Proposed Modifications to Engineering Design Guidelines Related to Resistivity Measurements and Spacecraft Charging

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Abstract

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A key parameter in modeling differential spacecraft charging is the resistivity of insulating materials. This determines how charge will accumulate and redistribute across the spacecraft, as well as the time scale for charge transport and dissipation. Existing spacecraft charging guidelines recommend use of tests and imported resistivity data from handbooks that are based principally upon ASTM methods that are more applicable to classical ground conditions and designed for problems associated with power loss through the dielectric, than for how long charge can be stored on an insulator. These data have been found to underestimate charging effects by one to four orders of magnitude for spacecraft charging applications.

A review is presented of methods to measure the resistivity of highly insulating materials—including the electrometer-resistance method, the electrometer-constant voltage method, the voltage rate-of-change method and the charge storage method. This is based on joint experimental studies conducted at NASA Jet Propulsion Laboratory and Utah State University to investigate the charge storage method and its relation to spacecraft charging. The different methods are found to be appropriate for different resistivity ranges and for different charging circumstances. A simple physics-based model of these methods allows separation of the polarization current and dark current components from long duration measurements of resistivity over day- to month-long time scales. Model parameters are directly related to the magnitude of charge transfer and storage and the rate of charge transport. The model largely explains the observed differences in resistivity found using the different methods and provides a framework for recommendations for the appropriate test method for spacecraft materials with different resistivities and applications. The proposed changes to the existing engineering guidelines are intended to provide design engineers more appropriate methods for consideration and measurements of resistivity for many typical spacecraft charging scenarios.

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Resistivity and Spacecraft Charging

As before, spacecraft accumulate charge and adopt potentials in response to the plasma environment.

The distribution and migration of this charge determines the extent of differential charging.

Resistivity of insulating materials determines:
- Where charge will accumulate
- How charge will redistribute across the spacecraft
- Time scale for charge transport and dissipation.

Our Spacecraft Charging Issues

New testing have identified a problem
- Charge Storage resistivity tests done on Polyimides, Mylar, Teflon, Glass, Circuit Boards, etc. (see Green).
- Results from new resistivity methods find $p \times 10^4$ times larger than handbook ASTM values.
- Charge can accumulate from many orbits.

What voltages/charge distributions are developed?
- What are the proper test procedures?
- How do we qualify a material for space flight?
- What are mechanisms of charge storage and dissipation?
**Definition of Resistivity**

Familiar with concept of resistance as the proportionality constant in Ohm’s Law:

\[ R = \frac{V}{I} \]

R is an *extrinsic* device property that measures resistance to flow of current I to a driving force V.

Resistivity is the proportionality constant in another form of Ohm’s Law:

\[ \rho = \frac{E}{J} \quad \text{such that} \quad \rho = \frac{R \cdot A}{L} = \frac{1}{\sigma} \]

\( \rho \) is an intrinsic material property.

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**Thin-film Capacitor Model for Spacecraft Dielectrics**

Most critical charging systems can be approximated as thin-film capacitors.

Charge accumulation and dissipation on a parallel-plate capacitor is well known.

Voltage (or charge) decay depends exponentially on time with decay constant \( \tau \).

\[ V(t) = V_0 e^{-t/\tau} \]

or

\[ \sigma(t) = \sigma_0 e^{-t/\tau} \]

Decay constant is product of:

\[ \tau = R \cdot C \quad \text{(extrinsic)} \]

\[ \tau = \rho \varepsilon_r \varepsilon_0 \quad \text{(intrinsic)} \]
Orbit Time and Charge Decay Time

Treating thin film insulator as simple capacitor, charge decay time proportional to resistivity.

Typical orbits from 1 to 24 hours.

Critical Time Scales and Resistivities

Decay time vs. resistivity base on simple capacitor model.

\[ \tau = \rho \varepsilon_r \varepsilon_0 \]
**Time Independent Capacitor Voltage:**

**A Simple Model**

\[
E = \frac{V}{d}
\]

\[
D = \varepsilon_0 E = \varepsilon_0 \varepsilon_r E = \varepsilon_0 E + P
\]

\[
\sigma_{Total} = \varepsilon_r \varepsilon_0 E \equiv D
\]

\[
\sigma_{Free} = \varepsilon_0 E
\]

\[
\sigma_{Bound} = (\varepsilon_r - 1) \varepsilon_0 E \equiv P
\]

\[
\sigma_{Total} = \sigma_{Free} + \sigma_{Bound}
\]

\[
\varepsilon_r = \frac{\text{total charge density}}{\text{free charge density}} = \frac{\sigma_{Total}}{\sigma_{Free}}
\]

---

**Capacitor Voltage with Leakage**

Consider decay of free charge:

\[
\sigma^{\text{Free}}(t) = \varepsilon_0 E(t) = \frac{\varepsilon_0}{d} V(t) = \frac{\varepsilon_0}{d} V_0 e^{-t/\tau_{DC}}
\]

\[
= \sigma^0_{Free} e^{-t/\tau_{DC}}, \quad \text{with} \quad \tau_{DC} = \rho_{DC} \varepsilon_0 \varepsilon_r
\]

\[
\sigma^{\text{Free}}(t) = \varepsilon_0 E(t) = \frac{\varepsilon_0}{d} V(t) = \frac{\varepsilon_0}{d} V_0 e^{-t/\tau_{DC}}
\]

\[
= \sigma^0_{Free} e^{-t/\tau_{DC}}, \quad \text{with} \quad \tau_{DC} = \rho_{DC} \varepsilon_0 \varepsilon_r
\]
Capacitor Voltage with Polarization

Consider build-up of bound charge:

\[ \varepsilon_r(t) = \left(1 - \varepsilon_r^\infty\right) e^{-t/\tau_p} + \varepsilon_r^\infty; \]

\[ = -\frac{\sigma_{\text{Bound}}}{\sigma_{\text{Free}}} e^{-t/\tau_p} + \left(1 + \frac{\sigma_{\text{Bound}}}{\sigma_{\text{Free}}}\right) = \frac{\sigma_{\text{Bound}}}{\sigma_{\text{Free}}} \left(1 - e^{-t/\tau_p}\right) + 1 \]

\[ \varepsilon_r(t) = \left(\varepsilon_r^0 - \varepsilon_r^\infty\right) e^{-t/\tau_p} + \varepsilon_r^\infty; \]

\[ = \left(\frac{\sigma_{\text{Bound}}}{\sigma_{\text{Free}}} - \frac{\sigma_{\text{Bound}}}{\sigma_{\text{Free}}}\right) e^{-t/\tau_p} + \left(1 + \frac{\sigma_{\text{Bound}}}{\sigma_{\text{Free}}}\right) \]

with \( \tau_p = \rho_p \varepsilon_0 \varepsilon_r^\infty \)

Polarization Time Scales and Mechanisms

\[ \varepsilon' \]

interfacial

orientational

atomic

electronic

\[ \sigma_{\text{Bound}} \]

\[ \sigma_{\text{Free}} \]

\[ \rho_p \]

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Dipolar sidegroups align with applied E-field through confirmation changes of polymer chains, inhibited by polymer entanglement.

Comparison of Resistivity Test Methods

ASTM Capacitor Method
- guard ring
- metal electrode
- insulator
- picoammeter
- Adjustable Voltage Source

Charge Storage Method
- aluminum
- metal electrode
- Adjustable Voltage Source
- Voltmeter
- Field Probe

\[ \rho = 1 \times 10^{16} \text{ (ohm-cm)} \quad \rho > 5 \times 10^{20} \]

For measurements on same sample of polyimide
Comparison of Typical Resistivity Results

ASTM Capacitor Method

Charge Storage Method

\[ \rho = -2 \times 10^{16} \text{ (ohm-cm)} \quad \rho > 5 \times 10^{19} \]

For measurements on samples of Kapton H

Constant-voltage (ASTM) Resistivity: Methods

Constant voltage replenishes free charge and supplies current to balance polarization.

Limited by small current measurements.

\[ \sigma_{CV}^{Total}(t) = \varepsilon_o \varepsilon_r(t) E_{CV} = \varepsilon_o \frac{V_{CV}}{d} \left[ \varepsilon_r^\infty - \varepsilon_r \right] e^{-t/\tau_p} + \varepsilon_r^\infty \]

with \( \tau_p = \rho_p \varepsilon_o \varepsilon_r^\infty \)

\[ I_{CV}(t) = I_P(t) + I_{Leak} = V_{CV} C_o \left[ \frac{\varepsilon_r^\infty - \varepsilon_r}{\tau_p} \right] e^{-t/\tau_p} + \frac{\varepsilon_r^\infty}{\tau_{DC}} \]
Constant-voltage (ASTM) Resistivity:

Instruments

Variable Voltage

7th grade of metal weight

Aluminum frame

Metal Plate

Sample

Poly Carbonate Mounting Block

Picosammeter

damp cardboard

Experimental setup
of the classical
ASTM method

Constant-voltage (ASTM) Resistivity:

Equations

For the Constant Voltage Method, the measured current as a function of elapsed time is

\[ I_{CV}(t) = I_{Leak} + I_P(t) = V_{CV} C_o \left[ \frac{\varepsilon_r^\infty - \varepsilon_r^0}{\tau_P} \right] e^{-t/\tau_p} + \frac{\varepsilon_r^\infty}{\tau_{DC}} \]

where

t = time, seconds
\(\tau_p\) = polarization decay constant, seconds
\(\tau_{DC}\) = dark current decay constant, seconds
\(\varepsilon_r^0\) = initial relative dielectric constant, F/m
\(\varepsilon_r^\infty\) = asymptotic relative dielectric constant, F/m
\(I_{CV}\) = measured current, amp
\(V_{CV}\) = constant applied voltage, volt
\(C_o\) = capacitance of the sample with e=1, farads
Constant-voltage (ASTM) Resistivity: Results for PET

Charge Storage Resistivity: Methods

Bound charge is saturated relatively quickly and free charge is dissipated and not replenished.

Less limited by small current measurements.

\[
V_{CS}(t) = \frac{\sigma_{\text{Total}}(t) d}{\varepsilon_0} = \frac{\sigma_{\text{Pre}}(t) d}{\varepsilon_0 \varepsilon_r(t)}
\]

\[
= \frac{d}{\varepsilon_0} \left( \frac{\sigma_{\text{Pre}}^\text{Bound}}{\sigma_{\text{Pre}}^\text{Free}} - \frac{\sigma_{\text{Pre}}^\text{Bound}}{\sigma_{\text{Pre}}^\text{Free}} \right) e^{-\frac{t}{\tau_{DC}}} + \sigma_{\text{Pre}}^\text{Free}
\]

with \( \tau_{DC} = \frac{1}{\sigma_{\text{Pre}}^\text{Bound}} \)

\[
V_{CS}(t) = \left( V_0 - V_{\infty} \right) e^{-\frac{t}{\tau_{DC}}} + V_{\infty}
\]

with \( \tau_{DC} = \frac{1}{\sigma_{\text{Pre}}^\text{Bound}} \)
Charge Storage Resistivity: Instruments

Experimental setup of the charge storage method

Charge Storage Resistivity: Equations

For the Charge Storage Method, the measured current as a function of elapsed time is:

\[ V_{CS}(t) = \left( V_o - V_\infty \right) e^{-t/\tau_{DC}} + V_\infty \left( \varepsilon_r^0 - \varepsilon_r^\infty \right) e^{-t/\tau_p} + \varepsilon_r^\infty \]  

with \( \tau_{DC} = \rho_{DC} \varepsilon_o \varepsilon_r \)

where
- \( t \) = time, seconds
- \( t_p \) = polarization decay constant, seconds
- \( t_{DC} \) = dark current decay constant, seconds
- \( \varepsilon_r^0 \) = initial relative dielectric constant, F/m
- \( \varepsilon_r^\infty \) = asymptotic relative dielectric constant, F/m
- \( V_0 \) = initial voltage, volts
- \( V_\infty \) = asymptotic voltage, volt
- \( C_o \) = capacitance of the sample with \( \varepsilon=1 \), farads
Charge Storage Resistivity: Results for PTFE

PTFE data: low stored current, high dark current resistivity.

Charge Storage Resistivity: Results for FR4

FR4 data: high stored current, modest dark current resistivity.
Charge Storage Resistivity: Results for Alumina

Alumina data: very high stored current, rapid polarization, lower dark current resistivity, evidence for a second dark current conduction mechanism.

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Charge Storage Resistivity: Summary of Results

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (cm)</th>
<th>$\varepsilon_r^*$</th>
<th>$\varepsilon_r^m$</th>
<th>$V_p$ (volt)</th>
<th>$V_m$ (volt)</th>
<th>$\tau_p$ (hr)</th>
<th>$\tau_{OC}$ (day)</th>
<th>$\rho_1$ parameter ($\Omega$-cm)</th>
<th>$\rho_2$ parameter ($\Omega$-cm)</th>
<th>$\rho_3$ parameter ($\Omega$-cm)</th>
<th>$\rho_4$ parameter ($\Omega$-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTFE</td>
<td>0.229</td>
<td>1.05</td>
<td>1.11</td>
<td>347</td>
<td>5.2</td>
<td>17.9</td>
<td>339</td>
<td>3.0×10^15</td>
<td>2.9×10^14</td>
<td>3×10^17</td>
<td></td>
</tr>
<tr>
<td>FR4</td>
<td>0.317</td>
<td>1.07</td>
<td>1.95</td>
<td>412</td>
<td>1.5</td>
<td>18.2</td>
<td>4.53</td>
<td>2.3×10^14</td>
<td>2.1×10^14</td>
<td>&lt;2×10^15</td>
<td></td>
</tr>
<tr>
<td>Alumina</td>
<td>0.102</td>
<td>1.02</td>
<td>3.00</td>
<td>423</td>
<td>4.7</td>
<td>6.35</td>
<td>21.3</td>
<td>2.9×10^17</td>
<td>3.0×10^17</td>
<td>3×10^3</td>
<td></td>
</tr>
</tbody>
</table>
**Time Scales for Polarization**

Ratio of resistivity measured at 1 min to the asymptotic limit of resistivity, $\rho_{DC}$, plotted as a function of polarization decay constant, $\tau_p$.

- DC Decay Time = 10 hr
- DC Decay Time = 1 day
- DC Decay Time = 10 day
- DC Decay Time = 1 year
- DC Decay Time = decade

**Instrument Resolution**

<table>
<thead>
<tr>
<th>Method</th>
<th>Maximum Detectable Resistance Values and Decay Time Constant</th>
<th>Typical Maximum Measurable Values (±6%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resistance</td>
<td>Current</td>
</tr>
<tr>
<td>Digital Multimeter</td>
<td>$-2 \times 10^{10} \Omega$ / $-5 \text{ sec}^{bd}$</td>
<td>$-10^{10} \Omega$</td>
</tr>
<tr>
<td>Electrometer—Resistance</td>
<td>$-10^{10} \Omega$ / $-3 \text{ days}^{bd}$</td>
<td>$-10^{14} \Omega$</td>
</tr>
<tr>
<td>Electrometer—Constant V</td>
<td>$-5 \times 10^{17} \Omega$ / $-150 \text{ days}^{d}$</td>
<td>$-5 \times 10^{16} \Omega$</td>
</tr>
<tr>
<td>Voltage Rate of change</td>
<td>$-4 \times 10^{15} \Omega$ / $-3 \text{ yr}$</td>
<td>$-4 \times 10^{6} \Omega$</td>
</tr>
<tr>
<td>Charge Storage Decay</td>
<td>$-4 \times 10^{8} \Omega$ / $-70 \text{ yr}$</td>
<td>$-2 \times 10^{7} \Omega$</td>
</tr>
</tbody>
</table>
## Summary for Resistivity Test Methods Model

- Instrumentation and methods have been successfully developed to measure resistivity with charge storage decay method and compare the results with classical method.

- Measurements confirm initial results that charge storage resistivity can be $>10^4$ times classical results.

- Theoretical model based on simple physical parameters:
  - Fits time-dependant data from different methods
  - Predicts disparities between different methods
  - Explains resolution limits of different methods
  - Confirms charge storage method as method of choice for very high resistance materials