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Satellite Survivability in a Harsh Space Environment: A Materials Perspective

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Satellite Survivability in Space: A Materials Perspective

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To paraphrase Douglas Adams,

“Space is [harsh]. Really [harsh]. You just won’t believe how vastly, hugely, mind-bogglingly [harsh] it is.

I mean, you may think it's a long way down the road to the chemist, but that's just peanuts to space.”

D. Adams--*Hitchhiker’s Guide to the Galaxy*
Interactions with this harsh space environment can modify materials and cause unforeseen and detrimental effects to spacecraft. Therefore, we:

- simulate the space environments,
- characterize their effects on materials properties,
- use these results to predict and mitigate space environment effects,
- work to understand the materials physics involved at the atomic scale to
- extend our work to more diverse problems and materials.

**Bottom line for the USU Materials Physics Group:**
The Space Environment

Typical Space Electron Flux Spectra

Solar Electromagnetic Spectrum.

Spacecraft/Environment Interactions

• The Sun gives off high energy charged particles, with dynamic fluxes.
• Particles interact with the dynamic Earth’s atmosphere and magnetic field in interesting and dynamic ways.
• Dynamics of the space environment and satellite motion lead to dynamic spacecraft interactions.
• High energy particles deposit charge and energy into spacecraft surfaces.
• Materials in spacecraft can modify the local space environment.
• Materials properties evolve in response to interactions with the environment.
• Evolving mission objectives, complexity, sensitivity, size.

Dynamic Space Environments:

• Solar Wind, Solar Flares, CME, Solar Cycle.
• Dynamic magnetic fields.
• Orbital eclipse, rotational eclipse.

Dynamic Fluxes:

• Electrons, e⁻.
• Ions, I⁺.
• Photons, γ.
• Particles, m.

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

- Single event interrupts of electronics
- Arcing
- Sputtering
- Enhanced contamination
- Shifts in spacecraft potentials
- Current losses

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
Critical Time Scales and Bulk Resistivities

Decay time vs. resistivity base on simple capacitor model.

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

Corresponding Decay Times (\(\varepsilon_r = 1\))

- 500 yr \(\rightarrow\) \(\rho \varepsilon_0 \sim 1 \times 10^{23} \Omega\text{-cm}\)
- 15 yr \(\rightarrow\) \(\rho \varepsilon_0 \sim 5 \times 10^{21} \Omega\text{-cm}\)
- 1 yr \(\rightarrow\) \(\rho \varepsilon_0 \sim 4 \times 10^{20} \Omega\text{-cm}\)
- 1 day \(\rightarrow\) \(\rho \varepsilon_0 \sim 1 \times 10^{18} \Omega\text{-cm}\)
- 1 hr \(\rightarrow\) \(\rho \varepsilon_0 \sim 4 \times 10^{16} \Omega\text{-cm}\)
- 1 min \(\rightarrow\) \(\rho \varepsilon_0 \sim 1 \times 10^{15} \Omega\text{-cm}\)
where materials testing fits into the solution

charge accumulation
- electron yields
- ion yields
- photovoltaic yields
- luminescence

charge transport
- conductivity
- radiation induced conductivity
- permittivity
- electrostatic breakdown
- penetration range

absolute values as functions of materials species, flux, fluence, energy, and temperature.
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 our work is the change in materials properties as a function of:

- Time (Aging), $t$
- Temperature, $T$
- Accumulated Energy (Dose), $D$
  - Dose Rate, $\dot{D}$
- Radiation Damage
- Accumulated Charge, $\Delta Q$ or $\Delta V$
  - Charge Profiles, $Q(z)$
  - Charge Rate (Current), $\dot{Q}$
- Conductivity Profiles, $\sigma(z)$
A Materials Physics Approach to the Problem

Measurements with many methods...

Interrelated through a...

Complete set of dynamic transport equations

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

\[ \frac{\partial}{\partial z} F(z, t) = \frac{q_e n_{tot}}{\epsilon_0 \epsilon_r} \]

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

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

\[ \frac{dn_t(z,\varepsilon, t)}{dt} = \alpha_{et} n_e (z, t) [N_t (z, \varepsilon) - n_t (z, \varepsilon, t)] - \alpha_{te} N_e \exp \left[ -\frac{\varepsilon}{kT} \right] n_t (z, \varepsilon, t) \]

...written it terms of spatial and energy distribution of electron trap states
Materials Physics Group Measurement Capabilities

- Electron Emission
- Photoyield
- Ion Yield
- Luminescence
- Conductivity
- Electrostatic Discharge
- Radiation Induced Cond.
- Radiation Damage

Dependence on: Press., Temp., Charge, E-field, Dose, Dose Rate
Electron Yields Determine Charge Accumulation

Electron yields characterize a material’s response to incident charged particles.

\[ \text{Yield} = \sigma = \frac{e_{\text{out}}}{e_{\text{in}}} \]

- Can be \(0 < \sigma > 1\)
- Leading to + or - charging
- Depends on material
- Incident electron energy
- Temperature
- Charge
  - Grounded conductors replenish net emitted charge in \(<\text{ps}\)
  - Yields of insulators change as charge accumulates in sample.
  - Intrinsic yield is zero charge yield

Electron Emission Spectra

Au TEY/SEY/BSEY
Hemispherical Grid Retarding Field Analyzer Electron Emission Detector

- 10 eV to 30 100 keV incident electrons
- Fully enclosed HGRFA for emission electron energy discrimination.
- Precision absolute yield by measuring all currents
  - ~1-2% accuracy with conductors
  - ~2-5% accuracy with insulators
- In situ absolute calibration
- Multiple sample stage
  - ~100 40 K < T < 400 K
- Reduced S/N

**Enhanced Low Fluence Methods for Insulator Yields**
- Low current (<1 nA-mm⁻²), pulses (<4 μs) with <1000 e⁻-mm⁻²
- Point-wise yield method charge with <30 e⁻-mm⁻² per effective pulse
- Neutralization with low energy (~5 eV) e⁻ and UV
- In situ surface voltage probe
Constant Voltage Conductivity

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

- Time evolution of resistivity
  - <10^{-1} \text{s} to >10^6 \text{s}
  - ±200 aA resolution
  - >5 \cdot 10^{22} \Omega \text{-cm}
  - ~100 K < T < 375 K
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 $N_T$, $E_d$, $\alpha$, $\varepsilon_{ST}$

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

**Charging**

\[
V_e(t) = \frac{q_e n_{\text{max}}}{\varepsilon_o \varepsilon_r} \left[ R(E_b) D \left( 1 - \frac{R(E_b)}{2D} \right) \right] \left[ t_o \right] \left[ 1 - e^{-\left( \frac{1}{\tau_Q} \right)} \left( \frac{\sigma_0}{\varepsilon_o \varepsilon_r} \right) + \left( \frac{\sigma^0_{\text{diffusion}}}{\sigma_0} \right)(t^{-1}) + \left( \frac{\sigma^0_{\text{dispersive}}}{\sigma_0} \right)(t^{-(1-\alpha)}) \right]^{-1}
\]

**Discharge**

\[
V(t) = V_o e^{-t\sigma(t)/\varepsilon_o \varepsilon_r} \approx V_o \left[ 1 - \left( \frac{\sigma_0}{\varepsilon_o \varepsilon_r} \right) t \left\{ 1 + \left[ \frac{\sigma^0_{\text{diffusion}}}{\sigma_0} \right] t^{-1} + \left[ \frac{\sigma^0_{\text{dispersive}}}{\sigma_0} \right] t^{-(1-\alpha)} \right\} \right]
\]
RIC chamber uses a combination of charge injected by a biased surface electrode with simultaneous injection by a pulsed penetrating electron.

Sample stack cross section
Low Temperature Cryostat

Used with:
- Constant Voltage Conductivity
- RIC
- Cathodoluminescence
- Arcing
- TE/SE/BSE Yields
- Surface Voltage Probe
- Photoyields and Ion Yields

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/Convection Gauges – Pressure
- Y. Residual Gas Analyzer – Gas Species
Cathodoluminescence & Induced ESD Measurements—Arc/Glow/Flare Testing

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/cm² to ~10 μA/cm² & ~10 eV to 50 keV
- 35 K < T < 350 K
- Multiple sample configurations to ~10x10cm
**Electron-Induced Luminescence**

- **Kapton XC**
  - 500 nA/cm²
  - 22 keV
  - 150 K

- **M55J**
  - 1 nA/cm²
  - 22 keV
  - 100 K

- **IEC Shell Face Epoxy**
  - Resin with Carbon Veil
  - 1 nA/cm²
  - 22 keV
  - 100 K

**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
- 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

**Sustained Glow**

**Flare**

**Ball Black Kapton**
- 22 keV
- 135 K
- 110 or 4100 uW/cm²
- 5 or 188 nA/cm²

**Diversity of Optical Emission Phenomena in Time Domain**

**Ball Black Kapton**
- 22 keV
- 135 K
- 110 or 4100 uW/cm²
- 5 or 188 nA/cm²

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**Sustained Glow**

**Flare**
Risk Due to Electron-Induced Luminescence

**Statement of Risk**

Critical JWST structural and materials and optical coatings were found to glow at potentially unacceptable levels under electron fluxes typical of storm conditions in the L2 environment.

Preliminary results of Vis/NIR glow at <0.2 nA/cm² show

Intensity is:
- visible with eye, SLR camera & NIR video camera
- estimated to exceed acceptable 2 µm stray light intensity into NIRCam
- Absolute sensitivity <20% of zodiacal background

Glow spectra:
- has been measured from ~250 nm to >1700 nm
- may well extend to much higher wavelengths
**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

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

Breakdown field measurements:

$$N_{\text{def}} \Delta G_{\text{def}} = \frac{\varepsilon_0 \varepsilon_r}{2} \cdot (F_{\text{ESD}})$$

Endurance time measurements:

$$t_{\text{en}}(F, T) = \left( \frac{\hbar}{2 k_B T} \right) \exp \left[ \frac{\Delta G_{\text{def}}(F, T)}{k_B T} \right] \text{csch} \left[ \frac{F^2 \varepsilon_0 \varepsilon_r}{2 k_B T N_{\text{def}}(F, T)} \right]$$
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.

- Energy Diagram incorporates information from:
  - Optical transmission (CB-VB gap)
  - Conductivity (shallow trap distribution, rates)
  - Surface Decay (shallow trap distribution, recombination)
  - RIC (shallow trap distribution & occupation, rates)
  - Electrostatic discharge (shallow trap distribution & occupation, rates)
  - Cathodoluminescence (deep trap distribution, defect types, trap occupation, rates, relaxation)
  - Optical & Thermal Stimulated CL (deep trap distribution, trap occupation, rates, relaxation)
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

Figure 4-1. Solar Probe mission summary.

Figure 4-2. Solar encounter trajectory and timeline. Science operations begin at perihelion —5 days (65 Rs) and continue until perihelion +5 days.
Charging Results: Temperature and Dose Effects

Modeling found a peak in charging at ~0.3 to 2 AU

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 $\sim r^{-2}$
Charging: Evolution of Contamination and Oxidation

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

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

SE Yield Evolution
(0 - 300 angstroms Carbon Contamination)

Onset of threshold charging

Approx. Contamination Thickness (nm)

Primary Energy (eV)

Contamination (Exposure Time in hours)

Neg. Charging
Pos. Charging

SE Yield Evolution
(C on Au)

Neg. Potential (10-V_eq) (in volts)
Reflectivity changes with surface roughness and contamination

→ Reflect → Charging → Contamination

→ Reflect → Emissivity → Temp → Contamination

→ Charging → Reflectivity

→ Radiation → Reflect → Emissivity → Temp → Contamination

Environmental Changes: Reflectivity as a Feedback Mechanism

See Donegan, Sample, Dennison and Hoffmann

Large Breakdown

Before After

Zoomed Images

Onset of threshold charging

JWST Structure: Charging vs. Ablation

See Lai & Tautz, 2006 & Dennison 2007
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 (>10⁸ Rad)

Medium Dosage (>10⁷ Rad)

Low Dose Rate (>10⁰ Rad/s)

“...Earth is for Wimps...” H. Garrett

Examples: RBSP, JUNO, JGO/JEO

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

Radiation induced Conductivity (RIC)

Temperature dependent strain

Transport and Emission Properties

Caused by bondbreaking and trap creation

Mechanical and Optical Materials Damage
Combined Temperature and Dose Effects

LDPE Study for JWST

**Dark Conductivity**

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

**RIC Electrostatic Breakdown**

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

**Dielectric Constant**

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

**Electrostatic Breakdown**

\[ E_{ESD}(T) = E^{RT}_{ESD} e^{-\alpha_{ESD}(T-298 K)} \]
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

MISSE 6 exposed to the space environment. The picture was taken on the fifth EVA, just after deployment.

The SUSpECS double stack can be seen in the bottom center of the lower case.
The Poster Child for Space Environment Effects

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?
Simulating Space in the Electron Emission Test Chamber
Electron Flux
A high energy electron flood gun (A) (20 keV – 100 keV) provides ≤5 X 10^6 electrons/cm^2 (~1 pA/cm^2 to 1 μA/cm^2) flux needed to simulate the solar wind and plasma sheet at more than the 100X cumulative electron flux. A low energy electron gun (A') (10 eV-10 keV) simulates higher flux conditions. Both have interchangeable electron filaments.

Ionizing Radiation
A 100 mCi encapsulated Sr90 radiation source (E') mimics high energy (~500 keV to 2.5 MeV) geostationary electron flux.

Infrared/Visible/Ultraviolet Flux
A commercial Class AAA solar simulator (B) provides NIR/VIS/UVA/UVB electromagnetic radiation (from 200 nm to 1700 nm) at up to 4 times sun equivalent intensity. Source uses a Xe discharge tube bulbs with >1 month lifetimes for long duration studies.

Far Ultraviolet Flux
Kr resonance lamps (C) provide FUV radiation flux (ranging from 10 to 200 nm) at 4 times sun equivalent intensity. Kr bulbs have ~3 month lifetimes for long duration studies.

Temperature
Temperature range from 60 K [4] to 450 K is maintained to ±2 K.

Vacuum
Ultrahigh vacuum chamber allows for pressures <10^-7 Pa to simulate LEO.
Simulating Space in the Space Survivability Test Chamber

Space Components
- Radiation induced arcing and material damage in Microwave antennas
- Radiation induced arcing in RF Cables
- Radiation damage of COTS Parts
- VUV Degradation of thermal control paints
- SDL Electronics Boards

Biological Tests
- Radiation damage of seeds
- Radiation damage of muscle cells

Dependence of ESD Breakdown Field Strength on TID and T
Simulating Space in the Space Survivability Test Chamber

Inverted Vacuum Chamber for Biological Tests

Simulating Radiation and Vibration of Radish Seeds exposed on Russian flight

Both radiation and vibrations enhance germination rate, as was seen in flight seeds.
Absolute Electron Emission Calibration: Round Robin Tests of Au and Graphite

Introduction

Accurate determination of the absolute electron yields of calibrating and evaluating materials is crucial for models of spacecraft charging and related processes involving charge accumulation and emission due to electron beam and plasma interactions. Measurements of absolute electron yields require careful attention to calibration, experimental methods, and uncertainties.

This study presents a round robin comparison of these absolute yields with measurements performed in four international laboratories. The primary objectives were to determine the consistency and uncertainties of such tests, and to investigate the effects of the circumstances and differences of the diverse facilities. Apparatus using various low-energy pulsed electron beam sources and methods to estimate charge accumulation have been developed and employed at these facilities.

Descriptions of Facilities and Methods

CSIC SEY Facility

The CSIC SEY Facility is located in Madrid, Spain. It utilizes a pulsed electron beam for measuring electron emission yields. The apparatus consists of a pulsed electron gun, a sample holder, and an electron energy analyzer. A detailed description of the equipment and methods is provided in the report.

LaSEINE TEY Facility

The Laboratory of Aerospace Engineering (LaSEINE) in France hosts a facility for measuring electron emission yields. The setup is equipped with a high-current electron gun and an electron energy analyzer. Key parameters and measurements are detailed in the report.

USU SEEM Facility

The University of Utah (USU) SEEM Facility in Salt Lake City, Utah, utilizes a pulsed electron beam to measure electron emission yields. The apparatus includes a pulsed electron gun, a sample holder, and an electron energy analyzer. The report provides a comprehensive description of the equipment and methods.

Round Robin Tests Results

Measurements were made of the absolute electron yields at several laboratories using an x & y format for the range of electron energy accessible with such apparatus. The results are consistent, with slight variations due to differences in the facilities and measurement techniques.

Gold

HOPG Graphite

Summary

Summary of results:
- Data from different laboratories are consistent.
- High degree of agreement between laboratories.
- Consistent trends observed for different materials.

Topics of future Round Robin analysis:
- Higher energy measurements of electron yields for further study.
- Evaluation of surface contamination effects on electron emission.
- Further investigation into the effects of different experimental conditions on electron yields.
A Multitude of Materials: 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

![Diagram](image-url)
Point-wise Electron Yield Tests of Highly Insulating Materials

- Current analysis program could show how yield changes over the course of a pulse. (~1% of total pulse charge)
  - Gold data should show no charging effects.
  - Zero charge plateau.
Support & Collaborations

Current Funding
- NASA GRC
- NASA MSFC
- AFRL
- NSF
- Box Elder Innovations
- Solar Probe Plus (Berkley Space Lab)
- ViaSat
- Lockheed Martin
- Times Microwave
- NASA Grad Res. Fellowships
- USU PDRF Fellowships
- Utah NASA Space Grant Consortium

Past Funding
- USU Space Dynanmics Lab
- NASA SEE Program
- JWST (GSFC/MSFC)
- Solar Probe Mission (JHU/APL)
- Rad. Belt Space Probe (JHU/APL)
- Solar Sails (JPL)
- AFRL
- Boeing
- Ball Aerospace
- Orbital
- LAM
- AFRL/NRC Fellowship
- Sienna Technologies
Backup Charts
MPG Space Environment Effects Materials Test Facility

Utah State University Space Environments Effects Materials (SEEM) Test Facilities

Electron Emission
- Electron emission studies for incident electron, ion, and photon interactions with precision, absolute yields of conductors, semiconductors, insulators & extreme insulators.
- Measurements include:
  - Total Emission Spectra versus energy (SCE) using <30 keV to 1 MeV monoenergetic electrons with % absolute uncertainty 2% - 11%.
  - Influence of Energy on Emission Spectra and yields for various <30 keV to 1 MeV monoenergetic electron beams.
  - Photoelectronic Emission Spectra and yields for 20 keV to 300 keV (100-1000 MeV) monoenergetic electrons.
  - Surface Voltage measurements of materials using 200 MeV proton beam. (10 keV to 1 GeV).
  - Ion-induced Electrons and Emission spectra for incident electrons.
  - Electron Emission Spectra versus energy (SCE) using <30 keV to 1 MeV monoenergetic electron beams.

Conductivity & Charge Transport
- Conductivity and charge transport studies for conductors, semiconductors, insulators, & extreme insulators.
- Measurements include:
  - Bulk and surface conductivity and charging processes:
  - Charge transport properties and charge dependence (300 K).
  - Photoelectron yield measurements (300 K).
  - Surface voltage measurements using 200 MeV protons at 10^12 cm^-2.
  - Conductivity and charge transport properties and charge dependence (300 K).

Space Simulation
- The Space Survivability Test Facility (SSTF) has unique capabilities for simulating and testing potential environmental-induced modifications of small satellites, components, materials, and their interactions with up to 350 km in a T-shaped cylinder. It is especially well suited for cost-effective tests of multiple small scale materials samples over prolonged exposure to extreme environmental conditions including:
  - Neutral gas atmosphere (Vacuum to 10^-6 Pa).
  - Temperature from 300 K to 500 K.
  - Electrons fluxes with simultaneous low and high energy electron guns from <3 keV to 1 MeV.
  - Ions in the form of 40 keV and 1 MeV ions.
  - Temperature capabilities from <300 K to >1300 K.
  - Higher temperatures under development.

Cathodoluminescence
- Absolute intensity and low level electronic-induced luminescence:
  - Spectra (Vacuum to 10^-3 Pa).
  - Temperature capabilities from <300 K to >1300 K.

Electrostatic Discharge & Arcing
- Electrostatic discharge and arcing fields strength (<30 keV at 10^3 V/m).
  - Temperature and vacuum capabilities from <300 K to >1300 K.
  - Electron-induced arcing current and spatially temporally resolved optical measurements from <3 keV to 500 keV.

Characterization & Preparation
- Extensive capabilities for sample preparation and characterization:
  - Bulk Composition: Scanning Electron Microscopy (SEM), FTIR, and Raman spectroscopy.
  - Surface Composition: Auger Electron Spectroscopy (AES) and AES mapping.
  - Vacuum Thermal Emitter: Various evaporation systems to 1 x 10^-7 Torr and temperatures up to 1500 K.
  - Optical Characterization: Optical and Diffuse Reflectance Spectroscopy, FTIR, Thermometry, Thermogravimetry.
  - Luminescence: Optical Spectroscopy, Photoluminescence (PL), Time Resolved Luminescence (TRL), Time Resolved Photoluminescence (TRPL).

Collaborative Facilities
- The MPG collaborates with nearly 10 facilities that extend our capabilities. These include:
  - U. S. Space Dynamics Laboratory for satellite and sensor development, fabrication, and integration.
  - SDL Nondestructive Evaluation Verification and Assessment (NDEVA) test facility for characterization and verification of sub-components and sub-systems performance.
  - ISAC Accelerator Center for high energy electron, proton, and positron beam and target facilities.
  - U. S. Microdosimetry Facility for single event upset and radiation damage.
  - USAU Luminosity Lab for optical and time resolved luminescence testing.

Space Dynamics
Utah State University Materials Research Foundation
Integration with Spacecraft Charging Models

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

Materials Research

NASCAP Upgrades

Typical SEE Handbook Simulation
Understanding the Physics

- conduction electrons
- holes
- empty traps
- filled traps
- radiation
- filled traps

CB

VB

\[ \sigma_{\text{intrinsic}} \]

\[ \sigma_{\text{TAH}} \]

\[ \sigma_{\text{VRH}} \]

\[ \Delta H \]

\[ \Delta H \]

\[ E_c \]

\[ E_\text{gap} \]

\[ E_0 \]

\[ E_v \]

\[ \sigma_{\text{RIC}} \]

luminescence

CB

VB

\[ \sigma_{\text{intrinsic}} \]

\[ \sigma_{\text{TAH}} \]

\[ \sigma_{\text{VRH}} \]

\[ \Delta H \]

\[ \Delta H \]

\[ E_c \]

\[ E_\text{gap} \]

\[ E_0 \]

\[ E_v \]

\[ \sigma_{\text{RIC}} \]

luminescence