2018

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PARAMETERIZATION OF SECONDARY AND BACKSCATTERED ELECTRON YIELDS FOR SPACECRAFT CHARGING

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Abstract

Spacecraft charging codes model the interactions between energetic electrons and spacecraft materials through material properties called electron yields (EY). The accuracy of spacecraft charging calculations can be critically affected by the availability of accurate EY data for materials and by how the measured data are parameterized for use with spacecraft charging codes. This work investigates the effectiveness of various EY fitting models.

Most often total electron yield (TEY) is characterized by two separate parameterized curves, a secondary electron yield (SEY) curve for low-energy emission <50 eV and a backscattered electron yield (BSEY) for high energies >50 eV. Typical semi-empirical models describe the SEY as a function of incident electron energy in terms of material properties such as atomic number, mean excitation energy, electron range, and mean free path. Other purely empirical models use parameters which define the shape of the resulting curves rather than physical material properties. The models are usually presented in reduced form, with yields scaled by the maximum yield δ_{max} and energies scaled by the energy E_{max} at δ_{max}. The complexity of SEY models considered here can be classified by the number of free fitting parameters, beginning with δ_{max} and E_{max} to include a total of 2, 3, 4 or 5 parameters. BSEY models considered include a single-parameter empirical model widely used in most spacecraft charging codes and extended empirical models with 3 and 4 free parameters.

Some electron yield models were found to be more effective than others at approximating the measured yield curves of certain materials or energy ranges; this has been quantified for each of several common spacecraft materials using χ^2 statistical analysis. The implementation of parameterized electron yield models in various spacecraft charging codes is also discussed.

I. Introduction

Electron induced electron yield describes how a material will charge electrically due to electron emission caused by incident electron, photon, or ion bombardment. Understanding this process is critical to the fields of spacecraft charging, electron microscopy, particle accelerators, as well as many others. Many spacecraft charging models use understanding of electron yield to predict how spacecraft will react to the space plasma environment and to mitigate negative effects such as electrostatic discharge, the production of stray electric fields, and cathodoluminescence. The effectiveness of these models relies heavily on the accuracy of available yield data and on the chosen mathematical models used to fit this data.

II. Assumptions

The majority of yield models all make some common assumptions. The most popular assumptions are listed below.

- The problem is limited to 1 Dimension (Normal incidence only is considered)
- A Continuous Slowdown approximation is made (Energy is deposited continuously over path of incident electrons.)
- The number of secondary electrons(SE) are assumed (Electrons produced per penetration depth ∝ energy deposited)
- The probability of emission is estimated (Probability of SE depends on an exponential decay term and the probability of overcoming the surface barrier)
- An electron range model is selected for SEY (various models exist the most common are power law models)

III. Secondary Electron Yield

The majority of secondary yield formulas are written in the Reduced Yield Formula[Baroody, 1950]. It is used in plots where $\frac{\delta(E_0)}{\delta_{max}}$ is plotted against $\frac{E_0}{E_{max}}$ and is only dependent on parameters m and n. Many models use some variation of this form. Table 1 gives a summary of many models listing their fixed and free parameters along with the appropriate ratios for $r = \frac{R(E_{max})}{\lambda_{SE}}$.

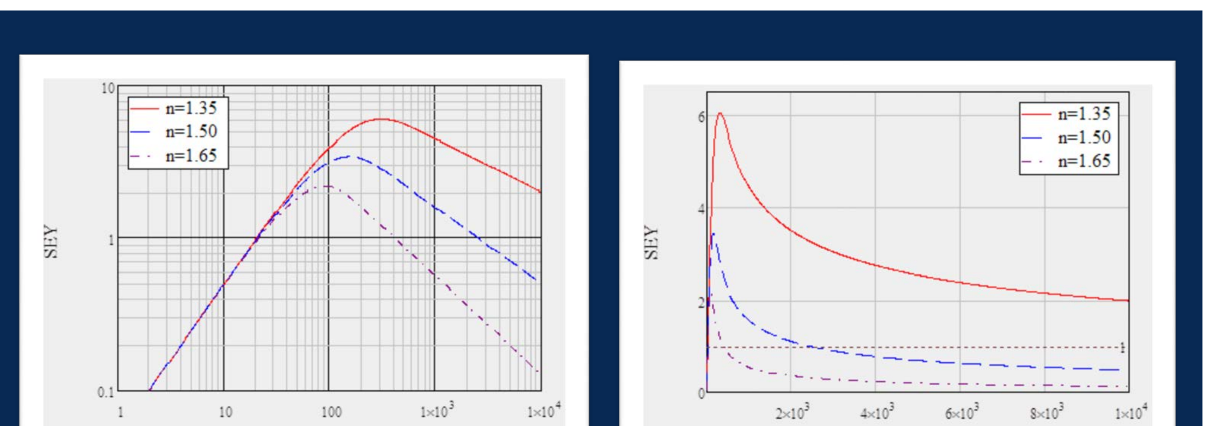
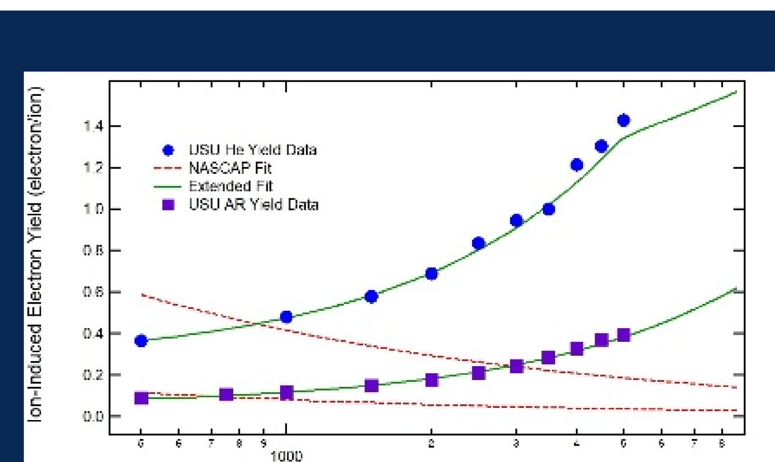
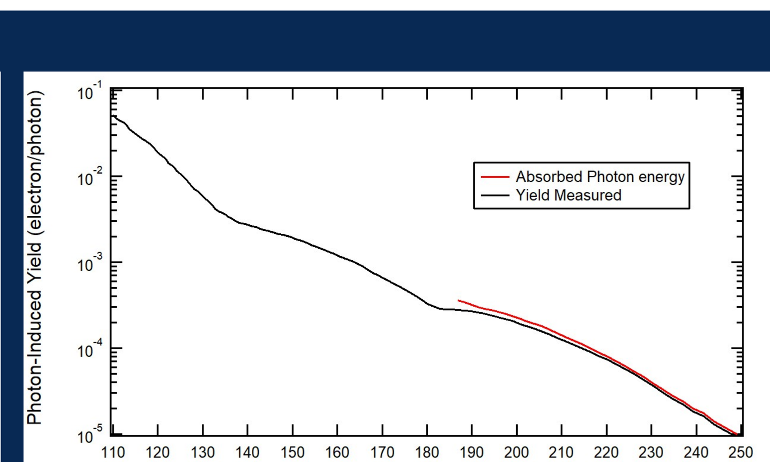


Fig. 1. Yield model comparisons. Graphs show the above model (Eq. 9) for $A = 0.05$, $\gamma = .001$, (solid), $n = 1.50$ (dashed), and $n = 1.65$ (dot-dashed) in (a) linear and (b) log-log form. Markers indicate first and second crossover energies (E_1 and E_2), as well as the energy of largest yield, E_{max}, with the associated yield, δ_{max}, for the $n = 1.5$ case.





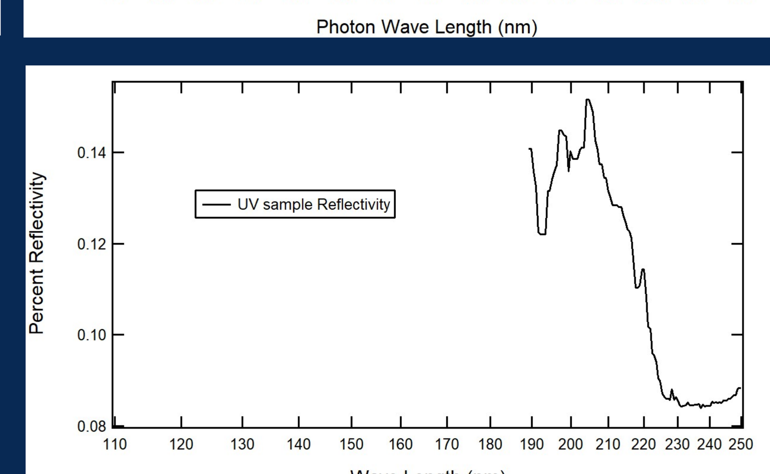


Fig. 2. (a) Comparison of low energy ion yield for Helium and Argon on a Gold sample. An Extended fit as well as the NASCAP fit has been included. (b) Photon-Induced yield as a function of Wavelength with electron yield (lower curve) and absorbed photon energy (red upper curve.) (c) Reflectivity of sample as a function of incident energy showing specular reflection for normal incidence.

IV. Backscattered Electron Yield

The equations that the USU MPG uses to model BSEY as a function of incident energy originate from NASA's spacecraft charging simulation software NASCAP 2k (Katz, *et al*, 1977). The formula that NASCAP uses to model BSEY has little to no physical basis. It was designed to reproduce the typical BSEY trends, which have been seen experimentally. This model has a fixed maximum height of 1.0 at 1000 eV, and the only free parameter η_0 adjusts the high-energy asymptotic value (See Table 2, Fig. 5).

NASCAP Parameterizes BSEY curves in terms of an effective atomic number Z_{eff}. The BSEY for normal incidence at high energies (above ~10keV), η_0, has a constant value [Burke, 1977; Darlington, 1972] given in terms of Z_{eff} by the relation [Katz, 1977] While the BSEY as a function of incident energy is given by [Katz, 1977](See Table 2).

The NASCAP model rises from zero at 50 eV, to a maximum value at 1000 eV, then it falls toward a horizontal asymptote of η_0. A similar method of calculating BSEY is utilized by the SPENVIS program assumes a value for η_0 as $1 - 0.7358^{0.037Z}$ for surface energy values 1,000 < E_s < 100,000. Where Z is the atomic number. With no explicit method mentioned in the SPENVIS literature, there are many options for users to determine Z in the case of polyatomic molecules. A simple mean atomic number as implemented in NASCAP[Mandell, 1993] is very popular method of determining Z.

$$Z = \frac{a \cdot Z_a + b \cdot Z_b + \cdots n \cdot Z_n}{a + b + \cdots n}$$

where a, b, …n are the atomic coefficients present in the molecule, and $z_a, z_b, \ldots z_n$ are the atomic numbers of the various atoms present in the compounds; eg., polyethylene $(CH_2)_n$ has a mean atomic number of (6 +1 +1)/3 = 2.7.

An alternative method to determine Z specifically meant to determine Z for photon-energy absorption, has been determined by Manohara [Manohara 2007] where $Z_{man} = \frac{\sigma_{a,en}}{\sigma_{e,en}}$ where $\sigma_{a,en}$ is the effective (average) atomic energy- absorption cross section, and $\sigma_{a,en}$ is the effective electronic energy-absorption cross section.

V. Photo-Yield and Ion-Yield

The total yield (TEY) is comprised of four different yield sources. SEY, BSEY, Ion yield, and photo-yield. $\sigma_{Tot} = \delta + \eta + \sigma_{Ion} + \sigma_{Photo}$ if σ_{Tot} dips below 1, ie. There are more electrons impinging on the surface than leaving, a net negative charge will begin to form. This net negative charge creates a repelling force towards low energy electrons and prevents their capture by the surface. Because this negative charge does not affect SE and BSE [Nickles, 2000], charge can accumulate rapidly, leading to an abrupt increase in negative charge accumulation. (σ_{Ion} is affected by negative charge accumulation due to the electrodynamic attraction between the negative surface and the positive ions. However, σ_{Ion} has a much smaller effect upon σ_{Tot} as observed by [Olsen, 1983].)

The total yield associated with ion bombardment of a sample is typically very small and so is often overlooked in favor of a electron yield consisting of SEY and BSEY only. The reasoning behind the practice of overlooking ion-yield can be made apparent from the small yields associated with the large Ion Energy. At 6keV the yield associated with He ions is a mere 1.4 electrons/ion.(See Fig.2a).

Photoemission at constant reflectivity [Lai, 2008] increases approximately as ${}^{1}/_{\cos\varphi}$, where φ is the angle of incidence from normal. Because reflectivity scales with $\cos\varphi$ and photo-yield is directly proportional to reflectivity, changes to the incidence angle will also affect the charge rate (See Fig. 2b,2c).

VI. References

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Model	m	n	c_1	c_2	$\frac{R(E_{max})}{\lambda_{SE}}$
(Young, 1957; Dionne, 1973;Whipple, 1981)	0	1.35	1.114	2.28	2.283
(Viatskin and Makhov, 1958)	0	1.4	1.1349	2.161	2.138
(Lane and Zaffarano, 1954)	0	1.66	1.24	1.626	1.629
(Lin and Joy, 2005)	0	1.67	1.28	1.614	1.614
(Burke, 1980)	0	1.73	1.53	1.28	1.533
(Reimer, 1928; Seiler, 1983)	0	1.8	1.31	1.45	1.45
(Whiddington, 1912; Terrill, 1923; ; Bruining, 1938; Baroody, 1950)	0	2	1.396	1.26	1.256
(Feldman, 1960)	0	$\frac{e^r - 1}{e^r - r - 1}$			r
(Sims, 1992)	0	variable	$\left(1 - \exp(1 - \frac{1}{n}[exp(r - 1)]\right)^{-1}$	$1 - \frac{1}{n}[exp(r - 1)]$	$x_m = \left(1 - \frac{1}{n}\right)[e^{x_m} - 1]$

Table 1. Comparison between several range and SEY models with their associated coefficients.

Incident Energy (E_s)	NASCAP $\eta_{nas}(E_0, \eta_0)$ [Katz 1977]	SPENVIS $\eta_{sp}(E_0)$ [ECSS, 2009]	USU Modified BSEY $\eta_{USU}(E_0)$
>100,000	$\left[0.1 \cdot e^{-\frac{-E_0}{5000\ eV}} + \eta_0\right]$	0	$\left[(\eta_{max} - \eta_0) \cdot e^{\frac{-(E_0 - E_{max})}{E_{max}}} + \eta_0\right]$
10,000-100,000		$1 - 0.7358^{0.037Z}$	
1,000-10,000 (USU $E_{max} < E_0$)		$1 - 0.7358^{0.037Z} + 0.1\ exp(\frac{-E_0}{5{,}000})$	
50-1,000 (USU 50 < E_0 < E_{max})	$\frac{\log({E_0}/{50\ eV})}{\log({1000\ eV}/{50\ eV})} \cdot \left[0.1 \cdot e^{\frac{-E_0}{5000\ eV}} + \eta_0\right]$	$\frac{\log {E_0}/{50\ eV}}{\log {1000\ eV}/{50\ eV}}\left[1 - 0.7358^{0.037Z} + 0.1 \exp\left(\frac{-E_0}{5{,}000}\right)\right]$	$\frac{log({E_0}/{50\ eV})}{log({E_{max}}/{50\ eV})} \cdot \left[(\eta_{max} - \eta_0) \cdot e^{\frac{-(E_0 - E_{max})}{E_{max}}} + \eta_0\right]$
<50	0	0	0

Table 2. Comparison between several BSEY models used by the most popular Charge modeling programs. Broken up by the ranges for which aspects of the models are effective.

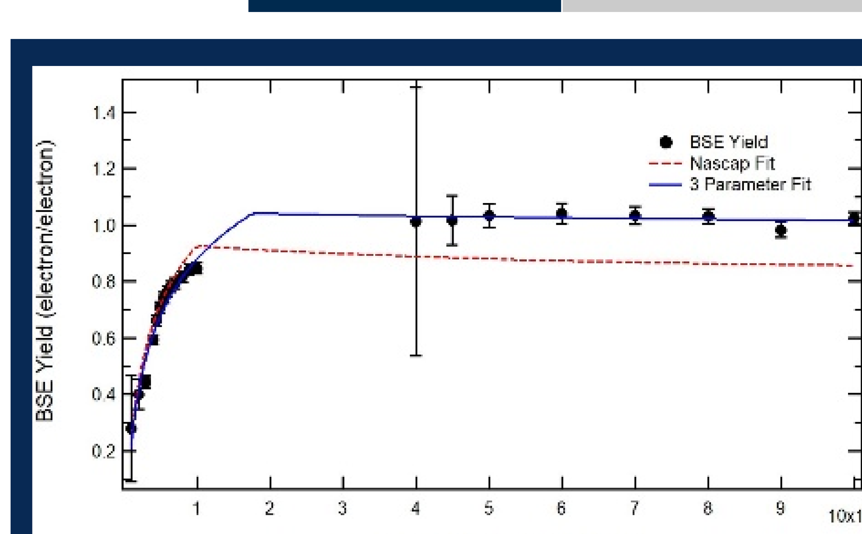

Fig. 5. BSEY vs incident beam energy for a clean polycrystalline Au surface. Measured data, using a low density electron beam. To show a comparison between different fitting methods BSEY data have been plotted with the NASCAP Fitting method as well as the USU MPG 3 parameter fitting method.

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We gratefully acknowledge contributions from other members of the Materials Physics Groups. This work was supported by a USU Blood Taylor Fellowship.

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