ELECTROMAGNETIC PULSE (EMP)

INTRODUCTION

With the growing awareness that most electronic systems essential to national security must function properly during and after exposure to a nuclear environment, many prime system procurement agencies now include radiation requirements as part of their system specifications. This implies a new facet to be considered by a contractor during the system design and development. Several aspects of the radiation-hardening problem are relatively unique, such as added program costs to achieve protection and extreme engineering difficulties encountered in subsystem- or system-level design.

A specific characteristic of the hostile nuclear environment is the multiplicity of kill mechanisms. Photon pulses can produce both current transients and catastrophic failures; device surface degradation modes can be caused by the ionizing dose deposited by the total radiation environment; and neutrons produce desirable changes in electronic parts characteristics.

An electromagnetic pulse (EMP) is another one of the products of a nuclear detonation. It presents a threat to electrical components since its presence can disable or cause malfuntions in electronic equipment.

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. Figure 1 is an illustration of the many products of a burst. 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. X radiation is often referred to as gamma radiation. 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. Damage effects will be discussed in a later section of this brochure.

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 (see Reference 2).
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. They represent the most severe radiation environment for future space applications.
4. Solar flare protons. The high-energy protons ejected from the sun during solar flares can produce significant radiation damage in parts and materials.

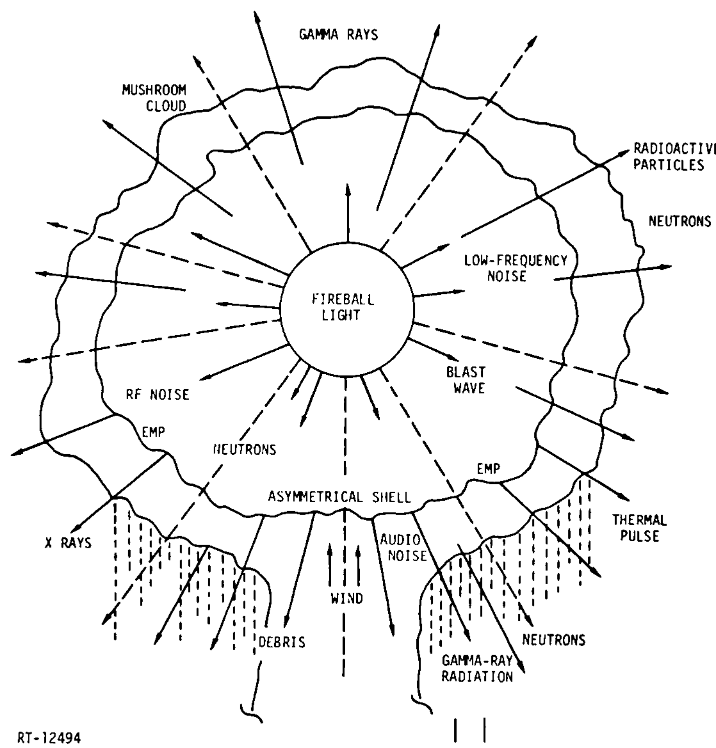

Figure 1. Products of a nuclear detonation.

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.

TERMINOLOGY

The terms and expressions used in defining the products and effects of radiation are numerous as one might expect in this branch of science. Therefore, it is worthwhile to present a few common definitions and relationships between dimensional quantities that an electronic system designer is likely to encounter in a radiation specification. The reader is referred to more extensive texts on nuclear fundamentals for a more complete dictionary of nomenclature (see References 3 through 8).

Absorbed 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).

Circumvention - The means by which a system can be protected during the transient irradiation period, primarily by utilizing decoupling or deactivation of power techniques.

Dose - The absorbed dose of energy is usually given in terms of rads, commonly referred to as accumulated or total exposure to radiation. It is a quantity of ionizing (or nuclear) radiation.

Electromagnetic Radiation - A traveling wave motion 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 9×10^{-28} g, diameter of 10^{-14} m. Negative electrons, surrounding the nucleus, are present in all atoms; their number is equal to the number of positive charges (or protons) in the particular nucleus. When used alone, the term electron commonly refers to these negative electrons.

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 1.6×10^{-12} erg.

Energy Level (E) - Particle energy; generally expressed in terms of electron volts.

EMP - Electromagnetic pulses radiating from a nuclear detonation. The E field can have maximum values in the order of 10^5 V/m with a pulse width (between half-peak points) of 20 nanoseconds. The corresponding H field has similarly shaped pulses with maximum values of approximately 260 ampere-turn/meter.

ERG/G(Si) - Equivalent to the energy absorbed from a gamma-ray field per unit mass of a limiting small volume of silicon (Si) under conditions of electronic equilibrium (2.2×10^9 photons/cm^2 at 1 MeV). Carbon, water, or silicon is often used as a reference. The unit is symbolized as ergs/g(material).

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 1.4×10^9 cm/sec. When this speed is reduced to 2.2×10^5 cm/sec, a thermal neutron is created.

Gamma Ray (γ) - Nuclear 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 material (high-Z material) is usually employed. This energy (about 1 MeV) of electromagnetic radiation has zero mass and zero size and travels at the speed of light. Physically, gamma rays are identical with x rays of high energy; the only essential difference is that the x rays do not originate from atomic nuclei but are produced in other ways [e.g., by slowing down (fast) electrons or neutrons of high energy].

Integrated Neutron Flux - The product of neutron flux and time, expressed in units of neutrons per square centimeter (n/cm^2). It is a measure of neutron fluence.

Ionization - The process of producing ions or changing an uncharged atom to a charged atom by either adding or removing an electron. The separation of a normally electrically neutral atom or molecule into its electrically charged components.

Megaton Energy - The energy of a nuclear (or atomic) explosion which is equivalent to 1 million tons (or 1000 kilotons) of TNT (i.e., 10^{15} calories or 4.2×10^{22} ergs).

Million Electron Volts (MeV) - A measurement of energy, where 1 million eV (MeV) corresponds to 1.6×10^{-6} ergs or 1.6×10^{-13} joule (J) (photons). For most materials, the absorption probability can be assumed to be constant from about 500 keV to about 2 MeV. Approximately 200 MeV of energy is produced for every nucleus that undergoes fission. The energy equivalent of mass consisting of one unit atomic weight is 931.43 MeV.

Neutron (n) - A neutral particle with mass of 1.7×10^{-24} g, diameter 3×10^{-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 produced by both fission and fusion reactions in nuclear (or atomic explosions).

Nuclear Hardening - The concept of making anything (components, circuits, 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 part (or system) is modified to make it less vulnerable to a specified radiation environment, or the design process aimed at improving the radiation tolerance of the part or system.

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 the 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 ergs/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 the parentheses. Carbon is used in many applications involving non-electronic materials. Total dose in rads is that measured by equipment sensitive to certain ranges of roentgen levels. Thus, the total dose may result from gamma rays or neutrons, as well as from other concurrent radiation effects.

1 rad = 3.0×10^7 electrons/cm^2 at 1 MeV (electrons)
1 rad = 1.0×10^6 protons/cm^2 at 1 MeV (protons)
1 rad = 3.0×10^6 neutrons/cm^2 at 1 MeV (neutrons)
1 rad = 2.2×10^9 photons/cm^2 at 1 MeV (photons)
1 rad(tissue) = 90.9 ergs/g (material)

Roentgen (R) - Exposure dose of 87.8 ergs/g (material) to air — the amount of radiation that produces ionization, 1 electrostatic unit (esu) of charge of either positive or negative sign in 1 cm^3 of air at normal temperature and pressure. This term specifies the amount of ionizing radiation (x ray or gamma radiation) released in standard temperature and air pressure. It is the quantity of radiation that produces 2.083×10^9 ion pairs per cubic centimeter of air at standard pressure, 760 mm, and standard temperature, 25°C or 77°F, at sea level. The rate of energy release is expressed in roentgens per second. It is defined precisely as the quantity of gamma (or x) radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 esu quantity of electricity of either sign.

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. Shock waves are also produced by underground volcanic action or by the breaking and shifting of rock in earthquakes. A shock wave in air is generally referred to as a blast wave because it resembles and is accompanied by strong, but transient, winds.

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 approximates the kinetic energy of the atoms in the matter causing the collisions. This energy is a fraction of an electron volt at ordinary temperatures. Because the energy is dependent on temperature, the term "thermal neutron" becomes appropriate.

Van Allen Radiation Belt - A trapped radiation belt centered around the geomagnetic equator of the earth. The belt consists of an inner region and an outer region. The inner region is located between the altitudes of 100 and 5000 miles and spreads out to approximately 40° on each side of the earth's equator. The radiation flux consists of protons ($E < 500$ MeV) and low-energy electrons ($E < 1$ MeV).
The outer region is located between the altitudes of 3000 and 20,000 miles and spreads out to approximately 60° on each side of the equator. The radiation flux is primarily electrons ($0.40 \text{ keV} < E < 1.6$ MeV).

RADIATION EFFECTS ON SYSTEMS

The system designer will encounter many variations in environmental specifications for nuclear and/or natural (space) radiation levels. These variations are due to operational needs during and after exposure as well as application. Most modern military communication satellite systems have both natural and weapons components of a radiation environment, while a land-based system would not have natural radiation specifications. In most cases, such systems must be designed for the natural environment and be capable of being hardened to a man-created hostile radiation situation. The discussions to follow are system and circuit design considerations for both environments. Table 1 is a listing of the components of each environment and basic effects induced by each.

The primary effect of a natural radiation environment will be on directly exposed items. Electrons will induce effects from ionizing materials, creating undesired charge build-up in these materials. Protons are typically less of a threat since they are charged particles and may be stopped by other direct energy conversion, but will produce damage in semiconductor material if directly exposed.

Primary consideration must be given to solar cells applications since they will experience degradation. Allowances must be made in any related designs to account for this degradation by increasing the cell quantity. Sensors and certain lens materials must be selected to withstand the effect of the electron and proton fluences. It is frequently necessary to place a cover glass over sensors to trap the protons and protect sensitive elements inside. Certain types of materials are sensitive to direct space radiation exposure and must be avoided. An example is Teflon, which may become brittle or decompose under ionizing-type radiation.

Grounding of a space vehicle's exterior components should be continuous with the rest of the vehicle's structure. Where rotational members are employed, grounds must be carried from one member to another, keeping the entire structure at equal potentials.

Hardening against thermomechanical effects produced by a nuclear weapons primarily consists of selection of proper materials and avoiding those with high Z (high atomic number). Thermomechanical effects are the result of low-energy x rays releasing their energy in the form of heat when deposited in a material. This occurs in a very short period of time, and is dependent on the x-ray fluence and the material type. Resulting thermomechanical stresses are often large enough to cause serious material degradation. Directly exposed material is more vulnerable than contained material; therefore, all high-Z material should be removed from the exterior of a system. Where this is impractical, protective coatings or material should be applied over the sensitive material. Solder should be closely investigated for possible spallation. If this is found to be the case, less vulnerable solders should be selected or conformal coatings applied. Solar cell cover glass may discolor and the adhesive weaken; therefore proper selection is required in these areas. Lenses on sensors may crack or glaze, which would require changing the lens material, putting a protective material in front of it, or reversing the observation technique by having it view through a mirror. Where tight mechanical tolerance must be retained with two adjacent dissimilar metals, any differential heating effect of a deposited X-ray environment must be considered. At high X-ray radiation fluences, it is often necessary to protect component housings with complete shields of a high-Z material (e.g., tantalum).

Most modern-day military systems are electronic in nature and use many types of semiconductor devices to perform their functions. Unfortunately, semiconductors are the most vulnerable to transient radiation effects while passive devices (e.g., resistors, inductors, and capacitors) are relatively "hard" to the most extreme radiation levels.

Transient radiation effects in electronics (**TREE**) are usually categorized as those transient in nature and those which generate permanent changes. The transient changes are caused by a prompt ionizing radiation environment creating electron-hole pairs in semiconductor material which produce a photocurrent for the duration of the ionizing period and until equilibrium has once again been established. Permanent changes, however, are the result of several independent radiation environments, each producing unique effects. A neutron environment produces permanent displacement in the molecular structure of semiconductor materials, altering the device characteristics. A total ionizing radiation environment also produces permanent changes in semiconductor surface effects or space charge. The other environment producing permanent effects is the x ray, which creates characteristic changes through thermomechanical effects and frequently produces catastrophic destruction of semiconductor devices and other affected materials.

The effect of prompt ionization manifests itself primarily in photocurrent generation within semiconductors. However, effects are also observed in dielectrics, crystals, and certain other materials. Generation of photocurrent in semiconductor junctions results in spurious circuit operations such as circuit upset, latchup, burnout, and lockup, all of which are dependent on the particular device and its application within the circuit in question.

Table 1.

PRIMARY COMPONENTS OF RADIATION ENVIRONMENTS

Natural Radiation	Units	Basic Effect(s)
Electron fluence	e/cm^2	Ionization of surface material. Causes degradation, deterioration and charge buildup on satellite surface components.
Proton fluence	P/cm^2	Permanent degradation in solar cells and other directly exposed semiconductor devices.
Weapon Radiation		
X-ray		
Thermomechanical	cal/cm^2	Mechanical deterioration in form of spallation, glazing, cracking, and weakening of mechanical integrity.
Ionization (prompt)	rad(Si)/sec	Induced photocurrents cause transient upset and high currents in all electrons. Potential latchup of junction isolated ICs.
γ-ray ionization (prompt)	rad(Si)/sec	Same as x-ray prompt ionization effects.
Total ionizing dose	rads(Si)	Total accumulated ionizing radiation causing permanent changes in semiconductors. MOS is most susceptible.
Neutron fluence	n/cm^2	Permanent displacement in semiconductor material lattice structure causing part degradation.
EMP and System-generated EMP (SGEMP)	V/m	SGEMP produced by x-ray environment. Both EMP and SGEMP induce currents in interconnecting cables, in antennas, and throughout the system.

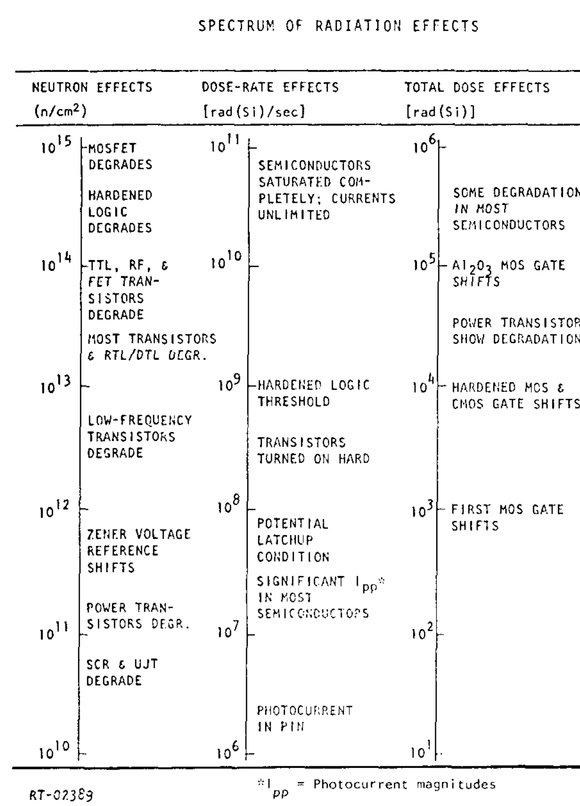

Figure 2. Spectrum of radiation effects on semiconductor components and estimated susceptibility ranges

A spectrum of prompt-ionization effects in typical devices is given in the middle column of Figure 2. The impact of these effects on a system will depend heavily on the susceptibility of the circuit usage and function. For example, in a missile application, the occurrence of an upset of a system may be critical to mission success, while in a satellite, a system upset could be nothing more than noise in the system. It is, therefore, essential that the mission goal and design criteria be considered when determining the critical nature of a transient upset.

Total ioizing dose exposure may be received in a relatively short period (minutes) or accumulated over a number of years. The effects from either type of exposure is basically the same, with primary degradation appearing first in semiconductor devices. A spectrum of typical total-dose effects is included in the third column of Figure 2. From this, it can be seen that MOS devices are the most sensitive. This is due to charge-trapping in the oxide insulation layer, which develops an opposing voltage and causes the gate voltage to shift. When this happens in circuits, the driving signal may be insufficient to generate switching and the circuit will no longer function as designed.

Total dose also affects the operation of transistors and other minority-carrier devices by altering the surface characteristics or introducing space charges within the device package. When this occurs, leakage currents increase, and as a result, gain is decreased. Since one of the variables determining the effects is surface area, larger electronic components, such as power transistors, are more susceptible than small-signal devices.

Other variables which have been found to determine the device susceptibility to total dose are package techniques such as surface coating and gases within the package. Total dose also has a very significant effect on solar cells, reducing their output power and, therefore, the power available in satellites. Space radiation contains a relatively high level of ionizing radiation which, over the life of a satellite's mission, can cause appreciable damage to the solar cells as well as to other associated electronics. In addition to semiconductors, crystals are also affected by total-dose ionization, causing frequency shifts similar to prompt ionization.

Permanent-displacement environments include all nuclear environments capable of causing atomic structural changes in a material which permanently alter that material's characteristics. In the first column of Figure 2, a spectrum of these effects is given for typical semiconductor devices. The neutron or proton fluence induces permanent changes in the semiconductor's crystal lattice structure which affect the carrier lifetime. These defects cause permanent parametric changes in the semiconductor devices.

The most common type of semiconductor element used in electronic circuit designs is the bipolar transistor. For this device, the most important neutron-sensitive parameters are common-emitter current gain (h_{FE}), base-emitter voltage (V_{BE}), saturation voltages $[\ V_{BE(SAT)}$ and $V_{CE(SAT)}\ ]$, and the base-collector diode leakage current (I_{CBO}). Signal and power diodes exhibit changes in forward and reverse voltages as a result of neutron displacement damage. Zener diodes will exhibit permanent shifts in zener voltage. These shifts are not significant for most design applications; however, if the zener is used in an application which demands a stability of less then $\pm 1\%$, special consideration must be given to the type as well as the manufacturer of the part. Digital integrated circuits undergo permanent changes in fanout, input current, and propagation delay time. Linear integrated circuits exhibit permanent changes in open- and closed- loop gain, offset voltages and currents, and input impedances as a result of neutron interaction.

The primary source of electromagnetic pulses (EMP) is the interaction of gamma radiation with the atmosphere producing very large electron currents. These currents produce the associated electromagnetic field pulse. The driving force for system-generated EMP (SGEMP) is the electron emission current resulting from the photon interaction with structural surfaces of a system. Magnetic and electric fields are produced, which, in turn, couple into a system's cables and circuits in the form of currents and voltages. These fields are a direct result of the practical nature of the construction of an electronic system, i.e., the need for various apertures, connector feedthroughs, and other deliberate penetrations in its "skin". In addition to SGEMP, currents are also induced on wires within a system by internal EMP (IEMP) fields and currents produced within the system enclosure. Such signals can cause functional upset of internal electronics (i.e., assume an undesirable state or mode) and, if they contain sufficient energy, will cause permanent damage or complete "burnout" of a piece part in a circuit. For those readers desiring more information and details on EMP effects, they are referred to a contemporary IRT brochure on the facts and principles behind EMP survivability and vulnerability programs for electronic systems (see Reference 1).

METHODOLOGY OF HARDENING

Electronic circuits are an integral part of the majority of modern weapons systems and space vehicles and satellites. They can be permanently damaged or made temporarily inoperative in a nuclear warfare environment,or by exposure to exoatmospheric space radiation. It is then the responsibility of circuit and systems designers/analysts to provide/assess the degree of radiation hardness to neutron and ionizing radiation effects relative to system mission, circuit function, and expected operational environment. Circuit hardness implementation/assessment is an integration process that involves the understanding of the anticipated radiation environment, functional circui/system requirements, and piece-part response to that environment. These basic circuit hardening considerations are the focal points of all hardening efforts.

To implement and to determine the level of nuclear hardening for a given system may, at first, appear as an overwhelming effort. This may be due to a lack of a systemized approach to the task and because of any combination of things such as system size, complication, operational and environmental requirements. The intent, therefore, of this section is to outline some of the considerations for implementing nuclear hardening procedures that are considered optimum throughout a system at all levels of integration, as well as the evaluation of their effectiveness. These considerations are presented below in such a manner that they will serve as a guide to any hardening effort, whether that task is implemented concurrently at the onset of a system design or must be applied to an existing system.

GENERAL CONSIDERATIONS

The overall emphasis of a hardening plan is on practicality combined with sound engineering judgment to isolate and address the most vulnerable components of a system. The first determination must be the appropriate reasonable threats for each system element. Next, these threats must be grossly related to system vulnerabilities and the system reviewed for the single item failure which could cause total system failure. Such single modes should be the first system elements to undergo more rigorous analysis or have more stringent specifications.

At this point, some type of systematic categorization as a function of vulnerability should be implemented that will, in a convenient manner, provide a hardness overview. This categorization may be done at the price-part, circuit, module, or subsystem level. More than one level of segregation is desirable in that it would tend to account for interaction effects between two or more circuits — for example, circuits which make up a module which, in combination, would not be as hard as each of its elements. One method, then, of providing this useful ordering is by way of a histogram. This type of graphic representation of a system, with increasing environmental increments plotted along the abscissa and with each circuit listed in the appropriate incremental column, would very likely flag vulnerable areas as well as provide a feeling of system hardness as a whole.

To provide a firmer basis for judgment as to the amount of effort that should be expended in hardening any one circuit that appears in a low-level increment of the histogram discussed above, a different ordering of these same circuits would also be desirable. In this case, a functional priority from the standpoint of mission success should then be assigned to each and plotted in a histogram format also. It may be found that this is a much more difficult task since some appreciation of overall, detailed, integrated-system operation must be available. Such considerations as to whether a circuit provides some redundant function or proper operation is essential after, rather than entirely before, any threat scenario during a system mission; this would be an example of ordering circuits into this second set. With this type of systematic arrangement, intelligent hardening cost trade-offs will be greatly facilitated, from both the vulnerability and functional priority points of view.

The histogram methods suggested above can be used throughout the entire design or hardening effort. If, at some time during the task, a circuit is determined not to be sufficiently hard as seen from its location on this vulnerability diagram, either more accurate analysis can be performed to gain a greater confidence as to its true susceptibility, or component substitution and/or redesign and analysis can be implemented to increase and verify its survivability. Such a circuit, if necessary, can then be relocated on the histogram and flagged by a convenient method. The advantage of a flag would be to convey the information that its location on the graph carries a higher certainty as to its level of hardness since more detailed analysis/design effort has been expended on it. The major advantages of such an approach throughout a design or analysis program are: (1) that the histogram method provides an instant status summary of all system circuits at any time during the course of the task, in that it would be continuously updated; (2) because of its currency, it facilitates correlation to budgeted funds expended by allowing for cost tradeoff judgments to be made as to whether additional analysis effort should be expended to increase the survivability confidence level of "safe" circuits but marginally close to a defined spec environment; and (3) that it allows for the relegation of a significant number (as is usually the case) into the area of "fail-safe," so that no additional effort need be devoted to them.

From this point, the design/analysis becomes more detailed by addressing specific system elements and considering the exact vulnerabilities. Up to this point, the design/analysis task has been primarily the responsibility of a system designer or analyst establishing the functional criteria for the system elements. Implementation of these design criteria is now the responsibility of hardware designers and analysts. One of the requirements for the hardware is operation in a specified radiation environment. To accurately interpret requirement and specification requires the hardware designer or analyst to comprehend system operation. At the same time, system designers imposing the specification must have some understanding of hardware limitations and capabilities. One of the prime objectives of a hardness implementation program is to document techniques which will facilitate this communication between hardware and system designers by providing an understanding of each other's requirements and limitations.

Another difficulty frequently encountered in the interchange between systems and hardware designers/analysts is in defining the effect radiation will have on the respective components. This may be thought of as quantifying the survivability of the item. The lack of a commonly accepted method of indicating equipment operation as a function of radiation level results in frequent erroneous conclusions which are an understandable outgrowth of differing points of view, which contributes to cost-ineffective efforts. As a result, unique techniques need to be developed for the system of interest that will reflect hardwave survivability/vulnerability in a well defined manner.

HARDENING PROCEDURES

Imposing nuclear hardening requirements on systems and their components may be accomplished in one of several ways: (1) specification of the threat environment and operational criteria; (2) component performance with an electrically simulated radiation signal and implementation of hardening guidelines; and (3) a combination of these methods. Each approach has advantages and disadvantages for specific application at various points in the system design and development. Obviously, specifying component hardening design guidelines at the system level is impractical, as is imposing a nuclear scenario at the component hardware level. Therefore, hardening design criteria must be selected which correspond to the level of consideration and knowledge of designers/analysts. Hardening of systems is best achieved through evaluation of scenarios and overall threat environments from which intelligent hardening techniques may be selected and system operational criteria established. From these criteria, the design and selection of specific components may proceed. This may be achieved by stipulating and defining the nuclear environment and then interpreting it through general design guidelines or from characteristic signals induced by the environment. This approach satisfies the condition where the designer is knowledgeable or unfamiliar with nuclear effects.

When defining hardening procedures, a second consideration is that of determining at what point in the design, development, or deployment of the system they may be imposed and verified. Studies have shown that hardening considerations imposed early in the design are most cost-effective; however, situations do prevail where early implementation of hardening techniques is impossible. In most cases, it is essential to be aware of what variations to the hardening procedures are necessary and which will give the highest confidence level for survivability.

The final considerations for hardening addresses the techniques of implementation. These approaches consist of proven design methods along with sound and ingenious techinques derived from unique applications. Frequently, it is necessary to combine several of these methods to achieve the hardness goal or trade off the hardening benefit in one environment while slightly increasing vulnerability in another. The starting point in establishing the techniques is from the threat definition which bounds the most severe condition to be met. This determination permits hardening techniques to be selected for the specific applications at various levels of design or analysis.

A simple example of hardening technique selection is solving the problem of a satellite's solar cell output degradation due to neutrons which typically limit the hardness level to this type of exposure. At the system level, the hardening technique is to use something other than solar cells for the primary power — a radioisotype thermonic generator (RTG), for example. If this is ruled out, solar cells must be specified and hardening techniques implemented at the component level. These might include increasing the solar cell population by the projected degradation or using lithium-doped cells which are slightly less vulnerable. Each hardening technique must be evaluated for its effect on the system or component performance and trade-off studies performed. A hardening technique which increases the survivability of confidence level "X" percent, while reducing the reliability by a like amount, would not be warranted except in unique situations, based upon some perhaps unusual operational mission requirements. This demonstrates the need for understanding the limitations of hardening techniques and the assumption on which they are based.

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Protection from EMP

In 1961, a study was performed at Fort Belvoir to select devices particularly capable of offering protection against EMP generated transients. The TransZorb® was found to be a good device for this application. An outgrowth of this finding was a feasibility study contract with General Semiconductor Industries to evaluate TransZorbs exposed to laboratory simulated EMP transients. There were two specific results from this contract. The first was the development of an rf TPD (Terminal Protection Device) for use in the Pershing Missile System for EMP hardening. Figure 1 depicts the electrical and mechanical characteristics of this device along with an oscillogram showing the response of the device to a 10KV incident simulated EMP transient[3].

The second was a series of questions on the effects of inductance in protection circuits and methods of reducing the TransZorbs effective capacitance. General Semiconductor was awarded a contract (DAAG39-72-C-0044) from Harry Diamond Laboratories to perform a feasibility study for the development of low inductance Rf TPD hardware.

A natural direction to follow would be to repackage the TransZorb into a configuration which would minimize overall inductance of the device. This was accomplished by removing the cell from the standard DO-13 package and sandwiching between two gold plated copper discs and coating the periphery with epoxy for protection. This sequence is shown in Figure 2.[4].

The disc TransZorbs were then placed in a prototype low inductance RF fitting fabricated using a configuration to allow one side of the disc to contact the center conductor and a retaining screw to contact the outer grounded case. In this design, sufficient space was provided to allow for multiple stacking of TransZorbs to achieve high operational voltages as required.

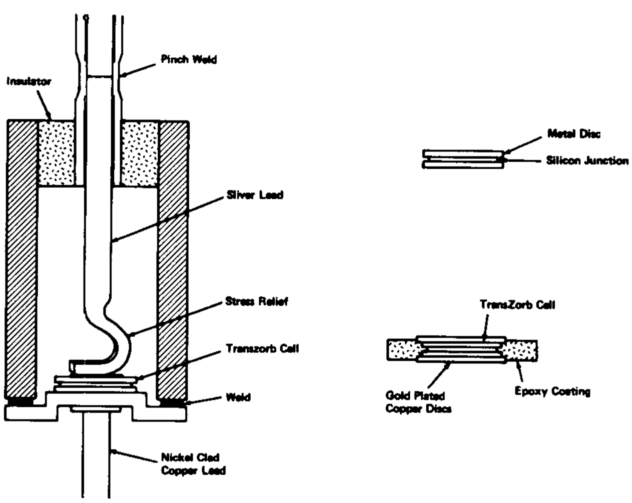
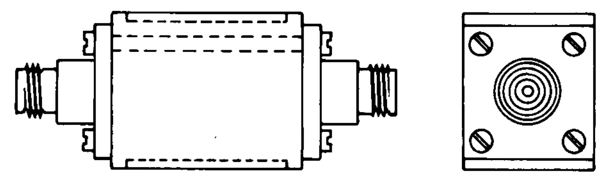


Figure 2 DO-13 TransZorb®

Testing

All tests described were made using the equipment as shown in Figure 3. The pulse generator was constructed in the laboratory at General Semiconductor Industries. An HP 183C scope with an 1830A amplifier and an 1840A time base was used in making oscillograms. A T & M Research current viewing resistor was found to be the most satisfactory in interfacing the device under test with the instrumentation. The charge cable approach appears to be limited to pulses of the order of 200A, but this was sufficient for these feasibility studies.

1) Breakdown Voltage - 450v $\pm$ 25v
2) Leakage Current @ 350v DC - 5 microamps max.
3) Clamping Voltage @ 10,000v Simulated EMP Pulse - 800v max.
4) Overshoot Voltage (same conditions as 3) - 1500v, 10 nsec max.
5) Max. Peak Pulse Power for 1 microsecond - 50,000 watts



Response Characteristics of the
R. F. Bi-Polar TPD
PULSE AMPLITUDE: 10,000v
PULSE WIDTH: 250 nsec
VERT. SENS: 500v/cm
HOR. SWEEP: 10 nsec/cm

Figure 1 Terminal Protection Device, TPD 525

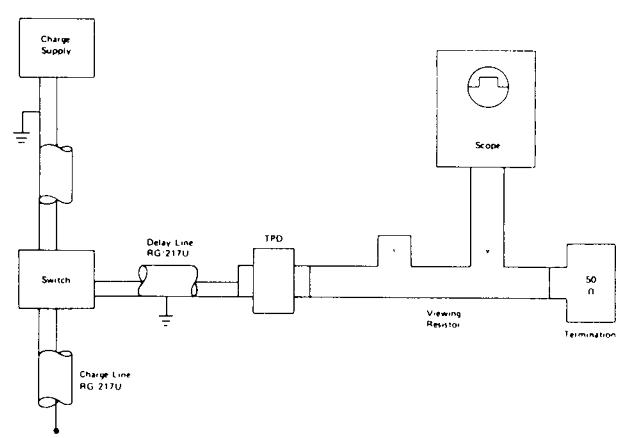


Figure 3 Current Measurement

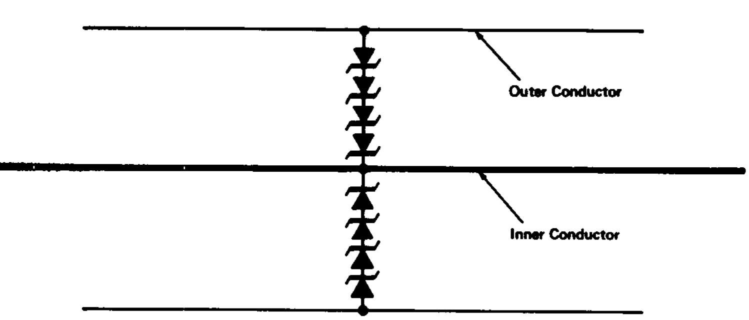


Figure 4 Parallel/Diametrically Opposed Current Path

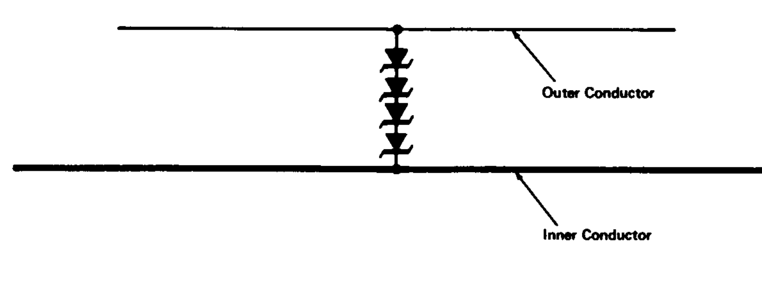
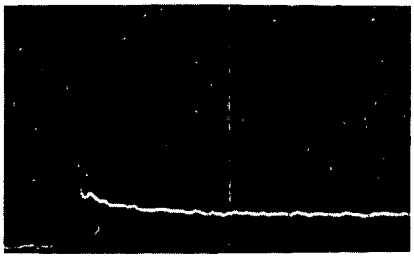


Figure 5 Single Side Current Path

TransZorb® - Trademark of General Semiconductor Industries, Inc.

TPD 525



Low Inductance TPD

Vertical Sensitivity: 200V/cm
Horizontal Sensitivity: 10 Nsec/cm

Figure 6

Figure 7

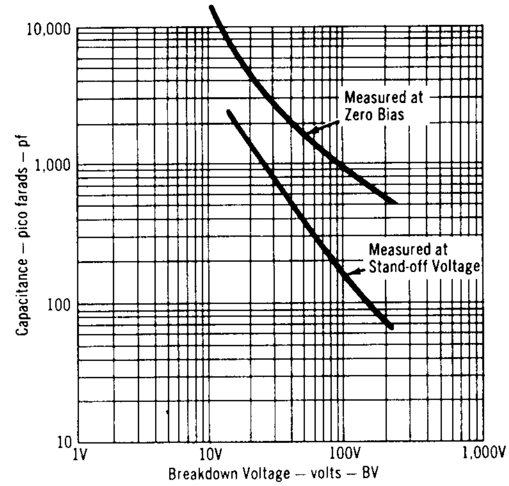


Figure 8 Capacitance of TransZorb

Test Results of Low Inductance TPD

The goals of these efforts were directed primarily toward reducing overshoot voltage generated by inductance in the TransZorb protective circuit. Using the general structure of the Model TPD 525, (as shown in Figure 1) which contains DO-13 TransZorbs as a baseline for measurements, comparisons were made with the Low Inductance TPD. Tests were made using parallel/diamentrically opposed current paths and single side current paths as shown in the schematics in Figures 4 and 5, respectively. Results comparing four each 30V TransZorbs stacked in series to yield 120V total and having parallel opposed current paths are shown in Figures 6 and 7. The incident simulated EMP pulse is 200A.

Capacitance Effects

Since the TransZorb is fabricated using a large area junction, so necessary for transient protection, the capacitance of the device is inherently very high, both at zero bias and at stand-off voltage. This is illustrated by the graph as shown in Figure 8.

Insertion loses of TPDs having capacitances as illustrated in Figure 8 are shown in Figure 9 and 10. The TPDs were swept from OMHz through 100MHz.

It is obvious from these results that these devices would be of little use in RF protection due to high insertion losses. However, there are methods of reducing the effective capacitance. Three circuits are shown below which can reduce the effective capacitance to less than 100pf. It follows that the low capacitance diodes be capable of withstanding the same pulse traveling through the TransZorb.

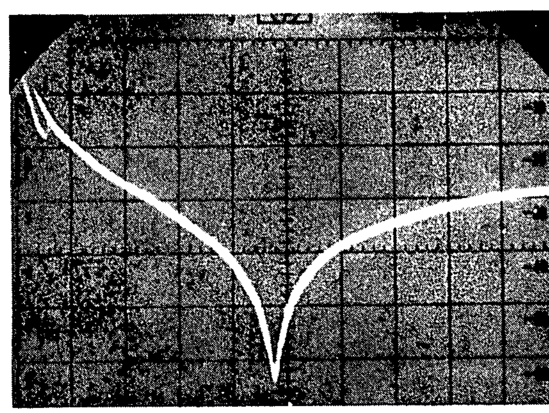


Figure 9 6V Bipolar

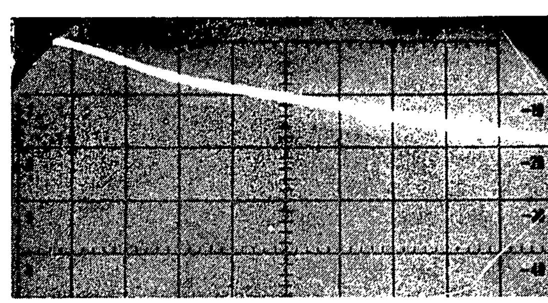


Figure 10 90V Bipolar

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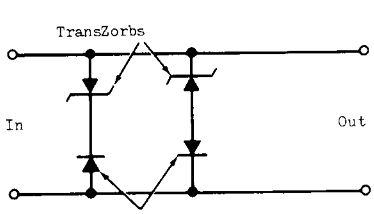

Figure 11 Parallel Circuit

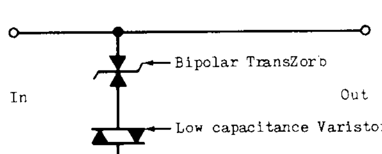

Figure 12 Series Circuit

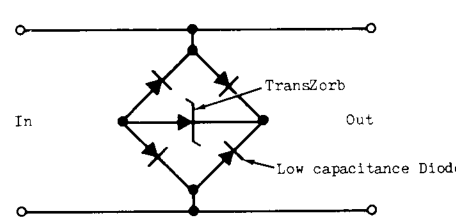

Figure 13 Bridge Circuit