Electronics Packaging Considerations for Space Applications

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Abstract

The functionality of spacecraft electronics must be maintained in the harsh environments found in space. The radiation environments can consist of either low-energy x-rays at the surface of the spacecraft or high-energy electrons, high-energy protons and high-energy photons within the spacecraft. Space radiation varies significantly and induces various types of effects (e.g., cumulative ionization, low dose rate effects, single event effects and displacement damage) in common device technologies. Harsh radiation environments can also induce electrical charging in spacecraft materials. Within the solar wind, direct irradiation by the Sun's emissions creates relatively low-voltage charging. Large particle currents, carried by the solar wind, interact with planetary magnetospheres creating trapped high-energy particle belts around certain planets (e.g., Earth, Saturn and Jupiter). Spacecraft passing through these belts can charge spacecraft materials with internal fields that can cause damaging electrostatic discharges. Another harsh environment found in space is extreme low temperature. This can affect the functionality of spacecraft electronics, particularly for interplanetary or deep space applications. Devices and assemblies can experience performance and reliability issues either at extreme low temperatures or as a result of cycling to extreme low temperatures. Mitigation of these damaging effects leads to understanding physics of failure and making changes in the device design, electronic assembly or the electronic packaging materials.

1. Introduction

Spacecraft encounter harsh extremes of radiation exposure and temperature variation to the extent that special considerations must be made in the packaging of the electronics to mitigate their harmful effects. This becomes particularly important as there is increasing interest in the use of unhardened commercial electronics technologies in space systems, driven by their higher performance, lower semiconductor manufacturing costs and advanced levels of integration. These advantages are partially offset by increased radiation testing, environmental testing costs and the risk that process changes in commercial technologies may inadvertently compromise their reliability. This paper will focus on how both space radiation and extreme cold environments can affect spacecraft electronics and will address considerations in packaging to mitigate their damaging effects.

2. Radiation Sources [1]

There are three primary components of the natural space environment; 1) high-energy electrons and protons trapped by planetary magnetic fields, 2) galactic cosmic rays (GCRs) originating from outside the solar system, 3) the anomalous component and 4) solar event particles. There may also be trapped heavy ions, but their energies are low enough to be stopped by typical spacecraft shielding.

2.1 High-energy electrons and protons can penetrate spacecraft shielding and are usually the only trapped particles that are a concern for Earth orbits. The regions of trapped electrons and protons, sometimes called Van Allen radiation belts, are most significant between the altitudes of approximately 1,000 km to 32,000 km. Their extent is greater than this, but the particle flux is much smaller outside this altitude range. The distribution of electrons and protons vary with altitude. Electrons, whose energies reach a maximum of about 7 MeV, show two altitude peaks at about 4,000 km and 24,000 km. The location of protons is restricted primarily to one belt, but their energies can be in excess of several hundred MeV.

The dipole that represents Earth's magnetic field is tilted and offset from its center. The result is a special geographic location off the coast of Brazil called the South Atlantic Anomaly, in which an intense radiation belt exists at an altitude lower than without the offset. This region reaches down to the upper part of the atmosphere and is not an issue for orbits that would be in the intense radiation belts anyway, but is an issue for spacecraft attempting to avoid harsh environments.

2.2 Galactic cosmic rays originate from outside the solar system and occur everywhere in space. These highly energetic particles with a wide range of atomic numbers, reach energies in excess of 10 GeV/nucleon. The flux rate is very low compared to the particles in the radiation belts. However, a single GCR can deposit sufficient charge in an integrated circuit transistor (or change the state of internal storage elements) and cause more complex behavior, such as latchup.

2.3 The anomalous component is another source of particles composed of helium and some heavier ions with energies less than ~50 MeV/nucleon. They were named this because their presence is random. The anomalous component is not a very severe environment compared to GCRs in interplanetary space behind moderate or heavy spacecraft shielding, because shielding is effective against this relatively low-energy environment. However, the anomalous component can be significant compared to GCRs for spacecraft heavily protected by magnetic shielding, but only lightly protected by mass shielding. The reason is that the anomalous component is only singly ionized and this tends to make it able to penetrate magnetic shielding. If mass shielding does not remove it, while magnetic shielding removes most of the GCR environment, the anomalous component can be a significant part of the surviving heavy ions.

2.4 Solar events produce varying quantities of electrons, protons and lower energy charged particles. Solar activity varies widely where very high fluxes of particles may occur over a period of hours or days. Solar event protons are the primary contributions to ionizing dose and displacement damage for spacecraft in interplanetary space. Also, the relative abundance of protons can be an important contribution to single event effects in proton-susceptible devices.

3. Radiation Effects [2]

3.1 Long-Term Ionization Effects. Damage to electronics and materials can arise from the long-term effects of ionizing radiation. When a photon or charged particle travels through a material, it interacts with electrons in the material and causes some of the atoms to become ionized, creating electron-hole (e-h) pairs. The damage can occur in both semiconductors and insulators. One distinction between semiconductor and insulator is whether this effect accumulates or dissipates. Device insulators e.g., gate or field oxides in a CMOS device, exhibit a cumulative effect. Some of this charge will be trapped at the semiconductor/insulator surface. In MOS structures, the trapped charge will cause a shift in the gate threshold voltage and can result in extremely large leakage currents. Mobility (which affects switching speed and drive current) is also degraded. The trapped holes will eventually become neutralized, as the oxide anneals, but the anneal time can take years at room temperature.

Long-term ionization effects in optical materials are evident as an increase in optical absorption. The absorption rate is a strong function of the type of material. For example, fused quartz generally colors less than alkali glasses from a given ionizing dose. Quartz crystal used for precision oscillators or filters can show significant resonant frequency shifts. Natural quartz shows the largest frequency shift; synthetic quartz shows less and swept synthetic quartz even less.

Accumulated trapped charge is measured by the accumulated ionization, which in turn is measured by the sum of the energy lost by the particles to the material via interactions with the electrons. The total energy, per unit mass of material, transferred to the material via ionization from all ionizing particles, is called the total ionizing dose (TID) or total dose. This dose is typically measured in rads (material specified), with one rad defined as 100 ergs of deposited energy per gram of material. Total dose levels encountered by satellites and space probes are typically between 10 and 100 krad (Si), although systems exist with requirements above and below this range.

The devices and materials of concern and the most serious radiation induced effects are:
1. MOS devices (threshold voltage shift, decrease in drive current and switching speed, enhanced leakage).
2. Bipolar transistors (h_{FE} degradation, especially at low collector current, I_C; leakage current), and junction field effect transistors (JFETs) (enhanced source-drain leakage current).
3. Analog microcircuits (offset voltage, offset current and bias-current changes, gain degradation).
4. Digital microcircuits (enhanced transistor leakage or logic failure due to ionizing dose induced h_{FE} & V_T changes).

5. Quartz resonant crystals (frequency shifts).
6. Optical materials (increased absorption).
7. External polymeric surfaces (mechanical degradation).

3.2 Transient Ionization Effects (Interference).

Interference is defined as transient ionization effects that persist only while the electronics are being irradiated. Interference effects depend primarily on the rate of ionization energy deposition, i.e., the dose rate measured in rads (material)/sec.

There are four types of interference in electronic devices and optical materials:
1. Primary photocurrents in low current input stages to the electronics.
2. Electron emission from cathodes of electron multiplier-type detectors.
3. Ionization-induced conductivity in photo-sensitive materials, such as those in detector surfaces.
4. Ionization-induced fluorescence in optical materials such as detector windows and lenses.

3.3 Displacement Effects.

Displacement of atoms in crystal lattices cause permanent changes to material properties. Only the most sensitive devices are affected significantly by displacement effects.

Displacement effects can affect the following devices and properties:
(1) Bipolar transistors with low f_T (h_{FE}, $V_{CE\ SAT}$, $V_{BE\ SAT}$).
(2) PN junction diodes (V_F, V_B).
(3) Light emitting diodes (V_F, V_B, light emitting efficiency).
(4) Semiconductor photodetectors (quantum efficiency).
(5) Devices incorporating lateral p-n-p transistors (h_{FE}, $V_{CE\ SAT}$, $V_{BE\ SAT}$).
(6) MOSFETs (resistance, leakage current).

4. Mitigation of Radiation Effects [3]

The energies of the trapped particles are low enough so that mass shielding thicknesses practical for spacecraft use can provide significant protection (particularly for the electrons). Shielding is very effective against the heavy-ion component of solar events and is less effective against the more penetrating protons. Localized or "spot" shielding may be needed to obtain adequate protection without adding excessive weight to the spacecraft. The amount of shielding is determined with the use of a "radiation design margin (RDM)". The definition of RDM is the ratio of radiation capability of the part or component to the expected radiation environment. The part/component radiation capability is defined as the fluence (or dose), flux (or dose rate) of charged particles or nuclear radiation which will produce enough degradation or radiation-induced interference in the part characteristics to cause the part to operate outside of its specification for the particular circuit application.

The general use of an RDM acknowledges uncertainties in environmental calculations and part radiation hardness determinations. The selection of an RDM may be somewhat arbitrary and will tend to be driven by mass limitations, acceptable risk versus cost and the overall radiation hardness program. RDM, which implies a margin, is really a misnomer, because is assumes that a conservative margin actually exists. It may be more appropriate to refer to a "radiation design factor".

Typically, once the mission design is confirmed, the TID as a function of shielding thickness (dose-depth data) are generated for a simplified geometric mass model, such as the spherical shell model. Figure 1 below is an example of a flight mission at 1 Astronomical Unit (AU) from the sun during the solar max period. Standard practice is to apply the dose-depth curve at 95% confidence level for the flight assembly (unit) design. This radiation dose curve can be used to obtain conservative "first-look" shielded dose values without hardware configuration modeling.

As electronics parts scaling continues, it is prudent to carefully re-examine RDMs of high magnitude or to refine the part radiation hardness determination technique if lower RDMs is demanded. The part radiation hardness test is generally a cost driver. This is primarily due to the fact that a more accurate test requires more samples, more realistic flight simulating radiation sources and conditions, and longer test time. More extensive radiation/shielding calculations also tend to be cost drivers, but it relieves the shielding requirement and therefore saves more mass.

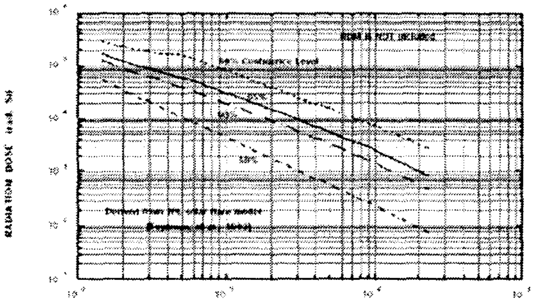

Figure 1. Radiation Dose from Solar Flare Protons for 1 year at 1 AU

5. Internal Charging Effects

5.1 NASA-HDBK-4002 [4], "Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects" describes internal charging, why it is of concern to spacecraft designers, general design guidelines, quantitative design guidelines and a typical materials characteristics list. Selected packaging-related excerpts from the handbook follow:

The handbook applies to any spacecraft whose circular Earth orbit is described by the labeled regions of Figure 2, as well as other energetic plasma environments.

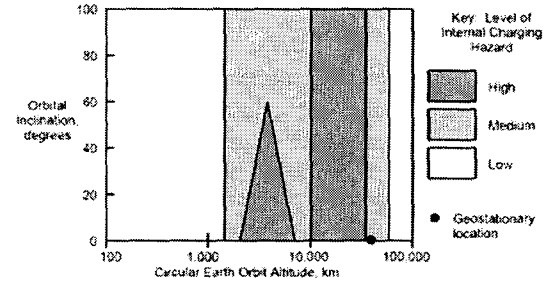

Figure 2. Earth Regimes of Concern for On-Orbit Internal Charging Hazards for Spacecraft with Circular Orbits

The distinction between "surface charging" and "internal charging" is that internal charging is caused by energetic penetrating particles that can penetrate and deposit charge very close to a potentially damaging site. Surface charging is on areas that can be seen and touched on the outside of a spacecraft. Surface discharges occur on or near the outer surface of a spacecraft and discharges must be coupled to an interior site. Discharge energy from surface arcs is attenuated by the coupling factors and therefore is less threat to internal electronics.

External wiring and antenna feeds are susceptible to this threat. Internal charging, by contrast, may cause a discharge directly to a circuit pin or wire with very little attenuation. Geosynchronous/geostationary (GEO) orbit (a circular orbit in the equatorial plane of the Earth at ~35,063 km altitude) is perhaps the most common example of a region where spacecraft are affected by internal electrostatic discharges, but the same problem can occur at lower Earth altitudes, polar orbits and at Jupiter.

Electrons and ions will penetrate matter. The depth of penetration of a given species (electron, proton or other ion) depends on its energy, its atomic mass and the composition of the target material. Figure 3 shows the depth of penetration versus energy of electrons and protons into aluminum. Only particles with an energy that corresponds to a range greater than the spacecraft shield thickness can penetrate into the spacecraft interior. If the material is not aluminum, an equivalent penetration depth may be approximated by substituting an equivalent material density.

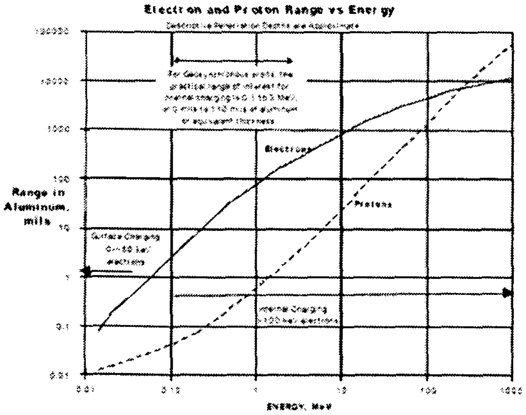

Figure 3. Electron/Proton Penetration Depths in Aluminum

Figure 4 illustrates the concept that energetic electrons (100 keV to 10 MeV) will penetrate into interior portions of a spacecraft. Having penetrated, the electrons may be stopped in dielectrics or on ungrounded conductors. If too many electrons accumulate, the resultant high electric fields inside the spacecraft may cause an electrostatic discharge to a nearby circuit.

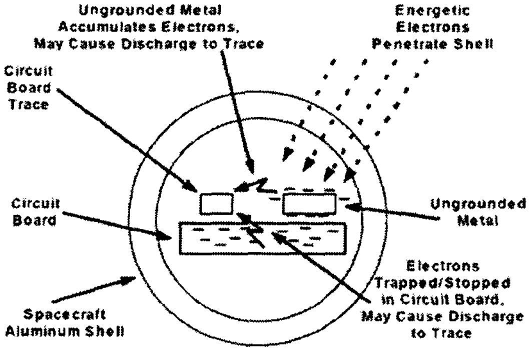

Figure 4. Illustration of the Internal Charging Process

5.2 General Packaging Design Guidelines for Mitigation of Charging Effects

- Shield all electronic elements with sufficient aluminum equivalent thickness so that the internal charging rate is benign.
- Ground all structural elements.
- Have a conductive path to the structure for all circuitry.
- Limit usage of excellent dielectrics.
- Make all interior dielectrics electrically leaky.
- Ground radiation spot shields.
- Use low pass filters on interface circuits.
- Isolate the primary and secondary windings of all transformers.
- Provide a conductive bleed path for sometimes forgotten conductors (including structural elements)
- Route cable harness away from apertures.
- Provide additional protection for external cabling.
- Carry grounds across all articulated and rotating joints.

6. Extreme Cold Temperature

In general, the surface temperature of the planets decreases with increasing distance from the Sun (Table 1). Venus is an exception because its dense atmosphere acts as a greenhouse and further heats the surface. Mercury rotates slowly and has a thin atmosphere. Consequently, night temperatures can be more than 500°C lower than the day temperature shown.

Mercury	-173 to 427
Venus	462
Earth	-89 to 58
Mars	-87 to -5
Jupiter	-148
Saturn	-178
Uranus	-216
Neptune	-214
Pluto	-233 to -223

Table 1. Planet Surface Temperatures, °C

Thermal control systems on spacecraft can sometimes be impractical, depending on the mission requirements. As the scaling of mechanical and electronic devices decreases, the ability to build smaller spacecraft and instruments increases. This enables missions that would not otherwise be possible and also increases the possibility for multiple spacecraft to increase coverage and mission reliability. Smaller spacecraft and instruments imply smaller volume, surface area and thermal mass. This, in turn, can result in larger thermal excursions for the spacecraft, but can also result in less solar radiation and hence, less energy available from solar panels and for heaters. For packaging, methods for minimizing heat loss between electronics and actuators or sensors should be developed. This highlights the need for electronics to operate and cycle in extreme colder environments.

The selection of devices for extreme cold environments becomes particularly important. Resistors appear to operate well, but multilayer capacitors and inductors show variations with decreasing temperatures. The performance of active devices varies and supports the need for testing to efficiently characterize them. MOSFETs, for example, exhibit hot carrier injection degradation that significantly reduces device lifetime, even as electrical parameters improve (channel resistance, propagation delay decreases and transistor gain, switching speed increases). Decreasing propagation delay increases the possibility of hold time errors. Thus, appropriate adjustments in design or timing margins need to be made for proper system performance.

Some temperature induced effects on electronics packaging include:

- Cyclic temperature variations induces low cycle fatigue of circuit interconnects, board vias and solder joints.
- Stresses due to coefficient of thermal expansion (CTE) mismatches in circuit materials can result in cracking and failure of components and/or their attachments.
- Dimensional changes in optical systems due to thermal material contraction and expansion of can affect the optical alignment and degrade efficiencies.
- Cold temperature cycling can enhance whisker growth in device terminations and package leads.

Thermal Design Requirements are used to ensure that the packaged assembly will operate as intended over the range of mission environments seen during its life. Design requirements usually include margin beyond the intended use environment that account for variations in the intended application and uncertainties in the predicted mission temperatures. Temperature affects most mechanical and electrical designs due to temperature-dependent material properties. Electronics and their packaging must be designed to accommodate these thermal effects to ensure their intended function over the anticipated thermal excursions.

7. Conclusions

At the present time, commercial devices can be applied successfully in many space applications even though they are susceptible to radiation damage. The key to success is thorough testing and characterization of devices, as well as an understanding of the various effects. In addition, it is possible to implement system architectures that can correct for damaging effects with the use of shielding. Similarly, an understanding of the effects of spacecraft charging and extreme cold temperature on spacecraft electronics and their packaging aids in developing procedures to mitigate these effects.

8. Bibliography

[1] L.D. Edmonds, C.E. Barnes, L.Z. Scheick, "An Introduction to Space Radiation Effects on Microelectronics", May 2000

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Internal document

[3] JPL IOM 5217-88-39(A) "Radiation Design Margins," S. B. Gabriel to Distribution, September 1988.

[4] NASA-HDBK-4002, "Avoiding Problems Caused by Spacecraft On-Orbit Internal Charging Effects", February 1999