=1,61)/.0005,.0092,.0629,.1772,.3015,
 1 .4080,.5207,.6374,.7142,.7975,1.0564,1.4396,
 2 1.7027,1.1598,2.0297,2.3607,2.6279,2.7755,
 3 2.8648,2.9503,3.0755,3.1491,3.1856,3.3083,3.4499,
 4 3.51755,3.5689,3.64795,3.7293,
 5 3.77685,3.802,3.8432,3.88435,3.9214,3.9699,
 6 3.9819,3.9936,4.0683,4.1241,4.13645,3.9622,
 7 4.1324,4.1199,3.8419,4.07,4.0493,3.4361,
 8 3.4196,4.0123,3.9999,3.7173,3.6846,
 9 3.7781,3.3293,2.7723,2.719,3.7067,3.6794,

APPENDIX A continued

```

10      3.6668,3.6598,3.6387/
DATA(AN(I),I=1,61)/26*6.4E4,5.8E4,5.3E4,4.9E4,4.5E4,
1      4.2E4,3.8E4,3.35E4,2.91E4,2.48E4,2.17E4,
2      1.88E4,1.62E4,1.44E4,1.25E4,1.1E4,9.8E3,
3      8.7E3,7.7E3,6.8E3,6.2E3,5.3E3,4.6E3,3.79E3,
4      2.88E3,1.04E3,4.55E2,2.37E2,1.18E2,6.1E1,
5      3.1E1,1.89E1,9,5.4,3,1.8/
DATA(AP(I),I=1,61)/26*6.4E4,5.8E4,5.3E4,4.9E4,4.5E4,
1      4.2E4,3.8E4,3.35E4,2.91E4,2.48E4,2.17E4,
2      1.88E4,1.62E4,1.44E4,1.25E4,1.1E4,9.8E3,
3      8.7E3,7.7E3,6.8E3,6.2E3,5.3E3,4.6E3,3.79E3,
4      2.88E3,1.04E3,4.55E2,2.37E2,1.18E2,6.1E1,
5      3.1E1,1.89E1,9,5.4,3,1.8/
DATA(LAMBDA(I),I=1,61)/300,310,320,330,340,350,360,
1      370,380,390,400,410,420,430,440,450,460,
2      470,480,490,500,510,520,530,540,
3      550,560,570,580,590,600,610,
4      620,630,640,650,660,670,680,690,700,710,720,
5      730,740,750,760,770,780,790,810,820,830,
6      840,850,860,870,880,890,900,910/
DATA(FFOQ(I),I=1,14)/.690,.722,.747,.769,.790,.803,
1      .816,.827,.836,.845,.854,.860,.866,.873/
DATA(CO(I),I=1,14)/.795,.824,.848,.868,.883,.895,
1      .905,.913,.919,.924,.929,.934,.937,.942/

DO 1250 K=1,1
      NA=NAN(K)
      W=SQRT(2.7E5*ALOG((NA*ND)/(NI**2))*(ND/(NA*(NA+ND))))
DO 1200 J=1,100
      X=(J*.0003*1E-4)
      WIDTHN(J)=X
DO 1100 I=1,NPTS
      CEN=(AN(I)*LP)/((AN(I)**2)*(LP**2)-1)
1      *((KP*LP+AN(I)*LP)/(KP*LP*SINH(X/LP)+COSH(X/LP))
2      -(EXP(-AN(I)*X)*(KP*LP+TANH(X/LP)))/(KP*LP*TANH(X/LP)+1)
3      -AN(I)*LP*EXP(-AN(I)*X))

      CEP=((AP(I)*LN)/((AP(I)**2)*(LN**2)-1)
1      *(EXP(-AP(I)*(X+W)))*((AP(I)*LN)-
2      TANH(Y/LN)-(AP(I)*LN*EXP(-AP(I)*Y))
3      *((COSH(Y/LN))-1)))

      CEW=(EXP(-AN(I)*X))*(1-EXP(-AP(I)*W))

      CE(I,J)=CEN+CEW+CEP
      JSC(J,K)=JSC(J,K)+((CEN+CEW+CEP)*FLUX(I)*.16)
      CONTINUE
JOREC(J)=2.24E-10*(LN**2)*W
JODIF(J)=3.02E-10*(NI/LN)*(1/NA+1/ND*(1/TANH(X/LN)))
VGC(J,K)=5E-2*ALOG(SQRT((JOREC(J)/(2*JODIF(J))**2+(JSC(J,K))/
1      JODIF(J))-(JOREC(J)/(2*JODIF(J))))

```


PROGRAM CALCULATES JSC,VOC,EFFICIENCY VS ACCEPTOR CONCENTRATION OR VS LOG10 OF THE INTERFACE RECOMBINATION VELOCITY. TO CHANGE FROM ONE TO THE OTHER, FIRST MAKE THE INDEPENDENT VARIABLE A ONE DIMENSIONAL ARRAY (IE NA BECOMES NA(80) IN THE DIMENSION STATEMENT AND NA(J) EVERYWHERE ELSE). SECOND, SET RANGE(I)=0 FOR ALL I. THIRD, CHANGE THE VARIABLES IN ARRAY ITITLE TO CONSTRUCT SUITABLE AXES TITLES. FOURTH, INSERT THE SUITABLE ARRAY NAMES INTO THE 'CALL USPLT' STATEMENT AND RUN PROGRAM USING COMMAND:
EX HETR16.FOR,REL:IMSL.REL/LIB

D = THICKNESS OF P LAYER (CM)
DELTA = LATTICE MISMATCH
DN = DIFFUSION COEF N LAYER (CM²/SEC)
DP = DIFFUSION COEF P LAYER (CM²/SEC)
EG1 = GAP WINDOW MATERIAL (EV)
EG2 = GAP ABSORBENT MATERIAL (EV)
EN = DIELECTRIC CONSTANT N MATERIAL
EO = CAPACITIVITY OF VACUUM (COULOMB/VOLT CM)
EP = DIELECTRIC CONSTANT P MATERIAL
JOD = MINORITY CARRIERS DIFFUSION DARK SATURATION CURRENT (MA/CM²)
JOREC = SPACE CHARGE RECOMBINATION DARK SATURATION CURRENT (MA/CM²)
JSC = SHORT CIRCUIT CURRENT (MA/CM²)
JSI = INTERFACE RECOMBINATION DARK SATURATION CURRENT (MA/CM²)
LN = DIFFUSION LENGTH N LAYER (CM)
LP = DIFFUSION LENGTH P LAYER (CM)
ME = CONDUCTION BAND EFFECTIVE MASS (GR)
MO = ELECTRON MASS (GR)
MV = VALENCE BAND EFFECTIVE MASS (GR)
ND = DONOR CONCENTRATION (CM⁻³)
PIN = POWER IN (MILLIWATTS/M²)
QUE = ELECTRON CHARGE (COULOMBS)
RHO = RESISTIVITY ABSORBENT MATERIAL (OHMS CM)
SMALLA = LOWEST LATTICE CONSTANT
T = TEMPERATURE (DEGREES K)
T1 = THICKNESS OF WINDOW MATERIAL (CM)
TAU = LIFETIME (SEC)
TAU2 = LIFETIME (SEC)
VOC = OPEN CIRCUIT VOLTAGE (VOLTS)

INITIALIZATION

DIMENSION FLUX(100),AP(100),IMAG4(5151),ITITLE(144),
1 RANGE(4),ICHAR(10),FFOO(14),CO(14)
REAL JP,JSC(80,20),JW,VOC(80,20),L,ME,MB,MV,SI(80),NC,ND,NV,
1 WP(80,20),K,Q,MO,LP,JSI,JOD,JOD1,JOD2,
2 KONE,KTWO,NI1,NI2,JOREC,MUSUBN,NA,ETA(80,20)

DATA XN/4.2/, XP/3.8/, EN/8.15/, EP/11/, DELTAA/4.82/,
1 SMALLA/8.13/, EO/8.85E-14/, Q/1.0/, PIN/71.39132/,
2 K/.8617E-4/, MV/1.1648E-28/, MO/9.1E-28/,
3 ME/9.1E-28/, MB/1E-28/, D/.050/, QUE/1.609E-19/
DATA ND/1E17/, L/2E-4/, TAU/1E-6/, EG1/3.2/, EG2/1.3/,
1 T/300/, S/0/, NPTS/61/, DN/.5/, DP/2.5/, NA/1E17/,
2 LN/2E-4/, LP/.5E-4/, T1/.1E-4/, TAU2/1E-6/

DATA(ITITLE(I),I=1,72)/30*' ','V','O','C',

1 ' ','V','S', ' ','L','O','G',

2 '1','0', ' ','S','I',27*' '//

DATA(ITITLE(I),I=109,144)/17*' ','V','O','C',

1 15*' '//

APPENDIX B continued

```

DATA(ITITLE(I),I=73,108)/14*' ','L','O','G','1','0',
1      ' ','S','I',14*' '/'
DATA(RANGE(I),I=1,4)/0,8,0,1/
DATA(RANGE(I),I=1,4)/4*0/
DATA(ICHAR(I),I=1,10)/10*' '/'
DATA(FLUX(I),I=1,61)/.0005,.0092,.0629,.1772,.3015,
1      .4080,.5207,.6374,.7142,.7975,1.0564,1.4396,
2      1.7027,1.1598,2.0297,2.3607,2.6279,2.7755,
3      2.8648,2.9503,3.0755,3.1491,3.1856,3.3083,3.4499,
4      3.51755,3.5689,3.64795,3.7293,
5      3.77685,3.802,3.8432,3.88435,3.9214,3.9699,
6      3.9819,3.9936,4.0683,4.1241,4.13645,3.9622,
7      4.1324,4.1199,3.8419,4.07,4.0493,3.4361,
8      3.4196,4.0123,3.9999,3.7173,3.6846,
9      3.7781,3.3293,2.7723,2.719,3.7067,3.6794,
10     3.6668,3.6598,3.6387/
DATA(AP(I),I=1,61)/26*6.4E4,5.8E4,5.3E4,4.9E4,4.5E4,
1      4.2E4,3.8E4,3.35E4,2.91E4,2.48E4,2.17E4,
2      1.88E4,1.62E4,1.44E4,1.25E4,1.1E4,9.8E3,
3      8.7E3,7.7E3,6.8E3,6.2E3,5.3E3,4.6E3,3.79E3,
4      2.88E3,1.04E3,4.55E2,2.37E2,1.18E2,6.1E1,
5      3.1E1,1.89E1,9,5.4,3,1.8/
DATA(FF00(I),I=1,14)/.690,.722,.747,.769,.790,.803,
1      .816,.827,.836,.845,.854,.860,.866,.873/
DATA(CO(I),I=1,14)/.795,.824,.848,.868,.883,.895,
1      .905,.913,.919,.924,.929,.934,.937,.942/

COMPUTATION
DO 125 J=1,80
DO 125 K1=1,1
    ND=K1*1E18
    SI(J)=10**(.1*J)
    NV=4.83E15*((MV/MO)**1.5)*(T**1.5)
    NC=4.83E15*((ME/MO)**1.5)*(T**1.5)
    DELTA1=K*T*ALOG(NV/NA)
    DELTA2=K*T*ALOG(NC/ND)
    DELTAX=XN-XP
    DELTEC=-DELTAX
    DELTEV=EG1-EG2+DELTAX

    IF(ND-NA)10,10,20
    A=(NA+ND)/(Q*NA)
        GO TO 30
    A=(NA+ND)/(Q*ND)

    VD=EG2-DELTAX-DELTA1-DELTA2
    PHI=(1/A)*(EG-DELTAX-DELTA1+DELTA2*(A-1))
    KONE=1/(1+(ND*EN/(NA*EP)))
    KTWO=1-KONE
    NI1=1E10*EXP(-((EG1-1.1))/(8.39E-5*T))
    NI2=1E10*EXP(-((EG2-1.1))/(8.39E-5*T))

    WN=SQRT(2*NA*EN*EP*EO*VD/(QUE*ND*(EN*ND+EP*NA)))
    WP(J,K1)=SQRT(2*ND*EN*EP*EO*VD/(QUE*NA*(EN*ND+EP*NA)))

```

APPENDIX B continued

```

DO 100 I=1,NPTS
  JW=.16*FLUX(I)*(1-EXP(-AP(I)*WP(J,K1)))
  JF=.16*FLUX(I)*(AP(I)*L/((AP(I)**2)*(L**2)-1))*
    (1/(S*TANH(D/L)+L/TAU))*
    ((EXP(-AP(I)*D)/COSH(D/L))*
    (S-(AP(I)*L*L/TAU))+
    (L/TAU)*(AP(I)*L-TANH(D/L))+
    S*(AP(I)*L*TANH(D/L)-1))*
    EXP(-AP(I)*WP(J,K1))
  JSI=(QUE*NC*SI(J)*EXP(-(EG2-DELTA)/((8.39E-5*T)))*1E3

  JOD1=(ND*DN*EXP((-VD+DELTEC)/((8.39E-5*T)))/(LN*TANH(D/LN))
  JOD2=(1/LP)*TANH(T1/LP+S*LP/DP)*NA*DP*
    EXP((-VD-DELTEV)/((8.39E-5*T))
  JOD=(QUE*(JOD1+JOD2))*1E3

  JOREC=QUE*((NI1/(2*KONE))*SQRT(DN/TAU)+
    (NI2/(2*KTWO))*SQRT(DP/TAU2))*
    (8.39E-5*T/(VD*(VD-.4)))

  VOC(J,K1)=(2*8.39E-5*T)*ALOG(SQRT((JOREC/(2*(JOD+JSI)))*2
    +JSC(J,K1)/(JOD+JSI))-JOREC/(2*(JOD+JSI)))

  COUNTR=20*VOC(J,K1)-5
  K2=COUNTR
  RESIDU=20*VOC(J,K1)-5-K2

  FFO=FFO(K2)+(FFO(K2+1)-FFO(K2))*RESIDU
  C=CO(K2)+(CO(K2+1)-CO(K2))*RESIDU
  MUSUBN=DN/((8.39E-5*T)
  RHO=1/(QUE*NA*MUSUBN)
  FF=FFO-(1E-3*JSC(J,K1)*RHO*D*C/VOC(J,K1))
  ETA(J,K1)=VOC(J,K1)*JSC(J,K1)*FF/PIN
  SI(J)=ALOG10(SI(J))

  ICHAR = ARRAY CONTAINING SYMBOLS WHICH REPRESENT PLOTTED POINTS
  IER = VARIABLE CONTAINING ERROR INFORMATION
  IMAG4 = ARRAY WHICH IS USED BY PLOTTING ROUTINE AS A WORKSPACE
  INC = DISPLACEMENT BETWEEN ELEMENTS OF INDEPENDANT VARIABLE
        VECTOR TO BE USED
  IOPT = WIDTH OF GRAPH (IOPT=0:80 COLUMNS: IOPT=1:100 COLUMNS)
  ITITLE = ARRAY CONTAINING TITLE INFORMATION
  IY=ROW DIMENSION OF DEPENDANT VARIABLE MATRIX
  M1 = NUMBER OF FUNCTIONS TO BE PLOTTED (1-10)
  N1 = DIMENSION OF INDEPENDANT VARIABLE VECTOR
  RANGE = VECTOR DEFINING SCALES ON AXIS, IF RANGE = 0 THEN
        DEFAULT AXIS SCALES SET

```

EMERGING MATERIALS CONTRACTORS DISTRIBUTION LIST

Boeing Aerospace Company
Electronics Technology
P. O. Box 3999
Seattle, WA 98124
Attn: Dr. Reid A. Mickelsen

Joint Center for Graduate Study
University of Washington
Richland, WA 99352
Attn: Dr. Larry C. Olsen

The Pennsylvania State University
276 Materials Research Laboratory
University Park, PA 16802
Attn: Dr. K. Vedam

Radiation Monitoring Devices, Inc.
44 Hunt Street
Watertown, MA 02172
Attn: Dr. Gerald Entine

Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, CA 90265
Attn: Dr. Ken Zanio

Research Triangle Institute
P. O. Box 12194
Research Triangle Park, NC 27709
Attn: Dr. J. Edward Andrews

Southern Methodist University
Dallas, TX 75275
Attn: Dr. Ting L. Chu

Stanford University
Stanford, CA 94305
Attn: Dr. Richard H. Bube
Department of Materials
Science and Engineering

Virginia Polytechnic Institute
and State University
346 Whittemore Hall
Blacksburg, VA 24061
Attn: Dr. Larry C. Burton, Research
Div.

Perkin-Elmer Corporation
Main Avenue
Norwalk, CT 06856
Attn: Mr. Donald Smith

John B. Mooney
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025