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A COMPUTER PROGRAM TO DETERMINE THE EFFECT OF CHARGED-PARTICLE IRRADIATION ON SOLAR-CELL OUTPUT POWER

A. F. OBENSCHAIN

MAY 1969

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

A major consideration in designing a solar array is the charged particle environment in which it will operate. The computer program described here, developed to calculate the effects of charged-particle flux on the power output of a single solar cell, will greatly reduce the lengthy and laborious hand calculations now necessary in designing an array. The program transforms the particle environment of a given orbit into a 1-Mev equivalent electron flux, and degrades an individual solar-cell I-V characteristic to account for the effect of this flux. The output of the program is the value of the damage-equivalent normally incident (deni) 1-Mev electron flux and a series of current-voltage points representing the I-V characteristic of the degraded solar cell.

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A COMPUTER PROGRAM TO DETERMINE THE EFFECT OF CHARGED-PARTICLE IRRADIATION ON SOLAR-CELL OUTPUT POWER

I. INTRODUCTION

A FORTRAN computer program has been developed to account for the effect of charged-particle irradiation on the power output of a single solar cell. The program converts the charged-particle environment of a given orbit to a damage-equivalent normally incident (deni) 1-Mev electron flux, then degrades the I-V (current/voltage) characteristic of a single solar cell to account for the effects of the computed flux and prints out the degraded I-V curve. Cells of either 1 or 10 ohm-cm nominal base resistivity may be used in the program.

The program consists of three parts:

- MAIN-reads input data, prints output data, and calls the subroutines as required.
- PHI-calculates the equivalent 1-Mev flux encountered by a solar cell during its orbital lifetime as a function of the coverglass and the back-shielding selected.
- DGRADE-degrades a solar cell I-V characteristic to account for the reductions in power caused by the equivalent flux.

This program is based on a paper by R. Rasmussen of RCA/AED[1] and the Manned Orbiting Power System (MOPS) Power Computer Program[2]; B. F. Poinsett performed most of the actual programming. The program, written in the FORTRAN II computer language is compatible with the IBM 7094 computer.

II. CALCULATION OF 1-MEV ELECTRON FLUX (SUBROUTINE PHI)

Because the power output of a solar cell depends on the equivalent flux the cell encounters during its orbit lifetime, an accurate method of determining the effect of this flux is essential. Subroutine PHI converts to a deni 1-Mev electron flux the known charged-particle spectrum of the four types of particles that damage solar cells most: trapped orbital electrons, trapped orbital protrons, solar-flare protons, and solar-flare alpha particles. Solar-cell irradiation degradation is usually defined in terms of this low-energy flux because the damage equivalency of 1-Mev electrons for each type and energy range of space particle has been defined.[1] Once calculated, the 1-Mev equivalent flux for each type of particle is summed to determine the total 1-Mev flux the cell experiences.

A flux table prepared for each type of particle contains the particle's flux population through specific energy ranges on a daily basis. At GSFC, G. Stassinopoulose of the Laboratory for Theoretical Studies usually makes flux tables for a particular orbit. Tables 1 through 4 list the energy ranges for each type of particle and give the population of each for a particular orbit. The electron environment is broken into 11 ranges; the other particle environments are divided into 18 ranges. The program will operate properly only when the particle populations are divided into the energy ranges specified in Tables 1 through 4.

Table 1

Electron-Flux Format

Energy-Range Number	ΔE (Mev)	N_e (Electrons/cm^2)
1	0-0.25	2.89 E13
2	0.25-0.50	2.35 E12
3	0.50-0.75	7.78 E11
4	0.75-1.0	2.5 E11
5	1.0 -2.0	1.06 E10
6	2.0 -3.0	4.09 E8
7	3.0 -4.0	3.89 E6
8	4.0 -5.0	2.95 E4
9	5.0 -6.0	3.1 E2
10	6.0 -7.0	1.8 E2
11	7.0 -8.0	1.0 E1

The program converts the daily input flux tables into total flux population tables by multiplying the population of each energy range by the number of days in orbit. (The "number of days in orbit," an input parameter specified by the program user, is merely the time in orbit for which the equivalent flux is calculated.) The program calculates the equivalent 1-Mev electron flux for each type of particle by applying a damage factor (KD) to the population of each energy range; damage factors depend on the effective coverglass and backshielding

Table 2

Proton-Flux Format

Energy-Range Number	ΔE (Mev)	N_p (Protons/cm^2)
1	0.0-1.0	2.32 E11
2	1.0-2.0	3.56 E8
3	2.0-3.0	4.1 E7
4	3.0-4.0	2.19 E7
5	4.0-5.0	1.23 E7
6	5.0-6.0	6.84 E6
7	6.0-7.0	5.47 E6
8	7.0-8.0	3.0 E6
9	8.0-9.0	1.191 E6
10	9.0-10.0	1.23 E6
11	10.0-11.0	1.09 E6
12	11.0-12.0	1.09 E6
13	12.0-13.0	1.09 E6
14	13.0-14.0	4.1 E5
15	14.0-15.0	3.12 E5
16	15.0-30.0	2.46 E6
17	30.0-100.0	2.32 E6
18	>100.0	3.83 E5

Table 3

Solar-Flare-Proton-Flux Format

Energy-Range Number	ΔE (Mev)	N_{fp} (Protons/cm^2)
1	0.0-1.0	0
2	1.0-2.0	1.66×10^8
3	2.0-3.0	4.1×10^8
4	3.0-4.0	2.19×10^7
5	4.0-5.0	1.23×10^7
6	5.0-6.0	6.8×10^6
7	6.0-7.0	5.4×10^6
8	7.0-8.0	3.0×10^6
9	8.0-9.0	1.91×10^6
10	9.0-10.0	1.23×10^6
11	10.0-11.0	1.09×10^6
12	11.0-12.0	1.09×10^6
13	12.0-13.0	1.09×10^6
14	13.0-14.0	8.2×10^5
15	14.0-15.0	6.8×10^5
16	15.0-30.0	4.9×10^6
17	30.0-100.0	$4\ 6 \times 10^6$
18	>100.0	5.4×10^5

Table 4

Solar-Flare Alpha-Particle Flux Format

Energy-Range Number	ΔE (Mev)	$N_{f\alpha}$ (Alpha Particles/cm^2)
1	16-18	1.09×10^5
2	18-20	8.2×10^4
3	20-22	8.2×10^4
4	22-25	8.2×10^4
5	25-30	1.09×10^5
6	30-32	5.4×10^4
7	32-35	5.4×10^4
8	35-40	5.4×10^4
9	40-45	5.4×10^4
10	45-47	2.7×10^4
11	47-52	3.2×10^4
12	52-57	3.5×10^4
13	57-65	1.36×10^4
14	60-80	8.76×10^5
15	80-100	5.4×10^4
16	100-200	6.1×10^4
17	200-400	1.23×10^3
18	>400	2.7×10^3

densities (gm/cm^2) of the solar cell. Tables 5 and 6 list damage factors for orbital electrons and protons, based on data reported by Brown, Gabbe, and Rosenzweig.[3] Although previously trapped orbital protons were distinguished from solar-flare protons because of the relative uncertainty associated with the solar-flare proton model, both proton classifications will use the same damage factor table. Damage factors for alpha particles, from the work of Smith and Blue,[4] are based on the relationship:

$$3.8\,\phi_P(E) = \phi_A(4E)$$

This relationship states that an alpha particle of four times the energy of a proton does 3.8 times the damage of the proton. Table 7 lists damage factors for alpha particles. The program user must specify an equivalent thickness of backshielding and coverglass for each computation; Table 8 lists available shielding densities, and equivalent thicknesses of fused silica coverglass and aluminum

Table 5

Damage Factors for Electrons (KDE)

Energy Range No.	Shielding Number				
	1.0	2.0	3.0	4.0	5.0
1	0	0	0	0	0
2	0.03	0.02	0	0	0
3	0.13	0.08	0.03	0	0
4	0.30	0.20	0.10	0.02	0
5	1.15	1.02	0.75	0.47	0.25
6	2.70	2.50	2.05	1.55	1.10
7	4.15	3.92	3.38	2.85	2.15
8	5.30	5.15	4.60	4.10	3.30
9	6.15	6.10	5.70	5.30	4.60
10	7.30	7.30	6.80	6.50	5.85
11	7.80	7.80	7.70	7.50	7.0

Table 6

Damage Factors for Protons (KDP)

Energy Range No.	Shielding Number				
	1.0	2.0	3.0	4.0	5.0
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	3000	0	0	0	0
6	3700	2000	0	0	0
7	3500	3100	0	0	0
8	3100	3100	200	0	0
9	2800	2800	1400	0	0
10	2700	2700	2600	0	0
11	2600	2600	2100	0	0
12	2500	2500	2100	100	0
13	2500	2500	2100	1000	0
14	2500	2500	2000	1400	0
15	2500	2500	2000	1500	100
16	2500	2500	2000	1800	1500
17	2300	2300	2000	2000	2000
18	1000	1000	1000	1000	1000

Table 7

Damage Factors for Alpha Particles (KDA)

Energy Range No.	Shielding Number				
	1.0	2.0	3.0	4.0	5.0
1	10000	0	0	0	0
2	13000	0	0	0	0
3	14000	7000	0	0	0
4	13700	11000	0	0	0
5	12500	12000	0	0	0
6	11500	11500	2500	0	0
7	11000	11000	5200	0	0
8	10400	10400	7200	0	0
9	9800	9800	7900	0	0
10	9500	9500	8000	1700	0
11	9500	9500	7800	3650	0
12	9500	9500	7700	5300	0
13	9500	9500	7600	5700	1600
14	9400	9400	7600	6300	4000
15	9200	9200	7600	7000	6400
16	8600	8600	7700	7400	7100
17	7000	7000	7000	7000	7000
18	4000	4000	4000	4000	4000

Table 8

Shielding Numbers

Shielding Density (gm/cm^2)	0.033	0.05	0.1	0.2	0.3
Equivalent mils of fused silica cover-glass	6.0	9.0	18.0	36.0	54.0
Equivalent mils of aluminum	5.0	7.5	15.0	30.0	45.0
Shielding Number for computer look-up	1.0	2.0	3.0	4.0	5.0

backshielding. If coverglass and backshielding with the correct thicknesses are not available for use in the program, the one nearest in thickness to the correct one should be used.

Once the charged-particle population of each type of particle has been entered into the computer, and the coverglass and backshielding thicknesses have been selected, the computer can calculate the total equivalent 1-Mev electron flux using the relationship:

$$\phi_T = \phi_e + \phi_P + \phi_{fP} + \phi_{f\alpha} \text{ (Ref. 1)}$$

where

ϕ_T = total 1-Mev equivalent flux
ϕ_e = electron 1-Mev equivalent flux
ϕ_P = proton 1-Mev equivalent flux
ϕ_{tP} = solar-flare proton 1-Mev equivalent flux
$\phi_{f\alpha}$ = solar-flare alpha particle 1-Mev equivalent flux

The contribution of each particle to the total flux is calculated separately by a summation process. For example, ϕ_P is calculated by multiplying the population of each of the 18 proton energy ranges by the appropriate damage factors for backshielding and coverglass, then summing each of these products.

The following expression demonstrates this summation process:

$$\phi_P = \sum_{\Delta E=1}^{18} \left[KDP \times NP|_{CG} + KDP \times NP|_{BS} \right]^1$$

where

KDP = proton damage factor for a given energy range
NP = number of protons in a particular energy range

The equivalent flux for each of the other types of particles is calculated similarly. (The value of NP above is the total flux population of a given energy range and not the input per-day population.)

In summary, the input to subroutine PHI is the charged-particle environment of each of the four types of charged particles, flux damage factor tables, number of days in orbit, and effective solar cell coverglass and backshielding thicknesses. The population of each energy range of a given particle is multiplied by damage factors for both coverglass and backshielding to determine the 1-Mev equivalent electron flux. The individual fluxes are summed to calculate the total deni 1-Mev electron flux.

III. CALCULATION OF SOLAR CELL I-V CURVE IRRADIATION DEGRADATION (SUBROUTINE DGRADE)

Subroutine DGRADE degrades a single solar cell I-V characteristic to compensate for the damage caused by an equivalent 1-Mev flux. The input to this subroutine is either the output of PHI or a user specified 1-Mev flux; in the latter case subroutine PHI is not called and the computer immediately enters subroutine DGRADE to degrade the I-V curve for the given flux.

The undergraded solar-cell I-V curve is entered into the computer as a series of voltage and current points (V_i and I_i) at room temperature and nominal solar intensity (140 mev/cm^2). The computer interpolates the original points to arrive at 100 current and voltage pairs at 10-mv increments. These interpolated points will then be shifted to account for the charged-particle irradiation degradation. The following describes I-V characteristic modification to account for the equivalent flux.

A curve shape correction dependent on the equivalent 1-Mev flux effectively sharpens the knee of the curve: the greater the flux, the sharper the knee. This curve shape change is obtained by adding a negative "radiation resistance" (RR) correction to each voltage point of the curve:

$$v_{i_{\text{corrected}}} = v_{i_{\text{initial}}} + I_i \times RR \qquad \text{(Reference 1)}$$

where RR, in ohms, is defined as "volts at short-circuit current (VISC) divided by the initial, undegraded value of short-circuit current (ISCO)." The program first calculates the value for VISC, based on the equivalent flux value and the solar cell base resistivity, according to the following equations:

1 ohm-cm

$$VISC = .005 \left[\log_{10}\left(\frac{\phi_T}{10^{13}}\right)\right]^{1.85}$$

$$\text{for} \quad 10^{13} < \phi_T < 3 \times 10^{14} \qquad \text{(Ref. 1)}$$

$$VISC = 0.01403 \log_{10} \phi_T - 0.1929$$

$$\text{for} \quad \phi_T \geq 3 \times 10^{14} \qquad \text{(Ref. 1)}$$

10 ohm-cm

$$VISC = .0047 \left[\log_{10}\left(\frac{\phi_T}{2.5 \times 10^{13}}\right)\right]^{1.43}$$

$$\text{for} \quad 2.5 \times 10^{13} < \phi_T < 2 \times 10^{15} \qquad \text{(Ref. 1)}$$

$$VISC = 0.0129 \log_{10} \phi_T - 0.1852$$

$$\text{for} \quad \phi_T \geq 2 \times 10^{15} \qquad \text{(Ref. 1)}$$

Figure 1 shows the effect of the curve shape correction. Curve 1 is the original I-V curve and curve 2 shows the sharpening of the knee of the curve caused by changed-particle irradiation.

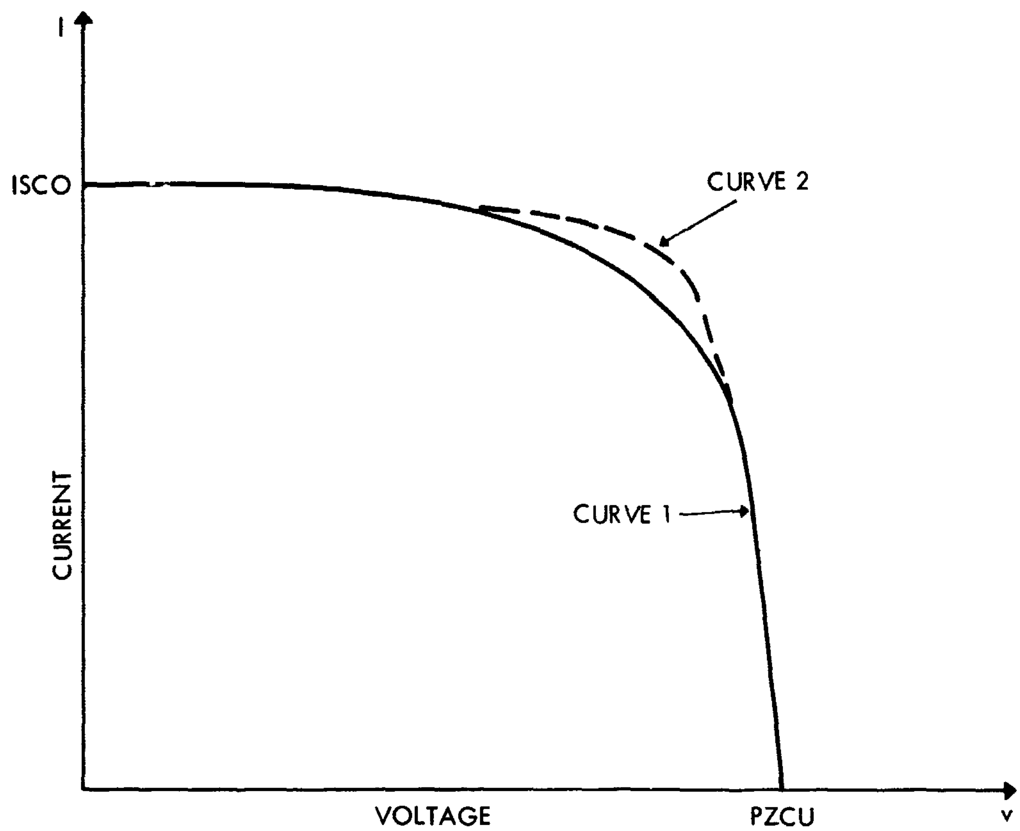

Figure 1. Curve shape correction.

Next the program shifts the total IV curve parallel to the current axis an amount ΔI to account for the reduction in short-circuit current caused by the equivalent flux. The program calculates the relative short-circuit current degradation factor (R I) by the following equations dependent on cell base resistivity and flux level:

1 ohm-cm $\quad RI = 1 - 7.13 \times 10^{-8.31} \left[\phi_T - 4 \times 10^{12}\right]^{0.451}$

for $\quad 4 - 10^{12} < \phi_T < 10^{15}$ (Ref. 1)

$$RI = 3.3 - 0.167 \log_{10} \phi_T$$

$$\text{for} \quad \phi_T \geq 10^{15} \qquad \text{(Ref. 1)}$$

10 ohm-cm

$$RI = 1 - 2.78 \times 10^{-7.34} \left[\phi_T - 5 \times 10^{12}\right]$$

$$\text{for} \quad 5 \times 10^{12} < \phi_T < 10^{15} \qquad \text{(Ref. 1)}$$

$$RI = 2.806 - 0.1325 \log_{10} \phi_T$$

$$\text{for} \quad \phi_T \geq 10^{15} \qquad \text{(Ref. 1)}$$

The current increment ΔI is calculated as ISCO $(1 - RI)$. Curve 3 of Figure 2 is determined by subtracting ΔI from each current point of curve 2: $I_i = I_i - \Delta I$. The point PZCD is not the actual degraded open-circuit voltage, but merely a temporary value of the "point of zero current" of the cell.

A final characteristic correction is made to account for the reduction of open-circuit voltage in the cell caused by the equivalent flux. The relative open-circuit voltage degradation factor (RV) is calculated by the following equations:

1 and 10 ohm-cm

$$RV = 1 - 0.022 \left[\log_{10} \left(\frac{\phi_T}{3 \times 10^{12}}\right)\right]^{1.67}$$

$$\text{for} \quad 3 \times 10^{12} < \phi_T < 10^{14} \qquad \text{(Reference 1)}$$

$$R_v = 1.779 - 0.0588 \log_{10} \phi_T$$

$$\text{for} \quad \phi_T \geq 10^{14} \qquad \text{(Reference 1)}$$

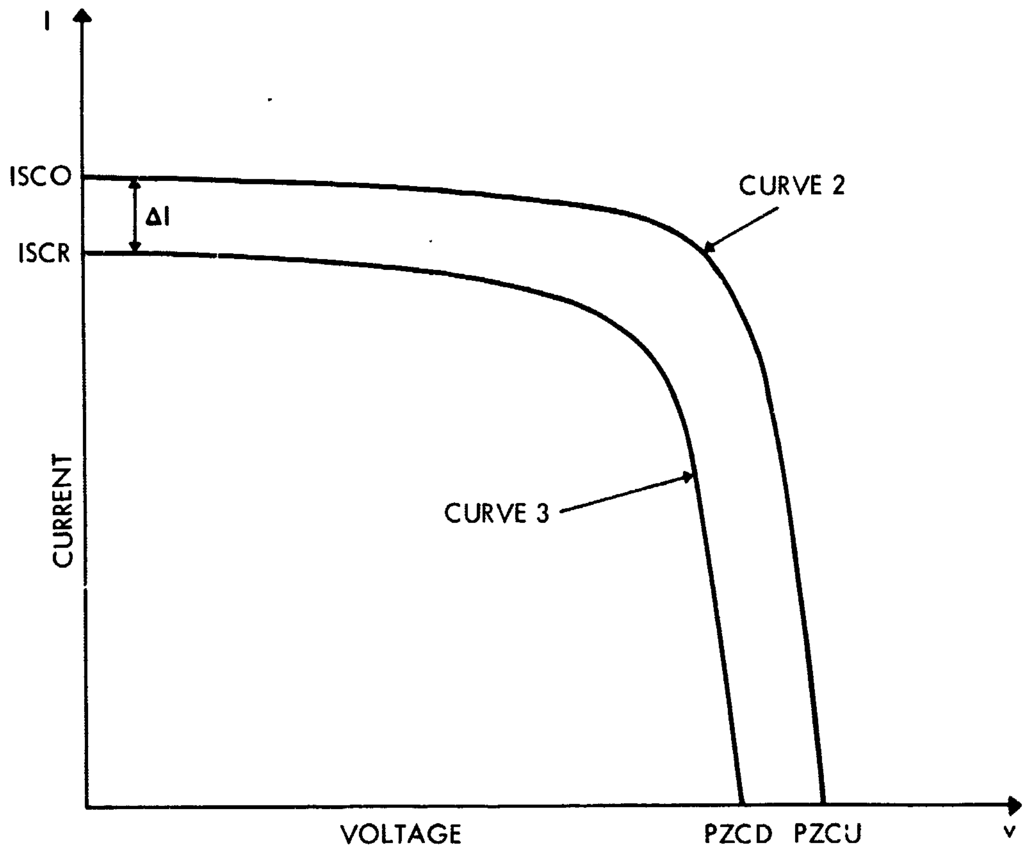

Figure 2. Short-circuit current correction.

(unlike the previous degradation parameters, Rv does not depend on the solar-cell base resistivity.) The degraded open-circuit voltage (VOCR) is calculated as (PZCU × Rv). The curve is then shifted parallel to the voltage axis an amount Δv--defined as (PZCD-VOCR)--by subtracting Δv from each voltage point ($V_i = V_i - \Delta v$). Curve 4 of Figure 3 shows the fully degraded solar-cell I-V curve.

In addition to degrading the solar cell I-V characteristic, subroutine DGRADE calculates the percentage of short-circuit current and maximum power degradation. If this additional calculation is desired, the user must input the initial I-V curve values of maximum power point current and voltage. Because the initial value of short-circuit current in the cell is already part of the input data (the first current point of the input I-V curve), this parameter need not be defined again.

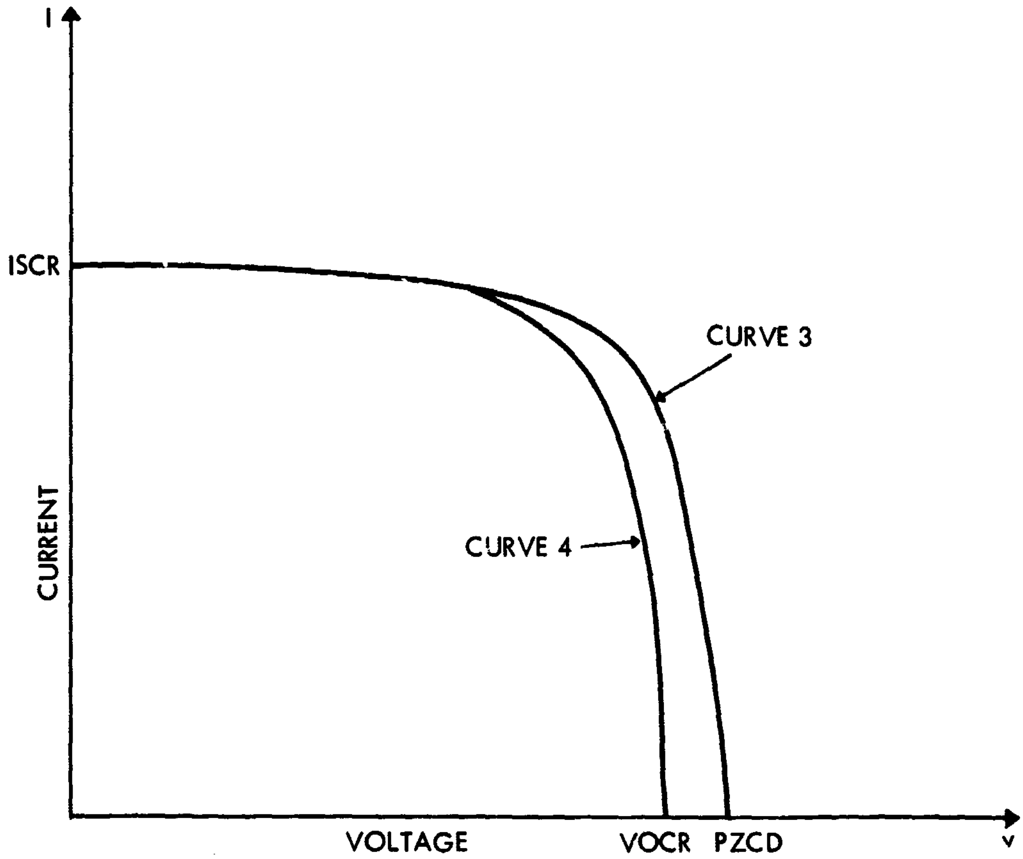

Figure 3. Open-circuit voltage correction.

IV. PROGRAM USAGE

The following describes the mechanics of using the program in "non-programmer" language.

The program is broken into two parts: a source deck and a data deck. Appendix A contains a complete source deck listing, whereas Appendix B shows a typical data deck setup. As the source deck (A) is merely read into the computer each time without modification, the following paragraphs will describe only the contents and format of the data deck. (Refer also to Appendix B.)

Asterisk Data

The initial data deck card is the asterisk data card. This card tells the computer that data is to be read next, and has the following format:

* .... Column 1

DATA .... Columns 7-10

The remainder of the card is blank.

Charged Particle Environment

This section of the data deck contains a portion of the information required by subroutine PHI: the population, through the energy range, of each of the four types of charged particles. Flux tables are entered in order for electrons, protons, solar-flare protons, and solar-flare alpha particles; a maximum energy range card precedes each table. This card gives the number of energy ranges of any particle population, and this number must agree with the number of ranges for each particle as shown in Tables 1 through 4. The range-card number is an integer, right-justified against the third column of the card. The remainder of the card is blank. Following the maximum-energy-range card, the population of the particle is read in a continuous format, with the energy ranges as stored parameters. That is, the computer will automatically equate the first number read with the population of the first energy range of the particle, the second number with the population of second energy range, and so forth until the entire flux table for the particle has been read. Erroneous results will be obtained if the tables are not entered in the correct order or the particle environment is not broken into the specified energy ranges.

Each particle population card contains eight 10-column fields; the population of each range is right-justified against the tenth column of each field in "E" notation. If a given particle type such as solar-flare alpha particles is not considered to exist for a given set of orbital conditions, the maximum range card and corresponding population data cards with a zero in each field must be entered into the computer.

Damage Factors

The next portion of the data deck contains the damage-factor tables. This section is preceded by an NMAX card which gives the maximum number of shielding densities—five, at present- the program can handle; NMAX is an integer number, right-justified against the third column of the card, with the remainder of the card blank. Following the NMAX card, damage factors for electrons are read in a continuous format, with shielding density numbers and energy ranges as stored factors. The first 11 numbers read give the damage factor of each of the 11 electron ranges, assuming a shielding density of 1.0. The next 11 numbers correspond to the energy ranges with a shielding number of 2.0. Therefore, the first 55 numbers entered after NMAX (5 shielding densities × 11 energy ranges) give the entire electron damage factor table. In a similar manner, the next 90 numbers (5 shielding densities × 18 energy ranges) make up the proton damage factor table. Trapped orbital and solar-flare protons both use the same damage factors. The last 90 numbers read make-up the alpha particle damage factor table.

Each card in this portion of the data deck contains eight 10-column fields; the damage factors are real numbers and are right-justified against the tenth column of each field. As the program can only use the shielding densities of Table 8, additional damage factor tables must be generated if other shielding thicknesses are required. However, satisfactory results may often be obtained from use of one of the available shielding thicknesses.

Run Information

The last section of the data deck contains the run information. Each card has the following format:

1. NRUN—run number, columns 1-3 (this number is an integer, right-justified against the third column, and is used to identify a particular run)

2. BS—backshielding thickness in mils, columns 4-13 (this real number is right-justified against column 13)

3. CG—coverglass thickness in mils, columns 14-23 (this real number is right-justified against column 23)

4. RHO—solar-cell base resistivity in ohm-cm, columns 24-33 (this real number, either 1.0 or 10.0 is right-justified against column 33)

5. PHIT—total 1-Mev equivalent flux if read as data, columns 34-43 (a real number in "E" notation is right-justified against column 43--these columns are left blank if no flux is to be read)

6. NPHI—signals computer that PHIT is read as input data, column 46 (the integer 1 is punched in column 46 whenever the total 1-Mev flux is read into the computer rather than being calculated--subroutine PHI will not be called)

7. NCELL—signals computer that a new solar cell I-V curve will be read in, column 49 (the integer 1 is punched in column 49; if the same solar cell I-V curve is to be used, column 49 is left blank)

8. DAYS—the actual number of days the solar cell is exposed to the charged-particle environment--columns 50-56 (this real number is left justified against column 50)

9. XPV—the solar cell I-V curve initial, undegraded maximum power-point voltage in volts--columns 60-69 (this real number is left-justified against column 60)

10. XPI—the I-V curve's initial maximum power-point current in amperes--columns 70-79 (a real number left-justified against column 70)

NOTE

If XPV and XPI are not entered as input data, the percentage degradation of maximum power and short-circuit current is not calculated.

When a run-information card indicates that a new solar-cell I-V curve is to be entered, the next card will be a solar-cell header card. This card contains the following information:

1. NTBL—the number of the I-V curve--columns 1-3 (this integer number is right-justified against the third column of the card)

2. NDTS—the number of current-voltage pairs--columns 4-5 (a 2-digit integer number)

3. DATE—a 6-digit date number (e.g. 020569 = February 5, 1969) columns 11-16

4. TITLE—descriptive title for solar cell--columns 21-80 (any alpha-numeric combination may be used to describe the solar-cell I-V curve)

The cards containing the cell I-V points follow the header card. The data are entered alternately--current value, voltage value, etc--starting with the short-circuit current. One data point requires 10 columns; thus, all 80 columns of one card will handle four I-V pairs. Each number is right-justified against the tenth column of its field.

For additional runs, merely add more run-information cards; each card will have the format explained in the foregoing. (The last portion of Appendix B shows a typical three-run data deck. Most of the possible user options have been demonstrated in this example.) The last card of the data deck contains the integer number 999 in its first three columns; the remainder of the card is blank. This card signifies that all data have been entered into the computer.

V. PROGRAM OUTPUT

The output of the computer program can be divided into three basic parts: input data, 1-Mev equivalent electron flux, and the irradiation-degraded I-V curve. The first section, containing all pertinent input data, is printed out with each run to give the user a quick and accurate tabulation of the data used by the program.

Input data included in the printout are:

1. Run number

2. Number of days in space for which the calculation is being made

3. Backshielding thickness in mils of aluminum

4. Coverglass thickness in mils of fused silica.

5. The population of each energy range of the four types of particles

6. Damage factors for each type of particle

7. The original I-V curve, as a series of current-voltage pairs.

The second section of the program output contains the equivalent 1-Mev flux for the four types of particles and the total 1-Mev equivalent electron flux experienced by the solar cell during a given number of days in orbit. Section three is a printout of the solar cell's degraded I-V curve as a series of current-voltage pairs and the cell's degraded values of open circuit voltage, short-circuit current, and maximum power current and voltage. If the undegraded values of solar cell maximum power current and voltage are given as input data, the percentage decrease in short circuit current and maximum power is also calculated and printed out.

The program can also plot the input and degraded I-V curves for each run. These plots will be made even if the same input I-V curves is used for several consecutive runs. Although these plots are more of a qualitative than a quantitative nature, they may prove helpful in a "quick-look" analysis to determine the relative decrease in power or current caused by various flux environments.

VI. SUMMARY

A computer program has been described which calculates a damage-equivalent, normally incident, 1-Mev electron flux from a given charged particle environment. The program will degrade a single solar-cell I-V curve to account for the equivalent flux. In addition, the program will permit the repetitive calculations necessary to determine the effect of different charged-particle environments and various coverglass and backshielding densities on the equivalent 1-Mev electron flux. This information is essential to the adequate design of a solar array.

REFERENCES

1. Rasmussen, R., "Calculation of 1-Mev Electron Flux and Irradiation Degradation of Solar Cell I-V Curves by Computer."

2. Siskind, S. M., "MOPS Power System Program Report," RCA/AED MOPS #180, November 22, 1966.

3. Brown, W., J. Gabbe, and W. Rosenzweig, "Results of the Telstar Radiation Experiments," Bell System Technical Journal, XLII, Part 2, July 1963.

4. Smith, A. and J. Blue, "A Comparison of Solar Cell Damage by Alpha Particles and Protons."

GLOSSARY

- AISC—interpolated current point of I-V curve
- B—backshielding thickness in mils
- C—coverglass thickness in mils
- CISC—original input data current point of I-V curve
- DA—solar flare alpha-particle damage factor; this parameter is called KDA in program writeup
- DATE—arbitrary 6-number figure, usually signifying the date on which a solar-cell I-V curve table was made up
- DAYS—number of days a solar cell is exposed to a given charged particle environment
- DE—Electron damage factor; parameter referred to as KDE in the program writeup
- DELTAI—I-V curve short-circuit current correction value, defined as ISCO (I-RI)
- DP—Proton damage factor; this parameter is called KDP in program writeup
- E—number of electrons in an energy range; referred to as N_e in the program writeup
- FA—number of alpha particles in an energy range; referred to as $N_{f\alpha}$ in the program writeup
- FP—number of flare protons in an energy range; referred to as N_{fp} in the program writeup
- I_i—a current point on the solar-cell I-V curve
- ISCO—initial, undegraded value of cell's short-circuit current
- I-V—designation signifying current/voltage
- KDA—damage factor for alpha particles; referred to as DA in the program

- KDE—damage factor for electrons; this parameter is called DE in the program

- KDP—damage factor for protons; referred to as DP in the program

- LEVELE—number of electron energy ranges in the flux table

- LEVELFA—number of solar-flare alpha-particle energy ranges in the flux table

- LEVELFP—number of solar-flare proton energy ranges in the flux table

- LEVELP—number of proton ranges in the flux table

- MOPS—Manned Orbiting Power System

- NCELL—signifies that a new solar cell I-V curve is to be entered as input data

- NE—number of electrons in an energy range; referred to as E in the program

- NFA—number of flare alpha particles in an energy range; referred to as FA in the program

- NFP—number of flare protons in an energy range; referred to as FP in the program

- NMAX—the maximum number of shielding thicknesses the program can handle

- NP—number of protcns in an energy range; referred to as P in the program

- NPHI—an integer which signifies that an equivalent 1-Mev flux will be entered as input data

- NPTS—number of input I-V curve voltage-current pairs

- NRUNS—the number of computer runs for a given data-deck setup

- NTBL—number of the I-V curve table

- P—number of protons in an energy range; this parameter is called NP in the program writeup

- PHIT—equivalent 1-Mev electron flux entered into computer as input data
- PWMT—temporary trial value of the maximum power
- PWR—maximum power of degraded solar-cell I-V curve
- PZCD—degraded point of zero current; a temporary parameter used in Subroutine DGRADE
- PZCU—point of zero current-the initial value of open-circuit voltage
- RHO—solar-cell base resistivity
- RI—relative short-circuit current degradation factor
- RR—radiation resistance, defined as VISC/ISCO
- Rv—relative open-circuit voltage degradation factor
- TITLE—tile of I-V curve
- v—irradiation-degraded voltage point of I-V curve
- VCC—original input-voltage point of I-V curve
- V_i—any particular voltage point on I-V curve
- VISC—volts at zero current; an equation
- VMP—maximum power point voltage of degraded I-V curve
- VOC—interpolated voltage point of I-V curve
- VOCR—degraded value of open-circuit voltage
- XI—irradiation-degraded current point of I-V curve
- XIMP—maximum power point current of degraded I-V curve
- XPI—maximum power point current of initial, undegraded solar-cell I-V curve
- XPv—maximum power point voltage of undegraded solar-cell I-V curve

- ΔI—decrease in short-circuit current caused by the equivalent flux; defined as ISCO-ISCR

- Δv—decrease in open-circuit voltage caused by the equivalent flux; defined as PZCD-VOCR

- ϕ_E—equivalent 1-Mev flux of electrons

- $\phi_{f\alpha}$—equivalent 1-Mev flux of solar-flare alpha particles

- ϕ_{fp}—equivalent 1-Mev flux of solar-flare protons

- ϕ_P—equivalent 1-Mev flux of protons

- ϕ_T—total 1-Mev equivalent flux

APPENDIX A

```
*      DATE04/16/68
* SOLAR CELL IRRADIATION DEGRADATION PROGRAM .
*      PAUSE
*      XEQ
C      MAIN PROGRAM
       DIMENSION E(11),P(18),FP(18),FA(18),DE(11,5), DP(18,5), DA(18,5),
      1XI(101),V(101)
C      ALL PERTINENT TABLES ARE STORED AT THIS TIME.
       READ INPUT TAPE 2,203,LEVELE, (E(I),I=1,LEVELE)
       READ INPUT TAPE 2,203,LEVELP, (P(I),I=1,LEVELP)
       READ INPUT TAPE 2,203,LEVLFP, (FP(I),I=1,LEVLFP)
       READ INPUT TAPE 2,203,LEVLFA, (FA(I),I=1,LEVLFA)
C      DAMAGE FACTOR TABLES ARE NOW READ IN.
       READ INPUT TAPE 2,204,NMAX
       READ INPUT TAPE 2,205,((DE(I,J),I=1,LEVELE),J=1,NMAX)
       READ INPUT TAPE 2,205,((DP(I,J),I=1,LEVFLP),J=1,NMAX)
       READ INPUT TAPE 2,205,((DA(I,J),I=1,LEVLFA),J=1,NMAX)
    11 READ INPUT TAPE 2,1 , NRUNS, B, C,R   ,PHIT,NPHI,NCELL,DAYS,XPV,XPI
       IF(NRUNS-999)3,2,2
     3 IF(NPHI) 21,20,21
    20 WRITE OUTPUT TAPE 3,207,NRUNS, DAYS,B,C
       WRITE OUTPUT TAPE 3,13
       DO14I=1,LEVELP
       IF(I-11)15,15,16
    15 WRITE OUTPUT TAPE 3,211,I,E(I),I,P(I),I,FP(I),I,FA(I)
```

```
      GO TO 14
16 WRITE OUTPUT TAPE 3,212,I,F(I),I,FP(I),I,FA(I)
14 CONTINUE
      WRITE OUTPUT TAPE 3,4
      DO6I =1,LEVLFP
      IF(I -11)8,8,9
 8 WRITE OUTPUT TAPE 3,208,I ,(DF(I ,J),J=1,NMAX),I ,(DP(I ,J),J=1,
    1NMAX)
      GO TO 6
 9 WRITE OUTPUT TAPE 3,209,I ,(DP(I ,J),J=1,NMAX)
 6 CONTINUE
      WRITE OUTPUT TAPE 3,12
      DO 7 I=1,LEVLFA
      WRITE OUTPUT TAPE 3,210,I,(DA(I,J),J=1,NMAX)
 7 CONTINUE
      GO TO 22
21 WRITE OUTPUT TAPE 3,2070,NRUNS
22 CALL PHI(D,C,PHIF,PHIP,PHIFP,PHIFA,PHIT,DE,DP,DA ,F,P,FA,FP,I,J,
    1 NMAX,LEVELE,LEVFLP,LEVLFA,LEVLFP,NPHI,DAYS)
      CALL UGRADE(PHIT,R,XI,V,NCELL,XPV,XPI)
      GO TO 11
 2 WRITE OUTPUT TAPE 3,10
      CALL EXIT
 1 FORMAT(I3,3F10.0, E10.0,2I3,F7.0,3X,2F10.0)
```

```
 10 FORMAT (20H0ALL RUNS COMPLETED.)
 203 FORMAT(I3/(3E10.0))
 204 FORMAT(I3)
 205 FORMAT(8F10.0)
 207 FORMAT(13H0 RUN NUMBER I3,10X,15H DAYS IN SPACE=F7.2//
    120H BACKSHIELD IN MILS=F5.1,5X,20H COVERGLASS IN MILS=F5.1)
2070 FORMAT(13H0 RUN NUMBER I3)
   4 FORMAT(50X,21H DAMAGE FACTOR TABLES//53X,13H USED IN THIS//
    156X,9H PROGRAM.////14X,29H DAMAGE FACTORS FOR ELECTRONS,
    226X,27H DAMAGE FACTORS FOR PROTONS/2X,6HENERGY,52X,6HENERGY/
    32X,5HRANGE,17X,15H SHIELDING NUMBERS,10X 5HRANGE,17X,15H SHIELDING
    4 NUMBERS/2X,6HNUMBER,4X,3H1.0,7X,3H1.5,7X,3H3.0,7X,3H6.0,7X,3H9.0,
    55X,6HNUMBER,4X,3H1.0,7X,3H1.5,7X,3H3.0,7X,3H6.0,7X,3H9.0)
 208 FORMAT(3X,I2,3X,5F10.3,2X,I2,3X,5F10.3)
 209 FORMAT(58X,3X,I2,3X,5F10.3)
  12 FORMAT(1 X,35H DAMAGE FACTORS FOR ALPHA PARTICLES/2X,6HENERGY/
    12X,5HRANGE,17X,19H SHIELDING NUMBERS/
    22X,6HNUMBER,4X,3H1.0,7X,3H1.5,7X,3H3.0,7X,3H6.[illegible],7X,3H9.0)
 210 FORMAT(3X,I2,3X,5F10.3)
  13 FORMAT(39X,43H PARTICLE POPULATIONS USED IN THIS PROGRAM./
    155X,5HSOLAR/71X,5HSOLAR,1[illegible]X,5HALPHA/1[illegible]X,6HENERGY,2X,[illegible]ELECTRONS,
    27X,6HENERGY,2X,7HPROTONS,[illegible]X 6HENERGY,2X,7HPROTONS,2X,6HENERGY,
    32X,9HPARTICLE/1[illegible]X,[illegible]HRANGE,6X,3HPER,10X,5HRANGE,6X,3HPER,11X,5H[illegible]
    4GE,6X,3HPL[illegible], [illegible]X,[illegible]RANGE,6X,3HPER/
```

```
 [illegible]5X,4H[illegible],4X,6H[illegible].CM.,[illegible]X,6HNUMBER,4X,6HSQ.CM.,8X,6HNUMBER,4X,
 6HSQ.C[illegible].,8X,6HNUMBER,4X,6H[illegible].CM./)
211 FORMAT(17X,I2,4X,E10.3,8X,I2,4X,E10.3,8X,I2,4X,E10.3,8X,I2,4X,E10.
 13)
212 FORMAT(41X,I2,4X,E10.3,8X,I2,4X,E10.3,8X,I2,4X,E10.3)
    END
    SUBROUTINE PHI([illegible],CG,PHIE,PHIP,PHIFP,PHIFA,PHI[illegible],DE,DP,DA,F,P,FA
   1 ,FP,I,J,NMAX,LEVELE,LEVELP,LEVLFA,LEVLFP,NPHI,DAYS)
    DIMENSION E(11),P(19),FP(1[illegible]),FA([illegible]),DE([illegible]), DP([illegible]), DA(9)
    IF(NPHI)2[illegible],21,2[illegible]
 21 GO TO [illegible]
2[illegible] [illegible]RITE OUTPUT TAPE [illegible],1[illegible],[illegible]IT
    RETURN
C    [illegible] [illegible] [illegible] FOR TABLE LOOK-UP.
  [illegible] IF([illegible]) 1[illegible],1[illegible]1,1[illegible]
 1[illegible] [illegible]
 [illegible] 1[illegible] FORMAT(5X,42H[illegible] [illegible]-OUT WILL USE 5.0MILS)
 1 1 [illegible]=1
    [illegible]
 1[illegible] IF([illegible]-7.[illegible])[illegible],1[illegible],1[illegible]
 [illegible]
    [illegible] 111
 [illegible] IF([illegible]-1[illegible].[illegible])[illegible],1[illegible],1[illegible]
 1[illegible]
```

```
      GO TO 111
  106 IF(BS-30.0)99,107,108
  107  NBS=4
      GO TO 111
  108 IF(BS-45.0)99,109,110
  109  NBS=5
      GO TO 111
  110 PRINT 2101
 2101 FORMAT(5X,41H BACKSHIELD TOO THICK - WILL USE 45.0MILS)
       NBS=5
      GO TO 111
C      COVERGLASS INTEGER NUMBER FOR TABLE LOOK-UP.
  111 IF(CG-6.0)112,113,114
  112 PRINT 2201
 2201 FORMAT(5X,42H COVERGLASS INCORRECT-BUT WILL USE 6.0MILS)
  113  NCG=1
      GO TO 2002
  114 IF(CG-9.0)111,115,116
  115  NCG=2
      GO TO 2002
  116 IF(CG-18.0)111,117,118
  117  NCG=3
      GO TO 2002
  118 IF(CG-36.0)111,119,120
```

```
119  NCG=4
     GO TO 2002
120  IF(CG-54.0)111,121,122
121  NCG=5
     GO TO 2002
122  PRINT 2301
2301 FORMAT(5X,40H COVER-GLASS TOO THICK WILL USE 54.0MILS)
     NCG=5
     GO TO 2002
2002 PHIE1=0.0
     PHIE2=0.0
     PHIP1=0.0
     PHIP2=0.0
     PHIFP1=0.0
     PHIFP2=0.0
     PHIFA1=0.0
     PHIFA2=0.0
     PHIE=0.0
     PHIP=0.0
     PHIFP=0.0
     PHIFA=0.0
     PHIT=0.0
     K=NCG
     J=NBS
```

```
      DO 123 I=1,LEVELE
      IK=(K-1)*LEVELE+I
      PHIE1 =(E(I)*DAYS*DE(IK))+PHIE1
      IJ=(J-1)*LEVELE+I
      PHIE2 =(E(I)*DAYS*DE(IJ))+PHIE2
  123 CONTINUE
C       1-MEV EQUIVALENT ELECTRON FLUX- PHIE.
       PHIE= PHIE1 + PHIE2
      DO 124  I=1,LEVELP
      IK=(K-1)*LEVELP+I
      PHIP1 =(P(I)*DAYS*DP(IK))+PHIP1
      IJ=(J-1)*LEVELP+I
      PHIP2 =(P(I)*DAYS*DP(IJ))+PHIP2
  124 CONTINUE
C       1-MEV EQUIVALENT PROTON FLUX -PHIP.
       PHIP= PHIP1 + PHIP2
      DO 125  I=1,LEVLFP
      IK=(K-1)*LEVLFP+I
      PHIFP1=(FP(I)*DAYS*DP(IK))+PHIFP1
      IJ=(J-1)*LEVLFP+I
      PHIFP2=(FP(I)*DAYS*DP(IJ))+PHIFP2
  125 CONTINUE
C       1-MEV EQUIVALENT SOLAR FLARE PROTON FLUX.
       PHIFP= PHIFP1 + PHIFP2
```

```
      DO 126  I=1,LEVLFA
      IK=(K-1)*LEVLFA+I
      PHIFA1=(FA(I)*DAYS*DA(IK))+PHIFA1
      IJ=(J-1)*LEVLFA+I
      PHIFA2=(FA(I)*DAYS*DA(IJ))+PHIFA2
  126 CONTINUE
C       1-MEV EQUIVALENT SOLAR FLARE ALPHA PARTICLE FLUX.
        PHIFA= PHIFA1 + PHIFA2
C       TOTAL 1-MEV EQUIVALENT OF ALL CHARGED PARTICLES.
        PHIT= PHIE + PHIP + PHIFP + PHIFA
      WRITE OUTPUT TAPE 3,2004, PHIT, PHIE, PHIP, PHIFP, PHIFA
      RETURN
 2004 FORMAT(26X,41H                 TOTAL EQUIVALENT-1-MEV FLUX=E10.3//
     120X,47H                EQUIVALENT 1 MEV ELECTRON FLUX=E10.3//
     220X,47H                  EQUIVALENT 1 MEV PROTON FLUX=E10.3//
     320X,47H       EQUIVALENT 1 MEV SOLAR FLARE PROTON FLUX=E10.3//
     420X,47H           1 MEV SOLAR FLARE ALPHA PARTICLE FLUX=E10.3)
 1000 FORMAT(1H0,44H  GIVEN AS INPUT DATA 1 MEV EQUIVALENT FLUX=E10.3,//
     1/)
      END
      SUBROUTINE DGRADE(PHIT,RHO,XI,V,NCELL,XPV,XPI)
      DIMENSIONVCC(101),CISC(101),VOC(101),AISC(101),XI(101),V(101)
      DIMENSION IMAGE(1717), NSCALE(5)
      IF(NCELL)2,2,1
```

```
    1 CALL PLOT1(NSCALE,10 ,10 ,10 ,10  )
      READ INPUT TAPE 2,100, NTBL, NPTS, DATE, TITLE
C      PRINT OUT OF ORIGINAL DATA POINTS OF THE I-V CURVE.
      WRITE OUTPUT TAPE 3,100,NTBL,NPTS,DATE,TITLE
      READ INPUT TAPE 2,101,(CISC(I),VCC(I), I=1,NPTS)
      WRITE OUTPUT TAPE 3,1010
      WRITE OUTPUT TAPE 3,102,(CISC(I),VCC(I),I=1,NPTS)
C     THE ORIGINAL DATA POINTS ARE NOW EXTRAPOLATED.
       VOC(1)=0.0
       AISC(1)=0.0
      DO 200 J=2,101
         AISC(J)=0.0
       VOC(J)=VOC(J-1)+0.010
  200 CONTINUE
         I= 1
      DO205J=1,100
      IF(VCC(I))2029,2031,2029
 2029 IF (VOC(J)-VCC(I   ))202,203,2030
 2030 I=I+1
  202 AISC(J)=AISC(J-1)+(CISC(I)-CISC(I-1))/(VCC(I)-VCC(I-1))*(VOC(J)-
     1 VOC(J-1))
      GO TO 2020
 2031 AISC(1)=CISC(1)
      I=I+1
```

```
      GO TO 2020
  203 AISC(J)=CISC(I   )
      I=I+1
 2020 N=J
      IF(CISC(I)) 204,2041,205
  205 CONTINUE
  204 PZCU =VOC(N-1)+AISC(N-1)*(VOC(N)-VOC(N-1))/(AISC(N-1)-AISC(N))
      GO TO 2042
 2041 VOC(N)=VCC(I)
      AISC(N)=0.0
       PZCU=VOC(N)
      N=N+1
 2042 DO 206 J=N,101
      AISC(J)=AISC(N-1)+ (AISC(N)-AISC(N-1))/(VOC(N)-VOC(N-1))*(VOC(N)
     1-VOC(N-1))
  206 CONTINUE
C     THIS COMPLETES I-V CURVE EXTRAPOLATION.
C     CURVE IS NOW DEGRADED. 1OHM-CM MATERIAL + 10.OHM-CM MATERIAL.
C      1 OHM-CM FIRST
    2 XMX=VCC(NPTS)+.05
      YMX=CISC(1)+.05
      CALL PLOT2 ( IMAGE ,XMX , 0.0 , YMX   , 0.0   )
      CALL PLOT3(1HO  ,VOC,AISC,101 )
      X=0.0
```

```
      Y=0.0
      X1=0.0
      Y1=0.0
      X2=0.0
      Y2=0.0
      X3=0.0
      Y3=0.0
      X4=0.0
      Y4=0.0
      RI=0.0
      RR=0.0
      RV=0.0
      VISC=0.0
      VLOG=0.0
      VLOG1=0.0
      VLOG2=0.0
       IF(RHO-10.0)207,208,208
  207 IF(PHIT -1.0E15) 209,210,210
  209 IF(PHIT- 4.0E12) 211,211,212
  210  RI=(3.3 -0.167*LOG10F(PHIT))
       GO TO 2217
  211  RI=1.0
       GO TO 2217
  212 RI=1.0-7.137/((10.0)**8.01)*((PHIT - 4.0E12)**0.451)
```

```
      GO TO 2217
C        10 OHM-CM
  208 IF(PHIT- 1.0E15)213,214,214
  213 IF(PHIT-5.0E12)215,215,216
  214  RI=(2.806 -0.1325 * LOG10F(PHIT))
       GO TO 2221
  215  RI=1.0
       GO TO 2221
  216 RI=1. -2.78/((10.0)**7.34)*((PHIT-5.0E12)**0.41)
       GO TO 2221
C      VOLTS AT ISC IS NOW DETERMINED.
C      1 OHM-CM FIRST.
 2217 IF(PHIT-3.0E14) 217,218,218
  217 IF(PHIT- 1.0E13) 219,219,220
  218  VISC=(0.01403*LOG10F(PHIT)-0.1929)
       GO TO 225
  219  VISC=0.0
       GO TO 225
  220  VLOG=(PHIT/1.0E13)
       VISC=(0.005*(LOG10F(VLOG))**1.85)
       GO TO 225
C      10 OHM-CM
 2221 IF(PHIT -2.0E1 ) 221,222,222
  221  IF(PHIT-2.5E13)223,223,224
```

```
  222  VISC=(0.0129* LOG10F(PHIT))-0.1852
       GO TO 225
  223  VISC=0.0
       GO TO 225
  224  VLOG1=(PHIT/2.5E13)
       VISC=(0.0047*(LOG10F(VLOG1))**1.43)
       GO TO 225
C      RELATIVE OPEN-CIRCUIT VOLTAGE DEGRADATION.
C      SAME EQUATIONS USED FOR BOTH 1OHM-CM AND 10 OHM-CM RESISTIVITIES.
  225 IF(PHIT- 1.0E14) 226,227,227
  226 IF(PHIT -3.0E12) 228,228,229
  227  RV=(1.779-0.0588*LOG10F(PHIT))
       GO TO 2230
  228  RV=1.0
       GO TO 2230
  229  VLOG2=(PHIT/3.0E12)
       RV=(1.0-0.0222*(LOG10F(VLOG2))**1.67)
       GO TO 2230
C      I-V CURVES ARE NOW DEGRADED USING THE FOLLOWING COMPUTED FACTORS.
C      VALUE OF RADIATION RESISTANCE RR.
 2230  RR= VISC/AISC(1)
       DO230 J=1,101
         V(J)=VOC(J)+ AISC(J)*RR
  230 CONTINUE
```

```
C       SHORT CIRCUIT CURRENT CORRECTION IS NOW MADE.
         DELTAI =AISC(1)*(1.0-RI)
        IF(DELTAI-AISC(1))2301,2302,2302
 2301 DO231 J=1,101
          XI(J)=AISC(J)- DELTAI
  231 CONTINUE
      GO TO 23112
 2302 DO23111J=1,101
      XI(J)=AISC(J)
23111 CONTINUE
C       DEGRADED SHORT CIRCUIT CURRENT.
23112 DO 2311J=1,101
      N=J
      IF ( XI(J) ) 2332,2333,2311
 2311 CONTINUE
C
 2332 DEL=(XI(J-1)*(V(J)-V(J-1)))/(XI(J-1)-XI(J))
      PZCD=V(J-1)+DEL
      GO TO 2334
 2333 PZCD=V(J)
C
 2334 SLOPE=(XI(N-1)-XI(N-2))/(V(N-1)-V(N-2))
      DO 2423 J=N,101
       XI(J)=XI(N-1)+(V(J)-V(N-1))*SLOPE
```

```
 2423 CONTINUE
C      UNDEGRADED OPEN CIRCUIT VOLTAGE IS PZCU.
C      DEGRADED OPEN CIRCUIT VOLTAGE IS PZCU*RV.
          VOCR= PZCU*RV
 2401 DELTAV=PZCD-VOCR
C      FINAL UPDATE OF VOLTAGES IN THE ARRAY
 2403 DO 2500J=1,101
      V(J)=V(J)-DELTAV
 2500 CONTINUE
      CALL PLOT3( 1HD,V,XI,101)
      DO33J=1,101
      IF(V(J))33,32,32
   32 XISC=XI(J)
      GO TO 34
   33 CONTINUE
   34 N=1
      PWR= -1000000.0
 2330 PWRT= V(N)*XI(N)
      IF(PWRT-PWR)234,235,236
  236 N=N+1
      PWR= PWRT
       GO TO 2330
  235 VMP =V(N)
      XIMP=XI(N)
```

```
      GO TO 45
  234 SLOPE=(XI(N-1)-XI(N))/(V(N)-V(N-1))
  237  VMP    =  V(N-1)+0.00015
      XIMP    = XI(N-1)-SLOPE*(VMP    -V(N-1))
      PWRT= VMP    *XIMP
      IF(PWRT -PWR) 45,45,238
  238 PWR=PWRT
        GO TO 237
C      FORMATS FOR PRINTING RESULTS.
   45 WRITE OUTPUT TAPE 3,2000
      WRITE OUTPUT TAPE 3,2003, VOCR
      WRITE OUTPUT TAPE 3,2004, XISC
      WRITE OUTPUT TAPE 3,2001, XIMP
      WRITE OUTPUT TAPE 3,2002, VMP
C     MAX. POWER DEGRADATION.
      IF(XPV) 4001,4001,4000
 4000 UMP=X[illegible]*XPI
      DMP=(UMP-VMP*XIMP)/UMP*100.0
C         SHORT CIRCUIT CURRENT DEGRADATION
      DISC =(CISC(1)-XISC)/CISC(1)*100.0
      WRITE OUTPUT TAPE 3,2010,DMP,DISC
 2010 FORMAT(10X,37H PERCENT OF MAXIMUM POWER DEGRADATIONF6.1/
     110X,45H PERCENT OF SHORT CIRCUIT CURRENT DEGRADATIONF6.1)
 2001 FORMAT(14H  I-MAX PWR    F7.4)
```

```
2002 FORMAT(14H  V-MAX PWR   F7.4)
4001 DO 2312 J=1,101,2
     WRITE OUTPUT TAPE 3,2005, J,(XI(J))
2005 FORMAT(4H0 I(I3,8H)        F7.4)
     WRITE OUTPUT TAPE 3,2006, J,(V(J))
2006 FORMAT(4H  V(I3,8H)        F7.4)
2312 CONTINUE
2000 FORMAT(50H0 IRRADIATION DEGRADATION OF SOLAR CELL I-V CURVE )
1010 FORMAT(32H0 ORIGINAL I-V CURVE DATA POINTS)
2003 FORMAT(14H  VOLTS OC    F7.4)
2004 FORMAT(14H  AMPS  SC    F7 4)
 100 FORMAT(I3,I2,5X,I6,4X,10A6)
 101 FORMAT(4(2F10.0))
 102 FORMAT(18H0 CURRENT IN AMPS=F10.4/18H VOLTAGE IN VOLTS=F10.4/ )
     CALL FPLOT4(23 ,23H          C U R R E N T )
     WRITE OUTPUT TAPE 3,104
 104 FORMAT ( 35X,9HV O L T S /// )
     RETURN
     END
```

APPENDIX B

* DATA

011

2.89E13	2.35E12	7.78E11	2.5E11	1.06E10	4.09E8	3.89E6	2.95E4
3.1E2	1.8E2	1.0E1					

018

2.32E11	3.56E8	4.1E7	2.19E7	1.23E7	6.84E6	5.47E6	3.0E6
1.91E6	1.23E6	1.09E6	1.09E6	1.09E6	4.1E5	3.12E5	2.46E6
2.32E6	3.83E5						

018

0.0E0	1.66E8	4.1E8	2.19E7	1.23E7	6.8E6	5.4E6	3.0E6
1.91E6	1.23E6	1.09E6	1.09E6	1.09E6	8.2E5	6.8E5	4.9E6
4.6E6	5.4E5						

018

1.09E5	8.2E4	[illegible]	8.2E4	1.09E5	5.4E4	5.4E4	5.4E4
5.4E4	2.7E4	3.2E4	3.5E4	1.36E4	8.76E5	[illegible]	6.1E4
1.23E3	[illegible]						

005

0.0	0.03	0.13	0.30	1.15	2.70	4.15	5.30
6.15	7.30	7.80	0.0	0.02	0.08	0.20	1.02
2.50	3.92	5.15	6.10	7.30	7.80	0.0	0.0
0.03	0.10	0.75	2.05	3.38	4.60	5.70	6.80
7.70	0.0	0.0	0.0	0.02	0.47	1.55	2.83
4.1[illegible]	5.30	6.50	[illegible]	0.0	0.0	0.0	0.0
0.25	1.10	2.15	3.30	4.60	5.85	7.0	
0.0	0.0	0.0	0.0	[illegible]	3700.0	3500.0	3100.

28[illegible]	2700.0	2600.0	2500.0	2500.0	2500.0	2500.0	2500.0
23[illegible]	10[illegible]	0.0	0.0	0.0	0.0	0.0	2000.0
31[illegible]	3100.0	2800.0	2700.0	2600.0	2500.0	2500.0	2500.0
2500.0	2500.0	2300.0	1000.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	200.0	1400.0	2000.0	2100.0	2100.0
21[illegible]	2000.0	2000.0	2000.0	2000.0	1000.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[illegible]	100.0	1000.0	1400.0	1500.0	1800.0	2000.0	1000.0
[illegible]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[illegible]	0.0	0.0	0.0	0.0	0.0	100.0	1500.0
2[illegible]	1000.0						
1[illegible]	13[illegible]	14000.0	13700.0	12500.0	11500.0	11000.0	10400.0
98[illegible]	9500.0	9[illegible]	9500.0	9500.0	9400.0	9200.0	8600.0
7[illegible]	4000.0	0.0	0.0	7000.0	11000.0	12000.0	11500.0
110[illegible]	10400.0	9800.0	9500.0	9500.0	9500.0	9500.0	9400.0
92[illegible]	86[illegible]	7000.0	4000.0	0.0	0.0	0.0	0.0
0.0	25[illegible]	520[illegible]	7200.0	7900.0	8000.0	7800.0	7700.0
7600.0	76[illegible]	7600.0	7700.0	7000.0	4000.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	1700.0
365[illegible]	5[illegible]	5700.0	6300.0	7000.0	7400.0	7000.0	4000.0
0.0	[illegible]	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	1600.0	4000.0	6400.0	7100.0
7[illegible]	4000.0						

001 45.0 6.0 10.0 1365.0 0.4200 0.1300

```
00118    011669     HELIOTEK 10 OHM CM CELL AT 30 DEG C
    0.1412     0.0     0.1410     0.1000     0.1405     0.2000     0.1398     0.3000
    0.1380     0.3500     0.1360     0.3800     0.1340     0.4000     0.1300     0.4200
    0.1240     0.4400     0.1200     0.4500     0.1100     0.4700     0.1000     0.4800
    0.0900     0.4900     0.0800     0.5000     0.0600     0.5150     0.0400     0.5280
    0.0200     0.536     0.0000     0.547
002     45.0     18.0     10.0                    365.0     0.4200     0.1300
003     15.0      6.0     10.0     2.0E15  1               0.4200     0.1300
999
                                                                        EOF E SY
```

```
    1 CALL PLOT1(NSCALE,10 ,10 ,10 ,10  )
      READ INPUT TAPE 2,100, NTBL, NPTS, DATE, TITLE
C      PRINT OUT OF ORIGINAL DATA POINTS OF THE I-V CURVE.
      WRITE OUTPUT TAPE 3,100,NTBL,NPTS,DATE,TITLE
      READ INPUT TAPE 2,101,(CISC(I),VCC(I), I=1,NPTS)
      WRITE OUTPUT TAPE 3,1010
      WRITE OUTPUT TAPE 3,102,(CISC(I),VCC(I),I=1,NPTS)
C     THE ORIGINAL DATA POINTS ARE NOW EXTRAPOLATED.
       VOC(1)=0.0
       AISC(1)=0.0
      DO 200 J=2,101
         AISC(J)=0.0
       VOC(J)=VOC(J-1)+0.010
  200 CONTINUE
         I= 1
      DO205J=1,100
      IF(VCC(I))2029,2031,2029
 2029 IF (VOC(J)-VCC(I   ))202,203,2030
 2030 I=I+1
  202 AISC(J)=AISC(J-1)+(CISC(I)-CISC(I-1))/(VCC(I)-VCC(I-1))*(VOC(J)-
    1 VOC(J-1))
      GO TO 2020
 2031 AISC(1)=CISC(1)
      I=I+1
```

```
      GO TO 2020
  203 AISC(J)=CISC(I   )
      I=I+1
 2020 N=J
      IF(CISC(I)) 204,2041,205
  205 CONTINUE
  204 PZCU =VOC(N-1)+AISC(N-1)*(VOC(N)-VOC(N-1))/(AISC(N-1)-AISC(N))
      GO TO 2042
 2041 VOC(N)=VCC(I)
      AISC(N)=0.0
       PZCU=VOC(N)
      N=N+1
 2042 DO 206 J=N,101
      AISC(J)=AISC(N-1)+ (AISC(N)-AISC(N-1))/(VOC(N)-VOC(N-1))*(VOC(N)
     1-VOC(N-1))
  206 CONTINUE
C     THIS COMPLETES I-V CURVE EXTRAPOLATION.
C     CURVE IS NOW DEGRADED. 1OHM-CM MATERIAL + 10.OHM-CM MATERIAL.
C      1 OHM-CM FIRST
    2 XMX=VCC(NPTS)+.05
      YMX=CISC(1)+.05
      CALL PLOT2 ( IMAGE ,XMX , 0.0 , YMX  , 0.0  )
      CALL PLOT3(1HU ,VOC,AISC,101 )
      X=0.0
```

```
      Y=0.0
      X1=0.0
      Y1=0.0
      X2=0.0
      Y2=0.0
      X3=0.0
      Y3=0.0
      X4=0.0
      Y4=0.0
      RI=0.0
      RR=0.0
      RV=0.0
      VISC=0.0
      VLOG=0.0
      VLOG1=0.0
      VLOG2=0.0
      IF(RHO-10.0)207,208,208
  207 IF(PHIT -1.0E15) 209,210,210
  209 IF(PHIT- 4.0E12) 211,211,212
  210  RI=(3.3 -0.167*LOG10F(PHIT))
       GO TO 2217
  211  RI=1.0
       GO TO 2217
  212 RI=1.0-7.13/((10.0)**8.31)*((PHIT - 4.0E12)**0.451)
```

```
      GO TO 2217
C     10 OHM-CM
  208 IF(PHIT- 1.0E15)213,214,214
  213 IF(PHIT-5.0E12)215,215,216
  214  RI=(2.806 -0.1325 * LOG10F(PHIT))
      GO TO 2221
  215  RI=1.0
      GO TO 2221
  216 RI=1.0-2.78/((10.0)**7.34)*((PHIT-5.0E12)**0.41)
      GO TO 2221
C     VOLTS AT ISC IS NOW DETERMINED.
C     1 OHM-CM FIRST.
 2217 IF(PHIT-3.0E14) 217,218,218
  217 IF(PHIT- 1.0E13) 219,219,220
  218  VISC=(0.01403*LOG10F(PHIT)-0.1929)
      GO TO 225
  219  VISC=0.0
      GO TO 225
  220  VLOG=(PHIT/1.0E13)
      VISC=(0.005*(LOG10F(VLOG))**1.85)
      GO TO 225
C     10 OHM-CM
 2221 IF(PHIT -2.0E15) 221,222,222
  221  IF(PHIT-2.5E13)223,223,224
```

```
  222  VISC=(0.0129* LOG10F(PHIT))-0.1852
       GO TO 225
  223  VISC=0.0
       GO TO 225
  224  VLOG1=(PHIT/2.5E13)
       VISC=(0.0047*(LOG10F(VLOG1))**1.43)
       GO TO 225
C      RELATIVE OPEN-CIRCUIT VOLTAGE DEGRADATION.
C       SAME EQUATIONS USED FOR BOTH 1OHM-CM AND 10 OHM-CM RESISTIVITIES.
  225 IF(PHIT- 1.0E14) 226,227,227
  226 IF(PHIT -3.0E12) 228,228,229
  227  RV=(1.779-0.0588*LOG10F(PHIT))
       GO TO 2230
  228  RV=1.0
       GO TO 2230
  229  VLOG2=(PHIT/3.0E12)
       RV=(1.0-0.0222*(LOG10F(VLOG2))**1.67)
       GO TO 2230
C      I-V CURVES ARE NOW DEGRADED USING THE FOLLOWING COMPUTED FACTORS.
C       VALUE OF RADIATION RESISTANCE RR.
 2230  RR= VISC/AISC(1)
      DO230 J=1,101
        V(J)=VOC(J)+ AISC(J)*RR
  230 CONTINUE
```

```
C     SHORT CIRCUIT CURRENT CORRECTION IS NOW MADE.
       DELTAI =AISC(1)*(1.0-RI)
      IF(DELTAI-AISC(1))2301,2302,2302
 2301 DO231 J=1,101
        XI(J)=AISC(J)- DELTAI
  231 CONTINUE
      GO TO 23112
 2302 DO23111J=1,101
      XI(J)=AISC(J)
23111 CONTINUE
C     DEGRADED SHORT CIRCUIT CURRENT.
23112 DO 2311J=1,101
      N=J
      IF ( XI(J) ) 2332,2333,2311
 2311 CONTINUE
C
 2332 DEL=(XI(J-1)*(V(J)-V(J-1)))/(XI(J-1)-XI(J))
      PZCD=V(J-1)+DEL
      GO TO 2334
 2333 PZCD=V(J)
C
 2334 SLOPE=(XI(N-1)-XI(N-[illegible]))/(V(N-1)-V(N-2))
      DO 2423 J=N,101
       XI(J)=XI(N-1)+(V(J)-V(N-1))*SLOPE
```

```
 2423 CONTINUE
C      UNDEGRADED OPEN CIRCUIT VOLTAGE IS PZCU.
C      DEGRADED OPEN CIRCUIT VOLTAGE IS PZCU*RV.
          VOCR= PZCU*RV
 2401 DELTAV=PZCD-VOCR
C      FINAL UPDATE OF VOLTAGES IN THE ARRAY
 2403 DO 2500J=1,101
      V(J)=V(J)-DELTAV
 2500 CONTINUE
      CALL PLOT3( 1HD,V,XI,101)
      DO33J=1,101
      IF(V(J))33,32,32
   32 XISC=XI(J)
      GO TO 34
   33 CONTINUE
   34 N=1
      PWR= -1000000.0
 2330 PWRT= V(N)*XI(N)
      IF(PWRT-PWR)234,235,236
  236 N=N+1
      PWR= PWRT
       GO TO 2330
  235 VMP =V(N)
      XIMP=XI(N)
```

```
      GO TO 45
  234 SLOPE=(XI(N-1)-XI(N))/(V(N)-V(N-1))
  237  VMP   =  V(N-1)+0.00015
      XIMP   = XI(N-1)-SLOPE*(VMP   -V(N-1))
      PWRT= VMP   *XIMP
      IF(PWRT -PWR) 45,45,238
  238 PWR=PWRT
        GO TO 237
C      FORMATS FOR PRINTING RESULTS.
   45 WRITE OUTPUT TAPE 3,2000
      WRITE OUTPUT TAPE 3,2003, VOCR
      WRITE OUTPUT TAPE 3,2004, XISC
      WRITE OUTPUT TAPE 3,2001, XIMP
      WRITE OUTPUT TAPE 3,2002, VMP
C     MAX. POWER DEGRADATION.
      IF(XPV) 4001,4001,4000
 4000 UMP=XPV*XPI
      DMP=(UMP-VMP*XIMP)/UMP*100.0
C          SHORT CIRCUIT CURRENT DEGRADATION
      DISC =(CISC(1)-XISC)/CISC(1)*100.0
      WRITE OUTPUT TAPE 3,20010,DMP,DISC
20010 FORMAT(10X,37H PERCENT OF MAXIMUM POWER DEGRADATIONF6.1/
     110X,45H PERCENT OF SHORT CIRCUIT CURRENT DEGRADATIONF6.1)
 2001 FORMAT(14H0 I-MAX PWR   F7.4)
```

```
2002 FORMAT(14H  V-MAX PWR    F7.4)
4001 DO 2312 J=1,101,2
     WRITE OUTPUT TAPE 3,2005, J,(XI(J))
2005 FORMAT(4H0 I(I3,8H)         F7.4)
     WRITE OUTPUT TAPE 3,2006, J,(V(J))
2006 FORMAT(4H  V(I3,8H)         F7.4)
2312 CONTINUE
2000 FORMAT(50H0 IRRADIATION DEGRADATION OF SOLAR CELL I-V CURVE )
1010 FORMAT(32H0 ORIGINAL I-V CURVE DATA POINTS)
2003 FORMAT(14H  VOLTS OC     F7.4)
2004 FORMAT(14H  AMPS  SC     F7.4)
 100 FORMAT(I3,I2,5X,I6,4X,10A6)
 101 FORMAT(4(2F10.0))
 102 FORMAT(18H0 CURRENT IN AMPS=F10.4/18H VOLTAGE IN VOLTS=F10.4//)
     CALL FPLOT4(23 ,23H            C U R R E N T )
     WRITE OUTPUT TAPE 3,104
 104 FORMAT ( 25X,9HV O L T S /// )
     RETURN
     END
```

APPENDIX B

```
*    DATA
011
   2.89E13    2.35E12    7.78E11    2.5E11     1.06E10    4.09E8     3.89E6     2.95E4
   3.1E2      1.8E2      1.0E1
018
   2.32E11    3.56E8     4.1E7      2.19E7     1.23E7     6.84E6     5.47E6     3.0E6
   1.91E6     1.23E6     1.09E6     1.09E6     1.09E6     4.[illegible]5     3.12E5     2.46E6
   2.32E6     3.83E5
018
   0.0E0      1.66E8     4.1E8      2.[illegible]     1.23E7     6.8E6      5.4E6      3.0E6
   1.91E6     1.23E6     1.09E6     1.09E6     1.09E6     8.2E5      6.8E5      4.9E6
   4.6E[illegible]     5.4E5
018
   1.09E5     8.2E4      8.2E4      8.2E4      1.09E5     5.4E4      5.4E4      5.4E4
   5.4E4      2.7E4      3.2E4      3.5E4      1.36E4     8.76E5     5.4E4      6.1E4
   1.23E3     2.7E3
[illegible]
   0.0        0.03       0.13       0.30       1.[illegible]5      2.70       4.15       5.30
   6.15       7.30       7.80       0.0        0.02       0.08       0.20       1.02
   2.50       3.92       5.15       6.10       7.30       7.80       0.0        0.0
   0.03       0.10       0.75       2.05       3.38       4.60       5.70       6.80
   7.70       0.0        0.[illegible]       0.0        0.02       0.47       1.55       2.85
   4.10       5.30       5.[illegible]      7.50       0.0        0.0        0.0        0.0
   0.25       1.10       2.15       3.30       4.60       5.85       7.0
   0.0        0.0        0.0        0.0        3000.0     3700.0     3[illegible]0.0     3100.0
```

2800.0	2700.0	2600.0	2500.0	2500.0	2500.0	2500.0	2500.0
2300.0	1000.0	0.0	0.0	0.0	0.0	0.0	2000.0
3100.0	3100.0	2800.0	2700.0	2600.0	2500.0	2500.0	2500.0
2500.0	2500.0	2300.0	1000.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	200.0	1400.0	2000.0	2100.0	2100.0
2100.0	2000.0	2000.0	2000.0	2000.0	1000.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	100.0	1000.0	1400.0	1500.0	1800.0	2000.0	1000.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	100.0	1500.0
2000.0	1000.0						
10000.0	13000.0	14000.0	13700.0	12500.0	11500.0	11000.0	10400.0
9800.0	9500.0	9500.0	9500.0	9500.0	9400.0	9200.0	8600.0
7000.0	4000.0	0.0	0.0	7000.0	11000.0	12000.0	11500.0
11000.0	10400.0	9800.0	9500.0	9500.0	9500.0	9500.0	9400.0
9200.0	8600.0	7000.0	4000.0	0.0	0.0	0.0	0.0
0.0	2500.0	5200.0	7200.0	7900.0	8000.0	7800.0	7700.0
7600.0	7600.0	7600.0	7700.0	7000.0	4000.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	1700.0
3650.0	5300.0	5700.0	6300.0	7000.0	7400.0	7000.0	4000.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	1600.0	4000.0	6400.0	7100.0
7000.0	4000.0						

001 45.0 6.0 10.0 1365.0 0.4200 0.1300

```
00118    011669    HELIOTEK 10 OHM CM CELL AT 30 DEG C
    0.1412     0.0    0.1410    0.1000    0.1405    0.2000    0.1398    0.3000
    0.1380    0.2500  0.1360    0.3800    0.1340    0.4000    0.1300    0.4200
    0.1240    0.4400  0.1200    0.4500    0.1100    0.4700    0.1000    0.4800
    0.0900    0.4900  0.0800    0.5000    0.0600    0.5150    0.0400    0.5280
    0.0200    0.536   0.0000    0.547
002    45.0    18.0    10.0                 365.0    0.4200    0.1300
003    15.0     6.0    10.0    2.0E15  1             0.4200    0.1300
999
                                                              EOF E SY
```