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EFFECTS OF SECONDARY YIELD PARAMETER VARIATION ON PREDICTED EQUILIBRIUM POTENTIAL OF AN OBJECT IN A CHARGING ENVIRONMENT

Carolyn K. Purvis
Lewis Research Center
Cleveland, Ohio

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Carolyn K. Purvis

National Aeronautics and Space Administration

Lewis Research Center

ABSTRACT

The sensitivity of predicted equilibrium potential to changes in secondary electron yield parameters has been investigated using MATCHG, a simple charging code which incorporates the NASCAP material property formulations. It has been found that equilibrium potential is a sensitive function of one of the two parameters specifying secondary electron yield due to proton impact (δ_p) and of essentially all the parameters specifying yield due to electron impact. It is further found that information on the electron generated secondary yield parameters can be obtained from monoenergetic beam charging data if charging rates as well as equilibrium potentials are accurately recorded.

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INTRODUCTION

Charging of geosynchronous spacecraft during geomagnetic substorm activity is modeled in terms of currents to spacecraft surfaces, with the condition for equilibrium being that the net current to a surface element be zero. This net current is the sum of incident, emitted and conducted currents, and depends upon environment, surface material properties and system electrical and physical configuration. The environment of concern consists of fluxes of kilovolt electrons and ions (H^+) injected into the magnetosphere during substorm activity, plus solar photons. Charged particle emission processes generally considered to be

important for charging calculations include secondary electron production by both ion impact and electron impact, electron backscattering and photoelectron emission. System configuration concerns include capacities among various system components and shadowing of spacecraft surfaces.

Presently available computer codes have been designed to calculate charging, and incorporate algorithms for computing currents due to the important particle emission processes. These require as input material property parameters. Many of the parameters needed to specify electron emission yields are poorly known or unknown for common spacecraft surface materials, such as kapton, teflon, mylar, solar cell cover slips and paints. An experimental program to determine accurately all of the required properties for all materials of interest would be prohibitive. One approach to reducing the magnitude of the experimental task is to conduct computer studies to identify the importance of the material property input parameters in determining potentials attained by surfaces in kilovolt charged particle environments. Such a study, utilizing the emission yield formulations of the NASA Charging Analyzer Program (NASCAP) (ref. 1) is reported here. A discussion of how the NASCAP material parameters are used to calculate yields is given in reference 1. In what follows, the present study is described and parameters varied are identified; results are presented; and implications of the results are discussed.

Two points should be noted at the outset. First, the present study is not an evaluation of the material property formulations used in NASCAP; it examines the impact of input parameters on predictions based on the NASCAP formulations. Second, the study does not predict potentials for any particular material; rather it examines the effect on predicted potential of various material property parameters.

STUDY DESCRIPTION

This study focuses on the influence of those parameters which determine yields of secondary electrons due to electron and ion impact on the potentials attained by surfaces in charging environments. In particular, it examines the influence of these parameters on predicted equilibrium potentials of surfaces exposed to an isotropic Maxwellian particle distribution and on predicted charging behavior of surfaces exposed to a monoenergetic electron beam.

The charging calculations have been performed with MATCHG (ref. 2), a code which uses the material property formulations of NASCAP to calculate surface charging, but does not consider multidimensional effects, photoemission, or leakage currents. MATCHG models the response of a "capacitor" with one "plate" grounded and the other exposed to either a monodirectional, monoenergetic electron beam (essentially, an infinite flat plate approximation) or an isotropic Maxwellian flux of electrons and ions (a spherical probe approximation). It is therefore a one dimensional analytical model which uses the material property parameters to determine net current to the exposed surface. Charging rate in this model depends on the specified dielectric constant and thickness of the material. Thus, charging calculations done with MATCHG do not give a good representation of the charging of a complex spacecraft, but this code does provide an efficient means of identifying the influence of material property parameters on surface charging. All calculations were performed with yields calculated for normally incident primaries (see refs. 1 and 2).

The Maxwellian environment used was characterized by electron and ion temperatures of 10 keV and number densities of $1/cm^3$. The electron beam was characterized by a beam voltage of 10 kV and a current density of 1 nA/cm^2. Calculations of equilibrium potential (φ_{eq}) in the Maxwellian environment

and charging history in the beam environment were made for a variety of combinations of secondary yield parameters. The yield of backscattered electrons, which in the NASCAP/MATCHG formulation depends only upon the atomic number (Z), was not varied systematically; however, calculations indicate that the backscatter yield varies slowly with Z. Consequently, φ_{eq} is not very sensitive to variations in Z. For the results presented here, Z was held constant at a value of 13. This is the correct value for aluminum, and is reasonably close to effective Z for polymers of interest. The parameters whose effects have been investigated in some detail are those which in the NASCAP/MATCHG formulation determine the yields of secondary electrons due to electron and ion impact. These are, for ion impact, the yield for 1 keV protons incident on the surface (δ_p) and the primary ion energy at which maximum yield is attained (E_p). For electron impact, the parameters are the maximum yield (δ_m), the primary electron energy for maximum yield (E_m), two range coefficients (r_1,r_2) and two exponents (n_1,n_2). The last four parameters define the electron range according to

$$R = r_1 E^{n_1} + r_2 E^{n_2} \qquad (1)$$

where E is the primary electron energy at impact. It is possible to set one of the coefficients to zero to obtain a single exponential form for R. This has been done for parts of the present study in order to clarify the impacts of the four parameters in R. There is also an option in the NASCAP/MATCHG material formulation under which the codes will generate a range coefficient and an exponent from the atomic number, atomic weight and material density according to formulae due to Feldman (ref. 3). This option has not been used for this study because the range exponent in this case is determined from the atomic number which, as noted above, also determines backscatter yield.

PROTON-GENERATED SECONDARY ELECTRONS

As noted above, two parameters, δ_p and E_p, determine the yield of secondary electrons due to ion impact as a function of ion energy at impact. The yield is calculated from

$$\delta(E) = \frac{CE^{1/2}}{(1 + E/E_p)} \qquad (2)$$

where C is a constant numerically equal to δ_p for E in keV. These were varied systematically, and equilibrium potentials calculated for several values of the electron-generated secondary yield parameters δ_m and E_m. The range parameters used are the nominal NASCAP parameters for aluminum. Results are illustrated in figure 1. The figure shows predicted equilibrium potential (φ_{eq}) as a function of δ_p parameterized by E_p and δ_m. The curves labeled "$\delta_m = 0$" indicate potentials calculated with secondary electron emission due to electron impact set to zero. Thus they represent an upper limit on φ_{eq} for the given Z and environment, independent of δ_m, E_m and the range parameters. It is clear from these curves that φ_{eq} is very sensitive to changes in δ_p, particularly when δ_p is small, but relatively insensitive to changes in E_p. This result holds true for the more realistic cases, $\delta_m \neq 0$, as is illustrated in the figure. It is expected that the basic result that φ_{eq} is sensitive to δ_p and insensitive to E_p also holds for other Maxwellian environments so long as $kT_i < E_p$. If the ion temperature were to exceed E_p, φ_{eq} would be more sensitive to E_p. However, since E_p is usually expected to be about 40 to 100 keV, and ion temperatures at geosynchronous are generally expected to be less than 40 keV, it seems reasonable to expect that E_p is not a critical parameter for charging calculations. δ_p on the other hand is a critical parameter.

ELECTRON GENERATED SECONDARY ELECTRONS

Yield of secondary electrons due to electron impact is determined by a total of six parameters: δ_m, the maximum yield; E_m, the primary energy for maximum yield; and the four range parameters described above. The yield is calculated from

$$\delta_e(E) = C_1 \int_0^{R_u} \left|\frac{dE}{dx}\right| e^{-C_2 x \cos} \, dx \qquad (3)$$

Here, $|dE/dx|$ is the energy loss rate of the primary electron in the material, dx is an element of path length, θ is the angle of incidence of the primary electron, R_u is the stopping distance, and C_1 and C_2 are constants.

The energy loss rate is related to the range R by

$$\left|\frac{dE}{dx}\right|_{x=0} = \left(\frac{dR}{dE}\right)^{-1}_{E=E_1} \qquad (4)$$

with E_I the energy of the incident primary at impact. NASCAP takes the first two terms of a Taylor series expansion, and uses

$$\left|\frac{dE}{dx}\right| = \left(\frac{dR}{dE}\right)^{-1}_{E=E_I} + \left(\frac{dR}{dE}\right)^{-3}_{E=E_I} \left(\frac{d^2R}{dE^2}\right)_{E=E_p} x \qquad (5)$$

with the empirical formula

$$R = r_1 E^{n_1} + r_2 E^{n_2} \qquad (1)$$

as noted above.

The stopping distance is defined from

$$\int_0^{R_u} \left|\frac{dE}{dx}\right| dx = E \qquad (6)$$

With these expressions for R_u and $|dE/dx|$, the constants C_1 and C_2 in equation (3) are determined by requiring that $\delta_e(E)$ have the user-specified values of δ_m and E_m.

Potentials in Maxwellian Environment

Results of varying δ_m and E_m for a fixed set of range parameters are illustrated in figure 2. This figure shows φ_{eq} as a function of δ_m parameterized by E_m and δ_p in a format analagous to figure 1 for the proton yield parameters. The range parameters are the same as those used for the calculations summarized in figure 1. The "$\delta_p = 0$" curves again represent an artifical upper limit to φ_{eq} for a given δ_m, E_m combination and the stated values for Z and range. The curves in figure 2 indicate that φ_{eq} is quite sensitive to δ_m, and somewhat less sensitive to E_m. The sensitivity of φ_{eq} to both these parameters is more pronounced for values of $\delta_m > 1$.

The discussion to this point has, as noted above, considered a particular combination of range parameters. It would be convenient if these parameters did not have a significant effect on φ_{eq}. Unfortunately, their effect is profound. In order to understand the effect of the various parameters on φ_{eq}, it is useful to examine their effect on the secondary yield curve itself. For the purpose of examining effects on charging behavior, it is helpful to plot "normalized" yield curves, such as the one shown in figure 3. This curve shows the yield of secondary electrons due to electron impact normalized to δ_m (i.e., δ/δ_m) plotted as a function of electron energy at impact normalized to E_m (i.e., E/E_m). The shape of this normalized curve depends only upon the range parameters. The roles of the various range parameters in determining the shape of this normalized curve can be clarified by considering first a single exponential expression for the range (i.e., setting one of the coefficients to zero). Then

$$R = rE^n \qquad (7)$$

In this case, varying the value of r was found to have no impact on the yield curve; varying n had a profound effect. Figure 4 shows normalized yield curves for four different values of n for E/E_m greater than 1, which is the range of interest for spacecraft charging calculations. The yield is clearly very sensitive to n. It is thus expected that φ_{eq} is very sensitive to n.

The yield curve calculated using a double exponential range expression, $R = r_1E^{n}1 + r_2E^{n}2$, must be between the two "single exponential range" curves determined by n_1 and n_2. The exact shape of the yield curve depends on both exponents and on the ratio of the coefficients, r_1/r_2; it does not depend on the magnitudes of r_1 and r_2. Figure 5 illustrates the effect of the coefficient ratio on predicted yield for the case $R = r_1E^{1.1} + r_2E^{2.0}$. The single exponent curves for $R = rE^{1.1}$ and $R = rE^{2.0}$ are drawn in for comparison. The yield curve falls off more slowly with increasing energy as r_1/r_2 increases. The differences in yield between the double exponential ranges and the single exponential range with $n = 2$ are smaller for large energies. The sensitivity of φ_{eq} to r_1/r_2 is thus expected to depend upon the temperature of the environment relative to E_m. For example, for the 10 keV Maxwellian environment being used here, and with $E_m = 0.3$ keV, $kT_e/E_m = 33\ 1/3$. The curves in figure 5 indicate that, at $E/E_m = 33\ 1/3$, the yield for $r_1/r_2 = 0.25$ is very similar to that for $n = 2$; the yield for $r_1/r_2 = 1$ is somewhat larger; and that for $r_1/r_2 = 4$ is significantly larger. It is thus expected that φ_{eq} will be reduced in magnitude as r_1/r_2 is increased.

The dependence of φ_{eq} on n for the single exponential range expression, and on n_1 (the lower exponent) and r_1/r_2 for values of n_2 of 1.6 and 2.0 is shown in figure 6. The other secondary yield parameters (δ_m,E_m, etc.) were held fixed at the values indicated on the figure. It is clear from this figure that φ_{eq} is very sensitive to n in the single exponential range case. In the double exponent case, φ_{eq} depends on all three variables, i.e., on n_2, n_1 and r_1/r_2; the sensitivity of φ_{eq} to these variables depends on the values of the variables. φ_{eq} is very sensitive to n_2; its sensitivity to n_1 depends on r_1/r_2, being high when r_1/r_2 is large.

Comparison of figures 4, 5, and 6 indicates that for a particular combination of the other parameters and environment, it is possible to estimate φ_{eq} for double exponential range expressions from values of φ_{eq} calculated from single range expressions by comparing the yields at kT_e/E_m. This provides a rough estimate rather than a precise one because the calculation of current due to secondary electronics from electronic impact involves integration of the secondary yield curve multiplied by the distribution function f(E) of incoming electrons, i.e.,

$$j_s = \text{Const} \int \delta_e(E) f(E)\, dE \qquad (8)$$

Thus this current, which is an important component in the current balance determining φ_{eq}, depends on the values of the yield over a range of energies, not simply that at kT_e/E_m.

The dependence of φ_{eq} on δ_m, E_m and n is summarized in figure 7, where φ_{eq} is plotted as a function of δ_m, parameterized by n and E_m. The curves in figure 7 indicate that both the range exponent and δ_m are critical parameter in determining φ_{eq}, with E_m of lesser importance.

The range parameters taken collectively, along with δ_m, are the critical determiners of φ_{eq} for double exponential range expressions. The importance of the individual parameters in determining φ_{eq} depends on their values, as discussed above.

Charging in Electron Beam

Spacecraft are charged by distributions of particles, which are usually modeled as Maxwellian distributions. In contrast, laboratory studies of charging behavior of materials have generally been performed using monoenergetic electron beams as particle sources. It is therefore of interest to understand how charging of material samples in a monoenergetic beam depends upon the material property parameters in the models and how laboratory charging data may be used to infer parameter values where direct measurements of secondary yield against energy are not available.

Figure 8 shows MATCHG results for φ_{eq} as a function of δ_m parameterized by E_m and n using a 10 kV beam of electrons as the environment. Again, φ_{eq} depends on all of these variables. Comparison with figure 7 indicates that φ_{eq} in the beam environment has a different dependence on n and δ_m than in a Maxwellian environment, particularly for small δ_m. In fact, φ_{eq} in a monoenergetic beam environment is determined by

$$e(V_B - |\varphi_{eq}|) = E_{II} \tag{9}$$

where V_B is the beam voltage, e the magnitude of the electronic charge and E_{II} the second unity crossover of the total yield curve (i.e., true secondary yield δ_e plus backscatter yield). This is exactly true in the MATCHG approximation of an infinite flat plate geometry and no leakage, and approximately

true in the three dimensional NASCAP calculations and in the true laboratory situation for high resistivity samples.

This implies that measurements of equilibrium potential in electron beams essentially give information about only one point on the yield curve. While E_{II} is an important point on the yield curve, knowing it is insufficient. As has been noted, equilibrium potential in a Maxwellian environment depends on the shape of the entire yield curve, multiplied by the environmental electron distribution function and integrated over energy (eq. (8)). Even if backscatter yield and δ_m and E_m are known, E_{II} does not uniquely determine the range parameters except in the case of a single exponential range expression.

While φ_{eq} in the monoenergetic beam case depends only on E_{II}, the charging behavior as a function of time depends upon the shape of the total yield curve at impact energies greater than E_{II}. Charging rate depends upon capacitance and charging current. The charging current depends on the beam current and the emitted current. The emitted current, in the MATCHG approximation, is determined by the value of the total yield at an impact energy

$$E_i = e(V_B - |\varphi|) \qquad (10)$$

where $|\varphi|$ is the magnitude of the surface potential. Large yields result in small net currents and therefore in low charging rates.

Figure 9 shows predicted charging behavior for $\delta_m = 3$, $E_m = 0.3$ keV and several range expressions for a 10 kV beam. Referring back to figures 4 and 5, one can see that the differences in charging behavior in figure 9 reflect the shapes of the secondary yield curves.

The initial charging rate for a sample with fixed capacitance is determined by the total yield at the beam energy eV_B. It is thus expected to depend on

the various secondary yield parameters, and on beam energy. The dependence of initial charging rate in a 10 kV beam on the secondary yield parameters is illustrated in figure 10. This figure indicates that initial charging rate is a very sensitive function of n for all values of δ_m.

Thus, accurate data on charging behavior versus time can be used to identify suitable values for the range parameters if δ_m and E_m are known.

SUMMARY AND CONCLUSIONS

Using the NASCAP/MATCHG material property formulations, the predicted equilibrium potential of a surface in an isotropic Maxwellian plasma has been found to be sensitive to almost all of the secondary electron yield parameters.

The yield of secondary electrons due to proton impact is dependent on two parameters, the yield for 1 keV incident protons (δ_p) and the energy for maximum yield (E_p). φ_{eq} has been found to be very sensitive to δ_p, particularly for values of δ_p less than unity. Accurate values of δ_p are thus required if surface potentials in space are to be predicted accurately. This is of particular concern because in general δ_p has not been measured for spacecraft surface materials. In addition, laboratory investigations of charging reported to date have used electron beams and thus do not provide any information on ion-generated secondary electrons. φ_{eq} has been found to be rather insensitive to the energy parameter E_p; it is thus not critical to know the value of this parameter accurately, provided that E_p is greater than the temperature of the ion distribution.

Secondary electron yield due to electron impact is determined by a total of six parameters: δ_m, E_m, r_1, r_2, n_1 and n_2, where the last four are coefficients and exponents in the range expression given by equation (1). One of the coefficients can be set equal to zero, resulting in a range expres-

sion of the form $R = rE^n$. The sensitivity of φ_{eq} to the various parameters in an isotropic Maxwellian environment has been investigated using both types of range expression.

Using single exponential range expressions, it was found that φ_{eq} was very sensitive to both n and δ_m, somewhat less sensitive to E_m, and completely insensitive to r. The degree of sensitivity to small changes in any one of the parameters (except r) was found to depend upon the values of all of them. In general, n and δ_m were critical parameters, with δ_m becoming more critical as δ_m was increased or n decreased. The value of E_m becomes more important in determining φ_{eq} as n and δ_m increase.

Calculations using double exponential range expressions indicated that φ_{eq} was sensitive to n_1, n_2, r_1/r_2, δ_m, and E_m, but not to the magnitudes of r_1 and r_2 individually. Again, the degree of sensitivity of φ_{eq} to variations in any one of these parameters depended on the values of them all. For small values of r_1/r_2, (i.e., < 1), the important parameters are n_2, δ_m, and E_m, as in the single exponential range case. For larger values of r_1/r_2, n_1 becomes increasingly important in determining φ_{eq}.

Thus it is necessary to obtain reasonably accurate values for all the parameters characterizing secondary yield due to electron impact, except for the magnitudes of the range coefficients r_1 and r_2. For some materials of interest to spacecraft charging such as teflon, kapton, and mylar (ref. 4), data on secondary yield as a function of impact energy, and thus values for δ_m and E_m, are available. For these materials it is possible to infer the needed range parameters from careful charging history data, since both the equilibrium potentials and the charging rates in monoenergetic electron

beams are sensitive to the secondary yield parameters. Charging rate data is essential to identification of suitable parameter values, because it can be used to infer yield as a function of primary energy at impact. Data on equilibrium potentials in monoenergetic beams essentially identifies only the energy at which the total yield is equal to one.

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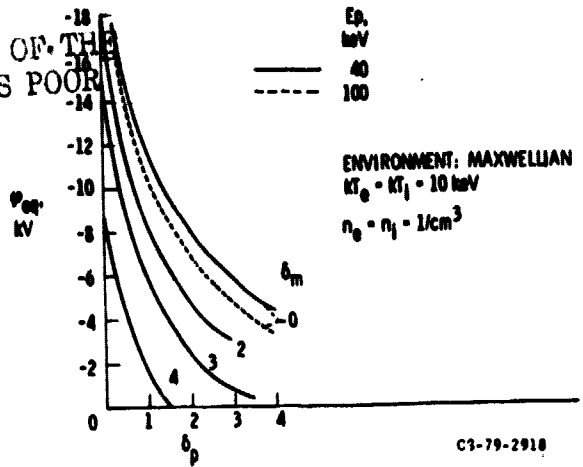

Figure 1. - Dependence of predicted equilibrium potentials on proton generated secondary yield parameters (Z = 13, $R = 260E^{-1.3} + 240E^{-1.73}$, $E_m = 0.3$ keV).

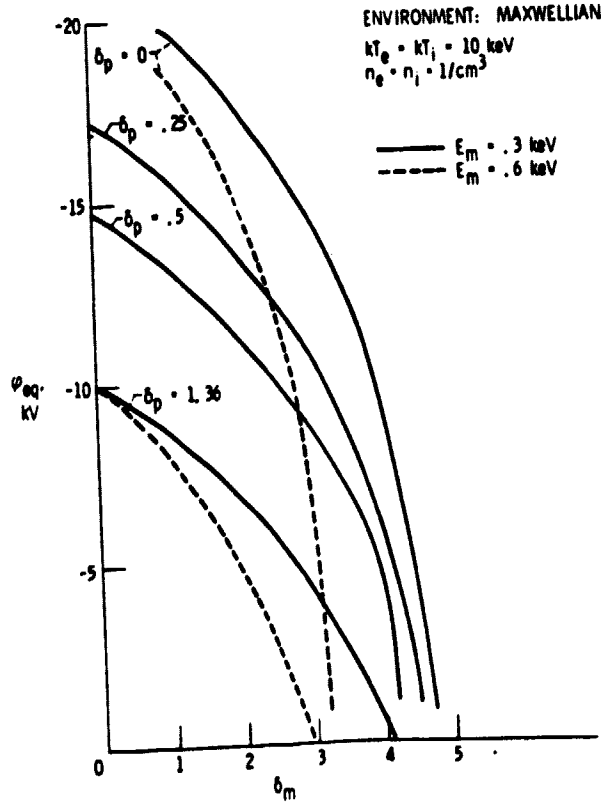

Figure 2. - Dependence of predicted equilibrium potentials on electron generated secondary yield parameters (Z = 13; $R = 260E^{-1.3} + 240E^{-1.73}$, $E_p = 40$ keV).

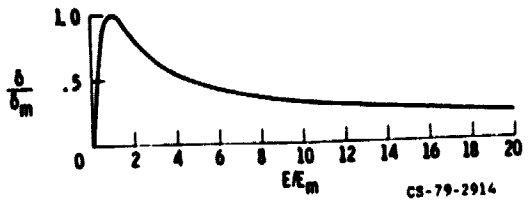

Figure 3. - Normalized electron generated secondary electron yield (NASCAP/MATCHG formulation range = $260E^{1.3} + 240E^{1.73}$).

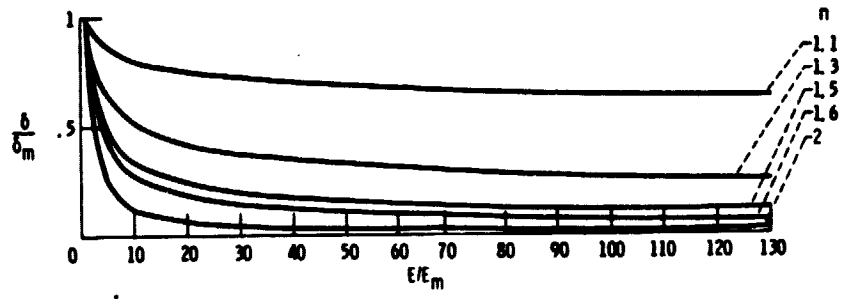

Figure 4. - Effect of range exponent on electron generated secondary electron yield (NASCAP/MATCHG formulation). (Single exponential range: $R = rE^n$).

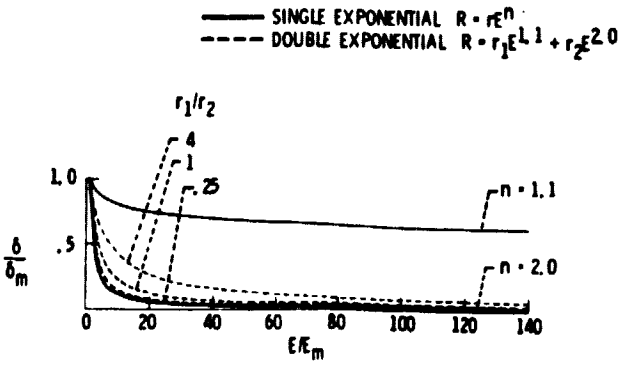

Figure 5. - Effect of range coefficient ratio on electron generated secondary electron yield (NASCAP/MATCHG formulation).

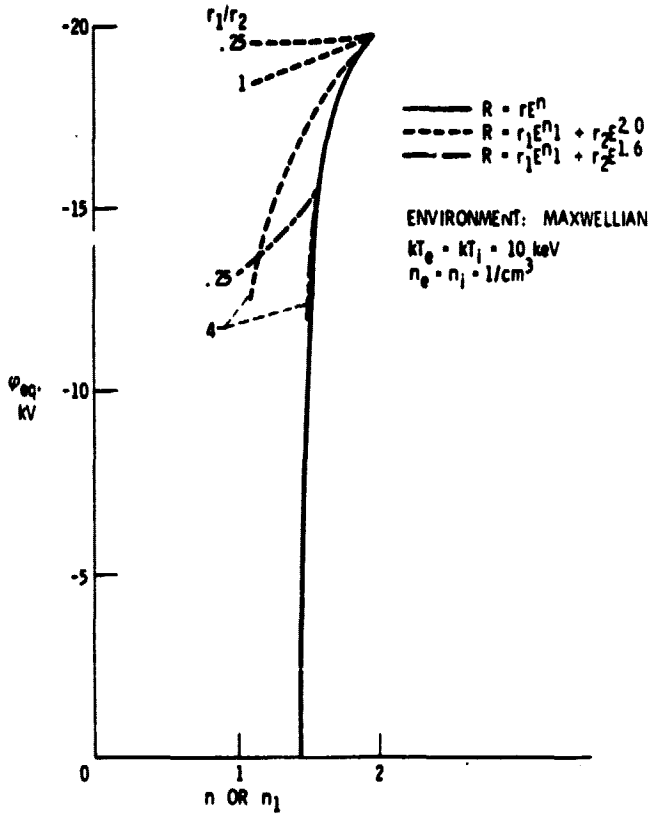

Figure 6. - Effect of range parameters on predicted equilibrium potentials ($Z = 13$, $\delta_p = 0$, $\delta_m = 3$, $E_m = .3$ keV).

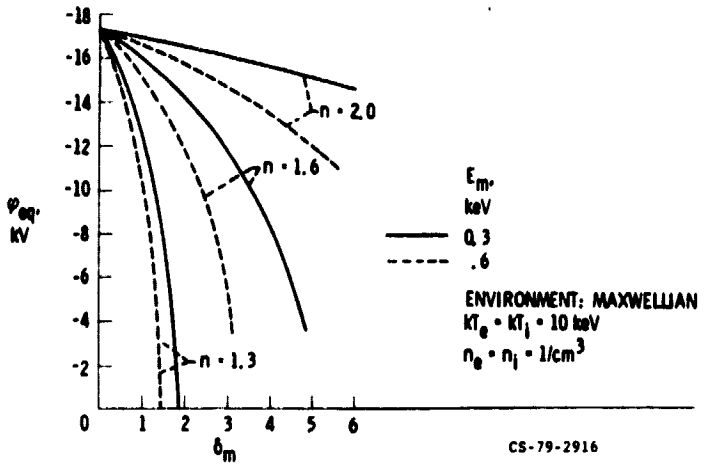

Figure 7. - Dependence of predicted equilibrium potentials (MATCHG) on electron generated secondary yield parameters (Z = 13, δ_p = 0.25, Ep = 40 keV, R = rE^n.

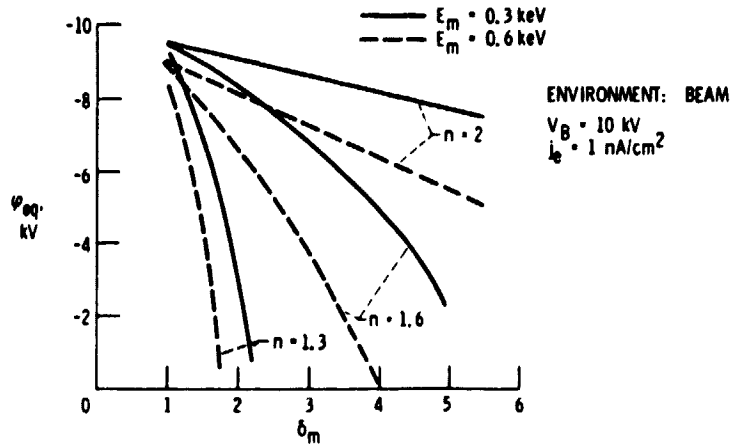

Figure 8. - Dependence of predicted equilibrium potentials (MATCHG) on electron generated secondary yield parameters (Z = 13, R = rE^n).

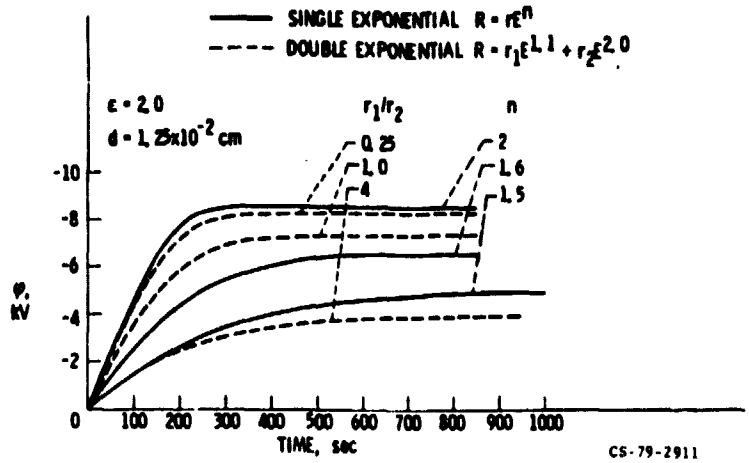

Figure 9. - Effect of range parameters on predicted charging histories in beam (MATCHG). (V_B = 10 kV j_e = $1x10^{-9}$ A/cm^2; δ_m = 3; E_m = 0.3 keV).

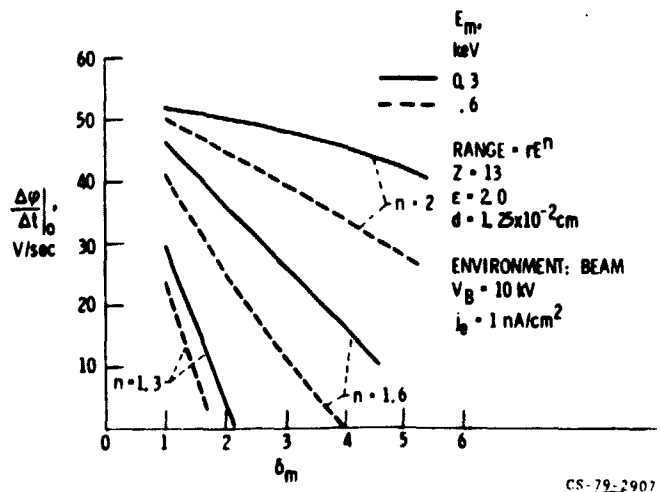

Figure 10. - Dependence of initial slope of charging history (MATCHG) on electron generated secondary yield parameters.

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15. Supplementary Notes

16. Abstract

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