9th Spacecraft Charging Technology Conference
April 4-8, 2005
EPOCHAL TSUKUBA, TSUKUBA, JAPAN

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

J.R. Dennison Prasanna Swaminathan, Randy Jost and Jerilyn Brunson
Utah State University
Nelson Green and A. Robb Frederickson
Jet Propulsion Laboratory

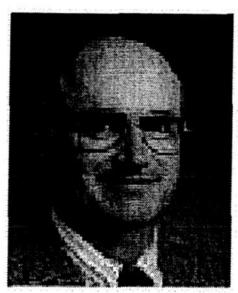
Utah State UNIVERSITY

NASA Jet Propulsion Laboratory
California Institute of Technology

9th Spacecraft Charging Technology Conference
April 4-8, 2005
EPOCHAL TSUKUBA, TSUKUBA, JAPAN

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

Supported by the NASA SEE Program, USU Research Office, and USU College of Science



A. Robb Frederickson
Jet Propulsion Laboratory

Abstract

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 resistivty 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.

Outline

1. Title page
2. Introduction
   1. Resistivity and spacecraft charging
   2. Definition of resistivity
   3. Thin Film Capacitor Model of Spacecraft Dielectrics
   4. Resistivity Charge Transport and Time Scales
   5. Time Scales and Spacecraft Charging
   6. Relevant scales for Spacecraft Charging
3. Time Dependence of Capacitor Voltage: A Simple Model
   1. Capacitor voltage with leakage
   2. Capacitor voltage with polarization
   3. Polarization mechanisms and time scales
   4. Polarization in polymers
   5. A charge picture
   6. Two ways charge can change with time
   7. The voltage or current picture

3. Two methods for measuring resistivity
   1. Constant-voltage (ASTM)
      1. Method
      2. Instrumentation
      3. Equations
      4. Results for PET
   2. Charge Storage Method
      1. Method
      2. Instrumentation
      3. Equations
      4. Results for:
         1. PTFE
         2. FR4
         3. Alumina
4. Conclusions
   1. Time scales for measurements and polarization
   2. Instrument resolution
   3. Conclusions to be drawn

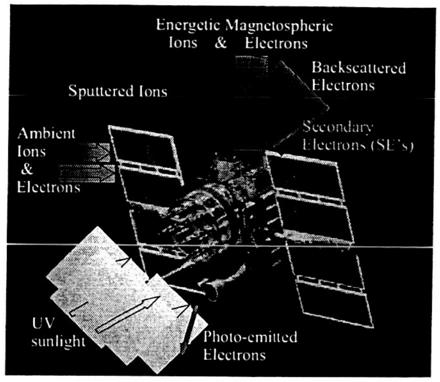
Resistivty and Spacecraft Charging

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

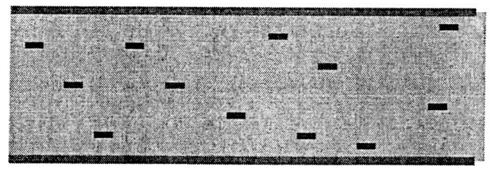
The distribution and migration of this charge determines the extent of differential charging.

Resistivity of insulating materials determines:

- Where charge will accumulate
- How charge will redistribute across the spacecraft
- Time scale for charge transport and dissipation.



Spacecraft Charging results from charge accumulation.



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 ρ 10^1-10^4 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:

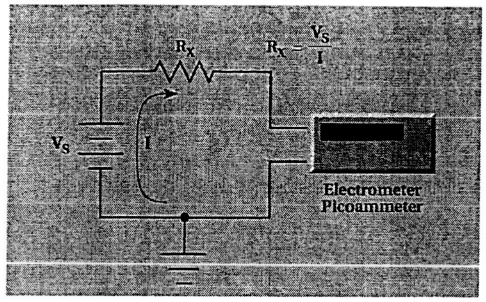
$R = V / I$

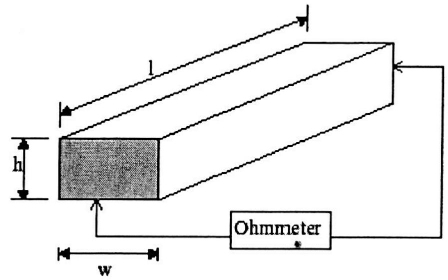
R is an *extrinsic* device property that measures resistance to flow of current I to a driving force V.

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

$\rho = E / J$ such that $\rho = R \cdot A/L \equiv 1 / \sigma$

ρ is a intrinsic material property.





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 τ.

$$V(t) = V_o\, e^{-t/\tau}$$

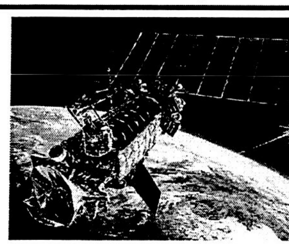
or

$$\sigma(t) = \sigma_0 \cdot e^{-t/\tau}$$

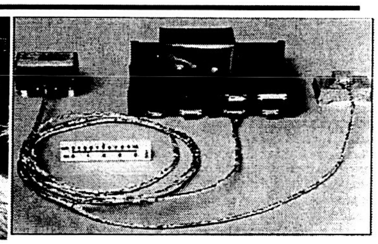
Decay constant is product of:

$\tau = R \cdot C$ (extrinsic)

$\tau = \rho\, \varepsilon_r\, \varepsilon_o$ (intrinsic)

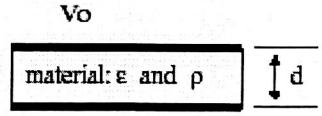


Exterior

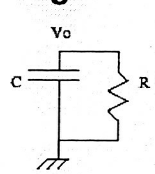


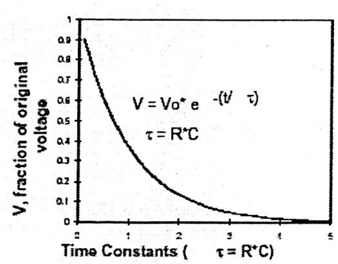
Interior

Capacitor

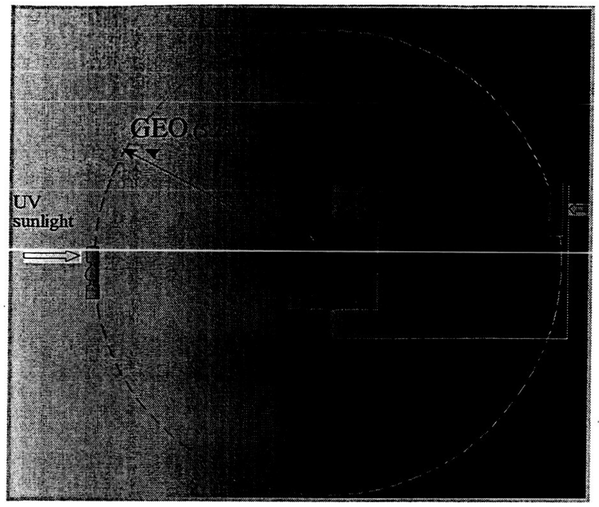


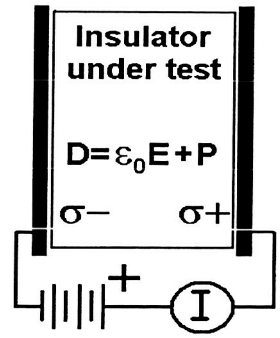
Capacitor Discharge





Orbit Time and Charge Decay Time



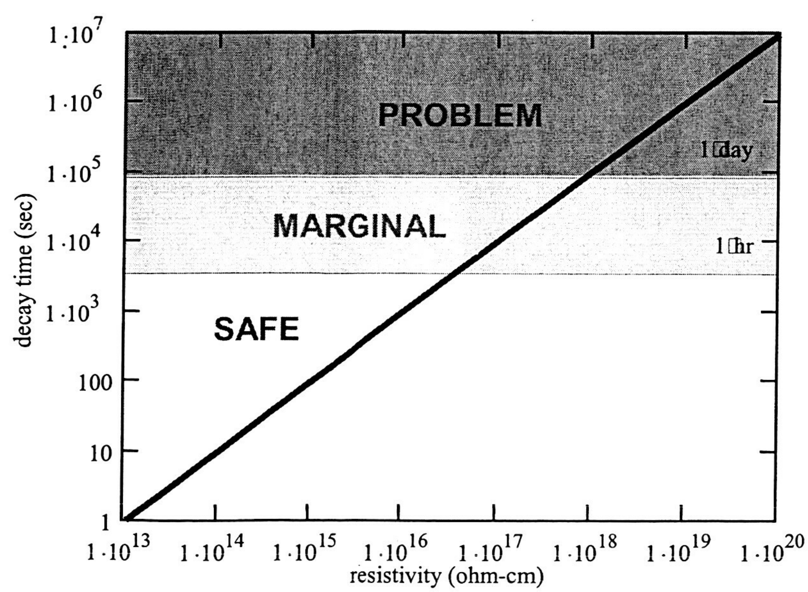


$$\tau = \rho \varepsilon_r \varepsilon_0$$

Typical orbits from 1 to 24 hours.

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

Critical Time Scales and Resistivites



Decay time vs. resistivity base on simple capacitor model.

$$\tau = \rho\ \varepsilon_r\ \varepsilon_o$$

Time Independent Capacitor Voltage: A Simple Model

$$E = V/d$$

$$D = \varepsilon E = \varepsilon_o \varepsilon_r E = \varepsilon_o E + P$$

$$\sigma^{Total} = \varepsilon_r \varepsilon_o E \equiv D$$

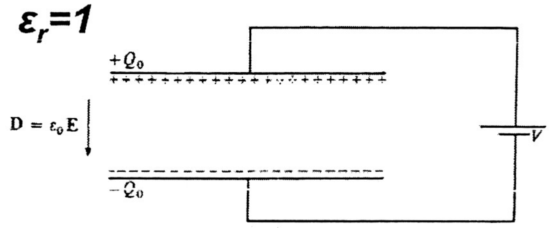
$$\sigma^{\text{Free}} = \varepsilon_o E$$

$$\sigma^{\text{Bound}} = (\varepsilon_r - 1)\, \varepsilon_o E \equiv P$$

$$\sigma^{Total} = \sigma^{Free} + \sigma^{\text{Bound}}$$

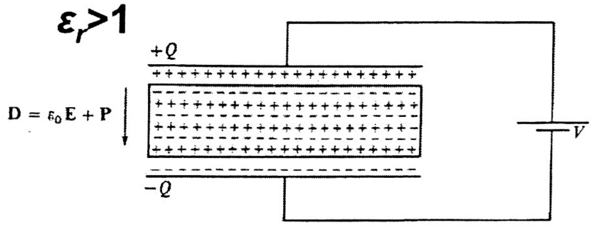
$$\varepsilon_r = \frac{\text{total charge density}}{\text{free charge density}} = \frac{\sigma^{Total}}{\sigma^{Free}}$$

ε_r=1



(a)

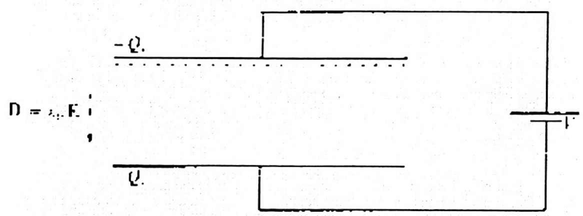
ε_r>1



(b)

Capacitor Voltage with Leakage

Consider decay of free charge:

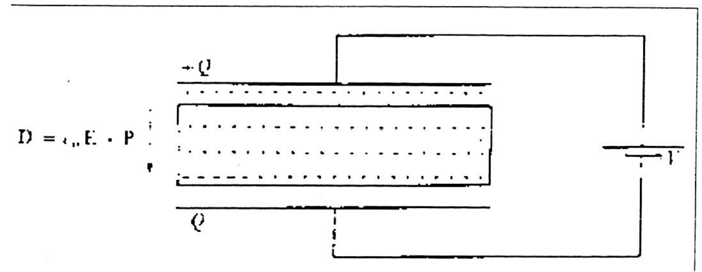


$$\sigma^{Free}(t) = \varepsilon_o E(t) = \frac{\varepsilon_o}{d} V(t) = \frac{\varepsilon_o}{d} V_o e^{-t/\tau_{DC}}$$
$$= \sigma_o^{Free} e^{-t/\tau_{DC}}, \quad with \quad \tau_{DC} = \rho_{DC}\, \varepsilon_o \varepsilon_r$$

$$\sigma^{Free}(t) = \varepsilon_o E(t) = \frac{\varepsilon_o}{d} V(t) = \frac{\varepsilon_o}{d} V_o e^{-t/\tau_{DC}}$$
$$= \sigma_o^{Free} e^{-t/\tau_{DC}}, \quad with \quad \tau_{DC} = \rho_{DC}\, \varepsilon_o \varepsilon_r$$

Capacitor Voltage with Polarization

Consider build-up of bound charge:



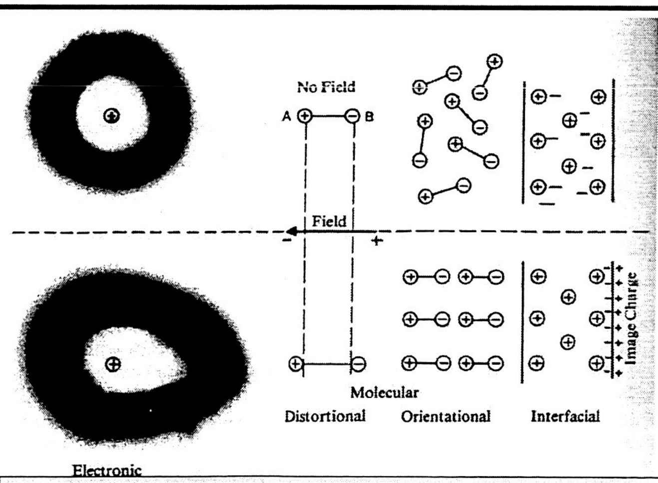
$$\varepsilon_r(t) = \left(1-\varepsilon_r^{\infty}\right)e^{-t/\tau_P} + \varepsilon_r^{\infty}\ ; \qquad \text{with } \tau_P = \rho_P \varepsilon_o \varepsilon_r^{\infty}$$

$$= -\frac{\sigma_{\infty}^{Bound}}{\sigma_{\infty}^{Free}} e^{-t/\tau_P} + \left(1+\frac{\sigma_{\infty}^{Bound}}{\sigma_{\infty}^{Free}}\right) = \frac{\sigma_{\infty}^{Bound}}{\sigma_{\infty}^{Free}}\left(1-e^{-t/\tau_P}\right)+1$$

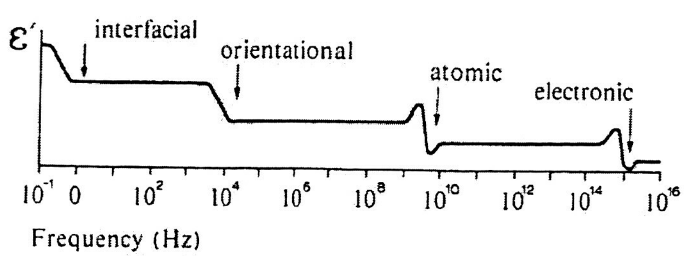
$$\varepsilon_r(t) = \left(\varepsilon_r^{o}-\varepsilon_r^{\infty}\right)e^{-t/\tau_P} + \varepsilon_r^{\infty}\ ; \qquad \text{with } \tau_P = \rho_P \varepsilon_o \varepsilon_r^{\infty}$$

$$= \left(\frac{\sigma_{o}^{Bound}}{\sigma_{o}^{Free}} - \frac{\sigma_{\infty}^{Bound}}{\sigma_{\infty}^{Free}}\right)e^{-t/\tau_P} + \left(1+\frac{\sigma_{\infty}^{Bound}}{\sigma_{\infty}^{Free}}\right)$$

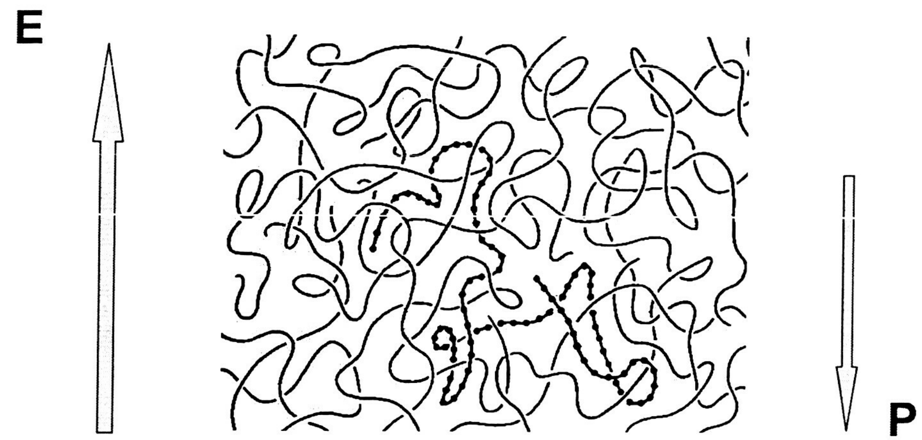
Polarization Time Scales and Mechanisms



← --- Fast ----------------------------- Slow --- →



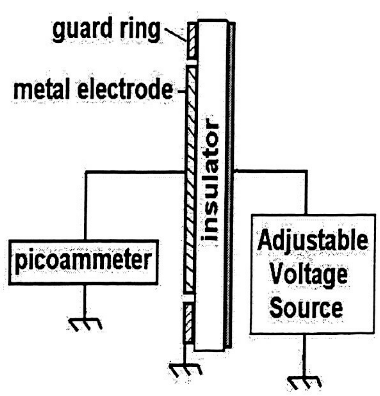
Polarization in Polymers



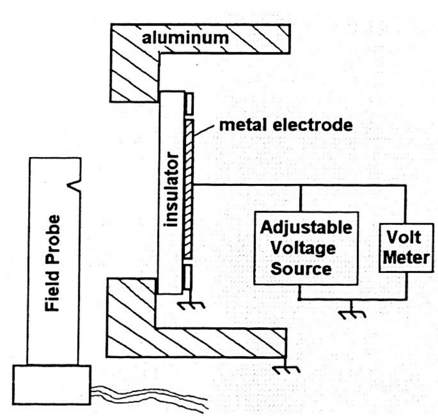
Dipolar sidegroups align with applied E-field through confirmation changes of polymer chains, inhibited by polymer entanglement.

Comparison of Resistivity Test Methods

ASTM Capacitor Method



Charge Storage Method

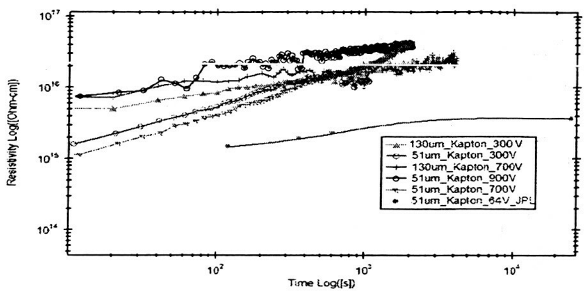


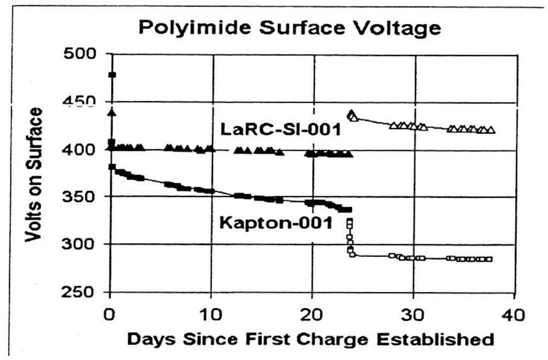
$\rho = 1 \times 10^{16}$ (ohm-cm) $\rho > 5 \times 10^{20}$

For measurements on same sample of polyimide

Comparison of Typical Resistivity Results

ASTM Capacitor Method | **Charge Storage Method**





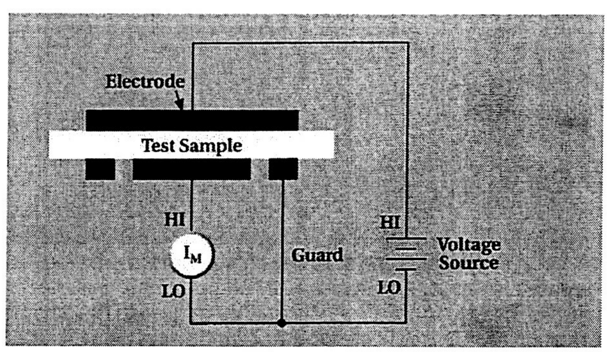
ρ = ~2×10^{16} (ohm-cm) $\rho > 5 \times 10^{19}$

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.



Charge:

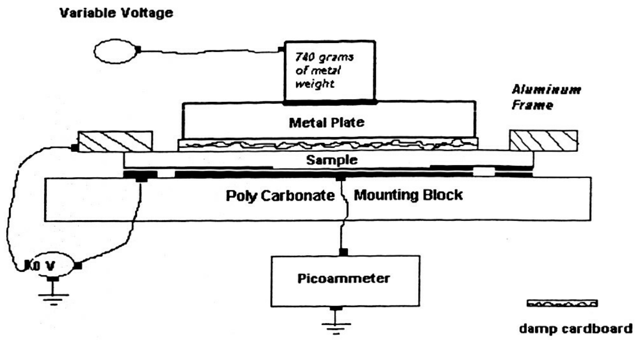
$$\sigma_{CV}^{Total}(t) = \varepsilon_o \varepsilon_r(t) E_{CV} = \frac{\varepsilon_o V_{CV}}{d}\left[\left(\varepsilon_r^o - \varepsilon_r^\infty\right) e^{-t/\tau_P} + \varepsilon_r^\infty\right]; \qquad \text{with } \tau_P = \rho_P \varepsilon_o \varepsilon_r^\infty$$

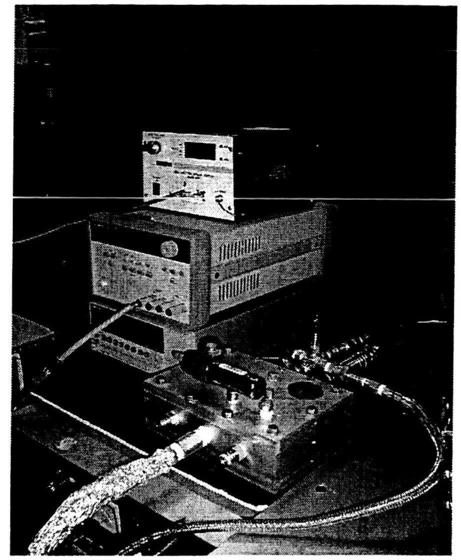
$$= \left(\sigma_o^{Bound} - \sigma_\infty^{Bound}\right) e^{-t/\tau_P} + \left(\sigma_{CV}^{Free} + \sigma_\infty^{Bound}\right)$$

Current:

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

Constant-voltage (ASTM) Resistivity: Instruments





Experimental setup of the classical ASTM method

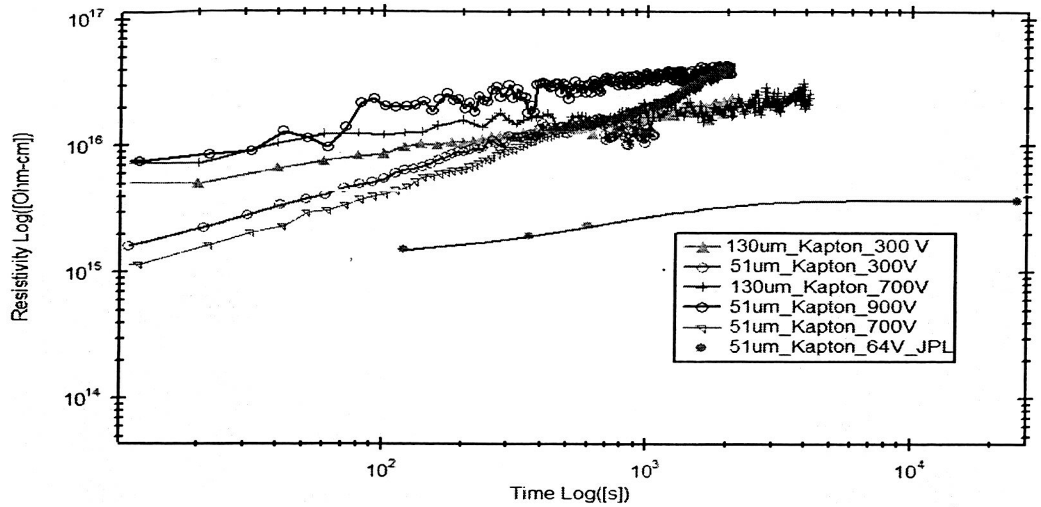
Constant-voltage (ASTM) Resistivity: Equations

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

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

where
t = time, seconds
t_P = polarization decay constant, seconds
t_{DC} = dark current decay constant, seconds
e_r^o = initial relative dielectric constant, F/m
e_r^{∞} = asmyptotic 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

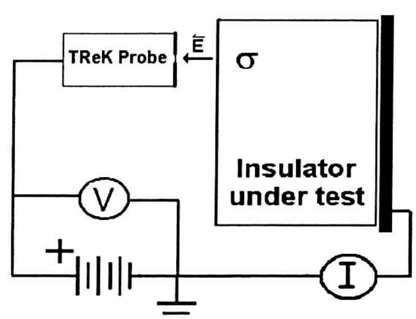


Pulsed

Charge Storage Resistivity: Methods

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

Less limited by small current measurements.

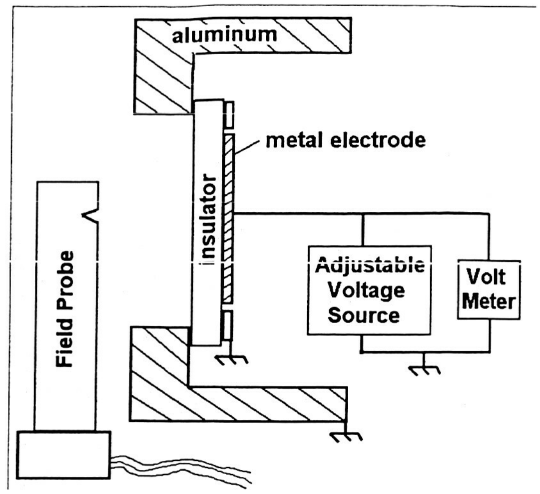


$$V_{CS}(t) = \frac{\sigma^{Total}(t)\, d}{\varepsilon_o} = \frac{\sigma^{Free}(t)\, d}{\varepsilon_o\, \varepsilon_r(t)}$$

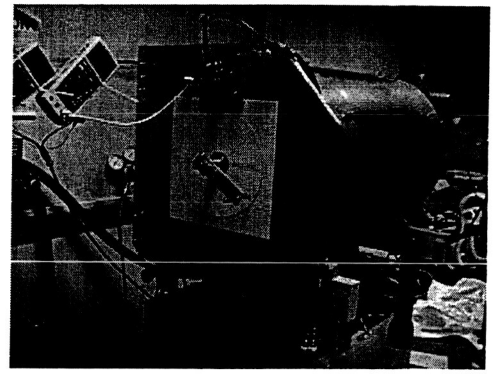
$$= \frac{d}{\varepsilon_o} \frac{\left(\sigma_o^{Free} - \sigma_\infty^{Free}\right) e^{-t/\tau_{DC}} + \sigma_\infty^{Free}}{\left(\frac{\sigma_o^{Bound}}{\sigma_o^{Free}} - \frac{\sigma_\infty^{Bound}}{\sigma_\infty^{Free}}\right) e^{-t/\tau_P} + \left(1 + \frac{\sigma_\infty^{Bound}}{\sigma_\infty^{Free}}\right)}, \quad with \quad \tau_{DC} = \rho_{DC}\, \varepsilon_o \varepsilon_r$$

$$V_{CS}(t) = \frac{\left[\left(V_o - V_\infty\right) e^{-t/\tau_{DC}} + V_\infty\right]}{\left(\varepsilon_r^o - \varepsilon_r^\infty\right) e^{-t/\tau_P} + \varepsilon_r^\infty}, \quad with \quad \tau_{DC} = \rho_{DC}\, \varepsilon_o \varepsilon_r$$

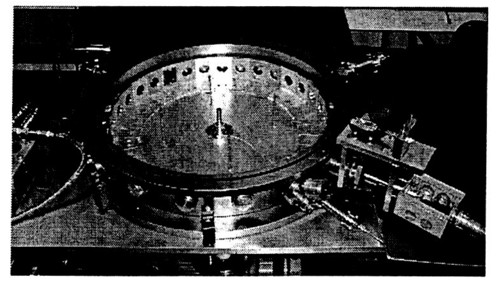
Charge Storage Resistivity: Instruments



Experimental setup of the charge storage method



JPL Test Chamber



USU Test Chamber

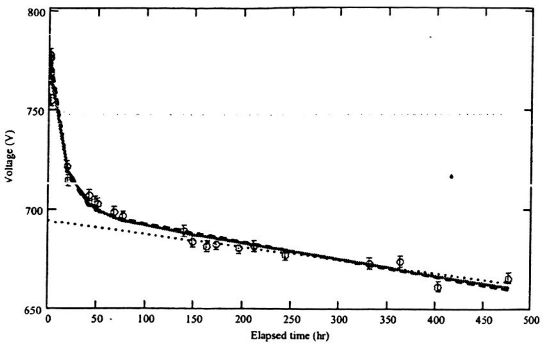
Charge Storage Resistivity: Equations

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

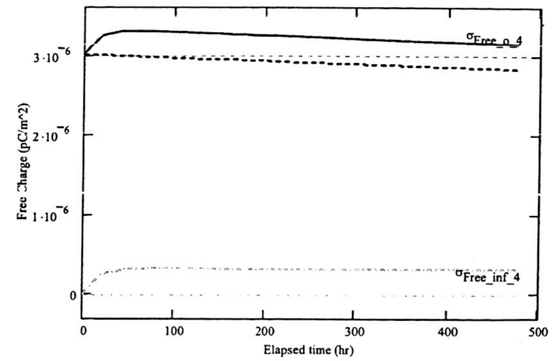
$$V_{CS}(t) = \frac{\left[\left(V_o - V_\infty\right)e^{-t/\tau_{DC}} + V_\infty\right]}{\left(\varepsilon_r^o - \varepsilon_r^\infty\right)e^{-t/\tau_P} + \varepsilon_r^\infty}, \qquad with \qquad \tau_{DC} = \rho_{DC}\,\varepsilon_o\varepsilon_r$$

where
t = time, seconds
t_P = polarization decay constant, seconds
t_{DC} = dark current decay constant, seconds
e_r^o = initial relative dielectric constant, F/m
e_r^∞ = asymptotic relative dielectric constant, F/m
Vo= initial voltage, volts
V_∞= asymptotic voltage, volt
C_o = capacitance of the sample with e=1, farads

Charge Storage Resistivity: Results for PTFE



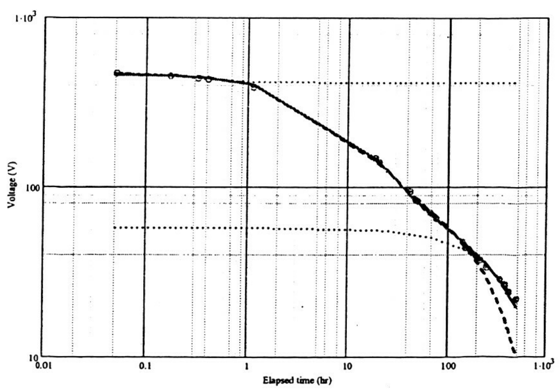
Voltage Decay Curve



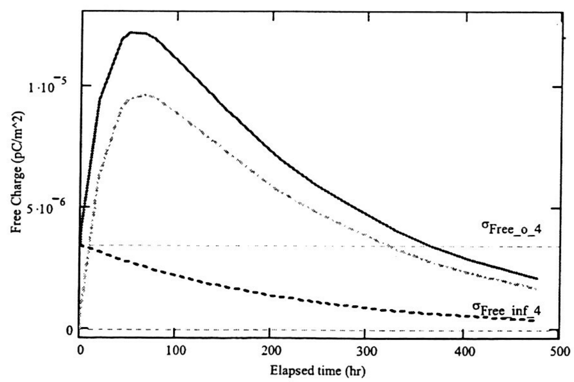
Charge Decay Curve

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

Charge Storage Resistivity: Results for FR4



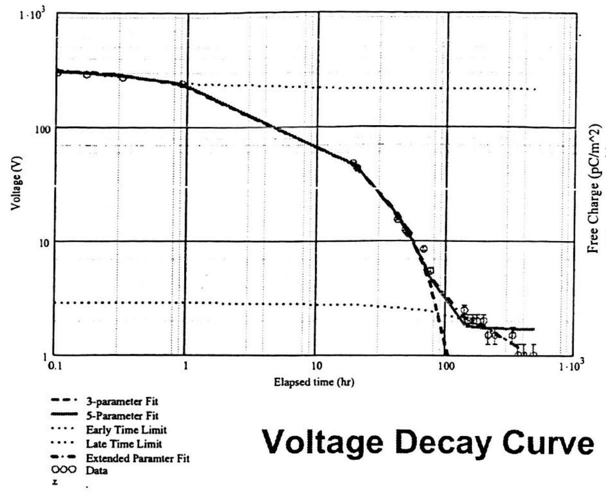
Voltage Decay Curve



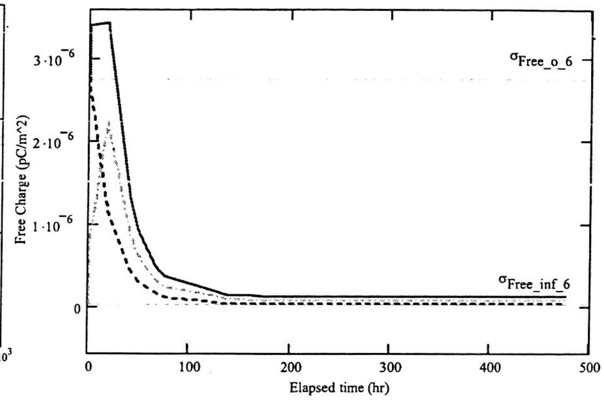
Charge Decay Curve

FR4 data: high stored current, modest dark current resistivity.

Charge Storage Resistivity: Results for Alumina



Voltage Decay Curve



Charge Decay Curve

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

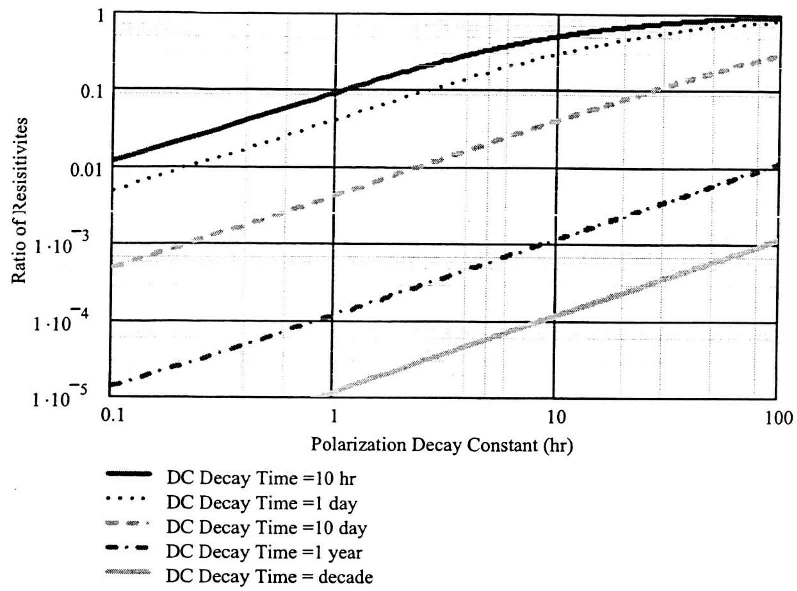
Charge Storage Resistivity: Summary of Results

Experimentally Determined Resistivity values for CRRES IDM samples

Material	Thickness (cm)	ε_r^o	ε_r^∞	V_o (volt)	V_∞ (volt)	τ_P (hr)	τ_{DC} (day)	$\rho_{5\ parameter}$ (Ω-cm)	$\rho_{3\ paramter}$ (Ω-cm)	$\rho_{5\ parameter}/\rho_{ASTM}$
PTFE	0.229	1.05	1.11	347	5.2	17.9	339	3.0×10^{20}	2.9×10^{20}	3×10^{2}
FR4	0.317	1.07	1.95	412	1.5	18.2	4.53	2.3×10^{18}	2.1×10^{18}	$<2\times10^{9}$
Alumina	0.102	1.02	3.00	423	4.7	6.35	21.3	2.9×10^{17}	3.0×10^{17}	3×10^{3}

Time Scales for Polarization

Ratio of resistivity measured at 1 min to the asymptotic limit of resistivity, ρ_{DC}, plotted as a function of polarization decay constant, τ_P



Instrument Resolution

Method	Maximum Detectable Resistance Values and Decay Time Constant[c]	Typical Maximum Measurable Values (±6%)			
		Resistance	Current	Resistivity	Decay Time Constant[d]
Digital Multimeter	$\sim 2\cdot10^{10}\ \Omega$ / ~5 sec[b,d]	$\sim 10^{10}\ \Omega$	$\sim 5\cdot10^{-9}$ A	$\sim 1\cdot10^{12}\ \Omega\cdot$cm	0.1 sec
Electrometer—Resistance	$\sim 10^{16}\ \Omega$ / ~3 days[b,d]	$\sim 10^{14}\ \Omega$[e]	$\sim 5\cdot10^{-12}$ A	$\sim 1\cdot10^{16}\ \Omega\cdot$cm	<45 min
Electrometer—Constant V	$\sim 5\cdot10^{17}\ \Omega$ / ~150 days[e]	$\sim 5\cdot10^{16}\ \Omega$	$\sim 1\cdot10^{-13}$ A[b,d]	$\sim 5\cdot10^{17}\ \Omega\cdot$cm	<1.5 day
Voltage Rate-of-change	$\sim 4\cdot10^{18}\ \Omega$ / ~3 yr ($R_{max}C=10^8\ \Omega\cdot F$)[b,e]	$\sim 4\cdot10^{16}\ \Omega$ ($R_{max}C=10^6\ \Omega\cdot F$)[c]	$\sim 1\cdot10^{-14}$ A	$\sim 4\cdot10^{18}\ \Omega\cdot$cm	<12 day
Charge Storage Decay	$\sim 1\cdot10^{20}\ \Omega$ / <70 yr ($R_{max}C=2\cdot10^9\ \Omega\cdot F$)[g]	$\sim 2\cdot10^{19}\ \Omega$ ($R_{max}C=4\cdot10^8\ \Omega\cdot F$)	$\sim 3\cdot10^{-17}$ A ($I_{min}=\Delta V/R_{max}$)[bf]	$\sim 2\cdot10^{21}\ \Omega\cdot$cm	<15 yr

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