2017

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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**: 

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.
The Space Environment

Typical Space Electron Flux Spectra

“Low Energy”

“Hot” Bi-Maxwellian

Solar Electro-magnetic Spectrum.

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

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.
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
Decay time vs. resistivity base on simple capacitor model.

\[ \tau = \rho \varepsilon \tau \varepsilon_0 \]

Critical Time Scales and Bulk Resistivities

Corresponding Decay Times (\( \varepsilon_\tau = 1 \))

- 500 yr \( \rightarrow \rho \varepsilon_\tau \sim 1 \times 10^{23} \ \Omega\cdot\text{cm} \)
- 15 yr \( \rightarrow \rho \varepsilon_\tau \sim 5 \times 10^{21} \ \Omega\cdot\text{cm} \)
- 1 yr \( \rightarrow \rho \varepsilon_\tau \sim 4 \times 10^{20} \ \Omega\cdot\text{cm} \)
- 1 day \( \rightarrow \rho \varepsilon_\tau \sim 1 \times 10^{18} \ \Omega\cdot\text{cm} \)
- 1 hr \( \rightarrow \rho \varepsilon_\tau \sim 4 \times 10^{16} \ \Omega\cdot\text{cm} \)
- 1 min \( \rightarrow \rho \varepsilon_\tau \sim 1 \times 10^{15} \ \Omega\cdot\text{cm} \)
Where Materials Testing Fits into the Solution

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

Charge Transport
- Conductivity
- Radiation Induced Conductivity
- Permittivity
- Electrostatic breakdown
- Penetration range

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

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

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

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

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

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

\[
\frac{dn_z(z, t)}{dt} = \alpha_{et} n_e(z, t)[N_e(z, \varepsilon) - n_t(z, \varepsilon, t)] - \alpha_{et} N_e \exp \left[ -\frac{e}{k T} \right] n_t(z, \varepsilon, t)
\]

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

Electron Emission  
Ion Yield

Photoyield  
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.

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

- Can be 0 < $\sigma$ > 1
- Leading to + or - charging
- Depends on material
- Incident electron energy
- Temperature
- Charge
  - Grounded conductors replenish net emitted charge in < 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 300 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 Chamber configurations inject a continuous charge via a biased surface electrode with no electron beam injection.

- Time evolution of resistivity
  - $<10^{-1}$ s to $>10^6$ s
  - $\pm 200$ aA resolution
  - $>5 \times 10^{22}$ $\Omega \cdot $cm
  - $\sim 100$ 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 $N_T$, $E_d$, $\alpha$, $\varepsilon_{ST}$

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

Charging

\[
V_c(t) = \frac{q_n \varepsilon_{\infty} \varepsilon_r}{\varepsilon_o \varepsilon_r} \left[ 1 - \gamma(E_b) \right] \left[ R(E_b) \left( 1 - \frac{R(E_b)}{2D} \right) \right] \left[ \frac{t_0}{t} \right] \left[ 1 - e^{-\left(1/t_0\right)} \left( 1 + \left[ \sigma_{\text{diffusion}}^0 \sigma_o \right] + \left[ \sigma_{\text{dispersive}}^0 \sigma_o \right] \left( t^{-(1-\alpha)} \right) \right) \right]^{-1}
\]

Discharge

\[
V(t) = V_o e^{-t \sigma(t)/\varepsilon_o \varepsilon_r} \approx V_o \left[ 1 - \left( \frac{\sigma_o t}{\varepsilon_o \varepsilon_r} \right) \left\{ 1 + \left[ \sigma_{\text{diffusion}}^0 \sigma_o \right] t^{-1} + \left[ \sigma_{\text{dispersive}}^0 \sigma_o \right] t^{-(1-\alpha)} \right\} \right]
\]
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.

Sample stack cross section
Low Temperature Cryostat

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

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

---

**Radiation Sources**
- 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
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)
- Electronic at ~1 pA/cm² to ~10μA/cm² & ~10 eV to 50 keV
- 35 K < T < 350 K
- Multiple sample configurations to ~10x10cm
Electron-Induced Luminescence

Diversity of Optical 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
- 110 or 4100 uW/cm²
- 5 or 188 nA/cm²

**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

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

**Electrometer**
- InGaAs Video Camera
  - (400 nm to 900 nm)
- CCD Video Camera
  - (900 nm to 1700 nm)

**SLR NIR Video**
- 33 ms exp.

---

"Flare" Sustained Glow

"Flare" Sustained Glow

"Flare" Sustained Glow

"Flare" Sustained Glow

---

Sustained Glow NIR Video

Sustained Glow 5 uA/cm²

Sustained Glow 22 keV 150 K

Sustained Glow 22 keV 150 K
**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

![Diagram showing glow sources and their impact on JWST components](image-url)
**F_{ESD} Breakdown: Dual (Shallow and Deep) Defect Model**

**Yields:**

Ratio of Defect energy to Trap density, $\Delta G_{def}/N_T$

Separate these with T dependence

$\Delta G_{def} = 0.97 \text{ eV}$

$N_T = 1 \cdot 10^{17} \text{ cm}^{-3}$

Breakdown field measurements:

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

Endurance time measurements:

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

Based on first breakdown

“Complete” Breakdown ~2-4X this field

$F_{ESD} = 20 \pm 2 \text{ MV/m at RT}$

$F_{ESD} = 27 \pm 2 \text{ MV/m at } 157 \text{ K}$

$F_{ESD} = 19.0 \pm 0.6 \text{ MV/m at RT and } 142 \text{ K (irradiated)}$
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 $\sim r^{-2}$
“All spacecraft surfaces are eventually carbon…”
--C. Purvis

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

Charging: Evolution of Contamination and Oxidation

Onset of threshold charging
Environmental Changes: Reflectivity as a Feedback Mechanism

Reflectivity changes with surface roughness and contamination

- Reflect $\rightarrow$ Charging $\rightarrow$ Contamination
- Reflect $\rightarrow$ Emissivity $\rightarrow$ Temp $\rightarrow$ Contamination
- Charging $\rightarrow$ Reflectivity
- Radiation $\rightarrow$ Reflect $\rightarrow$ Emissivity $\rightarrow$ Temp $\rightarrow$ Contamination

See Lai & Tautz, 2006 & Dennison 2007

JWST Structure: Charging vs. Ablation

Onset of threshold charging

Before

Zoomed Images

After

See Lai & Tautz, 2006 & Dennison 2007

JWST Structure: Charging vs. Ablation
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, JUNO, JGO/JEO

Mechanical and Optical Materials
Damage

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

Radiation induced Conductivity (RIC)

Temperature dependent tran...

Transport and Emission Properties

Caused by bondbreaking and trap creation.
Combined Temperature and Dose Effects

Dark Conductivity

\[ \sigma_{DC}(T) = \sigma_0^{DC} e^{-E_0/k_B T} \]

RIC Electrostatic Breakdown

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

Dielectric Constant

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

Electrostatic Breakdown

\[ E_{ESD}(T) = E_{ESD}^{RT} e^{-\alpha_{ESD}(T-298K)} \]
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 × 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 Sr^{90} 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 cathodoluminescence and imaging systems is crucial for model validation in various fields. In this study, we report on a round robin test involving electron emission measurements performed at four international laboratories. The primary objectives were to determine the consistency and uncertainties of each system and to investigate the effects of the different measurement techniques. Several facilities were used, including a high-resolution electron spectrometer and a field-emission scanning electron microscope. Measurement results are presented and analysis is performed to determine the accuracy and precision of the different systems.

**Descriptions of Facilities and Methods**

- **CSIC SEY Facility**: The CSIC facility is equipped with a high-resolution electron spectrometer (HREM) and a field-emission scanning electron microscope (FESEM). Measurements include electron energy distribution and intensity.
- **LaSEINE TEY Facility**: This facility uses a high-resolution electron spectrometer to measure electron energy distribution and intensity. The facility is equipped with a field-emission scanning electron microscope.
- **ONERA DEESE Facility**: The ONERA facility is equipped with a high-resolution electron spectrometer and a field-emission scanning electron microscope. Measurements include electron energy distribution and intensity.
- **USU SEEM Facility**: The USU facility is equipped with a high-resolution electron spectrometer and a field-emission scanning electron microscope. Measurements include electron energy distribution and intensity.

**Round Robin Tests Results**

Measurements were made of the absolute electron yields at several institutes. The results of the round robin tests showed good agreement among the different facilities. The electron yield measurements were performed using the same measurement techniques and data processing methods. The measurements were found to be consistent and reproducible, with a high degree of accuracy and precision.

**Summary**

- **Summary of results**:
  - Good agreement among all facilities
  - High level of confidence in the measurements
  - Opportunity for further improvements in measurement techniques

**Topics of future Round Robin analysis**:

- Impact of measurement uncertainties on calibration results
- Development of improved measurement techniques
- Role of calibration in model validation in various fields

**References**


[2] LaSEINE, Kyushu Institute of Technology, CSIC, Instituto de Ciencias de Materiales de Madrid.
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
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 Dynamics 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
Research Projects & Collaborations

The MPG Space Environment Effects Materials Test Facility Test Facility (STEFF) is a leading research center for the study of space environment effects on aerospace materials. The MPG performs experiments on a broad range of topics, including:

- Material testing under simulated space conditions
- Simulation of electromagnetic and plasma environments
- Evaluation of materials' long-term performance in space-like conditions

Collaborations:
- NASA Glenn Research Center
- NASA Langley Research Center
- NASA Marshall Space Flight Center
- NASA Goddard Space Flight Center
- Department of Energy
- Air Force Research Laboratory
- Defense Advanced Research Projects Agency
- National Science Foundation
- National Aeronautics and Space Administration
- Department of Defense

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MPG Space Environment Effects Materials Test Facility

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

Electron Environment

- Electron emission studies for incident electron, ion, and photon probes with precision absolute yields of conductors, semiconductors, insulators, & extreme insulators [12].

Conductivity & Charge Transport

- Conductivity and charge transport studies for conductors, semiconductors, & extreme insulators [12].

Simulation Space

- The Space Survivability Test (SST) chamber [10] has unique capabilities for simulating and testing potential environmental-induced modifications on small satellites, components, and materials of up to 450 cm² area. It is particularly well suited for cost-effective tests of multiple small scale materials samples over prolonged exposure to simulate critical environmental conditions including:
  - Neutral gas atmosphere / vacuum
  - Temperature from 273 K to >1823 K (1000°C)
  - Electrical fluxes with simultaneous low and high energy electron fluxes from 3×10⁻²⁴ to >10⁻²⁴ erg cm⁻² s⁻¹
  - Condensation on electrical hardware
  - Temperature capabilities from >30 K to >1823 K
  - High temperature under development

Cathodoluminescence

- Absolute intensity and low level electron-induced luminescence spectroscopy.
  - Spectra: 80-50, 200-1720 cm⁻¹ with 0.1 cm⁻¹ resolution
  - Absolute accuracy: 0.1 cm⁻¹

Electrostatic Discharge & Arcing

- Electrostatic breakdown field strength (3×10⁻²⁴ cm⁻² s⁻¹ V/m²)
  - Temperature and vacuum capability from >30 K to >320 K (100°C)
  - Electrostatic arcing with current and arc length continuously adjustable with output from 3×10⁻²⁴ to 3×10⁻²⁴ A

Characterization & Preparation

- Extensive capabilities for sample preparation and characterization. These include:
  - Bulk Composition Analysis: Raman, X-ray Diffraction (XRD), FTIR, and Mass spectrometry.
  - Surface Morphology Analysis: Scanning Electron Microscopy (SEM-EDS), Optical Microscopy (OM), Atomic Force Microscopy (AFM) and Scanning Tunneling (STM) microscopes.
  - Vacuum Thermal Ovens: Various ovens from 0°F to 260°F.
  - Optical Characterization: Spectroscopy and Diffuse Reflectometry.
  - Thermo-Hygroscopic, Flow, Thermoelectric, Temperature, Radiation.
  - Luminescence Analysis: Optical and Raman Spectroscopy (OSL), Time Resolved Luminescence (TRL), Time-Resolved Luminescence (TRL)

Collaborative Facilities

- The MPG collaborates with nearby facilities to extend our capabilities. These include:
  - Utah State University Space Dynamics Laboratory for satellite and sensor development, fabrication & integration.
  - SDL, the National Oceanic and Atmospheric Administration (NOAA) test facility for characterization and verification of sub-systems and subsystems performance for small scale systems.
  - Utah State University’s high energy accelerator center for high energy electron, proton, and neutron testing and simulation sources.
  - Utah State University’s Microscopy Facility for high resolution electron and optical microscopy.
  - Utah State University’s Materials Science Lab for optical and thermal stimulated luminescence testing.
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

\( \sigma_{\text{intrinsic}} \)

\( \sigma_{\text{TAH}} \)

\( \sigma_{\text{VRH}} \)

\( \Delta H \)

\( \Delta H \)

\( E_c \)

\( E_0 \)

\( E_{\text{gap}} \)

\( E_v \)

\( \sigma_{\text{RIC}} \)

luminescence