PROTON UPSETS IN ORBIT*

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Summary

This paper presents a method of predicting proton-induced single event upset rates in spacecraft RAMs. The approach uses a sensitivity parameter \( A \), determined from one or more experimental measurements of upset cross sections made at any proton energy above threshold. Parameter \( A \) uniquely determines a curve for the energy dependence of the upset cross section. This curve can be combined with the proton spectrum at the RAM to predict its upset rate. Predicted upset rates for 600 deg circular orbits are presented.

An alternative approach for examining proton induced upsets is to use nuclear reaction calculations. This was previously applied to calculate upsets for a 600 nm orbit.\(^8\) Sensitive devices can be upset by direct ionization. The upset near threshold for moderately sensitive devices are caused by recoils from elastic proton scattering. These upset rates can be estimated directly from elastic scattering data. Other reaction mechanisms are included as the proton energy increases. This approach has been applied to a number of orbits and the results are shown in Fig. 1. Limitations are that actual devices have widely varying dimensions and that there is only limited information available about cross section and energy deposition at high proton energies.

Introduction

Single event upsets (SEUs) due to protons are a significant problem in the electronic circuitry of earth-orbiting spacecraft. Unlike the case of a heavier ion, mere passage of a proton does not produce sufficient ionization to upset the usual circuits. However, a nuclear reaction initiated by a proton can produce sufficient ionization for an upset. The probability of proton-induced SEUs and the dependence of the upset cross section on proton energy can be investigated both experimentally and theoretically. These studies can be used to predict upset rates. A method is developed in this paper for estimation of upset rates in devices exposed to given proton fluxes within a particular spacecraft shielding. The discussions in this paper do not apply to the class of devices that upset for heavy ions but not for protons.

Soft errors in RAMs have been investigated by several groups\(^1\)\(^-\)\(^6\) using cyclotron protons. In general, the probability of upset increases rapidly as proton kinetic energy increases from about 20 to 100 MeV, and increases more slowly at higher energies. The results are orders-of-magnitude different for unlike RAMs.

Early measurements also showed some variation for supposedly identical units. These variations have been much smaller in recent measurements, perhaps due to improvements in dosimetry or in manufacture. When all of the experimental results are plotted as a function of energy, there is in general a consistent energy variation. It appears that the variation of cross section with energy is of a monotonically increasing nature.

The upset measurements have been made at energies of 4.2 GeV to 4.2 GeV. They indicate the character of the energy variation over this range. Unfortunately, there are few measurements that detail the threshold region, which varies from 40 MeV down to 10 MeV depending on the device sensitivity. A first approximation to the energy variation was made by assuming a uniform apparent threshold at 18 MeV and fitting the smooth energy variation at higher energies.\(^7\) When combined with proton spectra as a function of altitude, we obtained an orbital dependence similar to that developed later in this paper.

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Fig. 1. Single event upset rates in circular orbits, based on nuclear reaction data and using 3.6 eV deposition per electron-ion pair.

Nuclear reaction calculations have been performed by J.N. Bradford.\(^9\) His methods do not apply near threshold. Farrell and McNulty\(^10\) have also performed nuclear reaction calculations and appear to get good agreement with energy deposition measurements. These types of calculation are very promising, but still need to be extended to give good predictions of upset rates.

While the experimental data on upsets give a good picture of the energy dependence of proton-induced SEUs at intermediate energies, they produce a confused picture near threshold and at high energies. The nuclear reaction approach will be utilized to complement the data. The cross section vs. energy relationship developed can then be combined with the proton spectrum inside the spacecraft to give upset rates as a function of a device sensitivity parameter and orbit.

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Device Characteristics

In principle, one should be able to calculate SEUs from a knowledge of device specifications, particularly for heavy ions where direct ionization is sufficient to produce upsets. These specifications include the material, doping density, and substrate. The geometry enters as both shape and size. The funnel effect, in which charge is collected from the substrate as well as the depletion region, further complicates this approach. As an upset involves a circuit, the circuit design and operating voltage are additional variables. Materials (silicon) and geometry are considered in the nuclear reaction approach.12

Experimental Data

Data on proton-induced SEUs is presented in Fig. 2. The data on National Semiconductors 4044 devices are from Refs. 2 and 4. It is seen that individual devices of the same type may differ widely in some SEU tests. The protons were obtained as a 158-MeV beam from the Harvard Cyclotron, degraded by passing through matter. Thus, the protons used in the low-energy bombardments were not monoenergetic.

Fig. 2. Experimental upset cross sections as a function of proton energy.

The Motorola MCM 4116AC-20 and Mostek 4116J-2 data1,3 are from the NRL Cyclotron and from a 5 GeV/c beam of protons at the Brookhaven Alternating Gradient Synchrotron.

The five others are Fairchild devices tested by the Jet Propulsion Laboratory group5,6 at a number of radiation facilities. A factor in the scatter of these data is the use of different units with the same type number.

Our initial fit ignored the results at Brookhaven. The empirical equation used a universal threshold and shape, increasing at very high energy as $E_0^{0.444}$. This is inconsistent with the ratio of upsets at Brookhaven and NRL. We therefore sought other types of information as a guide, particularly at high energy.

Cross Sections at High Energy

The total proton inelastic cross sections for various nuclei are reviewed by Letaw and coworkers.12 They give equations as functions of atomic weight and energy. In their equation, the cross section involves a term in $\exp(-E/200 \text{ MeV})$ and approaches a constant value at high energy. Relative to the value at infinite energy, the cross section is 0.4 percent less at 1000 MeV and 14 percent less at 190 MeV. The cross section increases at lower energies.

If the ratio of upset-producing cross sections to total inelastic cross section is independent of energy, the upset yield will have the energy dependence given by Letaw. This is definitely not true at low proton energies, but it is a reasonable relationship at high energy. We therefore shall fit the accelerator data to an equation with constant SEU yield at high energy, decreasing near 1000 MeV.

Cross Sections at Low Energy

As illustrated elsewhere,8,11 the dominant upset mechanism is a function of the sensitivity of the device and of particle energy. A device sensitive to the ionization in a proton track would be grossly unfit for spacecraft use. Hence, we consider only devices insensitive to even the maximum length proton paths in the device, including the funneling effect. A nuclear reaction producing a highly-ionizing track is therefore required for a proton-induced SEU.

Elastic scattering. Consider the elastic scattering of a proton, with initial kinetic energy $E_1$, by a silicon atom. A kinetic energy transfer $Q$ occurs, with a maximum value of

$$E_{\text{cap}} = E_1/7.4$$

(1)

given to the recoiling atom for 180° scattering by the lightest isotope, $^{28}\text{Si}$. Let the critical recoil energy be $E_{\text{cr}}$, the energy needed to produce the minimum number of electron-ion pairs for upset. If $E_{\text{cr}} = 2.5$ MeV (about 7 x 10^9 pairs at 3.6 eV each), then Eq. (1) shows that $E_1$ must be at least 18.5 MeV. (We assume that the recoil Si stops within the sensitive region.) The critical energy deposition, $E_{\text{cr}}$, will be a little larger than $E_{\text{cr}}$ (perhaps 2.55 MeV) due to direct ionization by the proton before and after collision.

Let $E_{\text{cr}}$ be the energy required to produce an upset and $E_{\text{cr}}$ be the energy at which the upset yield starts to rise. Then

$$E_{\text{cap}} = E_{\text{cr}}$$

(2)

where $k$ is a constant. Integration from $E_{\text{cr}}$ to $E_{\text{cap}}$ produces

$$\sigma = (k/E_1^2) (E_{\text{cr}} - 1/E_{\text{cap}}).$$

(3)

With Eq. (1), this can be transformed into

$$\sigma = (k/E_1^2) (E_1 - 7.4 E_{\text{cr}}).$$

(3a)

Near threshold, the SEU yield is directly proportional to the energy in excess of 7.4 $E_{\text{cr}}$. As $E_1$ is increased, $\sigma$ reaches a maximum at $E_1 = 14.8 E_{\text{cr}}$ and then decreases.

Note that the scattering cross section is large at low energy; as bombarding energy $E_1$ is increased, SEUs occur only when the energy deposition becomes adequate.

Alpha production. For insensitive devices and moderate proton energies, the $\text{Si(p,p')Si}$ reaction will not yield sufficient recoil energy for SEUs. The
Si(p,α)Al and Si(p,α)Mg reactions result in greater recoil energy and also appreciable ionization by the helium ion produced.

Now consider the reaction \(^{30}\text{Si}(p,α)^{27}\text{Al}\). As the difference in total rest mass is 2.37 MeV, a proton of \(E_1 = 5\) MeV and the reaction products will deposit \(E_d = \frac{2.37}{30}\) MeV; this deposition can occur in 8 \(\mu\)m of Si. The ionization is almost as much as the maximum in the elastic scattering example with \(E_1 = 18.5\) MeV. However, a 3 percent isotope is involved and the reaction cross section is essentially zero, so upsets will not be observed. As the cross section increases rapidly with energy and all isotopes become involved, SEUs due to alpha production will be seen at significantly greater incident energy.

The experimental data on upsets will not show the "true" threshold but will indicate an energy at which the cross section becomes immeasurably small. Our empirical equation, therefore, uses a parameter called

\[ A = \text{apparent threshold.} \]

The value of this parameter, for a given device, is inextricably intertwined with the form of the equation fitted to the data.

Unlike elastic scattering, alpha-producing reactions can have adequate \(E_d\) at small incident energy \(E_1\); SEUs will be observed only when the reaction cross section is adequate.

Other reactions. The proton-induced reactions range from \(\text{Si}(p,n)\)P, in which no ionization is produced by the outgoing neutron, to fission into two major components. For sufficiently insensitive devices, only a breakup reaction such as \(28\text{Si}(p,α^{12}\text{C})^{16}\text{O}\) will produce enough ionization in a small volume. The cross section is very small until the proton energy becomes quite large, and the small upset cross section for an insensitive device is coupled with a large apparent experimental threshold.

Semi-Empirical Equation

The experimental SEU cross sections are to be fitted to a form which is constant at high proton energy, decreasing below about 1000 MeV. The data at 90 MeV and up are amenable to an exponential relationship, one which has evolved into

\[ \sigma = \sigma_0 \left[ 1 - \exp\left(-\frac{h}{h_0}\right) \right]. \]

Here, \(h\) is a constant and \(Y\) is a linear function of energy which, by definition, goes to zero at \(E_1 = A\).

At low energy, the SEU cross section for each reaction differs in shape; that of the total is unclear, but depends upon device sensitivity. Although bypassing much of the nuclear physics details in favor of an empirical threshold, two parameters remain for the formula given above. First, noting that \(A\) is a variable, is the function \(Y\) obtained from \(Z(E_1 - A)\) or \(E_1/A - 1\)? Each choice has some merit; we employ the normalized compromise relationship

\[ Y = \left(\frac{18}{A}\right)^{0.5} (E - A), \]

with \(E\) and \(A\) in MeV, here and in Eq. (6). Second, the cross section is what power of \((E - A)\) at "low energy"? For elastic scattering only, the answer is unity at threshold, then decreasing. For other reactions, involving barrier penetration, the answer is greater than one. For a sum of reactions with differing thresholds, the value is larger than for the initial reaction. A reasonable overall value is about 1.5.
The equation adopted is

$$\sigma = (24/A)^{14} \left[ 1 - \exp(-0.18 \gamma 0.5) \right]^4$$  \hspace{1cm} (6)

in units of $10^{-12}$ upsets per proton/cm$^2$ per bit.

This equation is plotted in Fig. 3 for various values of $A$. It fits the data quite adequately, although larger value of $A$ fits better. The value of $\sigma$ is proportional to $(E - A)$ to the $mn = 0.5 \times 4 = 2$ power at $E_1 = A$, but an average power of 1.5 is found between, for example, $Y = 5$ and 17.

If more consistent data are available, a better empirical curve can be obtained. Data in the threshold region are particularly needed. It does not appear feasible, either scientifically or in cost effectiveness, to experimentally determine the fine structure. One expects the rate (for a set of identical devices) due to one upset mechanism to rise rapidly (on a logarithmic scale), then flatten. New rises would occur when new reaction mechanisms or different parts of the circuit begin to produce upsets.

We have determined a value of $A$ for each device considered here. Some data were given lesser weight and measurements within 4 MeV of $A$ were ignored. The ratio of measured SEU cross sections to $\sigma(E, A)$ of Eq. (6) are shown on Fig. 4. Note that a different value of $A$ is assigned to each of the MM5280 and C2107 devices.

Proton Flux Inside Spacecraft

The average proton flux in circular earth orbits was tabulated in reports by Stassinopoulos.\textsuperscript{13,14} Inside a spacecraft, the exterior flux is degraded by the material around the point considered. We have used the energy loss given by proton range-energy tables, such as those of Janni.\textsuperscript{15}

Langworthy\textsuperscript{16} has calculated the mass distribution shielding a device in a "typical" location in a light (c 500 lb) spacecraft. The distribution was shown and used by Petersen.\textsuperscript{8} In this work, Langworthy's results are approximated by a

![Diagram](image)

Fig. 5. Upset rates versus altitude in circular orbits at 60° inclination and with typical shielding. Upset rates for devices at 1400 nmi are shown using the value of $A$ determined from the data of Fig. 2.

shield with 6 percent of the solid angle at each of 0.72, 0.79, 0.92, 1.12, 1.51, 2.71, 3.45, 4.73, 5.98, 7.55, 10.78, 14.53, 18.53, and 24.12 g/cm$^2$ Al, plus 4 percent each at 29.97, 35.71, 42.58, and 50.85 g/cm$^2$ Al.

Upset Rates

When the interior proton flux (in 20 energy bins) is folded with the cross sections of Eq. (5), the upset rates of Fig. 5 are obtained. For $A = 18$ MeV and 1400 nmi altitude, the calculated rate is 0.0067 upset per bit day. Of these upsets, only 4.4 percent are produced by protons with internal energy of 50 MeV or less. It is evident that moderate shielding changes will have little effect in this environment. For $A = 18$ MeV, relative production of upsets by these low energy protons is about 3 percent at 216 to 648 nmi, then increases with altitude to 22 percent at 3450 nmi and 60 percent at 5600 nmi. Additional shielding will be effective for proton-induced upsets at high altitude.

These curves, or interpolations between them, may be applied to specific devices. There must be experimental data permitting the assignment of a value for $A$. Note that a given shielding pattern is assumed; even within the specific spacecraft considered, an electronic component may be at a location with better or worse shielding. For the devices of Figs. 2 and 4, values of $A$ are determined and upset rates are shown at 1400 nmi.

For low altitude orbits of 50° to 90° inclination, the upset rates for protons and cosmic rays will be similar. Both rates need to be calculated. For low earth orbits at low inclination, the proton upset rates are expected to dominate.

The Solar Max Mission satellite has an orbit at 278 nmi altitude and 29° inclination. Using Fig. 5, one finds 7.5 upsets in 6 months at 278 nmi for a 1024-bit 93422 device with "typical" shielding at 278 nmi and 60°. Interpolating in the tables of Ref. 13, 3 upsets are predicted for the actual 29° orbit. Stewart\textsuperscript{17} reports that 10 upsets were observed under these conditions, in remarkably good agreement with our prediction. These upsets occurred only when traversing the proton belts at the South Atlantic Anomaly.

Complex Devices

The methods discussed here will work for complex devices as well as for memories. In this situation, the device upset cross section is measured using a realistic program. The upset cross section per bit is then obtained by dividing the measured cross section by the estimated number of registers involved. From this, the value of $A$ can be obtained from Fig. 3 and used in Fig. 5, or with a proton spectrum, to obtain the upset rate per bit. This value can then be converted to the upset rate per device. The results of this approach are not sensitive to errors in the number of registers assumed as the curves in Fig. 3 are nearly related by multiplicative factors.

Conclusions

This paper presents a practical method of predicting proton-induced upset rates in spacecraft. Experimental upset data must be available at one or more energies. This data is then used to obtain the sensitivity parameter $A$ which completely describes the energy dependence of the upset cross section.
The energy dependence was obtained by combining theoretical knowledge of behavior near threshold and at high energy with measured upset cross sections. The parameter A is suitable for a figure of merit for describing relative device sensitivity.

The following series of steps will produce an estimate of proton upset rates for RAMs in a given spacecraft.

1. a) Obtain the experimental proton upset cross section at one or more energies.
b) Determine the upset sensitivity parameter, A, by comparing the results with Eq. (6) or the curves of Fig. 3.
2. a) Obtain the average proton spectrum in the orbit considered.
b) Obtain the shielding distribution for the devices in the spacecraft.
c) Determine the proton spectrum at the devices.
3. Combine the upset cross sections with the spectrum to find upset rates. Fig. 5 was obtained by these steps.

In the intense part of the radiation belt, the upset rate in a multi-megabit RAM memory can be quite great. Careful selection of device type is now possible using the methods presented here.

References
17. W.N. Stewart, private communication.