TRW

DOE/ET/33006--025

Plasma Separation Process

Betacell (BCELL) Code User's Manual

Prepared Under Contract DE-AC03-77ET33006

Prepared for
U.S. Department of Energy
Washington, DC 20505

TRW Space & Technology Group
One Space Park
Redondo Beach, Ca 90278

TRW

DOE/ET/33006--025

Plasma Separation Process

DOE/ET/33006-025

DE88 006955

Betacell (BCELL) Code User's Manual

PSP-R1-1438

Prepared Under Contract DE-AC03-77ET33006

Prepared for
U.S. Department of Energy
Washington, DC 20505

Prepared by
M. Taherzadeh

TRW Space & Technology Group
One Space Park
Redondo Beach, Ca 90278

DISCLAIMER

Betacell Design and System Performance

M. Taherzadeh

The emergence of clearly defined applications for (small or large) amounts of long-life and reliable power sources has given the design and production of betavoltaic systems a new life. Moreover, because of the availability of the **plasma separation program**, (PSP) at TRW, it is now possible to separate the most desirable radioisotopes for betacell power generating devices. A computer code, named BCELL, has been developed to model the **betavoltaic concept** by utilizing the available up-to-date source/cell parameters. In this program, attempts have been made to determine the betacell energy device maximum efficiency, degradation due to the emitting source radiation and source/cell lifetime power reduction processes. Additionally, comparison is made between the Schottky and PN junction devices for betacell battery design purposes. Certain computer code runs have been made to determine the JV distribution function and the upper limit of the betacell generated power for specified energy sources. A Ni beta emitting radioisotope was used for the energy source and certain semiconductors were used for the converter subsystem of the betacell system. Some results for a Promethium source are also given here for comparison.

November 13, 1987

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

LIST OF PARAMETERS

Parameters	Definitions	Units
A	Perfection Parameter	---
A_{AS}	Source Assay	---
A_c	Converter Energy Absorption	---
A_s	Source Area	cm^2
b	q/kT	1/volt
D	Diffusion Constant	cm^2/sec
$\bar{D}$	Average Damage Dose	Rad
Eg	Energy Gap	eV
F	Radiation Face Factor	---
FF	Fill Factor	---
GM	Source Mass	gm
J	Current Density	$amperes/cm^2$
L	Diffusion Length	cm
L_c	Converter Width	cm
N_D	Impurity Density	cm^{-3}
n_i	Intrinsic Concentration	cm^{-3}
P	Power Density	$watts/cm^2$
Q	Quantum Efficiency	---
R_B	Source Reflection Coefficient	---
R_c	Converter Reflection Coefficient	---
R_s	Source Reflection Coefficient	---
S/ρ	Electron Stopping Power	---
T_s	Source Transmission Coefficient	---
V	Voltage	volts
W	Source Width	cm
ε	Expended Energy	ev
μ	Attenuation Coefficient	1/cm
λ	Source Decay Const	1/sec
τ_h	Minority Carrier Diffusion Time	sec
η	Betacell Efficiency	---
ϕ	Electron Fluence	e/cm^2

Betacell Design and System Performance

M. Taherzadeh

(1.0) Introduction

To generate useful electric power, one technique is to couple an energetic electron source with a converter cell so that the energy multiplication effect of the semiconductor junction can enhance the reproduced power. However, there are certain important problems with this betavoltaic concept so that under ordinary conditions these efforts become fruitless. The first problem is related to the **purity** of the electron source radiation. This means that most of the radioisotopes that emit electron radiation, emit other radiation as well. These interfering and unwanted radiations could damage the source, the converter and/or the media outside the energy source itself. One such unwanted radiation source is the **gamma** radiation which not only damages the converter but also damages targets outside the source. The other problem is related to the **purity** of the electron source radioisotopes existence in nature. This means that their natural abundances are small (like 3.7% for Ni^{62} radioisotope) and, consequently, the electron emitter radiation is overtaken by the radiation from other isotopes mixed in with the electron source radioisotope. That is why betacell development was not persued since the 1970's.

With the **success** of the TRW **plasma separation program** (PSP), it is now possible to separate the extremely desirable electron emitting radioisotopes from other isotopes. Utilizing the PSP process and the new technology advances on various converters, development of useful energy sources based upon the **betavoltaic** concept now has become close to reality.

In this report, we have analyzed various contributing factors to the overall behavior of beta emitters and solid state energy converters and have developed a computer code, named BCELL, based upon algorithms

representing these ideas.

(2.0) Fundamental Betavoltaic Concept

Betavoltaic energy conversion systems are based upon the production of electric power by coupling **a beta emitting source to a semiconductive bipolar barrier junction device.** The excess concentration of electrons on the conduction band creates a potential difference across the bipolar junction which results in an output power from the cell. The betacell output power degradation is caused by many factors including the source and the cell degradations. Other parameters contributing to power reduction are the beta and beta induced radiation fields. If a special electron emitting source is selected so that the power degradation due to the beta and beta induced radiation or other unwanted fields such as gamma radiation is small, then the only other parameters one should be concerned about are the cell lifetime and source half-life limitations. Utilizing PSP and producing a pure (or with a very high assay value) Ni^{63} radioisotope, for example, one can eliminate the portion of betacell degradation which is related to other radiation sources.

(3.0) Theoretical Model

Most of the energy of the beta-particles emitted from a beta source radioisotope dissipate through the absorbing medium by ionization of the atoms of the solid. The electron-hole pairs which are generated in this process are diffused to the vicinity of the rectifying junction. The excess electrons in the conduction band near the bandgap induce a voltage across the junction. When J and V represent the betacell current density and output voltage, the output power density can be clearly given by:

$$P_o(watts/cm^2) = J(amperes/cm^2)\, V(volts) \qquad (1)$$

The output current density of the betacell is given by :

$$J = J_{sc} - J_{loss} \tag{2}$$

J_{sc} is the short circuit current density of the cell and is given by:

$$J_{sc} = P_{\beta}/\epsilon \tag{3}$$

ϵ is the expended energy per electron-hole pair and P_{β} is the absorbed power in the converter and is given by :

$$P_{\beta} = P_{in} Q (1 - R_c) A_c \tag{4}$$

Q is the quantum efficiency of the cell, R_c is the converter reflection coefficient, A_c is the fraction of the β power absorbed in the converter and P_{in} is the initial power emitted from the β source and is given by :

$$P_{in} = GM(1 - R_B) T_s F A_{AS} e^{-\lambda t} / A_s \tag{5}$$

G is the source specific power (watts/gram), M is its total mass, R_B is the reflection coefficient of the barrier height, A_{AS} is the source assay, λ is the source disintegration constant, t is the time and T_s is the source transmission coefficient. A_s is the actual cross sectional area of the converter and F is the radiation face factor. For an extremely thin source, the transmission coefficient is given by :

$$T_s = \frac{1 - e^{-\mu W}}{\mu W} \tag{6}$$

W and μ are the source width and attenuation constant, respectively. For a thick source the above relationship will not be correct and the radiation length must be taken in the calculation (see section 4.0 and Appendix 1). A_c calculation is also complicated but for a thin converter it could approximately be given by :

$$A_c = 1 - Exp[-\mu_c L_c] \tag{7}$$

μ_c and L_c are the converter attenuation constant and its width. $\epsilon(ev)$ is the expended energy per electron hole pair and is given by:

$$\epsilon(ev) = 2.8\, E_g + \epsilon_L(ev) \tag{8}$$

Where ϵ_L is between 0.5 and 1 ev and E_g is the bandgap energy given in ev. The loss current is given by:

$$J_{loss} = J_0[e^{bV} - 1] + J_{0R}[e^{bV/A} - 1] \tag{9}$$

Where J_0 is the dark current density (amp/cm^2), J_{0R} is the recombination current density, A is the betacell circuit perfection parameter ($1 \leq A \leq 2$) and b relates to the temperature and is given in (1/volts). For PN junction devices the dark current density is given by:

$$J_0 = \frac{q\, n_i^2}{N_D}\left(\frac{L}{D}\right)_h \tag{10}$$

Where n_i is the intrinsic concentration density of the converter, N_D is the donor impurity density, L_h is the converter diffusion length of the minority carriers and D_h is the diffusion constant of the same carriers.

The recombination current density is given by:

$$J_{0R} = \frac{e\, n_i\, W_D}{2\,\tau_h} \tag{11}$$

Where W_D is the converter depletion depth and τ_h is the minority carrier diffusion time. The maximum output power density of the betacell, then, is given by:

$$P_{o,max}(watts/cm^2) = J_{mp}\, V_{mp} \tag{12}$$

Where "mp" stands for the **maximum power** output.

(4.0) Betacell Efficiency Enhancement

In this report, we have analyzed various contributing factors to the overall efficiencies of the solid state (in contrast to the electrode) betacells and have found that under certain experimental

conditions these efficiencies can be meaningfully maximized. Suggestions are made to test these ideas in a real experimental environments.

The overall performance of betacells depend strongly upon the time degradation of the radioisotopes utilized as energy sources. Disregarding this important efficiency reducing factor, we can analyze other parameters contributing to the overall degradation of the betacell efficiency. These parameters are the source and converter transmission coefficients, the source and the converter reflection coefficients, the source electrons angular distribution and finally the converter collection efficiency. Here, we first define the maximum betacell efficiency (the theoretical maximum efficiency) and, then, discuss the limitations on **minimizing** the effects of other parameters involved.

(4.1) Maximum Betacell Efficiency; η_{max}

If the radioisotope output power (input to the betacell) is defined by $P_i(watts/cm^2)$ and the solid state betacell output power is defined by $P_o(watts/cm^2)$, then, the following relationships must hold:

$$P_i(watts/cm^2) = W_g \frac{G}{A} \tag{13}$$

$$P_o = V_o J_o \tag{14}$$

$$\eta = \frac{P_o}{P_i} \tag{15}$$

Where W_g is the source specific output power in watts/gram and G is the number of grams of the source material. A is the source area facing the converter, V_o and J_o are the output voltage and current density of the betacell, respectively. To maximize η, we must increase the output/input ratio, however, the betacell efficiency can not be increased more than a limit; η_{max}. This means that the betacell efficiency can be defined in terms of η_{max};

$$\eta = \eta_{max} Q A_c (1 - R_c)(1 - R_s) P(\mu) \tag{16}$$

Where Q is the quantum efficiency of the collector, A_c is the converter absorption coefficient, R_s and R_c are the source and the converter reflection coefficients, respectively. $P(\mu)$ represents the emitted source electrons angular distribution function.

Using one example of the solid state betacell design based on the analytical model adapted for this purpose, we have calculated the η_{max} values for the two most important radioisotopes considered here; namely P_m^{147} and Ni^{63} power sources and a GaAs converter. The results are presented in Table 1. From this Table we notice that the maximum betacell efficiency for a GaAs cell, under the specified assumptions, is about 12% for a promethium source and about 7% for a Ni source. To obtain these values, we have used the following equation for the η_{max};

$$\eta_{max} = \frac{FF}{\epsilon(ev)\lambda} \ln[(J_{sc})_{max}/J_Z] \tag{17}$$

Where FF stands for the betacell fill factor, ϵ is the expended energy per electron pair production, J_Z is the minority carrier current density, J_{sc} is the maximum short circuit current and finally λ stands for the measure of the betacell junction temperature. The maximum short circuit current density of the betacell can be defined here:

$$(J_{sc})_{max} = (P_i)_{max}/\epsilon(ev) \tag{18}$$

$$(P_{input})_{max} = (watts/gm)(gm/A) \tag{19}$$

$$(P)_{input} = (watts/gm)(gm)(Face)T_s \tag{20}$$

T_s is the source transmission coefficient and Face is the radiation face factor. Various other parameters needed to calculate the specified η_{max} (Equation 17) are defined and are given in Table 1. Clearly, the definition of η_{max} is not unique and can be based on either the bombardment energy and/or on the absorbed energy of the ejected electrons from the radioisotopes.

(4.2) Betacell Efficiency

The maximum betacell efficiency for GaAs converter is about 12% for promethium and about 7% for nickel radioisotopes and a GaAs PN junction. One would like to achieve these optimum performances for any betacell design. However, there are a number of obstacles which are responsible for the reduction of the betacell efficiencies from the above ideal values. These factors were briefly referred to in Equation 16 above. Here we shall discuss them in more detail.

(4.2.1) Converter Reflection Coefficient; R_c

There are two types of electrons returning from the bombarded surface. The first type are the electrons which are reflected from the converter (PN junctions) or metal (Schottky junctions) surfaces. The second type are the electrons which have penetrated the target and have backscattered toward the source itself. The average energy of the reflected electrons is less than 50 ev and , therefore, they are not very important as far as betacell power conversion is concerned. The backscattering electrons, on the other hand, are important because their average energy is comparable to the source average electron energy ranging in tens of Kev's. It is important to notice that only a fraction of the initial electrons enter the target medium along perpendicular direction to the surface. Thus, the backscattered electrons return toward the source with a definite angular distribution. The electron yield of these backscattered electrons is obtained when the cross section of the scattering process is integrated over all these exit angles. The solution shows that the electron yield of the backscattered electrons is only a function of the atomic number of the target medium. Using the data obtained by **Everhart (1960)** and **Archard (1961)** and the CURVFIT code of the TRW-system routines, we have obtained the following relationship for the backscattered electron yield:

$$R_c = 1.92 \times 10^{-2} Z^{0.818} \qquad (21)$$

For a GaAs collector with a Z of 32, the reflection coefficient is about 33% and for the fused silica of a Z equal to 10.8 this reflection coefficient is about 13%. We should notice here that R_c is **energy independent** and, therefore, is the same for all radioisotopes used as energy sources. The backscattered electron yield defined by Equation 21 above yields values about 7% lower than similar values reported by **Rappaport** and **Linder (1953).**

(4.2.2) Source Reflection Coefficient; R_s

The source reflection coefficient is related to the electrons which do not have enough energy to cross over the potential height at the emitter's surface. As the electric field between the emitting source and the collector increases the source reflection coefficient decreases just because the low energy electrons have a better chance to cross over the barrier. In other words, the higher E-field pulls more low energy electrons over the barrier height. It has been estimated that at zero E-field, the maximum R_s, the source reflection coefficient, is about 5%.

(4.2.3) Source Transmission Coefficient; T_s

Any electron born anywhere within the source volume has a **certain** finite probability to escape the source completely. This escape probability, T_s, depends upon the electron range in the source material and the location where it is generated. Therefore, the escape factor or the transmission coefficient of the source is purely a geometrical parameter. Source transmission coefficient is related to the source absorption coefficient simply by $T_s = 1 - A_s$. The source absorption coefficient can be best determined by a Monte Carlo type computer code such that all differential scattering cross sections are included in the calculation. However, since the source width is usually less than the

electron range in the source, one can assume that most electrons born within a very thin source will escape. In this model, we have used neither one of the above concept and have calculated the transmission coefficient of the source based upon the average value of the electron exponential attenuation coefficient over the source width;

$$T_s(W,\mu) = \frac{1-e^{-\mu W}}{\mu W} \tag{22}$$

Where W stands for the radiation source width and μ for the source attenuation constants. The agreement between the Monte Carlo results (such as TIGER Code) and this method for the selected thin source used in betacells is good (**Taherzadeh 1986**). The transmission coefficient depends upon the source attenuation constant, μ, which is not always well defined and most of the disagreement arises from this uncertainty.

The source escape factor has a single peak at the zero source width, which can not be considered as an ideal design parameter. Hence, there will be some absorption in the source regardless of the source width, W, and/or source attenuation constant, μ. The source transmission coefficient decreases as the source width increases, however, the source total output power increases with the source width (Equation 13). Thus, we have to obtain the optimum source width, W, by maximizing the function $WT_s(W,\mu)$. This function increase with W exponentially according to the following approximation: $WT_s(W,\mu) = (1.0 - e^{-\mu w})/\mu$. What we really need to maximize is the source width to yield the maximum power density (watts/cc) at a given wafer width. Figure 1 shows the effect of the power density variation with respect to the source width change. The function, f(L,W), which is related to the power density (watts/cc), is presented in the following relationship:

$$f(W,L) = WT_s(W,\mu)/(L + W) \tag{23}$$

Where W is for the source and L is for the wafer width, respectively. Equation 23 has a maximum with respect to W given by the following:

$$[1 + \mu(L + W_0)]e^{-\mu W_0} = 1 \tag{24}$$

Solving 24 for the cell width as function of W;

$$L = \frac{1}{\mu}[e^{\mu W_0} - \mu W_0 - 1] \tag{25}$$

Figure 2 presents the maximum source width, W_0, leading to the maximum power density at a given cell width (L). For example, a 10 micron wafer needs a radiation source width of about 8 microns to give the optimum power density. With regard to the source material attenuation constant, materials with higher attenuation constants clearly gives lower transmission coefficients; (μ of a nickel source is assumed 7300 cm^{-1} and μ of a promethium source is assumed 1300 cm^{-1} for a GaAs wafer, for this calculation).

In order to include the effect of the source thickness, we have selected a beta radiation source of 1 cm^2 area and a width of W. The equation which relates the source transmission coefficient to the source width and a finite diameter, D, is given here (proof in Appendix 1).

$$T_s(W,D,\mu) = \frac{1}{2DW}\int_0^W dx \int_{-D/2}^{D/2} dy \int_{-\theta_1}^{\theta_2} e^{-\mu_s(W-x)/\cos\theta}\cos\theta d\theta \tag{26}$$

Where θ_1 and θ_2 are the two limiting angles defined by lines drawn from any source point to the edge of the finite diameter (see Appendix 1) and D is the diameter of the source. Figure 3 is plotted to show the difference between these two models. For a promethium source the maximum difference (11%) occurs at 14 μm source width. For a nickel source, at the same source width, this difference is even smaller.

(4.2.4) Converter Absorption Coefficient; A_c

Clearly, according to our definition, betacell efficiency is increased with higher converter absorption coefficient ($A_c = 1 - T_c$). Again this parameter can be determined by a Monte Carlo code but the analytical evaluation can also be carried out to give a relatively accurate result. We will not discuss the full mathematical modeling of this problem here, (see **Hine** and **Brownell (1956)** on Radiation Dosimetry for detail).

The lower converter transmission coefficient, T_C, is obtained for lower converter material densities, ρ_c, and larger distances, X, away from the radiation source surface. However, both of these features, the increase of X and decrease of ρ_c, are harmful to the betacell performance. The higher converter density will decrease the output power/mass and higher distances from the source surface will decrease the output power per unit volume. We shall return to this problem latter in this report.

(4.2.5) Collection Efficiency; Q

The collection efficiency is introduced in the betacell concept because not all the electron pairs generated by the absorption of energy from the source electrons are collected. Thus, the collection efficiency is equal to the rate of electrons collected over the electrons generated within the converter volume. The collection efficiency depends upon the minority carrier diffusion length (L_E and L_H) ratio, cell dimension (L), cell absorption constant (μ_c), cell depletion length ($L_{j\alpha}$) and the surface recombination velocity (S). To increase the magnitude of the parameter Q, one must increase the resistivity of the converter cell so that the minority carrier depth is increased. A maximum of 70% collection efficiency has been reported for a silicon base betacell exposed to promethium beta emitters (**Olson L. C. 1973**). Since the minority diffusion length is a function of the converter impurity concentration, N_D, the collection efficiency can

be altered by increasing or decreasing N_D. According to *Olson L. C.*[6], the collection efficiency of a betacell is given by:

$$Q = Q_E + Q_H \tag{27}$$

Where the electron and hole quantum efficiencies are:

$$Q_E = \frac{\mu_c L_E}{1-(\mu_c L_E)^2}[(A_E/B_E)e^{-\mu_c L_\mu} + \mu_c L_E(e^{-\mu_c L}/B_E - 1)] \tag{28}$$

$$Q_H = \frac{\mu_c L_H}{1-(\mu_c L_H)^2}[(A_H/B_H)e^{-\mu_c L_\mu} + \mu_c L_H(e^{-\mu_c L_\mu} - 1/B_H)] \tag{29}$$

Where $A_{E,H} = Sinh(L/L_{E,H})$ and $B_{E,H} = Cosh(L/L_{E,H})$ and other parameters were defined previously. Here, we have assumed that surface velocities are much less than the diffusion length/diffusion constant ratio.

Figures 4 and 5 present the functional dependence of the combined electron and hole collection efficiencies in terms of the cell width (L). Clearly, what is important with regard to the overall betacell efficiency, is not only the collection efficiency but also the product of this efficiency with the converter absorption coefficient,(Q_P, Figure 4). From these figures we notice that the best betacell design can not give total collection efficiency better than 45% for promethium and not better than 65% for nickel sources on GaAs wafers. Additionally, for nickel sources the optimum converter absorption coefficient times the collection efficiency is obtained for right about one diffusion length of the GaAs cell. For promethium sources a similar situation does not hold and the optimum collection efficiency is obtained at about twice the diffusion length. This difference, of course, depends upon the average energy of these two radioisotopes. The effect of the impurity concentration (within the range of 10^{16} and 10^{18}) on the collection efficiency is not very significant (Figure 6).

The betacell efficiency given by Equation 15 is easily obtained if both the output and the input power densities of the cell are known. On the other hand, the accurate value of the output power, however, depends upon the parameters used to define betacell efficiency (Equation 16). If we would like to present betacell efficiency in terms of the maximum efficiency, then, the maximum efficiency must be clearly defined (Equation 17). As we have seen previously, this definition is not unique. In this analysis we have multiplied η_{max} by the ratio of $(V_{oc})_{max}/(V_{oc})$. The reason for this η_{max} increase is apparent from the definition used for $(J_{sc})_{max}$. In Equation 17, we used the term $(J_{sc})_{max}$ rather than J_{sc}, therefore, η_{max} had become somewhat inflated. To correct for this we have reduced the overall efficiency by the $(V_{oc})_{max}/V_{oc}$ ratio.

The results presented in Table 2 show the effect of this correction factor. For the radioisotopes and converter selected for this calculation, the overall efficiency, $\eta_{1/2}$ is about 2.3 percent for promethium and about 2.4 percent for nickel sources, respectively. Utilizing the above correction factor, these betacell efficiencies reduce to 2.02 and 2.06 percent accordingly. If the theoretical maximum efficiency was possible to achieve, the ratio of $(V_{oc})_{max}/V_{oc}$ would be equal to unity and the higher values of the overall efficiencies would be obtained.

Neglecting the effect of the cell impurity (selected range of N_D is between 10^{16} to 2×10^{17}), the calculated results for certain betacell parameters are presented in Table 3. In this calculation, we have used a specified value for the source width ($2\mu m$) and a specified value for the cell width($8.75\mu m$) and have tried to analyze the betacell efficiency only.

(5.0) Degradation Of Betavoltaic Systems

Radiation damage effects in semiconductors due to the low energy beta particle radiation fields are discussed in this section. The criterion for the selection of beta emitting sources was based

upon their production probabilities and low energy spectra. Presently, we have focused on two beta emitters; Ni^{63} and Pm^{147} sources. With regard to the converter systems, we have limited ourselves to three components; silicon, fused silica and gallium arsenide. Additionally, we have assumed that these converters are n-type semiconductors and are of either PN or Schottky-type junctions (various Schottky junction betavoltaic parameters regarding electrical power generation are the subject of a future report). The results of this study show that under the aforementioned electron radiation environments, the percent increase of the reverse carrier current due to the displacement damage coefficient is very small (under 0.1 %) and ought to be dropped from the overall degradation consideration. The degradation of the betavoltaic systems due to the ionization scattering is also small for the low energy beta emitters. However, **exposure time** plays an important role in both cases. The majpr degradation of the betacells at low beta energies is due to the source degradation itself (finite lifetime) which is very damaging for the higher power density emitters. For example, for the Ni^{63} source and gallium arsenide converter after 10 years of exposure the power degradation due to the radiation (at $300^{o}K$) is about .13 % while the source degradation is about 9.5 %. For the Pm^{147} source, the betacell degradation after 2 years is about 15 %, while source degradation is about 53.7 %.

One of the the major questions regarding the design of a betacell should be concentrated on the degradation of this system due to the various radiation fields and source decay. It is generally known that radiation of any kind can bring about a change in the system only by virtue of the energy actually absorbed. The energy absorption in a medium can be calculated in terms of the energy **absorbed per gram** of the absorbing material (called dose and is given in rads). Then, this absorbed energy per gram can be used to relate cell degradation to the emitted energy spectrum which is the subject of this section. We first define various terms contributing

to the overall betavoltaic degradation and, then, calculate the magnitude of these terms for the n-type bipolar junctions based upon silicon, fused silica and gallium arsenide materials under the Ni^{63} and Pm^{147} radiation fields. We also assume that gold material of a very thin width (about 200 A) is used for Schottky junction formation.

(5.1) Radiation Damage Calculation

Radiation damage in semiconductors by electron beams becomes important only when the emitted beta energies are high (in Mev range) and when the radiation fluences are high (after many years of exposure). Since high power density sources decay very fast, radiation damage will take a back seat with respect to the source decay. For the low energy beta sources the power density is low and source degradation is low. Therefore, one can use betavoltaic systems coupled to the low energy beta sources with much longer lifetime. However, if the exposure time is too long, the time integrated flux becomes larger and higher possibility for the cell degradation would present itself.

As it is well known, the fundamental force which describes the interaction between the incoming electrons and the target nuclei is the Coulomb force. There are several ways in which electrons can lose energy when they make collisions with the target nuclei. These energy losses include energy loss due to **elastic scattering, ionization scattering, pair production, bremsstrahlung, electron electron scattering** etc. In the case of low energy electron sources, which are used for the betavoltaic systems to cut down radiation degradations, the processes that can occur the most are elastic scatterings and ionization collisions while bremsstrahlung radiation which is induced within the cell, exits the system. The gamma radiation so generated would demand additional unwanted shielding on the system and/or some degradation in the large assembly of the single betacells. For

low energy beta radiation fields, the ionization collision process generates much more degradation than the elastic scatterings. That is why when the *Monte Carlo* technique is used to calculate a dose depth profile at low beta energy, the elastic scattering is used not for the damage estimation but also for the angular distribution function calculation. The fundamental source of degradation, outside the source decay, then, is basically due to the ionization process.

The **bremsstrahlung** or the induced emission radiation clearly causes radiation damage and this degradation is stronger for Pm than Ni sources. The algorithms for generation and attenuation of this radiation field are not given here but they are included in BCELL. The dose damage due to bremsstrahlung radiation (given in mrem/hr) is also included in the BCELL code (see Appendix 2).

(5.2) Displacement Degradation

The magnitude of the degradation due to the elastic scattering is usually calculated in terms of the displacement damage. When electrons pass through an absorbing medium, they lose energy due to the nuclear scattering in a continuous-slow-down model. The amount of energy transferred to an atom via this type of scattering mechanism is given by;

$$\Delta T_E = 2(T_E + 2m_0c^2)(T_E/m_0c^2)(m_0/M) \qquad (30)$$

Where M is the mass of the target atomic nuclei and T_E is the threshold electron energy obtained from the beta emitter energy spectrum. At the value of damage threshold energy for silicon (145 Kev), this energy transfer is about 12.9 ev. The energy transferred to the atomic nuclei by this process may or may not be enough to displace the target nuclei. The displacement of the target atoms is generally considered as a secondary effect. The main effect from this process is that the transferred energy creates defects in the

semiconductor. These defects act as carrier trap centers which are introduced in the energy bandgap. If the semiconductor is used as a detector, these defects can reduce charge collection efficiency (pulse height), damage energy resolution and carrier's mobility and material resistivity. If the electron beam energy and/or fluence is large, then, the bound nuclei may be ejected from the lattice of the semiconductor. These ejected highly charged and heavy mass projectiles can create additional radiation damage in the cells and are capable of altering the cell's resistivity and **pulse height defect**, PHD, (for more detail see **Taherzadeh** 1973). The radiation damage due to the Compton scattering effect is expected to have some relationship with the number of defects produced per incoming particle. In a single collision of this type the average number of defects/electron so created is given by:

$$\bar{\nu}(E_d) = \bar{T}/2E_d \tag{31}$$

Where E_d is the average displacement energy/defect. E_d is usually taken as 3 to 5 times the lattice binding energy of the cell ($E_d \approx 25$ ev for silicon). The $\bar{T}$, here, is the average electron energy within the energy transferred spectrum and it is <u>not</u> the beta source average energy. $\bar{T}$ is given by;

$$\bar{T} = (1/\sigma_0) \int_{2E_d}^{T_{max}} T f(T)(d\sigma/dT)dT \tag{32}$$

Where f(T) is the fraction of the electron energy lost due to the nuclear scattering, $d\sigma/dT$ is the differential Rutherford scattering cross section and σ_0 is the total cross section. At T_{max} = 200 Kev, $\bar{T} \approx 225$ ev and $\bar{\nu}$ = 4 defects/ electron if all the energy transferred is due to the elastic scattering process. However, this is not the case and most of the energy transfer is due to ionization scatterings. If we take the electron - electron scattering process to be negligible and use silicon for the converter (with average excitation energy of 159 ev), the fraction of energy transferred due to the elastic

scattering is less than 12% and the average of defects/electron so created will be reduced to less than 0.5 defects/electron which is too small to generate any displacement degradation. Therefore, displacement damage is predicted to be small and must be considered as a background effect at these low electron energies (225.7 Kev for maximum beta energy of the Pm^{147} source , 65.7 Kev for the maximum beta energy of Ni^{63} source).

The degradation of the betavoltaic systems due to this source is generally shown by the percent of the reverse current increase. To estimate the magnitude of this damage parameter, we have used the following relationship (**Carter 1973**);

$$\Delta J_L(Te,T,t) = q n_i(T) X_c(Te,A) K_\tau(Te) \phi(Te,t)/2.0 \qquad (33)$$

T is the temperature, Te is the electron energy, t is the exposure time and A is the atomic mass number of the target nuclei. n_i is the intrinsic concentration of the cell, X is the cell's depth, K_τ is the minority carrier lifetime radiation damage coefficient per unit fluence and ϕ is the time integrated electron flux.

To estimate the magnitude of the reverse current increase, we have used the energy spectra and the radiation flux of the beta emitters mentioned previously and gallium arsenide (GaAs) semiconductor as the absorbing medium. The physical characteristics of this cell under the assumed conditions are given in Table 4. The corresponding electron maximum range for various cell hypotheses used here are given in Table 5. The range energy relationship can best be determined by a Monte Carlo type calculation in which all reactions and angular deflections are taken into account. However, for energy ranges of interest here, we may select an easy way out. The range of electrons in a medium has been calculated in many ways, one of which is presented (**Barkas** and **Berger (1964)**) in Table 6 and Figure 7. We have used the data given in Table 6 and have obtained the best fit to the data, the result is given here;

$$R(gm/cm^2) = \sqrt{(T/a)^2 + b^2} - b \qquad (34)$$

Where T is the electron energy in Mev and a and b are:

$$a(Mev/gm/cm^2) = 1.65$$

$$b(gm/cm^2) = 6.45\ x\ 10^{-2}$$

BCELL computer code uses the result of this range energy approximation for the two selected beta emitters and semiconductors utilized. Table 7 presents silicon semiconductor parameters.

The dark (or reverse) current increase is calculated by the carrier lifetime displacement damage parameter, the source fluence and the semiconductor intrinsic concentration (Equation 33). Since we have used the Schottky-type junctions, for example, the reverse current is a function of two parameters, namely the temperature and the semiconductor barrier height potential. The maximum minority current increase for the Pm^{147} beta source in gallium arsenide after 1 year of exposure is less than 0.1 % which is much smaller than the source decay degradation (after 1 year 31.9 %). For the Ni^{63} source this effect is orders of magnitude smaller.

(5.3) Ionization Collision Degradation

The highest percentage of the electron energy transfer at low energies is due to the ionization collisions which may contribute to the betavoltaic damage coefficient. Additionally, since not all beta emitters are pure sources of electron radiation, one should expect other sources of radiation such as gamma and alpha radiation fields to exist. These unwanted sources of degradation of betavoltaic systems can be generated either from the source impurities and/or from the decay products. Induced radiation, of course, is always present. Therefore, to estimate the overall damage, we should combine the effects of all sources of radiation. Neglecting the radiation from impurities, the unwanted radiations of the specified radioisotope becomes important. For a pure Pm^{147} source, we should

receive gamma rays of 0.121 and .103 Mev energies at a rate of .008 % of the time according to the disintegration scheme of this source. A pure Ni^{63} source does not emit any other radiation except the beta radiation. For this initial study, we have assumed that the two selected radiation sources are pure beta emitters. However, the bremsstrahlung radiation is allowed to generate within the cell itself.

When a beta particle with a kinetic energy Te penetrates through a depth in an absorbing medium (ΔS) it will lose or transfer a small amount of energy to the atomic nuclei by an ionization process (ΔT). Hence, on the average the stopping power of the medium is defined by;

$$S/\rho = <\Delta T/\Delta S> \tag{35}$$

The stopping power is calculated by **Attix** (1968) and is given by the following general formula;

$$\frac{S}{\rho} = \frac{0.1535}{\beta^2}\frac{Z}{A}\, x\, \ln\left\{\frac{2(\tau+2)}{(I/mc^2)^2}\right\} + F(\tau,\Delta) - \delta$$

$$x\left[1 + \tau(mc^2)\,\frac{Z}{700}\right] \tag{36}$$

Where I is the geometric-mean ionization and excitation potential of an atom and β is the normalized electron velocity and:

$$F(\tau) = 1-\beta^2 + ln[(\tau-\Delta)\Delta] + [\tau/(\tau-\Delta)]$$

$$+\frac{\beta^2/2 + (2\tau+1)ln(1-\Delta/\tau)}{(1+\tau)^2} \tag{37}$$

$\tau = \gamma-1$, $\gamma = (1-\beta^2)^{-1/2}$, $\Delta = \tau/2$ and finally δ is the energy loss due to the density effect (**Berger** and **Seltzer 1964**).

The term $[1 + \tau(mc^2)Z/700]$ presents the energy loss due to the bremsstrahlung radiation. From the above formalism we notice that:

(a) The bremsstrahlung radiation becomes important at high electron energy and for high Z materials.

(b) Other than the beta energy, the most important parameters contributing to the stopping power of the absorbing medium are the mean excitation energy of the individual atoms (I) and the average value of Z/A (see Table 4).

(c) The constant in the above equation is obtained from

$$20\pi mc^2 r_0^2 N_0 \approx 0.1535$$

(d) S/ρ is the energy stopping power at an energy Te and is given in Mev/gm.

The evaluation of the induced radiation term indicates that the calculated dose-depth profile should increase at the surface of the absorbing media and should decrease at any other depth within the media. The reason for this behavior is that, for the small thicknesses, the cell's induced radiation attenuates very little. To check this contribution, the bremsstrahlung term was calculated to be less than .1 % for the highest Z material and the highest electron source energy selected for this study. Also, the above stopping power was calculated with and without the bremsstrahlung term to see its percent contribution to the overall dose depth profile. The computer code utilized for this purpose is named PRELD and is used routinely by the TRW radiation hardening community. For the Ni^{63} radiation source, the surface dose increased by only 0.03 percent and at 1 mil of GaAs cell the dose decreased about 0.12 percent. Therefore, with regard to the dose-depth profile in a single cell, the contribution of the bremsstrahlung radiation to the betacell degradation is very small and can be neglected. However, there are two major areas in which this type of induced radiation may becomes important:

(a) When we stack-up the betacells in order to increase power density.

(b) When the gamma radiation from the entire cell assembly becomes significant enough to require extra protection shielding for the

energy producing device.

For the above reasons, it is necessary to obtain the amount of induced radiation exiting from the entire source geometry.

(5.4) Dose And One Mev Damage Equivalent Electron Fluence

From the above stopping power (S/ρ), we are able to calculate two important radiation damage parameters which will be discussed here:

(a) Dose-depth profile

The amount of energy absorbed/gram of material of the absorbing medium as a function of the penetration depth is the dose-depth profile presented by **Faelton** and **Gordon** (1974).

$$D_p(x) = \sum_{i=1}^{n} C(S/\rho)_i F(X,T_i) \qquad (38)$$

The constant C stands for the conversion parameter given in Rads/(Mev-gm), $D_p(x)$ is the point dose calculated at a point located at x of the absorbing material and (S/ρ) is the charged particle stopping power (one unit of rad, 100 Erg/gm, is equivalent to 6.25×10^7 Mev/gm). The integer n stands for the number of energy intervals selected from the differential fluence, F(Te). There are many computer codes which have been written to calculate dose-depth profile for various purposes. TIGER code calculates this profile for a multilayer absorber by using the Mont Carlo technique, SHIELDODE code uses the same calculation for certain media to obtain the dose-depth profile. An approximate method for a single layer absorber can also be used for dose-depth calculation. Such a code is developed by the TRW radiation effect group. The PRELD code, as it was mentioned above, was used here to obtain approximate doses for the three absorbing media mentioned above. For a multilayer system, an equivalent thickness was used for each layer with respect to the cell by using a material density factor. Additionally, the point dose was converted to average dose per interval of the layer by the following relationship:

$$\bar{D}(\Delta X_i) = \frac{D_p(X_{i-1}) - D_p(X_i)}{\ln[D_p(X_{i-1})/D_p(X_i)]} \qquad (39)$$

Where $\Delta X_i = X_i - X_{i-1}$.

Figure 8 shows the differential fluence, F(Te), for the Ni^{63} and Pm^{147} beta sources after one year of exposure. Figure 9 shows the dose depth profiles of the cell materials selected for this analysis, namely silicon, fused silica and GaAs cells and the nickel source. The results of a similar calculation for the Promethium 147 source are presented in Figure 10. Assuming that the source thickness is a part of the system itself, we may approximate the effect of the source thickness on the cell degradation. This estimation, however, is very crude and a multilayer code which includes the boundary problem and angular scattering must be used for detailed calculation. Figure 11 presents the amount of dose increase as exposure time increases. From these data, we notice that the dose received by the absorbing media is much smaller for a nickel source than a promethium source. For example, at 10 micron depth of gallium arsenide converter, the received dose is about 75 times larger for the promethium source.

(b) The damage equivalent 1 Mev electron fluence.

The electron (or any other charged particle) energy spectrum entering a medium can be used to determine the radiation damage equivalent to 1 Mev electron fluence (**Carter** 1973). This 1 Mev equivalent fluence is given by (**Faelton** 1974):

$$F(1\ Mev\ e^-) = (1/2)\sum_{i=2}^{n}[F_l(X_.>T_i) - F_l(X_.>T_{i-1})][D(T_i) + D(T_{i-1})] \qquad (40)$$

Where F(>T) presents the integral fluence and F(1 Mev) is the electron 1 Mev fluence giving the same damage. A subroutine is now incorporated in the *BCELL** code which uses the above relationship and calculates the 1 Mev electron fluence. Additionally, this electron

* Betavoltaic system modeling computer code

fluence is used to calculate the betavoltaic degradation under various beta emitting sources and cell temperatures.

Carter (1973) indicated that experience has shown that the degradation of the converter cell electrical properties can be expressed in the following general form:

$$F = A + B\ln L \tag{41}$$

Where F is either J_{sc} or V_{oc}, of the betacell, A gives the value of F at no radiation field, L is the absorbing medium diffusion length affected by the radiation fluence and B is a constant to be determined experimentally. BCELL code uses $B(J_{sc}) = 4.5\ mamp/cm^2$ and $B(V_{oc}) = 12.9$ mVolts. The diffusion length at zero fluence is determined by:

$$L_D = \sqrt{D\tau_c} \tag{42}$$

D is the diffusion constant of the cell and τ_c is the diffusion time. When electron radiation is allowed to strike the converter cell, these parameters will be altered. According to Carter the new diffusion length is:

$$L = \frac{L_D}{(1 + L_D K_L \phi)^{1/2}} \tag{43}$$

K_L is the diffusion length damage coefficient/unit fluence. The diffusion time under radiation also is changed:

$$\tau = \frac{\tau_0}{(1 + \tau_0 K_\tau \phi)} \tag{44}$$

K_τ is the diffusion time damage coefficient/unit electron fluence.

The betacell new parameters under radiation may be given by:

$$J_{sc}(\phi) = J_{sc}(\phi=0) - B_{sc}\ln(1 + \phi/\phi_c) \tag{45}$$

$$V_{oc}(\phi) = V_{oc}(\phi=0) - B_{oc}\ln(1 + \phi/\phi_c) \tag{46}$$

$$P_{max}(\phi=0) = FF.J_{sc}(\phi=0)V_{oc}(\phi=0) \tag{47}$$

$$P_{max}(\phi) = FF.J_{sc}(\phi)V_{oc}(\phi) \tag{48}$$

FF is the fill factor of the betacell I-V curve and ϕ_c is the critical electron fluence at which J_{sc} starts to change under the specified radiation field.

The damage equivalent 1 Mev electron fluence/year of the exposure time is equal to 9.2×10^{13} for the promethium and 2.2×10^{10} for the nickel sources. Figure 12 illustrates the comparison between the betacell output power loss for the nickel source and gallium arsenide converter system at various betacell exposure times (from 1 to 10 years).

(5.5) Degradation Overall Discussion

From the results of the above calculations presented in this report, we notice that the displacement degradation (which was evaluated in terms of dark current increase) is very small for the selected sources and converters. With regard to the ionization degradation, the nickel source coupled to the GaAs converter after 10 years of exposure shows less than 1 part in a 1000 degradation of output power. At the same time the source decay during this period is nearly 10 percent. Therefore, the radiation degradation for the nickel source in comparison with the source decay is negligible. This conclusion basically depends upon the values of two parameters (ϕ_c and B_{sc}) which have to be determined experimentally for any betacell design effort.

For a promethium source the situation is slightly different. At room temperature, after 2 years of exposure, the output power decreases nearly 7 percent while the source decay for the same period is about 54 percent. This means that source degradation is almost 8 times higher. As exposure time increases this ratio also increases. Therefore, for a 1 to 2 years radiation, we should expect on the average a 5 percent decrease in output power density of the GaAs cell due to the radiation. The same conclusion regarding the experimental values of ϕ_c and B_{sc} applies here also.

Furthermore, we conclude that a GaAs semiconductor has some advantages over a silicon converter: (1) GaAs reverse current is lower

because its barrier potential height is larger. Lower reverse current would result in the higher output power density. (2) The displacement damage is smaller for the GaAs semiconductor because its energy bandgap is larger. (3) The percent power decrease due the years of radiation will be less because the absorbed dose in GaAs is lower. However, the bremsstrahlung radiation output from GaAs material is higher because of the higher value of the average Z.

(6.0) Betacell Design Analysis

We have used the fundamental parameters related to the metal-semiconductor and PN -type junctions to compare the advantages and disadvantages of these devices utilized as betacell power sources based upon the betavoltaic concept. From the theoretical standpoint, the most important controlling parameter is the magnitude of the reverse current which depends upon the way these junctions are manufactured. Generally speaking, Schottky devices are easier to make and have lower cost values. Additionally, there are more choices of materials for the Schottky betacells than for the PN junctions and consequently less radiation damage is certainly possible. However, Schottky junctions have lower lifetimes and power outputs than the PN junctions. The final answer, thus, depends upon the way these betacells are actually manufactured and on the way they perform in certain specified environments. Finally, we have compared our results with a similar calculation performed by the SNL. The agreement between the data reported by the SNL and our calculations is very good.

(6.1) Comparison Between Schottky And PN Junctions

To produce efficient power sources based upon the concept of coupling beta emitters to rectifying junctions, one has to make a choice among the available materials and the type of the semiconductor contacts. These choices clearly depend upon the power

output, efficiency and lifetime requirements. The limitations on the beta emitters has been discussed previously (**Taherzadeh 1986**). This means that unless a better source is found to satisfy all requirements we should limit ourselves to only two beta-emitting sources, namely; Ni^{63} and Pm^{147}. With regard to the choice of materials, clearly we should look upon those materials with the highest bandgap energies and barrier height potentials. In addition, the selected materials should have the highest damage energy thresholds to beta emitters, be easily manufacturable, and be reproduced in mass quantities at lowest cost. With regard to the type of the junction to be selected, the choice is not simple. One can choose either PN-type junctions or a metal-semiconductor contact devices. Both of these betacells have advantages and disadvantages depending upon the specified requirements of the output power, efficiency and/or betacell lifetime (see comment). Schottky cells are generally used as detectors and PN junctions are used as solar cell power conversion devices. Due to the low conversion efficiencies of these devices, many suggestions are made by the power conversion industry to either enhance their efficiencies and/or their power densities. In this report, we have used a model (generated for the output power, efficiency and radiation damage calculations of betacells) and have compared the two types of betacells. In this calculation we have assumed that these cells are identical in all aspects and that they are different only in their reverse current densities.

The power Equation for both Schottky and PN junction devices is given by:

$$P(watts/cm^2) = FF\ J_{sc}\ V_{oc} \tag{49}$$

(C) We are not concerning ourselves here with the complicated impurity controlled or graded composition of heterojunction semiconductor and so on.

Where FF is the fill factor, J_{sc} is the short circuit current density and V_{oc} is the open circuit voltage. The short circuit current density and the open circuit voltage, when certain secondary effects are ignored, are basically related by the following equation:

$$J_{sc} = J_o \, e^{\beta V_{oc}/A} \tag{50}$$

Where $\beta = q/kT$, A is the circuit perfection parameter and J_o is the reverse current density.

Therefore, the only parameters which can distinguish between these devices are the parameter A and the reverse current density J_o (or the minority carrier current density). For the Schottky cells the perfection parameter A is about 1.0 to 1.1, while for the PN junction type devices it is somewhat higher (i.e. close to 2.). The minority carrier current density for the metal-semiconductor devices is given by:

$$J_o = A(T)^* \, T^2 \, e^{-\beta\phi_o} \tag{51}$$

$A(T)^*$ is the Richardson constant depending upon the temperature and ϕ_o is the barrier potential height of the metal- semiconductor junction. On the other hand, for the n-type PN junctions, the minority current density is:

$$J_o = \frac{e \, L_p \, P_n}{\tau_p} \tag{52}$$

L_p is the minority carrier diffusion length, τ_p is the minority carrier lifetime and P_n is the minority carrier concentration in an n-type PN junction.

For the Schottky junctions, the minority current is easily calculated if the barrier potential height of the junction and the effective masses of the holes and electrons in the active region are known.

For the PN junctions, however, L_p and τ_p must be given accurately. This means that these two parameters must be experimentally measured so that one can model the output power of the junction. This requirement, of course, does not mean that the reverse currents of the metal-semiconductor junctions are exactly determined by Equation 51. What we are saying here is that under similar situations the minority carrier lifetime, diffusion length and/or diffusion constant of the PN junctions can not be easily modeled. The reason for the need of experimental values for these parameters is that they depend upon the way the PN junctions are manufactured. L_p and τ_p depend upon the impurity concentration, junction temperature and donor/acceptor energy levels in comparison with the Fermi energy level.

(6.2) n-type PN-Junction

Utilizing an n-type gallium arsenide PN junction as a converter and assuming $\tau_p = 10^9/N_D$ with $N_d = 2 \times 10^{17}$, T= 300 Kelvin and the minority carrier mobility of 400 $cm^2/volts/sec$, we can estimate a value of 1×10^{-11} amp/cm^2 for the junction current density (Equation 52). As we shall see later, for a similar situation, SNL calculation indicate a value of 3.91×10^{-11} for the reverse current which, of course, may be for a different impurity density (N_D), a different minority carrier mobility and perhaps a different temperature. Using a similar situation for a Schottky junction, the reverse current (Equation 51) yields a much higher value (5.09×10^{-9}). Higher values of the reverse current density mean lower values for the open circuit voltage and consequently lower output powers/unit area (provided all other parameters are kept constant).

On the other hand, from 50 we obtain the following:

$$V_{oc} = \frac{A}{\beta} \ln[J_{sc}/J_o] \qquad (53)$$

Since the parameter A of the Schottky junctions have lower values than the PN junctions, one should expect to get lower values of V_{oc} for the Schottky cells when both systems are assumed to have the same reverse current densities.

Table 8 presents the input parameters used for this analysis. Here we have selected the same parameters used by the SNL group (**Lincoln 1986**). The semiconductor and the promethium source thicknesses are assumed to be equal to 5 and 2 microns, respectively. The densities are also selected from the same document for easier comparison. Other parameters in Table 8 are the estimated values. We should also notice that the converter is being irradiated from both sides while only one source thickness is used in the calculation. Table 9 illustrates the results of our computer code and the corresponding data reported by the SNL. The two sets of data given in the SNL column are related to the two values selected for the specific power inputs of the Pm^{147} source. If we select the reported .33 watts/gm of the SNL report, we obtain 12.8 $\mu watts/cm^2$ which is slightly lower than the 15.3 $\mu watts/cm^2$ reported. The difference between our results and the SNL data is in the values of the absorption coefficients. SNL used the TIGER-P computer code to obtain these coefficients and we have used the analytical results which are slightly different, namely; (see Table 9)

$$15.3 = (3.6/3.78)(0.6/0.75)(20.)$$

Our fill factor is also higher but, as was discussed above, the IV-curve of our device is not experimentally determined, hence it is an approximation. We should also emphasize here that a value of A= 2 was selected for our PN junction which could be slightly different from the actual value used by the SNL report. Additionally, we had to use the minority carrier current density (estimated from the SNL report) in our model so that the effect of the impurity concentration is eliminated from the discussion.

(6.3) Perfection Parameter A

The effect of the parameter A on the output power/unit area is shown in Figure 13. We may notice here that when J_o and T are kept constant, the higher value of A leads to higher output power. Since the Schottky devices have lower values of A and the nickel beta emitters have lower output powers, it seems that at the high output powers PN junctions are preferable and at the lower output powers the difference between the two betacells becomes insignificant. Having compared the two sets of data for the PN type betacells, we now can compare the metal-semiconductor devices with the PN junctions. Table 10 illustrates the results of one such calculation. Here we have presented two sets of data for the selected Schottky junction and one set of data for the PN junction reported previously in Table 9. The difference between the first and the second columns of Table 10 is in the values of the minority carrier current densities. In the first column we have used the previous value of the PN junction reverse current density and in the next column we have used the computer code calculated value of the reverse current density (Equation 51). We may notice that although the values of the J_{sc} parameters are the same for all three cases, the values of the V_{oc} are quite different and these differences are directly related to the parameter A.

Although the results presented in Table 10 are a proof that PN junction devices gives higher power/unit area, one can not ignore the fact that these results are based upon certain assumptions which may not be achievable experimentally. Other factors also play important parts in the design of an efficient long lived betacell. The curvature of the IV curve in the case of the Schottky junctions should make the conversion efficiencies of these power source comparable or even better than the PN junctions. At lower output power situations, the IV curves of the metal-semiconductor junctions are sharper or can be made sharper by better manufacturing. For the PN devices, the IV curves are primarily determined by the

doping levels. Since metals can be deposited on the semiconductors at much lower temperatures (**Yu 1970**) and with much less surface damage than can another layer of semiconductor, the PN junctions generally have shorter recombination lengths resulting in lower conversion efficiencies. Hence, the way these betacells are made and the way they can perform in specified environments are very important in determining the true advantages of one system over another depending upon the actual requirements of the betacell design. For nickel sources, the Schottky cells may give better efficiencies and because of their lower costs they may be preferable over PN junctions. This point, however, must be proven experimentally.

(7.0) Problems Regarding Betacell Design

Due to the low power density output of betavoltaic cells (10μ watts for P_m^{147}), the research efforts on this type of batteries were practically abandoned 10 years ago. The major problem is generally based upon the fact that the output power density of a beta-emitter isotope is inversely proportional to its half-life. This means, the higher power density is always accompanied by lower half-life and vice versa. For example, P_m^{147} has a relatively high power density (about 0.3 watts/gram) but a short half-life (about 2.6 years) and N_i^{63} has a long half-life (100 years) with low power density (about 0.006 watts/gram).

(7.1) Observations

(1) With the availability of the isotope separation process (PSP), we are now able to produce relatively pure beta emitter isotopes and in the process eliminate the unwanted radiation sources. By performing this enrichment process, we are decreasing the radiation damage on the converter, decreasing the battery volume for the same

power output (increasing power per unit volume) and increasing efficiency of the cell. We are now separating Ni^{62} from Ni and eventually make Ni^{63} for a low power but a long half-life betavoltaic cell source. Similarly, we are able to separate P_m^{147} for a high power but low half-life betavoltaic battery.

(2) Schottky, PN and PIN- type converters have been studied extensively for solar cell efficiency increase. Optimizations are achieved in increasing the energy bandgap of various semiconductors leading to higher efficiencies. Theoretically and experimentally, some researchers have been able to show that Schottky junctions can be developed with better power output and higher efficiencies for beta emitters (**Manasse and Tse 1976**).

(7.2) Basic Concept and Problems

The major questions regarding the design of a betacell are concentrated on the following topics:

(1) Beta Source Design:

(a) Power density requirements.

(b) Half-life requirements.

(c) Types of unwanted radiation that can be tolerated.

(d) Optimum source thickness.

(e) Isotope separation .

(f) Isotope handling procedures.

(g) Radiation dose tolerance requirements.

(h) Isotope 's by-products.

(i) What form of the beta-emitter is most suitable ? (metal or oxide)

(2) Converter Design:

(a) PN, PIN or Schottky junctions.

(b) Optimum dimensions.

(c) Radiation damage.

(d) Conversion efficiency requirement.

(e) Optimum power output (watts/cc).

(f) Availability.

(g) Costs of material research against market availability.

(h) How important is the Bremsstrahlung production, if any?

(7.3) Overall System Design

Clearly, due to the small size of a single betavoltaic device (for example a Schottky- type cell has been designed and tested with a total source+ Au+ converter volume of only .04 cc at 14μ watts or .35 m watts/cc), and the 100 m watts power requirements, one would assemble a number of these cells in a certain fashion, with concern for:

(a) Battery assembly.

(b) Reliability.

(c) Safety.

(d) General power source characterizations.

(e) Overall cost and cost/watt.

(7.4) Modeling requirements

To develop a betacell model by using the available and future data obtained from additional material tests and experiments, the following questions should be addressed:

(a) What is the maximum output power required ?

(b) What efficiencies are acceptable ?

(c) What are the source size limitations ?

(d) In what environment (temperature) is the beta power source being implemented ?

(e) How important is the power source cost?

(7.5) Converter Selection Criteria

For the best betavoltaic system performance, we may either use PN, PIN or ohmic junctions.. It may be shown (**Manasse** and **Tse** 1976) that under certain conditions imposed on betavoltaic systems, Schottky junctions are better performers than the PN junctions for the following reasons:

(1) Wider choice of materials.

(2) IV-curve has a better chance to be represented by a pure $e^{eV/kT}$ law.

(3) Converters can have longer recombination length.

(4) Converters can have less radiation damage problems.

(5) Lower costs

(6) Lower reversed carrier current under certain conditions, leading to higher power output.

These observations (or speculations) could easily be overshadowed by higher output power of specially designed PN-junction devices. Therefore, theoretical and experimental material tests should be performed for the best metallic and PN junctions suitable for optimum betavoltaic performance.

(a) Material Selection Criteria

(1) Materials with the highest possible barrier height potentials or band gaps (x + n type y : x metal, y semiconductor) junctions.

(2) Material availability

(3) Handling and processing.

(4) Manufacturing.

(5) Radiation damage energy threshold.

(6) Optimum dimensions.

(7) Costs.

(b) Some proposed ohmic junctions to be looked at are:

Au + n type Si (ϕ_b = 0.78)

Pt + n type Si (ϕ_b = .85)

Au + n type GaAs (ϕ_b = .90)

Au + n type ZnS (ϕ_b = 2.0)

Pt + n type ZnS (ϕ_b = 1.84)

Pt + n type ZnO (ϕ_b = 0.75)

Au + n type CdS (ϕ_b = .78)

Pt + n type CdS (ϕ_b = 1.10)

Au + n type GaP (ϕ_b = 1.30)

etc.

(7.6) Betacell Modeling

We have written a computer program, named BCELL, to simulate betavoltaic power generating systems. In this code options are included to utilize the betacell optimum parameters in accordance with the output power density, efficiency and battery size requirements. In Figure 14, one such procedure is shown. The important factor here is to know that whether with the application of the **plasma separation process**, the newly developed semiconductor devices are suitable for power battery development.

(7.7) Modeling Program

The following procedures are established for the betavoltaic modeling program.

(1) Betavoltaic basic physical concepts (metallic and semiconductor junctions).

(2) Fundamental equations governing junction power output

(a) Semiconductor devices.

(b) metallic devices.

(3) Computer code development

(a) Te_z^{ave} Te, momentum distribution functions, watts/curie, watts/grams, (μ/ρ) and optimum geometry of the source isotope.

(b) μ/ρ, Q, $Q[1.0-exp(-\mu x)]$, L_d, V_d and optimum geometry of the converter.

(c) J_β, $Flux_\beta$, J_0, m of the source coupled to the converter.

(d) $V_{max} = V_{oc}$, J_{sc}, $V_{m,p}$, $J_{m,p}$, P_{max}, η and IV-curve of the betacell.

(4) Comparing the results against the available experimental and theoretical data.

(5) Incorporating the most up-to-date technology of the Schottky/PN converter cells in the model for parametrization of the output powers and efficiencies.

(8.0) BCELL Computer Code

In this report, the betacell computer code description is summarized. This program was initiated and upgraded to model the betavoltaic systems by utilization of the data and ideas available in the literature. The most important segments of the BCELL are given here:

(8.1) BETACELL CAPABILITIES:

(a) Beta emitting sources (Ni^{63} and Pm^{147}).

(b) Converters (Si, GaAs, $Al_xGa_{1-x}As$, GaP).

(c) Junction types (PN, Schottky).

(d) Converter types (n-Type, p-Type).

(e) Substrate (fused silica, or anything else).

(f) Free parameters (temperature, source life-time, converter width, source assay, source radiation face factor, perfection factor).

(8.2) GENERAL OUTPUT PARAMETERS:

(a) Source beta energy and momentum spectra.

(b) Source beta energy spectrum attenuated within the converter.

(c) Source/converter single and multiple reflection coefficients.

(d) Source width leading to the optimum betacell power density.

(e) Most important solid state parameters relating to the selected source/converter system: source beta flux and current density; generation/recombination current densities; (electron, hole) conductivities, diffusion lengths, diffusion constants, mobilities, collision and diffusion lifetimes, etc.

(f) Total collection or quantum efficiency and multiplication factor.

(g) Source/converter transmission coefficients.

(h) Majority/minority and intrinsic concentrations.

(see Appendix 2)

(8.3) BETACELL POWER OUTPUT:

(a) Short circuit current density (J_{sc}), open circuit voltage V_{oc}, and loss/load current densities (J_{ls},J_{ld}).

(b) Current density distribution along the converter width and cell substrate.

(c) Electron dose distribution function.

(d) Power density output of the cell.

(e) Overall efficiency of the cell.

(8.4) RADIATION DAMAGE AND BETACELL DEGRADATION

(a) Source power degradation.

(b) Ionization radiation damage.

(c) Non-ionization radiation damage.

(d) Induced radiation damage.

(8.5) FUNCTIONS PLOTTED

(a) J(Loss) and J(Load) versus junction potential.

(b) JV-curve and power distribution function.

(c) Log [power] against potential.

(d) Log [power] against perfection parameter.

(e) Log [Jz] against perfection parameter.

(f) dN_e/dE against E_β.

(g) $dN_\eta/d\eta$ against η_β; η is the particle momentum.

(h) Source width against cell width leading to maximum power density ($watts/cm^3$).

(8.6) GENERAL REMARKS:

(a) Nearly all input parameters, utilized in the code, were selected from the data available in the literature.

(b) Certain parameters can be easily altered if more reliable and/or experimental data are obtained.

(c) To simulate an experiment, the related parameters can be easily altered in the code.

(d) A single run without the plotting routines may take less than 7 seconds CPU time of the micro-VAX computer.

(9.0) Input Data

Code input consists of five basic parameters:

ID = (1,2) ; 1 for PN and 2 for the Schottky junctions.

ITYPE = (1,2) ; 1 for n-type and 2 for p-type semiconductors.

JD = (1,2) ; 1 for Pm and 2 for Ni sources.

IC = 1,2,3,4 ; 1 for Si, 2 for GaAs ,3 for AlGaAs and 4 for GaP.

YR = betacell life-time in years.

(see Appendix 2)

BCELL computer code can run for multiple sources and converters. It can also run for single or multiple betacell life-times and output the accumulated effects.

(10.0) BCELL Limitations

(a) Most of the converter cell parameters used are obtained from the published data, and the code is highly dependent upon these parameters. In any actual betacell design situation, the experimental coefficients should be substituted the adapted parameters.

(b) BCELL presently is limited to two radioisotopes (P_m^{147} and Ni^{63}) and four converters (Si, GaAs, AlGaAs and GaP). Thus, for any other source or converter the corresponding parameters need to be replaced.

(c) The magnitude of the series resistivity is important in determining the JV-curve of the betacell. Thus, if this parameter is significant in a system design, additional programming may be needed.

(d) Some output results of the BCELL computer code are presented in this report. These output data include the effect of the circuit perfection parameter (A), the shunt and loss current densities and JV curve for the betacell characteristic function.

(11.0) RESULTS

We have shown that consideration of the source/cell degradation is very important for any betacell design effort and to maximize the output power one must look at the optimization of various parameters involved. The betacell efficiency, for the specified assumptions used in this report, is about 2.3% for a unit cell with 1/2 radiation face and for a 100% source assay. Certain betacell design parameters for N_i^{63} radioisotope coupled to silicon n-type PN-junction are given in Tables 11, 12, 13 and 14. Figures 15 and 16 represent the electron radiation spectra (energy and momentum) for a Ni^{63} source. Figure 17 gives the optimum radiation source width against the converter width for a maximum betacell efficiency and output power. Figures 18, 19, and 20 present the effect of the perfection parameter on the betacell dark current density, output voltage and power, respectively. Figures 21, 22 and 23 indicate betacell characteristic curves in terms of power and current densities against the circuit voltage. These results clearly depend upon the input parameters used and the assumptions made either on the source characteristics or on the converter performance. To give actual betacell design parameters, one has to use either experimental input data and/or up-to-date reported data.

(12.0) CONCLUSIONS

From the above discussions we have noticed that the betacell efficiency depends upon radioisotope and converter material parameters. Additionally, there is a limit for the overall betacell system efficiency which depends upon minority currents and junction temperature. Tables 1 and 2 presented an order of magnitude type calculation

of various parameters mentioned previously. The most damaging factors in this list are the **converter reflection coefficient** and the **betacell quantum efficiency.**

If we would like to increase the efficiency and consequently the output power of a betacell we should try to optimize the effects of certain parameters discussed here;

(a) Increase η_{max}

(1) Operate betacells at lower temperatures so that lower reverse currents are generated.

(2) Select a converter with a lower expended energy per electron pair production.

(3) Select a betacell system with higher fill factor.

(4) Select a source with longer lifetime(ie. lower source degradation).

(5) select a converter cell with a higher bandgap energy.

(b) Decrease the effects of other parameters causing efficiency reduction;

(1) Select a cell with a material of lowest atomic number so that the converter reflection is minimized.

(2) Select a converter with higher than one diffusion length thickness. This, however, will decrease the betacell power density(watts/cc) and wastes the extra unused portion of the wafer.

(3) Select a coverter cell with the lowest impurity level. This improvement, however, is small and may cause other degradation of the betacell such as diffusion lengths and diffusion times of the minority carriers.

(4) Select an electron source in a gaseous form and the Schottky metal part as the support(?). This way we may increase the source transmission coefficient.

(5) Make a break through in the source-converter system design for higher overall efficiency of the solid state beta-cell. For example, we may look at the case where the source material is allowed to diffuse in to the metal part of the Schottky cell(?).

(13.0) References

Archaed G. E., J. Appl. Phys. 32 1505 (1961).

Attix F. H., and Roesch W. C., Radiation Dosimetry Vol 1, 1968.

Barkas W. K., and Berger M. J., NASA SP3013, 1964.

Berger M. J. and Seltzer S. M., IEEE Trans. Nucl. Sci. NS-26 4896, 1979.

Carter J. R., TRW 21946-6001-RU-00, 1973.

Everhart, T. E., J. Appl. Phys., 31, 1483, (1960).

Faelton E. M. and Gordan J. D., TRW 99994-6272-TU-00, 1974.

Hine G. J. and Brownell G. L., Academic Press 1956.

Lincoln R. C., Private Communication May 5 1986.

Manasse F. K. and Tse A. N., Nuclear Technology 29, 222 (1976).

Olson L. C., Energy Conversion 13, 117, (1973).

Rappaport P. and Linder E. G. J. of Appl. Phys. 24(9)

, 1110, (1953).

Taherzadeh M., Nuclear Technology 18, 15, (1973).

Taherzadeh M., PSP- 9284 18 Feb 1986.

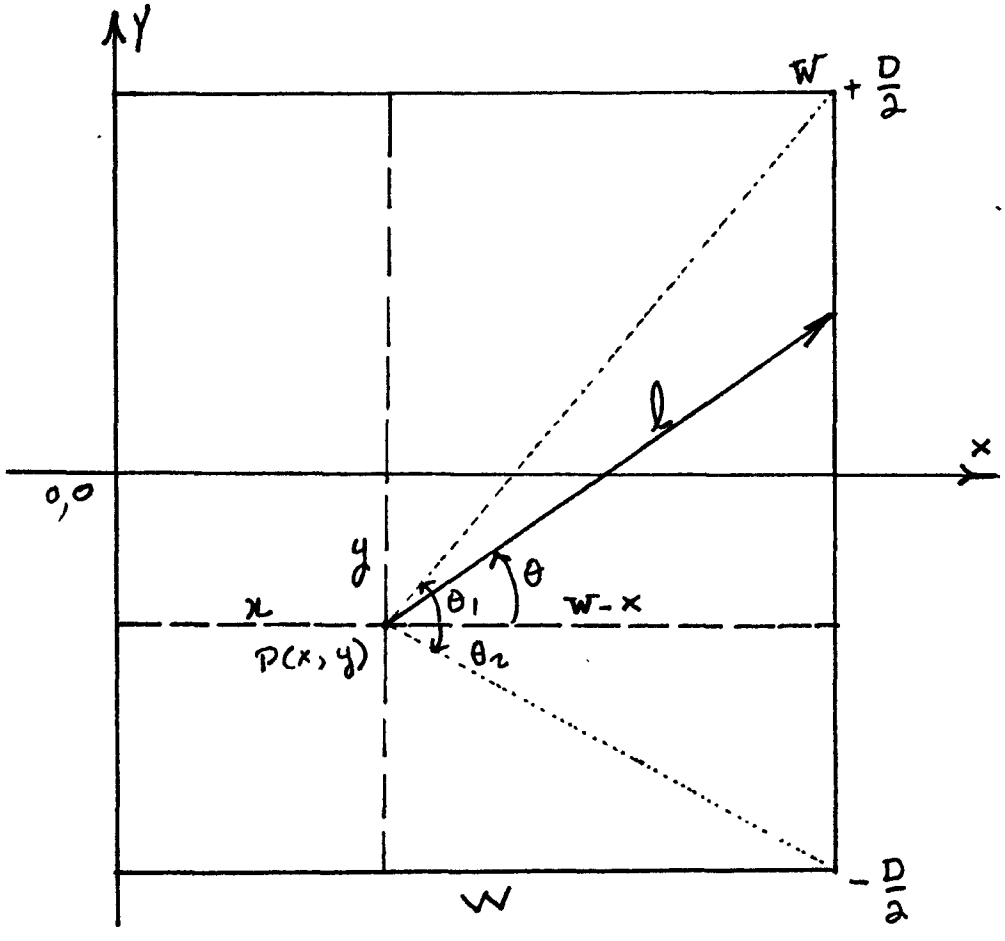
Taherzadeh M., PSP-TW- 415, July (1986).

Yu A. Y., IEEE Spectrum 1(3), 83, (1970).

Appendix (1)

Beta Source Transmission Coefficient

In order to determine the beta source transmission coefficient, we have used a beta source of a diameter D and a width W.



The source material attenuation constant is given by α. The ejected electron angular distribution function, $P(\mu)$, can have any form. However, the most reasonable assumption is that this distribution function is isotropic, therefore, we must have;

$$\int_{\Omega} P(\mu) d\Omega = 4\pi \qquad (1)$$

Assuming azimuthal symmetry, the isotropic angular distribution function, $P(\mu)$, can be represented by:

$$P(\mu) = \frac{1}{2} \tag{2}$$

$$\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} P(\theta)\cos\theta = 1 \tag{3}$$

With the above assumption, the average transmission of beta radiation form a finite point source located at (x,y) may be written;

$$T_s(W,D,\alpha) = \frac{1}{2WD}\int_0^W dx \int_{-D/2}^{D/2} dy \int_{-\theta 1}^{\theta 2} e^{-\alpha l}\cos\theta d\theta \tag{4}$$

Where all parameters of this equation are defined in the above diagram, α is the attenuation coefficient and l is the radiation path. The limiting angles, θ_1 and θ_2 are given by:

$$\theta_1 = \cos^{-1}\left\{\frac{W-x}{\sqrt{(W-x)^2 + (D/2+y)^2}}\right\} \tag{5}$$

$$\theta_2 = \cos^{-1}\left\{\frac{W-x}{\sqrt{(W-x)^2 + (D/2-y)^2}}\right\} \tag{6}$$

θ_1 , θ_2 are defined only in the [0, $\pi/2$] range. Attempts have been made to represent this equation in terms of closed functions in various publications. For this model, we have written a subprogram for evaluating the above integral numerically.

APPENDIX 2

BCELL OUTPUT DATA

ID	= 1	PN Junction
ITYE	= 1	n-type
JD	= 2	Ni^{63} Source
YI	= 10	Years of Exposure
ARY	= 0	For Every Year
IC	= 2	GaAs
KMAX	= 1	Only One T = 300
Assay	= 1	100% Assay
Face	= .5	
A	=1.25	Perfection
IPLOT	= 4	Plot All Parameters

```
1    1    2 10.0  1.0    2    1    1   1.0   0.5   1.3  4
              BETA SOURCE IS  NI(63 )  PN CONT
          ****************************************


        ATOMIC MASS NUMBER= 63.
             ATOMIC NUMBER=28.
      (S,CON)ATT CONSTANTS= 1.99E+04 1.30E+04  /CM
                     W/CI= 1.00E-04            WATTS/CURIE
                     W/GM= 5.69E-03            WATTS/GRAM
                HALF LIFE= 1.00E+02            YEARS
            DIS. CONSTANT= 2.20E-10            /SEC
    SOURCE ATOMIC DENSITY= 8.51E+22            ATOMS/CC
        SPECIFIC ACTIVITY= 5.68E+01            CURIES/GM  GM= 1.25E-03
             SOURCE WIDTH= 1.40E-04            CM   ACT= 2.10E+12  /S/CC
                 DIAMETER= 1.12838E+00         CM
            TOT(VOL,MAS)= 7.37E-04 4.73E-03  CM3,GM
                   S VOL= 1.40E-04
             SOURCE AREA= 1.00000E+00         CM2
             ACTIVE AREA= 1.00E+00
                  CURIES= 7.08E-02            CURIES
MAX. SOURCE CURRENT DENSITY= 7.32E-11         AMP/CM2
     SOURCE CURRENT DENSITY= 6.07E-11         AMP/CM2
            SOURCE CURRENT= 6.07E-11         AMPERES
               SOURCE FLUX= 3.79E+08         BETA/CM2/SEC
      SOURCE ENERGY FLUX= 6.39E+12            EV/CM2/SEC
                      ZC= 3.20E+01            AC= 1.45E+02
                     ZOA= 7.18E-01            RHOC= 5.83E+00   GM/CC
            IONIZATION E= 3.66E+01            EV
     CONV. ATOMIC DENSITY= 2.43E+22           ATOMS/CC
               GAP ENERGY= 1.42E+00           EV
          J CAPACITANCE= 2.12E-07             FARAD/CM
        J SPACE CHARGE= 7.48E-07              COULOMB
              J E FIELD= 5.99E+05             VOLTS/CM
  J (E,H)THERMAL VELOCITY= 4.51E+07 1.70E+07  CM/SEC
    J (E,H)DRIFT VELOCITY= 1.78E+09 1.05E+08  CM/SEC
    J (E,H)RECOM VELOCITY= 1.04E+07 3.92E+06  CM/SEC
       BUILD-IN POTENTIAL= 1.42E+00           VOLTS
             CAPACITANCE= 2.12E-07            FARAD/CM
             DEBY LENGTH= 4.00E-07            CM
       BREAK DOWN VOLTS= 2.79E+03             VOLTS
           SOURCE ASSAY= 1.00E+00
       EFF. PERMITTIVITY= 9.91E-13            FARAD/CM
          (E,H)EFF. MASS= 6.70E-02 4.70E-01   MS/M0
             EC-EF,EC-ED=-2.15E-02-1.94E-02   EV
```

```
          CONVERTER CONSTANTS          GAAS      N-TYPE
       ******************************************************
            RICHARDSON NO.S= 5.65E+01 5.45E+01  AMP/CM2/K
      (RB,1-RC)REFLECTIVITY= 3.00E-02 7.43E-01
       CON. BETA MAX. RANGE= 1.36E-03           CM   5.358E-01  MILS
       SOC. BETA MAX. RANGE= 8.91E-04           CM   3.507E-01  MILS
                       JZ= 5.37E-21             AMP/CM2
                (JZG,JZR)= 4.20E-10 9.84E-12    AMP/CM2
              MULT. FACTOR= 7.14E+03            AVE TE=1.688E-02 TAZ=3.20E-02
                (AKT,AKTA)= 3.2314E-02 3.2314E-02  EV
           CONVERTER AREA= 1.00E+00             CM2
        CONVERTER THICKNESS= 5.97E-04           CM   SPENT E= 4.48E-06
           CONVERTER ATTEN= 1.30E+04            CM-1
COLLECTION EFFICIENCY(Q,QP)= 8.80E-01 8.79E-01
            (E,H)COLL. EFF= 8.51E-01 2.91E-02
                   LAMBDA= 3.87E+01
                      T=300.0                   KELVIN   KT= 2.585E-02   EV
         (E,H)DIF CONSTANT= 7.67E+01 4.54E+00  CM2/SEC
      (E,H)DIFFUSION LENGTH= 5.37E-04 6.03E-04  CM
            (E,H)MOBILITY= 2.97E+03 1.76E+02  CM2/VOLTS/SEC
MAJ CON IN (N,P) SIDE AT EQ= 1.00E+18 3.52E+18  /CC  NC= 4.35E+17
MIN CON IN (N,P) SIDE AT EQ= 4.45E-06 1.27E-06  /CC  NV= 8.09E+18
    INTRINSIC CONCENTRATION= 2.11E+06           /CC
          (E,H)CONDUCTIVITY= 4.76E+02 9.91E+01  MHOS/CM/SEC
        (E,H)DIFF LIFETIME= 3.76E-09 8.02E-08  SEC
        (E,H)COLL LIFETIME= 1.69E-12 9.99E-14  SEC
           ION PAIR E/EGAP= 3.15E+00
         DEPLETION LENGTH= 4.67E-06             CM
    (ND,NA)DOPING DENSITIES= 1.00E+18 3.52E+18  /CC
        SHUNT CONDUCTIVITY= 1.00E-09            MHOS/CM2
     F OF P ABS IN(SRC,CON)= 7.02E-01 1.00E+00
               PERFECTION= 1.25E+00          HETEROFACE FRAC= 0.00E+00
       CONTACT RESISTIVITY= 4.81E+18           OHM-CM
              ANGULAR DIS= 1.00E+00            FACE= 5.00E-01
          (GEN,RECOM.)RATE= 1.42E+08 1.04E+33  /SEC
           (E,H)CAP. PROB.= 6.03E-03 3.57E-04
            (E,H)CAP. RATE= 6.03E+15 3.57E+14  /SEC
            (E,H)TRAP TIME= 1.66E-16 2.80E-15  /SEC
          (E,H)RECOM TIME= 9.62E-16 3.39E-15  /SEC
       (RS1,RC1)REFLECTION= 2.94E-01 3.28E-01
          N SIDE(P,N)AT EQ= 4.45E-06 1.00E+18  /CC
          P SIDE(P,N)AT EQ= 3.52E+18 1.27E-06  /CC
                    NSTAR= 7.79E+17             /CC
                       JS= 1.39E-07             AMP/CM2
       (E,H)CURRENT DENSITY= 1.35E-07 4.61E-09  AMP/CM2
```

INPUT POWER=	1.02E-06	1.02E-06	1.02E-06	1.03E-10	1.03E-10	W/CM2
INPUT DISTANCES=	0.00E+00	0.00E+00	0.00E+00	5.97E-04	5.97E-04	CM
AVE DOSE=	0.00E+00	0.00E+00	0.00E+00	1.67E+10	0.00E+00	RADS

INP JB= 5.66E-11 AMPS/CM2
FABS IN CONV= 1.00E+00

JSC AND DOSE AS A FUNCTION OF X
FROM THE SOURCE SURFACE

I	X	CUR(X)	CTOT(X)	PABS(X)	FABS(X)	DOSE(X)
1	0.00E+00	5.66E-11	5.66E-11	0.00E+00	0.00E+00	0.00E+00
2	0.00E+00	5.66E-11	5.66E-11	0.00E+00	0.00E+00	0.00E+00
3	0.00E+00	5.66E-11	5.66E-11	0.00E+00	0.00E+00	0.00E+00
4	4.67E-06	3.02E-11	1.40E-07	2.89E-07	2.82E-01	1.39E+11
5	6.44E-05	4.76E-13	1.26E-07	1.00E-06	9.79E-01	4.28E+10
6	1.24E-04	7.10E-14	1.14E-07	8.19E-07	7.99E-01	1.66E+10
7	1.84E-04	4.89E-15	1.04E-07	9.30E-07	9.07E-01	7.22E+09
8	2.44E-04	1.55E-16	9.38E-08	9.81E-07	9.57E-01	3.32E+09
9	3.03E-04	5.09E-19	8.49E-08	1.02E-06	9.96E-01	1.53E+09
10	3.63E-04	7.42E-22	7.69E-08	1.02E-06	9.98E-01	7.08E+08
11	4.23E-04	4.93E-25	6.97E-08	1.02E-06	9.99E-01	3.27E+08
12	4.82E-04	1.52E-28	6.31E-08	1.02E-06	1.00E+00	1.51E+08
13	5.97E-04	1.14E-32	5.22E-08	1.02E-06	1.00E+00	3.42E+07

VMAX= 3.09E-01 VOLTS JSC= 1.39E-07 YEARS=10.00

I	VOLTS	J(LOSS)	J(LOAD)	POWER	J SHNT
1	0.00E+00	0.00E+00	1.39E-07	0.00E+00	0.00E+00
2	6.18E-03	2.07E-12	1.39E-07	8.61E-10	6.18E-12
3	1.24E-02	4.58E-12	1.39E-07	1.72E-09	1.24E-11
4	1.85E-02	7.62E-12	1.39E-07	2.58E-09	1.85E-11
5	2.47E-02	1.13E-11	1.39E-07	3.44E-09	2.47E-11
6	3.09E-02	1.58E-11	1.39E-07	4.30E-09	3.09E-11
7	3.71E-02	2.12E-11	1.39E-07	5.16E-09	3.71E-11
8	4.33E-02	2.77E-11	1.39E-07	6.02E-09	4.33E-11
9	4.94E-02	3.56E-11	1.39E-07	6.88E-09	4.94E-11
10	5.56E-02	4.52E-11	1.39E-07	7.74E-09	5.56E-11
11	6.18E-02	5.68E-11	1.39E-07	8.60E-09	6.18E-11
12	6.80E-02	7.08E-11	1.39E-07	9.46E-09	6.80E-11
13	7.41E-02	8.78E-11	1.39E-07	1.03E-08	7.41E-11
14	8.03E-02	1.08E-10	1.39E-07	1.12E-08	8.03E-11
15	8.65E-02	1.33E-10	1.39E-07	1.20E-08	8.65E-11
16	9.27E-02	1.63E-10	1.39E-07	1.29E-08	9.27E-11
17	9.89E-02	2.00E-10	1.39E-07	1.37E-08	9.89E-11
18	1.05E-01	2.44E-10	1.39E-07	1.46E-08	1.05E-10
19	1.11E-01	2.98E-10	1.39E-07	1.55E-08	1.11E-10
20	1.17E-01	3.62E-10	1.39E-07	1.63E-08	1.17E-10
21	1.24E-01	4.41E-10	1.39E-07	1.72E-08	1.24E-10
22	1.30E-01	5.36E-10	1.39E-07	1.80E-08	1.30E-10
23	1.36E-01	6.51E-10	1.39E-07	1.88E-08	1.36E-10
24	1.42E-01	7.90E-10	1.38E-07	1.97E-08	1.42E-10
25	1.48E-01	9.59E-10	1.38E-07	2.05E-08	1.48E-10
26	1.54E-01	1.16E-09	1.38E-07	2.13E-08	1.54E-10
27	1.61E-01	1.41E-09	1.38E-07	2.21E-08	1.61E-10
28	1.67E-01	1.71E-09	1.37E-07	2.29E-08	1.67E-10
29	1.73E-01	2.07E-09	1.37E-07	2.37E-08	1.73E-10
30	1.79E-01	2.51E-09	1.37E-07	2.45E-08	1.79E-10
31	1.85E-01	3.04E-09	1.36E-07	2.52E-08	1.85E-10
32	1.92E-01	3.68E-09	1.35E-07	2.59E-08	1.92E-10
33	1.98E-01	4.46E-09	1.35E-07	2.66E-08	1.98E-10
34	2.04E-01	5.40E-09	1.34E-07	2.73E-08	2.04E-10
35	2.10E-01	6.54E-09	1.33E-07	2.79E-08	2.10E-10
36	2.16E-01	7.92E-09	1.31E-07	2.84E-08	2.16E-10
37	2.22E-01	9.60E-09	1.30E-07	2.88E-08	2.22E-10
38	2.29E-01	1.16E-08	1.28E-07	2.91E-08	2.29E-10
39	2.35E-01	1.41E-08	1.25E-07	2.94E-08	2.35E-10
40	2.41E-01	1.70E-08	1.22E-07	2.94E-08	2.41E-10
41	2.47E-01	2.06E-08	1.18E-07	2.93E-08	2.47E-10
42	2.53E-01	2.50E-08	1.14E-07	2.89E-08	2.53E-10
43	2.60E-01	3.02E-08	1.09E-07	2.82E-08	2.60E-10
44	2.66E-01	3.66E-08	1.02E-07	2.72E-08	2.66E-10
45	2.72E-01	4.43E-08	9.47E-08	2.58E-08	2.72E-10
46	2.78E-01	5.37E-08	8.54E-08	2.37E-08	2.78E-10
47	2.84E-01	6.50E-08	7.41E-08	2.11E-08	2.84E-10
48	2.90E-01	7.87E-08	6.04E-08	1.75E-08	2.90E-10
49	2.97E-01	9.53E-08	4.38E-08	1.30E-08	2.97E-10
50	3.03E-01	1.15E-07	2.37E-08	7.18E-09	3.03E-10
51	3.09E-01	1.40E-07	0.00E+00	0.00E+00	3.09E-10

BETAVOLTAIC RESULTS
****

VMP=	2.41E-01	VOLTS
JMP=	1.22E-07	AMP/CM2
P/AREA=	2.94E-08	WATTS/CM2
JSC MAX=	7.67E-07	VOC MAX= 1.05E+00
EFF(M)=	1.52E+01	PERCENT
MAX. EFFICIENCY=	1.61E+01	PERCENT
PMAX=	4.30E-08	WATTS/CM2
INPUT POWER=	1.02E-06	WATTS/CM2
FF=	6.83E-01	
RMP=	7.21E+17	OHMS - CM
TOTAL P=	2.94E-08	WATTS
P/TVOL=	3.99E-05	WATTS/CC
EFFICIENCY=	2.87E+00	PERCENT
S MASS/POWER=	4.24E-02	GM SOURCE/MICRO W P OUT
CONVERTER MATERIAL=	3.40E+01	CM2/MICRO W P OUT
UNIT CELL VOL=	2.51E-02	CC/MICRO WATTS
UNIT CELL MASS=	1.18E-01	GM/MICRO WATTS
(N IN P,P IN N)AT EDGE=	1.96E-01 6.90E-01	/CC

****

INDUCED DEFECT CONCENTRATION= 6.45E+09

BETAVOLTAIC DEGRADATION
DUE TO RADIATION DAMAGE AFTER
10.00 YEARS

KL= 1.76E-13 PHIC= 1.10E-18 OMEV= 6.45E+10
KTAU= 7.97E-13

TAUHZ= 8.02E-08	TAUH= 8.02E-08	0.00	PERCENT
LHZ= 6.03E-04	LH= 6.03E-04	0.00	
JSZ= 1.39E-07	JS= 1.39E-07	3.85	
VOCZ= 3.09E-01	VOC= 3.09E-01	0.00	
(P/A)Z= 2.94E-08	P/A= 2.93E-08	3.85	
TH=100.00	P/A= 0.00E+00	6.697	SOURCE DEGRAD
TOTAL P(Z)= 2.94E-08	TOTAL P= 2.93E-08	3.85	
P/VOL (Z)= 3.99E-05	P/VOL= 3.97E-05	3.85	
ETA (Z)= 2.87E+00	ETA= 2.86E+00	3.85	

1 MEV EQUIV. ELECTRON FLUENCE = 6.45E+10
DARK CURRENT INC= 7.05E+02 PERCENT
ABSORBED DOSE AT CELL END LAYER= 3.09E+07 RADS

INDUCED RADIATION SPECTRUM

I	EG	FG
1	0.00E+00	0.00E+00
2	2.75E-03	3.90E-03
3	5.49E-03	3.67E-03
4	8.24E-03	3.44E-03
5	1.10E-02	3.21E-03
6	1.37E-02	2.98E-03
7	1.65E-02	2.75E-03
8	1.92E-02	2.52E-03
9	2.20E-02	2.30E-03
10	2.47E-02	2.08E-03
11	2.75E-02	1.87E-03
12	3.02E-02	1.66E-03
13	3.29E-02	1.45E-03
14	3.57E-02	1.26E-03
15	3.84E-02	1.07E-03
16	4.12E-02	8.90E-04
17	4.39E-02	7.24E-04
18	4.67E-02	5.70E-04
19	4.94E-02	4.31E-04
20	5.22E-02	3.07E-04
21	5.49E-02	2.02E-04
22	5.77E-02	1.16E-04
23	6.04E-02	5.16E-05
24	6.32E-02	1.16E-05
25	6.59E-02	0.00E+00

DOSE IN TISSUE= 3.18E-05 REM/HR
ACC. DOSE IN TISSUE= 2.88E+00 REM
(AFTER 1.00E+01 YRS OF IRRADIATION)

TABLE 1.

Maximum Efficiency Of PN Junction GaAs Betacell

(Promethium 147 and Nickel 63)

Parameters	Promethium 147	Nickel 63
Source Width (μm)	2.0	2.0
Source Area (cm^2)	1.0	1.0
(PN)Wafer Width (μm)	8.73	8.73
W_g (m watts/gm)	339.0	5.37
Material Density (gm/cc)	7.22	8.9
Source Power (μ watts/cm^2) (1/2 Face Radiation)	216.0	2.5
Temperature (K)	300.0	300.0
J_Z ($pAmp/cm^2$)	29.7	29.7
$(J_{sc})_{max}$ (μ A/cm^2)	54.6	1.13
Expended Energy (ev)	4.5	4.5
FF (one example)	0.74	0.53
IV-Perfection Parameter	2.0	2.0
η_{max}	12.1	7.1

TABLE 2.

Efficiency Of PN Junction GaAs Betacell Exposed To Promethium 147 and Nickel 63 Sources

Parameters	Promethium 147	Nickel 63
Source width(μm)	2.0	2.0
conv. Atten Constant ($\mu_c \approx$)	1010.	4630.
Sourc Atten Constant ($\mu_s \approx$)	1290.	7290.
Source Transmission(T_s)	0.88	0.53
$(1-R_c)$	0.68	0.68
$(1-R_s)$	0.97	0.97
Converter Absorption (A_c)	0.42	0.78
Collection Efficiency (Q)	0.69	0.66
η_{max} (%)	12.1	7.0
η	2.31(2.02)	2.41(2.06)
η (R_c = 0.)	3.40(2.97)	3.6(3.03)
η/η_{max}	(0.25)	(.43)

The numbers in ( ) are based on the η correction factor(see text)

TABLE 3.

Betacell Design Parameters for GaAs Wafer

(Promethium 147 and Nickel 63 Sources)

Parameters	Promethium 147	Nickel 63
Face Radiation	0.5	0.5
Source Degradation	0.	0.
Source Width(μm)	2.0	2.0
Converter Width(μ m)	8.73	8.73
Max. Current($\mu Amp/cm^2$)	12.5	0.24
Max. Volts	.54	.35
η_{max}	12.1	7.1
η	3.4	3.55
Input Power($\mu Watts/cm^2$)	214.	2.66
Output Power($\mu watts/cm^2$)	6.69	0.082
Output Power Density (mWatts/cc)	6.23	0.077
source mass/power(Gm/mW)	.22	21.7
Con. mass/power(cm^2/mW)	150.0	12200.0

TABLE 4.

Semiconductor Material Constants

	<z>	<A>	<ZOA>	<ρ>	< I>	< ϕ>
Silicon	14	28	0.5	2.32	159.2	0.78
Fused Silica	10.8	28.1	0.49966	2.202	172.0	0.78
GaAs	32.0	71.7	0.72	5.81	36.9	0.9

(1) The potential height for the fused silica is assumed to be the same as silicon.

(2) < > stands for the atomic average values.

(3) $I(z) = z[9.76+58.8z^{-1.19}]$ ev.

(4) ϕ is the barrier potential height of the junction.

TABLE 5.

Maximum Beta Particle Range in Selected Semiconductors.

(Ni^{63}, Te(max)= 64.7 and Pm^{147}, Te(max)= 226 Kev)

	Ni Source			Pm Source		
	cm	mils	$gm\ cm^{-2}$	cm	mils	$gm\ cm^{-2}$
Silicon	.00487	1.92	0.0113	0.032	12.9	0.76
Fused Silica	.0051	2.02	0.0113	0.035	13.60	0.076
GaAs	.00195	0.76	0.0113	0.013	5.20	0.76

(1) $R(T) = \sqrt{(T/a)^2 + b^2} - b$

TABLE 6

Electron Range Energy Distribution in Silicon.

	Electron Energy (Mev)	Electron Range ($gm\ cm^{-2}$) $x\ 10^{-4}$
1	.01	3.52
2	.015	7.07
3	.02	11.65
4	.03	23.56
5	.04	38.83
6	.05	57.14
7	.06	78.22
8	.08	127.90
9	.10	186.40
10	.15	364.10
11	.20	577.20
12	.30	1077.00

TABLE 7.

Silicon Semiconductor Parameters.

Temperature(Kelvin)	250	275	300	325
Diffusion constant (cm^2/sec)	45.8	39.7	34.8	30.9
Diffusion Length (mils)	2.66	2.48	2.32	2.19
Carrier Mobility ($cm^2/volts/s$)$x\,10^3$	2.13	1.67	1.35	1.10
Conductivity ($mhos/cm/s$)$x\,10^3$	0.66	2.23	6.06	14.1
Collision Lifetime (sec)$x\,10^{-13}$	12.1	9.52	7.66	6.27
Majority Concentration ($/cc$)$x\,10^{13}$	1.07	4.59	15.5	44.1
Minority Concentration ($/cc$)$x\,10^5$	0.01	0.29	6.17	68.67
Intrinsic Concentration ($/cc$)$x\,10^9$	0.10	1.36	9.8	51.7
Reverse Current (Amp/cm^2) $x\ 10^{-8}$	0.14	4.38	80.9	967.0

TABLE 8.

Specified Betacell Constants (*)

Parameters	Constants	Units
Source Thickness(10^{-4})	2.0	cm
Cell Thickness(10^{-4})	5.0	cm
Side Radiation	2	-
Source Density	6.4	gm/cc
Cell Density	5.653	gm/cc
Expended Energy	4.5	ev
Source Mass(10^{-3})	1.28	gm
Cell surface Area	1.0	cm2
Source Effective Area	1.0	cm2
Total volume(10^{-4})	7.0	cm3
Total Mass(10^{-3})	4.1	gm
Average Density	5.866	gm/cc
Collection Efficiency	100.0	percent
Converter Reflection	0.0	-
Source Reflection	0.0	-

(*) Pm^{147} source and n-type GaAs were used.

TABLE 9.

Betacell Output Parameters (*)

Parameters	TRW w/gm= .339	SNL w/gm= .33(+)	SNL w/gm= .4
Input Power(μwatts)	434.0	422.4	512.
Source Absorption(%)	17.5	16.0(+)	16.0(+)
Cell Absorption(%)	47.5	38.0(+)	38.0(+)
Power absorption μ watts)	169.0	135.	163.8
$J_{sc}(\mu amp/cm^2)$	37.8	30.0	36.0(+)
V_{oc}(volts)	0.714	0.71(+)	0.71(+)
$J_o(picoamp/cm^2)$	39.1	32.6	39.1
FF	0.75	0.6(+)	0.6(+)
$P_{max}(\mu Watts/cm^2)$	20.	12.8	15.3(+)
Efficiency	4.66	3.0	3.5

(*) T= 300 K and A= 2

(+) Reported by SNL, others are estimated.

TABLE 10.

PN / Schottky Device Output Comparison

Parameters	Schottky(A= 1)	Schottky(A= 1)	PN(A= 2)
T(K)	300	300	300
J_{sc}(μamp/cm2)	37.8	37.8	37.8
V_{oc}(volts)	0.357	0.23	0.714
J_o(pico amp/cm2)	39.1	5090(*)	39.1
FF	0.75	0.67	0.75
P_{max}(μWatts/cm2)	10.	5.83	20.0
Efficiency	2.33	1.34	4.66
Power density(mW/cc)	14.3	8.3	28.6(+)

The difference between the two Schottky junctions is in their reverse currents.

(*) $J_o = 3.9110^{-11}$ can be obtained at T= 265 K.

(+) To form a PN junction the entire 5 micron cell can not be used for the active area. Hence, the comparision is not quite right.

TABLE 11.

Important Parameters of The Radioisotope Source

(Nickel 63)

Parameters	Values
Width(μm)	5.1
Area(cm^2)	1.0
Volume(cm^3)	5.1×10^{-4}
Mass(mGm)	4.54
Activity(no./s/cc)	2.1
Specific Activity(Curies/Gm)	56.8
Atomic Density(no./cc)	8.51×10^{22}
Disintegration Constatnt(/Sec)	2.2×10^{-10}
Number of Curies	0.2578
Material Density(Gm/cc)	8.9
Attenuation Constant(cm^{-1})	7290.
Power Density:	
(*Watts/Gm*)	5.7×10^{-3}
(*Watts/Ci*)	1.0×10^{-4}
Current Density ($pAmp/cm^2$)	46.8
Flux($no./sec/cm^2$)	2.92×10^8
Energy Flux ($Mev/sec/cm^2$)	4.93×10^6
Reflectivity(%)	3
Transmission Coefficient(%)	23.5
Absorption Coefficient(%)	76.5
Face Radiation(%)	50
Electron Maximum Range(μm)	8.9(0.35 mils)
Electron Maximum Temperature(ev)	0.065
Electron Average Temperature(ev)	0.017

TABLE 12.

Important Parameters Used For Betacell Design

(Silicon Converter)

Parameters	Values
Width (μm)	62.3
Area (cm^2)	1.0
Volume (cm^3)	62.3×10^{-4}
Mass (mgm)	14.52
Ionization Potential (ev)	172.0
Doping Density (/cc)	2.0×10^{17}
Atomic Density (no./cc)	4.99×10^{22}
Material Density (gm/cc)	2.332
Attenuation Constant (cm^{-1})	1910.
Collection Efficiency:	
Electrons (%)	92.9
Holes (%)	0.73
Total (%)	93.6
Gap Energy(ev)	1.12
Spent Energy(ev)	3.64
Ion pair/Energy Gap	3.25
Reflectivity(%)	0.
Transmission Coefficient(%)	0.1
Absorption Coefficient(%)	99.9
Electron Maximum Range(μm)	34.5(1.34 mils)
Heteroface Fraction	0.0

TABLE 13.

Important Parameters Used For Betacell Design

(n-type PN Junction)

Parameters	Values
Temperature (kelvin)	300.
Build-in Potential (volts)	0.96
Deby Length(A)	91.8
Space Charge (coul)	2.47×10^{-7}
Capacitance (farad/m)	1.37×10^{-7}
E- Field (volts/cm)	2.45×10^{5}
Intrinsic Concentration (/cc)	1.69×10^{9}
Majority Concentration (/cc)	1.29×10^{13}
Minority Concentration (/cc)	2.18×10^{5}
Conduction Band Density (/cc)	2.08×10^{18}
Valence Band Density (/cc)	8.87×10^{18}
Depletion Length (A)	770.0
Contact Resistivity (Ω)	9.4×10^{9}
Diffusion Length Damage Coefficient (/e)	1.76×10^{-13}
Diffusion Time Damage Coefficient	2.72×10^{-12}
Critical Fluence (e/cm^2)	9.09×10^{16}

TABLE 14.

Important Carriers Physical Parameters Used For Betacell Design

(Silicon on Nickel 63)

Parameters	Electrons	Holes
Thermal Velocity (cm/sec)	2.68×10^{7}	1.65×10^{7}
Drift Velocities (sm/sec)	3.64×10^{8}	1.46×10^{8}
Recombination Velocity (cm/sec)	6.17×10^{6}	3.80×10^{6}
Diffusion Constant (cm^2/sec)	38.8	15.5
Diffusion Length (cm)	6.23×10^{-3}	1.97×10^{-1}
Diffusion Time (sec)	1.0×10^{-6}	2.5×10^{-3}
Trap Time (sec)	1.73×10^{-15}	$4.32x \times 10^{-15}$
Recombination Time (sec)	2.56×10^{-7}	4.32×10^{-15}
Mobility ($cm^2/volt/sec$)	1.5×10^{3}	6.0×10^{2}
Conductivity (mohs/cm/sec)	3.09'x' 10^{-3}	2.09×10^{-11}
Generation Rate (/sec)	5.41×10^{7}	
Recombination Rate (/sec)	5.04×10^{19}	
Capture Probability	2.89×10^{-3}	1.16×10^{-3}
Capture Rate (/sec)	5.38×10^{14}	2.31×10^{14}
Current Density (amp/cm^2)	7.49×10^{-7}	5.86×10^{-9}

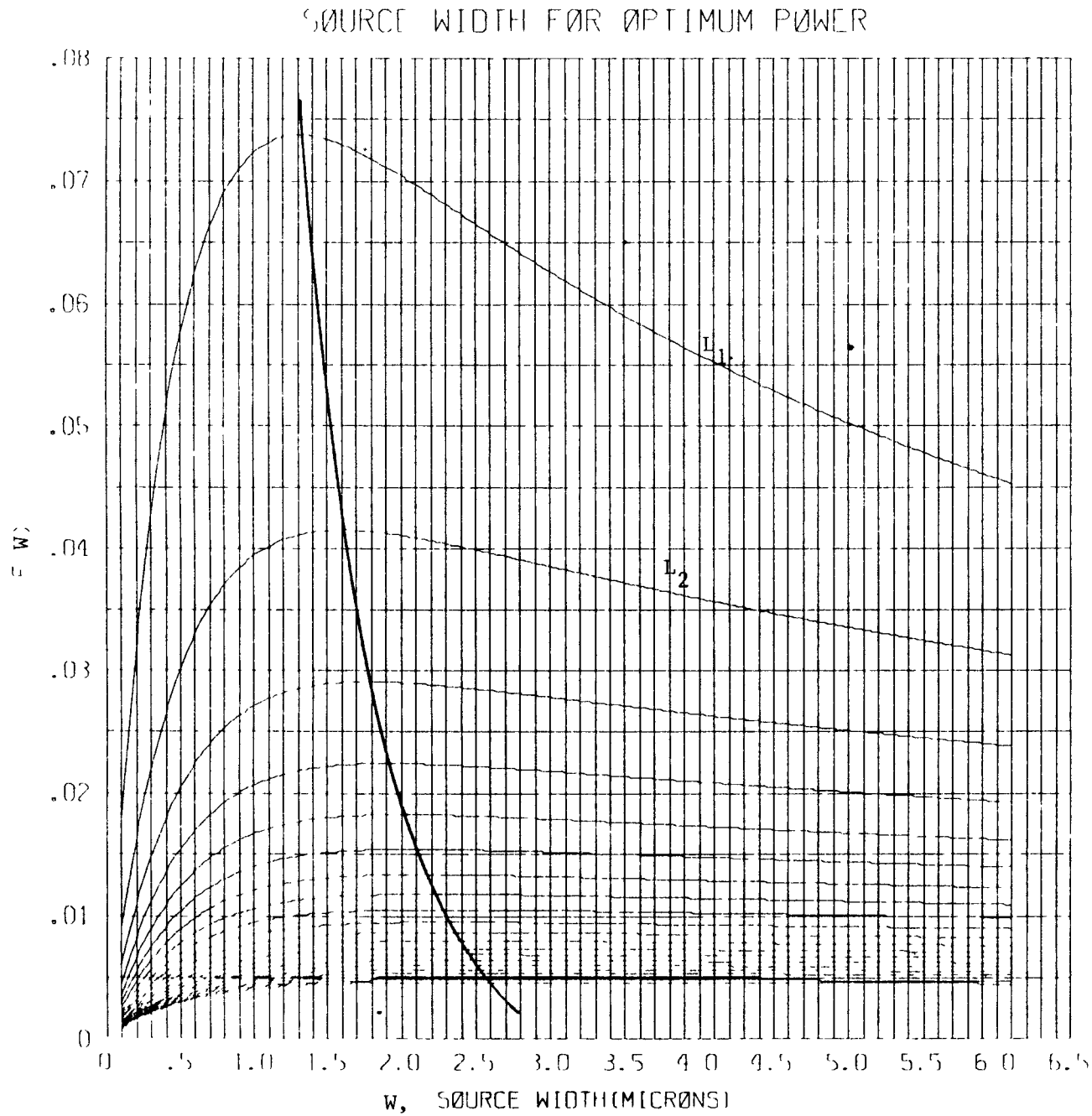


FIGURE 1

$$F(W) = \frac{W\,T_s\,(W)}{L+W}$$

(AT CONSTANT L)

L = CONVERTER WIDTH

W = SOURCE WIDTH

FIGURE 2 TRANSMISSIØN CØEFFICIENT

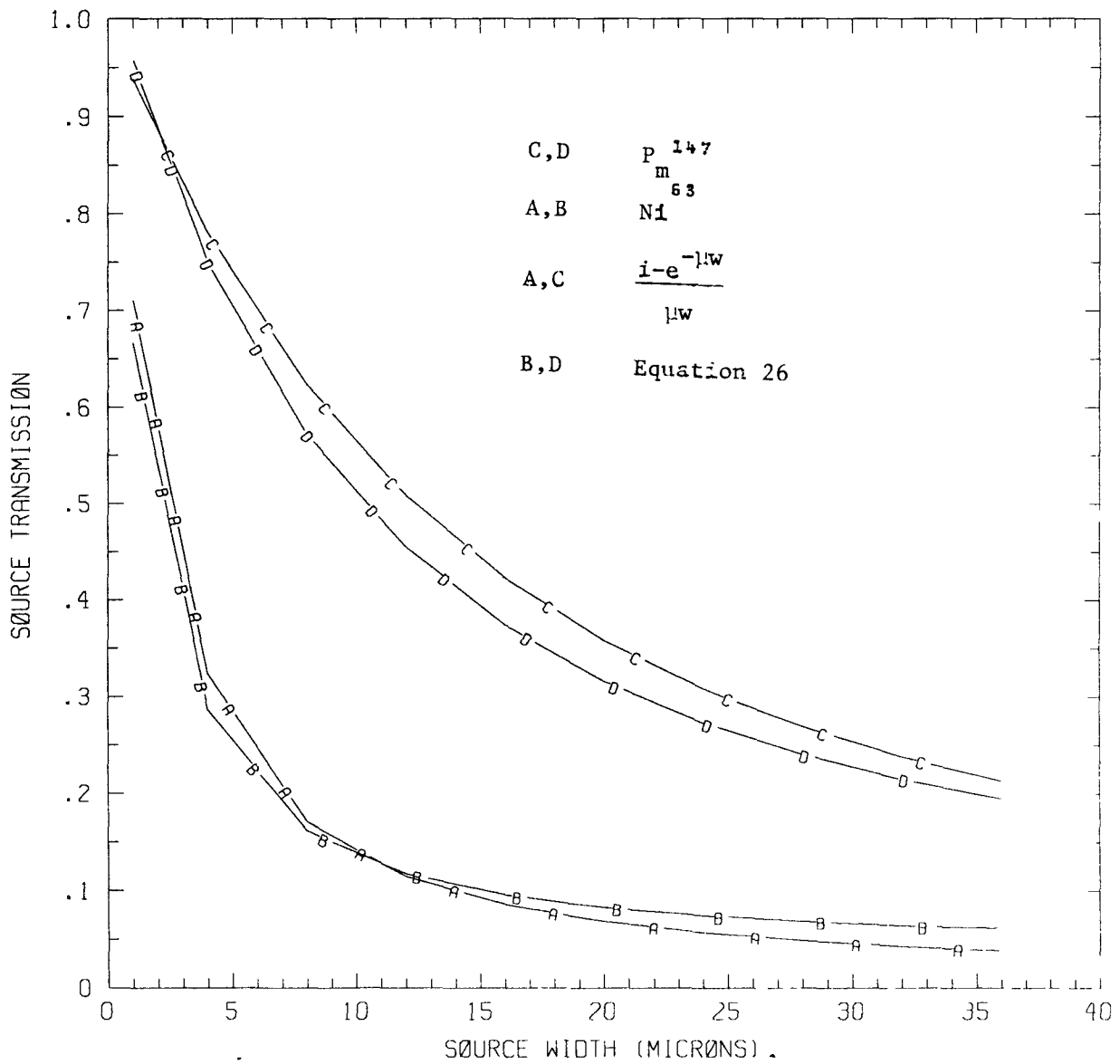


FIGURE 3 CELL/SØURCE WIDTH FØR MAX. PØWER

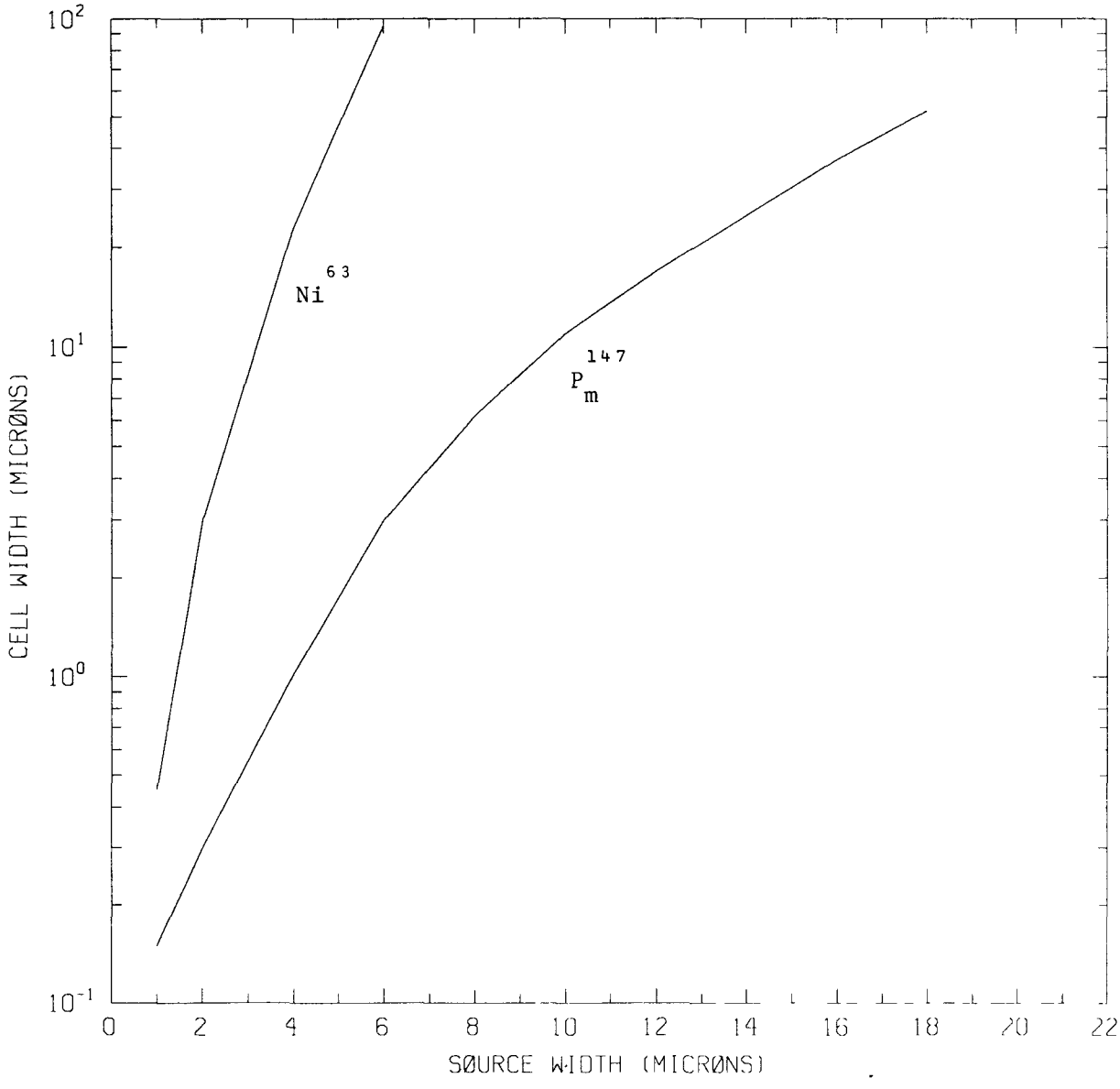
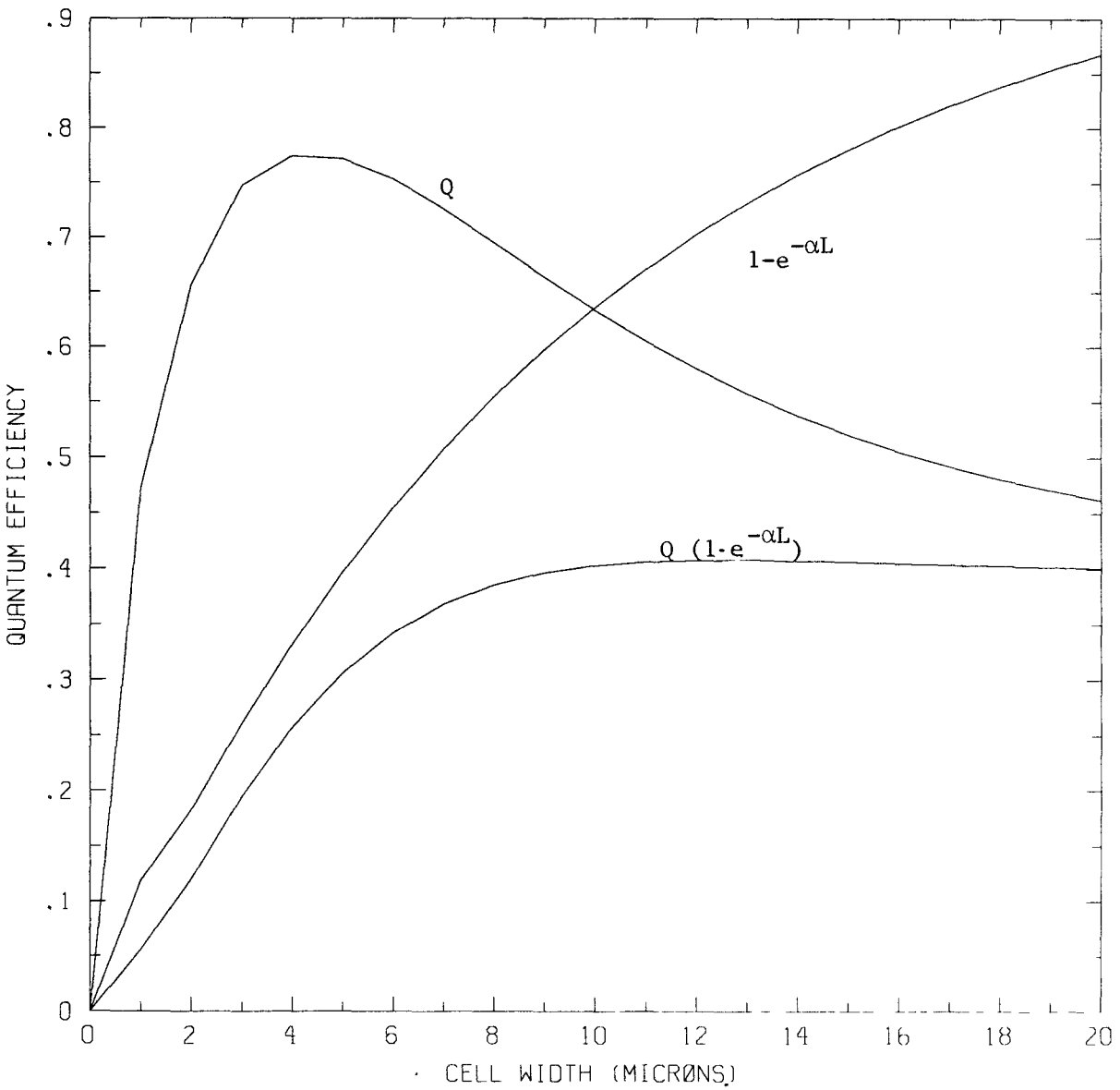


FIGURE 4 PM SØURCE ØN GAAS



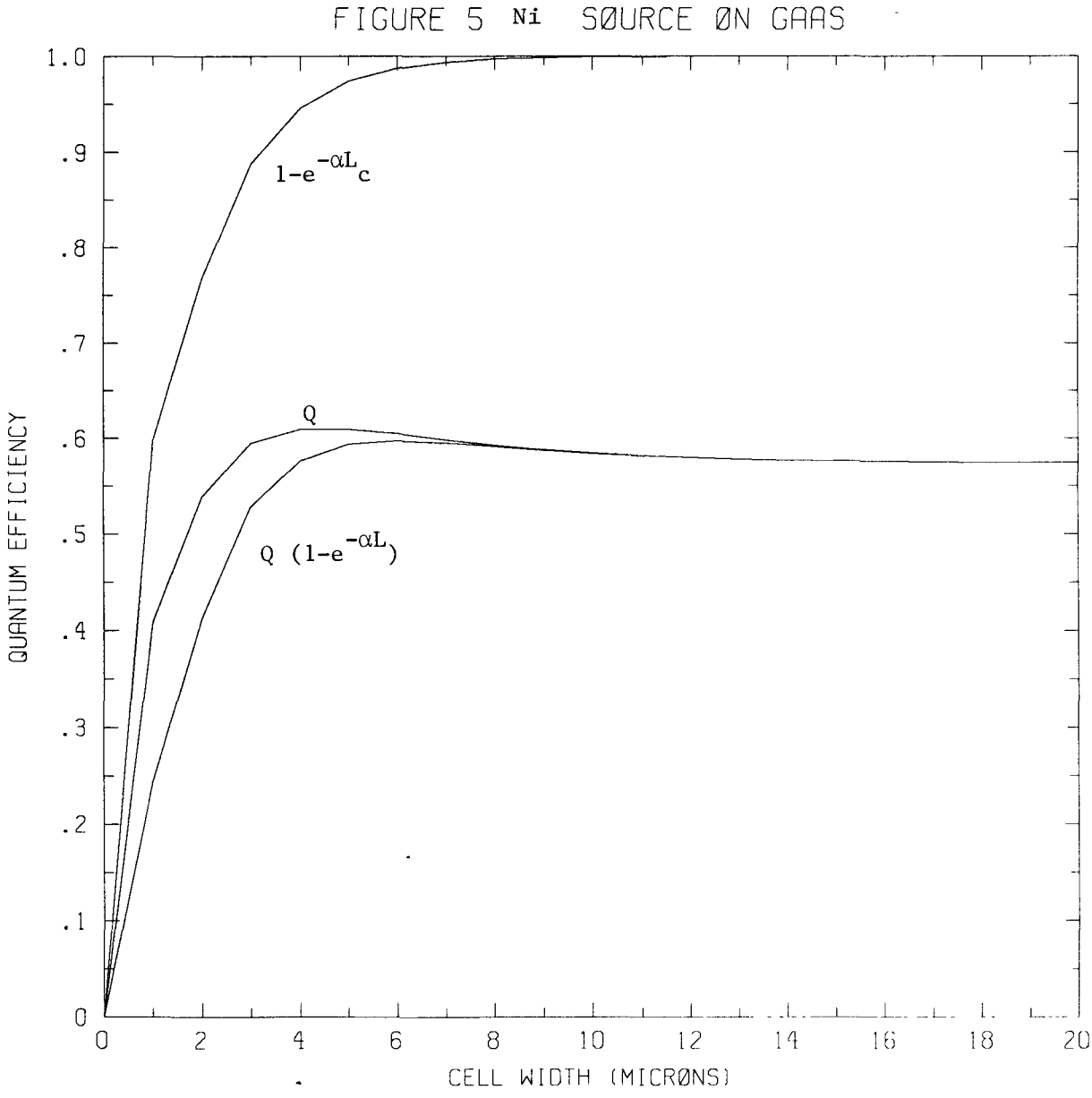


FIGURE 5 Ni SØURCE ØN GAAS
QUANTUM EFFICIENCY
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
$1-e^{-\alpha L_c}$
Q
Q $(1-e^{-\alpha L})$
0
2
4
6
8
10
12
14
16
18
20
CELL WIDTH (MICRØNS)

FIGURE 6 (NI AND PM) SØURCE ØN GAAS

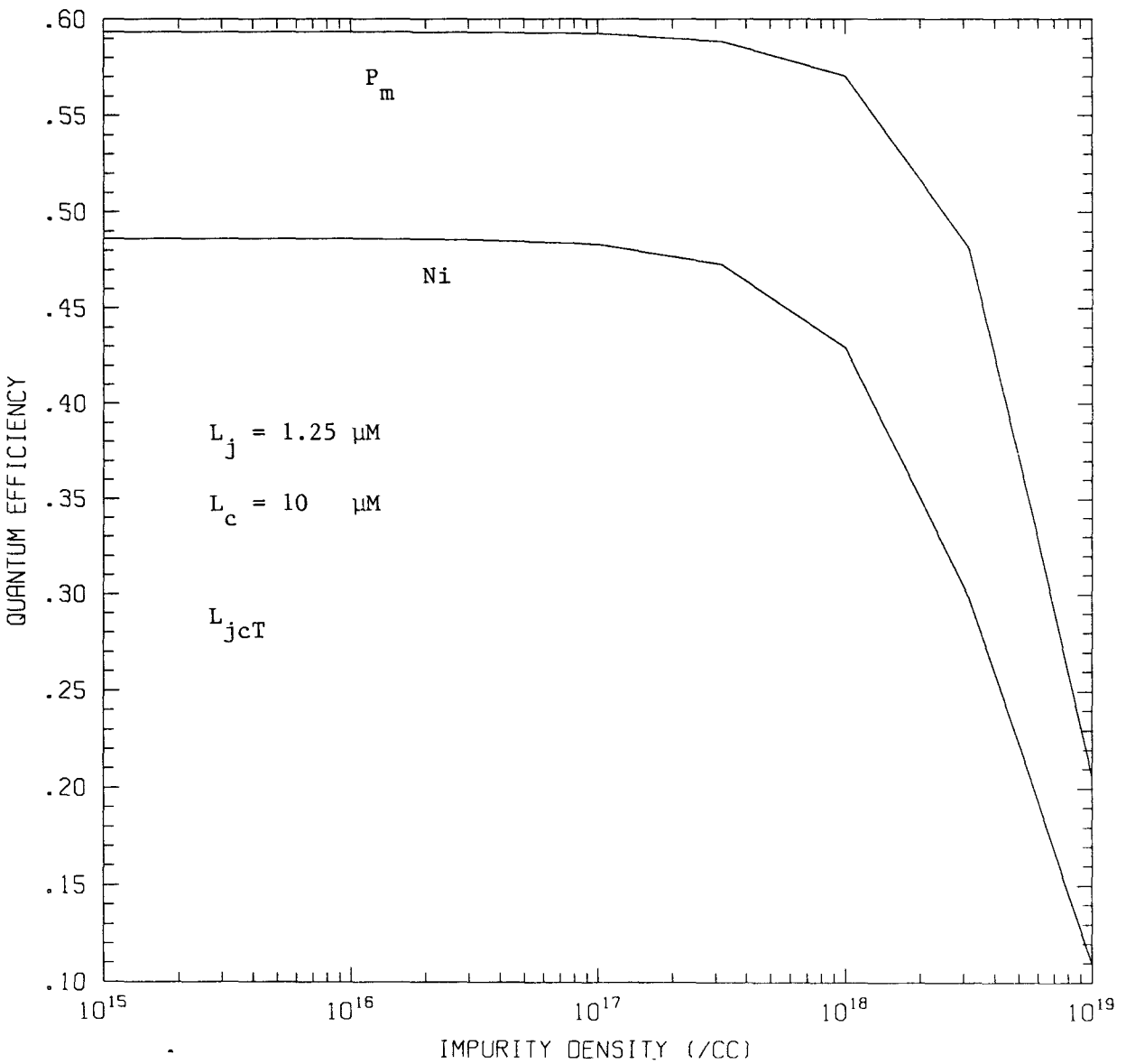


FIGURE 7 ELECTRØN RANGE ENERGY RELATIØN

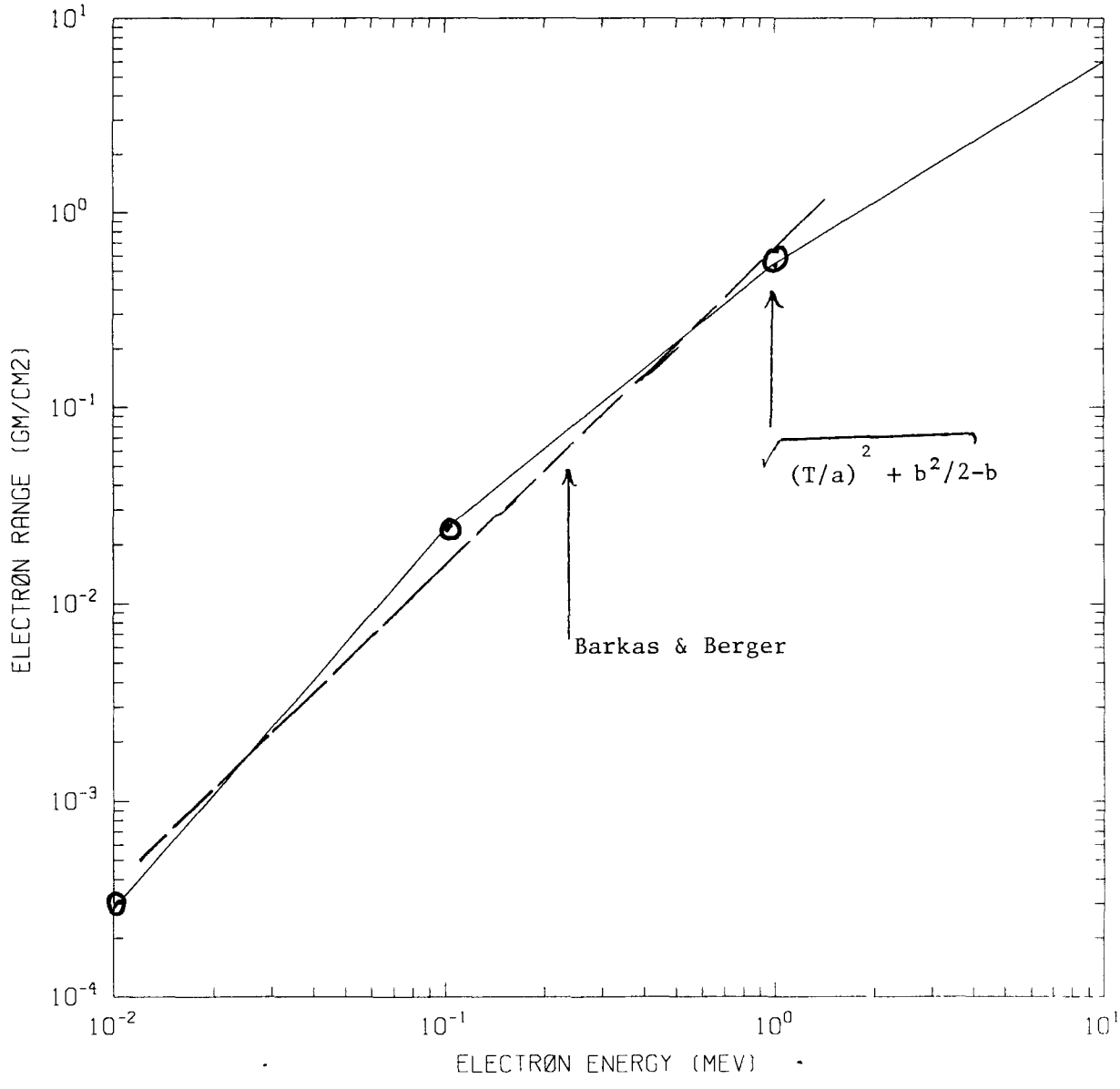


FIGURE 8 INTEGRAL FLUENCE FØR NI AND PM

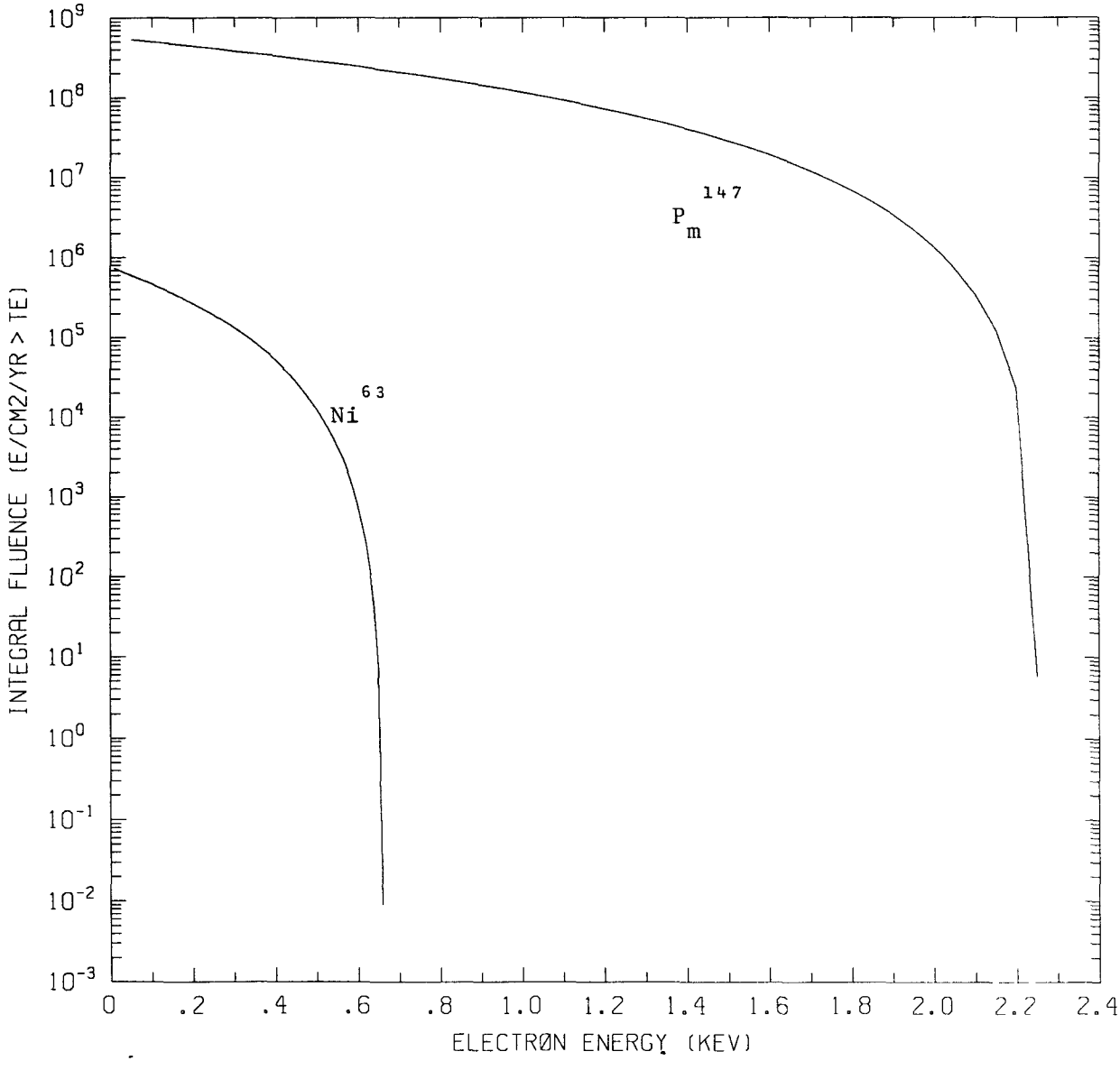


FIGURE 9 DØSE DEPTH PRØFILE BY NICKEL S

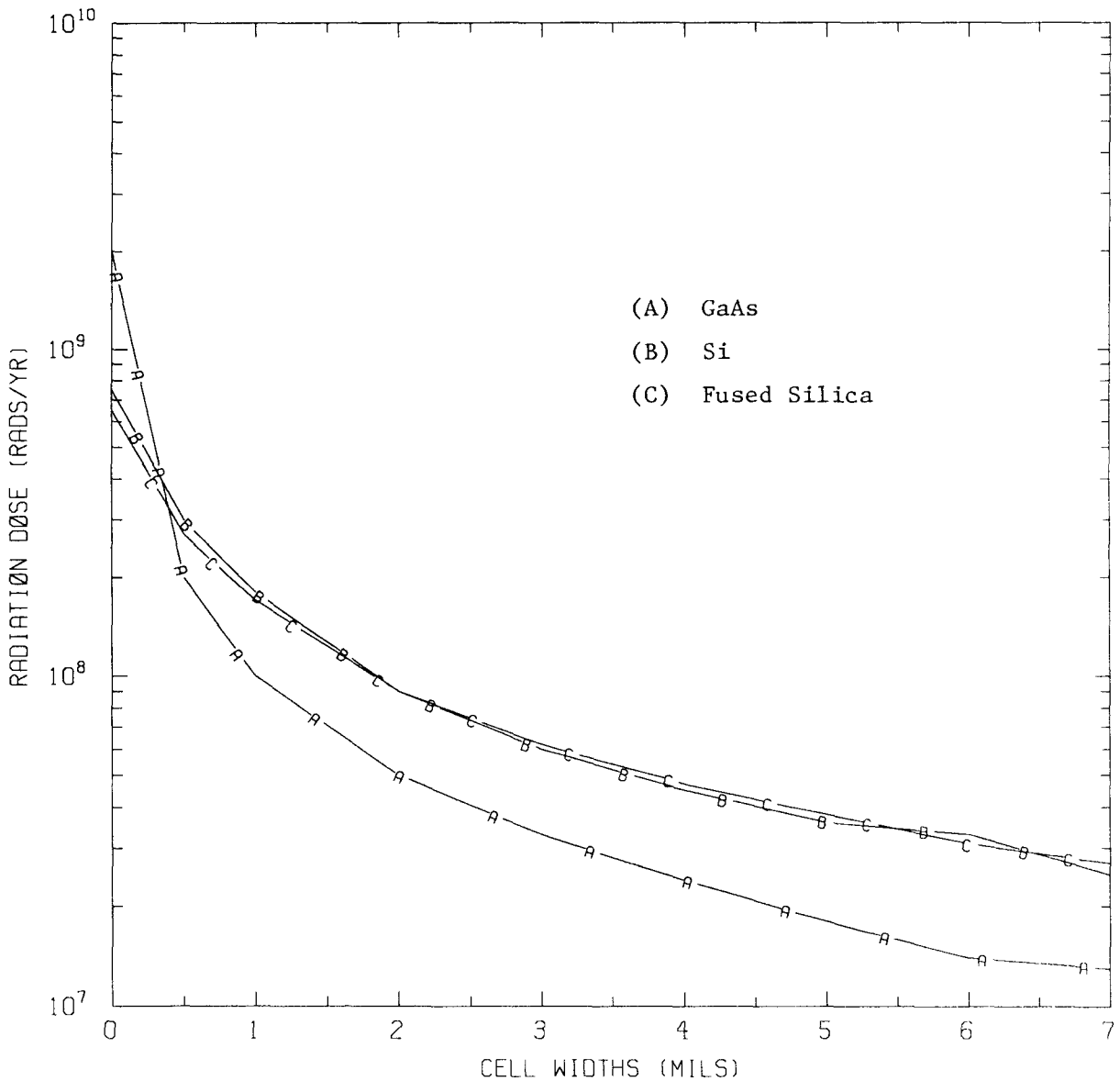


FIGURE 10 DØSE DEPTH PRØFILE BY PM SØURCE

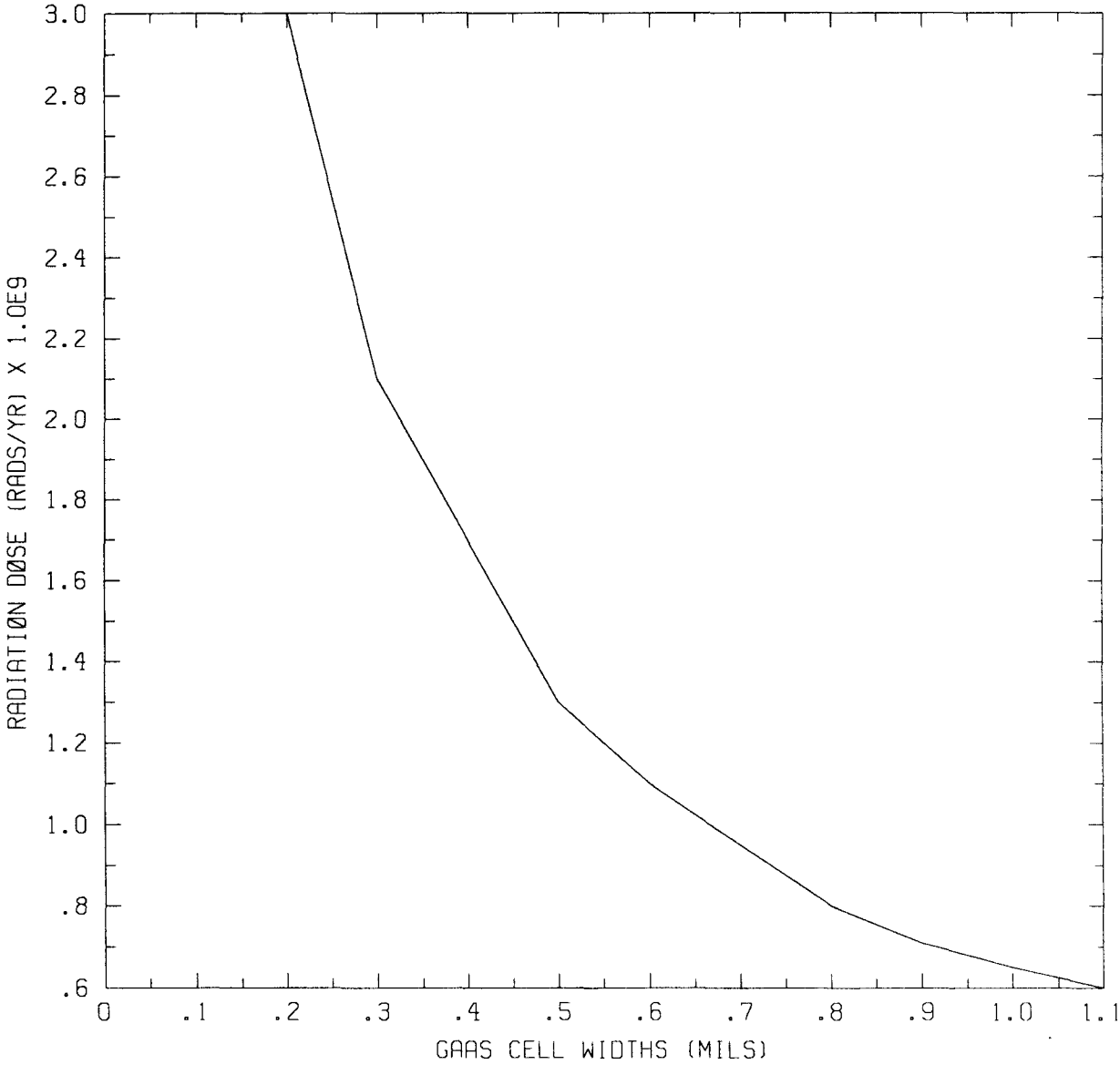


FIGURE 11 NICKEL SØURCE ØN GAAS

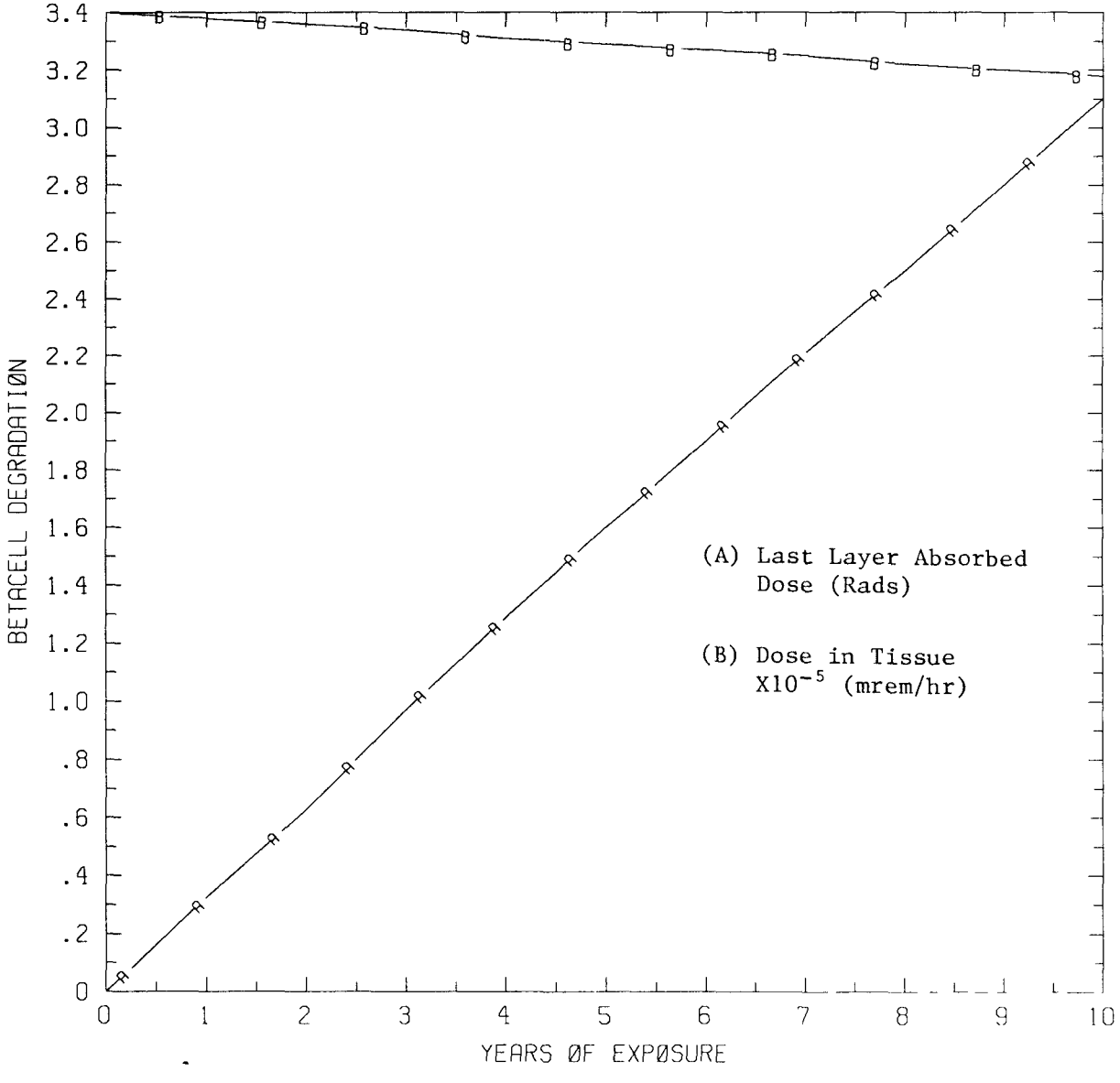


FIGURE 12 NICKEL SØURCE ØN GAAS

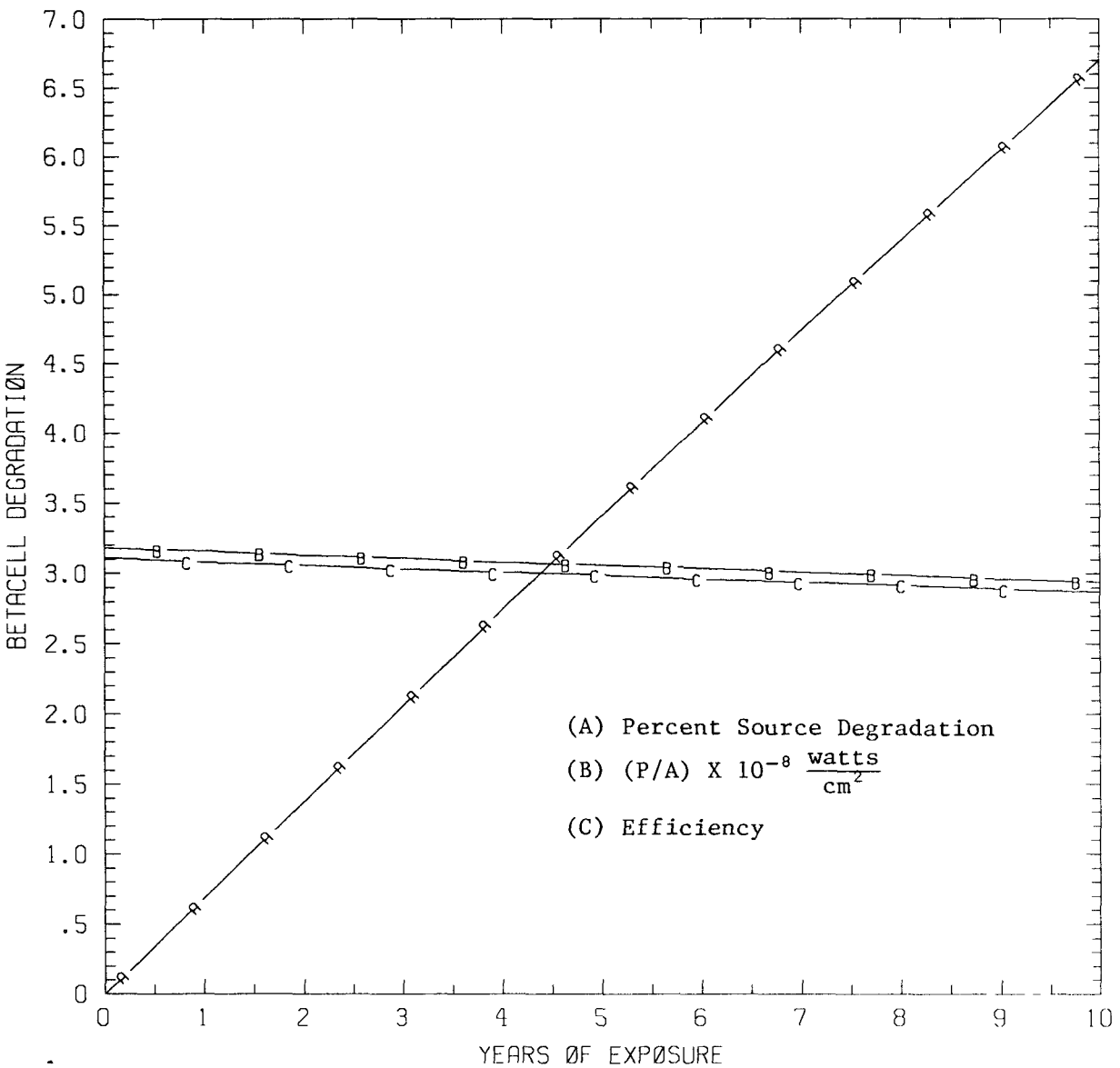
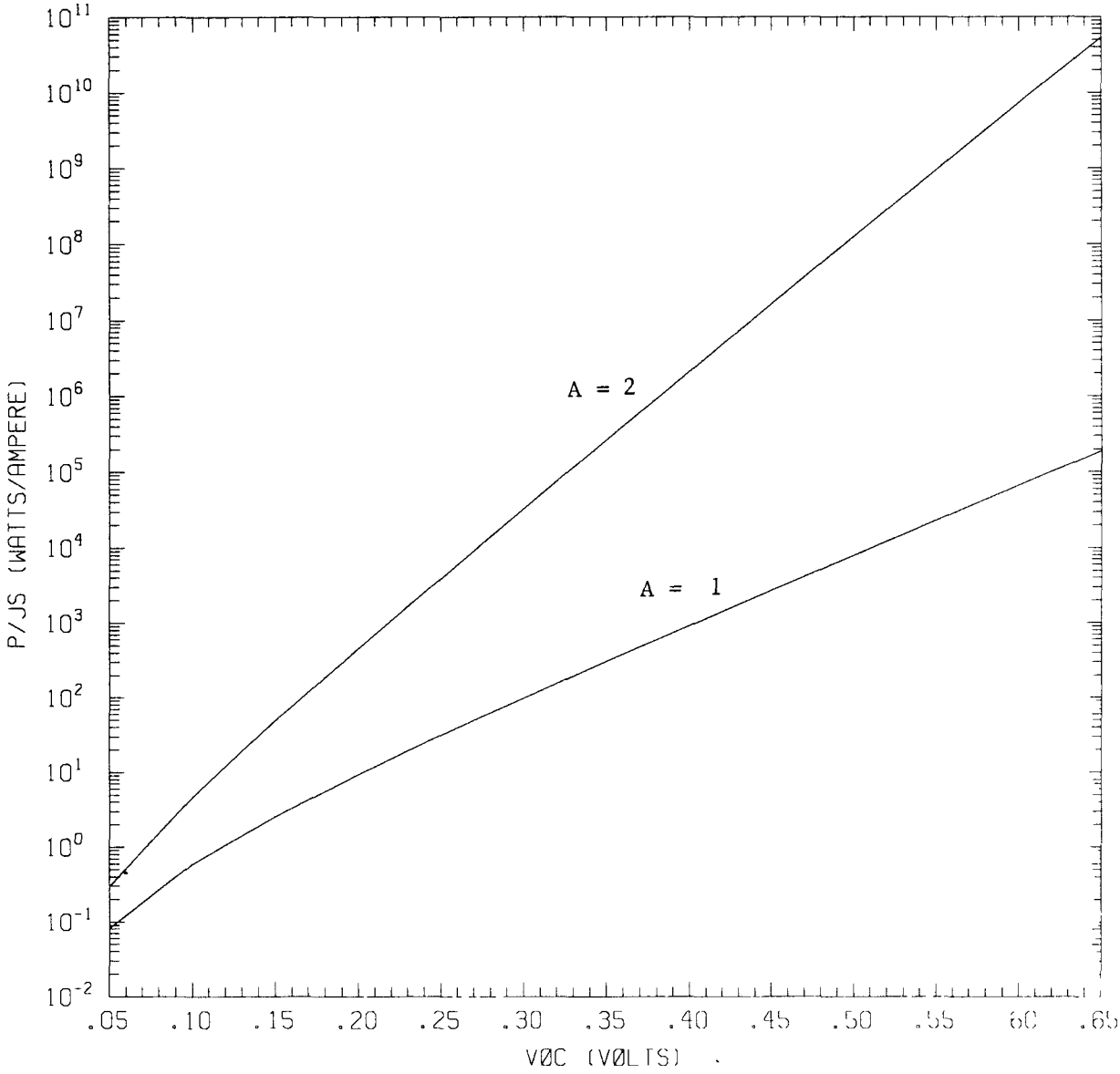


FIGURE 13 PERFECTIØN PARAMETER A



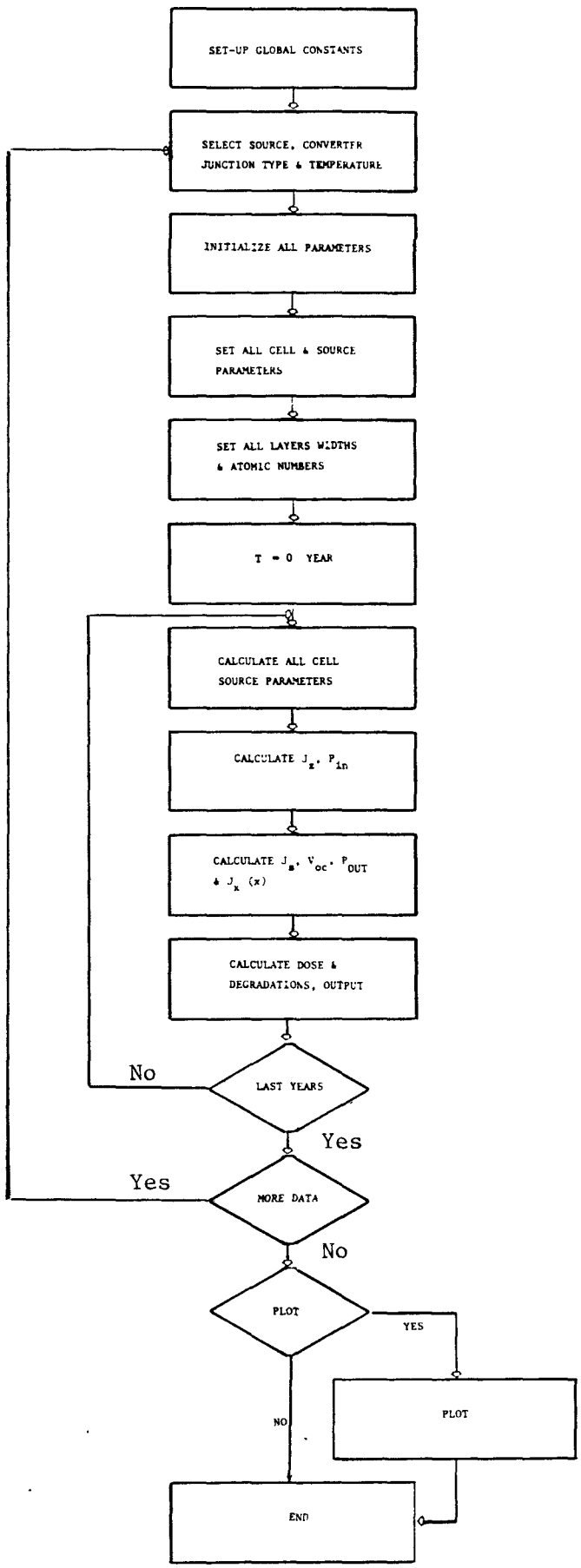


FIGURE 14. BCELL Flow Chart

Figure 15

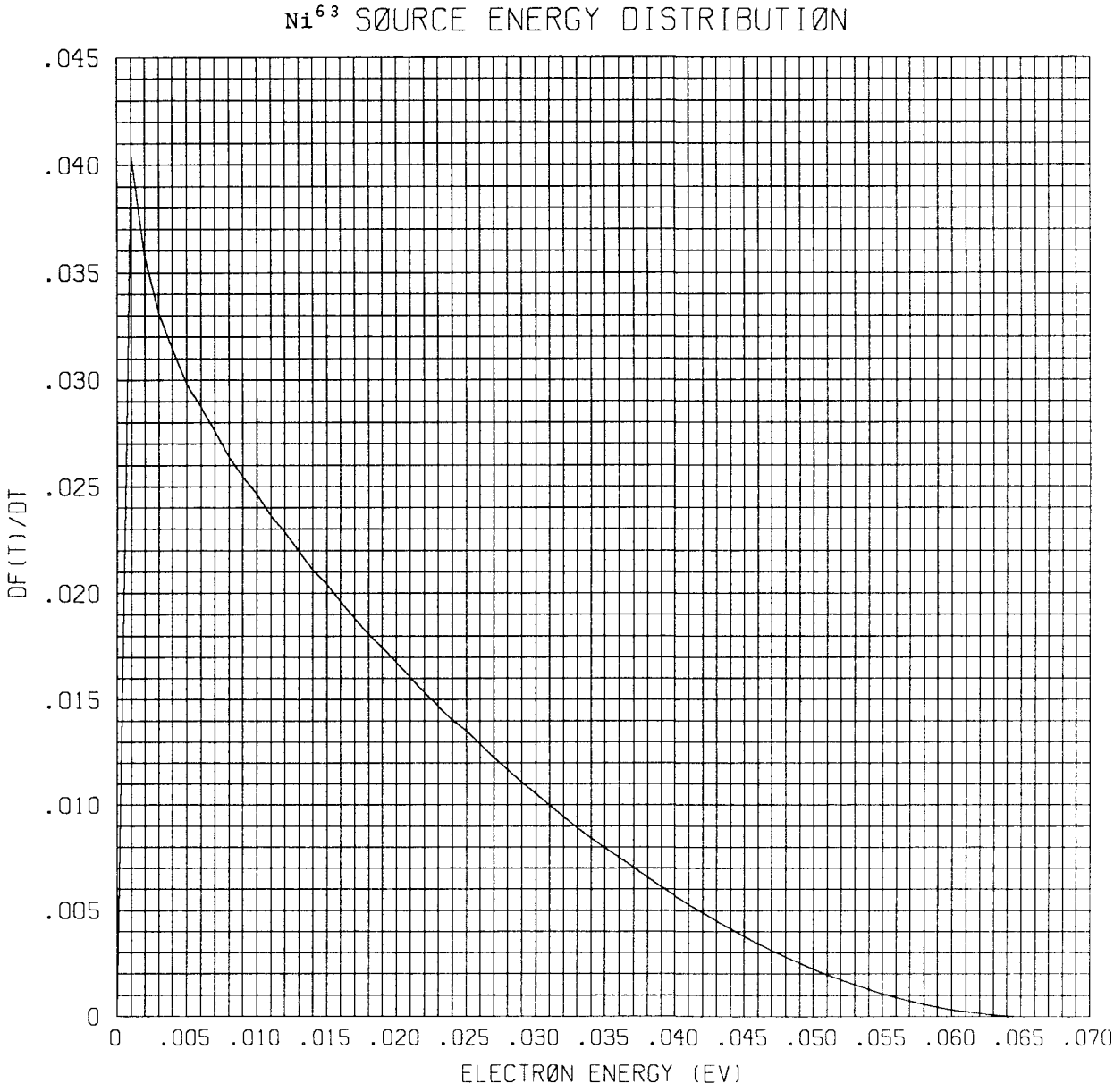
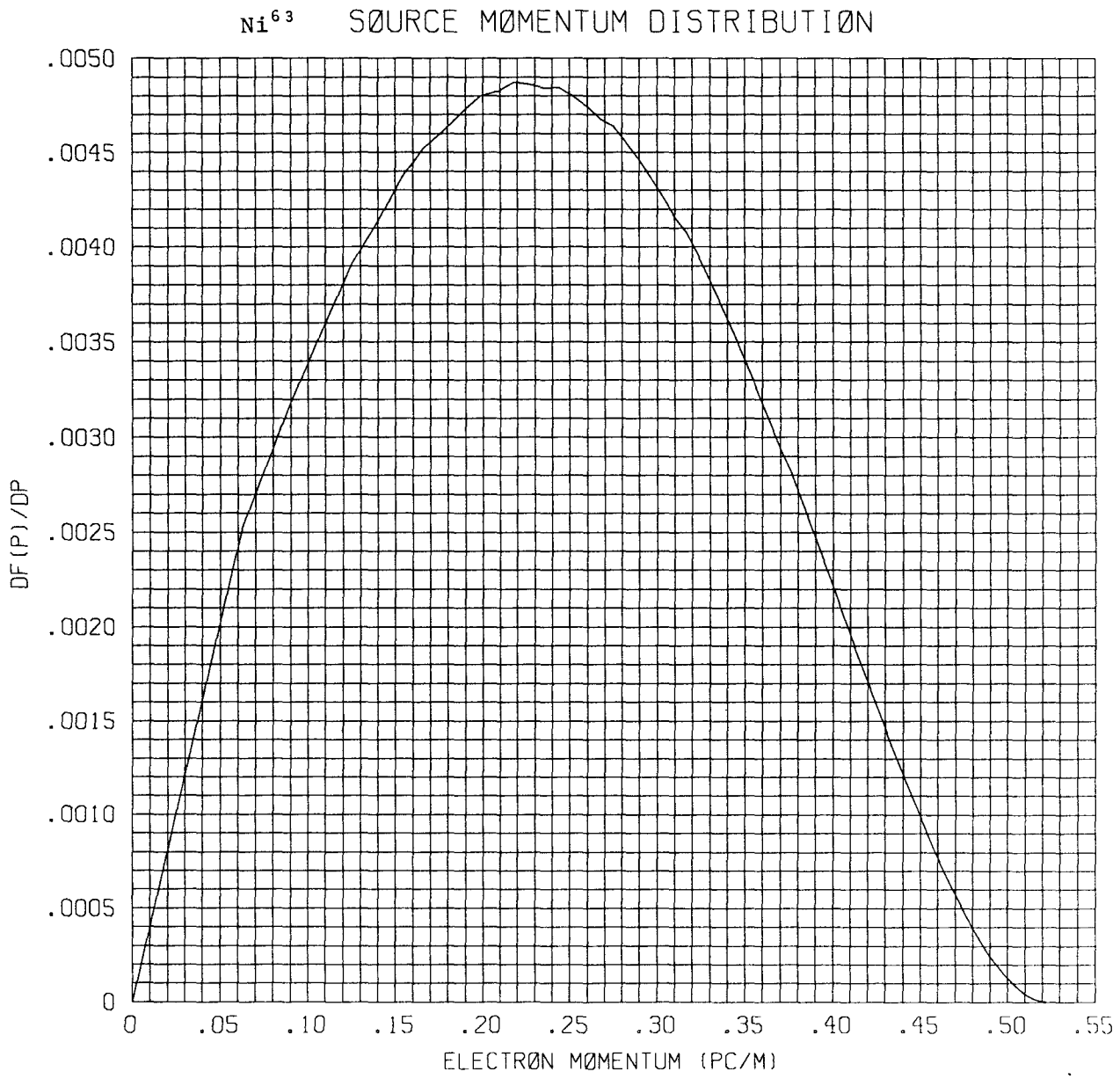

Ni63 SØURCE ENERGY DISTRIBUTIØN
.045
.040
.035
.030
.025
.020
.015
.010
.005
0
DF(T)/DT
0 .005 .010 .015 .020 .025 .030 .035 .040 .045 .050 .055 .060 .065 .070
ELECTRØN ENERGY (EV)

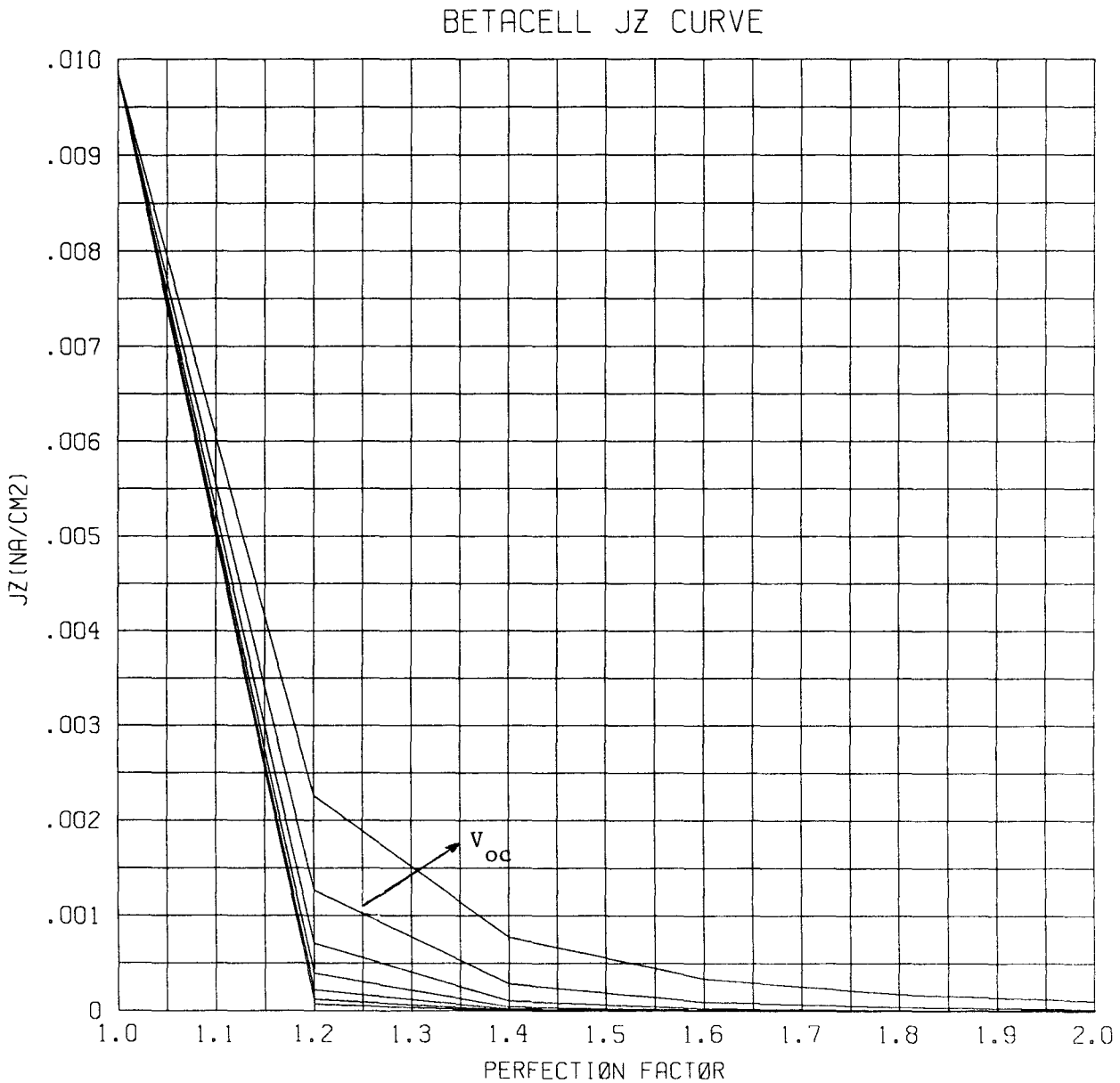
Figure 16


Ni63 SØURCE MØMENTUM DISTRIBUTIØN
.0050
.0045
.0040
.0035
.0030
.0025
.0020
.0015
.0010
.0005
0
DF(P)/DP
0
.05
.10
.15
.20
.25
.30
.35
.40
.45
.50
.55
ELECTRØN MØMENTUM (PC/M)

SØURCE WIDTH FØR ØPTIMUM PØWER
110
100
90
80
70
60
50
40
30
20
10
0
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
SØURCE WIDTH(MICRØNS)

Figure 17

Figure 18


BETACELL JZ CURVE
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
0
JZ(NA/CM2)
V_{oc}
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
PERFECTIØN FACTØR

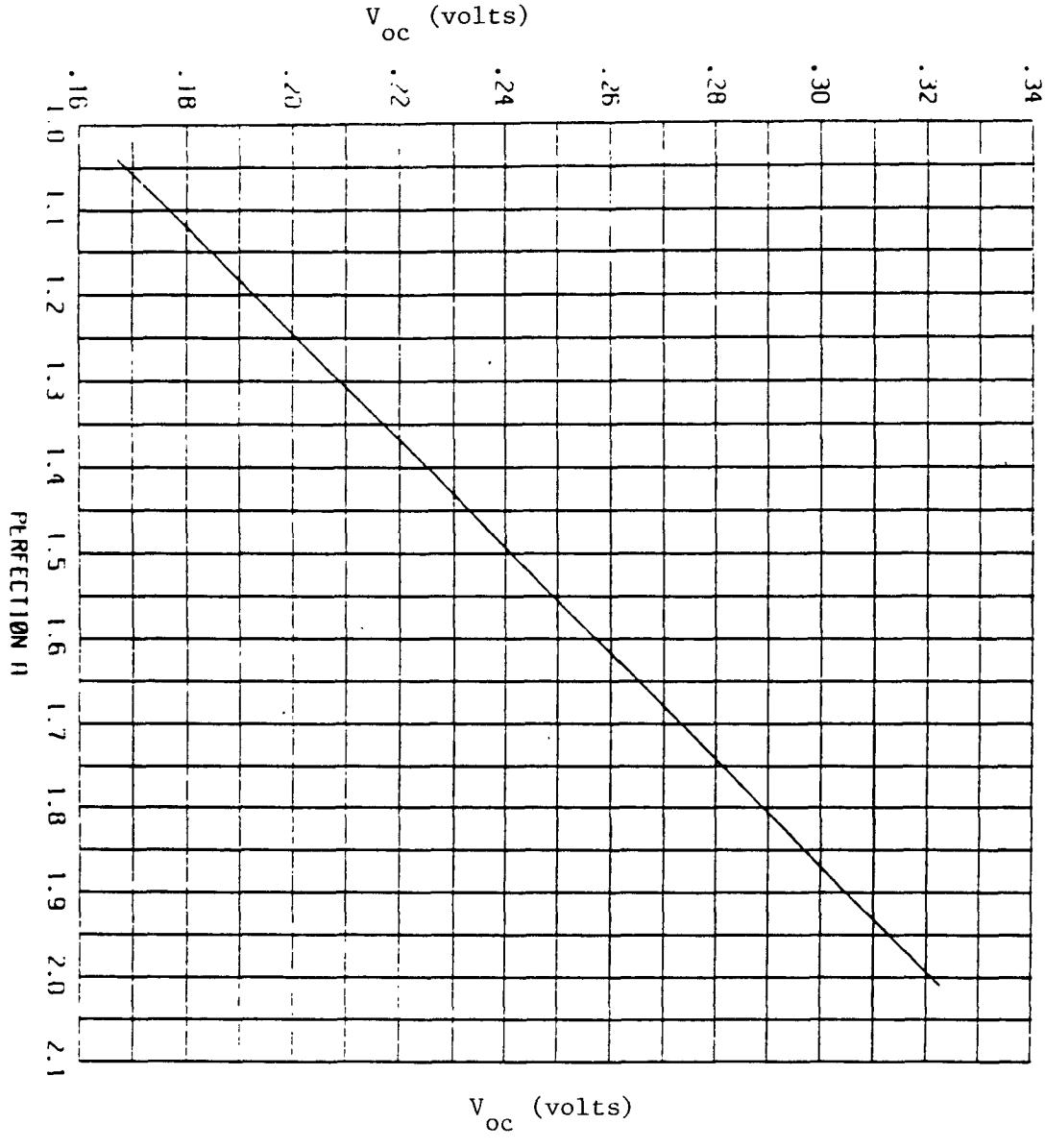


Figure 19 - Open Circuit Voltage

Figure 20

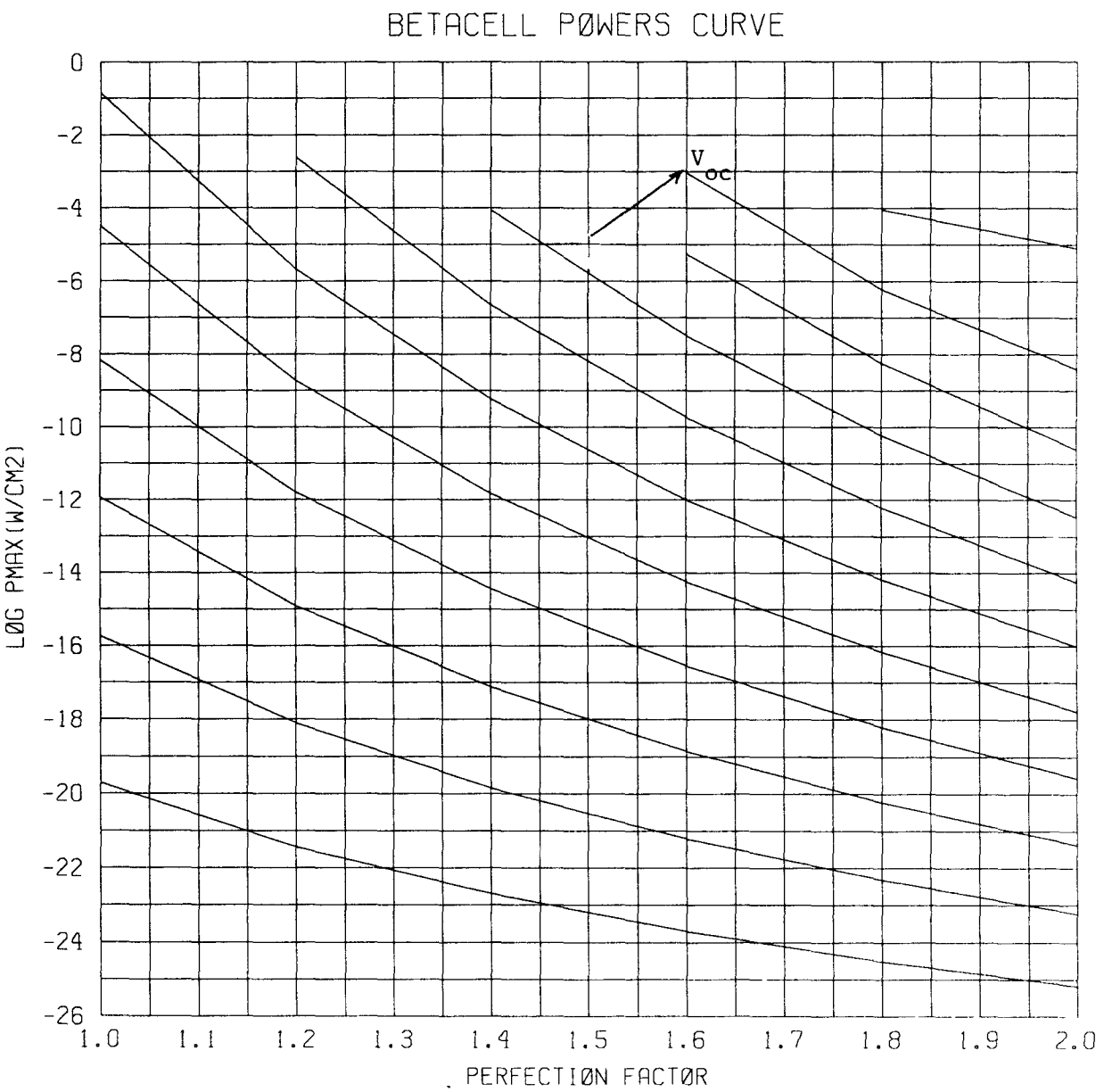

BETACELL PØWERS CURVE
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
LØG PMAX(W/CM2)
V_{oc}
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
PERFECTIØN FACTØR

Figure 21

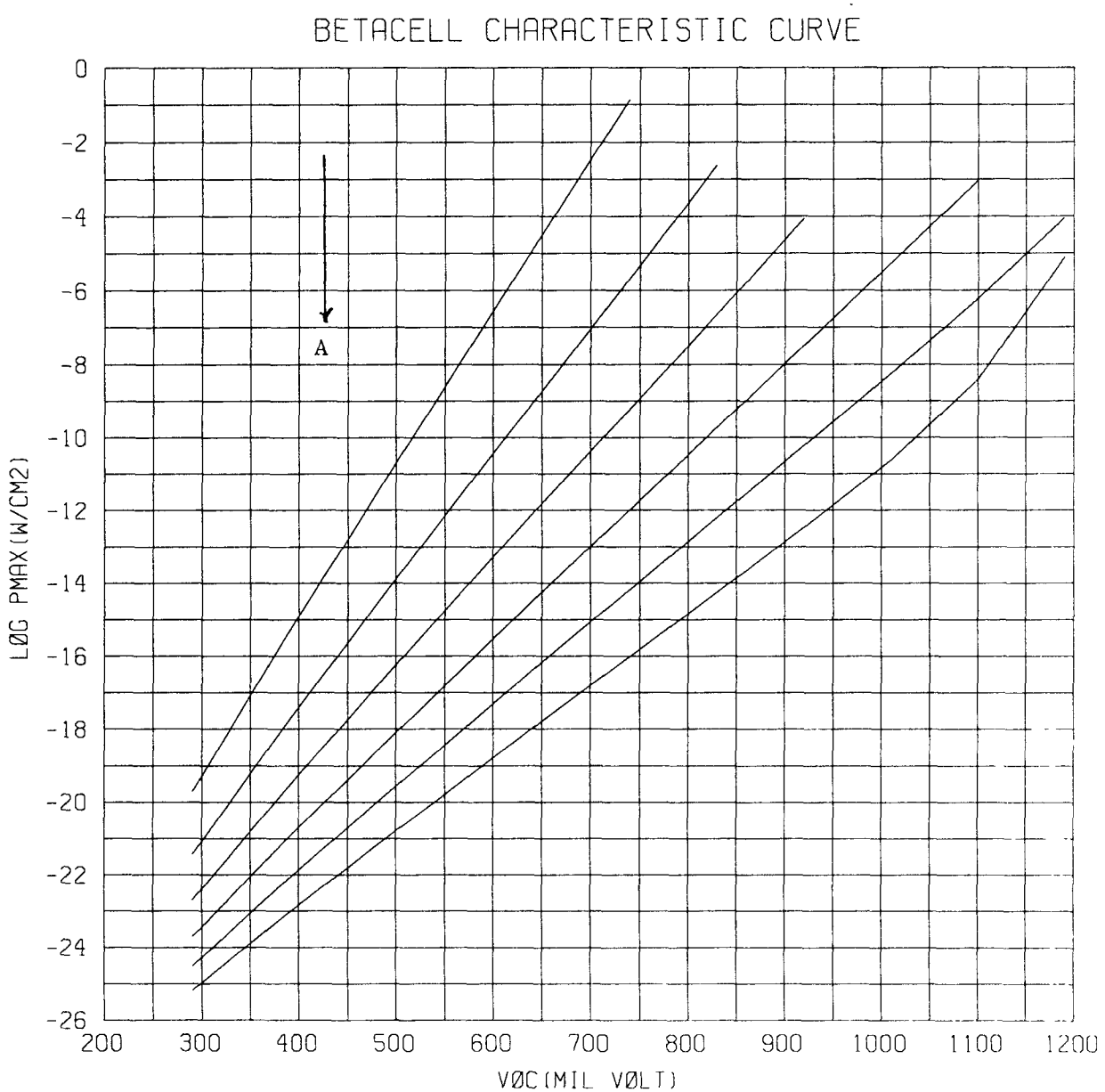

BETACELL CHARACTERISTIC CURVE
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
A
LØG PMAX(W/CM2)
200
300
400
500
600
700
800
900
1000
1100
1200
VØC(MIL VØLT)

Figure 22

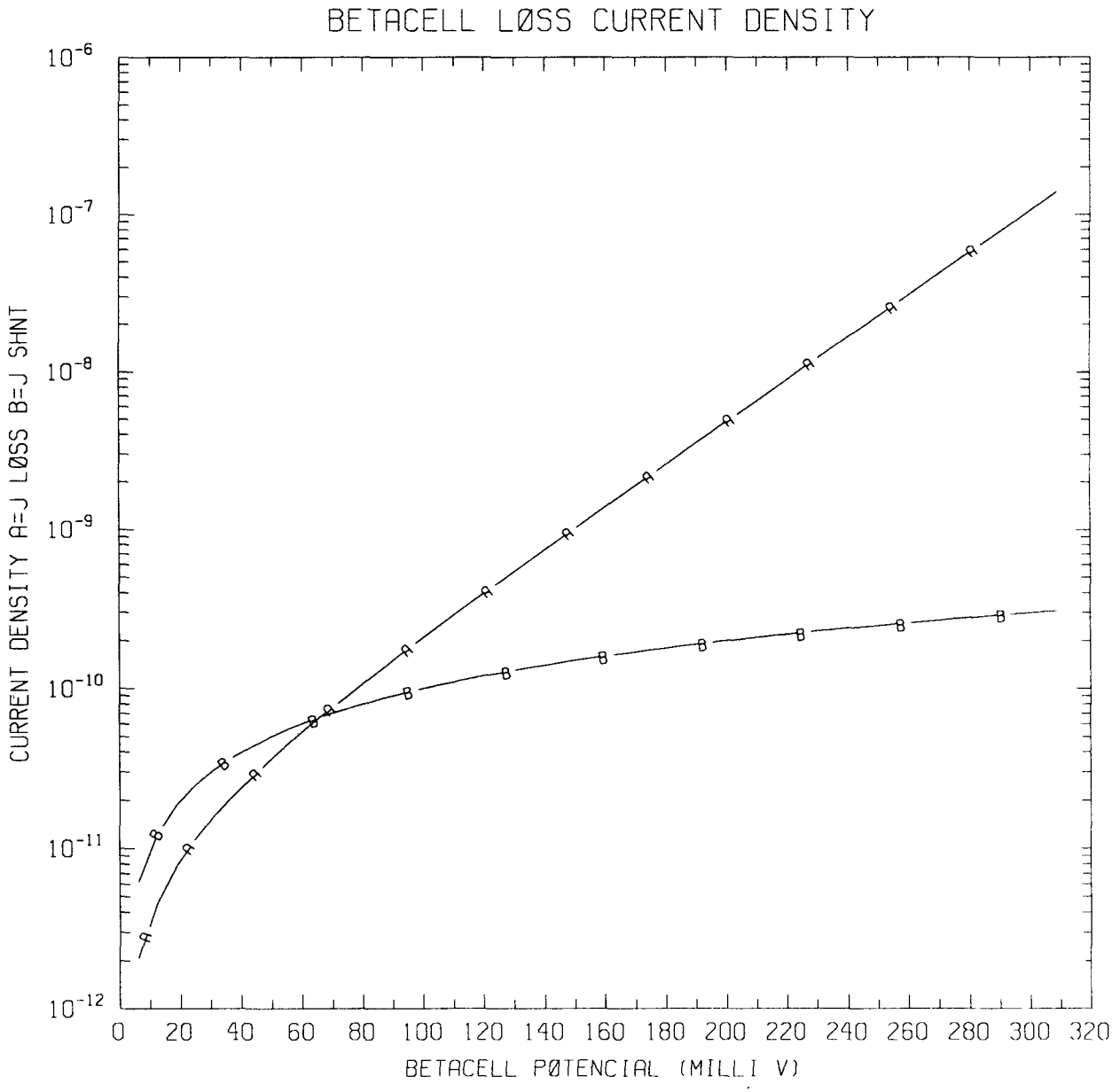
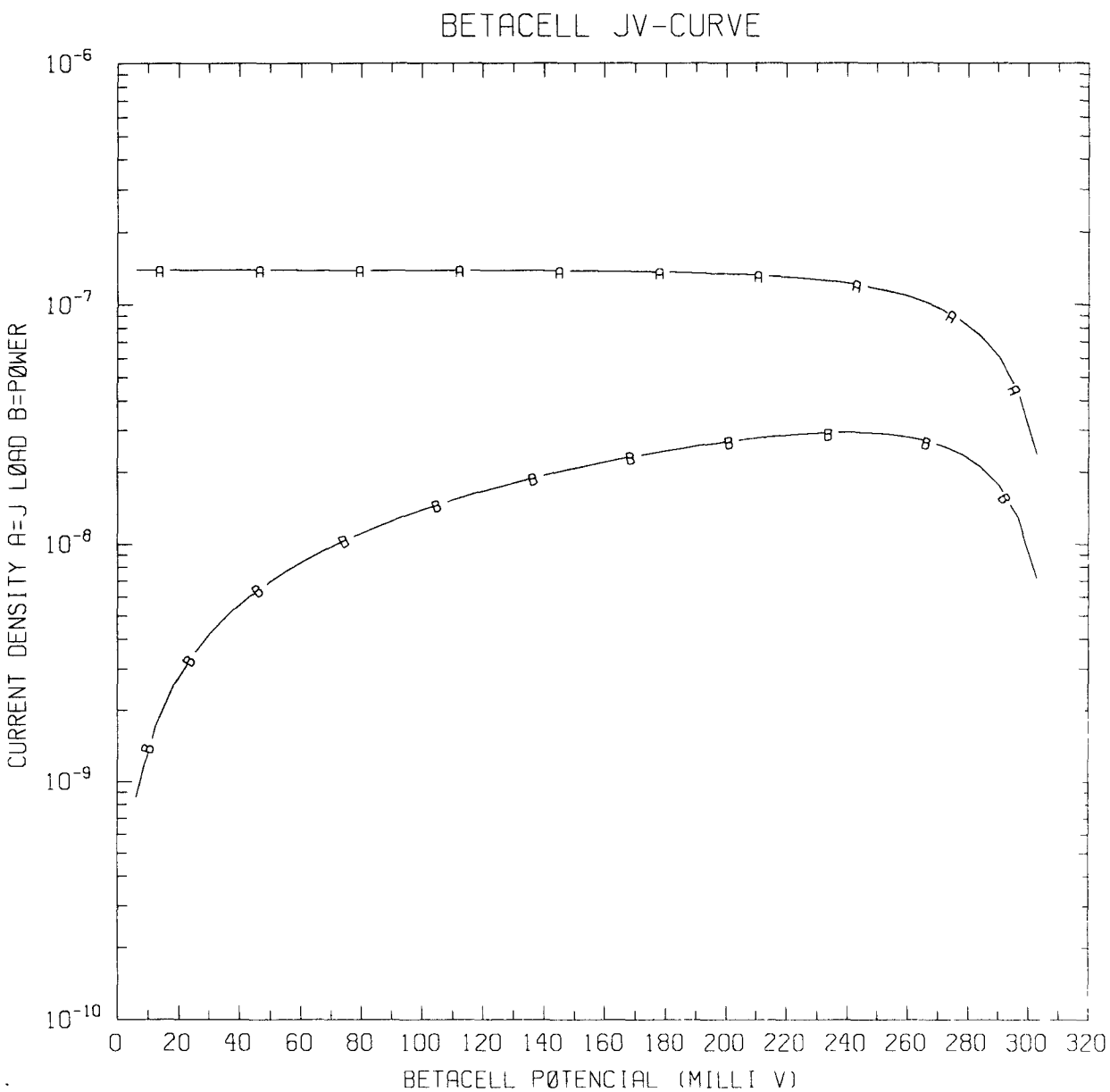

BETACELL LØSS CURRENT DENSITY
CURRENT DENSITY A=J LØSS B=J SHNT
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320
BETACELL PØTENCIAL (MILLI V)

Figure 23


BETACELL JV-CURVE
CURRENT DENSITY A=J LØAD B=PØWER
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320
BETACELL PØTENCIAL (MILLI V)

BCELL SOURCE LISTING

```
0001    C FILE BETA.FOR
0002    C     PROGRAM TO SIMULATE A BETACELL BASED ON THE BETAVOLTAIC
0003    C     CONCEPT
0004    C
0005          PARAMETER (M=51)
0006          DIMENSION PLOTP(1:M,1:2),PLOTZ(1:M,1:2),PLOTV(1:M)
0007          DIMENSION PM(1:7,1:2),FEF(1:235),OMEW(50)
0008          COMMON/SPEC/FE(1:235),TT(1:235),NR,FLUX
0009          COMMON/RANG/AX,BX
0010          COMMON/CONT/H,E,MZ,PI,EE,AB,ZB,CL,TOH,TC,SIGCAP,DECY
0011          COMMON/DCY/JS,VMZ,FF,TOTP,AREAC,PVOL,TVOL,PINT,ETA
0012          COMMON/CONV/ZC,AC,ZOA,RHOX,ION,FAC
0013          COMMON/SUBST/CS3,ZS3,AS3,RHOS3,CS2,ZS2,AS2,RHOS2,CM,RHOM
0014          COMMON/LENG/TEMAX,TEAVE,ACTIV,RHOB,W,KK,YUC,RHOC
0015          COMMON/CEFF/DIFLE,DIFLH,CELT,DEPL,MUC,OMRC,CC
0016          COMMON/CU/AKTA,VMAX,JZ,JZR,JZG,XNN,KT
0017          COMMON/PLOT/IPLOT
0018          LOGICAL TAPE4,TAPE5,TAPE6,TAPE7,TAPE8
0019          REAL KZ,MZ,NZ,NSTR,OEV,NA,NC,ND,JZ,KT,MUB,LAM,JB,IB
0020          REAL JS,JJ,JMP,JL,JSM,MUC,ION,ME,MH,JZG,JZR,JV,JP
0021          REAL N,NI,NNZ,NPZ
0022          DATA PM/147.,61.,7.22,.2247,2.62,4HPM(1,4H47 ),
0023         1        63.,28.,8.90,.0659,100.,4H NI(,4H63 )/
0024    C
0025    C     FUNCTION
0026          FION(Y)=Y*(9.76+58.8/(Y**1.19))
0027          XMS(X,Y)=(X+(1.-X)*Y)
0028    C     WITP(X)=(X/1.63E4)**.42
0029    C     WITN(X)=ALOG(X/3.8E-5)/1.0E+4
0030    C
0031          OPEN(4,FILE='BCELL.DAT4',STATUS='UNKNOWN')
0032          OPEN(5,FILE='BCELL.DAT5',STATUS='UNKNOWN')
0033          OPEN(6,FILE='BCELL.DAT6',STATUS='NEW')
0034          OPEN(7,FILE='BCELL.DAT7',STATUS='UNKNOWN')
0035          OPEN(8,FILE='BCELL.DAT8',STATUS='UNKNOWN')
0036          REWIND 4
0037          REWIND 5
0038          REWIND 6
0039          REWIND 7
0040          REWIND 8
0041    C
0042    C     GENERAL CONSTANTS ARE
0043    C-------------------------
0044          H=6.62517E-27
0045          KZ=8.6164E-5
0046          E=1.6026E-19
0047          CL=2.99793E10
0048          MZ=9.1083E-28
0049          NZ=6.02486E23
0050          OEVE=1.60206E-12
0051          OEVK=1.1605E4
0052          EPSZ=8.85434E-14
0053          NC=3.7E10
0054          RHOSI=2.328
0055          TC=3600*24*365
0056          PI=3.141592654
0057          EE=2.7182818281828
```

```
0058          TPI=2.0*PI
0059          FPI=4.0*PI
0060          C23=2./3.
0061          SQR2=1.0/SQRT(2.)
0062          ALFA=.9
0063          CNZ1=2*(TPI*OEVE)**1.5
0064          EOH=E/H
0065          HOM=H/MZ
0066          FEGL=0.5
0067    C     .5 < FEGL < 1.0
0068          FP=1.0
0069          FQ=1.0
0070    C
0071       99 PRINT *, 'MORE DATA ?   Y=1/N=0'
0072          READ *,YN
0073       98 FORMAT(A1)
0074          IF(YN.EQ.0)PRINT *, 'YOU ARE DONE  FOR THIS RUN'
0075          IF(YN.EQ.0)STOP
0076    C----------------------
0077          PRINT *,'ID ITYPE JD YR AYR IC KMAX MC ASSY FACE PERF IPLOT'
0078    C     READ *, ID,ITYPE,JD,YI,AYR,IC,KMAX,MC,ASSY,FACE,PERF,IPLOT
0079          READ(4,*,END=26,ERR=27)ID,ITYPE,JD,YI,AYR,IC,
0080         1KMAX,MC,ASSY,FACE,PERF,IPLOT
0081          WRITE(6,3)ID,ITYPE,JD,YI,AYR,IC,KMAX,MC,ASSY,FACE,PERF,IPLOT
0082          GO TO 28
0083    C--------------------
0084    C
0085        3 FORMAT(1H1,3I5,2F5.1,3I5,3F6.1,I3)
0086       26 PRINT *,'THERE IS NO MORE DATA ON DAT4'
0087          STOP 26
0088       27 PRINT *,'ERROR ON DAT4'
0089          STOP 27
0090       28 KK=0
0091          TYPE1=4HP-TY
0092          TYPE2=2HPE
0093          IF(ITYPE.EQ.1)TYPE1=4HN-TY
0094          IF(IC.EQ.1)ND=5.0E17
0095          IF(IC.EQ.2.OR.IC.EQ.3)ND=1.0E18
0096          IF(IC.EQ.4)ND=5.0E16
0097    C     D=(5.0/8.)*2.54
0098          D=2.0*SQRT(1.0/PI)
0099          AREA=PI*(D/2)**2
0100    C     FR=.50522
0101          FR=1.0
0102          AREAC=FR*AREA
0103    C     USED FORE EMISSION
0104    C     ACTIVE AREA
0105    C     ONE SIDE
0106          ANGD=1.0
0107          RB=.030
0108    C     SHNT=1.0E-7
0109          SHNT=1.0E-9
0110          RSER=0.
0111          CELSI=10.
0112          CELGA=10.
0113          TZERO=225.0
0114          TNOT=45.0
```

```
0115     C      IF(ID.EQ.1)PERF=2.
0116     C      IF(ID.EQ.2)PERF=1.15
0117            DTEMP=25.0
0118     C
0119     C-------------------------------------------------------
0120     C      BETA EMMITER INPUT
0121            JY=INT(YI)
0122            IY=JY+2
0123            IF(JY.EQ.YI)IY=IY-1
0124            IR=1
0125            NM=1
0126            LL=0
0127            LAST=3
0128            IF(JD.EQ.LAST)NM=LAST-1
0129            DO 60 NIS=1,NM
0130            NON=NIS
0131            IF(JD.NE.LAST)NON=JD
0132            LL=LL+1
0133            AB=PM(1,NON)
0134            ZB=PM(2,NON)
0135            ZOAB=ZB/AB
0136            RHOB=PM(3,NON)
0137     C      RHOB=6.4
0138            TEMAX=PM(4,NON)
0139            TOH=PM(5,NON)*TC
0140            TITB1=PM(6,NON)
0141            TITB2=PM(7,NON)
0142            IF(ID.EQ.1)TIT1=4HPN C
0143            IF(ID.EQ.1)TIT2=4HONT
0144            IF(ID.EQ.2)TIT1=4HSCHO
0145            IF(ID.EQ.2)TIT=4HTTKY
0146            IF(LL.GT.1)GO TO 1
0147     C
0148     C      CONVERTER SYSTEM INPUT
0149     C--------------------------
0150     C      (A) METAL
0151            TITM1=4HAU(1
0152            TITM2=4H97)
0153            IF(ID.EQ.1)TITM1=4H
0154            IF(ID.EQ.1)TITM2=4H
0155            AM=197
0156            ZM=79
0157            CM=200.0E-8
0158            RHOM=19.7
0159            ADENM=NZ*RHOM/AM
0160            ZOAM=ZM/AM
0161            IF(ID.EQ.1)CM=0.
0162     C
0163            GO TO (31,32,33,34),IC
0164     C      (B) CONVERTER (1) SI
0165        31  TITC1=4HSI(2
0166            TITC2=4H8)
0167            XF=0.
0168            AC=28.08
0169            ZC=14
0170            ZOA=ZC/AC
0171            PHI=.78
```

```
0172            EGAPZ=1.165
0173            ME=.98
0174            MH=.55
0175            XMSE=ME
0176            XMSH=MH
0177            EPSS1=11.8*EPSZ
0178            TAUE=1.0E-6
0179            TAUH=1.452E-5
0180            AEG=7.02E-4
0181            BEG=1108.
0182            RHOC=RHOSI
0183            ION=FION(ZC)
0184            ADENC=NZ*RHOC/AC
0185            GO TO 35
0186      C
0187      C-----(2)GALLIUM ARSENIDE
0188         32 TITC1=4HGAAS
0189            TITC2=4H
0190            XF=.00
0191            ZC1=31.
0192            ZC2=33.
0193            AC1=69.72
0194            AC2=74.91
0195            AC=AC1+AC2
0196            RHOC1=5.93
0197            RHOC2=5.73
0198            EGAPZ=1.52
0199            PHI=.90
0200            ME=.067
0201            MH=.47
0202            XMSE=ME
0203            XMSH=MH
0204            XMSE1=XMSE
0205            XMSH1=XMSH
0206            EPSS1=10.9*EPSZ
0207      C     APPROX
0208            EGAPZ=1.519
0209            AEG=5.405E-4
0210            BEG=204.0
0211            F1=AC1/AC
0212            F2=AC2/AC
0213            ZC=F1*ZC1+F2*ZC2
0214            ADENC1=NZ*RHOC1/AC1
0215            ADENC2=NZ*RHOC2/AC2
0216            ADENC=(AC1*ADENC1*F1+ADENC2*F2*AC2)/AC
0217            ZOA=(ZC1/AC1*RHOC1+ZC2/ZC2*RHOC2)/(RHOC1+RHOC2)
0218            XION1=ALOG(FION(ZC1))
0219            XION2=ALOG(FION(ZC2))
0220            SS=(ZC1/AC1)*RHOC1*XION1 +(ZC2/AC2)*RHOC2*XION2
0221            SY=1.0/ZOA/(RHOC1+RHOC2)
0222            ION=EXP(SY*SS)
0223            RHOC=F1*RHOC1+F2*RHOC2
0224      C     RHOC=5.653
0225            GO TO 35
0226      C
0227      C-----(3)AL(X)GA(1-X)AS
0228         33 TITC1=4HAXG1
```

```
0229            TITC2=4H-XAS
0230            XF=.50
0231            ZC1=(1.-XF)*31+13.0*XF
0232            ZC2=33.
0233            AC1=(1.0-XF)*69.72+2.7*XF
0234            AC2=74.91
0235            AC=AC1+AC2
0236            RHOC1=(1.-XF)*5.93+2.7*XF
0237            RHOC2=5.73
0238            PHI=.90
0239      C     CNZ=4.7E17
0240      C     CPZ=7.0E18
0241      C     CONCI=1.79E6
0242            ME=.068
0243            MH=.50
0244            XMSE=(XF-(1.0-XF)*ME)
0245            XMSH=(XF-(1.0-XF)*MH)
0246            XMSH1=MH
0247            XMSE1=ME
0248            EPSS1=12.8*EPSZ
0249      C     APPROX
0250            EGAPZ=1.52+0.7765*XF
0251            AEG=5.405E-4
0252            BEG=204.0
0253            F1=AC1/AC
0254            F2=AC2/AC
0255            ZC=F1*ZC1+F2*ZC2
0256            ADENC1=NZ*RHOC1/AC1
0257            ADENC2=NZ*RHOC2/AC2
0258            ADENC=(AC1*ADENC1*F1+ADENC2*F2*AC2)/AC
0259            ZOA=(ZC1/AC1*RHOC1+ZC2/ZC2*RHOC2)/(RHOC1+RHOC2)
0260            XION1=ALOG(FION(ZC1))
0261            XION2=ALOG(FION(ZC2))
0262            SS=(ZC1/AC1)*RHOC1*XION1 +(ZC2/AC2)*RHOC2*XION2
0263            SY=1.0/ZOA/(RHOC1+RHOC2)
0264            ION=EXP(SY*SS)
0265            RHOC=F1*RHOC1+F2*RHOC2
0266            RHOC=5.653
0267            GO TO 35
0268      C
0269      C-----(4)GALLIUM PHOSPHIDE
0270         34 TITC1=4HGAP
0271            TITC2=4H
0272            XF=.0
0273            ZC1=31.
0274            ZC2=15.
0275            AC1=69.72
0276            AC2=30.98
0277            AC=AC1+AC2
0278            RHOC1=5.93
0279            RHOC2=2.69
0280            EGAPZ=2.35
0281            PHI=1.30
0282      C     CNZ=4.7E17
0283      C     CPZ=7.0E18
0284      C     CONCI=1.79E6
0285            ME=.82
```

```
0286            MH=.60
0287            XMSE=ME
0288            XMSH=MH
0289            XMSH1=MH
0290            XMSE1=ME
0291            EPSS1=11.1*EPSZ
0292            AEG=5.56E-4
0293            BEG=200.0
0294            F1=AC1/AC
0295            F2=AC2/AC
0296            ZC=F1*ZC1+F2*ZC2
0297            ADENC1=NZ*RHOC1/AC1
0298            ADENC2=NZ*RHOC2/AC2
0299            ADENC=(AC1*ADENC1*F1+ADENC2*F2*AC2)/AC
0300            ZOA=(ZC1/AC1*RHOC1+ZC2/ZC2*RHOC2)/(RHOC1+RHOC2)
0301            XION1=ALOG(FION(ZC1))
0302            XION2=ALOG(FION(ZC2))
0303            SS=(ZC1/AC1)*RHOC1*XION1 +(ZC2/AC2)*RHOC2*XION2
0304            SY=1.0/ZOA/(RHOC1+RHOC2)
0305            ION=EXP(SY*SS)
0306            RHOC=F1*RHOC1+F2*RHOC2
0307         35 CONTINUE
0308            ZOAC=ZOA
0309            RHOX=RHOC
0310     C
0311     C      SUBSTRATES
0312     C      (1)AIR
0313            TITS1=4HAIR
0314            TITS2=4H
0315            AS1=30
0316            ZS1=(16*8+14*7)/30.
0317            CS1=0.0
0318            RHOS1=1.29E-3
0319            ADENS=RHOS1*NZ/AS1
0320            ZOA1=ZS1/AS1
0321     C
0322     C      (2) ALUMINUM
0323            TITS21=4HALUM
0324            TITS22=4HINUM
0325            AS2=2.7
0326            ZS2=13.
0327            CS2=0.0
0328            RHOS2=2.7
0329            ADENS2=RHOS2*NZ/AS2
0330            EPHI=PHI
0331            ZOA2=ZS2/AS2
0332     C
0333     C-----(3)FUSED SILICA AS SUBSTRATE
0334            TITS31=4HF SI
0335            TTIS32=4HLICA
0336            ZS3=10.8
0337            AS3=21.63
0338            CS3=3.70E-2
0339            CS3=0.
0340            RHOS3=2.202
0341            ADENS3=RHOS3*NZ/AS3
0342            ZOA3=ZS3/AS3
```

```
0343     C
0344     C-----(4)STAINLESS STELL
0345     C      CS4=25.0E-4
0346            CS4=0.
0347            RHOS4=11
0348     C
0349     C FOR BREMSS INCLUDE Z OF OTHER MAT IN ACTUAL DESIGN
0350            ZTOT=ZC+ZB
0351            YUC=XMU(JD,TEMAX)
0352     C
0353     C-----START TEMP LOOP
0354     C
0355            IF(KMAX.LE.1)PRINT *, 'ENTER TEMPERATURE'
0356            IF(KMAX.LE.1)READ *, TZERO
0357            DO 60 K=1,KMAX
0358            T=TZERO+(K-1)*DTEMP
0359            TSH=T+(ID-1)*TNOT
0360            AKTA=PERF*TSH/OEVK
0361            KT=AKTA/PERF
0362            AKT=AKTA
0363            EPSS=(1.0+T*9.0E-5)*EPSS1
0364     C
0365            RAS=4.0*PI*XMSH*((KZ*OEVE)**2)*EOH/(HOM*H)/AREAC
0366            GG=KT*XMSE
0367            CNZ=CNZ1*(GG/(H*HOM))**1.5
0368            GGX=KT*XMSH
0369            CPZ=CNZ1*(GGX/(H*HOM))**1.5
0370            EGAP=EGAPZ-AEG*T**2/(T+BEG)
0371            FEG=(2.8*EGAP+FEGL)*1.0E-6
0372            FEGEV=FEG*1.0E6
0373            FW=FEG/EGAP*1.0E6
0374            EXPKT=EXP(-EGAP/2/KT)
0375            SQND=SQRT(ND)
0376            SQNC=SQRT(CNZ)
0377            SQNV=SQRT(CPZ)
0378            NI=SQNC*SQNV*EXPKT
0379            SNI=NI**2
0380     C
0381            GO TO(24,25),ITYPE
0382         24 ECEF=KT*ALOG(CNZ/ND)
0383            ECED=ALFA*ECEF
0384            NA=(CNZ/ND)*CPZ
0385            DN=ND
0386            GO TO 7
0387         25 NA=ND
0388            DN=NA
0389            EFEV=KT*ALOG(CPZ/NA)
0390            ECEF=EGAP-EFEV
0391            EFED=ALFA*EFEV
0392            ECED=EFED+ECEF
0393            ND=(CNZ/NA)*CPZ
0394          7 PNZ=SNI/ND
0395            NNZ=ND
0396            PPZ=NA
0397            NPZ=SNI/NA
0398            N=ND
0399            P=NA
```

```
0400           NSTR=NA/(NA+ND)*ND
0401           IF(IC.EQ.1)XMOBE=1.4552258E3/(XMSE)**1.5/(T/300.)**2.5
0402           IF(IC.EQ.1)XMOBH=1.8355070E2/(XMSH)**1.5/(T/300.)**2.5
0403           IF(IC.EQ.4)XMOBE=110.0/(T/300.)**2.5
0404           IF(IC.EQ.4)XMOBH=75.0/(T/300.)**2.5
0405           IF(IC.EQ.2.OR.IC.EQ.3)
0406          1XMOBE=7200.*XMSE/XMSE1/((T/300.)**2.3+(DN/1.0E17)*
0407          2ALOG(1.0+(6.0E16/DN)**C23)*(300./T)**1.5)
0408           IF(IC.EQ.2.OR.IC.EQ.3)
0409          1XMOBH=370.*XMSH/XMSH1/((T/300.)**2.3+(DN/1.0E17)*
0410          2ALOG(1.0+(4.0E16/DN)**C23)*(300./T)**1.5)
0411           DLE=XMOBE*KT
0412           DLH=XMOBH*KT
0413           VTHH=SQRT(3.0*KT*OEVE/(XMSH*MZ))
0414           VTHE=SQRT(3.0*KT*OEVE/(XMSE*MZ))
0415           IF(IC.NE.4)GO TO 6
0416           SIGE=8.1E-23
0417           SIGH=4.3E-23
0418           SQDD=SQRT(CNZ/DN)
0419           TAUE=SQDD/(SIGE*DN*VTHE**2)
0420           TAUH=SQDD/(SIGH*DN*VTHH**2)
0421         6 IF(IC.EQ.1.OR.IC.EQ.4)DIFLE=SQRT(DLE*TAUE)
0422           IF(IC.EQ.1.OR.IC.EQ.4)DIFLH=SQRT(DLH*TAUH)
0423           IF(IC.EQ.1.OR.IC.EQ.4)GO TO 36
0424           DIFLE=(7.0E-4)*SQRT(T/300.)/(1.0+(DN/2.5E18)**1.3)
0425           DIFLH=(7.0E-4)*SQRT(T/300.)/(1.0+(DN/2.5E18)**2.0)
0426           TAUE=DIFLE**2/DLE
0427           TAUH=DIFLH**2/DLH
0428        36 CONDE=E*XMOBE*NNZ
0429           CONDH=E*XMOBH*PPZ
0430           COND=CONDE+CONDH
0431           TCOLE=5.6857E-16*XMOBE
0432           TCOLH=5.6857E-16*XMOBH
0433           SIGCAP=(4.0E-13)*(ZC**2+ZC)/(32**2+32)
0434           IF(ITYPE.EQ.1)CELT=DIFLE
0435           IF(ITYPE.EQ.2)CELT=DIFLH
0436           IF(ID.EQ.1.AND.ITYPE.EQ.1)CELT=DIFLE+DIFLH/CELGA
0437           IF(ID.EQ.1.AND.ITYPE.EQ.2)CELT=DIFLH+DIFLE/CELGA
0438           MUC=RHOC*YUC
0439           MUB=RHOB*YUC
0440           DELC=CELT
0441     C
0442     C------------------------
0443           THK=CELT/(2.54E-3)
0444           DO 60 ICO=1,MC
0445           CELT=DELC*ICO
0446     C     IF(JD.EQ.1)W=WITP(CELT)
0447     C     IF(JD.EQ.2)W=WITN(CELT)
0448     C SNL PARAMETERS
0449           W=SW(CELT,MUC,MUB)
0450           CELA=AREA
0451           VOL=W*AREA
0452           TVOL=VOL+(CELT+CS1+CS2+CS3)*AREA
0453           TMAS=VOL*RHOB+(CELT*RHOC+CS1*RHOS1+CS2*RHOS2+CS3*RHOS3)*AREA
0454           CMAS=CELT*AREA*RHOC
0455           IF(ID.EQ.1)GO TO 4
0456           TVOL=VOL+(CELT+CM+CS1+CS2+CS3)*AREA
```

```
0457           TMAS=VOL*RHOB+(CELT*RHOC+CM*RHOM+CS1*RHOS1+CS2*RHOS2+CS3*RHOS3)*AR
0458         4 VBI=KT*ALOG((NA/NI)*(ND/NI))
0459           VBR=60.*((EGAP/1.1)**1.5)*(DN/1.0E16)**.75
0460           DEPL=SQRT((2.0*EPSS)*(VBI-2.0*KT)/(E*NSTR))
0461           EFER=PHI-0.5*DN*E*DEPL**2/EPSS
0462           XNN=DEPL/(1.0+DN/NA)
0463           DEBY=SQRT(EPSS*KT/E/DN)
0464           CAP=EPSS/DEPL
0465           SCH=E*DN*DEPL
0466           EFLD=2.0*(VBI-KT)/DEPL
0467           VDE=XMOBE*EFLD
0468           VDH=XMOBH*EFLD
0469           VRE=VTHE/SQRT(6.0*PI)
0470           VRH=VTHH/SQRT(6.0*PI)
0471           PCAPE=FPI*E*XMOBE/EPSS
0472           WCAPE=DN*PCAPE
0473           TRAPE=1.0/WCAPE
0474           PCAPH=FPI*E*XMOBH/EPSS
0475           WCAPH=DN*PCAPH
0476           TRAPH=1.0/WCAPH
0477           RRATE=(N/(N*TRAPH+P*TRAPE))*P
0478           TRCE=N/RRATE
0479           TRCH=P/RRATE
0480           RASS=FP*FQ*RAS/(1.0+FP*FQ*VRH/VDH)
0481           DJZZ=0.5*NI*E*DEPL
0482       C
0483       C      EMITTER FUNCTIONAL CONSTANTS
0484       C-------------------------------
0485         1 CONTINUE
0486           IF(ICO.GT.1.OR.K.GT.1)GO TO 42
0487           CALL RANGE(TEMAX,RHOC,ZOAC,RAN)
0488           CALL RANGE(TEMAX,RHOB,ZOAB,RANB)
0489       C      IF(IC.EQ.1)RAN=RAN-CM*RHOM/RHOC
0490       C      IF(IC.EQ.2)RAN=RAN*RHOSI/RHOC-CM*RHOM/RHOC
0491       C      IF(IC.EQ.3)RAN=RAN*RHOSI/RHOC-CM*RHOM/RHOC
0492           CALL BETAE(TEMAX,RAN,RHOC,IR,TEAVE,TAVEZ)
0493           WPC=NC*TEAVE*1.0E6*E
0494           LAM=.6931472/TOH
0495           XN=NZ*RHOB/AB
0496       C
0497           ACTIV=LAM*NZ/AB
0498           G=ACTIV/NC
0499        42 GM=VOL*RHOB
0500           CI=G*GM
0501           WPG=WPC*G
0502           PARA=FACE*(1.0-RB)*ANGD*ASSY
0503           XJB=E*NC*G*RHOB*PARA/MUB/AREAC
0504           OME=1.0-EXP(-MUB*W)
0505       C      FABST=OME/(MUB*W)
0506           FABST=TRANX(MUB,W,D)
0507           FABSS=1-FABST
0508       C      JB=XJB*OME
0509       C      JB=XJB*FABST
0510           FLUX=LAM*W*XN*FABST*PARA
0511           JB=E*FLUX
0512           IB=JB*AREAC
0513       C      FLUX=JB/E
```

```
0514           EFLUX=TEAVE*FLUX*1.0E6
0515           PIN=WPG*GM*PARA
0516           PINA=PIN/AREAC
0517           PINT=PINA*FABST
0518     C
0519           SUM=0.0
0520           DO 21 II=1,NR
0521           I=NR-II+1
0522           IF(I.EQ.NR)DTY=ABS(TT(NR)-TEMAX)
0523           IF(I.LT.NR)DTY=ABS(TT(I+1)-TT(I))
0524           FEX=FE(I)*DTY*FLUX
0525           SUM=SUM+FEX
0526           FEF(I)=SUM
0527        21 CONTINUE
0528           IF(IPLOT.EQ.4)CALL PLOTC(JD,NR,TT,FEF)
0529           IF(K.GT.1)GO TO 17
0530           CALL BETAD(THK,NR,TT,FEF,1.0,ZOA,ZC,RHOC,OMEX)
0531           OMEW(ICO)=OMEX
0532           CALL EAB(2,CM+SC2+CELT,MUC,ZTOT,ANSD)
0533           THAF=TOH/TC
0534           CAPA=EPSS*AREA/DEPL
0535     C
0536     C     WRITE(6,100)
0537           WRITE(6,2)TITB1,TITB2,TIT1,TIT2,AB,ZB,MUB,MUC,WPC,WPG,THAF,
0538          1LAM,XN,G,GM,W,ACTIV,D,TVOL,TMAS,VOL,AREA,AREAC,CI,XJB,JB,IB,
0539          2FLUX,EFLUX
0540         2 FORMAT(18X,'BETA SOURCE IS ',2A4,2X,2A4/13X,42(1H*)///
0541          111X,'ATOMIC MASS NUMBER=',F4.0/
0542          216X,'ATOMIC NUMBER=',F3.0/
0543          39X,'(S,CON)ATT CONSTANTS='2(1PE9.2),2X,'/CM'/
0544          425X,'W/CI=',1PE9.2,11X'WATTS/CURIE'/
0545          525X,'W/GM='1PE9.2,11X,'WATTS/GRAM'/
0546          620X,'HALF LIFE='1PE9.2,11X,'YEARS'/
0547          716X,'DIS. CONSTANT='1PE9.2,11X,'/SEC'/
0548          88X,'SOURCE ATOMIC DENSITY=',1PE9.2,11X,'ATOMS/CC'/
0549          912X,'SPECIFIC ACTIVITY=',1PE9.2,11X,'CURIES/GM'2X,'GM='1PE9.2/
0550          117X,'SOURCE WIDTH=',1PE9.2,11X,'CM',3X,'ACT='1PE9.2,2X,'/S/CC'/
0551          221X,'DIAMETER=',1PE12.5,8X,'CM'/
0552          317X,'TOT(VOL,MAS)='2(1PE9.2),2X,'CM3,GM'/24X,'S VOL='1PE9.2,11X/
0553          418X,'SOURCE AREA=',1PE12.5,8X,'CM2'/18X,'ACTIVE AREA='1PE9.2/
0554          523X,'CURIES=',1PE9.2,11X,'CURIES'/
0555          62X,'MAX. SOURCE CURRENT DENSITY=',1PE9.2,11X,'AMP/CM2'/
0556          77X,'SOURCE CURRENT DENSITY=',1PE9.2,11X,'AMP/CM2'/
0557          815X,'SOURCE CURRENT=',1PE9.2,11X,'AMPERES'/
0558          918X,'SOURCE FLUX=',1PE9.2,11X,'BETA/CM2/SEC'/
0559          111X,'SOURCE ENERGY FLUX=',1PE9.2,11X,'EV/CM2/SEC')
0560     C
0561           WRITE(6,19)ZC,AC,ZOA,RHOC,ION,ADENC,EGAP,
0562          1CAP,SCH,EFLD,VTHE,VTHH,VDE,VDH,VRE,VRH,VBI,CAPA,DEBY,VBR,
0563          2ASSY,EPSS,ME,MH,ECEF,ECED
0564        19 FORMAT(27X,'ZC='1PE9.2,11X,'AC='1PE9.2/
0565          126X,'ZOA='1PE9.2,11X,'RHOC='1PE9.2,'   GM/CC'/
0566          217X,'IONIZATION E='1PE9.2,11X,'EV'/
0567          39X,'CONV. ATOMIC DENSITY='1PE9.2,11X,'ATOMS/CC'/
0568          419X,'GAP ENERGY='1PE9.2,11X,'EV'/
0569          516X,'J CAPACITANCE='1PE9.2,11X,'FARAD/CM'/
0570          615X,'J SPACE CHARGE='1PE9.2,11X,'COULOMB'/
```

```
0571          720X,'J E FIELD='1PE9.2,11X,'VOLTS/CM'/
0572          86X,'J (E,H)THERMAL VELOCITY='2(1PE9.2),2X,'CM/SEC'/
0573          98X,'J (E,H)DRIFT VELOCITY='2(1PE9.2),2X,'CM/SEC'/
0574          18X,'J (E,H)RECOM VELOCITY='2(1PE9.2),2X,'CM/SEC'/
0575          211X,'BUILD-IN POTENTIAL='1PE9.2,11X,'VOLTS'/
0576          318X,'CAPACITANCE='1PE9.2,11X,'FARAD/CM'/
0577          418X,'DEBY LENGTH=',1PE9.2,11X,'CM'/
0578          513X,'BREAK DOWN VOLTS=',1PE9.2,11X,'VOLTS'/
0579          617X,'SOURCE ASSAY=',1PE9.2/
0580          712X,'EFF. PERMITTIVITY=',1PE9.2,11X,'FARAD/CM'/
0581          815X,'(E,H)EFF. MASS=',2(1PE9.2),2X,'MS/M0'/
0582          918X,'EC-EF,EC-ED=',2(1PE9.2),2X,'EV')
0583     C
0584     C-------------------------------------------------------
0585     C     CONVERTER CURRENT
0586     C     -----------------
0587     C
0588        17 XM=TAVEZ/FEG
0589           GEN=XM*MUB
0590           IF(ITYPE.EQ.1)CALL QX(DIFLE,DIFLH,QE,QH,Q,QP)
0591           IF(ITYPE.EQ.2)CALL QX(DIFLH,DIFLE,QH,QE,Q,QP)
0592           RC=0.0
0593           ZOAX=ZOAC
0594           RHOX=RHOC
0595           ZZ=ZC
0596           IF(ID.EQ.1)GO TO 23
0597           ZOAX=ZOAM
0598           RHOX=RHOM
0599           ZZ=ZM
0600        23 RC1=XC(ZZ)
0601           RS1=XC(ZB)
0602     C     IF(CS1.NE.0.0)ANGD=0.50
0603           OMRC=(1.0-RC1)*(1.0+RC1*RS1+(RC1*RS1)**2)
0604           CC=OMRC*Q
0605           FAC=1.0
0606           CALL ABSO(1,ID,JD,JB,FEG,PINT,ANSF)
0607           FABSC=ANSF
0608     C
0609           IF(ID.EQ.2)JZ=(1.0-RB)*RASS*T*T*EXP(-EPHI/KT)
0610           IF(ID.EQ.2)GO TO 11
0611           GR=E*NI*DEPL
0612           GO TO(8,9),ITYPE
0613         8 JZR=GR/TAUH/2.0
0614           JZG=GR/TAUE
0615           JZ=E*(SNI/ND)*(DLH/DIFLH)
0616           GO TO 11
0617         9 JZR=GR/TAUE/2.0
0618           JZG=GR/TAUH
0619           JZ=E*(SNI/NA)*(DLE/DIFLE)
0620     C     ZER=2.546E19*(XMSE*XMSH**2)**0.75
0621     C     XNZER=ZER*(T/300.)**1.5
0622     C     JZ=3.81E-11
0623     C     SANDIA DATA
0624     C     JZ=(XNZER**2)*E*DIFLH/(TAUH*N)*EXP(-EGAP/KT)
0625     C
0626        11 XLAM=1.0/KT
0627           CRES=KT/JZ
```

```
0628           RANX=RAN/2.54E-3
0629           RANY=RANB/2.54E-3
0630           WRITE(6,100)
0631           WRITE(6,13)TITM1,TITM2,TITC1,TITC2,TYPE1,TYPE2,RAS,RASS,RB,
0632          1OMRC,RAN,RANX,RANB,RANY,JZ,JZG,JZR,XM,TEAVE,TAVEZ,AKT,AKTA,
0633          2AREA,CELT,FEG,MUC,Q,QP,QE,QH,XLAM
0634        13 FORMAT(14X,'CONVERTER CONSTANTS'2X,4A4,2X,A4,A2/9X,56(1H*)/
0635          114X,'RICHARDSON NO.S=',2(1PE9.2),2X,'AMP/CM2/K'/
0636          28X, '(RB,1-RC)REFLECTIVITY='2(1PE9.2),11X/
0637          39X,'CON. BETA MAX. RANGE='1PE9.2,11X,'CM',3X,E9.3,'  MILS'/
0638          49X,'SOC. BETA MAX. RANGE='1PE9.2,11X,'CM',3X,E9.3,'  MILS'/
0639          427X,'JZ='1PE9.2,11X,'AMP/CM2'/
0640          520X,'(JZG,JZR)='2(1PE9.2),2X,'AMP/CM2'/
0641          617X,'MULT. FACTOR=',1PE9.2,11X,'AVE TE='1PE9.3,' TAZ='1PE8.2/
0642          719X,'(AKT,AKTA)=',2(1PE11.4),2X,'EV'/
0643          815X,'CONVERTER AREA=',1PE9.2,11X,'CM2'/
0644          910X,'CONVERTER THICKNESS=',1PE9.2,11X,'CM',3X,'SPENT E='1PE9.2/
0645          114X,'CONVERTER ATTEN=',1PE9.2,11X,'CM-1'/
0646          22X,'COLLECTION EFFICIENCY(Q,QP)=',2(1PE9.2)/
0647          315X,'(E,H)COLL. EFF='2(1PE9.2)/
0648          423X,'LAMBDA=',1PE9.2,11X)
0649      C
0650           WRITE(6,18)T,KT,DLE,DLH,DIFLE,DIFLH,XMOBE,XMOBH,N,NA,CNZ,PNZ,
0651          1NPZ,CPZ,NI,CONDE,CONDH,TAUE,TAUH,TCOLE,TCOLH,FW,DEPL,ND,NA,SHNT,
0652          2FABSS,FABSC,PERF,XF,CRES,ANGD,FACE
0653        18 FORMAT(28X,'T='F5.1,15X,'KELVIN'3X,'KT='1PE10.3,3X,'EV'/
0654          112X,'(E,H)DIF CONSTANT='2(1PE9.2),2X,'CM2/SEC'/
0655          18X,'(E,H)DIFFUSION LENGTH='2(1PE9.2),2X,'CM'/
0656          216X,'(E,H)MOBILITY='2(1PE9.2),2X,'CM2/VOLTS/SEC'/
0657          32X,'MAJ CON IN (N,P) SIDE AT EQ='2(1PE9.2),2X'/CC'2X,'NC='1PE9.2/
0658          42X,'MIN CON IN (N,P) SIDE AT EQ='2(1PE9.2),2X'/CC'2X,'NV='1PE9.2/
0659          56X,'INTRINSIC CONCENTRATION='1PE9.2,11X,'/CC'/
0660          612X,'(E,H)CONDUCTIVITY='2(1PE9.2),2X,'MHOS/CM/SEC'/
0661          711X,'(E,H)DIFF LIFETIME='2(1PE9.2),2X,'SEC'/
0662          811X,'(E,H)COLL LIFETIME='2(1PE9.2),2X,'SEC'/
0663          914X,'ION PAIR E/EGAP='1PE9.2,11X/
0664          113X,'DEPLETION LENGTH='1PE9.2,11X,'CM'/
0665          26X,'(ND,NA)DOPING DENSITIES=',2(1PE9.2),2X,'/CC'/
0666          311X,'SHUNT CONDUCTIVITY='1PE9.2,11X,'MHOS/CM2'/
0667          47X,'F OF P ABS IN(SRC,CON)='2(1PE9.2),11X,/
0668          619X,'PERFECTION='1PE9.2,5X,5X,'HETEROFACE FRAC='1PE9.2/
0669          710X,'CONTACT RESISTIVITY='1PE9.2,11X,'OHM-CM'/
0670          818X,'ANGULAR DIS='1PE9.2,12X,'FACE='1PE9.2)
0671      C
0672           WRITE(6,16)GEN,RRATE,PCAPE,PCAPH,WCAPE,WCAPH,
0673          1TRAPE,TRAPH,TRCE,TRCH,RS1,RC1,PNZ,NNZ,PPZ,NPZ,NSTR
0674        16 FORMAT(13X,'(GEN,RECOM.)RATE='2(1PE9.2),2X,'/SEC'/
0675          114X'(E,H)CAP. PROB.='2(1PE9.2)/
0676          215X,'(E,H)CAP. RATE='2(1PE9.2),2X,'/SEC'/
0677          315X,'(E,H)TRAP TIME='2(1PE9.2),2X,'/SEC'/
0678          414X,'(E,H)RECOM TIME='2(1PE9.2),2X,'/SEC'/
0679          510X,'(RS1,RC1)REFLECTION='2(1PE9.2),2X/
0680          613X,'N SIDE(P,N)AT EQ=',2(1PE9.2),2X,'/CC'/
0681          713X,'P SIDE(P,N)AT EQ=',2(1PE9.2),2X,'/CC'/
0682          824X,'NSTAR=',1PE9.2,11X,'/CC')
0683      C--------------------------
0684      C
```

```
0685            XJBZ=JB
0686            DO 60 IYE=1,IY
0687            YR=IYE-1
0688            IF(IYE.EQ.IY.AND.YI.NE.IY)YR=YI
0689            IF(AYR.EQ.1)YR=YI
0690      C     IF(AYR.EQ.1)IYE=IY
0691            FAC=YR*TC +1.
0692            DECY=EXP(-LAM*FAC)
0693            OMEV=FAC*OMEW(ICO)
0694            AFLUEN=FAC*FLUX
0695            JB=XJBZ*DECY
0696      C     QJS=XM*JB*QP*OMRC
0697            QJS=PINT*CC*FABSC/FEGEV
0698            JS=QJS*DECY
0699            PJN=JS*QE/Q
0700            PJP=JS*QH/Q
0701            WRITE(6,12)JS,PJN,PJP
0702         12 FORMAT(27X,'JS='1PE9.2,11X,'AMP/CM2'/9X,
0703           1'(E,H)CURRENT DENSITY=',2(1PE9.2),2X,'AMP/CM2')
0704            XP=JS/(JZR*(JZ+JZG))
0705            VMAX=VOC(KT,JZ,JZR,JS,PERF)
0706            VMZ=VMAX
0707            CALL ABSO(2,ID,JD,JB,FEG,PINT,FABSC)
0708            M1=M-1
0709            DV=VMAX/M1
0710            PLM=0.
0711         14 FORMAT(10X,'VMAX=',1PE9.2,3X,'VOLTS',3X,
0712           1'JSC='1PE9.2,3X,'YERAS='F6.2///4X
0713           2,'I',9X,'VOLTS'9X,'J(LOSS)',7X,'J(LOAD)',8X,'POWER',
0714           312X,'J SHNT'/
0715           42X,3(1H-),5(7X,8(1H-)))
0716            WRITE(6,100)
0717            WRITE(6,14)VMAX,JS,YR
0718      C     CONTACT RESISTIVITY IS SET=0.
0719      C     JL=0.
0720      C     JV=0.
0721      C     JP=0.
0722      C     VSV=EG
0723      C     VDEGN=0.
0724      C     VDEGP=0.
0725      C     VSP=(VDEGN+VDEGP)/3.
0726            DO 20 I=1,M
0727            V=(I-1)*DV
0728            PLOTV(I)=V
0729            REV=(V+JS*AREA*RSER)/KT
0730            JJ=JZ*(EXP(REV)-1.0)+JZR*(EXP(REV/PERF)-1.0)
0731            PLOTP(I,1)=JJ
0732            SHC=SHNT*(V+JL*AREA*RSER)
0733            PLOTP(I,2)=SHC
0734            JL=JS-JJ-SHC
0735            PLOTZ(I,1)=JL
0736            PL=V*JL
0737            PLOTZ(I,2)=PL
0738            IF(PL.LE.0.)PL=0.
0739            IF(JL.LE.0.)JL=0.
0740      C
0741            WRITE(6,15)I,V,JJ,JL,PL,SHC
```

```
0742        15 FORMAT(2X,I3,5(1PE15.2))
0743           IF(PL.LT.PLM)GO TO 20
0744           PLM=PL
0745           VLM=V
0746        20 CONTINUE
0747           IF(IPLOT.EQ.1.OR.IPLOT.EQ.3)
0748          1CALL SPLOT(1,M,PLOTV,PLOTP,PLOTZ)
0749           WRITE(6,100)
0750     C
0751           VMP=VLM
0752           VN=(SNI/NA)*EXP(VMAX/KT)
0753           VP=(VN/ND)*NA
0754     C     PMP=JZ*(VMP**2)*XP/KT/(1.0+VMP/KT)
0755           PMP=PLM
0756           JMP=PMP/VMP
0757           XPMP=1.0/PMP/1.0E6
0758           RMP=1.0/(XLAM*JZ*EXP(XLAM*VMP))*AREA/CELT
0759         5 PP=VMAX*JS
0760           FF=PMP/PP
0761           TOTP=PMP*AREAC
0762           PVOL=TOTP/TVOL
0763           GMW=GM/TOTP/1.0E6
0764           UCV=1.0E-6/PVOL
0765           UCM=1.0E-6/(TOTP/CMAS)
0766           ETA=PMP/PINT*100.
0767           XJSCM=PINA/FEGEV
0768           XPM=1.0+XJSCM/JZ
0769           VOCM=AKT*ALOG(XPM)
0770           ETAMM=FF*VOCM/FEGEV*100.
0771           ETAM=FF*AKT*ALOG(1.+JS/JZ)/FEGEV*100.
0772           IF(IPLOT.EQ.2.OR.IPLOT.EQ.4)CALL GETP(KT,JZ,JZR)
0773     C
0774           WRITE(6,40)VMP,JMP,PMP,XJSCM,VOCM,ETAM,ETAMM,PP,PINT,FF,RMP,TOTP,
0775          1PVOL,ETA,GMW,XPMP,UCV,UCM,VN,VP
0776        40 FORMAT(30X,'BETAVOLTAIC RESULTS'/25X,30(1H*)///
0777          126X,'VMP=',1PE9.2,11X,'VOLTS'/
0778          226X,'JMP=',1PE9.2,11X,'AMP/CM2'/
0779          323X,'P/AREA=',1PE9.2,11X,'WATTS/CM2'/
0780          422X,'JSC MAX='1PE9.2,11X,'VOC MAX='1PE9.2/
0781          523X,'EFF(M)=',1PE9.2,11X,'PERCENT'/
0782          514X,'MAX. EFFICIENCY='1PE9.2,11X,'PERCENT'/
0783          625X,'PMAX=',1PE9.2,11X,'WATTS/CM2'/
0784          718X,'INPUT POWER=',1PE9.2,11X,'WATTS/CM2'/
0785          827X,'FF=',1PE9.2,11X/
0786          926X,'RMP=',1PE9.2,11X,'OHMS - CM'/
0787          122X,'TOTAL P=',1PE9.2,11X,'WATTS'/
0788          223X,'P/TVOL=',1PE9.2,11X,'WATTS/CC'/
0789          319X,'EFFICIENCY='1PE9.2,11X,'PERCENT'/
0790          417X,'S MASS/POWER='1PE9.2,11X,'GM SOURCE/MICRO W P OUT'/
0791          511X,'CONVERTER MATERIAL='1PE9.2,11X,'CM2/MICRO W P OUT'/
0792          616X,'UNIT CELL VOL='1PE9.2,11X,'CC/MICRO WATTS'/
0793          715X,'UNIT CELL MASS='1PE9.2,11X,'GM/MICRO WATTS'/
0794          87X,'(N IN P,P IN N)AT EDGE=',2(1PE9.2),2X,'/CC')
0795     CC    IF(K.EQ.1)CALL WTAP5(NR,FAC,RAN,TT,FE,FLUX,TITC)
0796           CALL DAMG(YR,TEAVE,KT,VTHH,TAUH,DLH,THK,TAUK,OMEV)
0797           DJZ=DJZZ*TAUK*OMEV*DECY
0798           DELJZ=(DJZ/JZ)*100.
```

```
0799          WRITE(6,63)OMEV,DELJZ
0800          DOSED=ANSD*FAC *DECY
0801          WRITE(6,64)DOSED
0802       64 FORMAT(1X,'ABSORBED DOSE AT CELL END LAYER='1PE9.2,13X,'RADS')
0803          IF(K.EQ.1.AND.IYE.EQ.1)
0804         1  CALL EAB(3,CELT,MUC,ZTOT,ANSG)
0805          ANSGT=ANSG*DECY
0806          ANSGTA=ANSG*(1.0-DECY)/LAM/3600.
0807    C     LAM IS IN SEC ANSG IS IN /HR
0808          WRITE(6,65)ANSGT,ANSGTA,YR
0809       65 FORMAT(///18X,'DOSE IN TISSUE='1PE9.2,13X,'REM/HR'/
0810         113X,'ACC. DOSE IN TISSUE='1PE9.2,13X,'REM'/
0811         213X,'(AFTER   '1PE8.2,13X,'YRS OF IRRADIATION)')
0812       63 FORMAT(2X,'1 MEV EQUIV. ELECTRON FLUENCE ='1PE9.2/16X,
0813         1'DARK CURRENT INC='1PE9.2,13X,'PERCENT')
0814          IF(AYR.EQ.1)GO TO 66
0815       60 CONTINUE
0816       66 LAST1=4HP$PR
0817          LAST2=4HELIN
0818          LAST3=4H L
0819          PAST1=4HAST=
0820          PAST2=4H4HLA
0821          PAST3=4HST
0822          ENDD1=4H $EN
0823          ENDD2=4HD
0824          WRITE(5,61)LAST1,LAST2,LAST3,PAST1,PAST2,PAST3,ENDD1,ENDD2
0825       61 FORMAT(6A4/2A4)
0826      100 FORMAT(1H1)
0827          GO TO 99
0828          END
```

```
0001    *ABS(J(X) AND D(X))
0002          SUBROUTINE ABSO(MON,ID,JD,JB,FEG,P1,ANSF)
0003    C
0004          REAL JB,MU,JZ,KT,JZR,JZG
0005          DIMENSION CURS(20),CURC(20),D(20),PC(20),X(20),FR(20)
0006          COMMON/SPEC/FE(1:235),TT(1:235),NR,FLUX
0007          COMMON/CONV/ZC,AC,ZOA,RHOX,ION,FAC
0008          COMMON/SUBST/CS3,ZS3,AS3,RHOS3,CS2,ZS2,AS2,RHOS2,CM,RHOM
0009          COMMON/LENG/TEMAX,TEAVE,ACTIV,RHOB,W,KK,YUC,RHOC
0010          COMMON/CEFF/DIFLE,DIFLH,CELT,DEPL,MUC ,OMRC,CC
0011          COMMON/CU/AKTA,VMAX,JZ,JZR,JZG,XN,KT
0012    C
0013    C     IF(MON.NE.1)GO TO 11
0014          ANS=0.
0015          FG=CC/(FEG*1.0E6)
0016
0017    C
0018          I=1
0019          X(I)=0.
0020          PC(I)=0.
0021          D(I)=0.
0022          CURS(I)=JB
0023          CURC(I)=CURS(I)
0024          D1=D(I)
0025          X1=X(I)
0026    C
0027          I=I+1
0028          MU=RHOS2*YUC
0029          X(I)=X1+CS2
0030          XD=CS2
0031          IF(XD.NE.0.)CALL EAB(1,XD,MU,0,ANS)
0032          IF(XD.NE.0.)CALL EAB(2,XD,MU,0,ANS2)
0033          FS2=ANS
0034          FR(I)=FS2
0035          PC(I)=FS2*P1
0036          P2=(1.0-FS2)*P1
0037          CURS(I)=CURS(I-1)*(1.0-FS2)
0038          CURC(I)=CURS(I)
0039          D(I)=ANS2
0040          X2=X(I)
0041          D2=D(I)
0042    C
0043          I=I+1
0044          MU=RHOM*YUC
0045          ANS=0.
0046          X(I)=X2+CM
0047          XD=X(I)-X2
0048          IF(XD.NE.0.)CALL EAB(1,XD,MU,0,ANS)
0049          IF(XD.NE.0.)CALL EAB(2,XD,MU,0,ANS3)
0050          FS3=ANS
0051          FR(I)=FS3
0052          PC(I)=FS3*P2
0053          P3=(1.0-FS3)*P2
0054          CURS(I)=CURS(I-1)*(1.0-FS3)
0055          CURC(I)=CURS(I)
0056          D(2)=ANS3
0057          D3=D(I)
```

```
0058          X3=X(I)
0059    C
0060          I1=I
0061          M=10
0062          DXC=CELT/M
0063          PP=PC(I)
0064          DO 10 I=1,M
0065          I2=I+I1
0066          X(I2)=X3+DEPL+(I-1)*DXC
0067          XD=X(I2)-X3
0068          IF(I.EQ.M)XD=CELT
0069          IF(I.EQ.M)X(I2)=XD+X3
0070    C
0071          SUM=0.
0072          SUN=0.
0073          DO 5 JJ=1,NR
0074          J=NR-JJ+1
0075          IF(J.EQ.NR)DTY=ABS(TT(NR)-TEMAX)
0076          IF(J.LT.NR)DTY=ABS(TT(J+1)-TT(J))
0077          MU=XMU(JD,TT(J))*RHOC
0078          SUM=SUM+FE(J)*DTY
0079          AS=0.
0080          ASS=0.
0081          IF(XD.LE.0.)GO TO 5
0082          CALL EAB(1,XD,MU,0,AS)
0083          CALL EAB(2,XD,MU,0,ASS)
0084        5 SUN=SUN+FE(J)*AS*DTY
0085          FRA=SUN/SUM
0086          IF(FRA.GT.1.0)FRA=1.0-EXP(-MU*XD)
0087          FR(I2)=FRA
0088          CURS(I2)=CURS(I2-1)*(1.0-FRA)*OMRC
0089    C     CURC(I2)=CURS(I2)+P3*(1.0-FRA)*FG
0090          D(I2)=ASS
0091          PC(I2)=PP+FRA*P3
0092          IF(CURS(I2-1).LE.0.0)PC(I2)=0.
0093          IF(CURS(I2-1).LE.0.0)FR(I2)=0.
0094       10 CONTINUE
0095          ANSF=FRA
0096          P4=(1.-FRA)*P3
0097          D4=(D(I1+1)-D(I2))/ALOG(D(I1+1)/D(I2))
0098          X4=X(I2)
0099          IF(MON.EQ.1)RETURN
0100    C
0101       11 VOT=JZ*(EXP(VMAX/KT)-1.)+JZR*(EXP(VMAX/AKTA)-1.0)
0102          DO 12 I=1,M
0103          I2=I+I1
0104          XD=X(I2)-X3
0105          CURC(I2)=ABS(CURS(I1)-VOT*EXP(-(XD-XN)/DIFLH))
0106          IF(I.EQ.1)CURC(I2)=VOT-CURS(I2)
0107       12 CONTINUE
0108    C
0109          PP=0.
0110          N=3
0111          I3=I2
0112          P5=P4
0113          X5=X(I3)
0114          D5=0.
```

```
0115          IF(CS3.LE.0.)GO TO 21
0116          DXSB=CS3/N
0117          PP=PC(I2)
0118          DO 20 I=1,N
0119          I3=I2+I
0120          X(I3)=X4+I*DXSB
0121          XD=X(I3)-X4
0122          SUN=0.
0123          DO 15 JJ=1,NR
0124          J=NR-JJ+1
0125          IF(J.EQ.NR)DTY=ABS(TT(NR)-TEMAX)
0126          IF(J.LT.NR)DTY=ABS(TT(J+1)-TT(J))
0127          MU=XMU(JD,TT(J))*RHOS3
0128          AS=0.
0129          IF(X(I3).LE.0.)GO TO 15
0130          CALL EAB(1,XD,MU,0,AS)
0131          CALL EAB(2,XD,MU,0,ASS)
0132       15 SUN=SUN+FE(J)*AS*DTY
0133          FRA=SUN/SUM
0134          IF(FRA.GT.1.0)FRA=1.0-EXP(-MU*XD)
0135          FR(I3)=FRA
0136          CURS(I3)=CURS(I3-1)*(1.0-FRA)
0137          CURC(I3)=CURS(I3)+CURC(I2)*(1.0-FRA)
0138          PC(I3)=PP+FRA*P4
0139          D(I3)=ASS
0140          IF(CURS(I3-1).LE.0.0)PC(I3)=0.
0141          IF(CURS(I3-1).LE.0.0)FR(I3)=0.
0142       20 CONTINUE
0143          P5=(1.0-FRA)*P4
0144          D5=(D(I2+1)-D(I3))/ALOG(D(I2+1)/D(I3))
0145       21 D1=D1*FAC
0146          D2=D2*FAC
0147          D3=D3*FAC
0148          D4=D4*FAC
0149          D5=D5*FAC
0150          DO 22 IA=1,I3
0151       22 D(IA)=D(IA)*FAC
0152    C
0153          WRITE(6,40)
0154       40 FORMAT(1H1)
0155          WRITE(6,43)P1,P2,P3,P4,P5,X1,X2,X3,X4,X5,
0156         1D1,D2,D3,D4,D5,JB,ANSF
0157
0158          WRITE(6,41)
0159       41 FORMAT(10X,'JSC AND DOSE AS A FUNCTION OF X'/
0160         113X,'FROM THE SOURCE SURFACE'/
0161         24X,1HI,8X,'X'9X,'CUR(X) '5X,'CTOT(X)',5X,'PABS(X)',5X,'FABS(X)',
0162         35X,'DOSE(X)'/
0163         44X'-'5X,4(1H-),7X,9(1H-),4(4X,8(1H-)))
0164          DO 42 I=1,I3
0165       42 WRITE(6,44)I,X(I),CURS(I),CURC(I),PC(I),FR(I),D(I)
0166       44 FORMAT(I5,6(1PE12.2))
0167       43 FORMAT(10X,'INPUT POWER='5(1PE10.2),4X,'W/CM2'/
0168         16X,'INPUT DISTANCES='5(1PE10.2),4X,'CM'/
0169         213X,'AVE DOSE='5(1PE10.2),4X,'RADS'///
0170         315X,'INP JB='1PE10.2,5X,'AMPS/CM2'/
0171         49X,'FABS IN CONV=',1PE10.2,5X//)
```

```
0172          RETURN
0173          END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	2356	PIC CON REL LCL SHR EXE R
1	$PDATA	362	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	804	PIC CON REL LCL NOSHR NOEXE R
3	SPEC	1888	PIC OVR REL GBL SHR NOEXE R
4	CONV	24	PIC OVR REL GBL SHR NOEXE R
5	SUBST	40	PIC OVR REL GBL SHR NOEXE R
6	LENG	32	PIC OVR REL GBL SHR NOEXE R
7	CEFF	28	PIC OVR REL GBL SHR NOEXE R
8	CU	28	PIC OVR REL GBL SHR NOEXE R
	Total Space Allocated	5562	

ENTRY POINTS

Address	Type	Name
0-00000000		ABSO

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
4-00000004	R*4	AC	6-00000008	R*4	ACTIV	8-00000000	
2-000001FC	R*4	ANS2	2-00000210	R*4	ANS3	AP-0000001C@	
5-00000018	R*4	AS2	5-00000008	R*4	AS3	2-00000258	
7-00000008	R*4	CELT	5-00000020	R*4	CM	5-00000010	
2-000001F0	R*4	D1	2-0000020C	R*4	D2	2-0000021C	
2-00000284	R*4	D5	7-0000000C	R*4	DEPL	7-00000000	
2-00000250	R*4	DTY	2-0000022C	R*4	DXC	2-00000288	
AP-00000014@	R*4	FEG	2-000001E8	R*4	FG	3-0000075C	
2-00000200	R*4	FS2	2-00000214	R*4	FS3	2-000001EC	
2-00000238	I*4	I2	2-00000278	I*4	I3	2-00000294	
4-00000010	I*4	ION	2-0000024C	I*4	J	AP-00000010@	
2-00000244	I*4	JJ	8-00000008	R*4	JZ	8-00000010	
6-00000014	I*4	KK	8-00000018	R*4	KT	2-00000228	
2-000001E0	R*4	MU	7-00000010	I*4	MUC	2-00000274	
7-00000014	R*4	OMRC	AP-00000018@	R*4	P1	2-00000204	
2-00000260	R*4	P4	2-0000027C	R*4	P5	2-00000230	
6-0000001C	R*4	RHOC	5-00000024	R*4	RHOM	5-0000001C	
4-0000000C	R*4	RHOX	2-0000023C	R*4	SUM	2-00000240	
6-00000000	R*4	TEMAX	8-00000004	R*4	VMAX	2-0000026C	
2-000001F4	R*4	X1	2-00000208	R*4	X2	2-00000220	
2-00000280	R*4	X5	2-000001F8	R*4	XD	8-00000014	
4-00000000	R*4	ZC	4-00000008	R*4	ZOA	5-00000014	

```
0001    *TRANS
0002          FUNCTION TRANX(ALFA,W,D)
0003    C
0004    C     TO CALCULATE SOURCE TRANSMISSION COEFFICIENT
0005    C
0006          REAL*4 COST,PI2,THT,THT1,THT2,DTHT,PI,YZ,DOT
0007          PI=3.141592654
0008          PI2=PI/2.
0009          M=20
0010          M1=M+1
0011    C
0012          DOT=D/2.
0013          DY=D/M
0014          DX=W/M
0015          SUMY=0.
0016          DO 7 II=1,M1
0017          YZ=-DOT+(II-1)*DY
0018          SUN=0.0
0019          DO 5 J=1,M1
0020          X=(J-1)*DX
0021          IF(X.GE.W)X=W-DX/100.
0022          THT2=ACOS((W-X)/SQRT((W-X)**2+(DOT-YZ)**2))
0023          THT1=ACOS((W-X)/SQRT((W-X)**2+(DOT+YZ)**2))
0024          DTHT=(ABS(THT1)+ABS(THT2))/M
0025          SUM=0.
0026          DO 3 K=1,M1
0027          THT=-THT1+(K-1)*DTHT
0028          IF(ABS(THT).GE.PI/2.0)GO TO 3
0029          COST=COS(THT)
0030          IF(COST.LT.0.0)COST=0.
0031          FX=EXP(-ALFA*(W-X)/COST)*COST
0032          SUM=SUM+FX
0033        3 CONTINUE
0034    C
0035          Y=SUM*DTHT
0036          SUN=SUN+Y
0037        5 CONTINUE
0038          SUMY=SUMY+SUN*DY
0039        7 CONTINUE
0040          T=SUMY*DX/(2.0*W*D)
0041          TRANX=T
0042    C     TT=(1.0-EXP(-ALFA*W))/(ALFA*W)
0043    C     PRINT 15,I,W,T,TT
0044    C     WRITE(6,15)I,W,T,TT
0045    C  10 CONTINUE
0046    C  15 FORMAT(5X,I5,3X,4E15.3)
0047    C  20 FORMAT(5X,I2,13X,'W',1XX,'T',13X,'TT')
0048          RETURN
0049          END
```

```
0001     *MU
0002           FUNCTION XMU(J,V)
0003     C     TO CALCULATE ATTENUATION CONSTANT
0004     C        FOR IMPINGING ELECTRONS
0005     C
0006     C     J=1,2  (PM,NI)
0007           T=V
0008           IF(T.GT.0.0)GO TO 3
0009           T=1.0E-6
0010         1 XMU=16.0/(T**1.4)
0011         2 RETURN
0012         3 IF(T.LE.0.036)GO TO 1
0013           XMU=18.2/(T-.036)**1.37
0014           RETURN
0015     C     XMU=22.0/(T**1.33)
0016     C   5 XMU=18.2/(T-.036)**1.37
0017     C     RETURN
0018           END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	95	PIC CON REL LCL SHR EXE R
2	$LOCAL	8	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	103	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	XMU

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
AP-00000004@	I*4	J	2-00000004	R*4	T	AP-00000008@	

LABELS

Address	Label	Address	Label	Address	Label
0-00000018	1	0-0000002D	2	0-00000032	3

```
0001     *REFLECTION
0002     C      FUNCTION XC(Z,RHO,TM,ZOA)
0003            FUNCTION XC(Z)
0004     C      TO CALCULATE REFLECTION COEFFICIENT
0005     C          FOR BETA RAYS
0006            DATA PI/3.141592654/,E4/2.0736E-26/
0007     C
0008     C      XC=.09+(Z-13.)*5.7971E-3
0009     C      XC=.05
0010     C      CALL RANGE(TM,RHO,ZOA,RA)
0011     C      G=PI*AN*(Z**2)*E4*RA/(4.0*TM**2)
0012            IF(Z.GE.40)GO TO 1
0013     C      G=.045*Z
0014     C      XC=(G-1+0.5**G)/(G+1)/G
0015            XC=1.923928E-2*(Z**0.81832455)
0016            IF(XC.LE.0.)STOP 20
0017            RETURN
0018          1 XC=(7*Z-80.)/(14.*Z-80.)
0019            RETURN
0020            END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	87	PIC CON REL LCL SHR EXE R
1	$PDATA	2	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	20	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	109	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	XC

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
2-00000008	R*4	E4	2-00000004	R*4	PI	AP-00000004@	

LABELS

Address	Label
0-0000003D	1

```
0001    *COLLECTION EFFICIENCY
0002          SUBROUTINE QX(LE,LH,Q1,Q2,Q,QP)
0003    C
0004    C     PROGRAM TO CALCULATE QUANTUM EFFICIENCY FOR PN AND SCHOTTKY CELLS
0005    C
0006          REAL L,LJ,LE,LH
0007    C
0008          COMMON/CEFF/XLE,XLH,L,LJ,A,OMRC,CCC
0009    C     DATA LE/5.24E-4/,LH/2.27E-4/,L/5.24E-4/,LJ/1.0E-4/,A/875./
0010    C
0011    C---------------------------------
0012    C
0013          X=(L-LJ)/LE
0014          X1=EXP(X)
0015          SH=(X1-1.0/X1)/2.0
0016          CH=(X1+1.0/X1)/2.0
0017          TH=SH/CH
0018          Y=EXP(-A*LJ)
0019          Y1=EXP(-A*L)
0020          ALE=A*LE
0021          QE=ALE/(1.0-ALE**2)*((TH-ALE)*Y+ALE*Y1/CH)
0022    C
0023          X=LJ/LH
0024          X1=EXP(X)
0025          SH=(X1-1.0/X1)/2.0
0026          CH=(X1+1.0/X1)/2.0
0027          ALH=A*LH
0028          B=(ALH+CH/SH)*Y-1.0/SH
0029          QH=ALH/(1.0-ALH**2)*B
0030          IF(QH.LE.0.)QH=B
0031    C
0032          QP=QE+QH
0033          Q1=QE/(1.0-Y1)
0034          Q2=QH/(1.0-Y1)
0035          Q=QP/(1.0-Y1)
0036          IF(QE.LE.0.0.OR.QH.LE.0.0)GO TO 2
0037        3 RETURN
0038        2 PRINT 1,QE,QH,Q,QP
0039        1 FORMAT(5X,'QX',4E12.2)
0040          STOP
0041          END
```

```
0001    *BETAE (DECAY E-SPEC)
0002          SUBROUTINE BETAE(TMAX,RAN,RHO,IR,TAVE,TAVEZ)
0003    C
0004    C     PROGRAM TO CALCULAYE BETA DECAY EENERGY SPECTRUM
0005    C
0006          REAL MIC
0007          DIMENSION FF(1:235),FUZ(1:235),ZTA(1:235),FT(1:235)
0008          DIMENSION DELP(1:235),TPR(1:235),FTT(1:235)
0009          COMMON/SPEC/FE(1:235),TT(1:235),NR,FLUX
0010          COMMON/RANG/AA,BB
0011          COMMON/CONT/H,E,XM0,PI,EE,A,Z1,C,TOH,TCC,SIGCAP,DECY
0012          COMMON/PLOT/IPLOT
0013          DATA KK/0/
0014    C
0015    C---------------------------------
0016    C  INPUT DATA
0017          KK=KK+1
0018          IF(KK.GT.1)GO TO 7
0019          MIC=1.0E4
0020          AQ=AA*AA
0021          BQ=BB*BB
0022    C     G=1.6E-49
0023          ALFA=1./137.04
0024          HBAR=H/(2.0*PI)
0025          HBC=HBAR/(XM0*C)
0026          XLP=ALOG(2.0*PI)
0027    C
0028          PI4=PI**4
0029    C     XM5=(XM0**5)*1.0E+100
0030    C     C4=C**4
0031    C     G2=G**2
0032    C     H7=(H**7)*1.0E+100
0033    C     CONS=64.0*PI4*XM5*C4*G2/H7
0034          CONS=64.0*PI4*2.31384E-8
0035          TAUZ=1.0/CONS
0036          RM=XM0*C*C/1.602E-6
0037        7 AL2=.69314718
0038          Z=Z1+1
0039          DZ=20.
0040          IF(TMAX.LT..1)DZ=5.
0041          TMIN=0.
0042          DT=.005
0043          IF(TMAX.LT.0.1)DT=.001
0044          N=INT(TMAX/DT+0.5)
0045          N3=1
0046          IF(N.GT.50)N3=N/30
0047    C     INPUT FOR MAX. RANGE
0048    C---------------------------------
0049    C
0050          AZ=ALFA*Z
0051          S=SQRT(1.-AZ**2)-1
0052          C13=1./3.
0053          R=1.5E-13*(A**C13)
0054          TS=2.0*S
0055          C1=(2.*R/HBC)**TS
0056          GAMX=GAMMA(3+TS)
0057          B1=C1*4.0*(1+S/2)/(GAMX**2)
```

```
0058          X=1+S
0059          GAMX2=GAMMA(X)**2
0060    C
0061          WM=1.0+TMAX/RM
0062          ETAM=SQRT(WM*WM-1)
0063    C---------------------------------
0064    C
0065          N1=N+1
0066          WRITE(7,8)
0067        8 FORMAT(1H1)
0068          WRITE(7,3)N1,R,S,ETAM,WM,B1,RM,TAUZ,GAMX,GAMX2
0069          WRITE(7,5)
0070          SUM=0.
0071          SUN=0.
0072          SUNA=0.
0073          SUMA=0.
0074          TT(1)=TMIN
0075          DO 2 I=1,N1
0076          TT(I)=TMIN+(I-1)*DT
0077          T=TT(I)
0078          IF(I.GT.1)GO TO 1
0079          ETA=0.
0080          ZTA(I)=ETA
0081          ETA2=0.
0082          W=1.
0083          B2=0.
0084          FUZ(I)=0
0085          FF(I)=0.
0086          GO TO 2
0087        1 W=1.0+T/RM
0088          ETA=SQRT(W*W-1.)
0089          ETA2=ETA*ETA
0090          ZTA(I)=ETA
0091          DELP(I)=ZTA(I)-ZTA(I-1)
0092          Y=AZ*W/ETA
0093          GAMY2=ABS(GAMI(X,Y))
0094          Q=GAMX2*GAMY2
0095          B2=(ETA**TS)*(EXP(PI*Y))*Q
0096          FEZ=B1*B2
0097          FUZ(I)=FEZ
0098          F=FEZ*((WM-W)**2)*ETA2
0099          FF(I)=F
0100          SUM=SUM+(ZTA(I)*FF(I)+ZTA(I-1)*FF(I-1))*DELP(I)/2.
0101          SUN=SUN+(FF(I)+FF(I-1))*DELP(I)/2.
0102          SUNA=SUNA+FF(I)
0103    C     WRITE(7,3)I,T,ETA,W,Y,B2,FEZ,F
0104        2 CONTINUE
0105        3 FORMAT(I5,9(1PE9.2))
0106
0107    C
0108          ETAA=SUM/SUN
0109          PAVE=ETAA*RM/C
0110          SUNP=SUNA
0111          SUM=0.
0112          SUN=0.
0113          SUMA=0.
0114          W1=1.0
```

```
0115          FT(1)=0.0
0116      C
0117          DO 10 I=2,N1
0118          W=1.0+TT(I)/RM
0119          FT(I)=FUZ(I)*W*SQRT(W*W-1)*(WM-W)**2
0120          DW=W-W1
0121          SUM=SUM+(W*FT(I)+FT(I-1)*W1)*DW/2.0
0122          SUN=SUN+(FT(I)+FT(I-1))*DW/2.0
0123          SUMA=SUMA+FT(I)
0124          W1=W
0125       10 CONTINUE
0126          WAVE=SUM/SUN
0127          TAVE=RM*(WAVE-1)
0128          NR=N1
0129          WRITE(8,12)NR
0130          CON=AL2/SUN/TOH
0131          ABSP2=CON*TAUZ
0132      C
0133          N2=1
0134          DO 11 I=1,N1
0135          FM=FT(I)/SUMA/RM
0136          FE(I)=FM
0137          FN=FF(I)/SUNP
0138          FTACT=FM*CON
0139          TP=(TT(I)/TMAX)*100.
0140          IF(I.LE.1)FP=0.
0141          IF(I.EQ.2)FP=100.
0142          IF(I.EQ.2)FX=FM
0143          IF(I.GT.2)FP=FM/FX*100.
0144          IF(I.NE.N2)GO TO 11
0145          WRITE(7,3)I,TT(I),TP,ZTA(I),FUZ(I),FTACT,FN,FM,FP
0146       12 FORMAT(I2)
0147          WRITE(8,3)I,TT(I),TP,ZTA(I),FUZ(I),FTACT,FN,FM,FP
0148          N2=I+N3
0149       11 CONTINUE
0150          XLL=ABSP2*SUN/TAUZ
0151          WRITE(7,4)TAVE,PAVE,WAVE,ABSP2,XLL
0152        4 FORMAT(//7X,'AVE. T(MEV)=',1PE10.3/
0153         1       5X,'AVE. P(MEV/C)=',1PE10.3/
0154         2       5X,'AVE. W       =',1PE10.3/
0155         3       5X,'ABS(P2)      =',1PE10.3/
0156         4       5X,'LAMBDA       =',1PE10.3)
0157        5 FORMAT(//,72(1H-))
0158          WRITE(7,5)
0159      C
0160      C     TO CALCULATE F(T) VS T AD VARIOUS THICKNESS
0161      C
0162          ZMAX=RAN*MIC
0163          RMAX=ZMAX*RHO
0164          M=INT(RAN*MIC/DZ +0.5)
0165          DZZ=(DZ/MIC)*RHO
0166          DO 20 J=1,M
0167      C     IN MICRON
0168          ZL=J*DZZ
0169          ZLL=J*DZ
0170          IF(J.EQ.1)ZL=1.0/MIC*RHO
0171          IF(J.EQ.1)ZLL=1.0
```

```
0172          IF(ZL.GT.RMAX)ZL=RMAX
0173          FTT(1)=0.
0174          TPR(1)=0
0175          DTTP=0.
0176          DO 13 I=2,N1
0177          ZK=(TT(I)/AA)**2+BQ
0178          ZQ=SQRT(ZK)
0179          TPR2=AQ*((ZQ-ZL)**2-BQ)
0180          IF(TPR2.LT.0.)I1=I
0181          IF(TPR2.LT.0.)GO TO 13
0182          TPR(I)=SQRT(TPR2)
0183          DTTP=(TPR(I)/TT(I))*(1.+ZL/SQRT(TPR2/AQ+BQ))
0184          FTT(I)=FT(I)*DTTP/RM
0185       13 CONTINUE
0186    C
0187          IF(IPLOT.EQ.3.OR.IPLOT.EQ.4)CALL BPLOT(ZTA,FF,N1,
0188         1TT,FT)
0189          IF(I1.GE.N1)RETURN
0190          I2=I1+1
0191          FTT(I1)=0.
0192          SUM=0.
0193          SUN=0.
0194          SUMA=0.
0195          DO 14 I=I2,N1
0196          IF(I.LE.1)GO TO 14
0197          DTPR=TT(I)-TT(I-1)
0198          DTPR=ABS(DTPR)
0199          SUM=SUM+(TT(I)*FTT(I)+TT(I-1)*FTT(I-1))*DTPR/2.
0200          SUN=SUN+(FTT(I)+FTT(I-1))*DTPR/2.
0201          SUMA=SUMA+FTT(I)
0202       14 CONTINUE
0203    C
0204          WRITE(7,16)RAN,ZMAX,ZLL
0205          FMM=0.
0206          DO 15 I=I1,N1
0207          FMM=FTT(I)/SUMA
0208       15 WRITE(7,3)I,TT(I),TPR(I),FTT(I),FMM
0209          TAVEZ=SUM/SUN
0210          IF(J.EQ.1)TAA=TAVEZ
0211          WAVE=1.0+TAVEZ/RM
0212          PAVE=(RM/C)*SQRT(WAVE**2-1)
0213          WRITE(7,4)TAVEZ,PAVE,WAVE
0214       16 FORMAT(1H1//5X,'MAX RANGE='1PE9.2,'  CM',3X,
0215         1  E9.2,'  MICRONS'/
0216         210X,'DEPTH=',E9.2,'  MICRON'/
0217         23X,1HI,3X,5HT(EV),2X,6HTP(EV),4X,4HF(T),4X,5HFM(T)/
0218         31X,4H----,4(2X,6(1H-)))
0219    C
0220          IF(IR.EQ.1)RETURN
0221       20 CONTINUE
0222          TAVEZ=TAA
0223    C     AT ONE DEPLITION LENGTH
0224          RETURN
0225          END
```

```
0001     *RANGE
0002           SUBROUTINE RANGE(T,RHO,ZOA,RAN)
0003     C     SUBPROGRAM TO CALCULATE THE RANGE OF
0004     C     BETA RAYS IN ANY MATERIAL BY INTERPOLATION
0005     C
0006           COMMON/RANG/A,B
0007           DATA A/2.0/,B/6.45E-2/,RHOS/2.321/,AS/28.09/
0008     C     A IN MEV/GM/CM2,B IN GM/CM2 DZ IN MILS
0009     C
0010     C-----------------------------
0011     C
0012           IF(RHO.EQ.2.7)GO TO 2
0013           R=SQRT(T**2/A**2+B*B)-B
0014           RX=R
0015     C     RX=1.16*R/(RHO*ZOA)
0016         1 RAN=RX/RHO
0017           RETURN
0018         2 XN=1.265-.0954*ALOG(T)
0019           RX=0.412*(T**XN)
0020           GO TO 1
0021           END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	133	PIC CON REL LCL SHR EXE R
2	$LOCAL	20	PIC CON REL LCL NOSHR NOEXE R
3	RANG	8	PIC OVR REL GBL SHR NOEXE R
	Total Space Allocated	161	

ENTRY POINTS

Address	Type	Name
0-00000000		RANGE

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
3-00000000	R*4	A	2-00000004	R*4	AS	3-00000004	
AP-00000010@	R*4	RAN	AP-00000008@	R*4	RHO	2-00000000	
AP-00000004@	R*4	T	2-00000010	R*4	XN	AP-0000000C@	

```
0001     *GAM(X)
0002           FUNCTION GAMMA(X)
0003     C
0004     C     GAMMA FUNCTION USING STIRLING FORMULA
0005     C
0006           PI=3.141592654
0007           TPI=2.0*PI
0008           SPI=SQRT(TPI)
0009           A=SPI*EXP(-X)
0010           B=X -0.5
0011           C=A*(X**B)*(1.0+1.0/(12.0*X)+1.0/(288.0*X*X)-
0012          1  139.0/(51840.0*(X**3)))
0013           GAMMA=C
0014           RETURN
0015           END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	152	PIC CON REL LCL SHR EXE R
2	$LOCAL	28	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	180	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	GAMMA

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
2-00000010	R*4	A	2-00000014	R*4	B	2-00000018	
2-0000000C	R*4	SPI	2-00000008	R*4	TPI	AP-00000004@	

FUNCTIONS AND SUBROUTINES REFERENCED

Type	Name	Type	Name
R*4	MTH$EXP	R*4	MTH$SQRT

```
0001    *GAM COMPLEX
0002          FUNCTION GAMI(X,Y)
0003    C
0004    C     GAMMA FUNCTION OF COMPLEX ARGUMENT
0005    C
0006          A=1.0/(1.+(Y/X)**2)
0007          DO 1 I=1,200
0008          B=1.0/(1.0+(Y/(X+I))**2)
0009          C=A*B
0010          IF(ABS(1.0-B).LE.0.01)GO TO 2
0011          A=C
0012        1 CONTINUE
0013          STOP 30
0014        2 GAMI=C
0015          RETURN
0016          END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	111	PIC CON REL LCL SHR EXE R
1	$PDATA	2	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	28	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	141	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	GAMI

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
2-00000004	R*4	A	2-0000000C	R*4	B	2-00000010	
AP-00000004@	R*4	X	AP-00000008@	R*4	Y		

LABELS

Address	Label	Address	Label
0-00000052	1	0-00000065	2

```
0001    *EAB
0002          SUBROUTINE EAB(J,Z,MU,ZTOT,ANS)
0003    C     PROGRAM TO CALCULATE THE ABSORBED ENERGY ,DOSE,
0004    C      AND BREMSSTRUHLUG PRODUCTION RATE
0005    C
0006          COMMON/SPEC/FE(1:235),TE(1:235),NR,FLUX
0007          COMMON/SUBST/CS3,ZS3,AS3,RHOS3,CS2,ZS2,AS2,RHOS2,CM,RHOM
0008          COMMON/LENG/TM,TA,ACT,RHOB,S,KK,YUC,RHOC
0009          COMMON/CEFF/DIFLE,DIFLH,CELT,DEPL,MUCX,OMRC,CC
0010          DIMENSION FG(25),EG(25),EGG(14),HMUR(14) ,OMUR(14)
0011          REAL MU,K,MUG,MUC
0012    C
0013          DATA EGG/.01,.015,.02,.03,.04,.05,.06,.08,.1,.15,.2,.3,.4,.5/
0014          DATA HMUR/.385,.376,.369,.357,.346,.335,.326,
0015         1          .309,.294,.265,.243,.211,.189,.173/
0016          DATA OMUR/5.58,1.62,.754,.335,.236,.199,.181,
0017         2          .162,.152,.134,.123,.107,.0954,.0871/
0018    C
0019    C     FUNCTIONS
0020          E(Z)=CON*(Y+EE*(1.0-EXP(-Z))/MU)
0021          D(Z)=CON*(Y+EXP(1.0-Z))
0022    C
0023    C-----------------------------------------------
0024    C
0025          IF(KK.GT.1)GO TO 4
0026          KK=KK+1
0027          RM=.511006
0028          PI=3.141592654
0029          TPI=2.0*PI
0030          FPI=4.0*PI
0031          EE=2.718281828
0032    C     XM3=MU**3
0033    C     TSSIUE COMPOSITION
0034          RHOO=1.428E-3
0035          RHOH=8.988E-5
0036          RHOT=1.1
0037    C
0038          C=3.11*EXP(-.55*TM)
0039          C2=C*C
0040          DB=(1.6E-8)*TA*ACT
0041          ALFA=1.0/(3.0*C2+EE*(1.-C2))
0042    C     CONA=0.5*DB*ALFA
0043          CONA=DB*ALFA
0044          CONE=100.0*CELT*RHOC/1.6E-6
0045    C
0046        4 GO TO(1,2,3),J
0047        1 W=MU*S
0048          WOC=W/C
0049          CON=CONA/CONE/Z
0050          IF(WOC.GE.1.)Y=0.
0051          IF(WOC.LT.1.)
0052         1Y=3*C2*S+C*C2*EE*(EXP(-WOC)-1.)/MU-0.5*C*S**2*MU*
0053         2(2.5-ALOG(WOC))
0054          EH=E(W)
0055    C---------
0056          SP=S+Z
0057          G=MU*Z
```

```
0058          GW=G+W
0059          GWOC=GW/C
0060          IF(GWOC.GE.1.)Y=0.
0061          IF(GWOC.LT.1.)
0062         1Y=3*C2*SP+C*C2*EE*(EXP(-GWOC)-1.)/MU-.5*C*SP**2*MU*
0063         2(2.5-ALOG(GWOC))
0064          EHX=E(GW)
0065    C-----------
0066          GOC=G/C
0067          IF(GOC.GE.1.)Y=0.0
0068          IF(GOC.LT.1)
0069         1Y=3*C2*Z+C*C2*EE*(EXP(-GOC)-1.)/MU-0.5*C*Z**2*MU*
0070         2(2.5-ALOG(GOC))
0071          EX=E(G)
0072          EZ=EX-(EHX-EH)
0073          FZ=EZ/EH
0074          ANS=FZ
0075          RETURN
0076        2 CONTINUE
0077          CON=CONA
0078          R=MU*Z
0079          R1=R
0080          ROC=R/C
0081          IF(ROC.GE.1)Y=0.
0082          IF(ROC.LT.1)
0083         1Y=C2*(3.-EXP(1.-ROC)-ROC*(2.0-ALOG(ROC)))
0084          DX=D(R)
0085    C
0086          R=R1+MU*S
0087          ROC=R/C
0088          IF(ROC.GE.1.0)Y=0.
0089          IF(ROC.LT.1.0)
0090         1Y=C2*(3.-EXP(1.-ROC)-ROC*(2.0-ALOG(ROC)))
0091          DXH=D(R)
0092          DS=ABS(DX-DXH)
0093          ANS=DS
0094          RETURN
0095        3 CONTINUE
0096          XMUS2=RHOS2*YUC
0097          TRAN=EXP(-XMUS2*CS2)
0098          EGM=TM
0099          MN=14
0100          M=24
0101          M1=M+1
0102          ZAVE=(16*8+1)/33.
0103          CON=1.4E-3*ZTOT
0104          DEG=EGM/M
0105          DO 15 I=1,M1
0106          FG(I)=0.
0107       15 EG(I)=(I-1)*DEG
0108          DRATE=0.
0109          DO 33 I=1,M1
0110          EGX=EG(I)
0111          W1=1.+EGX/RM
0112          CALL ENT(EGX,MN,EGG,HMUR,AH)
0113          CALL ENT(EGX,MN,EGG,OMUR,AO)
0114          MUG=.6*AH*RHOH+.4*AO*RHOO
```

```
0115          VV=(5.53E-5)*MUG*EGX
0116          SUM=0.
0117          SUN=0.
0118          DO 30 L=1,NR
0119          IF(TE(L).GT.EGX.AND.EGX.GT.0.)
0120         1SUM=SUM+(TE(L)-EG(I))*FE(L)
0121          SUN=SUN+FE(L)
0122       30 CONTINUE
0123          IF(SUN.LE.0.)STOP 33
0124          FG(I)=CON*SUM/SUN
0125       33 DRATE=DRATE+FG(I)*VV*DEG*FLUX
0126    C
0127          DRT=.96*DRATE
0128          ANS=DRT
0129    C     REM/HR
0130          WRITE(6,20)
0131       20 FORMAT(1H1,11X,'INDUCED RADIATION SPECTRUM'/
0132         1112X,1HI,5X,2HEG,10X,2HFG,/11X,2(1H-),4X,'---',9X,'---')
0133          WRITE(8,21)M1
0134       21 FORMAT(I2)
0135          DO 25 I=1,M1
0136          WRITE(6,10)I,EG(I),FG(I)
0137       25 WRITE(8,10)I,EG(I),FG(I)
0138       10 FORMAT(10X,I3,2(1PE12.2))
0139          RETURN
0140          END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	1643	PIC CON REL LCL SHR EXE R
1	$PDATA	97	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	700	PIC CON REL LCL NOSHR NOEXE R
3	SPEC	1888	PIC OVR REL GBL SHR NOEXE R
4	SUBST	40	PIC OVR REL GBL SHR NOEXE R
5	LENG	32	PIC OVR REL GBL SHR NOEXE R
6	CEFF	28	PIC OVR REL GBL SHR NOEXE R
	Total Space Allocated	4428	

ENTRY POINTS

Address	Type	Name
0-00000000		EAB

```
0001     *ENT
0002           SUBROUTINE ENT(EE,N,E,F,Z)
0003     C
0004     C      PROGRAM FOR LINEAR INTERPOLATION
0005     C
0006           DIMENSION E(1),F(1),T(25)
0007     C-----------------------------------------------
0008     C
0009     CCCCCCC
0010          2 IL=1
0011            IR=N
0012          3 IF((IR-IL).EQ.1)GO TO 7
0013            I=0.5*FLOAT(IL+IR)+.1
0014            IF(EE-E(I))4,5,6
0015          4 IR=I
0016            GO TO 3
0017          5 Z=F(I)
0018            RETURN
0019          6 IL=I
0020            GO TO 3
0021          7 Z=F(IL)+(F(IR)-F(IL))*(EE-E(IL))/(E(IR)-E(IL))
0022            RETURN
0023            END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	166	PIC CON REL LCL SHR EXE R
2	$LOCAL	176	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	342	

ENTRY POINTS

Address	Type	Name
0-00000000		ENT

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
AP-00000004@	R*4	EE	2-0000006C	I*4	I	2-00000064	
AP-00000008@	I*4	N	AP-00000014@	R*4	Z		

```
0001     *WTAP5  TO WRITE TAPE5 FOR DOSE
0002           SUBROUTINE WTAP5(NR,FA,T,TT,FF,FLUX,TITC)
0003     C
0004           DIMENSION TT(1),F(1:235),TIT(10) ,FF(1)
0005           COMMON/CONV/Z,A,ZOA,R,ION
0006     C
0007           DO 20 I=1,NR
0008        20 F(I)=FF(I)*FLUX
0009           PRHEAD1=4H$PRE
0010           PRHEAD2=4HLIN
0011           TIT(1)=4HHEAD
0012           TIT(2)=4H=30H
0013           TIT(3)=4HBETA
0014           TIT(4)=4H DOS
0015           TIT(5)=4HE
0016           TIT(6)=TITC
0017           TIT(7)=4H CON
0018           TIT(8)=4HVERT
0019           TIT(9)=4HER
0020           TIT(10)=4H
0021           U=1H,
0022           NN=-NR
0023           FAC=FA/2.0
0024     C     PRELD IS FOR 4 PI
0025           WRITE(5,21)PRHEAD1,PRHEAD2
0026           WRITE(5,21)(TIT(I),I=1,10),U
0027           WRITE(5,22)NN,TT(1),TT(NR),FAC,ZOA,Z,R,T,ION,
0028          1  (TT(J),U,J=1,4)
0029           WRITE(5,23)(TT(I),U,I=5,NR)
0030           WRITE(5,24)(F(J),U,J=1,4)
0031           WRITE(5,23)(F(I),U,I=5,NR)
0032           WRITE(5,25)
0033     C
0034        21 FORMAT(1X,2A4,10A4,A1)
0035        22 FORMAT(1X,'NIN='I3,',','EMIN='1PE9.2,',','EMAX='1PE9.2,','/1X,
0036          1'FACTOR='1PE9.2,',','ZOA='1PE9.2,',','Z=',F5.1,','/1X,
0037          2'DENS='F5.2,',','THK='1PE9.2,',','XION='1PE9.2,','/1X,'ENIN=',
0038          34(1PE9.3,A1))
0039        23 FORMAT(1X,5(1PE9.3,A1))
0040        24 FORMAT(1X,'FINP=',4(1PE9.3,A1))
0041        25 FORMAT(1X,'$END')
0042           RETURN
0043           END
```

```
0001    *DAMG
0002          SUBROUTINE DAMG(YR,TA,KT,VTHH,TAUZ,DL,THK,KTAU,OMEV)
0003    C
0004    C     PROGRAM TO CALLCULATE 1 MEV EQUIVALENT DAMAGE
0005    C
0006          REAL KL,KT,JS,JSZ,L,LZ,NDEF,KTAU
0007          COMMON/CONT/H,E,MZ,PI,EE,AB,ZB,CL,TOH,TC,SIGCAP,DECY
0008          COMMON/DCY/JSZ,VMZ,FF,TOTPZ,AREAC,PVOLZ,TVOL,PINT,ETAZ
0009          DATA C,CP/4.5E-3,1.29E-2/
0010    C
0011    C-----FUNCTIONS
0012          ZKL(T)=(T**1.5)*8.0E-11
0013          PHMO(T)=(T**1.5)*5.0E-16
0014    C     ADJUSTED FOR 1 MEV FLUENCE
0015    C
0016    C     OMEV IS FOR YR
0017    C--------------------------------------
0018    C
0019          LZ=SQRT(TAUZ*DL)
0020          KL=ZKL(TA)
0021          NDEF=0.1*OMEV
0022    C     KL=(NDEF/OMEV)*SIGCAP*VTHH
0023          PHM=PHMO(TA)
0024          KTAU=DL*KL
0025          L=1.0/((KL*OMEV+1.0/(LZ*LZ))**.5)
0026          TAU=1.0/(KTAU*OMEV+1.0/TAUZ)
0027          DELL=(1.0-L/LZ)*100.
0028          DELT=(1.0-TAU/TAUZ)*100.
0029          ALFA=ALOG(1.0+OMEV*PHM)
0030          JS=JSZ-C*ALFA
0031          VM=VMZ-CP*ALFA
0032          PMZ=FF*JSZ*VMZ
0033          PM=FF*JS*VM
0034          THALF=TOH/TC
0035          DECAY=DECY
0036          IF(YR.LE.0.)PZ=PMZ
0037          TOTP=PM*AREAC
0038          PVOL=TOTP/TVOL
0039          ETA=TOTP/(PINT*AREAC)*100.
0040          DELTP=(1.0-TOTP/TOTPZ)*100.
0041          DELPV=(1.0-PVOL/PVOLZ)*100.
0042          DELET=(1.0-ETA/ETAZ)*100.
0043          DELJ=(1.0-JS/JSZ)*100.
0044          DELV=(1.0-VM/VMZ)*100.
0045          DELP=(1.0-PM/PMZ)*100.
0046          DELPP=(1.0-DECAY)*100.
0047    C
0048          WRITE(6,1)NDEF
0049          WRITE(6,2)YR
0050          WRITE(6,3)
0051          WRITE(6,9)KL,PHM,OMEV,KTAU
0052          WRITE(6,4)TAUZ,TAU,DELT
0053          WRITE(6,5)LZ,L,DELL
0054          WRITE(6,6)JSZ,JS,DELJ
0055          WRITE(6,7)VMZ,VM,DELV
0056          WRITE(6,8)PMZ,PM,DELP
0057          WRITE(6,10)THALF,PZ,DELPP
```

```
0058           WRITE(6,11)TOTPZ,TOTP,DELTP
0059           WRITE(6,12)PVOLZ,PVOL,DELPV
0060           WRITE(6,13)ETAZ,ETA,DELET
0061     C
0062          1 FORMAT(1X,67(1H*)/
0063           110X,'INDUCED DEFECT CONCENTRATION='1PE9.2)
0064          2 FORMAT(15X,'BETAVOLTAIC DEGRADATION'/
0065           1       13X,'DUE TO RADIATION DAMAGE AFTER'/
0066           2       20X,F8.2,'  YEARS')
0067          3 FORMAT(1X,65(1H-))
0068          4 FORMAT(9X,'TAUHZ=',1PE9.2,4X,'TAUH='1PE9.2,5X,F6.2,' PERCENT')
0069          5 FORMAT(11X,'LHZ='1PE9.2,6X,'LH='1PE9.2,5X,F6.2)
0070          6 FORMAT(11X,'JSZ='1PE9.2,6X,'JS='1PE9.2,5X,F6.2)
0071          7 FORMAT(10X,'VOCZ='1PE9.2,5X,'VOC='1PE9.2,5X,F6.2)
0072          8 FORMAT(8X'(P/A)Z='1PE9.2,5X,'P/A='1PE9.2,5X,F6.2)
0073          9 FORMAT(10X,'KL='1PE9.2,4X,'PHIC='1PE9.2,5X,'OMEV='1PE9.2/
0074           110X,'KTAU='1PE9.2//)
0075         10 FORMAT(12X,'TH='F6.2,8X,'P/A='1PE9.2,5X,F6.2,2X,'SOURCE DEGRAD')
0076         11 FORMAT(4X,'TOTAL P(Z)='1PE9.2,1X,'TOTAL P='1PE9.2,5X,F6.2)
0077         12 FORMAT(5X,'P/VOL (Z)='1PE9.2,3X,'P/VOL='1PE9.2,5X,F6.2)
0078         13 FORMAT(7X,'ETA (Z)='1PE9.2,5X,'ETA='1PE9.2,5X,F6.2)
0079     C
0080           RETURN
0081           END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	1138	PIC CON REL LCL SHR EXE R
1	$PDATA	536	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	120	PIC CON REL LCL NOSHR NOEXE R
3	CONT	48	PIC OVR REL GBL SHR NOEXE R
4	DCY	36	PIC OVR REL GBL SHR NOEXE R
	Total Space Allocated	1878	

ENTRY POINTS

Address	Type	Name
0-00000000		DAMG

STATEMENT FUNCTIONS

Address	Type	Name	Address	Type	Name
0-00000444	R*4	PHMO	0-0000045B	R*4	ZKL

```
0001     *BETAD DOSE IN BETAVOLTAIC CELL
0002           SUBROUTINE BETAD(THK,NI,ENIN,FINP,FACTOR,ZOA,Z,DENS,DOSEX)
0003           DIMENSION FL(500),ENIN(NI),FINP(NI)
0004          1,ENER(500),DUMX(99),DUMY(99)
0005           COMMON NDOS
0006     C  INITIALIZE TO RUN FOR SIO2
0007           MORE=0
0008           LOGLOG=1
0009           EMAX=ENIN(NI)
0010           ZOASIO2=0.49966
0011           EMIN=ENIN(1)
0012           NIN=-NI
0013        38 CODE=3HJSC
0014           MOJ=IABS(NIN)
0015           IF(ENIN(1).GT.ENIN(2)) GO TO 43
0016           DO 41 I=1,MOJ
0017           J=MOJ-I+1
0018           DUMX(J)=ENIN(I)
0019        41 DUMY(J)=FINP(I)
0020     C
0021           DO 42 I=1,MOJ
0022           ENIN(I)=DUMX(I)
0023        42 FINP(I)=DUMY(I)
0024        43 CONTINUE
0025           K=0
0026           DO 1 I=1,MOJ
0027           IF(ENIN(I).LE.200.)GO TO 1
0028           K=K+1
0029         1 CONTINUE
0030     C
0031           MOJ=MOJ-K
0032           IF(K.EQ.0)GO TO 3
0033           DO 2 I=1,MOJ
0034           ENIN(I)=ENIN(I+K)
0035         2 FINP(I)=FINP(I+K)
0036           EMAX=ENIN(1)
0037           NIN=MOJ
0038        3  CONTINUE
0039     C
0040            NSTART=8
0041           IF(NIN.LE.0) NSTART=1
0042           NIX=IABS(NIN)
0043       51  DO 165 KK=1,NIX
0044      165  FINP(KK)=FINP(KK)*FACTOR
0045            NEND=NSTART+6
0046            NOEN=500
0047            DEN=(EMAX-EMIN)/499.
0048           IF(ENIN(2).GT.ENIN(1)) GO TO 7
0049           I=2
0050     C.....CREATE NEW SPECTRUM.............
0051           DO 6 J=1,500
0052           ENER(J)=EMAX-(J-1)*DEN
0053       4   IF(ENER(J).GE.ENIN(I)) GO TO 5
0054           IF(I.GT.NIX) GO TO 7
0055           I=I+1
0056           IF(ENIN(I).EQ.0.) GO TO 9
0057           GO TO 4
```

```
0058      5    TEMP=ALOG(FINP(I)/FINP(I-1))
0059             FACTOR1= (ENIN(I-1) - ENER(J))/(ENIN(I-1)-ENIN(I))
0060           IF(LOGLOG.EQ.1)FACTOR1=ALOG(ENIN(I-1)/ENER(J))/
0061          C ALOG(ENIN(I-1)/ENIN(I))
0062             TEMP = ALOG(FINP(I-1)) + FACTOR1*TEMP
0063           FLU   =EXP(TEMP)
0064           IF(J.EQ.1) GO TO 55
0065           FL(J-1)=FLU   -FLU1
0066        55 FLU1=FLU
0067       6   CONTINUE
0068           GO TO 9
0069       7   WRITE(6,8)
0070           STOP
0071       8   FORMAT(4X,' YOU RAN OUT OF INPUT OR ENERGY IN WRONG ORDER',///)
0072         9 DO 19 I=1,500
0073           IF(ENER(I).LE.0.0)ENER(I)=.80*ENER(I-1)
0074        19 CONTINUE
0075     C.....START INTEGRATION LOOP...........
0076           NDOS=1
0077           DOSE=0.0
0078           ND=1
0079           DO 160 KK=1,490
0080     C.....CALCULATE DAMAGE COEFICIENTS.....
0081           DOS    =0.5*(DAM(ENER(KK))+DAM(ENER(KK+1)))
0082       160 DOSE=DOSE+DOS*FL(KK)
0083           DOSEX=DOSE
0084           GO TO 71
0085       231 CODE=3HVOC
0086        71 CONTINUE
0087           DOSEX=DOSEX*ZOA/ZOASIO2
0088           RETURN
0089           END
```

```
0001     *DAMAGE COEFFICIENTS
0002           FUNCTION DAM(E)
0003           DIMENSION EE(65),DAME(455),DAMX(65)
0004           COMMON NDOS
0005           DATA(EE(I),I=1,65)/.01,.02,.025,.03,.04,.06,.08,.10,.12,.15,
0006          1.17,.20,.22,.25,.28,.30,.33,.36,.40,.45,.50,.55,.60,.65,.70,.80,
0007          2.90,1.0,1.1,1.2,1.4,1.6,1.8,2.0,2.25,2.5,2.75,3.0,3.25,3.5,3.75,
0008          34.0,4.25,4.5,4.75,5.0,5.25,5.5,5.75,6.0,6.25,6.5,6.75,7.0,8.,9.,
0009          410.,15.,20.,25.,30.,40.,3*0./
0010           DATA(DAME(I),I=1,65)/4.17E-5,9.79E-5,1.79E-4,4.21E-4,7.71E-4,
0011          C1.81E-3,
0012          13.32E-3,5.30E-3,7.78E-3,1.24E-2,1.62E-2,2.28E-2,2.92E-2,3.65E-2,
0013          24.45E-2,5.35E-2,6.54E-2,7.85E-2,9.8E-2,1.22E-1,.147,.175,.205,
0014          3.236,.269,.34,.417,.5,.583,.67,.859,1.06,1.26,1.47,1.73,2.,2.27,
0015          42.51,2.76,3.,3.25,3.5,3.72,4.17,4.4,4.62,4.84,5.06,5.28,
0016          C  5.49,
0017          55.71,5.93,6.15,6.88,7.6,8.3,10.6,12.3,13.6,14.7,16.5,4*0./
0018           DATA(DAME(I),I=66,130)/5*1.E-20,1.E-12,1.E-6,8.47E-6,3.05E-4,
0019          C 1.67E-3,3.2E-3,
0020          16.47E-3,9.98E-3,1.43E-2,1.96E-2,2.57E-2,3.38E-2,4.32E-2,5.79E-2,
0021          27.8E-2,9.99E-2,.124,.150,.177,.205,.269,.338,.414,.491,.573,.75,
0022          3.939,1.13,1.34,1.59,1.85,2.12,2.37,2.61,2.85,3.09,3.34,3.57,3.79,
0023          44.02,4.24,4.46,4.68,4.9,5.12,5.33,5.55,5.77,5.98,6.73,7.44,8.15,
0024          51.05E1,12.3,13.5,14.7,16.4,3*0.0/
0025           DATA(DAME(I),I=131,195)/7*1.E-20,1.E-12,1.E-6,8.96E-06,2.78E-4,
0026          C 1.52E-3,3.31E-3,
0027          15.85E-3,9.18E-3,1.34E-2,1.92E-2,2.62E-2,3.75E-2,5.38E-2,
0028          27.27E-2,9.38E-2,.117,.141,.166,.224,.287,.357,.43,.507,.675,
0029          3.856,1.04,1.24,1.49,1.74,2.01,2.26,2.49,2.73,2.97,3.22,3.45,
0030          43.67,3.89,4.12,4.34,4.55,4.77,4.99,5.2,5.41,5.63,5.85,6.6,7.32,
0031          58.02,10.4,12.2,13.5,14.6,16.4,3*0./
0032           DATA(DAME(I),I=196,260)/10*1.E-20,1.E-12,1.E-6,1.E-6,2.36E-4,
0033          C 1.05E-3,
0034          12.51E-3,5.07E-3,8.63E-3,1.51E-2,2.52E-2,3.82E-2,5.41E-2,7.43E-2,
0035          29.14E-2,.112,.16,.213,.274,.337,.406,.559,.725,.9,1.09,1.32,1.57,
0036          31.82,2.07,2.3,2.53,2.77,3.01,3.24,3.46,3.68,3.90,4.12,4.34,4.55,
0037          44.77,4.97,5.19,5.4,5.61,6.38,7.09,7.79,10.2,12.,13.3,14.5,16,
0038          53*0./
0039           DATA(DAME(I),I=261,325)/14*1.E-20,1.E-12,1.E-6,7.14E-5,7.E-4,
0040          C 2.75E-3,7.22E-3,
0041          11.41E-2,2.36E-2,3.6E-2,4.98E-2,6.56E-2,.103,.145,.195,.248,
0042          2.308,.442,.591,.751,.923,1.14,1.37,1.61,1.86,2.08,2.31,2.54,2.77,
0043          33.,3.22,3.44,3.65,3.87,4.08,4.3,4.51,4.71,4.92,5.13,5.34,
0044          46.12,6.83,7.52,10.,11.8,13.1,14.3,16.1,3*0.0/
0045           DATA(DAME(I),I=326,390)/17*1.E-20,1.E-12,1.E-6,3.E-4,2.11E-3,
0046          C 5.89E-3,1.19E-2,
0047          11.98E-2,3.E-2,5.61E-2,8.79E-2,.127,.169,.218,.332,.462,.604,
0048          2.76,.961,1.17,1.4,1.64,1.86,2.07,2.3,2.52,2.74,2.96,3.17,3.39,
0049          33.6,3.81,4.02,4.23,4.43,4.63,4.84,5.04,5.83,6.53,7.22,9.75,11.6,
0050          412.9,14.1,15.9,3*0.0/
0051           DATA(DAME(I),I=391,455)/22*1.E-20,1.E-12,1.E-6,7.89E-6,2.41E-3,
0052          C 1.01E-2,2.42E-2,
0053          14.31E-2,6.71E-2,.131,.213,.311,.424,.576,.746,.93,1.13,1.33,
0054          21.53,1.73,1.93,2.13,2.33,2.53,2.74,2.94,3.14,3.34,3.54,3.73,3.92,
0055          34.11,4.31,5.08,5.78,6.46,9.06,11.,12.4,13.6,15.4,3*0.0/
0056           IF(NDOS.GE.8)GO TO 60
0057           EMAX=40.
```

```
0058          DO 2 J=1,65
0059        2 DAMX(J)=DAME(J+65*(NDOS-1))
0060          TEN=1.0
0061          I=1
0062          IF(E.GT.40.) GO TO 35
0063          IF(E.LT.EE(1)) GO TO 15
0064       25 IF(E.LE.EE(I)) GO TO 175
0065          I=I+1
0066          GO TO 25
0067      175 ZIM=ALOG(EE(I-1)/EE(I))
0068          ZM=EXP(((ALOG(DAMX(I))*ALOG(EE(I-1)))-ALOG(DAMX(I-1))*ALOG(EE(I)))
0069         1   /ZIM)
0070          GO TO 325
0071       15 DAM=0
0072          RETURN
0073       35 CONTINUE
0074     C    WRITE(8,110) NDOS,E,EMAX
0075      110 FORMAT(1H1,10X,'NDOS=',I5,   /10X,'E =',E11.4,/10X,
0076         1'LARGEST VALUE OF E ALLOWED FOR THIS NDOS=',
0077         2E11.4)
0078          STOP
0079      325 DAM=TEN*ZM*E**((ALOG(DAMX(I-1))-ALOG(DAMX(I)))/ZIM)
0080       60 RETURN
0081          END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	313	PIC CON REL LCL SHR EXE R
2	$LOCAL	2368	PIC CON REL LCL NOSHR NOEXE R
3	$BLANK	4	PIC OVR REL GBL SHR NOEXE R
	Total Space Allocated	2685	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	DAM

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
AP-00000004@	R*4	E	2-0000092C	R*4	EMAX	2-00000928	
3-00000000	I*4	NDOS	2-00000934	R*4	TEN	2-00000938	

```
0001     *VOC
0002           FUNCTION VOC(KT,JZ,JZR,JS,A)
0003     C     TO SOLVE JS=JZ EXP(BVO)+JZR EXP(BVO/A)
0004           REAL JS,JZ,JZR,KT
0005     C
0006           AA=1.0/A
0007           EPS=0.01
0008           N=2000
0009           M=100
0010           ZM=M
0011         1 DO 2 I=1,N
0012           ZI=I
0013           P=ZI/ZM
0014           X=10**P
0015           Y=JZ*X+JZR*(X**AA)
0016           IF(ABS((Y-JS)/JS).GT.EPS)GO TO 2
0017           GO TO 3
0018         2 CONTINUE
0019           PRINT 4,JS,JZ,JZR,KT,A
0020           X=(JS/JZR)**A
0021         3 VOC=KT*ALOG(X)
0022         4 FORMAT(5X,'NO SOLUTION FOR JS=JZ*X+JZR*(X)**(1/A)',
0023          1' WE SET JZ=0.'/5E12.3)
0024           RETURN
0025           END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	251	PIC CON REL LCL SHR EXE R
1	$PDATA	64	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	48	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	363	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	VOC

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
AP-00000014@	R*4	A	2-00000004	R*4	AA	2-00000008	
AP-00000010@	R*4	JS	AP-00000008@	R*4	JZ	AP-0000000C@	
2-00000010	I*4	M	2-0000000C	I*4	N	2-00000024	
2-0000002C	R*4	Y	2-00000020	R*4	ZI	2-00000014	

```
0001    *SW (FIND PEAK W)
0002          function sw(xl,muc,mus)
0003          real*8 wl,w,wl,l,ll,lmu,wmu,fx,muc,mus
0004    c     open(6,file='peak.dat6',status='unknown')
0005          wl=5.0e-6
0006          ll=5.0e-5
0007    c     n=21
0008          m=301
0009    c     rewind 6
0010    c     do 1 j=1,n
0011    c     if(j.eq.1)muc=416.
0012    c     if(j.eq.1)mus=1290.
0013    c     if(j.eq.2)muc=1910.
0014    c     if(j.eq.2)mus=7290.
0015    c     if(j.eq.3)muc=4040.
0016    c     if(j.eq.3)mus=7290.
0017    c     write(6,5)j,muc,mus
0018    c     do 1 i=1,n
0019    c     l=1.0e-4+(i-1)*ll
0020    c     xl=l
0021          lmu=xl*muc
0022          sm=0.
0023          kk=0
0024          do 3 k=1,m
0025          w=1.0e-5+(k-1)*wl
0026          wmu=w*mus
0027          wl=w+xl
0028          fx=(1.0-exp(-wmu))/(mus*wl)
0029    c     write(6,2)k,xl,w,fx
0030          if(fx.lt.sm)go to 3
0031          sm=fx
0032          if(k.eq.1.or.k.eq.m)go to 3
0033          xll=xl
0034          ww=w
0035          sw=ww
0036          fxx=fx
0037          kk=k
0038        3 continue
0039          if(kk.gt.0)return
0040          if(kk.eq.0)go to 1
0041    c     write(6,2)kk,xll,ww,fxx
0042        1 continue
0043          print *,w,xl,fx,sm
0044        2 format(i10,2(1pe12.2),1pe15.5)
0045        4 format(i15,5x,'l(i)=',e10.2)
0046        5 format(i15,5x,'muc='e12.3,5x,'muc=',e12.3)
0047    c     call anotat('Source Width$','Cell Thickness$',2,1,1,65535)
0048    c     call ezmxy(w,1,50,2,n,'Source Thickness For Optimum Power$')
0049    c     call frame
0050          stop
0051          end
```

```
0001    *GET PLOT P VS VOC
0002          FUNCTION GETP(KT,JZ,JZR)
0003          PARAMETER(N=6,M=21)
0004          REAL KT,JZ,JZR,JZP(N,M),JMP
0005          REAL*8 X,JSC,CON
0006          DIMENSION A(N),VOC(M),PMAX(M,N),PX(N,M)
0007          DATA AMA/2./,AMI/1./,VOCM/1.8/
0008    C
0009          CON=1.0E36
0010          DVOC=VOCM/(M-1)
0011          DA=(AMA-AMI)/(N-1)
0012    C
0013          L=1
0014          DO 2 IA=1,N
0015          PR=1.0+(IA-1)*DA
0016          A(IA)=PR
0017          AA=1.0/PR
0018          J=0
0019    C
0020          DO 1 IV=1,M
0021          V=0.2+(IV-1)*DVOC
0022          BV=V/KT
0023          X=EXP(BV)
0024          JSC=JZ*X+JZR*(X**AA)
0025          IF(JSC.GT.1.)GO TO 1
0026          VMP=GETV(JSC,JZ,JZR,PR,KT)
0027          IF(VMP.GE.V)GO TO 1
0028          VOC(J)=V*1.0E3
0029          J=J+1
0030          Y=(1.-PR)*BV/PR
0031          ZJ=JZ+(JZR/PR)*EXP(Y)
0032          JZP(L,J)=ZJ*1.0E9
0033          CV=VMP/KT
0034          JMP=CV*ZJ*EXP(CV)
0035          POWER=VMP*JMP
0036          PMAX(J,L)=ALOG(POWER)
0037          PX(L,J)=PMAX(J,L)
0038        1 CONTINUE
0039          if(j.le.0)go to 2
0040          l=l+1
0041        2 CONTINUE
0042          L=L-1
0043          DO 4 LM=1,M
0044          IF(VOC(LM).LE.0.)VOC(LM)=CON
0045          DO 4 LN=1,N
0046          IF(PMAX(LM,LN).EQ.0.0)PMAX(LM,LN)=CON
0047          IF(PX(LN,LM).EQ.0.0)PX(LN,LM)=CON
0048          IF(JZP(LN,LM).LE.0.0)JZP(LN,LM)=CON
0049        4 CONTINUE
0050          A(L)=2.0
0051    C
0052          CALL DISPLA(0,0,1)
0053          CALL ANOTAT('VOC(MIL VOLT)$','LOG[PMAX(W/CM2)]$'
0054         1,2,1,1,65535)
0055          CALL EZMXY(VOC,PMAX,M,L,J,'BETACELL CHARACTERISTIC CURVE$')
0056    C
0057          CALL DISPLA(0,0,1)
```

```
0058           CALL ANOTAT('PERFECTION FACTOR$','JZ(NA/CM2)$',2,1,1,65535)
0059           CALL EZMXY(A,JZP,N,J,L,'BETACELL JZ CURVE$')
0060     C
0061           CALL DISPLA(0,0,1)
0062           CALL ANOTAT('PERFECTION FACTOR$','LOG[PMAX(W/CM2)]$'
0063          1,2,1,1,65535)
0064           CALL EZMXY(A,PX,N,J,L,'BETACELL POWERS CURVE$')
0065     C
0066           RETURN
0067           END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	634	PIC CON REL LCL SHR EXE R
1	$PDATA	161	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	1996	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	2791	

ENTRY POINTS

Address	Type	Name
0-00000000	R*4	GETP

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
2-00000694	R*4	AA	2-00000674	R*4	AMA	2-00000678	
2-00000668	R*8	CON	2-000006B4	R*4	CV	2-00000684	
2-0000068C	I*4	IA	2-0000069C	I*4	IV	2-00000698	
2-00000660	R*8	JSC	AP-00000008@	R*4	JZ	AP-0000000C@	
2-00000688	I*4	L	2-000006BC	I*4	LM	2-000006C0	
2-00000690	R*4	PR	2-000006A0	R*4	V	2-000006A8	
2-00000658	R*8	X	2-000006AC	R*4	Y	2-000006B0	

ARRAYS

Address	Type	Name	Bytes	Dimensions
2-000001F8	R*4	A	24	(6)
2-00000000	R*4	JZP	504	(6, 21)
2-00000264	R*4	PMAX	504	(21, 6)
2-0000045C	R*4	PX	504	(6, 21)
2-00000210	R*4	VOC	84	(21)

```
0001     * GET VMP
0002           FUNCTION GETV(JSC,JZ,JZR,PR,KT)
0003           PARAMETER(N=3800,M=100)
0004           REAL JZ,JZR,KT
0005           REAL*8 Q,QQ,JSC
0006           DATA AL10/2.302585/
0007     C
0008           AA=1./PR
0009           A=PR
0010           EPS=.05
0011           ZM=M
0012         1 DO 2 I=1,N
0013           ZI=I
0014           P=ZI/ZM
0015           X=10**P
0016           Y=P*AL10
0017           Q=JZ*(1.0+Y)*X+JZR*(1.0+Y/A)*(X**AA)
0018           Q1=10.*JSC
0019           IF(Q.GT.Q1)GO TO 2
0020           QQ=(Q-JSC)/JSC
0021           IF(ABS(QQ).GT.EPS)GO TO 2
0022           GO TO 3
0023         2 CONTINUE
0024           PRINT 4,JSC,JZ,JZR,KT,A,X,Y,Q
0025           X=(JSC/JZR)**A
0026         3 GETV=KT*ALOG(X)
0027         4 FORMAT(5X,'GET VMP: NO SOLUTION WAS FOUND'/7(1PE10.2))
0028           RETURN
0029           END
```

```
0001     *SPLOT
0002           SUBROUTINE SPLOT(N,M,X,Y,Z)
0003     C     SUBPROGRAM TO PLOT VARIOUC FUNCTIONS
0004     C
0005           DIMENSION X(1:M),Y(1:M,1:2),Z(1:M,1:2)
0006           DATA CON/1.0E36/
0007     C
0008           GO TO (1),N
0009         1 CALL DISPLA(0,0,2)
0010           CALL ANOTAT('BETACELL POTENCIAL (MILLI V)$','CURRENT DENSITY:
0011          1A=J LOSS B=J SHNT$',1,1,-1,65535)
0012           DO 10 I=1,M
0013           X(I)=X(I)*1.0E3
0014           IF(X(I).LE.0.)X(I)=CON
0015           DO 10 J=1,2
0016           IF(Z(I,J).LE.0.0)Z(I,J)=CON
0017           IF(Y(I,J).LE.0.0)Y(I,J)=CON
0018        10 CONTINUE
0019           CALL EZMXY(X,Y,M,2,M,'BETACELL LOSS CURRENT DENSITY$')
0020     C
0021           CALL DISPLA(0,0,2)
0022           CALL ANOTAT('BETACELL POTENCIAL (MILLI V)$','CURRENT DENSITY:
0023          1A=J LOAD B=POWER$',1,1,-1,65535)
0024           CALL EZMXY(X,Z,M,2,M,'BETACELL JV-CURVE$')
0025           RETURN
0026           END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	307	PIC CON REL LCL SHR EXE R
1	$PDATA	169	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	328	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	804	

ENTRY POINTS

Address	Type	Name
0-00000000		SPLOT

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
2-00000000	R*4	CON	2-00000004	I*4	I	2-0000000C	
AP-00000004@	I*4	N					

```
0001     *BPLOT FOR BEAT SPECTRUM
0002           SUBROUTINE BPLOT(P,FP,N,T,FT)
0003     C     SUBPROGRAM TO PLOT VARIOUC FUNCTIONS
0004     C
0005           DIMENSION P(N),T(N),FP(N),FT(N)
0006           DATA CON/1.0E36/
0007     C
0008           CALL DISPLA(0,0,1)
0009           CALL ANOTAT('ELECTRON MOMENTUM (PC/M)$','DF(P)/DP$'
0010          1,2,1,1,65535)
0011           DO 1 I=1,N
0012           IF(P(I).LT.0.)P(I)=CON
0013           IF(T(I).LT.0.)T(I)=CON
0014           IF(FP(I).LT.0.)FP(I)=CON
0015         1 IF(FT(I).LT.0.)FT(I)=CON
0016           CALL EZXY(P,FP,N,'SOURCE MOMENTUM DISTRIBUTION$')
0017     C
0018           CALL DISPLA(0,0,1)
0019           CALL ANOTAT('ELECTRON ENERGY (EV)$','DF(T)/DT$'
0020          1,2,1,1,65535)
0021           CALL EZXY(T,FT,N,'SOURCE ENERGY DISTRIBUTION$')
0022           RETURN
0023           END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	282	PIC CON REL LCL SHR EXE R
1	$PDATA	142	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	332	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	756	

ENTRY POINTS

Address	Type	Name
0-00000000		BPLOT

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
2-00000000	R*4	CON	2-00000004	I*4	I	AP-0000000C@	

```
0001    * plotc for electron fluence vs energy
0002          subroutine plotc(j,n,t,ft)
0003    c
0004          dimension t(1:n),ft(1:n)
0005    c
0006          DATA P/1.0E36/
0007          WRITE(8,3)
0008          WRITE(8,2)(T(I),FT(I),I=1,N)
0009    C
0010          if(j.eq.1)itype=2hpm
0011          if(j.eq.2)itype=2hni
0012          DO 1 I=1,N
0013          IF(t(I).LT.0)t(I)=P
0014          IF(ft(I).LT.0)ft(I)=P
0015        1 CONTINUE
0016        2 FORMAT(10X,F5.2,5X,1PE15.2)
0017        3 FORMAT(10X,'ELECTRON FLUENCE')
0018    c
0019          call displa(0,0,2)
0020          call anotat('ELECTRON ENERGY (KEV)$',
0021         1'INTEGRAL FLUENCE (E/CM2/YR >TE)$',1,1,1,65535)
0022          CALL EZXY(T,FT,N,
0023         1' INTEGRAL FLUENCE FOR ELECTRON SOURCE$')
0024          RETURN
0025          END
```

PROGRAM SECTIONS

	Name	Bytes	Attributes
0	$CODE	274	PIC CON REL LCL SHR EXE R
1	$PDATA	145	PIC CON REL LCL SHR NOEXE R
2	$LOCAL	188	PIC CON REL LCL NOSHR NOEXE R
	Total Space Allocated	607	

ENTRY POINTS

Address	Type	Name
0-00000000		PLOTC

VARIABLES

Address	Type	Name	Address	Type	Name	Address	T
2-00000004	I*4	I	2-0000000C	I*4	ITYPE	AP-00000004@	
2-00000000	R*4	P					