Degradation of Satellite Electronics Produced by Energetic Electrons

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A detailed radiation shielding analysis has been performed of an advanced design U.S. Air Force spacecraft, which contains several thousand complementary metal oxide semiconductors (CMOS). In order to precisely determine the on-orbit radiation dose to these semiconductors, a very extensive computer model of the entire satellite was prepared using engineering drawings, photographs, and direct measurements. Radiation transport calculations were then performed using this model, considering high-energy electrons entering through 512 solid angles to determine the electron radiation doses for a carefully selected sample of representative CMOS in each electronics subsystem. Shielding was then designed for the more sensitive components, with considerable care given to mass minimization. Simple design improvements in CMOS pacakaging and circuit board orientation can produce substantial increases in component lifetime with almost no weight penalty.

Introduction

An advanced design U.S. Air Force satellite will be placed into a 450-n.mi. circular polar orbit during the approaching cycle of maximum solar activity. The purpose of this paper is to report on a detailed radiation shielding study performed on this satellite. We also describe how the results of the work can be applied in the design of other space hardware systems. This study was performed to verify and improve the on-orbit lifetime of the satellite in the geomagnetically trapped radiation environment.

We begin with a brief description of the radiation environment. Next we discuss the method used to build a detailed computer model of the spacecraft and then treat the transport of the electron radiation enviroment through the spacecraft to the CMOS (complementary metal oxide semiconductor) components. Finally, we treat the design of optimum shielding (minimum mass) which will increase the useful on-orbit life of the vehicle, and describe CMOS packaging procedures and electronic box designs which are very helpful in increasing operating lifetimes while adding little additional mass. These procedures are of general utility and should be adopted for use in other spacecraft using CMOS components.

Radiation Environment

The geomagnetically trapped space radiation environment that will be encountered during solar maximum in a 450-n.mi. polar orbit will consist predominantly of electrons, with less significant contributions from protons. Although assessments of the proton contributions to the CMOS on-orbit doses have been made,[1] they are completely overwhelmed by the electron dose for the case under consideration. For these reasons our discussion is limited to the radiation doses caused by electrons and their associated bremsstrahlung.

Several radiation environments are available for use.[2-7] We selected the comprehensive electron data of Vampola,[2] which were obtained in 1966 and 1967 at a time period near the prior solar maximum. The orbit-averaged differential electron spectra which were used for active and quiet geomagnetic conditions during solar maximum are presented in Fig. 1. These spectra were corrected for Starfish contamination and are reasonable upper and lower limits for the average solar maximum electron environment. We applied a solid angle factor of 2.5 π to get omnidirectional fluxes and used logarithmic extrapolation below 0.3 MeV and above 2.3 MeV to obtain the spectral extremes down to 0.1 MeV and out to 5 MeV. The high-energy extrapolation may be somewhat conservative, slightly overestimating the flux near 5 MeV. The logarithmic extrapolation below 0.3 MeV had very little effect on the computed doses because electrons below 0.3 MeV were rarely able to penetrate the spacecraft shielding to reach any of the CMOS components.

One important difference between the geomagnetically active and quiet environments is the higher flux of electrons above 1 MeV during active times. These spectral differences become particularly important in computing doses due to primary electrons penetrating moderate to heavy shielding. The doses from the geomagnetically active environment where about 3 to 3.5 times higher than those from the quiet time environment. For very heavily shielded components, the primary electrons can not penetrate, and bremsstrahlung becomes the dominant contributor to the dose.

Spacecraft Geometrical Model

In order to calculate accurate doses to the CMOS components, it was necessary to develop a sophisticated computer model of the entire spacecraft geometry. The model was complete in all important aspects and contained considerable physical detail; however, the subsystems associated with the primary spacecraft mission were given priority. The secondary subsystems were not modeled exactly. To account for box-on-box shielding, they were included as homogeneous units of the proper size, mass, and orientation. The remainder of the spacecraft was modeled down to the circuit board level with individual CMOS components positioned in the correct locations. In cases where a board has many components, representative locations were selected. Small bolts, nuts, washers, and wires were not modeled. Most circuit board components other than CMOS were not included directly in the physical mock-up, but were conservatively accounted for by homogenizing the circuit boards. This procedure places lower limits on the dose calculations. About 160 CMOS locations were used as dose points. The worse case locations were found for each electronic box, and all mass that was important to the dose calculations was tediously accounted for.

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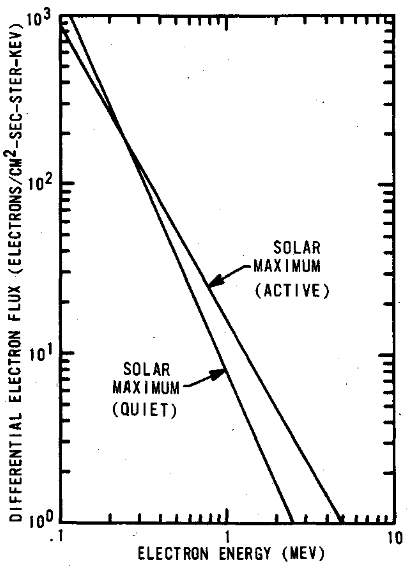

Fig. 1 Averaged differential electron spectra in a 450-n.mi. polar orbit during solar maximum for active and quiet geomagnetic conditions.

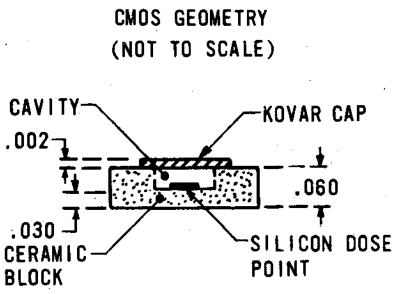

Fig. 2 Geometrical model used to represent CMOS components.

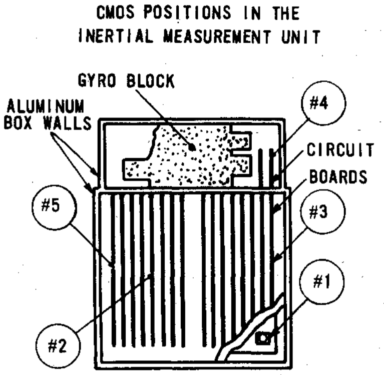

Fig. 3 Cross-sectional diagram of the IMU geometry with representative CMOS locations.

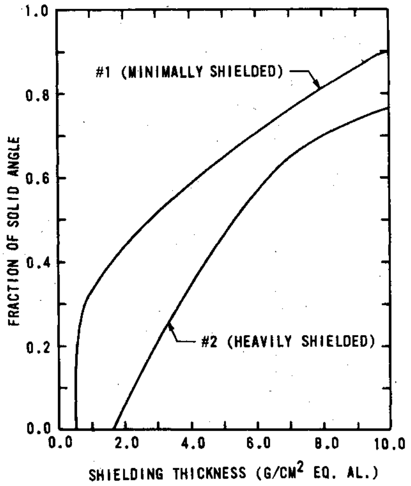

Fig. 4 Mass distribution for CMOS locations 1 and 2 in the IMU.

All of the CMOS components were modeled using the geometry that is illustrated in Fig. 2. Several thousand CMOS components were aboard the spacecraft, and each individual type had slightly different physical characteristics. Fortunately, the radiation shielding of the great majority of these components could be adequately represented by the model in Fig. 2. This model is constructed of a ceramic material having a minimum thickness of 30 mils directly behind the small integrated circuit. A 2-mil thick Kovar[§] metal cap covers the upper portion of the chip and is the most thinly shielded portion of the CMOS geometry. The approximate density of the packaging ceramic is 3.5 gm/cm^3 and the Kovar density is 8.9 gm/cm^3. Practical constraints did not permit altering the CMOS packaging in this spacecraft. However, we will demonstrate that the satellite operating lifetime could have been nearly doubled with very little increase in weight by increasing the Kovar cap thickness from 2 to 12 mils on each CMOS.

The computer code used for the spacecraft simulation was the Modified Elemental Volume Dose Program (MEVDP).[8] The code was improved and updated for this project. It allows the spacecraft to be "constructed" in the computer by assembling elemental volumes (spheres, cones, slabs, etc.) of the proper dimension and material type and placing them in the correct position in a primary coordinate system. For each CMOS location, the code then computes the shielding from each material encountered along various radials for use in the electron transport calculations.

In order to facilitate modeling the spacecraft geometry and to decrease the chance for error, a computer code called BUFFER was written to accept a simple input and interface it with the more complex MEVDP input. Two of the most useful features of the BUFFER code were its ease of use and its ability to check the input data stream for internal consistency before formulating the data for MEVDP.

[§]Kovar is the metal alloy used to make the CMOS cap.

After the spacecraft model was completed, it was checked for accuracy by developing computer-generated cross-sectional plots of the spacecraft through selected planes. Figure 3 was drawn directly from these cross-sectional plots of the Inertial Measurement Unit (IMU), and illustrates five of the CMOS locations that were selected as examples for later discussion. The cross-sectional plots were then carefully compared to the engineering drawings to locate any misplaced or omitted parts and to make appropriate corrections. The final spacecraft model consisted of approximately 3000 elemental volumes constructed from 50 different materials. The MEVDP code was set up to use 512 radial directions equally spaced in solid angle at each of the 160 CMOS locations to produce the shielding information for the electron transport and dose calculations.

The shielding encountered along the 512 radials for any CMOS component can be converted to equivalent aluminum and plotted to give a visual representation of the mass distribution around the dose point. Figure 4 shows two typical examples of these mass distributions. The ordinate is the fraction of the total solid angle around the CMOS location which is shielded by a lesser number of gm/cm^2 than indicated on the abscissa. The curve for CMOS position No. 1 (see Fig. 3) is representative of a minimally shielded CMOS component which is facing an outside wall near the corner of an electronics box. This configuration allows substantial amounts of radiation to enter through the Kovar cap and surrounding ceramic structure. The curve for CMOS position No. 2 is typical of a component buried deep within the electronics box and substantially shielded by nearby circuit boards. The large range in shielding around different components in the same box as illustrated in Fig. 4 is not unusual.

Dose Calculation

A series of computer codes were updated and modified as necessary to perform the dose calculations.[9] These codes use radiation interaction models to transport the environment through the space vehicle to the location of interest, where the dose is then calculated.

Detailed three-dimensional calculations of electron transport through actual spacecraft geometries are difficult and time-consuming. However, some successful attempts have been made[10] which have verified that the radiation transport of electrons through each radial sector can be treated to a good approximation as a one-dimensional multilayer problem. Therefore, incorporation of the spacecraft geometry into the radiation transport codes required a knowledge of the solid angle subtended by each sector and the material composition and thickness of each elemental volume encountered along a radial centered in the sector. Using this sectoring information, the transport codes calculated dose conversion factors, which were used to obtain dose rates from the external spectra shown in Fig. 1.

A dose conversion factor represents the average energy deposited at a dose point behind a shield per unit fluence incident upon the shield. The method of dose conversion factors is accurate, rapid, and well suited to the calculation of space radiation doses. This method has the advantage of separating dose calculations into two efficient independent steps. Penetration of the radiation through the vehicle shielding is computed first. This calculation is performed once and produces a table of dose conversion factors which are a function of exterior energy. Once the dose conversion factors are determined for a given shielding configuration, dose rates from any arbitrary external spectrum can be rapidly computed. To do this, the dose conversion factors are multiplied by the external differential energy spectrum and then summed to produce the rad (silicon) dose at the selected dose point. The total on-orbit dose is found by summing the flux at each trajectory point throughout the satellite lifetime, and then multiplying the fluence by the dose conversion factors.

Dose conversion factors were computed for penetrating electrons and the resulting bremsstrahlung. The electron transmission calculations were performed using the electron-photon Monte Carlo radiation transport code TIGER[11] to generate a data base of flux as a function of thickness for omnidirectionally incident electrons. Materials spanning the atomic number regime from 3 to 92 were used in conjunction with electron energies varying from 10 KeV to 5 MeV. The multilayer electron transmission calculations were performed using this data base.

The TIGER code is a one-dimensional, multislab geometry, coupled electron-photon transport code using the condensed history Monte Carlo method for the electron transport and conventional single scattering Monte Carlo techniques for the photon transport. The code accounts for secondary electron production by both electrons and photons, bremsstrahlung production, and K-shell x-ray production. Although bremsstrahlung was usually not a major contributor to the dose, it was included in the calculations. TIGER represents the state-of-the-art in one-dimensional multislab electron transport calculations. The data base generated by this code is accurate to within about 15%.

The greatest source of error in applying the data base to the three-dimensional satellite geometry was the one-dimensional radial transport approximation. In order to assess this effect, we compared the results of our approximate calculations with a set of high-accuracy experimental electron depth-dose data obtained in a three-dimensional geometry using omnidirectional incident electrons.[12] Those experiments measured the doses to electronic components inside complex multidimensional geometry. Using methods described by Van Gunten,[12] we obtained an accurate set of experimental dose data for many different incident energies in aluminum boxes of several thicknesses. Figure 5 shows a comparison of our calculations with the two incident spectra published by Van Gunten. The agreement of our approximate one-dimensional transport method with three-dimensional measurements at the center of omnidirectionally irradiated aluminum boxes is excellent. The spectra for the 450-n.mi. orbit lie between the two spectra used by Van Gunten.

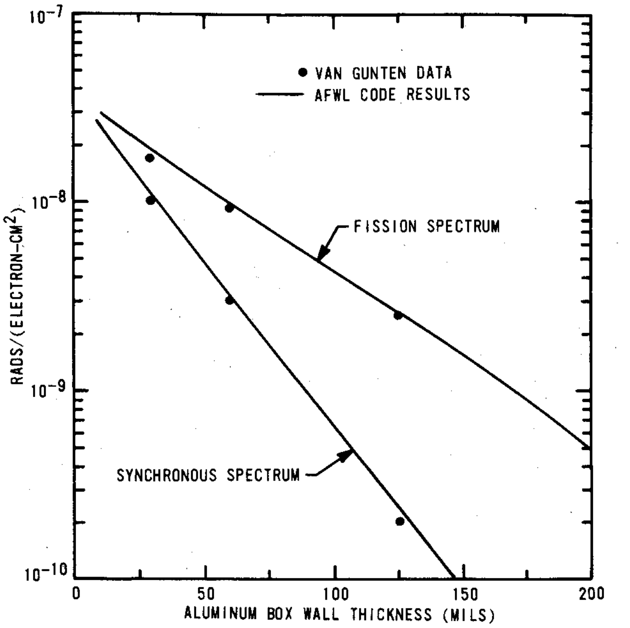

Fig. 5 Comparisons of Air Force Weapons Laboratory code results with the experimental data of Van Gunten.

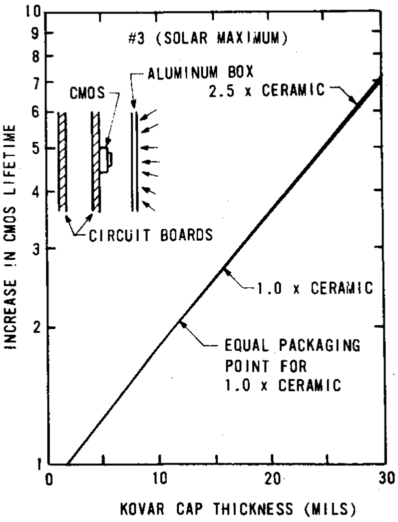

Fig. 6 Increase in lifetime vs ceramic density and Kovar cap thickness for CMOS position No. 3. The dominant effect is from increasing the Kovar cap thickness.

Shielding Results

An estimate of the wall thickness needed to protect each electronics box from penetrating electrons can be easily accomplished using a depth dose curve for the external electron spectrum integrated over the desired satellite lifetime. However, such an analysis overestimates the shielding, and consequently, the weight penalty is greater than necessary. Using this method to shield the spacecraft to the desired on-orbit lifetime required about 36 kg ($\approx$80 lb) of aluminum. The detailed model of the geometry allowed us to determine the directions of minimum shielding for each electronics box. Thus, we were able to tailor the shielding to the critical directions, taking into account the overall shielding effect provided by other spacecraft components. By optimizing the shielding in this manner, the same lifetime was achieved with only 7.71 kg (17 lb) of aluminum. Such a reduction in shielding weight can be crucial to a system that is already launch-weight limited.

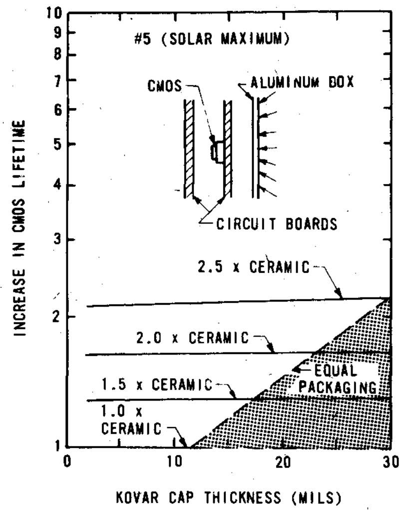

Fig. 7 Increase in lifetime vs ceramic density and Kovar cap thickness for CMOS position No. 5.

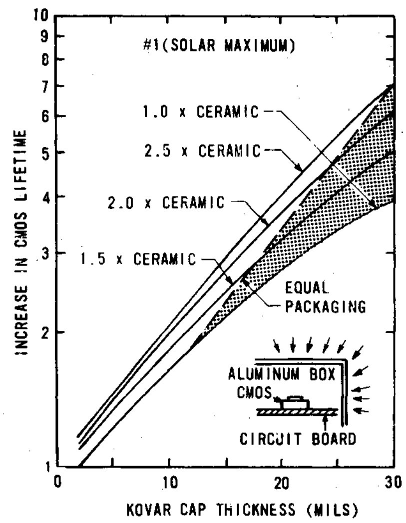

Fig. 8 Increases in lifetime vs ceramic density and Kovar cap thickness for CMOS position No. 1.

The detailed model also permitted the investigation of the effects of the CMOS packaging and circuit board orientation on the overall life of the spacecraft. A parametric study of component lifetime as a function of the density of the ceramic packaging material and the thickness of the Kovar metal cap was performed for the entire spacecraft. As an example we present the results for the IMU previously shown in Fig. 3.

Three extremes in geometry are given in Fig. 6-8. Figure 6 illustrates the increase in lifetime for CMOS position No. 3 as a function of ceramic density and Kovar cap thickness. This CMOS chip faces an outer box wall and is shielded from behind by several other circuit boards, as shown schematically in the upper left portion of the diagram. In this geometry almost all of the dose is caused by electrons entering through the box wall and the thin Kovar cap. Therefore, increasing the Kovar cap thickness gives large increases in lifetime. There is little lifetime dependence on ceramic density for this particular device, since the back is already adequately shielded by the other circuit boards. The individual lines for the ceramic are almost indistinguishable in the figure for this reason. The point of equal packaging (Kovar cap shielding equivalent to ceramic shielding) for the original ceramic density is indicated. In this example 12 mils of Kovar are required to provide shielding equivalent to the original 30 mils of ceramic backing the chip. This equal packaging increases the CMOS lifetime by slightly more than a factor of 2. Equal packaging for increased ceramic densities would yield even larger increases in lifetime.

Figure 7 illustrates the result for CMOS position No. 5. The geometry is similar to that in Fig. 5 except that the CMOS chip faces away from the outside wall. Since the direction through the Kovar cap is very heavily shielded by other circuit boards, increasing the thickness of the cap has almost no effect on lifetime. The absolute dose in this case is less than that in Fig. 5, but the primary direction from which the dose is received is again through the adjacent exterior wall. Therefore, increasing the ceramic density produces the dominant improvement on the lifetime, although a lifetime improvement was not really necessary for this particular component. We observed that when a CMOS was shielded by a circuit board and directed away from the spacecraft exterior, additional shielding was rarely needed.

An intermediate geometry is shown in Fig. 8. Here the CMOS chip is in position No. 1 facing an outside wall, but it is in the corner of the box. Dose is recieved primarily through the Kovar cap and secondarily through the surrounding ceramic. In this case the lifetime is extended by increasing both the ceramic density and the Kovar cap thickness. Lifetime increase as a function of ceramic density and Kovar cap thickness for CMOS positions 2 and 4 are not shown but are intermediate between Nos. 1 and 5.

Increases in lifetime and resulting shielding weights for the geomagnetically active solar maximum spectrum are summarized in Table 1 for the five CMOS positions in the IMU. Relative lifetimes are given for four different cases: the unshielded spacecraft; the optimally shielded model using 7.71 kg of aluminum; the unshielded spacecraft with equally packaged CMOS requiring 0.91 kg of Kovar; and the unshielded spacecraft using equally packaged CMOS with outside facing circuit boards turned inward. The standard CMOS packaging in position 1 of the IMU for the unshielded spacecraft was used as a reference and is unity in Table 1. All other shielding configurations produced lifetime improvements when compared to the unshielded spacecraft. For the optimally shielded model the IMU required 0.66 kg of aluminum applied to the outside walls to achieve the given relative lifetimes. Equal packaging of the IMU CMOS would have required only 0.0018 kg of additional Kovar and would have nearly doubled the IMU lifetime. If, in addition, the ouside boards were turned inward, the optimally shielded lifetime could have been achieved without appreciable increase in total weight. Relative increases in expected lifetime for the quiet time spectrum were somewhat larger than those given in Table 1.

These results are generally correct for the other spacecraft subsystems; therefore, mission lifetime could have been attained by CMOS equal packaging and circuit board orientation during the design phase of the spacecraft. The resulting added weight would have been only 0.91 kg instead of 7.71 kg. The detailed shielding analysis would still have been necessary to verify that the components were adequately protected; however, the additional shielding weight would have been saved.

Conclusions

CMOS devices are being used in increasing numbers in satellite systems because they provide increased capability

Table 1 Relative IMU lifetimes and shielding masses[a]

CMOS position	Unshielded spacecraft	Optimally shielded	CMOS equally packaged	Equal packaging with inward boards
1	1.0	4.9	1.9	5.0
2	49.	62.	55.	55.
3	1.0	4.8	2.1	5.0
4	5.3	5.3	5.9	5.9
5	5.1	5.2	5.2	5.2
Shielding mass, kg.	0.0	0.66	0.0018	0.0018

[a]The standard CMOS packaging in position 1 of the IMU for the unshielded spacecraft is used as the reference lifetime.

without making severe demands on spacecraft power and weight. It is important to maximize the lifetimes of these devices in space radiation environments. Two techniques available for this purpose are 1) the use of radiation-resistant devices and 2) the implementation of effective design standards regarding CMOS packaging, circuit board orientation, and optimum radiation shielding. Where the manufacture of radiation-resistant devices is costly or prohibitively difficult, as is now the case with many large-scale integrated circuits, use of techniques described in this paper substantially increases the component lifetime with minimum cost and mass penalties. The resources involved in generating the detailed shielding calculations are small compared to the initial spacecraft investment and shortened lifetime resulting from neglecting shielding considerations. This is particularly true since most spacecraft are at or near their mass limits and the cost of additional shielding mass not carefully added can have a detrimental impact on payload capabilities.

Our primary recommendations are 1) for spacecraft manufacturers to require equally packaged large-scale integrated circuits, 2) to orient circuit boards to augment component shielding, and 3) to perform a thorough shielding analysis to determine the placement and weight of additional shielding that may be necessary. When penetrating electrons produce the dominant doses, implementation of the first two recommendations are highly effective and incur almost no additional weight.

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