Energetic Particles and Technology

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Heliophysics Summer School – Year 2

Space Storms and Radiation: Causes and Effects

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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

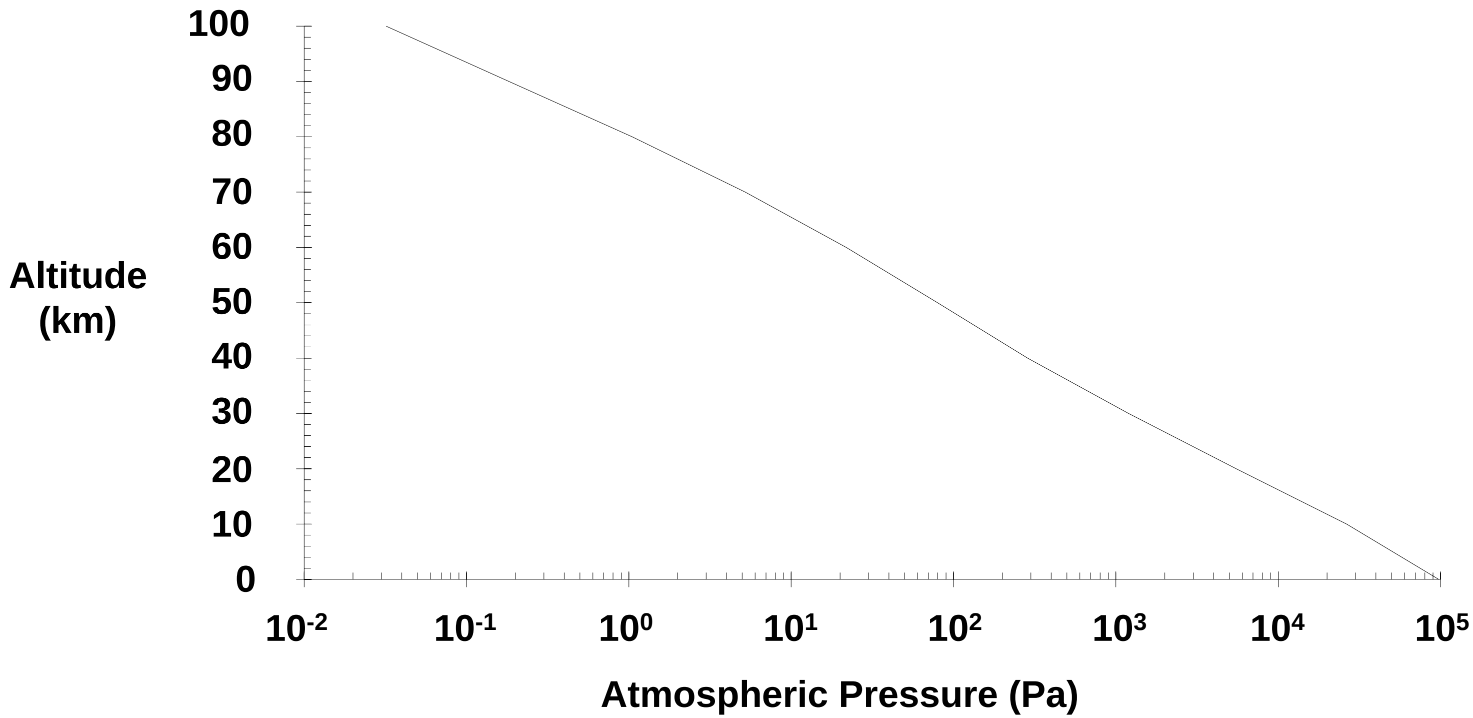
<table>
<tr><th colspan="2"></th><th colspan="11">Space Environments and Effects</th></tr>
<tr><th colspan="2"></th><th colspan="2">VACUUM</th><th colspan="4">NEUTRAL</th><th>PLASMA</th><th colspan="3">RADIATION</th><th>MMOD</th></tr>
<tr><th colspan="2"></th><th>Solar UV</th><th>Outgassing/ Contamination</th><th>Aerodynamic Drag</th><th>Sputtering</th><th>Atomic Oxygen Attack</th><th>Spacecraft Glow</th><th>Spacecraft Charging</th><th>Van Allen Belts</th><th>Galactic Cosmic Rays</th><th>Solar Proton Events</th><th>Impacts</th></tr>
<tr><th rowspan="8">Spacecraft Subsystems</th><th>Avionics</th><td></td><td></td><td></td><td></td><td></td><td></td><td>EMI From Arc Discharging</td><td colspan="3">Total Dose Degradation; Single Event Effects</td><td>EMI Due To Impacts</td></tr>
<tr><th>Attitude Determination & Control</th><td></td><td>Degradation of Sensors</td><td>Induced Torques</td><td colspan="2">Degradation of Sensor Coatings</td><td>Noise Source for Sensors</td><td>Torques Due to Induced Potentials</td><td></td><td></td><td></td><td></td></tr>
<tr><th>Electrical Power</th><td colspan="2">Reduction in Coverslide Transmittance</td><td></td><td colspan="2">Reduction in Coverslide Transmittance</td><td></td><td>Arcing on Solar Arrays</td><td colspan="3">Degradation of Solar Cell Output</td><td>Destruction/ Obscuration of Solar Cells</td></tr>
<tr><th>Environmental Control & Life Support</th><td></td><td>Toxic Fumes</td><td></td><td></td><td></td><td></td><td>EMI From Arc Discharging</td><td colspan="3">Total Dose Degradation; Single Event Effects</td><td>Penetration of Habitat</td></tr>
<tr><th>Propulsion</th><td></td><td></td><td>Drag Makeup Fuel Requirement</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Rupture of Pressurized Tanks</td></tr>
<tr><th>Structures</th><td></td><td></td><td></td><td></td><td></td><td></td><td>Dielectric Breakdown on Surfaces</td><td></td><td></td><td></td><td>Penetration</td></tr>
<tr><th>Telemetry, Tracking, and Communications</th><td></td><td>Degradation of Sensors</td><td></td><td></td><td></td><td></td><td>EMI From Arc Discharging</td><td colspan="3">Total Dose Degradation; Single Event Effects</td><td>EMI due to impacts</td></tr>
<tr><th>Thermal Control</th><td colspan="2">Change in Absorptance / Emittance</td><td></td><td colspan="2">Change in Absorptance / Emittance</td><td></td><td></td><td colspan="3">Cold Surfaces May Experience Heating</td><td>Change in Absorptance / Emittance</td></tr>
</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

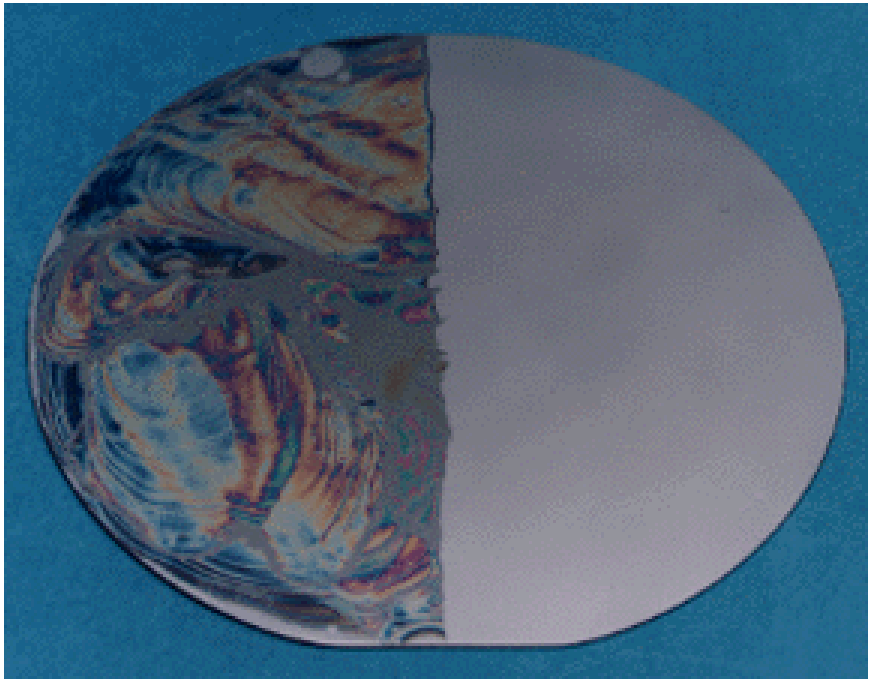
VACUUM: SOLAR UV DEGRADATION

- 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

CHEMICAL	BOND	BOND ENERGY (eV)	WAVELENGTH (μm)
C - C	SINGLE	3.47	0.36
C - N	SINGLE	3.17	0.39
C - 0	SINGLE	3.73	0.33
C - C	DOUBLE	2.52	0.49
C - N	DOUBLE	6.29	0.26
C - C	TRIPLE	7.64	0.16

VACUUM: MOLECULAR CONTAMINATION

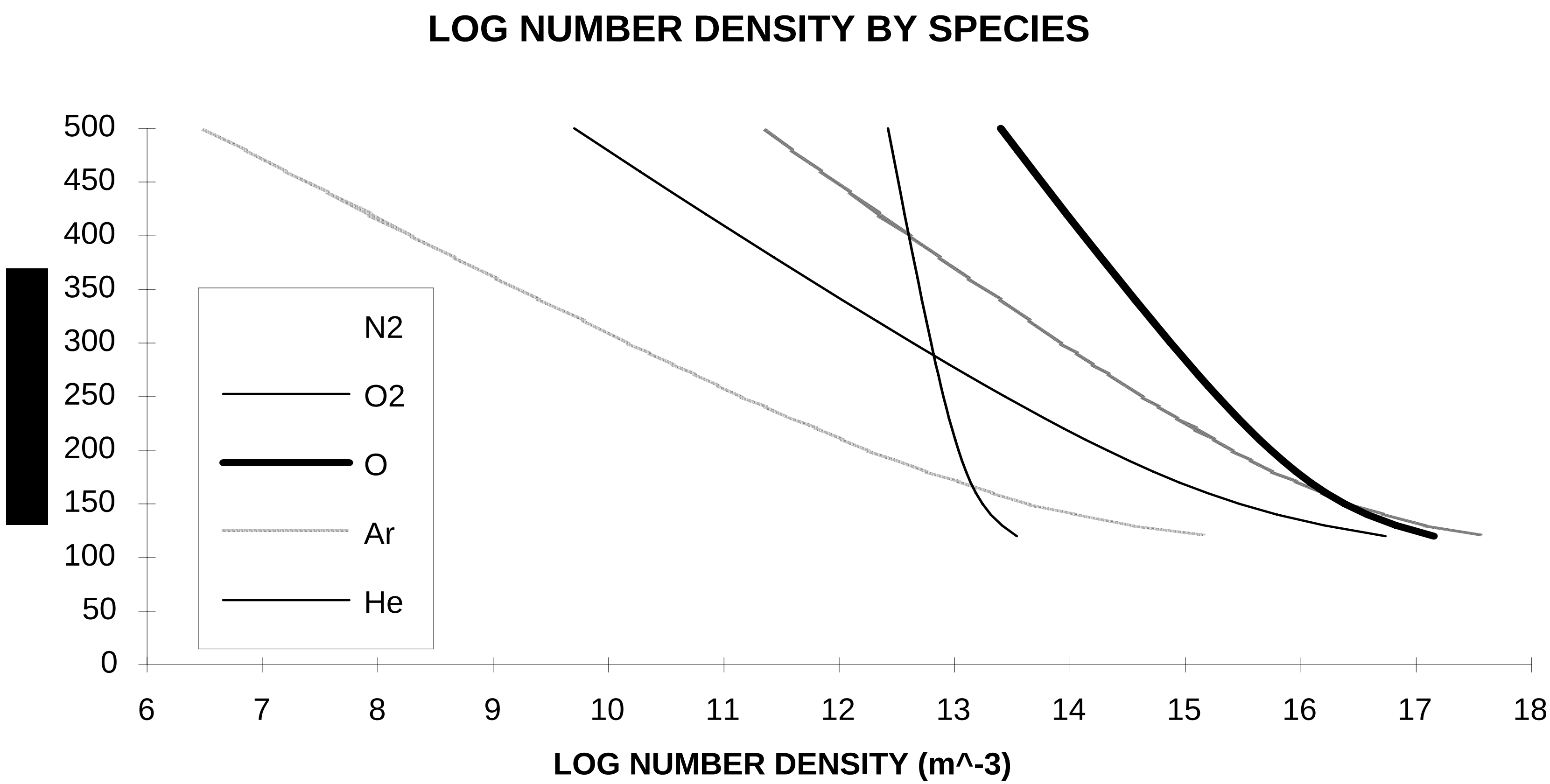
- Molecular films on the order of 1 μm thick may be deposited during on orbit operations
  - Degrades optical / thermal properties



VACUUM: PARTICULATE CONTAMINATION

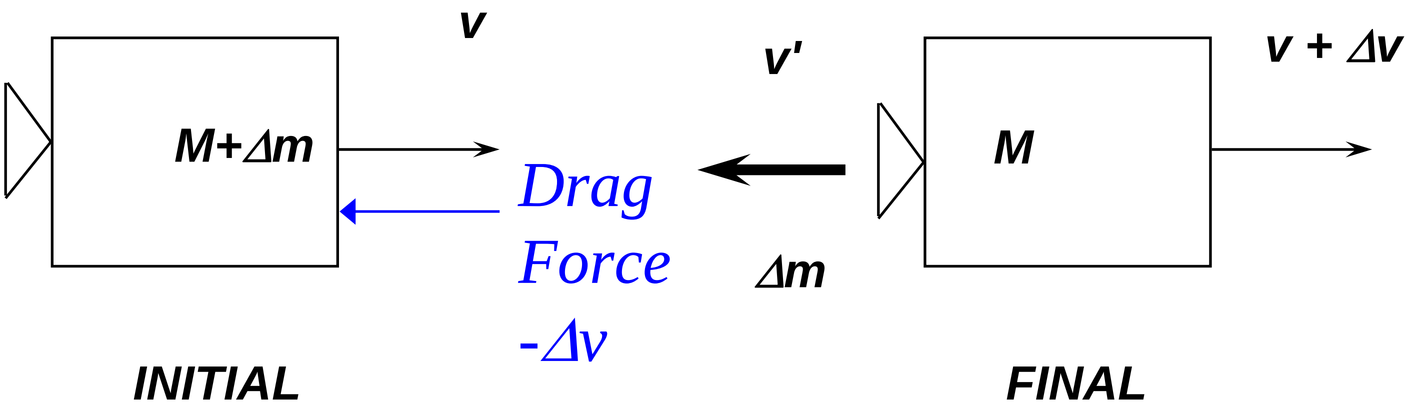
- Particulates on the order of 1 μm in size may be deposited during manufacturing, assembly, test, or launch
  - Degrades optical components

ATMOSPHERIC CONSTITUENTS



NEUTRAL: AERODYNAMIC DRAG

- An object of dry mass M, moving with velocity v, can change its velocity by ejecting a mass of fuel Δm at velocity v'.



- From Conservation of Momentum

$$(M+\Delta m)v = M(v+\Delta v) + \Delta m(v - v')$$

NEUTRAL: SPUTTERING

- **Neutral molecules carry significant amounts of kinetic energy upon impact with spacecraft surfaces in LEO**

$$qV = 1/2\, mv^2$$

	Species energy (eV/particle)					
Altitude (km)	**H**	**he**	**O**	**N2**	**O2**	**ar**
200	0.3	1.3	5.0	8.8	10.1	12.6
600	0.3	1.2	4.7	8.3	9.5	11.8
800	0.3	1.1	4.5	7.9	9.0	11.2

NEUTRAL: ATOMIC OXYGEN EROSION

Before: Fairly Smooth

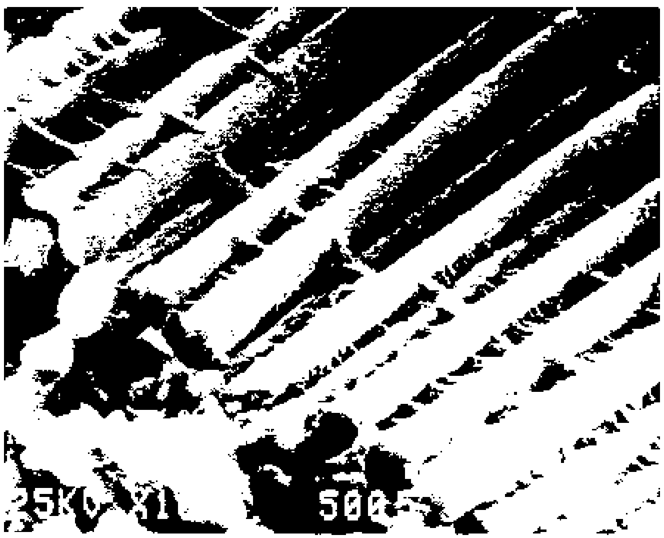


Fig. 6 Control carbon-epoxy specimen internal surface (1000X).

After: Obvious Pitting

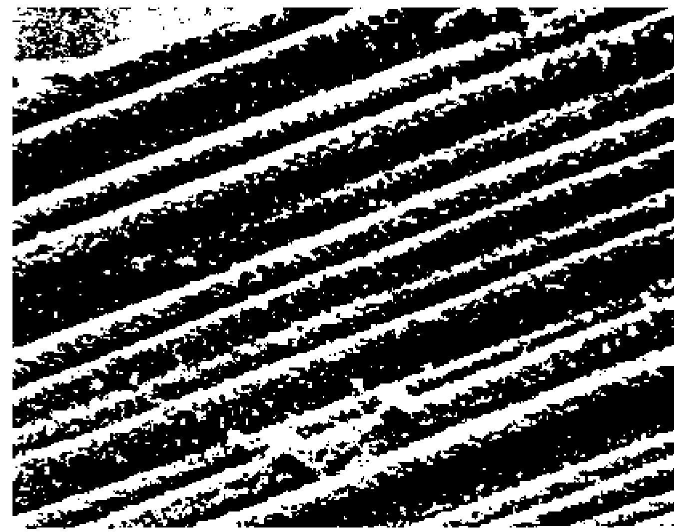
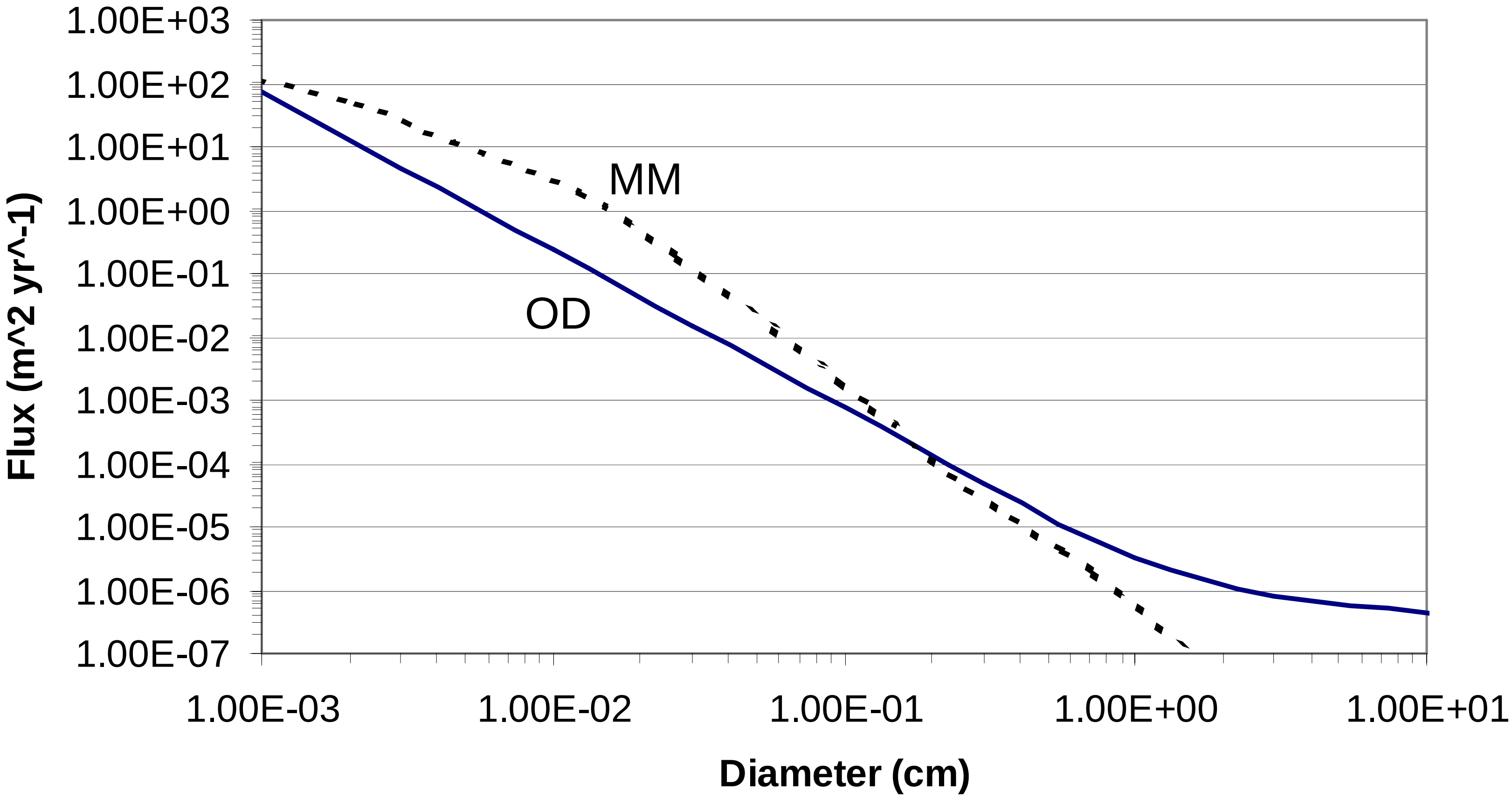


Fig. 5 Exposed carbon-epoxy specimen (1000X).

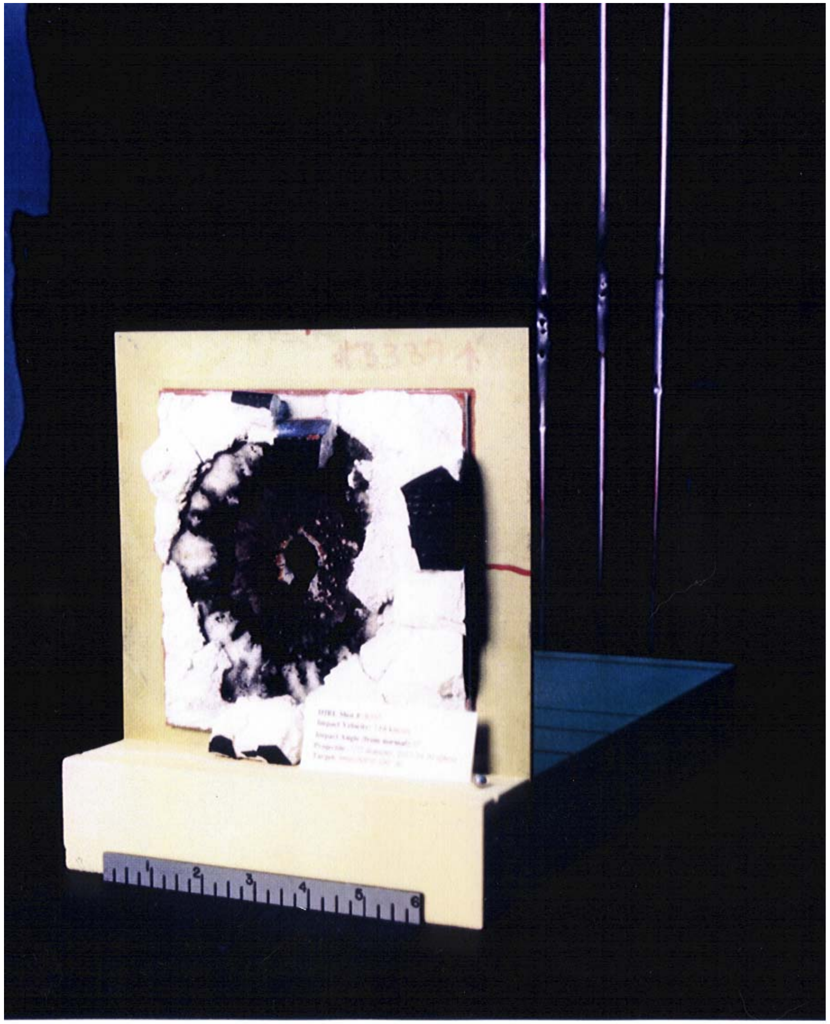
NEUTRAL: SPACECRAFT GLOW (AND AURORA)

MMOD COMPARISON



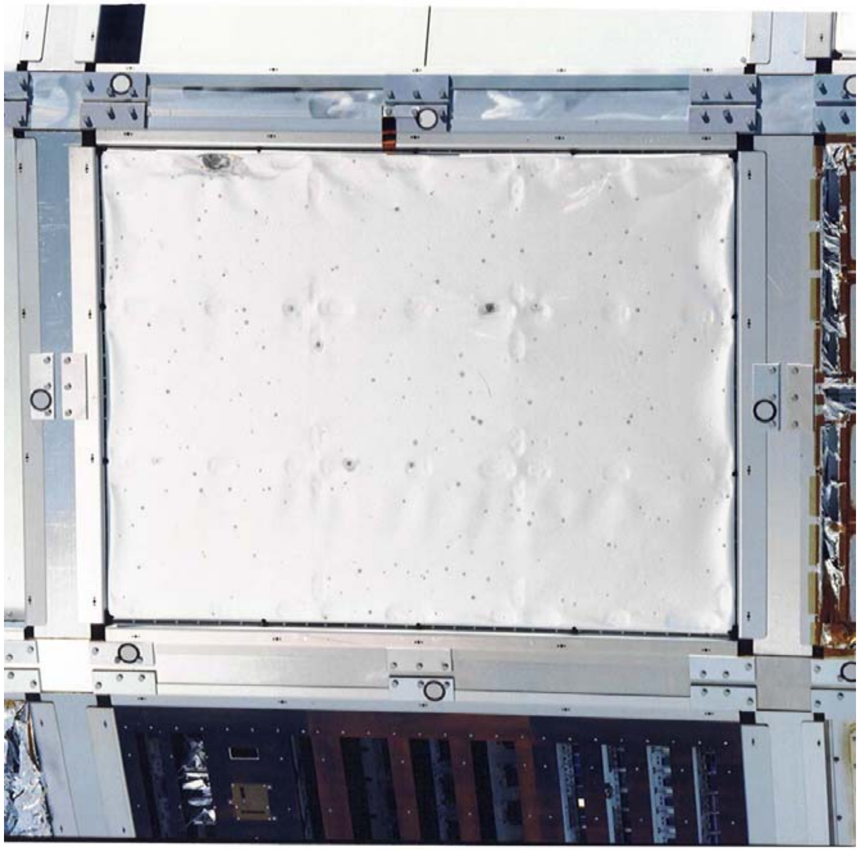
Year = 2000, Altitude = 400 km, Solar F10.7 = 175

MMOD: HYPERVELOCITY IMPACT

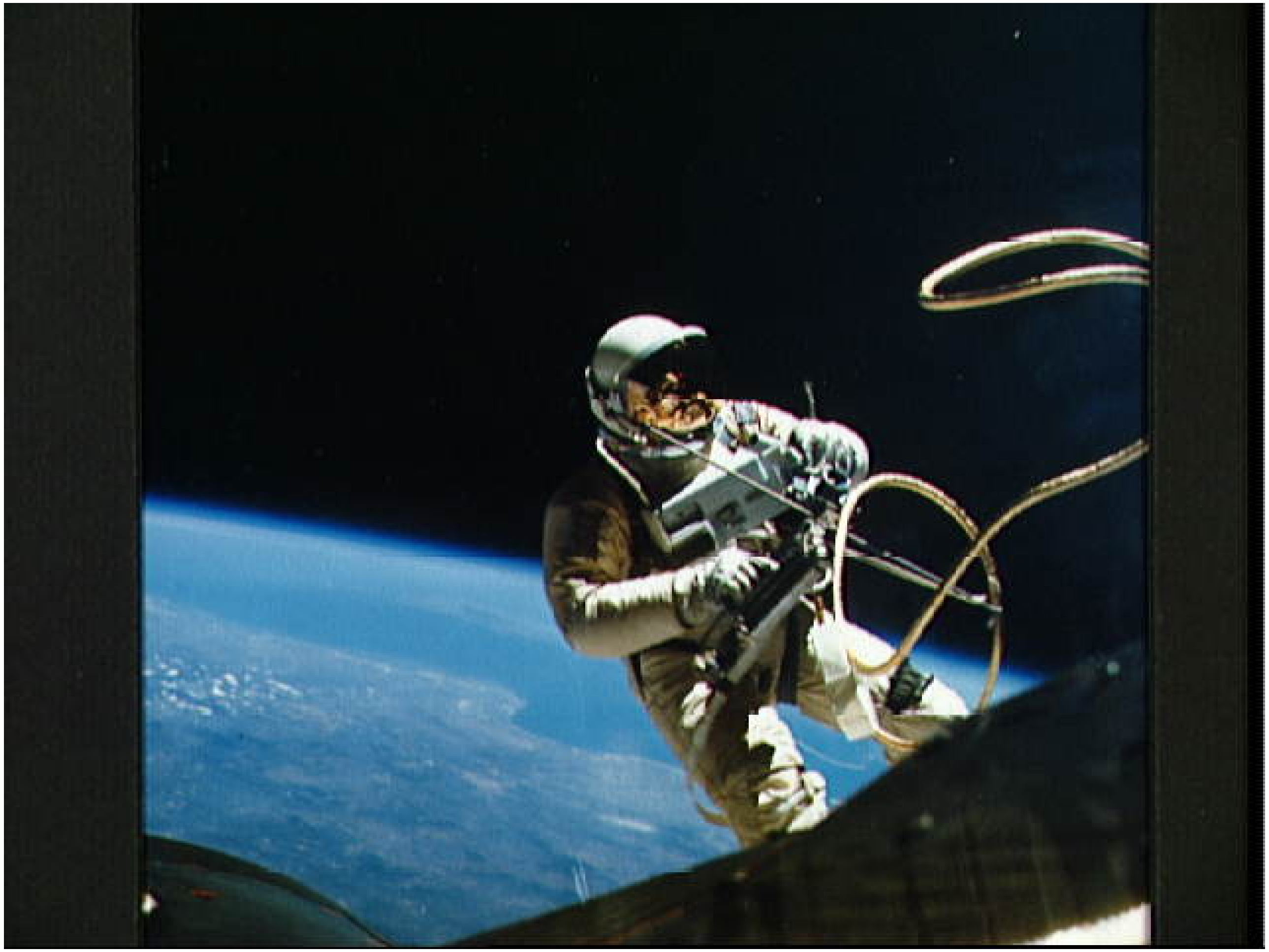


MMOD: CUMULATIVE EFFECTS

- 5 years exposure in LEO resulted in noticeable surface damage to many panels on the Long Duration Exposure Facility (LDEF)



ORBITAL DEBRIS: ED WHITE'S 1965 SPACE WALK



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^o Latitude)
    - The Worst of Both Worlds

THE LEO PLASMA ENVIRONMENT

Parameter	Value
Plasma Density	1×10^{11} m^{-3}
Plasma Temperature	1000 K (0.13 eV)
Debye Length	1 cm
Electron Gyroradius	1 cm
Ion Gyroradius	3 m
Electron Thermal Speed	200 km/s
Orbital Velocity	8 km/s
Ion Thermal Speed	1 km/s
Electron Plasma Frequency	2.8 MHz
Ion Plasma Frequency	16.6 kHz

A NEUTRAL OBJECT IN LEO - 1

- In LEO

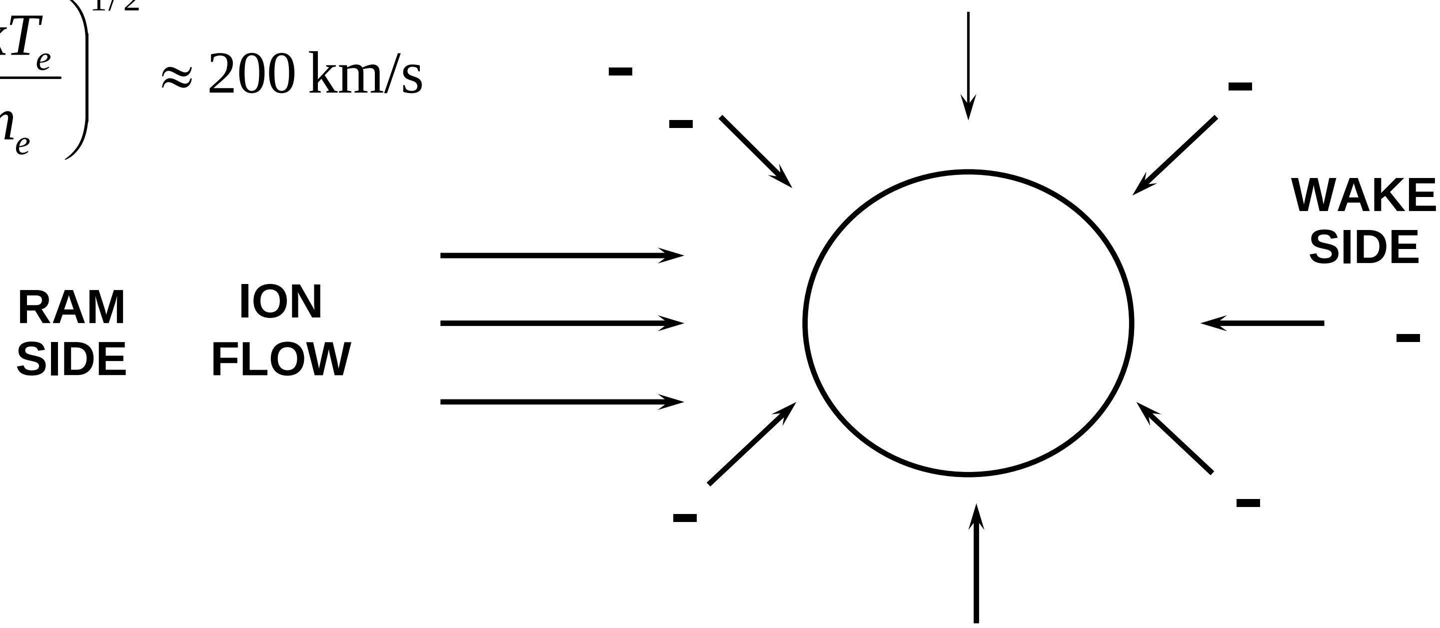
$$v_{i,th} = \left(\frac{3kT_i}{m_i} \right)^{1/2} \approx 1\,\text{km/s}$$

$$\text{v}_\text{o} \approx 8\,\text{km/s}$$

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

Ions impact on ram surfaces only

Electrons collected by all surfaces



A NEUTRAL OBJECT IN LEO - 2

- 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

A NEUTRAL OBJECT IN LEO - 3

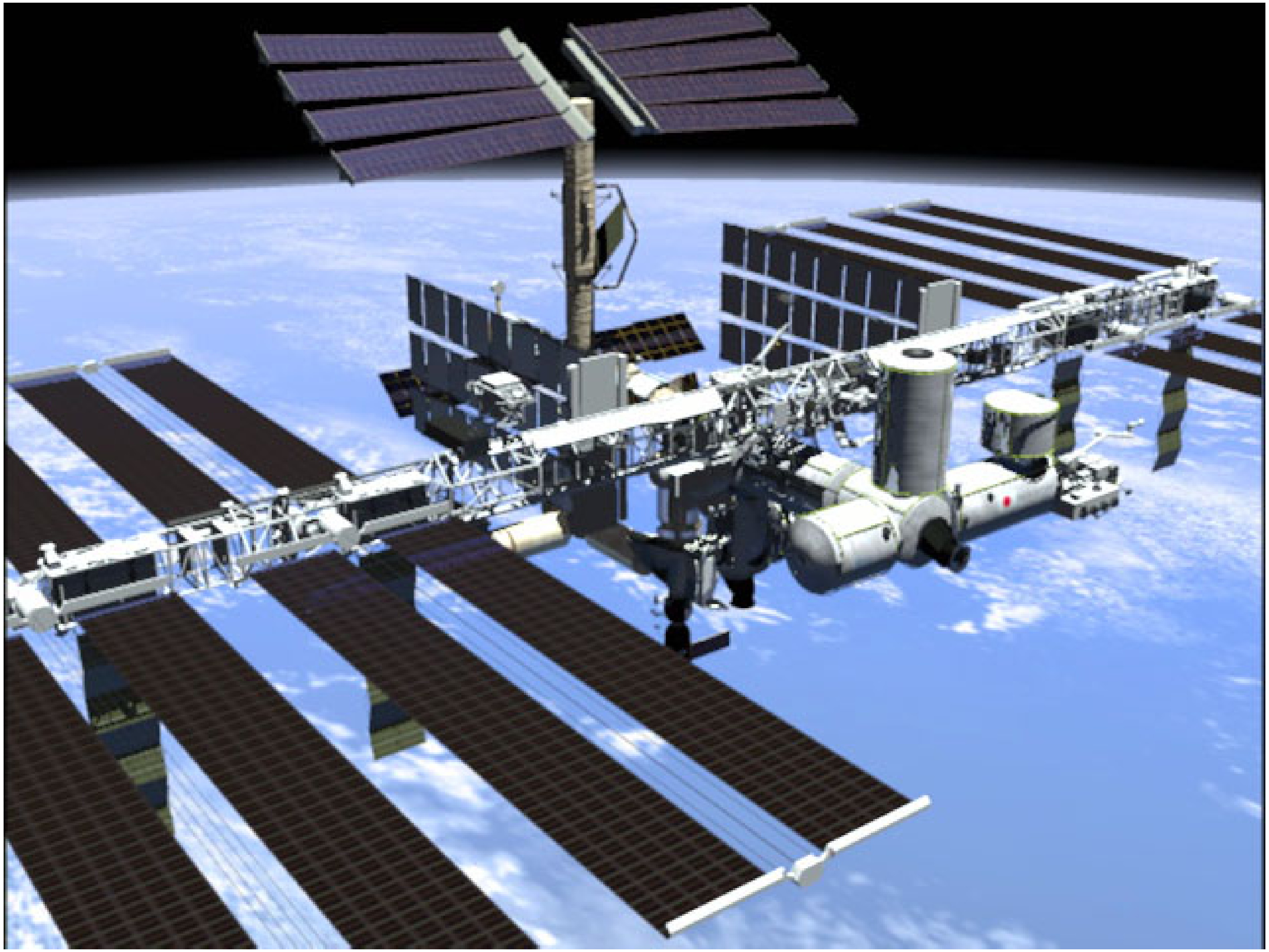
- The object will continue to charge until the negative potential is great enough to retard the collection of additional electron current
- Equilibrium is defined by current balance

$$I_i = I_e$$

- Solving this equation for the potential gives

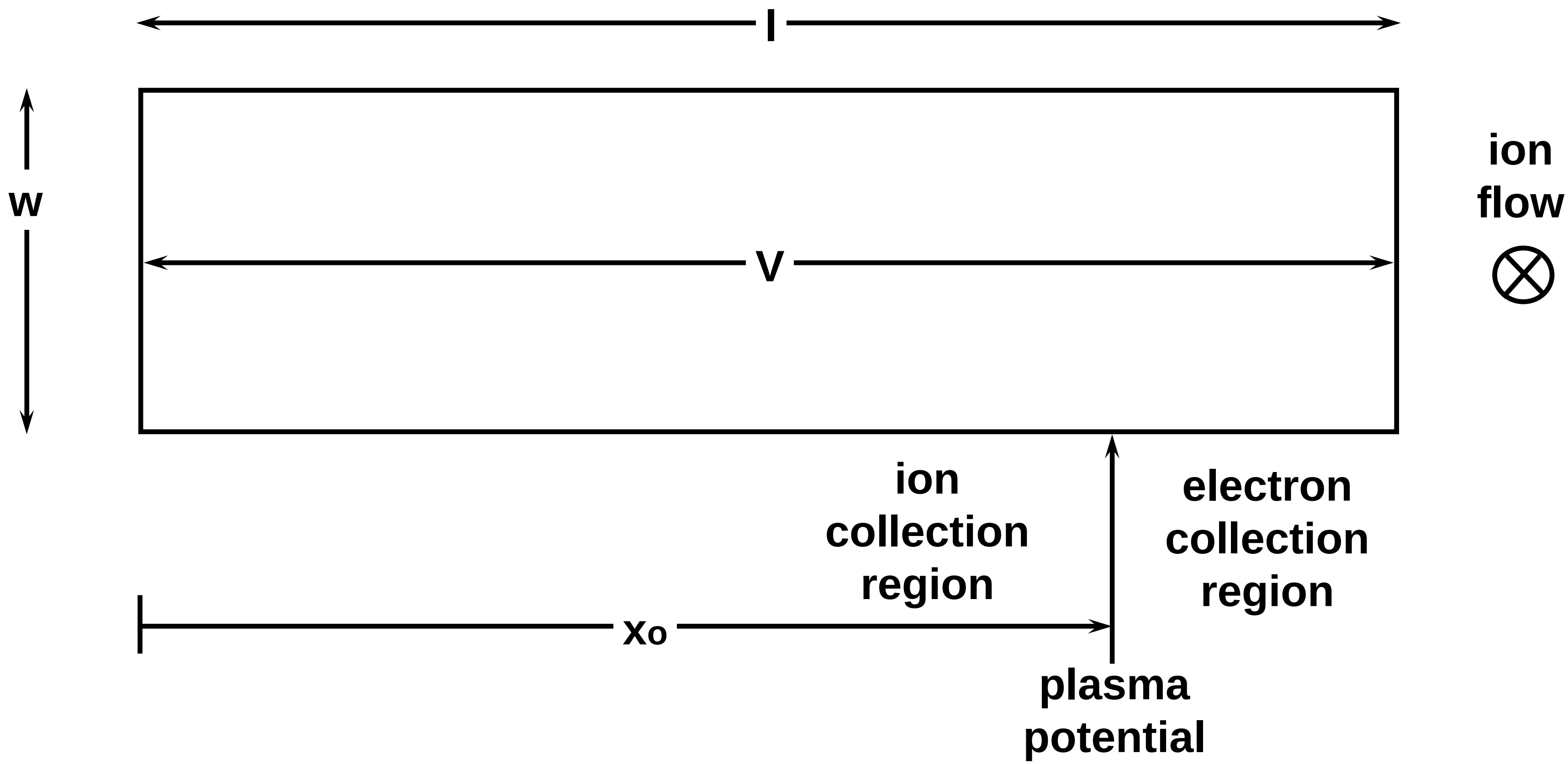
$$V_{fl} = \frac{-kT_e}{q} \ln\left[\frac{4 n_i v_o A_i}{n_e v_{e,th} A_e}\right]$$

SPACECRAFT GENERATE POWER VIA SOLAR ARRAYS



A SOLAR ARRAY IN LEO - 1

Consider the example of the solar array illustrated below



A SOLAR ARRAY IN LEO - 2

- 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, ϕ_i

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

- Electrons will be collected by those portions of the array biased less negatively than the electron impact energy, ϕ_e

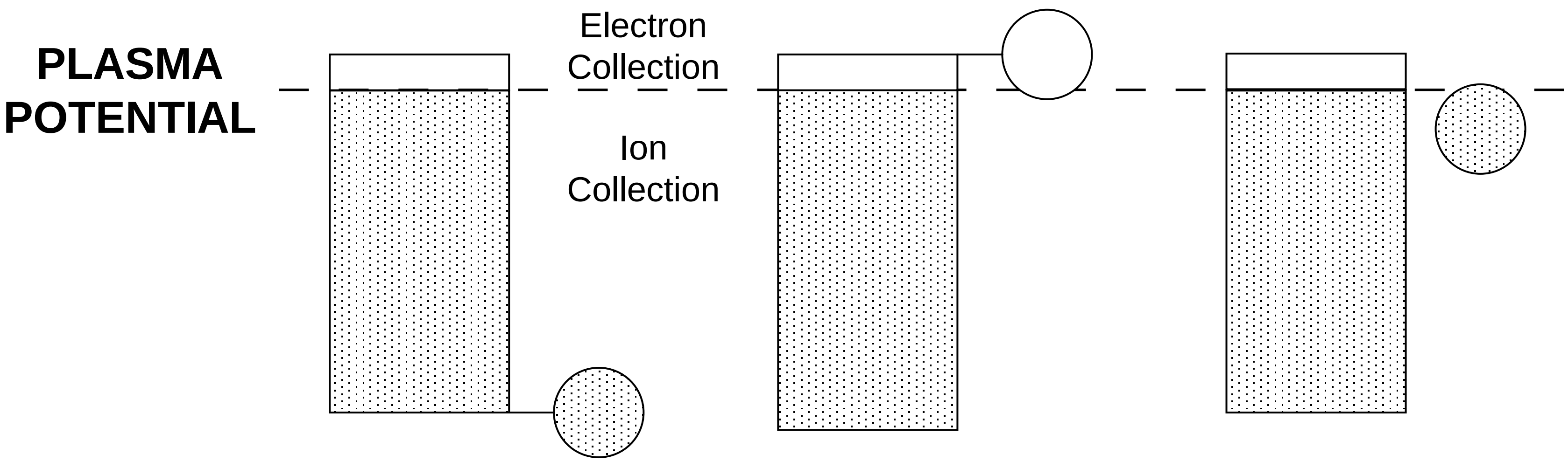
$$J_e = e n_e v_{e,th} \frac{(1 - f) V_a - \phi_e}{V_a}$$

- Where *f* is the fraction of the array floating negatively

A SOLAR ARRAY IN LEO - 3

- 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



NEGATIVE GROUND	POSITIVE GROUND	FLOATING GROUND
STRUCTURES ~ 90% OF ARRAY VOLTAGE NEGATIVE	STRUCTURES A FEW VOLTS POSITIVE	STRUCTURES A FEW VOLTS NEGATIVE

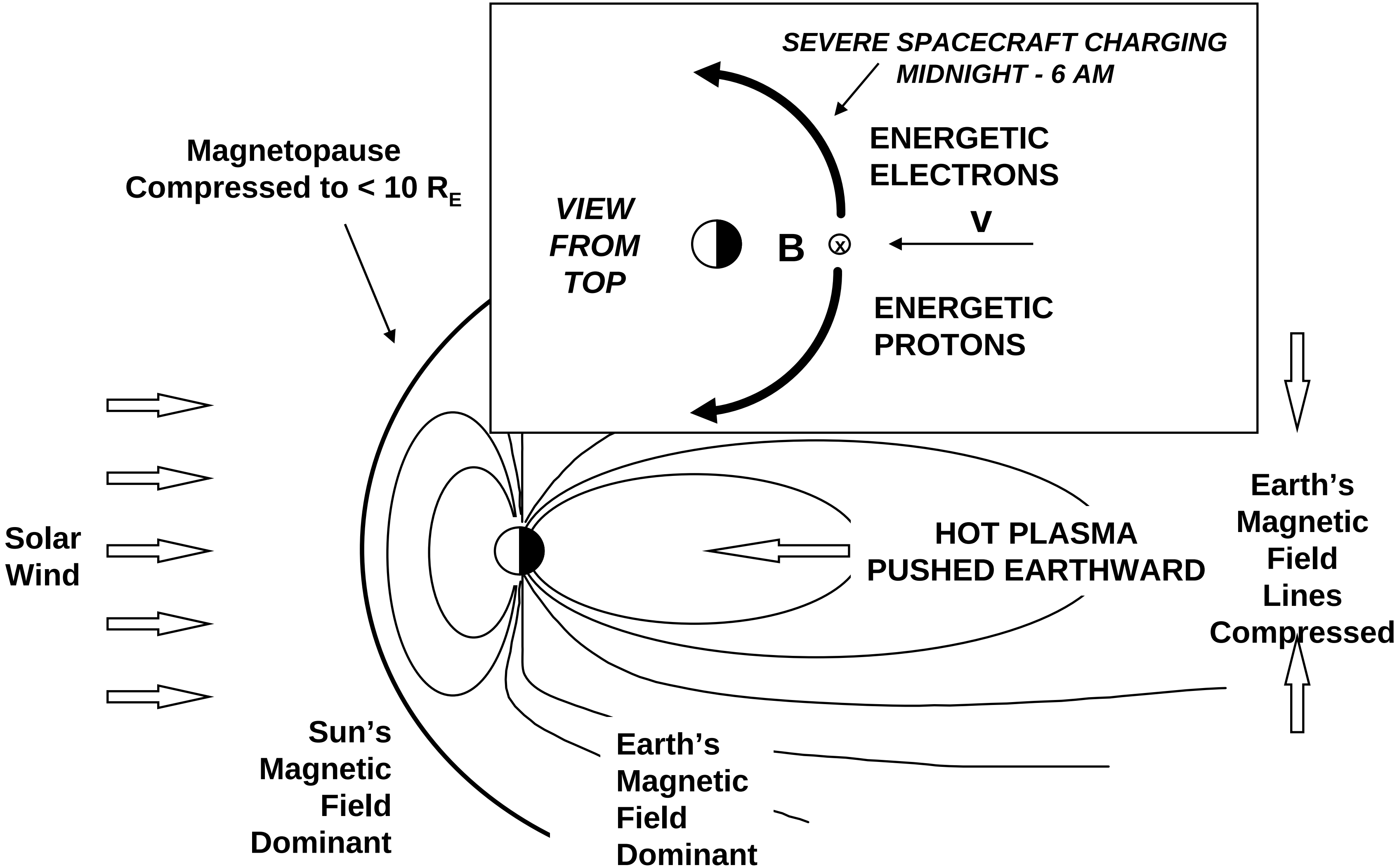
LEO VS GEO

- 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

Parameter	Value
Plasma Density	1×10^6 m^{-3}
Plasma Temperature	1,000,000 K (130 eV)
Debye Length	2 m
Electron Gyroradius	7.5 km
Ion Gyroradius	3 m
Electron Thermal Speed	6,000 km/s
Ion Thermal Speed	30 km/s
Orbital Velocity	3 km/s
Electron Plasma Frequency	900 Hz
Ion Plasma Frequency	50 Hz

SEVERE SPACECRAFT CHARGING



EVIDENCE OF S/C CHARGING

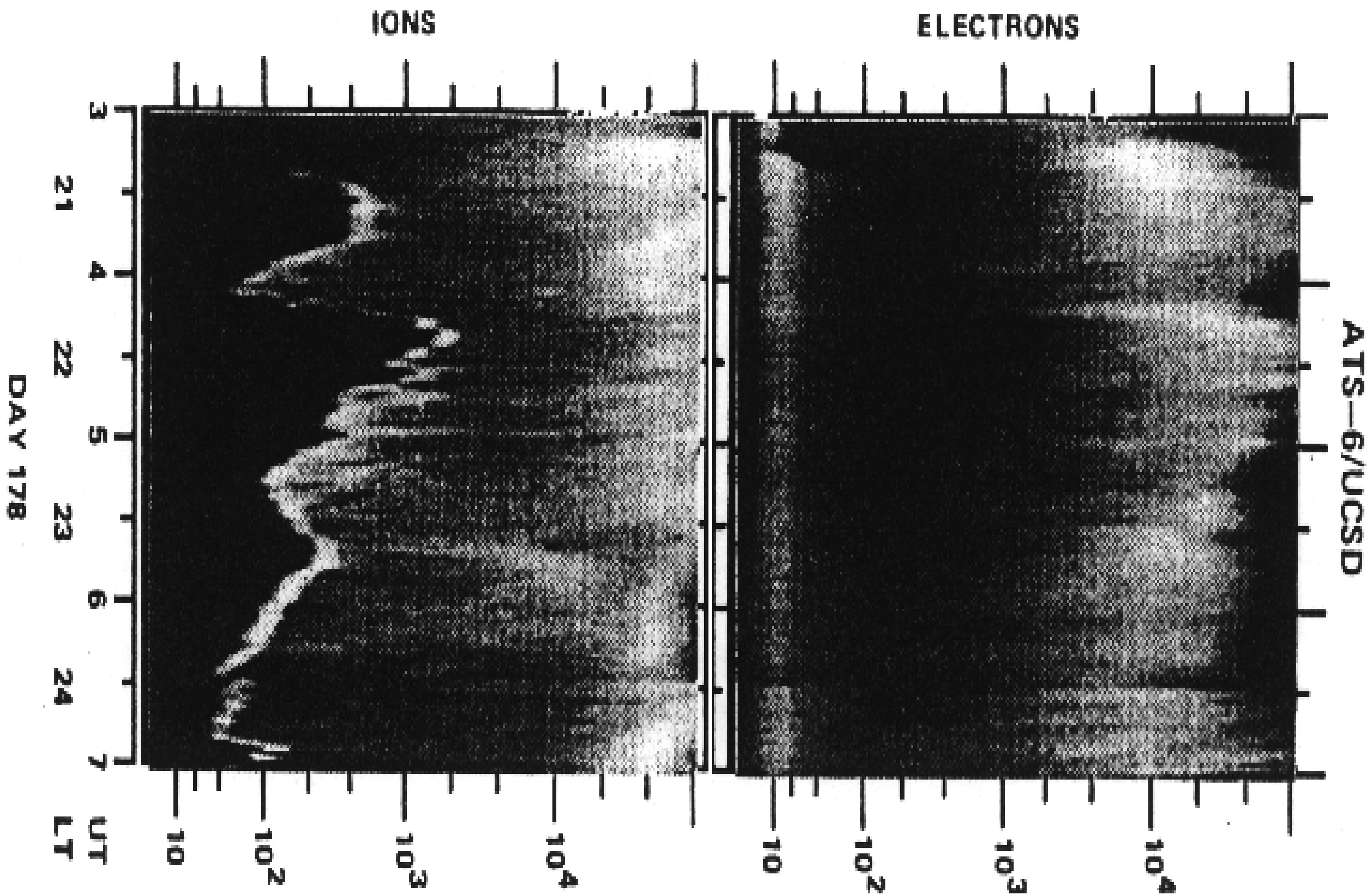
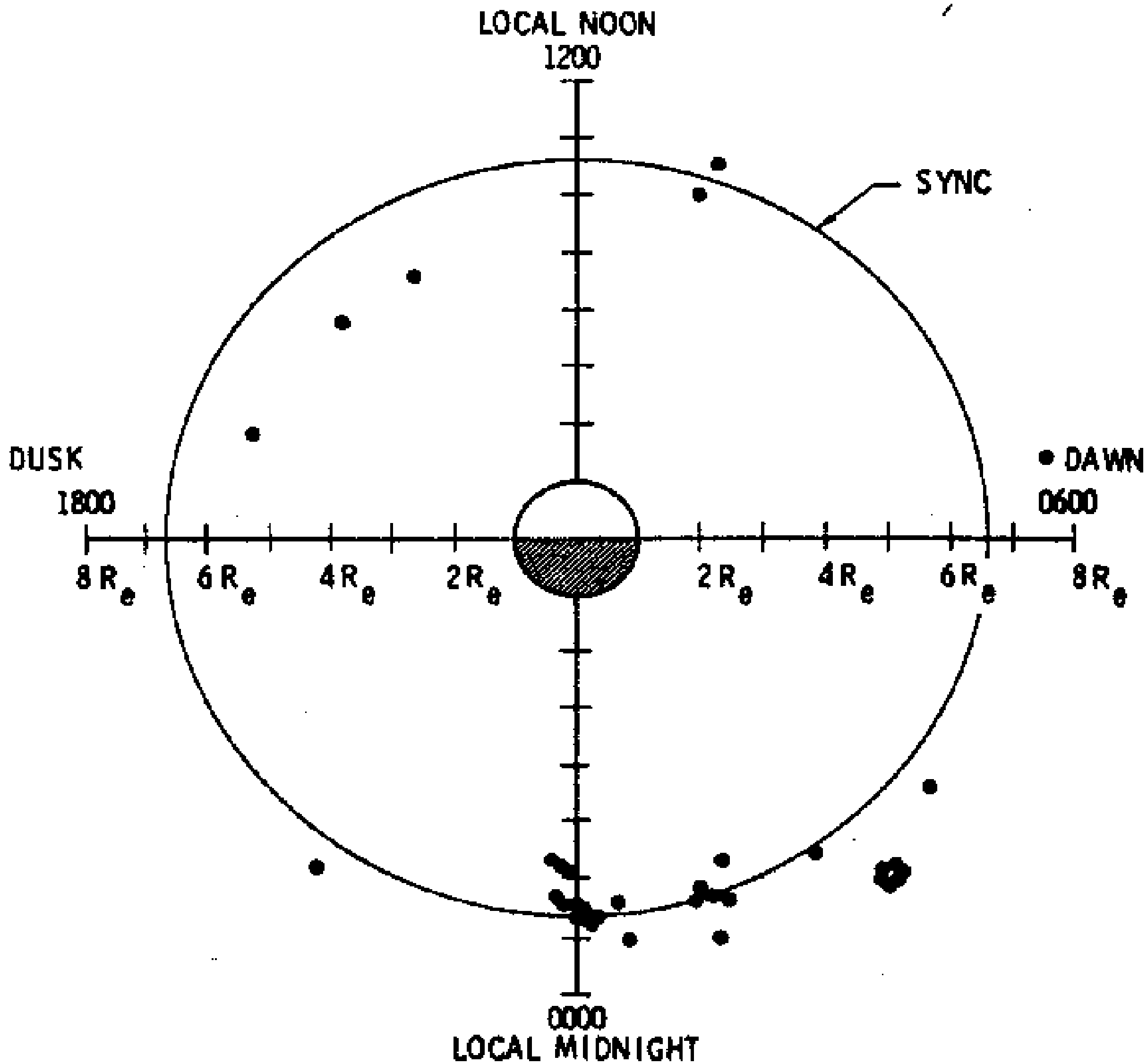


Fig. 8 Worst-case charging event, June 27, 1974.

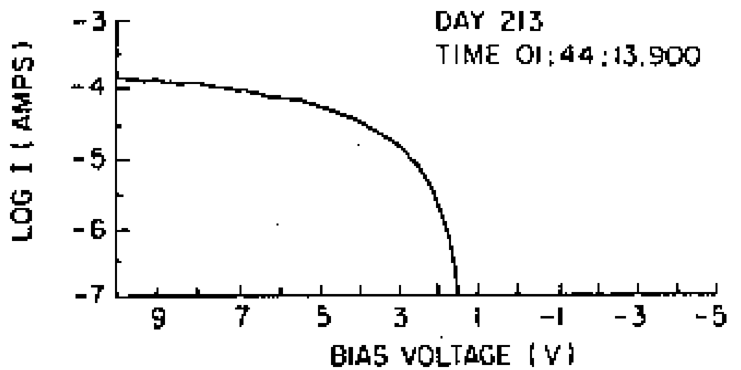
SPACECRAFT CHARGING ANOMALIES



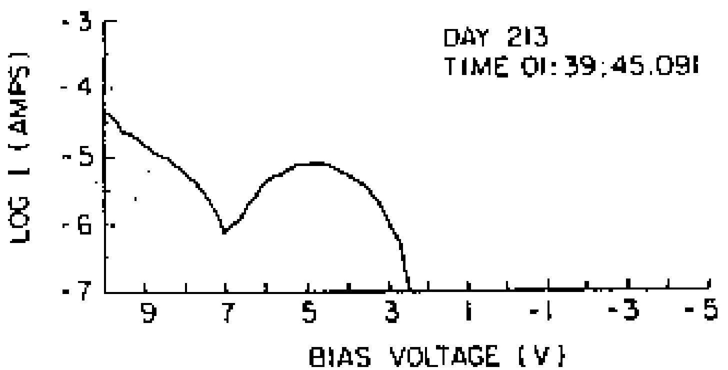
CHARGING EFFECTS: BIASING OF DATA

- 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.

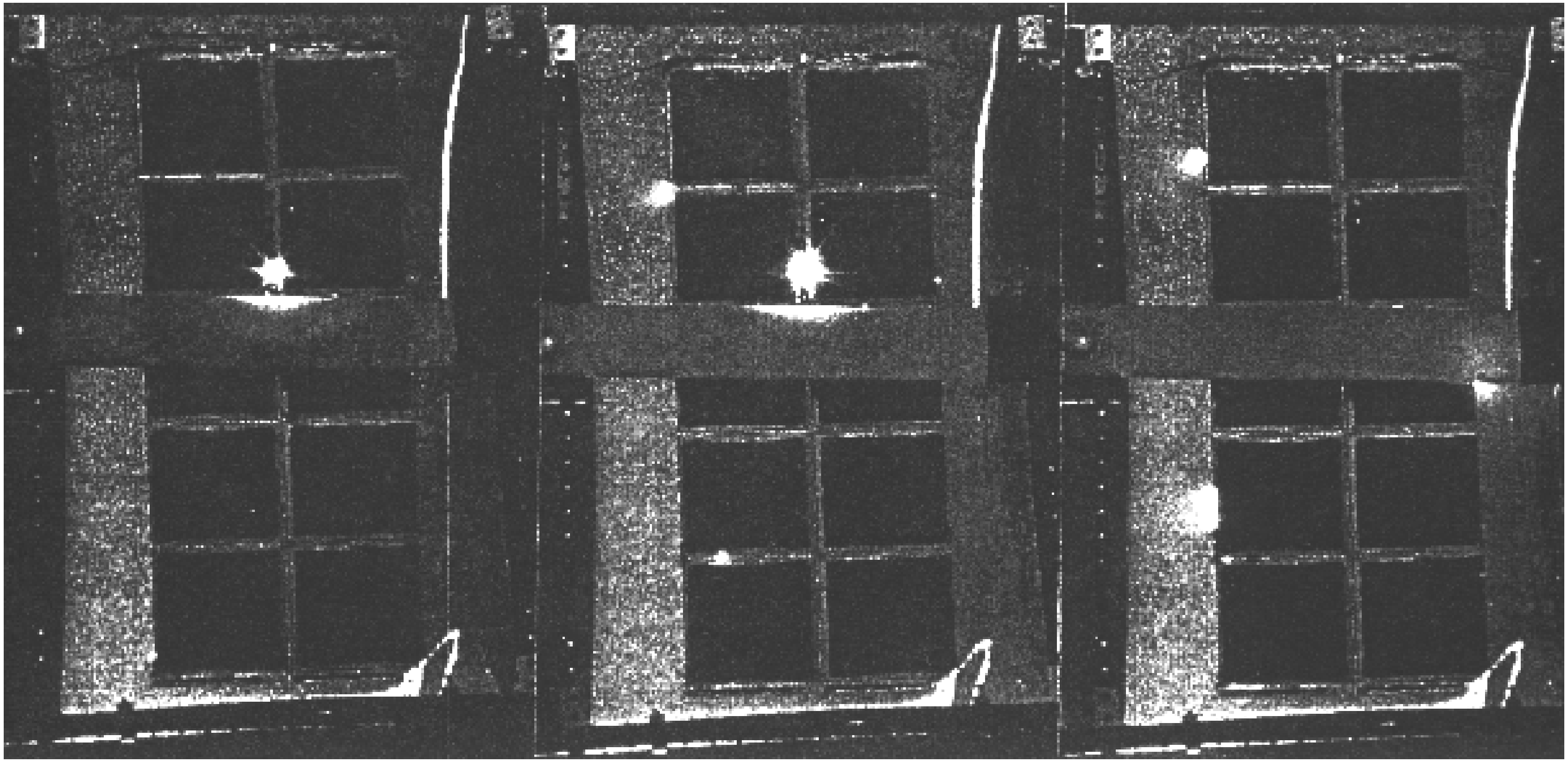
TYPICAL LANGMUIR CURVE



ANOMALOUS LANGMUIR CURVE



CHARGING EFFECTS: ESD



Solar arrays that are placed in plasma
Chambers are observed to arc.

CHARGING EFFECTS: DIELECTRIC BREAKDOWN

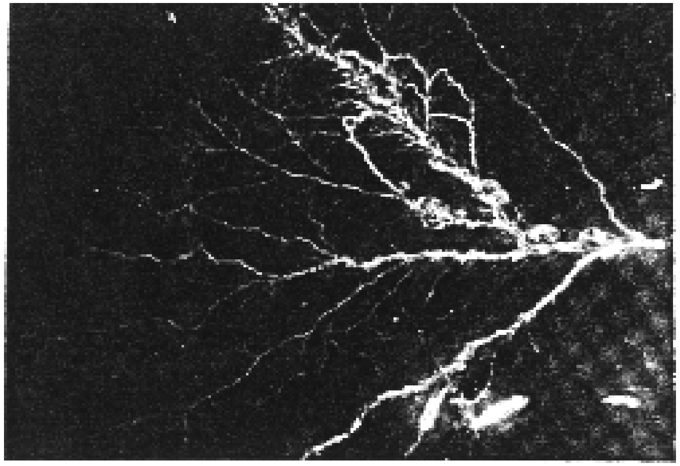
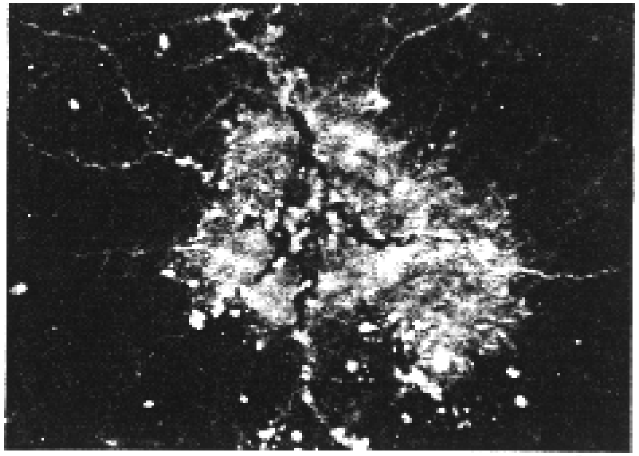
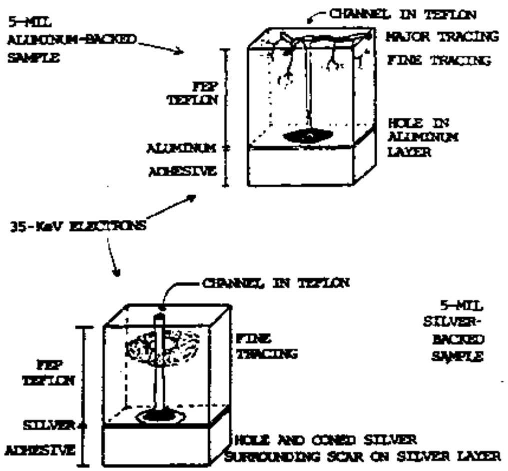
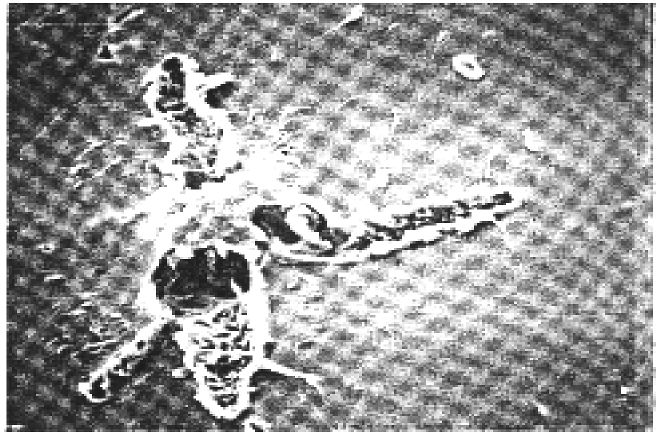


Fig. 1 Optical micrograph of microdamage on a 125-μm silvered FEP Teflon sample irradiated by a 35-keV electron beam.[1]



a) Optical micrograph showing subsurface filamentary structure (75×).





b) Scanning electron micrograph of breakdown site shown in Fig. 3a (190×).

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.

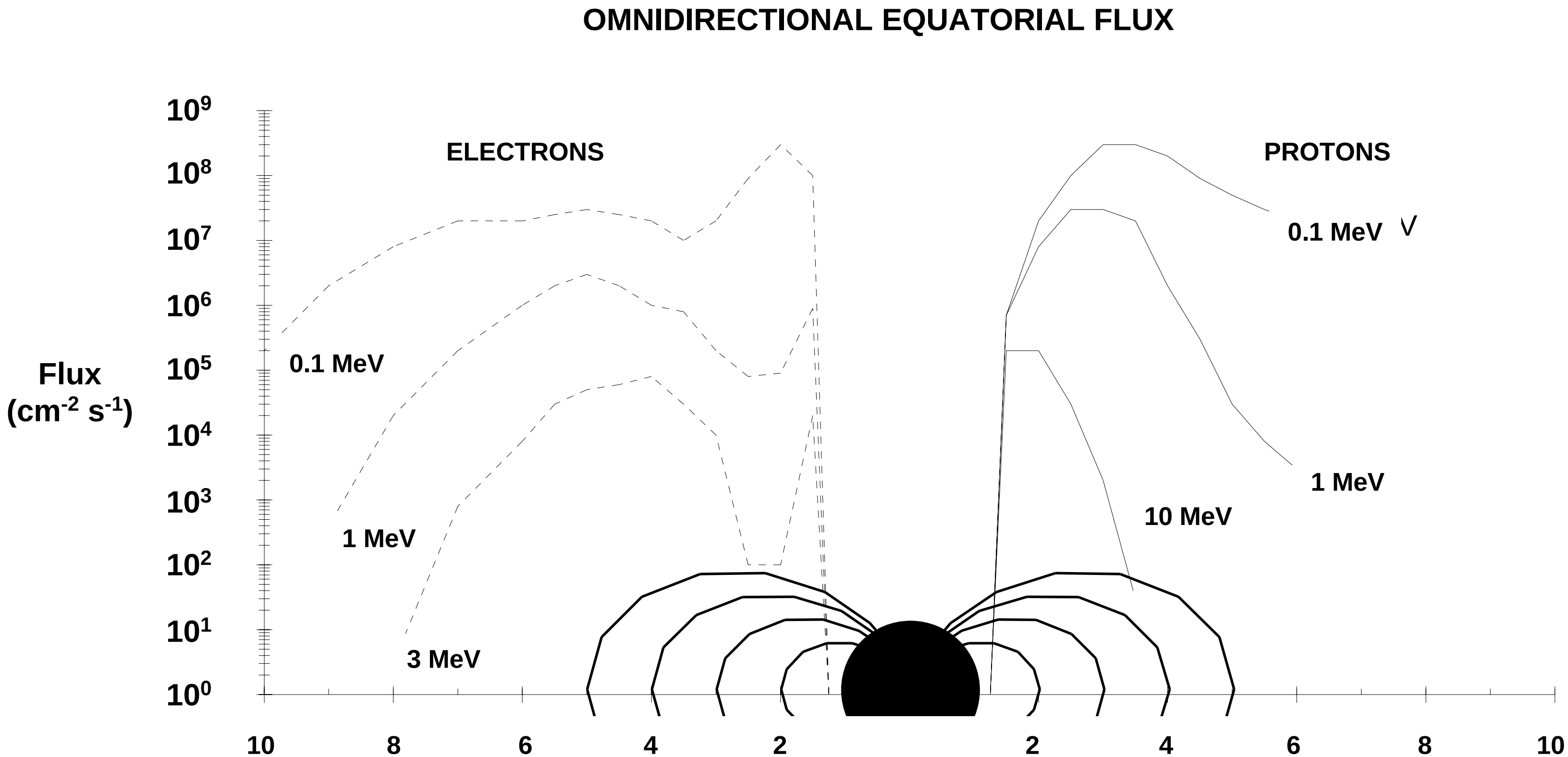
DAILY SOLAR ACTIVITY REPORTS

- 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

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)

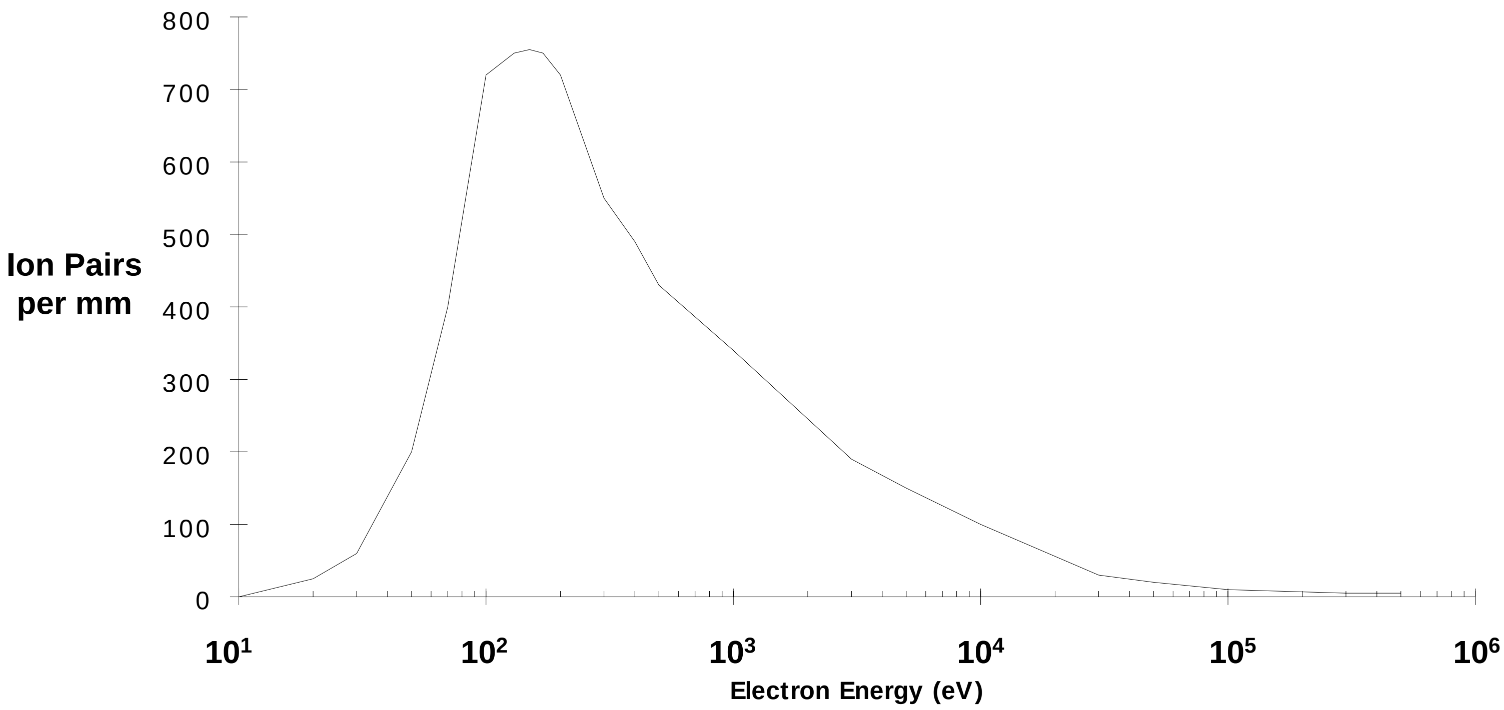
MEASURES OF ENERGY DEPOSITION

- 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

RADIATION DAMAGE THRESHOLDS

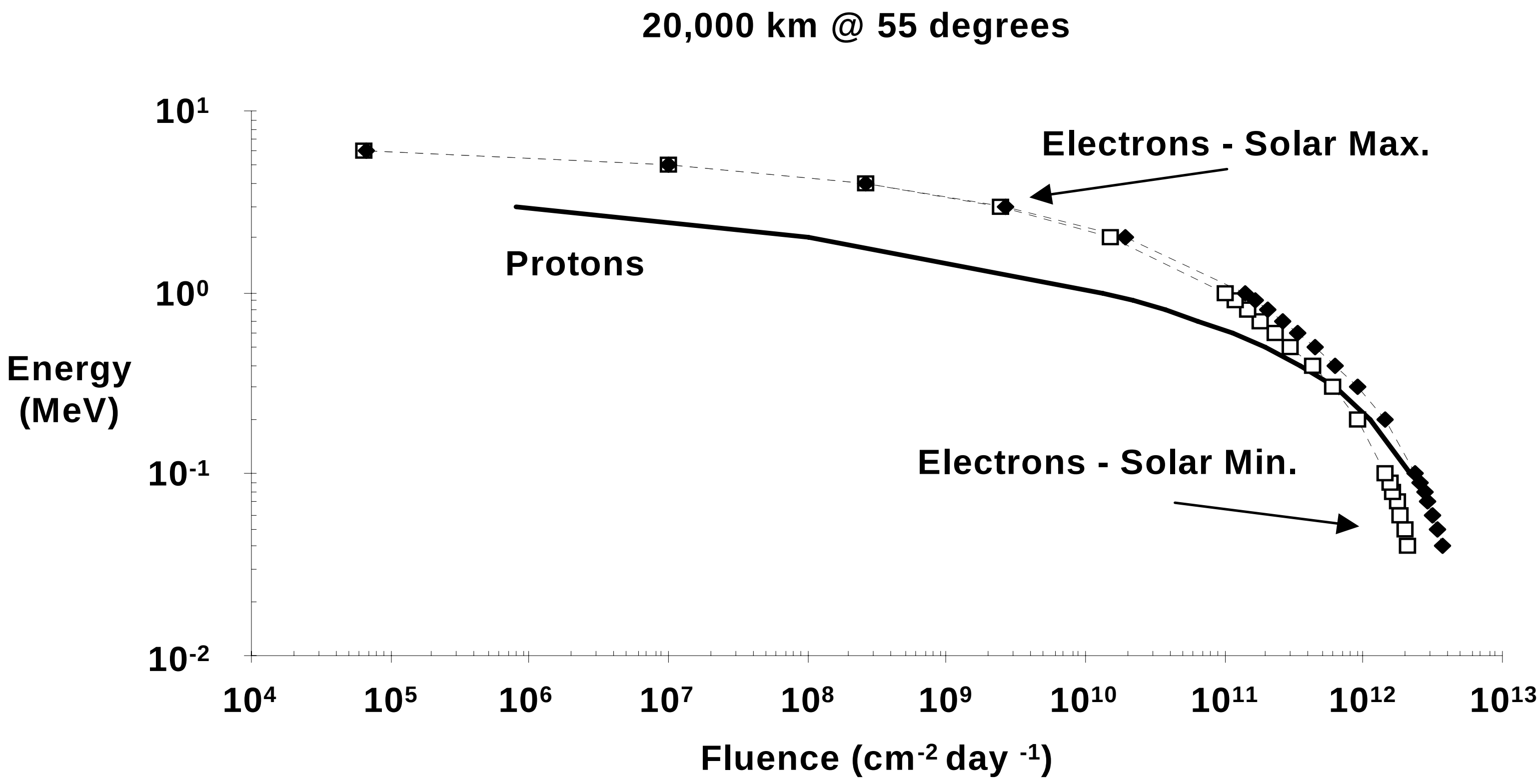
- In many materials, the total dose of radiation is the critical issue in determining useful lifetime

Material	Damage Threshold (Gray)
Biological Matter	10^{-1} - 10^{0}
Electronics	10^{0} - 10^{2}
Lubricants, Hydraulic Fluid	10^{3} - 10^{5}
Ceramics, Glasses	10^{4} - 10^{6}
Polymeric Materials	10^{5} - 10^{7}
Structural Metals	10^{7} - 10^{9}

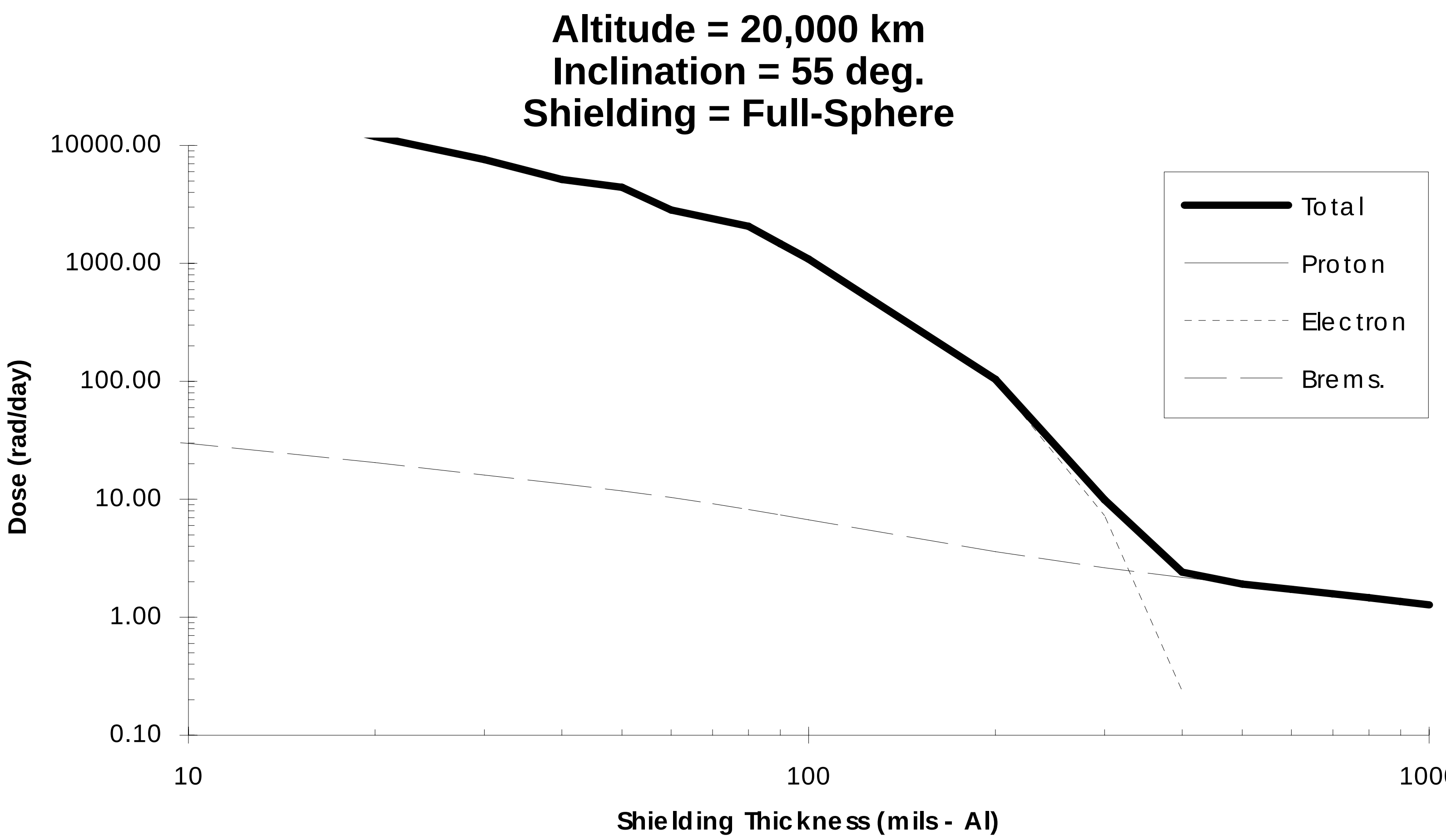
TRAPPED RADIATION DOSE EXAMPLES

- 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

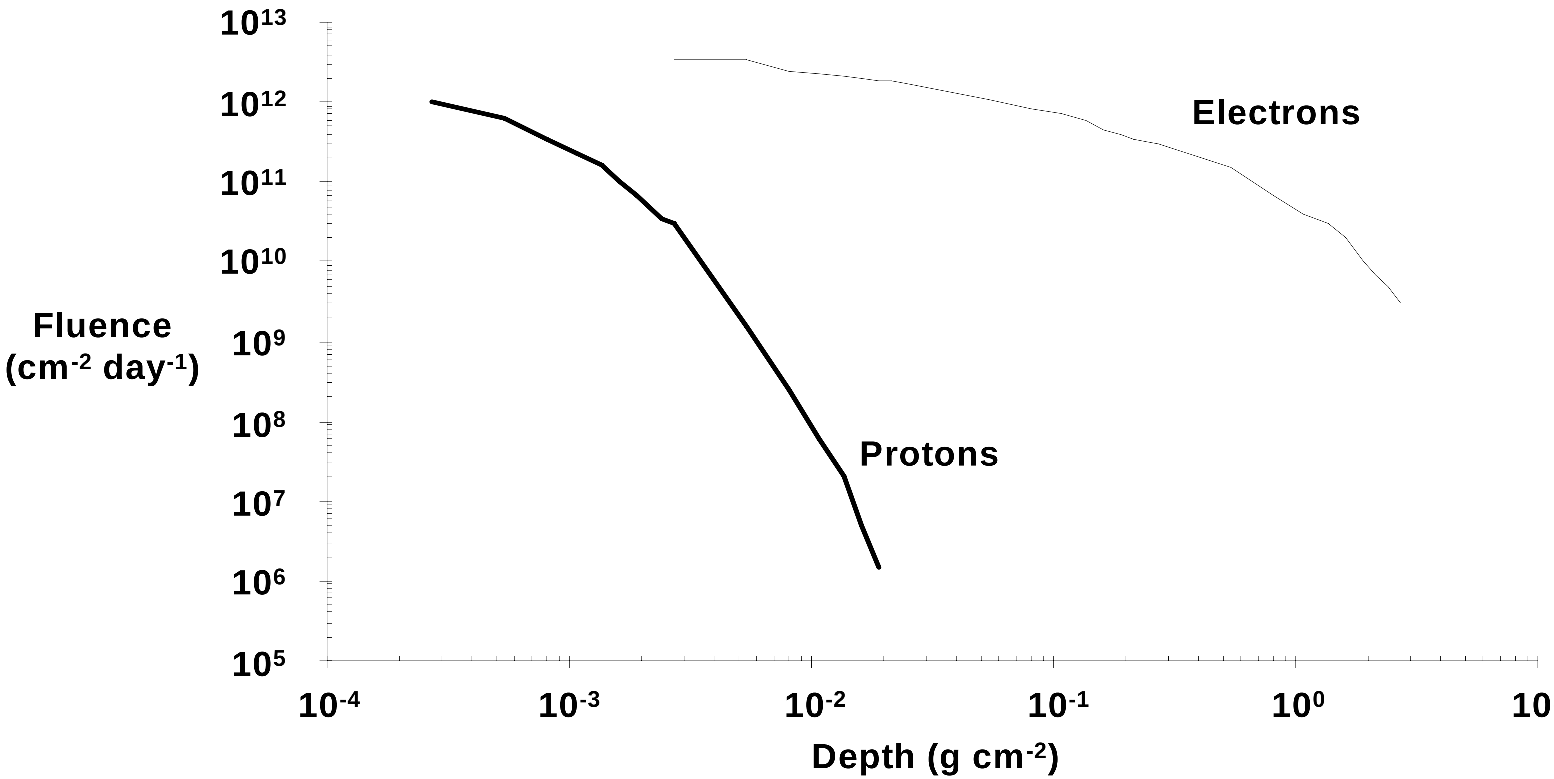
GPS RADIATION ENVIRONMENT



GPS RADIATION DOSE

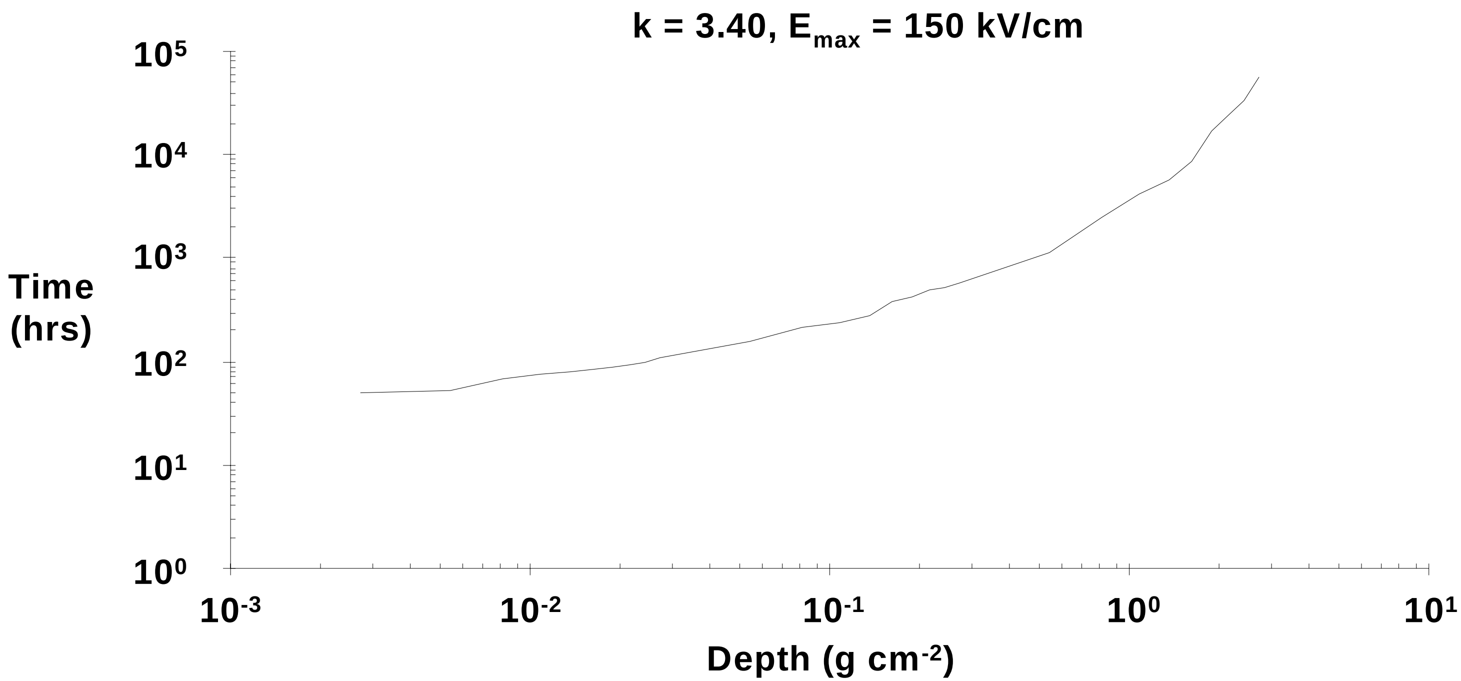


GPS CHARGE DISTRIBUTION

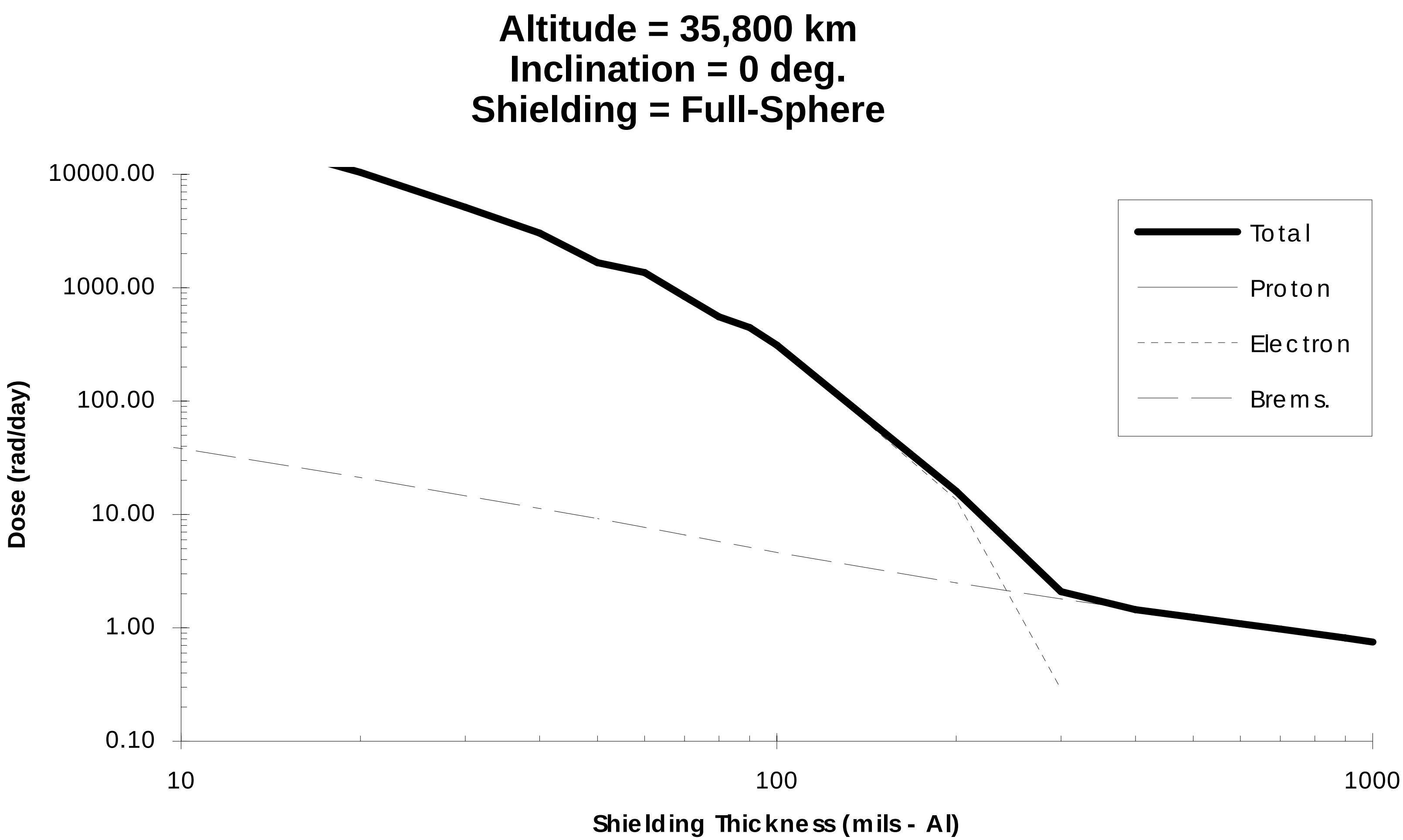


The Radiation Belts May Induce Deep Dielectric Charging

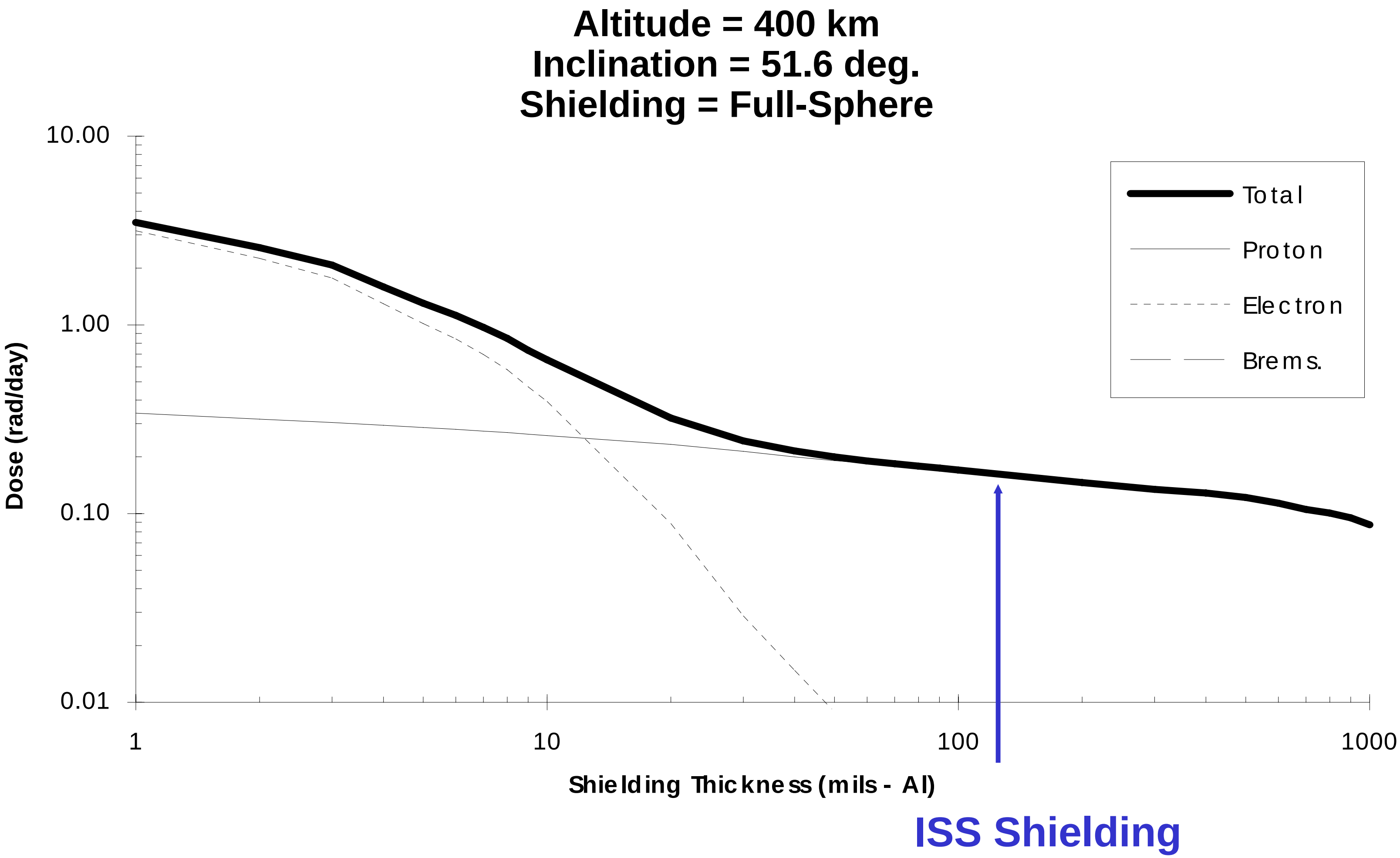
KAPTON DISCHARGE TIME



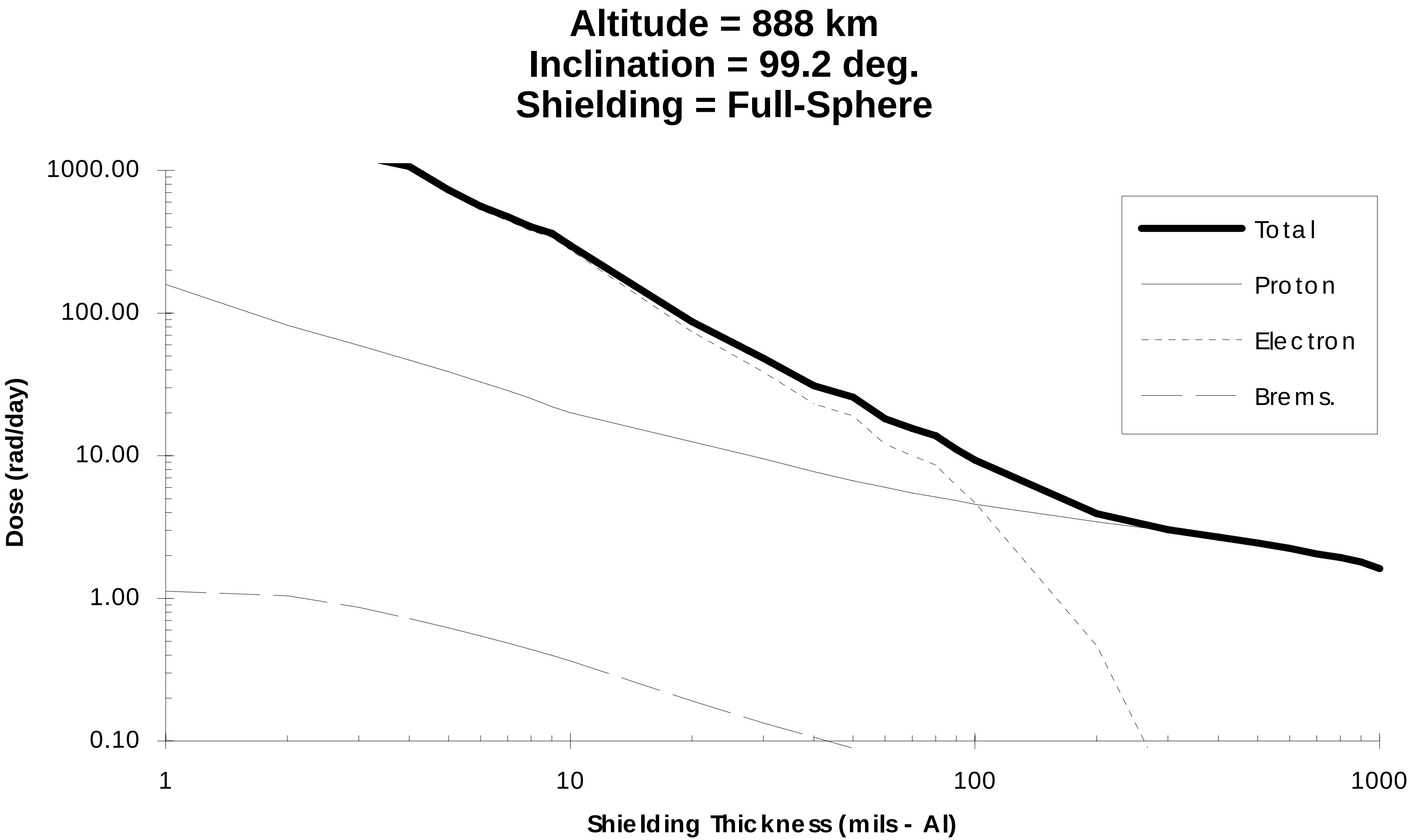
GEO RADIATION DOSE



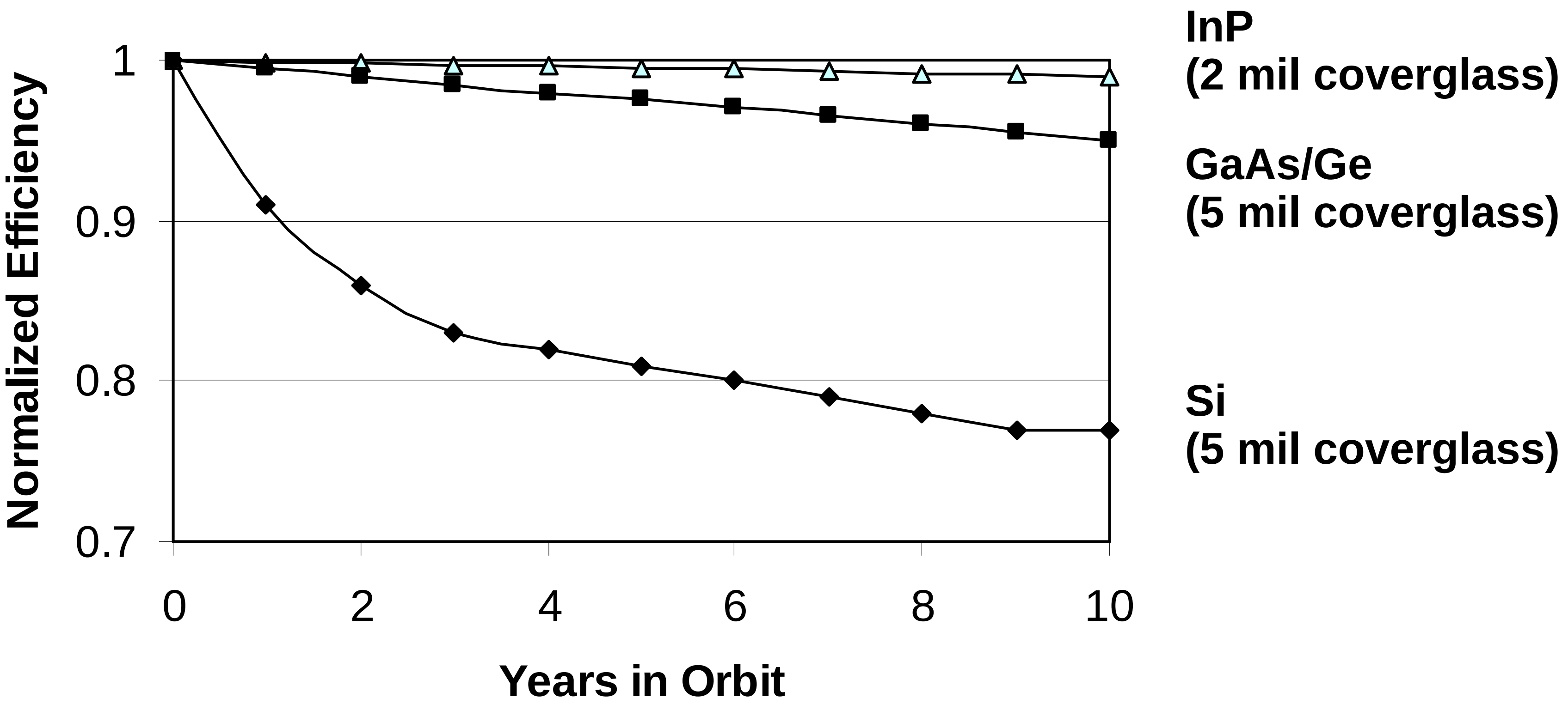
SPACE STATION RADIATION DOSE



SUN SYNCHRONOUS RADIATION DOSE



TOTAL DOSE EFFECT: POWER LOSS



Degradation Data is Obtained From the Solar Cell Manufacturer

TOTAL DOSE EFFECT: DRAM FAILED BITS

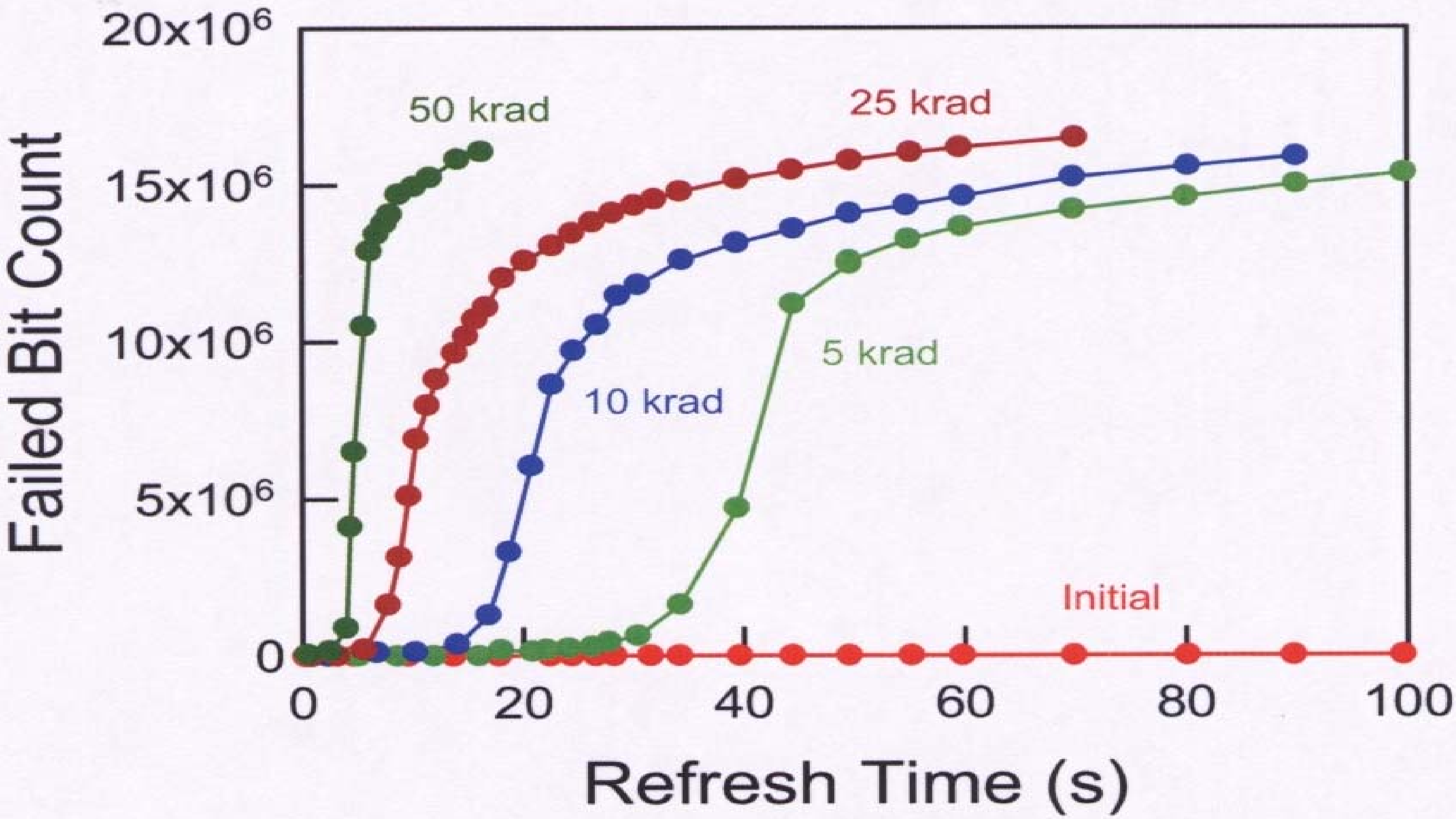


Figure 66: Number of failed bits versus refresh time for 16 Mb DRAMs irradiated with Co-60 gamma rays at total doses from 0 to 50 krad(Si). (After Ref. [219])

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?

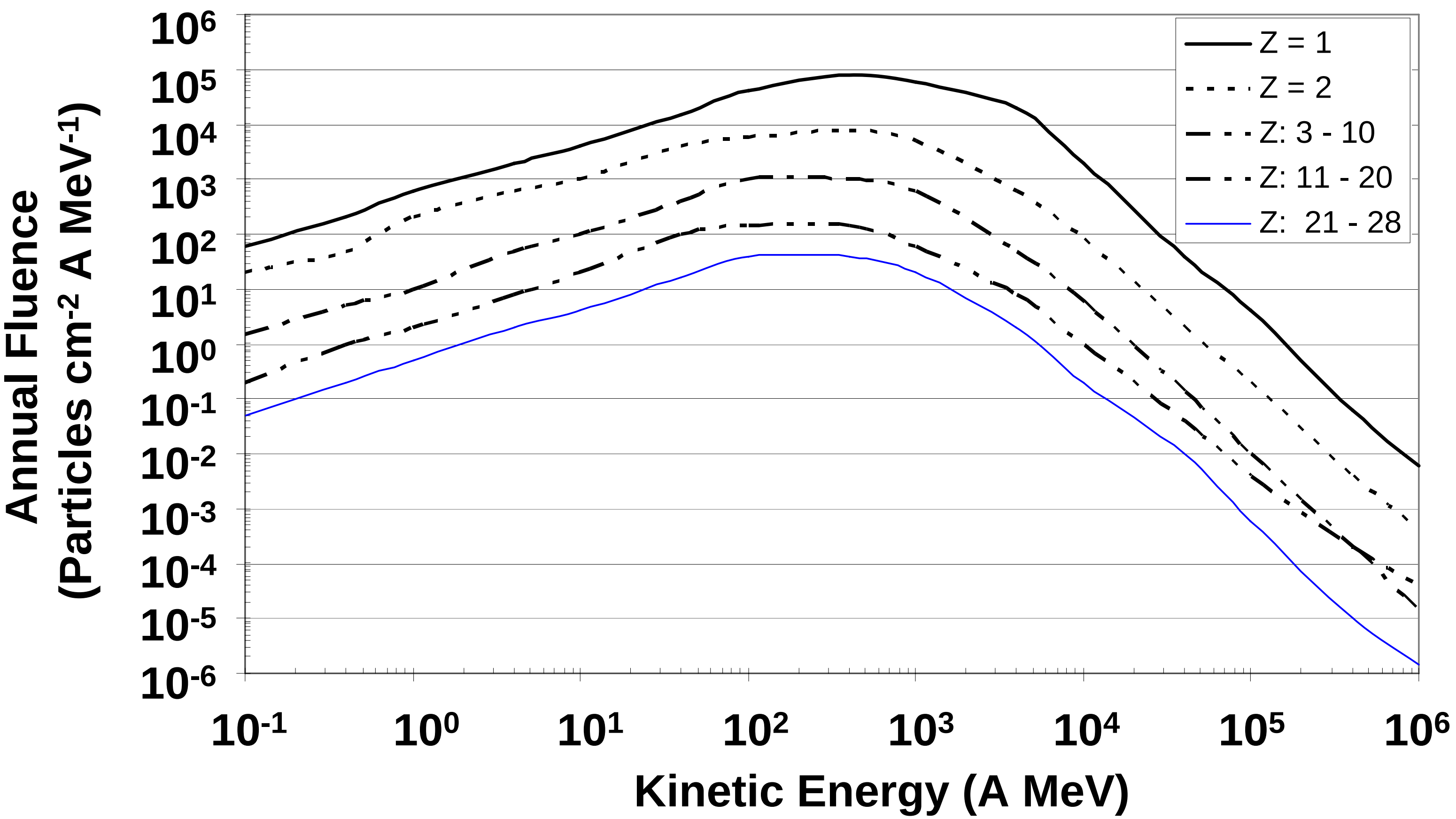
- Better models of the trapped radiation environment, and energetic particle environment, result in more accurate predictions of total dose to spacecraft systems.

- 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

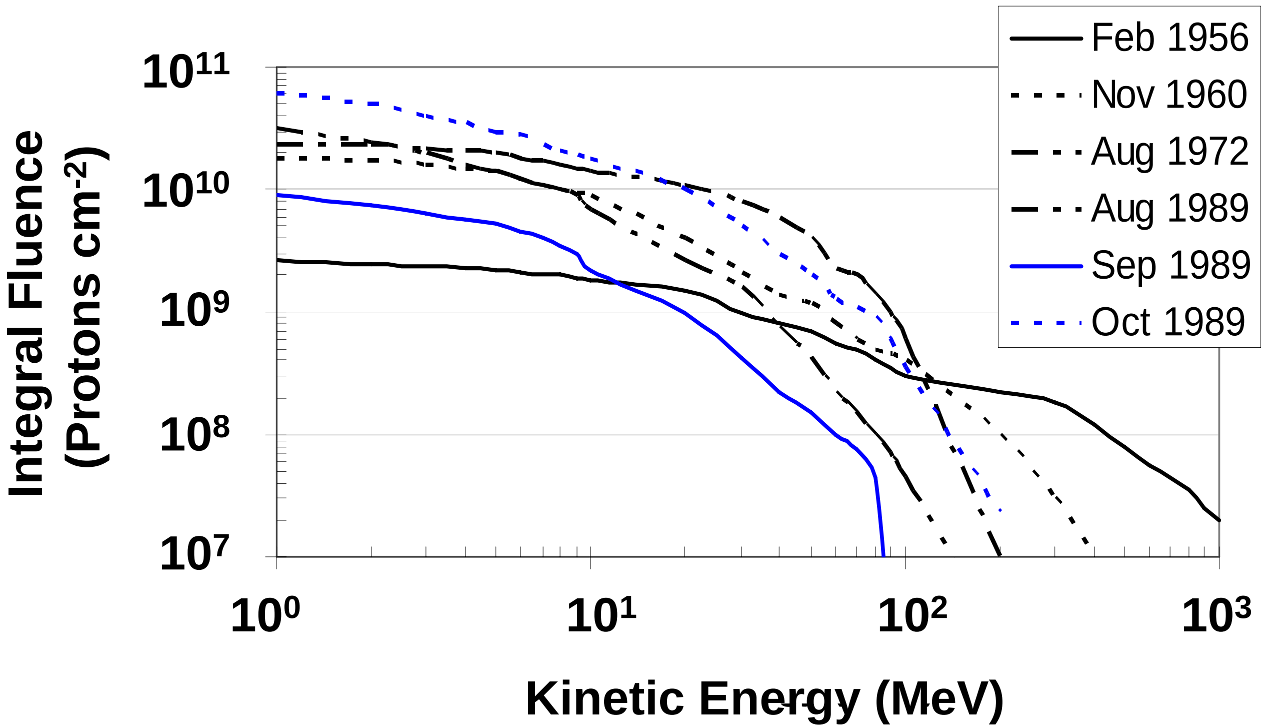
Single Event Effects

GeV PARTICLES – GALACTIC COSMIC RAYS



Wilson, J. W., Cucinotta, F. A., Simonsen, L. C., Shinn, J. L., Thibeault, S. A., and Kim, M. Y., "Galactic and Cosmic Ray Shielding in Deep Space", NASA TP 3682, December 1997

GeV PARTICLES – SOLAR EVENTS

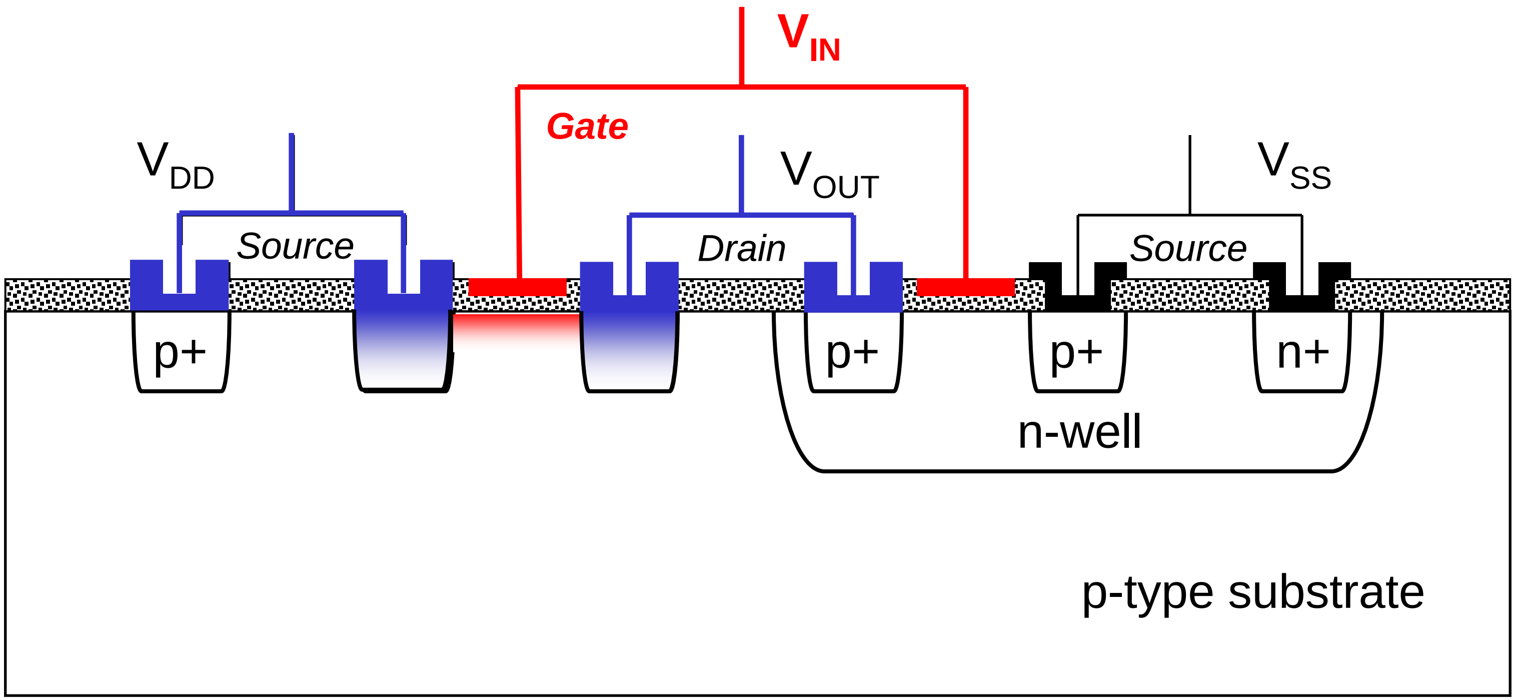


Wilson, J. W., Cucinotta, F. A., Simonsen, L. C., Shinn, J. L., Thibeault, S. A., and Kim, M. Y., "Galactic and Cosmic Ray Shielding in Deep Space", NASA TP 3682, December 1997

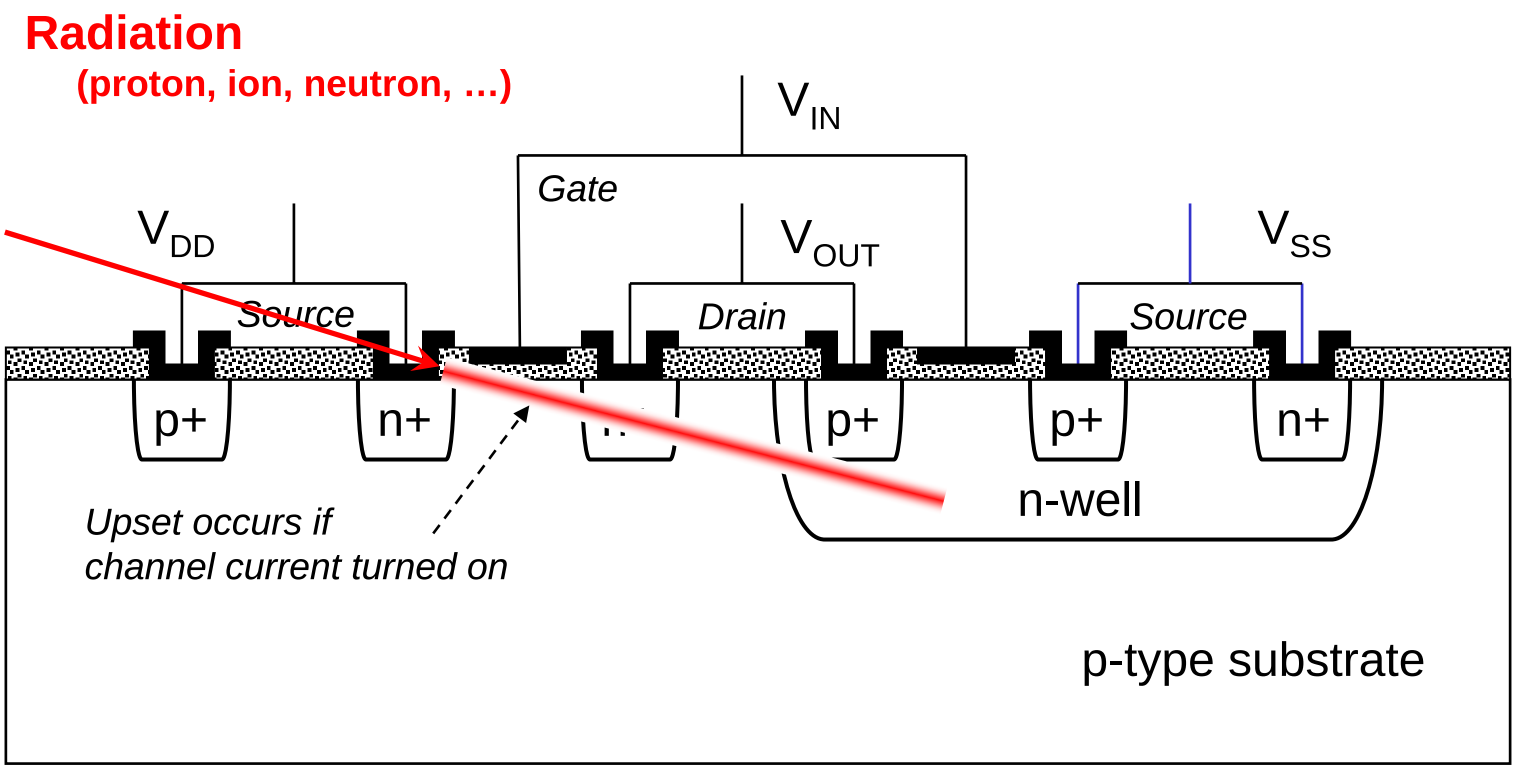
TYPES OF SEE

- 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

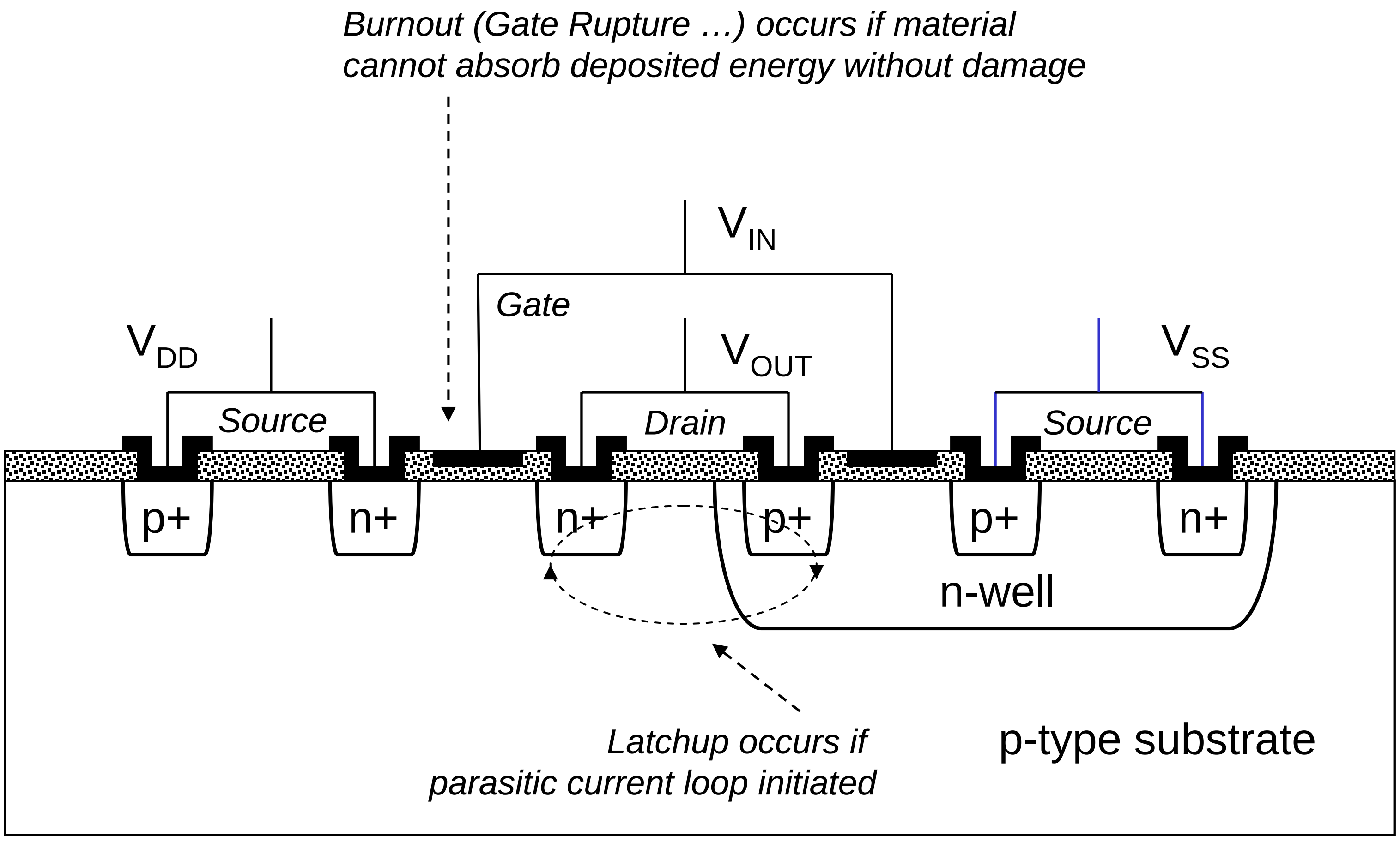
CMOS INVERTER



SEE ILLUSTRATION



SEE ILLUSTRATION

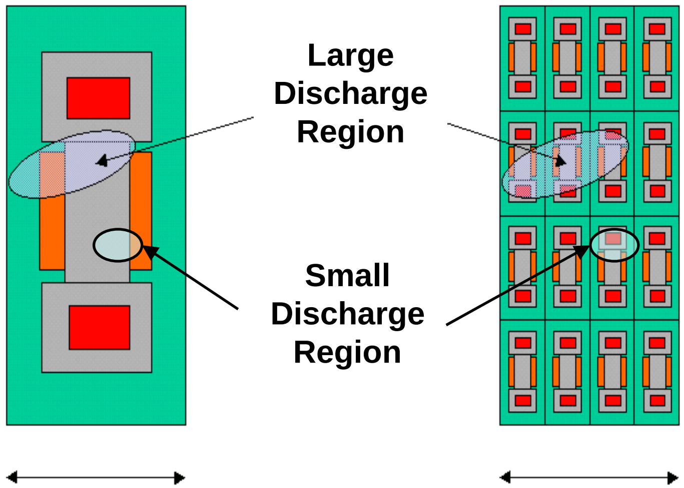


MICROPROCESSOR TRENDS

	1990	2002	2005	2014
Million Transistors / Chip	1	47.6	190	4,308
Feature Size (mm)	0.75	0.13	0.10	0.035
On Chip Frequency (MHz)	33	800	1,100	2,200
MPU Gate Length (nm)	600	85	65	20
Gate Oxide Thickness (nm)	12	2.2	1.3	0.6
Supply Voltage (V)	5	1.8	1.2	0.6

The Few “Rad Hard” Parts That Remain are Also Disappearing

MULTIPLE BIT UPSETS



One 1 μm Transistor

Four 0.25 μm Transistors

Large Discharges Cause SEUs

Small Discharges Have No Effect

Large Discharges Cause MBUs

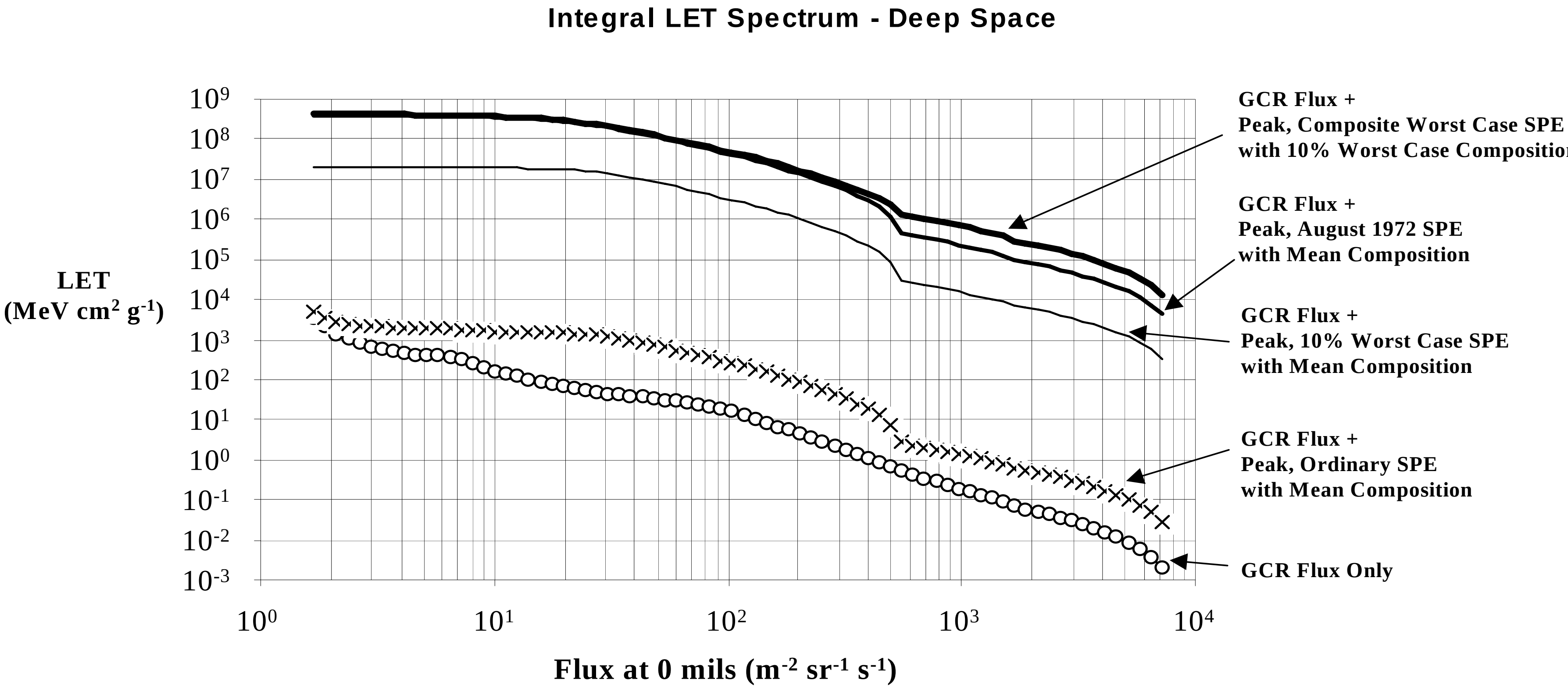
Small Discharges Cause SEUs

- 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

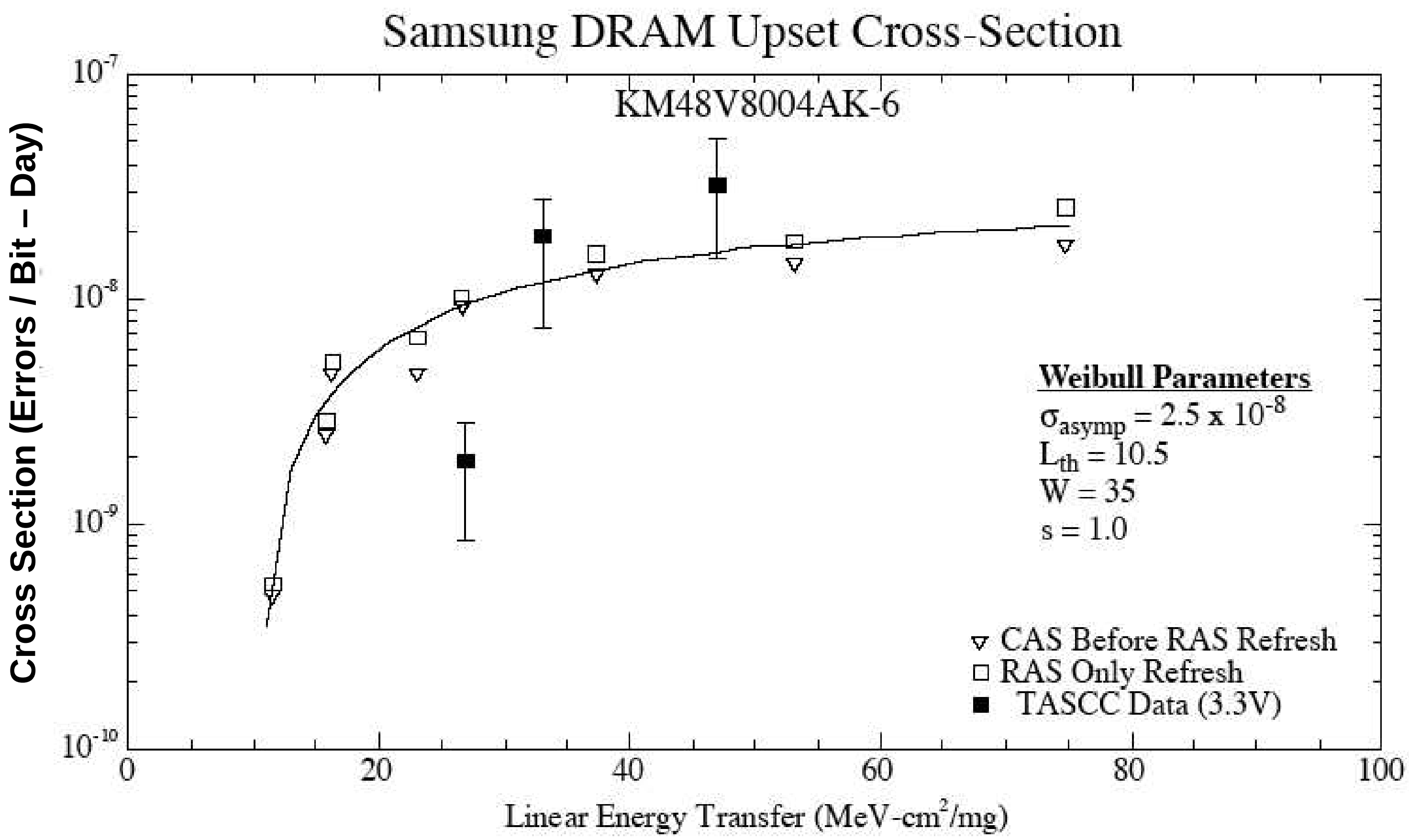
MEASURES OF ENERGY LOSS / PATH

- 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

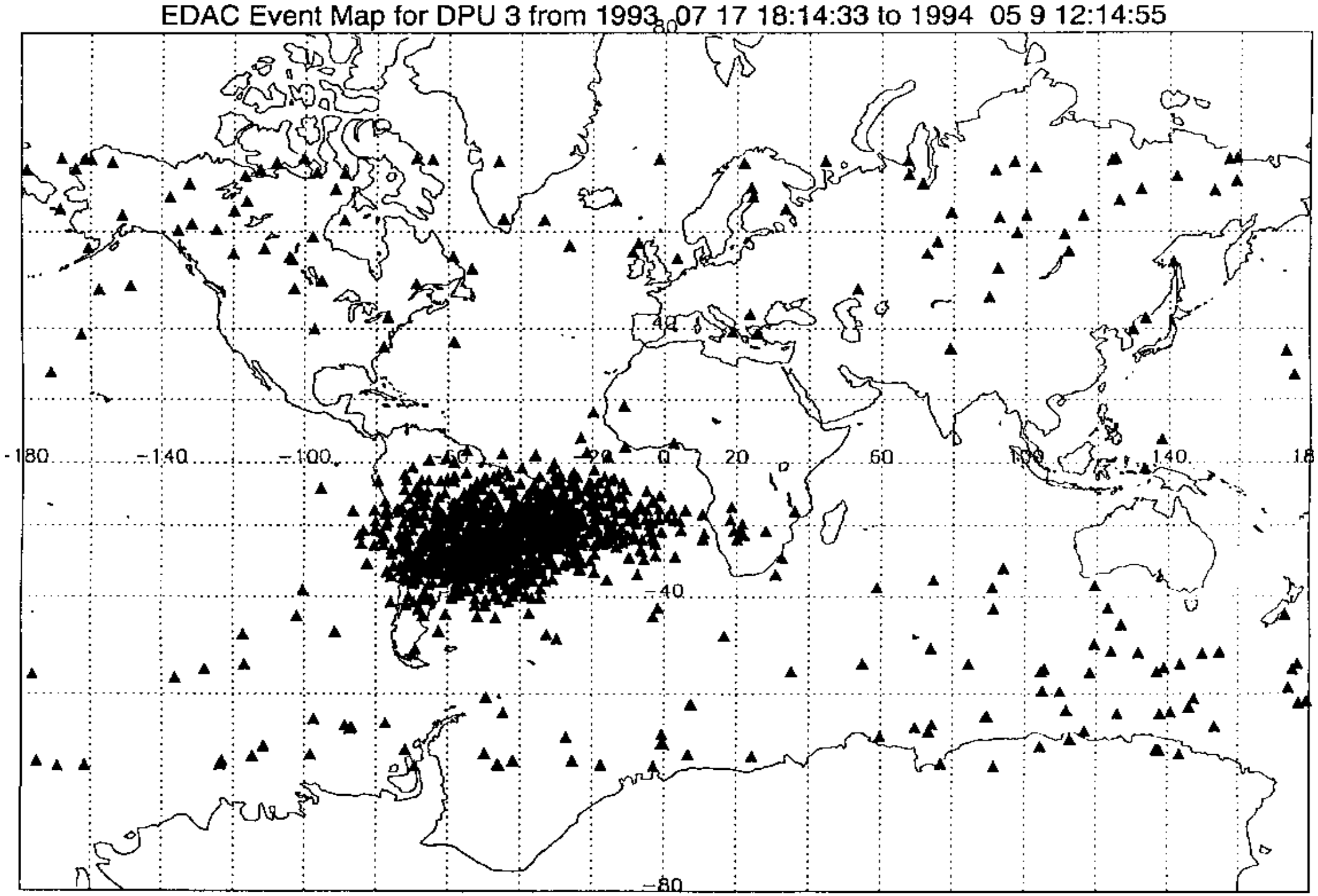
LINEAR ENERGY TRANSFER (LET)



SEU EXAMPLE: SAMSUNG DRAM



SEU FOR ALEXIS SPACECRAFT



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 = Solar Array Area (m^2)
  - P = Power Required (W)
  - η = 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 = Sun's Power Output (1367 W/m^2 at Earth Orbit)

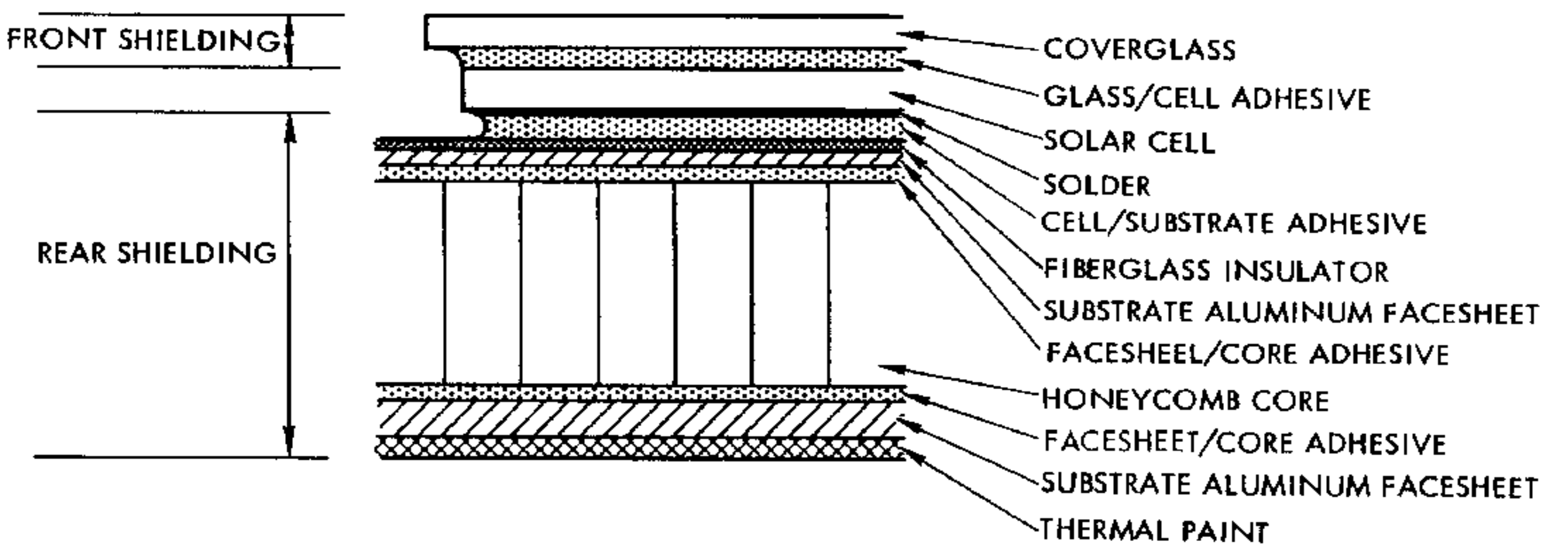
$$A = \frac{P}{\eta S}$$

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/m^2
  - Coverslide
    - Total Mass = Thickness of Coverslide Times Areal Density
      - 2.2 g/cm^3 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



SOLAR ARRAY DESIGN OPTIONS

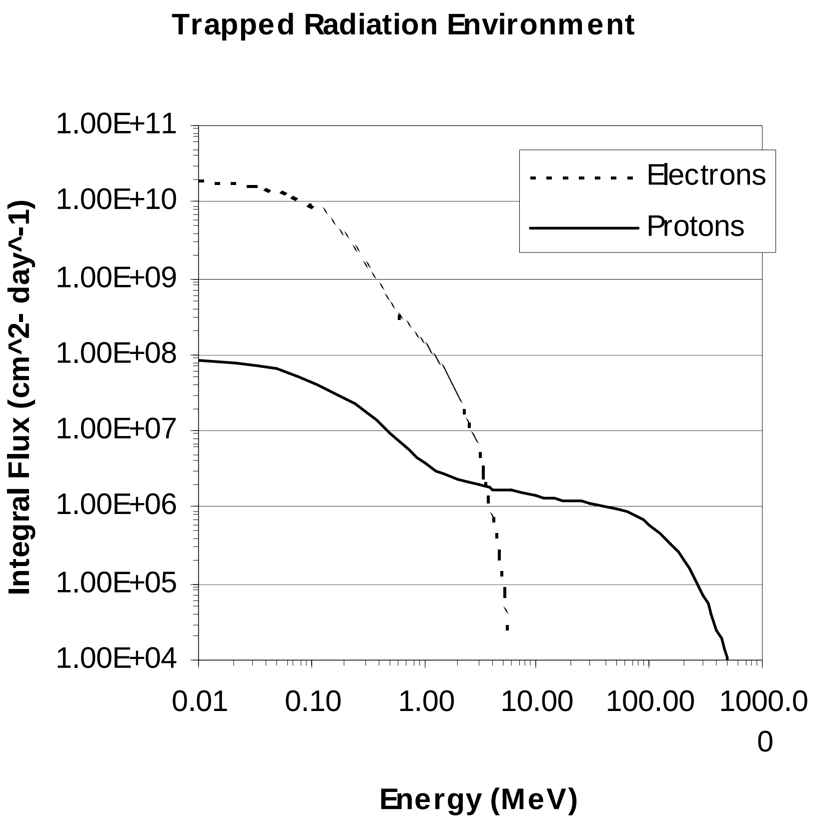
- Different Solar Cell Types
  - Silicon (Si)
    - Cost: Low (~$250/W)
    - Efficiency: Low (14%)
    - Radiation Resistance: Low
  - Gallium Arsenide (GaAs)
    - Cost: Medium (~ $600/W)
    - Efficiency: Medium (19%)
    - Radiation Resistance: Medium
  - Indium Phosphide (InP)
    - Cost: High (~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

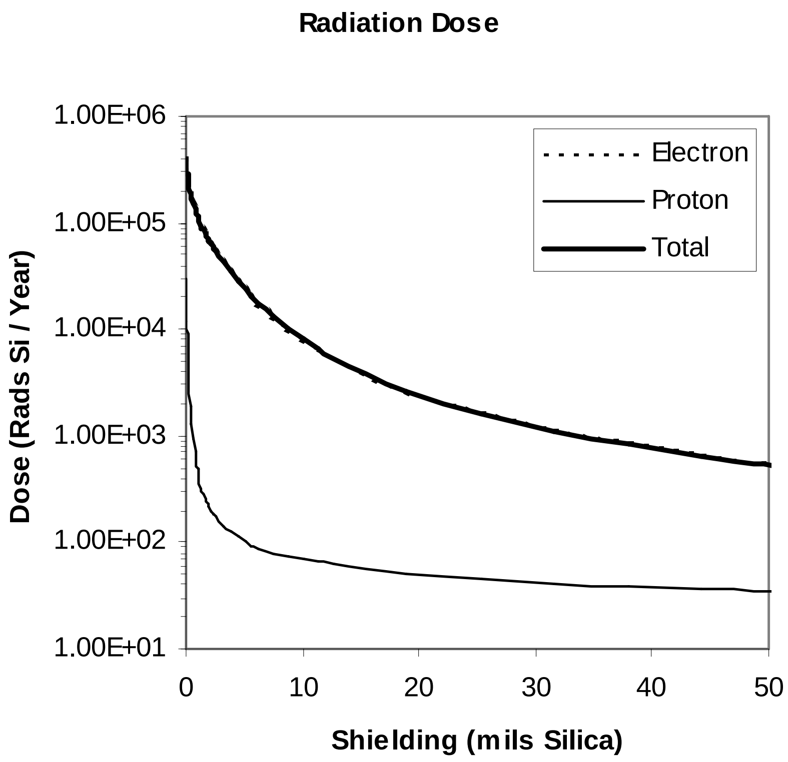
- Different Coverslide Thicknesses
  - 10, 20, 30, 40, or 50 mils
    - 1 mil = 1 milli-inch

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

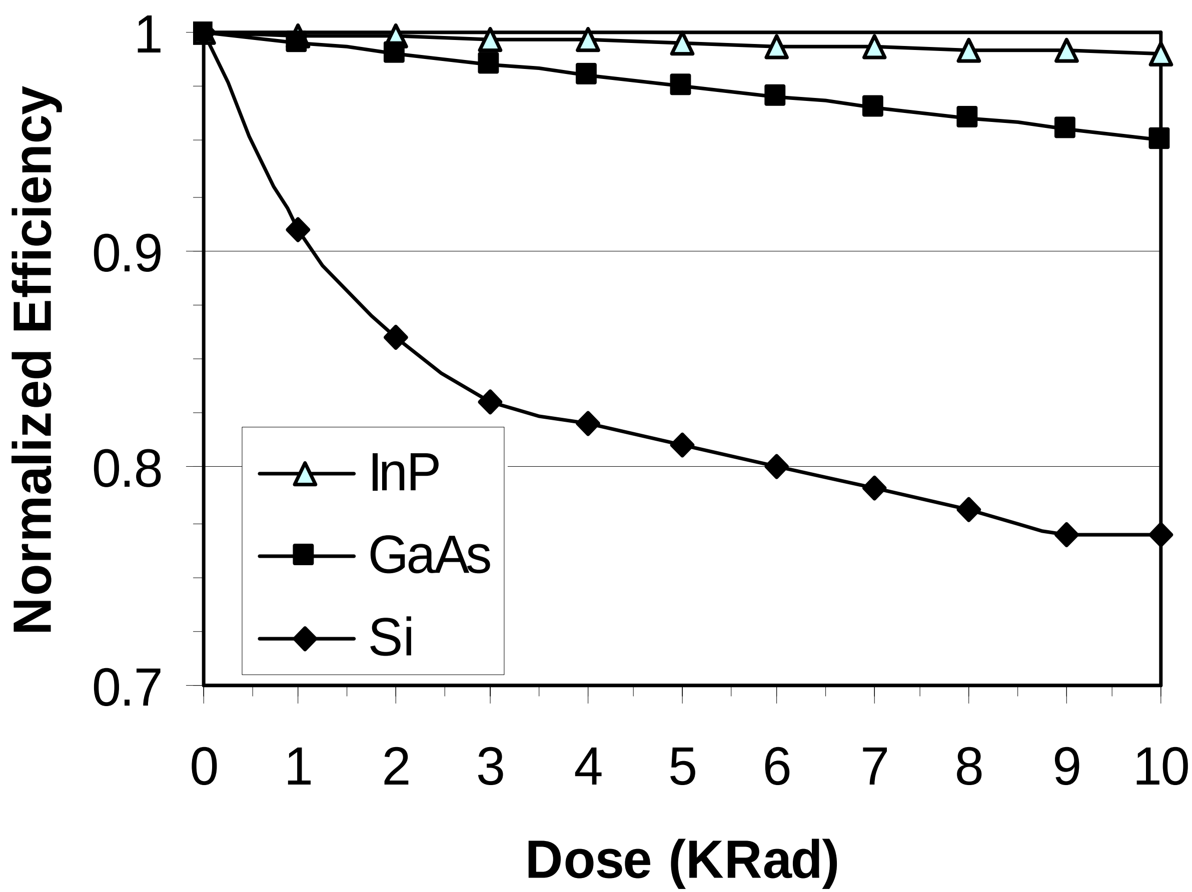
THE RADIATION ENVIRONMENT





Numerical Codes (Shieldose) Predict the Environment and Dose

SOLAR CELL DEGRADATION



EFFICIENCY VS. SHIELDING THICKNESS

Table 13.13 Radiation Dose as a Function of Coverslide Thickness.

	Shielding Thickness				
	10 mils	20 mils	30 mils	40 mils	50 mils
Dose (Krad)					

Table 13.14 Radiation Degradation Relative to Beginning of Life Efficiency.

	Shielding Thickness				
Solar Cell	10 mils	20 mils	30 mils	40 mils	50 mils
Si					
GaAs					
InP					

Table 13.15 End of Life Efficiency versus Shielding Thickness.

	Shielding Thickness				
Solar Cell	10 mils	20 mils	30 mils	40 mils	50 mils
Si					
GaAs					
InP					

RESULTS

- After One Year in Orbit, Protected by a 10 mil Coverslide, a Spacecraft Would Require a Solar Array of Size
  - Si Cells
    - $\boxed{}$ m^2 per 1000 W
  - GaAs Cells
    - $\boxed{}$ m^2 per 1000 W
  - InP Cells
    - $\boxed{}$ m^2 per 1000 W

MASS AND COST

Table 13.16 Solar Array Mass per 1000 Watts EOL Power.

	Mass (kg)				
Solar Cell	**10 mils**	**20 mils**	**30 mils**	**40 mils**	**50 mils**
Si					
GaAs					
InP					

Table 13.17 Solar Array Cost per 1000 Watts EOL Power.

	Cost ($K)				
Solar Cell	**10 mils**	**20 mils**	**30 mils**	**40 mils**	**50 mils**
Si					
GaAs					
InP					

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