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Review Article

Nuclear Power Reactors Driven Radiation Harden Environments

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Abstract

Radiation hardening, also known as “rad hardening,” and radiation survivability testing are of critical importance to defense, aerospace, and energy industries. Everyone knows that excessive exposure to radiation can cause severe damage to living things, but high radiation levels can also cause radiation damage to other objects, especially electronics. Ionizing radiation in particular, including directly ionizing radiation such as alpha and beta particles and indirectly ionizing radiation such as gamma rays and neutron radiation, is profoundly damaging to the semiconductors which make up the backbone of all modern electronics. Just one charged particle can interfere with thousands of electrons, causing signal noise, disrupting digital circuits, and even causing permanent physical radiation damage. Radiation hardening involves designing radiation-tolerant electronics and components that are tolerant of the massive levels of ionizing radiation, such as cosmic outer space radiation, X-ray radiation in medical or security environments, and high energy radiation within nuclear power plants. In order to test these components and determine whether they are sufficiently hardened, radiation-hardened electronics manufacturers perform rigorous testing as part of their product manufacturing processes. Components which pass these tests go into production and can be described as “radiation-hardened”; components that do not go back to design.

Keywords: Integrated Circuits; Digital Circuits; Radiation Shielding; Electromagnetic Pulse; Electromagnetic Interference, and Electromagnetic Compatibility; Nuclear Power Reactor; Radiation Environment

Introduction

To start with, we introduce the basic concept of radiation by describing what it is and then we move on to introduce types of shielding materials that we need to protect our assets, as well as going through different radiation types of radiation as illustrated in figure 1, that we need to shield ourselves, biologically, health care wise and medical imaging to the yields from nuclear energy burst, nuclear medicine and non-destructive testing cross different industries and on earth and in the space as well as ground assets within defense communities.

As illustrated in figure 1 to X-Ray radiation both cold and hot X-Ray radiation as well has High Energy Laser (HEL) radiation. We then talk about different source of radiation either man-made or natural ones that one need to shield against it no matter what field of application we are considering.

Under effort of As Low As Reasonable (ALARA) driving a principle that strives to minimize the exposure of ionizing radiation to people and environment by choosing and introducing the proper materials, while considering economics, technology, and social factors. Considering all the factors, and the number of materials to choose from, consulting with a shielding materials expert within such community of experts in the field of radiation shielding and survivability, is essential to finding the most effective solutions to your shielding needs.

It all starts with the type of radiation that is present. Materials interact differently with different types of radiation. For example, tungsten is able to attenuate gamma radiation effectively, but when exposed to neutron radiation, secondary gamma rays can be produced.

Materials that are strongest at attenuation gamma radiation are tungsten and lead, while high density concrete and borated polyethylene are better materials for stopping neutrons on its track. Figure 2 is illustration of such materials.

Choosing the right material will allow you to save space and use less material. A shield of high-density concrete can take half the space of regular concrete with the same shielding properties. Flexibility of a material is also important to think about when considering the space requirements.

Figure 1: Particle Radiation Characteristics (Courtesy of Paul Rochus, marsmetal.com).

A flexible material like metal impregnated polymers might be more suitable to shield a round object like a pipe, as it can be wrapped around tightly as figure 3, shows such wrapping materials.

Generally speaking, materials that are used in radiation shielding, are consistent of certain physical and chemical properties that would be able to enhance shielding to level of assigned survivability of certain Service Level Agreement (SLA), depending on the environmental conditions that need to take place.

Figure 2: Isolating Materials Layer Infrastructure (Source: MarShield.com).

Radiation shielding is imperative as radiation can be a serious concern in nuclear power facilities, industrial or medical x-ray systems, radioisotope projects, particle accelerator work, and a number of other circumstances. Containing radiation and preventing it from causing physical harm to employees or their surroundings is an important part of operating equipment that emits potentially hazardous rays. Preserving both human safety and structural material that may be compromised from radiation exposure are vital concerns, as well as shielding sensitive materials, such as electronic devices and photographic film.

Figure 3: Wrapping Materials (Source: MarShield.com).

From military application perspective, any Integrated Circuits (ICs) that are embedded in any electronic devices as part of military equipment's need to be Radiation Harden (RH) in case of directed exposure to X-Ray radiation either cold or hot as well type of particle radiation type shown in figure 1, here resulted from any nuclear explosion either Endo or Exo-atmospheric burst.

Integrated Circuits these days are more or less digital rather than analog if form of old tubes technology that we could find in any electronic devices such as old Radios representing Transistor, Capacitors or Resistors.

Digital circuits are designed and manufactured in Semiconductor's industries in form of either Bipolar or CMOS infrastructures. However, most of these industries are pushing CMOS approach that is heavily driven by reduction of chip's foot-print on these day's 25" wafer processing, toward sub-micron technology path.

Although from survivability, point of view the Bipolar IC's have a better chance than CMOS circuits to not to have any latch-up events due to Transient Radiation Effects on Electronics (TREE) from a Single Event Upset (SEU) or System Generated Electromagnetic Pulse (SGEMP) [1].

All these above events could take place either naturally as a source or man-made type such as nuclear explosion, where the intensity of radiation depending on the yield of weapons in question or in case application nuclear fission reaction for peace in case of nuclear power reactors as illustrated in figure 4, where it demonstrates Three Mile Island (TMI) schematic plant of nuclear reactor system.

Environments with large amount of ionizing radiation, either natural or man-made, create special design challenges for integrated circuits, typically for RF power amplifier chips [2]. A single charged particle can knock thousands of electrons loose, resulting in electronic noise and signal spikes. In the case of digital circuits, this can lead to results that are inaccurate or unintelligible. It is a particularly serious problem in designing artificial satellites, spacecraft, military aircraft, nuclear power stations and nuclear weapons.

As far as man-made radiation environment is concerned, there are numerous classes of systems that require or are to some degree dependent upon the application of radiation hardened electronics.

The present existing variety of applications that are in place have quite different radiation scenarios and each require their own radiation hardening conditions under their exiting circumstances.

For example, military systems can demand and impose certain requirements that are asking for more tolerance to very high rate radiation environments that exist for nanoseconds to microseconds degradation of system electronics on board of their equipment or assets exposed to hazardous radiation environment, whereas in case of space systems and nuclear power systems may desire electronics to operate at much lower rates. However, either way the must survive radiation environments that last for years to come after their deployments and life cycle is concerned.

The process of regulating the effects and degree of penetration of radioactive rays varies according to the type of radiation involved. Indirectly ionizing radiation, which includes neutrons, gamma rays, and x-rays, is categorized separately from directly ionizing radiation, which involves charged particles.

Figure 4: Plant Schematic of Nuclear Reactor System at Three Mile Island (TMI2) (Courtesy of U.S. Nuclear Regulatory Commission).

The process of regulating the effects and degree of penetration of radioactive rays varies according to the type of radiation involved. Indirectly ionizing radiation, which includes neutrons, gamma rays, and x-rays, is categorized separately from directly ionizing radiation, which involves charged particles. Different radiation shielding materials are better suited for certain types of radiation than others, as determined by the interaction between specific particles and the elemental properties of the shielding material.

Moreover, in the case of digital circuits, this can lead to results that are inaccurate or unintelligible. It is a particularly serious problem in designing artificial satellites, spacecraft, military aircraft, nuclear power stations and nuclear weapons. Typical sources of exposure of electronics to ionizing radiation are the Van Allen radiation belts for satellites, nuclear reactors in power plants for sensors and control circuits, residual radiation from isotopes in chip packaging materials, cosmic radiation for spacecraft and high-altitude aircraft and nuclear explosions for potentially all military and civilian electronics [3].

As part of protecting the ICs or any other assets against radiation threat is the shielding and packaging materials. Is the way to go, as it was stated in above.

When it comes to protecting against radiation, the basic radiation protection principals or radiation safety tips involve time, distance, and shielding. Time, in this case, means to limit exposure to the minimum amount possible. Distance means staying as far from radiation sources as possible as a best practice. The intensity of radiation generally follows the inverse square law, meaning that it falls off with the square of the distance from the source. Moving twice the distance away from a source of radiation reduces the intensity of exposure by a factor of $1/2^2$ or one fourth the value.

Beyond time and distance, making use of effective shielding is the other approach to managing exposure to radiation.

But what materials protect against radiation? The most common ones used include lead, concrete, and water - or a combination of these. Below.

X-Ray and gamma radiation shielding materials

Generally speaking, in most common cases, radiation such as X-Ray or Gamm-Radiation source, either natural or man-made, high density-density materials with high atomic number Z are more effective than low-density with atomic number Z alternatively has a better shielding effect for blocking or reducing the intensity of radiation.

However, low-density materials can compensate for the disparity with increased thickness, which is as significant as density in shielding applications. Lead is particularly well-suited for lessening the effect of gamma rays and X-Rays due to its high atomic number. This number refers to the number of protons within an atom, so a lead atom has a relatively high number of protons along with a corresponding number of electrons. These electrons block many of the gamma and x-ray particles that try to pass through a lead barrier, and the degree of protection can be compounded with thicker shielding barriers. However, it is important to remember that there is still potential for some rays making it through shielding and that an absolute barrier may not be possible in many situations [4].

Alpha and beta shielding

In most cases, high-density materials are more effective than low-density alternatives for blocking or reducing the intensity of radiation. However, low-density materials can compensate for the disparity with increased thickness, which is as significant as density in shielding applications. Lead is particularly well-suited for lessening the effect of gamma rays and x-rays due to its high atomic number. This number refers to the number of protons within atom, so a lead atom has a relatively high number of protons along with a corresponding number of electrons. These electrons block many of the gamma and x-ray particles that try to pass through a lead barrier, and the degree of protection can be compounded with thicker shielding barriers. However, it is important to remember that there is still potential for some rays making it through shielding and that an absolute barrier may not be possible in many situations [4].

Neutron shielding

Material such as Lead is quite ineffective for blocking neutron radiation, as neutrons are uncharged and can simply pass through dense materials. Materials composed of low atomic number elements are preferable for stopping this type of radiation because they have a higher probability of forming cross-sections that will interact with the neutrons. Hydrogen and hydrogen-based materials are well-suited for this task. Compounds with a high concentration of hydrogen atoms, such as water, form efficient neutron barriers in addition to being relatively inexpensive shielding substances. However, low-density materials can emit gamma rays when blocking neutrons, meaning that neutron radiation shielding is most effective when it incorporates both high and low atomic number elements. The low-density material can disperse the neutrons through elastic scattering, while the high-density segments block the subsequent gamma rays with inelastic scattering [4].

Because neutron radiation presents so many inherent dangers, top-of-the-line neutron shielding protection is critical. Neutrons have neither a positive nor a negative charge, resulting in a wide range of energy and mass levels that must be blocked. Neutron radiation dangers, therefore, must be handled with the utmost care and attention to detail, whether dealing with nuclear power facilities, medical X-ray systems, radioisotope projects, or particle accelerator work. Hazardous rays can cause serious and long-lasting physical harm to the people exposed to them, and structural material and environments can also be damaged beyond repair by radioactive waves. Electronic devices and photographic film, in particular, are a couple of the more sensitive mediums that can be easily damaged [5].

Given that lead is a heavy element or high atomic number Z (heavier than around 80% or so of the other elements found on the periodic table), it is a common choice for use in fabricating radiation shielding products. Lead is fabricated into different product forms to provide radiation shielding and protection, and which includes these types:

- Lead Sheets, Plates, Slabs, & Foils
- Lead Shot
- Lead Wools
- Lead Epoxies
- Lead Putties
- Lead Bricks
- Lead Pipe
- Lead-clad Tubing
- Lead-clad Pipe
- Lead Sleeves
- Lead Glass
- Lead-Polyethylene-Boron Composites

Lead can also be added to concrete or cinder blocks for use in wall construction. By adding unperforated sheets of lead to the blocks and extending the sheet beyond the edge of the concrete block and overlapping shield of lead can be embedded in a wall to form an effective radiation barrier utilizing a continuous lining of lead sheet. A similar approach can be used to create lead shielded doors and door frames. As with the wall construction, it is important to overlap the lead that is used in the door frame with the lead that is used in the wall construction to provide a continuous lead barrier that will function as an effective shield.

There are other source of event that is driven by man-made nuclear explosion that we need to protect both biological and integrated circuits from and few, which can be named are Electromagnetic Pulse (EMP), Electromagnetic Interference (EMI) that are driven by the yield from a nuclear explosion with Endo or Exo-Atmospheric burst.

An EMP that is resulting from above-atmosphere level detonation of a nuclear device produces enough radiation to wreak havoc with electrical systems. The blast produces a very brief but intense electromagnetic field that can quickly induce very high currents in electrical devices, shorting them out. The stronger the electromagnetic field — the "pulse" — the stronger the current, and the more likely electrical devices are to "blow out." It's akin to a power surge that shorts out your refrigerator or TV when too much voltage surges through the electrical outlet… on a whole other scale.

Any digital integrated circuit built in any electronic device requires to have a capability in order to be compatible to function in such environment or to be Electromagnetic Compatible (EMC). It is very obvious, when transition from analog circuit such as old tube moved into path of digital circuits and consequently manufacturing of transistor and eventually, Integrated Circuits (ICs) in form of semiconductor, the combination of package of sequence of events such as EMP and EMI driving a need for EMC for the ICs becomes a necessity for shielding such as electronic devices.

These semiconductor devices, however, are more susceptible to the effects of radiation than the old tubes and have to be made more survivable or obey the requirement for EMC.

The survivability of these semiconductor devices is combination of both an innovative design and shielding procedure. Packaging of these semiconductor ICs within a layer of combined materials such as Gallium (Ga)/Arsenide(As) provides a better protection layer against the concerned radiation by design and Gallium Arsenide Next Generation Semiconductors Market Expected to Grow to $22 Billion by 2026.

As illustrated in figure 5, Next generation GaAs semiconductors promise to bring a huge market, not totally replacing the existing semiconductor market, but ultimately making a huge dent in it.

Figure 5: Ga/As Integrated Circuits.

The ability to replace silicon semiconductors, a market that is $500 billion dollars in 2020 makes one sit up and take notice. The existing silicon semiconductor market is a pretty good size for a market that barely existed in 1975. Next generation GaAs support the signal speed that is needed to implement 5G. GaAs works in a way that silicon cannot. The potential for the next generation GaAs wafers is staggering, with the overall semiconductor market likely to surpass $20 trillion by 2026 as the new industrial revolution takes hold and 5G supports IoT that connects all things together. Once economies of scale are realized these semiconductor GaAs markets are expected to really take off. The sheer size of the global semiconductor market at $500 billion dollars in 2020 shows that the potential for next generation semiconductor technology is truly exciting.

The IC's built in wafer of GA/As and packaged with these two combined materials are the best way shielding against any natura or man-made radiation and they better opportunity of survivability over-time.

The gallium arsenide wafers are next generation technology because they operate faster than the silicon semiconductors, they support a new, faster network called 5G. Gallium arsenide GaAs represents the next generation of semiconductor chips because the chips can do things that the silicon chips cannot do. GaAs does have a considerably higher bandgap than silicon. It is a direct band-gap semiconductor with a zinc blende crystal structure. Sensing for autonomous and electric vehicles is one use of technology.

3D Sensing for consumer electronics and use for lasers is common. Units are used in radar and lasers. The benefits of using GaAs in devices derive in part from the characteristic that GaAs generates less noise than most other types of semiconductor components. As a result, it is useful in weak-signal amplification applications. Due to these benefits related to generating less noise, GaAs is a suitable replacement for silicon in the manufacture of linear and digital ICs. A gallium arsenide wafer is also known as the Gallium arsenide substrate.

Radiation environment in nuclear power plants

One of the man-made radiation environment is within any fission nuclear power plant made by the man to generate electricity for his or her demand.

Post nuclear accident conditions represent a harsh environment for electronics. The full station blackout experience at Fukushima shows the necessity for emergency sensing capabilities in a radiation-enhanced environment. Thus, there is a need for Nuclear Energy Enabling Technologies (NEET) research project in order to develop Radiation Hardened By Design (RHBD) electronics using commercially available technology that employs Commercial Off-The-Shelf (COTS) devices and present generation circuit fabrication techniques to improve the Total Ionizing Dose (TID) hardness of electronics. Such technology not only has applicability to severe accident conditions but also to facilities throughout the nuclear fuel cycle in which radiation tolerance is required. For example, with TID tolerance to megarads of dose, electronics could be deployed for long-term monitoring, inspection, and decontamination missions. The present work has taken a two-pronged approach, specifically, development of both board and Application-Specific Integrated Circuit (ASIC) level RHBD techniques. The former path has focused on TID testing of representative microcontroller ICs with embedded flash (eFlash) memory, as well as standalone flash devices that utilize the same fabrication technologies. The standalone flash devices are less complicated, allowing better understanding of the TID response of the crucial circuits.

Radiation can ionize atoms and disrupt a semiconductor's crystal structure. For electronics that are very close to a reactor, neutrons will create physical damage to the semiconductor crystal. But most chips will fail first because of leakage that's associated with the charging of insulators. In something like a metal-oxide-semiconductor device, for example, gamma rays and X-ray radiation will knock electrons off atoms in an insulator to create electron-hole pairs. The resulting trapped positive charges will shift the operating characteristics. Devices are designed to turn on and off at a well-defined point of operation, and if that operating voltage shifts, this can create difficulties.

The process of radiation hardening involves rigorous radiation survivability testing, also known as radiation effects testing. Radiation survivability testing involves bombarding materials with radiation to determine how long it can withstand harsh extremes of its operating environment and ultimately which material will be the best choice for a given radiation-hardened component.

As we known about any nuclear power plant in line of operation, most of the equipment and instruments in a nuclear power plant that must be radiation hardened are located in the Containment Building. The primary coolant loop (consisting of the nuclear reactor core, steam generations, pressurizer, and coolant pumps) is located within the Containment Building. These components are identified in the pressurized water nuclear reactor system identified in figure 4.

Figure 6 is illustration a more detailed sketch primary coolant loop of a Pressurized Water Reactor (PWR), where in this type of reactor, the primary, coolant operators at high pressure i.e., 2250 psi) and is hot water at about 600 ^{0}F.

Under normal operating conditions, the out of-core background radiation environment in containment comes primarily from the gamma rays that are getting released in neutron capture reactions in coolant water oxygen, per se.

Given the nature of above statement, these trapped gamma rays can be a serious threat to electronic instruments (i.e., 103 to 108 rad over 40 year), in particular post-accident events as we have seen around major nuclear accidents around the world, such as Three Mile Island in United States, in Russia.

Figure 6: Primary Coolant Loop of PWR (Source: www.wikipedia.org).

Chernobyl disaster, and the recent Fukushima Daiichi nuclear disaster in Japan.

As studies of gamma radiation impact on environment has shown, the corresponding operation induced from the operating radiation environment summed over the 40 year life of a nuclear power reactor plant is difficult to define, because of large variations in plant design, age, and location within the plant.

Moreover, few data are available; therefore, only typical environment can be taken under consideration and to be specified and that is presented in table 1 under normal operating environments, over 40-year life cycle of the power plant and compare them to a worst case scenario of estimated accident circumstances.

The gamma and neutron levels were obtained from several sources, including dosimetry measurements at six operating reactors that represent a cross section of plant types and vintage.

In case of an event of an accident in which the coolant water becomes contaminated may be hazardous to electrical systems. The most severe radiation environment would probably occur after a Loss-Of-Coolant Accident (LOCA).

Normal Operation		
Environment	**(40-year Aging)**	**Accident**
Gamma * rad/Si	10^3 10^4	2 x 10^7
Rad/(Si)	10^{-3} to 10^2	10^4
Neutron ** n/cm^2	10^9 to 10^{14}	--
n/cm^{2}s	10^0 to 10^5	--
Electron/Proton rad/(Si)	--	2 x 10^8
Temperature ^{0}C	24 to 66	260
Humidity RH at 20^0	10 to 100	100

Table 1: Range of Radiation Environments Possible in Nuclear Plant Containment Area.

* Gamma dose: 10^4 between primary and secondary shield; 10^4 outside secondary shield.

** Neutron radiation outside secondary shield, median energy 100 keV. The same damage in silicon from 1 – MeV neutrons would reduce the flux and fluence number for 100-keV neutrons by a factor of 10 to 20.

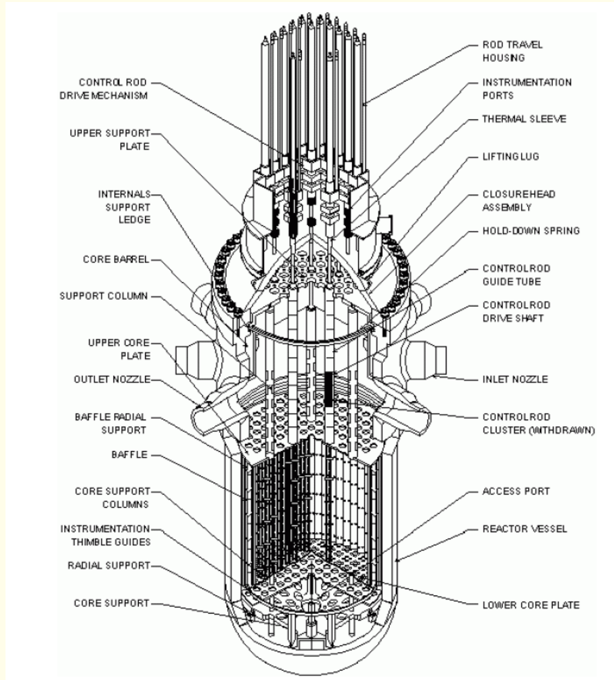

Figure 7: Pressure Vessels and their Safety Aspect [7].

Design basis accident (LOCA)

In the design basis accident scenario, a large break is assumed to occur in a pipe carrying primary coolant. This results in a rapid drop in coolant pressure, and water at 600 ^{0}F is converted to steam. This event is termed a blowdown.

The blowdown of the reactor coolant system is expected to end in roughly 20 t0 40s after the initial pipe break. As hot water is converted to steam, heat is removed from the reactor core as illustrated in figure 7 to provide the heat of vaporization of the water.

This flashing phenomenon causes the

Pressure system components (PSCs) are listed as follows:

- Pressure vessels: Pressure relief devices
- Pumps, Compressors: Pressure gauges
- Fans, Control valves: Pressure reducing valve (PRV)
- Piping system, Tracing Dump vessels: Non-return valve (NRV)
- Steam traps
- Insulation: Pressure controllers or regulators
- Vent for pressure relief: Utilities like steam, water, air, thermic fluid, inert gas etc.
- Pressure recorders.

Temperature of the fuel cladding to drop. Consequently, only a few or perhaps none of the fuel rods will fail during the 20 to 40s blowdown; however, the fuel rods may be partially uncovered (i.e., not completely surrounded by water). The Emergency Core Cooling System (ECCS) will refill the reactor vessel within 100 to 500s after the initial pipe break and being to cool the cladding.

During the initial blowdown, only the relatively small amount of radioactive material contained in the coolant from steady-state operation would be released to the containment.

Note that, even though control rods would have been inserted into the reactor core ramping down the fission process so that the reactor core becomes subcritical, two major sources of heat remain in the system as:

- Thermal energy, stored in the fuel rods as a result of previous fission events.
- The fission products that continue to decay by beta and gamma emission, thus heating the fuel rods.

This can be as high as 2% of the pre-shutdown power 1 hour after shutdown.

If the fuel rods are uncovered, the temperature of their cladding will begin to rise. When the temperature of the cladding reaches 2000 ^{0}F, zircalloy cladding begins to react with water and steam so that hydrogen is evolved. During this period some of the fuel rods may experience cladding failure. During the period when fuel-rod cladding failure may occur, radioactive gases and other fission products will be transported with steam flow through the break into the containment.

At the end, for those readers that have further interest in the subject of this short review, we recommend refer to textbook in the subject of shielding.

Conclusion

With the development of astronautic techniques, the radiation effects on Integrated Circuits (ICs) have been recognized by people. Environments with high levels of ionizing radiation create special design challenges for ICs. To ensure the proper operation of such systems, manufacturers of integrated circuits and sensors intended for the military aerospace markets adopt various methods of radiation hardening.

There are current effort research and work are in place has taken a two pronged approach, specifically, development of both board and Application-Specific Integrated Circuit (ASIC) level Radiation Harden By Design (RHBD) techniques. Moreover, the former path has focused on Total Ionizing Dose (TID) testing on Integrated Circuits (ICs) with Embedded Flash (eFlash) memory, as well as standalone flash devices that utilize the same fabrication technologies.

The standalone flash devices are less complicated, allowing better understanding of the TID response of the crucial circuits. Our TID experiments utilize biased components that are in-situ tested, and in full operation during irradiation. In this case, TID experiments utilize biased components that are in-situ tested, and in full operation during irradiation.

A potential pitfall in the qualification of memory circuits is the lack of rigorous testing of the possible memory states. For this reason, we employ test patterns that include all ones, all zeros, a checkerboard of zeros and ones, an inverse checkerboard, and random data.

With experimental evidence of improved radiation response for unbiased versus biased conditions, a demonstration-level board using the Commercial Off-The-Shelf (COTS) devices was constructed. Through a combination of redundancy and power gating, the demonstration board exhibits radiation resilience to over 200 krad. Furthermore, our ASIC microprocessor using RHBD techniques was shown to be fully functional after an exposure of 2.5 Mrad whereas the COTS microcontroller units failed catastrophically at <100 krad.

The environmental conditions that the shielding is placed in is also important to consider. How well a material can withstand heat, if the shielding will be moved and potentially bumped and if the material must hold any structural load are all important factors in the environment that need to be considered. Shielding properties can change when put under stress or heated. Dents and damage to the material may also lessen the ability for a material to shield properly [6].

Safety is important in selecting the right shielding solutions. Leaded glass for example comes in several options including safety glass. Clear Leaded Acrylic is also a viable option to making durable clear shielding that is shatter resistant. Exposed lead may not be permitted in some scenarios due to the toxicity of lead, so polymers mixed with bismuth, tungsten or iron may be a better, non-toxic alternative [6].

Cost is an important to consider when selecting the appropriate shielding material for a job. Lead is a very effective and inexpensive shielding material compared to materials like tungsten and could work just as well for a lot of scenarios. Related to cost, another factor that needs to be considered is the ease of shipping, handling, and installation. Choosing between installing leaded drywall or sheet lead is one example where shipping and installation need to be considered [6].

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