Bulk Charging of Dielectrics in Cryogenic Space Environments

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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.

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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 σ for semiconductors and insulating materials generally exhibits a ~ $1/T^N$ 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

$$\nabla \bullet E = \rho/\varepsilon \tag{1}$$

$$\frac{\partial \rho}{\partial t} = -\nabla \bullet \left(J_R + J_C\right) \tag{2}$$

where ρ 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 ε is related to the permittivity in free space ε_0 and dielectric constant κ through the relationship $\varepsilon = \kappa\varepsilon_0$. Conduction currents are defined as

$$J_C = \sigma E = \left(\sigma_{dark} + K\left(\frac{d\gamma}{dt}\right)^{\alpha}\right)E \tag{3}$$

where the bulk conductivity σ is divided into two terms: the σ_{dark} conductivity in the absence of exposure to radiation and a radiation induced conductivity (RIC) term which depends on the dose rate $d\gamma/dt$ and material dependent conductivity coefficient K and exponent α. Material electrical properties which are temperature dependent include σ, κ, and to a lesser extent the RIC parameters K and α.

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 $\sigma_B(T\leq100K)/\sigma_B(T\sim300K) \sim 10^{-2}$ to 10^{-5} [13,14] and the dielectric constants increase over the same temperature range by factors of $K_{T\leq100K}/K_{T\sim300K} \sim 1$ to 2 [15,16,17,14].

Table 1. Dielectric Electrical Properties

Property	300K	100K
σ	1.00×10^{-16} S/m	1.00×10^{-19} S/m
κ	3.71	7.42
K	2.76×10^{-16} S/m	2.76×10^{-16} S/m
α	1.00	1.00

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 ~~1x10^8 V/m dielectric strengths (red) reported in the literature for many polymers [18] and a more conservative ~1x10^7 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 ($\tau \sim \kappa\varepsilon_o/\sigma$) 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.

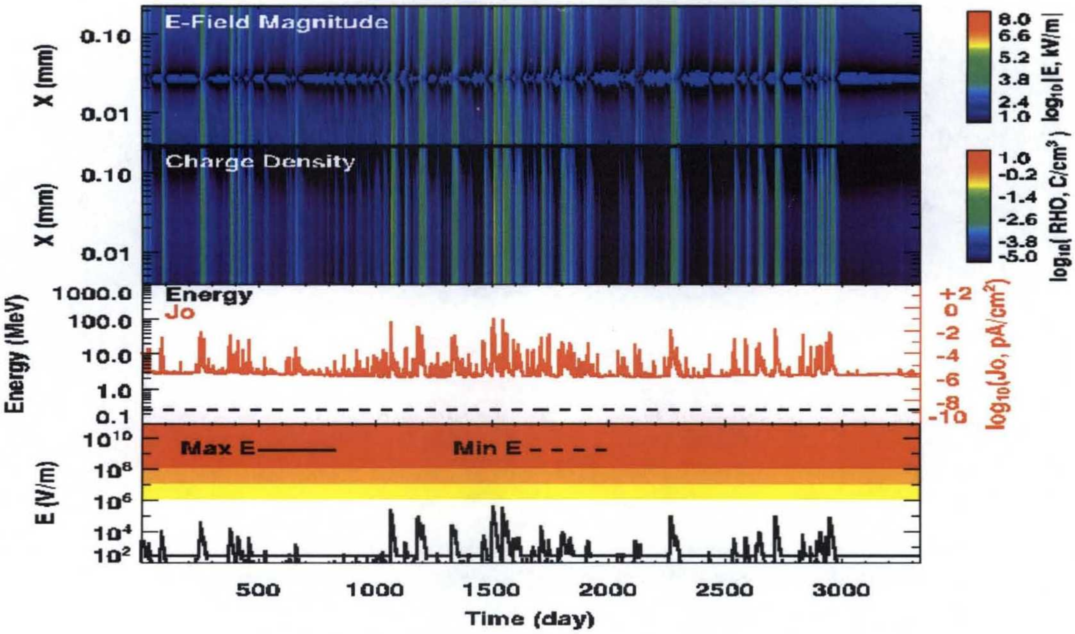

Figure 1. NUMIT T ~ 300K Results. A ~0.23 mm thick dielectric is exposed to 245 keV electrons for ~9.13 years with only moderate charging results during the high electron flux events.

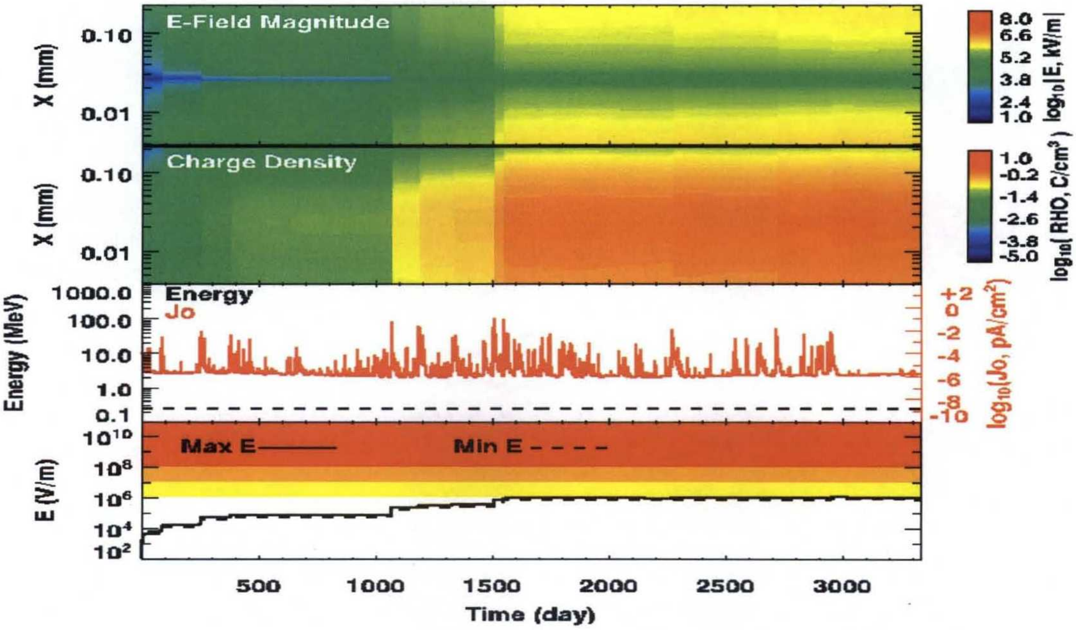

Figure 2. NUMIT T ~ 100K Results. Conductivity and dielectric constants are modified to the T~100K values in Table 1 with more extreme charging due to the greater charging time constants at lower temperatures. Equilibrium electric fields are still less than breakdown in this example.

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.

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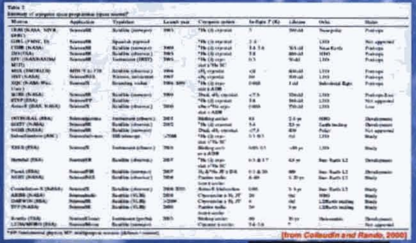
Abstract

The NUMIT ("numerical integration") 1-D bulk charging model [*Frederickson*, 1974, 1977, 1980, 1996; *Frederickson et al.*, 1992, 1992, 1996; *Frederickson and Brautigam*, 2004] is used 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. 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 [*Koons et al.*, 2000]. Charge accumulation is particularly important at cryogenic temperatures because the electrical conductivity σ for semiconductors and insulating materials generally exhibits a ~ $1/T^N$ 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.

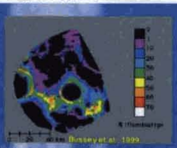
Background

Space systems operating at cryogenic temperatures are found in a number of applications [*Collaudin and Rando*, 2000]. 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 [*Mendell and Low*, 1974; *Vaniman et al.*, 1991] and temperatures as low as 40K to 50K will be encountered in the permanently dark craters at the lunar poles [*Ingersoll et al.*, 1992; *Vasavada et al.*, 1999; *Bussey et al.*, 2003]. 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.

Cryogenic Space Systems and Environments

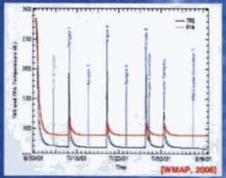


[from Collaudin and Rando, 2000]



Bussey et al., 1999

Lunar south pole mean T~210K
Lunar night, equator T_{min} ~90K
Permanently dark polar craters T ~ 40K
Infra-red observatories T~40K to 70K

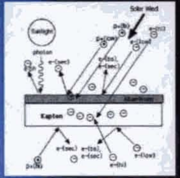


[WMAP, 2006]

Charging Physics and Model

Physics

$$\nabla \bullet D = \rho$$
$$D = \varepsilon E, \quad \varepsilon = \kappa\varepsilon_0$$
$$\frac{\partial \rho}{\partial t} = -\nabla \bullet J$$
$$J = J_R + J_C = J_R + \sigma E$$
$$= J_R + [\sigma_{dark} + \sigma_{radiation}]E$$
$$\sigma_{radiation} = k\left(\frac{d\gamma}{dt}\right)^{\alpha} \quad 0.5 < \alpha < 1.0$$



1-D Charging Model Geometry

–Planar geometry
–front, back of insulator grounded
–front electrode infinitely thin (no effect on radiation flux, energy)

Temperature dependent electrical conductivity models

ionic

$$\sigma(T) = \sum_i q_i n_i \mu_i$$

variable range hopping

$$\sigma(T) = \frac{A}{kT}\exp\left(-E_A/kT\right)$$

electric field dependence

$$\sigma(E,T) = \frac{A}{kT}\exp\left(-E_A/kT\right)\left[\frac{2+\cosh(\beta_F E^{1/2}/2kT)}{3}\right]\left[\frac{2kT}{eE\delta}\sinh\left(\frac{eE\delta}{2kT}\right)\right]$$

Temperature Dependent Bulk Charging Parameters

Conductivity (=1/resistivity)	$\sigma_{dark} = 1/\rho$
RIC parameters	k,x
Dielectric constant (relative permitivity)	κ, $\varepsilon = \kappa\varepsilon_0$
Electric (breakdown) strength	E_{BD}
Capacitance	κ, ε
Time constants	$\tau = \varepsilon/\sigma = \kappa\varepsilon_0/\sigma$

Time constants are important!

$\tau = \varepsilon/\sigma = \kappa\varepsilon_0/\sigma$ typical values are 10^{1} to $10^{[illegible]}$ second

Example, consider an insulator with κ~4:

Warm	τ ~ (4)(8.85x10-12 F/m)/(10-12 S/m) ~ 35 seconds
Cold	τ ~ (4)(8.85x10-12 F/m)/(10-14 S/m) ~ 3540 seconds
Cryogenic	τ ~ (4)(8.85x10-12 F/m)/(10-18 S/m) ~ 1.1 year

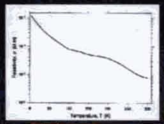
Electrical properties at low temperatures (≤77 K to 100K) are difficult to locate in literature for many materials

- Parameters may not be measured with techniques appropriate for space environments
  - –Conductivity needs to be measured with charge storage methods, not ASTM techniques [c.f., *Fredrickson*, 2003; *Swaminathan et al.*, 2004
- Inappropriate geometry
  - –Dielectric (electric breakdown) strength is thickness dependent for thin films

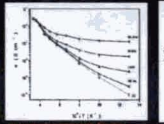
Material electrical properties need to be measured in vacuum, at operating temperature, and in as close to operational configuration as possible

Example Materials Properties as Function of Temperature

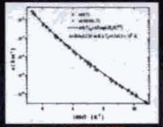
Bulk resistivity (=1/conductivity)



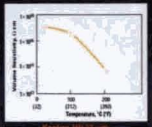
Polyester varnish
Gerhold, 1998



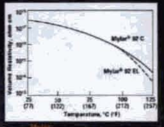
polypyrrole composite Aguilar-Hernandez, 2001



Capaccioli et al., 1998

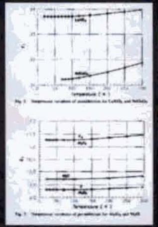


Kapton HN 25 um
Dupont, 2006a



Mylar
Dupont, 2006b

Dielectric Constant



Al_2O_3, MgO
Krupka et al., 1994

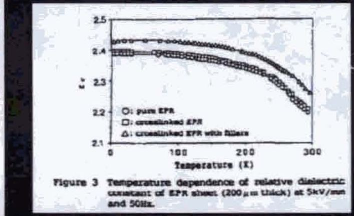
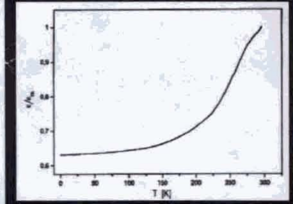


Figure 3 Temperature dependence of relative dielectric constant of EPR sheet (200 μm thick) at 5kV/mm and 50Hz.

Ethylene-propylene rubber
Mizuno et al., 1999



Stycast (unfilled epoxy)
Barucci et al., 1999

Electrical properties of many materials have been measured and are available in literature. However, it is important to determine whether the measurement techniques are relevant to space environments.

Temperature Dependent Conductivity Models

Simple.......when only limited information is available

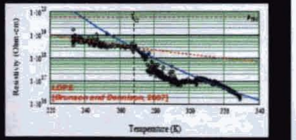
- adjust σ_{dark} to value appropriate for temperature of interest
- assume typical k, x values are independent of temperature
  k ~ 10-15 S-sec/cm-rad for many polymers [Frederickson et al., date]
  x ~ 1

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

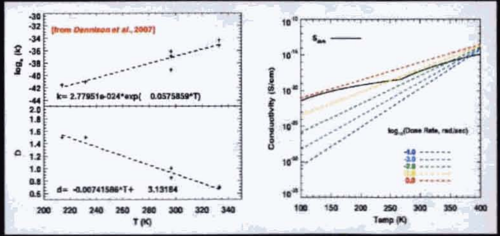
Better....... use well characterized materials including electrical properties measured over a range of temperatures

Example, low density polyethylene

$$\sigma(T) = \sigma_0\left[h_1(T)e^{T_1/T} + h2(T)e^{T_2/T_{VRH}}\right]^{-1} + k_0 e^{-\alpha T}\left[\frac{dD}{dt}\right]^{-\beta T + \delta}$$



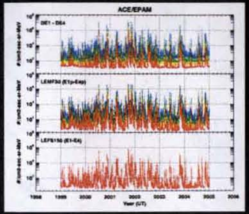
$\sigma_0 = 2\times10^{-8}$ S/cm γ1 = 6620K γ2 = 100K



ACE Interplanetary Environments

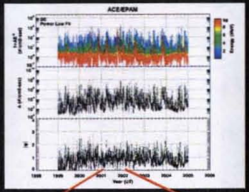
ACE EPAM data provides L1 solar wind environments that can be used to evaluate charging for L1, L2, and lunar environments

DE Electron Deflection
LEMS Low Energy Magnetic Spectrometer
LEFS Low Energy Foil Spectrometer

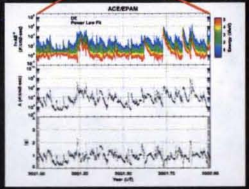


Limited ACE/EPAM electron energies

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



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



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

Cryogenic Charging in Environments Relevant to L1, L2

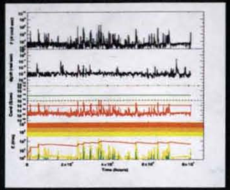
Case	σ (S/cm)	κ	kp	x
1	10^{-14}	4	10^{-15}	1.0
2	10^{-16}	4	10^{-15}	1.0
3	10^{-18}	4	10^{-15}	1.0

Conductivity Model 1

1 year = 8760 hours

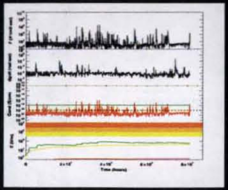
10 years = 87600 hours

30 years = 2.6e5 hours



Case	σ (S/cm)	κ	kp	x
1	10^{-18}	8	10^{-15}	1.0
2	10^{-20}	8	10^{-15}	1.0
3	10^{-22}	8	10^{-15}	1.0

Conductivity Model 1



Examples of bulk charging results using selected dark conductivity, RIC parameters.

Conductivity Models

Model 1

$$\sigma(T) = \sigma_0 + k_0\left[\frac{dD}{dt}\right]^x$$

Model 2

$$\sigma(T) = \sigma_0\left[h_1(T)e^{\gamma_1/T} + h2(T)e^{\gamma_2/T^{0.25}}\right]^{-1} + k_0e^{-\alpha T}\left[\frac{dD}{dt}\right]^{-\beta T+\delta}$$

$\sigma 0 = 2\times10^{-9}$ S/m $\gamma 1 = 6620.$ $\gamma 2 = 100.$

H1(T) = 1 for T≥298 K =0 for T<298 K

H2(T) = 0 for T≥298 K =1 for T<298 K

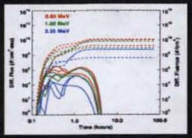
k_0 = 2.28x10-24 S-sec/cm-rad

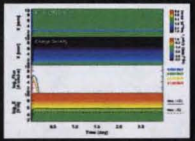
$\alpha = 0.0576\ K^{-1}$

β= -0.00742 δ= 3.132

Radiation Belt Transits

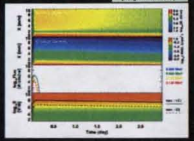
epoxy-fiberglass
$k_p \sim 0$
[Rodgers et al., 2003]





--30 deg inc
--AE-8 max
1x L ≥ 2

Material 3
σ ~ 10^{-19} S/m
τ ~ 31 days

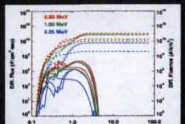


--30 deg inc
--AE-8 max
1x L ≥ 2

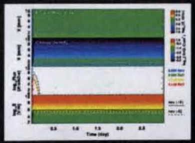
Material 4
σ ~ 10^{-18} S/m
τ ~ 50 hours

Conductivity Model 1

epoxy-fiberglass
$k_p \sim 0$
[Rodgers et al., 2003]

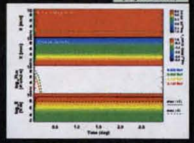


Charging to breaking fields possible depending on environment, material properties!!



--30 deg inc
--AE-8 max
10x L ≥ 2

Material 3
σ ~ 10^{-19} S/m
τ ~ 31 days



--30 deg inc
--AE-8 max
10x L ≥ 2

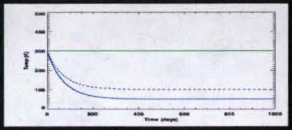
Material 4
σ ~ 10^{-18} S/m
τ ~ 50 hours

Conductivity Model 1

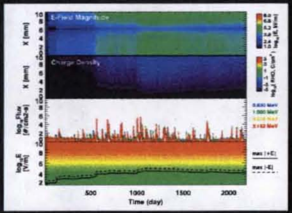
Radiation belt transit on lunar trajectories at cold temperatures represent a particular threat due to long periods required for charge to decay from insulating materials exposed to relativistic electrons.

Temperature Dependent σ(T), k, x

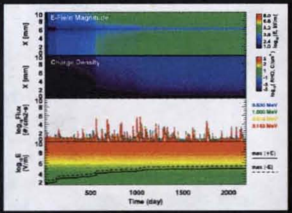
Temperature Histories



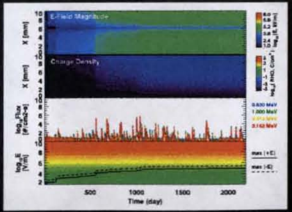
T = 300 K
LDPE
Cond. Model 2



Cooling
T=300K to 100 K
LDPE
Cond. Model 2



Cooling
T = 300 K to 50 K
LDPE
Cond. Model 2



Long time constants due to low conductivities result in long charge integration times at cryogenic temperatures. Increasingly lower temperatures do not create additional risk once the insulator has essentially become a "charge integrator."

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 σ, 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.

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