Modeling Electrostatic Fields Generated by Internal Charging of Materials in Space Radiation Environments

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Introduction

**Internal (deep dielectric) charging**

High energy (>100 keV) electrons penetrate spacecraft walls and accumulate in dielectrics or isolated conductors.

Threat environment is energetic electrons with sufficient flux to charge circuit boards, cable insulation, and ungrounded metal faster than charge can dissipate.

Accumulating charge density generates electric fields in excess of breakdown strength resulting in electrostatic discharge.

System impact is material damage, discharge currents inside of spacecraft Faraday cage on or near critical circuitry, and RF noise.

**Overview**

- Internal charging physics, model formulation
- Examples of two engineering models
  - ESA DICTAT
  - NASA NUMIT
- Other internal charging models

PMMA (acrylic) charged by ~2 to 5 MeV electrons
GOES Solar Cycle 21 Internal Charging Anomalies (GEO)

smoothed sunspot number

Day in solar rotation period

2-day fluence (F2) > 2 MeV electrons

- **Red:** \( F2 \geq 10^9 \text{ e}^- / \text{cm}^2 \cdot \text{sr} \)
- **Amber:** \( 10^9 > F2 \geq 10^8 \text{ e}^- / \text{cm}^2 \cdot \text{sr} \)
- **Green:** \( F2 < 10^8 \text{ e}^- / \text{cm}^2 \cdot \text{sr} \)
- **White:** no data

Black: GOES phantom commands

[Wrenn et al. 2002]
Internal Charging: Physics

\[ \nabla \cdot \varepsilon \mathbf{E} = \rho \]
\[ \varepsilon = \kappa \varepsilon_0 \]
\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot \mathbf{J} \]
\[ \mathbf{J} = \mathbf{J}_R + \mathbf{J}_C \]
\[ \mathbf{J}_C = \sigma \mathbf{E} \]
\[ = \left[ \sigma_{\text{dark}} + \sigma_{\text{RIC}} \right] \mathbf{E} \]
\[ \sigma_{\text{RIC}} = k \left( \frac{d\gamma}{dt} \right)^\alpha \quad 0.5 < \alpha < 1.0 \]

Solution to Poisson, continuity equation involves two problems:
- Radiation (electron) penetration with charge and energy deposition in material
- Electrostatic solution of fields from charge distribution in insulator
Internal Charging: Radiation Transport

- Computation of radiation dose and charge deposition as function of depth requires a radiation transport analysis.

- Analytical approximations are used in some codes to avoid time consuming Monte Carlo techniques.

- Monte Carlo radiation transport techniques (e.g., ITS, EGS) provide better results:
  - Empirical parameterization of Monte Carlo output provides fidelity of Monte Carlo radiation transport results with speed of analytical solution.
  - Monte Carlo results are best for general solutions.

\[ R = 0.55E[1 - 0.9841/(1+3E)] \ g/cm^2 \]
\[ a = \text{min}(0.283E, R) \]
Internal Charging: Electrostatic Models

• Generation-Recombination (GR) Model

Microscopic model explicitly treats the radiation generated charge carrier pairs, field induced drift of carriers, and loss through recombination

\[ \frac{\varepsilon}{\partial x} \frac{\partial E}{\partial x} = \rho_+ - \rho_- - \rho_{t-} \]  

(4)

\[ \frac{\partial (\rho_+ + \rho_{t-})}{\partial t} = - \frac{\partial J_0}{\partial x} + G - \alpha_f \rho_+ \rho_- - \alpha_t \rho_+ \rho_{t-} + \frac{\partial (\mu_- \rho_+ E)}{\partial x} \]  

(5)

\[ \frac{\partial \rho_+}{\partial t} = G - \alpha_f \rho_+ \rho_- - \alpha_t \rho_+ \rho_{t-} - \frac{\partial (\mu_+ \rho_+ E)}{\partial x} \]  

(6)

\[ \frac{\partial \rho_{t-}}{\partial t} = \frac{\rho_-}{\tau_-} \left( 1 - \frac{\rho_{t-}}{\rho_m} \right) - \alpha_t \rho_+ \rho_{t-} \]  

(7)

• Radiation Induced Conductivity (RIC) Model

Macroscopic model based on empirical relationship between radiation dose and conductivity

\[ \frac{\varepsilon}{\partial x} \frac{\partial E}{\partial x} = - \rho_- - \rho_{t-} \]  

(1)

\[ \frac{\partial (\rho_+ + \rho_{t-})}{\partial t} = - \frac{\partial J_0}{\partial x} + \frac{\partial (\mu_- \rho_+ E)}{\partial x} + \frac{\partial (gE)}{\partial x} \]  

(2)

\[ \frac{\partial \rho_{t-}}{\partial t} = \frac{\rho_-}{\tau_-} \left( 1 - \frac{\rho_{t-}}{\rho_m} \right) \]  

(3)

[Sessler et al. 2004]
Internal Charging: Electrostatic Models

• Generation-Recombination (GR) Model
Microscopic model explicitly treats the radiation generated charge carrier pairs, field induced drift of carriers, and loss through recombination

\[ \frac{\varepsilon}{\partial x} = \rho_+ - \rho_- - \rho_{\tau} \]  

\[ \frac{\partial (\rho_+ + \rho_{\tau})}{\partial t} = -\frac{\partial J_0}{\partial x} + G - \alpha_f \rho_+ \rho_- - \alpha_r \rho_+ \rho_{\tau} \]  

\[ + \frac{\partial (\mu_- \rho_- E)}{\partial x} \]  

\[ \frac{\partial \rho_+}{\partial t} = G - \alpha_f \rho_+ \rho_- - \alpha_r \rho_+ \rho_{\tau} - \frac{\partial (\mu_+ \rho_+ E)}{\partial x} \]  

\[ \frac{\partial \rho_{\tau}}{\partial t} = \frac{\rho_-}{\tau_-} \left( 1 - \frac{\rho_{\tau}}{\rho_m} \right) - \alpha_r \rho_+ \rho_{\tau} \]  

• Radiation Induced Conductivity (RIC) Model
Macroscopic model based on empirical relationship between radiation dose and conductivity

\[ \varepsilon \frac{\partial E}{\partial x} = -\rho_- \]

\[ \frac{\partial \rho_-}{\partial t} = -\frac{\partial J_0}{\partial x} + \frac{\partial [(\sigma_D + \sigma_{RIC}) E]}{\partial x} \]

\[ = -\frac{\partial J_0}{\partial x} + \frac{\partial [(\sigma_D + kD^x) E]}{\partial x} \]

[Sessler et al. 2004]
DICTAT Internal Charging Code

- DICTAT model evaluates possibility of dielectric breakdown of insulating materials due to radiation charging
  - Single material parameterized by electrical conductivity (dark and radiation induced) dielectric constant, density, temperature

**Example:** 1 mm Mylar exposed to FLUMIC (worst case) GEO electron environment

- **Resistivity** $10^{14} \, \Omega \cdot m$
  After 48.0 hours: Charging current= $7.0535 \times 10^{-13} \, \text{Amps/cm}^2$
  $E_{\text{max}} = 6.5170 \times 10^5 \, \text{V/m}$  
  Voltage= 464.5 volts
  The dielectric IS NOT liable to experience breakdown
  Maximum $E$ lower than Breakdown field= $1.00 \times 10^7 \, \text{V/m}$

- **Resistivity** $10^{16} \, \Omega \cdot m$
  After 48.0 hours: Charging current= $7.0535 \times 10^{-13} \, \text{Amps/cm}^2$
  $E_{\text{max}} = 1.4130 \times 10^7 \, \text{V/m}$  
  Voltage= 1.1678 $\times 10^4$ volts
  The dielectric IS LIABLE to experience breakdown
  Maximum $E$ higher than Breakdown field= $1.00 \times 10^7 \, \text{V/m}$

- **Resistivity** $10^{18} \, \Omega \cdot m$
  After 48.0 hours: Charging current= $7.0535 \times 10^{-13} \, \text{Amps/cm}^2$
  $E_{\text{max}} = 3.5881 \times 10^7 \, \text{V/m}$  
  Voltage= 2.8170 $\times 10^4$ volts
  The dielectric IS LIABLE to experience breakdown
  Maximum $E$ higher than Breakdown field= $1.00 \times 10^7 \, \text{V/m}$

[http://www.spnvis.oma.be/](http://www.spnvis.oma.be/)
DICTAT Internal Charging Analysis

- Simple first order evaluation of charging along trajectories through Earth’s radiation belts using standard trapped radiation models, mitigation of charging by shielding
  - 10 mm thick plexiglass shielded by aluminum 0.0 cm to 0.2 cm thick
    - Peak AE-8 GEO radiation flux (constant)
- Three 0.1 materials with conductivity varying from $10^{-16}$ to $10^{-12}$ S/m
  - AE-8 solar max electron flux
  - 250 km x 38,226 km x 0° inc, single orbit
- Grey levels indicate relative threat levels for electrostatic discharge assuming materials typically suffer dielectric breakdown at electric fields in the range of $10^6$ V/m to $10^7$ V/m.
DICTAT Internal Charging Analysis

• Electric field, surface voltage potential as function of time

• Allows quick screening for materials issues

• Simulation options limited by tool
  – Maximum time (48 hours)
  – Single material
  – Constant flux for user input
  – Radiation belt models for time variations in radiation flux
  – Only maximum E field is reported, no information on electric field as function of depth

\[ E_{\text{max}} = 1.7 \times 10^7 \text{ V/m} \]

Plexiglass, 10 cm
L=6.6, B/B_0=1 (GEO)
No shielding

\[ \Phi_{\text{max}} = 1.7 \times 10^6 \text{ volts} \]

Plexiglass, 10 cm
L=6.6, B/B_0=1 (GEO)
No shielding

http://www.spenvis.oma.be/
NUMIT ("numerical iteration") Codes

- Originally developed by A.R. Frederickson et al (AFRL, JPL)
- Tabata algorithm fits to Monte Carlo electron transport code for radiation dose, charge deposition
- Multiple material conductivity, dielectric constant
- Input electron spectrum, monoenergetic beams, fixed flux or time series of arbitrary duration (hours to years)
- Output electric fields, charge density, currents, radiation dose rates as function of depth in material
3 MeV electrons on PMMA

Charging beam
- 3 MeV electrons
- 0.01 nA/cm$^2$

Material
- PMMA (acrylic)
- $Z=6$, $A=12$
- ~10 cm thick
- $\sigma \sim 1 \times 10^{-16}$ S/m
- $\kappa = 3.71$
- $\rho = 1.19$ g/cm$^3$
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Beam off at 1 hour
No effect since $\tau \sim \kappa \varepsilon_0 / \sigma = 91$ hours
3 MeV electrons on PMMA

Charging beam
- 3 MeV electrons
- 0.01 nA/cm²

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- Z=6, A=12
- $\sigma \sim 1 \times 10^{-14}$ S/m
- $\kappa = 3.71$
- $\rho = 1.19$ g/cm³

Beam off at 1 hour
$\tau \sim \frac{\kappa \varepsilon_0}{\sigma} = 0.91$ hours
Geostationary Orbit 200 Day Time Series

LANL/GEO: 2006lanl01_5min.sav

0.050-0.075 MeV
0.075-0.105 MeV
0.105-0.150 MeV
0.150-0.225 MeV
0.225-0.315 MeV
0.315-0.500 MeV
0.500-0.750 MeV
0.750-1.1 MeV
1.1-1.5 MeV
0.7-1.8 MeV
1.8-2.2 MeV
2.2-2.7 MeV
2.7-3.5 MeV
3.5-4.5 MeV
4.5-6.0 MeV
6.0-7.8 MeV
7.8-10.8 MeV
10.8-25.8 MeV
Geostationary Orbit 200 Day Time Series

LANL/GEO: 2006lanl01_5min.sav

Day of Year

#/(cm²-sec-sr-MeV)

0.050-0.075 MeV
0.075-0.105 MeV
0.105-0.150 MeV
0.150-0.225 MeV
0.225-0.315 MeV
0.315-0.500 MeV
0.500-0.750 MeV
0.750-1.1 MeV
1.1-1.5 MeV
0.7-1.8 MeV
1.8-2.2 MeV
2.2-2.7 MeV
2.7-3.5 MeV
3.5-4.5 MeV
4.5-6.0 MeV
6.0-7.8 MeV
7.8-10.8 MeV
10.8-25.8 MeV
Geostationary Orbit, 200 Days

Charging current
- Energy, flux from GEO
electron measurement
- LANL-01A SOPA +ESA

Material
- PMMA
- $Z=6, A=12$
- ~2.5 cm thick
- $\sigma \sim 1\times10^{-17} \text{ S/m}$
- $\kappa = 2.00$
- $\rho = 1.0 \text{ g/cm}^3$
# Internal Charging Codes

<table>
<thead>
<tr>
<th>Model</th>
<th>Type*</th>
<th>Electron Transport</th>
<th>Features</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMIT (original) AFRL, JPL</td>
<td>A, MC</td>
<td>Tabata, Monte Carlo</td>
<td>1-D, single energy, $\sigma(E)$ models</td>
<td>Frederickson et al., 1974, 1977, 1980, 1983, 1993</td>
</tr>
<tr>
<td>NUMIT JPL</td>
<td>A</td>
<td>Tabata</td>
<td>1-D, spectrum, 3 materials</td>
<td>Jun et al. 2008</td>
</tr>
<tr>
<td>NUMIT MSFC</td>
<td>A</td>
<td>Tabata</td>
<td>1-D, spectrum, 5 materials</td>
<td>Minow et al. 2007, Jun et al. 2008</td>
</tr>
<tr>
<td>NUMIT Bethel University, AFRL</td>
<td>A</td>
<td>Tabata</td>
<td>1-D, 1 energy, 3 materials</td>
<td>Beeken and McIver, 2010</td>
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<tr>
<td>NUMIT SAIC</td>
<td>A</td>
<td>Tabata</td>
<td>1-D, spectrum, radiation shield</td>
<td>Davis et al., 2000, 2007</td>
</tr>
<tr>
<td>ESA Deep Dielectric Charging Code (ESA-DDC)</td>
<td>MC</td>
<td>Range-energy relationship</td>
<td>1-D, $\sigma(E)$ models</td>
<td>Soubeyran et al., 1993, 1994</td>
</tr>
<tr>
<td>Moscow State University</td>
<td>MC</td>
<td>GEANT-3</td>
<td>1-D</td>
<td>Mileev and Novikov, 2004</td>
</tr>
<tr>
<td>Xi’an Jiaotong University</td>
<td>A</td>
<td>1-D analytical solution</td>
<td>1-D, $\sigma(E)$ models</td>
<td>Li et al. 2010</td>
</tr>
<tr>
<td>Assessment Tool of Internal Charging for Satellites (ATICS)</td>
<td>MC</td>
<td>GEANT-4</td>
<td>1-D panels over a 3-D spacecraft, $\sigma(E)$ models</td>
<td>Zhong et al., 2007</td>
</tr>
<tr>
<td>Multi-Utility Spacecraft Charging Analysis Tool</td>
<td></td>
<td></td>
<td>1-D</td>
<td>Hatta et al. 2009, Cho et al. 2010</td>
</tr>
<tr>
<td>JPL</td>
<td>MC</td>
<td>ITS</td>
<td>3-D</td>
<td>Katz and Kim, 2010</td>
</tr>
<tr>
<td>Aerospace Corp</td>
<td>MC</td>
<td>GEANT-4</td>
<td>3-D</td>
<td>Lemon et al. 2010</td>
</tr>
</tbody>
</table>

*A = analytical, MC = Monte Carlo
Summary

• Internal charging is a risk to spacecraft in energetic electron environments

• DICTAT, NUMIT computational codes are the most widely used engineering tools for evaluating internal charging of insulator materials exposed to these environments

• Engineering tools designed for rapid evaluation of ESD threats, but there is a need for more physics based models for investigating the science of materials interactions with energetic electron environments

• Current tools are limited by the physics included in the models and ease of user implementation....additional development work is needed to improve models