Emerging Radiation Hardness Assurance (RHA) issues: A NASA approach for space flight programs

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Abstract

Spacecraft performance requirements drive the utilization of commercial-off-the-shelf (COTS) components and emerging technologies in systems. The response of these technologies to radiation is often complex. This engenders a set of emerging radiation hardness assurance (RHA) issues which include displacement damage in optocouplers, high-precision and hybrid devices, enhanced low dose rate (ELDR) and proton damage enhancement (PDE) in linear circuits, linear transients, and catastrophic single event effects (SEEs) phenomena. NASA has developed an approach to designing reliable space systems which addresses these emerging RHA issues. This programmatic methodology includes hazard definition, hazard evaluation, requirements definition, evaluation of device usage, and application of radiation engineering techniques with the active involvement of designers. Risk assessment is an integral constituent in the approach as is an established program to assess future technology needs for programs.

I. INTRODUCTION

Spacecraft and instrument design needs have changed greatly in the recent past. Increased performance requirements such as data handling capabilities are coupled with decreased spacecraft parameters such as power consumption, weight, volume, and cost to drive spacecraft design toward the use of COTS and newer emerging technologies.

Projects are no longer able to meet their design and performance requirements by using radiation hardened (RH) components. In many cases, RH devices are no longer available, and the RH integrated circuits (ICs) that are available do not come close to being "state of the art" (SOTA). A relevant example is in the semiconductor memory arena where RH devices are at least two generations behind COTS. The current SOTA RH devices are 1 to 4 Mbit static random access memories (SRAMs) compared to the 64 Mbit (or even 256 Mbit) COTS dynamice random access memories (DRAMs) that are available at this time. This performance gap is widening rapidly.

Three other issues that influence methodology in RHA programs involve the use of SOTA commercial and emerging technologies. These are:

- COTS and emerging technology devices are more susceptible to radiation effects (and in some cases have new effects) than their predecessors.
- There is much greater uncertainty surrounding radiation hardness because of the limited control and frequent processing changes associated with COTS device.
- With a trend toward minimization of spacecraft size as well as the use of composite structures, the amount of effective shielding against the external radiation environment has been greatly reduced, increasing the internal radiation environment.

The consequence is that we are now using more radiation sensitive devices with less protection.

II. REPRESENTATIVE RHA ISSUES

Several new phenomena have been observed in the last ten years that can heavily influence the use of COTS and emerging technology components in space [1]. Because circuit and system designers are not able to keep up to date on new effects, missions risk premature failure in space or costly last-minute fixes. Designers are further limited in their ability to address emerging RHA issues because information about the effects is not yet included in archival data.

Examples of the more significant new effects are highlighted below, divided into various categories. The list is not meant to be inclusive nor are the discussions comprehensive. The reader is strongly encouraged to supplement this information with the references provided.

A. Displacement Damage

As recently as two years ago, displacement damage in optocouplers was considered a "non-issue". For most NASA missions the radiation levels were low enough so that proton displacement damage on system electronics was a second-order problem. Also, devices that had been tested for displacement damage had shown relative insensitivity to this effect [2]. Because of this, nearly all radiation testing has concentrated on ionization damage.

Recent work has shown that some device technologies are far more affected by displacement damage than previously thought. Proton exposure of a different type of light-emitting diode (LED) used in certain optocouplers led to device degradation at fairly low fluences [3], [4]. In fact, severe degradation has been observed at (equivalent) total dose levels of 1-3 krad(Si).[5] Displacement damage does not occur with Co-60 exposure because of the low energy. Therefore, testing for RHA of optocouplers must go beyond traditional total ionizing dose (TID) tests. Figure 1 illustrates this point.

Displacement damage also occurs in other electronic system components. Examples include high-precision devices, such as voltage references or op-amps with extremely low input current and offset voltage. More recent work has shown that certain types of conventional linear ICs may be affected by displacement damage because they rely on higher performance of the internal pnp transistors [6]. It must be emphasized that, although some types of devices are guaranteed to withstand total dose levels above 100 krad(Si), they may fail at far lower levels when they are exposed to protons.

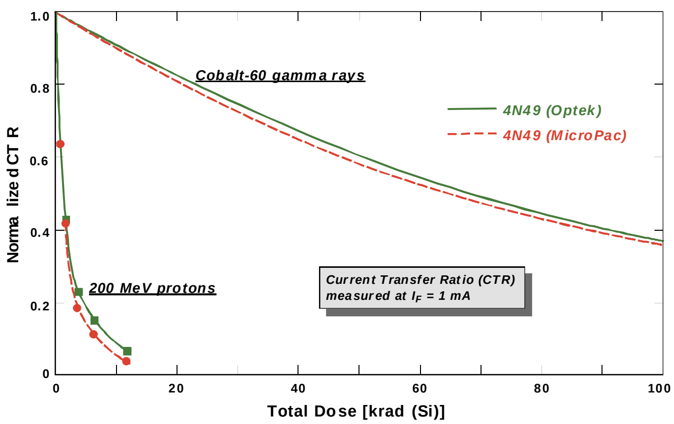

Figure 1. An optocoupler's response to Co-60 and proton irradiations, illustrates this issue.

B. Linear Bipolar Devices and Total Ionizing Dose/Proton Fluence

Subtle changes have occurred in linear bipolar technology in the last few years. More sophisticated designs have been developed with extremely close tolerances and lower power dissipation. Other modifications improve device performance and yield. These changes increased the impact of two separate radiation issues, namely, ELDR and PDE.

1. Ionization Damage: The ELDR effect in linear bipolar integrated circuits provides an example of a new effect that cannot be dealt with using traditional RHA methods. The basic problem is that certain types of bipolar devices degrade far more severely at very low dose rates (1 to 5 mrad(Si)/s) than at the high dose rate used in most older testing methodologies [7], [8], [9], [10], [11], [12]. Two aspects of the problem make it particularly difficult: (1) time periods of several months are required to do tests at sufficiently low dose rate to simulate rates in space, and (2) different failure modes can occur under low dose rate conditions, which makes it impossible to fully guardband the problem by overtesting at high dose rate. A further difficulty is that nearly all manufacturers of linear ICs produce some products with dose-rate sensitivity, but there are pronounced differences in the way that different devices and processing lines respond.

2. Proton Damage Enhancement: The second issue involves the response of a device in a ground irradiation versus its performance in the actual the space environment. A Co-60 test source is adequate for total dose testing for most device types even though protons and electrons cause the majority of the total ionizing dose damage in space. However, this is an issue for some linear devices such as precision voltage references (PVRs) because they degrade more from exposure to protons than from a Co-60 source [6]. This phenomenon is proton damage enhancement.

3. Design Margin Issues: Coupling ELDR and PDE effects together could yield up to an order of magnitude difference between in-flight failure at a low accumulated dose/fluence and predictions based on the Co-60 ground test data that were utilized to approve usage of the device. However, placing an across-the-board radiation design margin (RDM) of ten leads to unrealistic requirements for flight projects (say 100 kRads(Si) based on a nominal 10 kRads(Si) prediction). The key to solving this problem is careful selection of the types of devices that are used along with application-specific knowledge to assess degradation modes.

C. Circuit Technologies with Limited Tracability and High Risk

During the last five years several circuit technologies have been identified that are potentially high-risk for space applications. Sample issues are discussed below.

1. High-Precision Devices: Devices with very demanding electrical parameters are high risk simply because second- and third-order changes in internal components (or component matching) can cause them to degrade. Examples include precision references, analog-to-digital converters (14-bit and higher), and operational amplifiers with very low input specifications (e.g., V_{os} below 200 µV; I_b below 1 nA).

2. Hybrid Devices: Many hybrid devices are manufactured with only limited information and/or tracability about the internal components within the hybrid. Adding to this problem is the fact that most hybrid manufacturers consider their circuit designs to be proprietary. This means that nearly all hybrid devices must be evaluated for radiation susceptibility using inadequate information. The list of parts used in hybrid devices may be incomplete or simply unavailable.

A recent example is a series of power converter hybrids. These devices use many different internal components, including power metal oxide semiconductor field effect transistors (MOSFETs) and custom (proprietary) complementary metal oxide semiconductor (CMOS) and linear devices. Radiation concerns include ionization damage to the MOSFETs, CMOS and linear devices, SEEs such as possible shutdown from internal single event transients

(SETs) in the overvoltage detection comparator or latchup in the proprietary CMOS circuit. However, the most critical problem in one particular hybrid turned out to be degradation of an optocoupler used in the feedback circuit. Not only was this the dominant problem, but the optocoupler had not been included in the original parts list provided for the hybrid.

Because of the extreme degradation of the optocouplers, proton tests were performed on the optocouplers as well as on the completed circuits. Due to their high cost, only three hybrid modules were available for testing. Figure 2 shows the results of the circuit-level tests. The output of the circuit began to rise abruptly after the optocoupler degraded beyond the minimum value required to sustain operation. Because of the particular way in which the circuit is designed, a lower current transfer ratio was needed under high load conditions. Thus, the converter performed somewhat better when it was heavily loaded.

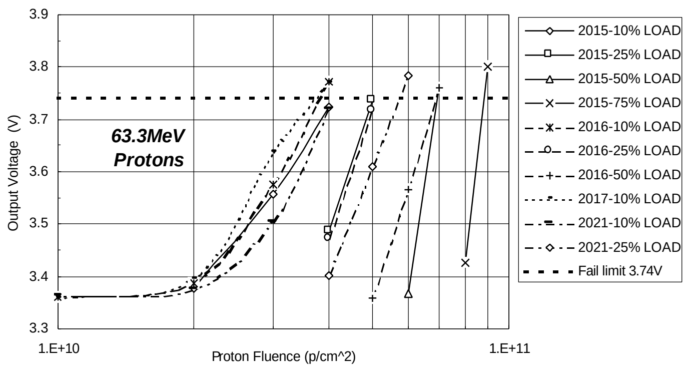

Figure 2: Failure levels of MDI power converters.

Although the test data appear straightforward, there are several other issues. First, the data represent only a very small sample of complex *circuits*, and do not take the sample-to-sample variability of the optocoupler radiation response into account. Other data on samples of the optocouplers show that the failure level would be about a factor of two lower if the variability of those components were taken into account. Second, LEDs are affected by temperature and aging (wearout mechanism). These very significant factors force designers to derate the acceptable radiation tolerance level of these converters by a substantial amount.

D. Complex single event upsets (SEUs)

1. Single event functional interrupts (SEFIs): We often think about SEUs in the context of bit flips in memories or storage cells from which systems can easily recover. However, even simple bit flips can produce circuit-level effects that cause strings of errors, or even result in a "lock-up" condition that requires removal of power and subsequent re-initialization to resume proper operation [13].

One example of a SEFI is seen in a basic DRAM. In this instance, an internal condition can place the DRAM into a special test mode (provided for ease of testing by the manufacturer). Earlier SEE tests of DRAMs did not detect this failure mode because the cross section was so small as shown in Figure 3 which compares the cross section for normal errors with that of functional interrupt. Unfortunately, this test mode can also be triggered by heavy ions in space. And, in spite of the small cross section, it is very important in solid-state recorders because of the large number of DRAMs that are used.

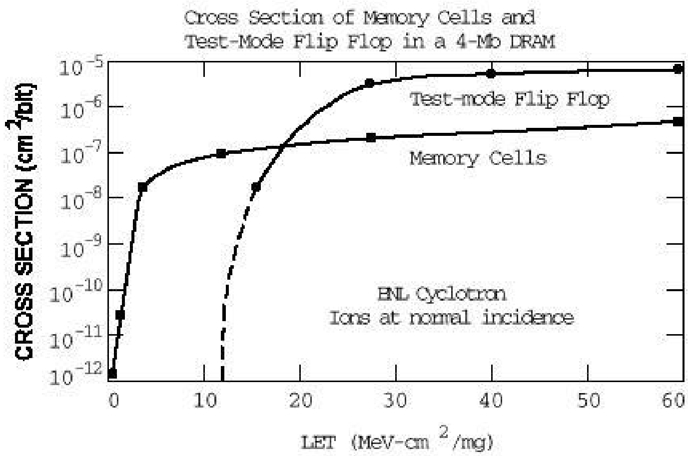

Figure 3: "SEFI" phenomenon in memory circuits.

Once the device is in the test mode, large sections of the memory can be corrupted, resulting in errors that are not consistent with simple error detection and correction (EDAC) approaches and could require complex power supply shutdown and system re-initialization. A solution is to periodically provide logic sequences to the memory that will bring it out of the test mode condition, minimizing the time window for errors if it is inadvertently placed in the test mode condition (a system-level solution). Once the problem is identified, it is easily handled. The difficulty is that of identifying it in the first place.

There are related phenomena in many complex circuits, i.e., flash memories, which contain very complex internal controllers. These effects can be very difficult to characterize in SEE tests. Again, the important point is that one may need to allow for power removal and reinitialization for some types of technologies. In fact, this may be the dominant issue in some circumstances.

2. SETs: Linear devices and optocouplers, again due to their technology changes and increased performance parameters, have become more susceptible to SETs [14], [15], [16], [17], [18], [19]. As before, hybrid DC-DC converters provide a good example of this problem. Certain DC-DC devices have a linear device that is transient-susceptible. When a transient occurs, output power is shut down for about 10 msec as seen in Figure 4. Mitigation of this power dropout results in a large increase in the circuit complexity and system design. In addition, SETs and their related transient pulse frequency, voltage differential, and width are not only a function of the particle type and energy, but of device power supply and circuit bias. This greatly complicates the problem of defining the size of the transients for designers who must take the SETs into account in their electrical designs. Optocouplers, in particular those that operate at higher speed, also have this issue [20].

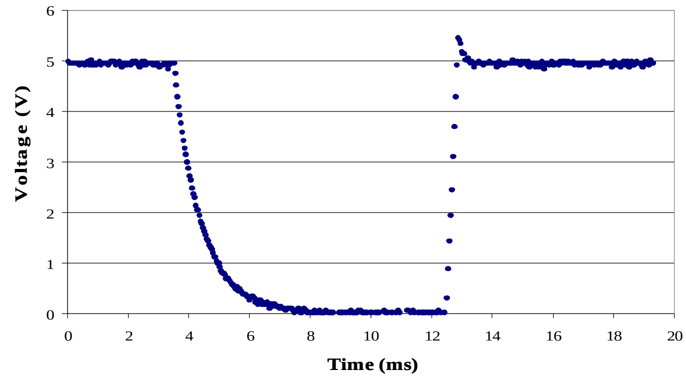

Figure 4. A transient output dropout induced by a SET in a non-RH Advanced Analog DC-DC hybrid converter.

E. *Catastrophic Single Event Effects*

In addition to single event latchup (SEL), there are new catastrophic SEEs. These include snapback (an older issue which has not received sufficient attention), burnout of integrated circuits because of the very high currents that occur when the circuits are exposed to heavy ions, dielectric rupture [21], and failures at the circuit or subsystem level because of short-duration transients that exceed the normal input conditions. Another new effect is gate rupture of small-area metal oxide semiconductor (MOS) devices from heavy ions [22].

F. *Other Device and System Radiation Issues*

In the sections above, several new phenomena were reviewed. There are a myriad of other radiation environment issues that space programs must address including issues related to uncertainties in the environment predictions, definition of worst case conditions, and the rapid pace of technology development. Specifically, some of these issues are:

- large uncertainty factors in older environment models,
- shielding effectiveness of composite materials,
- stuck bits and block errors in memories [23] (and potentially other devices in the future),
- microdose effects,
- neutron-induced upsets,
- multiple bit upsets (MBUs), where a single particle causes multiple events (typically in physically adjacent structure),
- microlatchup (a low-current version of traditional SEL),
- test methods for advanced packaged devices such as flip-chip, plastic encapsulated microelectronics (PEMs), and multi-chip modules (MCMs),
- "at-speed" testing and frequency dependencies,
- photonics and fiber optic devices and their associated high-speed test requirements, as well as a host of other issues.

III. The NASA Approach: A Programmatic Methodology

As shown above, the use of newer technologies greatly increases the need for radiation effects support to space flight programs. The question is: how does a small group work RHA issues related to COTS and emerging technology use and support a large number of space flight projects? The expertise needed to cover all these areas is obviously very diverse. Herein, we present NASA's approach to providing a reliable spacecraft design while dealing with these issues.

The first recommendation is to assign a lead radiation effects engineer to each space flight project. The RHA engineering process for spacecraft must be viewed in a manner similar to that used by a mechanical or thermal engineer who is assigned for the life of a project. With a single point of contact for all project radiation issues (environment, device selection, testing, etc.), each program has a radiation effects expert responsible for ensuring performance in the radiation environment.

The second recommendation is that the radiation effects expert follows a rough programmatic guide to radiation and flight projects from a systems perspective. By participating early in flight programs, cost may be reduced in the long run. For example, the cost of re-work of flight hardware may greatly exceed the cost of up-front radiation evaluations. The recommended programmatic methodology is as follows:

- define the hazard,
- evaluate the hazard,
- define requirements,
- evaluate device usage,
- "engineer" with designers, and,
- iterate process as necessary.

Each of these areas will be discussed.

A. *Define the hazard*

The first step of RHA in a program (often at the proposal stage) is to provide a "top-level" radiation environment definition based on parameters defined early in the mission. At this stage, the mission parameters will include orbit parameters, time of the launch and mission duration, and a nominal aluminum shield thickness. With this information, the radiation levels external to the spacecraft and behind nominal shielding are provided to the project as a top-level definition of the hazard. This definition includes contributions from trapped particles (protons and electrons), galactic cosmic ray heavy ions, and particles from solar events (protons and heavy ions) and should have the following components:

- particle levels outside of spacecraft:

  for trapped protons, electrons, solar event protons

  to evaluate solar cell and surface damage,
- particle levels inside spacecraft for "nominal" shielding:

  for trapped protons, electrons, solar event protons,

  to evaluate displacement damage and SEEs
- Linear-Energy-Transfer (LET) spectra inside spacecraft:

  for galactic cosmic ray and solar heavy ions

  to evaluate SEEs, and
- dose-depth curve for generic geometry model (usually solid sphere):

  for trapped protons and electrons, solar event protons, and secondary bremsstrahlung

  to evaluate total ionizing dose (TID) levels.

For SEE analyses, the "shielded" particle levels should also include a definition of the normal background levels under which all systems must operate and the peak levels (SAA peak or peak during a solar event) for critical systems.

As the program matures, the lead radiation engineer must be informed of any changes to the mission parameters so he can evaluate the need to redefine the environment. Reducing design margins implies that small changes in mission parameters can cause the radiation requirement to go out of range of the design margin. For example, there are extremely large variations in the particle levels that a spacecraft encounters depending on its trajectory through the radiation sources. Also, the levels of all of the particle sources are affected by the activity cycle of the sun. Improvements to the solar cycle dependence of the newer models (e.g., CREME96 [24] and Huston et al. [25]) mean that better estimates of variations in the environment due to the solar cycle are available. With this model capability, changes in launch dates can affect the environment definition.

B. Evaluate the Hazard

After the hazard is defined, the effects that it will have on the systems are evaluated. The effects that are important to consider in RHA for electronics are long term damage from total ionizing dose and displacement damage and single event effects. The top-level environment definition provides adequate information to assess the level of hazard that the environment imposes and to identify the suitability of COTS and emerging technologies for the program. For example, if the mission has a very high dose level, non-radiation hardened devices will probably not be acceptable for critical systems.

It is important at this stage in the program to communicate the RHA process to program managers and designers. The lead radiation effects engineer should address concerns specific to the program. These include potential problem areas as defined by the top-level environment definition, the latest issues related to new technologies, applying adequate derating of parts and allowing for design margins, lead times required for parts testing, and the importance of communicating changes to mission parameters to the radiation engineer. It is also important to provide guidance as to mitigation techniques. For example, many spacecraft engineers tend to think of "spot" shielding as a panacea for all radiation problems and do not realize that it is not effective in mitigating SEE problems or displacement damage due to protons. The result is costly delays in applying effective mitigation techniques.

C. Define Requirements

A top-level radiation hazard is often used to derive mission requirements for most programs that are early in the design stage. This allows the radiation effects engineer to specify a requirement based on a nominal effective spacecraft shielding (such as 70 mills Al) using a generic geometry (such as solid sphere) before design details of the spacecraft are known. Performance requirements must be defined for all three of the major radiation effects issues: TID, displacement damage, and SEE. Several things should be noted:

- TID RDMs of at least 2 should be included to cover uncertainties in the environment [26] and device radiation hardness variances. The RDM may be higher for certain technologies such as those that are ELDR sensitive. (See Section II.B.)
- Different requirements may be set for different systems depending on system performance requirements, criticality level, shielding differences, etc.
- Particle fluences (proton, electron, heavy ion, and neutron) need to be included for nominal, worst-case, and peak environments. For example, does the spacecraft need to gather science during a solar event (i.e., potential peak flux time period) or is a partial shutdown (safehold mode) acceptable?
- Displacement damage requirements may be based on an external spacecraft environment such as "must survive an integral particle fluence of Y particles/cm^2 for E > X MeV protons". One must remember to pay attention to non-ionizing energy loss (NIEL) and how it applies when the external particle spectrum is transported to an internal spacecraft environment. In particular, one must note that the higher energy protons have a reduced energy after transport and that their effect is more damaging on electronics. Displacement damage depends on energy, and has been investigated far more thoroughly for silicon devices than for GaAs. In the case of silicon, extensive work has been done on displacement damage using neutrons from nuclear reactors. It is common practice to compare the effect of displacement damage in silicon with that of 1-MeV equivalent protons, as noted by Summers, et al. [27]. Figure 5(a) shows this equivalence for protons of various energies. The net effect of protons in space applications in producing displacement damage must be obtained by weighting different

energies in the spectrum with the relative damage produced by protons. For typical spectra, these factors are in the range of 1.5 to 2.5; they essentially convert the effects of the proton spectrum to an equivalent number of 1 MeV neutrons.

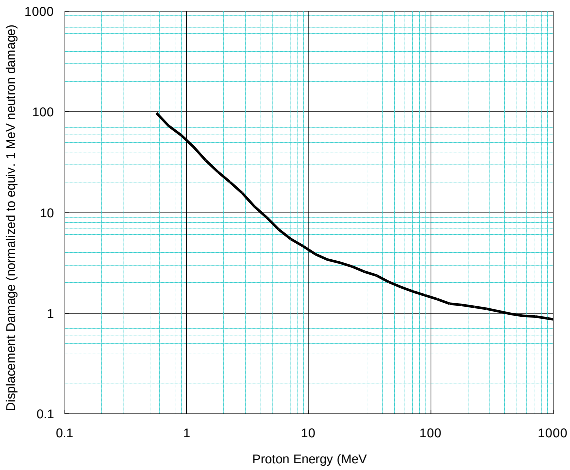

Figure 5a: Displacement damage equivalence in Si.

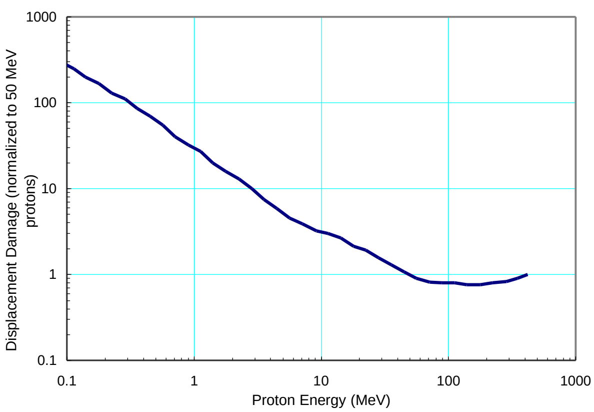

Figure 5b: Displacement damage equivalence in GaAs.

There is more uncertainty about displacement damage in GaAs. Summers, et al. addressed this issue in their 1988 paper [28] using data on GaAs JFETs, which are majority carrier devices. The results of that work are shown in Figure 5(b); note that the energy dependence is significantly steeper than that of silicon and that it actually increases somewhat at very high energies. Although one could also normalize GaAs displacement damage effects to equivalent neutron damage, there is a much larger difference in the effects of neutrons and protons in GaAs. Thus, it makes more sense to normalize the damage to a proton energy that (1) roughly corresponds to the peak in typical proton spectra within spacecraft, and (2) is easily obtained at typical facilities. A proton energy of 50 MeV has been selected on this basis.

More recent work by Barry, et al. has investigated the energy dependence for damage in light-emitting diodes, which are affected by minority carrier lifetime [Barry, 1995]. Their results differ considerably from the earlier work based on JFETs, particularly at high energies. This has little effect on the net damage for applications with relatively small amounts of shielding, but it can make a large difference in applications with large amounts of shielding where the peak in the energy distibution is shifted to energies above 100 MeV. This topic needs to be investigated more thoroughly.

- SEE is perhaps the most complex. The GSFC radiation effects and analysis homepage [29] includes a “generic” SEE specification for programs that allows for specifications to be set on a “system level”. In particular, this specification covers analysis of event rates, system implications of the effects, and verification of mitigation techniques. One further note is the use of a single event effect criticality analysis (SEECA) to determine acceptable event rates also available on the GSFC homepage [28]. For example, a thruster control (critical system) would have a much different SEE requirement than a solid state recorder (acceptable data loss). The concept of this specification is to allow the use of non-SEE immune devices (such as SOTA COTS) by evaluating their usage and system mitigation schemes on a system level. This is a form of risk management.

D. *Evaluate Device Usage*

The evaluation of device usage requires three processes: screening parts lists, radiation testing, and determining performance characteristics such as degradation or SEU rates. Each of these areas is discussed below.

1. Screen Parts List: Once a parts list is received, the existing industry knowledge base (RADATA, REDEX, GSFC test list, ERRIC, IEEE TNS and Data Workshop Records, etc.) is scanned for existing radiation data on each device type on the list. The basic method for this data search and definition of usability is seen in the attached flow chart of Figure 6.

If data do not exist on the device and radiation performance within the mission’s requirements is not guaranteed by the manufacturer, testing is required or a search for a device with similar non-radiation performance characteristics is undertaken. However, the existence of radiation data on a device does not necessarily indicate the device’s acceptability. General guidelines for acceptability of archive data follow:

- If the foundry/process has changed, the data are not applicable.
- If the lot date code (LDC) is different, testing is recommended, but may be waived if sufficient process information is gathered. Acceptable conditions for testing waiver are similar LDCs with known process changes, or devices for which the die topology and substrate characteristics are known to be the same as for an older lot of devices.
- If the test method is not applicable (e.g., performed at an incorrect dose rate), retesting is recommended.

- If the data are not complete (say, do not include high linear energy transfer (LET) data points), further testing may be required.
- If the data do not meet the requirement, either further application-specific analyses and/or mitigation will be required.

Perhaps the most difficult of these steps is determining whether the test method is applicable. A good example is evaluating test data for SETs in linear circuits. In this case, an understanding of what the sensitive parameters (or, for example, a SET's effect) are to a design's application is required. For instance, if the test data show a device exceeding manufacturer's specifications for offset voltage while the all other parameters remain within specified limits, the device may be usable if the application can live with that single parameter's drift.

The use of archival data is discussed in further detail under *Risk Assessment* in Section IV.B.

2. Radiation Testing: Once a parts or components list is reviewed versus archival data, a decision on which devices and what kinds of ground irradiations need to occur. For simplicity we assign devices to three categories: high, medium, and low risk. Each of these will be discussed in turn.

High risk devices are those that have unknown radiation characteristics or previous lots with "suspect" radiation characteristics. Examples include a new device on a scaled process or a device whose previous lot showed sensitivity to SEL.

Medium risk devices are those with some archival data or data from a "similar" device on the same process that indicates a potential issue but one that may be managed without extensive testing. In this category, examples include:

- a linear device with SET data for a different application where the possible transients could be filtered, or
- an op-amp built on the same process as another op-amp that has radiation test data meeting or exceeding mission requirements.

Finally, low risk devices are those that have lot-specific data or similar lots showing an excessive margin. This would include devices with sufficient test data or those where a previous lot's radiation characteristics exceed the mission requirements.

The type of testing depends on the type of device and mission requirements. As noted earlier, three specific areas are of concern (TID, displacement damage, and SEE). Typically, Co-60 sources are used for TID, proton and neutron sources for displacement (and in the case of protons, TID as well), and heavy ions and/or protons for SEE. Details of test methods are outside of the scope of this paper, however, the authors would like to point out that test results should apply to the specific circuit application, i.e., test it like you're going to fly it.

3. Determining Performance Characteristics: Once radiation test data have been obtained by test or from archival sources, the data must be applied to mission specific environment and application to determine device acceptability from the system level. Samples include:

- SEE rate predictions using tools such as CREME96 followed by determining circuit specific effects,
- circuit degradation based on a device's displacement damage such as diminished current transfer ratios (CTRs) with optocouplers, and
- determining the effect of TID-sensitive parameters on a circuit's performance.

It cannot be emphasized strongly enough that a test result is insufficient in determining device applicability without knowledge of the circuit, subsystems, and system effects. This implies the philosophy of risk management as opposed to risk avoidance. An example is using mitigation or circumvention of SEEs rather than using an SEE immune device. This philosophy was discussed with respect to linear transients in Section II.D.

(ASSUME COTS)
RADIATION TOLERANCE SEARCH FOR DEVICES (e.g., a 16-bit ADC)

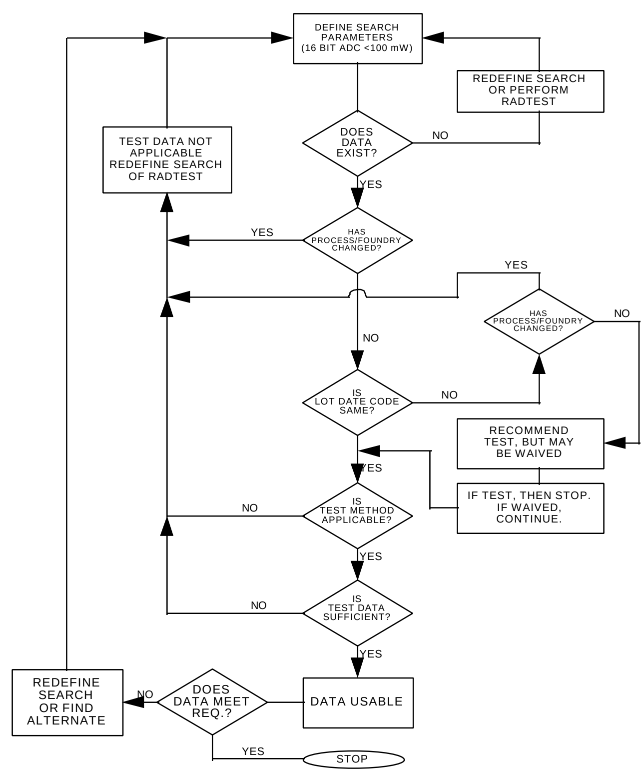

Figure 6: Basic method for data search and definition of part usability. The example is for a 16-bit ADC.

E. Engineer with Designers

On completion of the device usage evaluation, an engineering process with the spacecraft designers (and systems engineers) now occurs. For devices' whose data do not meet the mission requirements, alternative parts are now sought that may meet mission performance requirements (bandwidth, density, etc.) and have archival radiation data showing low or medium risk.

If such alternate components can not be located, radiation mitigation methods may be employed. For systems that fail to meet the mission total dose requirement defined by the top-level environment definition, it may be possible to redefine the hazard, especially if the requirement was set with a dose-depth curve. An effective approach is to utilize a spacecraft specific shielding definition to calculate total dose and particle levels at specific locations inside the spacecraft. Total doses can be calculated rapidly at hundreds of locations within the spacecraft model with 3-D sectoring/ray trace software. Typically, verification is performed with Monte Carlo particle traces on 5-10% of the locations within the model. By accurately defining the available shielding provided by spacecraft structures, boxes, boards, etc., the total dose and/or particle fluence requirement is lowered.

The number of programs that utilize 3-D radiation models of spacecraft has increased with the decreasing availability of rad-hard components. In the past, this method was viewed by many projects as prohibitively expensive. However, by using an iterative approach, 3-D sectoring/ray trace methods can be cost effective. The spacecraft model is developed in multiple steps. Modeling stops when the radiation requirement is low enough to qualify the part or when additions to the model fail to reduce the level. For example, if the sensitive parts are in a specific box, a model of that box alone is usually sufficient to lower the requirement. Or for more generic requirement definitions, the spacecraft skin, empty boxes, and electronic shelves can be modeled. For locations where radiation issues remain, details are added. Another advantage of having a 3-D model is the ability to analyze the effectiveness of mitigation techniques, e.g., moving boxes to locations that offer more protection or adding spot shielding to parts.

Three-D radiation models are used almost exclusively for total ionizing dose evaluations, however, studies [30] have shown that single events effects rates on parts that are predominately proton-induced vary by a factor of two depending on the location within the spacecraft. This is not likely to be a concern for low earth orbits, but it may be more important as interest in the higher altitude regime grows where the proton environment is severe. Although it is well known that galactic cosmic ray heavy ions are barely affected by shielding, the attenuation of solar heavy ions is much greater. Careful evaluation of shielding may be important for systems that must operate through the peak of a solar event.

Detailed methods for SEE mitigation are outside of the scope of this paper but the reader is referred to a discussion of representative SEE mitigation methods from the system perspective [31].

F. Iterate process

During the lifetime of a mission's design and development, multiple variables change. These include:

- updates to parts list,
- revised mechanical spacecraft layout,
- revised mission requirements such as mission duration,
- addition of new payloads, or
- the discovery of new radiation effects information.

Due to these and other factors, many of the steps in the approach may be revisited throughout the mission's radiation effects program. Reevaluating TID requirements was discussed above. Another timely example is the issue of displacement damage in optocouplers. When this concern reared its ugly head, many projects needed to revisit their circuit-specific optocoupler usage such as minimum current transfer ratio (CTR) required, etc.

IV. Risk Assessment

The issue of how much risk is acceptable to the mission may impact the particular way in which RHA problems are addressed. However, several general concepts are as follows:

A. Basic Concepts

Risk assessment is a deceptively complex topic that is difficult to extend to modern COTS-based devices and systems. Most earlier work on hardness assurance and risk assessment was based on circuits designed with discrete transistors. Although this is a good way to illustrate the underlying concepts, it does not consider the realities of present day circuit design, which is heavily dependent on integrated circuits.

Discrete transistors degrade in a smooth, regular way when they are exposed to ionizing radiation, without the complication of abrupt, catastrophic failure points that often occur with integrated circuits. Generally, it is easy to determine the minimum required gain of a transistor in a specific circuit and to determine how much margin exists compared to initial parameters. For discrete transistors, it is relatively straightforward to determine the risk of failure, either through statistical approaches or by requiring specific margins for degradation.

The situation is far more complicated for integrated circuits. For example, linear integrated circuits use several types of internal transistors with markedly different sensitivities to ionizing radiation and displacement damage. The net effect on the circuit depends not only on the inherent sensitivity of the internal components, but also on the specific circuit design. Unfortunately, in most cases, only the manufacturer knows the details of this design. The usual approach that is taken is simply to *characterize* the response of the circuit in a specific radiation environment. By necessity, this characterization is very limited in the number of electrical conditions and individual devices that are used.

Limited characterizations may lead to incorrect conclusions about the statistical nature of the device response as well as the "inherent" capability of the circuit in the specific radiation environment. Adding further confusion is the possibility for abrupt failure modes. The net effect is much more uncertainty in the depth of knowledge about the radiation response compared to the simple case of discrete circuits.

B. *Use of Archival Data*

As discussed in Section III.D, researching archival data in various data sources is often the first step in selecting devices for space systems. It clearly makes sense to use such data, but one must be aware of pitfalls and limitations. If archival data show that there is a great deal of margin (say a factor of ten or more) between the requirement and the level at which devices fail or exceed electrical specifications by significant factors, the usual approach is to eliminate future concern about radiation degradation. This includes eliminating lot-sample radiation testing. This is not a perfect approach (there are counterexamples where circuits could fail in space despite such a track record), but it is generally used.

A far more difficult situation occurs in practice, where either the margin is considerably less (factors of two to five), and/or where the data are not directly applicable. Data may not be applicable because testing did not involve the exact circuit type or did not overlap the application conditions, or perhaps the data are even "adapted" to a different circuit type from the same manufacturer. Clearly there are risks in using archival data in this way, and this would not have been done on older space systems with long development times and larger budgets.

Some specific issues relating to archival data are discussed in the next subsections.

1. Data Integrity and Applicability: In many cases archival data are the result of limited testing done for a specific program, not the product of a general characterization of the device or technology. Thus, the first step in examining such results is to get a sense of its completeness and accuracy. This generally requires experience and expertise in radiation hardness assurance and testing.

The first requirement is that the data set must include the fundamental parameters that are important for the technology, as well as the specific parameters and conditions required in the new application. Examples include:

- Archival data on linear circuits with power supply voltages of ±15 V cannot be used for +5 V applications.
- Data taken on unbiased samples cannot be used to determine how biased devices will respond.
- Data at high dose rate cannot be applied directly to low dose-rate conditions in space (this invalidates much of the archival linear device data).
- Data taken to characterize SEE effects from protons cannot be used for heavy-ion environments.
- Data that are not relevant to the device's application cannot be applied.

Consider the third issue listed above for linear bipolar devices and the ELDR effect. One must determine whether the typical high dose rate data is acceptable. Does sufficient margin exist? We recommend a factor of five for devices with unknown ELDR characteristics for most NASA missions, but the actual RDM is based on the mission's predicted radiation environment and the device response. If testing is required, a pre-screen using high and low dose rates (or other accelerated test method such as high temperature tests) may be utilized. However, given the issue of PDE, one must be careful in assuming that these tests are sufficient. Since proton damage testing is often not practical, the recommendation is to reanalyze the predicted space environment and determine if the potential for displacement-type effects is large. If so, the RDM should be increased accordingly. One must be aware of the trades, such as, cost and availability, that take place in purchasing devices which must meet a 100 kRad(Si) hardness level versus those that are substantially less tolerant.

The issue of SETs in linear devices illustrates the problems associated with using test data for different applications. Due to the SET sensitivity being based on the device's application (i.e., bias, power supply voltage, and sensitivity of the application to pulse width and amplitudes of transients), one needs to understand the data that exists or needs to be gathered. For example, are data that exist on a LM139 with a power supply voltage of 12V while acting as a 5V comparator applicable to a user's circuit with a 5V power supply voltage and a 500 mV analog comparison? The answer is probably not, but the full data sets must be examined to determine this.

The second requirement is that the results are reasonable and self consistent. Parametric degradation should steadily increase with increasing radiation levels. SEE data should be taken at several different LETs and plotted, and the number of events should be high enough to provide adequate counting statistics. Also, the electrical conditions during SEE testing must represent actual or worst-case conditions.

A third requirement, which can be very difficult for some devices, is that of data accuracy. Many new devices have extremely demanding electrical specifications, and there are many cases where radiation tests have been done with limited test capability. Examples include voltage references with "5-digit" specifications and "3-digit" characterization. The results may show no change but are not applicable to cases where the full capability of the reference devices is required.

2. Time Window: The most difficult problem in evaluating older data is assessing how likely it represents current production devices. This has always been a dilemma, but it is far more difficult now because of the pace of change of commercial IC technologies. In some cases technologies are stable (from the standpoint of radiation response) over long time periods, while in other cases changes that affect radiation hardness may occur frequently in the manufacturing process. There is no completely satisfactory way to address the issue for commercial technologies unless working agreements can be established with semiconductor manufacturers to identify the process along with changes that occur. Some approaches that can be used are as follows:

- Establish arbitrary time windows for applicability of older data (i.e., a fixed number of years).
- If archival data have been taken over several years, use the consistency of those results as a guide in establishing the time window for applicability.
- Compare photomicrographs of present production devices with older devices (if available) to get a sense of whether changes in device topography have occurred.
- Use spreading resistance measurements to determine the underlying doping profiles (SEE effects).
- Use "engineering judgment" to determine how older data applies, relying on radiation data for the technology, as well as data from technical papers and the Radiation Effects Data Workshop.

3. Extension to Similar Circuits: Often there are no archival data for the particular devices that are to be used. In some cases it is possible to extend data on one circuit type to another with the same basic design provided the processing is the same. Examples include using total dose data on a dual op-amp for a quad op-amp of the same design, or total dose data on devices from one logic circuit to others in the same family. There are clearly risks in doing this, and it is not recommended even though it is often done. Such extensions are far riskier for SEE effects because they are strongly affected by device topology.

A more extreme case is extension of results to devices of the same type from another manufacturer. This is not recommended for either total dose or SEEs. There are many examples where extreme differences in radiation behavior occur for the same circuit type from different manufacturers.

D. Identification of Critical Components

Not all components used in spacecraft have to withstand the total radiation level. Some components may only be needed early in the mission. There may be others where failure from radiation would have little impact on the overall mission performance (e.g., status indicators or circuits that are only essential for pre-launch evaluation) or where there are alternative backups in redundant circuitry or mission operation scenarios. From the standpoint of radiation effects, critical components are those that are essential to the mission and also carry an element of risk (or unknown risk) of radiation failure. There are many cases where seemingly important radiation risks have turned out to be unimportant because they did not directly impact the mission operation. Although this point may seem obvious, most spacecraft are designed by several different organizations and it can be very difficult to get operational requirements properly defined, particularly for modern subsystems which usually involve very complex digital operations.

E. Parts Control, Testing and Hardness Assurance and the Realities of Risk Assessment

Older hardness assurance programs used formalized approaches for hardness assurance. An example of the application of hardness assurance and parts control is shown in Figure 6 for a 16-bit analog-to-digital converter. As discussed earlier, this is a high-risk technology because of the precision of the device (for a 5 V converter the size of the least-significant bit is below 100 µV). Thus, particular attention must be given to parts control and hardness assurance. The approach shown in the figure is somewhat idealized. The first step is to determine whether radiation data exist (this is relatively straightforward). The second step is that of determining whether older data are really applicable, a difficult task. Although the flowchart shows a decision point labeled *"Has Process/Foundry Changed?"*, that is very difficult to establish in practice, and it is often the weakest link in the approach. Other key points include verifying that the test method was appropriate and applicable, that the test data are sufficient, and that the archival data are useable. The final step is that of determining whether the part meets radiation requirements. Note that the data must include TID, displacement, and SEE testing.

For many modern systems, the basic approach used for parts control and hardness assurance is somewhat different from the ideal case shown in Figure 6. It should be evident by now that one is unlikely to have enough knowledge about radiation effects in commercial devices to deal with risk in a precise, mathematical way. There are simply too many unknowns. Adding to this is the fact that successes in older programs were partly due to the fact that they used much more conservative approaches in selecting and testing electronic components than is possible in present-day systems. We really do not know how effective the pragmatic, COTS-based approaches that are being used today will be in building systems that survive in space. However, some valuable lessons from the past should be applied, remembering that these are high-value assets:

- Review of the parts list and the way that the parts are applied by a radiation effects expert is essential.
- Some form of arbitrary margin should always be required between test data and the expected radiation environment (at the minimum a factor of two; three or more for high-risk technologies).
- Particular attention should be given to key components, such as microprocessors, where the limitations in understanding and characterization create the possibility for unpredicted response modes from which it may be difficult or impossible to recover.
- New technologies, particularly those involving highly scaled devices, should be conservatively applied because of the limited knowledge of their radiation response and

the likelihood that they undergo frequent changes to remain competitive in the commercial marketplace.

- Using marginal technologies (such as latchup-sensitive parts with power supply detection and shutdown) is inherently risky, and is generally not recommended; similarly, optocouplers using highly sensitive LEDs should be eliminated rather than adapted or shielded because of the many uncertainties involved.
- Radiation effects in space are an evolving problems. It is important to maintain awareness of new problems and effects, not just establish a "cookbook" approach to the use and application of commercial components.
- Although radiation testing is expensive, the cost is far lower than that of premature in-flight failures or last-minute hardware changes.
- System solutions can often be used, particularly for SEE effects. In other cases changes in mission operations can overcome catastrophic failures of some components.

V. Anticipation of Future Technology Needs

An important aspect of the RHA methodology is looking ahead to assess possible future technologies for space flight programs. With aggressive flight program development schedules, it is not always possible to test and qualify newer enabling technologies for use within the time frame required by the program. Therefore, the RHA approach must include an established program that anticipates, identifies, and evaluates emerging technologies for space flight use. The program should include technology evaluation, testing, and identification of device and systems for flight test beds. A single program or institution cannot afford to fund this level of effort. By necessity, technology assessment programs must leverage off similar efforts at other institutions, including universities, research laboratories, industry, and government organizations.

VI. Summary

Changes in radiation hardness assurance programs are driven by the unavailability of rad-hard parts and high spacecraft performance requirements. The subsequent use of COTS and emerging technologies has changed the philosophy of risk management from a risk avoidance mode. Risk is now addressed at the system level rather at the device level. Risk is inherent so acceptable levels of risk must be defined and mitigation measures evaluated and implemented.

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