Radiation Effects and COTS Parts in SmallSats

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ABSTRACT

An emerging class of small satellite missions requires assured operational lifetime and rapid development on a moderate budget. This paper describes a "Careful COTS" approach to component selection and testing to meet these needs. Commercial parts are selected based on best practices, and radiation tested to limits based on the modeled mission environment. High-energy proton testing allows simultaneous exploration of total dose, displacement damage, and some single-event effects.

The authors have developed these methodologies over the course of a number of successful low-earth orbit missions. Provided the lifetime dose is under 30 krad, a solution can probably be realized with commercial parts. Various case studies of commercial parts that have failed under this dose are given.

INTRODUCTION

In past decades, small satellites have had a reputation as second-tier spacecraft, used primarily for amateur, educational and technology demonstration purposes. In these cases, lifetime was not of paramount importance. Often the bulk of the mission's utility lay in the design and fabrication of the spacecraft, and not in its on-orbit performance.

Today the secondary roles remain, but they are augmented by a growing number of operational constellations providing useful and necessary services. These include communications (i.e. ORBCOMM), remote sensing (i.e. Skybox Imaging) and science (i.e. BRITE). The owners of these missions require an assurance that their investments will operate successfully on-orbit for many years. Lifetime, both real and demonstrated, becomes of great importance.

Without careful attention, a satellite's life may be cut short by space radiation effects. This paper shows the approach used by the authors to design satellite electronics to meet a specific required lifetime while maintaining reasonable budget and rapid development cycle. It has been successfully demonstrated over dozens of spacecraft, with the eldest now operating usefully after 10 years on-orbit.

Definitions

In discussing space radiation effects, we start by defining some frequently used terms.

Total Ionizing Dose (TID) – Material damage caused by ionizing radiation sources. Quantified by deposited energy per mass for a given material with units of Gray (SI) or Rad.

Linear Energy Transfer (LET) – Rate at which energy is deposited in matter as an ionizing particle travels through. Typical units are MeV/cm or scaled by material density as MeV-cm^2/mg

Single Event Effects (SEE) – Disruption in function of electronic circuits due to single ionizing particle interaction. These may be:

- Single Event Upset (SEU)
- Single Event Latchup (SEL)
- Single Event Functional Interrupt (SEFI)
- Single Event Burnout (SEB)
- Single Event Gate Rupture (SEGR)

Particle energy – kinetic energy of a particle generally given in keV or MeV

RADIATION AND RELIABILITY APPROACHES

Broadly speaking, there are three different approaches to spacecraft parts selection in the context of radiation and reliability. On one side is the radiation hardened / space grade. At the other extreme is the buy-and-fly. We propose a middle path, which we term "Careful COTS".

Radiation Hardened / Space Grade

A radiation hardened or "space-grade" component is defined as one that is engineered by its manufacturer to provide specific radiation performance. This is typically accomplished by making certain process changes at the silicon foundry level[1]. A radiation hardened component will also be made with strict quality control including periodic testing to the rated radiation dose, and part-level environmental screening for latent defects and infant mortality.

Radiation hardened components tend to have the following properties:

- Rated radiation dose of 100 krad to > 1 Mrad
- No SEL, due to disabling of parasitic SCR structures
- Characterized single-event effects
- Hermetic packages
- Low degree of integration, and mature technology (~10 years behind cutting edge)
- No supplier stock, and long lead times
- High component cost

The use of radiation hardened components drives the cost of a space mission design. The actual component price, while high, is not the greatest effect. Instead, it is the long lead times and low density that lead to long engineering / build design cycles and relatively low performance when compared with commercial designs.

Radiation hardened components are appropriate for very high dose environments, where nothing else will work. This includes certain high altitude orbits, spacecraft operating near the outer planets, and military devices intended to survive nuclear war. They may also be suitable for extremely risk-averse programs, such as human spaceflight, where the cost of proving any other design to be safe would be overwhelming.

Careful COTS

An alternative to the radiation hardened / space grade approach has been coined Careful COTS. It involves proving radiation tolerance of specific commercial parts at the level required for the mission and implementing system-level design, screening and process control to improve reliability. A "radiation tolerant" component is defined as a commercial or industrial part that was not manufactured with space radiation in mind, but which has been found to be functional to a certain dose by test.

Most commercial components are radiation tolerant to 5 krad. Many are radiation tolerant to 20 krad or more. Some will fail before 1 krad. Without testing, it is impossible to predict which category a part will fall into.

Lot control and screening is critical to Careful COTS. Commercial vendors may change their manufacturing processes, or even the silicon foundry that produces their parts. A particular part made last year may be radiation tolerant, while parts made this year may not be. Parts that are used for flight must be known to be identical to parts that have been radiation tested.

Modern commercial part reliability is very high, with the majority of failures occurring early in a part's life due to an inherent defect. One manufacturer shows 14 failures from a sample of 10,403 plastic packaged ICs, tested at +135°C for 1000 hours[2]. This represents an approximate 0.14% defect rate, leading to unacceptable odds of failure for a satellite containing hundreds of parts.

To mitigate this problem, flight hardware must accumulate sufficient operating hours before launch so that the "infant mortality" risk is retired. This should be done by elevated temperature burn-in testing of integrated assemblies. Testing at the component level is unnecessary, and for many surface-mount package types impractical.

It is possible for a commercial subsystem (GPS, camera, computer, etc) to be tested and found to be radiation tolerant. However the odds are lower. For example, assume that a commercial camera uses 10 different types of IC and that each type of IC has a 90% probability of being radiation tolerant to the mission dose. The probability of the entire camera meeting the mission dose is only $0.9^{10} = 35\%$. Lot control is also difficult for commercial subsystems. Even if two cameras were made on the same day, can we be absolutely certain that the detectors on each come from the same lot?

Tin whisker risk must be mitigated by hot-solder dipping at the component level. Where lead-free commercial subsystems are acquired, they can be conformal coated.

Careful COTS designs are suitable for many small satellite missions where a high probability of mission success is required and access to cutting edge commercial technology is critical. They are not cheap, and may be out of reach of educational or demonstration missions.

Buy-and-Fly

A buy-and-fly philosophy takes a calculated risk in discounting the effects of radiation on electronics. Commercial components and subsystems are purchased, and provided they meet the other environmental requirements (vibration, temperature, etc.) they are integrated into the spacecraft. Both component and assembly quality can vary widely and generally little or no screening is performed.

Buy-and-fly is suitable for missions with extremely low radiation dose, either due to benign low orbits or short mission lives. These two factors tend to go together, as low orbit spacecraft re-enter quickly. It is also necessary for cost-constrained missions where risk of failure is tolerated.

CAREFUL COTS DESIGN SEQUENCE

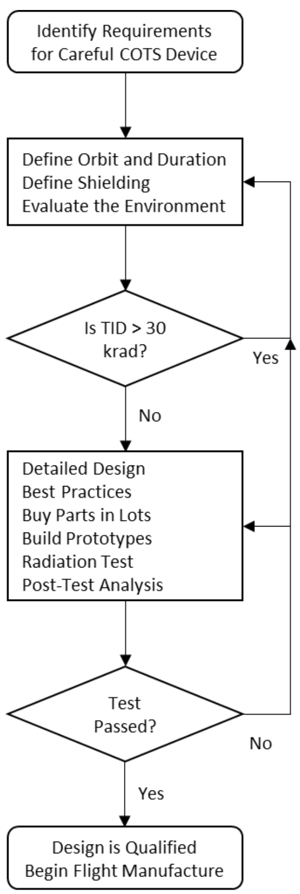

Figure 1: Careful COTS Design Flow Chart

ENVIRONMENT MODELLING

The space radiation environment consists of high-energy solar particles and photons, charged particles trapped in Earth's magnetic field, and extra-solar high-energy particles called galactic cosmic rays (GCRs). The largest sources of ionizing radiation in LEO and MEO are trapped proton and electrons, while solar origin particles dominate for higher orbits and interplanetary mission. Photons (X-rays, gamma rays), electrons, protons and heavier charged nuclei contribute through slightly different mechanisms to the TID a component receives during its lifetime. However only protons and heavier nuclei deposit enough localized energy in matter to generate single event effects.

The first step in a Careful COTS design is to understand the expected environment that the device must survive. The inputs to this analysis are:

- Mission orbit (or trajectory)
- Mission duration
- Device shielding

A simple mission will have a single orbit for a certain lifetime, such as "850 km sun-synchronous for 2 years". A more complex mission may have different phases that can be summed together, such as "two weeks in GTO plus three years in GEO". Interplanetary or low-thrust missions may describe continuous trajectories that must be piecewise integrated.

At this stage in the design the shielding estimate can be very approximate. The simplest model is a spherical aluminum shell, and this is often appropriate for components buried in the heart of a satellite. If a device has significantly more shielding on one side than another then a sectoring analysis is required – the problem is non-linear, so simply averaging the shielding thickness is not applicable. More detailed shielding analysis may include full particle transport monte-carlo in a tool suite such as Geant4, although other uncertainties in test and analysis generally make the effort involved in such an analysis unwarranted for all but the most critical missions.

If the shielding is a material other than aluminum, weighting by density is a reasonable first approximation. For example, aluminum has density 2700 kg/m3 and titanium has density 4500 kg/m3. Therefore 1.0 millimeter of titanium is equivalent shielding to 1.7 millimeters of aluminum.

The easiest place to perform this analysis is SPENVIS[3]. This is an online service provided by ESA that includes many industry-standard space radiation effects analysis tools in an easy-to-use interface. Registration is required, but it is free to use.

Radiation Environment Modelling Example

As an example, let us consider a hypothetical LEO mission carrying a Sinclair Interplanetary ST-16 star tracker. We set the orbit as 800 km altitude, dawn-dusk sun-synchronous. The mission life is 5 years. At this stage we may not know when in the 11-year solar cycle we will launch – unexpected delays of several years are not uncommon. The trapped electron environment is worst at solar maximum, and paradoxically the trapped protons are worst at solar minimum. To be conservative we will assume both worst environments.

Finally we must choose our solar proton model. Solar protons do not come in a steady flux, but are associated with discrete flare events. Some years may have exceptional flares, while some may be quiet. The models require a confidence level, expressed as a percentage chance of the result being an over-estimate of the actual environment the mission will see. Be careful with the degree of conservatism here. A 95% confidence, while reassuring, may lead to significant radiation overdesign. We choose 80%.

Table 1: SPENVIS Environment Inputs

Coordinate Generators	Spacecraft Trajectories	1 mission segment 5 year duration Heliosynchronous Start Jan 1, 2011 800 km altitude 0600 local ascending node
Radiation Sources and Effects	Trapped proton and electron fluxes	Proton model AP-8, solar minimum Electron model AE-8, solar maximum
	Long-term solar particle fluences	ESP-PSYCHIC (total fluence) Ion range: H to H Confidence level: 80%
	Galactic cosmic ray fluxes	Ion range: H to U Magnetic shielding: default
	Ionizing dose for simple geometries	SHIELDOSE-2 model Center of Al spheres Silicon target

The graphical output from the SHIELDOSE-2 model is shown. The report file contains tabulated data which will also be very useful. The plot shows that below 4 mm of shielding, trapped electrons are the dominant source of total dose. Above 4 mm of shielding, trapped protons dominate. Electrons are strongly affected by shielding, while trapped protons are not. As can be seen in Figure 2, shielding has very small marginal benefit beyond about 5mm (200 mil) thickness aluminum which makes for a good design rule-of-thumb.

Table 2: Continuous Stopping Distance in Aluminum and Tungsten

	Aluminum (Al)	Tungsten (W)	Al/W Ratio
Electrons			
1 MeV	0.5546 g/cm^2	0.7686 g/cm^2	0.722
10 MeV	5.861 g/cm^2	6.211 g/cm^2	0.945
Protons			
10 MeV	0.1705 g/cm^2	0.3452 g/cm^2	0.494
100 MeV	10.01 g/cm^2	15.96 g/cm^2	0.627

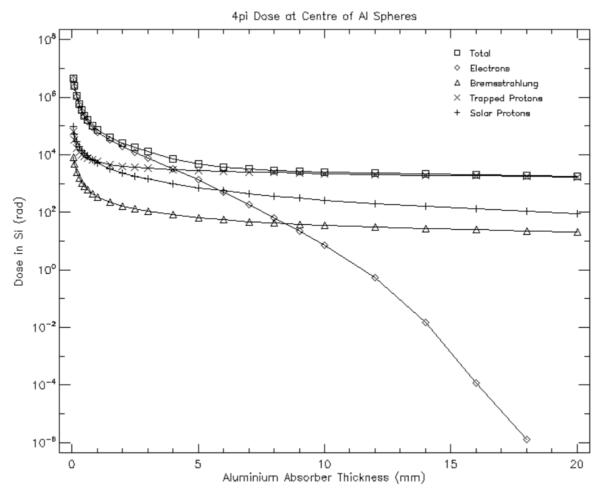

Figure 2: SHIELDOSE-2 Output

Next, we must determine the shielding of our device. Space electronics are seldom packaged in convenient aluminum spheres, so some approximations must be made.

Table 3: Star Tracker Sectoring Analysis

Fraction of sphere	Element	Equivalent Aluminum Thickness	5 Year Contributed Dose
22%	Lens	20 mm	0.39 krad
53%	Chassis side	2.5 mm	9.34 krad
25%	Satellite body	10 mm	0.64 krad
Total			10.37 krad

For each element, the "5 Year Contributed Dose" column is derived from the total dose in the SHIELDOSE-2 report file multiplied by the fraction of sphere. The great bulk of the star tracker's total dose comes from electrons penetrating the thin aluminum side wall of the chassis.

If we wanted a lower total dose we could consider adding additional shielding. A 1 mm thick tungsten shell has been manufactured to fit over the ST-16 star tracker. To evaluate its performance we must find the equivalent thickness of aluminum. Using the NIST e-star and p-star models[4], we find the continuous stopping distance approximation (CDSA) for electrons and protons in the two materials, shown in Table 2.

The particle energies of interest are chosen heuristically. Electrons much below 1 MeV have no chance of penetrating the shielding, while 10 MeV is about the maximum of the spectrum. The same arguments apply for 10 MeV and 100 MeV protons.

By rough averaging we can say that tungsten stops electrons equivalent to 85% of an equivalent mass of aluminum. It stops protons equivalent to 55% of aluminum. A 1 mm tungsten sheet has the same mass as a 7.1 mm aluminum sheet. So our tungsten shell looks like 6 mm of aluminum to electrons, and 4 mm of aluminum to protons. Bremsstrahlung X-rays are a small fraction of the total dose, and are ignored here.

Table 4: Sectoring Analysis with Shield

Fraction of sphere	**Element**	**Equivalent Aluminum Thickness**		**5 Year Contributed Dose**
22%	Lens		20 mm	0.39 krad
53%	Chassis side Tungsten shell	Electrons	8.5 mm	0.04 krad
		Protons	6.5 mm	1.64 krad
25%	Satellite body		10 mm	0.64 krad
Total				2.71 krad

In this case, 74% of the total dose can be eliminated by the addition of the tungsten shell.

It is interesting to note here that many people think of Hi-Z materials such as tungsten or lead as better radiation shields than Low-Z materials such as aluminum. This is the case from a shielding thickness perspective, but is not true from a mass perspective – aluminum is a superior shielding material for both protons and electrons when mass is the primary design consideration. Generally Hi-Z materials are superior for high energy photons (X-rays, gamma rays) as anyone who has worn a lead blanket during an X-Ray knows.

SPENVIS can also be used to look at single-event effects.

Table 5: SPENVIS Single-Event Effects Inputs

Radiation Sources and Effects	Shielded flux	2 g/cm^2 total thickness (Or as appropriate for your mission shielding) 0% Ta to Al mass ratio
	Long-term SEUs and LET spectra	0.7 cm Al shielding (or as appropriate for mission) Material: Si (SRIM2008)

The proton orbit averaged flux shows the proton energy spectrum that makes it past the shielding. It can be used to relate SEU rates found during proton testing to likely upset rates on orbit. For example, we know from testing that the SEU cross-section for each RAM bit in the ST-16's supervisor processor is 3.27 x 10^{-14} cm^2 for 105 MeV protons. The total proton flux striking the processor is approximately 100 particles per cm^2 per second. If we assume the cross-section is invariant with energy then we would expect each bit to upset every $3x10^{11}$ seconds. The processor has 67584 bits of RAM total, so one upset is expected every $4.4x10^6$ seconds, or 52 days. This is frequent enough that a software error-detection-and-correction scheme is used to mitigate the system impact.

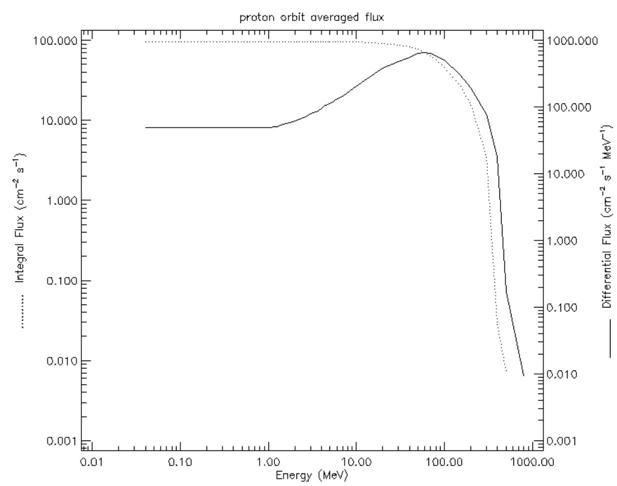

Figure 3: Proton Orbit Averaged Flux

The Shielded LET Spectra figure shows the number of heavy ion interactions in the target silicon device over the lifetime of the mission. Note that the LET units are MeV-cm^2/g. Divide by 1000 to get the more familiar Mev-cm^2/mg used in most literature.

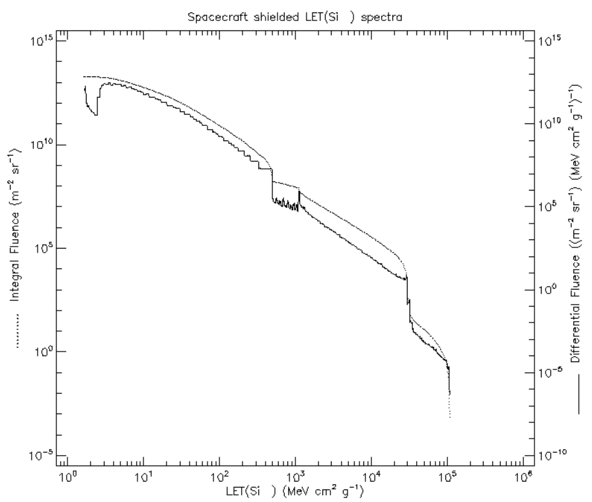

Figure 4: Shielded LET Spectra

Proton testing may be assumed to uncover SEE out to 25 MeV-cm^2/mg. This figure shows 2×10^4 particles/m^2/sr above this LET over the lifetime of the mission. The sensitive cross-section of a component cannot be larger than its physical size. If we imagine a component with physical area 10 mm^2, it can expect to see a single particle of greater than 25 MeV-cm^2/mg over the lifetime of the mission. Thus we can place upper limits on SEE effects that have not been directly tested with heavy ions.

CAREFUL COTS BEST PRACTICES

While radiation is the focus of this paper, success of a space mission depends on a number of other factors including design standards (de-rating, redundancy, etc), part selection and degree of test at unit and system level. References ESA ECCS-Q-30-11A[5] and NASA EEE-INST-002[6] are excellent references for the design factors outside of radiation effects that impact system reliability and won't be repeated here.

Exempt Components

Certain components can reasonably be assumed to be radiation tolerant to at least 30 krad when operated in proper and de-rated biasing conditions:

- Anything not containing a semiconductor. (resistors, capacitors, inductors, etc.)
- Single-junction diodes (standard, Schottky, Zener)
- Bipolar junction transistors (BJTs)

Be aware that there are two-terminal components that may look like diodes, but that may contain considerable complexity. These include some temperature sensors, voltage regulators and references, and current regulators. There is every possibility that these parts are also radiation tolerant, but it cannot be safely assumed.

Most non-electronic materials (PCB substrates, conductors, fasteners, etc.) can be considered radiation tolerant. One important exception is glass – certain optical designs may rapidly degrade under space radiation[7].

CMOS Logic Families

The use of discrete digital logic ICs (i.e. the 74 series) is decreasing as designs become more integrated. Nevertheless, these parts are still used and the designer will often need to choose between the different available families. A number of vendors have released white papers[8,9] claiming immunity to latchup. These claims must be treated carefully – often it is only the I/O structures that are protected. The authors' experience backs the assertion that some logic families are weak against SEL while other interchangeable parts are strong.

Operating voltage and Latchup

CMOS latchup is caused by parasitic bipolar SCR structures being turned on, effectively clamping the supply rail to the thyristor turn-on voltage. This voltage can never be less than the silicon PN voltage drop (~0.7 V) and is typically closer to 0.9 V. If the supply voltage is less than this value then latch-up becomes impossible.

Even if the supply voltage is high enough to allow latch-up, the cross section is reduced by selecting the lowest possible value within the operating range. Many modern digital components have core voltages around or below 0.9 V, and these can be expected to be latch-up free. However, these devices tend to have I/O circuitry that runs at higher voltages and these circuits are still subject to SEL. The designer should choose the lowest possible I/O rail voltages. 1.8 V is safer than 2.5 V. 2.5 V is safer than 3.3 V. There is little reason for a modern design to use 5.0 V. Obviously a move to lower voltages reduces the design's noise margins, and so good EMC practices are mandatory.

Power MOSFETs

Power MOSFETs can fail due to single-event effects, particularly single-event burnout (SEB) and single-event gate rupture (SEGR). N-channel MOSFETs also become depleted with increasing total dose, while P-channel MOSFETs become enhanced.

The best practices are:

1. Where performance is not critical, replace the MOSFET with a bipolar junction transistor (BJT).

2. Where possible, replace N-channel MOSFETs with P-channel MOSFETs. P-channel MOSFETs have no SEB mechanism, and total dose enhancement is seldom a problem.

3. Where possible, use MOSFETs with maximum gate voltage rating lower than the applied drain voltage. This mitigates SEGR. This is clearly not possible in high voltage applications. Limiting Vgs in circuit design will also reduce susceptibility to SEGR[10].

4. Massively derate the Vdss voltage rating for N-channel MOSFETs. 20% derating is appropriate[11]: use 150 V parts for a 28 V nominal application.

Single event burnout in power MOSFETs is very real, and we have been bitten by it before. In theory, N-channel MOSFETs will also become depletion-mode with significant total dose, leaking current in the off state. This can be mitigated by gate drive circuits that apply negative voltage. To date, at total doses of 20 krad, we have not seen problematic levels of depletion leakage.

Charge Pumps

Some ICs contain onboard charge-pumps to create high voltages. These include flash memories, N-channel high-side switch controllers, and TTL-to-RS232 converters. For many years the received wisdom was that these were radiation soft and should be avoided[12]. Our testing has not supported this claim. By all means avoid these parts if possible, but modern parts will probably work well to modest dose.

Reconfigurability

Many components can be reconfigured, based on the state of internal registers. A simple example is a power supply with an I2C interface that can be commanded to different output voltages. A more complex example is a microprocessor that contains thousands of bits of reconfigurable register. It is a good design practice to ensure that no combination of register states can cause hardware damage.

A general purpose logic pin may be configured as an input or an output. Any time that two pins are connected together, it is a good idea to include a series resistor. If the system becomes misconfigured such that both pins become outputs the resistor will limit the current flow to a manageable level.

If a power supply is adjustable, make sure no damage will occur at the extremes of its commandable range. If this is not possible, add a Zener diode to the output to limit its voltage – but make sure that something upstream will limit the current before the Zener overheats.

Often multiple power supply rails will require a certain sequencing order. For example, an IC with +5V and +3.3V inputs may require that the +5V rail be powered first and may enter a latch-up state if this is not done correctly. CMOS analog switches and multiplexers are particularly vulnerable here. The problem can be mitigated by the use of nominally reverse-biased Schottky diodes between the rails.

Latchup Mitigation

Almost every commercial IC has the potential to enter a latchup state where its power supply input is effectively shorted to ground. Typically no damage is done provided that the current flow is not so great as to cause burnout, and not of so a long enough duration to cause overheating.

Some degree of power supply protection is recommended. Most linear or switch-mode DC/DC converters have current and thermal limiting, and that should be sufficient. Complex circuit-breaker designs may ultimately reduce the reliability of the system through increased parts count.

Massive Integration

Experience shows no clear correlation between the complexity of an IC and its radiation tolerance. A commercial microprocessor may handle the environment fine, while a commercial temperature sensor IC may experience catastrophic latch-up. Tolerance is dictated largely by the manufacturing processes and not by the transistor count.

Given this, the design that is most likely to survive radiation testing is the design with the fewest types of IC. Where possible, use modern parts with massive integration so that one part can replace multiple conventional parts. This is in direct contrast to traditional radiation hardened design methodologies that typically use low-integration devices.

Idle State

If a component is not under bias it cannot suffer single-event effects. Its damage from total dose is minimized as electron-hole pairs are not pulled apart. Where possible, remove power from circuits that are not needed.

PURCHASE PARTS LOT

Once a detailed design and bill-of-materials has been prepared, purchase the components. It is recommended that the PCB layout be completed before parts are ordered. Often the layout exercise will result in a decision to change component packages. It is also recommended that PCBs not be fabricated until the parts arrive so that footprints can be directly checked.

Order a quantity of each component sufficient to last several years of anticipated production volume, and ensure that all components are from the same lot and date code. Only rarely will COTS parts have lot codes marked on the outer packaging. Many parts will have lot or date codes marked on the part itself, though the manufacturer-specific codes require some deciphering. Tiny parts (SOT23 and smaller) may not have any such text. In that event, parts from the same tape can be safely assumed to be from the same lot.

This step entails significant financial risk. You may be buying thousands of dollars of a part that has every chance of failing the radiation tests. This is the price of quality.

PROTOTYPE BOARDS

Build up at least three prototype boards. If GSE is needed to test functionality, built a set as well. Develop onboard software (if applicable) to the point where all hardware functions can be demonstrated and SEUs can be counted. There may be errors in the board design that prevent it from working properly. Apply cuts-and-jumps, dead-bug components, and other repairs as necessary to achieve the desired functions.

Prepare a functional test sequence to demonstrate operation. Board power consumption should be measured and logged externally. Run this test a number of times in the lab to develop a baseline.

RADIATION TEST

Test Types

Radiation testing for space electronics generally falls into three categories: cobalt-60 (gamma ray), proton and heavy ion.

Cobalt-60 generates high energy gamma rays with excellent penetration. It causes total ionizing dose, but no single event effects. It is cheap, and readily available.

Proton testing requires a cyclotron capable of accelerating protons to energies >50Mev. It causes ionizing dose, and single-event interactions with LET of up to 25 MeV-cm^2/mg. Cost and availability are moderate.

Heavy ion testing may be done with an accelerator, or with a radioisotope source. Very high LETs can be generated, allowing the full space environment to be explored. It also causes total ionizing dose. This testing tends to be expensive, and availability is poor.

We recommend proton testing as a key element of a Careful COTS design. It gives the biggest "bang for your buck", allowing board level testing for total dose effects, SEU and SEFI characterization, and screens for parts with unacceptably low SEL, SEB or SEGR tolerance.

The three prototypes will serve the following functions:

- Unit A: control, not irradiated
- Unit B: irradiated to expected mission dose (no margins)
- Unit C: irradiated to twice expected mission dose

Cobalt-60 Testing

The test method for cobalt-60 is laid out in MIL-STD-883G, method 1019.7. The board should be powered and running in a normal mode during irradiation so that components are biased in a representative fashion. Gamma ray penetration is such that an integrated unit can be successfully irradiated from any convenient angle. Power consumption should be logged during dose (Fluke 289 multimeters are very useful for this). Realtime telemetry may be gathered from the equipment, though in the absence of single-event effects this is seldom particularly interesting.

Cobalt-60 facilities are available at university and government labs worldwide. It is inexpensive, at <$200/hour. Similar results can be achieved using 10 keV X-ray sources[13], though package de-lidding is required and this is generally not useful for testing of complete boards.

Proton Testing

High energy protons pass through solid matter without leaving much energy behind, whereas low energy protons interact more frequently with the atoms they pass through, rapidly dumping energy until they come to a stop. Thus, proton LETs are higher at lower energies. But the LETs of even low energy protons are only 0.02 Mev-cm^2/mg and are not sufficient to trigger SEEs.

Occasionally a proton may strike a silicon nucleus and send it moving through the crystal lattice. This is a heavy ion generated directly inside the component. It may have[14] an LET as high as 8 MeV-cm^2/mg. On rare occasions, a proton may strike an even heavier nucleus. This could be aluminum, copper or gold in bond-wires or die metalization. Tungsten is also used as a silicon via fill material. Studies[15] show that these heavy ions can generate LET of up to 25 MeV-cm^2/mg. Production of these ions is a function of the proton energy, and for this reason it is recommended to test at the highest energy possible.

Protons have sufficient penetration that packaging and orientation are not significant concerns. Components on the back side of a PCB will be irradiated to essentially the same dose as parts on the front. Big metal chassis or heat sinks should be taken into account.

Irradiation should be performed on an active unit, running test software or otherwise exercised in a representative manner. It should be powered from its highest rated voltage to put the greatest stress on its power supply. Temperature is typically ambient to simplify logistics. Hot or cold tests may sometimes be done to investigate particular SEE mechanisms.

Examine telemetry in realtime. Stop the proton beam if an anomaly is seen. Attempt to return the unit to normal operation by commands, hardware reset, or power-cycle as appropriate. Statistics on all of the anomalies observed and the resolution method should be kept.

There are several labs world-wide that can perform proton testing[16]. Expect to schedule beam time months in advance. The price will be ~$500/hr and it may take three or four hours to test a particular design.

Table 6: Proton Testing Facilities in North America

Facility	Maximum Beam Energy
University of California at Davis	62 MeV
Texas A&M University	70 MeV
TRIUMF, Vancouver	105 MeV typical 500 MeV by request
Indiana University	200 MeV
Francis H. Burr Proton Therapy Center	230 MeV

Heavy Ion Testing

Heavy ions may be generated in an accelerator, typically by firing a beam of lighter particles at a metal foil target. Radioisotope sources that decay by spontaneous fission are less bulky, but have far lower energy and fluence.

The primary concern for test planning is the penetration of the ion beam. Some facilities have sufficient penetration that an integrated PCB can be tested in much the same way as in a proton test. However, other facilities have very limited penetration and the ion may be stopped by the component packaging before it reaches the silicon. In these cases the components must be "de-lidded" to expose the die. De-lidding of traditional space-grade hermetic parts is relatively straightforward. The same cannot be said for modern plastic components. They require expert attention to etch, grind, and otherwise remove the cover without damaging the silicon or bond wires. Very modern devices (such as PoP BGAs and flip-chips) are probably impossible to decapsulate.

Detailed heavy ion test design is outside the experience of the authors. There is a perception that it is expensive and hard to access. For a low Earth orbit mission, proton testing alone is typically sufficient.

POST-TEST ANALYSIS

Both proton and heavy-ion tests will leave some induced radioactivity in the boards, and it will be several days before they can be legally transported. Cobalt-60 tests leave no induced radioactivity, and the boards can be removed immediately.

When the hardware is returned, re-run the standard tests. If off-nominal results are found, probe the board with multimeters and oscilloscopes to better understand what is happening.

When the unit has been thoroughly tested, it should be annealed. MIL-STD-883 method 1019.7 contains schedules for both ambient and high-temperature annealing. The purpose of annealing is to acknowledge that the total dose that has been received in testing has accumulated at a rate thousands of times greater than it would in space. On-orbit some of the damage will recover over the years of mission life, even as more damage is being accumulated. Following annealing the board should be tested one last time.

It is worth noting that there is some disagreement as to the validity of highly accelerated radiation testing in bipolar parts due to Enhanced Low Dose Rate Sensitivity (ELDRS)[17]. However if a sufficient factor of safety is used in total dose testing, it should cover the ELDRS effects.

SUCCESS EVALUATION

The test can be considered an unqualified success if all of these statements is true:

- No destructive single-event effects were seen
- The single-event upset rate is manageable in the context of the overall system
- The unit remains functional up to the expected mission dose
- The unit is functional following annealing after twice the expected mission dose

In this case the design can be considered radiation tolerant for the application.

The test can be considered a marginal success if all of these statements is true:

- No destructive single-event effects were seen
- The single-event upset rate is manageable in the context of the overall system
- The unit is functional following annealing after the expected mission dose

In this case one of the following mitigating steps can be taken to declare the design radiation tolerant without further testing:

- Reduce the design life by 50%
- Apply shielding (possibly just spot shielding on the affected component) to reduce expected mission dose by 50%

The test can be considered a failure if any of these statements is true:

- Destructive single-event effects were seen
- The single-event upset rate is unmanageable in the context of the overall system
- The unit is not functional following annealing after the expected mission dose

In these cases the affected components must be identified, and replaced. Sometimes a drop-in equivalent part from a different vendor can be used. Otherwise the unit may require substantial redesign to replace a unique part. When redesign is complete, more parts must be purchased and the tests repeated.

RADIATION CASE STUDIES

It is instructive to look at the way in which parts change under dose. Complex parts will often lose functionality in one area while remaining unaffected in others. A complete and sudden failure is seldom seen. Here we relate some of Sinclair Interplanetary's experiences testing commercial parts under Co-60 and protons.

All of these case studies should be treated as anecdotal. They refer to results of specific tests on specific lots of parts. These results may not be applicable to your parts.

IR2104S MOSFET Driver

This IC is intended to drive a half-bridge of N-channel MOSFETs. It has a built-in 520 nsec dead-time delay when switching between MOSFETs.

At approximately 10 krad of total dose the dead-time begins to increase. At some point before 20 krad the dead time becomes infinite and the IC will no longer switch.

LT3012 Linear Regulator

The internal voltage reference of this IC is changed by radiation, and increases by 0.6% per krad of total dose. If the system tolerance on a power supply rail is 10%, then it will go out of tolerance after 15 krad. It remains functional in every other respect.

C8051F410 8-bit Microcontroller

The microcontroller includes a realtime clock section, intended to be powered from an external auxiliary battery. It contains a 20 kHz oscillator to keep track of time. A register bit indicates whether the oscillator is running properly. After moderate total dose this bit indicates failure. All functions of the microcontroller outside the realtime clock continue working well to beyond 20 krad.

C8051F580 8-bit Microcontroller

This microcontroller contains an onboard temperature sensor. At 12 krad total dose the temperature sensor begins to read lower than expected. It quickly degenerates to read -200 C. All other functions of the microcontroller continue working well to beyond 20 krad.

SN65HVD1781 RS485 Transceiver

This transceiver has a separate enable controls for the transmitter and receiver. If both are disabled the part enters a low power standby mode. The maximum specified wakeup time for the transmitter, from standby mode, is 9 μsec. Starting at 14 krad the wakeup time takes longer and longer. If the receiver is held always enabled, thus avoiding standby mode, the part remains fully functional beyond 20 krad.

ZXMN6A11DN8 Dual Power N-channel MOSFET

These are 60 V rated N-channel MOSFETs. When biased at 34 V they reliably and repeatedly fail in single-event burnout from 105 MeV protons. Note that the traditional MOSFET voltage derating rules (i.e. 75% from EEE-INST-002) assume radiation hardened components and cannot be applied to COTS parts.

SiM3C1XX 32-bit Microcontroller

This microcontroller proved to be extremely vulnerable to SEL. Over the course of 1 krad of 105 MeV proton dose it suffered 6 hard latches (>250 mA fault current). Some latches stopped the processor. Interestingly, the core did continue to operate through some of the latch events, sending plaintive error messages through the UART reporting that the on-chip SRAM was non-responsive. We hypothesize some sort of latchup within the bus controller.

LT3437 DC/DC Converter

This DC/DC converter will operate to greater than 20 krad with steady output voltage. However its minimum turn-on voltage will increase with dose. The datasheet specifies that with a +3.3 V output it requires a minimum of +5.5 V input to start, and +4.5 V to keep running. After 15 krad of total dose and a period of annealing the minimum start-up voltage is +13 V. The run voltage is unchanged at +4.5 V.

DDR DRAM

DDR memory manufacturers have implemented ECC in some modern parts in order to reduce refresh power consumption[18]. This has the happy side-effect of making them essentially immune to SEU. The authors have indirectly observed the effect of this undocumented internal ECC during proton testing.

CONCLUSION

In this paper we have presented a systematic approach to designing electronics for a particular radiation environment. This method has allowed us to build reliable and successful space missions from modern commercial components. Proton testing, together with controlled lot buys, assures parts will meet radiation requirements. Expensive rad-hard components and heavy ion testing are avoided.

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