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

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Yellowstone, NP
Tetons, NP
Arches, NP
Grand Canyon, NP

Logan, Utah
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, γ
- Particles, m

Typical Space Electron Flux Spectra [Larsen].

Solar Electro-magnetic Spectrum.

USU Materials Physics Group
Facilities & Capabilities

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 ↔ 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.

**Spacecraft Potential Models**

**Materials Properties**

Dynamics of the space environment and satellite motion lead to dynamic spacecraft charging

- Solar Flares
- Rotational eclipse

**Satellite Moving through Space**

**Space Plasma Environment**

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

Materials Research  
NASCAP Updates

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 ) (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_0 ) (input as -1 for conductors)</td>
<td>( 1 \cdot (4.26 \pm 0.04) \cdot 10^7 \text{ ohm}^{-1} \text{ m}^{-1} )</td>
</tr>
<tr>
<td>4. Effective mean atomic number ( Z_{\text{eff}} )</td>
<td>50.9 \pm 0.5</td>
</tr>
<tr>
<td>5. Maximum SE yield for electron impact, ( \delta_{\text{max}} )</td>
<td>1.47 \pm 0.01</td>
</tr>
<tr>
<td>6. Primary electron energy for ( \delta_{\text{max}} ), ( E_{\text{max}} )</td>
<td>(0.569 \pm 0.07) 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 \pm 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 keV)</td>
<td>0.5564 \pm 0.0003</td>
</tr>
<tr>
<td>12. Incident proton energy for ( \delta_{\text{max}} ), ( E_{\text{max}} )</td>
<td>(1238 \pm 30) keV</td>
</tr>
<tr>
<td>13. Photoelectron yield, normally incident sunlight, ( j_{\text{ph}} )</td>
<td>(3.44 \pm 0.4) \cdot 10^{-5} \text{ Å m}^{-2}</td>
</tr>
<tr>
<td>14. Surface resistivity, ( \sigma_0 ) (input as -1 for non-conductors)</td>
<td>1 ohm square (^{-1} ), NA</td>
</tr>
<tr>
<td>15. Maximum potential before discharge to space, ( V_{\text{dis}} )</td>
<td>2000 V, NA</td>
</tr>
<tr>
<td>16. Maximum surface potential difference before dielectric breakdown discharge; ( V_{\text{break}} )</td>
<td>2000 V, NA</td>
</tr>
<tr>
<td>17. Coefficient of radiation-induced conductivity, ( \sigma_0 ), ( k )</td>
<td>0 ohms(^{-1} \text{ m}^{-1} ), NA</td>
</tr>
<tr>
<td>18. Power of radiation-induced conductivity, ( \sigma_0 ), ( \Delta )</td>
<td>0, NA</td>
</tr>
</tbody>
</table>

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**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

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.
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 | Ag
Black Kapton | 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 Rs

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 Rs

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 (\(>10^6\) 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, JUNO, JGO/JEO

Mechanical and Optical Materials Damage

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Combined Temperature and Dose Effects

**Dark Conductivity vs T**

**RIC vs T**

**Dark Conductivity**

\[
\sigma_{DC}(T) = \sigma_{DC}^{0} e^{\frac{-E_o}{k_bT}}
\]

**RIC**

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

**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 Interactions with Space Plasma Environment

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 \( \Rightarrow \) \( \rho \varepsilon_0 \approx 4 \times 10^{16} \) \( \Omega \)-cm
- 1 day \( \Rightarrow \) \( \rho \varepsilon_0 \approx 1 \times 10^{18} \) \( \Omega \)-cm
- 1 yr \( \Rightarrow \) \( \rho \varepsilon_0 \approx 4 \times 10^{20} \) \( \Omega \)-cm
- 10 yr \( \Rightarrow \) \( \rho \varepsilon_0 \approx 4 \times 10^{21} \) \( \Omega \)-cm

Critical Time Scales and Resistivities

Decay time vs. resistivity base on simple capacitor model.

\[ \tau = \rho \varepsilon_r \varepsilon_0 \]
Extremely Low Conductivity

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

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

\[ \sigma(t) = \sigma_{DC} \left[ 1 + \frac{\sigma_{AC}(v)}{\sigma_{DC}} + \frac{\sigma_{pol}}{\sigma_{DC}} e_{pol} + \frac{\sigma_{diffusion}}{\sigma_{DC}} t^{-1} \right] \]

- Dark current or drift conduction—Defect density, \( N_p \), and \( E_F \approx 1.08 \text{ eV} \)
- Diffusion-like and dispersive conductivity—Energy width of trap distribution, \( \alpha \)
- Radiation induced conductivity—Energy width of trap distribution, \( \alpha \)
- Polarization—Rearrangement of bound charge, \( \epsilon_r^\infty \epsilon_o \) and \( \tau_{pol} \)
- AC conduction—Dielectric response, \( \epsilon_r(v) \epsilon_o \)

\[ \sigma_{DC} = q_N \mu_v \text{ dark current or drift conduction—very long time scale equilibrium conductivity.} \]

\[ \sigma_{AC}(v) \equiv \sum \left[ \left( \epsilon_r(v) - \epsilon_0^2 \right) \epsilon_0 \frac{1}{1 + (v/\nu)^2} \right] \]

\[ \sigma_{pol}(t) \equiv \left[ (\epsilon_r^\infty - \epsilon_0^2) \epsilon_o / \tau_{pol} \right] = \epsilon_0 \epsilon_r \text{ long time exponentially decaying conduction due to polarization} \]

\[ \sigma_{diffusion}(t) \equiv \sigma_{diffusion}(T) \cdot t^{1-x} \text{ diffusion-like conductivity from gradient of space charge spatial distribution.} \]

\[ \sigma_{dispersive}(t) \equiv \left\{ \begin{array}{ll} \sigma_{dispersive}(T) \cdot t^{1-x} & \text{for} \ t < \tau_{transit} \\ \sigma_{transit}(t) \equiv \sigma_{transit}(T) \cdot t^{1+\alpha} & \text{for} \ t > \tau_{transit} \end{array} \right\} \]

\[ \sigma_{RIC}(t; D, \tau_{RIC}) \equiv \sigma_{RIC}(D(t)) \left[ 1 - e^{-t_{RIC}/(t-t_{on})} \right] \left[ 1 + (t - t_{off}) / \tau_{RIC}^2 \right]^{-1} \]

Radiation induced conductivity term resulting from energy deposition within the material.

Refer to (Winale, 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 $=5 \times 10^{-18} \text{ (} \Omega \cdot \text{m)}^{-1}$</td>
<td>typical $=0.3 \times 10^{-18} \text{ (} \Omega \cdot \text{m)}^{-1}$</td>
</tr>
<tr>
<td>improved $5 \times 10^{-19} \text{ (} \Omega \cdot \text{m)}^{-1}$</td>
<td>“improved” same as typical</td>
</tr>
<tr>
<td>best guess $1.7 \times 10^{-19} \text{ (} \Omega \cdot \text{m)}^{-1}$</td>
<td>best guess same as typical</td>
</tr>
</tbody>
</table>

**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 $N_T, E_d, \alpha, v_{ST}$

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

**Charging**

\[
V_c(t) = \left[ \frac{\sigma_{\text{total}}}{\epsilon_0 \epsilon_r} (1-\gamma(E_d)) \right] \left[ \frac{R(E_d) D}{1 - \frac{R(E_d)}{2B}} \right] \left[ \frac{1}{\epsilon_r} \right] \left[ 1 - e^{-\frac{t}{\tau}} \right] \left[ \frac{1}{\sigma_0} \right] \left[ \frac{\sigma_{\text{diffusion}}}{\sigma_0} t^{-1} + \frac{\sigma_{\text{dispersive}}}{\sigma_0} (t^{-1} \alpha) \right]
\]

**Discharge**

\[
V(t) = V_0 e^{-\alpha (t) / \epsilon_r \epsilon_0}
\]

\[
\approx V_0 \left[ 1 - \frac{\sigma_0 t}{\epsilon_0 \epsilon_r} \right] \left[ 1 + \frac{\sigma_{\text{diffusion}}}{\sigma_0} t^{-1} + \frac{\sigma_{\text{dispersive}}}{\sigma_0} t^{-1} (1-\alpha) \right]
\]
Disorder introduces localized states in the gap

Delocalized in real space
\[ |\langle r \rangle^2| \]
Position \( r \)

Localized in momentum space
\[ |\langle q \rangle^2| \]
Momentum \( q \)

A quantum mechanical model of the spatial and energy distribution of the electron states

Localized in real space
\[ |\langle r \rangle^2| \]
Position \( r \)

Delocalized in momentum space
\[ |\langle q \rangle^2| \]
Momentum \( q \)

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 K < T < 350 K
- ±0.5 K for weeks
- Multiple sample configurations

ESD: Limit of Conductivity at High Fields

LDPE 20 μm
Kapton 20 μm
### F_{\text{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

$\Delta G_{\text{def}} = 0.97$ eV
$N_T = 1 \cdot 10^{17}$ cm$^{-3}$

**Breakdown field measurements:**

$$N_{\text{def}} \Delta G_{\text{def}} = \frac{E_0}{E_r} \cdot \left( F_{\text{ESD}} \right)^2$$

**Endurance time measurements:**

$$t_{\text{en}}(F, T) = \left( \frac{h}{2k_B T} \right) \exp \left[ \frac{\Delta G_{\text{def}}(F, T)}{k_B T} \right] \cdot \text{csch} \left[ \frac{F^2 E_0 E_r}{2k_B T N_{\text{def}}(F, T)} \right]$$

### Radiation Induced Conductivity Measurements

RIC chamber uses a combination of charge injected by a biased surface electrode with simultaneous injection by a pulsed penetrating electron.

**Top view of samples on window**

**RIC Chamber**

**Sample stack cross section**
**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**

$E_F^{\text{eff}} = 24 \text{ meV}$

**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 through the muon's decay.

“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

Ball Black Kapton
Runs 131 and 131A
22 keV
135 K
110 or 4100 uW/cm²
5 or 188 nA/cm²

Electrometer
CCD Video Camera
(400 nm to 900 nm)
InGaAs Video Camera
(900 nm to 1700 nm)
Photon Emission Measurements

Luminescence/Arc/Flare Test Configuration
- Absolute spectral radiance
- ~200 nm to ~5000 nm
- 4 cameras (CCD, iiCCD, InGaAs, InSb)
- Discrete detectors filters
- 2 Spectrometers (~200 nm to ~1900 nm)
- e\(^-\) at ~1 pA/cm\(^2\) to ~10μA/cm\(^2\) & ~20 eV to 30 keV
- 35 K < T < 350 K
- Multiple sample configurations to ~10x10cm

Cathodoluminescence—Deep and Shallow Trap DOS

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

\[ I_T(J_b, E_b, T, \lambda) \propto \frac{\dot{J_b}E_b}{D + D_{sat}} \left[ e^{-(\epsilon_{ST}/k_bT)} \right] \left[ 1 - e^{-(\epsilon_{ST}/k_bT)} \right] \]

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

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

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

Incident Beam Energy

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

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 $L/R(E_b)$.

Cathodoluminescence intensity ($\lambda$ emitted power)

$$I_{\lambda}(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D}_{\text{sat}}} \left[ e^{-\frac{\varepsilon \tau}{k_B \theta}} \left( 1 - e^{-\frac{\varepsilon \tau}{k_B \theta}} \right) \right]$$

Dose rate ($\lambda$ adsorbed power)

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

Measure of charge required to fill traps.

~10 GY/s for SiO$_2$ coatings.
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

\[ I = q_e n_e(x, t) \mu \frac{dE(x, t)}{dx} \]

\[ \frac{d}{dx} f(x, t) = \frac{q_e}{\varepsilon_0} \frac{dE(x, t)}{dx} \]

written it 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!)