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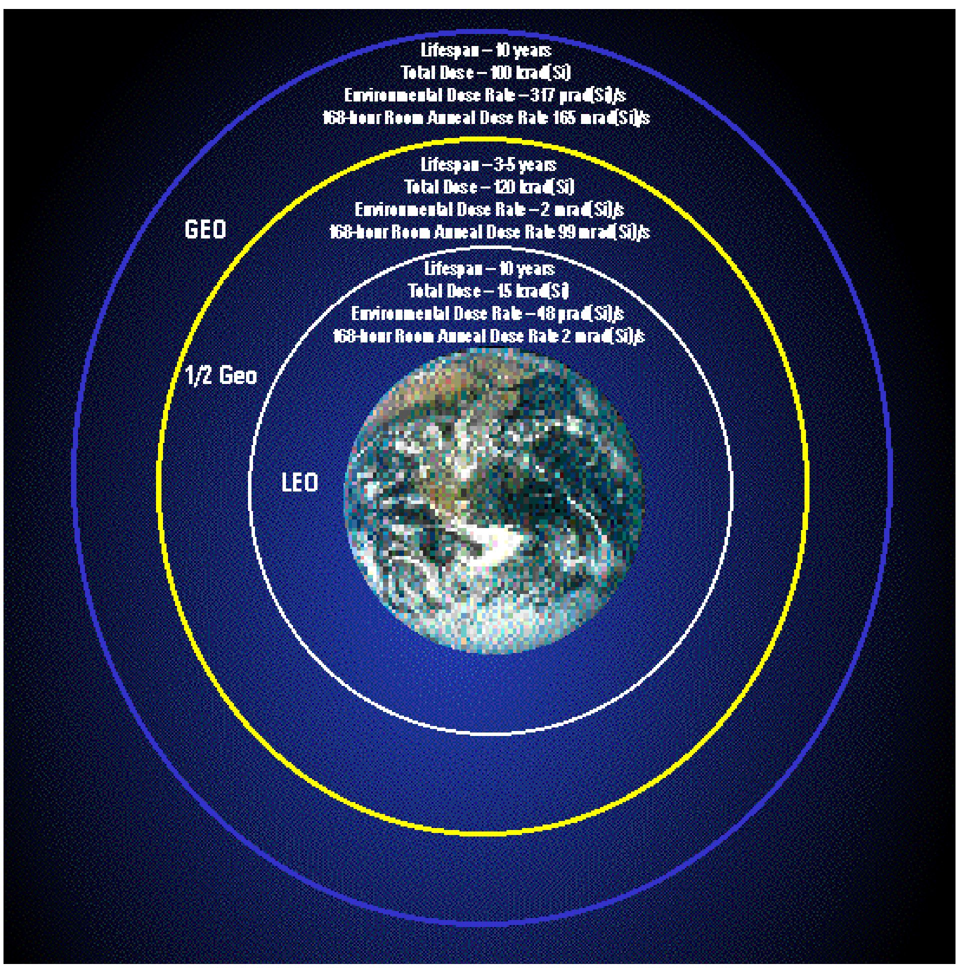
Radiation Needs Today

As we enter the 21st century, significant changes will continue to affect the semiconductor industry. Continuous progress in processes, packaging, materials, interconnect, lithography, and many other key areas in the production of integrated circuits will generate more complex devices (e.g., system on a chip), higher performance, and lower cost. CMOS technology will continue as the dominant technology of choice. Most of the rapid technology development is occurring in CMOS and shall continue into the first ten years of the new century.

These rapid changes will create many new challenges, including greater susceptibility to radiation effects. In fact, as CMOS technology scales down to the 0.1µm level, these effects will become increasingly important. The radiation failure mechanisms that we know and understand today may no longer be valid as a new set evolves. New sources of radiation will become evident as a result of new lithography equipment, process equipment, new techniques, and the use of new materials that enable manufacture of the 0.1µm semiconductor feature size.

The Semiconductor Industry Association's *"National Technology Roadmap for Semiconductor Technology Needs"* indicates that by the year 2006 the 0.1µm process will be in production, 300mm wafers will be preferred, and 3.5GHz will enable chip-frequency-on-chip. Because scaling down the feature size also will decrease the gate dielectric, bits will take less energy to flip. Single-event upset will become a major radiation problem even at sea level. Reduced power supply voltage also will contribute to radiation failure. Of continuing concern will be total dose degradation and neutron damage in radiation environments.



Radiation failures will not disappear. In fact, some radiation effects will become worse. National Semiconductor is a leading of supplier of integrated circuits to the military and aerospace community. Within this *Radiation Owner's Manual* is information that you can use to increase the radiation tolerance of your systems – today and for the future.

Providing a Unique & Cost-Effective Approach to Your Radiation Resistance Needs

Exposure to high-energy radiation can result in transient and/or permanent changes to a semiconductor's material and electrical properties. Use of radiation-resistant products, however, can prevent system malfunction or failure.

In harsh environments, such as space, the lack of accessibility to institute repairs as well as the space system's longevity mandate that semiconductors used in these systems maintain the highest reliability levels. Through all of this, electronic components must retain complete parametric integrity. As man ventures deeper into space, it is increasingly necessary to harden systems against the natural radiation environments of space.

Radiation effects are also a concern for tactical applications. Today's rapidly changing global political climate is significantly influencing the military strategies of all countries. Regardless of political changes, nuclear weaponry remains a viable threat. As long as a first-strike capability exists, radiation-hardened strategic and tactical systems will be designed.

Designing and producing radiation-hardened survivable systems is time intensive and financially expensive. Rather than risk premature demise, myriad precautions must be taken to ensure that satellites, for example, will survive their life expectancies. Because of the necessity to orbit for ten or more years, satellites incur high costs due to emphasis on performance, reliability, and radiation resistance. Radiation hardening entire systems is a paramount concern.

Radiation Health Hazards

- o Ionizing radiation types
  - Alpha
  - Beta
  - X-ray
  - Gamma ray
  - Neutrons
- o Natural background
  - Cosmic rays – 26 mrem/yr
  - Food/drink – 25 mrem/yr
  - Medical – 20 mrem/yr
  - Air travel – 1mrem/2500 miles
  - Soil – 15 mrem/yr
- o Man made
  - Nuclear power plants
  - Nuclear device tests
  - Radioactive wast product

Radiation Resistance Level	Application
0 - 3 krads	Commercial: industrial, robotic, nuclear, biomedical, space shuttle
3 - 30 krads	Tactical: submarines, tanks, missiles, airborne, ground (field radar, communications), space station
20 - 50 krads	Space: low orbit
50 - 200 krads	Space: high orbit
200+ krads	Deep space Strategic: military

National's Mil/Aero Radiation Effects Laboratories (REL) in South Portland, Maine, and in Santa Clara, California, certify that products are resistant to defined radiation levels. Flexible testing flows meet the needs of strategic, space, and tactical applications. Complete radiation data can be supplied with each order, providing detailed radiation information. Customers may choose QML (MIL-PRF-38535) Class V or Q products, QPL (MIL-PRF-38535, Appendix A), Class S or B products, or specify SCDs to either of previous classifications of QML. Electrical requirements for post-radiation performance may also be specified by customers' SCDs and may include:

- o Fully meeting pre-radiation electrical parameters
- o Meeting specified drift limits on specified parameters
- o Meeting relaxed post-radiation electrical parameters as defined by the customer

The Growing Radiation Market

As man-made radiation environments increase coupled with the growing worldwide interest in exploring and employing the knowledge of space, use of semiconductors in radiation-intensive environments is expanding at an unprecedented rate.

Applications that require radiation resistance are generally segmented as outlined on page 9. The majority of radiation-resistant applications are in the tactical arena and low and high space orbits.

Market Segment Current Needs

Segment	Total Dose	Dose Rate Upset	Dose Rate Latchup	Neutron	Single Event Upset	Single Event Latchup
Tactical	<30 krad(Si)	<1E9 rad(Si)/s	<1E9 rad(Si)/s	<1E13 neutron/cm^2	Not applicable	Not applicable
Avionics	<30 krad(Si)	<1E9 rad(Si)/s	<1E10 rad(Si)/s	<1E13 neutron/cm^2	<1GeV*	<1GeV*
Space Low Orbit (military)	20 - 50 krad(Si)	Application dependent	Application dependent	Application dependent	>40 MeV/(mg/cm^2)	>100 MeV/(mg/cm^2)
Space High Orbit (military)	100 krad(Si) - 1 Mrad(Si)	Application dependent	Application dependent	Application dependent	>40 MeV/(mg/cm^2)	>100 MeV/(mg/cm^2)
Commercial Satellites	20 - 100 krad(Si)	Not applicable	Not applicable	Not applicable	>40 MeV/(mg/cm^2)	>100 MeV/(mg/cm^2)
Strategic Systems (military)	<1 Mrad(Si)	<1E12 rad(Si)/s	<1E12 rad(Si)/s	<1E14 neutron/cm^2	>40 MeV/(mg/cm^2)	>100 MeV/(mg/cm^2)
Nuclear (power plant)	LOCA** 5 x 10E8rad(SI)	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Robotics & Biomedical	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

* *Single event upsets or single event latchup may occur when neutrons impact ICs at high atmospheric altitudes.*
** *LOCA : Loss of Coolant Accident*

Incorporating Radiation Design

Most critical at the conceptional stage is a thorough understanding of the system's mission relative to its potential radiation environment. Decisions can be made on the use of different types of components in different circuit applications depending on the mission [i.e., satellite (commercial or military), tactical avionics (nuclear weapon), or commercial application (nuclear power plant or medical)]. Occurring at this stage are evaluation of proper semiconductor technology, determination of the extent of shielding, and evaluation of prototype IC technologies that will offer full availability by the time the system is in production.

Space systems will be exposed to radiation as will nuclear power plants. Strategic and tactical systems may be exposed, and must be prepared for a nuclear event. In the past, radiation-sensitive space systems have been shielded in a variety of materials. But because the pound-to-thrust cost ratio of the payload is a critical concern, better methods, such as radiation-resistant ICs, are required to harden a system. Where shielding space systems is very expensive, shielding for underground tactical radiation environments can be economical. Shielding is not used for most tactical systems. One exception is tanks.

Shielding remains a viable and economical approach for today's industrial, robotic, nuclear, and biomedical applications.

Dealing with an Array of Radiation Exposures

A system exposed to radiation must resist a variety of potentially lethal doses. Gamma rays, cosmic rays, neutrons, electrons, alpha particles, and prompt dose radiation are ever present in space and ground environments. In large doses, all can affect standard off-the-shelf semiconductors, influencing the dependability and longevity of the system they are in. Exposure to high-energy radiation can change the electrical properties of a semiconductor or even destroy the device.

Initial decisions for space system design are based on whether the use will be military or commercial. Radiation hardness requirements also depend on the orbital inclination and mission duration. Semiconductors in a satellite experience varying degrees of radiation degradation depending on whether they reside on the satellite's exterior panels or are buried within its body. In space environments, major exposure comes from electron/proton irradiation and cosmic rays.

When designing a tactical system (such as for aircraft, shipboard, ground hardware, or equipment housed in missile silos or ground bunkers), designers must know whether that system must operate throughout a nuclear event or shut down until the event has passed. Systems subjected to a nuclear event must withstand gamma ray dose rate irradiation and neutron radiation.

The land-based commercial environment has the easiest-to-accommodate radiation hardness levels.

Although some equipment parts are exposed to severe hostile radiation environments, most parts can be protected with lead shielding or thick cement walls. Major concerns here stem from gamma ray total dose and neutron radiation.

Radiation is essentially generated from two sources:

- Those occurring naturally via the sun, galactic and extra-galactic, the Earth's Van Allen Belt, and naturally-occurring radioactive materials found on Earth
- Those initiated by man, i.e., nuclear burst, nuclear reactors, and biomedical

System and circuit designers contend with these major radiation environments:

- Total dose ionization (gamma ray)
- Transient irradiation (dose rate/gamma ray)
- Single event phenomena (SEP)
- Neutron radiation
- Electromagnetic pulse (EMP)

The two most important space radiation effects are Total Dose Ionization (at a low dose rate) and Single Event Phenomena.

In the tactical environment, transient (dose rate) radiation (primarily associated with nuclear explosion) and neutron effects are the major concerns. Neutron radiation is not a concern for CMOS logic radiation design as long as the fluence is under 10^{14} neutrons/cm^2.

At the present time, EMP environments are addressed at the system level, not by the component's technology.

Product Migration

Over the next ten years, integrated circuit technology will continue its rapid pace to increase technology performance and reduce cost. National Semiconductor is committed to this challenging future, particularly in support of the military and aerospace industry and RHA products.

The industry's roadmap shows that by the year 2006, products will have a 100nm (or 0.1 microns) feature size that will use affordable technology design and processing. Rather than today's six metal levels, products using the 100nm feature size will have fourteen layers. The increased speeds of the new technologies will approach the fundamental limits of the wavelengths that can be used with this chip size and its packaging. At the present time, National Semiconductor has the capability of producing 350nm and 250nm technology. At the research and development level, National is committing resources in developing 150nm technology.

Over 75% of today's semiconductors are CMOS technology. With its high performance, low power consumption, and low noise, CMOS technology also will be the future technology of choice. Advances in CMOS technology will be a driving force as advances are made to other technologies.

Semiconductor manufacturers' knowledge of radiation's adverse affects will mitigate some adverse effects in upcoming product families. But as technologies are driven to smaller feature sizes and higher performance, semiconductors will become more susceptible to new radiation failure mechanisms – both external and local.

Focusing on Military & Space Environments

Ref. Nos. 2, 5, 6, 16

As noted, each environment contains a different radiation source. For this discussion, the environments are limited to those covering military and space radiation.

Military Environment

The military environment is generally equated with the nuclear explosion scenario. In a nuclear explosion at the Earth's surface, there is a high dose rate gamma flux (typically $>10^8$ rads(Si)/s), delayed total ionizing dose [less than 10^4 rad(Si)], and neutron fluence (greater than 10^{14}n/cm^2). The x-rays generated at the Earth's surface are absorbed by the surrounding air and are responsible for the large nuclear fireball. By contrast, these x-rays are not absorbed in space and travel very long distances.

The predominant radiation effects for the military scenario are:

- Displacement damage
- Transient dose rate
- Total ionizing dose (TID)

Additionally, military equipment must address other detrimental nuclear effects, such as thermal shock, mechanical shock, and EMP (electromagnetic pulse).

In general, bipolar technology is more sensitive to neutron irradiation than CMOS technology. Bipolar technology depends upon minority carrier lifetimes and minimal lattice defects in order to meet its electrical performance criteria. CMOS technology is a majority carrier and surface-operation device.

Space Environment

Compared with the nuclear space environment, the natural space radiation environment is considered to be benign. In truth, however, space contains a number of other powerful radiation environments, including solar flares and interplanetary environments. While knowledge of space radiation is increasing, today it remains in its infancy as radiation effects continue to be measured and investigated.

In general, the space radiation environment is affected by numerous variables and many conditions excluding man-made space radiation environments. Therefore, the space radiation environment is always in constant transformation. This discussion begins with the near-space radiation of Earth and works outward toward the geosynchronous/interplanetary environment.

There are five major divisions within the natural space environment. Each has its own set of radiation effects and requirements.

- Low Earth orbit (LEO)
- Mid-Earth orbit (MEO)
- Geosynchronous Earth orbit (GEO)
- Geostationary orbit
- Interplanetary excursions

These divisions are dominated by two types of radiation – ionizing radiation and heavy ion particles. Each type of radiation involves charged particles and exhibits different radiation effects that degrade the electronic systems contained on board the satellite.

Trapped Particles in Space

Natural space
- Protons
- Electrons
- Heavy ions

Transient radiation in space
- Galactic cosmic ray (GCR) particles
- Solar events [coronal mass ejections (CME) and solar flares]

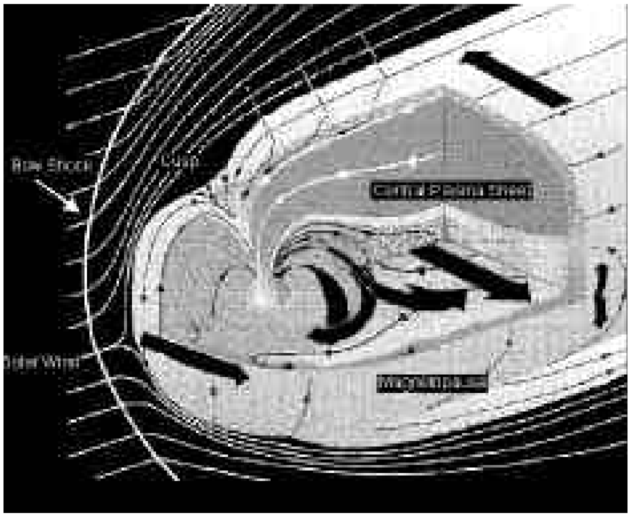
Trapped particles – near-Earth environment
- Van Allen Belts
  - Proton
  - Electrons
  - Heavy ions

Influence of the Earth's Magnetic Field *(Ref. No. 4)*

The following information is based on a 1997 IEEE NSREC short course entitled Modeling Space Radiation Environments. Permission for this use is granted by Janet Barth of the NASA/Goddard Space Flight Center.

The Earth's magnetic field provides a natural radiation shield from charged particles, heavy ions, cosmic rays, and other minor space effects. It is the sum of two magnetic fields – the internal magnetic field and the external magnetic field.

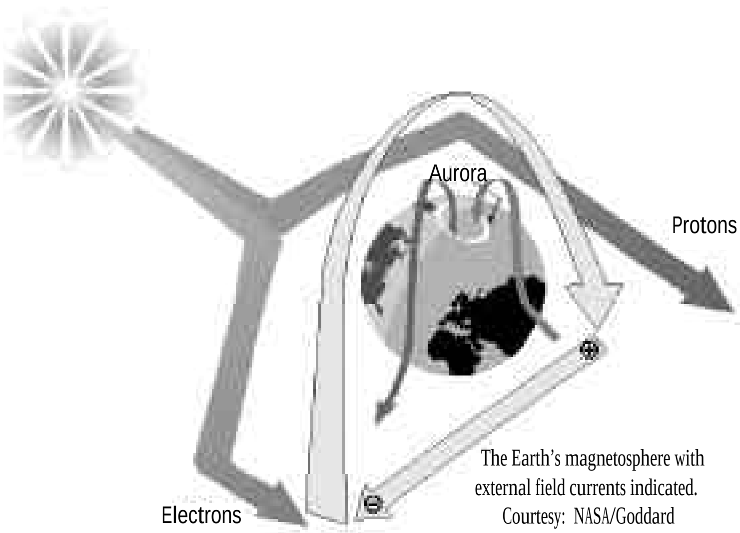
The internal magnetic field is a quasidipolar magnetic field generated by the Earth's core. The magnetic North Pole of Earth is positioned approximately 76˚ north latitude and 100˚ west longitude; while the magnetic South Pole is found at approximately 60˚ south latitude and 139˚ east longitude. At the higher attitudes, the interior magnetic field strength decreases and the external magnetic field strength becomes a contributor to the Earth's total magnetic field strength.



The Earth's magnetosphere is formed by the interaction of the solar wind and the Earth's magnetic field. Courtesy: NASA/Goddard

The external magnetic field strength results from the magnetic fields that are transported by the solar wind and those fields which the solar wind induced into the Earth's magnetosphere. The magnetosphere is created by the interaction of the solar wind and the Earth's magnetic field *(see figure below)*. The external magnetic field is unstable in comparison with the internal magnetic field. The causes for this instability are not fully comprehended. This external magnetic field is comprised of:

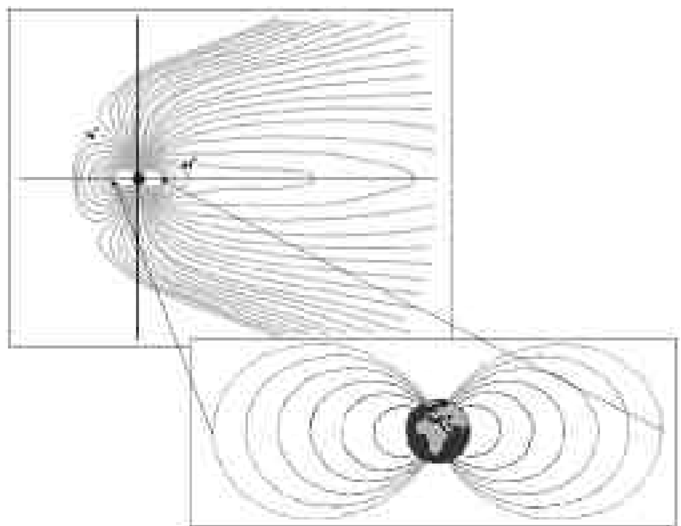
- Magnetopause current
- Neutral sheet current
- Ring current



The Earth's magnetosphere with external field currents indicated. Courtesy: NASA/Goddard

Each of these magnetic currents is affected by the solar wind activity during any given time.

The Earth's magnetosphere is defined by its lower boundary (the ionosphere) and its upper boundary (the magnetopause – the interface between the solar wind plasma and the Earth's magnetic field). As charged particles in the solar wind travel around the Earth, some of the particles cross the Earth's magnetic field and leak into the magnetosphere. Some charged particles are trapped by the Earth's magnetic field and contribute to the Van Allen belts. Others collect in the magnetic tail and create poles of opposite charge. This produces a generator that transports the charged particles along magnetic field lines at the poles. The collection of plasma particles in the magnetotail is the neutral plasma sheet.

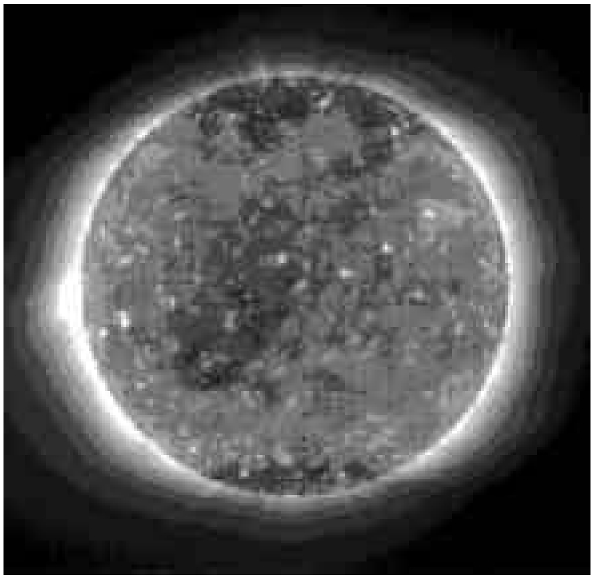


Dipole field lines calculated with internal and external field models. Courtesy: NASA/Goddard

Solar Activity

The Sun's activity impacts near-Earth and interplanetary radiation levels. The resulting solar magnetic field is highly variable and unpredictable.

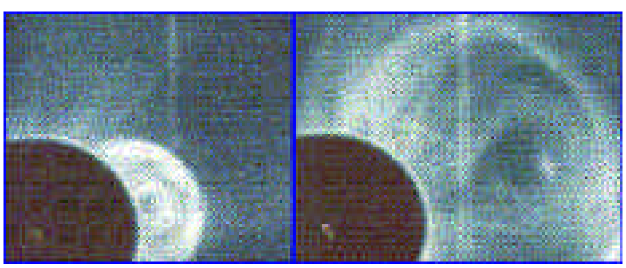
Solar activity is the result of a two-storm event that occurs at the Sun – solar flares and coronal mass ejection. The solar flares are observed as sudden brightenings in the photosphere layer of the Sun, which is located near the sunspot. The flares are the release of high energy and involve a tearing and reconnection of strong magnetic field lines. The energy released from



Bright rim around the Sun is the chromosphere. Courtesy: NASA/Goddard

these flares accelerate the particles in the solar plasma to higher energies.

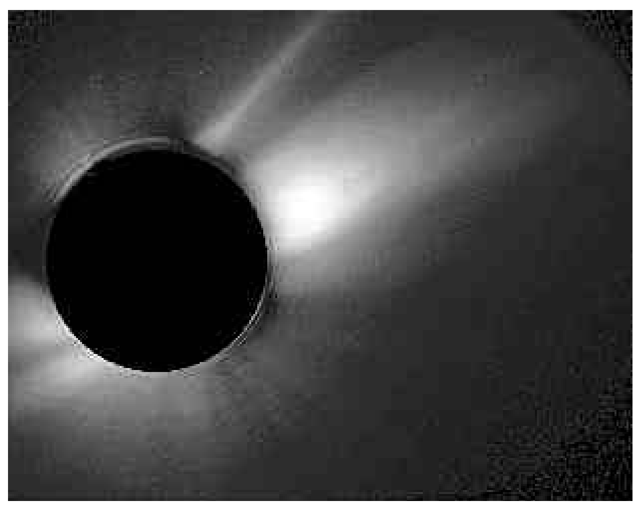
The coronal mass ejections (CME) occur in the layer of the Sun that is outside of the photosphere, e.g., the chromosphere. These ejections are comprised of large bubbles of gas and assorted magnetic fields. A plasma is created and released into space. While the mechanism for the plasma release is not fully understood, it is responsible for significant increases in the solar wind velocity. Particle acceleration and magnetic storms at Earth are the result of the shock wave of the plasma release.



Bubble of gas associated with a coronal mass ejection. Courtesy: NASA/Goddard

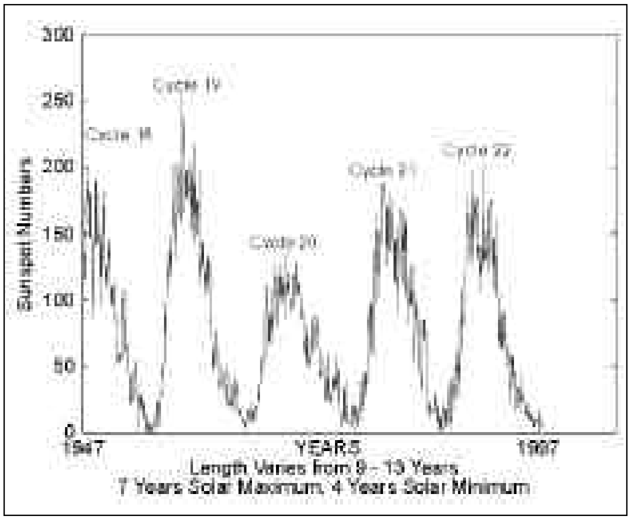
The corona is the outer atmosphere of the Sun and extends several solar diameters into interplanetary space. It continuously emits a stream of charged particles, such as protons, electrons, doubly charged helium ions, and small amounts of other heavy ions. This stream is collectively called the solar wind. The high temperature of the corona causes electrons to escape the gravitational pull of the Sun. The electron ejections cause an imbalance, which in turn results in the ejection of protons and heavy ions from the corona. This electrically neutral plasma streams radially from the Sun. The solar wind velocity and density can vary greatly over a short period of time.

The activity of the Sun is cyclical and maintains a certain frequency. The solar cycle has a range of 9 to 13 years. The typical average is 11 years, consisting of a 7-year solar maximum phase and a 4-year solar minimum phase. The Earth's radiation environment is dominated by the Sun's activity. During the solar wind maximum period, protons and heavier ions are accelerated that penetrate the Earth's radiation belts. Solar wind particles become trapped in the outer regions of these radiation belts. Solar cycles impact the galactic cosmic ray (GCR) heavy ions. GCR levels are cyclic and correspond to the Sun's activity. Atmospheric neutrons are secondary effects. As they result when GCR heavy ions collide with the oxygen and nitrogen atoms in the Earth's atmosphere, their levels are modulated by the solar cycle. The levels of the trapped particles are modulated by long-term variations in solar activity and solar storm events.



The corona extends several solar diameters. Courtesy: NASA/Goddard

It has been noted that major perturbations in the geomagnetic field can occur with changes in the solar wind density (solar flares), the solar wind velocity (affected by CME), and the orientation of the embedded solar magnetic field. Disturbances made by the solar wind and its interaction with the Earth's magnetosphere cause mag-



Yearly sunspot numbers for the most recent solar cycles. Courtesy: NASA/Goddard

netic storms and substorms that redistribute particles in the Earth's magnetosphere. Magnetic storms can cause variations in the Earth's magnetic field from a few hours to 10 days. Under normal magnetospheric conditions, substorms can occur every 2 to 3 hours; however, during magnetic storms, they occur with greater frequency and intensity.

Van Allen Belts

The near-Earth radiation environment of the Van Allen Belts consists of trapped particles and transient radiation. These belts are divided into three sections:

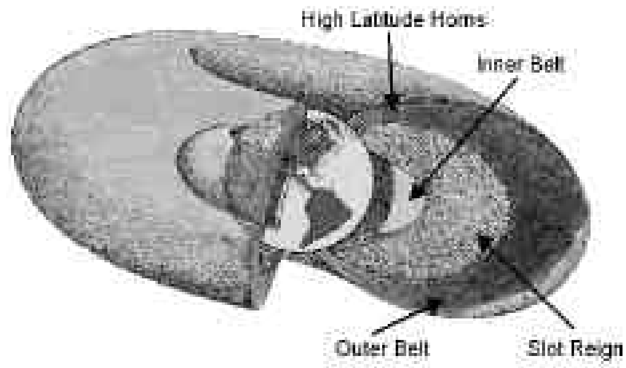
- Inner Belt
- Slot Region
- Outer Belt

The figure *(above right)* depicts these sections as well as another section – the High Latitude Horns.

The Inner Belt is centered about 1.5 Earth radii (5,973 miles); the Outer Belt, 5.0 Earth radii (19,910 miles). Between these two belts is the Slot Region. The High Latitude Horns wrap around the Inner Belt.

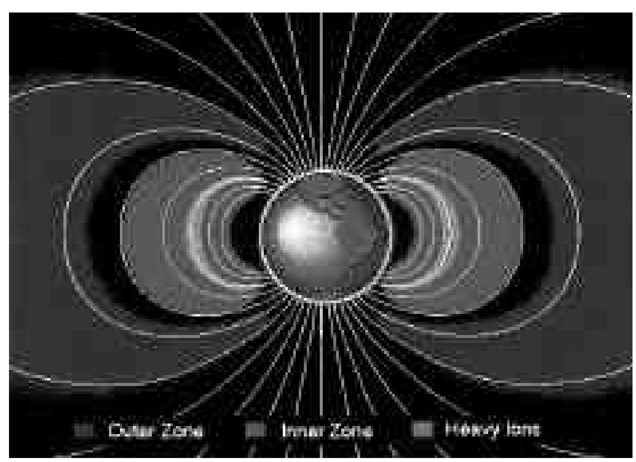
The Earth's atmosphere is the lower boundary of these radiation belts. The upper boundary is determined by the strength of the geomagnetic field. This magnetic field decreases to the point where stable trapping can no longer occur as the distance from the Earth increases.

The trapped charged particles contained in the Van Allen Belts provide a significant source of radiation, particularly Total Ionizing Dose damage. Ever present in these belts are heavy ions, protons, and electrons. The electrons and protons become trapped due to the Earth's magnetic field. This constrains their motion perpendicular to the magnetic field vector, and keeps them well within a defined region around the Earth.



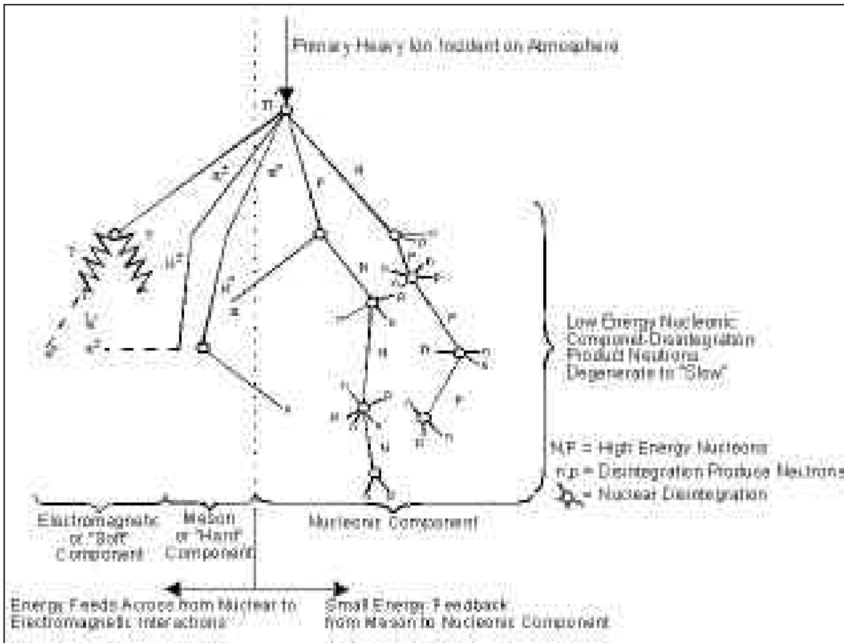
An artist's representation of the Van Allen belts. Courtesy: NASA/Goddard

The Lorentz electromagnetic force is responsible for this confinement and is a function of the particle's charge, its velocity, and the magnetic field. As a result, the charged particles spiral around, oscillating back and forth between the Earth's northern and southern hemispheres. Particles do not mirror back to exactly their originating point due to the non-uniformity of the geomagnetic field. Therefore, the third motion imposed on charged particles is a drift vector with protons transversing in the westward direction and electrons drifting in the eastward direction. This opposite drift direction is the result of the opposing charges producing opposite spiral directions.



A cross-section of the Van Allen Belts showing the location of the trapped heavy ions.
Courtesy: NASA/Goddard

The frequency of the spiral motion (gyration) at 625 miles altitude is 500kHz for low energy electrons and 300MHz for low energy protons. At higher energy levels, the period will decrease because of the increase in relative mass. The bounce period at 625 miles altitude is 1 second for 1MeV protons and 0.1 seconds for 1MeV electrons. It requires 1/2 hour for 1MeV protons to complete one azimuthal drift cycle at 625 miles altitude and about 1 hour for 1MeV electrons. The three motions – gyration, bounce, drift – are uncoupled because the frequencies are different orders of magnitude.



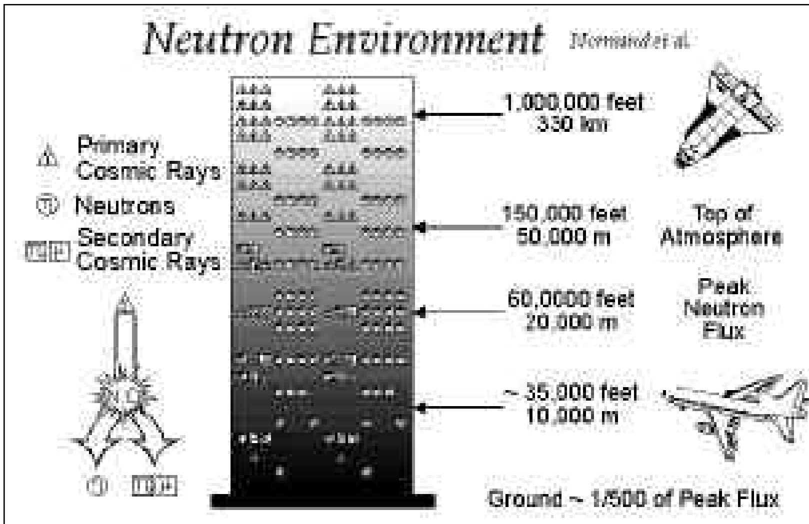
Cosmic rays hit the top of the atmosphere and disintegrate into neutrons. Courtesy: NASA/Goddard

Atmospheric Neutrons

In the mid-1980s, single event upsets were detected in aircraft systems flying at high altitude (>70,000 feet). At that time, the cause of this phenomena was not clear. It is now known that upset rates correspond with neutron flux levels. As with protons, the recoil and secondary products resulting from collisions between neutrons in the environment and atoms in the material near the sensitive region of the device are responsible for neutron single event upsets.

Atmospheric neutrons result from cosmic ray particles interacting at the top of the atmosphere with the nitrogen and oxygen atoms. This complex interaction from cosmic ray showers causes the generation of protons, electrons, neutrons, heavy ions, muons, and pions. The neutron levels are a function of altitude. Studies show that at altitudes below 60,000 feet, neutrons are the dominant factor in producing SEUs. Above 70,000 feet, heavy ions from cosmic rays begin to dominate. The neutron flux is not only a function of altitude, but also latitude and energy. The energy spectrum of the neutron flux ranges from keV to hundreds of MeV. For SEU applications, only energies greater than 1MeV are significant.

The neutron flux is modulated by solar events. Because galactic cosmic rays (GCR) are the primary particles that produce the secondary neutrons and protons in the atmosphere, variations in the GCR's intensities cause most of the variations that are observed in the secondary neutrons and proton levels. Neutron levels rise and fall in the same 11-year solar cycle that modulates the GCRs. The ability of a heavy ion to penetrate the magnetosphere is determined by its magnetic rigidity. In turn, this is dependent upon the geomagnetic latitude. Magnetic disturbances occur more frequently during the active phase



A representation of the neutron environment as a function of altitude. Courtesy: NASA/Goddard of the solar cycle, increasing the ability of GCRs to penetrate the magnetosphere. Atmospheric conditions, especially barometric pressure, also affect neutron levels.

Man-Made Particles

Man-made particles are generated from atmospheric or exo-atmospheric explosions. The nuclear environment in space is composed of particles created by the detonation (i.e., fission) of thermonuclear (i.e., fission-fusion) weapons. The products of the primary weapons environment are neutrons, electrons, alpha particles, fission fragments, gamma rays, and x-rays. For atmospheric bursts, interaction with the air and ground produce more gamma radiation.

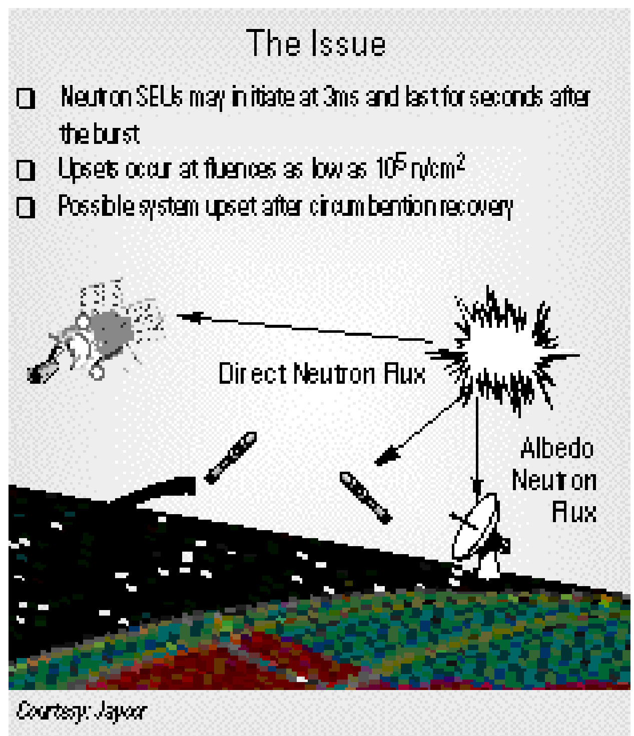
The environment from initial nuclear radiation is transient, but the effect can be transient or permanent. Transient radiation can affect both electronics and optical materials. In a nuclear space explosion, the primary and secondary gamma rays and x-rays are responsible for the total ionizing dose effect on the electronic components. Gamma rays also cause dose rate reactions. Neutrons cause parameter degradation of electronics by disrupting the atomic lattice structures, and can also induce single event effects. While shielding can help to mitigate the effect of x-ray radiation, it cannot attenuate the gamma and neutron radiation since they are extremely penetrating.

During the late 1950s and early 1960s, the United States of America and the U.S.S.R. detonated nuclear bombs at altitudes above 125 miles. The most dramatic of these high altitude tests was the U. S. detonation on July 9, 1962 (program name – Starfish). Ten known satellites were lost because of radiation damage – some immediately after the explosion. The Starfish explosion injected enough fission spectrum electrons with energies up to 7MeV to increase the fluxes in the inner Van Allen Belt by at least a factor of 100. Effects were observed out to 5 Earth radii. The Starfish electrons that became trapped dominated the inner zone environment (≈ 2.8 Earth radii at the equator) for five years and were detectable up to eight years in some regions. The regions where particles were trapped depends on the latitude of the explosion. At greater than 50˚ latitude, the particles appeared at geostationary orbits; at less than 50˚ latitude, it appeared in the low Earth orbit domains.

Neutron Single Event Effects (NSEE)
(Ref. Nos. 9, 10, 11, 12, 13)

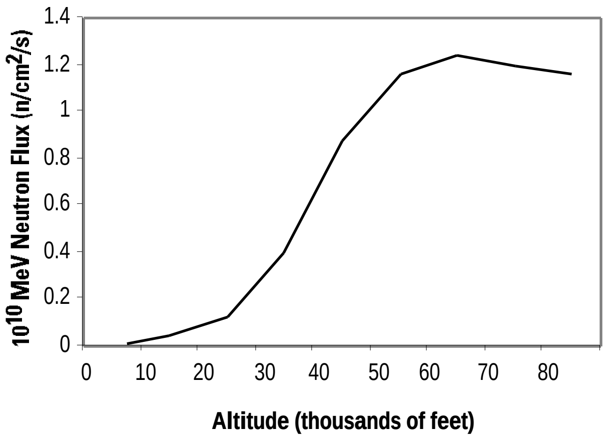
The latest radiation environment to be addressed by designers of radiation-hardened systems is Neutron Single Event Effects (NSEE). This focus is attributable to the introduction of COTS products into these systems as well as the reduced feature size of new, state-of-the-art technologies. Because COTS products do not consider the effects of radiation and because newer technologies require less energy to change the output of devices, NSEE is a growing concern.

The single event effects of the neutron have been observed and studied since the late 1970s. By the mid-1980s, the effect was being observed in avionics systems at 70,000 feet. NSEE are now observed at altitudes of 40,000 feet. In the near future, NSEE are expected to impact those ground-level systems that use the latest technologies.



While NSEE generally have the same effects on systems as protons and heavy ions (i.e., upset and latchup), the mechanisms differ as both fast neutrons and thermal neutrons must be considered. It is believed that low energy neutrons are an important source of Neutron Single Event Upsets (NSEU) and will generate NSEU more efficiently than fast neutrons. NSEU occur when neutrons

Neutron Flux versus Altitude



Courtesy: Jaycor
Ref: IEEE NS, Vol. 43, pp 463, E. Normand, "Single-Event Effects in Avionics"

cause a device to upset as a result of the recoil that occurs when interactions with the neutron deliver sufficient energy into the sensitive area of the device.

The neutron interaction and subsequent primary recoil of the atom's energy result in two types of delivered energy. Part of the energy is transferred to the electrons, resulting in direct ionization. The other delivered energy is referred to as the nuclear part. This nuclear portion is converted into ionization, vacancy generation, and manufacturing of phonons.

Published literature has reported that neutrons cause Single Event Burnout (SEB) in power MOSFETs due to high energetic neutrons. It also has been reported that Dynamic Random Access Memories (DRAMs) are less susceptible to NSEU than are SRAMs. Therefore, DRAMs may become the preferred memory product for avionics systems. NSEE that occur in COTS product have low neutron fluxes. This effect does not appear to be an issue with some specifically hardened product.

Hardening techniques to mitigate NSEE are being investigated. More work is required to better understand the mechanisms of NSEE, the combined environments of neutron and total ionizing dose (TID), exposure rate, and the sensitive parameters that exist in devices that are subjected to the neutron environment. It will be important to understand the vendor's process in order to characterize a device's NSEE response.

Focus also is needed on Neutron Single Event Latchup (NSEL) since there is very little available information. While many of the mitigation techniques that were developed for heavy ion susceptibility can be used for NSEE, additional techniques might need to be developed to account for NSEE mechanisms. Neither test methods nor assurance methods are presently available in order to evaluate both present and future systems' vulnerabilities.

System Impacts Observed

System	NSEE	Neutron Source(s)	Date
ICBM Guidance Computer	23 errors or 1 x 10^{-6} error/p/cm^2	Solar flare protons > 20MeV in polar region	1989 Los Alamos
ESA ERS-1 Satellite	NEC 64 Kbit CMOS memory latchup caused experiment shutdown	Proton AP8 MAX SAA	1991 ESA
Military Avionic Units E-31 AWACS NASA ER-2	SRAM upsets 1.1 x 10^{-8} to 5 x 10^{-9} upset/bit-hr. Project >1 upset/flight by 1998	Natural 29 K ft. 45° 65 K ft. 35° to 70°	1993 Boeing
Avionics Units Commercial AC	200 to 400 upsets 19 to 46 fc 2 to 4 upsets 0.6 to 1.5 pc	Natural High Latitude and 40 to 55 K/t	1994 England/Sweden
Avionics Units ARINC Receivers & Gate Arrays	1 x 10^{-9} upsets/bit-hr. to 5.2 x 10^{-10} upsets/bit-hr.	Natural 40 K ft. 5800 n/cm2-hr at >10MeV	1995 Boeing
Fermilab Computer Cray YMP-8	2.3 error/mod-yr double and single bit error	Natural >10 MeV Ground level	1996 boeing/IBM
Avionic Test Equipment (CUTE)	489 upsets in flight 960 upset ground test	Natural at altitude 5 to 160 MeV, three sources	1998 Sweden
Implanted Cardioverter Defibrillator	9.3 x 10-12 upsets/bit-hr. 1 DRAMs 22 upsets, 2 multiple	Natural, ground Level 1 >100 MeV	1998 Australia

Courtesy: Jaycor

Radiation Environments

Ref. Nos. 2, 6, 16

Four of the five major radiation environments can cause concern in the manufacture of an IC – neutron, total ionizing dose, transient radiation effects (a.k.a., dose rate), and single event effects. An IC manufacturer can minimize these effects through layout, design rules, process design, and circuit design. At this time, the fifth major environment – electromagnetic pulse (EMP) – is relegated to system manufacturers and is addressed as part of the system design criteria. In the future, this environment may be dealt with at the IC device level.

Radiation Sources

Neutron Sources

- o Nuclear explosion
- o Nuclear reactors
- o Radioactive contaminants

Total Ionizing Dose Environment

- o Nuclear explosion
- o Space
- o X-ray machines
- o Materials
- o Charged particles
- o IC manufacturing equipment
- o Biomedical

Transient Radiation

- o Nuclear explosion

Single Event Effects

- o Galactic cosmic rays
- o Materials
- o Neutrons
- o Protons

Total Dose Environment

The total dose environment is a composite of gamma rays, x-ray radiation, and other ionization radiation. The total amount of absorbed radiation energy varies according to the absorption material. As applied to semiconductors, the material is silicon dioxide and total dose is expressed as rad(Si) or rad(SiO_2), respectively.

Total dose radiation can degrade parameters to the point where a circuit's operation is detrimentally affected. For example, increased propagation time can result. Parametric concerns include changes to I_{CC} (standby current), I_{OZ} (TRI-STATE® leakage current), V_{IL}, V_{IH}, V_{OL}, and V_{OH}. Prevention comes through understanding degradation, how device parameters are affected, and how to achieve a radiation-hardened design by properly applying the device in the circuit and the system.

Ionizing radiation affects the gate and field oxide of a CMOS semiconductor. When gamma rays strike the oxide, photons generate electron-hole pairs. The electrons are swept out of the oxide (gate/field) leaving the holes behind (trapped charge). This trapped charge causes threshold voltages to change. Trapped positive charge and interface-state generation combine with subsequent annealing effects to constitute time dependent effects (TDE).

Transient (Dose Rate) Radiation

In the military radiation environment, transient (high dose rate) radiation is a major concern.

Transient irradiation is associated with nuclear explosion and is a major concern for designers of tactical equipment. Characterized by a narrow pulse width (usually 3ns - 10µs) containing a total dose of 1000 rad(Si) or greater, it represents the amount of total dose irradiation given in a specified time interval. Transient radiation is expressed in rad(Si)/s or rad(SiO_2)/s.

A dose rate pulse will generate excess charge in a short period of time. Adverse effects of transient irradiation include upset (soft error), latchup, junction burnout, short transient pulse on the output, and saturated outputs which depend on the amount of photocurrent (excess charge) generated and the output loading.

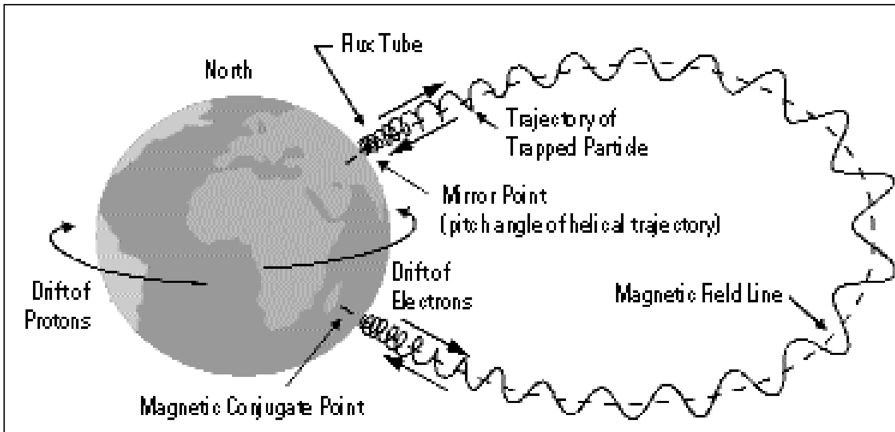
Semiconductors subjected to transient radiation generate a large magnitude of photocurrent within each device. When a threshold level of excess charge is attained in a CMOS device, adverse effects can cause:

- o Device latchup – A parasitic SCR (silicon controlled rectifier) effect that may cause catastrophic failure
- o Junction burnout – Also catastrophic to the device
- o Transient upset – A "soft" error that causes temporary degradation. Upset error can be addressed through a circumvention approach, by recycling the computer, or with error detection and correction (EDAC) techniques.

Other effects are a short transient pulse on the output and saturated outputs. These depend upon the amount of photocurrent (i.e., excessive charge) generated and the output loading.

The worst-case scenario for transient latchup testing is a short radiation pulse, high V_{CC} voltage, and high temperatures. This assures that the largest amount of photocurrent can be generated in the shortest amount of time and with the greatest efficiency of electron-hole pair generation. The high temperature causes changes that permit a lower triggering current level of the parasitic SCR. In turn, the parasitic SCR turns ON and the device has latchup.

The worst-case condition for transient upset is a wide radiation pulse (greater than 100ns), low temperature (generally room temperature), and V_{CC} set at a low voltage. Slower devices have better radiation upset tolerance than faster devices. Sequential logic circuits suffer from "soft" error. Combinatorial logic devices see a "transient" upset before returning to their original output state. The concern with transient upset is that the upset spike may be propagated to subsequent circuits with sufficient amplitude and energy to cause a sequential circuit to upset.



The three motions of the trapped particles form drift shells. Courtesy: NASA/Goddard

Upset level sensitivity is also affected by:

- The output states of the device
- The relative position between the occurrence of the radiation pulse and the device's clock pulse

Thin Epi-CMOS, such as used in the manufacture of FACT logic, is inherently latchup immune to transient radiation.

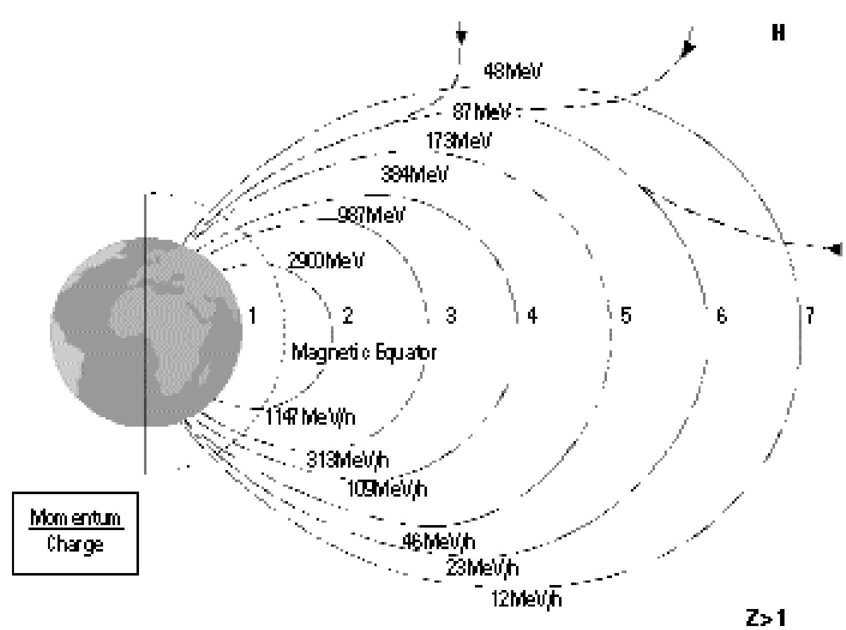
Single Event Phenomena (SEP)

Cosmic radiation and trapped protons are associated with SEP. Observed in the early 1960s, this was not a concern until the late 1970s. As technology evolved to decreased geometries, feature sizes, and gate oxide volume while increasing device speed, the energy required for gate switching was reduced. As a result, low energies (0.5 pico joules) can now switch device gates, making charged particles an important radiation concern.

SEP hardness design is dependent on mission requirements and circuit application of the part type. Mission requirements affecting SEP design include orbit placement (polar or geosynchronous), space duration, and orbit inclination. Because the Earth's geomagnetic field acts as an energy filter, in general minimal SEP effects occur in low altitude orbits with inclination angles lower than 45˚. The South Atlantic Anomaly is an exception since it is less than 45˚; however, it is a concern for SEP, particularly SEU.

Single event phenomena is generated by these charged particles:

- Heavy ions are caused by solar flares and are included in the spectrum of galactic cosmic rays. They provide the worst-case SEP environment for electronic space systems.



The relationship between the dipole shell parameter and cut-off rigidity is often used to determine the particle energy required to penetrate the magnetosphere. Courtesy: NASA/Goddard

- Low-energy alpha particles cause upset in sequential logic or memory devices. Low-energy alpha particles are the result from the decay of radioactive materials and cause single event effects (SEE). Thorium, a radioactive material used in ceramic packages, is a source for alpha particles.
- High-energy protons originate in the Van Allen Belts or by solar flares. Only protons having energy greater than 10MeV will cause an SEE problem.

Detrimental SEP effects on electronic systems include transients, soft error, and permanent damage. Latchup is the major permanent damage, with burnout possible in some devices. This and other effects, such as the funnel effect, result when a high-energy charged particle passes through a sensitive area.

In general terms, if a device does not suffer from single event upset (SEU) or latchup in a heavy ion environment, it will be unaffected in a high-energy proton or low-energy alpha environment. If an alpha particle upsets a component, then upset or, more likely, latchup will occur in a proton or heavy ion environment.

Neutron Radiation

Neutron radiation-induced defects significantly affect the electrical behavior of semiconductor devices. In bipolar devices, it causes lattice structure damage; thereby affecting a device's minority carrier lifetime and transistor gain. CMOS technology is immune to neutron irradiation below 10^{14} neutrons/cm^2.

Five basic effects occur in the silicon bandgap due to neutron radiation:

- Thermal generation of electron-hole pairs occurs due to a radiation-induced defect center near the midgap. This causes dark current while increasing leakage currents.
- Recombination of electron-hole pairs is increased due to the neutron-induced defect centers. The recombination rate is determined by the defect center density, the free carrier concentration, the electron and hole capture cross-sections, and the energy level position. Recombination centers cause the recombination lifetime to decrease and is the major cause for bipolar transistor gain degradation.
- There is temporary trapping of carriers by the neutron-induced defect centers. This process is responsible for increasing the transfer inefficiency in charged-coupled devices.
- There is compensation of donors or acceptors by the neutron-induced defect centers. The result of compensation is "carrier" removal that causes a change in the doping concentration. An increase in bipolar collector resistance can also occur.
- Tunneling of carriers occurs through the potential barrier of a bandgap energy state by means of defect energy levels in the energy bandgap. This process increases the reverse current in pn-junction diodes or increases the junction leakage current in a MOSFET.

Other neutron radiation damage causes carrier mobility to decrease since neutron radiation-induced defects also act as scattering centers.

Particle Interaction

Particle interaction is categorized as:

- Photons
- Charged particles
- Neutrons

Each category interacts with the target material's atoms through two processes: Excitation and ionization. The particle interaction is a function of the mass, charge, and energy of the incident particle and the atomic mass, atomic number, temperature, and density of the target material.

The photon interaction is complex and consists of:

- Primary processes: Photoelectric, Compton Scattering, pair production
- Secondary processes: Compton electrons, Auger electrons, photoelectrons, characteristic X-rays, Compton photons, etc.
- Tertiary processes: Electrons, photons, X-rays

Charged particle interactions are primarily electrons, protons, alpha particles, and heavy ions. Electrons interact with the target materials through excitation and ionization. Some of the electrons cause Coulomb Scattering interaction. Electron interaction also generates two other effects:

- Charge deposition by the electrons when they are stopped in the target material
- The attenuation of the penetrating electrons in the target material causes a gradient of electron-driven current density.

Irradiating Particles

- Neutrons
- Gamma rays
- X-rays
- Electrons
- Protons
- Alpha particles
- Ions
- Cosmic rays
  - Protons
  - Electrons
  - Alpha particles
  - Heavy ions

Protons are another source of charged particles that interact with the target material in a similar manner as the electrons (e.g., excitation/ionization); but protons also lose energy by displacement of atoms due to Coulomb Scattering.

Neutron interaction with the target material is through either absorption or scattering. "Slow" neutrons are absorbed while "fast" neutrons are associated with the scattering. A result of "slow" neutron absorption generates the emission of an alpha particle or a proton. Fast neutrons undergo two types of scattering – inelastic and elastic – depending on the energy level of the neutron.

Particle Categories

- Photons
  - X-rays
  - Gamma rays
- Charged particles
  - Electrons
  - Protons
  - Alpha particles
  - Ions (cosmic rays)
- Neutrons

Photon Interaction Types

Photons are bundles (i.e., packets) of energy that cover a wide range of wavelengths from soft x-rays through ultra violet (UV) and visible to infrared (IR). Photons have zero rest mass and are electrically neutral. They interact with the target material's atoms through three effects that are based upon the photon's energy and the atomic number Z of the target material. The following occurs when silicon is the target material:

- Photoelectric effect – dominates at energies below 50keV
- Compton scattering effect – dominates between energies greater than 50keV and less than 20MeV
- Electron-hole pair production – dominates when photon energy is greater than 20MeV

The photoelectric effect process states that incident photon energy is completely absorbed by the emitted electron (photoelectron). The Compton Scattering effect process states that the incident photon gives up only a portion of its energy to scatter an atomic electron. It is important to note that incident photon energy is much greater than the binding energy of the target material's atomic electrons. After the impact, the incident photon continues through the target material, giving up a portion of its energy to generate another energetic Compton electron. This process continues until the photon energy no longer has sufficient energy to generate another energetic electron.

The pair production process creates an electron-positron pair. The threshold energy for this process is 1.02MeV. Above this energy, an incident photon striking the target material can be completely absorbed and can generate an electron positron pair. The positron has the same rest mass as an electron, but its charge is positive.

Charged Particle Interactions

When striking the target material, charged particles can cause displacement and ionization This interaction as well as excitation of the atomic electrons occurs as a result of Rutherford scattering. Heavy ions are charged particles that emulate similar nuclear interactions as neutrons.

Rutherford scattering (also known as Coulomb scattering) is caused by an incident charged particle impinging on the target material. This causes the atomic electrons to become excited and then liberated. Once an atomic electron is liberated, the ionization activity causes an imbalance in the semiconductor material. Excess charged particles are created between the densities of electrons and holes, and begins a very complex ionization process. Secondary electrons with various high energy levels are subsequently created. This further increases the ionization process, and a cascading effect ensues.

Particle Interaction with Target Materials

The nature of interaction is dependent on the following:

- Particle property
  - Mass
  - Charge
  - Kinetic energy
- Target properties
  - Mass
  - Charge
  - Density

Radiation & Charged Particles

Category	Source	Interaction
X-ray and gamma ray	Nuclear weapon, particle collisions	Photoelectric, Compton scattering, pair production
Charged particles	Electrons, protons, alpha, ions	Rutherford scattering, nuclear interactions
Neutrons	Nuclear weapon, material	Elastic scattering, inelastic scattering, transmutation

Neutron Interactions

In the case of displacement damage, when the neutron particle strikes the target material it will generate defect centers through elastic scattering, inelastic scattering, or transmutation reactions. Elastic scattering is the incident neutron hitting the lattice atom, causing displacement of the lattice atom and generating a vacancy/interstitial pair-defect. The neutron continues to strike other atoms, resulting in further displaced atoms until its energy is less than the displacement energy (typically 25eV). Both the displaced atom and incident neutron release energy to ionization.

Inelastic scattering is the second type of interaction associated with displacement damage and neutron radiation. In this case, the incident neutron is absorbed by the target atom and subsequently emits another particle at a lower energy. This interaction causes the target atom to be excited, possibly displaced. At some point the excited target atom will return to its original energy state. In doing so, the target atom may emit a gamma ray.

When a transmutation reaction occurs, the incident neutron is captured by the lattice atom's nucleus and subsequently emits a charged particle (proton or alpha). The result of transmutation reaction is that the original material is transmuted into another type of material.

Radiation Damage Effects

Two types of radiation damage effects occur in solid-state electronic products: Displacement damage and ionization effects. Displacement damage is the movement of atoms from their normal position in the lattice to another placement, causing a defect in the lattice material. Ionization damage effect is the generation of electron-hole pairs within the material that causes radiation effects. A quantity of excess carriers in the material results from the interactions of charged or uncharged particles. These excess carriers subsequently impact the electrical performance of the electronic device, regardless of its passive or active state. Ionization damage generates temporary as well as permanent damage.

Displacement Damage

Displacement damage within the silicon material results from high-energy particles – such as a neutron – causing crystal lattice defects. These defects are known as vacancies, di-vacancies, interstitials, or defect clusters. These defects generate energy levels in the forbidden bandgap of the material lattice, causing degradation or possible failure of the integrated circuit. Bipolar products are most susceptible to displacement damage. The presence of the lattice defects in a bipolar device causes the minority carrier lifetime to be reduced and the transistor gain to be degraded.

In addition to the displacement damage associated with high energy particles, a secondary effect is caused through the interaction of particles (proton, neutron) with the atomic lattice of the particular material. The resulting ionization radiation can cause photocurrent generation in a semiconductor function or trapped charge in an insulation material of a semiconductor.

Ionization Effects

When charged particles penetrate the semiconductor material, the resulting ionization then causes the majority of integrated circuit failures. The interaction of an energetic charged particle in the semiconductor material or insulator causes an electron to become excited in the valance band, then to cross through the forbidden-bandgap into the conduction band. A certain amount of electrons and holes that are generated will initially recombine. The remainder will drift through the material, assuming an electric field is present. The resulting effects of this ionization are the generation of photocurrents or radiation-induced trapped centers. These ionization effects are responsible for parasitic leakage paths, mobility degradation, threshold voltage shifts, transient radiation effects, and single event effects.

Radiation Design Issues & Considerations

The most efficient and cost-effective approach to designing a radiation-hardened system is to start at the conceptual stage. This is where proper evaluation and selection of semiconductor technology and other factors occur, i.e., determining the extent of shielding, selecting viable existing technologies, and evaluating prototype IC technologies that will be available when the system is in production. Most critical at the conceptual stage is a thorough understanding of the system's mission relative to its potential radiation environments.

Incorporating Radiation Design

To ensure the best RHA (Radiation Hardness Assured) design, it is necessary to understand the complete radiation response of each component in the system circuit, e.g., what electrical parameters are affected by which radiation environments. This includes variable and functionality (attribute) data to the level of radiation failure. Variable data as performed in a step-stress radiation approach permits observance of non-monotonic behavior for each electrical parameter's radiation response. For example, standby current attributed to a field oxide leakage is non-linear and exhibits significant increases in value above its pre-radiation value.

When designing a radiation-hardened system, guidelines must be based on the system's mission and required survivability. After the conceptual phase comes selection of the proper components for the investigative Engineering Development Phase. This is often the most costly phase as testing procedures include components, circuit board, systems assembly, and software documentation.

Most older logic technologies have low radiation-tolerance limits. Their use, therefore, precipitates costly design-assurance techniques. Mature technologies are also subject to the uncertainties associated with continued assured supply.

While using customized products can reduce the cost of design-assurance techniques, this one-of-a-kind approach significantly extends leadtimes and substantially escalates product costs.

Once the radiation environment is identified, radiation test procedures must be set and a Hardness Assurance Plan & Program instituted. Establishing a Change Control Board ensures that circuit design modifications do not impact the system's hardness assurance.

When a system design is approved to radiation-hardness criteria, other documentation must be initiated to prevent compromise to the established radiation hardness level. Written specifications include radiation test conditions. Acceptance test procedures ensure that components identified as HCI (Hardness Critical Items) are properly tested.

To ensure the best Radiation Hardness Assurance (RHA) design, it is necessary to understand how each component will respond in the system circuit, e.g., what electrical parameters are affected by which radiation environments. This includes variable and functionality (attribute) data to the level of radiation failure. Variable data (as performed in a step-stress radiation approach) permits observance of non-monotonic behavior for the radiation response of each electrical parameter.

Part procurement drawings, assembly drawing schematics, and purchase orders require complete specifications of radiation requirements, including a worst-case circuit analysis. Worst-case analysis requires extensive system and circuit knowledge with respect to different radiation environments. Factors to consider include:

- Analysis of which circuit functions must operate through a particular radiation environment and those that would not
- The amount of available radiation shielding
- Selecting manufacturers with radiation-resistant components

Piece-part testing is one of the more costly efforts when radiation hardening a system. Here each component's radiation response is determined by different radiation environment simulators.

Importance of Characterization Data

By having characterization data, system designers can review a function's response to each radiation environment and thereby tailor their approach to hardening the circuit and system design. This data also identifies radiation-sensitive parameters, enabling designers to adjust system circuitry for minimal parametric degradation or for evaluating the product's applicability.

Device design margins and circuit design margins are determined from characterization data. However, the most important use of characterization data is to establish parameter end-point limits for device qualification.

For example, a device to be used in the tactical environment is typically specified with a radiation level of 3 krad(Si). To eliminate lot acceptance testing, a design margin of 10x total dose level [30 krad(Si)] would have to be attained with an acceptable parametric end-point limit and no functional failure.

Selecting RHA Components

Once a technology is selected, the next step is to choose RHA components. Use of RHA devices reduces cost, improves reliability, and ensures that the system's radiation hardware requirements will be met. RHA component qualification does not guarantee the devices are impervious to adverse radiation effects, but that they have end-point electrical values which take into account radiation degradation.

If the system's manufacturer determines RHA acceptability via its own radiation testing program, the system's cost will significantly increase. In addition to the system manufacturer's involvement in comprehensive radiation testing, the OEM bears the burden of scheduling and purchasing costly radiation time at test facilities.

A better, less costly method is for OEMs to work with RHA-qualified IC manufacturers. In general, RHA devices are qualified for a neutron environment and total dose irradiation, but are not specified for transient (dose rate) environment or single event phenomena.

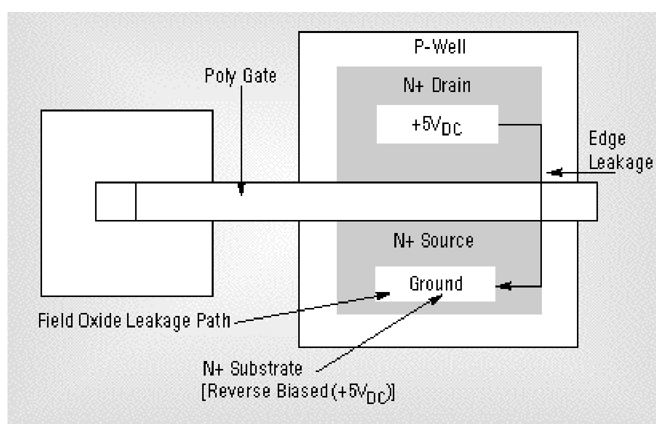
Concerns associated with RHA components include examining vendor's data for outstanding issues, annealing, lot-to-lot variation, wafer-to-wafer variation, and radiation test conditions. It is important to select a semiconductor manufacturer that provides either the specified data or eliminates a particular concern. By choosing the correct technology and component manufacturer, a radiation-hardened system can be produced with minimal cost, fewer components, and maximum survivability. The technology of choice to meet these radiation requirements is a CMOS with a thin epitaxial (epi) layer or silicon-on-insulator (SOS or SOI process).

Ionizing (Total Dose) Radiation & CMOS Devices

Total ionizing dose radiation affects CMOS products in two areas – threshold voltage shifts and radiation-induced leakage current. The radiation creates trapped positive charge in the gate and field oxides. A positive trapped charge in the gate oxide causes enhancement mode n-channel MOSFETs to approach depletion while enhancement mode p-channel MOSFETs are driven further into enhancement. Other generated trapped charges (a.k.a., interface states) cause the n-channel MOSFET threshold voltage to increase after having decreased toward depletion operation. This rebound effect is a reliability concern for long-term space flight. P-channel MOSFETs are slightly affected by interface states. Trapped-positive charge and interface-state charge generation combine with subsequent annealing effects to constitute TDE of total dose ionization.

The two major parametric concerns are leakage currents and propagation times. Depending on a vendor's CMOS processing, other parameters (such as V_{IL}, V_{IH}, V_{OL}, V_{OH}) may also change.

When designing a radiation-hardened CMOS system circuit, devices which use NAND gates are more tolerant than those with NOR gates. Depending on circuitry, CMOS device response may degrade, e.g., a flip-flop composed of NAND gates has a different total dose degradation than one using inverters and transmission gates.



Radiation-induced leakage paths

As the number of inputs increases for a particular gate, radiation degradation accelerates as total dose levels increase. With increased circuit complexity, radiation degradation shifts from parameter failure to circuit functionality failure. Therefore, a microprocessor may fail functionality prior to circuit parameter failure. This is also true for gate array designs. Each gate array has its own radiation response because of the internal "personalization" of metal connections to each cell; radiation hardness characteristics change with the design of each gate array.

Design margin also is important in CMOS logic design. It is used if a device function fails to meet or exceeds the radiation requirements of a specific application. Design margin is essentially a ratio of total dose radiation failure level of the design to the specified total dose radiation level. Design margins are determined by statistical analysis methods and can be applied as device, circuit, or system criteria. For CMOS devices, possessing a design margin greater than 100 requires minimal radiation testing. If the CMOS device's design margin is less than 10, it must have lot acceptance testing and specified controls.

Transient (Dose Rate) Radiation & CMOS Logic Design

Transient irradiation is primarily associated with a nuclear explosion and is a major concern for circuit and system designers of tactical equipment. The dose rate is the time rate of change of the total dose irradiation.

The effect of the dose rate pulse is generation of excess charge in a short period of time. The quantity of excess charge is dependent on the total ionizing dose in the pulse. The concentration of these excess carriers is determined by the dose rate and carrier lifetime. Excess charge results when the ionizing pulse occurs at a faster rate than can be recombined. When a threshold level of excess charge is attained in a CMOS device, these radiation-induced effects can cause temporary effects or catastrophic failures:

- Upset (soft error)
- Latchup
- Junction burn-out

Other effects are a short transient pulse on the output or saturated outputs. These depend on the amount of generated photocurrent (excess charge) and output loading.

When Designing with CMOS . . .

- Do not use NMOS technology, if possible.
- Use enhanced mode MOSFET design.
- Use CMOS product with thin gate oxide less than 300Å thick.
- Use low voltage (power supply) product.
- Use design margin of 2 or greater.
- Use CMOS product that does not have the rebound effect with the total ionizing dose level to be used.
- Use circumvention schemes for dose rate and single event environments.
- Use current-limiting resistors when necessary to prevent latchup. This increases power consumption as well as increases propagation time.
- Use sequential logic that uses capacitive or resistive elements. This increases RC times to prevent upset.
- Employ CMOS product that uses a low resistivity substrate as well as a very thin, low resistive epi layer.
- To minimize leakage current of the n-channel and threshold voltage of the p-channel, do not use NOR gates. Do use NAND gates.

Since there is no permanent damage, upset of output data is a soft error. Combinatorial circuits will upset, then return to their original state. This type of upset generates a transient voltage at the output pin which might or might not affect the next IC. Sequential logic circuits upset and remain in this condition until reset.

While logic upset is acceptable for some projects, the dose rate threshold level is important to designers who must work around the upset condition. Latchup occurs when a sufficiently large quantity of radiation-induced photocurrent initiates a parasitic silicon-controlled rectifier (SCR) action. Once activated, this SCR acts as a low resistance path between ground and power supply. This usually leads to catastrophic failure, such as blown bond wires or die metalization.

Junction burnout is another catastrophic failure in the dose rate environment. It occurs when sufficiently large photocurrent accumulates in the sensitive junction and cannot be distributed quickly. As a result, thermal energy increases to a level which causes junction burnout. For most technologies, the junction area is fairly large so that heat can be dissipated. At very high dose rate levels, junction burnout is a major concern.

Single Event Effects & CMOS Logic Design

SEP results when a high-energy charged particle passes through a sensitive area and deposits energy along its path. The rate of energy loss in the material is Linear Energy Transfer (LET). This energy loss generates a plasma of electron-hole pairs. If this plasma occurs in a depletion area of the sensitive region, the result is generation of induced current. This induced current is primarily collected from the depletion region and the funnel region. Latchup is the major permanent damage caused by SEP.

The detrimental results of SEE on electronic systems include transients, soft errors, and permanent damage. Single event transient spikes are generally associated with combinatorial logic circuits. The transient spike resulting from a single event strike has a short time duration, but could contain sufficient energy to cause a subsequent sequential or combinatorial logic input to change. While combinatorial logic outputs have transient upset, the inputs will force the output to its original state. Soft errors are temporary single event upsets and are defined as bit flips.

Induced current is a function of circuit parameters, the voltage applied at the sensitive node, and node capacitance. The amount of charge required to generate a change of state in a memory cell or sequential logic device is defined as the critical charge. Associated with the critical charge are the sensitive nodes of an IC. Sensitive nodes are the reversed-biased nodes, e.g., the OFF drains of the p- and n-channels of a memory cell. The collected charge at these sensitive nodes causes a voltage transient to develop and be applied to other cross-coupled inverters of the memory cell or sequential logic device that generates the change of state at the output of the device.

Latchup in the single event effects environment can affect devices manufactured on CMOS, bipolar, and ECL processes. Because of heavy ions, latchup in CMOS technologies is generally associated with a bulk technology or with devices fabricated on a thick Epi substrate. While similar to transient (dose rate), SEE latchup is generated by heavy ions. Since SEE latchup usually has catastrophic results, designers must select components that will be impervious to a single particle strike, e.g., devices which are fabricated with guard rings, built on a very thin EPI, or that use dielectrially-isolated CMOS technologies (SOS, SOI).

Plastic Packaging, Temperature & Radiation

As space and military designers reduce system cost and weight, plastic is more frequently viewed as an alternative to traditional ceramic packaging. While plastic appears more cost-effective, data describing its performance in radiation environments (total ionizing dose, neutron, dose rate, and single event) is minimal.

Testing on National Semiconductor's FACT 54AC02 Quad 2-Input NOR Gate circuit was presented at the 1995 Nuclear Space & Radiation Effects Conference (NSREC) in a paper entitled *Plastic Packaging & Burn-In Effects on Ionizing Dose Response in CMOS Microcircuit.* *(See paper in its entirety on page 107 of this Radiation Owner's Manual.)* This investigation sought to:

- Study burn-in effects on total ionizing dose degradation
- Compare the degradation differences between plastic and ceramic packages

For this test, all die were subjected to the same RHA tests. Ceramic packages were assembled and final tested to Class Q requirements. Plastic-packaged devices were manufactured by National Semiconductor and SEI. *(Note: Different companies use varying plastic materials and encapsulating processes that could yield significantly different total ionizing dose results for the same die.)*

MIL-Spec programs require high elevated-temperature-biased stresses be conducted on all military/aerospace product. In 1994 Sandia National Labs first reported that burn-in screens affect radiation-tolerant CMOS as well as radiation-hardened technologies *("Effects of Burn-In on Radiation Hardness", IEEE Trans. Nuclear Science, NS-41 2550 – M. R. Shaneyfelt, D. M. Fleetwood, J. R. Schwank, T. L. Meisenheimer, and P. S. Winokur).* This is supported by National Semiconductor's tests that show non-burned-in CMOS product has less radiation degradation than burned-in CMOS product. Because reliability screens such as burn-in can affect radiation responses, these affects must be taken into consideration when developing the lot acceptance plan.

The effect of burn-in screens on CMOS product is increased standby leakage current over non-burned-in product in a total dose environment. It is believed this effect is caused by reduced interface trap generation. The mechanism for this reduction is not well understood. While the results stated in the 1995 NSREC paper demonstrated similar results, plastic package burned-in product had significantly worse results than ceramic burned-in product. This impacts the radiation hardness qualification testing when using plastic packages in the radiation environment.

Note that in the manufacture of commercial ICs, these temperature-biased stresses are performed during the early qualification stage to detect early mortality issues. Once production is initiated, burn-in tests on commercial products are only performed at set intervals when production line samples are evaluated under operating-life test requirements. This operating-life test confirms that the process is unchanged and is under control.

Another important conclusion is that high dose rate [>10 rad(Si)/s] is the predominant mechanism for generating radiation-induced parasitic leakage path between source and drain of the n-channel MOSFET while low dose rate [<1 rad(Si)/s] is responsible for a different radiation-induced parasitic path, i.e., n-channel source to n+ substrate. Again, these results impact RHA test methodology and application. Parts irradiated at low dose rate demonstrated a minimal rate of anneal after irradiation. Parts irradiated at high dose rate had a rapid annealing rate of the standby leakage current.

The 1995 NSREC paper does not determine the physical mechanism for increased radiation damage in plastic-packaged or burned-in product. However, it does state that condition A of MIL-STD-883, Method 1019 is conservative for space applications. Caution is recommended when employing plastic/burned-in product in a total ionizing dose environment. Radiation test samples should be representative of the product being used in the system design.

Designing with Linear Bipolar Products

In the past, the major radiation concerns for linear bipolar product came from environments where neutron and dose rate were issues. The effect of neutron irradiation on linear bipolar basically affects ß (dc gain), drive current (fan-out), and V_{CE} (saturated). There was little concern with total dose and Single Event Effects (SEE).

Recently, it has been noted that linear bipolar devices show total dose sensitivity to low dose rate. This is known as the enhanced low dose rate (ELDR) Effect.

In the single event phenomena (SEP) environment, single event transient (SET) and single event burnout (SEB) are of greatest concern for linear bipolar devices.

The hardening of bipolar circuitry generally results by implementing geometrical considerations as well as adding current sources and resistors to accommodate different radiation environments. Some radiation hardening can be acquired through a set of radiation hardening design rules. Avoiding certain design techniques (i.e., serpentine resistors), minimizing the use of lateral and substrate PNP transistors in the device design, and avoiding Darlington circuit design. Additional parameters that affect bipolar performance and lead to radiation-induced failure are Early Voltage (VA) changes, input impedance, and output impedance. All result in a degraded device that has reduced output drive current and increased load sensitivity.

Low Dose Rate Sensitivity & Bipolar Linear Design

In the past, high dose rate irradiation was used on all bipolar product to simulate the total dose environment. As with CMOS technology, this was considered to be the worst-case scenario. It is now known that low dose rate is sometimes the worst-case condition. The radiation test community has investigated this effect for the past seven years. The phenomena is known as the Enhanced Low Dose Rate (ELDR) effect. The original discovery of ELDR was made on new technologies that use poly-emitters, but now include most bipolar technologies – both old and new. ELDRs are observed when the linear bipolar product is operating in a low dose rate environment that is similar to space or when irradiated at a low dose rate, e.g., less than 1 rad(Si)/s. A low dose rate environment can degrade a linear bipolar device by a factor of 2x to greater than 10x for a particular parameter as compared with a high dose rate environment.

This makes enhanced low dose rate effect a major concern for space system designers who use linear bipolar product. To complicate the situation, the ELDR effect does not affect all linear bipolar products or fabrication processes – old or new. All bipolar devices under consideration for use in space system design should be evaluated for enhanced low dose rate degradation.

At a low dose rate, the total dose response rate is affected by two radiation-induced failure mechanisms that can occur simultaneously in the low dose rate environment of space [less than 1 rad(Si)/s]:

- Time-Dependent Effects (TDE)
- True Dose Rate Effect (TDRE)

TDE continues long after the linear part is removed from the environment. For example, a satellite that passes in and out of the Van Allen Belts is subject to TDE. However, the true dose rate effect only exists while the device/system is within the low dose rate environment. Both failure mechanisms contribute to the degradation of linear bipolar parameters.

TDE can be segmented into two mechanisms: Positive oxide trapped charges (high dose rate effect) and interface trap charges (low dose rate effect). Positive oxide trapped charges affect standby current, DC gain, slew rate, open-loop gain, etc., and generally are not an issue in space since they are generated as a result of high dose rate irradiation. However, interface trap charge generation is a major concern since it is a result of low dose rate irradiation. This detractor causes reduction in DC gain, creates parasitic leakage paths, input offset current and input bias current failures as well as input offset voltage failures, etc.

At this time National Semiconductor's Radiation Engineering Group is investigating the use of a high temperature, biased, one-week anneal to determine if low dose rate Time Dependent Effects (namely, interface trap generation) exist when using a high dose rate irradiation technique. Essentially, the +100˚C, 168-hour biased anneal removes the positive oxide trapped charges leaving only the interface traps as the sole degradation mechanism. If parametric failures occur after this anneal, then users must be concerned about the system design based upon space application, space orbit, and shielding. If functional failure occurs at any time, the product must be rejected.

The second cause of linear bipolar failure at low dose rate irradiation is the True Dose Rate Effect. Degradation resulting from this effect only occurs while the device is in the actual low dose rate environment. The low dose rate mechanism is the lack of space charge generation within the particular oxide area of concern. These oxides are formed directly above the base-emitter junctions of the transistors and are relatively radiation soft to low dose rate effects. The more sensitive transistors to low dose rate radiation are the lateral pnp and substrate pnp. Since there is a lesser amount of space charge developed at low dose rate, the net positive trapped oxide charge is greater at low dose rate due to a reduction in electron trapping caused by the small space change. Greater net positive charge at low dose rate results in increased surface recombination velocity at the emitter-base junction, causing a further increase in Ib (base current) and a reduction in the gain of the device.

Because the ELDR effect is relatively new, it is difficult to simulate these effects without fully understanding the mechanisms that cause them. New approaches to simulation are in various stages of development.

At this time there is no approved method for simulating the True Dose Rate effect for linear bipolar devices. An approach that is being considered is to perform high dose rate irradiation at an elevated temperature for simulation of the Enhanced Low Dose Rate Effect. Other methodologies are also being investigated, but no final conclusions have been decided.

For the true dose rate effect, a proposed method is included in the new ASTM document, *Standard Guide for Ionizing Radiation (Total Dose) Effects Testing of Semiconductor Devices (ASTM-F1892)*. Total ionizing dose irradiation allows three options:

- Irradiate at the intended use dose rate
- Perform the accelerated test method as described in the document. This approach is used when it is impractical to irradiate and test within a reasonable time.
- Perform irradiation using one of two methods:
    1. Irradiate at room temperature and low dose rate and apply a design margin factor of 2.
    2. Irradiate at +100˚C, employing a dose rate between 1 rad(Si)/s and 10 rad(Si)/s, then apply a design margin factor of 3.

National Semiconductor is investigating the use of Method 2 of the third option.

Shielding

Sometimes the product that you need just isn't available with inherent radiation resistance. This is where shielding is a consideration.

Shielding to protect integrated circuits from radiation environments has long been used in the military and aerospace industries. Over the years, shielding has developed into a science, replete with the latest simulation design tools and techniques. Beginning with a single layer material, shielding has evolved into multiple layers of high Z and low Z materials that are integrated into IC packages. Perhaps even more important than the type of material used is understanding the radiation environments to which the integrated circuits will be exposed. Today's

Typical Shielding Evaluation Process

1. Evaluate the radiation environments
    - o Electron
    - o Proton
    - o Neutron
    - o Photon
    - o Cosmic rays
2. Determine the radiation requirements
3. Identify the components, sub-assemblies or assemblies of each sub-system or system that does not meet the radiation design margin or acceptable radiation levels
4. Determine the radiation environment within the satellite or LRU (Line Replaceable Unit) through radiation analysis or modeling codes
5. Can inherent shielding within the satellite or LRU be used? Or is local shielding at the sensitive sub-assembly or part type needed?
6. If shielding is required, then determine the shield configuration and mass needed. Determination is based upon the remaining radiation environment.

radiation hardness design techniques enable system designers to use shielding as the last resort. It is only justified when circuit redesign is not possible, a radiation harder part is not available, or the radiation design margin is at its minimal limit.

Shielding is employed in military systems, space satellites, and the nuclear commercial business. Each application has unique shielding requirements and associated costs. The purpose of shielding is to reduce radiation degradation to an acceptable level based upon the application, safety issues, survivability needs, and radiation design margins. Shielding analysis begins by evaluating the need for shielding as based upon radiation environments, design margins, and restrictions. Once shielding needs are identified, the next step is to evaluate the available (inherent) shielding of the application's environment as well as additional local shielding, either on-board or at the part level.

Shielding is easiest with stationary ground facilities (i.e., nuclear power plants) where earth, cement, and lead can be used readily and the predominant limiting factor is cost. Mobile military systems are somewhat harder to shield. This is where weight, size, and cost are restricting factors — particularly those systems that will be directly exposed to nuclear blast or must operate through the radiation environment. Space systems present the greatest obstacles for shielding. Here, weight is critical, service life is greater than five years, there is no available maintenance to replace failed systems, and size limitations are essential.

Since fixed military ground installations and commercial radiation sources can be shielded with readily available material, this discussion focuses on mobile military and space systems. Note that at this time there is no practical method to completely shield systems from gamma rays or neutrons due to the mass of shielding material that would be required.

To provide insight to the design of the shield configuration, radiation analysis for shielding must include all transport codes for electron and proton environments. Another key consideration is knowing what materials are located between the radiation-sensitive IC and the radiation environment. It may be possible to use these materials as a part of the shielding. This approach can be combined with the possibility of relocating the part, board, or assembly to another position of the spacecraft or aircraft. If these evaluations fail to provide the required minimal radiation level, a determination may be made to use local shielding for a sensitive part and its configuration. Or the answer may be for a general mass shielding to be applied to the system or LRU.

Recent investigations show multi-layer shielding is very effective, particularly with the electron and proton environments of space. For example, a tri-layer shield configuration can significantly reduce radiation degradation. A shield configuration consisting of a high Z material sandwiched between two layers of low Z material will reduce the electron and proton radiation significantly. The high Z material shields against the penetrating electrons while the low Z material facing the part-type or system electronics shields against the proton environment. The first layer of low Z material could be part of the system's chassis cover or the surface of the spacecraft or aircraft. Thin layers of shielding also will have a small effect of reducing cosmic ray low energy spectrum component.

Another option to shield radiation-sensitive part is to use a special package that employs the multi-layer shield concept. This shielded package is applicable for the electron and proton environments, but does not stop the effects of gamma or cosmic rays (heavy ions). These packages are costly and trade-offs are required.

Changing Technology

Most importantly, wherever possible, select vendors that have radiation-tolerant/radiation-hard product and use the QML approach. This will provide a standardized product, a consistently reliable product base, cost-effectiveness, and diverse product selection.

Integrated circuit technology changes about every 1 1/2 to 2 years. With the decrease in feature sizes and the frequent changes in processing, it is necessary to stay in tune with the industry. Radiation damage is not going away with new technology advancements. In fact, in some aspects it may worsen. More testing needs to be done in the proton and neutron upset environments.