Radiation Test Requirements for Ionization and Displacement Damage

JPL Document D-18002
July 29, 1999

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I. Introduction

This document discusses radiation testing requirements for ionization and displacement damage in space systems. Single-event effects are not addressed, even though they are very important for most space systems. The purposes of the document are outlined below:

(1) to clarify how the actual environment differs from the "de-facto standard" cobalt-60 gamma ray test environment,

(2) to recommend an approach to deal with dose-rate effects and displacement damage, which are generally ignored by documents used in older JPL programs,

(3) to discuss the impact of device processing variability and lack of control that results from the pace of change in the semiconductor industry along with the demise of most of the older approaches for process control and wafer-level identification, and

(4) to discuss possible impacts of the use of modern plastic packaged devices in radiation environments.

In addition to these topics, there is also a brief discussion about the implementation and interpretation of tests at the module or subsystem level. The document is intended to serve as a guideline, incorporating several new topics and concerns that are not included in older documents that address total dose testing.

II. Radiation Environments

A. General Considerations

Spacecraft encounter relatively large fluences of high-energy protons and electrons during their missions. Mission requirements are usually "lumped" into an integrated equivalent total dose value which is obtained by considering only the ionization damage component of protons and electrons during the mission. The mission requirement document usually assumes a thin, spherical shield when this initial calculation is done (typically 60 to 100 mils of aluminum).

There are several limitations to this approach. One difficulty is that for most systems the thin shield reduces the contribution of electrons, increasing the relative contribution of protons in the internal spacecraft environment (after shielding). Protons introduce significant amounts of displacement damage as well as ionization, and the importance of displacement damage has been largely ignored in recent years. Displacement damage can be a major factor for some types of components, notably optocouplers, light-emitting diodes, and bipolar (as well as BiCMOS) linear integrated circuits. Figure 1 shows how one type of optocoupler is severely degraded by equivalent total dose levels of only a few krad(Si) when it is irradiated with protons, whereas the device will function satisfactorily at 100 krad(Si) if it irradiated with cobalt-60 gamma rays.

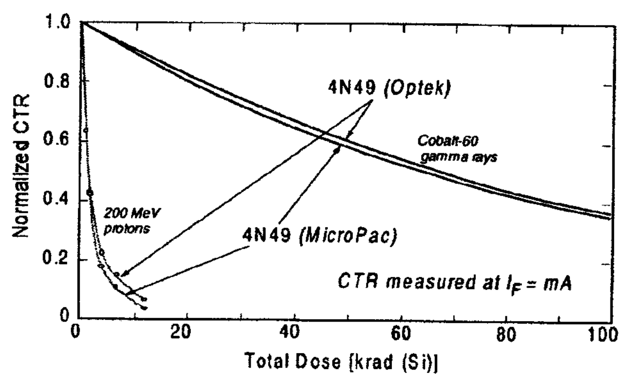

Figure 1. Extreme sensitivity of an optocoupler to proton displacement damage.

The second difficulty is that the thin shield used to calculate the nominal requirement is not representative of the shielding that is present in most of the system. Therefore, the radiation level in the specification is far larger than that in the actual environment. This has two important consequences. First, it is often possible to reduce the internal spacecraft environment by factors of 2-3 by doing a detailed shielding calculation that takes the actual configuration of the spacecraft into account. Second, it affects how one interprets the past success of JPL missions. Older missions, such as Galileo and Cassini, were very large spacecraft. So much shielding is present from the spacecraft structure that the actual internal environment is a factor of 5-10 lower than the nominal requirement *[150 krad(Si) for Galileo, and 100 krad(Si) for Cassini]*. Part of the success of these missions is due to the fact that the structure provides considerable additional margin for radiation degradation. Self-shielding from the spacecraft structure is much less for new, smaller spacecraft, reducing the additional margin by a considerable amount compared to that of older systems.

B. High-Energy Protons

Earth-orbiting spacecraft encounter significant amounts of radiation from the Van Allen belts, which are regions with trapped electrons and protons. For most earth-orbiting spacecraft, the majority of the electrons are shielded by the spacecraft structure. Consequently, high-energy protons (E > 10 MeV) are the main contribution to the radiation environment for low- and medium-altitude spacecraft (except for electronics with minimal shielding). The "edge" of the Earth's proton belts extends to about 700 km, but even spacecraft that operate at lower altitudes will encounter significant numbers of trapped protons when they go through the south Atlantic anomaly, where the proton belt is distorted so that it extends (locally) to much lower altitude. The proton fluence varies with altitude and inclination. Table 1 shows annual proton fluences for some typical missions.

Note the rapid increase in trapped proton fluence with increasing altitude. At GEO, spacecraft no longer go through the Van Allen belts, and the proton fluence is dominated by solar flares.

Table 1.
Annual Proton Fluences for Representative Earth-Orbiting Spacecraft

(assumes spherical shield of 60 mil aluminum)

Spacecraft	Altitude (km)	Inclination (degrees)	Annual Proton Fluence (p/cm^2)
- - -	300	60	6×10^8
EOS	705	98	3.6×10^9
Topex-Poseidon	1334	66	5×10^{10}
(MEO)	10,400	55	1.9×10^{11}
(GEO)	22,400	- -	$\sim 10^9$ (solar flares)

C. Special Requirements for Deep-Space Missions

Requirements for deep-space missions can be quite different. Fluences from solar flares depend on distance from the sun, and are much lower for missions to the outer planets compared to those to inner planets. Trapped radiation belts are very different as well. Some planetary missions have very high radiation requirements with environments that are considerably different from those encountered near the earth. Figure 2 compares the environments for the Europa mission, which traverses the trapped electron belts around Jupiter, to the environment of a typical earth-orbiter. Note that the proton energy spectrum for the Europa mission does not extend to the high proton energies encountered by earth-orbiters. Conversely, the electron spectrum for Europa extends to much higher energies.

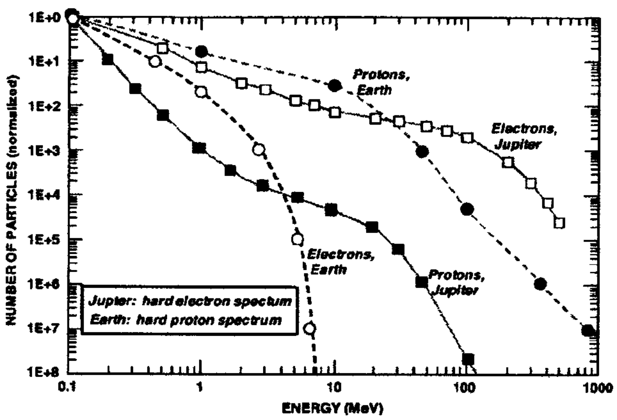

Figure 2. Spectrum of high-energy proton and electron environments for Europa and earth-orbiting environments.

III. Total Dose: General Issues

A. Time Profile

Total dose exposure in space occurs over a long time period. When averaged over the entire mission life, the mean dose rate is on the order of 0.0001 to 0.005 rad(Si)/s. It is impractical to test devices at such low dose rates in the laboratory because it requires time periods of several months or years to complete the tests.

Although the average dose rate is low, the dose rate in space is not constant. Solar flares and passages through trapped radiation belts contribute "pulses" of radiation with dose rates on the order of 0.1 to 2 rad(Si)/s for most missions. The actual dose rate profile is very complicated.

Earlier work on total dose effects in discrete transistors showed that tests could be done at high dose rate in the laboratory with conservative test results. Consequently, tests with cobalt-60 gamma rays were recommended at a nominal dose rate of 100 rad(Si)/s in order to define a standard testing approach. This dose rate is about six orders of magnitude higher than the mean dose rate encountered in space, and about three orders of magnitude higher than the peak dose rate from solar flares or radiation belt encounters.

B. Damage Linearity

Initial work on ionization damage was done on discrete transistors. Standard parameters (such as common-emitter current gain, h_{FE}) do not change linearly with either ionization or displacement damage. However, it is possible to interpret such parameters in a way that results in nearly linear behavior for many transistors by analyzing the results in terms of the change in the parameter $[h_{FE}]^{-1}$.

For more complex devices, many key parameters change in a highly nonlinear way with ionization damage. This creates a great deal of confusion in the interpretation of radiation test results, particularly for integrated circuits. Nonlinear behavior may cause wide variations in the failure level of integrated circuits, as well as inconsistent results for annealing or other time dependences.

C. Effects of Bias

Ionization damage in discrete transistors is greater when they are biased during irradiation compared to the unbiased case. The physical reason for this is that ionization damage depends on transport of trapped charge through the silicon-dioxide (insulator) at the surface of the device, which depends on the electric field that is present. Consequently, radiation tests are normally done with bias applied to the device during irradiation.

However, the issue of how devices are biased needs to be addressed very carefully. Damage in discrete transistors can be considerably higher when devices are forward biased compared to the "off" condition (bias applied to the device, but no current flowing through the emitter-base junction). Test conditions need to be closely related to use conditions. For example, biasing a 2N2222 transistor with V_{CB} = 50 V results in 21/2 times more damage compared to results with V_{CB} = 10 V [Ref. 1].

It is also important to point out that unbiased devices still undergo substantial ionization damage. Several programs have assumed that devices that are unbiased are only slightly affected by ionizing radiation. This concept is blatantly incorrect. Damage in unbiased discrete transistors can be as much as 1/2 of the damage of biased devices. Linear integrated circuits can actually be more sensitive to ionizing radiation when they are irradiated without bias.

D. Damage Stability and Annealing

Damage in some types of transistors tends to partially recover (anneal) with time after irradiation. Bias and temperature conditions affect the amount of annealing that occurs.

Annealing and damage linearity are inter-related. Parameters such as power supply current in CMOS devices are usually very nonlinear with total dose, and apparent recovery of such parameters after irradiation to a specified radiation level may occur with relatively slight amounts of recovery to the internal transistors that are involved in the post-radiation change.

Work in the 1980'showed that damage instability in MOS transistors could lead to different failure modes at very low dose rate because of two different types of trapped charge at the silicon-silicon dioxide interface, where most charge trapping occurs [Ref 2]. This led to the possibility of very serious misinterpretation of annealing effects. In some cases devices would recover after short time intervals, but if the annealing was allowed to proceed, the device would fail at longer time intervals because the second type of charge traps (interface traps) would dominate [Ref 3].

These results also lead to an apparent dose-rate dependence for damage in MOS devices. These effects make it impossible to use annealing data at face value; additional steps (covered by later versions of the military standard document on total dose testing [Ref 4]) are required.

In the 1990's it was found that some types of bipolar devices exhibit an actual dose-rate effect which can result in more damage at low dose rates compared to damage at high dose rate. Consequently, tests at high dose rate are no longer conservative.

E. Standard Testing Approach for Discrete Transistors

The standard approach for testing discrete transistors is to do a series of irradiations at various radiation levels, applying bias to the devices during irradiation. Several issues must be dealt with, including:

(1) bias conditions need to closely correspond to use conditions (see earlier comments about the effect of bias on damage in 2N2222 transistors);

(2) measurements at high currents may raise the device temperature, inadvertently causing part of the damage to recover, seriously underestimating the amount of degradation that would occur if the device were used at lower currents;

(3) measured parameters must include leakage current and forward voltage as well as h_{FE}; and

(4) a lead-aluminum shield must enclose the device to shield low-energy scattered gamma rays that can cause errors of 30-40% in dosimetry (source calibration).

A sample size of ten devices is recommended. The manufacturer, date code and lot number must be identified, along with bias conditions. The time between successive irradiations must be shorter than two hours (preferably much shorter).

Most of the detailed requirements for total dose testing are contained in Mil Standard 1019.4, and assume that gamma rays from a cobalt-60 cell are used for testing. However, test standard 1019.4 does not address some important new effects that can affect total dose behavior in space.

Total dose test requirements differ for various device technologies. They can be grouped into four categories: (1) CMOS devices, which require special tests to evaluate "rebound" effects; (2) bipolar integrated circuits, which may exhibit significantly more damage at the low dose rates in space than at the high dose rates typically used for laboratory radiation tests, ***and thus must be evaluated at low dose rate***; (3) BiCMOS devices, which combine bipolar and CMOS devices within the same process and may involve different failure modes that correspond to both CMOS and bipolar part technologies; and (4) conventional discrete semiconductors, such as transistors and diodes, which were discussed earlier in this subsection.

F. Damage Uniformity and Statistics: Radiation Design Margins

Even for transistors from a single wafer, ionization damage may vary significantly for different units. This variability needs to be taken into account both in planning and interpreting test results. The effects of aging and temperature also have to be considered when total dose damage results are interpreted. Tests done with a "typical" transistor at room temperature will seriously overestimate the post-radiation gain in real applications.

Damage variability was investigated for 21 different types of discrete transistors that were used on the Cassini program. The coefficient of variation (standard deviation divided by the mean value) of delta $[h_{FE}]^{-1}$ ranged from 8 to 40%. These rather large statistical variations show that variations of a factor of two in damage are possible even for devices procured from a single wafer lot. Differences of up to a factor of three were encountered when radiation test results were compared for different wafer lots from the same manufacturer, even though the lots were produced within a one-year time interval. These results illustrate the degree of variability that is inherent in most total dose effects.

A ***radiation design margin*** (RDM) is nearly always included when considering the maximum radiation level at which devices can be used [Ref 5]. Many system designers misinterpret the RDM, failing to realize the rationale for its inclusion. It should be clear from the preceding discussion that laboratory test results on a small test sample are necessarily limited in accuracy and scope. The RDM is intended to allow for a combination of uncertainties in how radiation test results relate to the actual space radiation environment coupled with uncertainties in the radiation environment.

Recommended values of RDM are as follows:

(1) an RDM of two for applications that do not involve shielding or "herculian" reductions in the radiation level from shielding calculation using detailed mass models; and

(2) an RDM of three for applications where spot shielding or detailed mass model calculations are required to use otherwise unacceptable parts.

The reasons for the larger RDM in the second case are first, to take into account the larger uncertainties in the radiation environment that result when extreme shielding is used; and second, to account for possible uncertainties in the statistics or testing approaches that are used with parts that are highly susceptible to radiation damage.

IV. Total Ionizing Dose for CMOS Devices

Total dose responses depend on many factors, including the bias applied during and after irradiation. Total dose tests are destructive tests on a small sample. A sample size of ten devices is recommended. Generally the radiation tests and post-radiation measurements are done at room temperature. The effects of higher and lower temperatures on post-radiation performance is an important issue that must be taken into account when the radiation data is analyzed.

Ionization effects in CMOS devices can be time dependent because of annealing. Although annealing would normally be expected to make devices less susceptible to failure at low dose rate, a competing charge mechanism ("rebound") can actually cause devices to fail at lower levels at low dose rate, with different failure modes. For CMOS, annealing at 100 °C after irradiation at high dose rate can be used to determine whether rebound-related failures occur. This approach is covered adequately by Mil Std 1019.4. Note however that the high-temperature annealing test provides information only about rebound failures at the last radiation test level. It provides no information about the response of devices under (equivalent) low dose rate conditions at lower or higher radiation levels. Consequently, considerable attention must be given to selecting the conditions and radiation levels for high-temperature rebound tests. They are at best a compromise.

Mil Std 1019.4 recommends exposing CMOS devices to a radiation level that is 50% greater than the required radiation level before doing the high-temperature "rebound" test. This requirement was invoked because the high-temperature test approach is not exactly equivalent to a low dose-rate test. However, the physics of the oxide regions in CMOS are understood sufficiently well that it is generally unnecessary to test CMOS devices at low dose rate provided the additional 1.5 margin is included in the test procedure.

V. Total Ionizing Dose for Bipolar Integrated Circuits

A. Low Dose Rate Effects

Unlike CMOS devices, bipolar devices can be directly affected by dose rate. The physical reason is that many bipolar devices use very thick oxides with low electric fields. Under these conditions, it can take very long times -- days to weeks -- for the carriers produced by ionization in the oxide to finally transport to an equilibrium position near the interface.

Dose-rate effects are particularly important for linear integrated circuits; there are cases where the failure level is two orders-of-magnitude lower at low dose rate than at high dose rate. Very low dose rates --approximately 0.001 rad(Si)/s -- are required in order to reach the point where damage is no longer dose-rate dependent. Figure 3 shows how one type of integrated circuit, originally used in hardware on Cassini, was affected by dose rate. Fortunately, low dose-rate tests were done on these parts as part of the qualification program. Because of the extreme degradation at low dose rate, this part type was eliminated.

Note that it is not possible to deal with the low dose-rate problem by imposing additional derating factors in design, or by "overtesting" at high dose rate. Derating factors don't help at all if the part fails catastrophically, or if a parameter (such as output drive current) is affected that was not considered in the derating process. Devices usually fail at low dose rates because of different mechanisms (or failures in different types of internal transistors), and more elaborate testing or derating of data at high dose rate cannot be used as a reliable indicator of performance at low dose rate.

Tests at low dose rate require very long time periods, which are impractical for routine evaluations unless the required total dose level is relatively low. In addition, they do not consider the fact that dose rates are not constant in most spacecraft, but consist of a low (approximately constant) background rate with short-duration periods at higher dose rate because of solar flares, or travel through radiation belts.

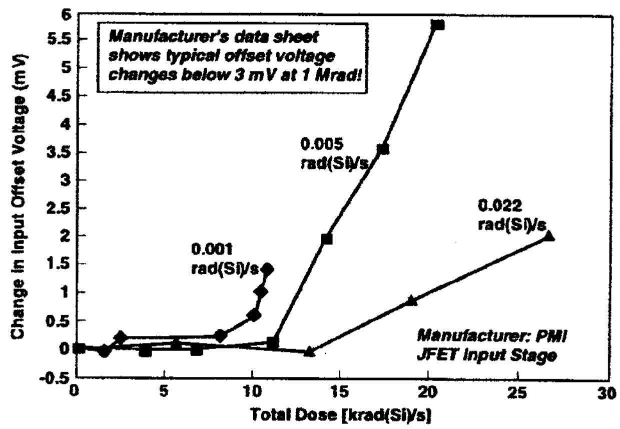

Figure 3. Comparison of the total dose response of the OP-42 op-amp at high and low dose rate.

B. Recommended Approach for Radiation Levels below 30 krad(Si)

For cases where the required radiation level is 30 krad(Si) or lower, it is possible to do tests at low dose rate in a period of about 10 weeks using dose rates of 0.005 to 0.01 rad(Si)/s. The approach recommended by JPL requires doing tests on bipolar devices at both low and high dose rate, comparing the results to determine how the device will respond. If there is a large difference in the response at low and high dose rate with significant parametric or functional degradation at radiation levels that are comparable to the system requirements, then the part should not be used.

Specific requirements are as follows:

(1) Test the device at a high dose rate [50 to 300 rad(Si)/s] to a maximum level of 50 krad(Si) or twice the required total dose level *[including the radiation design margin]* for the system specification, whichever is greater.

(2) Test the device at low dose rate [0.005 rad(Si)/s recommended, but 0.01 rad(Si)/s acceptable in some cases] to a maximum level 1.5 times greater than the system specification.

(3) Compare the results at low and high dose rate. Do not use the device if functional failure occurs at either dose rate at a level < 1.5 times greater than the system specification. Derate parametric degradation data to account for statistical variability, using the maximum parametric degradation that occurs with the worst set of data.

(4) ***Under no circumstances should bipolar linear devices be used without supporting data at low dose rates.***

C. Recommended Approach for Total Dose Levels above 30 krad(Si): High-Temperature Testing

If the radiation level is too high, then it is impractical to do tests at dose rates that are low enough to determine whether the device is sensitive to dose-rate effects. Fortunately, most JPL systems have relatively low radiation requirements. However, there are exceptions, such as the X-2000 program, which has levels of 100 krad (Si) or more.

The reason for the low dose-rate effect is the very slow transport of charge in thick oxides. By heating the device during irradiation, it is possible to speed up the charge transport process by several orders of magnitude [Ref 6]. This suggests that irradiating devices at high temperature (with bias applied) is a possible alternative to testing devices at low dose rate. However, if the temperature is too high it will affect the amount of charge that is eventually trapped (similar to annealing mechanisms), reducing the amount of damage that occurs. Thus, the temperature must be selected with extreme care. If it is too high, then the elevated temperature will cause far less damage, and the test will allow unacceptable parts to be used.

Several laboratories - Sandia, JPL and Aerospace - have investigated the use of elevated temperature as a possible alternative test approach to tests at low dose rate [Ref 7-10]. Most of these studies have attempted to find a temperature that will allow equivalent low dose rate testing using the "standard" nominal high dose rate of 100 rad(Si)/s, simply because many radiation sources are restricted to a very narrow range of dose rates. The results show that the "optimum" temperature for getting equivalent damage varies considerably for different processes. For some devices most of the damage anneals away if the irradiation is done at a temperature above 100 °C, while for other devices it is possible to get near equivalence at temperatures above 200 °C.

JPL has a more versatile radiation source than most laboratories. JPL has investigated how one could trade off dose rate and temperature. As shown in Figure 4, it is possible to do elevated temperature tests at somewhat lower temperature by using an intermediate dose rate. Although this increases the test time somewhat, it is still possible to do the tests in time periods of 2-3 days, an acceptable alternative.

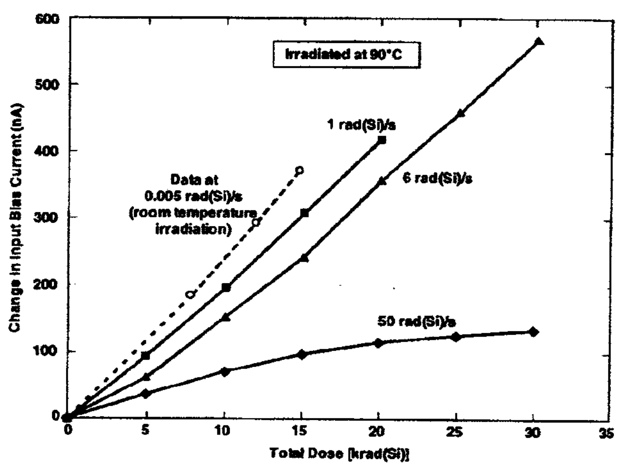

Figure 4. Effcct of elevated temperature on the degradation of input bias current at different dose rates and temperatures.

Power dissipation is a possible interference when tests are done under bias at high temperature. Although this is not very important for low power linear circuits, it can be very important for some types of parts with higher operating currents and voltages. This can cause the junction temperature to be much higher than the temperature of the chamber (or "plate") that is used to heat the devices during the irradiation. If the junction temperature is too high, then the damage may anneal.

For these reasons, JPL recommends that tests on bipolar devices for systems with high radiation levels should be done with the following conditions:

(1) ***use a dose rate of 0.5-2 rad(Si)/s***

(2) ***heat the device to 90 °C during irradiation, under bias***

(3) ***compare the tests done in this way with tests at high dose rate at room temperature.***

Based on experience to date, the high-temperature conditions are expected to be nearly equivalent to tests at a dose rate of 0.002 to 0.005 rad(Si)/s. The 90 °C temperature is below the temperature at which trapped holes anneal. Consequently, there is less danger that the damage will inadvertently anneal, and much less concern about possible interference from increases of 10-20 ° in junction temperature due to the thermal profile of the die within a package.

Although irradiations at elevated temperature appears to increase the damage to the point where it is close to that of results at low dose rate, the precise temperature conditions are not the same for different device types and processes. For that reason we recommend adding an additional factor of two to the radiation design margin when the elevated temperature approach is used in lieu of tests at low dose rate.

VI. BiCMOS Integrated Circuits

BiCMOS devices need to be treated as dose-rate sensitive, because the bipolar structures within them can be affected by dose rate. Different failure modes may occur at low and high dose rate for BiCMOS devices because of the presence of the two types of internal devices. In one recent case, a BiCMOS A-to-D converter failed at about 20 krad(Si) when tests were done at high dose rate because of very high leakage current at the output due to threshold shifts in the CMOS transistors. At intermediate dose rates, the device would function beyond 30 krad(Si). However, when tests were done at very low dose rate [0.002 rad(Si)/s] a new failure mode came into play because of the increased damage in the bipolar transistors in the BiCMOS process. This mechanism caused catastrophic failure to occur at about 3 krad(Si). The point here is that BiCMOS devices can have very different failure modes because of the presence of two very different types of internal transistors, and that tests at low dose rate have to be done at dose rates that are sufficiently low in order to properly bound the failure level.

No work has been done to investigate how elevated temperature testing will affect BiCMOS devices. Therefore, the high temperature approach for bipolar devices when levels above 30 krad(Si) are required cannot be accepted at face value for BiCMOS devices. It is not possible to recommend an exact "recipe" for dealing with BiCMOS devices with high radiation requirements. The best that can be done at this point is to compare tests at low dose rate up to levels of 30 krad(Si) or more with tests at high dose rate at room temperature and tests at elevated temperature that are extended to the higher radiation levels (including the RDM). These results will have to be evaluated on a case-by-case basis, paying particular attention to parametric changes that occur under the three different test conditions. One must recognize that there is potentially more risk in using BiCMOS devices compared to bipolar device technologies because of the low dose-rate damage problem, and that insufficient information is available to guarantee satisfactory performance of these devices from accelerated test methods.

VII. Displacement Damage

Protons and electrons, which are both present in the natural space environment, cause displacement damage in addition to ionization damage. Neutrons, produced by RHUs and RTGs, also cause displacement damage. For space environments in most JPL systems, the effects of displacement damage are minimal for most electronic devices, and displacement effects have been largely ignored in the past. However, there are important exceptions: (1) linear integrated circuits, (2) optocouplers, (3) some types of optical sources, and (4) optical detectors. Recent on-board failures in optocouplers that occurred on Topex-Poseidon were caused by displacement damage effects that were not considered in radiation analyses prior to launch.

Displacement damage will add to the damage from ionization damage, and radiation degradation based solely on gamma-ray testing will underestimate the amount of damage that occurs. This can be a serious problem, even for some hardened part technologies. Figure 5 shows how one hardened device, specified for operation at a minimum total dose of 100 krad(Si), degrades with protons [Ref 11]. The part performs very well in a gamma-ray test environment, working to levels more than seven times greater than the guaranteed level in the specification. However, when it is tested with protons the device fails ***catastrophically*** between 50 and 70 krad(Si). No hint of this failure mode was apparent from gamma-ray tests, even when they were carried out at much higher radiation levels.

The part list should be reviewed by a radiation parts specialist to determine which parts are potentially susceptible to displacement damage. For cases where proton displacement damage is potentially important, proton testing should be done using proton energies between 10 and 200 MeV, with parts biased during irradiation. The damage depends on energy, increasing for lower energies. Because of the continuous spectrum of proton energies in the actual environment, data from proton tests must be corrected to account for the energy spectrum.

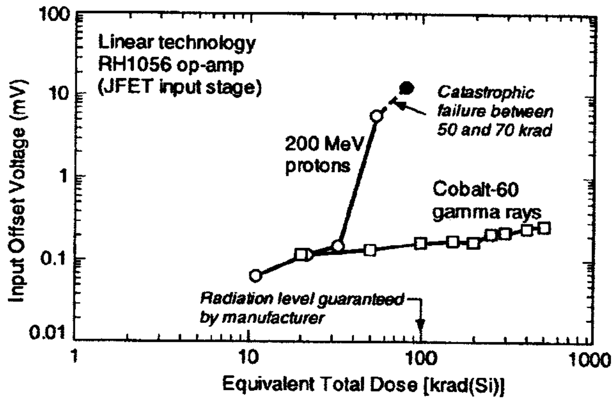

Figure 5. Degradation of the RH1056 hardened op-amp from equivalent total dose levels with protons and gamma rays.

There are also cases where displacement damage from high-energy electrons can be important, i.e., X-2000. In such cases, electron displacement damage testing should be done using energies of 3 MeV or higher. The measured results with a single laboratory test energy must be corrected to account for the energy dependence of electron displacement damage effects. This depends on the spectrum of electron energies that occur in the actual space environment.

Some systems use internal nuclear power sources (RTGs), which produce significant amounts of neutrons. In cases where electronic devices are located close to the RTG.s, the integrated neutron fluence may be high enough to be important. In those instances, neutron testing should be done using a nuclear reactor, which has a neutron spectrum that is close to that of the RTGs.

VIII. Commercial Devices ["COTS"]

A. General Issues

During the last twenty years the semiconductor industry has evolved to the point where the overwhelming majority of devices in the industry are intended for commercial applications. Many devices are not available in versions that will function over the wider temperature range traditionally required by the "high reliability" market, and often devices are only available in low-cost plastic packages. Along with these changes, the aerospace industry has been increasingly frustrated by the inability to impose the levels of identification and control that were used in the past. Identification of specific lots and wafers is only possible for selected devices, and the entire "lore" imposed by the Class S and Class B approach to reliability simply does not work for most of the part types that are being considered today.

Consequently, there is potentially more variability in the radiation response of devices produced by a specific manufacturer. There is also an increasing trend to use more and more different types of devices in spacecraft design , with little or no resources available for radiation testing. This creates a great deal of confusion in the aerospace community.

There is no sure-fire way to deal with the issue of how commercial devices will respond in space. The conservative approach is to require more frequent radiation testing, and to place even less emphasis on the use of archival radiation test data than was done in the past. However, that approach is often inconsistent with the realities of producing spacecraft with limited budgets and compressed schedules.

Fortunately, there does not appear to be any *a priori* reason to expect the radiation performance of "COTS" devices to be different from their more robust Class B and Class S cousins, other than the issues of potentially more frequent processing changes along with faster evolution of new design methods and technologies.

B. Plastic Packages

Another issue related to "COTS" is that of plastic packages. There are fundamental reasons why the ionizing radiation response of devices in plastic packages could be different from their hermetic counterparts, including the possibility that impurities in the plastic could diffuse into the die, affecting the results. Another factor is moisture; plastic devices are not hermetic, and charge trapping in semiconductor oxides is known to be sensitive to hydrogen.

Several technical papers have attempted to address this issue, with limited success. One early paper compared hermetic and plastic devices that were packaged from the same wafer lot [Ref. 12]. They concluded that results for plastic and hermetic devices were identical for parts that were not subjected to burn-in prior to irradiation, but that plastic devices had a significantly worse response if they were burned in at 125 °C prior to irradiation. However, the die used in their work were prepared differently from die that are intended for plastic packages. Normally an additional layer of compressible material (usually a polyimide) is deposited over the die before packaging in order to relieve stress on the die from direct contact with the plastic encapsulant. Without the polyimide layer, extreme thermal stresses can occur, affecting both the reliability and the radiation response. It is highly likely that the reason for the larger radiation response of the plastic packaged devices in their study is due to the stress caused by heating the devices with no buffer material.

Later work with CMOS has not shown the same sensitivity of radiation damage to plastic packages. A recent study by Sandia Laboratories concluded that plastic packages have little or no effect on radiation sensitivity, even for devices that are subjected to burn-in [Ref. 13].

The plastic packaging issue is very complex. Many different compounds and processes can be used for commercial packages, and the results may also be affected by the way that devices are handled and stored because of moisture penetration. The actual plastic parts used in spacecraft are likely to be carefully controlled in "dry packs" or other low-humidity containers. The evidence to date suggests that plastic packages do not directly affect radiation response unless high temperature burn-in, well above the maximum operating temperature, is used as part of the part qualification process.

IX. Use of Existing or Archival Data on Electronic or Optoelectronic Parts

One of the key issues relating to the radiation response of electronic and optoelectronic parts is how archival data can be used to make decisions about part survivability. This ultimately requires judgment about the *stability* of the radiation response of a particular part technology over some arbitrary time period. For example, there are many documented cases where the radiation response of a particular part type has changed radically because of changes in the manufacturing process. This issue is particularly troublesome for parts that are made with commercial technologies (with no guarantee or concern about radiation hardness by the manufacturer). It is impossible to completely solve this problem without requiring radiation tests on each specific lot of devices. Although 100% lot-sample testing is the best approach, some systems are willing to use a less rigorous approach for monitoring and controlling radiation response.

The following guidelines are recommended when using archival data :

(1) Archival data must exist for parts from the same manufacturer that will supply parts in the actual system. ***Data from other manufacturers cannot be used.***

(2) For most part technologies, data for parts that were manufactured more than five years ago cannot be used unless the margin between degradation and the application exceeds a factor of ten. If it is less than five years old, it may be used, with some cautions and exceptions [*see (3), below*].

(3) For rapidly evolving technologies, such as microprocessors and advanced memories, data that is more than one year old cannot be used unless there are specific controls and identification of the process used by the manufacturer.

(4) A radiation parts specialist should make the final decision about the applicability of archival data.

The presence of archival data does not necessarily mean that it can be applied, even if it is relatively recent. Other critical factors regarding archival data are (a) the quality and self-consistency of the data; and (b) whether the measurements that were made and the radiation environments to which the devices were tested are consistent with the requirements of the proposed system.

Examples of problems with data quality include total dose data on precision devices with measurements that are too coarse or imprecise to provide meaningful results; inconsistencies in measurements at successive radiation levels; and omission of parameters or operating characteristics that are critical for applications (such as short-circuit current for operational amplifiers).

Examples of data that is not directly applicable include total dose data on linear devices at high dose rate, with no information about the response at low dose rate; gate-rupture data with bias conditions that do not encompass the bias conditions in the applications; and data on optocouplers that is restricted to ionization damage, without considering displacement damage effects.

X. Hybrid Devices and Board-Level Tests

The conventional way to test semiconductor devices is to do tests on individual components, measuring the effect of radiation on all of the electrical parameters as well as the overall functionality of the device. This provides quantitative information about how the device behaves, allowing the effect of changes in critical parameters to be determined for overall performance of a circuit application, including the effects of variations in other components use in the eventual circuit application along with temperature and aging.

Recently, some projects have attempted to use radiation tests at the board or subsystem level to evaluate all of the devices used on such assemblies in a single radiation test. The problem with such testing is that it only addresses the performance of individual devices within a "typical" application at room temperature. Several devices could be just on the verge of failure, with no indication that there was any issue with performance. Alternatively, the parametric shifts may be large enough so that some failures would occur if the initial device parameters were shifted somewhat towards either the upper or lower pre-irradiation parameter limit.

Although board-level testing will most likely identify parts that fail catastrophically, they are not a satisfactory substitute for evaluation of individual components. If board-level tests are used, additional margins -- factors of three or more, based on statistical variability of a wide range of device types -- should be insisted upon. That is, the board-level test should show normal operation to levels at least a factor of three beyond the required system level (including RDM).

Similar issues are involved when hybrid devices are tested. However, the situation is even less clear with hybrids because there is more uncertainty about what specific device types are actually present in the hybrid units. With board-level tests, one can at least identify the markings on the package. For hybrids, one is forced to take the manufacturer's word (and limited control) at face value.

An example of the difficulty faced with hybrids is provided by recent tests of DC-DC power converters from one manufacturer. Earlier versions of the part used optocouplers that were (inadvertently) made with a light-emitting diode that was relatively insensitive to proton displacement damage. Later versions were made with an optocoupler from the same (optocoupler) supplier, but with an LED of longer wavelength that was extremely sensitive to proton damage. The net result was a decrease in the total dose failure level (for an environment dominated by protons) from about 30 krad(Si) to 2 krad(Si)!!! The hybrid manufacturer had no record of which version of the optocoupler was used in his various products.

XI. Conclusions

This document has discussed some of the issues that are involved in specifying radiation environments, in doing radiation tests, and in evaluating radiation test data. Basic recommendations for dealing with dose-rate effects for various technologies are summarized in Table 2, below.

Table 2. Summary of Low-Dose Rate Testing Recommendations

Technology	Dose-Rate Effects	Recommendations
Discrete transistors	no	- - -
Linear bipolar ICs	yes	LDR tests required; tests at 1 rad(Si)/s and 90°C for high levels
BiCMOS ICs	yes	LDR tests required; no established alternative for high radiation levels
CMOS ICs	yes ("rebound")	High-dose rate tests followed by high-temperature annealing after last radiation level

One must keep in mind that the response of semiconductor devices in space environments it is a complex problem that continues to evolve with the frequent changes that occur in the semiconductor industry in processing as well as in device design. Thus, it is likely that further additions or modifications to these requirements will be required as semiconductor devices continue to change.

Certain points need to made to put this material in perspective. First, the success of past JPL missions has been partly due to the very thorough testing done on most of the components used in those systems along with the extra margin that occurs from self-shielding of the spacecraft. Note however that even though the Cassini spacecraft was built with older technology parts, two parts were identified during testing with extreme low dose rate sensitivity. These parts were thrown out of the part list, and almost certainly would have caused failures in their applications early in the mission if radiation testing had not been done. Note also that most of the parts tested for Cassini passed the radiation requirements easily. The two problem part types were only found because the program adopted a conservative approach for radiation testing and qualification.

Second, JPL has very limited experience with newer technologies, including highly scaled VLSI logic devices and high-performance low-power linear devices. Most of these parts will perform satisfactorily at the modest radiation levels that are in place for most projects, and one could probably successfully fly most of these devices with little or no radiation testing, particularly in deep space applications during "solar quiet" times (little chance of solar flares). However, just as for Cassini, some of these devices will be extremely susceptible to radiation damage. Identification of the problem parts and technologies that can potentially bring down a spacecraft requires a combination of analysis, judgment and testing by spacecraft designers and radiation part specialists. One way to do this is to encourage frequent interaction between these groups.

Third, there are many different ways to do radiation testing. In many cases it is possible to find radiation test data that was taken under the wrong test conditions, or failed to include the electrical parameters that are critical for the design that may initially indicate that the parts are acceptable. Test data must be evaluated with extreme care because of the new effects that can occur with modern devices along with the cost and complexity of electrical characterization measurements. Data that is too old, taken at the wrong dose rate, or available for a different manufacturer of the same generic part type cannot be used as a substitute for radiation testing.

Finally, it is extremely important to understand that new radiation issues continue to arise as semiconductor devices evolve. One such example is in flash memories, which require very high internal voltages for writing and erasing. New flash memory devices are extremely susceptible to total dose damage [Ref.14], and will likely remain among the most sensitive components. Similar issues may arise with advanced microprocessors and logic devices that are optimized for low power and low operating voltage, as well as for advanced DRAMs, which are the key component used in solid-state recorders. Although using state-of-the-art devices provides many advantages, it also involves potentially more risk from the standpoint of radiation performance.

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