Appendix D
Internal Charging Analyses

See Appendix G for surface charging analyses.

D.1 The Physics of Dielectric Charging

As stated earlier, the computations involved in estimating dielectric charging resemble surface charging calculations with the inclusion of space charge. That is, the basic problem is the calculation of the electric field and charge density in a self-consistent fashion over the volume of interest. In other words, Poisson's equation is solved subject to the continuity equation. The relevant formulas are Poisson's equation (in one dimension):

$$\frac{\partial(\varepsilon(x)E(x,t))}{\partial x} = \rho(x,t) \tag{D.1-1}$$

and the continuity equation (in one dimension):

$$\frac{\partial\rho(x,t)}{\partial t} = -\frac{\partial(J_c(x,t) + J_R(x,t))}{\partial x} \tag{D.1-2}$$

and Ohm's law (for electrons):

$$J_c(x,t) = \sigma(x,t)E(x,t) \tag{D.1-3}$$

These can be combined to give:

$$\frac{\partial(\varepsilon(x)E(x,t))}{\partial t} + \sigma(x,t)E(x,t) = -J_R(x,t) \tag{D.1-4}$$

where:

E = electric field at x for time t

ρ = charge density at x for time t

σ = conductivity in $(\Omega\text{-cm})^{-1} = \sigma_O + \sigma_r$

σ_O = dark conductivity

σ_r = radiation-induced conductivity

ε = $\varepsilon_O\ \varepsilon_r$

ε_O = free-space permittivity = 8.8542×10^{-12} F-m^{-1}

ε_r = relative dielectric constant

J_R = incident particle flux (current density) where $-\partial J_R / \partial x$ = charge deposition rate at x

J_c = particle flux (current density) due to dark conductivity at x

This equation follows from Poisson's equation and current continuity with the total current consisting of the incident current J_R (primary and secondary particles) and a conduction current σE. It is solved at a given time t to give the charge variations in x in the dielectric. The results are then stepped forward in time to compute the time-varying charge and electric field.

A simple solution for this equation assuming σ and J_R are independent of time for a dielectric between two metal plates with an initial imposed field is:

$$E = E_o \exp(-\sigma t/\varepsilon) + (J_R/\sigma)[1 - \exp(-\sigma t/\varepsilon)] \tag{D.1-5}$$

where:

E_o = imposed electric field at t = 0

This is only a crude approximation to reality as geometrical effects, time variations in the conductivity and incident current, and other effects make numerical solution a necessity. It is, however, useful in understanding the time constants ($\tau = \varepsilon/\sigma$) involved in charging the dielectric—as time increases, the initial field E_o dies away tending toward the radiation-induced field given by

J_R/σ with a time constant of τ and $\sigma = \sigma_O + \sigma_r$. Typical values for τ range from ~10 s to 10^3 s for $10^{-16} < \sigma < 10^{-14}$ $(\Omega\text{-m})^{-1}$. Where the dose rate is high (enhancing the radiation conductivity σ_r), the E field comes to equilibrium rapidly. In lightly irradiated regions, where the time constant is long (the dark conductivity σ_o dominates), the field takes a long time to reach equilibrium.

The peak electric field (E_{max}) in the irradiated dielectric has been estimated [1] for radiation with a broad energy distribution to be:

$$E_{max} = (A/k) / (1 + \sigma/kD) \sim (A/k) \qquad \text{(D.1-6)}$$

where:

A = 10^{-8} s-V/Ω-rad-m^2

k = coefficient of radiation induced conductivity in s/m-Ω-rad

D = average dose rate in rad/s

The second approximation follows for high flux conditions [1] when the radiation conductivity σ_r can be approximated by:

$$\sigma_r \sim k\, D^{\delta} \qquad \text{(D.1-7)}$$

where:

σ_r > σ_O for high fluxes

δ ~ 1

The equation is in agreement with analytic solutions when they exist and, for some configurations, more complex numerical solutions. Typical values of k are $10^{-16} < k < 10^{-14}$ for polymers [1]. Inserting the range of values for k, E_{max} varies up to 10^6 to 10^8 V/m, respectively, the range where breakdowns are expected.

This simple analysis demonstrates several important concepts. First, by charging a dielectric surface and measuring how long it takes for the charge to bleed off (in the absence of radiation-induced conductivity (RIC)), one can estimate σ_O from $\sigma_O = \tau\,\varepsilon$, where τ is measured by the experiment. In the presence of radiation, the foregoing demonstrates how the charge can be bled off by the RIC σ_r. The equations imply that σ_r is proportional to dose. Ultimately, these equations can be used to estimate whether the potential will

build up sufficiently in a dielectric to cause arcing—the key issue of concern here.

D.2 Simple Internal Charging Analysis

The following example of a simple and conservative analysis (Table D-1) will be used to estimate the current flux deposited in a dielectric of a spacecraft at GEO. This method of analysis has matched a TIGER internal charging analysis to within 40 percent or better; it provides a good start to determine if there is a level of concern. If the simple analysis indicates that the flux is close to the design limit, then a complete analysis should be used to determine if the criteria is exceeded. In fact, if the simple analysis shows a level of concern, the region in question should probably have its design changed, if possible, or otherwise protected from internal charging. The example determines the flux of electrons in a 10-mil thick layer of Teflon® under a 10-mil thick sheet of aluminum. Figure 2-3 provides mean penetration depth versus energy, and Fig. 2-6 presents fluxes versus energy. Tables 6-1 and 6-2 list material densities.

In this example, the electron charge/flux entering and exiting each layer is calculated; the difference is the electron flux deposited in that layer. For dielectrics, if the deposited current in the layer is >0.2 pA/cm^2, that is considered as a potential concern, and a more exact analysis should be done. The assumed electron environment is the worst-case GEO environment as shown in Fig. 2-6. In Fig. 2-3, 10 mil of aluminum require 250 keV energy electrons to penetrate the aluminum and enter the Teflon®. Teflon® density is 78 percent of aluminum (Table 6-1); therefore, 10 mil of Teflon® is equivalent to 7.8 mil of aluminum. Electrons with greater than 300 keV can penetrate through the 17.8 mil aluminum equivalent and exit the sandwich. Referring to Fig. 2-6, the worst-case flux entering the Teflon® is about 6×10^6 e/cm^2-s-sr while the exiting flux is about 4.5×10^6 e/cm^2-s-sr, leaving a net flux rate of accumulation of 1.5×10^6 e/cm^2-s-sr in the Teflon®. Equivalent normally incident flux is more than the omnidirectional flux. For this simple example covered by 10 mil of aluminum, it is taken to be a factor of three times the omnidirectional flux. Converting to current requires multiplying by 1.602×10^{-19} A/e-s. The net (approximate) result is that the charging rate in the 10-mil layer of Teflon® is 0.72 pA/cm^2.

Table D-1. Simple charging example.

Electron Flux	Penetration Energy	Exiting Integral Flux
(1) Into 10 mil of aluminum	~250 keV	6×10^6 e/cm^2-s-sr
(2) Through 10 mil of Teflon® (equivalent to 7.8 mil of aluminum, total 17.8 mil)	~300 keV	4.5×10^6 e/cm^2-s-sr
(3) The net electron flux in the Teflon® is:	j1 = 6–4.5 × 10^6 e/cm2-s-sr = 1.5×10^6 e/cm^2-s-sr	
(4) Convert to normal incidence flux:	j2 = ~j1 × 3 = $1.5 \times 3 \times 10^6$ e/cm^2-s = 4.5×10^6 e/cm^2-s	
(5) Convert flux to current in the Teflon®:	I = $1.602 \times 10^{-19} \times 4.5 \times 10^6$ = 0.72 pA/cm^2	

According to Fig. 2-5 and Section 3.2.3.2.2, the charging rate in this Teflon® sample exceeds the safe level of 0.1 pA/cm^2. Therefore, this sample is threatened by occasional discharges. More than 10 mil of aluminum shielding equivalent are required on top of this sample to reduce the charging rate in the Teflon® layer to less than 0.1 pA/cm^2.

Note: The analysis in this section uses deposited flux of 0.1 pA/cm^2 as a criterion rather than incident flux of 0.1 pA/cm^2 as used throughout the rest of this document. This is less conservative than the incident flux criterion. A flux of 0.1 pA/cm^2 in 10 hr accumulates 2×10^{14} e/m^2 in 10 hour, which will create an electric field of 2×10^6 V/m ($\varepsilon_r = 2$) if all electrons stop in the material in accordance with the criterion used in this paragraph. Assuming an incident flux of 0.1 pA/cm^2 will be more conservative because not all electrons will be stopped in the material. The latter assumption is the better one unless the dielectric strength of the material in question is known to be high as in this example for Teflon®. See [2] which challenges the 10-hour accumulation time for highly resistive materials.

D.3 Detailed Analysis

A proper analysis should be performed using the models and tools listed in Appendices B and C to determine charge deposition rates (fluxes and fluences). The analysis should determine if sufficient charge exists for breakdown (ESDs).

Detailed formulations, e.g., NUMIT and DICTAT, have been developed for determining the development of electric fields in irradiated insulators. In the end, for good insulators at high fluxes, the electric field builds up to and stabilizes at 10^5 and rarely to 10^6 V/cm (10^7–10^8 V/m).

The conductivity of the material is a critical parameter to assess breakdown fields and generally is not known well enough to provide meaningful calculations. For proper answers, one should know the conductivity under irradiation, temperature, and vacuum to perform a meaningful detailed analysis. Even then, predicting pulse amplitudes and rates is only a guess.

As a matter of comparison, a computer code was used to replicate the previous simple example. The results were that the electron flux in the Teflon® was computed to be about 40 percent of the result from the simple analysis. This shows that, for the test case, the simple analysis was conservative by a factor of 2.5. Although shown to be conservative as calculated for the case shown in Appendix D.2, the simple analysis should always be treated with some suspicion.

Note: TIGER calculations have demonstrated that tantalum reflects some electrons at the surface and thus the simple calculations above will lead to higher deposited electron fluences than in the actual case (our one example had double the fluence of the TIGER-calculated case). Other physics effects may also be present. Fortunately this phenomenon does not happen for aluminum.

D.4 Spacecraft Level Analysis

A spacecraft level of analysis is used to predict the current density (flux) within the spacecraft interior. It can use radiation analysis tools modified as required to accomplish the task. Conventional radiation analyses inside a spacecraft use transport codes to carry out 3-D tracking of energetic particles through the spacecraft walls to a specific target. The output of these codes is the radiation dose as a function of a detector material (usually Si). Several computer codes that use electron spectra and spacecraft geometry as inputs can also be used to determine internal fluxes or radiation dose at specific sites (Appendix C). This is first done with only the walls and shelves in place. Once the isoflux contours are determined, the flux levels are compared to the critical flux level. If the predicted levels exceed the critical levels, then a box-level analysis is conducted. If the flux level inside the box still exceeds the critical flux level, then additional shielding should be considered.

The criterion to be used for IESD is that the current (flux) should be less than 0.1 pA/cm^2 for any period of 10 hr. If this criterion is satisfied, there should be few problems with internal charging.

D.4.1 Dose-to-Fluence Approximation

To determine an approximate electron flux/fluence from a radiation transport code, a simple equivalence from dose (rad-Si) to electron fluence can be used if the dose has been already calculated or if it is easier to calculate dose. Dose and fluence are related by the equation[3,4]:

$$\text{Fluence (e/cm}^2) = 2.4 \times 10^7 \times \text{Dose (rad-Si)} \qquad \text{(D.4-1)}$$

Although the actual conversion factor varies with energy, this equation is valid for electron energies from ~0.2 to 30 MeV. This is adequate for most internal charging assessments based on typical space environments and can be used for lower energies without loss of "back-of-the-envelope" accuracy already inherent in this method.

As the results from this simple conversion are typically conservative (it predicts greater electron fluence than actually exists), its use would lead to a conservative design and hence greater cost. Coakley [5], for example, says that a 416-krad dose is equivalent to 2×10^{13} e/cm^2 fluence, or fluence (e/cm^2) = $5 \times 10^7 \times$ dose (rad-Si). This is within a factor of two of Eq. (D.4-1).

References

[1] A. R. Frederickson, D. B. Cotts, J. A. Wall, and F. L. Bouquet, *Spacecraft Dielectric Material Properties and Spacecraft Charging*, *AIAA Progress in Astronautics and Aeronautics*, vol. 107, American Institute of Aeronautics and Astronautics, Washington, District of Columbia, 1986. Contains dielectric properties data, especially relating to spacecraft charging. Worth obtaining and reading.

[2] M. Bodeau, "High Energy Electron Climatology that Supports Deep Charging Risk Assessment in GEO," AIAA 2010-1608, *The 48th AIAA Aerospace Sciences Meeting*, Orlando, Florida, 2010. A fine work with good concepts, explained and illustrated with actual space data, and estimates of fluence accumulation versus material resistivity. Bodeau challenges the 0.1 pA/cm^2 and 10 hr flux integration guidelines.

[3] E. P. Wenaas, M. J. Treadaway, T. M. Flanagan, C. E. Mallon, and R. Denson, "High-Energy Electron-Induced Discharges in Printed Circuit

Boards," *IEEE Transactions on Nuclear Science,* vol. NS-26, no. 6, pp. 5152–5155, 1979.

[4] J. W. Haffner, G. Gigas, J. E. Bell, D. T. Butcher, R. A. Kjar, C. T. Kleiner, and G. C. Messenger, *The Effects of Radiation on the Outer Planets Grand Tour*, SD 71-770, NASA-CR-127065, Jet Propulsion Laboratory, Pasadena, California, 316 pages, November 1971.

[5] P. Coakley, *Assessment of Internal ECEMP with Emphasis for Producing Interim Design Guidelines*, *JAYCOR Report*, AFWL-TN-86-28, Air Force Weapons Laboratory, at Kirtland Air Force Base, New Mexico, June 1987.