Strategies for Determining Electron Yield Material Parameters for Spacecraft Charge Modeling

Phil Lundgreen and J. R. Dennison

Materials Physics Group, Utah State University, Logan, UT, USA

Abstract Accurate modeling of spacecraft charging is essential to mitigate well-known and all-too-common deleterious and costly effects on spacecraft resulting from charging induced by interactions with the space plasma environment. This paper addresses how limited availability of electron emission and transport properties of spacecraft materials—in particular, secondary electron yields—and the wide ranges measured for such properties pose a critical issue for modeling spacecraft charging. It describes a materials charging database for electron emission properties under development, which facilitates more accurate spacecraft charge modeling when used in concert with the strategies outlined herein. These data and techniques provide tools for more accurate material selection, increased confidence in charge models, and a concomitant decrease in mission risk. They also allow better customization of models in response to prolonged space environment exposure and specific mission requirements, which may evolve materials properties.

1. Introduction

The space environment is harsh and can adversely affect mission effectiveness through its interaction with spacecraft, components, and materials (Dennison, 2015; Hastings & Garrett, 1996; Lai, 2011). Indeed, environmentally induced anomalies are dominated by spacecraft charging effects (Koons et al., 1999), with the majority related in some way to electrostatic discharge or charging effects (Bedingfield et al., 1996; Leach & Alexander, 1995).

To mitigate these risks, various agencies (e.g., Air Force Research Laboratories, European Space Agency, Japan Aerospace Exploration Agency, and National Aeronautics and Space Administration [NASA]) have devoted significant resources to develop modeling tools for spacecraft charging due to spacecraft interactions with the plasma. Modeling space plasma environment-induced effects on spacecraft requires knowledge of the following:

- Environment and impinging fluxes during spacecraft orbits, which are mission-specific and can be incorporated through environmental models and databases (Hastings & Garrett, 1996; Lai, 2011).
- Satellite geometry and orientation in the space environment accomplished through charging codes. The three most prominent codes are NASCAP-2k (Mandell et al., 2006; Davis et al., 2000; Mandel et al., 1976; Katz, et al., 1977), European Space Agency (2018), and MUSCAT (Muranaka et al., 2008).
- Precise descriptions of the materials used in spacecraft construction, for the specific spacecraft design (Toyoda, 2014; Dennison et al., 2007).
- Relevant materials properties characterizing the interaction of these specific materials with the environment and how these properties may change with exposure to the space environment. (Dennison et al., 2002; Dennison et al., 2007; Katz et al., 1977; Parker, 2018)

A reliable, comprehensive database of spacecraft materials and the characterization of those materials is being created in the form of a materials charging database to be used in conjunction with existing charging codes (Lundgreen & Dennison, 2019). This is being done to provide an improved, more informed modeling tool to be used by researchers for environment-induced spacecraft charging and data validation. The accuracy of charge modeling will be improved as knowledge concerning inputs is increased.

2. Proposed Strategies

This paper focuses exclusively on secondary electron yield (SEY), as this material property has been shown to have one of the most critical effects on spacecraft surface charging (Dennison et al., 2007; Lai, 2010; Katz...
et al., 1986). The paper presents strategies for determining the best available SEY data to use when modeling materials in specific spacecraft applications. To demonstrate the strengths and weaknesses of the different strategies, a simple ubiquitous spacecraft material—aluminum—is analyzed here in detail. A similar study has been done recently for copper (Lundgreen & Dennison, 2018). Aluminum provides an illustrative example, as many studies of ostensibly the same material exhibit a wide variety of reported SEY values (see Figure 1a), which we attribute to the disparities that exist between elemental and technical aluminum with clean, oxidized, contaminated, and rough surfaces.

A three-tiered strategy for determining appropriate electron yield material parameters for specific spacecraft charge modeling is proposed.

1. The easiest approach is to select parameterized yield properties from a limited database of materials tabulated for use with the standard charging codes mentioned above (Dennison et al., 2002; Dennison et al., 2007; Drolshagen, 1994; Mandel et al., 1976; Mandell et al., 1993; Mandell et al., 2006; Parker, 2018).

2. A second method involves the review of available literature to identify data of more directly applicable materials not presently tabulated in these databases (e.g., Joy, 1995; Walker et al., 2008).

3. The third, most sophisticated—and most time consuming—method requires selecting materials and specific data sets, which are most mission specific to relevant charging concerns and to possible changes in materials with prolonged exposure to the space environment.

Electron yield studies of nominally similar materials often show widely differing results (see Figure 1a). Indeed, even round-robin studies in different laboratories of carefully selected “standard” calibration materials such as Au and graphitic carbon show smaller but still significant, variation in yields (see Figure 2; Dennison et al., 2016); these can be attributed to subtle differences in instrument calibration, measurement methods, and sample preparation differences at the different facilities—details which are seldom provided in standard literature. Indeed, even the definition of “SEY” can differ for different studies and lead to ambiguities (see Appendix A).

2.1. Select Parameterized Yield Properties From a Limited Database of Materials

The easiest method for selecting electron yield material parameters entails selecting parameterized yield properties from a limited database of materials, as tabulated for use with standard charging codes. Table 1 lists the model parameters in the default materials database included with successive versions of NASCAP (Davis et al., 2000; Mandel et al., 1976; Mandell et al., 1993; Mandell et al., 2006). These are used to characterize SEY with the Katz et al. (1977) or far less accurate Feldman (1960) models mutually incorporated in the three NASCAP-2 k, SPENVIS, and MUSCAT codes. The parameters are as follows:

- the maximum SEY, \( \delta_{\text{max}} \);
- the energy \( E_{\text{max}} \) associated with \( \delta_{\text{max}} \); and
- two amplitudes, \( b_1 \) and \( b_2 \), and two exponents, \( n_1 \) and \( n_2 \), for an analytic biexponential range expression.
  (Note that there are actually only five independent parameters, including only \( b_1/b_2 \) rather than \( b_1 \) and \( b_2 \) (Chang et al., 2000; Purvis et al., 1984).)

Values selected from such parameterized yield properties tabulated in one of the standard charging codes, unfortunately,

- are severely limited for novel materials and more demanding mission requirements;
- are occasionally inaccurate or misreferenced;
- do not provide the necessary information to identify details about the tabulated materials;
- do not reflect the nature of specific composition or surface modifications appropriate to many spacecraft applications; and
- do not address the evolution of material properties with space environment exposure.

Table 1 lists the SEY parameters in the default materials database for five elemental conductors, three bulk insulating materials, and five spacecraft materials; these values are also included with current versions of SPENVIS and MUSCAT charging codes. The entries in the default material database in Table 1 are certainly severely limited in terms of the number of tabulated common spacecraft materials and do not contain novel materials or materials used for more demanding mission requirements (e.g., carbon fiber/epoxy composites,
Figure 1. Secondary electron yield (SEY) curves versus energy for Al studies. A full listing of the various studies plotted is given in Table 2. (a) Linear plot of SEY versus energy. The inset legend identifies the lines associated with each study. The “best” representative studies for various conditions selected are highlighted as solid lines. (b) Linear plot of SEY showing datasets classified by surface conditions. (c) Log-log plot of reduced SEY, $\delta/\delta_{\text{max}}$, versus reduced energy, $E_0/E_{\text{max}}$. For (b) and (c) the solid, dashed, and dotted lines signify studies of smooth, rough, and unknown surfaces, respectively. The green, red, and blue lines signify studies of clean, oxidized, and unknown contaminated surface coverages, respectively. Bulk Al$_2$O$_3$ (sapphire) SEY curve are indicated with purple lines (Christensen, 2017).
multilayer insulation, layered optical materials, conduction enhanced nanodielectric materials, and lubrication compounds).

In addition, this database method often incorporates inappropriate or inaccurate values. Sometimes tabulated values are extracted from sources that are not fully documented. Even when specific references are cited, in many instances the original sources are difficult to locate, do not provide necessary information to identify details about the materials studied, or do not reflect the nature of specific composition or surface modifications appropriate to spacecraft applications.

As an example, consider the values of $\delta_{\text{max}}$ and $E_{\text{max}}$ for Al in the default NASCAP database (see Table 1; Mandel et al., 1976). These values are not well documented and appear to be significantly lower than many other SEY values for Al (see discussion below; Figure 1, and Table 2). The origin of the NASCAP values is obscured: Mandel et al. (1976) and Katz et al. (1977) cited Dekker (1958) as the source for $\delta_{\text{max}}$ and $E_{\text{max}}$; a Dekker plot of $\delta_{\text{max}}$ versus work function, $W$, was traced to two different plots from Baroody (1950), one a reduced yield curve of $\delta/\delta_{\text{max}}$ versus $E/E_{\text{max}}$ and another of $\delta_{\text{max}}$ versus $W$; and Baroody, in turn, cited (Bruining & De Boer, 1938), which lists original experimental data for $\delta/\delta_{\text{max}}$ versus $E/E_{\text{max}}$ and $\delta_{\text{max}}$, but does not include information on $E_{\text{max}}$. The Bruining dataset is for “secondary electron emission of [an] aluminum layer deposited by sublimation in a vacuum Bruining & De Boer, 1938,” although specifics of the level of surface roughness, oxidation, and contamination (in particular, from the 1938 vintage diffusion and getter pumps and glass vacuum system) are not fully identified. Thus, in verifying the patronage and integrity of the default NASCAP values, it appears that these values for $\delta/\delta_{\text{max}}$ versus $E/E_{\text{max}}$ and $\delta_{\text{max}}$ are (at least at some level) for smooth, clean elemental Al, though origin the values used for $E_{\text{max}}$ and associated sample conditions are not traceable. The listed low $\delta_{\text{max}}$ in the database is expected for low-Z materials and is consistent with studies of other clean elemental Al samples, but inconsistent with higher $\delta_{\text{max}}$ expected for technical Al with more oxidized surfaces.

The implications associated with using significantly different yield values for materials not appropriate to spacecraft applications, such as clean smooth elemental Al in lieu of rough, oxidized, and contaminated technical Al, are potentially troubling as they can lead to substantially inaccurate predictions from charging models. Baglin et al. (2000) measured the change in $\delta_{\text{max}}$ as an oxide layer was removed from a technical Al sample using Ar sputtering. Dennison et al. (2007) performed trade studies of the effects of changing yields on the charging of hypothetical idealized spacecraft in representative space environments, based on evolving SEY measurements of oxidized Al to clean Al to carbon-contaminated Al (Davies & Dennison, 1997) and on clean Au to carbon-contaminated Au (Chang et al., 2000); such changes in SEY due to surface modifications were shown to potentially lead to dramatic threshold charging effects (Chang et al., 2000; Dennison et al., 2007).

A cursory, investigation of recent studies returned a substantial list of references, which assumed that the NASCAP default values for Al were appropriate for their modeling, including Davis et al. (2017), Marchand and Lira (2017), Wang et al. (2017), Hughes and Schaub (2018), Schmidt et al. (2018), Wolfley (2018), Bengtson et al. (2019), and Pandya et al. (2019). It is significant to note that this ambiguity for Al has also been propagated by other international charging codes, including MUSCAT (Nakamura et al., 2018) and European Space Agency (2018). A newer SPENVIS materials database does include a technical Al material, with a rougher more oxidized surface (Drolshagen, 1994).

In a similar vein, the value in Table 1 of $\delta_{\text{max}}$ for Mg is more consistent with other results for smooth, clean elemental Mg (Bruining & De Boer, 1938; Joy, 1995; Walker et al., 2008) than technical Mg with rougher and

![Figure 2. Total electron yield curves for (a) high-purity polycrystalline Au and (b) atomically clean, flat highly oriented pyrolytic graphite, from a round robin study performed by Office National d’Etudes et de Recherches Aérospatiales (ONERA), Laboratory of Spacecraft Environment Interaction Engineering (LaSeine), Consejo Superior de Investigaciones Científicas (CSIC), and Utah State University Materials Physics Group (USU) (Dennison et al., 2016).](image-url)
Table 1

| Material | $\delta_{\text{max}}$ | $E_{\text{max}}$ (keV) | $b_1$ (Å) | $n_1$ | $b_2$ (Å) | $n_2$ |
|----------|-----------------------|------------------------|-----------|-------|-----------|-------|
| Bulk elemental conductors | | | | | | |
| Aluminum (Al) | 0.970 | 0.300 | 154 | 0.800 | 2,200 | 1.76 |
| Aquadag (colloidal graphite, C)$^a$ | 1.00 | 0.300 | 374$^b$ | 1.55$^a$ | 2 | 12.0 |
| Gold (Au) | 0.880 | 0.800 | 88.8 | 0.920 | 53.50 | 1.73 |
| Magnesium (Mg)$^a$ | 0.920 | 0.250 | 399$^a$ | 1.75$^a$ | 1.74 | 24.3 |
| Silver (Ag) | 1.00 | 0.800 | 84.5 | 0.82 | 79.4 | 1.74 |
| Bulk insulators | | | | | | |
| Kapton™ | 2.10 | 0.150 | 71.5 | 0.600 | 312 | 1.77 |
| Teflon™ | 3.00 | 0.300 | 45.4 | 0.400 | 218 | 1.77 |
| SiO₂ | 2.40 | 0.400 | 116 | 0.81 | 183 | 1.86 |
| Spacecraft materials | | | | | | |
| Conductive paint | 2.10 | 0.150 | 71.5 | 0.600 | 312 | 1.77 |
| Nonconductive paint$^a$ | 2.10 | 0.150 | 55.6$^a$ | 1.56$^a$ | 1.05 | 0.98 |
| Solar cell with coverglass | 2.05 | 0.410 | 77.5 | 0.450 | 156 | 1.73 |
| Indium tin oxide coating$^a$ | 1.400 | 0.800 | 23.6$^a$ | 2.29$^a$ | 7.18 | 55.5 |
| Screen (absorber) | 0 | 1 | 10 | 1.5 | 0 | 1.0 |

Note. Mandell et al. (1993). Abbreviation: SEY: secondary electron yield.

$^a$Uses Feldman’s formula (Feldman, 1960) for SEY, which provides a method for estimating the parameters in terms of the density and stoichiometry of a material even when SEY data are lacking. From Feldman, $n_1 = n_f \equiv 1.2/[1-0.29 \log(Z)]$ and $b_1 = b_f \equiv (250 \bar{\rho}/\rho_m)(Z)^{-2.8n_f}$ are determined from the mass density $\rho_m$ (g/cm$^3$; as listed here in column 6), the mean atomic weight $\bar{\rho}$ (as listed here in column 7), and the mean atomic number $Z$ with $n_2 \equiv b_2 \equiv 0$.

Table 1 and the default NASCAP database (Mandel et al., 1976; Mandell et al., 1993) list three common bulk insulating spacecraft materials. The values are in reasonably good agreement with other studies of similar materials (Dennison et al., 2007; Joy, 1995, and references therein), although yields of highly insulating materials are notoriously difficult to measure (Hoffmann & Dennison, 2012).

There are four spacecraft materials listed in Table 1 and the default NASCAP database. These listings are more values from representative categories of spacecraft surface components than actual materials; even more than the conducting and insulating entries discussed above these are severely limited for myriad functionally similar materials or novel materials, do not provide necessary information to identify details about the components, do not reflect the nature of specific composition or surface modifications appropriate to specific spacecraft applications and more demanding mission requirements, and do not address the evolution of material properties with space exposure.

2.2. Review of Available Literature for Data of More Directly Applicable Materials

The second method involves a more extensive review of available literature to identify data of more directly applicable materials not presently tabulated in these databases. This requires investigations into source background information to select materials parameters based on specific knowledge of proposed mission-specific conditions and applications and on materials characteristics known for individual studies.

However, selecting appropriate values of $\delta_{\text{max}}$ and $E_{\text{max}}$ from such a thorough literature analysis is often confusing, as data can show a large variation. This is illustrated for representative data from 22 studies of the ubiquitous spacecraft material Al in Figure 1a, which shows SEY curves, and in Table 2, which lists the associated fitting parameters $\delta_{\text{max}}$ and $E_{\text{max}}$, as well as limited details about the materials studied. Many studies have limited ranges of measured energies (see Figure 1a), making it difficult, or impossible, to determine all the fitting parameters for SEY models. As noted above, often, the literature does not provide sufficient details of sample characterization and preparation, experimental methods, or data analysis to properly choose from myriad and often conflicting results. Again, a word of caution is in order to determine the appropriate use of the terms SEY versus total electron yield (TEY), as discussed in Appendix A. These studies of Al illustrate that in reviewing only a selected number of papers, discrepancies can occur.

more oxidized surfaces (Layered bulk MgO has very high $\delta_{\text{max}}$ of from 3 to 15). Values in Table 1 of $\delta_{\text{max}}$ for Ag and Au are both less than 1 and are well below values for smooth, clean elemental surfaces (~1.6 for Ag and 1.4 to 1.8 for Au; Dennison et al., 2016; Joy, 1995, and references therein); these perhaps result from significant carbon-rich contamination layers. The value of $\delta_{\text{max}}$ for Aquadag™ (a rough coating of colloidal microcrystalline graphite) in Table 1 agrees well with other studies of such forms of carbon (Dennison et al., 2007; Joy, 1995) and is lower, as expected, than that of smooth, clean highly oriented pyrolytic graphite graphite (Dennison et al., 2016).

Conductive and nonconductive paint values appear to be derived from the listed values of Kapton™, with only modified conduction properties; conductive paint may be a surrogate for conductive carbon-loaded Black Kapton™ (Dennison et al., 2007). The values listed for solar cell are much more like those of SiO₂ than Si (Joy, 1995; Dennison et al., 2016, and references therein), suggesting that this may be intended to simulate a semiconductor solar cell (of unspecified type) with a thick insulating uncoated SiO₂ coverglass. The composition and thickness of the indium tin oxide coating are not specified; as no information about an underlying substrate is provided, this is presumably bulk indium tin oxide. The fifth entry in this category, SCREEN, is an idealized electron absorbing element with no electron emission, rather than an actual material.
An example of large variations in yield values can be manifest even in careful studies on ostensibly similar samples. As previously mentioned, calibration studies of TEY values for standard elemental materials, Au and graphitic carbon, often used as calibration standards for electron yield instrumentation (Kite, 2007), were performed by groups at Utah State University (USU), Office National d’Etudes et de Recherches Aérospatiales (ONERA), Laboratory of Spacecraft Environment Interaction Engineering (LaSeine), and Consejo Superior de Investigaciones Científicas (CSIC; Dennison et al., 2016). In this round-robin study, where a good agreement for TEY values was expected, significant variations in maximum TEY were found, with values for Au varying from 1.3 to 1.8 and highly oriented pyrolytic graphite varying from 1.3 to 1.5.

Most spacecraft applications are better served by using data for rougher, heavily oxidized surfaces typical of technical materials. Thus, for spacecraft charging models, it is better to select studies of technical Al

| Source                  | Surface | Morality | \( \delta_{\text{max}} \) (keV) | \( E_{\text{max}} \) (keV) | \( n \) | \( m \) | RC1 (Å) | REXP1 (Å) | RC2 (Å) | REXP2 (Å) |
|-------------------------|---------|----------|-------------------------------|---------------------------|------|------|--------|----------|--------|----------|
| Prokopenko (Clean)      | 1980    | X        | 0.97                          | 0.30                      | -    |      | -      | -        | -      | -        |
| Bronstein               | 1969    | X        | 0.66                          | 0.35                      | 0.79 | 1.58 | 0.00   | 0.80     | 1.0    | 1.5      |
| Bruining (Cleaned)      | 1938    | X        | 2.17                          | 0.40                      | 0.56 | 1.27 | 0.51   | 0.42     | 1.0    | 1.28     |
| Kanter (Bulk)           | Kanter, 1961 | X | - | - | - | 0.27 | 0.40 | 1.0 | 1.96 |
| Gibbons (Cleaned)       | 1964    | X        | 0.97                          | 0.30                      | -    |      | -      | -        | -      | -        |
| Bruining                | 1938    | O        | 2.50                          | 0.35                      | -    |      | -      | -        | -      | -        |
| Kanter (Thin Film)      | 1961    | O        | 2.60                          | 0.35                      | -    |      | -      | -        | -      | -        |
| Dennison (Oxidized)     | 2002    | O        | 2.34                          | 0.37                      | 0.69 | 1.79 | 0.04   | 0.90     | 1.0    | 2.25     |
| Gibbons (Oxidized)      | 1964    | O        | 2.50                          | 0.35                      | -    |      | -      | -        | -      | -        |
| Prokopenko (Technical)  | 1980    | O        | 2.60                          | 0.35                      | -    |      | -      | -        | -      | -        |
| Shimizu                 | Shimizu (1974) | R+ | - | - | - | 1.74 | 0.99 | 0.60 | 1.0 | 2.0 |
| Baglin (Heavily oxidized) | 2000 | O | 3.21 | 0.35 | 0.50 | 1.55 | 1.35 | 1.0 | 1.84 |
| Dennison (Technical)    | Dennison et al., (2005) | O | - | - | - | 1.43 | - | - | - |
| Czaja                   | 1966    | O        | 2.04                          | 0.30                      | 0.55 | 1.71 | 1.0    | 0.57     | 1.0    | 1.86     |
| Copeland                | 1938    | O+       | 3.44                          | 0.40                      | 0.62 | 1.86 | 0      | 0.5      | 1.0    | 2.0      |
| Farnsworth              | Farnsworth, 1935 | O+ | - | - | 0.51 | - | - | - | - |
| Warnecke (heated)       | Warnecke, 1936 | O+ | 2.70 | 0.35 | 0.60 | 1.37 | 1 | .40 | 1.0 | 1.6 |
| Warnecke (annealed)     | Warnecke, 1936 | O | - | - | - | 1.25 | 0.39 | 0.62 | 1.42 | 1 | 0.42 | 1.64 |
| Walker, (Cleaned)       | 2008    | O        | 2.04                          | 0.42                      | -    | 1.66 | 0.32   | 0.67     | 1.0    | 1.65     |
| Reimer                  | Reimer & Tollkamp, 1980 | CO | - | - | - | 1.79 | - | - | - |
| Moncrieff               | Moncrieff & Barker, 1978 | CO | R+ | - | - | 1.64 | 0.3 | 0.6 | 1.0 | 1.7 |
| Warnecke (Native)       | Warnecke, 1936 | CO+ | R | 2.75 | 0.35 | 0.59 | 1.35 | - | - | - |
| Walker (Native)         | Walker (Native) | 2008 | CO | ? | - | - | 1.79 | 0.3 | 0.8 | 1.0 | 1.7 |
| Christensen (bulk Al2O3) | 2017 | O++ | 5.00 | 0.60 | 0.40 | 2.09 | 1.5 | 0.56 | 1.0 | 1.95 |

Note. Sources, plotting symbols, and fitting parameters for equation 1 and NASCAP fitting formula are listed. Contamination: X: clean; O: oxidized; C: contaminated; ?: unknown; Morphology: S: smooth; R: rough; ?: unknown. The bold text represents the best fit for specific surface conditions. Abbreviation: SEY: secondary electron yield.
materials—which have SEY curves closer to those of bulk crystalline Al₂O₃ (sapphire; Christensen, 2017), and typically have δ_max values 2 to 2½ times that of smooth, clean elemental Al—from the multitude of data shown in Figure 1 and listed in Table 2. Compare for example two materials reported by Prokopenko and Laframboise (1980), with δ_max values of 0.97 for clean, smooth elemental Al (green dot, Figure 1) and 2.6 for heavily oxidized Al (red dot, Figure 1; Gibbons, 1964). The implications associated with using more appropriate yield values for technical Al, rather than elemental aluminum, were discussed in the previous section. Four representative studies have been identified as most appropriate for technical oxidized rough Al (Dennison et al., 2002), clean, smooth elemental Al (Bruining & De Boer, 1938), highly oxidized Al (Baglin et al., 2000), and bulk crystalline Al₂O₃ (sapphire; Christensen, 2017); these are denoted as the bold solid lines in Figure 1a and the bold entries in Table 2.

2.3. Selecting Materials and Specific Data Based on Mission Specifications and Charging Concerns

As is evident in the sections above, different studies of ostensibly the same material can have a wide range of values for δ_max (see Table 2) and their SEY curves (Figure 1a). While section 2.1 offered some general explanations for trends in δ_max, there was insufficient information to distinguish the results of different studies based on the nature of the materials studied. The likely causes for the SEY variations in the identified studies on Al include the following:

- variations in bulk composition or material preparation;
- surface morphology;
- surface contamination and oxidation;
- net surface charge of the sample; and
- methods of data acquisition and parameterization.

These causes, which are often not stated explicitly in the literature, can sometimes be inferred through careful analysis of the full yield curves using a database of multiple SEY measurements or by consideration of prevailing experimental methods when the data were taken. These causes of SEY variations can be partially understood in analogy to photo-induced electron yields or photoyields; photoyields depend on energy transfer due to the photoelectric effect and other interactions of photons with the materials, resulting in absorption, reflection, and transmission curves as functions of incident photon energy (Dennison et al., 2007; Lai & Tautz, 2006).

Surface morphology can affect SEY, as illustrated in Figure 3a. Rougher surfaces, with features on the (typically sub-micron) scale of electron penetration depths and with higher depth-to-width aspect ratios, enhance the recapture of emitted electrons through surface collisions, thereby lowering SEY (Baglin et al., 2000; Bergeret et al., 1985; Wood et al., 2019). The effects of surface roughness are less for higher energy backscattered electrons, which have a narrower distribution of emission angles than lower energy secondary electrons (SE; Nickles et al., 2000; Reimer, 1985; Wood et al., 2019). By contrast, smooth surfaces minimize recapture by maximizing the solid angle for the escape of emitted electrons without further collisions with the surface. The effects of surface roughness are more pronounced at lower incident energies, where more SEs tend to be generated near the surface. Common methods affecting surface roughness include material preparation, deposition, or formation of high aspect ratio textured or dendritic surfaces, chemical etching, mechanical abrasion, polishing, sputtering, and thermal annealing. Such methods are routinely used to intentionally reduce electron emission from surfaces (Baglin et al., 2000; Bergeret et al., 1985; Montero et al., 2016; Wood et al., 2019).

Surface coatings can also change SEY (Baglin et al., 2000), although their effects on SEY are more nuanced and varied than the effects due to roughness (Wilson, 2019). Coatings of low-Z conducting materials (e.g., C) will typically lower SEY, while high-Z conducting materials (e.g., Au) will typically increase SEY, though thin surface layers can produce complicated incident energy-dependent effects from the underlying
substrate (Wilson, 2019). The presence of absorbed water vapor can significantly increase SEY; for example, for Al or Cu surfaces, condensation of water can greatly enhance yields, while a vacuum bakeout has been shown to reduce this increase (Baglin et al., 2000). Similar changes in yield can be affected by ion bombardment with sputtering or ion glow discharge using various gases, which can act to either increase or decrease the SEY (Baglin et al., 2000).

Two common coating effects considered explicitly here are the formation of oxide layers and carbon-rich contamination layers. In many cases formation of highly insulating oxides (e.g., Al₂O₃ and SiO₂) can significantly increase the elemental material yields. The formation of semiconducting oxides (e.g., Cu₂O) typically acts to reduce yields. Note that the increase in δₘₐₓ as the oxide layer on Al increases for clean, smooth elemental Al (Bruining & De Boer, 1938) to technical oxidized rough Al (Dennison et al., 2002) to highly oxidized Al (Baglin et al., 2000) to bulk crystalline Al₂O₃ (sapphire; Christensen, 2017; see Table 2 and their SEY curves Figure 1a). Also note how the SEY curves of two highly oxidized studies in Figure 1a (Baglin et al., 2000; Copeland, 1935) follow the yield curve for sapphire up to ~350 eV, then deviate and begin to approach less oxidized technical and elemental Al at high energies; this is consistent with the incident electrons reaching sufficient energy to penetrate the oxide layers.

Carbon-rich contamination layers are often formed under electron bombardment; this is a phenomenon well known to electron microscopists (Reimer, 1985). Formation is believed to result from ionization of residual carbon species in the vacuum system (e.g., CO, CO₂, and hydrocarbons) or molecules desorbed from surfaces during electron irradiation, which are then propelled toward the sample surface by the electron beam, and subsequently cracked leaving disordered C-rich surface layers (Andritschky, 1989; Baglin et al., 2000). C-rich surface layers are commonly encountered in SEY studies, from studies in lower vacuum (e.g., scanning electron microscope systems) and systems employing diffusion pumps (e.g., most—but not all—studies done prior to the mid-1960s). C-rich surface layers are similarly present in space applications. Indeed, Caroline Purvis (1995)—one of the central developers of the original NASCAP code—once quipped, “All spacecraft surfaces eventually turn into carbon” via deposition of organic contamination and outgassing.

Net surface charge of a sample—from either an applied bias or accumulated charge—can affect SEY (Hoffmann & Dennison, 2012), as illustrated in Figure 3c. Negatively charged samples (V_{bias} < 0) will repel emitted SE and SEY will be largely unchanged. Positively biased samples (V_{bias} > 0) will reattract low-energy SE, and SEY will decrease. Although this effect is typically not considered in spacecraft charging codes, it is important to recognize that it may well occur in materials studies measuring yields from bulk insulators, nonconductive coatings, or biased samples as these materials are most likely to retain charge (Hoffmann & Dennison, 2012). Olano et al. (2019) describes an interesting system where surface roughness and charging effects of conductor/dielectric composites are evident.

The studies for conducting Al discussed here were all taken at or near room temperature (though specific temperatures were seldom cited). Temperature is not expected to have a large effect on SEY for conducting materials; this has been confirmed by limited studies at studies both above and below room temperature (Nickles, 2002). By contrast, there may be modest temperature effects for SEY in semiconducting and smaller bandgap insulating materials (Grais & Bastawros, 1982; Nickles, 2002) where electron-hole pair creation and recombination can significantly affect carrier concentrations of more weakly bound electrons (Alig & Bloom, 1975), which are most likely to be involved in SE emission (Nickles, 2002); this is also borne out by limited experimental studies (Grais & Bastawros, 1982).

The same data sets shown in Figure 1a are shown in Figure 1b with the yield curves color coded to indicate surface morphology (smooth, rough, and unknown) and surface layers (clean, oxidized, C-rich coatings, and unknown surface layers). The increasing trend in δₘₐₓ with increased thickness of oxide layer noted above becomes much more evident in Figure 1b. Similarly, though to a lesser extent, an increase in E_{max} with increased oxide thickness can also be identified. A novel method for determining material characterization is outlined next, which involves the use of reduced format SEY curves. Figure 1c shows the same Al studies from Figures 1a and 1b, plotted in a reduced format (δ/δₘₐₓ versus E₀/Eₘₐₓ) on log-log axes. This method produces reduced yield curves with a consistent “inverted V” shape, which emphasizes the power-law behavior of the yield curves for the reduced data well above or below E₀ = Eₘₐₓ. The reduced yield curve is modeled with a reduced power-law yield model:
where $E_0$ is the incident energy and $r_o$ is a constant fully determined by $n$, $m$, and $E_{\text{max}}$ (Lundgreen & Dennison, 2019; Wood et al., 2019). This is similar to one of the SEY models employed in SPENVIS (Sims, 1992). The parameters $m$ and $n$ determine the slopes of the log-log plots of SEY well above and below $E_0/E_{\text{max}} = 1$, respectively. Figure 1b emphasizes trends in the parameters $\delta_{\text{max}}$ and $E_{\text{max}}$, whereas the reduced yield curves in Figure 1c emphasize trends in the parameters $n$ and $m$, as $\delta_{\text{max}}$ and $E_{\text{max}}$ have been factored out in the reduced format.

Table 2 lists these four fitting parameters for the 22 Al studies plotted in Figure 1. Bulk smooth Al$_2$O$_3$ (sapphire) is also included as it represents a limiting case for oxidation, as the bulk limit of an infinitely thick fully oxidized aluminum sample (Christensen, 2017). Each study in Table 2 has been characterized in terms of surface morphology as smooth or rough and in terms of surface layers as clean, oxidized, or C-rich contamination. The designations are subjective and are classified as unknown when there was insufficient information given in the source study. The conventions established for the plotting symbols for each study used in Figure 4 based on these designations are shown below Figure 4, as are the line symbols used for Figures 1b and 1c. Figures 4a–4d show plots of these four fitting parameters, using the designated plotting symbols to visualize the relationship between surface conditions and the fitting parameters. Using the results displayed in Figures 1b and 1c and 4a–4d and Table 2, we have attempted to establish correlations between the various yield curves and their surface properties.

**Figure 4.** Plots of the values of the four secondary electron yield fitting parameters used in equation 1 for Al studies listed in Table 2. The three rows of symbols in each plot display values for smooth, rough, and unknown surface layers, respectively. The table below the figures identifies the plotting symbols used in these plots and listed for each specific Al study in Table 2. Filled symbols indicate smooth samples, open symbols indicate rough samples, and lines symbols indicate unknown surface morphology. Green symbols indicate clean samples, red symbols indicate oxidized samples, blue symbols indicate samples with C-rich coatings, and black symbols indicate unknown surface layers. Bulk Al$_2$O$_3$ (sapphire) fits are indicated with purple circles.
Studies of specific samples treated so as to explore a range of oxidation layer thicknesses have established a trend for higher $\delta_{\text{max}}$ for oxidized surfaces (Baglin et al., 2000; Bruining & De Boer, 1938; Chang et al., 2000). The curves displayed in Figure 1b in general confirm this trend, with most oxidized surfaces (red curves) lying between a lower bound for smooth clean Al (green curves) and bulk Al$_2$O$_3$ (purple curve); the same is true for $\delta_{\text{max}}$ values plotted in Figure 4a with clean Al with $\delta_{\text{max}} < 1$ and oxidized Al with $2 < \delta_{\text{max}} < 4$. However, these trends are not as obvious when considering the full SEY curves, most likely as a result of other differences between the various studies including roughness, C-layers, experimental methods, and calibration.

$E_{\text{max}}$ values shown in Figure 4b in general show lower values for clean samples (green symbols) and higher values for rough or oxidized samples (open or red symbols); an approximate boundary occurs at $\sim 0.34$ keV as indicated in Figure 4b. Again, this trend is not as immediately apparent in the yield curves of Figure 1b.

Correlations between the slopes $n$ and $m$ of the reduced yield curves in Figure 1c—where the dependence on $\delta_{\text{max}}$ and $E_{\text{max}}$ have been removed through the use of a reduced form—allow for further distinguishing between sample characteristics. Figure 4c shows that oxidized samples (red symbols) and rough (open symbols) have consistently larger slopes $n$ for SEY below $E_0/E_{\text{max}} = 1$ than smooth samples (solid purple or green symbols; Bronshtein’s low energy slope is anonymously large), with an approximate boundary at $n \sim 0.45$ as indicated on Figure 4c. The curves displayed in Figure 1c corroborate this trend, with all smooth surfaces (solid curves) lying below rougher surfaces (dashed curves).

In Figure 4d $m$ slope values tend to be lower for clean smooth surfaces (solid green symbols) than for rough samples (open symbols). Oxidized samples (red symbols) have $m$ values between clean surfaces (green symbols) and heavily oxidized sapphire (purple symbol). These trends are born out in the order of lines in Figure 1c for $E_0 > E_{\text{max}}$, with oxidized (red) curves falling between clean (green) and heavily oxidized sapphire (purple) curves.

These apparent trends identified above are not entirely consistent, as there are exceptions and complications owing to multiple surface modifications; but, for the most part, the conclusions are supported. In general, the observed trends are consistent with physics-based expectations discussed at the beginning of this section.

### 3. Conclusions and Future Work

Careful selection of appropriate materials SEY data can provide significantly improved modeling of spacecraft charging (Dennison et al., 2007). Skill is required in selecting material studies based upon mission specifications and charging concerns, as they are related to environment and material choices for specific mission requirements. Specifically, for Al, use of values for technical alloys with rough surfaces and thicker oxide layers is most often preferred over values for elemental clean, smooth surfaces for beginning-of-life space simulations and technical Al with thin C-rich contamination is often more appropriate for end-of-life modeling. Thus, utilizing only the default tabulated NASCAP SEY values for Al best suited for clean, smooth elemental Al can often introduce large uncertainties in spacecraft charging models. For this reason, care must be made in selecting specific data sets that are applicable to mission specifications and the charging concern associated with the environment and objectives proposed. The bold denoted data sets in Figure 1a and Table 2 offer three studies of Al SEY that are deemed representative of clean, smooth, elemental Al (Bruining & De Boer, 1938); heavily oxidized, rough Al (Baglin et al., 2000); and technical Al with modest oxidation and unpolished surface as is commonly encountered in typical spacecraft operation (Dennison et al., 2002). Analysis of the data collected for the USU SEY database was critical to determine these best studies.

Trends observed in fitting parameters for numerous reported SEY studies under varying sample conditions can be exploited to the spacecraft modeler’s advantage to identify which experimental studies best match conditions for a specific space mission. This requires knowledge of both the specific mission environments, objectives, and materials, as well as the potential causes of variations in SEY of the materials. This evaluation can identify which studies of similar materials are most applicable to a specific mission and can also provide guidance on the extent of changes expected from environmentally-induced materials surface evolution. For example, many samples will develop an oxide coating (typically 0.001 to 0.1 μm) prior to launch or as they are exposed to atomic oxygen in space, many sample surfaces will develop C-rich contamination layers...
due to outgassing (typically 0.001 to 1 μm), or they will develop some type of roughened surface (roughness on the order of 0.1 to 10 μm) due to mechanical treatment of the material or to environmental effects such as ion-sputtering from the solar wind.

To facilitate this approach to improved materials modeling, a database of multiple SEY studies is being compiled with the capability to sort and identify individual data sources based upon materials characteristics of the various studies. While the database has not yet been made available to the public, work is ongoing with the NASA Engineering and Safety Center to make this resource available to the spacecraft charging community.

Appendix A

A word of clarification on the definition of SEY in the context of spacecraft charging codes is necessary. The electron yield of a material is universally defined as the ratio of emitted electrons per incident electron. This is traditionally separated into two subcategories, SEY and backscattered electron yield (BSEY). From an operational perspective, the separation is made in terms of the energy of the emitted electrons: SEs are emitted with energies <50 eV, while backscattered electrons are emitted with energies >50 eV (Sternglass, 1954). This operational distinction is used in the spacecraft charging community and the NSM charging codes, in scanning electron microscopy literature (Joy, 1995; Reimer, 1985), and numerous other fields. Therefore, this operational definition of SEY is also the one used for data presented in this paper. From an alternate physics perspective, the separation is made in terms of the origin of the emitted electrons: backscattered electrons originate in the incident beam and can undergo one or more quasi-elastic collisions before escaping back out of the surface of the material; alternately, SEs originate in the material, are excited into mobile states by energy deposited by incident electrons, and escape the material. These are sometimes referred to as “true secondary electrons” (Czaja, 1966). Physical models of electron emission—including equation 1 presented in section 2.3—are usually based on this physics perspective.

The sum of BSEY and SEY gives the total number of emitted electrons per incident electron, which is called the TEY. Some researchers use the term “secondary electron yield” (SEY) to mean the same thing as TEY, without differentiating between the two mechanisms, which produce emitted electrons. Most notably this potentially ambiguous use of SEY has been adopted by the European space community as a standard definition (Space Engineering, 2013), even though the models used in SPENVIS make the clear distinction between SEY and BSEY as the two components for the total electron emission (European Space Agency, 2018). This fails to adequately model electron yield and often creates confusion, so it is important to distinguish between the two uses of SEY. Also, some studies of electron yield (e.g., Baglin et al., 2000; Czaja, 1966)—or more commonly, some compilations of electron yield studies—fail to identify whether measured SEY refers to TEY or SEY. For many applications, the difference between TEY and SEY is not critical, as the BSEY yield is usually a modest fraction of the total yield and reasonably constant over intermediate incident energies. However—for more precise studies, for studies emphasizing low incident energies or high incident energies where BSEYs have a smaller or larger contribution, respectively, or for materials where the BSEY contribution is a larger fraction of TEY (e.g., higher atomic number metals)—misidentification of SEY or TEY values can introduce significant error.

References

Alig, R. C., & Bloom, S. (1975). Electron-hole creation energies in semiconductors. Physical Review Letters, 35(22), 1522–1525. https://doi.org/10.1103/physrevlett.35.1522

Andritschky, M. (1989). Damage of oxide layers on an Al-alloy by electron bombardment. Vacuum, 39(7–8), 649–652. https://doi.org/10.1016/0042-207x(89)90008-0

Baglin, V., Bojko, J., Scheuerlein, C., Gröbner, O., Taborelli, M., Henrist, B., & Hilleret, N. (2000). “The secondary electron yield of technical materials and its variation with surface treatments,” Proc. EPAC 2000, Vienna, Austria.

Baroddy, E. (1950). A theory of secondary electron emission from metals. Physics Review, 78(6), 780–787. https://doi.org/10.1103/physrev.78.780

Bedingfield, K. L., Leach, R. D., & Alexander, M. B. (1996). “Spaceship system failures and anomalies attributed to the natural space environment.” NASA Ref. Pub. 1390, NASA MSFC.

Bengtson, M., Hughes, J., & Schaub, H. (2019). Prospects and challenges for touchless sensing of spacecraft electrostatic potential using electrons. IEEE Transactions on Plasma Science, 47(8), 3673–3681. https://doi.org/10.1109/tps.2019.2912057

Bergeret, H., Seipter, A., & Drechsler, M. (1985). Nottingham effect of a superconducting metal. Phys. Rev. B, 31(1), 149–153. https://doi.org/10.1103/physrevb.31.149
Kite, K. (2007).
Lai, S. T. (2010). Importance of surface conditions for spacecraft charging.
Katz, I., Parks, D., Mandell, M. J., Harvey, J. M., & Wang, S. S. (1977). NASCAP, a three-dimensional charging analyzer program for complex spacecraft.
Gibbons, D. I. (1964). Secondary electron emission. In A. H. W. Beck (Ed.), Handbook of vacuum physics—Part I: Electronic properties of materials with application to spacecraft charging, NASA Space Environments and Effects Program as part of the Charge Collector Knowledgebase 1st Ed. http://see.msfc.nasa.gov/ee/db_chargecollector.htm [cited January 10, 2019]
Dennison, J. R., Christensen, J., Dekany, J., Thomson, C., Nickles, N., Davies, R. E., et al. (2016). Absolute electron emission calibration: Round robin tests of Au and polyimide. Proc. 14th Spacecraft Charging Tech. Conf., ESA/ESTEC, Noordwijk, NL.
Dennison, J. R., Friedrichson, A. R., Green, N. W., Benson, C., Brunson, J., & Swan, R. (2006). Materials database of resistivities of spacecraft materials. Final Report, NASA Space Environments and Effects Program, Contract No. NASA-02031, “Measurement of Charge Storage Decay Time and Resistivity of Spacecraft Insulators,” 739 pp.
Dennison, J. R., Hoffmann, R. C., & Abbott, J. (2007). “Triggering threshold spacecraft charging with changes in electron emission from materials,” Paper AIAA-2007-1098, Proc. 45th Am. Inst. Aeronautics and Astronautics Meet. on Aerospace Sci., Reno, NV.
Dennison, J. R., & Lundgreen, P. (2019). “Aluminum secondary electron yield,” Paper 87. available https://digitalcommons.usu.edu/all-datasets/87. https://doi.org/10.26078/897dk79
Droshagen, G. (1994). “List of materials and properties for charging simulations,” as cited in SPENVIS, (2018). http://dev.spis.org/projects/spine/home/tools/data/nasca
European Space Agency (ESA) (2018). “Space Environment Information System (SPENVIS),” URL: https://www.spenvis.oma.be/help/models/equipot.html [cited January 10, 2018].
Farnsworth, H. E. (1925). Electron bombardment of metal surfaces. Physics Review, 25(1), 41–57. https://doi.org/10.1103/physrev.25.41
Feldman, C. (1960). Range of 1 keV electrons in solids. Physical Review, 117(2), 455–459. https://doi.org/10.1103/physrev.117.455
Gibbons, D. I. (1944). Secondary electron emission. In A. H. W. Beck (Ed.), Handbook of vacuum physics—Part III, p. 301. New York: Mcmillan.
Gras, K. I., & Bastawros, A. M. (1982). A study of secondary electron emission insulators and semiconductors. Journal of Applied Physics, 53(7), 5239–5242. https://doi.org/10.1063/1.331403
Hastings, D., & Garrett, H. (1996). Spacecraft-environment interactions (pp. 318), Cambridge, UK: Cambridge University Press.
Hoffmann, R. C., & Dennison, J. R. (2012). Methods to determine total electron emission yields over broad range of conductive and nonconductive materials. IEEE Transactions on Plasma Sci., 40(2), 298–304.
Hughes, J., & Schaub, H. (2018). “Electrostatic tractor analysis using a measured flux model,” Proc. 15th Spacecraft Charging Tech. Conf., Kobe, Japan.
Joy, D. C. (1995). “A database on electron solid interactions.” Scanning 17, 5 270–275. [The complete database, containing tabulations of all available data sets as well as a comprehensive bibliography, can be downloaded as a Microsoft Word document from http://web.utk.edu/srcutk/htm/interact.htm ] (2006.)
Kanter, H. (1961). Contribution of backscattered electrons to secondary electron formation. Physics Review, 121(3), 681–684. https://doi.org/10.1103/physrev.121.681
Katz, I., Mandell, M., Jongeward, G., & Gussenhoven, M. S. (1986). The importance of accurate secondary electron yields in modeling spacecraft charging. Journal of Geophysical Research, 91(A12), 13,739–13,744. https://doi.org/10.1029/ja091ia12p13739
Katz, I., Parks, D., Mandell, M. J., Harvey, J. M., & Wang, S. S. (1977). NASCAP, a three-dimensional charging analyzer program for complex spacecraft. IEEE Transactions on Nuclear Science, 24(6), 2276–2280. https://doi.org/10.1109/tns.1977.4329206
Kite, K. (2007). “Secondary electron production and transport mechanisms by measurement of angle-energy resolved cross sections of secondary and backscattered electron emission,” PhD Dissertation, Utah State Univ., Logan, UT.
Koons, H., Mazur, J., Seleninck, R., Blake, J., & Fennell, J. (1999). “The impact of the space environment on space systems,” Aerospace Corp, El Segundo Technical Operations, El Segundo Ca.
Lai, S. T. (2010). Importance of surface conditions for spacecraft charging. Journal of Spacecraft and Rockets, 47(4), 634–638. https://doi.org/10.2514/1.48824
Lai, S. T. (2011). Fundamentals of spacecraft charging: Spacecraft interactions with space plasma. Princeton Univ. Press. http://ebook-central.proquest.com/lib/social/detail.action?docID=3111693
Lai, S. T., & Tautz, M. (2006). Aspects of spacecraft charging in sunlight. IEEE Transactions on Plasma Sciences, 34(5), 2053–2061. https://doi.org/10.1109/tps.2006.883362
Leach, R.&Alexander, M. (1995). “Failures and anomalies attributed to spacecraft charging,” NASA STI/Recon Technical Report N 96, 11,547.
Lundgreen, P., & Dennison, J. R. (2018). “An analysis of variations in published secondary electron yield measurements of copper,” Fall 2018 Four Corner Section Meeting of the American Physical Society. Paper 76. https://digitalcommons.usu.edu/mp_post/76
