GEOMETRICAL FACTORS IN SEE RATE CALCULATIONS

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Abstract

The prediction of single event rates depends upon a number of geometrical factors that affect the interpretation of the ground test data and the approach to rate calculations. This paper presents a critical review of these factors. The paper reviews heavy ion rate prediction methods and recommends a standard approach.

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I. INTRODUCTION

There are a number of geometrical effects and approximations that enter into single event effect (SEE) rate calculations. Reference 1 discussed many of the approximations that enter into the standard form of calculation that assumes a rectangular parallelepiped (RPP) charge collection geometry. This paper will reexamine the interpretation of the cross section curve, reexamine the finite depth effects discussed in reference 1, examine some implications of the funnel effect, and compare the methods and results for several non-RPP approaches to upset rate calculation.

Modern devices are much smaller and more complicated than those initially described in the traditional models. Several experimentalists have observed unusual behavior and said that the traditional models did not work, but did not suggest alternative approaches that could be applied for the general case. This series of papers attempts to extend the traditional models as necessary to explain the "unusual" data. This will give the community a better idea of where the models really break down, and new models needed.

We reexamine the interpretation of the basic cross section curve. Reference 1 interpreted it as a sensitivity curve. We find it necessary to return to a geometrical interpretation, at least for some devices.

The paper will examine a number of possible geometrical effects that may show up in either upset measurements or upset calculations. The geometrical effects will be examined with respect to a number of unusual experimental measurements and will attempt to fit these results into a common set of concepts. In most cases the results will not be decisive and there will still be room for alternate analysis. In some of these cases it may be necessary to perform detailed charge collection or microbeam experiments in order to reach closure. However, we believe that the concepts and questions that we introduce are fundamental for a complete understanding of single event upsets in modern devices. In particular, we continue to maintain that the basic upset cross section curve can be represented by a single smooth curve.

Interpretation of geometry effects enters into SEE rate calculations at two distinct stages: (i) reduction of that accelerator data used to characterize a device and (ii) estimation of device performance in a space environment. In the reduction of accelerator data, the experimenter attempts to interpret his/her results in terms of the RPP geometry, a critical charge, and a funnel length. Corrections applied at this stage reconcile different cross section curves obtained with different beam angles and LET. It is essential at this stage to resolve any inconsistencies in the data. Care in the treatment of funnel and finite geometry effects is often
necessary to achieve a complete understanding of the accelerator data.

Estimation of device performance in space is closely linked with interpretation of accelerator data. At a minimum, a space environment modeling tool should allow for the RPP geometry, critical charge, and funnel. If the accelerator data interpretation requires additional features, those features must be reflected in the space modeling tool. Of particular interest in this regard is the possibility that funnels may be truncated by device features such as a very heavily doped substrate, or a non-conducting substrate.

The single event rate in space depends acutely on the size and geometry of the device, as well as on its sensitivity and on the space environment. A number of methods of calculating rates in space have been presented and used. Some of these use accurate models, some use approximate models, and some use inappropriate models. We discuss most of the common models and compare some of their results.

The funnel effect may make an important contribution to the charge collection in some devices. Unfortunately it is not completely clear which ones. We will summarize the knowledge of the funnel effect and indicate approaches for including the funnel into upset rate predictions.

It should be understood that we are attempting to model the upset process with simplified charge collection models coupled with a model of idealized geometry. In reality, the processes involved in upset may be quite complex. Upsets are measured in terms of bits. The circuit that comprises a bit may be simple, as in an NMOS SRAM, or it may be a chain of gates, as a J-K master-slave flip-flop. Different devices made with identical transistor geometries may have quite different upset responses to ion bombardment, depending on the circuit. In multi-layered structures there are phenomena such as the shunt effect to confound the process.

Our models are based on the assumption that there is a fixed geometry for the region sensitive to upset, and that there is a critical charge for each node. There may be statistical distribution of critical charges and there may be a distribution of charge collection across the sensitive region. We ascribe all of the variability to either a distribution of critical charge, or to changes in the effective area for charge collection. These two sources of variability are essentially equivalent as far as the calculation of upset rates is concerned. The justification for our total set of assumptions is that they are reasonable, they form a coherent picture, and they work for older devices for which there are flight data.

II. IMPORTANCE OF THE DATA

The analysis of SEU test data consists of two parts. The first part requires that the sensitivity of the storage elements be determined. Sensitivity is defined in terms of critical charge required to upset the data storage or bit stream. The second part requires that the probability of exceeding the critical charge be determined for the environment of interest.

For each case it is required that the amount of charge collected be determined in order to either define the critical charge or to detect if it was exceeded. It is important to point out that the methods used to determine the charge collected differ somewhat in each case.

The cross-section vs. effective LET curve represents the only measured information that is available for the device under study. All other information must either be derived from previous knowledge or by making an educated guess. For most experimenters, the other information must come from making educated guesses. For these reasons, the cross-section curve becomes the only link to real upset data. Because the cross-section curve represents the only measured information, the correct interpretation of this curve is critical for the most accurate modeling of an upset rate. The cross-section curve can be misleading due to uncertainties on either axis.

The basic assumption that is made when interpreting the cross-section curve is that it represents the cross-section of the entire chip as a function of effective LET. This seems like a simple statement, but is it the cross-section of each individual cell that appears to increase or decrease as a function of effective LET and ion, or is it that the number of sensitive storage cells is changing with LET? How much of the measured cross-section is due to the top surface of the sensitive volume and how much is due to the side of the sensitive volume? Does the path have to pass through the entire depth of the sensitive volume? In addition to questions associated with the cross-section, there are also questions about effective LET. Is the LET of the ion within the region where charge is collected what it is believed to be? Does the charge deposited within the charge collection region follow the cosine law? Both of these questions must be answered when using the concept of effective LET.

III. INTERPRETATION OF CROSS SECTION CURVE (REVISITED)

One of the basic concepts behind the approach to upset rate calculation is the interpretation of the heavy ion cross section curve. Reference 1 attempted to make a case that the curve represented a distribution of cell sensitivities. In this approach, a data point at 20% of the limiting cross section indicates that only 20% of the cells will upset at that effective LET. This is consistent with the interpretation of bulk CMOS data by Kohler and with previous unpublished measurements of Cousins (2,3). It is inconsistent with the knowledge that some technologies, e.g., bipolar and GaAs have several sensitive regions, of different sensitivities, and that even CMOS has two different regions. It is also inconsistent with some experimental observations that charge collection efficiency seems to depend on the location of the hit, even in a single structure.

Massengill has recently examined a SOI CMOS SRAM(4). He has concluded that the distribution of
parasitic structures in the SOI, particularly bipolar gain, can account for the spread in the measured cross sections. There is a variation of critical charge with location across individual cells, due to geometrical variations of the bipolar gain, and a statistical distribution of critical charge due to process variation effects on the parasitic bipolar beta.

Cutchin and Marshall attempted to examine this issue experimentally in a GaAs device (5). Rather than examining carefully the bit locations in a series of runs, they took a series of cumulative runs and examined the total number of bits upset from their initial values. In this approach the bits will start to reflip, and the total number of upset bits will have a probability distribution saturating at 50% of the upsettable bits. They were testing the device in fig 2b at a LET of 2.5 MeV/mg/cm², corresponding to approximately 20% of the limiting cross section. In the sensitivity interpretation, their curve should saturate at 10% of the total number of cells. Figure 1 shows their results. The data follows the curve to be expected if all of the cells are susceptible with a cross section of 20% of the limiting cross section.

The introduction of the geometrical interpretation of the cross section curve introduces complications in the interpretation of the data. If the ascending portion of the curve is due to larger and larger areas being sensitive, then over much of the curve the depth of the sensitive volume may play a significant role in the measurements. Furthermore the role changes as the area changes. Although we will have relatively simple equations to approximate the depth effects, their application will depend not only on the angle of the beam, but on the portion of the curve being sampled.

We need to reexamine the influence of interpretation of the upset curve on the upset rate calculation. If the differences are appreciable, then it may be necessary to have two types of calculation. The examination, later in the paper, shows that the two different interpretations of the curve have very little impact on the predicted upset rates.

IV. GEOMETRICAL FACTORS

Charge Collection

Charge is collected by diffusion from neutral regions and by drift in depletion regions augmented by funnels.

Diffusion is a relatively inefficient process, since about half of the charge from a source migrates to inactive regions of the device. Furthermore, charge collection from distances greater than about 2μm is much slower than that collected by drift. Kirkpatrick and Edmonds have given analytical treatments of the diffusion process with different boundary conditions (6,7). According to Kirkpatrick, the charge collected in a sensitive region from a point source is proportional to the solid angle subtended by the region from the source.

The efficiency of charge collection by drift (enhanced by the effects of funnels) approaches 100%. Furthermore the process is fast. Circuits with short time constants (a few nanoseconds) will respond only to the drift component of charge collection. Diffusion is important for the slow (millisecond) circuit of modern NMOS RAMs because of the large efficiency for charge collection.

The collection of charge by drift is enhanced by the effects of funnels. Funnel effects arise when the ion track distorts the electric field lines in a device in such a way that charge is collected beyond the normal depletion region. This can affect the device sensitivity and upset rates, especially for bulk technologies. We want to consider the approaches to upset measurements and rate calculations that attempt to include the funnel effects. Previously it has been shown that errors in the funnel length assumption tend to cancel, to first order, but if the error rates are more accurately modeled by the integration of the measured LET curve with the known space environment, we will be losing some of the built-in margin. The use of improved calculational approaches means that we must be careful to model the other assumptions more accurately.

Funnels as a phenomenon of charge collection were first reported by Hsieh (8). He and his coworkers made a numerical study of charge collection from alpha particles on diodes and verified it with measurements with fast oscilloscopes. They distinguish collection by drift and collection by diffusion with the time dependence. There was no general analysis to show the systematics of the process as it depends on the ion properties. They noted that a near miss (1μm) would result in charge collection by a funnel. One study at 45° showed that the fields were not axisymmetric.

A model was published by Hu in 1982 (9). He gives the depth of collection in an n-p junction as:

\[ \text{depth} = \left( 1 + \frac{\mu_n}{\mu_p} \right) W \]
where $W$ is the depletion width at the end of the strike and the ratio is of the mobilities in the column. The collection length for an ion at an angle is the depth multiplied by $\sec \theta$. The dependence of the collection depth on doping is an inverse square root, the same as for an abrupt junction. The model predicts a collection depth independent of the LET of the incident ion.

McLean and Oldham (M-O) also published a model for heavy ions in 1982, with later updates (10,11,12). The M-O model has been tested only for ions at normal incidence. McLean and Oldham gave the caveat that their model is least accurate for ions of high LET, such as those used in simulation tests. Further, that it was developed for "thick" diodes, and was not intended to describe charge collection in layered structures that complicate the charge collection process.

The M-O model linearizes and separates some of the complex processes of the funnel. It too should not be extended to more complex situations, but it does explain fairly well the observations for ions at normal incidence on large diodes. There are some non-linear features of the model, and the solution for the collection depth must be found by iteration. Even if the Hu angular distribution is used, the M-O model should give a more accurate estimate of the depth of the drift region.

Picket examined the experimental data available in the early charge collection experiments and obtained an empirical model for the dependence on LET and doping (13). The results of this work are outlined in appendix b.

All of the funnel models are essentially phenomenological models not to be taken too seriously. We will see later that the upset rate does not depend strongly on particular funnel assumptions. However, with the advent of improved charge collection codes it is perhaps time to revisit funneling.

Symmetrical treatment of the funnel is crucial during accelerator data reduction and during upset rate calculations. It affects the calculation of collected charge, and therefore the calculated critical charge and error rate in space. The calculated collected charge is determined from the sum of the depletion depth $z$ and the funnel length $F$ by (in Silicon):

$$Q(pC) = 0.01 \times L(\text{MeV/mg/cm}^2) \times (z+F) \mu \text{m}$$

**Measurements of Angular Distributions**

Our models of funnels are based on test with ions incident perpendicular to the surface of diodes with a large lateral dimension. There are only three sets of measurements reported for the angular dependence of charge collection. The first measurements of the dependence of charge collection in diodes were reported by Campbell and his coworkers in 1983 (14). They used accelerators of a relatively low energy to study ions from H to Cu that had nearly the same range of about 15$\mu$m in silicon. They made measurements on diode structures with epitaxial construction and n on bulk p. Although they used both fast and slow charge collection systems, the angular dependence studies were for total charge collection.

Campbell observed a radically different efficiency for total charge collection in the bulk material and in the structures with epitaxial construction. The charge collection efficiency increases almost linearly in the secant for the epi device. If plotted as a function of effective LET, the collected charge increases nearly linearly. This would be expected for the Hu model.

The collected charge in the bulk devices decreases with the secant of the angle. When plotted versus effective LET, the curve actually decreased. The authors state that this behavior is consistent with the diffusion theory of Kirkpatrick.

Another measurement of angular distribution was made by Shanfield and co-workers using the fast portion of the current collection pulse for alpha particles incident on diodes (15). They concluded that the amount of charge collected by funneling was proportional to the path length through the depletion region.

A recent set of measurements has been made by McNulty and co-workers (16,17) They observe the effective cross section for the total charge collection pulse as a function of incident angle. This seems to scale with the area corresponding to particles passing through the entire depth of the depletion region. Unfortunately their measurements are made with no voltage on the device and include only the funnel from the junction potential, and so say little about the angular dependence with funneling.

**Data Discontinuities**

The basic experimental data obtained at a particle accelerator in SEE tests consists of a series of points of upset cross section as a function of particle linear energy transfer (LET) and angle. The data are ordinarily plotted as a function of effective LET as discussed in reference 1 and later in this paper. The data may or may not appear as a smooth function of LET for different particles. The data are often presented on a logarithmic scale of cross section, so that discontinuities are obscured.

Figure 2 shows examples of data that do not fall on a single smooth curve. The cross sections have been calculated using $\cos \theta$ and the LET has been changed to effective LET using $\cos \theta$ as applied to the LET at the surface of the device. The data is plotted using lines to connect data points obtained with a given ion. None of these cases can be represented with cross section as a smooth function of LET.
Figure 2. Data showing discontinuities in the measured cross section when ions are changed to give the same effective LET.

Figures 2a and 2b show results where the data obtained at 60 degrees are higher than expected when compared with normal incidence results. Figures 2c and 2d show results where the data at 60 degrees is lower than expected.

The devices that led to the discontinuities shown in figure two are the following:

a) 6504RH, CMOS on epi (18) The structure was discussed by McNulty (17) and in many earlier papers.

b) GaAs complementary heterostructure insulated gate FET(5). The active region in this device may be shaped like an inverted mushroom, so that the apparent area for charge collection increases as the ions come in at an angle.

c) AS 200 CMOS bulk, 1 micron feature size gate array. Data furnished by Aerospace (19) Similar data has been observed with UTMC gate arrays.

d) SNL 89 1 micron cmos twin tub on thin epi (20).

There are four possible reasons (at least) for the measurement of different cross sections with different ions of the same nominal effective LET: [1] Energy loss of the ion as it penetrates to the sensitive region so that its LET is not the surface LET (1), [2] The device has an appreciable depth so that the cosθ correction to the cross section is not appropriate (20,1), [3] The funnel effect is important so that the cosθ correction is not appropriate for the LET calculation (21,22). [4] Two ions of same nominal LET may have entirely different track structure, so that the effective area of device plus track changes (23).

We will examine the first three of these and see what impact that they have on the interpretation of the results. We will retain as long as possible the assumptions that the single event phenomena should be able to be represented as a smooth function of some effective LET, and that data points
obtained at normal incidence accurately measure this behavior.

Energy loss effects

An integrated circuit is composed of an active device region covered by a relatively thick passivation region. Any energy lost by the ion within the passivation region will change the LET of the ion before it reaches the active device region. This loss in energy must be considered. Just as the energy of the ion decreases as it passes through the passivation region, the ion will also lose energy as it passes through the region of the device where charge can be collected. This loss in energy must be considered.

Reference 1 discussed the effects of energy loss with representative beams and gave several examples of the necessary modification of LET. The devices in figures 2a and 2b have had this correction applied. Clearly none of the discontinuities are entirely removed by applying this correction, and one can not examine the corrections in this way to determine a unique device depth. It is necessary to apply some knowledge of the device structure in order to determine the appropriate depth for the energy loss correction.

Influence of device structure.

The basic RPP approach assumes a very simple structure with a well-defined rectangular parallelepiped charge collection region. The introduction of effective LET added the assumption that this volume was thin. These assumptions have been adequate to describe a great amount of experimental data and therefore to serve as the basis of upset rate calculation. Reference 1 summarized these approaches and demonstrated that a number of data samples fit these pictures.

CMOS devices can be fabricated on either bulk or epitaxial starting material. Epitaxial starting material is commonly used to minimize the possibility of CMOS latch-up. CMOS technology is the most common method for manufacturing integrated circuits today and for that reason it is very likely that there is some thickness of a lightly doped epitaxial layer over a heavily doped substrate. The charge collection depth will be limited if the heavily doped substrate is encountered before the natural limits of charge collection. By natural limits, we refer to funnel length that is dependent only on the well doping and the applied bias. The charge deposited in the heavily doped substrate is the same as in the other regions of the silicon substrate, but because of the very short carrier life times, recombination of the charge is more likely. Heavily doped n-type substrates limit the charge collection more efficiently than heavily doped p-type substrates. The reason for this difference is that the diffusion rate of the typical p-type dopant (boron) is much higher than that of the typical n-type dopant (antimony) and this limits the ultimate allowable dopant concentration. Because of the lower dopant concentration, it is believed that charge collection can extend into a heavily doped p-type substrate. This is much less likely on heavily doped n-type substrate.

It becomes necessary to look at more detail of the device structure when we attempt to reconcile the discontinuities in the data observed in more careful measurements and in recent small scale devices. The features that we need to be aware of are the following:

a) a well defined charge collection volume, but one with an appreciable length compared to lateral dimensions.

b) possibility of charge collection due to funneling from below the device.

c) any barriers that may truncate the charge collection process.

d) possibility of charge collection from the sides of the device due to device structure or funneling.

e) features of the device that can lead to angular dependence in charge collection or charge collection response.

V. FINITE DEPTH EFFECTS AND CROSS SECTIONS

The second possible explanation for these effects is based on the realization that some devices can not be approximated as being very thin. Figure 3 shows the geometry for a well-defined collection volume and experimental arrangement. The device cross section for normal beam incidence is x times y. The distance y is the length of the device measured into the plane and x is the width of the device. If the beam is rotated some angle θ around the y-axis, the cross section is y times another distance p, the projected chord. The ratio of x/p is the factor needed to convert the cross section measured at the angle θ, σ_m, back to the cross section at normal incidence, σ_0.

\[
σ_0 = σ_m \times \left(\frac{x}{p}\right) \tag{2}
\]
For a thin target the projected chord \( p \) is \( x \cos \Theta \) (the distance \( a \) in figure 3). The actual cross section is larger than the measured cross section and the correction is:

\[
\sigma_0 = \sigma_R = \sigma_w \times (\cos \Theta)^{-1}
\]

This expression is normally assumed to describe the cross section and the value of cross section that is reported is \( \sigma_R \). In cases below, where this assumption does not apply, the actual cross section is obtained by substituting:

\[
\sigma_w = \sigma_R \times \cos \Theta.
\]

Sexton assumes that the correction should be for a projected chord of length \( b \), and is the ratio of \( x \) to \( b \) \((20)\). This corresponds to an upset any time that a particle intersects any part of the sensitive volume. This approach corresponds to assuming that high LET particles are incident that can upset regardless of the path length. This corresponds to the upper end of the \( \sigma \) vs. LET curve, unless funneling is important. If there is charge collection by funneling from the sides of the device, then tracks that intercept the corners may still cause upset and the correction applies at all LETs. This approach may describe devices such as a and b that may have charge collection from the sides.

\[
\sigma_0 = \sigma_w \times \left(\cos \Theta + \frac{z}{x} \sin \Theta\right)^{-1}
\]

The effect of this correction is to reduce the reported cross section at large angles for all LETs.

The correction introduced by Petersen assumes that the correction should be for the ratio of \( x \) to \( c \) \((1)\). This assumes that upset can only occur if the particle passes through the full path length available, and corresponds to the lower LET end of the \( \sigma \) vs. LET curve. This correction will also apply to certain charge collection experiments. These examine the cross section corresponding to full energy deposition by counting the number of events that occur in a charge collection peak with no voltage applied, thus without the funnel effect. \((16, 1, 17)\)

\[
\sigma_0 = \sigma_w \times \left(\cos \Theta - \frac{z}{x} \sin \Theta\right)^{-1}
\]

This correction may also apply to devices with funneling if the funnel depends on the particle passing through the entire depletion depth.

If the RPP assumption is truly valid, and funneling is not important, then these corrections apply only in the extreme and the actual correction must pass smoothly from one expression to the other. Appendix A derives an expression for this transition behavior. This correction may apply to devices that have well-defined charge collection regions both laterally and vertically. The effect of the correction is to raise the large angle data at small LETs and reduce the reported cross section at large LETs.

The two types of geometrical effects discussed here do not explain all types of observed discontinuities, in particular the species dependence at normal incidence observed by Criswell \((24)\).

### VI. EFFECT OF FUNNEL ON EFFECTIVE LET

Several authors have suggested that discontinuities in the data, such as observed in figure 2, result from the breakdown of the effective LET approach. Golke was the first to present this on a quantitative basis, based on the funneling concepts \((21, 22)\). We will present arguments parallel to his, but arriving at what we believe is an even stronger conclusion. Remember that the concept of effective LET appears only in the calculation of experimental data, and that it does not appear in upset rate calculations.

Figure 4a shows again a simple structure with the path lengths corresponding to two angles. The idea of effective LET was introduced to compare the amount of charge produced (corresponding to energy deposited) by the two tracks. As path \( x1 \) at \( 60^\circ \) has twice the length of \( x1 \), for the same LET ion, there will be twice the charge generated. It is then convenient to plot effective LET to represent the charge deposition.

\[
E = \frac{dE}{dx} \times \frac{x}{\cos \Theta} = LET_{\text{eff}} \times x
\]

Figure 4b shows the same volume with an additional length \( F \) added to the track, corresponding to a funnel length. Here we are assuming that the funnel length is independent of angle. The energy deposited in this case is:

\[
E = \frac{dE}{dx} \times \left(\frac{x}{\cos \Theta} + F\right)
\]

We cannot introduce an effective LET in this case, and the common usage of doing so introduces an error.
Consider two ions with the same effective LET, one at normal incidence (a), and the other at 60°(b), with x = F. 

\[
E(a) = \text{LET}_\text{eff}(a) \times (x + F) = 2 \times \text{LET}_\text{eff}(b) \times 2x = 4 \times \text{LET}_\text{eff}(b) \times x
\]

\[
E(b) = \text{LET}_\text{eff}(b) \times \left( \frac{x}{\cos \theta} + F \right) = \text{LET}_\text{eff}(b) \times 3x = 3 \times \text{LET}_\text{eff}(b) \times x = \frac{3}{4} \times E(a)
\]

In this example a data point obtained at 60° corresponds to 3/4 of the LET at 0°, and may have a much lower cross section if taken on the threshold portion of the cross section curve. This effect can lead to significant discontinuities for experiments that use several ions. 

The inverse argument can now be made, assuming constant funnel length. If there is significant funneling with a constant length funnel, there should be observable discontinuities in the cross section data. Indeed, it appears that the discontinuities are a measure of how much of this type of funneling there is. If discontinuities are not observed, that is an argument for no funneling for funnels of constant length. This type of discontinuity would not be observed for funnels of constant depth. However funnels of constant depth may lead to the discontinuities described by equation 5 above.

The effect is slightly more complicated if the funnel region is truncated by a device structure at D in figure 4b, with the natural funnel length F being longer than the distance d. In this case the energy deposition will follow the cosine law for angles at which the funnel is intercepted by the substrate layer, and this form of discontinuity will not be observed.

Following Golke, we introduce a corrected effective LET such that the charge deposition is still calculated using the available depth at normal incidence. The LET of the ion is normalized for the actual path length relative to the path length at normal incidence.

\[
\text{LET}_{\text{eff}, x} = \frac{x}{\cos \theta} \left[ \frac{\text{LET}_\text{eff}(b) \times \left( \frac{x}{\cos \theta} + F \right)}{(x + \min(F, d))} \right]
\]

The energy deposition that is calculated to obtain the charge deposited is:

\[
E = \text{LET}_{\text{eff}, x} \times (x + \min(F, d))
\]

It is presumed that you have some information about x, and perhaps about x+d. The values of F and d can then be adjusted so that the discontinuities in the data are removed and a single smooth cross section curve is obtained. Golke interpreted his version of equation 10 so that the funnel has to interpret structure D before a corrected LET could be uniquely determined. We believe that these concepts apply in the more general case. Note that in this interpretation it is possible to calculate the funnel length from an assumed x (if d > F).

An analytic curve is fit through the normal incidence points, so that any other cross section value will be at a well-defined \( L_\text{C} \). For a point obtained for an ion of LET \( L_0 \),

\[
F = x \times \left( \frac{L_\text{C}}{L_0} \cos \theta - 1 \right) \left( 1 - \frac{L_\text{C}}{L_0} \right)
\]

The effect of this correction is to reduce the reported effective LET for data obtained at large angles, moving the upper end of individual particle results to lower LET.

If the funnel is very long, so that the structural limit at D in figure 4 defines the funnel charge collection at all angles, then the discontinuity due to effective LET may not be apparent. The discontinuity due to area should still be apparent unless the basic charge collection region is very shallow. If the funneling depends on full penetration of the depletion region, then a similar discontinuity will appear that is described by equation 5. In this case the correction raises the large angle points, while the funnel correction in equation 10 shifts them to the left.

VII. APPLICATION OF GEOMETRICAL AND FUNNEL CORRECTION TO REPORTED DATA.

We will apply these corrections to data from several real devices but will use geometry that may be simpler than the actual device layout. The sensitive regions may be L shaped or they may be rectangular with different orientations from device to device on the chip. We are emphasizing the application of the concepts. A detailed analysis of specific parts may involve combining similar calculations for several areas. In most cases a detailed analysis is not necessary as the purpose of this analysis is to show that the data can be placed on a smooth single curve, and to perhaps indicate slight corrections to the upset rate parameters (depth or funnel characteristics).

If we accept the geometrical interpretation of the sensitivity curve, then the corrections expressed in equations 4 and 5 need to have the a/x factor a function of the location of the zero degree point on the cross section curve. x should vary as the square root of the area, so that a/x for a set of points with the zero degree point at 1/10 of the limiting cross section should be larger by a factor of \( \sqrt{10} \) times the corresponding points at the limiting cross section. Another consequence of this approach is that data taken slightly above onset, representing very small surface area, may have upsets at small or intermediate angles, and no upsets at larger angles, as the ion path does not pass through enough of the
depletion region to form an adequate funnel. This phenomenon may explain a portion of the data presented by Golke (22).

The effect of a funnel on the apparent cross section was indicated above in equation 4. If the device charge collection is constrained to a thin layer due to the presence of a conduction or insulating layer, then the only funneling is at the edge of the device. In this case the angular dependence of cross section does not follow the cosine of the angle, and the data at large angles is larger than expected. This leads to situations such as figure 2a and 2b. Figure 5 shows this data corrected for z/x ratios of 0.2 and 0.3.

Sexton attempted to apply this correction to the data of figure 2d (20). In this case the correction is in the wrong direction and he concluded that it was not appropriate. Ecoffet applied the same correction to similar data, although apparently not thinking of the funnel effect (25). In his case he also modified the effective LET to an average value in the RPP structure and this aspect led to an apparent smoother cross section curve. This application appears to assume that any ion touching the RPP causes upset, whereas most of the correction is necessary at the lower portion of the cross section curve, where the ions need to pass through the entire device to cause upset and the correction term should approach equation 5. In this case the authors' LET correction would also have the opposite sign.

The funneling correction to effective LET should apply to bulk devices such as c and d. The data in figure 2c and 2d has been corrected empirically for this effect and the results are shown in figures 6c &d. The correction indicated in equation 5 was applied equally successfully to device d in reference 1. Either approach will lead to a smooth curve through the zero degree points. We need additional information to distinguish the two approaches.

Devices that do not have corrections due to the funnel either in depth or to the sides still have a geometrical correction due to the apparent change of area for beams incident at large angles. This is described in appendix A.

The basic conclusion of this section is that discontinuities in the data can be removed by making simple assumptions about the charge collection. The discontinuities are not important for adequate upset rate predictions.

Figure 5. The data of figures 2a and 2b corrected for finite geometry effects assuming that the device upsets if hit anywhere in the sensitive volume.

Figure 6. The data of figures 2c and 2d corrected assuming that the effective LET approximation is wrong. Points at large angles and LETs are corrected by moving to lower LETs.
Funneling can be incorporated into modeling in a number of ways. We examine three approaches below.

Funnel approach 1: The funnel is included in the rate calculation by the use of an effective chord that includes depletion region, funnel, and diffusion. The dimensions of the device are increased to allow for these effects. The upset calculation uses the RPP calculation and includes only the chords interior to the RPP. The original intent of using an extended volume was to account for extra charge collected by diffusion for the RPP in a dynamic RAM case (26). The extended volume may be appropriate in devices with long collection times where diffusion plays a major role.

Approach 1 attempts to represent all salient features of the funneling process without altering the standard RPP model approach. That is, the critical charge and the RPP dimensions are altered to account for all charge collection processes. The same depth is used for calculation of charge deposition in experiments and for the extension of the volume for the upset calculations. The initial standard upset rate calculations in CRIER, CRUP, and CREME used a single fixed volume so that they correspond to approach 1 (27, 28, 29). This approach is also available in the SPACERAD code (30). The discussion in reference 1 assumed that this combination gives an adequate approximation to the actual upset rate in space for most devices, but left the question open for devices in which funneling makes a major contribution. We do not know of any applications of this approach in cases where an appreciable funnel was expected. The funnel has always been handled by method 2 below.

The drawback of this approach is shown in Figure 7. Ion track (a) in Figure 7 passes through the sensitive volume and also accumulates charge in a funneling region. Difficulties occur with tracks (b) and (c). Track (b) passes through the sensitive volume, but has no funneling. Track (c) does not pass through the sensitive volume, but has a non-zero chord length from the funnel. It therefore contributes to the upset rate when it should not. Similar arguments apply if the device is also extended to the sides.

Approach 1 should not be used as the method of including devices with funnel effects. Approach 2 (below) is easily implemented in the upset rate codes and is the approach of choice.

Funnel approach 2a: Assume a small RPP corresponding to the depletion region and then add additional length to each chord to include the additional charge collection due to the funnel.

This approach to funneling was proposed in reference 31. If the calculation used \( C(s) \) as the integral chord length distribution without funneling, then funneling is included by replacing this with the transformed distribution \( C(s + F(L)) \) where the funnel length depends on the LET of the particle. Pickel developed an empirical model using a variable funnel length that has been used in CRIER (13). Appendix B presents this approach. Others have commonly used a single funnel length to describe both the experimental measurements and the upset rate. Modified versions of CRIER and CRUP have been made available that allow either the standard calculation or a case that corresponds to a fixed funnel length (13, 32). This has been the standard approach to funneling used in all versions of SPACERAD (30). This approach is shown in figure 8. Tracks (a) and (c) are treated correctly in this model; however, track (b) has no funnel on one side of the sensitive volume. The approach shown in figure 8 is functionally equivalent to the floating box approach suggested later by Edmonds (33).

Funnel Approach 2b. Assume a small RPP corresponding to the depletion region and then add additional length to each chord to include the additional charge collection due to the funnel, but allow for funnel truncation, or, equivalently, for the funnel having a fixed depth.

There may be limits to charge collection by funneling due to device structures. The funnel is truncated by heavily doped or insulating regions below active epitaxial layers. Charge sharing by neighboring junctions such as the well-substrate junction effectively truncates the funnel. Alternatively, the
situation may be that described above by Hu and by Shanfield where the funnel length is proportional to the length in the depletion region, or that the funnel is truncated by an epi layer.

The approach for truncating the funnel in the upset calculation is based on simple geometrical relations. Consider figure 9a where the depletion region is x and the active epi region is x+d. Charge collection is not allowed beyond d. For an ion path, S, through the depletion region, there is an associated funnel distance SF. From geometrical considerations, \( S/x = (S+SF)/(x+d) \). Then \( S+SF = (x+d)\cdot(S/x) \) is the maximum charge collection distance when \( S/x > 1 \). For \( S/x < 1 \), we define \( SF = (x+d)\cdot S/x \). Notice that the funnel is shortened for paths through the corners of the depletion region. Figure 9b shows the funnels for several ion paths.

Approach 2 can be criticized for not including the cases for which funnels form on both sides of the RPP. This is a rare case, and when it occurs, there are additional complications due to probable doping density differences near the surface as compared to deeper, which will affect the funnel formation, and different recombination kinetics between near surface and deeper down, which will affect recombination. These complications are at least as important as a two-sided funnel.

We would be fooling ourselves if we claim to have modeled the process exactly. We need to remember that this is one of a number of simplifying approximations of a very complicated process. All we need is something that works in terms of giving reasonably accurate results and provides a reasonable unique answer for a set of test data that everybody can calculate for themselves. The other side of the coin is that anyone reporting upset results should give adequate details so that others can repeat their calculations. In particular, for areas such as funneling where there are several options, the option chosen should be spelled out.

IX. ENERGY LOSS IN SEE RATE CALCULATIONS

The cosmic ray energy loss should not enter into generic upset rate calculations because of the very high energies of the cosmic rays and the corresponding very small energy loss as they penetrate materials. However, the standard cosmic ray environment developed by Adams that is used in all of the upset rate codes has a problem in this respect (34). This environment used the best data available at the time that it was developed, and that data hinted at a large low energy component. If this environment is used with no shielding, the predicted upset rate is too high. The undocumented standard is to use 50 or 100 mils of aluminum shielding in the upset rate calculation.

The results of upset rate calculations will vary depending on the shielding thickness and the shielding material. These variations can be easily explored in SPACERAD, which includes 14 shielding materials including aluminum, water, tantalum, CR-39, and lunar soil. Low-atomic weight materials, such as water and plastic, are much more effective at shielding against galactic cosmic radiation than aluminum.

There is a large flux of high-LET heavy ions below 10 MeV in the CREME model. These ions are stopped by 25 mils of aluminum. There can be a large difference in upset rate between 0 and 25 mils for insensitive devices because high-LET ions are causing all of the upsets. Sensitive devices, such as the 93L422, are upset by both low-LET and high-LET ions. Their upset rates do not display great variability with shielding. As the thickness is varied from 25 mils to 100 mils, the 93L422 rate decreases 5%, the 6508RH decreases 10% and the TCS130 decreases 15%.

X. SAMPLE DEVICE CHARACTERISTICS

The following table gives the parameters that are necessary for upset rate calculations. The cross section curve has been reduced to its Weibull parameters: threshold \( L_0 \), width \( W \), and shape \( s \). \( cs \) is the limiting cross section per bit that is used with the Weibull parameters for fitting the experimental data (1). If the experimental cross section curves are discontinuous with ion, either the cross sections or LETs have been corrected using the geometrical arguments above; or much more weight has been given to the normal incidence points.

\[
F(L) = 1 - \exp \left( -\left( \frac{L}{L_0} \right)^s \right) \quad \text{for} \quad L > L_0 \\
= 0 \quad \text{for} \quad L \leq L_0
\]  

13
The depth is assumed to be the depletion region. We have neglected the funnel length on some bulk devices. Section XII shows the effect of including the funnel on the calculated upset rates for these devices. The barrier term applies when there is a limit to the charge collection depth, greater than the depletion depth, and less than the funnel length plus depletion depth. It also applies to constant depth funnels.

Figure 10 shows the Weibull curves for several of these devices. The devices are chosen to provide a range of parameters. The parameters for the 93L422 are from early measurements (35). Later measurements by Shoga and coworkers (36) would give L,W,s,cs of 0.535, 4.27, 0.867, 141e-5 for the AM93L422 and 0.78, 5.6, 1.78, 1.40e-5 for the FSC93L422. We present Weibull parameters for the GaAs device discussed in this paper. The upset rate calculations for this set of parameters should be performed using the GaAs LET spectrum. Only one of the standard SEU codes (SPACERAD)is capable of working with GaAs devices, so for convenience our comparisons were done pretending that this is a silicon device. The actual rates will be 60% of the rates shown in the tables. The R4-25, R50-25, R160-25 device has a very large surface area as it is a D-latch (37). The large area will lead to a relatively large upset rate, even though the device has a high threshold.

![Normalized Cross Section Using Weibull Parameters](image)

Figure 10. Normalized Weibull curves for representative devices.

<table>
<thead>
<tr>
<th>Device</th>
<th>Technology</th>
<th>$L_0$ MeV mg/cm²</th>
<th>W MeV mg/cm²</th>
<th>s</th>
<th>cs cm²</th>
<th>Depth μm</th>
<th>Funnel μm</th>
<th>barrier μm</th>
<th>Ref.</th>
</tr>
</thead>
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<td>nmos</td>
<td>0.487</td>
<td>4.95</td>
<td>1.422</td>
<td>1.71e-6</td>
<td>3</td>
<td>1</td>
<td></td>
<td>16</td>
</tr>
<tr>
<td>93422</td>
<td>bipolar</td>
<td>0.58</td>
<td>5.5</td>
<td>0.8</td>
<td>3.7e-5</td>
<td>2</td>
<td>1</td>
<td></td>
<td>1</td>
</tr>
<tr>
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<td>bipolar</td>
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<td>0.7</td>
<td>2.6e-5</td>
<td>2</td>
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<td></td>
<td>1</td>
</tr>
<tr>
<td>82S212</td>
<td>bipolar</td>
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<td>6.0</td>
<td>0.8</td>
<td>8.7e-6</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
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<td>11.0</td>
<td>1.2</td>
<td>6.65e-7</td>
<td>3</td>
<td>3</td>
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</tr>
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<td>cmos bulk</td>
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<td>30.0</td>
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<td>3.12e-6</td>
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<td>3.5</td>
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<td>fig 2c</td>
</tr>
<tr>
<td>4042</td>
<td>SOS</td>
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<td>25.0</td>
<td>1.4</td>
<td>1.2e-7</td>
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<td>0.5</td>
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<td>1</td>
</tr>
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<td>23.7</td>
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<td>57.0</td>
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<td></td>
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<td>50.0</td>
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<td>4.9e-6</td>
<td>4</td>
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<td>1</td>
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<td></td>
<td></td>
<td>1</td>
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Table I

Characteristics of a number of devices.
XI. COMPARISONS OF VARIOUS UPSET RATE CALCULATIONS

A number of techniques have been used for upset rate calculations. Some of the methods are exact, some are good approximations, some are poor approximations, and some are wrong. It is important that the user have some way of estimating the quality of his results. This section compares the results of calculations for the set of devices in table 1. These devices cover a range of thresholds and shapes and should be a good test of the various methods.

Table 2 shows the results of the calculations. The various methods are discussed below. The method numbers are stated at the top of the table.

The results are for geostationary solar minimum conditions, with 100 mils of aluminum shielding, unless otherwise stated. The environment can be obtained in CREME using M=1 and year=1975.144. If you choose M=3 in CREME, the year is ignored and you get 90% worst-case model. A good approximation is to assume that 90% case is 1.7 times the solar min. case. 90% worst case is useful for estimating the peak, instantaneous cosmic-ray intensity during a mission. On a long mission there will be many 6-hour periods that exceed the 90% worst-case. On a short mission (<2 days) it is conservative to assume that you will encounter the 90% worst-case environment. Solar minimum environment is useful for estimating the average environment encountered in space on a long mission. If you want the mission-integrated upset rate, you should definitely use solar minimum. The solar minimum case seems much more appropriate for device comparisons (1)

1. RPP calculation using Weibull curve and integral.

These calculations use the standard RPP calculations with integration over the Weibull distribution. The calculations were done using the CRIER code. The inputs are cs, L0, w, and s. The area of the RPP is assumed to be the limiting cross section. The collection volume (L, W, H) of each bit is assumed to be the same with L=W=Dcs and H as defined by depth in the input. However the critical charge for each bit is different, determined by the corresponding LET. Each bit is then treated in the normal method for calculating the rate for a RPP and the results are summed with a weighting based on the Weibull function. The calculations assume no funnel except for the 2164, the AS200 and the RK1-05 that have the fixed length funnels indicated in table 1. The results for the integral method will depend on the number of bins. It appears that the results converge and that an adequate number of bins is 50, used in these calculations.

2. The same set of calculations using SPACERAD.

Calculations using CRIER were approximately 10-20% higher. This is very close agreement.

3. Alternative Integral Formulation.

The integration technique used in columns 1 and 2 assumes that the upset cross section varies with LET because each bit in a device has a different critical charge. The cross section curve is measuring a sensitivity distribution. The geometrical cross section is assumed to be the same for each bit.

In section III we presented an argument for the cross section curve actually measuring a variation of physical cross section, with all bits being able to upset at any given LET. This alternative formulation is considered in column 3. Each bit in a device is assumed to be identical. The entries in column 3 were computed with a customized version of SPACERAD. The greatest difference between integral formulations occurs for devices with large aspect ratios (9/sqrt 3).

Generally the alternative formulation gives a result slightly less than the standard formulation (cols. 1 & 2). There is no definitive answer to which integration technique is best. We prefer the standard formulation at this time because it is more conservative.

4. Effective flux approach, Greater upper bound approach

An approximate method of rate calculation that does not depend on the details of device geometry nor on charge collection was initiated by Binder and generalized by Chlouber (38, 39). A similar approach was used by Edmonds (40). The device is modeled as a plane lamina, but the maximum path is limited to the diameter of the device. There is a single critical charge. The rate per unit area in the plane of the device has the same units as flux, so the rate function has been called the "effective flux" by some writers, although it is not a flux in the sense of transport theory. The method was not designed for use on very hard parts.

The SEU rate per unit area is given by:

$$R = \frac{4\pi}{L^2} \int_{\theta_0}^{\theta} 2F(\lambda)d\lambda$$

where L is the onset LET, F(L) is the integral ion flux per steradian, and d is the ratio of the diameter to the thickness of the lamina.

The rates for our set of devices were calculated for the CREME solar minimum environment, a shield thickness of 0.25 inch, and a ratio of diameter to thickness of 10. The rates are insensitive to values of d near 10.

5. Distributed Flux Approach

This approach is a variation of the Effective flux approach (41). It also allows one to calculate the upset rate without making any assumptions about the charge collection depth. The redistributed flux approach also does not require one to know how many sensitive junctions are within a bit. This approach allows one to calculate the upset rate for the entire chip, without being concerned about which circuit elements are contributing to the upsets.

The main assumptions are: 1) The measured cross-section curve represents the probability of an upset at a given
Comparison of Upset Rate Prediction by several common methods. The units are upsets/bit-day.

<table>
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<tr>
<th>Device</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<td>4.91e-2</td>
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<td>3.2e-4</td>
<td>8.51e-4</td>
</tr>
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<tr>
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</table>

Table II.

Figure 11. Comparison of upset rate predictions for a number of devices. Method 1 (equivalent to method 2) is the baseline calculation, using an integral RPP approach. The modified figure of merit (method 6) is the best of the approximate approaches. Methods 4 and 5 are effective flux approaches, while method 7 uses a single, low LET threshold, RPP integral.
LET condition, 2) The effective LET concept is valid, 3) The cross-section can be treated as a two-dimensional surface and the charge collection depth can be ignored, 4) The integral ion flux can be redistributed to take into account the probability of an ion strike at any angle. 5) The natural ion flux is isotropic. 6) For ion strikes at angles between 80 and 90 degrees, the effective LET is based on an angle at 80 degrees. 7) Cross-section rolloff, at high angles is not considered.

Results for specimen devices are shown in column 5 in table 2.

6. Figure of Merit and Modified Figure of Merit approaches

The Figure of Merit approximation for heavy ion upset rate was introduced in 1983 before the common distribution of the more exact calculations (30). The equation was meant for quick device comparison and assumed the Adam's 90% worst case environment for geosynchronous orbit. The equation (modified for the units in common use) is:

\[ R = 500 \times \frac{\sigma_L}{I_{0.25}} \left( \frac{\text{upsets (MeV/mg/cm}^2\right)}{\text{bit-day cm}^2} \]

where \( \sigma_L \) is the limiting cross section and \( I_{0.25} \) is the LET at 25% of the limiting cross section. The equation is known to predict overly high rates for devices for which most of the upset contribution arises from ions with LET's greater than \( 30 \), generally corresponding to upset rates in the range of \( 10^{-2} \) and below. The values for the 90% environment will be about 70% above the values for the solar minimum environment. The predicted rates for our sample set of devices are:

<table>
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<tr>
<th>Device</th>
<th>Rate</th>
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<td>93L422</td>
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<tr>
<td>GaAs</td>
<td>1/1e-5</td>
</tr>
<tr>
<td>6516</td>
<td>7.8e-6</td>
</tr>
<tr>
<td>AS200</td>
<td>1.3e-6</td>
</tr>
<tr>
<td>4042</td>
<td>8.6e-8</td>
</tr>
<tr>
<td>RK1-05</td>
<td>4.8e-8</td>
</tr>
<tr>
<td>6508RH5V</td>
<td>8.6e-7</td>
</tr>
<tr>
<td>R50-25</td>
<td>2.7e-7</td>
</tr>
</tbody>
</table>

Table III

Upset Rate Using Figure of Merit, 90% Environment

The rates for the first four devices are about a factor of three high relative to the results using the integral RPP method for the 90% environment. The results are not closer due to the use of the integral method rather than a single threshold approach. The last five devices differ by factors of ten to eighty, as would be expected for relatively hard devices. We feel that the figure of merit approximation should be used only for estimates, and with an awareness of its lack of applicability for hard devices. If this form of an approximation is to be used, it should be modified for the solar minimum environment and have a revised constant:

\[ R = 200 \times \frac{\sigma_L}{I_{0.25}} \left( \frac{\text{upsets (MeV/mg/cm}^2\right)}{\text{bit-day cm}^2} \]

The column labeled 6 indicates the results using this approximation. The results agree very well for soft devices and give an upper limit for hard devices. This appears to be the only method that combines a good approximation to the exact results with never underestimating the upset rate. This same approach can be used for other environments by scaling the constant according to the intensity of the space LET spectrum. The approximation appears to be as good as the various effective flux approaches, and is much simpler to apply.

7. Single low LET threshold approach (Aerospace or JPL threshold) with RPP integral.

The semiannual compilations of part susceptibility compiled by the groups at JPL and Aerospace quote a threshold and cross section (42). JPL defines the LET threshold as that value of LET where soft errors are first counted at fluences of \( 10^6 \) ions/cm². This threshold will be a function of both the bit cross section and the number of bits on the chip. The Aerospace Corporation defines their LET threshold as that point where the measured upset cross section is one percent of the measured maximum cross section. The quoted cross sections for softer devices are the cross sections measured near a LET of 40. The values may be limiting cross sections for harder devices. Reference to figure 10 indicates that a LET of 40 may be valid for devices with threshold below 10, but questionable for devices with higher thresholds.

The values from these tables are sometimes used for calculations of upper limits for upset rates. The question is then: how do values obtained in this way scale relative to an exact calculation? Column 7 shows the type of results that might be obtained with these numbers. The calculation was performed using the critical charge derived by using the one percent threshold, assuming a depth of one micron, and the limiting cross section in table 2. The calculation was performed with CRUP and the solarmin environment.

The results are high for sensitive devices and for devices with appreciable funneling. There is not a uniform scaling between this calculation and the more exact approach. In one case this method under estimates the upset rate.

8. Not upset at a LET of 40, or not upset for protons. (Not in table).

Specifications are sometimes written in this form or in the form of not upsetting for a particular ion at a particular angle (Krypton at normal incidence). An examination of tables one and two shows a rough value for this specification. It there is to be no upset for devices with a threshold near 40, the upset rate could be in the range of \( 10^{10} \) to \( 10^7 \) upset/bit-day for
this environment. The upper limits may or may not be acceptable for the mission.

The second form of the specification is even stricter, although not many realize it. If we assume a LET threshold near 40, then the expected upset rate in the heart of the proton belt will be nearly $10^{10}$ (43). The proton upset cross section for this device would be approximately $5 \times 10^{-18}$ cm$^2$ at 200 MeV; small but not zero (44). Cross sections this small are difficult to measure if the devices have any total dose sensitivity.

9. Shape dependent approach (not in table)

The shape dependent approach was introduced by Langworthy so that exact path length distributions could be used with rounded shapes (45). In this approach the cross section is fit using the limiting cross section and a two parameter function:

$$\sigma = \sigma_0 \left(1 - \left(\frac{L}{L_0}\right)^p\right)^2$$

where $L_0$ is the threshold and $p$ is a shape parameter. A hemispherical shape will have $p=2$, while $p<1$ is inconsistent with the physical model. The shape of this curve with $p=1.5$ nearly corresponds to the curve in figure 10 for the 6508RH Weibull function. However, for most of the other devices, a third parameter is needed to match the data or the distinctive shape of the Weibull curve. The approach also has trouble for the devices with $L_0$ less than 10, for if the data is approximately fitted using the threshold and 50% values, the shape parameter wants to be less than 1, especially for the 93L422. This approach also assumed only normally incident ions. As the front and back surfaces are not parallel, the effective LET concept does not apply. The problem of the interpretation of the normal experimental data was not addressed.

Langworthy's initial application of this technique to the calculation of CRRES upset rates (46) gave results that scaled with the use of a single threshold at onset, and did not match the part to part variation observed with those parts in flight (47). Langworthy no longer recommends using this approach, so we do not include it in our compilation (48).

Langworthy has recently added two extensions to his basic concept. He discusses added the effects of the funnel in reference 49, but the implementation is somewhat unclear. In a more recent work, he discusses the necessity of allowing for variance of critical charge (50). Doing this changes the interpretation of the threshold and shape parameters. This shape dependent approach has not been examined relative to interpretation of data taken at a range of angles of incidence. It appears that this set of approaches still requires further development, and have not reached the maturity needed for a critical evaluation.

10. LET flux x cross section approach (not in table)

The use of the product of the measured LET cross section curve and the space ion flux at that LET is conceptually completely wrong for the calculation of heavy ion upset rates. This approach ignores the importance of the amount of charge deposited in the sensitive volume, which is very dependent on the path length and ion direction. Practically the approach is wrong because it would predict nearly zero upsets for all ions above an effective LET of 30, whereas in practice these ions make very important contributions to the upset rate in many devices.

This approach appears to be parallel to the method of calculating proton induced upset rates. In this the upset rate depends on a cross section that is independent of path length or ion direction. The upset rate is the summation of the products of the cross section and differential proton spectrum when both are a function of the proton energy. The basic phenomena are entirely different in the proton and heavy ion cases and the upset rate calculations must be approached entirely differently. The plots of cross section vs. LET for heavy ions and the plots of cross section vs. energy for protons are representing entirely different types of phenomena. The heavy ion data does not have the traditional characteristics of cross section used in the nuclear physics community. It is a parallel usage, but not the same usage.

An apparent variation of this approach is to multiply 10% of the saturated cross section times the flux at the onset threshold. We have trouble imagining any possible basis for this.

It appears that the modified figure of merit approach is the most satisfactory of the several approximate approaches studied. It does very well for soft devices and is slightly conservative for hard devices. It is also the simplest approach to apply. The other approaches are more complicated and not consistently conservative.

XII COMPARISON OF VARIOUS APPROACHES TO FUNNELING IN UPSET CALCULATIONS

The paper has mentioned various plausible assumptions concerning charge collection depth and charge funneling. We have explored the effects of these assumptions for a representative set of devices with Weibull parameters as listed in table I. This calculations can be thought of as being calculation of upset rate for any devices with these approximate Weibull parameters, not necessarily limited to the particular devices from which we obtained these parameters.

1. RPP, Weibull integral calculation using additional funnel length.

The first column gives the rate for a fixed funnel length. The lengths are either 1 micron, or a longer length if so shown in table I.

2. Same calculation using Space Radiation code.

3. Same Calculation as 1 assuming funnel length of zero.
4. Same calculation as 2 assuming funnel length of zero.

5. CRIER calculation assuming a depth of 2 microns for all devices, without funneling.

6. CRIER calculation assuming a depth of 6 microns without funneling.

7. CRIER calculation assigning a funnel depth of 4 microns for all devices. This can be compared to calculation 3 (no funnel) and calculation 1) to investigate the effect of funnel length assumptions.

This table demonstrates the importance of the assumed funnel length for relatively hard bulk CMOS devices. The upset rates for the AS200 and RK1-05 devices vary appreciably for zero funnel length, the assumed funnel length, and a funnel length of four microns. The 6508 shows a noticeable change between zero funnel and one micron funnel.

<table>
<thead>
<tr>
<th>device</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
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<tr>
<td>2164</td>
<td>4.96e-5</td>
<td>4.86e-5</td>
<td>5.87e-5</td>
<td>5.74e-5</td>
<td>6.49e-5</td>
<td>5.49e-5</td>
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<tr>
<td>93L422</td>
<td>1.66e-3</td>
<td>1.54e-3</td>
<td>2.11e-3</td>
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<td>2.11e-3</td>
<td>2.12e-3</td>
<td>1.24e-3</td>
</tr>
<tr>
<td>GaAs(Si LET)</td>
<td>4.70e-6</td>
<td>3.57e-6</td>
<td>4.70e-6</td>
<td>4.40e-6</td>
<td>5.37e-6</td>
<td>4.10e-6</td>
<td>4.70e-6</td>
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<td>1.68e-6</td>
<td>1.53e-6</td>
<td>2.18e-6</td>
<td>1.99e-6</td>
<td>3.50e-6</td>
<td>2.18e-6</td>
<td>1.16e-6</td>
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<tr>
<td>AS200</td>
<td>4.65e-8</td>
<td>3.87e-8</td>
<td>3.40e-7</td>
<td>2.96e-7</td>
<td>3.24e-7</td>
<td>1.82e-7</td>
<td>4.00e-8</td>
</tr>
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<td>2.14e-8</td>
<td>3.73e-9</td>
<td>2.14e-8</td>
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<td>5.97e-9</td>
<td>1.46e-9</td>
<td>2.14e-8</td>
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<tr>
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<td>3.64e-10</td>
<td>2.73e-10</td>
<td>2.02e-9</td>
<td>1.58e-9</td>
<td>2.02e-9</td>
<td>1.17e-10</td>
<td>6.31e-11</td>
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<tr>
<td>6508RH,5v</td>
<td>6.50e-8</td>
<td>5.03e-8</td>
<td>1.56e-7</td>
<td>1.23e-7</td>
<td>1.55e-7</td>
<td>8.03e-8</td>
<td></td>
</tr>
<tr>
<td>R50-25</td>
<td>1.12e-8</td>
<td>9.91e-9</td>
<td>6.72e-8</td>
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<td>3.89e-8</td>
<td>1.52e-8</td>
<td></td>
</tr>
</tbody>
</table>

Table IV.

Upset rate prediction using several different funneling assumptions.

<table>
<thead>
<tr>
<th>device</th>
<th>N 1e+15</th>
<th>N 1e+16</th>
<th>N 1e+17</th>
<th>P 1e+15</th>
<th>P 1e+16</th>
<th>P 1e+17</th>
</tr>
</thead>
<tbody>
<tr>
<td>93L422</td>
<td>1.98e-3</td>
<td>2.07e-3</td>
<td>3.90e-3</td>
<td>1.76e-3</td>
<td>1.87e-3</td>
<td>2.40e-3</td>
</tr>
<tr>
<td>GaAs(Si LET)</td>
<td>7.98e-6</td>
<td>7.98e-6</td>
<td>7.98e-6</td>
<td>7.98e-6</td>
<td>7.98e-6</td>
<td></td>
</tr>
<tr>
<td>6516</td>
<td>2.16e-6</td>
<td>2.31e-6</td>
<td>3.21e-6</td>
<td>1.89e-6</td>
<td>1.97e-6</td>
<td>2.44e-6</td>
</tr>
<tr>
<td>AS200</td>
<td>1.49e-7</td>
<td>1.55e-7</td>
<td>3.73e-7</td>
<td>9.35e-8</td>
<td>9.52e-8</td>
<td>1.72e-7</td>
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<td>4042</td>
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<td>3.78e-8</td>
<td>3.78e-8</td>
<td>3.78e-8</td>
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<td>RK1-05</td>
<td>6.60e-10</td>
<td>5.95e-10</td>
<td>2.05e-9</td>
<td>2.63e-10</td>
<td>4.23e-10</td>
<td>6.73e-10</td>
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<tr>
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<td>7.04e-8</td>
<td>1.75e-7</td>
<td>4.06e-8</td>
<td>4.00e-8</td>
<td>7.79e-8</td>
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<tr>
<td>R50-25</td>
<td>1.79e-8</td>
<td>1.23e-8</td>
<td>5.57e-8</td>
<td>6.14e-9</td>
<td>4.63e-9</td>
<td>1.32e-8</td>
</tr>
</tbody>
</table>

Table VI.

Upset calculations using variable length funnels

The next table shows the effect of funnel using the variable funnel length described in the Appendix. The six columns in this table give the rate calculated with variable funneling based on the empirical funneling model for cases of n-substrate (i.e., p+/n junction as in a PFET) and cases of a p-substrate (i.e., n+/p junction as in a NFET). Note that the rates are not strongly dependent on choice of substrate type or doping for most cases.

The results shown in both of these tables indicate that the upset rate calculated assuming charge collection by funneling is not strongly dependent on the assumptions used to calculate the funnel length. This indicates that the most reasonable model for a particular device should be used but that it is not necessary to go into excessive detail. At the same time, the funneling cannot be ignored and must be included for bulk devices.

There is still need for a standard approach to the assignment of funnel length. The modern numerical charge collection codes may lead in this direction.

XIII. SUMMARY.

This paper has examined a number of topics relative to the calculation of single event upset rates. Clearly there are still a number of outstanding question. However, there does appear
to be a standard group of simplifying assumptions. Many of
these were summarized in reference 1. The one assumption
of that paper that needs reexamining is the question of
interpretation of the cross section curve. It appears however
that assumption has little impact on the actual prediction of
upset rates. A reexamination of the theories and evidence
about charge funneling shows that there are still a number of
uncertainties here. It is time to revisit this topic with the
improved calculational and experimental tools now available.
Of particular interest is the angular variation of the funnel
diffusion charge collection processes

A number of recent experiments have shown
discontinuities in the experimental data as the ion used in the
testing is changed. These effects can be explained on the
basis of finite depth effects. However, the relationship of the
finite depth effects and the device structure needs further
examination.

The funnel effect can also lead to data discontinuities.
This occurs when there is a fixed length funnel and the
concept of effective LET no longer applies.

The basic conclusion from our study of data
discontinuities is that they are an artifact of the experiment,
and that the data can be corrected so that it falls on a smooth
curve through the points taken at normal incidence. The
discontinuities are not important for adequate upset rate
predictions.

The funnel is important in upset rate predictions for some
devices. Variations of the standard RPP calculations are
straightforward to allow for either a fixed length funnel or for
a funnel of constant depth. The later calculation also applied
to the important case of funnel truncation by epi layers.

A comparison of various methods of upset rate calculation
indicated that most of the methods are conservative relative to
the integral RPP methods. Now that this method is readily
available, it is the method of choice. If an approximate
method is needed for quick device comparisons, a modified
figure of merit approach suffices.

A comparison of various methods of including funneling
in the integral RPP approach indicates that there is not
extreme sensitivity to the approach. The most physically
reasonable approach should be used for the device in
question, but it is wrong to neglect the funneling in bulk
devices.

Acknowledgments

Some of the data presented is for test structures or
prototype devices and does not necessarily reflect
performance of commercially available parts from the
manufacturer.

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Appendix A

Figure A1 shows an idealized measurement of the upset cross section as a function of the effective LET. If we consider an arbitrary incident LET of $L_x$ ($L_y < L_x < L_z$), that LET is upsetting a few cells when it is incident so that the path length corresponds to passage through the entire depth $z$. However, the cells that upset with a lower LET $L_y$ passing through the entire depth now can be upset with the larger $L_x$ passing through a shorter distance corresponding to $z_x$ (figure A2).

The various values of LET between $L_y$ and $L_z$ will all produce upset in some cells for a corresponding depth that increases with LET, from $z_y$ to $z$. Therefore the effective area is a complicated function of LET, and of the cross section for upset at that LET. It is necessary to obtain an approximation for this effective area. This approximation should lead to a smooth transition from equation 5. to equation 4. with increasing LET, of the form:

$$\sigma_0 = \sigma_m \times \left( \cos \theta + F(L_x) \frac{z}{x} \sin \theta \right)^{-1}$$

We will assume that an effective area for an incident LET of $L_x$ can be defined by a corresponding depth $z_d$. This will produce a modification of equation 4:

$$\sigma_0 = \sigma_m \times \left( \cos \theta + \frac{z}{x} \sin \theta \frac{2z_d}{x} \sin \theta \right)^{-1}$$

The depth $z_d$ scales with a corresponding LET $L_d$:

$$z_d = \frac{L_d}{L_x} \times z$$
Equation a2. then becomes:

$$\sigma_0 = \sigma_m \times \left( \cos \theta + \frac{z}{x} \sin \theta \left(1 - 2 \frac{L_d}{L_x} \right) \right)^{-1}$$  \hspace{1cm} a4)$$

The treatment here differs from that in the appendix to reference 31 as that assumed that the depletion region was also extended to the sides of the device. Note that this equation can be used in its present form if you assume a single critical threshold value for $L_d$.

Equation a4 can be evaluated separately for the three regions of the curve in figure A1; the region below $L_0$, the region $L_0 - L_1$, and the region above $L_1$. For region two we will assume that $L_d$ is defined where one half of the population corresponding to $L_1$ upsets. If we further assume that the cross section curve has the form shown in figure A1, proportional to log LET in this region.

$$L_d = \sqrt{L_0 L_1} \hspace{1cm} L_0 \langle L_x \rangle / L_1$$

$$\sigma_0 = \sigma_m \times \left( \cos \theta + \frac{z}{x} \sin \theta \left(1 - 2 \frac{L_0}{\sqrt{L_x}} \right) \right)^{-1} \hspace{1cm} a5)$$

The appropriate form in region one is then

$$\sigma_0 = \sigma_m \times \left( \cos \theta - \frac{z}{x} \sin \theta \right)^{-1} L_x \langle L_0 \rangle \hspace{1cm} a6)$$

Correspondingly, for the region above $L_1$, we will assume that $L_d$ corresponds to the mean of the population between $L_0$ and $L_1$. The depth corresponding to this mean is a function of $L_x$.

Equations a5, a6, and a7 correspond to equations 5 and 4 in the limits of very small or very large LETs. The three equations join at $L_0$ and $L_1$, but with discontinuities in the slope, due to the approximations to the cross section at those points.

Note that the effect of this correction is to raise the large angle low LET data, while lowering the large angle high LET data. The use of earlier equations 4 or 5 either raises or lower data at both ends of the LET spectrum.

Appendix B. Empirical Funneling Model

Charge collection can be divided into a prompt component and a delayed component. The prompt component is due to drift of charge generated in the nominal depletion region and in an extended depletion region along the ion path, which is designated the funnel region. Fast diffusion of charge into the depletion or funnel regions that is within the circuit of resolving time also contribute to the prompt charge. For most circuits which have feedback recovery mechanisms, such as CMOS, the delayed charge does not affect the upset mechanism. For SEE rate modeling purposes, it is convenient to divide the prompt charge into a depletion component, $Q_d$, and a funneling component, $Q_f$. We describe an empirical approach to quantifying the depletion and funneling components of prompt charge based on measurement of prompt charge using diodes with known junction characteristics and ions with known LET.

The experimental data are derived from prompt charge measurements of Hseih [8,51], McLean [10] and Oldham [11] and are contained in Table B1. The data are for 5 V bias except for Hseih's which are at 7.5 V bias.

The partition of prompt charge, $Q_p$, into $Q_d$ and $Q_f$ can be determined analytically by assuming that $Q_d = S \cdot SP$ where $S$ is the path length of the ion through the original depletion region (depletion width before the junction is disturbed by the funnel process) and $SP$ is the linear charge deposition rate (which is directly related to LET) and is assumed to be constant along the path through the depletion and funneling regions. If we measure $Q_p$ then we determine $Q_f$ by $Q_f = Q_p - Q_d$.

The experimental data base for the prompt component of charge collection on which the model is based (Table B1) consists of a total of 26 data points for p-type and n-type substrates. A reasonably close fit was found for 20 of the 26 points based on the following algorithms:
p-type substrate:
\[ Q_p = (22 \times SP^{0.8-24}) - 7.4 \times SP^{0.8} \times \log_{10}(Na/1E15) \] (b1)

n-type substrate:
\[ Q_p = (0.8 \times SP^{0.8-24}) - 7.4 \times SP^{0.8} \times \log_{10}(Nd/1E15) \] (b2)

where the units are
\[ Q_p \text{ [pC], } SP \text{ [MeVcm}^{-2}\text{mg]} \]
Na or Nd [cm\(^{-3}\)].

The last column of Table B1 shows the results calculated with equations 1 and 2. Figure B1 gives example model outputs for the prompt charge as a function of LET and doping over the ranges of interest.

For SEE modeling, it is convenient to work in units of pC/cm for SP and µm for S. Equations 1 and 2 are converted accordingly, resulting in

p-type substrate:
\[ Q_p = (1.86 \times SP^{0.8}) \times (2.97 - \log_{10}(Na/1E15))^{-0.024} \] (b3)

n-type substrate:
\[ Q_p = (1.86 \times SP^{0.8}) \times (2.38 - \log_{10}(Nd/1E15))^{-0.0192} \] (b4)

where the units are
\[ Q_p \text{ [pC], } SP \text{ [pC/µm], } Na \text{ or Nd [cm}^{-3}\text{].} \]

The experimental data in Table B1 are all for ion beams at normal incidence. The depletion region width, \( W_d \), for the diodes in the charge collection measurements can be estimated with the one-sided abrupt junction approximation. \( Q_d \) is calculated as \( Q_d = W_d \times SP \). \( Q \) is then determined through the relation \( Q_f = Q_p - Q_d \).

It is common in error rate calculation codes to define the nominal charge collection volume as a rectangular parallelepiped determined by the depletion volume at the junction. To include the effects of funneling in this calculation, the prompt charge deposited along each path \( S \) of a path length distribution can be determined as the sum of the \( Q_d \) from the path \( S \) through the RPP and \( Q_f \) as determined by the junction type, doping and voltage using equations 3 and 4. The width of the depletion region is calculated by

\[ W_d = \sqrt{2 \times e \times (V + V_{bi})/(q \times NB)} \] (b5)

where \( e \) is the dielectric constant for Si,
\( q \) is electron charge,
\( NB \) is substrate doping concentration,
\( V \) is absolute value of applied bias voltage, and
\( V_{bi} \) is the built-in junction potential given by

\[ V_{bi} = kT/q \times \log_{10}(Na \times Nd/n_i^2) = 0.0259 \times LN(0.476 \times NB) \] (b6)
in volts, where \( k \) is Boltzmann's constant,
\( T \) is absolute temperature, and
\( NB \) is the substrate doping density.

Equations 3 through 6 are the elements of the algorithms for estimating the prompt charge in the code. Equations 3 and 4 are based on 5 V junction bias. We calculate the depletion width appropriate for the experimental condition for which the prompt charge algorithms were determined, \( W_0 \) by solving equation 5 for \( V = 5 \) V and the other parameters as appropriate. Multiplying \( W_0 \) by the SP of the ion under consideration and subtracting from the results of equations 3 or 4 yields \( Q_f \) for a specific combination of doping and SP but independent of bias.

The following constitutes the algorithms for solving \( Q_p \) in the CRIER code for a given stopping power, SP, and path length, \( S \):

p-type substrate:
\[ V_{bi} = 0.0259 \times LN(0.476 \times Na) \] [V] (b7)
\[ W_0 = 3.267 \times 10^7 \times ((5 + V_{bi})/Na) \] [µm] (b8)
\[ W_d = 3.627 \times 10^7 \times ((V + V_{bi})/Na) \] [µm] (b9)
\[ Q_p = 1.86 \times SP^{0.8} \times (2.97 - \log_{10}(Na/1E15))^{-0.0240 + SP \times (s - W_0)} \] [pC] (b10)

n-type substrate:
\[ V_{bi} = 0.0259 \times LN(0.476 \times Nd) \] [V] (b11)
\[ W_0 = 3.267 \times 10^7 \times ((5 + V_{bi})/Nd) \] [µm] (b12)
\[ W_d = 3.627 \times 10^7 \times ((V + V_{bi})/Nd) \] [µm] (b13)
\[ Q_p = 1.86 \times SP^{0.8} \times (2.38 - \log_{10}(Nd/1E15))^{-0.0192 + SP \times (s - W_0)} \] [pC] (b14)

Figure B1. Empirical prompt charge collection versus LET for N- and P-substrate doping.
### Measured Prompt Charge Data Base - N-Type Substrates

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<th>Ref.</th>
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<th>Energy MeV</th>
<th>Max. Avail.</th>
<th>Range μm</th>
<th>Initial SP IC/μm</th>
<th>Measured Qp IC</th>
<th>Model Qp IC</th>
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### Measured Prompt Charge Data Base - P-Type Substrates

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Table BI. Modeled and measured prompt charge collection. The corrected references, in order, are 8, 51, 10, 11.