Space Radiation Effects and Reliability Considerations for the Proposed Jupiter Europa Orbiter

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Abstract − **The proposed Jupiter Europa Orbiter (JEO) mission to explore the Jovian moon Europa poses a number of challenges. The spacecraft must operate for about seven years during the transit time to the vicinity of Jupiter, and then endure unusually high radiation levels during exploration and orbiting phases. The ability to withstand usually high total dose levels is critical for the mission, along with meeting the high reliability standards for flagship NASA missions. Reliability of new microelectronic components must be sufficiently understood to meet overall mission requirements.**

I. INTRODUCTION

NASA flagship missions, such as the proposed JEO mission to Europa, are expected to operate for long periods of time in the harsh radiation environment of space. Design and operational rules have been established to achieve this goal, as evidenced by previous deep space missions (Galileo and Cassini), as well as in Mars surface exploration missions and the Hubble space telescope.

The unusually high total dose levels of the proposed JEO mission affect part performance as well as reliability. A related problem is device scaling, which introduces new issues for reliability and radiation effects that were not important for the 1970 and 1980 technologies used in older flagship missions with high radiation levels.

This paper discusses some of the underlying issues in selecting suitable components, testing and qualifying them for this unique environment, and incorporating system design methods that can be used for such a mission.

II. JOVIAN RADIATION ENVIRONMENT

A. Total Dose

The Jovian trapped belts are far more intense than the earth's radiation belts, primarily because Jupiter has a magnetic field that is about 20 times higher than the earth. The trajectory selected for the proposed mission avoids the inner proton belts; most of the radiation is due to trapped electrons with energies up to several hundred MeV. Electrons with such energies require much thicker shielding compared to electrons in earth orbits, limiting the effectiveness of shielding (particularly spot shielding). Selection of radiation-tolerant microelectronics is critically important because of the difficulty of adding additional shielding.

Figure 1 shows the total dose for a mission with a 105 day orbit as a function of aluminum shield thickness, along with the specification for the previous Galileo mission [1]. The initial Galileo environment is shown, along with the actual environment after several extensions of the original mission. Note that the Europa requirement is slightly above the extended mission environment of Galileo.
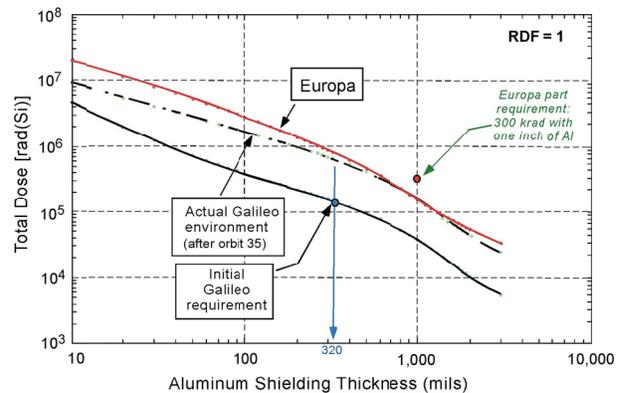

Fig. 1. Total dose vs. shielding thickness for the proposed JEO mission, along with the requirements and actual total dose for Galileo.

B. Galactic Cosmic Rays and Solar Particles

Although the solar particle intensity is lower at Jupiter compared to regions near the earth, the charged particle environment that produces single-event effects (SEE) is not very different from that of other deep space missions. Various SEE (such as upset, functional interrupts, and latchup) remain important issues for the proposed mission, but are similar to other space missions. Therefore single event effects will be discussed only briefly in this paper, emphasizing synergistic effects between SEE sensitivity and total dose damage. SEE effects are discussed in more detail in references 2 through 4.

C. Displacement Damage

Displacement damage is also a concern. There are two possible sources: neutrons from the potential on-board radioisotope power system, and electrons from the natural environment. Contributions from neutrons depend on the location of components relative to the power system, and are expected to be less than 1/3 of the overall displacement damage requirement, except in special circumstances.

Electrons are less effective than protons in producing displacement damage, but that mechanism is still important because of the high energy and high fluence. For the proposed JEO mission, the equivalent neutron damage for a shielding thickness of one inch is 5×10^{11} n/cm^2 [1]. Displacement

damage is particularly important for detectors, but also affects conventional components using bipolar technology.

Figure 2 shows how gain degradation of a 2N2222 transistor is affected by displacement damage. Below 100 krad(Si) ionization damage dominates, but displacement damage becomes more important at higher radiation levels due to saturation of ionizing radiation damage. One of the reasons for saturation is the buildup of internal electric fields within the oxide as charge accumulates near the silicon-SiO_2 interface.
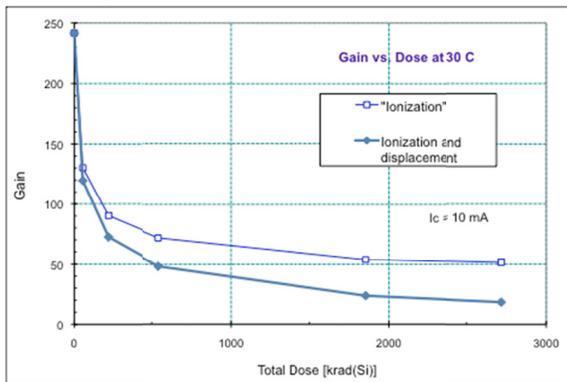

Fig. 2. Effect of electron displacement damage on transistor gain degradation.

Displacement damage is even more important for bipolar linear circuits, which typically contain wide-base pnp transistors. Figure 3 compares shifts in the internal bandgap reference voltage of a voltage regulator when it is irradiated with gamma rays and protons; displacement damage causes much more damage [5].
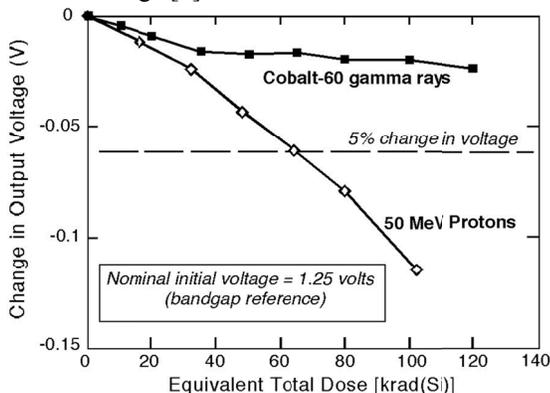

Fig. 3. Proton and gamma ray tests of a voltage regulator. The output voltage scales with changes in the internal bandgap reference.

The key point is to require evaluation of displacement damage effects in addition to total dose damage for most bipolar devices. Certain types of light-emitting diodes (LEDs) are also highly sensitive to displacement damage; for example, the Galileo tape recorder failed at the end of the mission due to LED displacement damage [6].

III. DEALING WITH HIGH RADIATION REQUIREMENTS

A. Basic Issues

The high total dose level is a major issue for the proposed mission. It is not only higher than that of other space missions, but is above the maximum radiation level used to qualify most hardened components. Consequently, little information is available about whether devices will actually function at those

levels, imposing additional risk for component selection. Other difficulties include:

a. Substantial shielding is planned to reduce the total dose level to lower levels. Consequently, adding additional shielding to further reduce the total dose for problem components is a costly and weight-penalizing option.

b. The actual total dose will be close to the design requirement, with reduced margins compared to typical space missions.

c. Qualification methods used by manufacturers begin with tests at high dose rate, followed by an annealing step which is applicable to missions with very low dose rate, but may not be appropriate for the somewhat higher dose rate conditions of the proposed JEO mission during the orbiting phase.

B. Total Dose and Displacement Damage

General Concerns

For initial design concept purposes, it is convenient to divide active components into basic categories. There is generally less concern about digital devices, first because radiation-hardened components are readily available; and second, because total dose hardness generally increases with scaling [7]. The most critical component families are detectors, analog circuits, and power control devices.

Many analog circuits exhibit more damage when they are exposed at the low dose rates in typical space environments compared to tests at high dose rate; the term "ELDRS" (enhanced low-dose rate sensitivity) is often use to describe this effect [8].

Although the ELDRS phenomenon has been investigated for many devices, most tests are not carried out above approximately 50 krad(SiO_2) because of the lengthy time required for irradiation, and the fact that few space missions have requirements above 100 krad(SiO_2). Figure 4 compares tests at high and low dose rate for an analog-to-digital converter, used on the Juno program [50 krad(SiO_2) requirement]. Although this part was acceptable for that mission, catastrophic failure occurred for unbiased parts when the tests were extended to higher levels in order to evaluate their potential use for JEO. No precursor was observed for the onset of catastrophic failure from the tests at 50 krad(SiO_2).
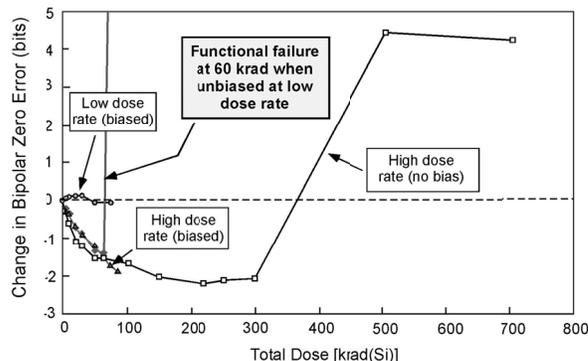

Fig. 4. Evaluation of a radiation-tolerant analog-to-digital converter at low dose rate in the region above 50 krad(SiO_2).

This illustrates the importance of evaluating analog bipolar parts under low-dose rate conditions at high radiation levels,

despite the long testing times. Fortunately, the dose rate for the JEO orbiting phase is ~ 40 mrad(SiO₂)/s [1], about an order of magnitude higher than that of conventional space missions, which reduces the overall test time.

ELDRS in Scaled CMOS

CMOS devices with feature sizes ≤ 0.25 μm use shallow trench isolation (STI). STI oxides extend laterally for distance of 0.08 to 0.25 μm, a distance that is comparable to the oxide thickness in bipolar oxides. Recent work has shown that an effect similar to ELDRS occurs in STI oxides, with more damage taking place when tests are done at low dose rate [9]. Figure 5 illustrates this, along with test results for 10-keV X-rays, which further overestimates radiation hardness.
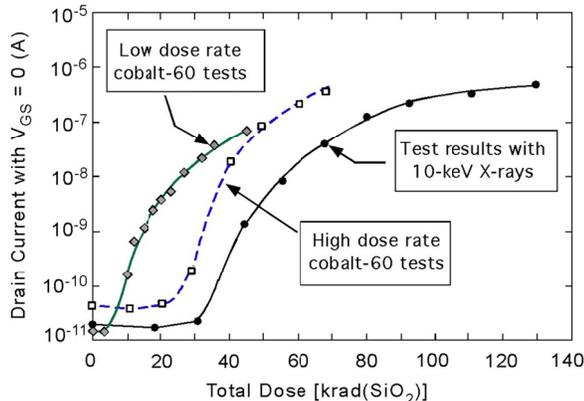

Fig. 5. Increase in drain current vs. total dose for test transistors from a CMOS process with 180 nm feature size [9]. The total dose for inversion is significantly lower at low dose rate compared to test results at high dose rate.

This result was unexpected because leakage current in CMOS devices typically anneals, leading to the conclusion that less damage should occur at low dose rate. The mechanism is related to the long transport time for holes in thick oxides; increased recombination at higher dose rates decreases the charge that is actually transported to the interface region between the STI and the body region of the MOS transistor.

Lot Variability

There can be large differences in the radiation hardness of different production lots [10]. An example is shown in Fig. 6 for a voltage regulator. Two points are important: first, the total dose hardness differs by a factor of 2.2 to 3.5 (depending on the load conditions) for devices produced within about 15 months; and second, short circuit current is a critical parameter for applications of this type of device. If the device load exceeds the current drive capability, large changes in output voltage will take place that usually disable circuits that are powered by the regulator unless the load can be reduced. It is far more difficult to deal with this type of response compared to gradual parametric shifts that often allow circuits to continue functioning with some degradation in performance.

Displacement Damage

Even though the displacement damage requirement for JEO is relatively low, it can still be important. One reason for this is saturation of total dose damage at higher radiation levels (see Fig. 2); displacement damage does not saturate, and can

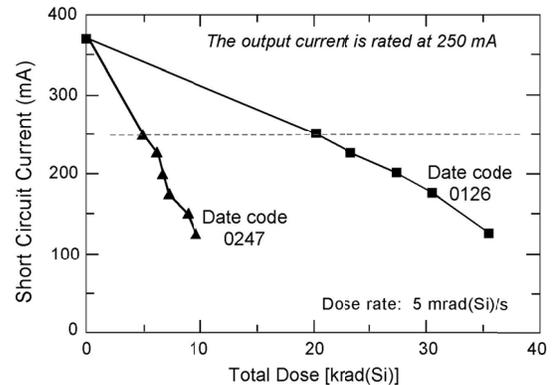potentially affect the overall hardness of some types of components.

Fig. 6. Lot variability of radiation degradation of short-circuit current of a voltage regulator.

It is usually impractical to perform radiation tests with the exact type of particle and energy range that occurs in the environment. Although total dose and displacement damage are produced simultaneously in the real space environment, the effects are generally considered separately from the standpoint of test and qualification. One approach that can be used when displacement damage effects are expected to be less than total dose damage is to pre-irradiate qualification samples to the expected displacement dose before total dose tests are performed.

Fortunately, the displacement damage fluence is low enough for JEO so that relatively few components are affected. Table 1 lists the device types where displacement damage is potentially important. For detectors and light-emitting diodes, displacement damage is often the dominant source of damage. It can usually be considered as second-order for bipolar linear circuits and discrete transistors.

Table 1. Components Affected by Displacement Damage

Device Type	1-MeV Fluence Damage Threshold (n/cm²)	Comments
Detector	10^9 to 10^{10}	Depends on technology
Light-emitting diode	2×10^{10}	Dominant failure mode
Bipolar linear circuit	4×10^{10}	TID and displacement effects are both important
Discrete transistor	3×10^{11} to 10^{12}	Mainly effects low frequency transistors

IV. RELIABILITY STRATEGIES FOR SPACE MISSIONS

Several steps are necessary in order to obtain the high reliability needed for space missions such as JEO. The very high reliability of earlier flagship missions is frequently cited to show the effectiveness of existing practices for reliability. However, the components used in those missions were designed and fabricated quite differently from present-day

devices. New reliability challenges introduced by device scaling and complexity are not necessarily solved by older reliability methods [11,12]. Compound semiconductors impose additional reliability difficulties because of their limited history (other than GaAs MESFETs) and use of new fabrication technologies [13,14].

The specific environment for JEO must be taken into account for reliability evaluation. Some space missions (such as those involved in Mars surface exploration) must endure (Martian) daily temperature cycles; consequently, reliability tests based on thermal cycling are heavily emphasized. The proposed JEO mission is quite different. The spacecraft will undergo extreme vibration during launch, but the thermal environment after launch is relatively benign.

A. Component Testing and Qualification

The first reliability step is thorough electrical testing and burn-in of all components. In the past this has included tracking devices at individual wafer levels, as well as logging parametric data before and after burn-in. Although this approach was highly successful for the less complex components used in earlier missions, there may be limitations in its effectiveness for newer technologies.

CMOS reliability mechanisms are heavily influenced by advances in manufacturing technology [15]. Manufacturers continue to evaluate fundamental mechanisms such as threshold shifts from hot carriers, time-dependent dielectric breakdown, and electromigration. From a user standpoint, the most effective way to deal with these topics is to review the design rules and methods used in manufacturing to verify reliability. Other issues are more difficult. The most important is probably the extremely large number of transistors on a single die. Performance variations are caused by statistical fluctuations in threshold voltage (due to the small number of dopant atoms in each transistor) [16] along with manufacturing defects, including mask misalignment, that may allow individual transistors to function during initial tests, but reduce margins when we consider the very long operational life. Although "outliers" can often be identified by testing completed devices, statistical fluctuations are inherent in the technology and generally cannot be eliminated by testing. New approaches need to be developed to deal with these issues. Note that older methods (such as I_{ddq} testing) have limited effectiveness, particularly for processes with many levels of metallization.

Packaging is another concern. Nearly all components in previous flagship missions have used hermetic packages, and the general approach towards testing and qualification is focused on such package types. Non-hermetic packages (e.g., ball grid or column grid arrays) may be the only option for digital parts with high frequency response and large numbers of pins. For the typical range of activation energies associated with most failure mechanisms, burn-in temperatures for these types of packages are too low to establish reliability thresholds for long life applications.

Reliability of complex packages is likely to be one of the most important issues [17,18]. Much of the work on emerging package technologies has emphasized thermal cycling, which causes cracks to form in BGA and CGA packages [19].

Although appropriate for some missions, the relatively constant temperature of electronics on JEO diminishes the importance of thermal cycling.

An example of ongoing work on package reliability is work by Lall, *et al.*, [20]. They proposed using the growth of intermetallic compounds in BGA test structures during thermal aging as a reliability indicator when limited thermal cycling is expected. Thickness was evaluated by (destructively) sectioning some of the samples from a larger group at periodic intervals, using a SEM to measure intermetallic thickness. As shown in Fig. 7, the data fit a $\sqrt{t}$ dependence, consistence with a diffusion-controlled mechanism.
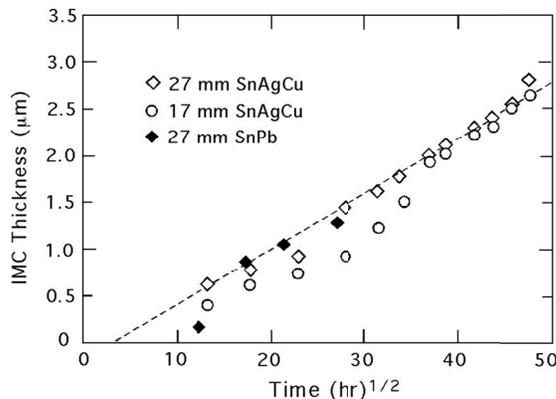
Fig. 7. Time dependence of inter-metallic compounds in ball grid arrays (after Lall, *et al.* [20]).

B. Derating

The second reliability step, which is probably the most important, is component derating. Although individual components are designed and tested to work over an extended temperature range[1], temperature ranges in typical applications are much narrower. Additional derating factors have been used in older flagship missions, where power dissipation, chip temperature, current and voltage are reduced from the maximum values allowed by manufacturers. For example, the maximum application voltage of a power MOSFET is 75% of the manufacturer's rating, with an additional derating factor for single-event gate rupture.

These derating methods provide significant margins in the operating stress of individual components. Although no attempt is made to quantify the improvement in reliability, the approach appears satisfactory for older components and will likely be beneficial for new technologies as well (including the inherent difficulties associated with advanced packaging).

C. System Design

The typical approach used to evaluate components is to combine worst-case values for initial parameters, reliability, temperature, and radiation damage in an additive mode. Although it is somewhat conservative, it can usually be accommodated by systems with less stringent requirements. For JEO, the inherent hardness of some parts is so close to the actual requirement that it becomes very difficult to use such an approach.

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[1]The military temperature range (-55 to 125 °C) was used in the past, but narrower ranges may be necessary for large-scale devices.

A statistical design approach is being considered for JEO that reduces some of the conservatism by using statistical representations of radiation degradation, reliability, temperature, and initial parameter values. The concept is illustrated in Fig. 8, recognizing that it is not practical to carry out statistical analyses to the point where the actual statistical distribution is characterized. A significant improvement in mission lifetime can be obtained with this approach, as illustrated in the figure.
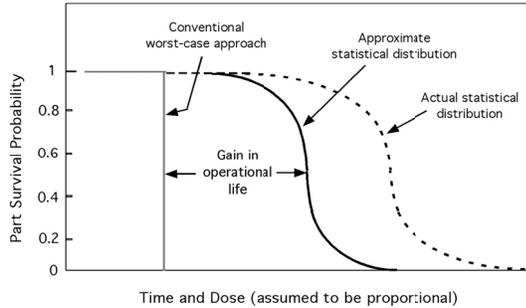

Fig. 8. Relationship between worst-case and statistical approaches for system lifetime.

D. Concerns and Synergistic Effects for JEO

Identification of Key Problem Areas

Reliability is a complex topic. Fundamental reliability mechanisms are usually evaluated using special test structures, and nearly always are taken into account in establishing design rules for complex circuits. For a mission like JEO, we need to know why devices really fail in field applications, and concentrate on ways to decrease the actual failure rate, relying on manufacturers to deal with the more fundamental mechanisms that have to be dealt with at the root manufacturing level. Field failure data from manufacturers may be helpful in identifying the key failure mechanisms, even though the conditions may differ from those used in space.

When we consider the design and thermal derating methods that are likely to be imposed by JEO, the main concerns are probably interconnects and packaging. As discussed earlier, new approaches will have to be identified for those factors in large-scale devices.

Other areas of concern for reliability are new technologies (particularly compound semiconductors), and special device technologies used in instruments, particularly detectors [21,22].

Synergistic Effects

Restricting operating conditions, power dissipation and temperature generally improve overall reliability. However, we have to consider possible interactions between the unusually high radiation environment and reliability mechanisms that can potentially make the overall reliability problem worse [23,34].

One example is the effect of small changes in the internal threshold voltage of SRAMs with small feature size. Although tests of highly scaled CMOS have shown that gate threshold leakage and leakage through the STI isolation regions are negligible [25], that is not the case for devices with narrow channel widths, such as those used in SRAMs; cache memories are designed with very narrow changes, and must be able to function with "5 sigma" parameter valuations at the 90 nm

feature size node. Figure 9 shows how small changes in the internal switching point affect the write margin of an SRAM [26]. This particular case is for 90 nm cache cells, which are only affected at radiation levels > 1 Mrad(SiO_2). The effect has not been investigated for larger feature sizes, but it will likely affect devices manufactured at the 130 nm as well. From total dose scaling studies [27], we expect that such effects would become important between 200 and 500 krad(SiO_2) at that node.
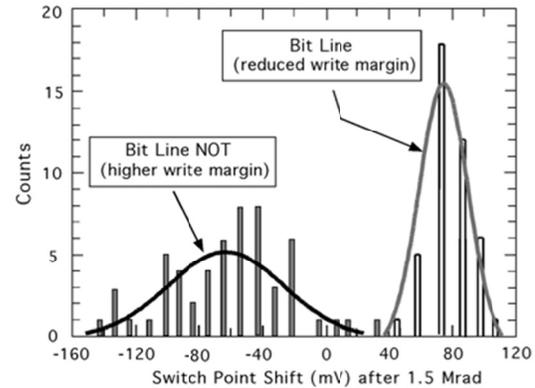

Fig. 9. Influence of small changes in the internal switching margin from total dose degradation on the SEU response of an SRAM with 45 nm feature size [26]. The margin is reduced for the normal bit line (compared to the bit line NOT line), increasing the SEU rate compared to an unirradiated device.

Other synergistic effects are more obvious, including the effect of gradual increases in standby leakage (or overall power consumption for bipolar devices) as the total dose increases during the mission. This not only increases the load on power distribution systems, but may increase the temperature of other components on conduction-cooled circuit boards, affecting reliability as well as performance characteristics.

CONCLUSIONS

The proposed JEO mission to Europa must deal with fundamental reliability issues as well as an usually high level of total ionizing dose, beyond the normal range considered for most radiation-hardened components. Improvements in hardened part technology combined with the very high reliability of older flagship missions show that it is possible to meet the demanding requirements of this mission.

The main areas of concern are those related to new technologies, where older methods of design and reliability do not necessarily apply. Additional work is needed on packaging and interconnect reliability, as well as on synergistic effects between reliability and radiation damage for advanced devices, where the approaches used by device manufacturers to maintain reliability will not necessarily apply.

We also have to be concerned about the special components used in detectors for spacecraft control (including star scanners), as well as those used in instruments. Earlier missions (including the Galileo mission) were able to deal successfully with those components. The challenge for the proposed JEO mission is to ensure that more advanced components of this type could also meet the demanding requirements of the mission.

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