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SECONDARY ELECTRON EFFECTS ON SPACECRAFT CHARGING

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SUMMARY

Calculations have been carried out to determine the effects of electron-produced secondary electrons on the net charging current and the equilibrium voltage of spacecraft surfaces immersed in hot (keV) plasmas. The ratio of secondary to primary electrons as functions of the primary electron energy, E, was fit by expressions of the form $A(e^{-aE} - e^{-bE})$ where A, a, and b were material-dependent parameters. Materials evaluated were aluminum, Mylar, Teflon, and Kapton.

The energy, E, at which the secondary/primary electron ratio has a maximum was in the 0.1- to 1-keV region. Assuming a Maxwellian primary electron energy distribution, the secondary electrons were found to limit equilibrium spacecraft voltage only for plasma temperatures $\lesssim$3 keV. The charging rate was reduced for higher-temperature plasmas, but only until spacecraft voltages reached ~10 keV. The limited effectiveness of the secondary electrons in limiting spacecraft charging parameters (voltage, current) was due to the low primary electron energies at which they were produced.

INTRODUCTION

In an electrically neutral plasma there will be equal densities of negative and positive charges. (If the plasma is not fully ionized there will be neutral particles as well. These will be ignored in this discussion.) Usually the negative charges are electrons. Near geosynchronous orbit the positive charges are mostly protons, and the small neutral component is largely made up of hydrogen atoms.

Because of collisions, both the negative component (electrons) and the positive component (mostly protons) of the geosynchronous orbit plasma have quasi-Maxwellian energy distributions with comparable (within ± a factor of 2) average energies. Since neither the electrons nor the protons are relativistic (velocities <0.01 c), the electrons have $\sim\sqrt{1836} = 42.85$ times the average velocity of the protons. Therefore, the electrons will impact any surface within the plasma (e.g., a spacecraft skin) much more often than the protons will. Assuming that comparable fractions of the impacting electrons and protons stick, the surface will acquire a negative charge. As the surface acquires a negative charge the rate at which electrons impact it will decrease while the proton impact rate will increase. When the rate at which the net charge transfers to the surface equals zero, charging stops and the surface will have an equilibrium potential (voltage).

While there are other charge transfer mechanisms to and from the surface beside the impacts of primary electrons and protons (such as secondary electrons and photoelectrons leaving the surface), only the impacts of these primary particles will be considered in this section. The rate of the electron impacts will decrease exponentially as the spacecraft surface acquires a negative voltage because the electrons in the plasma are subsonic (the directed component of their velocity is less than the thermal velocity component). Thus

$$J_e(V) = J_o \; e^{-V/V_o}$$

where

$J_e(V)$ = current density of electrons of energy (voltage) V

V_o = average energy (voltage) of the electrons (it is also a measure of the plasma temperature)

J_o = $N \, q \, \bar{v}$

N = density of electrons in the plasma

q = charge/electron

$\bar{v}$ = average electron velocity

For the purposes of this discussion, V_o will be considered to remain constant.

The total primary electron current density consists of all electrons able to reach the spacecraft surface — i.e., those with energies > V. Thus

$$J_e(>V) = \int_V^\infty J_e(V) \, dV = J_o \, V_o \, e^{-V/V_o}$$

This expression shows that the total primary electron current density increases with V_o (which is a measure of plasma temperature) and that the larger V_o is, the more slowly the current density decreases with spacecraft voltage (V).

The primary positive current density when the spacecraft is uncharged will be approximately

$$J_p(V) \approx \frac{J_o}{42.85}$$

However, as the spacecraft surface acquires a negative voltage the primary positive current only increases linearly because the protons are supersonic (their directed velocities exceed their thermal velocities). Thus the total primary proton current density as a function of spacecraft voltage is

$$J_p(>V) = \int_{-V}^{\infty} J_p(V)\, dV = \frac{J \cdot V_o}{42.85}\left(\frac{V}{V_o} + 1\right)$$

The equilibrium voltage (if no secondary effects are operating) occurs when

$$\frac{1}{42.85}\left(\frac{V}{V_o} + 1\right) = e^{-V/V_o}$$

As can be seen from Figure 1, this occurs when $V/V_o \approx 2.5$. This figure also shows two other crossover points — one at $V/V_o \sim 2.7$ (if the proton integral current is proportional to V/V_o instead of $V/V_o + 1$) and the other at $V/V_o \sim 3.75$ (if the proton current does not increase as V increases). These other values of V/V_o at equilibrium are sometimes quoted in the literature, but $V/V_o \sim 2.5$ is correct for the primary currents (secondary electron and photoelectron emission will reduce this value).

As V_o (the average energy of the particles in the plasma) increases, the magnitudes of the primary currents and the equilibrium voltage also increase (see Figure 2). Thus the time to reach equilibrium is essentially independent of V_o. This time is a function of the capacitance/unit area and typically is on the order of a few minutes.

SECONDARY ELECTRONS

When charged particles impinge upon matter they will displace electrons in that matter from their equilibrium positions. Some of these electrons may acquire sufficient energy in the backward direction to escape from the matter completely. These are called secondary electrons, as contrasted to backscattered electrons. Backscattered electrons result when the incident charged particles are electrons and some of them are reflected in the backward direction. Thus if the incident particles are not electrons, no backscattered electrons can be produced (but secondary electrons can be produced). If the incident particles are electrons, both backscattered electrons and secondary electrons can be produced. The backscattered electrons usually have energies which are a considerable fraction of the incident electrons' energies, while the secondary electrons will have lower energies — typically <1 keV — and while the ratio of backscattered electrons to incident electrons will always be ≤1, the ratio of secondary electrons to incident particles (electrons or anything else) is often >1.

Both backscattered electrons and secondary electrons are important in spacecraft charging. They affect the rate at which the spacecraft will acquire charge (and hence voltage) and also (assuming there is no electrical breakdown) the equilibrium voltage to which the spacecraft will charge. This is due to the fact that every electron which leaves the spacecraft cancels the charging effects of every electron which impacts the spacecraft. When the number of electrons leaving minus the number of electrons arriving equals the number of positive charges arriving, an equilibrium is achieved and the spacecraft no longer acquires additional charge.

There have been measurements of both backscattered and/or secondary electrons from many materials. Often little or no attempt has been made to separate these two types of electrons, so the results are presented as the ratio of emergent/incident electrons as a function of incident electron energy. Typical of such measurements is that for aluminum (Reference 1), shown in Figure 3. This figure shows that the measured ratio (secondary electron current/primary electron current) has a maximum of ~1.1 at an incident electron energy of ~0.4 keV. Attempts to fit this ratio by an analytical function which could be multiplied by an exponential and integrated led to the calculated curve, viz.,

$$\frac{J_e'(V)}{J_e(V)} = 1.1 \left(e^{-0.1\ V} - e^{-10\ V}\right)$$

where

$J_e(V)$ = primary electron current density (amp/cm^2)

$J_e'(V)$ = secondary electron current density (amp/cm^2)

V = energy of primary electrons (keV)

The primary electron current density as a function of electron energy (V) is

$$J_e(V) = J_e\ e^{-V/V_o}$$

where V_o is the hot plasma temperature (keV). The current density due to electrons with energies >V is

$$J_e(>V) = J_e \int_V^\infty e^{-V/V_o}\, dV = J_e\ V_o\ e^{-V/V_o}$$

Thus, if the spacecraft voltage is V, which means that only electrons with energies >V will be able to reach it, the primary electron current will be exponentially decreased from the primary electron current able to reach an uncharged spacecraft.

If the ratio of secondary electron current to primary electron current is given by the expression

$$\frac{J_e'(V)}{J_e(V)} = K\left(e^{-aV} - e^{-bV}\right)$$

the secondary electron current will be

$$J_e'(V) = J_e\, e^{-V/V_o}\, K\left(e^{-aV} - e^{-bV}\right)$$

$$= J_e\, K\left[e^{-\left(a + \frac{1}{V_o}\right)V} - e^{-\left(b + \frac{1}{V_o}\right)V}\right]$$

In these expressions K, a, and b are parameters which depend upon the spacecraft surface material. Integrating this expression to obtain the net electron current on a spacecraft surface of voltage, V, yields

$$J_e'(>V) = \int_V^{\infty} J_e'(V)\, dV$$

$$= J_e\, K\left[\frac{e^{-\left(a + \frac{1}{V_o}\right)V}}{a + \frac{1}{V_o}} - \frac{e^{-\left(b + \frac{1}{V_o}\right)V}}{b + \frac{1}{V_o}}\right]$$

For aluminum K = 1.1, a = 0.1, and b = 10. This function (for $J_e = 1$) is shown graphically in Figure 4. It shows that for $V = 0$ (an uncharged spacecraft) the secondary current is approximately proportional to V_o (the plasma temperature). However, as the spacecraft becomes charged (V/V_o increases) the secondary electron current decreases, and that decrease is more rapid if the plasma has a high temperature (large V_o) than if it has a low temperature. This is to be expected since for a large V_o the importance of the 0.1 - 10 keV region (where secondary electrons are important in aluminum) is less than it is for a small V_o.

By noting the intersections of the curves in Figure 2 (the net primary current) with the corresponding curves in Figure 4 (the secondary electron current) it is possible to obtain the equilibrium voltage to which aluminum will charge in the absence of sunlight. The results of such a graphical solution are listed in Table 1.

The effects of sunlight are to increase the secondary electron current by ~0.5 nanoamps/cm². If the primary electron current (when the spacecraft is uncharged) is 1 nA/cm², the total secondary electron current is obtained by increasing the ordinates of the curves in Figure 4 by 0.5. This has been done to obtain the curves shown in Figure 5. While the effects of the photoelectrons are relatively small at $V = 0$, as V (the spacecraft potential) increases the photoelectrons dominate the secondary electron current. This accounts for the asymptotes at ~0.5 of the curves in Figure 5. By overlaying Figure 5 with Figure 2, the equilibrium voltages may be obtained from the intersections of the corresponding curves, as before. After multiplying by V_o, the results are listed in Table 1.

If the primary electron current density is 10 nA/cm², the curves of Figure 4 are increased by 0.05, yielding the curves of Figure 6. Proceeding as before yields the equilibrium potentials listed in the last column of

Table 1. As expected, if the initial ($V=0$) primary electron current density is small (e.g., 1 nA/cm^2), the equilibrium voltage is fairly low because the secondary electrons only have to approach half of this amount (the photoelectrons accounting for the remainder). However, if the initial primary electron current density is large (e.g., 10 nA/cm^2) the effect of sunlight is small, leading to an equilibrium voltage little different from that in the absence of sunlight. The effects of the photoelectrons, unlike those of the secondary electrons, do not depend upon the value of V_o (the temperature of the plasma).

The ratios of secondary electron current to primary electron current for three common plastics (Mylar, TFE Teflon, and Kapton) are shown in Figure 7 (References 2, 3, and 4). Since these curves exhibit the same general peaked behavior as a function of primary electron energy as aluminum, the same type of analytical expression was used to approximate this behavior. Proceeding as for aluminum, the secondary electron currents for these three plastics are

Mylar $K = 9 \quad a = 3 \quad b = 15$

$$J_e' = 9\,J_e\left[\frac{e^{-\left(3+\frac{1}{V_o}\right)V}}{3+\frac{1}{V_o}} - \frac{e^{-\left(15+\frac{1}{V_o}\right)V}}{15+\frac{1}{V_o}}\right]$$

TFE Teflon $K = 5.8 \quad a = 1 \quad b = 5$

$$J_e' = 5.8\,J_e\left[\frac{e^{-\left(1+\frac{1}{V_o}\right)V}}{1+\frac{1}{V_o}} - \frac{e^{-\left(5+\frac{1}{V_o}\right)V}}{5+\frac{1}{V_o}}\right]$$

Kapton $K = 3.5 \quad a = 2 \quad b = 15$

$$J_e' = 3.5\,J_e\left[\frac{e^{-\left(2+\frac{1}{V_o}\right)V}}{2+\frac{1}{V_o}} - \frac{e^{-\left(15+\frac{1}{V_o}\right)V}}{15+\frac{1}{V_o}}\right]$$

Proceeding as for aluminum, the secondary currents as functions of plasma temperature (V_o) and the mechanisms acting (secondary electrons, photoelectrons) have been calculated from these equations (the photoelectron current was taken as 0.5 nA/cm^2 for all cases). By overlaying these secondary current curves with the net primary current, curves of Figure 2 yielded the equilibrium voltages listed in Table 2.

It is seen that the secondary electron emission for Mylar and Kapton is too small to effectively limit the equilibrium potentials for most of the plasma temperatures considered (2 to 10 keV). If sunlight is present, the photoelectrons limit the equilibrium potentials if the plasma temperature (V_o) is not too high and if the primary electron current initially present (J_e) is not too high. The secondary electron emission for TFE Teflon limits the equilibrium potentials for low plasma temperatures ($V_o = 3$ keV) even in the absence of sunlight and helps prevent charging in the presence of sunlight until plasma temperatures exceed a few kilovolts.

Examining Figure 7 with these results in mind shows that it is the energy region over which the secondary electron emission is active that determines its effectiveness for the plasma temperatures considered. For incident (primary) electron energies ≥1 keV, only Teflon has much secondary electron emission. Comparing the effects of secondary electron emission from aluminum (Figure 3 and Table 1) with those from the plastics (Figure 7 and Table 2) shows that the higher the incident electron energies as which secondary electrons are emitted, the more effective the secondary electrons are at limiting the equilibrium potentials — especially at high plasma temperatures. Considerable effort is being expended in trying to develop such materials (Reference 5) as well as in looking for conductive coatings with desirable thermophysical properties (Reference 6).

The effects of secondary electrons upon the spacecraft voltage as a function of time may be calculated by obtaining the average current as a function of V/V_0 and summing the inverses of these currents for convenient-sized voltage steps. For example, in the absence of secondary electrons, the net primary current is 1 if $V/V_0 = 0$, 0.75 if $V/V_0 = 0.25$, 0.56 if $V/V_0 = 0.50$, etc. The average time to charge from $V/V_0 = 0$ to $V/V_0 = 0.25$ will be ~1/0.875 or 1.14 units, while the average time to charge from $V/V_0 = 0.25$ to $V/V_0 = 0.50$ will be ~1/0.655 or 1.53 units, etc. The time to charge from 0 to $V/V_0 = 0.25$ is thus 1.14 units, while the time to charge from 0 to $V/V_0 = 0.50$ is 2.67 units, etc. By proceeding in this manner, the curves shown in Figure 8 were generated for aluminum in the absence of sunlight. It is seen that the secondary electrons slow down the charging process even in those situations in which they have a negligible effect upon the equilibrium potential as $t \rightarrow \infty$. Thus if there are electrical breakdowns which prevent the equilibrium potential from being reached, the secondary electrons (and the photoelectrons as well, if sunlight is present) act to reduce the frequency of such breakdowns.

Many plastic materials have a dielectric strength of ~500 volts/mil of thickness. While handbook values of this quantity vary or show ranges of values, 500 volts/mil is a good average for the three plastics considered here (Teflon, Mylar, and Kapton). Based upon this dielectric strength, it is possible to calculate the minimum thickness necessary to prevent electrical breakdown in plasma of a given temperature (V_0). If $V_0 = 10$ keV (a reasonable upper limit, since the maximum measured spacecraft potential due to hot plasma has been ~19 keV) plastic surfaces should be ~50 mils thick unless they will be continually exposed to sunlight (in which case some reduction can be made for synchronous orbits).

CONCLUSIONS

The equilibrium voltage attained in a hot plasma due to primary protons and primary electrons only is shown to be ~2.5 V_0 (the electron thermal energy). The effects of secondary electrons produced by the primary plasma electrons were examined for aluminum and three common plastics (Teflon, Mylar, and Kapton). One result of this investigation was that it is the primary electron energy region over which the secondary electrons are emitted (rather than the ratio of secondary to primary electrons) which determines the effectiveness of the secondary electrons in limiting the net charging current. Thus aluminum (which has a maximum secondary electron/primary electron ratio of ~1.1 at ~0.4 keV) is more effective in this regard than any of the plastics (even though the plastics have maximum secondary electron/primary electron ratios up to 4.8). This is due to the fact that the plastics have these ratios at 0.1 to 0.3 keV. A second result is that while the electron-produced secondary electrons decreased the charging current, they had little effect upon the equilibrium voltages attained. This is due to the fact that as the spacecraft voltage becomes high (≥10 kilovolts negative) the only primary electrons able to reach it are too energetic to produce a significant number of secondary electrons. Under these conditions only the photoelectron current (which is ~ constant, independent of negative spacecraft voltages) acts to decrease the equilibrium voltage.

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Table 1. Equilibrium Voltages for Aluminum Spacecraft Surfaces in Hot Plasma (Temperature V_o)

V_o (keV)	Equilibrium V(keV) No Secondary e^- No Sunlight	Equilibrium V(keV) Secondary e^- No Sunlight	Equilibrium V (keV) Secondary e^- Sunlight	
			$J_e = 1 \frac{nA}{cm^2}$	$J_e = 10 \frac{nA}{cm}$
1	2.5	0.6	~0	0.2
2	5.0	3.5	~0	1.5
3	7.5	6.3	~0	4.2
5	12.5	11.5	~0	9.25
10	25.0	24.5	~0	20.5

Table 2. Equilibrium Voltages for Various Plastic Spacecraft Surfaces

Material	V_o (keV)	Equilibrium V(keV) No Secondary e^- No Sunlight	Equilibrium V(keV) Secondary e^- No Sunlight	Equilibrium V (keV) Secondary e^- Sunlight	
				$J_e = 1 \frac{nA}{cm^2}$	$J_e = 10 \frac{nA}{cm^2}$
Mylar	1	2.5	~ 0	~0	~ 0
	2	5.0	~ 5.0	~0	~ 0
	3	7.5	~ 7.5	~0	~ 6.3
	5	12.5	~12.5	~3.0	~10.5
	10	25.0	~25.0	~6.0	~21.0
Kapton	1	2.5	~ 2.5	~0	~ 2.1
	2	5.0	~ 5.0	~0.4	~ 4.2
	3	7.5	~ 7.5	~1.8	~ 6.3
	5	12.5	~12.5	~3.0	~10.5
	10	25.0	~25.0	~5.0	~21.0
Teflon	1	2.5	~ 0	~0	~ 0
	2	5.0	~ 0	~0	~ 0
	3	7.5	~ 0	~0	~ 0
	5	12.5	~12.5	~0	~10.5
	10	25.0	~25.0	~6.0	~21.0

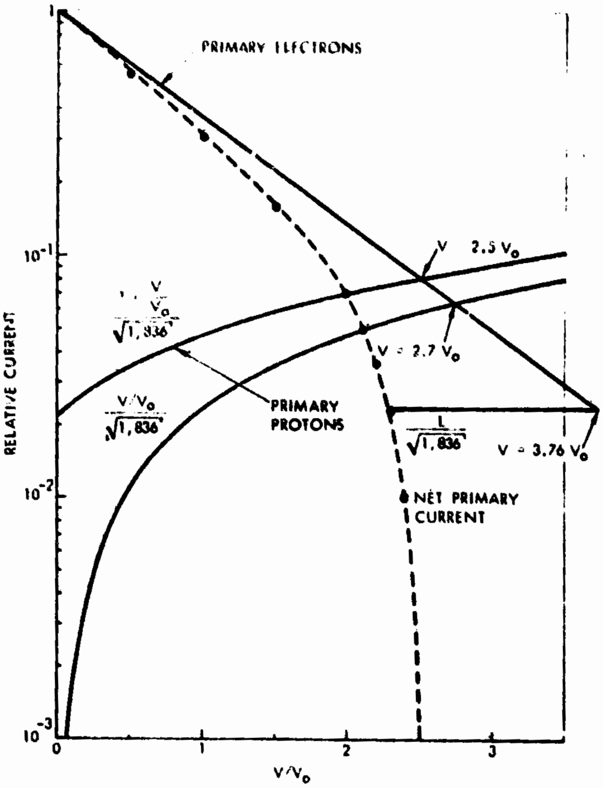

Figure 1. Net Primary Current as a Function of Spacecraft Voltage/ Plasma Temperature Ratio

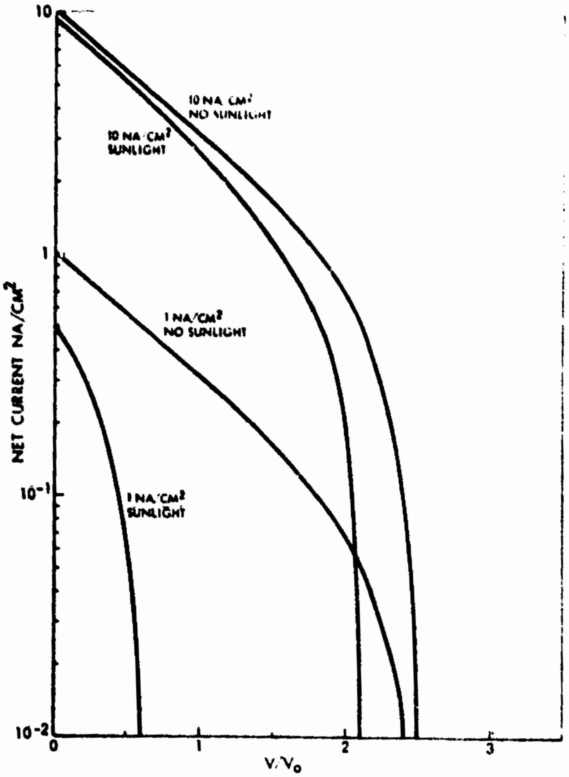

Figure 2. Net Primary Current With and Without Sunlight

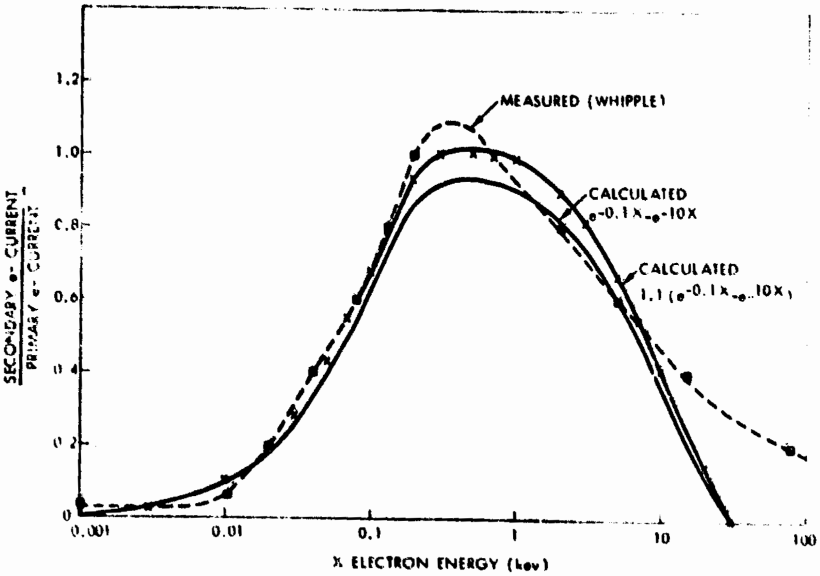

Figure 3. Secondary Electron Emission Due to Primary Electrons on Aluminum

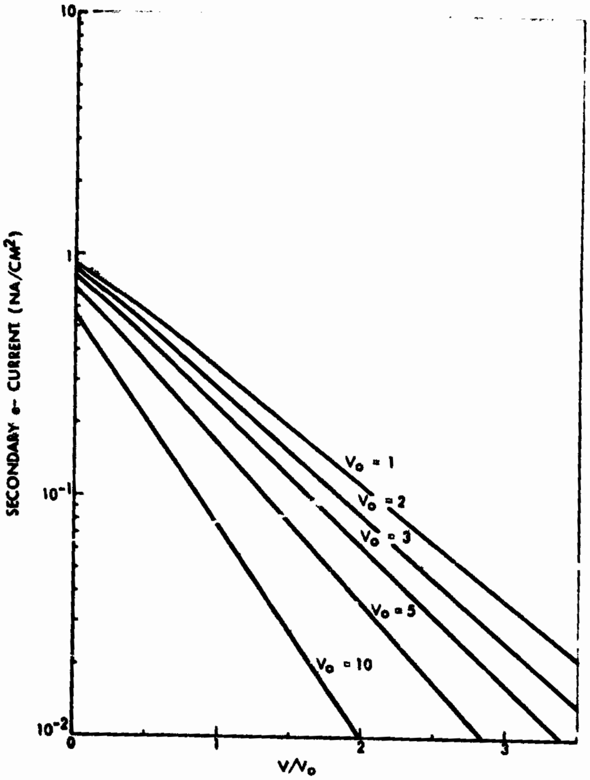

Figure 4. Secondary Electron Current from Aluminum Due to 1 Na/cm^2 Primary Electron Current, No Sunlight

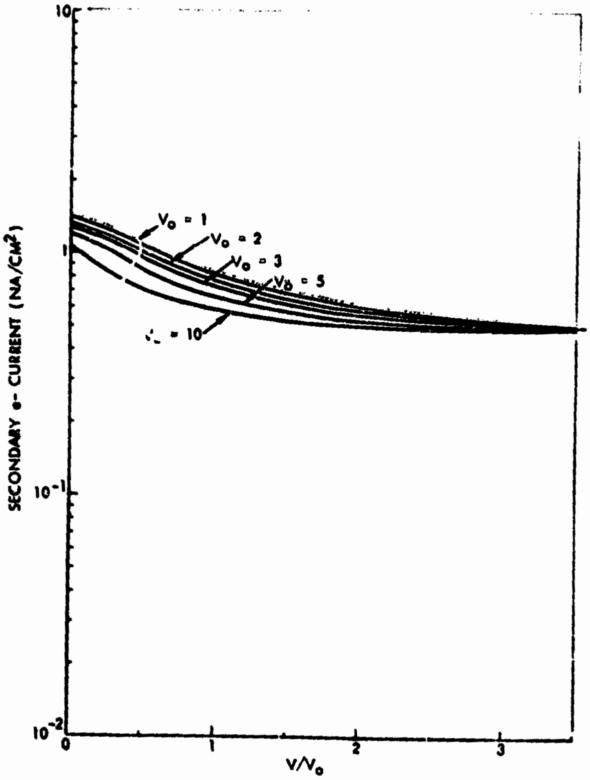

Figure 5. Secondary Electron Current from Aluminum Due to 1 Na/cm^2 Primary Electron Current, in Sunlight

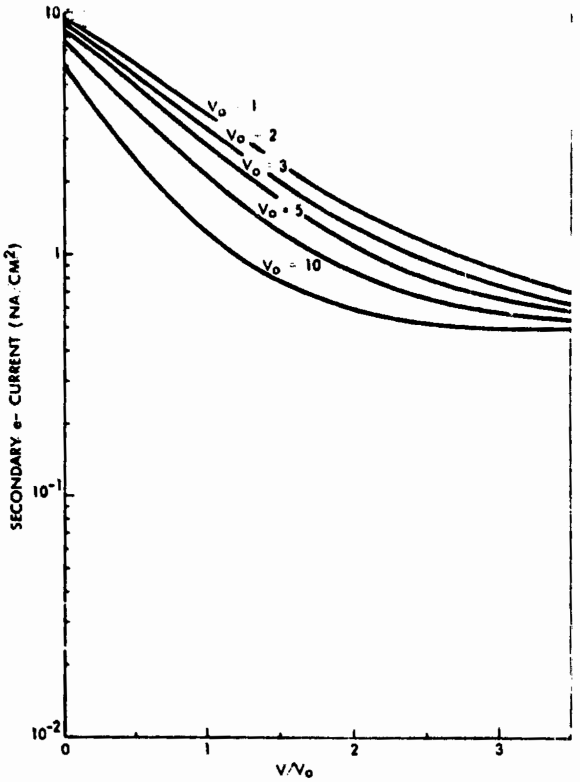

Figure 6. Secondary Electron Current from Aluminum Due to 10 Na/cm^2 Primary Electron Current, in Sunlight

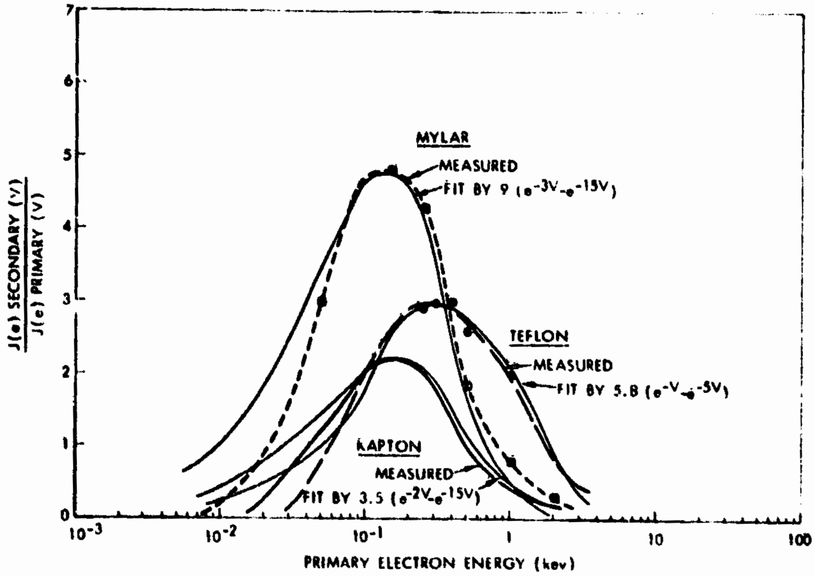

Figure 7. Secondary Electron Emission Due to Primary Electrons on Mylar, Teflon, and Kapton

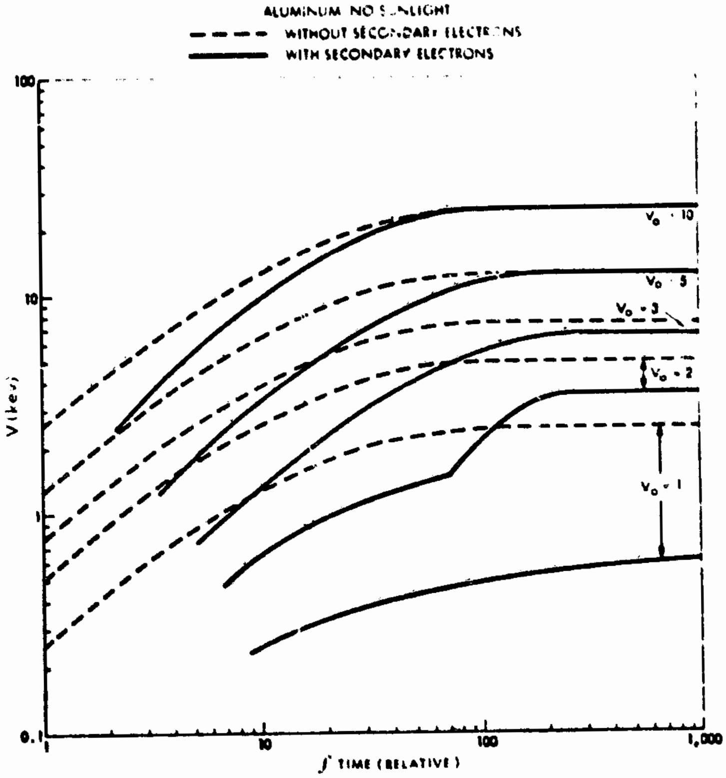

Figure 8. Effect of Secondary Electrons on the Charging Rates Due to Hot Plasma on Aluminum