MONTE CARLO METHODS FOR PREDICTING SRAM VULNERABILITY TO 
MUON AND ELECTRON INDUCED SINGLE EVENT UPSETS

By

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Dissertation
Submitted to the Faculty of the
Graduate School of Vanderbilt University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY
in
Electrical Engineering
May 11, 2018
Nashville, Tennessee

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Sokrates Pantelides, Ph.D.
For my mother, Ann Reichheld, and father, Charles Trippe, my lifelong role models
ACKNOWLEDGEMENTS

First, I’d like to thank both the Arnold Engineering Development Complex and the Defense Threat Reduction Agency for directly funding this work. None of this research would have been possible without your continuous support. I’d also like to thank the various groups that provided beam testing facilities for us, including AEDC, LBNL, and TRIUMF. The Broadcom Corporation, especially through Balaji Narasimham, has also provided a significant amount of technical expertise. The backing of funding agencies and facilities such as these is an invaluable asset to our academic community. Furthermore, my interactions with the staff members of all these groups have been positive and supportive, enriching this work significantly. I cannot thank you all enough for your contributions.

I would also like to thank the members of my dissertation defense committee starting with my academic advisor Professor Robert Reed. He has always provided me with exactly the right amount of guidance while also encouraging my independence. I’d like to thank Professor Robert Weller who demonstrated unwavering dedication to imparting his impressive knowledge across all disciplines on his students. I’d like to thank Professor Brian Sierawski for being a mentor who always pushed me to do a little more to prove myself while working hard to make sure our shared projects were successful. I’d like to thank Professor Ronald Schrimpf who made sure I argued my points well to ensure the story my research told had value. I’d like to thank Professor Sokrates Pantelides for being one of the first members of the Vanderbilt community to encourage me to go to graduate school at all. Finally, though he was not a part of my committee, I’d like to thank my previous academic advisor Professor Marcus Mendenhall. Both his enthusiasm for scientific discovery and impassioned brilliance are unrivaled in anyone I have ever met.

Any members of the Vanderbilt EECS faculty and ISDE staff that were not mentioned above have also been constantly providing encouragement and guidance throughout my time here. I have never been so privileged to be a part of such a strong core of academics, and I thank you all
for your contributions to this work. The graduate students here have similarly been a never ending source of support. Rebekah Ann Austin, Charles Arutt, and Isaak Samsel in particular each shared the bulk of this journey with me and were always there to lend a helping hand.

I’d also like to thank Rain Xue, not only for helping me proofread this dissertation but also for being there whenever I needed it. No one has been as singularly important to me completing this dissertation as you have been. Finally, I’d like to thank my other family and friends who have been by me for as long as I can remember. I have received nothing but words of reassurance whenever I have doubted myself. Thank you all very much.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEDICATION</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xi</td>
</tr>
<tr>
<td>Chapter</td>
<td></td>
</tr>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II. BACKGROUND</td>
<td>5</td>
</tr>
<tr>
<td>II.1 Mechanisms of single event effects</td>
<td>6</td>
</tr>
<tr>
<td>II.1.1 Definition of Linear Energy Transfer</td>
<td>7</td>
</tr>
<tr>
<td>II.1.2 Direct and Indirect Ionization</td>
<td>9</td>
</tr>
<tr>
<td>II.2 Charge collection mechanisms</td>
<td>10</td>
</tr>
<tr>
<td>II.3 SEUs in SRAM devices</td>
<td>13</td>
</tr>
<tr>
<td>II.3.1 Example SRAM Layout</td>
<td>14</td>
</tr>
<tr>
<td>II.3.2 Single event effects in SRAMs</td>
<td>16</td>
</tr>
<tr>
<td>II.3.3 Heavy ion, proton, and muon-induced SEU properties</td>
<td>18</td>
</tr>
<tr>
<td>II.4 Lightly ionizing particle environments</td>
<td>21</td>
</tr>
<tr>
<td>II.4.1 Earth orbit environments</td>
<td>23</td>
</tr>
<tr>
<td>II.4.2 Jovian space environment</td>
<td>30</td>
</tr>
<tr>
<td>II.4.3 Terrestrial muon environment</td>
<td>31</td>
</tr>
<tr>
<td>II.5 Using Monte Carlo tools to model SEUs</td>
<td>32</td>
</tr>
<tr>
<td>II.5.1 Monte Carlo simulations of ion transport</td>
<td>34</td>
</tr>
<tr>
<td>II.5.2 Modeling SEUs with MRED</td>
<td>36</td>
</tr>
<tr>
<td>II.5.3 Previous work by others on calibrated models</td>
<td>39</td>
</tr>
<tr>
<td>II.6 Vanderbilt CubeSat program</td>
<td>42</td>
</tr>
<tr>
<td>III. EXPERIMENTAL RESULTS</td>
<td>45</td>
</tr>
<tr>
<td>III.1 28 nm SRAM operation</td>
<td>45</td>
</tr>
<tr>
<td>III.2 Heavy ion test results</td>
<td>48</td>
</tr>
<tr>
<td>III.3 Proton test results</td>
<td>48</td>
</tr>
<tr>
<td>III.4 Muon test results</td>
<td>50</td>
</tr>
<tr>
<td>III.5 Monoenergetic electron test results</td>
<td>52</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Figure 1: Deposited energy required to upset a representative inverter as a function of technology node. Example energy depositions of ionizing radiation for a given path length are provided for comparison [7].

Figure 2: Flowchart demonstrating the method for performing a rate prediction as outlined in this paper. Heavy ion and proton SEU test data are used to parametrize a calibrated multi-SV model. Electron SEU test data can be added to the calibration if electron-induced SEU rates are of interest. Using an environment differential flux model, an SEU rate prediction is performed using a Monte Carlo tool.

Figure 3: Time evolution of a single event transient for an ion striking a sensitive region (red) [1].

Figure 4: Simulations of the stopping power curve of protons in silicon produced by PSTAR [16].

Figure 5: Proton induced SEUs can be caused by direct ionization (left), scattering (middle), and nuclear reactions (right). Particle energy increases left to right [11].

Figure 6: Assumed potential distribution $V_o$ along particle track $x$. (A) Original depletion region before particle strike. (B) After an alpha particle strike. (C) Original model after passage of a high dE/dx particle. (D) Revised model after same particle as curve C. (E) Revised model after passage of an ion with higher dE/dx than curve D. Taken from [22].

Figure 7: Typical structure of a 6T SRAM cell. Original image credited to [29].

Figure 8: 6T SRAM for reference (right) and “butterfly plot” showing the measurement of VTC and SNM for a 6T SRAM using the “maximum squares” method (left) [30].

Figure 9: Path an incident heavy ion takes through a W-E angle (a) and N-S angle (b) as a function of angle off of normal incidence. Rotating the beam angle off of normal increases the path length for the axis of rotation in (a) but decreases it for (b) [8].

Figure 10: Proton test results as a function of beam energy and tilt angle for an IBM 65 nm SOI device. Increasing the angle of incidence increases the SEU cross-section induced by direct ionization ($< 20$ MeV) but not nuclear reaction induced SEUs ($> 20$ MeV) [50].

Figure 11: Simulated muon kinetic energy distributions, as seen at the front of the part, corresponding to experimental momenta including upstream energy losses and straggling (bottom). Error counts for 65 nm, 45 nm, and 40 nm SRAMs versus estimated muon kinetic energy at 1.0 V bias (top). Dashed horizontal line represents an approximate muon-induced SEU cross section for reference [5].

Figure 12: Fluxes for protons >10 MeV (top) and electrons >1 MeV (bot) as a function of distance from Earth based on AP-8 and AE-8 models [59]. Note that the protons do not extend into the outer bands.

Figure 13: Long-term (1992–2013) record of electrons measured primarily by the SAMPEX spacecraft at low altitude.
Figure 14: Plot of fluence for protons with > 0.88 MeV measured between 1974 and 2002 [59]. Top axis shows division between solar maximum and solar minimum regions.................................................................27

Figure 15: High energy cosmic ray spectra for ions with 8 < Z < 26 [64]......................................................28

Figure 16: Average electron (left) and proton (right) fluxes for each orbit of interest [9]. .........................30

Figure 17: Fluxes for electrons and protons determined for the Europa Clipper and Juno missions. Europa clipper is denoted as the “peak” for electrons and protons [9].........................................................31

Figure 18: Flux spectra extracted from EXPACS for neutrons and muons at New York City. Comparisons are made to muon measurements taken by Allkofer in [76]. Plot originally from [75].........................32

Figure 19: Approximations for π as calculated using the Monte Carlo method. From left to right, the approximation improves as the number of points simulated (N) increases.......................................................33

Figure 20: Architecture of MRED, including additional modules. UNIX script mred calls run_mred.py, which in turn runs the code further up the pipe in the diagram [78]..............................................................35

Figure 21: Rectangular parallelepiped model of the 28 nm SRAM used for some MRED simulations. The particles are generated normally incident to the front of the BEOL in a random pattern. Exact values of SV and BEOL dimensions withheld at the manufacturer’s request.................................................................37

Figure 22: Energy deposition vs. counts in the SV for 2.5 MeV protons normally incident on a simple RPP model similar to the one in Figure 21. An arbitrary Qcrit is marked for illustrative purposes..............38

Figure 23: Solid model for 25μm SRAM used for modeling in [12, 28]. SV sizes and charge collection efficiencies are informed from TCAD simulations.................................................................39

Figure 24: Comparison of 25 μm SRAM heavy ion tests results and simulations. Predicted cross-sections match experimental results closely due to the sophistication of the MRED and TCAD models........40

Figure 25: Heavy ion calibrated model for a 65 nm SRAM. Each volume corresponds to a heavy ion data point [11]..............................................................................................................................41

Figure 26: Proton test results compared to MRED simulation predictions for the 65 nm SRAM [11]......41

Figure 27: AO-85 spacecraft composed of a 1-unit CubeSat. Inside is an experiment board which measures a COTS SRAM’s on-orbit SEU rate [90]....................................................................................42

Figure 28: SEU data on a COTS SRAM taken by AO-85. Top left plot gives cumulative upsets for the mission length, top right gives the daily upsets as a function of time, bottom left bins the daily upsets by the number of days they occurred, and finally the bottom right plot is the SEU rate versus time. [90]....43

Figure 29: Timing diagram for the experiment. The initial read and write, and the post read are done at nominal voltage. During exposure, the SRAM Bias is dropped to the test bias. The exposure time is dependent on the fluence and upset rate. Original image from [6]...........................................................................46
Figure 30: Experimental setup used at AEDC for the 28 nm SRAM. Similar setups were used at other facilities. The board in the test chamber is controlled remotely via I2C.

Figure 31: Normalized proton-induced SEU cross sections for the Broadcom 28 nm SRAM taken at TRIUMF for bias voltages of 0.5 V [91].

Figure 32: Monoenergetic proton data taken at Vanderbilt University for the 28 nm SRAM. Biases of 0.85 V and 0.35 V were used [13].

Figure 33: Scintillating materials present in TRIUMF beamline past the initial energy selection. Conditions were simulated in MRED, using starting beam momenta as an initial condition.

Figure 34: Simulation results for beam momenta spectra simulated in MRED using the conditions in Figure 33.

Figure 35: Muon-induced SEU cross-section data taken on the M20B beamline for the 28 nm SRAM. Results are normalized to the peak value at 20.7 MeV/c.

Figure 37: Experimental results from monoenergetic electron tests at AEDC. Error bars derived from the square root of the number of observed upsets [9].

Figure 38: Decay probabilities for Strontium-90 and Yttrium-90, as well as the total combined from a Strontium-90 source. Image from [93].

Figure 39: Placement of the Strontium button source during the experiments. The SRAM is located in the socket. The source sits directly above the delidded part, resting on the packaging.

Figure 40: 28 nm SRAM data from Strontium-90 tests. Error bars are too small to be visible on the plot.

Figure 41: Model of sensitive volume (red) and surrounding volume (gray). The green lines represent the isotropic particle flux. The sensitive volume in each simulation is either (10 nm)$^3$, (50 nm)$^3$, and (250 nm)$^3$.

Figure 42: Low (left) and high (right) energy deposition events for 40 keV and 100 keV primary electron beam energies. The size of the Si box is (50 nm)$^3$, set in (480 nm)$^3$ of SiO$_2$. In low energy deposition events, the primary electron (blue) passes through without interacting. To produce the higher energy deposition events, the primary electron must produce a -ray (red) that stops in the sensitive region [9].

Figure 43: Comparisons of integral cross sections as a function of deposited energy between 40 keV and 100 keV electron beams [9].

Figure 44: Simulation setup for relative rate calculations employing an omnidirectional spectrum.

Figure 45: Ratio of electron to proton charge generation event rates for inner belts orbits 1-3 [9].
Figure 46: Energy deposition event rates for electrons for high orbits where protons do not penetrate shielding for sensitive volumes of size (50 nm)$^3$. GCR-induced rates included for comparison [9].

Figure 47: MRED charge deposition vs. event rate simulation results for a (50 nm)$^3$ sensitive volume using the Europa clipper environmental spectrum. The spectrum passes through 100 mils, 730 mils, and 870 mils of aluminum shielding.

Figure 48: Differential spectrum of electrons produced from Strontium-90 decay chain. Decay probabilities taken from [97] then converted to a differential spectrum.

Figure 49: Normalized integrated counts as a function of energy deposited for three SV sizes and air gaps using an MRED model of the Sr-90 electron source.

Figure 50: Rectangular parallelepiped model of the 28 nm SRAM used for MRED simulations. The particle trajectories are generated perpendicular to the front of the BEOL in a random pattern. Exact values of sensitive volume and BEOL dimensions withheld at the manufacturer’s request.

Figure 51: Comparison of MRED results for 1.45 MeV protons and 0.31 MeV muons. Deposited energy is converted to generated charge by 22.5 keV/fC. An arbitrary $Q_{crit}$ is included only to illustrate the similarity between the integrated muon and proton results beyond that point.

Figure 52: Muon window of vulnerability predictions for simulations and experiments on the 28 nm SRAM [98].

Figure 53: Heavy ion calibrated model of the 28 nm SRAM used throughout this work. SV dimensions withheld at the request of the manufacturer.

Figure 54: Heavy ion SEU data (a) and proton SEU data (b) for the 28 nm SRAM originally presented in Figure 25 and Figure 26. Data points used to calibrate volumes in Figure 53 are circled.

Figure 55: SEU cross-section predictions by the calibrated 850 mV 28 nm SRAM model compared to experimental results from a monoenergetic proton beam.

Figure 56: Upset per muon predictions by the calibrated 850 mV 28 nm SRAM model compared to experimental results from a muon beam. XS in this plot is an abbreviation for cross-section.

Figure 57: Monoenergetic muon response predicted by the multi-SV 28 nm SRAM model.

Figure 58: Two volume model of a planar SRAM calibrated for prediction electron-induced upset rates. The top volume is intended to collect electron-induced events occurring along the drains surface while the bottom is calibrated to account for the remaining proton induced upsets.

Figure 59: NYC sea level environmental differential spectra for neutrons, protons, and muons generated in PARMA after transport through 10 cm of concrete.

Figure 60: Aeronautical (39,000 feet) environmental differential spectra for neutrons, protons, and muons generated in PARMA after transport through typical airplane cabin conditions.
LIST OF TABLES

Table 1: Earth orbits used in this work. Orbits 1-3 are LEO, 4-5 are MEO, and 6 is GEO [9]. .................. 29

Table 2: Variation of muon window of vulnerability thickness with BEOL .............................................. 72

Table 3: Relative modeling parameters across bias voltages for the 28 nm SRAM ................................. 80

Table 4: Terrestrial rate predictions for the 28 nm SRAM using the multi-SV model ............................. 85

Table 5: Predicted proton and electron SEU rates for the 28 nm SRAM for LEOs Inner Belt Minimum Electron Flux (Orbit 1), Horn Region (Orbit 2), and Inner Belt Maximum Electron Flux (Orbit 3). Rates are normalized to an arbitrary value. .......................................................... 87

Table 6: Predicted proton and electron SEU rates for Jovian orbits, scaled by the same factor used in Table 5. ........................................................................................................................................ 88
CHAPTER I

INTRODUCTION

Microelectronic devices receive exposure to radiation in both terrestrial and space environments. Ionizing particles constituting this radiation deposit energy while passing through materials, generating charge through interactions with the surrounding medium. This charge can dramatically alter a device’s operation by inducing a transient current in sensitive regions [1, 2]. In a static random access memory (SRAM), this transient current can cause enough charge to collect on a sensitive node in a transistor to change the state of a bit cell, an event called a single event upset (SEU). An accurate assessment of the vulnerability of an SRAM device to SEUs caused by ionizing particles helps engineers determine how reliably it will operate in a radiation environment. As device sizes have been scaled down in response to industry demands for reduced surface area and power consumption, the reduction of capacitance on sensitive nodes has contributed to reducing the amount of charge required to change the state of an SRAM cell [3]. Low energy protons and muons, as well as secondary δ-rays, have been shown to induce upsets in small feature sized SRAM cells [4, 5, 6]. Given the large range of potential conditions for which a sub-100 nm device could experience an SEU, modernization of SRAMs has introduced significant reliability concerns in the face of various radiation environments. Figure 1 demonstrates the decrease in energy deposited within the transistor’s sensitive drain regions required to change the state of an inverter representative of the technology node on the top axis. Several examples of energy depositions from ionizing radiation are given as break points, indicating the significant decrease in resistance against radiation induced errors as technology nodes have decreased over the years [7]. Shifts in processing techniques to FinFETs have altered this trend as the fin structures are more robust to SEU effects compared to planar devices [8]. Still, the increased robustness due to the adoption of FinFETs only helps so much compared to the effects of reducing the technology node across the decades.
Figure 1: Deposited energy required to upset a representative inverter as a function of technology node. Example energy depositions of ionizing radiation for a given path length are provided for comparison [7].

In particular, low energy muon and electron-induced upsets are on the razor’s edge of potentially becoming a significant reliability concern in terrestrial and trapped radiation belt environments, respectively [5, 9]. Unfortunately, compared to heavy ion and proton sources, the relative scarcity of facilities that produce stable muon beams contribute to engineers being unable to perform these tests [10]. The goal of this work is to use Monte Carlo modeling methods to predict an SRAM’s vulnerability to these particles without needing manufacturer information to define model parameters. The term vulnerability in this work refers to whether a device can be upset by particles of a given species at any energy common to relevant environments. Similarities are exploited between various ion-induced SEUs to develop a suite of modeling strategies for designers to use to estimate device vulnerability to muons and electrons. Specifically, heavy ion and proton SEU test data are used for calibration since these types of tests are easier to perform. The methods presented in this work are validated using a 28 nm planar CMOS SRAM as an example. Comparisons are made between model predictions and observed SEU cross-sections from muon, proton, and electron tests.

Previous work has resulted in modeling techniques for predicting SEU cross-sections for devices down to the 65 nm node [11, 12]. These models were produced, in part, from manufacturer device information. In this work, new modeling methods are presented for muon and electron induced SEUs in
planar SRAMs. In all cases, the manufacturer withheld information about the structure of the SRAM and prohibited reverse engineering measurements from being taken.

Figure 2 presents an overview of the procedure for producing a rate prediction using the methods in this dissertation. In most cases, heavy ion and proton SEU test data for a memory are used to produce a calibrated multiple sensitive volume (multi-SV) model [13]. An estimate of the critical charge can be used but is not entirely necessary if the proton data points are taken from the lowest energies for which upsets occur to energies where the proton SEU cross-section saturates. Electron SEU test data can be incorporated for the purposes of performing electron-induced SEU rate predictions. Rate predictions for muon terrestrial environment need neither muon nor electron testing to be performed. Finally, an environmental model accounting for the various particle differential fluxes as a function of energy is required to perform the rate prediction. Simplified versions of this process are provided as alternatives, using only proton data.

![Flowchart](image)

Figure 2: Flowchart demonstrating the method for performing a rate prediction as outlined in this paper. Heavy ion and proton SEU test data are used to parametrize a calibrated multi-SV model. Electron SEU test data can be added to the calibration if electron-induced SEU rates are of interest. Using an environment differential flux model, an SEU rate prediction is performed using a Monte Carlo tool.

Predictions for the muon-induced SEU rate are made for both sea level and 39,000 km altitude muon environments. Electron rate predictions are made for various LEO orbits and for two Jovian mission environments. Muon-induced SEU rate predictions for the 28 nm SRAM are compared to the neutron contribution for terrestrial environments. Neutrons are found to dominate the response at both sea level and 39,000 km, in line with predictions for similarly sized planar technologies in [14]. Rate
predictions for SEUs induced by electrons and protons are similarly performed for LEO and Jovian environments for the 28 nm SRAM. In general, electrons do not significantly contribute to the overall rate in most cases but are a significant contributor to the SEU rate for high inclination LEO orbits.

Chapter II of this dissertation provides detailed background information related to this research. Included are the physical processes governing the mechanisms of SEUs, effects of SEUs in SRAM devices, an overview of the particle environments used in this work, a discussion of using Monte Carlo tools to simulate SEUs, and a brief discussion of the Vanderbilt CubeSat program which will be flying the 28 nm SRAM as part of an on-orbit data gathering mission. Chapter III outlines experimental results for SEU testing performed on the 28 nm SRAM, including proton, muon, heavy ion, and electron data. Chapter IV contains a mechanisms study of primary electron-induced δ-ray upsets as well as a device-agnostic assessment of the role of electron-induced upsets in space environments. Chapter V goes over the rate prediction method for electrons and protons, including single and multiple sensitive volume muon models as well as the electron model. Rate predictions for the muon and electron models of interest are performed in Chapter VI. Finally, Chapter VII provides a brief conclusion of this work.
CHAPTER II

BACKGROUND

Stable operation of microelectronic devices is essential for ensuring reliable performance in a wide variety of applications. Ionizing radiation presents a threat to this stability by depositing charge which can affect the device’s state. Quantifying the vulnerability of a device to SEUs is a requirement for many high reliability applications. While some devices are constructed specifically to be robust to radiation effects, often times these come with area, power, or cost penalties that designers prefer to avoid. In addition, robust-by-design microelectronics tend to lag behind their commercial off-the-shelf (COTS) counterparts in terms of technology node. Engineers dealing with these tradeoffs often prefer to perform radiation testing to assess the effect of the radiation environment on the part in question. As device sizes continue to shrink, the range of particle species and energies that devices are vulnerable to continue to increase, which in turn necessitates a wider range of accelerated testing. Lightly ionizing protons [4, 11], muons [5, 14], and electrons [6, 9] are now a reliability concern.

Cost efficiency is a primary reason for the use of COTS parts in high reliability applications. However, radiation qualification is required in order to ensure reliable performance, which drives up the cost significantly. Many designers also do not have the experience, infrastructure, or facility access to perform a wide range of required SEU tests. Device models informed by TCAD information [12] have been used successfully to predict proton and heavy ion device responses. Designers may have difficulty acquiring TCAD decks or other sources of information on the device’s doping profiles, making that approach impossible. This work provides a solution to these problems by using a selected set of simple, low cost radiation tests to inform Monte Carlo simulations of the SEU response of a circuit; this approach provides a cost-effective alternative to performing exhaustive tests.

This chapter details the fundamental physical processes responsible for inducing SEUs, operation of SRAM devices such as the 28 nm device used in this work, ion-induced effects in SRAMs, radiation
environments, and previous work on Monte Carlo modeling methods. Each of these topics is instrumental to describing how the modeling method was derived and how it was validated. Section II.1 discusses the fundamental physical processes behind single event effects with a focus on lightly ionizing particles. An outline of SRAM design, operation, and SEU vulnerabilities is contained in Section II.2. Section II.3 expands the discussion to relevant radiation environments for high reliability applications. In Section II.4, Monte Carlo tools and their relevance to ion transport are discussed. Finally, Section II.5 provides a brief background on the CubeSat mission that will measure the on-orbit SEU response of the 28 nm SRAM.

II.1 Mechanisms of single event effects

In 1975, investigations into error rates on satellites led Binder et al. to show that bit flips were being induced by charge generated from cosmic rays [15]. Since then, a wide range of single event effects (SEEs) including single event upsets (SEUs), single event latchups (SELs), and single event gate ruptures (SEGRs) have been investigated. The focus of this section and the rest of the dissertation is on SEUs.

Single event upsets are caused when an incident particle instigates a series of physical events resulting in the release of enough charge from the semiconductor material to initiate an observable change in the device operation. Charged particles transfer energy to atoms in a material lattice through various interactions including electronic stopping, nuclear stopping, excitation, electron capture, and radiation emission. Lightly ionizing particles, such as protons, muons or δ-rays, primarily lose energy through electronic stopping. As the particle moves through the electric field produced by electrons in a material such as a silicon lattice, it transfers energy to the surrounding medium by virtue of the electro-magnetic force. Much of this energy transfer simply vibrates electrons in their shells, essentially becoming thermal noise. However, if the energy imparted is large enough, the electron escapes its orbit, becoming free charge. In silicon, the total energy deposited by the primary particle can be converted to charge generated by 3.6 eV/e-h pair or 22.5 keV/fC [1]. Figure 3 shows the time evolution of a single event transient.
A memory state stored in an SRAM is corrupted when the charge collected in a sensitive region causes a change in the operating condition of a transistor in the bit cell, whereupon the state can potentially settle either as a 1 or a 0. The amount of charge required to induce this change is called the critical charge ($Q_{\text{crit}}$). Critical charge is primarily a function of operating voltage and device capacitance. Lower operating voltages and capacitances associated with modern technology nodes mean less charge needs to be collected to alter the state of the circuit [2].

### II.1.1 Definition of Linear Energy Transfer

Particles with a higher linear energy transfer (LET) deposit more energy in a sensitive region. LET is defined as energy deposited per unit distance normalized to material density and is commonly associated with a particle’s stopping power. A particle’s LET is not a simple function of energy as it is modulated by a complex combination of physical processes, each of which dominates at different particle energies. An example plot of LET vs energy for protons incident on silicon is given in Figure 4, which shows that for energies up to 1 MeV the particle LET increases with decreasing energy. Since low kinetic energy implies low velocity, the local maximum LET is therefore achieved near where a particle stops within the sensitive region. Lightly ionizing particles have been shown to cause upsets when stopping or near stopping in modern technology nodes [4, 5]. This stopping region is called the Bragg peak.
Mathematically, the relationship between particle energy and stopping power is best described by the Bethe-Bloch equation for lightly ionizing particles near stopping. Using the first order Born approximation, the mean stopping power is given by Equation 1 [17].

\[
-d\frac{E}{dx} = \frac{4\pi}{m_e c^2} \times \frac{n z^2}{\beta^2} \times \left( \frac{e^2}{4\pi \varepsilon_0} \right)^2 \times \left[ \ln \left( \frac{2m_e c^2 \beta^2}{I \sigma^* (1 - \beta^2)} \right) - \beta^2 \right]
\] (1)

\(dE/dx\) is the energy loss per unit path length, \(m_e\) is the mass of the particle, \(z\) is the charge of the particle, \(n\) is the target electron number density, \(I\) is the mean excitation potential, and \(\beta\) is the velocity of the particle relative to light. For identically charged particles, \(\beta\) largely dominates the relationship. Equation 1 is valid for proton energies above about 1 MeV.

Since protons, muons, and electrons share the same elementary charge, their stopping power relative to each other is determined largely by their velocity. Heavy ions have higher charges and thus deposit significantly more energy at the same velocities. Matching velocities for particles requires scaling the beam energy to the mass of the ion since \(E = \frac{1}{2} mv^2\). For example, protons have a mass of 938 MeV/c² and muons have a mass of 106 MeV/c² so matching a proton’s velocity to a 1 MeV muon
requires the proton to have an energy of 8.8 MeV. This relationship is used in future sections to match particles based on their LETs.

II.1.2 Direct and Indirect Ionization

Categorizing the physical processes governing the induction of errors during an SEU begins with the distinction between direct and indirect ionization. Direct ionization occurs when the incident particle imparts enough energy through Coulomb interactions alone. An indirect ionization event requires another step, most commonly a scatter or nuclear reaction [18]. Protons, for instance, can cause upsets through direct ionization, scattering, or nuclear reactions. Direct ionization dominates for low energy protons near the Bragg peak. Scattering takes over at higher energies, until nuclear fragments are generated, after which nuclear reactions become a major contributor. An example of each mechanism is presented in Figure 5.

![Proton SEUs are induced through:](image)

Figure 5: Proton induced SEUs can be caused by direct ionization (left), scattering (middle), and nuclear reactions (right). Particle energy increases left to right [11].

While LET has historically been the standard for performing single event effects analysis [2, 19], particle stopping and secondary generation have required more detailed analysis with Monte Carlo tools [5, 20]. Modeling direct ionization-induced upsets is relatively straightforward because no intermediate
particle generations or scatterings are required. In this case, the particle’s charge and velocity are the primary considerations for whether a particle induces an upset while stopping. Particle species has little impact, as predicted from Equation 1 [17]. Indirect ionization events require a stochastic approach to model. Interaction cross-sections between the incident ion and the target material determine the probability of these events occurring. Since lightly ionizing particles primarily induce upsets near stopping through direct ionization, the process is largely particle species agnostic if the primary particles have the same charge.

Several mechanisms have been shown to govern electron-induced SEUs in microelectronic devices. Trippe et al. demonstrated that coulumn interactions between an incident low energy electrons and orbital electrons could liberate a $\delta$-ray which induces an SEU [9]. Gadlage et al. observed SEUs induced by 10 MeV electrons in field-programmable gate arrays due to nuclear reactions in nearby materials [21]. Tali et al. similarly observed electron-induced SEUs in an SEU monitor from nuclear reactions occurring from 200 MeV electrons [22]. Inguimbert et al. identified three main causes of electron-induced SEUs in nanometric volumes: direct ionization, electron/nuclei interactions, and electronuclear interactions [23]. Finally, Akkerman et al. concluded that direct ionization, nuclear reactions, and Bremsstrahlung radiation from the incident electron could all potentially induce SEUs in sufficiently sensitive devices [24]. Only electron-induced upsets induced through direct ionization via $\delta$-ray production are considered in this dissertation. Higher energy events such as nuclear reactions and Bremsstrahlung were not tested for nor modeled, though could be a consideration for future work.

II.2 Charge collection mechanisms

When ionizing radiation deposits energy that generates charge, the mechanisms which govern the collection of this charge determine whether or not the charge has any effect on the device. Experiments performed by T. Oldham et al. led to the development of a model that predicts the total charge collected as a function of incident LET by utilizing the concept of a “charge funnel” [25, 26]. Incident ions induce a field around the initial ion track that decays with radial distance. Several models were proposed of
varying sophistication for low and high LET particles. Results are given in Figure 6. Without going into excessive detail of the evolution of Oldham’s model over the years, the longer transient lengths for high LET particles necessitated a different distribution of voltage vs. distance. In all cases where the ion struck the device, the voltage along its track within the depletion region increased. Increasing the potential indicates that charge is being liberated and is available to be collected by the device.
Carriers produced in the charge funnel are subject to the potentials in the transistor. Typically, these are modeled by the drift and diffusion equations presented in Equations 2 and 3. Electrons and holes have current densities $J_n$ and $J_p$ respectively. Drift current is induced by the potential difference across the node while diffusion current is the result of the differing carrier concentrations between regions of the device. Drift current is a function of the electric field, $E$, the charge of an electron $q$, the carrier mobility $\mu$, and the carrier concentration ($n$ or $p$). Diffusion current is also dependent on $q$, the diffusion coefficient $D$, and the carrier concentration gradient ($dn/dx$ or $dp/dx$) [27]. Charge generated in the funnel effectively modulates the local carrier concentration and its gradient, resulting in a shift of the total current densities. Furthermore, the charge is frequently swept up into sensitive nodes as a result of this current [28, 29].

$$J_n = q\mu_n n E + qD_n \frac{dn}{dx} \quad (2)$$
\[ J_p = q\mu_p E + qD_p \frac{dp}{dx} \quad (3) \]

Modeling this charge collection can be simplified with the introduction of the sensitive volume (SV). In older applications, the RPP model is used for predicting whether or not a heavy ion induces an upset in a device \([10, 30]\). An RPP SV is given by a rectangular box that represents the device’s sensitive regions where charge can be swept up. Traditional usage of RPP SVs requires that the incident ion’s LET does not change significantly along the length of the SV. Future work would adjust the model to allow for LETs that vary in the sensitive region as long as the change in LET is accounted for, typically by a simulation tool \([31, 32]\). For this work, a sensitive volume is defined as a region where charge can be collected from an incident ion strike with efficiency \(\alpha\). While \(\alpha\) is always derived from empirical test data in this work, it is fundamentally related to the strength of the electric field and the carrier concentration gradient in that region. Typically, SVs near regions of strong fields have larger \(\alpha\) while those extending further have smaller values. Totaling the charge in all the RPP SVs assigned to a transistor gives the total collected charge.

II.3 SEUs in SRAM devices

SRAM devices provide an excellent research tool for understanding SEUs. Part of a class of memories known as volatile memories, SRAMs only maintain their state while powered. SRAMs fall into several categories including six transistor (6T) and four transistor (4T) cells. Notably in this work, the structure of the 28 nm SRAM used in experiments and simulations was not known. For this section, a simple 6T cell is used for illustrative purposes but is not representative of the actual circuit used within the 28 nm SRAM. After this explanation, SEU effects in SRAMs are discussed in the general sense before discussing heavy ion, proton, muon, and electron effects in particular.
II.3.1 Example SRAM Layout

![SRAM Cell Diagram]

Figure 7: Typical structure of a 6T SRAM cell. Original image credited to [33].

A typical 6T SRAM cell’s structure is provided in Figure 7. The state \( Q \) is locked between two looped inverters consisting of transistors M1-M2 and M3-M4. \( Q \) serves as the input to the inverter constructed from M1-M2 which stores \( Q \)'s complement \( \overline{Q} \). In turn, \( \overline{Q} \) inputs to the M3-M4 inverter which stores \( Q \). Changing the state of the cell requires simultaneously setting \( Q \) and \( \overline{Q} \) using M6 and M5, respectively, to connect the inverter inputs to the bit line BL. Turning on M5 and M6 to access the cell requires that the word line WL is pulled up to the operating voltage \( V_{dd} \). Writes require BL to be set to the appropriate state with the word line high. For reads, the bit line should be left floating and the word line set high. Additional peripheral circuitry senses the state of the bit line by comparing the voltage on the bit line to its complement. Any time the word line is low but \( V_{dd} \) is still applied the SRAM holds its state in its lowest power configuration. Once \( V_{dd} \) is no longer applied, the SRAM turns off and loses the state of the memory.

With the word line floating, the inverter loop maintaining \( Q \) is essentially isolated from the rest of the circuit, assuming \( V_{dd} \) remains unchanged. In this case, the state does not change unless charge from an outside source enters the inverter. This could be the result of cross-talk, thermal noise, or ionizing
radiation. Regardless of the source, an SRAM’s resistance to noise is frequently described by its static noise margin (SNM), which is determined from a measurement of the SRAM’s voltage transfer characteristics (VTC). Figure 8 shows a sample measurement of the VTC and SNM for a 6T transistor.

Figure 8: 6T SRAM for reference (right) and “butterfly plot” showing the measurement of VTC and SNM for a 6T SRAM using the “maximum squares” method (left) [34].

Coupling inverters produces a feedback loop between nodes V1 and V2 where the state of the SRAM is stored. Alternating V1 from on to off alters the state of V2 from off to on and vice versa. A “butterfly plot” gives the VTC of the inverters with nodes V1 and V2 as a function of input voltage placed on the opposite node. Noise on either node affects the other but does not change the inverter’s state if the SNM is high enough. The “maximum squares” method provides an estimate of the SNM by drawing the largest possible square between the VTC of V1 and the VTC of V2 in the window between the two curves. SNM is then given as the horizontal distance the square crosses, as this is the maximum amount the input voltage can deviate before the state of the circuit becomes indeterminate [35]. These concepts intersect with the concept of the critical charge $Q_{\text{crit}}$ discussed in the introduction of this section. If the amount of charge generated in either node V1 or V2 exceeds $Q_{\text{crit}}$, a shift in voltage exceeding the SNM occurs, corrupting the state of the memory.
II.3.2 Single event effects in SRAMs

One type of SEE is a single bit flip in an SRAM or other memory device. When a single particle passes through a device, the charge generated can exceed $Q_{\text{crit}}$ and change the state of the memory, causing a single bit upset (SBU). In analog circuits, a similar problem is a current transient caused by an incident particle called a single event transient (SET). Since analog circuits read inputs as continuous, even small SETs can cause enormous problems for sensitive circuits [36]. In either case, the SEE can propagate through the system and impact the output.

A single particle can cause multiple bit upsets (MBUs) in one pass, either by passing at an angle or generating particles which themselves cause upsets. Heavy ions can produce nuclear reaction fragments that are highly ionizing. These fragments can impact separate devices on the same chip, upsetting multiple cells [37]. Some studies have shown that $\delta$-rays produced by heavy ions could meaningfully contribute to the upset rate [38, 39], while others have claimed that they do not [40, 41]. Another source of MBUs is charge sharing at the circuit level. Charge from an ion strike near one device’s drain region diffuses around trench isolation layers and enters another device’s drain, upsetting both. More than two devices can be upset in this manner depending on the amount of charge in the initial strike and the diffusion paths within the semiconductor [42]. Regardless of the source, MBUs cause errors spatially correlated with the layout of the circuit and the path of the particle. This makes predicting the impact on the output of the whole circuit a layout dependent problem [43].

The quantitative laboratory assessment of a device’s vulnerability is typically its SEU cross-section determined from exposure to a particle beam. Properties such as the energy and flux are set by the beam operator prior to exposure. Frequently the beam is composed of a spectrum of energies. Experimental cross-section is determined by dividing the number of upsets observed by the beam fluence $\Phi$. Generally, this is done with multiple particle species and incident energies to vary the LET of the incoming particles. Additionally, the beam angle can have a significant effect on the observed SEU cross section [44, 45]. Whether changing the angle increases or decreases the observed SEU cross-section
depends on the change of the track pattern in the device sensitive region. Figure 9 shows that for a FinFET device, changing the angle can either increase or decrease the SEU cross-section depending on the axis of rotation [8]. Once the experiment is complete, the SEU cross-section can be plotted as a function of beam energy, particle LET, angle of incidence, or another experimental parameter as required to investigate the mechanisms at work.

![Diagram](image)

Figure 9: Path an incident heavy ion takes through a W-E angle (a) and N-S angle (b) as a function of angle off of normal incidence. Rotating the beam angle off of normal increases the path length for the axis of rotation in (a) but decreases it for (b) [8].
II.3.3 Heavy ion, proton, and muon-induced SEU properties

In this subsection, SEUs in SRAMs from heavy ion, proton and muons are covered. While many similarities exist in the mechanisms between the three, each induces different types of SEE under specific conditions. Particle mass, and therefore LET as a function of velocity, decreases from heavy ions to protons to muons.

The first reported SEUs were due to heavy ion radiation, as older devices flown in space had large feature sizes and operating voltages, making them resistant to SEUs from other sources [20, 46]. Investigations into their mechanisms have continued for almost half a century. Heavy ions consist of the set of ionized particles with $Z > 1$. Thus, heavy ions are generally more ionizing than lighter particles. Heavy ions produce upsets from direct ionization and indirect ionization. Much study has been done on heavy ion track structure. One seminal work on the topic was published by Kobetich and Katz in 1969 which described the heavy ion track structure [47]. By bombarding an emulsion with heavy ions, the researchers correlated the track structure with incident particle energy and charge. When studying SEUs induced by heavy ions, a common simplification is to assume that the energy deposited by the ion is described exclusively by its LET and range. Heavy ion SEU data are usually plotted as SEU cross-section vs. LET for this reason. Still, significant evidence exists that the heavy ion track structure and incident energy have effects on the observed SEU cross-section prior to saturation [19, 48, 49]. For this work, the LET approximation is generally used as long as the LET is constant in the device sensitive volume.

Several different types of radiation induced effects can be caused by heavy ions and their nuclear reaction products. SEUs from direct or indirect ionization are the most common. SELs are also possible if the LET is high enough [50]. MBUs can also occur if charge sharing is possible in the device or if the ion’s angle takes it through multiple sensitive regions [51].

Proton-induced SEUs were first discovered in association with their nuclear reaction products. Protons interacting with the surrounding material produce nuclear reaction fragments which in turn induce the SEU [52]. As designers shrunk the area and operating voltage of their devices, proton-induced
SEUs from scattering events and eventually direct ionization became possible. Rodbell et al. attributed increased proton SEU cross-sections to direct ionization upsets by adjusting the angle during testing [4]. As the roll angle increased from normal incidence, the proton’s path through the sensitive volume increased in distance which resulted in larger SEU cross-sections. Since then, considerable testing has been performed to determine the impact of low energy proton-induced upsets on SRAMs and other devices [11, 53].

Stopping protons have much higher LETs than protons passing through a sensitive region. Thus, stopping protons are much more likely to induce an SEU. Figure 10 shows proton data taken from an IBM 65 nm SRAM SOI device at multiple tilt angles [54]. Increasing the tilt angle for this device causes an increase in the SEU cross-section below about 20 MeV but has much less effect at higher energies. Similar to the work in [4], the positive correlation between the tilt angle and the proton track length provides strong evidence that at lower energies, the upsets are induced by stopping protons.
Figure 10: Proton test results as a function of beam energy and tilt angle for an IBM 65 nm SOI device. Increasing the angle of incidence increases the SEU cross-section induced by direct ionization (~< 20 MeV) but not nuclear reaction induced SEUs (~> 20 MeV) [54]

Muon-induced SEUs occur in a similar fashion to protons. Stopping muons deposit more charge than their non-stopping counterparts. Figure 11 presents experimental results for several technology nodes. Muon SEU data were taken at the TRUMF M20B beam facility with a muon beam that had significant energy spread based on the momentum selection. Simulated kinetic energy distributions at the device surface are given on the bottom plot. Above, the SEU data in the form of upsets per muon are given for 65 nm, 45 nm, and 40 nm technologies [5]. Similar to the protons in Figure 10, low-energy stopping muons produce significantly more upsets than the muons passing through the device. Further
investigations of the effect of muons on FinFETs [14] and flash memories [55] have been performed with similar conclusions.

Figure 11: Simulated muon kinetic energy distributions, as seen at the front of the part, corresponding to experimental momenta including upstream energy losses and straggling (bottom). Error counts for 65 nm, 45 nm, and 40 nm SRAMs versus estimated muon kinetic energy at 1.0 V bias (top). Dashed horizontal line represents an approximate muon-induced SEU cross section for reference [5].

II.4 Lightly ionizing particle environments

Historically the main causes of SEUs in both space and terrestrial environments were heavy ions, either directly from cosmic rays or as secondaries generated from proton or neutron nuclear interactions [18]. Protons reach peak energies of almost 500 MeV in the trapped belts, which result in upsets through both direct ionization and nuclear reactions [56].

21
Modern devices have been shown to be vulnerable to low-energy stopping particles such as protons [4], muons [5], and δ-rays [6, 9]. Low-energy protons are relevant in low and middle earth orbits as there are far more low energy protons than high energy protons [56]. Muons are byproducts of interactions between galactic cosmic rays (GCR) and Earth’s atmosphere and thus are a purely terrestrial concern. Currently the predicted neutron-induced upsets are dominant over muons in terrestrial applications, though with sufficiently low critical charge, future devices may be more vulnerable to muons [5]. δ-rays are potential byproducts of any Coulomb interaction between an ion and the surrounding material. Upsets due to δ-rays are possible for any environment, though have not been proven to dominate due to lack of experimental evidence [41]. Simulations have previously indicated future devices may be dominated by δ-ray induced upsets in geosynchronous orbit or in the Jovian environment [9].

Simulations in this work require input of environmental differential energy flux files in order to generate beam profiles consistent with the intended operating conditions. Rate predictions in Chapters IV and VI employ differential flux spectra generated from Excel-based Program for Calculating Atmospheric Cosmic-ray Spectrum (EXPACS) [57] for terrestrial environments and The Space Environment Information System (SPENVIS) [58] for space environments.

EXPACS uses data generated with the PHITS-based Analytical Radiation model (PARMA) [59]. PHITS stands for the Particle and Heavy Ion Transport Code System and is a general-purpose Monte Carlo tool used for ion transport [60]. PARMA used this tool to calculate differential energy spectra for a wide variety of atmospheric conditions. EXPACS provides an easy to use Excel-based tool for extracting the spectra for predetermined environmental conditions. Differential energy spectra for the terrestrial muon, neutron, and proton were generated for sea level NYC and atmospheric conditions.

Several environments are relevant to this work. The following subsections discuss both earth and Jovian space environments. The terrestrial environment is also covered.
II.4.1 Earth orbit environments

Microelectronic devices find their way into orbit around Earth to fulfill many practical applications. Each year the number of satellites launched increases, and each needs to be as efficient and reliable as possible. Depending on the track the orbit takes and the solar weather conditions, devices are exposed to particles trapped in the Earth’s magnetosphere, products of solar ejections, and galactic cosmic rays.

II.4.1.1 Trapped Particle Environment

Earth’s magnetic field traps protons, alpha particles and electrons in the Van Allen belts, named after the researcher who originally measured the differential energy flux of the particles trapped there [61]. In the decades since, several more studies have been performed to improve the community’s understanding of the composition of the belts. This work mainly employs the AE-8 model for electrons and the AP-8 model for protons [56, 62]. These tools contain a wide range of environment data consolidated from many missions. SPENVIS takes orbit parameters including apogee, perigee, inclination, and mission duration as inputs and then predicts the differential flux of electrons and protons the part is planned to be exposed to. Improved models AE-9 and AP-9 had become available in the interim of this work, but to maintain continuity from earlier work, AE-8 and AP-8 are used.

The Van Allen belts are divided into the inner and outer belts. Inside the inner belts, both protons and electrons are trapped. Only electrons are present in the outer belts. Ionizing radiation in these energy ranges can cause total ionizing dose, displacement damage, and SEEs in modern devices. Electrons range from 10 keV to 10 MeV while protons range from 100 keV to 400 MeV. Figure 12 shows the flux for trapped protons and electrons as a function of orbital position.
Figure 12: Fluxes for protons >10 MeV (top) and electrons >1 MeV (bot) as a function of distance from Earth based on AP-8 and AE-8 models [63]. Note that the protons do not extend into the outer bands.

Both protons and electrons primarily induce SEUs while near stopping [9, 11]. Spacecraft shielding slows and attenuates the proton and electron spectra, impacting the distribution of stopping
particles near the device’s sensitive regions. For example, while 100 mils of shielding stops electrons with energies below 1.25 MeV [16], the remaining spectrum is degraded so that there are still low energy electrons at the surface of the device. Unless the shielding is sufficient to attenuate all protons and electrons in the given environment, a low-energy tail of particles can reach the device and stop in the sensitive regions. Spacecraft shielding must therefore be taken into consideration when determining the particle spectrum on a case-by-case basis.

Changes in space weather are known to affect the shape and composition of the Van Allen belts significantly. A demonstration of the variance in the peak electron fluxes is evident from measurements taken from the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) space probe [64]. Figure 13 shows the results of the mission. On the bottom plot, the color-coded axis is a logarithmic scale of electron flux in arbitrary units. The vertical axis is the radial distance (L) for the orbit, and the horizontal axis is time in years. In the upper panel, the smoothed sunspot number (black) and solar wind speed (red) are shown for comparison.
Figure 13: Long-term (1992–2013) record of electrons measured primarily by the SAMPEX spacecraft at low altitude.

Solar wind speed has a profound impact on the composition of the outer electron belts [65]. During the SAMPEX mission duration, minimums in electron flux and band width occurred in 2008 while maximums occurred in 1994. These corresponded to minimums and maximums in solar wind speed as well.

Solar particles come from two primary sources: coronal mass ejections (CMEs) and solar flares. CMEs occur when plasma released from the surface of the sun sends a cloud of ionizing radiation into space. Solar flares similarly eject charged particles when the electric field on the surface of the sun breaks down [63]. Energy and particle signatures for the two types of solar events are distinct. CMEs generally last longer than solar flares and are more disruptive to electronics in space. Solar events follow predictable patterns as a function of time, as shown in Figure 14. Time periods are split into solar...
maximums, where a large number of events occurred close together, and minimums, which were relatively quiet.

Figure 14: Plot of fluence for protons with > 0.88 MeV measured between 1974 and 2002 [63]. Top axis shows division between solar maximum and solar minimum regions.

II.4.1.2 Galactic Cosmic Rays

GCRs are the third major source of ionizing radiation in space. Victor Hess earned the 1936 Nobel Prize in physics by taking the first measurements of the cosmic ray spectrum using a hot air balloon. By taking readings on an electrometer at various heights and during a solar eclipse, Hess confirmed both that the radiation was originating from outside Earth’s atmosphere and not from the sun [66]. GCRs also were the source of the first SEUs proven to occur in microelectronic devices [46]. Originating from super novae and other interstellar processes, the GCR spectrum contains a wide range of ionized heavy ions at a variety of energies. Stable ions from hydrogen to uranium are represented, though atoms larger than iron are far rarer. Figure 15 shows the high energy cosmic ray spectra for a sample of heavy ions. The flux ranges over 30 orders of magnitude, and the energy ranges almost 10 as well. Since most of these particles are highly energetic cosmic rays, SEEs are the largest concern. In addition to
causing SEUs, SELs, and SEGRs as a primary particle, cosmic rays can interact with shielding materials, producing secondary particles that also pose a reliability threat [67].

Figure 15: High energy cosmic ray spectra for ions with $8 < Z < 26$ [68].

II.4.1.3 Environmental considerations between orbits

A satellite’s orbit ultimately dictates what parts of the space radiation environment it encounters. For the purposes of this work, the three main altitudes considered are low earth orbit (LEO), medium earth orbit (MEO), and geosynchronous orbit (GEO). Additionally, for LEO, inclinations of 0 and 60 degrees are considered. Orbits in LEO are partially shielded from the GCR and solar event spectra and thus the trapped radiation belts are the primary concern. The higher inclination orbits also pass through the “horn” region near the poles where the belts bend, increasing the satellite’s exposure. MEOs similarly primarily deal with the trapped radiation belts. GEO orbits are not as well-protected by Earth’s magnetic
field and thus GCR and solar radiation environments contribute more to the overall event rate. Furthermore, the proton belt does not extend to GEO, meaning that only electrons are present from the trapped particle environment [69].

Table 1: Earth orbits used in this work. Orbits 1-3 are LEO, 4-5 are MEO, and 6 is GEO [9].

<table>
<thead>
<tr>
<th>Orbit #</th>
<th>Description</th>
<th>L-Shell (Earth radii)</th>
<th>Radius (km)</th>
<th>Inclination (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Inner Belt Min.</td>
<td>1.16</td>
<td>7,360</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Horn Region</td>
<td>1.16</td>
<td>7,360</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>Inner Belt Max.</td>
<td>1.57</td>
<td>10,000</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Boundary</td>
<td>2.8</td>
<td>17,839</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Outer Belt Max.</td>
<td>5</td>
<td>31,855</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Geo</td>
<td>5.61</td>
<td>35,786</td>
<td>0</td>
</tr>
</tbody>
</table>

Flux spectra used in this work are the product of the SPENVIS tool. Table 1 presents the example orbits chosen for this work. Orbits 1-3 are all LEO orbits. Orbit 1 is the inner belt minimum electron flux; orbit 2 is the same distance from Earth but at a 60-degree inclination so it passes through the horn region, while orbit 3 is the maximum for the inner belt. Orbits 4 and 5 are selected MEO orbits, while orbit 6 is a typical example of a GEO orbit. Trapped electrons are present in all six orbits but trapped protons only exist in orbits 1-3. Differential electron and proton flux spectra from SPENVIS for each orbit are plotted in Figure 16. Fluxes assume that the spacecraft has 75 mils of aluminum shielding.
II.4.2 Jovian space environment

Missions to Jupiter and its moons encounter a high energy trapped electron environment in addition to the GCR and solar proton environments [70, 71]. Measurements by the Galileo probe indicate that the radiation belts have the most intense trapped electron environment in our solar system. NASA’s Jet Propulsion Laboratory (JPL) constructed the Galileo Interim Radiation Electron model (GIRE) in order to simulate the effects of the belts on satellites [71]. This dissertation uses GIRE2, an updated version from 2012 [72, 73]. When developed, the major concerns were surface charging and TID effects, but King proposed in his dissertation that electron-induced SEUs could be a significant problem [74]. GIRE2 considers electrons with energies between 10 keV – 100 MeV out to ~50 Jovian radii based off of current models for the Jovian space weather conditions. Electron fluxes vary from about $10^5$ down to $10^{-7}$ (cm-keV-s-sr)$^{-1}$ between 0.1 and 50 Jovian radii. Thus, for a given mission with multiple orbits, significant variation in exposure to the electron environment may occur.

Two missions are considered in this work: the Juno mission, whose parameters were determined from GIRE2 [70, 72], and the Europa clipper mission, whose parameters were defined from an internal JPL document in [75]. The Europa clipper mission is considered the “worst case” for both trapped electrons and protons. Simulated differential fluxes for both missions are in Figure 17. Simulations were
performed by taking the mission parameters and inputting them into SPENVIS to generate the proton and electron fluxes.

![Graph showing electron and proton fluxes for the Europa Clipper and Juno missions.](image)

Figure 17: Fluxes for electrons and protons determined for the Europa Clipper and Juno missions. Europa clipper is denoted as the “peak” for electrons and protons [9].

### II.4.3 Terrestrial muon environment

Muons are not a concern in space environments because they decay quickly. On Earth’s surface however, particle showers produced from cosmic ray interactions in the upper atmosphere contain muons. Incident GCRs strike air molecules in the upper atmosphere at enormous energies and induce nuclear reactions that lead to the generation of a wide variety of particles. Most of these undergo further nuclear disintegrations and decays as they travel to the Earth’s surface, leading to a spectrum of radiation consisting of a wide variety of particles. Historically, in the field of radiation effects, the most significant terrestrial concern is neutrons which induce nuclear reactions in the material surrounding the device sensitive volume [76, 77]. Alpha particles from the primary shower and secondary reactions also have
been shown to induce SEUs [78]. Shrinking device sizes have recently led various researchers to theorize that terrestrial muons could also be a threat, which has led to a bevy of investigations [5, 14, 55].

Using the EXPACS simulation suite, sea level muon and neutron spectra were simulated in [79] and presented here in Figure 18. Comparisons were made to measurements taken in [80]. Above about 300 MeV, the muon flux is higher than the neutron flux. Transporting the spectrum through concrete further attenuates the muon spectrum. Furthermore, protons also are a significant component of the terrestrial spectrum. For this work, the spectra from EXPACS were transported through an additional 10 cm of concrete using MRED. Details are provided in section VI.1.

Figure 18: Flux spectra extracted from EXPACS for neutrons and muons at New York City. Comparisons are made to muon measurements taken by Allkofer in [80]. Plot originally from [79].

II.5 Using Monte Carlo tools to model SEUs

Monte Carlo simulations take an input randomly sampled from a probability distribution and propagate it through a deterministic process in order to produce the output. Stanislaw Ulam is famously credited with inventing the technique. While playing solitaire, he considered playing thousands of games
with a randomly generated deck to determine the probability of winning. As a scientist working on the Manhattan project, he realized that the new ENIAC computers could perform these games as simulations. John von Neumann, a fellow scientist working on the Manhattan project, recognized that Ulam’s method had applicability to neutron transport physics. Named the Monte Carlo method after the casino of the same name, this stochastic approach to problem solving became a cornerstone of computational science [81]. Ion transport, thermal motion, and fluid dynamics are just a few of the many disciplines where Monte Carlo tools are employed.

A classic example of the Monte Carlo method is to calculate the value of \( \pi \). An estimate of \( \pi \) can be obtained by taking the area of a square, \( A_{sq} \), and the area of the arc that subtends the quadrant from one corner to another \( A_{arc} \). The value of \( \pi \) is then equal to \( 4\frac{A_{arc}}{A_{sq}} \). Using Monte Carlo to perform the approximation begins by defining a grid that extends from \( x = 0 \) to \( x = 1 \) and \( y = 0 \) to \( y = 1 \). This forms the square with area \( A_{sq} \). Next, the arc formed from the equation \( l = x^2 + y^2 \) is drawn on the circle. \( N \) points are randomly sampled in \( x \) and \( y \) across the grid and separated into two categories: inside the arc and outside. An approximation for \( \pi \) is given by four times the ratio of the number of points inside to the total number of points. Figure 19 shows the result of this procedure for values of \( N = 100, N = 1000, \) and \( N = 10000 \).

![Figure 19: Approximations for \( \pi \) as calculated using the Monte Carlo method. From left to right, the approximation improves as the number of points simulated (N) increases.](image)

33
Using the Monte Carlo method, the deterministic variable $\pi$ was estimated using randomly sampled inputs followed by a relatively simple calculation. While a simple example, the fundamental Monte Carlo method used here can be extended to a wide range of applications and algorithms. More advanced treatments of the general topic of Monte Carlo simulations in physics can be found in [15]. For the purposes of this dissertation, the focus is on using Monte Carlo to transport particles through a medium.

II.5.1 Monte Carlo simulations of ion transport

Monte-Carlo Radiative Energy Deposition (MRED) is an ion transport code that employs Monte-Carlo techniques to probabilistically predict the cross-sections for energy deposition events in stacks of materials. Weller et al. developed this tool specifically to simulate energy deposition during SEEs [31, 82].

Geant4 provides the fundamental physics package for MRED [83, 84]. C++ classes included in Geant4 handle the transport physics, particle generation, and bookkeeping needed to have a comprehensive ion transport framework. A tool called Simplified Wrapper Interface Generator (SWIG) automatically modifies the C++ code to be usable as a Python module [85]. This adaptation allows for more flexibility for setting up runs without disrupting the core Geant4 package. Several other physics modules not native to Geant4 were added through collaborations with outside parties. JQMD, LAQGSM, and CEM03 were added to assist in handling nuclear reactions [86, 87]. PENELLOPE tracks electrons down to lower energies than Geant4 [88]. This is particularly useful in this work, given the small size of the 28 nm SRAM’s sensitive regions and mechanisms of lightly ionizing particle-induced SEUs. Figure 20 shows the architecture of MRED.
MRED assumes that the “binary collision” approximation is valid. This states that the incident particle interacts only with the stationary particles in the material. For the case of an SEU, this generally holds true since the state of the material is not changing. A full mathematical treatment of Monte Carlo and its applications to MRED is too complex to be recounted here. Weller et al. in [82] provide a good resource. Here, we begin with defining the rectangular parallelepiped (RPP) device model. RPP models have an extensive history of use in radiation effects [89, 90]. In an RPP model, the sensitive region is defined as a simple rectangular box. RPP models require a few assumptions to be valid. Particles passing through the box must have a constant LET so that the energy deposited is singularly determined by the length of the chord that traverses the RPP. Furthermore, the device must be upset if and only if the energy deposited exceeds a threshold energy, $E_c$.

Let $A$ be the total surface area of the RPP, $z$ is the particle type, $\Phi$ is the particle flux, $E$ is the energy deposited, $E_c$ is the energy required to produce an SEU, and $S$ be the LET. With some reductions, the rate, $R_e$, can be defined by Equation 2 [82].

$$R_e(E_c) = \pi A \sum_z \int \Phi(z,E) P_c \left( \frac{E_c}{S(z,E)} \right)$$

(2)
$P_c$ describes the integral probability distribution of chord lengths through the RPP and is a function of the dimensions of the RPP. Work performed in [82] analytically demonstrated that Monte Carlo simulation results with MRED approach more traditional, deterministic approaches with RPP models. MRED makes finding the result much more convenient and can take into account a larger range of conditions.

MRED performs Monte Carlo simulations for each step that the incident particle travels within the world material. At each step, probabilities for various interactions including scattering, nuclear reactions, and $\delta$-ray production are calculated from the physics modules provided considering the current state of the simulation. Then, a random number is generated which is used to choose the process that affects the particle. Secondary particles are generated accordingly and each particle’s physical attributes such as energy and direction are updated. For particles whose energy is low enough that any secondaries which would travel less distance than the “range cut”, the particle ceases producing secondaries and deposits its remaining energy according to continuous energy loss. The range cut is effectively an energy threshold, but units of distance are used to make it independent of the materials the particle passes through as well as the particle species. The primary reason for employing a range cut is to save computing resources by switching from a stochastic process to a deterministic one. Its value is set by the user according to the geometry of the problem.

Because MRED adaptively determines particle energy and secondary processes, constant LET approximations are not required. Furthermore, the customization of adding physics modules makes modeling SEUs produced by lightly ionizing, stopping particles a reality.

II.5.2 Modeling SEUs with MRED

MRED has been used many times to accurately predict a device’s SEU response [5, 12, 91]. Successful modeling of the device SEU response requires detailed knowledge of the device structure and/or experimental data for calibration. To begin with, a materials stack such as in Figure 21 represents the structure of the device around the sensitive region and BEOL. The sensitive volume (SV) in this case
is defined as a simple 1-volume RPP model. Above the SV is the BEOL. The particle mainly interacts with the BEOL by slowing down, so the primary concern is the layer’s effect on slowing the particle. Often the average thickness of each material layer is sufficient in place of a detailed description. If there are high-Z materials such as tungsten in the BEOL, more detail may be necessary due to the increased likelihood of nuclear reactions [20].

Next the particle, beam energies, and spatial distribution are chosen. Most fundamental particles are available by default in MRED while heavy ions can be defined by atomic number and mass. Beams can either be monoenergetic or selected from an environmental spectrum. Spatial distributions have many options, with the most common choices being a dithered beam, directional flux normal to the surface, or isotropic flux.

![Figure 21: Rectangular parallelepiped model of the 28 nm SRAM used for some MRED simulations. The particles are generated normally incident to the front of the BEOL in a random pattern. Exact values of SV and BEOL dimensions withheld at the manufacturer’s request.](image)

Each particle has its position randomly generated according to the spatial distribution and launched at the device with the energy generated by the beam spectrum. The particle loses energy and undergoes physical interactions with probabilities determined from physical models in MRED. Energy deposited within the SV is tracked for each particle strike. Each event is tallied into a histogram similar to Figure 22. The y-axis represents the number of counts, or relative probability, of an energy deposition event versus the total energy deposited in those events. Total energy deposited in the SV is on the x-axis.
Accurate simulation results require good statistics, generally enough for error bars of 10% or less. Sample sizes of ions depend on the area of the sensitive region and the probability for an upset to occur.

MRED results can be used to generate a rate prediction which represents the number of errors in a device over a certain time frame for a given environment. A properly calibrated MRED model and well understood environment spectrum are both required to perform a rate prediction. Also relevant is a reliable estimate of the device Q\(_{\text{crit}}\). In Figure 22 an arbitrary Q\(_{\text{crit}}\) is marked on the x-axis for illustrative purposes. Each event depositing more energy (converted to charge by \(22.5 \text{ keV/\text{fC}}\) [1]) than Q\(_{\text{crit}}\) contributes to the total upset rate, while those below do not. Thus, the fraction of particles for these beam energies that induce upsets is the number whose generated charge exceeds Q\(_{\text{crit}}\) divided by the total number of ions that strike the device.

![Figure 22: Energy deposition vs. counts in the SV for 2.5 MeV protons normally incident on a simple RPP model similar to the one in Figure 21. An arbitrary Q\(_{\text{crit}}\) is marked for illustrative purposes.](image)

Layout changes can have a profound impact on SEU vulnerability. Fabricating devices with a new layout only to find the vulnerability has increased beyond tolerable limits can potentially cost a
significant amount of time and money. Simulations employing calibrated models can reveal differences in vulnerabilities between processes without the need for fabrication. (For the 28 nm SRAM used in this work, bit cell structural information was not available so a study on the effect of layout changes on the SEU response was impossible.) Examples of MRED being used to analyze charge collection in devices with detailed layout considerations can be found in [91, 92].

II.5.3 Previous work by others on calibrated models

In the last subsection of this Monte Carlo discussion, previous work by other authors on constructing models in MRED were discussed. Models have been produced using layout process details or TCAD information, sometimes with heavy ion informed parameters included. Multi-SV models use multiple RPP models to refine the definition of the sensitive region.

Warren et al. demonstrated a method for predicting heavy ion, proton, alpha and neutron induced SEU cross-sections with calibrated models in MRED [12, 32]. Shortcomings in the RPP model became apparent as devices scaled down. The physical assumptions that go into RPP modeling break down when device sizes shrink to the point that the scale of the width of the ion tracks is on the same order of magnitude as the device SV. Warren et al. addressed these hurdles by adding a stack of sensitive volumes with varying dimensions and charge collection efficiencies. The sum of the charge collected in these

Figure 23: Solid model for 25μm SRAM used for modeling in [12, 32]. SV sizes and charge collection efficiencies are informed from TCAD simulations.
volumes is the total charge collected in the device. TCAD simulations and manufacturer device information were used to inform the layout of the structure and the value of $Q_{\text{crit}}$. Figure 23 shows the model used in [32]. This solid model was used to predict the SEU test results and environmental event rates for various particle species. Heavy ion test and simulation results are presented in Figure 24. Predictions from simulations closely match the experimental results.

Figure 24: Comparison of 25 μm SRAM heavy ion tests results and simulations. Predicted cross-sections match experimental results closely due to the sophistication of the MRED and TCAD models.

Knowledge from the manufacturer was required to properly calibrate the model in [32]. Since this is not always available, an alternative method employs an empirical strategy by calibrating the model using heavy ion data to predict proton SEU cross-sections [11, 32]. Sensitive volume areas and critical charges are inferred from heavy ion data through the observed cross section and LET respectively. Heavy ion data experimental results produce a point $i$ which has cross-section $\sigma_i$ and LET$_i$. Associated volume $V_i$ with $i > 1$ has dimensions $d_i = \sqrt{\sigma_i}$ and charge collection efficiency $\alpha_i = Q_{\text{crit}}/(\text{LET}_i \times d_i)$. $Q_{\text{crit}}$ must be estimated ahead of time but can be used as a free parameter for calibration. $V_1$ sits above the other volumes and is calibrated according to either limited manufacturer knowledge or peak cross-section. $V_1$ always has $\alpha_1 = 1$ [11]. Figure 25 shows a demonstration of this method for a 65 nm SRAM.
Figure 25: Heavy ion calibrated model for a 65 nm SRAM. Each volume corresponds to a heavy ion data point [11].

Proton test results were compared to simulation results using the above calibrated model in Figure 26. Proton and heavy ion data are both well predicted with the same model, reinforcing that the physical assumption inherent in the multi-SV model does not change based on particle species. Low energy proton events in particular are subject to high angle scattering events and are most prone to upsetting the device when stopping [4, 11]. Unlike heavy ions which pass through with relatively constant LET, stopping protons have high variance in energy deposition properties which simple RPP models can fail to capture. Multi-SV heavy ion calibrated models still encapsulate these effects despite this difference in energy deposition mechanisms between protons and heavy ions.

Figure 26: Proton test results compared to MRED simulation predictions for the 65 nm SRAM [11].
II.6 Vanderbilt CubeSat program

Accelerated testing and modeling can only be taken so far to predict modern technologies vulnerability in the space environment. Small satellites such as CubeSats provide a platform to send experiment boards into LEO at reduced cost. Invented by a collaboration between Stanford University and California Polytechnic State University, CubeSats are 10 x 10 x 11 cm cubes weighing up to 1.3 kg that are ejected into orbit off of scheduled launch vehicles [93]. Vanderbilt has run a CubeSat platform in conjunction with the Amateur Satellite Corporation (AMSAT) in order to fly commercial off the shelf (COTS) parts. Space agencies prefer to fly legacy parts over COTS parts since they are proven for flight but understanding the radiation effects in these parts is instrumental to modernizing space systems. CubeSat satellites are cost efficient and launches are provided by NASA to educational institutions at reduced cost.

Figure 27: AO-85 spacecraft composed of a 1-unit CubeSat. Inside is an experiment board which measures a COTS SRAM’s on-orbit SEU rate [94].
Vanderbilt’s first successful CubeSat spacecraft, AO-85, carried a COTS SRAM into orbit and measured the SEU rate. The CubeSat unit is pictured in Figure 27. Within it is a two-board experiment developed by Vanderbilt and a spacecraft bus developed by AMSAT. The experiment itself is run by the Low Energy Proton (LEP) board which periodically writes to the SRAM, waits a fixed amount of time, and reads back to check for errors. Results from the exposure are communicated to the other board called the Vanderbilt Controller (VUC) which in turn is capable of communicating with the AMSAT module [94]. Figure 28 shows SEU data taken on the AO-85 mission. Large variations are observed in the SEU rate across time which has since been attributed to changes in orbit.

In addition to saving money by using CubeSats, the Vanderbilt program has found an additional advantage by partnering with AMSAT. A veritable army of amateur radio enthusiasts constantly communicate with AO-85 and download the SEU data collected by the experiment. Because the amateur satellite community has a strong international presence, the satellite constantly uplinks to at least one of the many operators around the world as it orbits. This allows for a highly effective “crowdsourcing” of the data collection. Furthermore, geolocation and temporal isolation of the SEUs occurring on orbit become possible [69].

Figure 28: SEU data on a COTS SRAM taken by AO-85. Top left plot gives cumulative upsets for the mission length, top right gives the daily upsets as a function of time, bottom left bins the daily upsets by the number of days they occurred, and finally the bottom right plot is the SEU rate versus time. [94]
The connection between CubeSats and the work in this dissertation is that the 28 nm SRAM is being flown on Fox 1-B, the launch which followed the AO-85 launch. Carrying the Radiation Effects Measurement (REM) experiment, the Fox 1-B satellite was launched late in 2017. Data on the 28 nm SRAMs on-orbit SEU rate are being collected as this dissertation is being written. Since this part has been shown to be vulnerable to electron-induced SEUs [9], it may be possible that the SEU rate on orbit is partially due to trapped electrons in addition to protons. The LEO orbits presented in section II.3.1 are representative of the orbit Fox 1-B is taking. Still, many months of exposures are required for the data set to reach the maturity of AO-85.
CHAPTER III

EXPERIMENTAL RESULTS

Proton, heavy ion, electron, and muon SEU tests were performed on the 28 nm and 45 nm SRAMs at various facilities. This section describes the operation of the DUT and the experimental results for each of the tests. The data taken in these tests are used for model calibration and validation in further sections.

III.1 28 nm SRAM operation

Operation of the 28nm SRAM was standardized for all SEU tests performed for this work. Nominal operation for the device is between 0.9V and 1.1V, but it is designed to hold a memory state down to 0.3V. Modulating this voltage allows for an effective modulation of the device critical charge during exposures. Each exposure begins with the SRAM being booted up at nominal voltage and writing a checkerboard pattern. Next, the bias is reduced for exposure and the beam is turned on. Exposure time is determined by the need to achieve good statistics. In general, this means accumulating at least 100 errors for a standard error of 10%. Error bars are given for most plots in this section showing the standard error for each measurement. Following exposure, the bias is raised back to nominal and a read is performed to check for errors. Figure 29 presents the timing for bias changes for the experiments.
Figure 29: Timing diagram for the experiment. The initial read and write, and the post read are done at nominal voltage. During exposure, the SRAM Bias is dropped to the test bias. The exposure time is dependent on the fluence and upset rate. Original image from [6].

On the experiment board, a PIC24 microcontroller communicated with the 28 nm SRAM. Commands sent remotely from a laptop to the microcontroller via the I2C protocol allowed for remotely reading, writing, and powering the SRAM. Power supplies were remotely operated to bias the board for exposures. An example test set up for the monoenergetic electron tests performed at the Arnold Engineering and Development Complex (AEDC) is presented in Figure 30. Tests performed at other facilities used a similar set up.
Figure 30: Experimental setup used at AEDC for the 28 nm SRAM. Similar setups were used at other facilities. The board in the test chamber is controlled remotely via I2C.

In some cases, the part was “delidded.” This process removes the upper layer of plastic from the device using a chemical treatment, exposing the back end of line (BEOL). By reducing the amount of material between the sensitive regions and the beam source, lower energy beams can reach the device and less straggle is introduced. Since the 28 nm SRAM is a production part, the delidding process sometimes introduces bad or weak bits likely due to the chemicals damaging materials in the BEOL. Bad bits are accounted for before each exposure and ignored. Weak bits introduce a resting error count independent of beam conditions. Before each experimental condition, a run is performed with the beam off to count the resting errors. None of the experiments performed for this work had resting error accumulations contributing greater that 10% of the total error count during the experiment and were subtracted out of the final data point. Error accumulation while resting increased dramatically around 0.35 V, indicating that at near-threshold voltage levels the bit cell becomes considerably less reliable at holding its state.

Information about the number of bits and cross-section data are withheld at the request of the manufacturer. Instead, each plots’ data sets are normalized to a different constant than the others.
III.2 Heavy ion test results

Heavy ion data on the 28 nm SRAM were taken at Lawrence Berkley National Laboratory (LBNL). LETs ranged from 1.6 MeV·cm²/mg to 25 MeV·cm²/mg. The SRAM was operated in bias conditions of 0.35V and 0.85V. Test results are presented in Figure 31:

![Figure 31: Heavy ion data taken at 0.35 V and 0.85 V. Data are normalized to the peak SEU cross-section. Error bars were not available for heavy ion data.](image)

The 28 nm SRAM’s heavy ion induced SEU cross-section saturates at 17 MeV·cm²/mg for both biases. A factor of 50 separates the saturation cross-section between the 0.85 V bias and 0.35 V bias. Trends observed here are consistent with trends in bias and LET observed in other heavy ion tests [2]. Heavy ion data are used in this work as a parameter setting tool for modeling.

III.3 Proton test results

Proton tests were performed on the 28 nm SRAM at TRIUMF at higher energies and Vanderbilt for lower energies. The part was tested at both reduced and nominal biases at all energies.

The TRIUMF tests utilized bias modes of 0.5 V and 0.9 V. In each test, the memory was written and exposed to the beam before being checked for errors. The first set of tests performed at TRIUMF used a 70 MeV proton beam in air. Beam energy was selected using degraders, causing straggling in the...
energy distribution. The part was not delidded for these experiments. Mean energies between 2.5 MeV and 70 MeV were used for the experiments. Results are shown in Figure 32.

![Normalized proton-induced SEU cross sections for the Broadcom 28 nm SRAM taken at TRIUMF for bias voltages of 0.5 V [95].](image)

Figure 32: Normalized proton-induced SEU cross sections for the Broadcom 28 nm SRAM taken at TRIUMF for bias voltages of 0.5 V [95].

SEU cross-section peaks at lower energies, where stopping particles are depositing their remaining energy. At higher energies, scattering and nuclear reactions dominate the response. Because of the beam energy straggle and the fact that the part was not delidded, the width of the Bragg peak is right shifted and exaggerated.

Monoenergetic proton data were taken at the Vanderbilt Pelletron. This beam can be tuned from 250 keV to 4 MeV with a full-width half max spread of no more than 50 keV. Characterizing the SEU cross-section distribution near proton stopping becomes much easier since the beam has so little straggle. The part was operated at several bias voltages from 0.35 V to 0.85 V to modulate the bit cells’ critical charge. Energies were selected by ranging out to the device BEOL and increasing until the cross-section saturates. This technique was used to resolve the region where the protons were stopping from just inside the device sensitive regions through to the point where the only contributors were scatters. Parts were delidded for this experiment.
Figure 33: Monoenergetic proton data taken at Vanderbilt University for the 28 nm SRAM. Biases of 0.85 V and 0.35 V were used [13].

Trends in bias and energy again indicate that protons are causing the errors as opposed to weak bits or charging. The peak observed in the Pelletron experiments is much narrower in energy than for the degraded beam at TRIUMF. This effect can be attributed to the delidding procedure and lack of straggle. Peak cross-sections for both 0.85 V and 0.35 V biases are much closer together than their saturation cross-sections. The broadness of the 0.35 V data set is attributed to its operation in a near threshold condition, dramatically increasing its sensitivity to proton-induced SEUs. While bit cell information is not known, it is assumed that this peak is roughly the area of the device since stopping protons affect it almost equally regardless of bias.

III.4 Muon test results

Muon tests were performed at the M20B beamline for the same 28 nm SRAM. The beam is produced by striking a Beryllium target with high energy protons. Pions produced from the collision decay within 22 ns to form muons. Beam momentum is selected by a magnet after which the muons are transported through scintillating material to the DUT. This beam was simulated in MRED by transporting the beam’s initial spectrum after energy selection to the DUT. The material stack is presented in Figure 34.
Figure 34: Scintillating materials present in TRIUMF beamline past the initial energy selection. Conditions were simulated in MRED, using starting beam momenta as an initial condition.

MRED simulations are compared to surface barrier detector measurements taken at the DUT. Initial conditions are chosen based on the initial muon beam momentum selection. An MRED bullseye placed past the last air layer captures the muon energy distribution at the DUT. Results are presented in Figure 35.

Figure 35: Simulation results for beam momenta spectra simulated in MRED using the conditions in Figure 34.

Generally, simulations agree on the mean energy for the momentum selections captured on the surface barrier detector. Spectra are not centered on an energy corresponding with the initial selection.
because the amount of degrading material is so large. Significant spread in energy is observed for each selection. Muon-induced SEU tests were performed on the 28 nm SRAM at all momentum selections in Figure 35, but errors were only observed for momenta at 21.6 MeV and below. Experiments were done at 0.85V bias only. Results are presented in Figure 36, normalized to the peak value.

![Figure 36: Muon-induced SEU cross-section data taken on the M20B beamline for the 28 nm SRAM. Results are normalized to the peak value at 20.7 MeV/c.](image)

SEUs are clustered around the lower momentum selections, similar to proton data in Figure 32 and Figure 34. This implies that the stopping muons are what contribute the most to the SEU cross-section, consistent with conclusions in [79].

### III.5 Monoenergetic electron test results

Recently δ-ray induced upsets have become a reliability concern due to the shrinking of device feature sizes. Experimental evidence in [6] demonstrated that 45 nm and 28 nm devices operating at reduced bias are vulnerable to photoelectrons produced from x-rays. Upsets caused by δ-rays undergo significantly different mechanisms than muons or protons. δ-rays are produced according to probabilistic
mechanisms and then must stop within the sensitive region. This section details experiments used to characterize the δ-ray induced upset response of the 28 nm SRAM while the next section contains a comparison of the predicted upset rates for electrons and protons in the space environment for an arbitrary (50 nm)$^3$ SV. Rate predictions for the 28 nm SRAM δ-ray response require a more advanced and well calibrated multi-SV model than the ones used in proton and muon simulations. Section IV.2 covers the strategy for calibrating this model.

Electron-induced δ-rays were shown to cause upsets in this 28 nm SRAM as well as a similar 45 nm SRAM originally used by King in [6]. Both SRAMs only demonstrated upsets under low bias conditions [9]. Experiments were performed at the Arnold Engineering Development Complex (AEDC) using a monoenergetic electron beam. Results are presented in Figure 37 for the 28 nm and 45 nm SRAMs. Beam energies of 40 keV and 100 keV were used on the 45 nm SRAM, but only 40 keV was used for the 28 nm SRAM as the device failed due to charge build up in the first run at 100 keV.

![Figure 37: Experimental results from monoenergetic electron tests at AEDC. Error bars derived from the square root of the number of observed upsets [9].](image-url)
The SEU cross section increases with decreasing technology node, beam energy, and bias voltage as observed between data sets 1 & 3, 3 & 4, and 1 & 2 respectively. These trends strongly indicate that the upsets were caused by the electron beam as the part became more susceptible by decreasing the bit cell critical charge or by increasing the beam’s LET. Chapter IV contains simulation results for the experimental beam conditions and mechanisms study.

### III.6 Sr-90 electron test results

Further work was performed on the 28 nm SRAMs using a strontium-90 beta emitter. Strontium-90 decays into yttrium-90 with a decay energy of 0.511 MeV and half-life of 28.8 years and then to zirconium-90 with a decay energy of 2.28 MeV and half-life of 64 hours. Both decays are beta decays [96]. Because the Yt decay’s half-life is so short, the ratio of Sr-90 and Yt-90 decays is 1:1. Decay probabilities from this chain are shown in Figure 38.

![Figure 38: Decay probabilities for Strontium-90 and Yttrium-90, as well as the total combined from a Strontium-90 source. Image from [97].](image)

Parts were delidded for the experiment to prevent attenuation of the low energy electron tail at the sensitive region. The strontium source was rested directly atop the device package to minimize the
distance from the source to the device. An image of the Strontium source’s placement is given in Figure 39.

Figure 39: Placement of the Strontium button source during the experiments. The SRAM is located in the socket. The source sits directly above the delidded part, resting on the packaging.

Accurately measuring the distance between the source and SRAM was not possible given the setup. An estimate of 0.5 mm was made by measuring the distance from the surface of the package to the surface of the delidded part. However, the source may not have rested evenly on the surface. Uncertainty in this distance makes simulations in Chapter IV less accurate, since the size of the air gap significantly affects the electron spectrum at the device surface. The source was considerably thicker and wider than the chip.

Runs were performed by writing to the SRAM, placing a Strontium emitter button source near the surface of the device, adjusting the bias to the test voltage, performing a 5-minute run, and counting the number of upsets. Errors were observed at biases between 0.35 V and 0.5 V. Biases above 0.5 V did not result in SEUs. Experimental data from the Strontium-90 tests on the 28 nm SRAM are presented in Figure 40.
Figure 40: 28 nm SRAM data from Strontium-90 tests. Error bars are too small to be visible on the plot.

The trend of increasing SEU cross section with decreasing bias indicates that the upsets were caused by the electrons and not by other factors. These were the same devices tested at AEDC and were similarly vetted to ensure that the “weak bits” were not causing resting upset rates on the order of the rate when exposed. Mechanisms are explored in Chapter IV.

III.7 Summary of SEU test results for the 28 nm SRAM

SEU testing of the 28 nm SRAM demonstrated that the part is vulnerable to a wide range of particles in various conditions. High energy proton, low energy proton, heavy ion, and muon SEU data were collected to support the modeling work in future sections. Furthermore, a monoenergetic electron beam used to induce low energy electron upsets in this device. Presented in [9], this was the first time SEUs were observed from lightly ionizing electrons. The mechanism that caused the upset was not fully understood, and Chapter IV provides simulations that explain these phenomena.
CHAPTER IV

ELECTRON-INDUCED SEU MECHANISMS

Mechanisms behind electron-induced SEUs are discussed in this section. Data from the monoenergetic electron tests performed at AEDC and MRED simulations are used to explore how electron-induced upsets occur. Comparisons are drawn to similar work on photoelectron-induced upsets in [6]. Both cases involve the stopping of secondary electrons, either from secondary delta-rays or photoelectrons that are causing the SEUs.

IV.1 Simulation of AEDC test conditions

Monoenergetic electron tests performed at AEDC provide the most straightforward data set for simulating electron-induced upsets. MRED simulations employ the beam conditions outlined in Section 5 of Chapter III. The beam is assumed to be strictly monoenergetic, consistent with information provided by the beam operators. Detector measurements of the beam profile are not available. Beam energies of 40 keV and 100 keV are simulated.

While detailed modeling of the 28 nm SRAM is described in Chapter V, the work in this section uses a more generic approach so any conclusions drawn can be extended to other applications. An RPP cube of silicon represents the device sensitive region. This cube is set in another larger cube of SiO₂ to mitigate dose enhancement effects. Figure 41 illustrates the simulation set up.

Determining the possibility that an electron induces an SEU in a device requires a general idea of the critical charge. For comparison, the critical charge of 22 nm devices is estimated to be around 0.09 fC [79]. Two types of events were captured. The first deposited about 0.01 fC, not enough to upset a 22 nm device. The second deposited more than 0.1 fC, sufficient enough to induce an upset. MRED was used to capture the electron tracks for both cases. Results are presented in Figure 42 for 40 keV and 100 keV monoenergetic electron beams.
Only the events in the right-hand column of Figure 42 deposit significant energy compared to 0.09 fC. These events occur when the primary electron generates a δ-ray that stops within the sensitive region. In events in the left-hand column, the primary electron alone does not produce enough energy deposition from its own LET to exceed the critical charge of modern devices. Thus, the physical mechanism behind low energy electron-induced upsets is the generation of an energetic stopping δ-ray. This is similar to the generation and stopping of photoelectrons observed in [6]. Scattering events between incident electrons and orbital electrons liberate the orbital electron with a fraction of the incident electron’s kinetic energy, imparting energies on the order of tens of keV [98].
Figure 42: Low (left) and high (right) energy deposition events for 40 keV and 100 keV primary electron beam energies. The size of the Si box is (50 nm)$^3$, set in (480 nm)$^3$ of SiO$_2$. In low energy deposition events, the primary electron (blue) passes through without interacting. To produce the higher energy deposition events, the primary electron must produce a -ray (red) that stops in the sensitive region [9].

Another conclusion from the mechanism study is the upper limit on the δ-rays energy deposition. Further MRED studies (Figure 43) on 40 keV and 100 keV electron energies for the 28 nm SRAM model show that the maximum energy deposition is above 1.8 keV for both beam energies. The maximum silicon K-shell energy is 1.8 keV [99], so the events which deposit the most energy are those where the K-shell electron is ejected with maximum energy, which then deposits all of it within the sensitive region. This upper bound on energy deposition explains how δ-rays are responsible for the most energetic events observed, indicating other mechanisms are not contributing.
Compared to proton and muon induced upsets, electrons do not primarily cause SEUs due to direct ionization of the primary particle. This distinction makes electron-induced upsets somewhat unique. These upsets are induced only by lightly ionizing electrons produced as secondary particles, not direct ionization. Production of secondary delta-rays is a predominately stochastic process, so while initial beam energy determines the probability of a secondary forming, it does not singularly determine its energy.

IV.2 Vulnerability of devices to electrons in space environments

Electron-induced upsets are primarily a concern if they are relevant in the space environments compared to other particle species that currently dominate the SEU response. Protons and electrons are both found in the inner Van Allen belts, while the outer belts contain only electrons. In any space environment, the galactic cosmic ray (GCR) spectrum is also a consideration. Comparisons, originally from [9], between protons and electrons for inner belts are performed by simulating the environmental spectra from [56] and [62] in MRED using an Si cube with sides of 50 nm as a sensitive region. An omnidirectional spectrum is used as shown in Figure 44. Each Si cube is surrounded with enough SiO₂ to

Figure 43: Comparisons of integral cross sections as a function of deposited energy between 40 keV and 100 keV electron beams [9].
ensure the results do not change with additional material. The environments chosen are the same as in Table 1. The first three are inner belts with trapped protons, and the last three are outer belts where trapped protons are not present.

![Simulation setup for relative rate calculations employing an omnidirectional spectrum.](image)

**Figure 44:** Simulation setup for relative rate calculations employing an omnidirectional spectrum.

Simulation results for the inner belts are presented in Figure 45 for the (50 nm)$^3$ volume. The x-axis gives the charge deposited while the y-axis gives the ratio of electron events with that charge deposition to proton events with the same charge deposition. Charge deposited is defined here as the energy deposited divided by a factor of 22.5 keV/fC [1]. Due to the maximum energy of the δ-rays, the electrons do not contribute until the charge deposition is below ~0.2 fC. Above the 22 nm threshold of 0.09 fC [79], the electrons do not contribute more than 40% of the proton-induced rate, and thus are not a significant contributor to the overall rate. Within inner belts the total contribution of electrons is less than that of protons unless the device critical charge is extremely low (< 0.05 fC).

Results of the outer belt simulations are presented in Figure 46. Protons are not a factor in the outer belts, but the GCR spectrum is. The x-axis is charge deposited and the y-axis event rate is events/s. GCR rates were determined from CRÈME simulations [82, 100, 101] for the same (50 nm)$^3$ sensitive volume. The electrons contribute significantly to all charge depositions compared to GCR.
Figure 45: Ratio of electron to proton charge generation event rates for inner belts orbits 1-3 [9].

Figure 46: Energy deposition event rates for electrons for high orbits where protons do not penetrate shielding for sensitive volumes of size $(50 \text{ nm})^3$. GCR-induced rates included for comparison [9].

For the trapped Earth environments, electrons do not meaningfully contribute to the observed upset rate for the inner Van Allen belts but could be relevant in the outer belts if the device critical charge is below 0.2 fC.
Further simulations were performed for the Juno [70] and Europa Clipper mission [75] trapped particle environments. Spectra were transported through 100 mils, 730 mils, and 870 mils of aluminum shielding. Results for the (50 nm)$^3$ sensitive volume in the Europa Clipper mission environment are presented here, in Figure 47. The x-axis is the deposited charge while the y-axis is the ratio of electron to proton event rates.

![Figure 47: MRED charge deposition vs. event rate simulation results for a (50 nm)$^3$ sensitive volume using the Europa clipper environmental spectrum. The spectrum passes through 100 mils, 730 mils, and 870 mils of aluminum shielding.](image)

Based on this model, trapped electrons meaningfully contribute to the overall event rate compared to trapped protons in the Jovian environments. With 870 mils aluminum shielding, the electron event rate is dramatically higher than the proton rate (10x at 0.2 fC), making electrons the primary contributor to the event rate in this case. Even at lower values of shielding, the electron event rates are of similar orders of magnitude of the protons around 0.1 fC. Due to the high contribution of electron-induced charge
deposition event rates in the trapped Jovian environment, devices on missions to this region should undergo electron testing to assess the vulnerability to electron-induced upsets.

**IV.3 Simulations of Strontium-90 test conditions**

SEU data acquired on the 28 nm SRAM using the Strontium-90 beta emitter are presented in section III.5. Unlike the monoenergetic electron data, a simulation of the environment during these tests requires simulating a block source above the DUT separated by an air gap. Electrons generated from decays within the Strontium source are emitted with a differential energy spectrum plotted in Figure 48. Decay probability statistics are taken from [102] for Strontium-90 and Yttrium-90, combined, and scaled to the bin width.

![Differential Energy Spectrum of Electrons Produced from the Strontium-90 Decay Chain](image)

Figure 48: Differential spectrum of electrons produced from Strontium-90 decay chain. Decay probabilities taken from [102] then converted to a differential spectrum.

A 1mm x 1mm x 10um block of aluminum source constructed in MRED with an air gap of 500 μm separating a chunk of silicon below represents the surface barrier detector. A bullseye placed in the sensitive region of the silicon a variable depth below the surface measures the differential electron
Sr-90 emits electrons from the bulk of the aluminum source with an angular spectrum that is isotropic. A random box source is defined in MRED using the bounds of the aluminum block as the extent of the source. Electrons are sampled using the differential energy spectrum from Figure 48. A plot of counts in the sensitive region versus energy deposited for three sensitive volume depths and three air gap distances is provided in Figure 49. A simulation size of $2 \times 10^8$ ions is used in each case.

Figure 49: Normalized integrated counts as a function of energy deposited for three SV sizes and air gaps using an MRED model of the Sr-90 electron source.

Changing the depth of the sensitive volume affected the count distribution significantly more than affecting the size of the air gap. Still, variations in the air gap between 0.5 mm and 0.1 mm led to a $\sim$10% difference in the low energy tail’s distribution. Most starkly, the 1 nm SV had a dramatically reduced spectrum compared to the 10 nm SV, indicating that small changes in small SVs have a significant impact.
in the energy the electrons deposit. This is especially important for small feature sized devices such as a 28 nm SRAM. The shape of the spectra for the 100 nm SV is similar to that of the beta decay spectra for Sr-90, lending credence to the simulation result.
CHAPTER V

MODELING METHODOLOGY AND VALIDATION

SEU rate predictions for a wide variety of particles can be made with heavy ion and proton informed Monte Carlo models but without manufacturer bit cell information. Data from Chapter III are used for calibration and validation.

Logistically, testing devices for the wide range of conditions required to understand the response in the radiation environment is becoming less tenable. Monte Carlo simulations provide an opportunity to perform rate predictions for a device without the need for individually testing each combination of particle and energy. Instead, a limited set of tests on a given device can be performed to calibrate a stack of sensitive volumes in MRED which then can be used for rate prediction simulations for an environment of interest. The work completed in this chapter next focuses on developing methods with varying degrees of simplicity and predictive power for constructing these models utilizing more commonly available particle beams. Limited device information was available for constructing the sensitive volume models so proton and heavy ion SEU data were used for the entire calibration, demonstrating the power of this approach to predict results when the device is exposed to other environments.

Most of the focus is on predicting muon and electron test results with models calibrated with proton and heavy ion sources. Interest in both muons and electrons is surging due to the high potential impact of these particles in terrestrial and space environments. Especially for devices operated in near-threshold modes, exhaustive testing for muon and electron SEUs are required. Methods for circumnavigating these testing requirements can save engineers significant time and resources identifying vulnerabilities in their devices to muon and electron-induced SEUs.

V.1. Modeling muon induced upsets

Both a proton-calibrated RPP model and ion-calibrated multi-SV model are provided so two options for assessing muon vulnerability exist. A tradeoff exists between the two modeling methods. RPP
models take only proton data to calibrate but also estimate only the vulnerability of the device to stopping muons. Multi-SV models take both heavy ion and proton data to calibrate but can accurately estimate the actual muon-induced SEU cross-section. The choice between them is dependent on the application and the resources available to the designers. No structural information on the 28 nm SRAM is available, so ion data are used to calibrate the models.

V.1.1 Proton-calibrated RPP model

In some cases, simply determining whether or not muons of a certain energy can cause upsets is sufficient. Proton tests provide a solid starting point for assessing this vulnerability. Previous work has shown that devices susceptible to low energy protons are also vulnerable to muons [79]. This RPP modeling method takes this idea slightly further. Proton data are used to calibrate the RPP model which then was used to estimate the energy ranges for which muons induced upsets. In exchange for only predicting vulnerability, calibrating RPP models requires only proton data and takes less time than the multi-SV model presented in the next section. Because only proton data are used for the calibration, these RPP models are insufficient for prediction the impact of electron-induced SEUs.

The model uses the peak proton cross-section as a calibrating parameter for volume size while varying $Q_{crit}$ as a free parameter. Monoenergetic proton data presented in Figure 33 are used to calibrate the RPP model shown in Figure 50. Dimensions for the red volume marked SV are set by taking the peak proton cross-section at 800 keV as the area. SV’s depth is set by simply setting it to the same dimensions as the square that forms the area. The result is that SV is defined as a cube with dimensions equal to the square root of the peak proton cross-section. If available, manufacturer information on the drain size can be used instead. Structure for the BEOL is assumed to be composed of equal part copper and SiO$_2$. The total BEOL thickness is varied in MRED simulations until proton-induced SEUs are observed right at 500 keV, the ranging out point. Simulated runs are performed using a normally incident beam and incrementing the BEOL thickness until 500 keV protons just penetrate the BEOL and reach the SV.
Regions around the SV not bound by the BEOL are surrounded with several micrometers of silicon to ensure dose enhancement effects are not an issue.

Figure 50: Rectangular parallelepiped model of the 28 nm SRAM used for MRED simulations. The particle trajectories are generated perpendicular to the front of the BEOL in a random pattern. Exact values of sensitive volume and BEOL dimensions withheld at the manufacturer’s request.

Since only proton data are used for calibration, a feedback system from the proton tests minimizes error in the final muon prediction. This relies on the premise of “effective muon energies” to compare muon and proton simulation results. Effective muon energies are a useful way to use proton data SEU to predict muon SEU data. Using the critical charge approximation as demonstrated in [7], proton energies are matched to muon energies by running MRED simulations incorporating the model in Figure 50. The matching is performed by first selecting a range of proton energies and muon energies likely to produce SEUs for comparison. Proton energies are best determined from the test energies used in monoenergetic proton tests in Figure 26. Muon energies in the range 0-1 MeV in 10 keV steps are selected for comparison. A script loops over the muon energy results to determine the counts in the SV which deposited more charge than the critical charge and compares these numbers to the proton simulations. Once a muon energy is matched to a proton energy, that proton energy is said to have an “effective muon energy” equal to that muon energy. Counts past $Q_{en}$ relate to the number of SEUs induced at that beam energy, regardless of the ion inducing them. Monte Carlo tools are required for this matching procedure to compute the predicted number of upsets induced by muons at a specific energy. For the illustrative example chosen in Figure 51 the 1.45 MeV proton has an effective muon energy of
0.35 MeV for the arbitrary $Q_{\text{crit}}$ marked on the plot. This analysis is bias dependent as $Q_{\text{crit}}$ will vary between operating voltages. Note that the effective muon energy is device model SV dimension and material dependent, not a property of the proton energy itself.

![CollectedChargeCurve](image)

Figure 51: Comparison of MRED results for 1.45 MeV protons and 0.31 MeV muons. Deposited energy is converted to generated charge by 22.5 keV/fC. An arbitrary $Q_{\text{crit}}$ is included only to illustrate the similarity between the integrated muon and proton results beyond that point.

Energies for which muon induced upsets are observed are defined as the “muon window of vulnerability.” Muon experiments directly measure the muon window of vulnerability. The method presented here estimates this window by mapping the proton energy to its effective muon energy with MRED and using the corresponding proton test results to determine the width of the window. Proton SEU cross-sections from the monoenergetic tests are mapped to their effective muon energy. Muons are predicted to produce upsets when the cross-section observed is larger than the saturation cross-section. Proton energies with SEU cross-sections near saturation are ignored since they are primarily the result of indirect ionization which are not expected to induce muon SEUs [5]. The 28 nm SRAM’s muon window of vulnerability produced using this method is compared to the experimental window of vulnerability in
Figure 52. Also included are predictions using proton and muon simulations alone without matching. Thus “proton simulation” refers to predicting the muon window of vulnerability with proton simulations instead of proton tests but using the mapping. “Muon simulation” gives the window employing only muon simulations using the RPP model. The “proton method” uses the mapping combined with proton tests to predict the mapping. “Muon experiment” is a direct measurement of the window from TRIUMF muon testing.

![Graph showing upset observations vs. effective muon energy](image)

**Figure 52:** Muon window of vulnerability predictions for simulations and experiments on the 28 nm SRAM [103].

Simulations alone predict muon-induced upset cross-sections at energies larger than observed during muon experiments. Proton tests mapped back to muon energies accurately bound the muon test results. Simulations alone using a simplified RPP model are insufficient for predicting the experimental results, but they provide a mapping for proton tests that led to an accurate assessment of the window of vulnerability. Relative comparisons between proton and muon upset characteristics are still valid with a simplified RPP model since inaccuracies in SV structure and charge collection efficiencies roughly cancel out in the comparison.
The muon window of vulnerability can be used to predict a conservative muon-induced SEU FIT/Mb rate using this simplifying assumption: all muons in terrestrial environment which strike the device and have energies within the energy ranges of the muon window of vulnerability would cause an upset. Thus, the integral over the vertical muon flux using the bounds of the window gives a conservative estimate of the muon-induced SEU rate. This is presented in Equation 3 where \( X_\mu \) is the muon-induced per-bit SEU rate, \( A \) is the device area per-bit, \( W_{\text{max}} \) and \( W_{\text{min}} \) are the maximum and minimum bounds of the muon window of vulnerability, \( \Phi_\mu \) is the differential muon flux in the environment, and \( E \) is the energy of the muon.

\[
X_\mu \leq A \int_{W_{\text{min}}}^{W_{\text{max}}} \Phi_\mu(E) dE
\]  

At sea level with no shielding there is a significant slope in the differential muon spectra. However, the differential muon flux through 10 cm of concrete is roughly \( 2 \times 10^{-6} \) muons/cm\(^2\)-sec-MeV up to muon energies of about 3 MeV [104]. In the first case, the absolute bounds of the window, rather than the width, matters significantly more than in the second case.

Table 2: Variation of muon window of vulnerability thickness with BEOL

<table>
<thead>
<tr>
<th>Window (keV)</th>
<th>Attenuation</th>
<th>Predicted Maximum Rate (FIT/Mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Max</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 200</td>
<td>no concrete</td>
<td>3</td>
</tr>
<tr>
<td>100 200</td>
<td>10 cm concrete</td>
<td>35</td>
</tr>
<tr>
<td>500 600</td>
<td>no concrete</td>
<td>5</td>
</tr>
<tr>
<td>500 600</td>
<td>10 cm concrete</td>
<td>35</td>
</tr>
<tr>
<td>100 600</td>
<td>10 cm concrete</td>
<td>180</td>
</tr>
<tr>
<td>1100 1600</td>
<td>10 cm concrete</td>
<td>145</td>
</tr>
</tbody>
</table>

This rate prediction is not performed for the 28 nm SRAM in this work at the request of the manufacturer. However, to give a general idea of how the window of vulnerability width translates to a conservative rate, Table 2 presents predictions for a few windows at sea level with and without 10 cm of concrete. The calculations assume a (100 nm)\(^2\) device area. The rate at sea level is less than the
attenuated rate since there is a greater number of low energy muons after attenuation [13]. If concrete is attenuating the beam, the spectrum flattens in energy and the absolute bounds of the window matter less than the window width. Without concrete, the bounds matter more since the spectrum has a much larger energy dependence. In all cases, the FIT/Mb rates predicted are considerably larger than predictions made in other work for similarly sized devices [13, 14]. Thus, this primarily serves as an approximation of the absolute worst-case scenario by assuming every muon upsets the device and thus does not provide an accurate representation of the muon-induced SEU rate. Even with the larger estimate, these muon-induced FIT/Mb rates are fairly low compared to neutron-induced rates in similarly sized devices.

In this case, exact SEU cross-section calculations made with the RPP model were significantly inaccurate. Errors of up to factors of ten were observed in the muon-induced cross-section predictions made with this method compared to TRIUMF experimental results. The proton-calibrated RPP method is best used for determining the worst-case scenarios for if a device is vulnerable and if it may be vulnerable in a specific environment. If the device’s muon window of vulnerability is nonexistent or small enough that the worst-case rate is small, no further work is required. The multi-SV method presented in the following section provides an alternative that, with a little more effort, accurately predicts the muon-induced cross-section.

V.1.2 Proton and heavy ion calibrated multi-SV model

Rectifying the weaknesses of the simplified RPP model involved the addition of multiple SVs. But that comes with a significant time penalty associated with model development. Manufacturer information was not provided regarding the layout, critical charge, or BEOL structure of the 28 nm SRAM, so an empirical method was used. Sierawski et al. demonstrated a method for calibrating multiple sensitive models using heavy ion data to set modeling parameters in [11]. Combining that method with the RPP method presented in the previous section yields a model that accurately predicts the muon-induced SEU cross-sections for the 28 nm SRAM. Heavy ion and proton data available for the 28 nm SRAM were used to calibrate the model shown in Figure 53. For reference, heavy ion and proton data
from Section III are presented again in Figure 51. Color coding is shared between the two figures to illustrate how a selected data point in Figure 51 is used to calibrate a volume in Figure 53.

Figure 53: Heavy ion calibrated model of the 28 nm SRAM used throughout this work. SV dimensions withheld at the request of the manufacturer.

Figure 54: Heavy ion SEU data (a) and proton SEU data (b) for the 28 nm SRAM originally presented in Figure 25 and Figure 26. Data points used to calibrate volumes in Figure 53 are circled.

Ion-calibrated models can be constructed by calibrating each volume in Figure 53 based on the energy deposition of a single ion and the measured SEU cross-section for that ion. In [6], V1 was calibrated to the device feature size, but since this information is unknown for the 28 nm SRAM, the proton SEU cross-section at an energy associated with the Bragg peak is used instead. V1 is therefore
assigned an area equal to that SEU cross-section and charge collection efficiency of 1. Heavy ion data are used to calibrate volumes V2-V4 as described in [6]. Data points with progressively higher LETs and higher SEU cross-sections in Figure 54(a) indicate regions of the device where less charge is collected but contribute to the overall SEU cross-section since the ions deposit more charge. Thus, the areas of volumes V2-V4 are assigned to the SEU cross-sections of data points 2-4 on Figure 54(a). The fifth data point is left out since its SEU cross-section is essentially identical to the fourth’s and thus would have a similarly sized volume. Similarly, the first data point is thrown out since MRED simulations showed the ions slowed significantly in the SV and therefore does not have a constant LET.

Charge collection efficiencies are assigned according to \( \propto_i = Q_{crit}/(LET_i \times d_i) \) where each heavy ion with \( LET_i \) exceeds the device \( Q_{crit} \) travelling to depth \( d_i \) in the volume. Each depth \( d_i \) is initially set to the square root of the volume’s incident area, forming a cube. Values for \( d_2-d_4 \) were then fine-tuned by simulating charge collection by proton events and matching to the experimental proton data in Figure 54(b). In addition to the 0.85 V model, a 0.35 V model was made using heavy ion and proton data. One major difference was the considerably lower critical charge. The results of this calibration method are not presented here, but were performed in the same way as the 0.85 V case.

Critical charge approximations utilize the proton data in Figure 54(b). Simulated monoenergetic proton energies used for testing were run incident on the device model in Figure 53 and SEU cross-sections were extracted. After each simulation, the critical charge was iterated until the proton response of the model matched the experimental results in Figure 54(b). Increasing the critical charge tends to force the tails of the proton distribution down, decreasing the SEU cross-section at energies where scattering dominates. At the manufacturer’s request, the value of the critical charge is not publishable.

Another useful function of the proton data set is to determine the thickness of the BEOL. The back end of line (BEOL) is 50/50 SiO₂ and Cu. To determine the thickness, MRED simulations were performed to determine the simulated ranging out point and increasing the model’s BEOL thickness until
the spectrum was shifted on the x-axis into the correct position. Thickening the BEOL tends to shift the distribution to the right on the x-axis as the extra material results in energy loss.

After these adjustments, the simulated proton data closely matches the shape of the experimental data taken on the 28 nm SRAM at 0.85V. Figure 55 compares the results.

![Figure 55: SEU cross-section predictions by the calibrated 850 mV 28 nm SRAM model compared to experimental results from a monoenergetic proton beam.](image)

The calibrated model accurately tracks the shape of the Bragg peak of the proton data and trails off with energy at a similar rate. Unlike the RPP model, the multi-SV model accounts for the effects of higher energy protons and therefore allows for more accurate calibration of $Q_{\text{crit}}$ through iteration. Larger, lower efficiency SVs allow for increased charge collection for deeply penetrating, low LET, high energy particles but not for high LET stopping particles. While stopping protons dominate the response in Figure 55, higher energy protons still produce upsets in the 28 nm SRAM. The model best predicts the proton response near stopping ($< 1.0$ MeV) and near saturation ($> 2.0$ MeV). In [11], it was determined that proton data were best reproduced for events corresponding to direct ionizations and nuclear reactions. Events where the incident proton scattered off of a silicon atom occur near these medium energies and are
predicted poorly in that work as well. An intermediate volume between V1 and V2 may remedy this somewhat, but for the usages in this work the four volume model provides an accurate enough response.

V.1.3 Reproduction of muon experimental results

Muon induced SEU cross-sections are not well predicted by the simple RPP model described in Section V.1.1, so the heavy ion calibrated model in Figure 53 is used instead. Muon data were also taken at 0.85 V, so the critical charge values derived in Figure 55 can be used. Unlike when energy bounding was the goal as discussed in Section V.1.1, exact energy spectra from the M20B beamline at TRIUMF are needed to predict the muon cross-sections over beam momenta. Normally distributed energy spectrums around the momentum selection are transported with MRED through the mylar window, scintillator, and air gaps placed in front of the device, as described in Section III.3. This technique was performed in [79] using Geant4 with similar results. Results of this transport are presented in the experimental section in Figure 35. The transported spectra were then used to predict the muon-induced SEU cross-section. Results in Figure 56 are given as upsets per muon since the beam spatial distribution was not uniform.

Figure 56: Upset per muon predictions by the calibrated 850 mV 28 nm SRAM model compared to experimental results from a muon beam. XS in this plot is an abbreviation for cross-section.
Predictions using the multi-SV model generally match the trend of the muon response of the 28 nm SRAM observed at TRIUMF. Muon induced upsets are predicted for the 22.4 MeV/c case but are not observed in experiments. Low statistics in experiments compounded with the broad energy distribution of lower momentum selections could be contributors to why these upsets were not observed. Regardless, the multi-SV model accurately predicts muon experimental results. The muon data are not used in the calibration; only proton and heavy ion data are used.

Due to our decision to spread the muon beam using scintillating materials, the muon experiments we performed using the TRIUMF M20B beamline do not predict the monoenergetic muon response well. Significant spread in both the muon spatial and energy distributions were observed. Simulations using the model are presented as an alternative to predict the monoenergetic response. Confirmation that the multi-SV model predicts muon-induced upsets with a transported beam in the 28 nm SRAM lends confidence that the model can also predict the monoenergetic muon response. In these simulations, muon energies are incremented in 50 keV steps from 0 to 1 MeV. Results are presented in Figure 57, using energy for the x-axis instead of momentum since these are simulated monoenergetic spectra.

Figure 57: Monoenergetic muon response predicted by the multi-SV 28 nm SRAM model.

78
Since upsets occur only around the Bragg peak, stopping muons are contributing to the observed cross-section. This result is consistent with predictions made through simulations in [79]. Producing a model from heavy ion and proton data, then simulating the monoenergetic muon response is a method for predicting a device’s muon response without the need for muon tests, TCAD simulations, or detailed knowledge of the device structure. Given the difficulty of acquiring beam time [79] this method saves a considerable amount of time when determining the muon-induced upset rate compared to experimental testing.

V.2 Predicting electron-induced SEUs

Modeling δ-ray induced upsets in the 28 nm SRAM requires finer calibration than for muons, protons, or heavy ions. δ-ray induced upsets occur when an incident ion or photon liberates an electron from its orbit which then stops within a sensitive region, depositing all its energy locally. Proton and heavy ion calibrated models used for predicting muon effects are not sufficient due to the highly localized stopping of the electron. The proton stopping volume used previously does not resolve the electric field well enough to capture the electron effects. Figure 58 contains modifications to the basic RPP model to account for δ-ray induced upsets with Monte Carlo simulations. Volumes d1 and d2 combined form V1 in the multi-SV calibrated model in Figure 53. Protons and muons stopping the SV have considerably less energy and range than the low energy δ-rays in electron and photon induced upsets. Calibrating a single volume as with muons to account for stopping is insufficient; d1 is used to account for the electrons while d2 accounts for stopping protons. Because proton data cannot be used to calibrate d1, electron data from AEDC are used. While this means electron tests must be performed, the calibration can still be done without knowledge of the device bit cell structure.
Figure 58: Two volume model of a planar SRAM calibrated for prediction electron-induced upset rates. The top volume is intended to collect electron-induced events occurring along the drains surface while the bottom is calibrated to account for the remaining proton induced upsets.

Starting with the AEDC data taken at 0.45 V, the depth of d1 was iterated to match the simulated electron-induced SEU cross-section to the value observed in the electron tests. Using the same depth, the SEU cross-sections observed at 0.55 V are reproduced to within 10% by adjusting only the critical charge. While dimensions and critical charges cannot be explicitly given, some normalized parameters are shared in Table 3. Models for the 0.35 V and 0.85 V multi-SV models without the d1-d2 separation are provided for comparison. All values are normalized to the 0.35 V value except for the charge collection efficiency of d2 ($\alpha_2$) which is given as-is.

Table 3: Relative modeling parameters across bias voltages for the 28 nm SRAM

<table>
<thead>
<tr>
<th>Bias Voltage</th>
<th>Depth of d1</th>
<th>Depth of d2</th>
<th>Critical Charge</th>
<th>$\alpha_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 V</td>
<td>0.014</td>
<td>0.44</td>
<td>4</td>
<td>0.075</td>
</tr>
<tr>
<td>0.55 V</td>
<td>0.014</td>
<td>0.44</td>
<td>5.7</td>
<td>0.075</td>
</tr>
</tbody>
</table>

Since these were the only two biases tested at AEDC, another form of validation had to be found. Sr-90 SEU test results for the 0.35 V and 0.45 V models were also reproduced using the same models to
within 20%. The same beam spectra from Figure 48 were used in these simulations using the electron-calibrated models. However, given the dependence on the SEU cross-section on the air gap size, it is possible a significant amount of error was introduced.

A major downside of this method is that monoenergetic electron data are required to fine-tune the model. For some applications, the proton model approximation may be sufficient, but it is recommended to also calibrate to electron test results unless details of the doping profile are known for further refinement of $d_1$. Between calibrations using the monoenergetic electron tests and validation within 20% of the SEU cross-section observed during Sr-90 tests, the calibration method presented well reproduces the device’s electron SEU cross-section. This method is only valid for electrons near-stopping. In the Jovian environment, electrons have energies up to at least 100 MeV. Other sources of electron-induced SEUs such as Bremsstrahlung and nuclear reactions are not accounted for in this model.
CHAPTER VI

RATE PREDICTIONS

Ultimately the goal of constructing these Monte Carlo device models is to perform accurate rate predictions for environments where electrons and muons are a possible SEU threat. This section details rate predictions for the 28 nm SRAM for terrestrial muon and LEO electron environmental conditions performed with the Monte Carlo models developed in Chapter VI. A brief discussion of the implications of muon and electron-induced SEUs in the context of these and future devices is included.

VI.1 Muon SEU Rate Predictions

PHITS-based Analytical Radiation Model (PARMA) environmental data [59] are used to predict both neutron and muon event rates using the ion calibrated multi-SV model. Positive and negative muons are both accounted for. Two different environments are used: a NYC sea level and NYC aeronautical environment at 39,000 feet. In the first case, the muon spectrum is transported through 10 cm of concrete using MRED to resolve the low energy distribution of the muons. For the latter case, built-in airplane-cabin transport models are used from the EXPACS tool, which employs the same PARMA models [57]. Both positive and negative muons are considered in the analyses. MRED handles the differences in capture cross-sections and decay rates by virtue of the physics modules inherited from Geant4. The sea level and aeronautical environmental spectra are presented in Figure 59 and Figure 60, respectively. The x-axis gives the particle energy in MeV and the y-axis is the differential flux.
Figure 59: NYC sea level environmental differential spectra for neutrons, protons, and muons generated in PARMA after transport through 10 cm of concrete.

Figure 60: Aeronautical (39,000 feet) environmental differential spectra for neutrons, protons, and muons generated in PARMA after transport through typical airplane cabin conditions.
Previous experiments in [5, 14] and predictions in [104] predicted muon rates to be substantially lower than neutron rates but allowed for the possibility of critical charges shrinking to the point at which the muon rate could exceed the neutron rate. While the 28-nm SRAM used in this work is larger than the 14-nm and 22-nm 3D Tri-Gate technologies used in [14], it is smaller than the 32 nm planar device and has low power modes that increase its susceptibility to muon-induced SEUs. Simulated SEU rates are obtained by exposing the multi-SV device model to protons, neutrons, and muons sampled from the differential flux spectra produced from PARMA. Furthermore, additional proton and heavy ion data are used to form a second multi-SV model for the 28-nm SRAM’s lowest bias mode at 0.35 V. Sea level predictions are made for this case as well. The three simulation results are presented in Table 4, normalized to the simulated neutron rate for the 0.85 V model at NYC sea level.
Table 4: Terrestrial rate predictions for the 28 nm SRAM using the multi-SV model

<table>
<thead>
<tr>
<th>Particle</th>
<th>Normalized Error Rate</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron (Simulated)</td>
<td>1</td>
<td>2.27*10^3</td>
</tr>
<tr>
<td>Neutron (Manufacturer Prediction)</td>
<td>1.55</td>
<td>N/A</td>
</tr>
<tr>
<td>Positive Muon</td>
<td>1.83*10^{-3}</td>
<td>1.97*10^{-5}</td>
</tr>
<tr>
<td>Negative Muon</td>
<td>1.57*10^{-3}</td>
<td>1.70*10^{-5}</td>
</tr>
<tr>
<td>Proton</td>
<td>4.20*10^{-5}</td>
<td>5.08*10^{-7}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle</th>
<th>Normalized Error Rate</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron (Simulated)</td>
<td>4.32</td>
<td>9.35*10^{-3}</td>
</tr>
<tr>
<td>Neutron (Manufacturer Prediction)</td>
<td>7.20</td>
<td>N/A</td>
</tr>
<tr>
<td>Positive Muon</td>
<td>9.54*10^{-3}</td>
<td>1.90*10^{-6}</td>
</tr>
<tr>
<td>Negative Muon</td>
<td>8.68*10^{-3}</td>
<td>2.40*10^{-6}</td>
</tr>
<tr>
<td>Proton</td>
<td>1.41*10^{-3}</td>
<td>3.44*10^{-6}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle</th>
<th>Normalized Error Rate</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron (Simulated)</td>
<td>1.15</td>
<td>2.78*10^{-2}</td>
</tr>
<tr>
<td>Neutron (Manufacturer Prediction)</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Positive Muon</td>
<td>1.85*10^{-3}</td>
<td>5.5*10^{-6}</td>
</tr>
<tr>
<td>Negative Muon</td>
<td>5.03*10^{-4}</td>
<td>1.3*10^{-6}</td>
</tr>
<tr>
<td>Proton</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Neutron-induced SEU rates are simulated using a multi-SV model calibrated specifically with stopping particles in mind. In the 0.85 V and 0.35 V cases, the neutron rate predicted by the model is within a factor of 1.5 of the sea level rate predicted by the manufacturer. The manufacturer’s prediction is used for comparison to muon rates, since they are based directly on the results of neutron experiments.

In all three cases, the muon-induced portion of the total SEU rate is considerably lower than the neutron rate provided by the manufacturer. While the sea level ratio of muon-induced rate to neutron-induced rate is higher at 0.35V than at 0.85V, neither muon rate approaches a meaningful fraction of the relevant neutron rate. Furthermore, there is not a significant difference in relative muon to neutron SEU rates between sea level and aeronautical environments. This is attributed to similarities in the muon low energy tail after transport through concrete or airplane shielding. In the 0.35 V worst-case scenario, muons still contribute less than 2% of the total upset rate compared to neutrons.

Muon rate predictions indicate that muons do not contribute significantly compared to neutrons to the overall terrestrial SEU rate for this 28-nm SRAM, even at low bias. This is consistent with conclusions from Seifert et al. in [14], reinforcing the conclusion that neutrons still dominate the SEU rate for current technology generations in terrestrial environments. However, predictions in [79] indicate that, should device critical charges continue to decline, the possibility exists that muon-induced SEU rates could reach a significant fraction of the neutron-induced SEU rate.

VI.2. Earth orbit rate predictions

Proton and electron SEU rates for the 28 nm SRAM operated at 0.5 V bias are calculated for LEO for the first three orbits in Table 1: Inner Belt Minimum Electron Flux (Orbit 1), Horn Region (Orbit 2), and Inner Belt Maximum Electron Flux (Orbit 3). The same conditions are used as in Section IV.2 and each spectrum was the same as plotted in Figure 16. Instead of the simple RPP cube in Figure 41, the 28 nm SRAM’s multi-SV δ-ray calibrated model from Figure 58 was used. Relative to the comparative event rates presented in Figure 45, expectations for a device flying in Orbit 1 were that the proton rate would dominate by a significant margin, whereas for Orbits 2 & 3 the electron rate may be significant if the
critical charge was low enough. $10^8$ particles were used for each simulation. Results for these orbits are presented in Table 5, normalized to an arbitrary factor to protect the manufacturer. Standard error for each entry was no greater than 5%.

Table 5: Predicted proton and electron SEU rates for the 28 nm SRAM for LEOs Inner Belt Minimum Electron Flux (Orbit 1), Horn Region (Orbit 2), and Inner Belt Maximum Electron Flux (Orbit 3). Rates are normalized to an arbitrary value.

<table>
<thead>
<tr>
<th>Orbit</th>
<th>Electron SEU Rate (A.U.)</th>
<th>Proton SEU Rate (A.U.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit 1</td>
<td>0.00</td>
<td>5.03</td>
</tr>
<tr>
<td>Orbit 2</td>
<td>1.67</td>
<td>2.01</td>
</tr>
<tr>
<td>Orbit 3</td>
<td>0.529</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Relative SEU rates predicted here are reasonably consistent with the expectations set in [9]. Electrons had no statistically significant contribution for Orbit 1 but contribute about 33% of the total SEU rate for Orbits 2 and 3. When this SRAM is flown on its CubeSat mission, it may be possible to use this rate prediction to isolate the on-orbit electron contribution. The actual on-orbit SEU rate observed during the mission will be used for this comparison once enough data have been collected sometime in the future. For now, agreement with previous predictions lends some confidence that the model is sufficiently mature.

VI.3 Jovian orbit rate predictions

Jovian rate predictions for the 28 nm SRAM operated at 0.5 V bias are performed in similar fashion to the Earth rate predictions. Europa Clipper and Jovian mission spectra from Figure 17 were used for simulations. $10^8$ particles were used in each simulation with an omnidirectional source. Rates by orbit and shielding are given in Table 6. In all cases, electrons were insignificant to the overall rate and protons dominated. Spacecraft shielding is sufficient to prevent electron-induced SEUs entirely excepting the 100 mils for the Europa Clipper mission. Compared to the previous rate predictions, the shielding values considered here were all thicker than the 75 mils used for Earth orbits. Electrons are attenuated significantly more due to shielding than protons, and thus despite the more intense electron environment
most of the incident electrons are stopped before reaching the device. As long as electronic devices on these Jovian missions are shielded with greater than 730 mils of aluminum, electrons are not expected to penetrate enough to induce SEUs.

Table 6: Predicted proton and electron SEU rates for Jovian orbits, scaled by the same factor used in Table 5.

<table>
<thead>
<tr>
<th>Shielding (mils)</th>
<th>100</th>
<th>730</th>
<th>830</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electron</td>
<td>Proton</td>
<td>Electron</td>
</tr>
<tr>
<td>Juno Orbit</td>
<td>0</td>
<td>66.1</td>
<td>0</td>
</tr>
<tr>
<td>Europa Clipper</td>
<td>0.0085</td>
<td>600</td>
<td>0</td>
</tr>
</tbody>
</table>

Compared to the RPP results in Section IV.2, no electron induced upsets were predicted to occur with the multi-SV model. The discrepancy here can be attributed largely to the slightly larger critical charge of this SRAM device than the cutoff-point where upsets were predicted in Figure 47. Because of the extremely sharp increase in relative contribution of electrons near that point, no upsets were observed here. Should the critical charge shrink even slightly, a significant increase in electron SEU cross-section would be observed.
CHAPTER VII

CONCLUSION

New SEU mechanisms have become relevant as shrinking device feature sizes reduced the amount of charge required to flip the state of the SRAM cell. Within the last couple of decades, vulnerabilities in devices have been demonstrated for low energy protons, muons, and electrons stopping in the sensitive region. This dissertation presents new methods for predicting the vulnerability of devices to lightly ionizing particles by using commonly-taken heavy ion and proton data to parameterize a Monte Carlo model. Two options are provided for predicting the muon SEU cross-section: a proton calibrated RPP model and a heavy ion calibrated multi-SV model. An example calibration is performed with a 28 nm SRAM. Simulation results using this model accurately reproduce the 28 nm SRAM muon test data.

An investigation of electron-induced SEUs mechanisms shows that δ-ray production is required to upset the SRAM used in this work. This result indicates that the SV model must be modified to account for small distances over which electrons stop compared to heavier ions. Electron-induced SEU data were required to calibrate a two-volume model to formulate a predictive model. Experimental results from both AEDC and the Strontium-90 beta emitter were used to validate the two-volume electron model.

Rate predictions for the SRAM were done for terrestrial and space environments of interest. Compared to neutrons, terrestrial muons do not appear to be a significant reliability concern. Similarly, protons completely dominate the response for most Earth and Jovian orbits but electrons may be significant contributors for high-angle LEO conditions. Overall these predictions are relatively consistent with previous work.

Based on the predictions in this dissertation and other sources, lightly ionizing muons and electrons do not appear to cause a significant number of SEUs in devices at modern planar technology nodes compared to other sources of radiation [5, 14]. Assessing the next generation of devices’
vulnerability to these particles will still be a significant concern. The methods and techniques laid out in this work can serve as a guide for investigation of muon and electron-induced SEUs by using simulations to determine if ground testing is required. Furthermore, fabrication labs are moving past planar CMOS into FinFET and even more advanced device structures. SEUs in these devices are still being researched and understood. Lightly ionizing muons and electrons could suddenly become a serious concern if one of these new structures is especially vulnerable. Ion calibrated multi-SV models are an excellent tool for assessing these particles’ abilities to induce upsets in newer structures.

Researchers performing future work on this topic could consider the following ways to improve these techniques. FinFETs and SOI devices would likely have a significantly multi-SV model structure than planar devices, and thus the modeling techniques here need to be refined should they be used in those cases. Higher energy electron events, such as nuclear reactions and Bremsstrahlung, can induce SEUs but were not considered in the low energy electron SEU models. Performing these tests on an SRAM, constructing a model, and verifying its accuracy for those cases would allow for more accurate Jovian environmental rate predictions to be made. Finally, data collected on the CubeSat flying this part should be checked against the rate predictions made here. That would be the ultimate test of the validity of this modeling method for protons and electrons.
REFERENCES


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[79] B. D. Sierawski, R. Reed, M. Mendenhall, R. A. Weller, R. D. Schrimpf, S. Wen, R. Wong, N. Tam


