Effects on Spacecraft Charging of Modification of Materials by Space Environment Interactions

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Abstract

While the effects on spacecraft charging from varying environmental conditions and from the selection of different construction materials have been studied extensively, modification of materials properties by the space plasma environment can also have profound effects on spacecraft charging. This presentation focuses on measurement methods and modeling employed to assess the effects of environment-induced material modifications on physical properties relevant to spacecraft charging simulations. It also reviews several specific studies in which environment-induced material modifications have significant impact on predicted spacecraft charging.

We present an overview of testing and modeling conducted by the Utah State University (USU) Materials Physics Group and other investigators to quantify the changes in charging, discharging and emission as materials properties are modified by variations in temperature, charge accumulation and electrostatic fields, radiation dose and damage, surface modifications including roughening and contamination, and the duration, rate and history of imposed environmental test conditions. Such changes have been shown to affect measurements of the following material properties: electron-, ion- and photon-induced electron emission yields, spectra, and yield decay curves; dark current and radiation induced conductivity; electrostatic discharge and charge decay curves; electron-induced surface charging, discharge and luminescence; and UV/VIS/NIR reflectivity, transmissivity, absorptivity, and emissivity. We also highlight a unified set of parameters and equations developed to relate these experimental methods to basic theories of electron transport.
Abstract

Recent USU studies related to several specific missions have highlighted the operational effects of such environment-induced changes on material properties and ultimately on spacecraft charging. For example, studies of surface coatings for the 2005 concept of the Solar Probe Mission found that absolute and differential surface charging depended strongly on increased conductivity from higher temperatures and on radiation flux through enhanced charge accumulation and radiation induced conductivity; interplay between these effects led to the prediction of a maximum in charging at intermediate distances over the Probe’s orbital range spanning from Jovian distances to within 4 solar radii of the Sun. Extreme demands dictated by the science objectives of the James Webb Space Telescope have placed particularly stringent requirements on materials and have potentially increased risks from spacecraft charging: low temperatures lead to low charge transport and dissipation rates; long mission duration, prolonged eclipse conditions, and inaccessibility for maintenance lead to extremely long charge accumulation times; large, unusually exposed surface areas lead to larger charge accumulation and increased probability of discharge; and very sensitive electronics and optics lead to low tolerance for charging, electrostatic discharge, and electron and photon emission. Extreme radiation dose rates and fluences for potential polar and Jovian missions have been found to substantially modify electron transport and to affect other properties such as reflectivity, emissivity and electrostatic discharge.

Given the increasingly demanding nature of space missions, there is clearly a need to extend our understanding of the dynamic nature of material properties that affect spacecraft charging and to expand our knowledge base of materials’ responses to specific environmental conditions so that we can more reliably predict the long term response of spacecraft to their environment.
Let us assume a spherical satellite....
A simplified approach to spacecraft charging modeling...

- Materials Properties
- Spacecraft Potential Models
- Satellite Moving through Space
- Space Plasma Environment

- $I^+$
- $e^-$
- $Y$
What do you need to know about the materials properties?

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

**Charge Transport**
- Conductivity
- RIC
- Dielectric Constant
- ESD

As functions of materials species, flux, and energy.

Complex dynamic interplay between space environment, satellite motion, and materials properties.

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

- Solar Flares
- Rotational eclipse
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, \( \sigma(z) \)
Complex dynamic interplay between space environment, satellite motion, and materials properties

USU Studies

Environment Conditions ↔ Materials Conditions ↔ Materials Properties ↔ Spacecraft Charging
“New Frontiers” from a Materials Perspective

Consider 5 Cases of Dynamical Change in Materials:

- Contamination and Oxidation
- Surface Modification
- Radiation Effects (and t)
- Temperature Effects (and t)
- Radiation and Temperature Effects
Case I: Evolution of Contamination and Oxidation

“All spacecraft surfaces are eventually carbon…”
--C. Purvis

This led to lab studies by Davies, Kite, and Chang

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Graph showing SE yield evolution over primary energy for Au and C on Au, with approximate contamination thickness in nm on the x-axis and negative potential (10^-V_eq) on the y-axis. Two graphs showing positive and negative charging effects over contamination exposure time in hours.
Case I: Evolution of Contamination and Oxidation

Wake Side

- 13 Grounded Samples
- 12 Biased Samples: 3 sets of 4 samples with low current biases for charge-enhanced contamination studies
- 6 Concealed Samples

Sample Holders

- Holder area 5 cm x 15 cm
- 9 mm diameter exposed sample area

Materials Modifications Slide 11

See poster by Dennison, Evans and Prebola

SUSpECS on MISSE-6

Before

After

Black Kapton

Ag coated Mylar with micrometeoroid impact

Grounded Guard Plate

-5 VDC

+5 VDC

-15 VDC
Case II: Surface Modification

Reflectivity changes with surface roughness

See poster by Evans

Successive stages of roughened of Cu

Absorption Coefficient from Diffuse Reflection

Reflectivity Change

Particle Size (microns)
Cases I and II: Reflectivity as a Feedback Mechanism

Reflectivity changes with surface roughness and contamination

Reflect \rightarrow \text{Charging} \rightarrow \text{Contamination}

Reflect \rightarrow \text{Emissivity} \rightarrow \text{Temp} \rightarrow \text{Contamination}

\text{Charging} \rightarrow \text{Reflectivity}

Radiation \rightarrow \text{Reflect} \rightarrow \text{Emissivity} \rightarrow \text{Temp} \rightarrow \text{Contamination}

B. Mihaljcic in Guild’s 11th SCTS Talk

See Lai & Tautz, 2006 & Dennison 2007

JWST Structure: Charging vs. Ablation
Case III: 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
Transport and Emission Properties
Caused by bondbreaking and trap creation
(see Hoffmann & A Sim posters)

Mechanical and Optical Materials Damage
(see Hoffmann & A Sim posters)
Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Transport
• Conductivity
• RIC
• Dielectric Constant
• ESD

Examples:

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

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

Inner Planetary Mission
SPM, Ulysses, Magellan, Mariner

(see A Sim and C Sim posters)
Case IV: Temperature Effects

Strong T Dependence for Insulators

Charge Transport
- Conductivity
- RIC
- Dielectric Constant
- ESD

\[
\sigma_{VRH} \sim \exp(T^{-1/4}) \\
\sigma_{TAH} \sim \exp(T^{-1})
\]

\[
\ln(\text{Ln(Calculated Resistivity (Ohm-cm))})
\]

\[
k(T) = k_{RICO}
\]

Uniform Trap Density
\[
\Delta(T) \rightarrow 1
\]

Exponential Trap Density
\[
\Delta(T) \rightarrow \frac{T_c}{T + T_c}
\]

\[
k(T) \rightarrow k_{RICO} \left[ \frac{2}{2\pi\hbar^2} \right]^{3/2} \left( \frac{m_e m^*}{m_e m^*} \right)^{3/4} T^{\Delta(T)}
\]

\[
\sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)}
\]
## Case IV: Temperature Effects—JWST

### JWST

<table>
<thead>
<tr>
<th>Very Low Temperature</th>
<th>Large Open Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtually all insulators go to infinite resistance—perfect charge integrators</td>
<td>Large fluxes</td>
</tr>
<tr>
<td><strong>Long Mission Lifetime (10-20 yr)</strong></td>
<td>Minimal shielding</td>
</tr>
<tr>
<td>No repairs</td>
<td>Variation in Flux</td>
</tr>
<tr>
<td>Very long integration times</td>
<td>Large solar activity variations</td>
</tr>
<tr>
<td><strong>Large Sunshield</strong></td>
<td>In and out of magnetotail</td>
</tr>
<tr>
<td>Large areas</td>
<td><strong>Complex, Sensitive Hardware</strong></td>
</tr>
<tr>
<td>Constant eclipse with no photoemission</td>
<td>Large sensitive optics</td>
</tr>
<tr>
<td></td>
<td>Complex, cold electronics</td>
</tr>
</tbody>
</table>
Case V: 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 Rₚ
Case V: Temperature and Dose Effects

“We anticipate significant thermal and charging issues.”

J. Sample

Charging Study by Donegan, Sample, Dennison and Hoffmann
(See Donegann Poster for update)
Case V: Temperature and Dose Effects

- **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!
**Case V: Temperature and Dose Effects**

**Dark Conductivity vs T**

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

**RIC**

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

**Dielectric Constant**

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

**Electrostatic Breakdown**

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

A peak in charging at ~0.3 to 2 AU

“...Curiouser and curioser...

--Alice
Case V: 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 $T$-dependent conductivity increases faster at closer orbits
Conclusions

• Satellites are not cows…
  Complex satellites require:
  • Complex materials configurations
  • More power
  • Smaller, more sensitive devices
  • More demanding environments

• 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 a whole herd of new problems
Acknowledgements

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