Chapter 9 Environmental Effects on Space Systems - Part 2 Radiation Effects

A Passage of ionization through matter.

Ionizing radiation means that enough energy can be transferred to an atomic electron in a single interaction to detach the electron from the atom. The energies required to do this depend on the target atom and range from 5 to 25 eV, usually called the ionization energy. This is for the most loosely bound electron. The inner electrons may require high energies up to several thousand electron volts.

Ordinary matter is very open when viewed on an atomic scale. If we represent a nucleus by a dot 0.1 mm in diameter (just visible) then the next nucleus in a typical solid will be about 10 meters or 30 ft away! So there is plenty of room for ions, electrons or photons to penetrate into the solid. The space between the nuclei is filled with an electron cloud which has little mass but which generates strong electromagnetic fields which really hold the solid together and make it "solid".

There are 4 classes of particles or "radiations" of interest to us:

(1) Heavy, charged particles such as protons, a particles or heavier ions
(2) High energy photons - UV, X Rays, and gamma rays
(3) Electrons.
(4) Neutral particles - mostly neutrons.

All of these can cause ionization if they have enough (kinetic) energy.

1 Penetration of heavy charged particles

When a heavy charged particle such as a proton or an α particle (He^{++}) enters a solid it interacts almost entirely with the distributed electrons each of which has a much smaller mass than the projectile:

$$\frac{\text{Proton mass}}{\text{Electron mass}} \cong 1835 \qquad \frac{\alpha \text{ particle mass}}{\text{Electron mass}} \cong 7340$$

We know from mechanics that in collisions of heavy projectiles with a light target only a small fraction of the projectile energy can be transferred to the target:

$$\frac{\Delta E}{E} = \frac{(4)(\text{mass of target})}{\text{Mass of projectile}} \text{ is maximum fractional energy transfer.}$$

Thus as the proton travels through the electron cloud it makes many collisions losing a small fraction of its kinetic energy in each collision until it finally stops. Thus a heavy charged particle has well defined range which represents the distance beyond which no particle in an incident mono-energetic beam will penetrate as shown in Figure 9.1

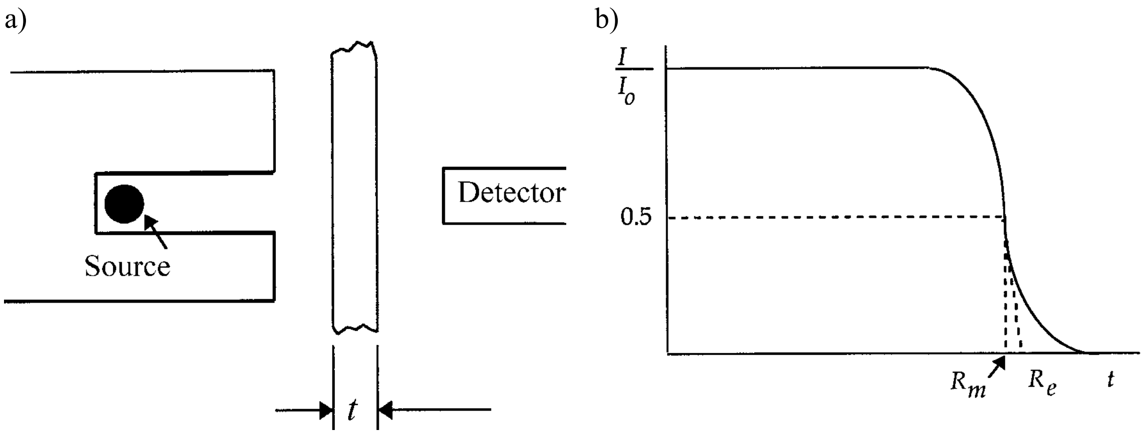


Figure 9.1. An alpha particle transmission experiment. *I* is the detected number of alpha particle through an absorber thickness, *t*, whereas I_0 is the number detected without the absorber. The mean range R_m and extrapolated range R_e are indicated.

Another important concept is the stopping power usually written as $-\frac{dE}{dx}$ and shown schematically in Figure 9.2. It is also called the Specific Energy loss.

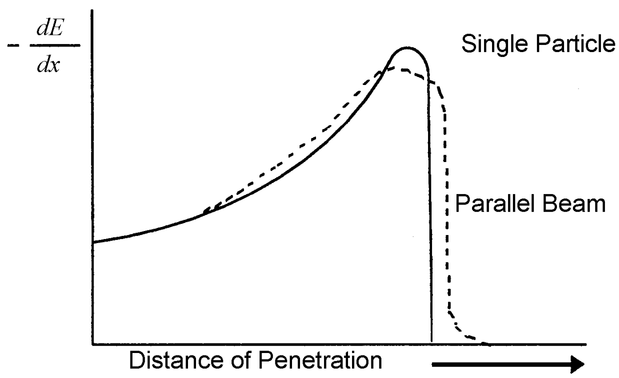


Figure 9.2. The stopping power along an alpha particle track.

As the notation implies $-\frac{dE}{dx}$ represents the rate of energy loss with respect to distance traveled along the trajectory. $-\frac{dE}{dx}$ is small at first when the incident particle velocity is high and then rises to a peak near the end of the range and drops abruptly to 0.

The relation between range R and $-\frac{dE}{dx}$ is fairly simple.

$R = \int_0^{E_0} \frac{dE}{\left(dE/dx\right)}$ since $\frac{1}{\left(dE/dx\right)}$ = the distance traveled for a loss of unit energy. The units are almost as peculiar as the dimensions, again due to the nature of the ultimate applications:

It would be most logical to specify range in centimeters and $\frac{dE}{dx}$ in energy/distance such as MeV/cm. However, it often turns out to be more useful to specify range in terms of the amount of mass of target material penetrated. Hence:

$$R\left(\frac{gr}{cm^3}\right) = \rho\, R(cm)$$

where ρ = density of the target material in $\frac{gr}{cm^3}$. Similarly,

$$\frac{dE}{dx}\left(\frac{MeV}{gr/cm^3}\right) = \frac{1}{\rho}\frac{dE}{dx}\left(\frac{MeV}{cm}\right)$$

The reason for these units is the fact that R and $\frac{dE}{dx}$ expressed in gr/cm^2 and $\frac{MeV\ cm^2}{gr}$ respectively are approximately the same for elements close to each other in the periodic table, such as Si and Al. Figure 9.3 shows both the range and the stopping power $-\frac{dE}{dx}$ for protons in silicon, a material of great interest in space applications.

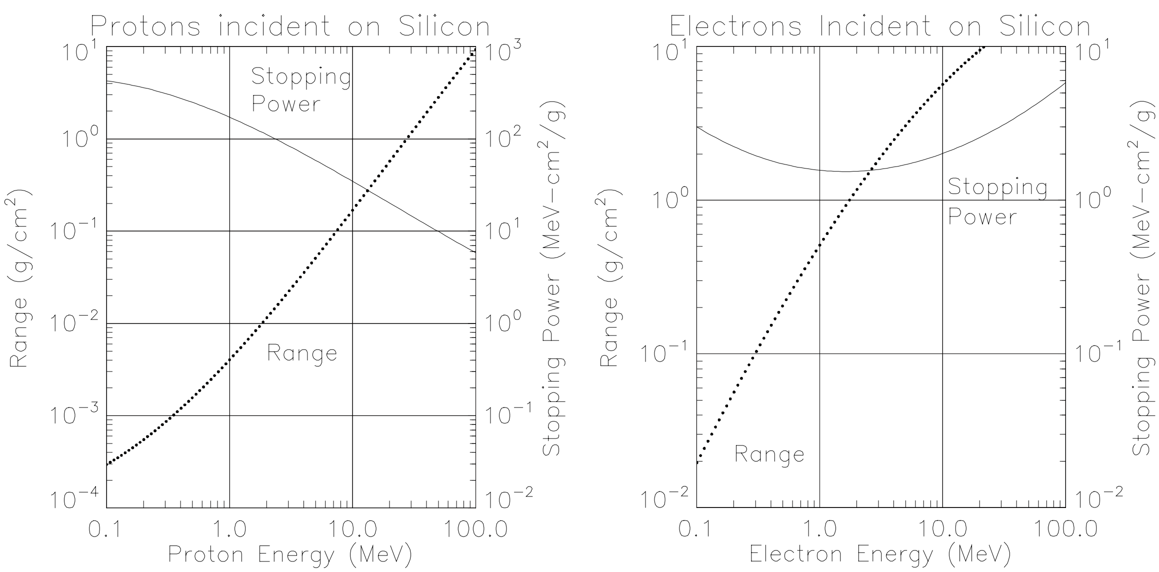


Figure 9.3. Stopping Power and Range Curves for Protons and electrons in Silicon

Another material of considerable importance in spacecraft construction is aluminum.
Figure 9.4a gives the range-energy curve for protons in aluminum, water and lead for protons; Figure 9.4 b shows ranges for electrons. Note that the shapes of the curves are similar - the scales have simply shifted. Typical spacecraft skins area bout 1/8 inch (0.3 cm) or 0.86 gm/cm^2. From the curve in Figure 9.4, this would correspond to the range of approx. a 30 MeV proton.

a) b)

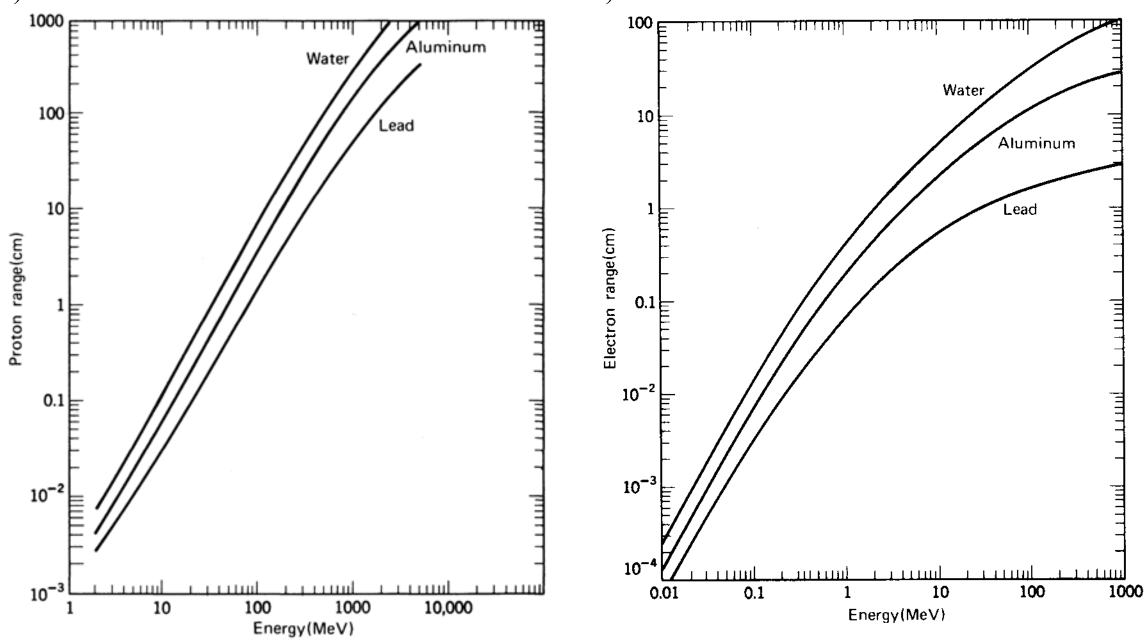


Figure 9.4 Range-Energy Relation for protons in Al for proton energies 0-10^4 MeV

2 Interaction of Fast Electrons with Matter

Compared to heavy charged particles electrons loose energy at a much lower rate and the path of the fast electron is usually convoluted rather than an essentially straight line path. Large deflection in the incident electron's path are possible because the masses of the projectile and target are equal and therefore a much larger fraction of the incident energy can be lost in a single encounter.

For electrons there also exists a second mechanism by which energy is lost, namely radiation of electromagnetic energy when the incident electron undergoes a sudden acceleration e.g. a collision. This process is usually called Bremstrahlung (Braking Radiation).

Thus, the total $\frac{dE}{dx}$ for the incident electron has two parts:

$$\frac{dE}{dx}=\left(\frac{dE}{dx}\right)_{coll}+\left(\frac{dE}{dx}\right)_{rad}$$

There exists a rule of thumb to estimate the relative magnitude of these two contributions

$$\frac{\left(\frac{dE}{dx}\right)_{rad}}{\left(\frac{dE}{dx}\right)_{coll}}=\frac{EZ}{700}$$ E = the incident energy in MeV and Z is the atomic number of the target

For electrons of a few MeV and targets such as AL(13) or Si(14) the above ratio is small showing that collisional energy loss dominates.

Electron Range and Transmission Curves

If we repeat the absorber experiment described above in Figure 9.1 using a source of mono-energetic fast electrons we get a curve like the one shown in Figure 9.5 below.

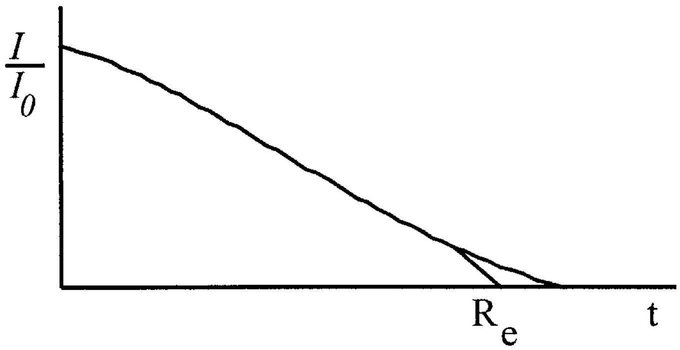


Figure 9.5. Transmission curve for mono-energetic electrons R_e is the extrapolated range.

As can be seen from the curve even for a very thin absorber some electrons are lost because they are scattered out of the beam and do not reach the detector. Thus the plot of the detected number of electrons vs absorber thickness begins to drop immediately and gradually approaches zero for large absorber thickness.

The concept of range is less definite for fast electrons than heavy charged particles. Normally the electron range is taken from a plot such as Figure 9.5 by extrapolation of the linear portion of the curve to zero and represents the absorber thickness required to assure that almost no electrons can penetrate the entire thickness

For equivalent energy the specific energy loss $\frac{dE}{dx}$ is much lower for electrons than that of heavy charged particles so their actual path length in typical absorbers is hundreds of times greater. As a rough rule of thumb electron ranges are about 2mm/MeV for the materials of interest to us (Si and Al) See Figure 9.3 above and 9.6 below

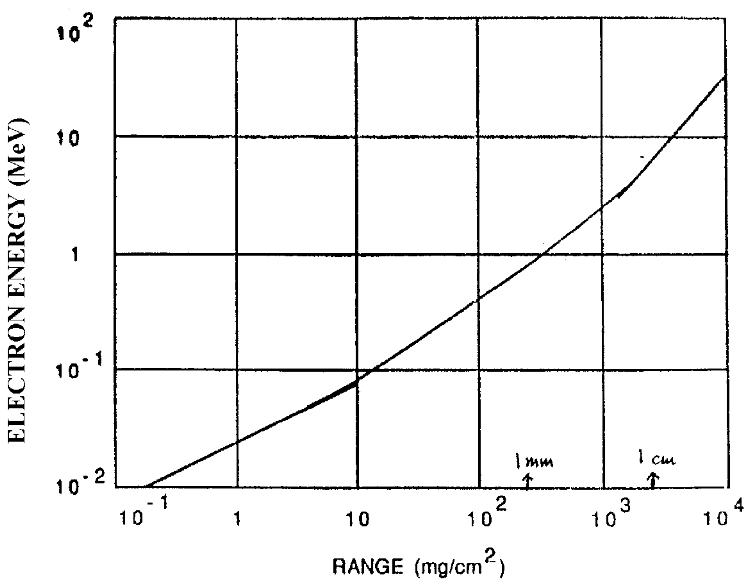


Figure 9.6. Electron Energy Versus Range in Aluminum

3 Interaction of energetic photons with matter

The process by which photons interact with matter is fundamentally different from that of charged particles. The photon will transfer all of its energy in a single interaction and vanish in the process. This leads to an exponential decrease of intensity I (photons/area/sec.) with penetration depth into the absorber. Thus intensity at depth t is $I(t) = I_0 e^{-mt}$ where m is called the linear attenuation coefficient and has units of cm^{-1}. This type of attenuation illustrated in Figure 9.7.

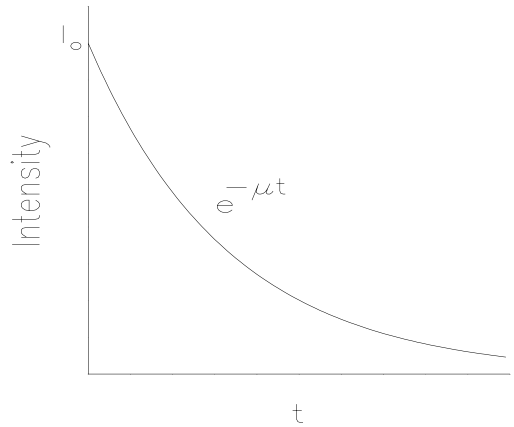


Figure 9.7. The exponential transmission curve for gamma rays measured under "good geometry" conditions.

It again turns out to be convenient to define a <u>mass attenuation</u> coefficient

$\mu_m = \frac{\mu}{\rho}\left(\frac{cm^2}{gr}\right)$ and write the depth in the units of $t_m = \rho\, t \left(\frac{gr}{cm^2}\right)$ which yields

$$I(t) = I_0 e^{-\left(\mu/\rho\right)(\rho t)} = I_0 e^{-\mu_m t_m}$$

Where m (and μ_m) are functions of the target material and the energy of the incident photons. Figure 9.8 shows μ_m for various materials in the keV and MeV energy range.

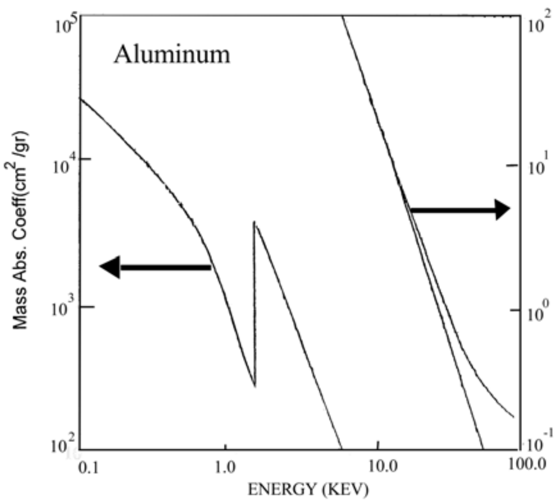


Figure 9.8 a Mass absorption coefficient for X-Rays in aluminum

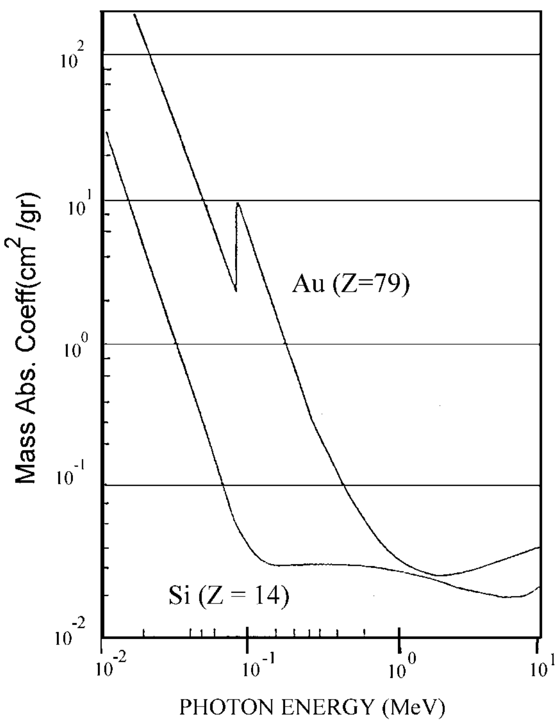


Figure 9.8 b Figure 9.6: Mass Absorption Coefficients for Si, Au for X-Rays of various energies

4 Neutrons

Finally a word about neutral particles, particularly neutrons. Since they carry no charge their primary interaction is with the small but massive nuclei. When such a collision occurs the neutron may be swallowed up by the target nucleus or at the very least suffer a big change in energy. Thus the intensity of a collimated neutron beam decays exponentially as

$$I(t) = I(0)e^{-(\Sigma_{total})t},$$

where $\Sigma_{total} = \Sigma_{scatter} + \Sigma_{absorb} + \ldots\ldots\ldots\ldots$

Neutrons are rare in the natural space environment, but are important in the vicinity of nuclear reactors or nuclear detonations.

B Radiation Units

We are interested in the effects of radiation in matter including biological tissue. We shall here only describe the four basic quantities which are used to do this (They are often loosely and incorrectly applied).

(a) The curie (ci) is a measure of the activity of a radioactive source and is defined as 1 ci = 1 curie = 3.70×10^{10} disintegrations/sec. This says nothing about the nature of decays. This unit is generally used to describe radioactive sources or materials.

(b) The Roentgen [R] is a measure of exposure. Specifically one Roentgen is defined as the exposure which would deliver 8.78 mJ to 1 kg of dry air. A proper use would be to say: This dental X-Ray beam provided an exposure of 300 mR/sec. Although we use dry air as a measurement substance the exposure itself is independent of materials.

(c) The RAD (from Radiation Absorbed Dose) is a measure of the dose actually absorbed by a specific object in terms of the energy transferred to it. An object is said to have received and absorbed dose of 1 RAD when 10mJ/kg have been deposited in it by ionizing radiation. A proper statement using the concept of absorbed dose would be:

"A whole body short term gamma ray dose of 500 RAD will cause death in 50% of the population exposed to it."

The SI unit for absorbed dose is the Gray defined by

1 Gray (Gy) = 100 RAD = 1(J/kg)

(d) The REM stands for (Roentgen Equivalent in Man) and takes account of the fact although different radiations may deliver the same energy/pr unit mass to a body the biological effects can be very different because of the different dE/dx for different types of radiation.

To account for this we multiply the absorbed dose in RAD's by a factor called the Relative Biological Effectiveness or (RBE) factor. For X-Rays and electrons RBE~1, for slow neutrons ~5 and for α particles 10-20, etc.

Thus (REM) = (RAD)(RBE) converts RADs into REMs.

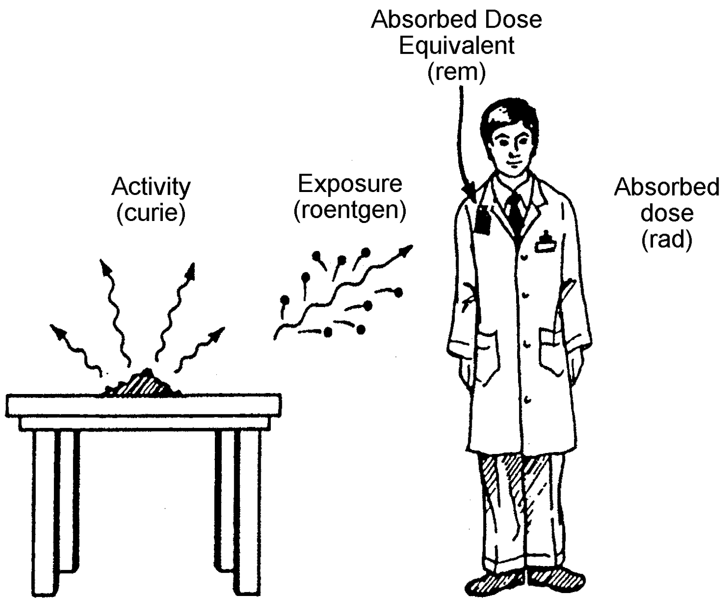


Figure 9.9. (from: Fundamentals of Physics by Halliday & Resnick: Wiley & Sons, 1988)
This sketch should help to clarify the distinction between the curie, the roentgen, the RAD, and the REM.

Table 1 - Acute Dose Effects on Humans (Whole Body Exposure)

Dose (RADs)	Probable Effect
0-50	No obvious effects, blood changes
80-120	10% chance of vomiting/nausea for 1 day
130-170	25% chance of nausea, other symptoms
180-220	50% chance of nausea, other symptoms
270-330	20% deaths in 2-6 weeks, or 3 month recovery
400-500	50% deaths in 1 month, or 6 month recovery
550-750	Nausea within 4 hours, few survivors
1000	Nausea in 1-2 hours, no survivors
5000	Immediate incapacitation, death within 1 week

C Effects of Space Radiation on Systems

Space contains large numbers of high speed atomic particles and energetic photons. Any object placed in space will be impacted by these particles and photons and depending on circumstances varying degrees of radiation damage will result.

Although the mechanisms by which different types of ionizing radiation interact with the target material are quite different the net effect in all cases is the deposition of energy in the target usually in the form of kinetic energy of electrons and atoms. Often these collision products will have enough energy to cause further ionization or dislocations and by this avalanche process a single high energy particle entering a target can cause considerable biological, electrical or mechanical damage.

There are four major areas of concern which involve the radiation environment and its effect on space system and space crews:

(1) Long term exposure to moderate electron and proton fluxes in the Earth's Radiation Belts. These effects include slow changes in properties of semiconductors, optical and other sensor surfaces, thermal radiative properties of materials. Another potentially serious problem for Space Systems in the accumulation of charge in insulating materials which can lead to internal and external electric discharges. The effects on biological systems particularly man can usually be controlled by fairly straight-forward shielding measures.

(2) Solar Proton Events: As a result of major eruptions on the solar surface, intense, high energy pulses of protons lasting on the order of hours to days will reach the near-earth space environment. Both proton fluxes and energies can be several orders of magnitude larger than normal conditions with potentially severe consequences for both materials and personnel.

(3) Galactic Cosmic Rays: Near-earth space is traversed by a very weak flux of extremely high energy nuclei originating outside the solar system. These give rise to Single Event Upsets (SEU) in which dense deposition of energy and subsequent separation of electric charge in a p-n junction can induce a change of state in an electronic circuit or memory element. Under certain conditions electronic components may be permanently disabled.

(4) As a result of exo-atmospheric nuclear detonations a space craft may be exposed to intense pulses of x rays, gamma rays and neutrons. In addition there are important secondary effects such as artificial radiation belts and electromagnetic pulses which can have serious effects on space craft and their missions.

1 Radiation Thresholds

Ionizing radiation affects many components of space systems. The thresholds above which radiation effects must be considered vary greatly as shown in the table below:

Table 2. Radiation Damage Thresholds

Material	Damage Threshold (RAD)
Biological matter	10^1-10^2
Electronics	10^2-10^6
Lubricants, hydraulic fluid	10^5-10^7
Ceramics, glasses	10^6-10^8
Polymeric material	10^7-10^9
Structural metals	10^9-10^{11}

As might be expected biological matter is the most radiation sensitive but solid state electronics is not far behind. As electronic components become smaller and smaller this sensitivity is likely to increase. These thresholds do not mean that people or equipment cannot operate above them but their operation must be considered in equipment and mission design.

2 Radiation Dose in the Belts

In Figure 9.10 to 9.17 are shown a series of plots of the daily dose (due to electrons and protons) for satellite orbits for various orbital inclinations. All orbits are assumed to be circular. the multiple curves shown on each plot correspond to the absorbed dose in the presence or various thicknesses of shielding (aluminum) The altitudes cover the range from low earth orbit (few hundred km) to geosynchronous orbit (about 36,000 km)

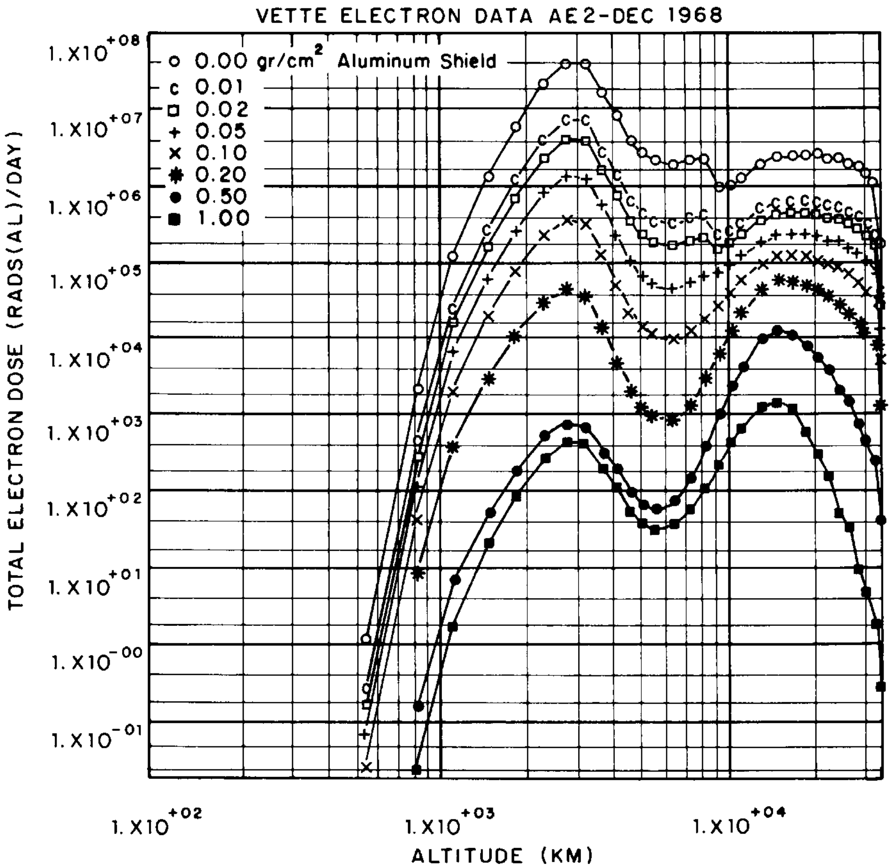


Figure 9.10 Daily dose (natural electrons) for a circular orbit satellite as a function of satellite altitude for 0° orbital inclination, with various shielding thickness.

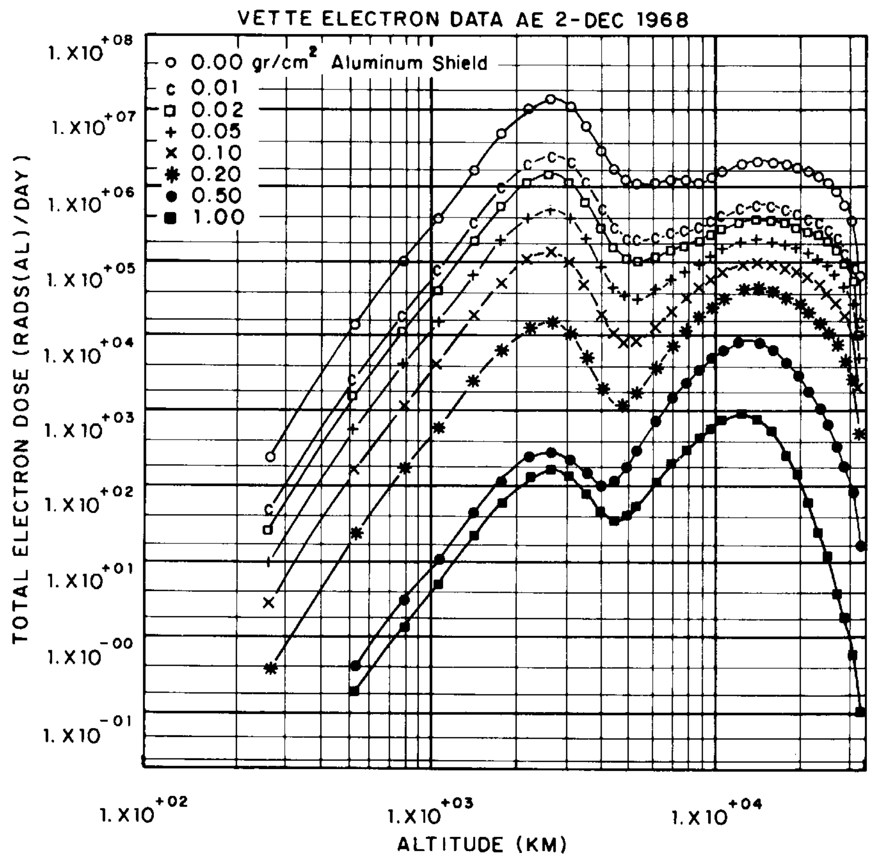


Figure 9.11 Daily dose (natural electrons) for a circular orbit satellite as a function of satellite altitude for 30° orbital inclination, with various shielding thickness.

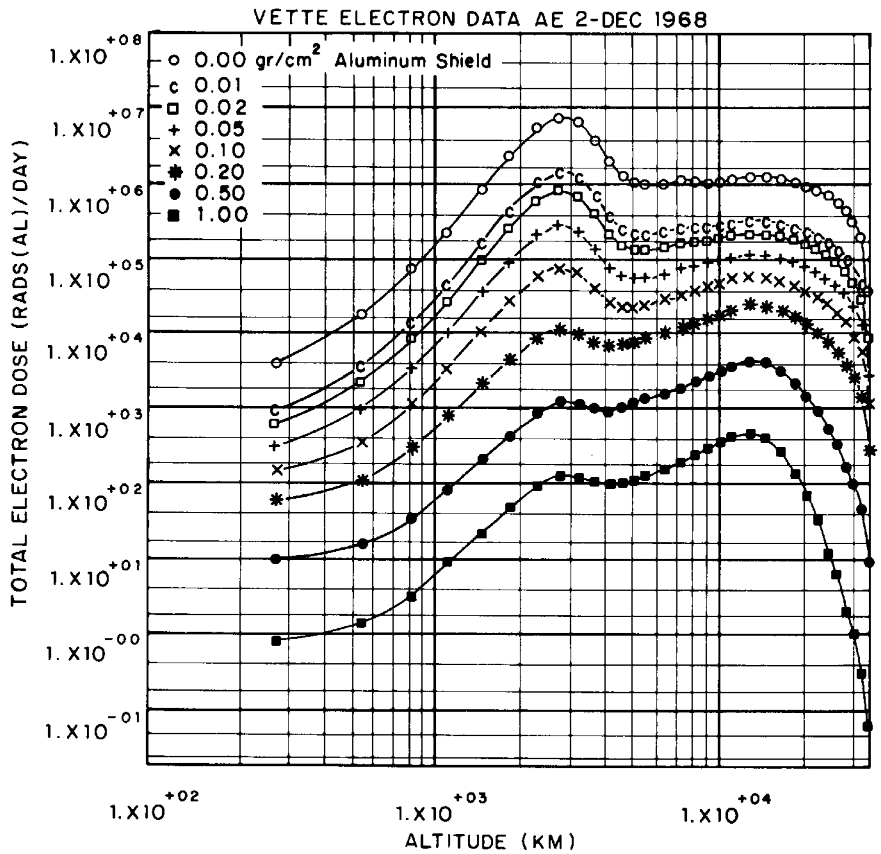


Figure 9.12 Daily dose (natural electrons) for a circular orbit satellite as a function of satellite altitude for 60° orbital inclination, with various shielding thickness

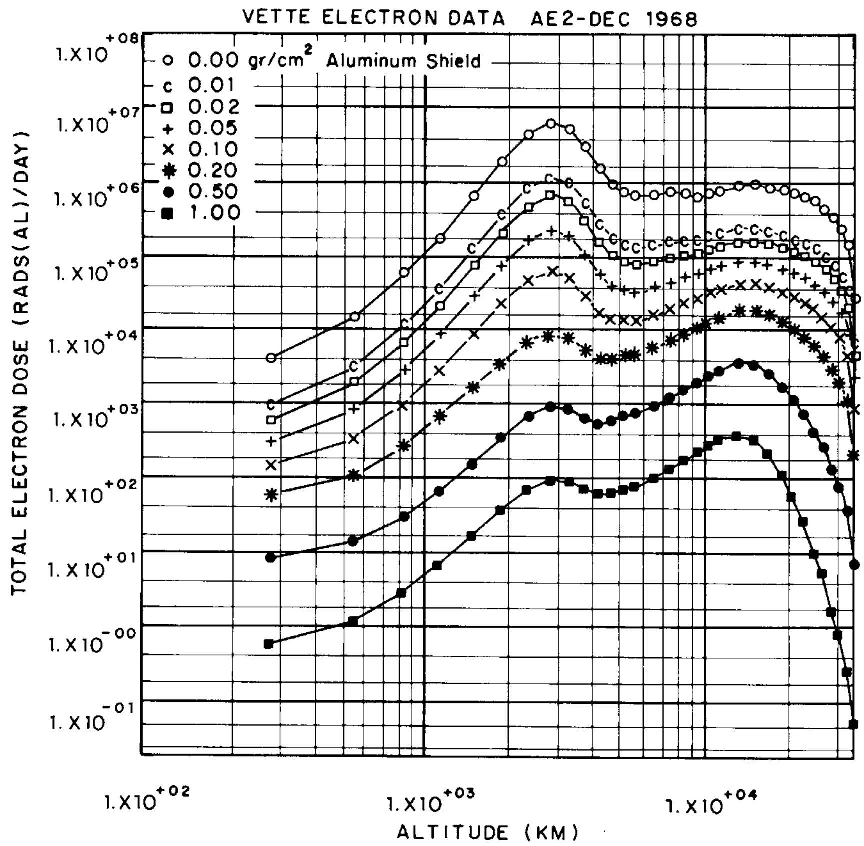


Figure 9.13 Daily dose (natural electrons) for a circular orbit satellite as a function of satellite altitude for 90° orbital inclination, with various shielding thickness

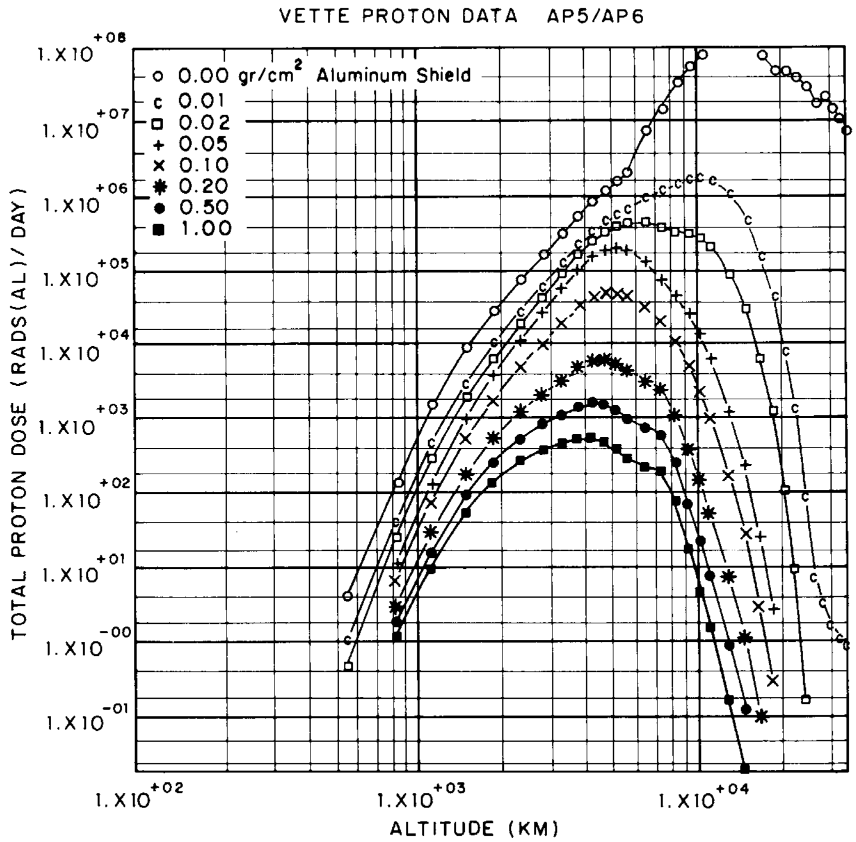


Figure 9.14 Daily dose (natural protons) for a circular orbit satellite as a function of satellite altitude for 0° orbital inclination, with various shielding thickness

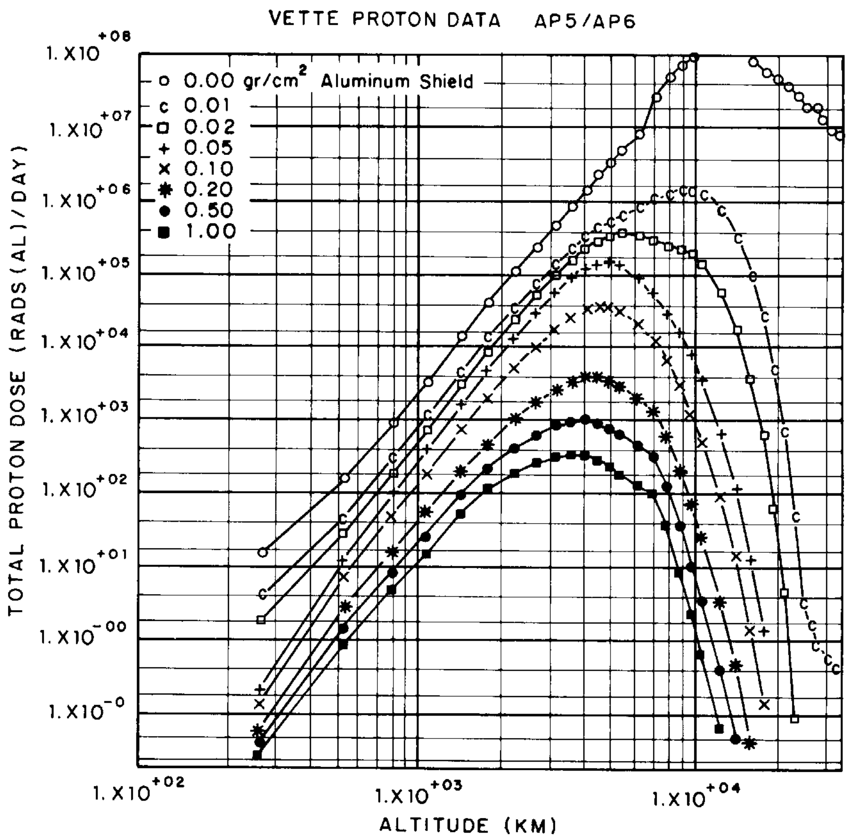


Figure 9.15 Daily dose (natural protons) for a circular orbit satellite as a function of satellite altitude for 30° orbital inclination, with various shielding thickness

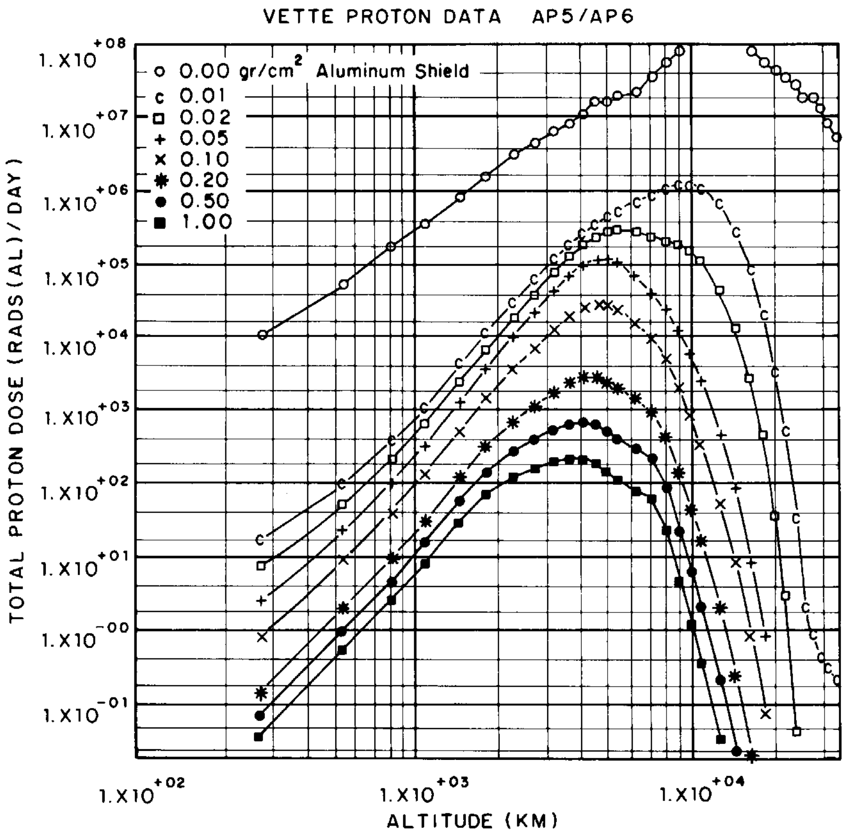


Figure 9.16 Daily dose (natural protons) for a circular orbit satellite as a function of satellite altitude for 60° orbital inclination, with various shielding thickness.

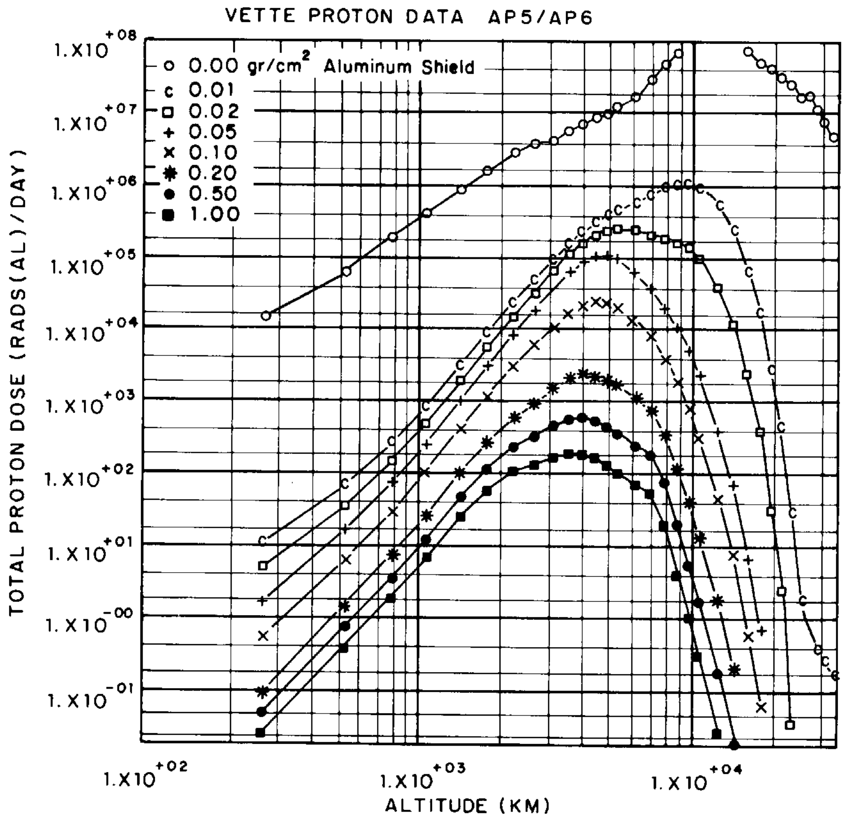


Figure 9.17 Daily dose (natural protons) for a circular orbit satellite as a function of satellite altitude for 90° orbital inclination, with various shielding thickness.

An example: Solar Cell Degradation

Solar cells are the most common power source for operational satellites, many of which operate in regions of appreciable ambient radiation. The power output of a solar cell may decline by 30%-40% over the lifetime of the satellite due to radiation-induced damage.

A typical solar cell consists of a n-p junction located about 0.2 microns below the surface with the n type material occupying the region between the surface and the junction and the bulk of the cell being p type material.

Exposing the cell to sunlight will generate free electrons mostly in the bulk p type material below the junction. Blue light is 99% absorbed within 0.2 microns of the surface where as red light penetrates about 200 microns before being 99% absorbed. Thus the majority of the free electrons produced within the cell must diffuse through the crystal to the n-p junction, be accelerated across the junction into the n type material and to the electrical contacts on the surface which connect to the external circuit. Typical solar cell efficiencies are about 11.5% meaning that 88.5% of the incident solar radiation is lost in the form of heat.

Radiation affects solar cells in two major ways:

(1) Darkening of coverslides.
(2) Decrease of charge carrier lifetimes.

(1) Coverslides: If a free electron is created in the coverslide it may be trapped by an impurity atom and form a charged defect called a color center. A color center is an atom-like structure with a set of energy levels and the trapped electrons can absorb solar photons passing through the initially transparent material. This process leads to a decrease in the incident solar flux and a reduced power output from the cell.

(2) Decreased carrier life time: Radiation can displace atoms in the crystal lattice forming positively charged interstitials. An electron diffusing through the crystal on its way to the n-p junction can get trapped into an orbit around an interstitial atom and can no longer contribute to the current flow. The average life time of the free charge carriers has been reduced by this process, meaning that fewer electrons will reach the junction and the output current will drop.
Figure 9.18 shows the effect of prolonged radiation on the power output of solar cell.

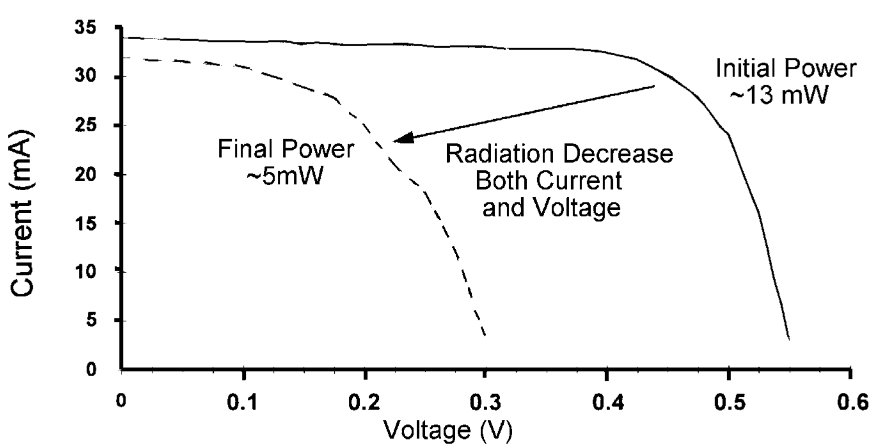


Figure 9.18. Effect of radiation dose on power production

To determine the effect of radiation on a particular solar cell we need to integrate over the energy spectrum of the radiation present. For ease of comparison it is customary to convert the actual fluences into equivalent fluences of either 1 MeV electrons or 10 MeV protons. That is, the damage produce by a distributed spectrum of particles is equated to the number of mono energetic particles that would be required to produce the same damage. The relative damage coefficients for electrons and protons are shown in Figure 9.19.

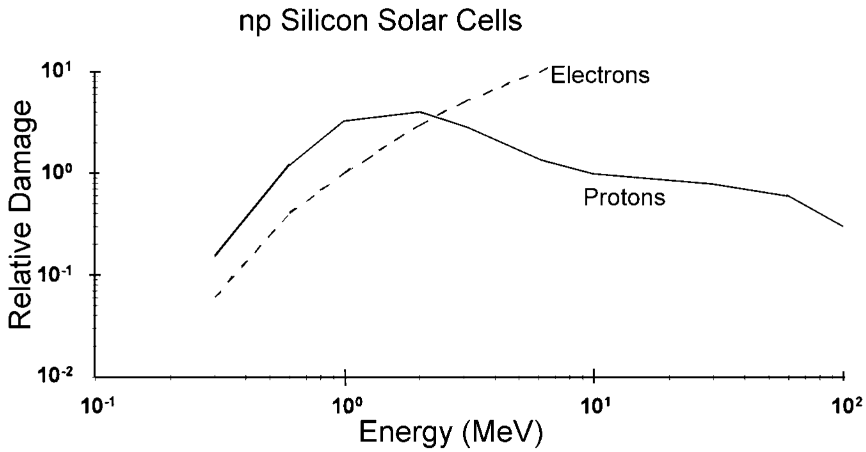


Figure 9.19. Relative damage coefficients for protons and electrons.

It should be noted that the absolute magnitude of the damage is quite different for protons and electrons: One 10 MeV proton produces the same damage as approximately three thousand 1 MeV electrons.

3 Solar Proton Events

Periodically the sun emits significant numbers of high energy protons (and some heavier ions) during severe solar disturbances usually referred to as Solar Proton Events (SPE). The length of the pulse is on the order of days with a range of hours to more than a week. Figure 9.20 shows typical doses near the earth due to a large SPE. There was a very large event in August 1972 and again in Oct 1989 and it is estimated that an astronaut on the moon shielded only by a space suit probably would have received a lethal dose of radiation.

To calculate the dose received from a fluence Φ we have that

$$\text{Dose (RAD)} = 1.6\times 10^{-8}\left(\frac{\text{dE}}{\text{dx}}\right)(\Phi), \text{ where } \Phi = \int_{o}^{t}(\text{flux})\,dt$$

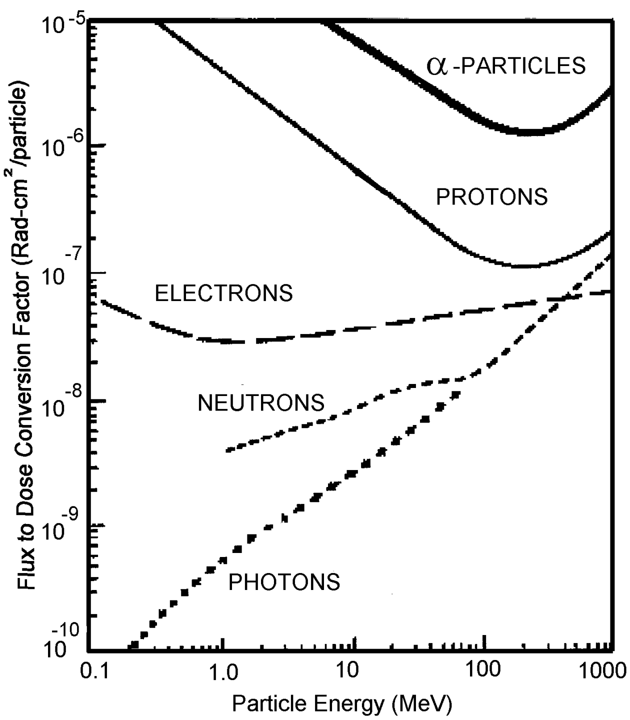


Figure 9.20 illustrates the fluence to dose conversion

Figure 9.21 shows the dose delivered by a range Solar Protons Event as a function of shielding thickness. Recall that 300 RADS is a 50% lethal dose

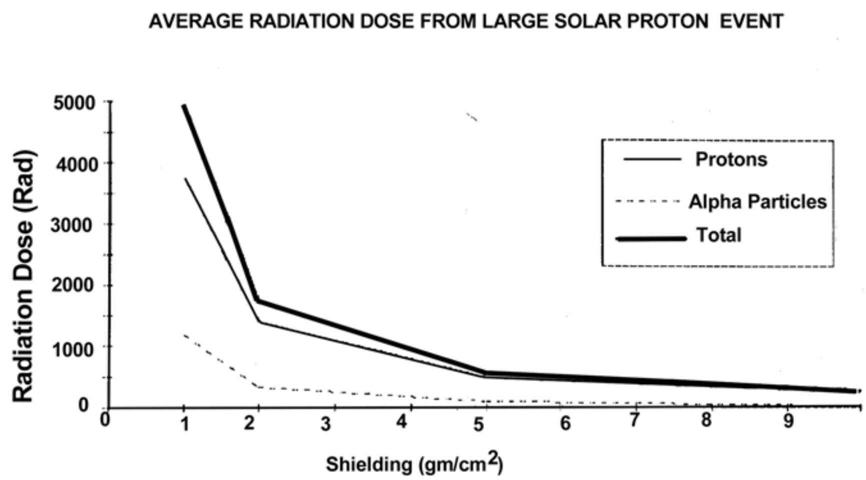


Figure 9.21

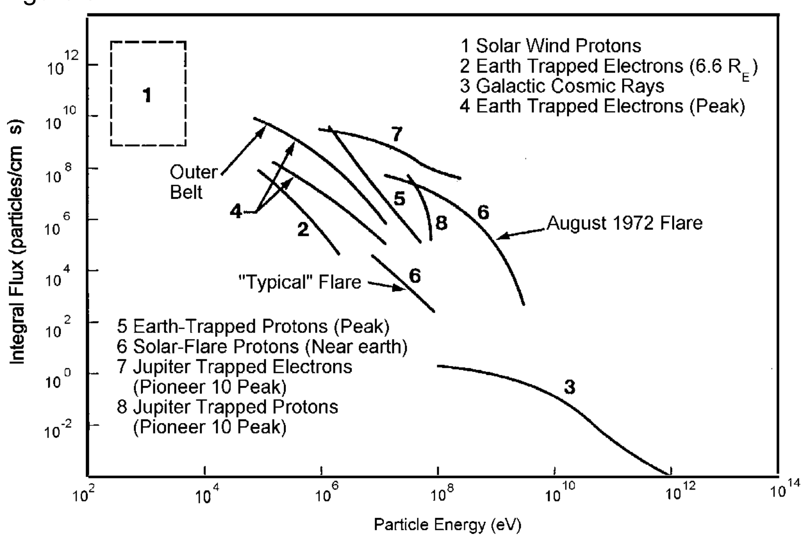


Figure 9.22. Radiation Environments of concern to spacecraft. This figure provides a summary of particle fluxes for trapped radiation as well as fluxes due to solar Proton Events and Galactic Cosmic Rays. JPL figure.

4 Galactic Cosmic Rays

There exists a low flux (~ 4 $\frac{\text{particles}}{\text{cm}^2\ \text{sec}}$) of very high energy particles which appear to fill our galaxy isotropically. This flux is mostly protons (85%), He (14%) and 1% heavier ions with energies up to 10^{19} eV. The total dose due to these particles is quite small (a few RADs/year). They do present a problem by causing single event phenomena in electronics.

If a cosmic ray particle passes through or close to a p-n junction a current will be generated which is proportional to the dose rate

Many modern electronic devices have dimensions so small that the dose rate currents arising from the passage of a single energetic particle may be sufficient to alter the operating characteristics of the device in question. The resulting disruptions are called *single event phenomena* (SEP) or *single event effects* (SEE). An effect is classified as "soft" if the damage is transitory and the device can recover. An example of a soft error is the reversible flipping of a memory bit. An effect is classified as "hard" if the damage is permanent and the device is lost, such as an irreversible bit flip. Two specific examples of SEE warranting further discussion are *latchup* and *upset*.

Latchup is said to occur when the device is transformed to an anomalous state that no longer responds to input signals. Latchup is usually confined to bulk complementary metal oxide semiconductor (CMOS) devices. For typical integrated circuits the latchup threshold is on the order of 10^8 RAD/s. Upset occurs when a device is caused to function in a manner that is not consistent with its design characteristics. For example, the resulting localized electric fields and currents associated with radiation-induced currents may cause a memory register to change its state. The register is said to have been upset by the radiation. Upset thresholds are dependent on the design specifics of the device in question and may be as low as 10^7 RAD/s or as high as 10^{21} RAD/s. Upsets resulting from the passage of a single particle of radiation are termed *single event upsets* (SEUs). One characteristic of SEUs is that they are statistically guaranteed to occur in any device that proves to be susceptible to them. In the GEO environment upset rates may be as low as 10^{-10} errors/bit-day or as high as 10^{-4} errors/bit-day depending on the nature of the device in question. Upsets are directly dependent on the cross section, or LET, of the radiation for the device in question.

D High-Altitude Nuclear Burst Effects

An explosion of a nuclear weapon creates an environment which is extremely hazardous to life and equipment. In general, nuclear detonations can be classified into four broad categories: (1) air burst, (2) high altitude bursts, (3) surface bursts, and (4) sub-surface bursts. Although certain gross aspects of all four burst categories are similar, the high-altitude nuclear burst, sometimes referred to as an exo-atmospheric burst, presents the most significant danger to space operations. High-altitude nuclear bursts can seriously degrade communications systems, damage satellites, blanket large geographical areas with electronic and electrical equipment damaging radiation and electromagnetic energy, and expose humans to life threatening doses of radiation.

1 Characteristics Of A Nuclear Detonation

A nuclear detonation results from either the fission of isotopes of the elements uranium or plutonium, or, by the fusion of light elements such as deuterium. In both cases, the process releases large amounts of energy and radiation in a small amount of time and space. The altitude at which the blast occurs will, to a large degree, dictate how this energy and radiation is coupled into the surrounding environment. Figure 9.23 depicts the principal environments resulting from a nuclear explosion. In general, the principle effects of a nuclear detonation can be divided into blast and shock, thermal radiation, initial and residual nuclear radiation, and the electromagnetic pulse (EMP). Table 3 defines the effects of a nuclear explosion for different types of bursts.

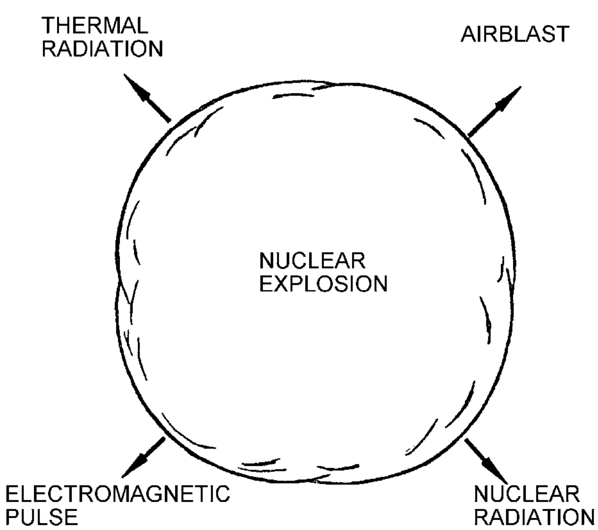


Figure 9.23 Principal Environments Resulting from a Nuclear Explosion

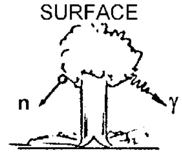
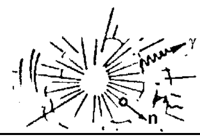
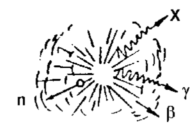
BURST ENVIRONMENT	UNDERGROUND 	SURFACE 	ATMOSPHERIC 	EXO-ATMOSPHERIC 
β-PARTICLES				✓
X-RAYS				✓
γ-RAYS		✓	✓	✓
NEUTRONS		✓	✓	✓
EMP		✓	✓	✓
BLAST	✓	✓	✓	
THERMAL	✓	✓	✓	
DUST/PEBBLE	✓	✓		
SHOCK	✓	✓		
CRATERING	✓	✓		
EJECTA	✓	✓		

Table 3. Summary of Burst Types and Environments

High-altitude burst are nuclear bursts which occur at altitudes above 30 km. In this region the scarcity of the atmosphere supports little coupling of the burst's energy into blast and thermal effects. The energy which is associated with a high-altitude nuclear burst is in the form of the initial prompt radiation, the kinetic energy associated with the debris, and the residual or delayed radiation. X-Rays account for between 75-80 percent of the initial radiation, gamma rays approximately .3 percent, and neutrons approximately 1 percent. The debris kinetic energy will account for between 15-20 percent of the total energy, and the residual radiation in the forms of gamma rays will account for approximately 5 percent of the total weapon output.

Unlike the lower altitude air, surface, and sub-surface burst whose effects are confined to a relatively small radius about the detonation point by the atmosphere, the effect associated with a high-altitude burst creates a post-detonation environment which is spread out over a wide area. The effects fall into four categories:

1. Ionization Effects in the Atmosphere

2. Electromagnetic Pulses (EMP)

3 Radiation Induced Damages in Space Systems

4 Artificial Radiation Belts

2 Ionization Effects In The Atmosphere

When a high-altitude nuclear burst occurs, the radiation will isotropically propagate outward from the detonation point. The volume of the atmosphere which is irradiated is known as the deposition region. Figure 9.24 depicts the formation of the deposition region following a high-altitude nuclear burst. The altitude to which the radiation will penetrate is known as the stopping altitude and is defined as the altitude in the vicinity of which a specified ionizing radiation coming from above deposits most of its energy by absorption in the atmosphere. For a large yield-weapon detonated just above the ionosphere, the deposition region will be about 1500 km in diameter and about 30 km thick. The prompt and residual radiations and their associated stopping altitudes are shown in Table 4.

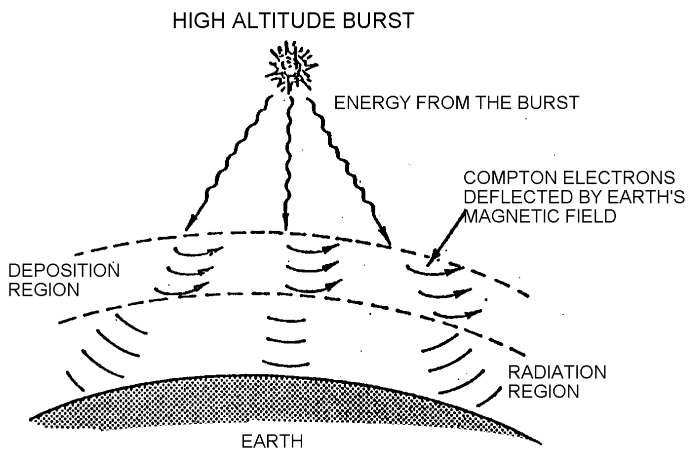


Figure 9.24: Formation of the Deposition Region

Table 4. Approximate Stopping Altitude for Radiation Causing Ionization

Weapon Output	Stopping Altitude (km)
Prompt radiation	
X-rays	60 to 90
Neutrons and gamma rays	25
Debris ions	110
Delayed radiation	
Gamma rays	25
Beta particles	60

The deposition region represents a large volume of the upper atmosphere which has been partially ionized by the prompt X-Rays and Gamma rays emitted by the detonation. A large number of free electrons are produced via the photoelectric effect and the Compton Effect.

The ionization of the upper regions of the atmosphere can seriously affect radar and communication systems. Electromagnetic radio and radar waves which pass through the deposition region will experience attenuation, signal distortions, and in some cases complete absorption. Satellite communication systems which rely on phase shifting or frequency shifting techniques may experience unwanted shifts in frequency and phase because of ionization induced changes in the propagation velocities of electromagnetic waves which pass through the deposition region.

3 Electromagnetic Pulse (EMP)

Nuclear explosions of all types are accompanied by the generation of an electromagnetic pulse (EMP) which is a sharp, pulse of electromagnetic radiation produced when an explosion occurs in an unsymmetrical environment. It is characterized by intense electric and magnetic field with rise times on the order of a few nanoseconds (10^{-9} sec), and decay times of a few tens of nanoseconds. The energy associated with EMP will be contained in this high intensity, short duration, electromagnetic wave with a sharp leading edge. This energy can be collected by a suitable collector and transferred to other components and equipment and since the energy is received in such a short period of time, intense currents are produced which can severely damage equipment.

There are two types of EMP which will be discussed, Deposition Region Generated EMP, and System Generated EMP.

4 Deposition Region Generated EMP

Under the proper circumstances a significant portion of the energy release during a nuclear detonation can appear as an electromagnetic pulse. The Deposition Region Generated EMP, usually referred to as just the EMP, is important for several reasons, listed below:

1. The effects of the EMP can have a lethality radius of thousands of miles.

2. The EMP is a fast rise time broad bandwidth pulse which posses a significant threat to almost all electrical and electronic equipment with the radius of lethality

3. Countermeasures to the EMP significantly increase the cost, weight, and complexity of space systems

The mechanism primarily responsible for the generation of the EMP is the Compton scattering of prompt gamma rays. As the gamma rays are scattered, the electrons which are emitted will have energies on the order of .5 MeV. These electrons will travel in a forward direction and will be influenced by the earth's geomagnetic field. They will travel along geomagnetic field lines in a spiral path until they are stopped by collisions with air molecules. The electron motion about the geomagnetic field lines produces a strong electrical current transverse to the propagation direction of the gamma rays. This transverse current radiates an electromagnetic wave which is the EMP. The fact that the forward scattered electrons travel close to the velocity of light causes radiation emitted at various altitudes to be approximately in phase thus greatly increasing the intensity of the final pulse. Table 5 gives a comparison of the electric fields generated by various sources.

Table 5. Electric Field Intensities (Ref. 3)

Source	Intensity (volts/meter)
EMP	100,000
nearby radar	200
nearby communications	10
Metro area	0.01

Unlike man-made (radar) and intense natural electromagnetic fields (lighting) which tend to be localized to a small area, the EMP is orders of magnitude higher and widely distributed. The EMP caused by a single high-altitude nuclear burst could cripple electrical and electronic systems for thousands of miles from the detonation point. Figure 9-25 shows the effective radius of a typical high-altitude burst detonation over the United States.

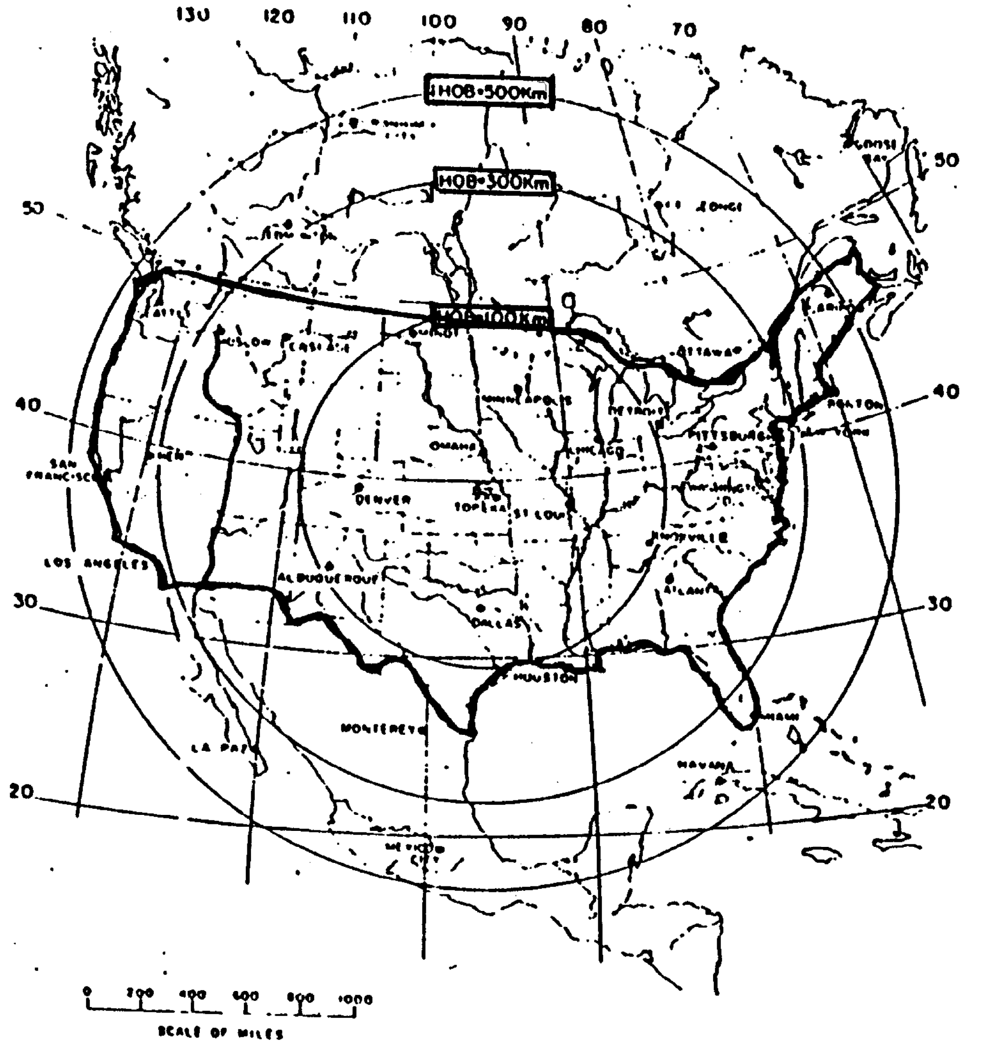


Figure 9.25. The Effective Radius of a High-Altitude Nuclear burst

5 System Generated EMP/Internal EMP

Another significant effect associated with a high-altitude nuclear bursts which is important to satellites is the electromagnetic pulse called the "system-generated EMP/Internal EMP" (SGEMP/IEMP). The mechanisms which are responsible for the creation of SGEMP/IEMP are similar to those responsible for the generation of the deposition-generated EMP. When the ionizing radiation from a high altitude nuclear burst, particularly gamma rays and X-Rays, interact with the body of a satellite, the irradiated material will release electrons due to Compton scattering and the photoelectric effect creating large electron emission currents and intense electromagnetic fields. This electromagnetic environment is coupled into the interior of the structure and is defined as SGEMP. In addition, since the satellite is basically a cavity, very high electronic fields will be induced across the interior of the spacecraft. These intense electric fields will in turn induce currents in the electrical and electronic components on-board the satellite. Figure 9.26 illustrates the generation of SGEMP/IEMP.

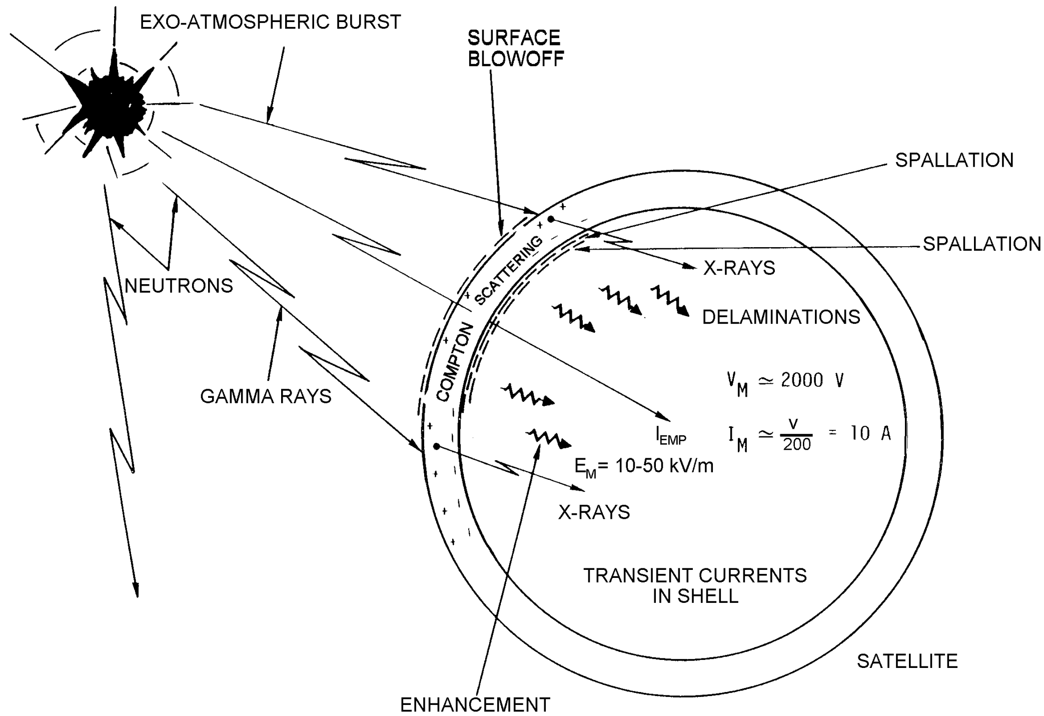


Figure 9.26. System Generated EMP and Internal EMP

6 Artificial Radiation Belts

Following a series of exo-atmospheric tests conducted by the U.S. and the Soviet Union in the 1960's substantially increased charged particle densities were observed in the Trapped Radiation Belts. Some of these artificial belts persisted for weeks to months and the population did not return to normal for about two years. A number of operational satellites were partially or totally incapacitated by the increased radiation encountered.

E Design Considerations Relative to Radiation

There are 4 categories of countermeasures

1. Shielding: Material surrounding sensitive components or placement of structures or less sensitive equipment to act as radiation absorbers

2. Part Selection: Utilize components which are known to be more radiation tolerant and have high resistance to latch up and upsets. Safety factors >5 are desirable if available

3. Redundancy: Oversize solar arrays and circuit redundancy including coincidence requirements and backup circuitry and parts.

4. Recovery Algorithms: Software capable of recovering the system from latchup or upsets

All of these measures add cost and weight but depending on circumstances they may be critical to the success of the mission

Blank page

Appendix 1 USEFUL EQUATIONS

EM Waves

$\lambda f = c$; $E = hf$; $\lambda = \dfrac{hc}{\Delta E}$; $c = 2.998 \times 10^{8}$; 1 eV = 1.602×10^{-19} Joules

$$h = \text{Planck's Constant} = \begin{cases} 6.626 \times 10^{-34} \text{ Joule-seconds} \\ 4.136 \times 10^{-15} \text{ eV-seconds} \end{cases}$$

$$\Delta E(\text{eV}) = \frac{1.24 \times 10^{-6}}{\lambda(m)} = \frac{1.24}{\lambda(\mu m)}$$

Bohr Atom:

$$r_n(\text{meters}) = n^2 \times 0.528 \times 10^{-10} / Z.$$

$$E_n = -\frac{1}{2}\left(\frac{Z e^2}{4\pi \varepsilon_0 \hbar}\right)^2 \frac{m}{n^2} = Z^2 \frac{E_1}{n^2}; \qquad E_1 = -\frac{me^4}{32\pi^2 \varepsilon_0^2 \hbar^2} = -13.58 \text{ eV};$$

$$number \propto e^{-\frac{\text{Bandgap Energy}}{\text{Thermal Energy (kT)}}}$$

Black Body Radiation

$$c = 3 \times 10^8 \tfrac{m}{s};\ h = 6.626 \times 10^{-34}\ joule-s;\ k = 1.38 \times 10^{-23} \tfrac{Joule}{Kelvin}$$

$$Radiance = L = \frac{2\,hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

Stefan Boltzmann Law: $R = \sigma \varepsilon T^4 \left(\text{Watts}/\text{m}^2\right)$

ε = Emissivity; $\sigma = 5.67 \times 10^{-8} \left(\text{W}/\text{m}^2\,\text{K}^4\right)$; T = Temperature (K)

Wien's Law: $\lambda_{max} = a/T$ $\quad a = 2.898 \times 10^{-3}$ (m K)

$R_{earth} = 6.38 \times 10^{6}$ m,