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Importance of Surface Conditions for Spacecraft Charging

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This paper studies the importance of secondary and backscattered electrons in spacecraft charging. The secondary and backscattered electron yields from surface materials are affected not only by the energies of the incoming electrons but also by the surface condition. Some typical parameters characterizing the surface condition are the surface smoothness, thickness, surface composition, and surface contamination. By using the published formulae of secondary and backscattered electron yields, the critical temperature values for the onset of spacecraft charging are calculated. The results found are different for different yield formulae. The yields are not only important in governing the current balance at equilibrium and the onset of spacecraft charging, but also in affecting the accuracy of model calculations of the spacecraft potential. This paper suggests that, for predicting spacecraft charging or in spacecraft design, it is inadequate to look up published tables of the yields for a given type of surface material. It is necessary to measure the secondary electron and backscattered electron yields of an actual piece of the surface material, because the thickness, smoothness, surface composition, and so forth can affect the yields and, in turn, spacecraft charging.

Nomenclature

A	=	a coefficient in the backscattered electron formula
B	=	a coefficient in the backscattered electron formula
C	=	a coefficient in the backscattered electron formula
E	=	primary electron energy
E_0	=	parameter specifying the enhancement falloff rate of η, which is material specific.
$E_{\max}$	=	primary electron energy at which the secondary electron yield is maximum
η	=	backscattered electron yield (also called backscattered electron coefficient or reflection electron yield)
eV	=	electron volt
$f(E)$	=	electron velocity distribution expressed in terms of electron energy
$I(\omega)$	=	intensity of incident photons of frequency ω
$J(\omega)$	=	photoelectron flux generated by incident photons of frequency ω on a surface
k	=	Boltzmann's constant
m	=	electron mass
n	=	electron density
ω	=	photon frequency
q_e	=	electron charge
q_i	=	ion charge
R	=	surface reflectance
s	=	parameter of surface condition
T^*	=	critical electron temperature for the onset of spacecraft charging
T_e	=	electron temperature, kT_e in eV
T_i	=	ion temperature, kT_i in eV
v	=	electron velocity
Y_{ph}	=	photoelectron yield per incoming electron
α	=	exponent in the Mott–Smith Langmuir attraction term
δ	=	secondary electron yield (also called secondary electron emission coefficient)
$\Delta\eta$	=	additional term for modifying the backscattered electron yield formula of [1]
$\delta_{\max}$	=	maximum value of secondary electron yield
ϕ	=	spacecraft surface potential, V

I. Introduction

THE ambient plasma environment and the spacecraft surface properties determine the spacecraft potential at equilibrium. Whereas the ambient plasma environment can be measured in situ and in real time, the surface properties are measured in the laboratory and empirical formulae of surface properties are obtained from the laboratory measurements. This paper addresses the importance of surface conditions in determining the spacecraft surface potentials.

Spacecraft charging to multiple kV (negative kilovolts) may affect electronic measurements onboard and, in some cases, may be harmful to the health of onboard electronics. Charging to kV volts occurs mostly at near geosynchronous orbits during energetic (multiple keV) plasma events. The basic reason for spacecraft charging is the accumulation of electrons on the surface. As an incoming (primary) ambient electron hits a surface with energy E, there is a probability $\delta(E)$ of a secondary electron going out. This probability is commonly called the secondary electron coefficient or the secondary electron yield (SEY) in the literature. In addition, there is a probability of $\eta(E)$ backscattered electrons going out. This probability is commonly called the backscattered electron coefficient, backscattered electron yield (BEY), or simply the reflection coefficient.

Depending on the surface material property and electron energy E, $\delta(E)$ may exceed unity, meaning that for every electron coming in, there is more than one electron going out. This situation implies surface charging to positive volts. However, secondary electrons have only a few eV in energy and therefore positive voltage charging is up a few volts only. Backscattered electrons are almost as energetic as the primary electrons. However, $\eta(E)$ is usually very small ($\ll 1$) compared with the SEY $\delta(E)$.

The onset of spacecraft charging is governed by the balance of the incoming current of primary electrons and the outgoing current of secondary and backscattered electrons. The current balance equation is of the form

$$\int_0^\infty \mathrm{d}E E f(E) = \int_0^\infty \mathrm{d}E E[\delta(E) + \eta(E)] f(E) \qquad (1)$$

where $f(E)$ is the electron velocity distribution with $E = (1/2)mv^2$. One can solve Eq. (1) analytically if one inputs the $\delta(E)$, $\eta(E)$, and $f(E)$ functions. For Maxwellian space plasmas, the $f(E)$ function is of the form

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$$f(E) = n(m/2\pi \mathrm{kT})^{3/2} \exp(-E/\mathrm{kT}) \tag{2}$$

Equation (1) can be written in a more compact way as follows

$$< \delta + \eta > = 1 \tag{3}$$

where

$$< \delta + \eta > = \frac{\int_0^\infty \mathrm{d}E E f(E)[\delta(E) + \eta(E)]}{\int_0^\infty \mathrm{d}E E f(E)} \tag{4}$$

Using the $\delta(E)$ formula [2] and the $\eta(E)$ formula [1] for various materials, one can solve Eq. (1) or (3) for the critical temperature T^*. Below T^*, there is no charging; above it, charging occurs. Indeed, the charging data obtained on the Los Alamos National Laboratory geosynchronous satellites have repeatedly confirmed the existence of critical temperature for the onset of spacecraft charging [3–5]. The observed critical temperature agrees well in order of magnitude with the theoretical values.

As the ambient electron temperature increases beyond T^*, the magnitude of the spacecraft potential (negative volts) increases with the temperature. The ambient ions are attracted and collected. As a good approximation, the charging level ϕ at equilibrium is given by the current balance equation

$$I_e(0)[1 - <\delta + \eta>] \exp\left(-\frac{q_e \phi}{kT_e}\right) - I_i(0)\left[1 - \frac{q_i \phi}{kT_i}\right]^\alpha = 0 \tag{5}$$

where the notations are as in [3]. In short hand notation, Eq. (5) can be written as $I_e(\phi) = I_i(\phi)$. The ambient electron and ion currents $I_e(\phi)$ and $I_i(\phi)$ at $\phi = 0$ are of the following forms, respectively:

$$I_e(0) = \int_0^\infty \mathrm{d}E E f_e(E) \tag{6}$$

and

$$I_i(0) = \int_0^\infty \mathrm{d}E E f_i(E) \tag{7}$$

where $f_e(E)$ is as given in Eq. (2) and $f_i(E)$ is similar but with the ion mass and ion temperature instead of those of electrons. Because the magnetic fields (~100 nT) at geosynchronous altitudes are weak, the $\mathbf{V} \times \mathbf{B}$ fields are negligible compared with the sheath electrostatic fields. For simplicity, we assume that the angular integration terms cancel each other in Eq. (5) and likewise for the surface area terms. The Mott–Smith and Langmuir [6] orbit-limited ion collection factor in square brackets, Eq. (5), is applicable in the geosynchronous environment. The power $\alpha = 1$ is for a sphere, $\frac{1}{2}$ for an infinite cylinder, and 0 for a plane. The normalized outgoing electron current is given in Eq. (4). As a side note, q_i is positive and the charging voltage is negative, rendering the ion collection factor greater than unity, Eq. (5). As the magnitude of the charging level ϕ increases, the electron current $I_e(\phi)$ is reduced by the exponential factor while the ion current $I_i(\phi)$ is enhanced by the ion collection factor.

In sunlight, the spacecraft surface emits a photoelectron current I_{ph}. For simplicity, no local potential well or differential charging will be considered here. The spacecraft potential at equilibrium is governed by the current balance equation [4]

$$I_e(0)[1 - <\delta + n>] \exp\left(-\frac{q_e \phi}{\mathrm{kT}_e}\right) - I_i(0)\left[1 - \frac{q_i \phi}{\mathrm{kT}_i}\right]^\alpha - I_{\mathrm{ph}} = 0 \tag{8}$$

II. Secondary Electron Yield

As Eqs. (1–8) indicate above, SEY plays an important role in each aspect of spacecraft charging, viz., onset of spacecraft charging, spacecraft charging voltage in ambient electrons and ions during a eclipse, and spacecraft charging in sunlight. Indeed, good attention has been paid [7] previously to the importance of SEY in spacecraft charging. The Sternglass $\delta(E)$ formula [2,8] have been used for years in spacecraft charging calculations, Eqs. (1–8). From time to time, however, there are journal papers reporting on new measurements, or new formulae, of SEY $\delta(E)$, each one likely claiming to be better than all previous ones. Which one is really the best? If we know which is the best or most appropriate, we can input it to the above equations for more accurate results.

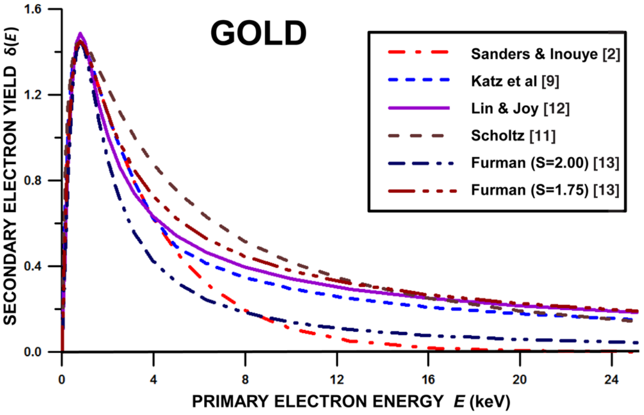

Fig. 1 Some of the best secondary electron yield $\delta(E)$ functions [9–12] obtained in recent years. What one is the best?

Figure 1 shows the calculated SEY $\delta(E)$ for gold using some [9–12] of the best formulae published in recent years.

The graphs in Fig. 1 are similar in the low-energy regime below the peak $\delta(E)$, i.e., for primary electron energies $E < E_{\max}$. Above $E_{\max}$, all are different. It is a good question which graph is the best? Figure 2 shows the critical temperature T^* calculated by using Eqs. (1) and (3) with some of the best SEY $\delta(E)$ formulae [2,9,11–13] of Fig. 1. In Fig. 2, the results corresponding to [9] are obtained with its own $\delta(E)$ and $\eta(E)$ formulae. Similarly, given a SEY $\delta(E)$ or BEY $\eta(E)$ formula of choice, one can calculate the spacecraft potential using Eqs. (5) and (8). Good inputs generate good outputs. Which set of input is the best?

III. Effect of Surface Condition on Secondary Electron Yield

The SEY $\delta(E)$ of a surface material is not only a function of primary energy and incident angle but also the surface condition. Surface condition includes the physical features, the chemical composition, the surface smoothness, the lattice structures, the dose

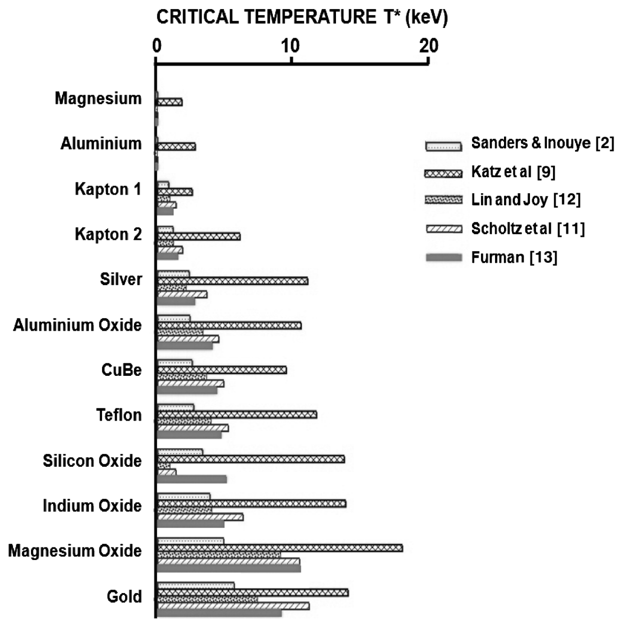

Fig. 2 Critical temperature for the onset of spacecraft charging calculated by using various best δ functions. The critical temperatures obtained by using Furman's formula with $s = 1.75$ are shown in sold bars.

of electrons or ions deposited, the surface temperature, the thickness of layers, etc. $\delta(E)$ depends also on the incidence angle of the primary electrons. For a coarse surface, the incidence angle varies from one point to another on the surface. For surfaces with grooves, the groove walls can partially reabsorb the secondary electrons emitted from the depth of the grooves.

In space, prolonged bombardment by energetic ambient electrons or ions may affect the surface composition and the lattice structure near the surface. Protons or ions can cause sputtering, knocking out neutral atoms, although the rate of sputtering is usually very slow. Energetic electron penetration into dielectrics can build up significant internal electric fields, depending on the dose and fluence. Energetic protons or ions, because of their large cross sections and masses compared with electrons, may cause knock-on cascade ionization. In a knock-on event, the target atom recoils, colliding with more atoms in turn.

If the material is very thin, secondary electrons can come out not only from the front side but also from the back side. If the material is composed of a thin layer on top of another material, the primary electrons, passing through the top thin layer with diminished energies, may reach the layer underneath which may have different material properties. The surface temperature effect on SEY has been generally overlooked in the past. It is worthwhile to investigate the temperature effect, especially for very cold temperature situations as we may expect in future explorations of the outer planets.

In LHC (Large Hadron Collider), Switzerland, where the most important and extremely precise (or at least the most expensive) physics experiments will be conducted, serious attention is being paid to the problem of secondary electrons inside the accelerator tubes. There, they have adopted the Furman SEY $\delta(E)$ formula [13], which features an empirical surface condition parameter s which one can adjust according to the measured secondary electron yield from the actual surface materials. The Furman formula [13] is as follows:

$$\delta(E) = \delta_{\max} \frac{s(E/E_{\max})}{s - 1 + (E/E_{\max})^s} \tag{9}$$

$$E_{\max}(\theta) = E_{\max}(0)[1 + 0.7(1 - \cos\theta)] \tag{10}$$

$$\delta_{\max}(\theta) = \delta_{\max}(0)\exp[0.5(1 - \cos\theta)] \tag{11}$$

where $90^\circ \geq \theta \geq 0^\circ$ is the primary electron incidence angle measured relative to the normal to the surface (see Fig. 4).

IV. Backscattered Electron Yield

For the BEY, the Prokopenko and Laframboise $\eta(E)$ formula [1] has been used in spacecraft charging, Eqs. (1–6), for decades. It needs to be updated. The backscattered electron formula of [1] is of the form

$$\eta(E) = A - B\exp(-CE) \tag{12}$$

where A, B, and C depend on the surface material. The energy integrals in Eqs. (1) and (6) are from $E = 0$ to ∞. The ambient electron distribution $f(E)$ is maximum at near $E = 0$ and decreases to negligibly small values as E increases to about 40 keV. In the limit of E approaching 0, the Prokopenko–Laframboise $\eta(E)$ formula [1] gives a nearly flat curve and a small finite value ($\ll 1$) at $E = 0$.

Recently, Cimino et al. [14] and Cimino [15] reported measurements of SEY and BEY of copper surfaces for the LHC, European Organization for Nuclear Research. Earlier measurements, with less details, were obtained by Jablonski and Jiricek [16] using other surface materials. Cimino's measurement results (Fig. 3) show clearly that the value of $\delta(E)$ varies significantly depending on the surface condition. At very low energies, the backscattering electron yield BSE $\eta(E)$ clearly dominates over the secondary electron yield. The $\eta(E)$ function of copper rises to unity as the primary electron energy E decreases to 0.

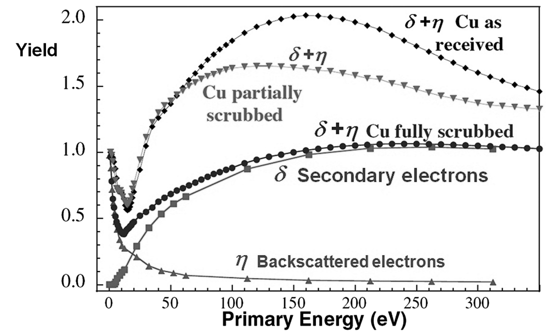

Fig. 3 The Cimino [15] measurements of SEY $\delta(E)$ of copper.

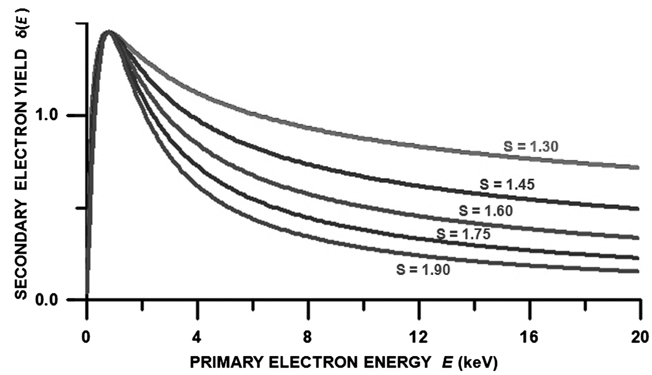

Fig. 4 SEY $\delta(E)$ of gold calculated by using Furman's formula [13]. The empirical parameter s characterizes the condition of a given surface material.

Cimino et al. [14] cited that similar results can also be obtained by using quantum mechanical model calculations. Apparently, the property that $\eta(0) \to 1$ as $E \to 0$ seems general and not for copper surfaces only.

In view of the results of [14–16] and the quantum calculations, Lai and Tautz [17] modified the Prokopenko and Laframboise η formula by adding a term $\Delta\eta$

$$\eta \to \eta + \Delta\eta \tag{13}$$

$$\Delta\eta = (1 - A + B)\exp\left(-\frac{E}{E_0}\right) \tag{14}$$

where $E_0 = 0.05$ keV for gold (see Fig. 5). The parameters A and B are the same ones appearing in the Prokopenko and Laframboise

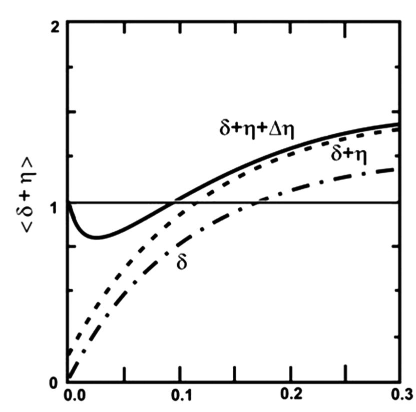

Fig. 5 Current balance equation $<\delta + \eta> = 1$ for the anticritical temperature with and without enhanced scatter for the surface material gold. We have used $E_0 = 0.05$ keV for the enhancement falloff parameter (from Lai [18]).

BSY $\eta(E)$ formula. The parameter E_0 specifies the enhancement falloff rate, which is material specific. Indeed, the enhanced backscattering formula, Eqs. (13) and (14), gives an η value rising to unity at $E = 0$. Lai and Tautz [17] demonstrated that the added term $\Delta\eta$ affects the value of the anticritical temperature in spacecraft charging.

The value of the parameter E_0 [Eq. (14)] is lacking for other spacecraft surface materials. Similar to our comments in the previous section on SEY, the effects on backscattering due to surface coarseness and contamination need to be studied. For dielectric materials, which cannot be grounded, the experimenter must be careful in determining the effect of the negative potential built up as a result of electron bombardments on the material sample. Also, in a very low-energy electron beam, electron mutual repulsion due to the beam space charge may be present. These effects may affect the measurements of the backscattering coefficient, especially at low energies of the incoming electrons.

V. Photoemission

Photoemission yield from surfaces depends not only on the surface material but also the surface condition. Surface reflectance depends on the surface roughness and the incidence angle of the incoming photon. The photoelectron yield $Y_{\text{ph}}(R)$ per incoming photon decreases as the reflectance R increases

$$Y_{\text{ph}}(R, \omega) = (1 - R(\omega))Y_{\text{ph}}(0, \omega) \tag{15}$$

The reflectance R is a function of the photon frequency ω. If there is no reflectance ($R = 0$), every incoming photon is absorbed. With a finite R, some photons are reflected, resulting in less energy transfer from the incident light to the surface material. The photoelectron flux $J(R)$ generated from a surface is given by

$$J(R, \omega) = J(0, \omega)(1 - R(\omega)) = I(\omega)Y_{\text{ph}}(R(\omega)) \tag{16}$$

where

$$J(0, \omega) = I(\omega)Y_{\text{ph}}(0, \omega) \tag{17}$$

In Eqs. (16) and (17), $I(\omega)$ is the incident light intensity that is a function of the photon frequency ω or photon energy $h\omega$. For sunlight at geosynchronous altitudes in the magnetosphere, the most important solar spectral line is the Lyman Alpha, which has about 10 eV in energy.

Depending on the reflectance R, the photoelectron yield $Y_{\text{ph}}(R, \omega)$ and, therefore, the photoelectron current I_{ph}, varies. Varying the photoelectron current I_{ph} affects the current balance [Eqs. (1–6)] in spacecraft charging, and, the spacecraft potential varies accordingly (Fig. 6).

A highly reflective surface ($R \to 1$) generates little or no photoemission [$J(R) \to 0$, Eq. (16)]. For spacecraft charging calculations, it is insufficient to use a value for the photoelectron yield Y_{ph} of a given surface material. It is necessary to specify the surface condition, especially the reflectance.

As an example of the reflectance effect, let us consider a mirror in space. If a highly reflective surface is located next to a nonreflective one, the difference in their photoemissions renders differential charging between the surfaces in sunlight [18]. Differential charging is known to pose discharge hazard, which, in turn, may cause satellite anomalies. Highly reflective mirrors have been used for concentrating sunlight onto solar cells on satellites such as Telesat Anik F1, Telesat Anik F2, and PamAmSat's Galaxy 11[†]. Because the mirrors are highly reflective while the solar panel adjacent to the mirrors is not, the mirrors and the panel may charge to very different potentials. That suggests harmful differential charging may emerge under adverse space conditions. In general, however, the exact causes of most satellite anomalies are unknown.

[†]Data available online at http://sat-index.com/failures/702arrays.html [retrieved MONTH YEAR].

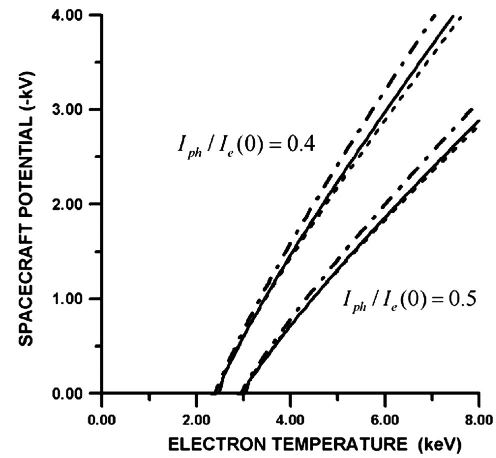

Fig. 6 Calculated surface potentials of aluminum oxide in 1-D, 2-D, and 3-D with $I_{\text{ph}}(0) = 0.4 \times I_e(0)$ and $0.5 \times I_e(0)$. Dot-dash-dot is for 1-D, solid is for 2-D, and dash for 3-D (from Lai and Tautz [4]).

We should also mention that surfaces with deep grooves emit less photoelectrons than smooth surfaces. Though the incident photons may be well absorbed by the material, the photoelectrons generated from the deep grooves may be reabsorbed by the walls of the grooves.

VI. Discussion

In spacecraft charging calculations, secondary and backscattered electron emissions are centrally important. They control the critical temperature T^*, which is ambient electron temperature at which the onset of spacecraft charging occurs. They also control the spacecraft charging voltage, which is given by the balance of all incoming and outgoing currents. It has been customary to use a value of SEY $\delta(E)$ and a value of BSY $\eta(E)$ for a given surface material. It is insufficient to use the "best" values of $\delta(E)$ and $\eta(E)$ published in the literature. It is necessary to specify the surface condition. Similarly, spacecraft charging in sunlight requires the knowledge of the photoelectron yield $Y(\omega)$ for a given surface material. Again, it is necessary to specify the surface condition, especially the reflectance.

Perhaps it should be mentioned that a surface with deep groves emits less secondary, backscattered, and photoemission electrons. This is because such low-energy electrons liberated from the depth of a groove are likely to be reabsorbed by the groove walls. The reason for the likely is because the secondary electrons acting as primary electrons for the next-generation secondary electrons have low energies (a few eV) rendering the SEY less than unity.

In general, it may be insufficient to characterize the smoothness by using a parameter such as the s in the Furman formula [Eq. (9)]. For improved characterization, the groove shape, depth, and homogeneousness require at least three parameters. With sufficient characterization, one can predict the deviation of the yield from its ideal value.

Because the condition of a surface material can significantly affect the secondary and backscattered electrons yields, we suggest to abandon the common practice of relying on taking data from standard material property tables. For spacecraft charging predictions and for spacecraft design engineering, it would be better to measure the $\delta(E)$, $\eta(E)$, and $Y_{\text{ph}}(\omega)$ yields from the actual pieces of surfaces before assembly. Care should be taken to preserve the surface condition, such as smoothness, cleanliness, and surface temperature, so that the yield functions in space will remain almost the same as measured in the laboratory.

However, if the yield functions change slowly in the hazardous space environment because of bombardments by energetic electrons and protons, all careful measurements before launch would be in vain. In situ monitoring of the yield functions would be helpful but perhaps not practical.

VII. Conclusions

We have stressed that the secondary and backscattered electron yields are important factors in determining the onset of spacecraft charging and the spacecraft potentials. In the literature, there are often new sets of measurement data and new empirical yield formulae published. It is a good question which one is the best to use. We have chosen some of the "best" recent formulae and showed that they give different calculation results for the onset of spacecraft charging. In the literature, the secondary and backscattered electron yields, $\delta(E)$ and $\eta(E)$, respectively, are commonly written as functions of the primary electron energy E only. We have stressed that surface conditions can significantly affect the yields. It is difficult to quantify the surface conditions rigorously. Smoothness and contamination are examples characterizing the surface condition. The condition, in turn, can affect the secondary electron yield, the backscattered electron yield, and even the photoelectron yield from the spacecraft surfaces. We suggest that instead of choosing the best sets of data, or best formulae, from previous measurements or standard material tables, it would be better to measure directly the yields from actual pieces of surface materials to be used. This is because the yields depend very much on the surface conditions. We have also mentioned, however, that the surface condition, and therefore the yields, can also change slowly in space.

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