Published in final edited form as:

IEEE Trans Nucl Sci. 2016 December 19; Volume 64(Iss 1): 301–308. doi:10.1109/TNS.2016.2640948.

Evaluating Constraints on Heavy-Ion SEE Susceptibility Imposed by Proton SEE Testing and Other Mixed Environments

R. Ladbury [Member, IEEE],

NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA (phone: 301-286-1030; fax: 301-286-4699)

J.-M. Lauenstein [Member, IEEE]

NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

R. Ladbury: Raymond.L.Ladbury@nasa.gov; J.-M. Lauenstein: jean.m.lauenstein@nasa.gov

Abstract

We develop metrics for assessing effectiveness of proton SEE data for bounding heavy-ion SEE susceptibility. The simplest metric is just the areal coverage for the test, which can be expressed as the area on the test part which is struck on average by a single ion. This simple quantity can yield important insights into the efficacy of a given SEE test. We also develop methods for bounding heavy-ion SEE rates with proton data for both nondestructive and destructive SEE modes and for identifying the SEE response characteristics that render such bounding methods ineffective.

Index Terms

Heavy Ions; probabilistic risk assessment; proton radiation effects; radiation hardness assurance methodology; single-event effects; single-event latchup

I. Introduction

The difficulties and expense of heavy-ion single-event effects (SEE) testing, and the fact that protons cause SEE in most devices via production of light-ion (atomic #, 3 Z 15) recoils, have led to attempts to bound heavy-ion SEE susceptibility through use of high-energy proton data.[1–4] Although these attempts have bounded SEE rates for some technologies in benign radiation environments, they are also problematic, particularly for destructive SEE, where proton recoil characteristics (e.g. range, angular dependence, Z) result in underestimates of destructive SEE rates if the test detects the susceptibility at all.[5] Protons are also inefficient test ion generators: 200-MeV protons produce only about one recoil ion for every 289,000 incident protons, while every proton contributes dose. The resulting high total ionizing dose (TID) limits fluences that can be used in a proton test, especially for system-level tests, where the weakest part limits the dose the system can tolerate.

Unlike a heavy-ion test, where ions in a test run all have the same atomic number (Z), energy and angle of incidence, proton recoils span a wide range in all of these factors, and the characteristics of an ion that causes a given SEE will not be known. This raises questions about how to interpret proton SEE test results for the purpose of bounding heavy-ion SEE susceptibility: Is the recoil ion fluence sufficient to reveal all SEE modes likely to mission

performance? Do recoil ions have sufficient range and Linear Energy Transfer (LET) to reliably realize potential SEE modes? Perhaps most important, what is the upper bound for a SEE mode if it was not observed in the proton test? Do the answers to these questions change if the mission radiation environment is relatively mild?

This work develops methods for answering these questions and for better interpreting the bounds proton SEE data can place on heavy-ion SEE rates. We used CRÈME-MC[6] to generate Monte Carlo simulations of proton-recoil ($3 \leq Z \leq 15$) and cascade ion (mainly He nuclei) energy deposition in simplified representative sensitive volume (SV) models. The methodology used to generate these simulations has been described previously.[5] There, we used the results to demonstrate the challenges of using short-range recoil ions to investigate susceptibility to destructive SEE. Here, we investigate how well a given proton SEE test elucidates the potential light-ion SEE susceptibilities in a device—both for nondestructive and destructive SEE. The standard proton SEE test we consider is described in [1–4]—a fluence of 10^{10} 200-MeV protons/cm². However, we look at energy and fluence dependence as well. Also, although we start by considering piece-part testing, we briefly treat some challenges of interpreting board and box-level tests. We begin with the simplest measure of an SEE test's efficacy—coverage, or the extent to which the test reveals the SEE susceptibilities of the DUT. We then examine the constraints a proton test may place on heavy-ion SEE rates and use these techniques to estimate upper bounds on SEE rates based on proton test results.

II. Coverage of an SEE Test

Coverage—which we define as the extent to which a test reveals all the SEE modes to which a test device is susceptible—is a fundamental measure of SEE test quality. If a test does not reveal an SEE mode to which a part is susceptible, we cannot know its consequences or to any accuracy, its rate of occurrence, making risk estimation impossible. At its most general, coverage depends on a variety of factors. A complex device having more different feature types, technologies, and a greater variety of error modes would require a greater ion fluence for a representative test than would a simple device. The application conditions, logic state and function of the device when the SEE occurs can affect its rate and/or consequences. However, the areal coverage of the ion fluence illustrates the importance of coverage and requires little a priori knowledge about the part.

Fig. 1 illustrates the concept of areal coverage by looking at simulated recoil ion strikes from proton-Si collisions within a $\sim 60 \times 70 \mu\text{m}^2$ portion of an Elpida EDS5108 512 Mbit SDRAM. Each white dot corresponds to a $1 \mu\text{m}^2$ area in which a single recoil ion is generated. A fluence of 10^{10} 200-MeV protons/cm² generates a mean of ~ 1.45 recoil ion strikes in such an area, while increasing the proton fluence by $100\times$ generates 145 ions—within $3\times$ of the 420 ion strikes expected from a heavy-ion test run of 10^7 ions/cm². Fig. 1 illustrates that for the SDRAM, fluences of either the 10^{12} proton/cm² or 10^7 ion/cm² do a reasonable job of covering a representative proportion of the discernibly different features on the die. Of course, this analysis is an oversimplification. The recoil ions include atomic numbers $3 \leq Z \leq 15$ and a broad range of LET, energy/range and angle of incidence, while the heavy-ion test run includes only ions of a single, known ion species, energy/range, LET and angle, and

would usually be one of many runs. Still, the expected ion density on the device is a first approximation for a coverage metric, especially if we know something about the device. For instance, knowing the Intel I7 quad-core processor fabricated in 45 nm CMOS contained 731 million transistors in a 2.63 cm² area,[7] we know that the expected area per proton recoil ion (2891 μm²) contains an average of over 8000 transistors. (For comparison the Intel 8080 8-bit processor had 6000 transistors.)

These are average coverages. It is also reasonable to ask how large an area on a chip could be missed by a test. Since an observation of 0 events implies an upper 90% confidence level (CL) on the Poisson mean of ~2.31, 10% of areas where we expect 2.31 recoil ions (e.g. nearly 6650 μm² for a fluence of 10¹⁰ 200-MeV protons/cm² or nearly 18500 transistors on the I7) on the chip would have 0 hits. Moreover, since we can divide the device into many areas of the same size, each with the same probability of having 0 hits, we can view each such area as an independent binomial trial (0 hits or >0 hits). Thus for the I7, the standard 10¹⁰ 200-MeV proton/cm² test has a 10% chance of missing an area of 78858 μm² containing over 213000 transistors (for comparison, an Intel 80386 processor had 275000 transistors). In contrast, a fluence of 10¹² protons/cm² has a 10% chance of leaving an area with 3092 transistors unexposed, and for a 10⁷ ion/cm² heavy-ion test run, the largest unexposed areas would contain fewer than 1,114 transistors with 90% confidence. Fig. 2 indicates how these metrics of areal ion coverage of a 200-MeV proton test scale with proton fluence, in this case for a chip with die area of 1 cm². These metrics yield only an approximate (and optimistic) view of coverage, since they treat all recoil ions alike despite the fact that the broad range of ion characteristics result in the ions having different efficacies for realizing an SEE in the DUT. Fig. 3 shows how ion fluence vs. LET falls off if we require the particles to have ranges of more than a few microns, which is important for destructive SEE and in some bipolar technologies for nondestructive SEE. If we require range > 6 μm, fluences are down by nearly an order of magnitude, and coverage suffers commensurately. We next consider the effect of the cross section (σ) vs. LET curve on coverage and use the results to estimate upper bounds on heavy-ion SEE susceptibility based on proton test data.

The σ vs. LET curve describes how ion SEE efficacy changes with its LET.

We assume a Weibull form for σ vs. LET, with small limiting cross section and depth (σ_{sat}=1 μm² and d = 1 μm):

$$\sigma(\text{LET}) = \sigma_{\text{sat}} \times \left(1 - \exp \left[-\left\{ \frac{(\text{LET} - \text{LET}_0)}{w} \right\}^s \right] \right) \quad (1)$$

where LET₀=onset LET, s=shape and w=width.

As a first approximation, the number of events, N_E due to a given fluence F(LET_{Eff}) of proton-Si recoil ions is

$$N_E = N_{SV} \times \int_{LET_0}^{LET_{Max}} F(LET_{Eff}) \times \sigma(LET_{Eff}, LET_0, w, s) dLET_{Eff} \quad (2)$$

where N_{SV} is the number of $1\text{-}\mu\text{m}^2$ SVs in the device. Although LET varies little over a small SV, we use equivalent LET[5],

$$LET_{EQ} = E_{Dep} / (\rho \times d) \quad (3)$$

where ρ is the density of Si and d is the depth of the SV. LET_{EQ} is a generalization of LET_{EFF} and can be thought of as the constant LET that would result in the same E_{Dep} if the ion traversed the SV at normal incidence. As such, substituting LET_{EQ} for LET_{EFF} in (2) makes the expression exact.

In trying to bound heavy-ion SEE rates with proton data, we do not know the heavy-ion σ vs. LET, but we do know the proton test event count. This event count fluctuates according to the Poisson distribution. Thus, even if we observe 0 events, the expected (Poisson mean) number of events could (with 10% probability) be as high as 2.31 (upper limit μ_{UL} for the Poisson mean for the 90% CL) for the device. Moreover, the integral in (2) is the number of events expected for a single SV, which we can calculate for each candidate σ vs. LET model if we know the recoil ion fluence vs. LET_{EQ} . Setting N_E equal to μ_{UL} for the desired CL and solving for N_{SV} allows us to bound the number of $1\text{-}\mu\text{m}$ cube SVs in the device (for that CL) for each candidate σ vs. LET model.

We focused on σ vs. LET curves with low values of LET_0 (0.5, 1.5, 2.5, 3.5, 4.5, 5.5 and 6.5 MeVcm^2/mg), w (5, 10, 15, 20 and 25) and s (0.5, 1, 1.5, 2 and 2.5). For such models σ approaches saturation before the proton recoil flux drops to negligible levels ($LET < \sim 10 \text{ MeVcm}^2/\text{mg}$). Proton testing is less effective for higher values of LET_0 , w and s because there are fewer recoil ions to detect the SEE susceptibility—and fewer ions results in a higher bound on the SEE rate.

We used CREME96 to estimate the SEE rate at the international space station (ISS) for a single SV for each candidate σ vs. LET. The highest resulting rate (product of N_{SV} and the CREME96 rate) represents the bounding SEE rate for the CL reflected by the upper limit for the Poisson mean. (This procedure can also be done for a positive SEE test by setting μ_{UL} equal to the upper confidence limit for the Poisson mean given the observed events—e.g. if 1 SEE is seen, the 90% upper limit for the Poisson mean is $\mu_{UL}=3.89$ events.)

Fig. 4 illustrates the results for the GCR environment at the ISS given a null result in a proton test with 10^{10} 200-MeV protons/ cm^2 . As can be seen, high bounds occur for both high LET_0 and low LET_0 . The high LET_0 results arise because there are relatively few proton recoils for LET or $LET_{EQ} > 10 \text{ MeVcm}^2/\text{mg}$, so unless the proton fluence is high, a proton test will not effectively cover the device and limit the SEE cross section. At low LET_0 , one might expect the bounds on SEE rates to improve, since the fluence now includes

not just the recoil ions, but also cascade alpha particles with LET from 0.25-1.57 MeVcm²/mg. Unfortunately, the Galactic Cosmic Ray (GCR) fluence increases even more rapidly in this LET range, especially in LEO orbits (~30×) so the improved coverage is not sufficient to bound the rate at a low level.

Fig. 4 illustrates that the proposed bounding method breaks down if LET₀ is too high or σ vs. LET rises too slowly. For such models, the recoil-ion fluence runs out before the cross section rises to the point where a recoil ion has an appreciable chance of hitting a sensitive node. Additional assumptions are required to bound the saturated cross section of the die if the LET₀>6.5 MeVcm²/mg. This becomes even more evident when considering SEE with larger and deeper SV. The results in fig. 4 are consistent with those in ref. [4], given that the latter quoted bounding rates at the 63% CL, while the rates in fig. 4 are at the 90% CL.

III. Generalizing to Deep Sensitive Volumes

Bounding rates with proton data is more complicated for thick SEE SV (e.g. for SEL and other DSEE) for several reasons. First, cross section actually scales with deposited charge rather than ion LET, and charge deposited by a proton recoil ion is limited by range rather than LET in deep SV. Using LET_{EQ} better reflects this dependence, making it easier to extrapolate test results to environments (e.g. GCR) where ions are not range limited. The fluence vs. LET_{EQ} distribution changes rapidly with SV depth (see fig. 5). Second, changing chord length distributions as the SEL cross section rises, coupled with the limited and variable recoil ion ranges leads to a complicated geometric problem. The rapidly falling recoil ion fluence distributions in fig. 5 suggest that the form of σ vs. LET_{EQ} will be important, raising the question of how to handle the changing chord length distributions. A step-function rising to σ_{sat} at the onset may significantly overestimate the expected number of events from the test. However, a continually changing particle fluence vs LET_{EQ} distribution poses intractable problems, particularly as we will be considering many candidate forms for σ vs. LET_{EQ}.

Warren et al. [7] suggested that a series of nested sensitive volumes with varying charge collection efficiency could yield more accurate Monte Carlo SEE rate estimates than a single sensitive volume. We follow a similar strategy here to account for the changing distribution of chord lengths with SV dimensions. To better approximate the Weibull form of the σ vs. LET curve, we constructed a series of SV having charge collection depth of 10 microns, but with areal cross sections ranging from 1% to 100% of the 10μm×10μm area of the individual SV. (See Fig. 6.)

We used the recoil fluence vs. LET_{EQ} distribution pertaining to the cross section for each sub-volume and tallied its contribution to the events for the entire SV. In essence, the fluence vs. LET_{EQ} distributions serve as CRÈME-MC emulators, approximating the results of a Monte Carlo simulation without the computational overhead each time.

As expected, given the rapidly falling fluence vs. LET_{EQ} distribution for the 10 micron cube in Fig. 5, proton testing only weakly constrains SEL rates. Fig. 7 shows that unless the candidate σ vs. LET curve has low LET₀ and rises rapidly with increasing LET (small

Weibull w and s), a proton test with 10^{10} 200 MeV protons/cm² fails to place any meaningful bound on the cross section—and therefore on the rate. For slowly rising σ vs. LET or if $LET_0 > 3$ MeVcm²/mg, we expect few proton recoil induced SELs because the fluence falls rapidly long before σ vs. LET nears saturation. Increasing the fluence to 10^{11} protons/cm² improves the likelihood of seeing susceptibility if it is present in the device. By 3×10^{11} protons/cm², the worst-case (WC) rate at the 90% CL (for the ~60% of σ vs. LET models where the method bounds the rate) decreases to less than 1 in 10 years. Fig. 8 shows how the 90% CL WC rate scales with proton fluence. The 10^{th} WC rate is also shown to demonstrate that the WC is not an outlier.

This shows that proton tests cannot reliably detect DSEE. Increasing proton fluence helps, but it is very difficult to achieve a sufficiently high fluence of higher LET ions with sufficient range to cause SEL in a susceptible part if the onset LET is high or if the SEL cross section rises slowly with LET (or LET_{EQ}). Moreover, the analysis we have shown here is for SEL SV with a depth of 10 μm . For deeper SV, proton testing will be even less effective in bounding on SEL rates.

We also examined whether testing at different or multiple energies could improve the efficacy of proton testing for bounding SEL rates. Fig. 9 shows the percentage of σ vs. LET models $\sigma(LET, LET_0, W, s)$ where a null proton test result fails to meaningfully bound the SEL cross section for a device.

For 3×10^{11} 400-MeV protons/cm², the method fails to bound rates only for $LET_0 > 6$ MeVcm²/mg and/or $s > 2$. This suggests observations of ref. [9] that higher energy protons more effectively reveal SEL susceptibility may hold even absent high-Z materials in the package.

In general, testing at multiple energies will not improve the ability of a proton test regime to detect SEL susceptibility—lower energy protons are less likely to cause SEL. However, multiple energies can yield tighter bounds than a single energy test—even if the total fluence for all energies and total # of events observed are kept constant. This is because moving from a higher energy where a SEL is observed to a lower energy tells us whether the SEL cross section is saturated at the higher energy or not. To examine the impact of using multiple energies, we proceeded as above for a single energy. Each σ vs. LET_{EQ} model had an expected event count for the i^{th} proton energy E_{pi} and fluence F_i , $\mu(F_i, E_{pi}, LET_0, W, s)$ for the nested SV. Since we have event counts for multiple energies, we use a generalized linear model to combine results over multiple energies (as in [10]) and maximized the likelihood

$$\mathcal{L} = \prod_{i=1}^{N_E} \text{Poisson}(N_i, N_{SV} \times \mu(F_i, E_{pi}, LET_0, W, s)) \quad (4)$$

over N_{SV} . If at least one of the energies yields a positive result ($N_i > 0$), this approach can bound the device rate for that SEE somewhat more tightly than merely using the single-positive result. As an example, if one SEL is observed with $E_p = 400$ MeV, and one has a choice of an identical run with $E_p = 400$ MeV or a run to the same fluence at $E_p = 200$ MeV, the latter will yield a bound ~3x lower if the result is null at the lower energy or about 2x

lower if the lower energy also yields a single SEL. This advantage decreases as proton fluence rises, and if irradiations at all energies yield null results, one should merely follow the procedure in section IV for the single highest proton energy.

IV. Discussion and Possible Improvements

The results for sections III and IV show that the deeper the SV for the SEE mode, the more problematic it is to place meaningful bounds on the rate using protons. This is because for deep SV, ion energy deposition tends to be limited by particle range rather than LET, forcing us to analyze proton results in terms of LET_{EQ} if we wish to extrapolate the results to GCR and SPE environments. As SV depth increases, recoil fluence vs. LET_{EQ} distributions are compressed to the left. More σ vs. LET models have low cross sections where proton recoils are plentiful and so the proton test fails to provide adequate coverage for the SEE mode. (See Table I.)

One way of avoiding these limitations is to use independent data to bound the limiting SEL cross section or to show that if the device is susceptible, σ vs. LET/LET_{EQ} most likely rises rapidly near threshold (small w and s). Although a review of recent literature[11,12] finds that most SEL limiting cross sections are less than 10^{-4} cm^2 (equating to $< 2\text{-}3\text{E-}5$ SELs per day in the ISS environment), some analog to digital converters had limiting cross sections on the order of 10^{-3} cm^2 , [11] and some SRAMs[12] had cross sections $>10^{-2} \text{ cm}^2$. Moreover, reference [13] found that even for similar devices in a single fabrication process from a single vendor, SEL cross sections did not follow a well behaved, compact distribution. Similarly, data reveal that some SEL σ vs. LET curves rise rapidly with LET and some do not. Regardless of the approach one takes, it is essential that the assumptions that supplement the proton data be stated explicitly so their validity can be assessed. In this regard, it makes sense to use a Bayesian approach with prior data limiting behavior of the σ vs. LET curve to regions where proton testing is effective (if possible). This ensures that assumptions underlying the prior probability distribution are made explicit and holds out hope that proton testing can effectively bound heavy-ion SEL susceptibility for some parts.

V. Additional Applications

Although the techniques above were developed to bound heavy-ion SEE susceptibility with proton SEE data, they are useful for other applications where the radiation environment is mixed. For instance, if one wishes to use heritage data from a past mission to bound SEE rates in other radiation environments, one can use the approach outlined in either section III or IV, substituting the LET or LET_{EQ} distribution for ions generated or present in the environment of interest (e.g. particle accelerator, space mission, etc.). In addition, we can look at the coverage provided by the heritage mission. For example, a device in the ISS environment with a limiting SEL cross section of 0.01 cm^2 and onset $LET \sim 10 \text{ MeVcm}^2/\text{mg}$ would require 86 device-years of exposure to have a reasonable chance of observing a SEL.

Another timely application of some techniques developed here concerns the recent proton-induced failures of Analog Devices OP470 op amps, which have been attributed to fission products of Au ions knocked off of the gold-plated package lid by incident protons.[14]

These observations have generated concern because a fluence of $\sim 10^{10}$ 200 MeV protons/cm² incident on 1 μm of Au plating yields roughly 2250 Au fission events/cm², yielding ions with Z as high as 50, energies up to 90 MeV and LET $\sim$ 40 MeVcm²/mg. However, the particles do have short range, suggesting that an analysis in terms of LET_{EQ} may be appropriate when comparing this radiation environment to heavy-ion test data. To estimate the LET_{EQ} distribution, we assumed that if the SV has depth greater than the ion range, the ion deposits its entire energy inside the SV. Thus for shallow SV the LET_{EQ} distribution is equivalent to the LET distribution, while for deep SV, the LET_{EQ} distribution represents a worst case. Fig. 10 shows that the LET_{EQ} distribution shifts leftward as SV depths increase. By $d=30\ \mu\text{m}$, common for many SEL, SEGR and SEB SV, 80% of ions have LET_{EQ} in the single digits. This suggests that these proton-induced fission events will likely not pose a serious threat for most DSEE modes.

The discussions of energy dependence in section IV also illustrate that the techniques discussed here will be useful in planning future proton testing efforts.

VI. Interpreting System-Level Tests

Although board/box-level testing can decrease testing costs, several factors complicate interpretation of board- and box- level proton test results—particularly their use for limiting heavy-ion SEE susceptibility. Even ignoring potential complications such as whether logical or temporal masking could hide nondestructive SEE or whether post-irradiation tests will reveal latent damage from DSEE modes, testing at the board level exacerbates the coverage related concerns that can limit the effectiveness of proton testing at the part level.

For SEE with a shallow SV, the most serious challenge is that as onset LET rises above about 6-7 MeVcm²/mg, the coverage provided by the flux of recoil ions decreases to the point where it provides no meaningful constraint on the limiting cross section of the test unit. If the test unit is an individual piece part, one can usually impose an independent limit on SEE cross section, e.g. the size of the die or some fraction thereof (based on data for similar parts). When testing a board or a box, there is nothing to stop the sum of piece-part SEE limiting cross sections (and therefore the bounding SEE rate) from increasing linearly with the number of parts on the board. As test items increase in complexity, it becomes more important to test with a high test fluence (10^{11} protons/cm²) and if possible a higher proton energy to minimize the probability that serious SEE modes go undetected. However, if only proton testing is conducted, the bounding rate should scale with the number of components in the test unit.

For destructive SEE and other SEE modes with deep SV, the problem is similar—inadequate coverage of proton recoil ions as onset LET increases or for modes where σ vs. LET rises slowly with LET. However, the situation is complicated by the fact that each destructive SEE mode for each device may have a different SV depth, so the recoil ion fluence vs. LET_{EQ} may be different for every susceptible device in the test unit. Not only does the compression of recoil ion fluence distributions toward lower LET_{EQ} result in increasing bounds on DSEE rate with increasing SV depth, at some point protons fail to provide any meaningful bounds at all, even for high fluences. Table I shows that for 200-MeV protons, even a 10- μm SV

depth requires additional evidence or assumptions to place meaningful bounds on SEL (or other DSEE) rates. If the SV depth $\sim 30\ \mu\text{m}$ —not uncommon for SEL, SEB or SEGR—then even high fluences ($>10^{11}\ \text{cm}^{-2}$) of 400-MeV protons fail to bound the failure rate. This suggests that it is important to understand as much as possible about the technologies of the potentially vulnerable parts that make up the test system.

VII. Conclusions and Future Work

We have developed techniques for evaluating the constraints proton SEE test results can place on heavy-ion SEE susceptibilities by proton SEE test results. These techniques range from simple geometric criteria to bounding SEE rates based on proton test results. Even if little is known about the device being tested, the areal coverage figures from section II provide a metric for evaluating the thoroughness of a test (proton or heavy-ion) in realizing SEE modes of the device. If one can estimate the onset LET or other characteristics describing SEE susceptibility, the metric can be refined. If one knows the feature size, the areal coverage can be converted into an effective number of transistors to provide a measure of the complexity of areas not probed for SEE susceptibility.

The rate-bounding procedures use a CRÈME-MC emulator, which summarizes results of Monte Carlo simulations of energy deposition of proton recoil and cascade ions in representative single and nested sensitive volumes in terms of distributions of ion fluence vs. equivalent LET (LET_{EQ}). We then use these results to bound the number of such sensitive volumes that could be present in a device and still give rise to a null result for a test with a given fluence of protons of a given energy. These studies show that for shallow sensitive volumes (and so most nondestructive SEE), protons can bound rates adequately as long as LET_0 for the SEE mode is less than $\sim 6\ \text{MeVcm}^2/\text{mg}$ and the SEE cross section rises rapidly above LET_0 (Weibull parameters $s < 2$ and $W < 20$). Bounding rates for destructive SEE is more problematic. For $3 \times 10^{11}\ 200\text{-MeV protons/cm}^2$ incident on SV with depth $= 10\ \mu\text{m}$, over 40% of even the models with low LET_0 and rapidly rising σ vs. LET fail to find a meaningful bound. Although 400-MeV protons perform better (nearly 90% of models considered resulting in meaningful bounds), these also fail as SV depth increases to $30\ \mu\text{m}$ (not uncommon for SEL in bulk Si CMOS). These results show that additional assumptions or data (perhaps incorporated into Bayesian priors) are needed to supplement the relatively weak constraints proton testing imposes on heavy-ion destructive SEE susceptibility.

Finally, we pointed out some of the additional complications that result when testing is carried out at the board or box level rather than the piece-part level. In particular, the fact that SEE sensitive volumes having different depths may experience a different recoil ion fluence vs. LET_{EQ} .

Acknowledgments

The authors thank the NASA program and the NASA Engineering and Safety Center for supporting this research.

References

1. O'Neill PM, et al. Risk Assessment for Heavy Ions of Parts Tested with Protons. IEEE Trans Nucl Sci. 44(6):2311.1997; [PubMed: 11542769]
2. O'Neill P, Badhwar G, Culpepper W. Internuclear cascade- evaporation model for LET spectra of 200 MeV protons used for parts testing. IEEE Trans Nucl Sci. 45:2467–2474.Dec.1998 [PubMed: 11542300]
3. Hiemstra DM, Blackmore EW. LET Spectra of Proton Energy Levels From 50 to 500 MeV and Their Effectiveness for Single Event Effects Characterization of Microelectronics. IEEE Trans Nucl Sci. 50(6):2245.2003;
4. Foster CC, O'Neill PM, Kouba CK. Risk Assessment Based on Upset Rates from High Energy Proton Tests and Monte Carlo Simulations. IEEE Trans on Nucl Sci. 55(6):2962–2969.Dec; 2008
5. Ladbury R, Lauenstein J-M, Hayes KP. Use of Proton SEE Data as a Proxy for Bounding Heavy-Ion SEE Susceptibility. IEEE Trans Nucl Sci. 62(6):2505–2510.2015;
6. Adams JH, et al. CRÈME: The 2011 Revision of the Cosmic Ray Effects on Micro-Electronics Code. IEEE Trans Nucl Sci. 59(6):3141–3147.2012;
7. Intel I7. www.intel.com/pressroom/kits/quickreffam.html, 1/6/2016
8. Warren KM, et al. Application of RADSAFE to Model the Single Event Upset Response of a 0.25 μm CMOS SRAM. IEEE Trans Nucl Sci. 54(4):898.2007;
9. Schwank JR, et al. Effects of Particle Energy on Proton-Induced Single-Event Latchup. IEEE Trans Nucl Sci. 53(6):2622–2629.2005;
10. Ladbury R. Statistical Properties of SEE Rate Calculation in the Limits of Large and Small Event Counts. IEEE Trans Nucl Sci. 54(6):2113.2007;
11. Irom F, Agarwal SG. Compendium of Single-Event Latchup and Total Ionizing Dose Test Results of Commercial Analog to Digital Converters. IEEE Radiation Effects Data Workshop 2012. :50–63.2012
12. George JS, et al. SEE Sensitivity Trends in Non-Hardened High Density SRAMs with Sub-Micron Feature Sizes. IEEE Radiation Effects Data Workshop 2003. :83–88.2003
13. Ladbury R, Campola MJ. Bayesian Methods for Bounding Single-Event Related Risk in Low-Cost Satellite Missions. IEEE Trans Nucl Sci. 60(6):4464–4469.2013;
14. Turflinger TL, et al. RHA Implications of Proton on Gold-Plated Package Structures in SEE Evaluations. IEEE Trans Nucl Sci. 62(6):2468–2475.2015;

Fig. 1.

Because only one of $\sim 289,000$ 200-MeV protons generates a recoil ion, 10^{10} cm^{-2} (a) generate enough ions to strike only a few of the feature types in this $60 \times 70 \text{ } \mu\text{m}^2$ area of an ELPIDA EDS5108 512 Mbit SDRAM. Increasing the proton fluence by $100\times$ generates (b) only $\sim 3\times$ fewer ions than the area would see on average in a typical heavy-ion test run with fluence 10^7 ions/cm^2 (c) and provides reasonable coverage of the different feature types in the SDRAM. Bounding Heavy-Ion SEE rates with Protons.

Fig. 2.

In a test with a low ion fluence, fluctuations can lead to areas much larger than the average area per ion that see no ions during the test. The black, solid line shows the mean area that receives a single recoil-ion strike. Poisson fluctuations mean that 10% of areas with sizes along the solid dark grey curve and 1% of areas with sizes along the light grey curve had 0 recoil ion strikes. And in testing multiple chips (e.g. in a board-level test), 10% of the chips would have contiguous areas of the sizes along the dashed grey curve with 0 ion strikes. The right vertical axis shows the approximate transistor count for the 45-nm CMOS generation found in the areas on the left vertical axis.

Fig. 3. Recoil ion fluence vs. LET falls rapidly with ion range. Requiring 6- μm range reduces fluence $\sim 10\times$; requiring 10- μm drops the fluence by $\sim 100\times$.

Fig. 4.

Knowing the fluence vs. LET_{EQ} generated by a proton test and the number of events observed allows one to determine the candidate σ vs. LET curves that are consistent with the observed result for a given confidence level. The σ vs. LET curve that yields the worst rate then bounds the rate for the proton test at that confidence level (in this case, the 90% CL).

Fig. 5.

Fluence vs. equivalent LET (LET_{EQ} , defined in Eq. 3) becomes increasingly depleted in higher- LET_{EQ} ions as the depth of the sensitive volume increases. For depths greater than $\sim 10 \mu\text{m}$ (common for destructive SEE), constraints on heavy-ion rates will be weak.

Fig. 6.

To better capture the increase of SEL σ vs. LET, while keeping manageable the number distributions of recoil ion fluence vs. LET_{EQ} , the sensitive volume was approximated as a series of nested SV. Fluence vs. LET distributions were generated using CRÈME-MC for each sub-volume.

Fig. 7.

Bounding rates at the 90% CL for 10¹⁰ (a) and 3×10¹¹ (b) 200 MeV protons/cm² as a function of onset LET (LET₀) and Weibull width and shape parameters w and s. The device limiting cross section is the value that yields an expected event count equal to the Poisson mean upper limit for the observed event count (in this case, 0). For σ vs. LET_{EQ} models where the proton test method fails to place a meaningful limit on the cross section or rate, the rate is represented as a black rectangle having 0 height.

Fig. 8.

90% WC and 10th WC roughly follow power laws as a function of increasing proton fluence. (The 10th WC is determined by ranking the SEL rates for all models from worst to best and selecting the model whose rate falls in 10th place. That it follows similar trends to the WC shows that the WC is not an outlier.)

Fig. 9.

Efficacy of protons for bounding heavy-ion SEL rates increases with proton fluence. High energies maximize the probability of finding a bound.

Fig. 10.

Although fission fragments resulting from p+Au reactions start with high LET, their ranges are limited, so LET_{EQ} decreases steadily as the depth of the SV for an SEE mode increases. For SEE modes with SV depth > 30 μm, fewer than 20% of fission daughter ions have LET_{EQ} > 10 MeV•cm²/mg.

Table I

Parameters w/>50% Successful Bound

Parameter	LET ₀ (MeVcm ² /mg)	s	w
Fluence (cm ⁻²)			
200 MeV, 10 ¹⁰	<2	<1	<10
200 MeV, 3×10 ¹¹	<5	<1.7	<22
400 MeV, 10 ¹⁰	<3.5	<1.2	<12
400 MeV, 10 ¹¹	<6.5	<2.2	<25