A compendium of radiation effects topics for space, industrial and terrestrial applications

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Robert Baumann

Early in his 29 year career at TI, Robert Baumann discovered that the reaction of $^{10}$B with low-energy cosmic neutrons was a dominant reliability risk in digital electronics and developed mitigation schemes that reduced product failure rates nearly ten-fold. From 1993-1998, He was involved in transistor and radiation effects reliability and advanced failure analysis at TI's Mihomura Fab and Tsukuba R&D Center in Japan. When he returned to Dallas he led radiation effects programs for the advanced technology reliability group. He co-led the SIA’s expert panel, which successfully negotiated with the U.S. Government to change ITAR export control laws that posed a serious risk of export restriction to advanced commercial technologies. Baumann was one of the primary authors of the JEDEC (JESD89, 89A) industry standard for radiation characterization in the terrestrial environment for which he was awarded the JEDEC Chairman's Award. In 2012 he moved to the high reliability product group focused on improving the characterization, modeling and reporting of radiation effects. Baumann was elected TI and IEEE Fellow. He has coauthored and presented more than 90 papers and presentations, two book chapters and has fifteen U.S. patents. Baumann retired from TI in 2018.

Kirby Kruckmeyer

Kirby Kruckmeyer started his career at National Semiconductor (acquired by Texas Instruments in 2011) as a process engineer, developing processes for the world’s first 5-inch analog wafer fab. During this time, Kruckmeyer gained experience with semiconductor physics, passivation charging effects and radiation-hardened processing. From 1990-1992, Kruckmeyer was an assignee from National Semiconductor to Semiconductor Manufacturing Technology (SEMATECH), an industry consortium established to improve processing technology in the United States. There, he supervised engineers from other companies in the development of 150-mm process technologies. After finishing his assignment, Kruckmeyer returned to National, where he moved into product development and eventually was the product line manager for National’s Automotive Systems group. In 2005, Kruckmeyer moved in the High Reliability product group. He was instrumental in developing National Semiconductor’s leadership in space-grade data converters, enhanced low dose rate sensitivity-free products and radiation testing. At Texas Instruments, Kruckmeyer continues to support space applications, radiation testing and space product development. He has authored and presented over 20 papers, sits on radiation testing standards committees, and participates in radiation conferences.
Foreword: Texas Instruments space flight history

Texas Instruments has one of the longest space-flight histories of any semiconductor vendor. Even before Texas Instruments engineer Jack Kilby conceived and built the first integrated circuit (IC) in September 1958, Texas Instruments transistors had flown into space on the U.S.'s first satellite, Explorer 1, which launched on Jan. 31 that same year.

Since then, products from Texas Instruments have flown on many space missions. Notable and historic missions with Texas Instruments products on board include:

- Telstar 1, the first broadcast TV satellite
- Apollo 11, marking the first man on the moon
- Mariner 2, the first successful interplanetary spacecraft
- Voyager 1, still traveling after 40 years and now the farthest human-made object from Earth
- Every Space Shuttle mission from 1981-2011
- Navigational satellites supporting GPS and the Global Navigation Satellite System (GLONASS)
- The Hubble space telescope
- The International Space Station
- Rosetta and Philae, the European Space Agency comet orbiter and lander, respectively
- The Mars Rover
- Mangalyaan, the Indian Space Research Organization Mars orbiter
- KickSat, a group of 104 microsatellites launched on a single rocket into low Earth orbit in 2014

Former Texas Instruments researcher Mary Ellen Weber served as an astronaut on Discovery Space Shuttle mission space transportation system (STS)-70.

Numerous commercial, scientific and governmental satellites using Texas Instruments products have launched since 1958 and continue to launch weekly.

Through its acquisitions of Unitrode in 1999 and National Semiconductor in 2011, Texas Instruments added significant product breadth, expertise and technology to its internal space-grade semiconductor capabilities. Building on this long heritage in space flight, Texas Instruments continues to innovate and bring new products to the space ecosystem. Texas Instruments offers one of the industry’s broadest portfolios of ICs for space applications, covering a wide range of device types. Power management, data converters, amplifiers, clocks and timing, interface, processors, and sensors are just a few of the device types Texas Instruments provides for space electronics systems. Texas Instruments’ portfolio includes both Class-V qualified manufacturer list (QML) and radiation-hardness assured (RHA) ICs, demonstrating the company’s long-standing commitment to the space electronics market.
Chapter 1: Radiation environments

The type and magnitude of radiation effects observed in electronics are largely defined by specific device properties and the radiation environment in which the devices are used. In this chapter, we review three of the primary radiation environments: the natural space environment encountered outside the protective shielding of the Earth’s atmosphere; the natural terrestrial radiation environment in which most electronic applications operate; and the specialized man-made radiation environments encountered in some medical, industrial and military applications. In later chapters, we will deal with the different radiation effects and how they manifest in different device types.

1.1 The space radiation environment

Three sources of radiation define the space environment in our solar system:

- Galactic cosmic rays (GCRs), a nearly isotropic flux (same in all directions) predominantly comprising extremely energetic protons impacting the Earth from outside our solar system.
- Solar radiation, comprising a stream of lower-energy photons, plasma and magnetic flux that the sun emits continuously in all directions, like an ever-present “wind” of particles. This solar wind is punctuated by sporadic emissions from solar storms.
- Radiation belts, accumulations of energetic particles diverted and trapped into toroidal-shaped regions around planets in response to their magnetic fields.

Solar flares and coronal mass ejections (CMEs) generate localized intense particle bursts with much higher energies and fluxes than the steady-state solar wind.

- Radiation belts, accumulations of energetic particles diverted and trapped into toroidal-shaped regions around planets in response to their magnetic fields.

The reliability of microelectronic components in the harsh space radiation environment is characterized by the accumulation of ionizing and displacement damage dose (DDD), as well as a high rate of single-event effects (SEEs). The radiation exposure that on-board electronics receive is a function of the orbit of the spacecraft, the mission duration, the amount of shielding, and the number and magnitude of solar flares or CMEs that might have also occurred during the mission.[1-3]

The Earth's magnetic field has a varying effect on shielding space radiation, depending on the mission orbit.[4] Figure 1-1 shows the different orbit types and their properties. Leaving the Earth's surface, Figure 1-1 shows the low Earth orbit (LEO), a geocentric orbit with an altitude ranging from 0 to 2,000 km (1,240 miles). In order to keep a satellite in orbit with minimum energy, it is crucial to eliminate atmospheric drag, so practical Earth orbits begin at approximately 167 km (100 miles), and have an orbital period between one and two hours.

**Figure 1-1. Illustration of orbit types, shapes and properties.**
LEOs are relatively low-altitude orbits and thus the least expensive in terms of energy expended to achieve orbit. In LEO, round-trip signal distances are the shortest; signal communication delays are minimal, and surface details are better resolved than for higher orbits. The orbital periods of LEO satellites range from approximately 1 1/2 hours to a bit more than two hours.

Medium Earth orbit (MEO) is defined between LEO and geostationary orbit (GEO) at 35,786 km (22,236 miles). MEO is usually used for navigation (GPS), communication and science observation missions. The orbital periods of MEO satellites range from approximately two to nearly 24 hours.

Geosynchronous orbit (GSO) and GEO both match the Earth’s rotation, and thus complete one full orbit every 24 hours. A satellite in GSO stays exactly above the equator, while a satellite in GEO will swing north to south during its orbit. Any orbiting spacecraft with an altitude above GEO is considered to be in high Earth orbit (HEO). HEOs are orbits usually reserved for missions that need to get away from the heavy electromagnetic traffic present in lower orbits, such as those focused on monitoring deep space.

LEO – particularly equatorial orbits, where the magnetic shielding effect is maximized – provides the greatest benefit in terms of minimizing radiation effects. At higher altitudes, orbits such as MEO or GEO, and/or highly inclined orbits or polar orbits, the shielding provided by the Earth’s magnetic field is significantly reduced, leading to higher particle fluxes and a higher probability of more disruptive events. Missions with high inclinations or polar orbits will be exposed to higher fluxes and higher energy particles since the Earth’s magnetic shielding becomes less effective at higher/lower latitudes away from the equator. For interplanetary flights far from the Earth’s protective magnetic field, the spacecraft is exposed to the high fluxes of energetic particles.

Galactic cosmic rays

Before focusing on the local space environment of our solar system, consider the environment on a bigger scale. “Outer space” is often portrayed as a complete absence of material (empty space), but in actuality, even the vast seemingly empty spaces between the stars are filled with matter and energy. The material that occupies the space between the stars, called the interstellar medium, mostly consists of hydrogen, with a smaller fraction of helium and trace amounts of heavier elements, plus a smattering of dust. The interstellar medium is not a perfect vacuum, but has an extremely low density from $10^{-4}$ to $10^5$ atoms/cm$^3$. In stark contrast, our atmosphere has a density of $\sim 10^{19}$ atoms/cm$^3$.

The interstellar gas usually forms large “clouds” of neutral atoms or molecules. Near stars or other energetic bodies plus the dilute gas clouds become ionized. The gas in the interstellar medium is not static but moving, compressing or dissipating in response to the local interplay of magnetic, thermodynamic, gravitational and radiation processes. This turbulence drives the dynamic evolution of the interstellar gas, slowing or halting collapse over larger ranges while initiating local compression and star formation at more localized smaller ranges. Interstellar gas is both the substrate and the source of galaxies and stars.

The interplanetary medium of our solar system begins where the interstellar medium ends. The solar wind, or flux of energetic particles emitted continuously and spreading radially away from the sun, eventually slows down to subsonic velocities at a distance about twice the distance of Pluto’s orbit in a region known as the termination shock. In this region, the solar wind density is so low that it is effectively impeded by the “force” of the interstellar medium. The heliopause is the outer extent of the sun’s magnetic field and solar wind. Within the heliopause is the heliosphere, a spherical bubble that encompasses the sun and planets. The heliosphere acts as a giant electromagnetic shield, protecting the planets from some of the incident GCR flux. Cosmic-ray particles with less than ~50 MeV of kinetic energy are unable to penetrate within the heliosphere due to the energy of the solar wind within this volume, such that nearly 75% of the incoming GCR particles are stopped.

Figure 1-2 shows the heliosphere, heliopause and solar system. GCRs are a major part of the space radiation environment. As their name implies, GCRs originate outside of the solar system and consist of high-energy electrons and ions.

Scientists believe that GCRs accelerate due to high kinetic energies caused by shock waves from supernova explosions propagating in the interstellar medium. GCR composition consists of 89% ionized hydrogen (protons) and 9% ionized helium (alpha particles), with the remaining 2% consisting of heavier ions and electrons. The galactic magnetic field deflects the charged GCRs, thus accelerating them around circular paths – confining them to the disk of the galaxy.

Radioisotope dating has determined that most GCRs have been traveling in our galaxy for tens of millions of years. Their direction has been randomized over time such that they are isotropic. GCRs are traveling at a large fraction of the speed of light, with the majority of particles having kinetic energies of ~1 GeV. The GCR flux below ~100 MeV is deflected by the heliosphere. Above 1 GeV, the cosmic ray flux decreases fairly consistently with an increase in particle energy: the higher the energy of the particle, the rarer it is. The highest-energy cosmic rays measured have kinetic energies in excess of $10^{20}$ eV!
Sunspot activity that constitute the two poles of a magnet. Sunspot activity is regions of high magnetic field strength. They usually form in pairs as dark spots on the photosphere, are ultimately sinks back to the cooler interior (darker areas). Sunspots, which appear as dark spots on the photosphere, are regions of high magnetic field strength. They usually form in pairs that constitute the two poles of a magnet. Sunspot activity is transient, usually lasting for days to weeks. Sunspot activity follows an 11-year cycle characterized by approximately four years of relatively “inactive sun” where the number of sunspots is at a minimum, followed by seven years of “active sun” with increased numbers of sunspots. Sunspot activity is correlated to magnetic storms that produce the most harmful radiation.

Solar activity can be divided into three components: solar wind, solar flares and CMEs. The temperature of the sun’s corona is so high that solar gravity cannot keep the energetic particles from escaping. These particles, called the solar wind, stream out of the corona continuously in all directions at speeds ranging from 300-800 km/s. The solar wind consists of highly energized photons, electrons, protons, helium ions and a small number of heavier ions. Solar wind couples to the Earth’s magnetic field and produces storms in the Earth’s magnetosphere. Compared to intense sporadic solar-storm phenomena, the solar wind tends to be significantly less harmful to spacecraft electronics and crews, because most of the flux consists of much lower-energy particles, with a significant portion of the lower-energy flux deflected and trapped by planetary magnetic fields.

In stark contrast, coronal shock waves, prominences, solar flares and CMEs can have a large impact on microelectronic reliability by accelerating solar particles to much higher energies. When viewed head-on, flares manifest as sudden, rapid and intense variations in brightness, which occur when built-up magnetic energy is suddenly released. Flares occur around sunspots where intense and spontaneous discontinuities in magnetic field strength precipitate sudden releases of magnetic energy and plasma stored in the corona, literally shooting large chunks of the coronal surface into space with high velocity. During a flare event, radiation is emitted across the electromagnetic spectrum, from radio waves to gamma rays. As magnetic energy is released during the flare, electrons, protons and heavier nuclei are heated and accelerated to high kinetic energies. CMEs are often associated with solar flares and prominences. As with sunspot activity, the frequency of CMEs varies with the 11-year sunspot cycle. Flares and CMEs are much more frequent during the active phase of the solar cycle. For example, the frequency of CMEs at solar minimum is approximately one CME per week, while at solar maximum, the number of CMEs increases to a couple per day.
Of key concern are the solar energetic particles (SEPs), electrons, protons and heavier ions accelerated during solar flares or CME-induced shock waves. During such events, the intensity of SEPs can increase by hundreds to millions of times. The maximum energy reached by SEPs is typically somewhere in the range of 1 MeV to 1 GeV.

Figure 1-6 shows example spectra comparing solar wind, SEP and GCR proton events. Since flare and CME events are highly directed, they affect a relatively small region of space, but are characterized by very high particle fluxes lasting hours to days.[7-12] The fluxes can exceed the normal space radiation levels by many orders of magnitude. For example, CMEs can generate in excess of 500,000 protons-cm-2sec-1. Being caught in a flare or CME is hazardous to crews and microelectronics in space vehicles – an example of being in the wrong place at the wrong time.

Radiation belts

Radiation belts can form around any planetary body that has a magnetic field (magnetosphere) of sufficient strength to divert and capture particles before they can enter the planet’s atmosphere. The radiation belts consist of captured particles from the solar wind as well as lower-energy GCRs. Mercury, Venus and Mars have weak or insignificant planetary magnetic fields; thus, these planets do not trap appreciable radiation and do not appear to have belt structures.

Despite having magnetic fields similar to Earth’s, Saturn and Uranus trap much less radiation in their belts. In contrast, Jupiter has an extremely powerful magnetic field – more than 10x that of Earth – that creates a radiation belt system considerably larger and more intense than Earth’s. The Earth’s magnetic field collects and traps protons and electrons, creating doughnut-shaped (toroidal) concentrated regions of trapped charged particles in the vicinity of Earth. These belts were discovered by Dr. James Van Allen and a team of scientists in a series of experiments starting with the Explorer I mission in 1958, the United States’ first artificial satellite.

Figure 1-7 is a simplified illustration of the two concentric belts of radiation trapped by the Earth’s magnetic field.

The belts are thicker at the equator where the Earth’s magnetic field is strongest (where it is parallel to the surface) and get thinner at higher and lower latitudes. They disappear totally at the poles where the Earth’s magnetic field becomes oriented normal to the Earth’s surface.[13] The inner belt contains high concentrations of electrons with kinetic energies of ~1-5 MeV and protons with kinetic energies ~10 MeV. The outer belt consists mainly of electrons with kinetic energies of ~10-100 MeV. The outer belt’s particle population fluctuates dramatically in response to solar activity.

In general, since the radiation belts are regions where radiation exposure will be greatly increased, travel through them is minimized or avoided whenever possible. LEOs are safely below the radiation belts and hence are the most benign, limited to a region of relatively low particle flux. LEOs are also partially shielded from GCRs by the belts.
An occasional transitory third radiation belt has been recently observed\textsuperscript{[14]} that forms and dissipates by temporarily splitting off from the outer belt. The omnidirectional particle fluxes within the inner and outer belts peak at approximately $10^4$-$10^6$ cm$^{-2}$-sec$^{-1}$. In contrast, the flux of particles between the Earth’s surface and inner belt is $10$-$100$ cm$^{-2}$-sec$^{-1}$, while in the region between the two belts, it is $\sim10^3$-$10^4$ cm$^{-2}$-sec$^{-1}$. The Earth’s magnetic field is tilted about 11 degrees from the rotation axis. As a result, the radiation belts do not align exactly with the Earth’s surface. This asymmetry causes the inner belt, with a nominal altitude of 1.3 km, to drop to 200-800 km in a specific region. This extension of the inner belt to lower altitudes is located over South America off the coast of Brazil, and extends over much of South America (as shown in Figure 1-8), forming the so-called South Atlantic Anomaly (SAA).\textsuperscript{[15]} While the particle fluxes in the SAA are significantly lower than at higher altitudes deeper within the belt, they are significantly higher than anywhere else in the Earth’s orbit at that altitude. For example, most of the radiation dose exposure that the International Space Station receives occurs while it flies through the SAA. The SAA is shown in the cross-section and external view in Figure 1-8.

While the electrons and protons trapped in the belts have much lower energies than most GCRs or SEPs, the much higher flux levels are dangerous to crew and electronics if they are exposed for extended periods. Mission orbits/paths are therefore specifically tailored to minimize the spacecraft’s exposure time to radiation belts because of high particle fluxes. Minimizing exposure to the radiation belts greatly reduces the rate of SEEs and the accumulation of dose effects. Additionally, in some cases, electronics are powered down during the times when they are in the radiation belts to reduce total ionizing dose (TID) effects, which are made worse by the presence of electric fields.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{saa.png}
\caption{Cross-section view.}
\end{figure}

\textit{Figure 1-8. Cross-section showing the extent of inner-belt ingress at the SAA (left), and the location and extent of SAA relative to the globe (right).}\textsuperscript{[18]}
1.2 The terrestrial radiation environment

The terrestrial radiation environment exists within the Earth’s atmosphere, from sea level to flight altitudes (typically up to a maximum of 13 miles or 22 km) and at all latitudes and longitudes. Three sources of radiation dominate microelectronic reliability failures in the terrestrial environment:

- Very localized alpha-particle radiation (<50 μm from active silicon devices), emitted by the natural radioactive decay of unstable isotopes like uranium, thorium and their daughter isotopes.
- High-energy cosmic-ray neutron radiation, produced as a byproduct of nuclear reactions between galactic and solar high-energy protons with the nitrogen and oxygen nuclei in the Earth’s atmosphere. The resulting neutron flux depends on the altitude, latitude, longitude and solar activity.
- The interaction of low-energy cosmic-ray neutrons with an unstable isotope of boron (10B) in a microelectronic device.

SEEs dominate microelectronic reliability in the terrestrial environment. Most reliability failures are related single-event upsets (SEUs) – the flipping of digital bits in memories and sequential logic and the occasional single-event latchup. Additionally, in high-voltage power devices, single-event burnout can be a reliability concern in the terrestrial environment.

TID and displacement damage (DD) are not considered major effects in the terrestrial environment because neutron and alpha-particle event rates are simply too low to cause an appreciable accumulation of dose for typical electronic product lifetimes (decades). The reliability of microelectronics in the terrestrial environment is thus the sum of failures induced by the three natural radiation mechanisms: alpha particles, which are localized within a few tens of microns from active device areas; nuclear reactions between nuclei in the device and penetrating high-energy cosmic-ray neutrons; and nuclear reactions induced by low-energy cosmic-ray neutrons and 10B. In order to accurately determine the reliability impact of SEEs on any device, you must account for the contribution of each of the three components in the terrestrial environment.

Alpha particles

A significant source of ionizing radiation in microelectronic devices comes from alpha particles emitted by the decay of naturally occurring radioactive impurities.\textsuperscript{17,18} Radioactive impurities are present in trace amounts in the materials used to manufacture and package microelectronic devices. The natural radioactive decay process that produces alpha particles is the result of a spontaneous breakdown of heavy nuclei that do not have enough nuclear binding energy to hold the nuclei together, rendering these nuclei unstable.

The ratio of neutrons to protons must fall within a certain range for an element to be stable. Unstable nuclei emit radiation usually in a multistep process, until a stable ratio of nucleons is reached. Nuclear decay occurs with the emission of an alpha particle, a beta particle, a gamma photon, a positron or the nuclear capture of an inner electron.

Of these processes, the emission of alpha particles is the primary radiation of concern because alpha particles are the most highly ionizing and therefore the most potentially damaging to the operation of microelectronic devices. Although there are many radioactive isotopes, uranium and thorium and their associated daughter products have the highest activities of the naturally occurring radioactive species. They are therefore the dominant source of alpha particles in materials. Uranium and thorium are both heavy elements, and it takes multiple decays into successive unstable daughter products to ultimately shed enough excess nuclear mass for them to become stable isotopes of lead.

Figure 1-9 shows the full decay chain for the $^{232}$Th thorium isotope.

\begin{center}
\begin{tabular}{c}
\textbf{Figure 1-9. Radioactive decay chain showing all daughters of a $^{232}$Th parent isotope.}
\end{tabular}
\end{center}
The time listed below each isotope in Figure 1-9 is the time that it would take for half of a large population of that isotope to decay. An equilibrium population of $^{232}$Th will emit six alpha particles with energies from 4.081-8.955 MeV. The decay chain for the $^{238}$U uranium isotope is similar (although the daughters are different), emitting eight different alpha particles with kinetic energies ranging from 4.270-7.833 MeV.

When considering a large population of a specific unstable isotope, one key characteristic of the rate of decay is the average decay time. It is impossible to predict when a single specific unstable nucleus will undergo decay because it is a completely random process defined by quantum mechanics. However, when a large ensemble of unstable nuclei is present, the time for a specific fraction to decay is very well-defined.

The fraction of interest is set to 50%, indicating the time for 50% of the initial population of nuclei to decay. This is referred to as the half-life. Radioactive decay is a simple exponential decay process; after a time period of one half-life, only 50% of the original population remains. After two half-lives, 50% of the remaining 50% decays, so the population is 25% of its initial size, and so on.

The longer the half-life, the longer it takes for an isotope population to decay. A longer half-life therefore implies a lower activity, measured in decays/time. Equation 1-1 is a simple equation for the exponential decay of an initial population, $N_i$, of unstable nuclei. Equation 1-2 relates the activity, $\lambda$, to the half-life, $\tau_{1/2}$:

$$N(t) = N_i \cdot e^{-\frac{\tau_{1/2}}{t}}$$

*Equation 1.1.*

$$\lambda = \frac{\ln 2}{\tau_{1/2}}$$

*Equation 1.2.*

The alpha particle emitted during a decay event consists of two neutrons and two protons – a doubly ionized helium atom (\(^{4}\text{He}^{2+}\)) – emitted with an energy in the range of 4 MeV to 9 MeV. The original unstable nucleus is therefore transformed by the emission of the alpha particle into a nucleus whose mass number is reduced by four (a loss of four nucleons) and whose atomic number is reduced by two (a loss of two protons).

The alpha-particle emission energy is specific to the nucleus that is emitting it, with each unstable isotope having a single unique alpha-particle emission energy (and in a few cases, several closely spaced emission energies). For a sample of $^{232}$Th in equilibrium, a single alpha-emission energy or set of energies will be observed for each alpha decay. Figure 1-10 shows the alpha-emission spectrum from a thin film of $^{232}$Th.

Of course, in a real situation in which the alpha emitter is a trace impurity in the die or packaging materials, it will be distributed in different layers, materials and concentrations. Thus, the distinct energy “lines” shown in Figure 1-10 will not be visible because the emission can occur anywhere within the metal film. The distinct lines are broadened to lower energies because energy is lost as the alpha travels from where it was emitted. Figure 1-11 shows the alpha-particle energy spectrum as it would look at the silicon surface after having been emitted from various locations within a complex package representing a distributed alpha source.

![Figure 1-10. Simulation of the alpha emission from a thin layer of $^{232}$Th source material illustrating the discrete alpha energies.](image)

![Figure 1-11. Simulation of the alpha-particle spectrum at the active device surface from all sources within a packaged device.](image)
Alpha emissions from impurities in package mold compound or underfill, which are essentially “thick” sources, produce a broadened alpha-particle spectrum. A notable exception of this broadening occurs if the alpha source is confined to a thin layer, so that all of the alpha-particle emission essentially occurs at or very near the surface. One example of a thin source would be the residue of alpha-emitting impurities left after a wet-etch with certain batches of phosphoric acid or surface emission from solder bumps. It has been reported that the primary alpha-emitting impurity (210Po) in standard lead-based solders segregates to the surface of solder bumps. This effect would also lead to a sharp spectrum.

Comprehending the shape of the energy spectrum of the alpha particles incident on a silicon device is crucial in accurately determining the type and rate of SEEs. Indeed, the probability that an alpha particle causes a soft error is based largely on its energy and trajectory. The wrong assumption about the alpha-particle energy spectrum can lead to a significant overestimation or underestimation of the SEE rate from accelerated experiments. The activity of a particular isotope is directly proportional to its natural abundance and inversely related to its half-life. Secular equilibrium is only valid if the material has not undergone any chemical separation, because under such conditions, the various isotope concentrations can become depleted or enriched.

Because virtually all semiconductor materials are highly purified, in general, alpha-emitting impurities will not be in secular equilibrium (a situation in which a quantity of a radioactive daughter product remains constant because its production rate by decay of a parent is equal to its decay rate). Simply accounting for the amount of 238U and 232Th trace impurities present in the material will not guarantee that the alpha emission rate is below a certain level, because the daughter concentrations can be very far from equilibrium, and in many cases undetectable. In other words, low 238U and 232Th levels are necessary but not sufficient to ensure that a material has low alpha emissions. Thus, alpha-counting investigations are necessary to determine the alpha-particle flux from materials. Bateman equations can be used to calculate nonequilibrium daughter concentrations.

Table 1-1 summarizes alpha-particle emissions from some key production materials determined by high-sensitivity (large-area) alpha counting. The alpha emission rates are reported at a 90% confidence level. Depending on grade and type of material, a large range of alpha-emission rates exists.

<table>
<thead>
<tr>
<th>Material</th>
<th>Emissivity (a/cm²-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully processed wafers</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>30-µm-thick Cu metal (UBM)</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>20-µm-thick AlCu metal</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Packaging mold compound</td>
<td>&lt;0.024 - &lt;0.001</td>
</tr>
<tr>
<td>Flip-chip underfill</td>
<td>&lt;0.002 - &lt;0.001</td>
</tr>
<tr>
<td>Eutectic Pb-based solder</td>
<td>&lt;7.200 - &lt;0.002</td>
</tr>
</tbody>
</table>

Table 1-1. Typical alpha-emission rates from various materials.
High-energy cosmic-ray neutrons

The second significant source of SEE in microelectronics in the terrestrial environment is related to high-energy cosmic-ray neutrons. “High energy” in this case defines neutrons with energy ≥1 MeV. As noted in the section on space radiation, the Earth’s upper atmosphere is bathed in radiation from primary GCRs with E_{max}>1 GeV and SEPs with E_{max}<1 GeV. They consist of 92% protons, 6% alpha particles (He), and 2% gamma photons and heavier nuclei.

Coulombic interactions in the upper atmosphere quickly stop the alpha particles and heavier ions, leaving only the high-energy protons to react in the upper atmosphere. The protons undergo nuclear reactions via strong force, with oxygen and nitrogen nuclei producing huge and complex cascades of “secondary” particles that shower down through the atmosphere to the Earth’s surface. The reaction products or secondaries include short-lived pions and kaons that decay into muons, neutrons and gamma rays, as well as electrons and positrons produced by muon decay and follow-on interactions between gamma-ray photons and other atmospheric atoms. Figure 1-12 illustrates a schematic of a cascade.

Figure 1-12. Particle cascade or “shower” created when a high-energy cosmic-ray proton interacts with a nitrogen or oxygen nucleus in the upper atmosphere. Image courtesy of International Business Machines Corp., © International Business Machines Corp.

Less than 1% of the primary flux reaches sea level. The predominant particle fluxes at sea level include muons, protons, electrons, neutrons and pions. Due to their relatively high flux and stability, the neutrons are the most likely cosmic radiation to cause SEEs in devices at terrestrial altitudes. Pions and muons are short-lived, and the lower-energy protons and electrons are effectively attenuated by Coulombic interactions.

Figure 1-13 shows the differential energy spectra for the primary cosmic-ray particles encountered at sea level. These curves define the number of particles at any given energy that are incident on a microelectronic device (or anything else) at sea level. Ultimately, the Earth’s atmosphere can be considered a thick filter layer of reactive matter that converts the high flux of incident cosmic-ray protons into a lower flux of lower-energy terrestrial neutrons. Significant numbers of cosmic-ray muons and protons are also produced, but their impact on microelectronics is much less significant.

![Differential flux for the primary cosmic-ray particles at sea level. The total flux of muons is actually higher than that of neutrons, but muons are less able to generate errors.](image)

If the neutron curve in Figure 1-13 is replotted as the neutron flux times the neutron energy, then the areas under the spectral peaks represent similar fluxes. The replotted neutron spectrum shown in Figure 1-14 has three broad peaks:

- A high-energy peak centered around 100 MeV, which is defined by the highest-energy cosmic-ray neutrons reaching sea level.
- A peak centered around 2 MeV and attributed to nuclear reactions between secondary and tertiary cosmic-ray particles and oxygen and nitrogen nuclei – the so-called nuclear evaporation peak.
- A neutron peak at the lowest energy that comprises neutrons that have been slowed down by scattering and are in thermal equilibrium with atoms in surrounding materials.
Altitude can have a significant impact on the rate of SEEs. For microelectronic devices used at flight altitudes, the cosmic-ray flux can be hundreds of times higher than it is at sea level; thus, neutron-induced events dominate reliability in avionics.

Latitude, or, more specifically, geomagnetic rigidity as a function of geographical location, is a secondary factor that can modulate the neutron flux by about 2x at terrestrial altitudes and ~5x at commercial flight altitudes. The neutron flux increases from equatorial to polar regions. The Earth’s magnetic field deflects incoming cosmic-ray protons from equatorial regions where the field is parallel to the Earth’s surface. But in areas where the field orientation approaches normal incidence at the poles, the magnetic field provides only weak shielding at north/south magnetic latitudes in excess of 55 degrees. Figure 1-16 shows the neutron flux as a function of latitude.

The third and weakest variable modulating the terrestrial neutron flux is the solar activity cycle. Solar activity usually accounts for <±30% variations in neutron flux. Because the neutron flux at terrestrial altitudes is linked to the proton flux incident on the upper atmosphere, it follows that solar activity will have some impact on the neutron flux at sea level. In times of “normal” solar activity, where the activity increases relatively slowly, the upper atmosphere has time to respond to changes in conditions and becomes more highly ionized, thereby creating an electrostatic repulsion field that actually deflects a greater number of incoming protons.

As might be expected, the increased shielding effect during high solar activity reduces the number of protons that get into the atmosphere, thus producing fewer neutrons (muons, etc.). So for typical high solar activity, the neutron flux at terrestrial altitudes is reduced.

Occasionally, sporadic flares and CMEs can occur so suddenly that the Earth’s ionosphere cannot respond quickly enough. The ionospheric charging and resulting screening effect do not have time to respond, so the terrestrial neutron flux actually increases during such short-lived events. Figure 1-17 shows the terrestrial neutron flux as a function of solar activity cycle under longer-term variations.
High-energy neutron interactions with silicon and other chip materials are extremely complicated and depend on the energy of the incident neutrons. One of the primary reactions by which cosmic-ray events induce SEEs in microelectronics is the neutron-induced silicon recoil (elastic and inelastic). When neutrons with kinetic energies in excess of about 100 keV collide with silicon nuclei, enough of their energy can transfer to the nucleus to knock it from its position within the silicon lattice (this is also an example of DD discussed in Chapter 3, although in this case the event rate is simply too low to produce a dose effect), generating enough charge through Coulombic interactions to upset many microelectronic technologies.

For incident neutrons with energies above about 2 MeV, a host of nuclear reaction pathways become viable. In these reactions, the silicon nucleus absorbs the neutron in an inelastic reaction that produces a burst of highly ionizing secondary products. The original nucleus breaks apart into energetic fragments, including a heavy recoil nucleus and lighter ions and/or nucleons, each of which can potentially induce SEEs or other nuclear reactions. As neutron energies increase above 100 MeV, the wavelength of the neutron is so small that it no longer interacts with the entire nucleus, but actually exchanges its energy with single nucleons in a process called spallation. In spallation, the secondaries produced are individual nucleons ejected by an incoming neutron. All neutron reactions occur at a rate defined by the neutron flux, the energy of each neutron and the neutron reaction cross-section, which also has a function of key variables can be found at http://www.seutest.com/cgi-bin/FluxCalculator.cgi for sea-level NYC neutron flux (>10 MeV) of 13 n/cm²-hr. Assuming an area of 1 cm² for the device, you can expect 13 neutron events per hour or 0.0036 neutrons per second at sea level — much more if the device operates at higher altitudes or latitudes.

If every neutron caused an SEE, the microelectronic device would suffer a failure rate of approximately 3.6 million FIT. However, since neutrons do not have charge, they cannot directly ionize silicon. In other words, the actual event rate will be defined by the flux of neutrons and the neutron reaction cross-section for the materials through which the neutrons are traveling. Cross-sections vary tremendously with neutron energy and material, but in general for silicon (assuming a rough cross-section for reactions that can cause secondary products with enough energy to create SEEs), an estimated one SEE is observed per 1,000 to 10,000 neutrons. Thus, the neutron-induced SEE rate drops to approximately 3,600 to 360 FIT for a 1-cm² device.

Unlike alpha-particle mitigation schemes focused on the purification of materials, keep-out zones and/or shielding layers, the ever-present cosmic-ray neutron flux cannot easily be reduced at chip level with die shields, keep-out zones or high-purity materials. Simulation has shown that hydrogen-rich materials such as concrete (due to its relatively high moisture content) can offer some reductions in cosmic-ray neutron flux — approximately a fourfold reduction per meter of concrete thickness.

Neutron detector studies confirm that in the basements of concrete buildings, reductions of cosmic-ray neutron flux as high as an order of magnitude are possible. While hiding out in a basement location may be a viable option for mainframes, server farms and supercomputer clusters, for personal desktop applications or portable electronics, little can be done to reduce SEEs produced by high-energy neutron events. Designers must therefore deal with cosmic-ray SEEs by reducing the sensitivity of microelectronics, either by design or process modifications.

Low-energy cosmic-ray neutrons and ¹⁰B

The third significant source of ionizing particles in some microelectronic devices is the secondary radiation induced from the interaction of low-energy cosmic-ray neutrons and ¹⁰B. While the previous discussion focused on high-energy neutron reactions, this reaction is dominated by low-energy neutrons that have been thermalized by numerous interactions with materials around them (~0.025 eV). This affects only devices with large concentrations of a certain isotope of boron. Boron is used extensively as a P-type diffusion and implant species in silicon, in the formation of boron-doped phosphosilicate glass (BPSG) (2%-8% by weight) dielectric layers. Boron is used as a formation or carrier gas for several processes. While implantation processes tend to be fairly mass-specific and usually implant ¹¹B, diffusion and gas processes typically use boron that has not been isotopically separated. Boron consists of two isotopes: ¹¹B (80.1% abundance) and ¹⁰B (19.9% abundance). The ¹⁰B is unstable when exposed to neutrons. ¹¹B also reacts with...
neutrons; however, its reaction cross-section is nearly 1 million times smaller, and its reaction products (gamma rays) generally do not cause problems. The thermal neutron capture cross-section of $^{10}$B is extremely high compared to most other isotopes present in semiconductor materials (three to seven orders of magnitude higher), as illustrated in Figure 1-18.

Unlike most isotopes that emit relatively harmless gamma photons, after absorbing a thermal neutron, the $^{10}$B nucleus breaks apart with an accompanying release of energy in the form of an excited $^7$Li recoil nucleus and an alpha particle. A prompt gamma photon is also emitted from the lithium recoil soon after fission occurs. In the $^{10}$B(n,a)$^7$Li reaction, the alpha particle and lithium nucleus are emitted in opposite directions to conserve momentum. The lithium nucleus is emitted with a kinetic energy of 0.840 MeV 94% of the time and 1.014 MeV 6% of the time. The alpha particle is emitted with an energy of 1.47 MeV, as shown in Figure 1-19.

The lithium recoil has a peak LET of 25 fC/µm, while that of the alpha particle is 16 fC/µm. In most cases, calculations have shown that the range of the alpha particle and lithium recoils in silicon and silicon oxide is very limited: less than 1.5 mm. If the reaction occurs more than 1 mm away from sensitive device nodes (deeper in the substrate or in the layers over the silicon), neither the lithium recoil nor alpha particle will have sufficient energy to induce SEEs.

Figure 1-20 shows the lineal charge generation and range of both secondary products. Generally, only $^{10}$B in close proximity to the active silicon layer needs to be considered. For conventional semiconductor processes, BPSG is the dominant source of boron reactions, and in some cases can be the primary cause of soft errors. The alpha and the lithium recoils are both capable of inducing SEEs in microelectronics, particularly in advanced low-voltage technologies. The event rate from the $^{10}$B(n,a)$^7$Li mechanism is a function of the thermal neutron flux, the thermal neutron cross-section for the reaction and the amount of $^{10}$B in the device close to the active silicon device layers. Several groups have measured the terrestrial thermal neutron flux and it is between 4-20 n/cm²-hr, basically a little less or similar in magnitude to the high-energy neutron flux. The $^{10}$B(n,a)$^7$Li reaction has a thermal neutron cross-section of 3,838 barns (1 barn = 10⁻²⁴ cm² per nucleus).

Assuming a 1-cm² device area covered with a 1-mm layer of BPSG doped with 8% boron, an upper bound for the SEE event rate can be calculated by assuming that one of the two secondary products will produce a detectable SEE. Because the secondaries are emitted in opposite directions, only one of them will traverse the active devices. Actually, since the secondary products will be emitted in or near the active silicon device volumes, it is very likely that each event will be capable of upsetting a sensitive volume. In any case, using the assumptions above, an event rate of 0.0126 reactions/hr-cm² is the upper bound, or, assuming that each event is an upset, a failure rate of 17 kFIT. Clearly, this is an overestimation, but compared to

![Figure 1-18. Comparison of thermal neutron capture cross-sections for $^{10}$B and several common semiconductor materials. This plot demonstrates the anomalously high thermal neutron reaction cross-section of $^{10}$B. Note, a “barn” is a nuclear physics unit of area equivalent to $10^{-24}$ cm².](image18.png)

![Figure 1-19. Capture of a thermal neutron by a $^{10}$B nucleus and the secondary products: an alpha particle, a lithium recoil nucleus and prompt gamma photon.](image19.png)

![Figure 1-20. Differential charge generation and range in silicon as a function of particle energy from the alpha particle and lithium recoil produced by the $^{10}$B(n,a)$^7$Li reaction.](image20.png)
the other two mechanisms (the terrestrial thermal neutron flux and the alpha particles), the $^{10}\text{B}(n,a)^{7}\text{Li}$ mechanism can cause reliability issues in microelectronics that have BPSG layers close to the silicon substrate, or those that use borane-based fabrication processes and leave $^{10}\text{B}$ residue near the active silicon.

It’s possible to mitigate SEEs caused by the activation of $^{10}\text{B}$ in BPSG in several ways. The first and most direct is simply to eliminate BPSG, borane or other boron-containing compounds from the process flow. Due to the limited range of the alpha and lithium recoil emitted during the $^{10}\text{B}(n,a)^{7}\text{Li}$ reaction, there is no need to replace or modify concentrations of $^{10}\text{B}$ outside this range because the secondary products will never reach active silicon. In cases where the unique reflow and gettering properties of boron are needed, or the boron compound is required in the process, the boron source material should be replaced with one enriched with $^{11}\text{B}$, thereby mitigating $^{10}\text{B}$ without changing the desired physical or chemical properties and without requiring new equipment or processing steps.

Finally, if the process cannot be changed, such as in the case of a foundry process, the packaging materials can use materials rich in $^{10}\text{B}$ to provide a thermal neutron shield. For example, in a plastic molded package, the silica filler could be doped with $^{10}\text{B}$, thus providing effective shielding for thermal neutrons. Because the resultant secondary alpha-particle and lithium recoils only have a range of <2 μm, they would be completely absorbed by the silica and mold compound or die materials long before any of the radiation would reach the sensitive active silicon device volume.

### 1.3 Artificial radiation environments

This section focuses on man-made artificial radiation environments, situations where microelectronics are exposed to – and must function in – radiation environments produced in a host of medical, industrial and defense applications. In medical applications, the radiation exposure occurs most often in diagnostic or treatment equipment such as X-ray and proton-beam therapy machines. High doses of electron-beam (e-beam) or gamma-ray irradiation are also used for sterilizing surgical instruments and implantable electronics in operating rooms.

There are numerous industrial uses of radiation. A wide range of applications rely on X-ray, gamma- and e-beam irradiation, from waste treatment to inspection to security screening. Microelectronics are exposed to doses of neutrons and gamma rays when used in high-radiation areas inside nuclear power plants. In the defense environment, electronics must be hardened against brief but intense gamma-ray and neutron exposures, as well as against follow-on electromagnetic pulse (EMP) effects from nuclear detonations. For microelectronics in most medical and industrial applications, TID is the primary radiation effect concern, while in the defense environment, the concern includes the full spectrum of SEEs, TID, DDD and prompt-dose (high-dose-rate) effects.

**Medical radiation environments**

In the medical field, devices that produce X-rays are ubiquitous, from simple dental X-ray machines to full-body scanners (dental X-rays, fluoroscopes, computerized axial tomography [CAT] scanners, etc.). Figure 1-21 shows an evacuated tube with electrodes at each end producing X-rays. One electrode, the filament, is heated by running a high current through the wire filament. The filament current is the source of electrons for the acceleration process that produces the X-rays. The heated wire emits electrons from the surface of the wire, which is excited by thermionic emission.

![Figure 1-21. Cross-sectional diagram of an X-ray tube.](image)

In this process, the electrons gain enough kinetic energy from heating to be able to overcome the work function of the material, which is the energy required to liberate an electron from inside a material. The filament itself is surrounded by a grounded metal cup with an aperture at the end, facing the other electrode. The other electrode, the target, is biased with a high positive voltage with respect to the filament cup (usually 10-150 KeV) such that the high electric field immediately sweeps the electrons emitted through the aperture in the cup toward the target electrode. Because the electrons are traveling in a vacuum, they suffer no energy-robbing collisions with gas molecules and thus are accelerated to high energies by the field.

When these energetic electrons collide with the target (usually a high-z metal such as tungsten), various scattering effects (see Chapter 2) produce X-rays. The target is usually canted at an angle to enable the X-ray radiation to radiate out of the side of the tube, unobstructed. The amount of radiation exposure in diagnostic applications near the equipment or in the patient is not high enough to pose a risk to microelectronics because the X-ray dose is tightly controlled (humans are much more sensitive to radiation exposure than electronics), and the X-ray equipment is heavily shielded so that no X-rays radiate outside the target treatment area.

As an example of a typical patient dose, consider the very popular computer tomography (CT) or CAT scanner, which provides cross-sectional images of the body constructed from a series of multiple X-ray exposures from different radial positions, as illustrated in Figure 1-22.[45] This type of diagnostic will usually give a maximum X-ray dose, as a large number of X-ray exposures is required to build up the image.
Table 1-2 shows a comparison of the patient dose received as a function of the type of X-ray diagnostic. The unit of millisieverts (mSv) defines an “effective dose” received from radiation exposure based on different tissue types and their relative sensitivity to specific types of radiation. To put this into perspective, with regards to doses relevant to microelectronics, 1 mSv is equivalent to 0.1 rad(Si).

For a microelectronic device implanted in a patient, given a single CT abdomen scan, you would expect a maximum dose of ~2 rad(Si). Even the weakest commercial electronics would not be sensitive to such a low dose.

What about SEEs occurring during irradiation? To be certain that CT scans do not interfere with implanted devices, several medical studies used CT scanner X-rays to directly irradiate the electronics of pacemakers and cardio defibrillators (simulating a coronary CT angiography or multipass abdomen CT scan). While some did report “electronic interference,” the probability that this interference would cause clinically significant adverse events was deemed extremely low.

For example, the interference observed on an internal node did not translate into a functional interruption during irradiation.

It is possible to completely avoid the risk of any interference when the implantable device is outside the primary X-ray beam of the CT scanner. In general, microelectronics implanted in patients are unlikely to be exposed to any radiation that would damage them because of the high-dose sensitivity of the human body compared to silicon devices.

The one medical environment where microelectronics may be exposed to high chronic doses of X-rays is in the solid-state detectors and supporting electronics housed inside of an X-ray machine. In these locations, the patient receives an X-ray dose; therefore, a single exposure will represent a relatively low dose. However, the fact that the machine is used on many patients over hours, days, months and years of service means that internal electronics can accumulate high TIDs.

Vendors of such equipment alleviate this problem by ensuring that metal of sufficient density/thickness shields all microelectronics that are not physically part of the actual imaging, so that X-ray exposure is minimized or eliminated completely. Image sensors will necessarily be exposed to X-rays and will accumulate significant doses over time. In cases such as these, even well-designed or radiation-hardened imagers and support circuits will likely suffer dose effects and will need to be replaced occasionally. Since dose failures involve the shifting of device parametrics over dose (time), self-test startup routines can detect when an imager is reaching its end of life and alert users that a replacement is required.

In the medical environment, there is an increasing use of ionizing radiation to sterilize surgical instruments and implantable devices that would otherwise be damaged by the high temperature and humidity of autoclave sterilization. Sterilization by irradiation with e-beams, X-rays and gamma rays works because the radiation has sufficient energy to ionize atoms. Ionization directly damages DNA and creates reactive free radicals. One major free radical forms when the ionizing radiation breaks the covalent bond between two oxygen atoms in an oxygen molecule (O₂). The two oxygen-free radicals are energetically predisposed to find an additional electron, causing them to become highly reactive. The free radicals cause additional damage to the cell and further degrade its DNA.

Table 1-2. The effective doses of various diagnostic X-ray procedures.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT-abdomen and pelvis, repeated</td>
<td>20 mSv</td>
</tr>
<tr>
<td>with/without contrast</td>
<td></td>
</tr>
<tr>
<td>CT – colonography</td>
<td>6 mSv</td>
</tr>
<tr>
<td>Coronary computed tomography</td>
<td>12 mSv</td>
</tr>
<tr>
<td>angiography (CTA)</td>
<td></td>
</tr>
<tr>
<td>Radiograph – lower GI tract</td>
<td>8 mSv</td>
</tr>
<tr>
<td>Radiograph – spine</td>
<td>1.5 mSv</td>
</tr>
<tr>
<td>Radiograph – extremity</td>
<td>0.001 mSv</td>
</tr>
<tr>
<td>CT – chest</td>
<td>7 mSv</td>
</tr>
<tr>
<td>CT – lung cancer screening</td>
<td>1.5 mSv</td>
</tr>
<tr>
<td>Radiograph – chest</td>
<td>0.1 mSv</td>
</tr>
<tr>
<td>Dental intraoral X-ray</td>
<td>0.006 mSv</td>
</tr>
<tr>
<td>Bone densitometry (DEXA)</td>
<td>0.001 mSv</td>
</tr>
<tr>
<td>Mammography</td>
<td>0.4 mSv</td>
</tr>
</tbody>
</table>

For a microelectronic device implanted in a patient, given a single CT abdomen scan, you would expect a maximum dose of ~2 rad(Si). Even the weakest commercial electronics would not be sensitive to such a low dose.

Figure 1-23 shows the DNA of the cell’s control and reproduction mechanism being affected by radiation. With a sufficient dose, enough damage accumulates such that the cell no longer functions properly, cannot reproduce and ultimately dies.
Studies on inactivating viruses and bacteria by ionizing radiation indicate that a single exposure is sufficient to sterilize a sample, provided that the dose is high enough. Because no patient is involved and the bacteria and viruses must be neutralized to a very high degree (usually to $10^{-6}$ or better), sterilization using radiation is performed at extreme dose levels – a maximum dose considered to fully sterilize a sample is ~50 kGy (5 Mrad). This type of dose actually exceeds most defense and space application requirements and thus poses a real challenge for any microelectronics located in a piece of equipment that must be sterilized. However, most electronics in devices being sterilized will be powered down during irradiation, which can significantly reduce the amount of charge trapped and somewhat lessen the effective dose.

The medical radiation environment is primarily limited to X-ray, gamma-ray or e-beam exposures. Proton-beam therapy is also used for cancer treatments, but these are characterized by highly focused, targeted exposures that deliberately steer clear of implanted electronics. It is unlikely that medical microelectronics implanted in a patient would suffer permanent dose-related damage because the irradiation is limited by dose allowances that patients can tolerate (very low dose levels). Even microelectronics inside X-ray machines or other devices that produce ionizing radiation are usually shielded to keep the dose to a manageable level.

Electronics that must be in a radiation beam (like imagers) constitute the primary exception. They will eventually accumulate enough doses that they may need to be replaced occasionally. The radiation doses encountered in medical sterilization applications are also extremely challenging, and most microelectronics will not be able to tolerate these dose levels without being shielded or radiation-hardened. TID effects are the primary concern for microelectronics used in medical instrumentation or implantable devices sterilized with ionizing radiation.

**Industrial radiation environments**

Industrial applications use radiation extensively: in the processing of materials to induce chemical/physical changes, in the sterilization of food and waste, for the inspection and monitoring of physical properties of materials, for the mitigation of static in assembly processes, in the defect inspection of manufactured components, and in security screening applications. Some examples of industrial radiation applications are shown in Figure 1-24.

Radiation sources for industrial applications include many types and geometries of sealed sources containing radioactive materials that emit radiation continuously and machines that produce radiation by accelerating particles (e-beam and X-ray machines). The sealed sources are usually encapsulated in metal shields, with a shuttered port or window that allows the radiation out. Sealed gamma-ray sources most commonly use cobalt-60 (half-life ~5.2 years) and have an advantage in that they do not require external power to generate radiation.

The spontaneous fission of Californium-252 or sources that combine a source of alpha particles with light (low-z) metals such as lithium or beryllium will emit neutrons (for example, plutonium-beryllium, americium-beryllium, americium-lithium) when bombarded by alpha particles.

![Figure 1-24. X-ray image of the contents of a bag in an airport security line (top); a portable X-ray machine to scan for pipe defects (bottom).](image)

The main issue with many sealed source applications is that the source intensity decays with time, because the source isotope produces the radiation as a byproduct of the natural decay. Dose-rate correction is necessary on a regular basis, with the time interval defined by the half-life of the isotope. Other issues with sealed sources include the potential for contamination – the release of the radioactive material into the environment if the seal is breached – and ultimately their disposal when the radiation intensity has decayed below a useful flux, even though the source is still radioactive.

Accelerators and other powered devices energize charged particles such as ions (most commonly protons) or electrons by using very high accelerating voltages to give these particles a high kinetic energy. At this point, they are used directly as a radiation source or directed onto a target material converting the incident radiation into secondary radiation.

Accelerated protons incident on metal targets generate neutrons, while accelerated electrons on metal targets produce X-rays. Accelerators require lots of energy to produce radiation, so they tend to be large and in-place installations. Unlike sealed sources, accelerators do not pose a portable contamination risk.
Particle beams, however, especially ion and neutron beams, induce nuclear reactions within any materials in the beam, potentially making them radioactive. For lighter materials, the degree of activation is usually not a concern, as the amount of radiation produced is short-lived, but some heavier elements that can have longer-lived radioactivity require caution. The activation produces gamma-ray radiation, as the unstable isotopes created by the nuclear reactions in the target material decay to stable ones.

Microelectronics are present in most industrial applications, either as an integral part of the equipment producing the radiation or embedded in equipment being irradiated. In places where operators or other personnel are present, the radiation sources must be well-shielded and controlled such that radiation emission and contamination is either eliminated or constrained to levels deemed safe for humans. Microelectronics in these types of areas are usually not at risk. Additionally, microelectronics inside accelerators (e-beams and proton beams), X-ray machines or sealed sources that produce ionizing radiation are generally heavily shielded to keep dose exposures low. The doses encountered in industrial applications are extremely well-controlled.

There are two exceptions where dose exposure can accumulate to levels that will damage or destroy microelectronics:

- In industrial applications, where the microelectronics are part of the imaging or detection systems and must be in the radiation field during operation. This applies to X-ray imagers as well as radiation, liquid-level and other detectors used in nuclear power plants.
- In processing/sterilization applications, where the electronics will be irradiated and will accumulate dose; for example, in electronic radio-frequency identification (RFID) tags used to label foods and drugs.

Nuclear fission reactors operated by the power industry to produce electricity also create high radiation areas rich in neutrons and gamma rays from both the reactor vessel and spent fuel in the storage pools. All power plants – whether nuclear-, coal-, oil- or gas- driven – boil water to produce steam that actives turbines, which in turn produce electricity. In nuclear reactors, the process of nuclear fission produces the heat needed to obtain steam.

Most reactors are based on isotopes of uranium (\(^{238}\text{U}\) and \(^{235}\text{U}\)) that have a high-fission cross-section. Fission or splitting of the uranium nucleus can occur spontaneously, albeit at a very low rate, or if it is exposed to neutrons. The absorption of an extra neutron renders the uranium nucleus much less stable. The excess energy of the uranium nucleus is released when it splits into two energetic fission fragments, emitting additional neutrons and gamma rays. This is a key point, because fission of the nucleus without the production of additional neutrons would not allow subsequent fissions to occur. So uranium nuclei fissions release neutrons that feed follow-on fission reactions such that the process can be self-sustaining, usually referred to as a controlled chain reaction. The uranium fuel consists of small pellets assembled into long fuel rods placed in the main reactor vessel in vertical bundles, as illustrated in Figures 1-25 and 1-26.

Interspersed between the array of uranium fuel bundles are rods of neutron absorbers. They consist of elements that are capable of absorbing many neutrons without themselves undergoing fission. These control rods slow down or speed up the rate of fission reactions by modifying the number of neutrons available to drive the fission process. By adjusting the height of the control rods within the reactor vessel, the fission rate adjusts, as does the rate of steam production and ultimately the power output of the reactor.

The heat energy is actually derived from the kinetic energy of the fission fragments created during the reaction. The entire fuel assembly is submersed in a deep pool of water. The water itself absorbs some neutrons, but its main purpose is to keep the core below melting temperatures while converting the waste heat by turning water into steam, which in turn drives a turbine and generator to create electricity. While uranium fuel is used in the reactor, it gradually accumulates fission products – transuranic elements (the production of nonfissile isotopes by neutron absorption) that cause an increase in the neutron absorption of the reactor components. The control rods can be adjusted to compensate, but after several years, the increasing neutron absorption, along with the structural changes

![Figure 1-25. Nuclear reaction core cross-section.](image)

![Figure 1-26. Photograph of a nuclear reactor core in operation. The blue color is Cherenkov radiation given off as charged particles pass through the water at speeds greater than the speed of light in water, an effect analogous to the sonic boom produced by aircraft traveling faster than the speed of sound in air.](image)
in the fuel rods and assemblies induced by displacement damage, requires replacing the spent fuel rods. The fuel assemblies are removed and stored in spent fuel pools and replaced with fresh fuel rods. Approximately half of the fissile material remains, and thus the rods are still highly radioactive.

The radiation environment in a nuclear reactor comes from two sources:

- The fission reaction itself bathing the reactor vessel area with a high flux of gamma rays and neutrons.
- The alpha, beta and gamma radiations emitted from the products of fission; the primary radiation, unstable fission fragments and radioactive isotopes created by transmutation in fuel; and reactor vessel materials from the high neutron flux.

The primary areas in the nuclear facilities are the reactor and the spent fuel containment area, as illustrated in Figures 1-27 and 1-28. Both areas use a large volume of water to shield neutrons and to some extent gamma rays emitted from the core and the spent fuel assemblies (alphas and betas do not have enough energy to escape the pool). In addition, thick concrete and metal shields help keep operators safe.

One critical application in nuclear reactors is the monitoring of water levels in the pools that house the active reactor vessel and spent fuel rods, because a loss of water in either of these areas could expose workers to critical radiation levels and lead to a meltdown of both operating and spent fuel rods. Based on issues that occurred following the tsunami damage to the Fukushima power plant in 2011, the U.S. Nuclear Regulatory Commission issued an order directing U.S. facilities to install fail-safe and redundant water-level monitoring instrumentation in each pool.\[61, 62\]

In general, the industrial-radiation environment includes X-ray, gamma-ray, e-beam or neutron exposures. TID effects are the primary concern for microelectronics used in industrial radiation environments. Most inspection applications use X-rays, and the doses are fairly limited such that under regular circumstances, most microelectronics will not be affected.

Similarly, for most electronics inside the sealed source or accelerator equipment that produces ionizing radiation, shielding keeps the doses to a manageable level. Microelectronics that must operate in a radiation beam or field (like imagers, dosimeters, etc.) or in high-radiation areas (like detectors and gauges in nuclear power plants) pose a challenge. In such industrial applications, electronics will not be able to tolerate the high accumulated dose levels unless they are radiation-hardened. In many cases, even with robust design, certain applications will ultimately accumulate enough dose that the electronics will need to be periodically replaced to ensure that the end equipment operates reliably.

**Defense radiation environments**

In addition to the reactor environment in nuclear power plants installed in some navy vessels, the primary defense radiation environment is created during and after the detonation of a nuclear weapon. The physical consequences of detonating a fission or fusion weapon include blast, thermal, ionizing radiation and residual radiation effects. The level of destruction is defined by the total energy released by the weapon (this is based on the specific design and the reaction mass of the weapon) and the environment in which it detonates. Many of the physical damage effects of a nuclear weapon detonation are similar to those of conventional explosives, but the fission/fusion processes release millions of times more energy per reaction mass.

Nuclear weapons can be detonated on the ground, in air, underground, underwater or in space, all with differing effects. The volume of material around the detonation (usually air) is filled with intense radiation, raising temperatures to tens of millions of degrees. The vaporized material forms a fireball (\(-1\) km in diameter for a 1-megaton device) of incredibly high-temperature plasma, which in turn creates a high-pressure shockwave. For detonations in air, Figure 1-29 shows that at least half of the weapon’s energy is converted into the physical blast.
Two concurrent mechanisms cause blast damage: damage from the drastic increase in air pressure exerted by the shockwave and additional damage caused by the high-velocity winds created by dynamic pressure changes in the wake of the shockwave. The shockwave creates overpressures capable of destroying concrete walls and collapsing buildings (~5-10 psi), and the dynamic pressure variations cause wind speeds in excess of 1,000 km/hr. The range of shockwave and wind effects capable of destroying concrete structures is 5 to 7 km from the detonation of a 1-megaton device. Another 30-40% of a nuclear weapon’s energy is converted to thermal radiation (including visible and ultraviolet radiation), which causes localized heating and can ignite combustible materials at significant distances from the detonation (for example, thermal radiation from a 1-megaton explosion will have a range of ~10 km).

Concurrent with the thermal radiation, ~5% of the detonation energy is emitted as an intense burst of initial radiation comprising X-rays, gamma rays and neutrons. Since the gamma rays and neutrons can travel great distances through the air in a general direction away from the detonation point, they are the primary radiation threat to sensitive microelectronics.

**Figure 1-30** shows the energy-rate output as a function of time after a nuclear detonation. The peak prompt-gamma dose occurs rapidly, in this case within tens of nanoseconds. Obviously, the timescale is a function of the distance between the detector and the point of detonation – the further away the detector, the more expanded the timescale. The magnitude of the gamma-energy rate increases with increasing kilotonnage. The emitted gamma rays expand from the detonation point at the speed of light, while the neutrons travel outward more slowly. Most of the neutrons released by the fission process will be fast neutrons with a peak kinetic energy of 12-14 MeV, corresponding to a velocity that is ~15% the speed of light.

The radiation emission from a detonation follows the inverse-square law, so if the gamma-ray and neutron flux will drop with the square of the distance; in other words, a target that is twice as far away as another target will receive only a quarter of the radiation of the closer target. About 10% to 15% of the blast energy is in the form of residual radiation and consists of radioactive fission products and secondary neutron-activated products that “fall out” of the upper atmosphere hours, days and weeks after the explosion. For surface or low-air burst nuclear detonations, residual radiation comes from two sources:

- Some of the neutrons emitted as initial radiation react with metals in the soil and become radioactive isotopes. The induced radiation is generally created in a circular area centered at the detonation point. The intensity decreases over time, as the newly formed radioisotope decays to safe levels within about a week.
- The radioactive dust (or fallout) falls out of the sky hours, days and weeks after a nuclear explosion. Fallout consists of a combination of radioactive materials, including carbon-14 created by neutrons, radioactive fission fragments (spent nuclear material), unspent fissile material and weapons-casing materials activated by neutrons. The various radioactive species have different decay half-lives.

The intense radiation emission during a nuclear detonation interacts with the Earth’s atmosphere, ionosphere and magnetic field to produce a secondary radiation effect called the EMP. As opposed to direct radiation effects by neutron and gamma irradiation suffered by microelectronics within a few kilometers of a nuclear weapon detonation, the EMP manifests as spurious currents in conductors and overvoltage transients (electrical effects only), but over a range of hundreds and even thousands of kilometers.

**Figure 1-31** shows a diagram of an EMP generated by a high-altitude (400-km) detonation, which is represented by the black dot on the map. The initial radiation absorbed by the air creates a large region of highly ionized gas: the excited electrons spiral in the geomagnetic field, which produces a very high pulse of electromagnetic energy to be radiated to ground level.
This transient burst of electromagnetic energy couples to the power grid via long transmission lines, damaging or destroying power infrastructures and control electronics. The EMP has three phases that occur over different timescales, with differing effects:

- The first phase, characterized by a narrow electromagnetic spike, is caused when oxygen and nitrogen atoms in the atmosphere absorb a large fraction of the gamma rays and are consequently ionized. This effect is maximized in high-altitude detonations: the excess electronic charge spirals in the geomagnetic field, radiating electromagnetic radiation over a large region. This radiated electromagnetic field produces high currents and overvoltages that can destroy transformers, breakdown junctions and insulators. The transient peaks within a few nanoseconds and dissipates within <1 μs.

- The second phase of the EMP is produced by scattered gamma rays and those produced during reactions between nuclei in the air and neutrons emitted by the detonation. This phase starts after the dissipation of the first transient and lasts approximately 1 s after the detonation, producing effects similar to lightning strikes. While many electronics and power systems are designed to handle lightning strikes, the first transient can degrade or destroy the protection circuits, thus allowing additional damage from this second phase.

- The last phase of the EMP event manifests in a relatively slow pulse lasting from seconds to minutes. The radiation emitted during a nuclear detonation causes a large ionization disturbance in the upper atmosphere, ionosphere and magnetosphere, similar to that caused by solar flares and CMEs. The ionization temporarily distorts the Earth’s magnetic field, producing geomagnetic transients that couple to and create current transients in long power distribution lines, temporarily overloading or permanently burning out transformers in the power grid.

The gamma-ray and neutron radiation emitted by a nuclear detonation and the subsequent EMP are the primary concerns for microelectronics outside the blast damage zone. Both dose-rate (prompt-dose or prompt-gamma) and dose effects are a concern for microelectronics operating in a nuclear detonation environment. EMP is not a direct particle-radiation effect but a coupled electromagnetic disturbance, usually manifesting in microelectronics as high transient overvoltages on the inputs or power rails.
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