Energetic Particles and Technology

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Heliophysics Summer School – Year 2
Space Storms and Radiation: Causes and Effects
Boulder, Colorado  30 July 2008
OBJECTIVE

• The purpose of this chapter is to provide space scientists with detailed knowledge of how the environment of space interacts with, and degrades, spacecraft systems.
CATEGORIES OF STUDY

• Vacuum Environment Effects
  – Phenomena associated with the absence of a substantial atmosphere

• Neutral Environment Effects
  – Phenomena associated with the presence of a tenuous neutral atmosphere

• Plasma Environment Effects
  – Phenomena associated with the presence of low energy (keV range) charged particles

• Radiation Environment Effects
  – Phenomena associated with the presence of high energy (MeV – GeV range) particles / photons

• Micrometeoroid / Orbital Debris Effects
  – Phenomena associated with the presence of hypervelocity particles
SPACE ENVIRONMENT EFFECTS

• Vacuum Environment Effects
  – Solar UV Degradation
  – Molecular Contamination
  – Particulate Contamination

• Neutral Environment Effects
  – Aerodynamic Drag
  – Sputtering
  – Atomic Oxygen Erosion
  – Spacecraft Glow

• Micrometeoroid/Orbital Debris environment Effects
  – Hypervelocity Impact Damage

• Plasma Environment Effects
  – Spacecraft Charging
    • Arc Discharging
    – keV Energy Particles

• Radiation Environment Effects
  – Total Dose Effects
    – MeV Energy Particles
  – Single Event Effects
    – GeV Energy Particles
## SPACE ENVIRONMENT EFFECTS

<table>
<thead>
<tr>
<th>Spacecraft Subsystems</th>
<th>VACUUM</th>
<th>NEUTRAL</th>
<th>PLASMA</th>
<th>RADIATION</th>
<th>MMOD</th>
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<td>Avionics</td>
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<td>EMI From Arc Discharging</td>
<td>Total Dose Degradation; Single Event Effects</td>
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<tr>
<td>Attitude Determination &amp; Control</td>
<td>Degradation of Sensors</td>
<td>Induced Torques</td>
<td>Degradation of Sensor Coatings</td>
<td>Noise Source for Sensors</td>
<td>Torques Due to Induced Potentials</td>
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<tr>
<td>Environmental Control &amp; Life Support</td>
<td>Toxic Fumes</td>
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<td>Propulsion</td>
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<td>Drag Makeup Fuel Requirement</td>
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<td>Structures</td>
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<td>Dielectric Breakdown on Surfaces</td>
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<tr>
<td>Telemetry, Tracking, and Communications</td>
<td>Degradation of Sensors</td>
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<td></td>
<td>EMI From Arc Discharging</td>
<td>Total Dose Degradation; Single Event Effects</td>
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<tr>
<td>Thermal Control</td>
<td>Change in Absorptance / Emittance</td>
<td>Change in Absorptance / Emittance</td>
<td></td>
<td></td>
<td>Cold Surfaces May Experience Heating</td>
</tr>
</tbody>
</table>
WHY STUDY SPACE ENVIRONMENTS & EFFECTS?

• Spacecraft anomalies
  – 1/3 of all spacecraft anomalies related to the environment

• Spacecraft failures
  – 1/4 of all spacecraft failures related to the environment
THE ATMOSPHERE BELOW 100 KM

Spacecraft Must Be Designed to Operate in Extremely Low Pressure Environments
**VACUUM: SOLAR UV DEGRADATION**

- The energy carried by UV light is of sufficient energy to sever many kinds of molecular bonds
- The result is a degradation of material properties

<table>
<thead>
<tr>
<th>CHEMICAL</th>
<th>BOND</th>
<th>BOND ENERGY (eV)</th>
<th>WAVELENGTH (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C - C</td>
<td>SINGLE</td>
<td>3.47</td>
<td>0.36</td>
</tr>
<tr>
<td>C - N</td>
<td>SINGLE</td>
<td>3.17</td>
<td>0.39</td>
</tr>
<tr>
<td>C - 0</td>
<td>SINGLE</td>
<td>3.73</td>
<td>0.33</td>
</tr>
<tr>
<td>C - C</td>
<td>DOUBLE</td>
<td>2.52</td>
<td>0.49</td>
</tr>
<tr>
<td>C - N</td>
<td>DOUBLE</td>
<td>6.29</td>
<td>0.26</td>
</tr>
<tr>
<td>C - C</td>
<td>TRIPLE</td>
<td>7.64</td>
<td>0.16</td>
</tr>
</tbody>
</table>
VACUUM: MOLECULAR CONTAMINATION

- Molecular films on the order of 1 μm thick may be deposited during on orbit operations
  - Degrades optical / thermal properties
VACUUM: PARTICULATE CONTAMINATION

- Particulates on the order of 1 μm in size may be deposited during manufacturing, assembly, test, or launch
  - Degrades optical components
ATMOSPHERIC CONSTITUENTS

LOG NUMBER DENSITY BY SPECIES

LOG NUMBER DENSITY (m^-3)

N2
O2
O
Ar
He

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Space Storms and Radiation: Causes and Effects

Particle Interaction With Technology
Tribble
Slide #11
**NEUTRAL: AERODYNAMIC DRAG**

• An object of dry mass $M$, moving with velocity $v$, can change its velocity by ejecting a mass of fuel $\Delta m$ at velocity $v'$.

\[
(M + \Delta m)v = M(v + \Delta v) + \Delta m(v - v')
\]

• From Conservation of Momentum
Neutral molecules carry significant amounts of kinetic energy upon impact with spacecraft surfaces in LEO

\[ qV = \frac{1}{2} mv^2 \]

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>H</th>
<th>he</th>
<th>O</th>
<th>N2</th>
<th>O2</th>
<th>ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.3</td>
<td>1.3</td>
<td>5.0</td>
<td>8.8</td>
<td>10.1</td>
<td>12.6</td>
</tr>
<tr>
<td>600</td>
<td>0.3</td>
<td>1.2</td>
<td>4.7</td>
<td>8.3</td>
<td>9.5</td>
<td>11.8</td>
</tr>
<tr>
<td>800</td>
<td>0.3</td>
<td>1.1</td>
<td>4.5</td>
<td>7.9</td>
<td>9.0</td>
<td>11.2</td>
</tr>
</tbody>
</table>
Before: Fairly Smooth

After: Obvious Pitting

**NEUTRAL: ATOMIC OXYGEN EROSION**

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Fig. 5 Exposed carbon-epoxy specimen (1000X).

Fig. 6 Control carbon-epoxy specimen internal surface (1000X).
NEUTRAL: SPACECRAFT GLOW (AND AURORA)
MMOD COMPARISON

Year = 2000, Altitude = 400 km, Solar F10.7 = 175
MMOD: HYPERVELOCITY IMPACT
MMOD: CUMULATIVE EFFECTS

- 5 years exposure in LEO resulted in noticeable surface damage to many panels on the Long Duration Exposure Facility (LDEF)
Ed white’s space walk in 1965 generated some orbital debris when a glove floated out of the open hatch of the capsule.
Effects of keV Energy Particles

Spacecraft Charging
PLASMA ENVIRONMENTS

• Low Earth Orbit (LEO)
  – High Density (~$10^5$ cm$^{-3}$ = $10^{11}$ m$^{-3}$)
  – Low Temperature (~1,000 K)
  – Oxygen (O$^+$) and Electrons (e$^-$)

• Geosynchronous (GEO)
  – Low Density (~1 cm$^{-3}$ = $10^6$ m$^{-3}$)
  – High Temperature (~1,000,000 K)
  – Protons (p$^+$) and Electrons (e$^-$)

• Auroral or Polar
  – Short Term Transitions Through High Energy Plasma When Crossing the Auroral Region (> 60° Latitude)
  • The Worst of Both Worlds
## THE LEO PLASMA ENVIRONMENT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma Density</td>
<td>$1 \times 10^{11}$ m$^{-3}$</td>
</tr>
<tr>
<td>Plasma Temperature</td>
<td>1000 K (0.13 eV)</td>
</tr>
<tr>
<td>Debye Length</td>
<td>1 cm</td>
</tr>
<tr>
<td>Electron Gyroradius</td>
<td>1 cm</td>
</tr>
<tr>
<td>Ion Gyroradius</td>
<td>3 m</td>
</tr>
<tr>
<td>Electron Thermal Speed</td>
<td>200 km/s</td>
</tr>
<tr>
<td>Orbital Velocity</td>
<td>8 km/s</td>
</tr>
<tr>
<td>Ion Thermal Speed</td>
<td>1 km/s</td>
</tr>
<tr>
<td>Electron Plasma Frequency</td>
<td>2.8 MHz</td>
</tr>
<tr>
<td>Ion Plasma Frequency</td>
<td>16.6 kHz</td>
</tr>
</tbody>
</table>
• In LEO

\[ v_{i,th} = \left( \frac{3kT_i}{m_i} \right)^{1/2} \approx 1 \text{ km/s} \]

\[ v_o \approx 8 \text{ km/s} \]

\[ v_{e,th} = \left( \frac{3kT_e}{m_e} \right)^{1/2} \approx 200 \text{ km/s} \]

Ions impact on ram surfaces only

Electrons collected by all surfaces

A NEUTRAL OBJECT IN LEO - 1
• Because the electron flow is dominant the object will charge negatively
• The ion current flow to the object is controlled by the orbital velocity

\[ I_i = qn_i v_i A_i = qn_o v_o A_i \]

• The electron current is controlled by the electron thermal velocity

\[ I_e = qn_e v_e A_e = \frac{1}{4} qn_o v_{e,th} A_e \exp\left(\frac{-eV}{kT_e}\right) \]

\( A_i \) is the cross sectional area, \( A_e \) is the total surface area
The object will continue to charge until the negative potential is great enough to retard the collection of additional electron current.

Equilibrium is defined by current balance:

\[ I_i = I_e \]

Solving this equation for the potential gives:

\[ V_{fl} = \frac{-kT_e}{q} \ln \left[ \frac{4n_i v_o A_i}{n_e v_{e,th} A_e} \right] \]
SPACECRAFT GENERATE POWER VIA SOLAR ARRAYS
Consider the example of the solar array illustrated below.
• Consider a simplistic, one dimensional model, of the array current collection

• Ions will be collected by those portions of the array biased less positively than the ion impact energy, $\phi_i$

$$J_i = en_i v_i \frac{f V_a - \phi_i}{V_a}$$

• Electrons will be collected by those portions of the array biased less negatively than the electron impact energy, $\phi_e$

$$J_e = en_e v_{e,th} \frac{(1 - f) V_a - \phi_e}{V_a}$$

• Where $f$ is the fraction of the array floating negatively
• It is easily seen that the nominal value for $f$ is quite close to one

• Consequently, the majority of a solar array will float negatively with respect to the plasma
SOLAR ARRAY GROUNDING OPTIONS

PLASMA POTENTIAL

NEGATIVE GROUND

STRUCTURES ~ 90% OF ARRAY VOLTAGE NEGATIVE

POSITIVE GROUND

STRUCTURES A FEW VOLTS POSITIVE

FLOATING GROUND

STRUCTURES A FEW VOLTS NEGATIVE
LEO VS GEO

• In LEO the thermal current dominates photoemission
  – Spacecraft nominally charge negatively, with the value of the potential being related to the solar array voltage

• In GEO the situation is reversed, photoelectron emission is dominant
  – Spacecraft nominally charge positively, independent of the array voltage
    • But severe negative charging can occur during magnetospheric storms
## NOMINAL GEO CONDITIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Plasma Density</td>
<td>$1 \times 10^6 \text{ m}^{-3}$</td>
</tr>
<tr>
<td>Plasma Temperature</td>
<td>1,000,000 K (130 eV)</td>
</tr>
<tr>
<td>Debye Length</td>
<td>2 m</td>
</tr>
<tr>
<td>Electron Gyroradius</td>
<td>7.5 km</td>
</tr>
<tr>
<td>Ion Gyroradius</td>
<td>3 m</td>
</tr>
<tr>
<td>Electron Thermal Speed</td>
<td>6,000 km/s</td>
</tr>
<tr>
<td>Ion Thermal Speed</td>
<td>30 km/s</td>
</tr>
<tr>
<td>Orbital Velocity</td>
<td>3 km/s</td>
</tr>
<tr>
<td>Electron Plasma Frequency</td>
<td>900 Hz</td>
</tr>
<tr>
<td>Ion Plasma Frequency</td>
<td>50 Hz</td>
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</table>
SEVERE SPACECRAFT CHARGING

Magnetopause Compressed to < 10 $R_E$

Solar Wind

Sun’s Magnetic Field Dominant

Earth’s Magnetic Field Dominant

HOT PLASMA PUSHED EARTHWARD

ENERGETIC PROTONS

ENERGETIC ELECTRONS

SEVERE SPACECRAFT CHARGING MIDNIGHT - 6 AM

VIEW FROM TOP

B

Earth’s Magnetic Field Lines Compressed
EVIDENCE OF S/C CHARGING

Fig. 8: Worst-case charging event, June 27, 1974.

IONS

ELECTRONS

ATS-6/UCSD
SPACECRAFT CHARGING ANOMALIES

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Space Storms and Radiation:
Causes and Effects

Particle Interaction With Technology
Tribble
Slide #35
**CHARGING EFFECTS: BIASING OF DATA**

- Low voltage, spacecraft charging, was seen on the Plasma Diagnostics Package in LEO.
  - It was indirectly induced by a high voltage (2.2 kV) instrument on the spacecraft.

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**TYPICAL LANGMUIR CURVE**

- Diagram showing a typical Langmuir curve with a smooth decrease in current as the bias voltage increases.

**ANOMALOUS LANGMUIR CURVE**

- Diagram showing an anomalous Langmuir curve with a peak in current at a certain bias voltage, indicating a deviation from the typical behavior.
Solar arrays that are placed in plasma
Chambers are observed to arc.
CHARGING EFFECTS: DIELECTRIC BREAKDOWN

Fig. 1. Optical micrograph of microdamage on a 125-μm silvered FEP Teflon sample irradiated by a 35-keV electron beam.1

Fig. 3. Microdamage on 75-μm silvered Teflon samples irradiated by a 26-keV electron beam.2

MITIGATION TECHNIQUES

• To control the absolute value of the floating potential
  – Actively balance the currents to the spacecraft
    • Use plasma contactors, plasma thrusters, ...

• To control differential charging between surfaces
  – Ensure that surfaces are of uniform conductivity
    • Conductive coatings
HOW CAN SPACE SCIENTISTS HELP?

• Improved models of the environment would result in better prediction of spacecraft charging events.
  – The most significant need is an increased ability to predict severe spacecraft charging events in GEO.
    • Space weather forecasting

• Note:
  – In this context, we mean a model of “what” the environment is, rather than “how” it got to be that way.
DAILY SOLAR ACTIVITY REPORTS

• Daily Reports of Solar Activity Are Available From NOAA’s Space Environments Center
  – www.sec.noaa.gov

• Example
  – Joint USAF/NOAA Report of Solar and Geophysical Activity SDF Number 277
    • Issued at 2200Z on 04 Oct 2006
  – IA. Analysis of Solar Active Regions and Activity from 03/2100Z to 04/2100Z: Solar activity was very low. A CME was first observed off the west limb on LASCO imagery at 04/0854 UTC. This CME probably originated from active Region 915 (S06, L=291) which rotated around the west limb on 03 October. The ejecta was directed to the west and is not expected to be geoeffective.
  – IB. Solar Activity Forecast: Solar activity is expected to be very low.
  – IIA. Geophysical Activity Summary 03/2100Z to 04/2100Z: The geomagnetic field was quiet. The greater than 2 MeV electron flux at geosynchronous orbit reached high levels again today.
  – IIB. Geophysical Activity Forecast: The geomagnetic field is expected to be mostly quiet.
Effects of MeV Energy Particles

Total Dose Effects
OMNIDIRECTIONAL EQUATORIAL FLUX

Flux (cm\(^{-2}\) s\(^{-1}\))

- **ELECTRONS**
  - 0.1 MeV
  - 1 MeV
  - 3 MeV

- **PROTONS**
  - 0.1 MeV
  - 1 MeV
  - 10 MeV

MeV PARTICLES – TRAPPED RADIATION BELTS
WHAT IS RADIATION?

• As an energetic particle passes through matter it will create atomic displacements and/or ionize atoms in the material.
• As a result the material properties will be altered.
• Radiation can be thought of as anything that deposits energy in a material.
  – Charged particles (electrons, protons)
  – Uncharged particles (neutrons)
  – Photons (gamma rays, x-rays)
MEASURES OF ENERGY DEPOSITION

- **Total Ionizing Dose (TID)**
  - A measure of the amount of energy lost due to ionizations
  - TID is a function of
    - The radiation
      - Energy and type
    - The target material

- **Displacement Damage (DD)**
  - A measure of the amount of energy lost due to displacements
  - DD is a function of
    - The radiation
      - Energy and type
    - The target material
SPECIFIC IONIZATION OF AIR

• As an electron passes through air it will leave a trail of ionized particles in its wake
RADIATION DOSE UNITS

• Roentgen (R)
  – The amount of radiation that will produce one electrostatic unit (ESU) of charge of either sign in one cubic cm (0.001293 g) of air

• Radiation Absorbed Dose (RAD)
  – The amount of any kind of radiation that deposits 100 ergs per gram of material
  • 0.01 J/kg

• Gray
  – The amount of any kind of radiation that deposits 1 J/kg of material
  • 1 gray = 100 RADS
• In many materials, the total dose of radiation is the critical issue in determining useful lifetime

<table>
<thead>
<tr>
<th>Material</th>
<th>Damage Threshold (Gray)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biological Matter</td>
<td>$10^{-1} - 10^0$</td>
</tr>
<tr>
<td>Electronics</td>
<td>$10^0 - 10^2$</td>
</tr>
<tr>
<td>Lubricants, Hydraulic Fluid</td>
<td>$10^3 - 10^5$</td>
</tr>
<tr>
<td>Ceramics, Glasses</td>
<td>$10^4 - 10^6$</td>
</tr>
<tr>
<td>Polymeric Materials</td>
<td>$10^5 - 10^7$</td>
</tr>
<tr>
<td>Structural Metals</td>
<td>$10^7 - 10^9$</td>
</tr>
</tbody>
</table>
TRAPPED RADIATION DOSE EXAMPLES

- GPS
  - 20,000 Km Altitude, 55 Degree Inclination
- GEO
  - 35,900 Km Altitude, 0 Degree Inclination
- Space Station
  - 400 Km Altitude, 51.6 Degree Inclination
- Sun Synchronous
  - 888 Km Altitude, 99.2 Degree Inclination
GPS RADIATION ENVIRONMENT

20,000 km @ 55 degrees

Fluence (cm\(^{-2}\) day\(^{-1}\))

Energy (MeV)

Protons

Electrons - Solar Min.

Electrons - Solar Max.

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Space Storms and Radiation:
Causes and Effects

Particle Interaction With Technology
Tribble
Slide #50
Altitude = 20,000 km
Inclination = 55 deg.
Shielding = Full-Sphere

GPS RADIATION DOSE

Shiriding Thickness (mils - Al)

Dose (rad/day)

Total
Proton
Electron
Brems.
The Radiation Belts May Induce Deep Dielectric Charging
KAPTON DISCHARGE TIME

\[ k = 3.40, \quad E_{\text{max}} = 150 \text{ kV/cm} \]
Altitude = 35,800 km
Inclination = 0 deg.
Shielding = Full-Sphere

GEO RADIATION DOSE

Dose (rad/day)

Shielding Thickness (mils - Al)

- Total
- Proton
- Electron
- Brems.
SPACE STATION RADIATION DOSE

Altitude = 400 km
Inclination = 51.6 deg.
Shielding = Full-Sphere

ISS Shielding

Dose (rad/day)

Total
Proton
Electron
Brems.

Shielding Thickness (mils - Al)

ISS Shielding
SUN SYNCHRONOUS RADIATION DOSE

Altitude = 888 km
Inclination = 99.2 deg.
Shielding = Full-Sphere

Total
Proton
Electron
Brems.

Dose (rad/day)

Shielding Thickness (mils - Al)

SUN SYNCHRONOUS RADIATION DOSE

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Space Storms and Radiation: Causes and Effects

Particle Interaction With Technology
Tribble
Slide #56
TOTAL DOSE EFFECT: POWER LOSS

Degradation Data is Obtained From the Solar Cell Manufacturer
Figure 66: Number of failed bits versus refresh time for 16 Mb DRAMs irradiated with Co-60 gamma rays at total doses from 0 to 50 krad(Si). (After Ref. [219])
MITIGATION TECHNIQUES

• Shielding
  – Prevent the radiation environment from reaching the crew or sensitive electronics

• Parts selection
  – Choose parts or materials that can withstand the total dose environment anticipated

• Margin
  – Allow for degradation in the design of the subsystem
HOW CAN SPACE SCIENCE HELP?

• Better models of the trapped radiation environment, and energetic particle environment, result in more accurate predictions of total dose to spacecraft systems.

• Tools that generate dose vs depth curves (Shieldose, Spacerad, …) use models of the radiation belts (AE-8, AP-8) as input.
Effects of GeV Energy Particles

Single Event Effects
TYPES OF SEE

• Single Event Upset (SEU)
  – Transient Change in State of a Digital Circuit
    • Switching of Memory Register From 1 to 0
  – No Damage to the Circuits
    • Circuit Continues to Function Properly Afterward
    • Only the Data May be Corrupted

• Single Event Latchup (SEL)
  – Temporary Change in the Device
    • Device Hangs Up, Draws Excessive Current, ...
  – Device Will Not Work Unless Powered Off and Back On
    • No Long Term Effects on the Device Seen

• Single Event Burnout (SEB)
  – Permanent Failure of the Device
CMOS INVERTER
SEE ILLUSTRATION

Radiation
(proton, ion, neutron, …)

Upset occurs if channel current turned on
Burnout (Gate Rupture …) occurs if material cannot absorb deposited energy without damage

Latchup occurs if parasitic current loop initiated

SEE ILLUSTRATION
The Few “Rad Hard” Parts That Remain are Also Disappearing
MULTIPLE BIT UPSETS

- Less energetic particles, (which are more numerous), are capable of causing SEUs in smaller devices
  - Larger devices would be immune

- Scaling of semiconductor device geometries now causing MBUs
  - Traditional redundancy and EDAC methods ineffective for these MBUs

![Diagram of transistor and discharge regions](image)

1 \( \mu \text{m} \) Transistor

Large Discharge Region

Small Discharge Region

Four 0.25 \( \mu \text{m} \) Transistors

Large Discharges
Cause SEUs

Large Discharges
Cause MBUs

Small Discharges
Have No Effect

Small Discharges
Cause SEUs
MEASURES OF ENERGY LOSS / PATH

• Linear Energy Transfer (LET)
  - Measures the amount of energy lost per unit path length due to ionizations

• Non-Ionizing Energy Loss (NIEL)
  - Measures the amount of energy loss per unit path length due to displacements
LINEAR ENERGY TRANSFER (LET)

Integral LET Spectrum - Deep Space

- GCR Flux + Peak, Composite Worst Case SPE with 10% Worst Case Composition
- GCR Flux + Peak, August 1972 SPE with Mean Composition
- GCR Flux + Peak, 10% Worst Case SPE with Mean Composition
- GCR Flux + Peak, Ordinary SPE with Mean Composition
- GCR Flux Only

Flux at 0 mils (m^-2 sr^-1 s^-1)

LET (MeV cm^2 g^-1)
SEU EXAMPLE: SAMSUNG DRAM

Samsung DRAM Upset Cross-Section

KM48V8004AK-6

Weibull Parameters

\[ \sigma_{\text{asym}} = 2.5 \times 10^{-8} \]
\[ L_\text{th} = 10.5 \]
\[ W = 35 \]
\[ s = 1.0 \]

- \( \triangledown \) CAS Before RAS Refresh
- \( \square \) RAS Only Refresh
- \( \blacksquare \) TASCC Data (3.3V)
Single Event Effects Often Maximize Over The SAA
MITIGATION TECHNIQUES

• Shielding
  – Prevent the radiation environment from reaching the crew or sensitive electronics
  • Not effective on very energetic (GeV) charged particles

• Parts selection
  – Choose parts or materials that can withstand the total dose environment anticipated
  – Choose parts that are immune or resistant to SEE

• Fault tolerance
  – Hardware
    • Redundancy, majority voting, …
  – Software
    • Error Detection and Correction (EDAC), Hamming codes, …
HOW CAN SPACE SCIENCE HELP?

• Better predictions of the size and frequency of energetic particle events will help designers better quantify, and mitigate, the risk.
FOR MORE INFORMATION

• NASA Marshall Space Flight Center
  – Space Environments and Effects Program
    • http://see.msfc.nasa.gov
• NASA Glenn Research Center
  – Space Environments Branch
    • http://satori2.lerc.nasa.gov
• NASA Goddard Space Flight Center
  – Space Radiation Branch
    • http://flick.gsfc.nasa.gov/radhome/
  – National Space Science Data Center (NSSDC)
    • http://nssdc.gsfc.nasa.gov
• NASA Jet Propulsion Laboratory
  – Radiation Effects Database
    • http://radata.jpl.nasa.gov
• NOAA Space Environments Lab
  – Space Weather Forecast
    • http://www.sel.noaa.gov/today.html
• European Space Agency (ESA)
  – http://www.esa.int
• National Space Development Agency (NASDA) of Japan
  – http://www.nasda.go.jp/index_e.html
• Japan Aerospace Exploration Agency (JAXA)
  – http://www.jaxa.jp/index_e.html
• U.S. Air Force Research Laboratory
  – Space Vehicles Directorate
    • http://www.vs.afrl.af.mil/
• Space Weather
  – Science News and Information
    • http://www.spaceweather.com
• Instructor’s Web Site
  – Links to Site’s of Interest
    • http://www.atribble.com
Solar Array Design Example
THE PROBLEM

• Conduct a design trade of a Solar Array to determine:
  – The solar cell technology, and
  – The amount of shielding,
• That will satisfy the mission requirements.

• The final answer will be both a function of cost and mass.
DESIGN EXAMPLE: SOLAR ARRAY SIZING

- Solar Array Size is Driven by the Amount of Energy That Must be Produced
  - $A = \text{Solar Array Area (m}^2\text{)}$
  - $P = \text{Power Required (W)}$
  - $\eta = \text{Efficiency}$
    - Efficiency is Degraded by Radiation
      - BOL Value is Greater Than the EOL Value
    - Efficiency Loss is Minimized by Adding a Transparent Shield
      - Coverslide
  - $S = \text{Sun’s Power Output (1367 W/m}^2\text{ at Earth Orbit)}$

$$A = \frac{P}{\eta S}$$
DESIGN TRADE: COST VS. MASS

- Solar Array Cost
  - Procurement
    • Total Cost = Cost of Individual Cell Times the Number of Cells Required
  - Manufacturing
    • Depends on the Array Design

- Solar Array Mass
  - Cells
    • Roughly 10 kg/m²
  - Coverslide
    • Total Mass = Thickness of Coverslide Times Areal Density
      - 2.2 g/cm³ for Silica
SOLAR CELL CONSTRUCTION

- The Cell Coverglass Provides Shielding From Above
  - The Coverglass Thickness is Tailored to Provide More Shielding if Needed
- The Cell Substrate (Usually) Provides Much Better Shielding From Below

![Diagram of Solar Cell Construction]

- COVERGLASS
- GLASS/CLEAR ADHESIVE
- SOLAR CELL
- SOLDER
- CELL/SUBSTRATE ADHESIVE
- FIBERGLASS INSULATOR
- SUBSTRATE ALUMINUM FACESHEET
- FACESHEET/CORE ADHESIVE
- HONEYCOMB CORE
- FACESHEET/CORE ADHESIVE
- SUBSTRATE ALUMINUM FACESHEET
- THERMAL PAINT
SOLAR ARRAY DESIGN OPTIONS

• Different Solar Cell Types
  – Silicon (Si)
    • Cost: Low (~$250/W)
    • Efficiency: Low (14%)
    • Radiation Resistance: Low
  – Gallium Arsenide (GaAs)
    • Cost: Medium (~ $600/W)
    • Efficiency: Medium (19%)
    • Radiation Resistance: Medium
  – Indium Phosphide (InP)
    • Cost: High (~ $1,000/W)
    • Efficiency: High (24%)
    • Radiation Resistance: High

• Different Coverslide Thicknesses
  – 10, 20, 30, 40, or 50 mils
    • 1 mil = 1 milli-inch
ANALYSIS PROCESS

• Step One
  – Quantify the Radiation Environment and the Resulting Radiation Dose
    • Radiation Dose as a Function of Shielding Depth

• Step Two
  – Quantify the Solar Cell Efficiency as a Function of Radiation Dose

• Step Three
  – Determine Solar Array Mass and Cost for Various Options of Cells and Coverslides
THE RADIATION ENVIRONMENT

Trapped Radiation Environment

![Graph showing integral flux vs energy for electrons and protons.]

Radiation Dose

![Graph showing dose vs shielding for electron, proton, and total.]

Numerical Codes (Shieldose) Predict the Environment and Dose
SOLAR CELL DEGRADATION

Normalized Efficiency vs. Dose (KRad)

- InP
- GaAs
- Si

Dose (KRad)

Normalized Efficiency
### EFFICIENCY VS. SHIELDING THICKNESS

Table 13.13  Radiation Dose as a Function of Coverslide Thickness.

<table>
<thead>
<tr>
<th>Shielding Thickness</th>
<th>10 mils</th>
<th>20 mils</th>
<th>30 mils</th>
<th>40 mils</th>
<th>50 mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dose (Krad)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Table 13.14  Radiation Degradation Relative to Beginning of Life Efficiency.

<table>
<thead>
<tr>
<th>Solar Cell</th>
<th>Shielding Thickness</th>
<th>10 mils</th>
<th>20 mils</th>
<th>30 mils</th>
<th>40 mils</th>
<th>50 mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 13.15  End of Life Efficiency versus Shielding Thickness.

<table>
<thead>
<tr>
<th>Solar Cell</th>
<th>Shielding Thickness</th>
<th>10 mils</th>
<th>20 mils</th>
<th>30 mils</th>
<th>40 mils</th>
<th>50 mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InP</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
RESULTS

• After One Year in Orbit, Protected by a 10 mil Coverslide, a Spacecraft Would Require a Solar Array of Size
  
  – Si Cells
    • \(\text{m}^2\) per 1000 W
  
  – GaAs Cells
    • \(\text{m}^2\) per 1000 W
  
  – InP Cells
    • \(\text{m}^2\) per 1000 W
### MASS AND COST

Table 13.16  Solar Array Mass per 1000 Watts EOL Power.

<table>
<thead>
<tr>
<th>Solar Cell</th>
<th>10 mils</th>
<th>20 mils</th>
<th>30 mils</th>
<th>40 mils</th>
<th>50 mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>71.65</td>
<td>66.88</td>
<td>63.78</td>
<td>63.05</td>
<td>62.70</td>
</tr>
<tr>
<td>GaAs</td>
<td>42.79</td>
<td>41.27</td>
<td>40.86</td>
<td>40.69</td>
<td>40.69</td>
</tr>
<tr>
<td>InP</td>
<td>32.25</td>
<td>32.25</td>
<td>32.22</td>
<td>32.22</td>
<td>32.22</td>
</tr>
</tbody>
</table>

Table 13.17  Solar Array Cost per 1000 Watts EOL Power.

<table>
<thead>
<tr>
<th>Solar Cell</th>
<th>10 mils</th>
<th>20 mils</th>
<th>30 mils</th>
<th>40 mils</th>
<th>50 mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>325</td>
<td>303</td>
<td>289</td>
<td>286</td>
<td>284</td>
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<tr>
<td>GaAs</td>
<td>632</td>
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<td>603</td>
<td>601</td>
<td>601</td>
</tr>
<tr>
<td>InP</td>
<td>1002</td>
<td>1002</td>
<td>1001</td>
<td>1001</td>
<td>1001</td>
</tr>
</tbody>
</table>

For Comparison Only
DESIGN TRADE SUMMARY

• The Highest Level Trade is Between Reducing Mass and Reducing Cost
  – InP Cells Offer the Lowest Mass Solar Array
    • But the Highest Cost
  – Si Cells Offer the Lowest Cost
    • But the Highest Mass
      – Note That Increasing the Coverslide Thickness Reduces Both Mass and Cost
      – Thicker Coverslides Provide More Radiation Protection Which Results in a Smaller - Less Massive / Costly - Array