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An Overview of the Dynamic Interplay between the Space Environment & Spacecraft Materials

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An Overview of the Dynamic Interplay between the Space Environment & Spacecraft Materials

JR Dennison

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Utah State University
Logan, Utah USA
Support & Collaborations

NASA SEE Program
JWST (GSFC/MSFC)
Solar Probe Mission (JHU/APL)
Rad. Belt Space Probe (JHU/APL)
Solar Sails (JPL)
AFRL
Boeing
Box Elder Innovations
Ball Aerospace
Orbital
LAM
USU Blood Fellowship
USU PDRF Fellowships
AFRL/NRC Fellowship
NASA Grad Res. Fellowships

USU MPG Webpage
Spacecraft Charging

The sun gives off high energy charged particles.

These particles interact with the Earth’s atmosphere and magnetic field in interesting ways.

High energy particles imbed charge into spacecraft surfaces.

Space environments affect spacecraft and their performance. How do we quantify these effects and mitigate degradation?
The Space Environment

Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging (min to decades)

- Solar Flares, CME, Solar Cycle
- Orbital eclipse, Rotational eclipse

Solar wind and Earth’s magneto-sphere structure.

Incident fluxes of:
- Electrons, $e^-$
- Ions, $I^+$
- Photons, $\gamma$
- Particles, $m$

Typical Space Electron Flux Spectra [Larsen].

Solar Electro-magnetic Spectrum.
Conductivity
Electrostatic Discharge
Induced Arcing
Pulsed Electroacoustics

Electron Induced Emission
Ion Induced Emission
Photon Induced Emission: Cathodoluminescence

Radiation Damage
Environmental Simulations
Sample Characterization & Preparation

Environment Conditions ↔ Materials Conditions ↔ Materials Properties ↔ Spacecraft Charging
Some Unsolicited Advice for Students (and an outline for the talk)

- Define the problem
- Develop useful skills
  - Advanced knowledge
  - Experimental skills
  - Modeling skills to tie these together
  - Breadth to recognize important trends
- Keep your eyes open!

Let me share four examples
Primary Motivation For Our Research—Spacecraft Charging

NASA’s concern for spacecraft charging is caused by plasma environment electron, ion, and photon-induced currents. Charging can cause performance degradation or complete failure.

Majority of all spacecraft failures and anomalies due to the space environment result from plasma-induced charging

- Single event interrupts of electronics
- Arching
- Sputtering
- Enhanced contamination
- Shifts in spacecraft potentials
- Current losses
Where Materials Testing Fits into the Solution

Charge Accumulation
- Electron yields
- Ion yields
- Photoyields

Charge Transport
- Conductivity
- RIC
- Dielectric Constant
- ESD

As functions of materials species, flux, and energy.

Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging
- Solar Flares
- Rotational eclipse

Complex dynamic interplay between space environment, satellite motion, and materials properties
Integration with Spacecraft Charging Models

SEE Handbook or NASCAP predicts on-orbit spacecraft charging in GEO and LEO environments

Typical SEE Handbook Simulation
What do you need to know about the materials properties?

**STATIC** Charging codes such as NASCAP-2K SPENVIS, or MUSCAT and NUMIT2 or DICTAT require:

**Charge Accumulation**
- Electron yields
- Ion yields
- Photoyields
- Luminescence

**Charge Transport**
- Conductivity
- RIC
- Permittivity
- Electrostatic breakdown
- Penetration range

**ABSOLUTE values as functions of materials species, flux, fluence, and energy.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] Relative dielectric constant; $\varepsilon_r$ (Input as 1 for conductors)</td>
<td>1, NA</td>
</tr>
<tr>
<td>[2] Dielectric film thickness; $d$</td>
<td>0 m, NA</td>
</tr>
<tr>
<td>[3] Bulk conductivity; $\sigma_o$ (Input as -1 for conductors)</td>
<td>$-1; (4.26 \pm 0.04) \cdot 10^7 \text{ohm}^{-1}\cdot\text{m}^{-1}$</td>
</tr>
<tr>
<td>[4] Effective mean atomic number $&lt;Z_{\text{eff}}&gt;$</td>
<td>50.9 ± 0.5</td>
</tr>
<tr>
<td>[5] Maximum SE yield for electron impact; $\delta_{\text{max}}$</td>
<td>1.47 ± 0.01</td>
</tr>
<tr>
<td>[6] Primary electron energy for $\delta_{\text{max}}$; $E_{\text{max}}$</td>
<td>$(0.569 \pm 0.07) \text{keV}$</td>
</tr>
<tr>
<td>[7] First coefficient for bi-exponential range law, $b_1$</td>
<td>1 Å, NA</td>
</tr>
<tr>
<td>[8] First power for bi-exponential range law, $n_1$</td>
<td>1.39 ± 0.02</td>
</tr>
<tr>
<td>[9] Second coefficient for bi-exponential range law, $b_2$</td>
<td>0 Å</td>
</tr>
<tr>
<td>[10] Second power for bi-exponential range law, $n_2$</td>
<td>0</td>
</tr>
<tr>
<td>[11] SE yield due to proton impact $\delta''(1\text{keV})$</td>
<td>$0.3364 \pm 0.0003$</td>
</tr>
<tr>
<td>[12] Incident proton energy for $\delta''<em>{\text{max}}$; $E''</em>{\text{max}}$</td>
<td>$(1238 \pm 30) \text{keV}$</td>
</tr>
<tr>
<td>[13] Photoelectron yield, normally incident sunlight, $j_{\text{pho}}$</td>
<td>$(3.64 \pm 0.4) \cdot 10^5 \text{A}^{-2}\cdot\text{m}^{-2}$</td>
</tr>
<tr>
<td>[14] Surface resistivity; $\rho_s$ (Input as -1 for non-conductors)</td>
<td>$-1 \text{ohms-square}^{-1}$, NA</td>
</tr>
<tr>
<td>[15] Maximum potential before discharge to space; $V_{\text{max}}$</td>
<td>10000 V, NA</td>
</tr>
<tr>
<td>[16] Maximum surface potential difference before dielectric breakdown discharge; $V_{\text{punch}}$</td>
<td>2000 V, NA</td>
</tr>
<tr>
<td>[17] Coefficient of radiation-induced conductivity, $\sigma_{\gamma}$; $k$</td>
<td>$0 \text{ohms}^{-1}\cdot\text{m}^{-1}$, NA</td>
</tr>
<tr>
<td>[18] Power of radiation-induced conductivity, $\sigma_{\gamma}$; $\Delta$</td>
<td>0, NA</td>
</tr>
</tbody>
</table>
Spacecraft Assembly Facilities

Curtesy of NASA JPL
Spacecraft Materials and Uses

This large communication satellite incorporates materials which are contained in SUSpECS.

- Graphite Composite
- Au/Mylar
- Kapton
- Black Kapton
- Aquadag
- Al
- White Paint
- ITO
- RTV
- FR4
- Coverglass

Curtesy of JAXA

<table>
<thead>
<tr>
<th>SUSpECS Material Samples List</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Source</td>
</tr>
<tr>
<td>G01 COIC AS/N720 Oxide</td>
<td>ATK</td>
</tr>
<tr>
<td>G02 COIC S360 Nonoxide CMC</td>
<td>ATK</td>
</tr>
<tr>
<td>G03 Thiolol Carbon-Carbon Composite #1</td>
<td>ATK</td>
</tr>
<tr>
<td>G04 Thiolol Carbon-Carbon Composite #2</td>
<td>ATK</td>
</tr>
<tr>
<td>G05 Thiolol Fiber Filled Carbon-Carbon Composite</td>
<td>ATK</td>
</tr>
<tr>
<td>G06 Thiolol Carbon-Phenolic Composite</td>
<td>ATK</td>
</tr>
<tr>
<td>G07 Thiolol Graphite Epoxy Foil - No Hole</td>
<td>ATK</td>
</tr>
<tr>
<td>G08 Thiolol Graphite Epoxy Foil - With Hole</td>
<td>ATK</td>
</tr>
<tr>
<td>G09 COIC S460 Nonoxide CMC</td>
<td>ATK</td>
</tr>
<tr>
<td>G10 COIC S200H Nonoxide CMC</td>
<td>ATK</td>
</tr>
<tr>
<td>G11 COIC S360 Nonoxide CMC</td>
<td>ATK</td>
</tr>
<tr>
<td>I01 Kapton on Aluminum</td>
<td>Sheldahl</td>
</tr>
<tr>
<td>I02 Teflon on Aluminum</td>
<td>Sheldahl</td>
</tr>
<tr>
<td>I03 Mylar on Aluminum</td>
<td>Sheldahl</td>
</tr>
<tr>
<td>I04 Nylon 6/6</td>
<td>McMaster-Carr</td>
</tr>
<tr>
<td>I06 SiO₂ (Fused Quartz)</td>
<td>UGG Optics</td>
</tr>
<tr>
<td>I07 Al₂O₃ (Sapphire)</td>
<td>UGG Optics</td>
</tr>
<tr>
<td>I11 Germanium on Kapton</td>
<td>Sheldahl</td>
</tr>
<tr>
<td>I12 Anodized Aluminum</td>
<td>NASA / MSFC</td>
</tr>
<tr>
<td>I13 Anodized Aluminum</td>
<td>NASA / MSFC</td>
</tr>
<tr>
<td>I14 UV Ce-doped Cover Glass</td>
<td>OCLI</td>
</tr>
<tr>
<td>I15 FR4 Printed Circuit Board Material</td>
<td>CRRES NASA</td>
</tr>
<tr>
<td>I18 CV-1147 RTV on Copper</td>
<td>Boeing</td>
</tr>
<tr>
<td>I19 Q3/3-500 RTV on Copper</td>
<td>Boeing</td>
</tr>
<tr>
<td>28 Borosilicate Glass</td>
<td>UGG Optics</td>
</tr>
<tr>
<td>T01 Gold (99.99% Purity)</td>
<td>ESPI</td>
</tr>
<tr>
<td>T02 Aluminum (99.99% Purity)</td>
<td>ESPI</td>
</tr>
<tr>
<td>T03 316 Stainless Steel</td>
<td>McMaster</td>
</tr>
<tr>
<td>T04 Gold(2um)/Nickel(2um)</td>
<td>Gold Plating</td>
</tr>
<tr>
<td>T05 OFHC Copper (99.9% Purity)</td>
<td>McMaster</td>
</tr>
<tr>
<td>T06 Silver (99% Purity)</td>
<td>United Material</td>
</tr>
<tr>
<td>T07 Inconel on Silver on Teflon on ITO</td>
<td>Sheldahl</td>
</tr>
<tr>
<td>T08 p-c (Graphite Amorphous Carbon) on Copper</td>
<td>Arizona Carbon</td>
</tr>
<tr>
<td>T11 Aquadag on Copper</td>
<td>LADD Research</td>
</tr>
<tr>
<td>T12 100XC Black Kapton</td>
<td>Sheldahl</td>
</tr>
<tr>
<td>T13 Thick Film Black</td>
<td>Sheldahl</td>
</tr>
<tr>
<td>T14 TO on Teflon on Inconel</td>
<td>Sheldahl</td>
</tr>
<tr>
<td>26 White Paint (Zinc Oxide Thermal Control Paint)</td>
<td>SDL</td>
</tr>
<tr>
<td>27 Composite (GIFTS Carbon Composite)</td>
<td>SDL</td>
</tr>
</tbody>
</table>
Dale Ferguson’s “New Frontiers in Spacecraft Charging”

#1 Non-static Spacecraft Materials Properties
#2 Non-static Spacecraft Charging Models

These result from the complex dynamic interplay between space environment, satellite motion, and materials properties.

Specific focus of this talk is the change in materials properties as a function of:

- Time (Aging), $t$
- Temperature, $T$
- Accumulated Energy (Dose), $D$
- Dose Rate, $\dot{D}$
- Accumulated Charge, $\Delta Q$ or $\Delta V$
- Charge Profiles, $Q(z)$
- Charge Rate (Current), $\dot{Q}$
- Conductivity Profiles, $\sigma(z)$
Case Study One

The Poster Child for Space Environment Effects

It is important that students bring a certain ragamuffin barefoot irreverence to their studies; they are not here to worship what is known, but to question it.

—Jacob Bronowski, The Ascent of Man
SUSpECS on MISSE 6

The International Space Station with SUSpECS just left of center on the Columbus module.

Deployed
March 2008
STS-123

Retrieved
August 2009
STS-127
SUSpeCS Samples on the ISS

MISSE 6 exposed to the space environment. The SUSpeCS double stack can be seen in the bottom center of the lower case. The picture was taken on the fifth EVA, just after deployment.
Evolution of Contamination and Oxidation

Before | After
--- | ---
Kapton, HN

Before | After
--- | ---
Ag

Before | After
--- | ---
Black Kapton

Before | After
--- | ---
Ag coated Mylar with micrometeoroid impact
Evolution of Materials Properties

Ag coated Mylar

- Atomic Oxygen removes Ag
- UV Yellows clear PET
- Micrometeoroid impact
- Continued aging

Dynamic changes in materials properties are clearly evident.

How will changes affect performance?

How will changes affect other materials properties?
Study of Materials Properties

UV Exposure

Atomic Oxygen Exposure

Electron Flux Exposure

Hypervelocity Impact
Case Study Two

A Grand Tour of Space Environments and Their Effects

Know the physics of your problem

“We anticipate significant thermal and charging issues.”

J. Sample
A Puzzle from Solar Probe Plus: Temperature and Dose Effects

**Wide Temperature Range**

<100 K to >1800 K

**Wide Dose Rate Range**

Five orders of magnitude variation!

**Wide Orbital Range**

Earth to Jupiter Flyby

Solar Flyby to 4 $R_s$

**Charging Study by Donegan, Sample, Dennison and Hoffmann**
A Very Wide Range of Environmental Conditions

Wide Orbital Range
Earth to Jupiter Flyby
Solar Flyby to 4 $R_s$

Wide Temperature Range
<100 K to >1800 K

Wide Dose Rate Range
Five orders of magnitude variation!
Temperature Effects on Materials Properties

Strong T Dependence for Insulators

Charge Transport
- Conductivity
- RIC
- Dielectric Constant
- ESD

Examples:

IR and X-Ray Observatories
JWST, WISE, WMAP, Spitzer, Herscel, IRAS, MSX, ISO, COBE, Planck

Outer Planetary Mission
Galileo, Juno, JEO/JGO, Cassini, Pioneer, Voyager,

Inner Planetary Mission
SPM, Ulysses, Magellan, Mariner
Radiation Effects

Large Dosage (>10^8 Rad)

Medium Dosage (>10^7 Rad)

Low Dose Rate (>10^0 Rad/s)

“...Earth is for Wimps…” H. Garrett

Examples: RBSP, MMS, JUNO, JGO/JEO

“...auroral fields may cause significant surface charging...” H. Garrett

Examples: RBSP, MMS, JUNO, JGO/JEO

Mechanical and Optical Materials Damage
**Combined Temperature and Dose Effects**

**Dark Conductivity vs T**

\[
\sigma_{DC}(T) = \sigma_0^{DC} e^{-\frac{E_o}{k_B T}}
\]

**RIC**

\[
\sigma_{RIC}(T) = k_{RIC}(T) \Delta(T)
\]

**Dielectric Constant**

\[
\varepsilon_r(T) = \varepsilon_{RT} + \Delta \varepsilon (T - 298 K)
\]

**Electrostatic Breakdown**

\[
E_{ESD}(T) = E_{ESD}^{RT} e^{-\alpha_{ESD}(T-298 K)}
\]
Charging Results: Temperature and Dose Effects

Modeling found a peak in charging at ~0.3 to 2 AU
Explanation of the Temperature and Dose Effects

**General Trends**

- **Dose rate decreases as** $\sim r^{-2}$
- **$T$ decreases as** $\sim e^{-r}$
- **$\sigma_{DC}$ decreases as** $\sim e^{-1/T}$
- **$\sigma_{RIC}$ decreases as** $\sim e^{-1/T}$
- and decreases as $\sim r^{-2}$

**A fascinating trade-off**

- **Charging** increases from increased dose rate at closer orbits
- **Charge dissipation** from $T$-dependant conductivity increases faster at closer orbits
Case Study Three

Electron Transport Measurements and Spacecraft Charging

Unexpected consequences from unexpected sources
Spacecraft adopt potentials in response to interaction with the plasma environment.

- **Incident fluxes and electron emission govern amount of charge accumulation**

- **Resistivity governs:**
  - Where charge will accumulate
  - How charge will redistribute across spacecraft
  - Time scale for charge transport and dissipation

- **Conservation of charge implies:**

\[
Q_{\text{net}} = \{ Q_{\text{Incident}} - Q_{\text{Emitted}} \}
\]
Orbit Time and Charge Decay Time

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

\[ \tau = \rho \varepsilon_r \varepsilon_0 \]

1 hr \( \rightarrow \rho \varepsilon_0 \sim 4 \cdot 10^{16} \text{ } \Omega\text{-cm} \)

1 day \( \rightarrow \rho \varepsilon_0 \sim 1 \cdot 10^{18} \text{ } \Omega\text{-cm} \)

1 yr \( \rightarrow \rho \varepsilon_0 \sim 4 \cdot 10^{20} \text{ } \Omega\text{-cm} \)

10 yr \( \rightarrow \rho \varepsilon_0 \sim 4 \cdot 10^{21} \text{ } \Omega\text{-cm} \)

Typical orbits from 1 to 24 hours.
Critical Time Scales and Resistivities

Range of Charge Storage Method

- 1 min $\rightarrow \rho \cdot \varepsilon_o \sim 1 \cdot 10^{15} \ \Omega\cdot\text{cm}$
- 1 hr $\rightarrow \rho \cdot \varepsilon_o \sim 4 \cdot 10^{16} \ \Omega\cdot\text{cm}$
- 1 day $\rightarrow \rho \cdot \varepsilon_o \sim 1 \cdot 10^{18} \ \Omega\cdot\text{cm}$
- 1 yr $\rightarrow \rho \cdot \varepsilon_o \sim 4 \cdot 10^{20} \ \Omega\cdot\text{cm}$
- 10 yr $\rightarrow \rho \cdot \varepsilon_o \sim 4 \cdot 10^{21} \ \Omega\cdot\text{cm}$
- 500 yr $\rightarrow \rho \cdot \varepsilon_o \sim 1 \cdot 10^{23} \ \Omega\cdot\text{cm}$

Decay time vs. resistivity based on simple capacitor model.

$$\tau = \rho \cdot \varepsilon_r \cdot \varepsilon_0$$
Extremely Low Conductivity

Constant Voltage Conductivity

- Time evolution of conductivity
- $<10^{-1}$ s to $>10^{6}$ s
- ±200 aA resolution
- $>5 \cdot 10^{22}$ $\Omega$-cm
- $\sim 100$ K $< T < 375$ K
Constant Voltage Conductivity

Constant Voltage Chamber configurations inject a continuous charge via a biased surface electrode with no electron beam injection.

- Polarization
- Diffusion
- Pre-Transit
- Dark Current
\[ \sigma(t) = \sigma_{DC} \left[ 1 + \frac{\sigma_{AC}(\nu)}{\sigma_{DC}} + \frac{\sigma_{\text{pol}}}{\sigma_{DC}} e^{t_{\text{pol}}} + \frac{\sigma_{\text{diffusion}}}{\sigma_{DC}} t^{-1} + \frac{\sigma_{\text{dispersive}}}{\sigma_{DC}} t^{-(1-\alpha)} + \frac{\sigma_{\text{transit}}}{\sigma_{DC}} t^{-(1+\alpha)} + \frac{\sigma_{\text{RIC}}}{\sigma_{DC}} \left( 1 - e^{-\tau_{\text{RIC}}/(t-t_{on})} \right) \left( 1 + \frac{(t - t_{off})}{\tau_{\text{RIC}}^{2}} \right)^{-1} \right] \]

- **Dark current or drift conduction** — Defect density, \( N_T \), and \( E_d \approx 1.08 \text{ eV} \)
- **Diffusion-like and dispersive conductivity** — Energy width of trap distribution, \( \alpha \)
- **Radiation induced conductivity** — Shallow trap density and \( \varepsilon_{\text{ST}} \)
- **Polarization** — Rearrangement of bound charge, \( \varepsilon_{\infty} \varepsilon_o \) and \( \tau_{\text{pol}} \)
- **AC conduction** — Dielectric response, \( \varepsilon_r (\nu) \varepsilon_o \)
\[ \sigma(t) = \sigma_{DC} \left[ 1 + \frac{\sigma_{AC}(v)}{\sigma_{DC}} + \frac{\sigma_{pol}}{\sigma_{DC}} e^{-\frac{t}{\tau_{pol}}} + \frac{\sigma_{diffusion}}{\sigma_{DC}} t^{-1} + \right] \]

- **\( \sigma_{DC} \equiv q_{e} n_{e} \mu_{e} \)** dark current or drift conduction—very long time scale equilibrium conductivity.
- **\( \sigma_{AC}(v) \equiv \sum_{i} \left[ (\varepsilon_{r} (v) - \varepsilon_{r}^{0}) \varepsilon_{o} \frac{1}{1+(v/v_{i})^{2}} \right] \)** frequency-dependent AC conduction—dielectric response to a periodic applied electric field.
- **\( \sigma_{pol}(t) \equiv \left[ (\varepsilon_{r}^{\infty} - \varepsilon_{r}^{0}) \varepsilon_{o} / \tau_{pol} \right] e^{-\frac{t}{\tau_{pol}}} \)** long time exponentially decaying conduction due to polarization.
- **\( \sigma_{diffusion}(t) \equiv \sigma_{0}^{diffusion} \cdot t^{-1} \)** diffusion-like conductivity from gradient of space charge spatial distribution.
- **\( \sigma_{dispersive}(t) \equiv \left\{ \begin{array}{ll} \sigma_{0}^{dispersive} \cdot t^{-(1-\alpha)} & ; (for \ t < \tau_{transit}) \\ \sigma_{transit}(t) \equiv \sigma_{0}^{transit} \cdot t^{(1+\alpha)} & ; (for \ t > \tau_{transit}) \end{array} \right. \)** broadening of spatial distribution of space charge through coupling with energy distribution of trap states.
- **\( \sigma_{RIC}(t; \dot{D}, \tau_{RIC}^{1}, \tau_{RIC}^{2}) \equiv \sigma_{0}^{RIC}(\dot{D}(t)) \left( 1 - e^{-\tau_{RIC}^{1}/(\tau_{on}-t)} \right) \left( 1 + (t - t_{off}) / \tau_{RIC}^{2} \right)^{-1} \)** radiation induced conductivity term resulting from energy deposition within the material.

Refer to (Wintle, 1983), (Dennison et al., 2009), and (Sim, 2012)
**CRRES IDM Pulse and Environmental Data**

A. Robb Frederickson & Donald H. Brautigam

- Characterize electron flux data
- Model charge profile from dose rate and stopping power
- Calculate internal electric field
- Model transport with measured resistivity
- Predict pulsing rate and amplitude with only environment data, materials parameters, and Maxwell equations !!!

<table>
<thead>
<tr>
<th>Dark Conductivity</th>
<th>Radiation-Induced Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>typical =5x10^{-18} (\Omega\cdot m)^{-1}</td>
<td>typical = 0.3x 10^{-18} (\Omega\cdot m)^{-1}</td>
</tr>
<tr>
<td>improved 5x10^{-19} (\Omega\cdot m)^{-1}</td>
<td>“improved” same as typical</td>
</tr>
<tr>
<td>best guess 1.7x10^{-19} (\Omega\cdot m)^{-1}</td>
<td>best guess same as typical</td>
</tr>
</tbody>
</table>

Sample 8 in its mounting on the CRRES spacecraft.

Dark Conductivity Radiation-Induced Conductivity
typical =5x10^{-18} (\Omega\cdot m)^{-1}
typical = 0.3x 10^{-18} (\Omega\cdot m)^{-1}

Improved 
5x10^{-19} (\Omega\cdot m)^{-1}

“improved” same as typical

Best guess 
1.7x10^{-19} (\Omega\cdot m)^{-1}

Best guess same as typical

CRRES IDM Pulse and Environmental Data

Electric Field, V/m

Pulse Rate, #/10-hr

Orbit Number

At Front

At Rear

Typical Sample

Improved Sample

Typical Sample

Typical Sample
Surface Voltage Charging and Discharging

Uses pulsed non-penetrating electron beam injection with no bias electrode injection.

Fits to exclude AC, polarization, transit and RIC conduction.

Yields $N_T$, $E_d$, $\alpha$, $\varepsilon_{ST}$

$\sigma(t) = \sigma_0 \left\{ 1 + \left[ \frac{\sigma_{\text{diffusion}}^0}{\sigma_0} \right] t^{-1} + \left[ \frac{\sigma_{\text{dispersive}}^0}{\sigma_0} \right] t^{(1-\alpha)} \right\}$

Charging

$$V_s(t) = \frac{[q_e \eta t_{\text{max}}^\text{max} \varepsilon_0 \varepsilon_r [1-\gamma(E_b)]] [R(E_b)D \left( 1 - \frac{R(E_b)}{2D} \right)] [\varepsilon_0 \varepsilon_r t_{\text{max}}^\text{max}]}{\left\{ 1 + \left( \frac{t \sigma_0}{\varepsilon_0 \varepsilon_r} \right) \cdot \left[ 1 + \frac{\sigma_{\text{diffusion}}^0}{\sigma_0} (t^{-1}) + \frac{\sigma_{\text{dispersive}}^0}{\sigma_0} (t^{(1-\alpha)}) \right] \right\}^{-1}}$$

Discharge

$V(t) = V_0 e^{-t \sigma(t) / \varepsilon_0 \varepsilon_r}$

$\approx V_0 \left\{ 1 - \left[ \frac{\sigma_0}{\varepsilon_0 \varepsilon_r} t \right] \left\{ 1 + \left[ \frac{\sigma_{\text{diffusion}}^0}{\sigma_0} \right] t^{-1} + \left[ \frac{\sigma_{\text{dispersive}}^0}{\sigma_0} \right] t^{(1-\alpha)} \right\} \right\}^{-1}$
Disorder introduces localized states in the gap

Delocalized in real space

Localized in momentum space

\[ |\psi(r)|^2 \]

Position \( r \)

\[ |\psi(q)|^2 \]

Momentum \( q \)

A quantum mechanical model of the spatial and energy distribution of the electron states
Tunneling Between Traps—and Mott Anderson Transitions

Anderson transition between extended Bloch states and localized states caused by variations in well depth affects tunneling between states.

Mott transition between extended Bloch states and localized states caused by variations in well spacing which affects tunneling between states.


Low Temperature Cryostat

Used with:
- Constant Voltage Cond.
- RIC
- SEE/BSE
- Cathodoluminescence
- Arcing
- Surface Voltage Probe

Closed Cycle He Cryostat
- $35 \text{ K} < T < 350 \text{ K}$
- ±0.5 K for weeks
- Multiple sample configurations

Radiation Sources
A Electron Gun

Sample Mount
B Sample Pedestal
C Sample
D Sample Mount
E Sample Mask Selection Gear
F Interchangeable Sample Holder
G In situ Faraday Cup
H Spring – Loaded Electrical Connections
I Temperature Sensor
J Radiation Shield

Analysis Components
K UV/Vis/NIR Reflectivity Spectrometers
L CCD Video Camera (400-900 nm)
M InGaAs Video Camera (800-1200 nm)
N InSb Video Camera (1000-5000 nm)
O SLR CCD Camera (300-800 nm)
P Fiber Optic Discrete Detectors
Q Collection Optics

Instrumentation (Not Shown)
Data Acquisition System
Temperature Controller
Electron Gun Controller
Electrometer
Oscilloscope

Chamber Components
R Multilayer Thermal Insulation
S Cryogen Vacuum Feedthrough
T Electrical Vacuum Feedthrough
U Sample Rotational Vacuum Feedthrough
V Turbomolecular/Mech. Vacuum Pump
W Ion Vacuum Pump
X Ion/Convectron Gauges – Pressure
Y Residual Gas Analyzer – Gas Species
ESD: Limit of Conductivity at High Fields

LDPE 20 µm

Kapton 20 µm
F_{ESD} Breakdown: Dual (Shallow and Deep) Defect Model

Yields:
Ratio of Defect energy to Trap density, $\Delta G_{\text{def}}/N_T$
Separate these with $T$ dependence
$\Delta G_{\text{def}} = 0.97 \text{ eV}$
$N_T = 1 \cdot 10^{17} \text{ cm}^{-3}$

$F_{\text{ESD}} = 20 \pm 2 \text{ MV/m at RT}$
$F_{\text{ESD}} = 27 \pm 2 \text{ MV/m at 157 K}$
$F_{\text{ESD}} = 19.0 \pm 0.6 \text{ MV/m at RT and 142 K (irradiated)}$

Endurance time measurements:

$$t_{en}(F, T) = \left( \frac{h}{2k_bT} \right) \exp \left[ \frac{\Delta G_{\text{def}}(F, T)}{k_bT} \right] \text{csch} \left[ \frac{F^2 \varepsilon_0 \varepsilon_r}{2k_bT N_{\text{def}}(F, T)} \right]$$
RIC chamber uses a combination of charge injected by a biased surface electrode with simultaneous injection by a pulsed penetrating electron.
Complementary Responses to Radiation

Modified Joblonski diagram

- VB electrons excited into CB by the high energy incident electron radiation.
- They relax into shallow trap (ST) states, then thermalize into lower available long-lived ST.
- Three paths are possible:

(i) relaxation to deep traps (DT), with concomitant photon emission;
(ii) radiation induced conductivity (RIC), with thermal re-excitation into the CB; or
(iii) non-radiative transitions or e⁻-h⁺ recombination into VB holes.
RIC T-Dependence

Shallow Trap DOS Profile
Exponential DOS Below $E_c$

Effective Fermi Level
$E_F^{\text{eff}} = 24 \text{ meV}$

Uniform Trap Density
Exponential Trap Density

\[
\sigma_{\text{RIC}}(T, D) = k_{\text{RIC}}(T) \cdot D^{\Delta(T)}
\]

$\Delta(T) \rightarrow 1$

$\Delta(T) \rightarrow \frac{T_c}{T + T_c}$

$k(T) \rightarrow k_{\text{RICO}}$

$k(T) \rightarrow k_{\text{RIC1}} \left[ \frac{2 \left( \frac{m_e k_B T}{2 \pi \hbar^2} \right)^{3/2} \left( \frac{m_e^* m_{h}}{m_e m_e} \right)^{3/4}}{T + T_c} \right]^{T}$

Temperature (K)
High energy cosmic rays interacting with the upper atmosphere decay into Muons that are present at the surface. Due to interactions with the atmosphere, they have a decay rate that is proportional to the altitude. With this correlation we were able to determine counts per minute on the order of ~1/hour in Logan Utah (altitude 1370 m). Fig. 2 also shows an angle dependence though the muon's decay.

Decay of cosmic rays into muons [Drake 2012]
Case Study Four

Electron Induced Arcing and Unexpected Consequences

“JR, could you come downstairs to the lab for a minute?”
Case Four: JWST—Electron-Induced Arcing

JWST

Very Low Temperature
Virtually all insulators go to infinite resistance—perfect charge integrators

Long Mission Lifetime (10-20 yr)
No repairs
Very long integration times

Large Sunshield
Large areas
Constant eclipse with no photoemission

Large Open Structure
Large fluxes
Minimal shielding

Variation in Flux
Large solar activity variations
In and out of magnetotail

Complex, Sensitive Hardware
Large sensitive optics
Complex, cold electronics
Diversity of Emission Phenomena in Time Domain

**Surface Glow**
- Relatively low intensity
- Always present over full surface when e-beam on
- May decay slowly with time

**Edge Glow**
- Similar to Surface Glow, but present only at sample edge

**“Flare”**
- 2-20x glow intensity
- Abrupt onset
- 2-10 min decay time

**Arc**
- Relatively very high intensity
- 10-1000X glow intensity
- Very rapid <1 us to 1 s
Photon Emission Measurements

Luminescence/Arc/Flare Test Configuration

- Absolute spectral radiance
- ~200 nm to ~5000 nm
- 4 cameras (CCD, iiCCD, InGaAs, InSb)
- Discreet detectors filters
- 2 Spectrometers (~200 nm to ~1900 nm)
- e⁻ at ~1 pA/cm² to ~10 uA/cm² & ~20 eV to 30 keV
- 35 K < T < 350 K
- Multiple sample configurations to ~10x10 cm
Cathodoluminescence—Deep and Shallow Trap DOS

Cathodoluminescence intensity  \((\alpha\ \text{emitted power})\)

\[
I_\gamma (J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D} + \dot{D}_{\text{sat}}} \left[ e^{-(\varepsilon_{\text{ST}}/k_BT)} \right] \left[ 1 - e^{-(\varepsilon_{\text{ST}}/k_BT)} \right].
\]

Dose rate  \((\alpha\ \text{adsorbed power})\)

\[
\dot{D}(J_b, E_b) = \frac{E_b J_b [1 - \eta(E_b)]}{q_e \rho_m} \times \begin{cases} 
\left[ \frac{1}{L} \right] & ; \quad R(E_b) < L \\
\left[ \frac{1}{R(E_b)} \right] & ; \quad R(E_b) > L
\end{cases}
\]

- \(J_b\): incident current density  
- \(T\): temperature  
- \(E_b\): incident beam energy  
- \(\lambda\): photon wavelength  
- \(q_e\): electron charge  
- \(\rho_m\): mass density  
- \(\varepsilon_{\text{ST}}\): shallow trap energy  
- \(D_{\text{sat}}\): saturation dose rate  
- \(R(E_b)\): penetration range  
- \(L\): Sample thickness
Cathodoluminescence—$E_b$ and Range Dependence

**Incident Beam Energy**

\[
\dot{D}(J_b, E_b) = \frac{E_b J_b [1 - \eta(E_b)]}{q_e \rho_m} \times \begin{cases} 
                [1/L] & ; R(E_b) < L \\
                [1/R(E_b)] & ; R(E_b) > L 
\end{cases}
\]

**Nonpenetrating Radiation** \( \{R(E_b) < L\} \):  
all incident power absorbed in coating and intensity and dose rate are linear with incident power density

**Penetrating Radiation** \( \{R(E_b) > L\} \):  
absorbed power reduced by factor of \( L/R(E_b) \).

**Nonpenetrating: Low \( E_b \), Thick**

**Penetrating: High \( E_b \), Thin**

Can map \( R(E_b) \) with inflection points
Cathodoluminescence—$J_b$ and Dose Dependence

Cathodoluminescence intensity ($\alpha$ emitted power)

$$I_{\gamma}(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D} + \dot{D}_{sat}} \left\{ e^{-\left(\frac{\varepsilon_{ST}}{k_B T}\right)} \right\} \left[ 1 - e^{-\left(\frac{\varepsilon_{ST}}{k_B T}\right)} \right]$$

Dose rate ($\alpha$ adsorbed power)

$$\dot{D}(J_b, E_b) = \frac{E_b J_b [1 - \eta(E_b)]}{q_e \rho_m} \times \left\{ \begin{array}{ll} [1/L] & ; R(E_b) < L \\ [1/R(E_b)] & ; R(E_b) > L \end{array} \right.$$
Cathodoluminescence Emission Spectra

Photon Emission Spectra
Peak Wavelength

Multiple peaks in spectra correspond to multiple DOS distributions

Peak positions ↔ Center of DOS
Peak amplitude ↔ \( N_T \)
Peak width ↔ DOS width
A Path Forward for Dynamic Materials Issues

For dynamic materials issues in spacecraft charging:

- **Synthesis of results** from different studies and techniques
- **Development of overarching theoretical models**

allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space.
Does Cosmic Background Radiation Explain “Flares”

“Flare”

- 2-20x glow intensity
- Abrupt onset
- 2-10 min decay time
The Next Case: Multilayer/Nanocomposite Effects???

**Length Scale**
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth

**Time Scales**
- Deposition times
- Dissipation times
- Mission duration

C-fiber composite with thin ~1-10 µm resin surface layer

Black Kapton™ (C-loaded PI)

Thin ~100 nm disordered SiO2 dielectric coating on metallic reflector
Conclusions

• Complex satellites require:
  • Complex materials configurations
  • More power
  • Smaller, more sensitive devices
  • More demanding environments
  • More sophisticated modeling with dynamic materials properties

• There are numerous clear examples where accurate dynamic charging models require accurate dynamic materials properties

• It is not sufficient to use static (BOL or EOL) materials properties

• Environment/Materials Modification feedback mechanisms can cause many new and unexpected problems

• Understanding of the microscale structure and transport mechanisms are required to model dynamic materials properties for dynamic spacecraft charging models
A Truly Daunting Task....

To address:
• Myriad spacecraft materials
• New, evolving materials
• Many materials properties
• Wide range of environmental conditions
• Evolving materials properties
• Feedback, with changes in materials properties affecting changes of environment

Requires:
• Conscious awareness of dynamic nature of materials properties can be used with available modeling tools to foresee and mitigate many potential spacecraft charging problems
• For dynamic materials issues in spacecraft charging, as with most materials physics problems, synthesis of results from different studies and techniques, and development of overarching theoretical models allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space.
• Solid State models based on defect DOS provide synergism between methods for more extensive and accurate materials properties.
A Materials Physics Approach to the Problem

Measurements with many methods...

Interrelated through a...

Complete set of dynamic transport equations

\[ J = q_e n_e(z, t) \mu_e F(z, t) + q_e D \frac{dn_{tot}(z, t)}{dz} \]

\[ \frac{\partial}{\partial z} F(z, t) = q_e n_{tot} / \varepsilon_0 \varepsilon_r \]

\[ \frac{\partial n_{tot}(z, t)}{\partial t} - \mu_e \frac{\partial}{\partial z} [n_e(z, t)F(z, t)] - q_e D \frac{\partial^2 n_e(z, t)}{\partial z^2} = N_{ex} - \]

\[ \alpha_{er} n_e(z, t)n_{tot}(z, t) + \alpha_{et} n_e(t)[N_e(z) - n_i(z, t)] \]

\[ \frac{dn_h(z, t)}{dt} = N_{ex} - \alpha_{er} n_e(z, t)n_h(z, t) \]

\[ \frac{dn_e(z, \varepsilon, t)}{dt} = \alpha_{et} n_e(z, t)[N_e(z, \varepsilon) - n_e(z, \varepsilon, t)] - \]

\[ \alpha_{te} N_e \exp \left[ -\frac{\varepsilon}{kT} \right] n_e(z, \varepsilon, t) \]

...written in terms of spatial and energy distribution of electron trap states
Some Unsolicited Advice for Students (and a summary of the talk)

- Define the problem
- Develop useful skills
  - Advanced knowledge
  - Experimental skills
  - Modeling skills to tie these together
  - Breadth to recognize important trends
- Keep your eyes open!

Good luck (and have fun!)