Bulk Charging of Dielectrics in Cryogenic Space Environments

J.I. Minow¹, V.N. Coffey¹, W.C. Blackwell², Jr., L.N. Parker³, I. Jun¹, and H.B. Garrett³

¹NASA, Marshall Space Flight Center, Huntsville, AL 35812
²Jacobs Engineering, ESTS Group, Huntsville, AL 35812
³The Jet Propulsion Laboratory, The California Institute of Technology, Pasadena, CA 91109

35 Word Abstract

We use a 1-D bulk charging model to evaluate dielectric charging at cryogenic temperatures relevant to space systems using passive cooling to <100K or extended operations in permanently dark lunar craters and the lunar night.

Corresponding (and presenting) Author:

Joseph I. Minow, NASA, Marshall Space Flight Center, EV13/Natural Environments Branch, Spacecraft and Vehicle Systems Department, Huntsville, AL 35812 (USA), phone: 256-544-2850, fax, 256-544-0242, e-mail: joseph.i.minow@nasa.gov

Contributing Authors:

Victoria N. Coffey, NASA, Marshall Space Flight Center, EV13/Natural Environments Branch, Spacecraft and Vehicle Systems Department, Huntsville, AL 35812 (USA), phone: 256-961-7635, fax, 256-544-7216, e-mail: victoria.n.coffey@nasa.gov

William C. Blackwell, Jr., Jacobs Engineering, ESTS Group, Marshall Space Flight Center, Huntsville, AL 35812 (USA) phone: 256-544-6741, fax, 256-544-0242, e-mail: william.c.blackwell@nasa.gov

Linda N. Parker, Jacobs Engineering, ESTS Group, Marshall Space Flight Center, Huntsville, AL 35812 (USA) phone: 256-544-5313, fax, 256-544-0242, e-mail: linda.n.parker@nasa.gov

Insoo Jun, The Jet Propulsion Laboratory, The California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California, 91109, USA phone: 818-354-7107, fax, 818-393-4699, e-mail: insoo.jun@jpl.nasa.gov

Henry B. Garrett, The Jet Propulsion Laboratory, The California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California, 91109, USA phone: 818-354-2644, fax, 818-393-4699, e-mail: henry.garrett@jpl.nasa.gov

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INTRODUCTION

Internal electrostatic discharges (IESD) originating in dielectric materials charged during exposure to the space radiation environment accounts for over half of the anomalies and failures of spacecraft and space systems that have been attributed to the space environment [1]. Charge accumulation is particularly important at cryogenic temperatures because the electrical conductivity $\sigma$ for semiconductors and insulating materials generally exhibits a $\sim 1/T^N$ temperature dependence where $N$ depends on the material and physical mechanism for electrical conductivity (which varies with temperature). The reduced conductivity at low temperatures greatly limits current flow from the charged dielectric allowing charge densities to accumulate for longer periods of time. This effect increases the risk of dielectric breakdown and IESD due to the enhanced electric fields generated by the buried charge.

Space systems operating at cryogenic temperatures are found in a number of applications [2]. One example is infrared and microwave astronomy missions because low operating temperatures reduce the background of long wavelength photons and increase the sensitivity of infrared and microwave sensors. Passive cooling to ~70K is currently used by the Wilkerson Microwave Anisotropy Prove spacecraft in orbit about the Sun-Earth L2 point and will also be used to cool the instrument systems on the James Webb Space Telescope to ~40K (also bound for L2). Passive cooling technologies represent a particular threat to charging because the requirement that systems be exposed to the cold background of space to achieve low operating temperatures also means they are exposed to the space radiation environment responsible for charging. Cold environments will also be encountered in future lunar exploration where lunar night time temperatures of approximately 85K are observed immediately before sunrise [3,4] and temperatures as low as 40K to 50K will be encountered in the permanently dark craters at the lunar poles [5,6,7]. Radiation environments at lunar and L2 distances are generally considered relatively benign compared to the extreme bulk charging environments within the Earths radiation belts. However, evaluation of bulk charging is an important step in the design and qualification of space systems. This is particularly true for systems at cryogenic temperatures because of the potential threat of enhanced charging due to the reduced conductivity of insulating materials at cold temperatures.

We first describe a bulk charging model developed for evaluating electrostatic discharge risk in insulating materials exposed to radiation environments. We use the model to evaluate the electric fields generated in cold insulators exposed to interplanetary radiation environments applicable for both the earth-sun L2 and lunar destinations. The model results are used as a screening tool; demonstrating the order of magnitude charging risks anticipated for standard aerospace insulating materials at both ambient and cold conditions.

BULK CHARGING MODEL AND SIMULATION RESULTS

The 1-dimensional bulk charging model is a modified version of the NUMIT (for "numerical integration") code originally developed by the late Dr. Robb Frederickson [8,9] using the radiation induced conductivity approach [10] for solving the charging equations

$$\nabla \cdot E = \frac{\rho}{\varepsilon}$$  \hspace{1cm} (1)

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (J_R + J_C)$$  \hspace{1cm} (2)

where $\rho$ is the charge density, $E$ the electric field, $J_R$ and $J_C$ the incident radiation current density and conduction currents, respectively, and the dielectric permittivity $\varepsilon$ is related to the permittivity in free space $\varepsilon_0$ and dielectric constant $\kappa$ through the relationship $\varepsilon = \kappa \varepsilon_0$. Conduction currents are defined as
\[ J_C = \sigma E = \left( \sigma_{\text{dark}} + K \left( \frac{dy}{dt} \right)^\alpha \right) E \]

where the bulk conductivity \( \sigma \) is divided into two terms: the \( \sigma_{\text{dark}} \) conductivity in the absence of exposure to radiation and a radiation induced conductivity (RIC) term which depends on the dose rate \( \frac{dy}{dt} \) and material dependent conductivity coefficient \( K \) and exponent \( \alpha \). Material electrical properties which are temperature dependent include \( \sigma, \kappa \), and to a lesser extent the RIC parameters \( K \) and \( \alpha \).

NUMIT solves equations (1) to (3) numerically yielding self-consistent solutions for the electric fields generated by the charge density deposited in insulating materials exposed to the space radiation environment. We have modified NUMIT to extend the original fixed radiation current and mono-energetic electron energy input to allow for reading a time series of electron flux data from spacecraft measurements. In addition, options for electron flux input to the model includes use of mono-energetic flux from individual energy channels as well as spectral fits to extend the spectra to arbitrary energies or use of a complete spectrum. The mono-energetic flux option is used for its simplicity in the examples given here. Radiation current inputs are derived from ~9.13 years of 245 keV electron flux measurements at L1 by the Deflected Electrons (DE) detector component of the Energetic, Proton, and Alpha Monitor (EPAM) instrument on board the Advanced Composition Explorer (ACE) spacecraft. Transport of the radiation environment into the dielectric material required to obtain the charge deposition and dose rates are accomplished using look-up tables for dose as a function of depth [11,12]. This method provides a computationally efficient method for updating dose rates and charge deposition at each simulation time step.

We adopt the representative electrical parameters given in Table 1. Dielectric conductivity at cryogenic temperatures (T<100K) compared to values at ambient temperatures (T~300K) suggest conductivity ratios for polymers of interest to aerospace applications are \( \sigma_B(T<100K)/\sigma_B(T~300K) \sim 10^{-2} \) to \( 10^5 \) [13,14] and the dielectric constants increase over the same temperature range by factors of \( K_{T<100K}/K_{T~300K} \sim 1 \) to 2 [15,16,17,14].

<table>
<thead>
<tr>
<th>Property</th>
<th>300K</th>
<th>100K</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma )</td>
<td>1.00x10^{-16} S/m</td>
<td>1.00x10^{-19} S/m</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>3.71</td>
<td>7.42</td>
</tr>
<tr>
<td>( K )</td>
<td>2.76x10^{-16} S/m</td>
<td>2.76x10^{-16} S/m</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Output from NUMIT for T~300K conditions is shown in Figure 1. Electric field magnitude and charge density as a function of depth in the insulator is given in the top two panels. Electron current density (blue) of the 139 keV charging electron beam (black) is given in the third panel. The bottom panel is the maximum (black) and minimum (blue) electric field extracted from the results in the top panel. The orange and red lines provide guidance on the approximate nominal and extreme electric fields, respectively, where dielectric failure may occur based on \( \sim1x10^8 \) V/m dielectric strengths (red) reported in the literature for many polymers [18] and a more conservative \( \sim1x10^7 \) V/m value (orange) suggested for use in space applications [19]. In this example we demonstrate that exposure to 139 keV electrons at T~300K may charge the material to values approaching the lower breakdown strength but never exceeding critical values for dielectric failure. Charge densities and electric fields within the material are elevated only when directly exposed to the high flux events and the electric fields rapidly decay with time constants on the order of days when the electron flux decreases to background values.

Charging results for the T~100K electrical properties from Table 1 are given in Figure 2. Reducing the conductivity and increasing the dielectric constant to values appropriate for cryogenic conditions increases the charging time constant (\( \tau \sim \kappa \varepsilon_0 / \sigma \)) to such a large value that the dielectric integrates charge over the complete exposure period and electric fields approach the breakdown strengths of polymers in environments generally considered relatively benign for bulk charging.
Figure 1. NUMIT T ~ 300K Results. A ~0.23 mm thick dielectric is exposed to 245 keV electrons for ~9.13 years with only moderate charging results during the high electron flux events.

Figure 2. NUMIT T ~ 100K Results. Conductivity and dielectric constants are modified to the T-100K values in Table 1 with more extreme charging due to the greater charging time constants at lower temperatures. Equilibrium electric fields are still less than breakdown in this example.

CONCLUSIONS

We have described an application of the NUMIT 1-dimensional bulk charging model for evaluating radiation charging of dielectric materials in space environments. Novel features of the modified version
of the NUMIT model include the capability of reading long (~years) electron flux time series for use in screening environments for potential risk of electrostatic discharge when dielectric materials are exposed to the radiation environment at both ambient and cryogenic temperatures. The model facilitates bulk charging evaluations for spacecraft design and operations support as well as anomaly analyses when appropriate environment data is available. In addition, the model provides a useful tool for evaluation of total radiation dose, dose rate, and electric field effects. This information can be used to define parameters for incident electron beams in laboratory test protocols for the qualification of materials for space environments.

REFERENCES

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NASA, Marshall Space Flight Center, Huntsville, AL 35812
Jacobs Engineering, ESTS Group, Huntsville, AL 35812

The Jet Propulsion Laboratory, The California Institute of Technology, Pasadena, CA 91109

Abstract

The SURF model, which simulates bulk charging effects in dielectric materials, has been adapted to simulate charging in cryogenic space environments. This model takes into account the unique properties of dielectric materials at low temperatures, including their ability to store and release electrical charges. The model can be used to predict charging effects in dielectric materials used in spacecraft components, which is crucial for preventing electrical discharge events that can damage sensitive electronics.

Background

Spacecraft systems operating at cryogenic temperatures are subject to a variety of challenges, including the charging of dielectric materials. These materials can store and release electrical charges, which can cause problems such as electrical discharge events. The SURF model has been adapted to simulate charging effects in cryogenic space environments for a more accurate prediction of these effects.

Example Materials Properties as a Function of Temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (ω)</th>
<th>Effective Medium</th>
<th>Dielectric Constant</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene</td>
<td>10^-12 S/m</td>
<td>1000</td>
<td>2</td>
<td>200</td>
</tr>
<tr>
<td>Polyamide 66</td>
<td>10^-12 S/m</td>
<td>2000</td>
<td>2.5</td>
<td>200</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>10^-12 S/m</td>
<td>1500</td>
<td>2.2</td>
<td>200</td>
</tr>
</tbody>
</table>

Temperature Dependent Bulk Charging Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductivity</td>
<td>10^-12 S/m</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>3</td>
</tr>
<tr>
<td>Time constants</td>
<td>10^-6 to 1 second</td>
</tr>
</tbody>
</table>

The model takes into account the unique properties of dielectric materials at low temperatures, including their ability to store and release electrical charges. This is crucial for predicting charging effects in cryogenic space environments for spacecraft components.

Conclusion

The adapted SURF model can be used to simulate charging effects in cryogenic space environments, which is crucial for predicting and mitigating electrical discharge events that can damage sensitive electronics.

Animal

Charging Physics and Model

Debye-Screened Geometry

Potential

A thin layer of material can be modeled as a Debye-Screened Geometry, where the potential at a distance r from a charged material is given by the equation:

$$ V(r) = \frac{Q}{4\pi\varepsilon_0 r} \left[1 - \frac{1}{\sqrt{1 + a^2 r^2}}\right] $$

where a is a characteristic length scale of the charge distribution.

Temperature Dependent Conductivity Models

Simple...when only limited information is available

- Select a low value for parameters that are not of interest
- Assume a fixed value for parameters that are independent of temperature

$$ \sigma(T) = \sigma_0 \left[1 + \alpha (T - T_0)\right] $$

However, it is difficult to extrapolate electrical properties to cryogenic temperatures based on limited or no data at ambient temperatures.

Better...use well-characterized materials including electrical properties measured over a range of temperatures

Example, low density polyethylene

$$ \sigma(T) = \sigma_0 \left[1 + \alpha (T - T_0)\right] $$

where $\sigma_0$ is the conductivity at room temperature, $\alpha$ is the temperature coefficient, and $T_0$ is the reference temperature.
ACE Interplanetary Environments

ACE EPAM data provide L1 bow shock environments that can be used to validate charging for L1, L2, and lunar environments.

DE
LEMS
LEPS

Limited ACE/EPAM electron energies

DE1 38 - 53 keV
DE2 53 - 103
DE3 103 - 175
DE4 175 - 315

Power law representation of DE electron flux allows extrapolation to lower energies required for bulk charging analysis.

Exposure to ACE L1 environments are not generally considered a threat to bulk charging due to relatively low electron flux in interplanetary space compared to rotation test environments.


d(\gamma) = \sigma T \gamma \ln(\gamma)

\gamma = a_0 + a_1 \ln(T)

\sigma = \sigma_0 \ln(T)

Conductivity Models

Model 1

Model 2

Conductivity Model 1

Conductivity Model 2

Cryogenic Charging in Environments Relevant to L1, L2

Summary

- Reduced conductivity of insulating materials at low temperatures result in long charge integration periods.
- Low conductivity materials may be used if necessary if it can be shown that the maximum charge accumulation results in electric fields less than the breakdown strength of the material.
- Bulk charging models require values of \(a_0, k, x\) over the complete range of temperatures that will be encountered by the material to accurately assess the threat of dielectric breakdown. Laboratory measurements of these values are critical for quantitative bulk charging assessments at cryogenic temperatures.

References