RADIATION EFFECTS IN QUARTZ OSCILLATORS

A Tutorial

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6th Quartz Devices Conference and Exhibition
August 28-30, 1984

OUTLINE

• General Information on Radiation Effects

• Radiation Effects in Quartz Oscillators

• Summaries of Effects

• Appendices (Space Radiation, Nuclear Explosions, Definitions and References).
General Information on Radiation Effects

Why Study Radiation Effects?

1. **Research** - Radiation effects can provide important insights into the properties of quartz.

2. **Quality Control** - Response to irradiation can be used to separate "good" quartz from "bad," and "good" resonators from "bad."

3. **Military and Space Applications** require radiation hardened oscillators (next revisions of MIL-C-3098 and MIL-O-55310 will include radiation hardness requirements).

**PROPOSED MIL SPEC (MIL-C-3098)**

- **Total Dose** - If specified, the radiation-induced changes in frequency and resistance shall not exceed the values specified when tested as specified.

- **Dose Rate** - If specified, the maximum radiation-pulse-induced changes in frequency and resistance shall not exceed the values specified when tested as specified. The radiation-pulse-induced changes in frequency and resistance after the specified time interval shall not exceed the values specified.

- **Neutrons** - If specified, the neutron-induced changes in frequency and resistance shall not exceed the values specified when tested as specified.

- **Accumulated Time Error** - If specified, the time integral of the radiation-induced frequency change for the specified time interval shall not exceed the value specified when tested as specified.
# Primary Components and Effects of Radiation

<table>
<thead>
<tr>
<th>Natural Radiation</th>
<th>Units</th>
<th>Basic Effect(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron fluence</td>
<td>e/cm²</td>
<td>Ionization of surface material. Causes degradation, deterioration and charge buildup on satellite surface components.</td>
</tr>
<tr>
<td>Proton fluence</td>
<td>p/cm²</td>
<td>Permanent degradation in solar cells and other directly exposed semiconductor devices.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weapon Radiation</th>
<th>Units</th>
<th>Basic Effect(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermomechanical</td>
<td>cal/cm²</td>
<td>Mechanical deterioration in form of spallation, glazing, cracking, and weakening of mechanical integrity.</td>
</tr>
<tr>
<td>Ionization (prompt)</td>
<td>rad(Si)/sec</td>
<td>Induced photocurrents cause transient upset and high currents in all electronics. Potential latchup of junction isolated ICs.</td>
</tr>
<tr>
<td>Y-ray ionization (prompt)</td>
<td>rad(Si)/sec</td>
<td>Same as x-ray prompt ionization effects.</td>
</tr>
<tr>
<td>Total ionizing dose</td>
<td>rads(Si)</td>
<td>Total accumulated ionizing radiation causing permanent changes in semiconductors and quartz resonators.</td>
</tr>
<tr>
<td>Neutron fluence</td>
<td>n/cm²</td>
<td>Permanent displacement in lattice structure causing part degradation.</td>
</tr>
<tr>
<td>EMP and System-generated EMP (SGEMP)</td>
<td>V/m</td>
<td>SGEMP produced by x-ray environment. Both EMP and SGEMP induced currents in interconnecting cables, in antennas, and throughout a system.</td>
</tr>
</tbody>
</table>
Effects on Oscillator Circuit Components

1. **Capacitors** - increased conductivity of dielectric (equivalent to a time-dependent shunt resistance); photovoltage at capacitor interfaces

2. **Resistors, inductors, wires, circuit boards, etc.** - charge transfer between interfaces (metal-insulator, air-metal, air-insulator), leakage currents between conductors.

3. **Semiconductor components** - see next page.
## Effects on Semiconductor Components

<table>
<thead>
<tr>
<th>NEUTRON EFFECTS ( (\text{n/cm}^2) )</th>
<th>DOSE-RATE EFFECTS ( (\text{rad(Si)/sec}) )</th>
<th>TOTAL-DOSE EFFECTS ( (\text{rad(Si)}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{15} ) MOSFET DEGRADES</td>
<td>( 10^{11} ) SEMICONDUCTORS SATURATED COMPLETELY; CURRENTS UNLIMITED</td>
<td>( 10^6 ) ECL DEGRADES</td>
</tr>
<tr>
<td>HARDENED LOGIC DEGRADES</td>
<td></td>
<td>SOME DEGRADATION IN MOST SEMICONDUCTORS</td>
</tr>
<tr>
<td>( 10^{14} ) TTL, RF, &amp; FET TRANSISTORS DEGRADE</td>
<td>( 10^{10} ) HARDENED LOGIC THRESHOLD</td>
<td>( 10^5 ) ( 10^2 ) ( 10^{12} ) ( 10^6 ) DEGRADED, HARDENED CMOS &amp; OTHER MOS SHOW DEGRADATION</td>
</tr>
<tr>
<td>MOST TRANSISTORS &amp; RTL/DTL DEGRADE</td>
<td>TRANSISTORS TURNED ON HARD</td>
<td>POWER TRANSISTORS SHOW DEGRADATION</td>
</tr>
<tr>
<td>( 10^{13} ) LOW-FREQUENCY TRANSISTORS DEGRADE</td>
<td>( 10^9 ) HARDENED LOGIC THRESHOLD</td>
<td>( 10^4 ) COMMERCIAL PMOS/CMOS GATE SHIFTS</td>
</tr>
<tr>
<td>( 10^{12} ) ZENER VOLTAGE REFERENCE SHIFTS</td>
<td>( 10^8 ) POTENTIAL LATCHUP CONDITION</td>
<td>( 10^3 ) ( 10^2 ) ( 10^{12} ) ( 10^1 ) FIRST COMMERCIAL CMOS GATE SHIFTS</td>
</tr>
<tr>
<td>POWER TRANSISTORS DEGR.</td>
<td>( 10^7 ) SIGNIFICANT ( I_{pp} ) IN MOST SEMICONDUCTORS</td>
<td></td>
</tr>
<tr>
<td>SCR &amp; UJT DEGRADE</td>
<td>( 10^6 ) PHOTOCURRENT IN PIN</td>
<td></td>
</tr>
<tr>
<td>( 10^{10} )</td>
<td>( 10^1 )</td>
<td></td>
</tr>
</tbody>
</table>

*Ipp = PHOTOCURRENT MAGNITUDES

Spectrum of radiation effects on semiconductor components and estimated susceptibility ranges (as of 1976).
Radiation - Crystal Unit Interactions

1. "Radiation" throughout this tutorial refers to "ionizing radiation", which consists of electromagnetic waves/particles ("photons") and material particles that have sufficient energy to ionize (i.e., remove electrons from) atoms or molecules. The binding energies of valence electrons in atoms are on the order of 10eV.

2. "Particles" of primary interest are electrons, photons (X-ray and γ-ray), and neutrons. Particles originating from nuclear reactions have energies that are typically in the range of 1 to 10 MeV. (Protons and α-particles are stopped at the surfaces of solids.)

3. Nuclear "particle" interacts with "atom", i.e., transfers energy to atom.

4. Atom can be in any part of the crystal unit (quartz, electrode, enclosure).

5. Energy transfer can result in: a. electronic excitation of atom, b. ionization of atom (produces free electron), c. creation of new particles (e.g., electron-position pairs), d. atomic displacement, and e. nuclear transmutation. Secondary effects include changes in the material's chemical and physical properties (both bulk and surface), and in its temperature.

Interaction of Beta Particles with Matter

Four types of interactions:

1. Inelastic collision with atomic electrons - either excites or frees atomic electron ("secondary" electron)

2. Inelastic collision with nucleus - incident electron is deflected; a photon may be emitted (Bremstrahlung radiation - see below)

3. Elastic collision with atomic electrons

4. Elastic collision with nucleus

Inelastic collisions are the primary mechanism by which beta particles lose energy in matter. "Critical energy" is the energy for which collision and radiative losses are equal - see next page.
Beta Particle Critical Energy as a Function of Z

Critical Energy (MeV) vs. Atomic Number

Radiation Losses Dominate

Collision Losses Dominate
Photon Induced Electron Emission

When an electromagnetic wave (photon) collides with an electron, the electric field of the wave accelerates the electron. (See next page).

The photoelectric and Compton effects are the primary collision processes for the range of photon energies of interest in radiation effects. For these processes the freed electrons are called photoelectrons and Compton electrons. (See p. 10.)

Most of the kinetic energy of a freed electron is lost through ionization and excitation interactions with atoms while being brought to rest in the parent material (emitter). Electrons freed close to the emitter surface, however, may escape before losing all their kinetic energy.

The emission of electrons leaves the emitter with a charge imbalance (space charge). The space charge will be neutralized if a current path exists. Long-lived space charges will occur if no good conductive current path exists; e.g. the emitter is an insulator. Such charges will also occur if some of the electrons imbed themselves in an insulator.

Photon - Electron Interaction

When a plane polarized electromagnetic wave, given by \( E_x = E_0 \cos \omega t \), interacts with a free electron of charge \( e \) and mass \( m \), the electron receives an acceleration of

\[
\ddot{Z} = \frac{e}{m} E_0 \cos \omega t
\]

The displacement of the electron is given by

\[
Z = -\frac{e}{m \omega^2} E_0 \cos \omega t
\]

The time varying acceleration of the electron creates a time varying dipole moment \( \mathbf{D} = ez \), and a radiation field. In the photoelectric effect (see p. 10) the kinetic energy, \( T \), of the electron is \( T = h\nu - E_i \), where \( E_i \) is the ionization energy of the electron. In the Compton effect, \( \hbar \omega = h\nu' + T \). (For further details, see atomic and nuclear physics textbooks.)
Photon Attenuation and Absorption

\[ I = I_0 e^{-\mu t X} \]

where

- \( I_0 \): initial intensity of monoenergetic beam of photons, in photons/cm\(^2\)
- \( I \): intensity of unaffected photons
- \( \mu_t \): total attenuation cross section in cm\(^2\)/gm
- \( \mu_{\text{photoel}} + \mu_{\text{Compton}} + \mu_{\text{pair pr.}} = \mu_{\text{absorption}} + \mu_{\text{scattering}} \)
- \( X \): mass thickness in gm/cm\(^2\) = density \( \times \) thickness

Note: Dose is normalized to 1 at the front surface of the lead.

Dose Profile in Lead Irradiated by \( ^{235}\text{U}\) Gamma Spectrum
Interactions of X and \( \gamma \) - Rays with Matter

a. Photoelectric effect

\[\text{Photon} \rightarrow \text{Electron from atom} \]

b. Compton effect

\[\text{Incident photon } \nu_0 \rightarrow \text{Recoil electron} \]

\[\text{Scattered photon } \nu' \]

c. Pair production

\[\text{Photon} \rightarrow \text{e}^- \text{electron} \]

\[\text{Atom} \]

\[\text{e}^+ \text{positron} \]
Relative Importance of the Photoelectric and Compton Effects, and Pair-Production as a Function of Atomic Number and Photon Energy
Attenuation and Absorption Cross Sections as a Function of Photon Energy for Silicon and Tungsten

Photon Fluence per rad(Si) as a Function of Photon Energy

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Intensity (10^3 photons/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>163</td>
</tr>
<tr>
<td>0.15</td>
<td>136</td>
</tr>
<tr>
<td>0.2</td>
<td>108</td>
</tr>
<tr>
<td>0.3</td>
<td>71</td>
</tr>
<tr>
<td>0.4</td>
<td>53</td>
</tr>
<tr>
<td>0.5</td>
<td>42</td>
</tr>
<tr>
<td>0.6</td>
<td>35</td>
</tr>
<tr>
<td>0.8</td>
<td>27</td>
</tr>
<tr>
<td>1.0</td>
<td>22.4</td>
</tr>
<tr>
<td>1.5</td>
<td>16.2</td>
</tr>
<tr>
<td>2.0</td>
<td>12.9</td>
</tr>
<tr>
<td>3.0</td>
<td>9.4</td>
</tr>
<tr>
<td>4.0</td>
<td>7.4</td>
</tr>
<tr>
<td>5.0</td>
<td>6.1</td>
</tr>
<tr>
<td>6.0</td>
<td>5.2</td>
</tr>
<tr>
<td>8.0</td>
<td>4.0</td>
</tr>
<tr>
<td>10.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

EFFECTS ON MAN

- **Average Person** (in N.J.) absorbs about 0.2 rads per year due to: cosmic rays (0.05 rads/yr.), ground and buildings (0.04 rads/yr.), air and food (0.03 rads/yr.), and medical/dental X-rays (0.09 rads/yr.).

- **Latent Lethality** - 500-800 rads is the limit of survivability. Some may respond to medical treatment and survive, most will be functionally impaired until they die several weeks after exposure to this dose.
Neutron Damage

A fast neutron displaces about 50 - 100 atoms before it comes to rest. Most of the damage is done by the recoiling atoms. Net result is that each neutron can cause numerous vacancies and interstitials.

Radiation Effects in Quartz Oscillators

1. Total dose effects (rad [Si])

2. Dose-rate effects (rad [Si] per sec)

3. Neutron effects (n/cm²)
Radiation Induced Frequency Shifts

Idealized behavior of frequency vs. time for quartz resonators following exposure to a pulse of ionizing radiation.

Effects of Low and High Level Radiation on Crystal Oscillator

Oscillator was preconditioned with $>10^4$ rads

$\Delta f/f = \begin{cases} 
10^{-11} & \text{for natural quartz} \\
10^{-12} & \text{for cultured quartz} \\
10^{-13} & \text{for swept cultured quartz} 
\end{cases}$

* for 1 Mrad dose
Frequency Change (Hz) vs Rad (Si), for 5 MHz, 5th overtone resonators fabricated from both synthetic and natural quartz. (From B. R. Capone, et al)

Effects Of Repeated Irradiations

Initial slopes:
1st: $1 \times 10^{-9}$/rad
2nd: $1 \times 10^{-11}$/rad
3rd: $3 \times 10^{-12}$/rad
4th: $3 \times 10^{-12}$/rad
5th: $5 \times 10^{-12}$/rad

Annealing of Radiation Induced f Changes

P. FREYMUTH und G. SAUERBREY

Fig. 3. Ausheilung der strahlungsinduzierten Frequenzänderung einer 4-MHz-Quarzplatte. $\Delta f_1$: ausgeheilte Frequenzänderung, $\Delta f_0$: Sättigungsfrequenzänderung, $T$: Ausheiltemperatur.

1. Absorbed dose of $6 \times 10^6$ Rads (of X-rays) produced $\Delta f = 41$ Hz.

2. Activation energies were calculated from temperature dependence of annealing curves.

3. The experimental results can be reproduced by two processes, with activation energies $E_1 = 0.3 \pm 0.1$ eV and $E_2 = 1.3 \pm 0.3$ eV.

4. Annealing is complete in less than 3 hours at $> 240^\circ$C.
Transient Change after Pulsed $\gamma$-Irradiation

(AT-cut vs. SC-cut)

- Experimental data, dose $= 1.3 \times 10^6$ Rads, SC-cut
- Experimental data, dose $= 2.3 \times 10^6$ Rads, AT-cut
- Model calculation: AT-cut

Warmup Characteristics of AT and SC-Cut Resonators

Deviations from static $f$ vs. $T = A \frac{dT}{dt}$, where, for example, $A \approx 15$ ppm/°C/sec for 5 MHz 5th overtone AT-cut resonator.

Oven warmup time
Effects of Flash X-Rays on $R_s$ (4 $\times$ 10$^4$ Rad pulse)

Series Resonance Resistance (or $Q^{-1}$) vs Time for several types of 32 MHz resonators. Swept synthetic resonators show no change in $R_s$ from the earliest resolution time (1 nsec) after exposure, at room temperature.

Frequency Change due to Neutrons

Curve showing linear increase in resonant frequency of crystal unit 3-25-1, normalized at room temperature, as a function of reactor irradiation.
Q Change due to Neutrons

Curve showing linear increase in acoustic absorption of crystal unit 3-25s⁻¹ with integrated neutron flux.
f vs. T Change due to Neutrons and its Annealing

Frequency-temperature characteristic curves for crystal unit 3-25s-1 shown before and after neutron irradiation and again after annealing at 500°C for 160 hours.
Alpha - Quartz Unit Cell

Showing a three dimensional representation of a unit cell of a right-handed a-quartz crystal.
Ions in Quartz - Simplified Model

Aluminum Associated Defects

$\text{Al-OH}^- \text{ CENTER}$

OH$^-$ MOLECULE

$\text{Al-M}^+ \text{ CENTER}$

INTERSTITIAL ALKALI

$[\text{Al}_E^+\text{H}^0 \text{ CENTER}]$

(aluminum-hole center)

HOLE TRAPPED IN NON-BONDING OXYGEN $P$ ORBITAL
Hydrothermal Growth of Quartz

The autoclave is filled to some predetermined factor with water plus mineralizer (NaOH or Na₂CO₃).

The baffle localizes the temperature gradient so that each zone is nearly isothermal.

The seeds are oriented single-crystals.

The nutrient consists of small (≈ 1") pieces of single crystal quartz.

The temperatures and pressures are typically about 350°C and 800 to 2,000 atmospheres; T₂ - T₁ is typically 4°C to 20°C.

The nutrient dissolves slowly, diffuses to the growth zone, and deposits onto the seeds.

Sweeping

Sweeping is a purification process which removes certain impurities from the quartz and thereby improves the radiation hardness and etching properties of quartz crystals. It is an electric field driven solid state diffusion process that is performed at an elevated temperature. The major steps of a typical sweeping process consist of applying electrodes to the Z-surfaces of a lumbered quartz bar, heating the bar slowly to 500°C, applying a voltage to the electrodes such that the electric field along the Z-direction is about 1 kV/cm, monitoring the current through the bar (as the sweeping progresses, the current decreases), and after the current decays to some constant value, cooling the bar slowly to room temperature, then removing the voltage.

Under the influences of the high electric field and the high temperature, the positive impurity ions, such Li⁺ and Na⁺, diffuse to the cathode and are removed when the electrodes are removed in subsequent processing.

In addition to improving radiation hardness, sweeping also greatly reduces the number of etch channels that are produced when quartz is etched.
Typical Sweeping Setup

Summary - Steady State Radiation Results

1. Dose vs. F change is nonlinear; F change per rad larger at low doses.

2. At dose > 1 Krad, F change is quartz impurity dependent. The ionizing radiation produces electron-hole pairs; the holes are trapped by the impurity Al sites while the compensating cation (e.g., Li or Na) is released. The freed cations are loosely trapped along the optic axis. The lattice near the Al is altered, the elastic constant is changed; therefore, the F shifts.

3. At 1 Mrad dose, F change ranges from $10^{11}$ per Rad for natural quartz to $10^{16}$ per Rad for high quality swept quartz.

4. Frequency change is negative for natural quartz; it can be positive or negative for cultured and swept cultured quartz.

5. Frequency change saturates at doses > 10^6 rads.

6. Q degrades if quartz contains high concentration of alkali impurities; Q of swept cultured quartz is unaffected.

7. Radiation can also rotate F vs. T characteristic.

8. Frequency change anneals at T > 240°C in less than 3 hours.

9. Preconditioning (with doses > $10^5$ rads) reduces the high dose radiation sensitivities upon subsequent irradiations.

10. At dose < 100 Rad, F change is not well understood. Radiation induced surface effects (adsorption, desorption, dissociation, polymerization and charging) may be significant.
Summary - Pulse Irradiation Results

1. For applications requiring circuits hardened to pulse irradiation, quartz resonators are the least tolerant element in properly designed oscillator circuits.

2. Resonators made of unswept quartz or natural quartz can experience a large increase in $R_s$ following a pulse of radiation.

3. Natural, cultured, and swept cultured AT-cut quartz resonators experience an initial negative frequency shift immediately after exposure to a pulse of X-rays (e.g., $10^4$ to $10^5$ Rad of flash X-rays). $\Delta f/f$ is as large as -3 ppm at 0.02 sec after burst of $10^{12}$ Rad/sec.

4. Transient $f$ offset anneals as $t^{-1}$; the non-thermal transient part of the $f$ offset is probably due to the diffusion and retrapping of hydrogen at the $Al_{3+}$ trap.

5. Resonators made of properly swept quartz experience a negligibly small change in $R_s$ when subjected to pulsed ionizing radiation. (The oscillator circuit does not require a large reserve of gain margin).

6. SC-cut quartz resonators made of properly swept high $Q$ quartz do not exhibit transient frequency offsets following a pulse of ionizing radiation.

7. Crystal oscillators will stop oscillating during an intense pulse of ionization because of the large prompt photoconductivity in quartz and in the transistors comprising the oscillator circuit. Oscillation will start up within 15 $\mu$sec after burst unless natural quartz is used and insufficient gain margin is built into the oscillator circuit.

Summary - Neutron Irradiation Results

1. Neutron irradiation with fast neutrons results in displacement damage.

2. Frequency increases linearly with fluence at rates ranging from $+0.6 \times 10^{21}/n/cm^2$ to $+3 \times 10^{-21}/n/cm^2$ for AT and SC-cut quartz.

3. Neutron irradiation rotates $f$ vs. $t$ characteristic.

4. Most of neutron damage was annealed after baking at 500°C for 160 hours.

5. Neutron damage changes both the elastic constants and the density of quartz.
Comments on the Measurement of Radiation Effects

- To measure radiation effects on the resonator alone, before and after measurements are inaccurate due to hysteresis and annealing effects.

- Total dose and dose rate effects on the resonator can be measured real time in a properly constructed and shielded oscillator that contains a radiation window, or in a reflectometer.

- For measuring neutron effects on the resonator alone, the reflectometer method is preferred because it is not practical to shield an oscillator circuit from fast neutrons - (reflectometer can provide the required accuracy while being located remotely.)

Some Significant Remaining Questions

1. The mechanisms of low level radiation effects; how does one minimize the effects?

2. Differences between the responses of resonators made of swept quartz and of unswept low Al content quartz. How will resonators made of "zero" Al content quartz behave? What, if any, role does Fe play? What, if any, role do etch channels play?

3. How long does preconditioning last? How does the effect anneal as a function of temperature?

4. What are the relationships between susceptibility to twinning and quartz purity, defect density and Q?

5. How can one deal with neutron effects?
APPENDIX A

SPACE RADIATION

The pertinent characteristics of space radiation can be summarized as follows.

1. Cosmic rays, consisting primarily of high-energy protons and heavier particles, but with fluxes generally too small to produce significant radiation effects in materials or components.
2. Trapped electrons and protons, such as occur in the Van Allen belt, possibly augmented by high-altitude nuclear detonations. The importance of these radiations in producing degradation of space systems, especially solar cell power systems, has been adequately demonstrated by researchers.
3. Neutron and gamma rays from nuclear reactor power plants in space for such applications as propulsion systems. As in ground-based nuclear reactors, the fast neutrons and high-energy gamma rays can produce severe damage in many systems within the host spacecraft.
4. Solar flare protons. The high-energy protons ejected from the sun during solar flares can produce significant radiation damage in parts and materials.

Radiation effects produced by space exposure are similar to those from a nuclear detonation and fall into three general classes: displacement, transient, and chemical. Displacement radiation effects are the result of the displacement of one or more atoms from their normal site, usually in a crystalline lattice. Transient radiation effects are manifestations of the excitation of electrons, usually into conducting states, and the associated recombination processes. Chemical radiation effects are defined as changes in chemical bonding which frequently results from the deposition of ionization energy in a material.
APPENDIX B

NUCLEAR EXPLOSIONS

Nuclear weapons are similar to those of more conventional types insofar as their physical destructive action is due mainly to blast or shock. On the other hand, there are several basic differences between nuclear and high-explosive weapons. First of all, it is feasible for a nuclear explosion to be millions of times more powerful than the largest conventional detonation. Second, a healthy percentage of the energy in a nuclear explosion is emitted in the form of light and heat, generally referred to as thermal radiation. Third, the nuclear explosion is accompanied by highly penetrating and harmful invisible rays, called the "transient nuclear radiation". Finally, the substances remaining after a nuclear explosion are radioactive, emitting similar radiations over an extended period of time; this is known as the "residual nuclear radiation".

The immediate phenomena associated with a nuclear explosion, as well as the effects of shock and blast, and thermal and nuclear radiations, vary with the location of the point of burst relative to the earth's surface. Within less than a microsecond of the detonation of a nuclear weapon, the extremely hot residues radiate large amounts of energy, mainly as invisible x-rays which are absorbed within a few feet in the surrounding atmosphere. This leads to the formation of a hot and highly luminous spherical mass of air and gaseous residues known as a "fireball". The surface brightness decreases with time, but can be many times more brilliant than the sun at noon for a short period. Quite early in the ascent of the fireball, cooling of the outside by radiation and the drag of the air through which it passes bring about a change in shape. The roughly spherical form becomes a toroid, although this shape and its associated motion are often soon hidden by the radioactive cloud and debris. As it ascends, the toroid undergoes a violent internal circulatory motion forming a "mushroom" shape. The color of the radioactive cloud is initially red or reddish-brown due to the presence of various-colored compounds at the surface of the fireball.
RADIATION FROM A NUCLEAR EXPLOSION

Within the first second after detonation, a nuclear burst releases all of its energy, producing both initial and residual radiation—invisible, highly penetrating, and harmful rays and particles that are undetectable by human senses.

Initial radiation is arbitrarily defined as that emitted from both the fireball and the cloud within one minute of the explosion. It is during this first minute that the high-intensity ionizing radiation and neutron irradiation of major concern in electronics are produced. Residual radiation, produced more than one minute after detonation, is classified as fallout and neutron-induced activity.

Radiation energy is released within the first second after detonation in the form of alpha and beta particles, gamma rays, x rays, neutrons, electrons, and neutrinos. The energy and range of alpha and beta radiation are small and, consequently, of little concern to electronic components.

However, the effects of gamma rays and neutrons are of major importance because of their high energy content. Gamma radiation is short-wave electromagnetic energy that originates from the nucleus of an atom, while x radiation originates when an electron falls into an unfilled orbital of an atom and it has less energy.

Neutrons are released from the atom's nucleus (exclusively the result of a fission or fusion process). Neutrons can be classified into three groups:

1. Thermal (with energies of approximately 0.025 eV),
2. Epithermal, and
3. Fast (with energies of 10 keV and greater).

Fast neutrons are of major significance in electronic systems employing semiconductor components.

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Slow</td>
<td>0 &lt; E ≤ 1 keV</td>
</tr>
<tr>
<td>II</td>
<td>Intermediate</td>
<td>1 keV &lt; E ≤ 500 keV</td>
</tr>
<tr>
<td>III</td>
<td>Fast</td>
<td>0.5 MeV &lt; E ≤ 10 MeV</td>
</tr>
<tr>
<td>IV</td>
<td>Very Fast</td>
<td>10 MeV &lt; E ≤ 50 MeV</td>
</tr>
<tr>
<td>V</td>
<td>Ultrafast</td>
<td>50 MeV &lt; E</td>
</tr>
</tbody>
</table>
APPENDIX C

Definitions

**Dose** - The amount of energy imparted by nuclear (or ionizing) radiation to unit mass of absorbing material. The commonly used unit is the rad (see definition to follow).

**Absorbed Dose** - The absorbed dose of energy is usually given in terms of rads (see page 9), commonly referred to as accumulated or total exposure to radiation.

**Electromagnetic Radiation** - A traveling wave resulting from oscillating magnetic and electric fields. Familiar electromagnetic radiations range from x rays (and gamma rays) of short wavelength, through the ultraviolet, visible, and infrared regions, to radar and radio waves of relatively long wavelength. All electromagnetic radiations travel in a vacuum with the velocity of light.

**Electron (e)** - Negative charged particle with mass of $9 \times 10^{-28}$ g, effective diameter of $10^{-14}$ m.

**Electron Volt (eV)** - The kinetic energy of an electron accelerated from rest through a potential difference of 1 V (i.e., the work done by the electric field of 1 V on an electron). It is equivalent to $1.6 \times 10^{-12}$ erg, and also to the energy of a 1.24 μm wavelength photon.

**EMP** - Electromagnetic pulses radiating from a nuclear detonation. The E field can have maximum values on the order of $10^5$ V/m, with a pulse width which can range from 100 nsec to 30 μsec, depending on burst height. The corresponding H field has similarly shaped pulses with maximum values of approximately 260 ampere-turn/meter.

**Fluence** - A term used to specify a measure of integrated particle flux. Most often used to specify integrated neutron flux in units of n/cm$^2$. 

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Flux - The number of particles passing through a sphere of unit cross-sectional area per unit time. Units are n/cm²·sec, p/cm²·sec, etc.

Gamma Ray (γ) - Electromagnetic radiation of high energy originating in atomic nuclei. Gamma rays accompany many beta particles as they are emitted from the fragments of heavy atoms split in a nuclear detonation. Gamma rays are very penetrating, and for practical shielding, a considerable amount of dense (high-Z) material must be employed. This energy (about 1 MeV) of electromagnetic radiation has zero mass and zero size and travels at the speed of light.

Ionization - The process of producing ions from an uncharged atom by removing an electron. The separation of a normally electrically neutral atom or molecule into its electrically charged components - an ion and a free electron. Ionization associated with a nuclear explosion is normally categorized as having prompt and delayed components. Prompt ionization from gammas released by the fission process of the explosion is usually less than 100 msec wide. The delayed ionization results from gammas released by neutrons interacting with the atmosphere and system material.

Megaton Energy - The energy of a nuclear (or atomic) explosion which is equivalent to 1 million tons (1000 kton) of TNT (i.e., 10¹⁵ calories or 4.2 x 10²² ergs).

Million Electron Volts (MeV) - A measurement of energy. 1 MeV corresponds to 1.6 x 10⁻⁶ erg or 1.6 x 10⁻¹³ joule (J). Approximately 200 MeV is released for every nucleus that undergoes fission. The energy equivalent of mass consisting of unit atomic weight is 931.43 MeV.
Neutron (n) - A neutral particle with mass of $1.7 \times 10^{-24}$ g, effective diameter $3 \times 10^{-15}$ m. This is a particle of approximately unit mass, present in all atomic nuclei except those of ordinary (light) hydrogen. Neutrons are required to initiate the fission process, and large numbers of neutrons are released by both fission and fusion reactions in nuclear explosions.

Fast Neutrons - Neutrons with high kinetic energies. The energy level above which neutrons are considered to be fast is not universally established. Generally, it implies energies greater than 10 keV. A fast neutron of 1 MeV has a speed of about $1.4 \times 10^9$ cm/sec.

Thermal (or slow) Neutron - After a number of collisions with nuclei, the speed of a neutron is reduced to such an extent that its energy approximately the kinetic energy of the atoms is the matter causing the collisions. This energy is a fraction of an electron volt at ordinary temperatures (approximately $1/40$ eV at room temperature). Because the energy is dependent on temperature, the term "thermal neutron" becomes appropriate.

Nuclear Hardening - The concept of making piece parts, circuits, subsystems, and systems less susceptible to nuclear radiation, which may be gamma rays, neutrons, thermal energy, or radioactive debris, as well as electromagnetic pulses. The process by which a vulnerable unit is modified to make it less vulnerable to a specified radiation environment, or the design process aimed at improving the radiation tolerance of a unit.

Overpressure - The transient pressure, usually expressed in pounds per square inch (psi), exceeding the ambient pressure, manifested in the shock (or blast) wave from an explosion. The variation of overpressure with time depends on the energy yield of the explosion, the distance from the point of burst, and the medium in which the weapon is detonated. The peak overpressure is the maximum value
of the overpressure at a given location and is generally experienced at the instant the shock (or blast) wave reaches that location. It is a factor to consider when designing mechanical fixtures and housings for systems.

**RAD** (Roentgen-Absorbed-Dose) - Absorption dose of 100 erg/g (material). The rad is a measure of radiated energy absorption of any form (particle or electromagnetic) in any material. It is important to specify the material when this term is used. Because silicon is a common reference material, its symbol (Si) is often found in parentheses. Carbon is used in many applications involving non-electronic materials. 1 rad = 6 X 10$^{13}$ eV/gm; also,

1 rad(Si) = 3.0 x 10$^7$ electrons/cm$^2$ at 1 MeV (electrons)
1 rad(Si) = 1.0 x 10$^6$ protons/cm$^2$ at 1 MeV (protons)
1 rad(Si) = 3.0 x 10$^6$ neutrons/cm$^2$ at 1 MeV (neutrons)
1 rad(Si) = 2.2 x 10$^9$ photons/cm$^2$ at 1 MeV (photons)

**Gray** - 100 rads (Gray is the accepted international unit of absorbed dose).

**Röentgen (R)** - This term specifies the amount of ionizing radiation (x ray or gamma) that produces ionization of 1 electrostatic unit (esu) of charge of either positive or negative sign in 1 cm$^3$ of air at standard temperature and pressure. This produces 2.083 x 10$^9$ ion pairs per cm$^3$. Exposure to 1 roentgen results in an absorbed dose of 0.878 rad (air).

**Shock Wave** - A continuously propagated pressure pulse (or wave) in the surrounding medium which may be air, water, or earth, initiated by the expansion of the hot gases produced in a nuclear explosion. A shock wave in air is generally referred to as a blast wave because it resembles and is accompanied by strong, but transient, winds.

**TRE** - Transient Radiation Effects

**TREE** - TRE in Electronics.
References


