Application of Reactors for Testing Neutron-Induced Upsets in Commercial SRAMs¹

Patrick J. Griffin, T. F. Luera, F. W. Sexton, P. J. Cooper, S. G. Karr, G. L. Hash

Sandia National Laboratories, P.O. Box 5800

Albuquerque, NM, 87185-1146

E. Fuller

Novus Technology, Inc.

Albuquerque, NM, 87185

RECEIVED

JUL 30 1997

OSTI

Abstract

Reactor neutron environments can be used to test/screen the sensitivity of unhardened commercial SRAMs to low-LET neutron-induced upset. Tests indicate both thermal/epithermal (< 1 keV) and fast neutrons can cause upsets in unhardened parts. Measured upset rates in reactor environments can be used to model the upset rate for arbitrary neutron spectra.

I. INTRODUCTION

Neutron-induced upsets are a matter of growing concern as the feature size in semiconductors continues to shrink. Previous papers [1, 2] have reported on mechanisms for thermal and fast neutrons to cause upsets in sensitive electronics. The neutron environment of concern for commercial parts comes from spallation neutrons resulting from cosmic ray interactions in the atmosphere. The traditional atmospheric neutron single event upset (SEU) test sources, such as the Los Alamos Neutron Scattering Center (LANCE) Weapon Neutron Research (WNR) facility [3], produce spallation neutrons by impacting high energy (~800 MeV) proton beams on high-Z targets. Device SEU hardness levels can also be determined by testing at heavy ion facilities or screening at fission product sources [4]. The purpose of this paper is to explore the role and application of reactors for neutron SEU testing.

Reactors can produce neutrons in copious amounts which facilitates the rapid testing of semiconductor upset hardness levels. The reactor neutron spectra, however, do not extend up to the high energies (~100 MeV) that are found in spallation sources. Figure 1 compares the low energy part of the atmospheric neutron spectrum with the neutron spectra from several reactor configurations. The low energy shape of the atmospheric neutron spectrum is seen to be similar to that from down-scattered reactor sources. This paper compares the linear energy transfer (LET) which can result from reactor neutron spectra and proposes a test methodology for identifying/distinguishing the thermal and fast neutron sensitivities of devices. Test results are provided for a variety of commercial SRAMs that range from

older large-feature-sized intrinsically hard memories to state-of-the-art SRAMs with a small feature size and increased sensitivity to neutron upset. The experimentally observed upset rates and the characterization methodology developed in this paper can be used to predict device upset in other neutron environments of concern to the users.

Figure 1: Neutron Spectra From Reactor and Atmospheric Sources

II. NEUTRON UPSET

Single event upset in semiconductors is produced when sufficient charge is deposited in a sensitive volume to change the storage state. Neutrons can cause upsets when the recoil products in a neutron interaction deposit sufficient energy in the sensitive volume. Figure 2 shows the neutron energy dependence of the average recoil from the primary knock-on atom (PKA) in silicon interactions. The LET (represented here by the mass stopping power) is proportional to the local charge production by the recoiling atom in the media. Figure 3 shows the LET in silicon from the recoil of various charged particles and energies. The LET was computed using the SRIM/TRIM-96 code [5]. Figure 4 shows the average LET produced from the neutron reactions in silicon as a function of the incident neutron energy.

¹Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Boron is often present in semiconductors as a dopant, in a glass passivation layer, or as a contaminant material. Figure 2 also shows the average recoil from $^{10}\text{B}(n,\alpha)$ PKA. In addition to the recoil of the residual nucleus or PKA, charged particles from (n,p) or (n, α) reactions can also deposit significant amounts of charge.

Figure 2: Silicon and ^{10}B PKA Recoil Energy

Figure 3: Particle Energy Dependence of LET

Figure 4: Average LET of Reaction Products

A. Fast Neutrons

Figure 2 shows that, in silicon, the PKA recoil energy is significant only for neutron interactions with an incident energy greater than ~ 100 keV. The elastic, inelastic, (n,p), and (n, α) interactions can result in a significant recoil energy. The recoil energy is typically a distribution that is dependent upon the energy and angle of the resulting particles. Figure 5 shows the PKA recoil energy distributions from elastic reactions and some charged particle reactions on silicon. Table 1 shows the LET and ion range that correspond to the energy and mass of typical reaction products in semiconductors. The ENDF/B-VI cross sections [6] were used to define the reaction probability. A modified version¹ of the NJOY94 code [7] was used to apply the reaction kinematics and to fold the ENDF/B-VI energy/angle distribution into neutron energy-dependent angle-integrated average LET values for the neutron reactions.

Figure 5: Silicon PKA Recoil Energy Distributions

B. Thermal Neutrons

Figure 2 shows that thermal and resonance energy neutron interactions on silicon do not result in significant recoil energy. However, boron is often found in and near the sensitive region in SRAMs, in a glass passivation layer or as the result of doping. Natural boron is 19.9% ^{10}B and 80.1% ^{11}B . The $^{10}\text{B}(n,\alpha)$ reaction has a very large thermal cross section that falls off as $1/v$. From the 2.8 MeV Q-value for the reaction and the kinematics one can show [8] that for thermal neutrons the recoil energies of both the resulting alpha particle (1.47 MeV) and the residual ^7Li particle (0.84 MeV) are significant. A 0.478 MeV gamma-ray is emitted 94% of the time from the decay of the excited ^7Li nucleus and accounts for the remaining energy balance. These particles and energies correspond to LETs of 1.18 and 2.22 MeV/(mg/cm²), respectively.

Upset thresholds in current commercial off-the-shelf (COTS) high density memory are often in the range of 1 - 3 MeV/(mg/cm²), and thus thermal neutron-induced boron interactions are more than sufficient to cause upsets. The residual

1. The NJOY modifications were relatively minor and only affected the HEATR module. The modifications will be provided to readers upon request to one of the authors (PJG).

^7Li particle as well as the alpha particle from the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction has a high enough LET to cause upsets in COTS SRAMs. If the boron is located in a passivation layer the longer mean free path of the alpha particle makes it a more likely source of upsets than the residual ^7Li particle.

Table 1: Recoil Particle LET Values

Particle Type	Energy	LET (MeV/(mg/cm ²))	Range (μm)
^{28}Si	50 keV	2.35	0.43
	500 keV	2.81	1.92
	1 MeV	4.53	3.78
	2 MeV	7.67	7.02
^4He	1.5 MeV	1.18	5.07
	4 MeV	0.71	17.23
	7 MeV	0.50	39.22
^1H	100 keV	0.57	0.88
	5 MeV	0.06	213
^{10}B	100 keV	1.23	0.34
^7Li	0.8 MeV	2.22	2.42

III. EXPERIMENTAL RESULTS

Figure 6 shows the test configuration used to gather the neutron upset data using the Sandia National Laboratories (SNL) Sandia Pulsed Reactor (SPR-III) reactor as a neutron source. Table 2 shows the measured upsets for a variety of SRAMs in various neutron environments with a V_{cc} of 8 volts.

The details of the neutron spectra, depicted in Figure 1, are described in Reference [9] and in internal SNL memoranda. The neutron environments were selected to vary the relative proportions of thermal and fast neutrons. There was significant upset variability between the various tested SRAMs and even between different SRAMs of the same type. The “poly-2” environment corresponds to an irradiation environment with a shield of 8 inches of polyethylene between the reactor and the test device. The “nb-poly-2” environment is identical to the “poly-2” environment except that borated polyethylene was used rather than normal polyethylene. Figure 1 shows that the neutron spectra in these two environments are nearly identical in the high and intermediate energy regions. The difference lies in the depressed thermal neutron population in the “nb-poly-2” environment due to the large low energy $1/v$ absorption cross section from the boron. An inspection of the Table 2 column 6 measured neutron upset rates in these reactor environments immediately highlights the importance of thermal neutrons in the observed single event upset rates.

Figure 6: Experimental Test Configuration

Table 2: SRAM Upset Results

Manufacturer Part Type	Boron Upset Coefficient [err/(n/cm ²)-b]	Silicon Upset Coefficient [err/(n/cm ²)-b]	Boron Upset Fraction	Spectrum	Measured Error Rate (bit err/MJ)	Modeled Error Rate (bit err/MJ)
1. Sharp, 128k x 8	$\alpha = 4.743 \times 10^{-13}$ cor = 94%	$\beta = 7.596 \times 10^{-9}$	33%	n-free-2	339	339
			92%	poly-2	635	635
			26%	nb-poly-2	71.3	71.8
2. Sharp, 128k x 8, 20% shrink	$\alpha = 1.470 \times 10^{-11}$ cor=99%	$\beta = 6.939 \times 10^{-18}$	100%	n-free-2	1857.	3502
			100%	poly-2	18467.	18150
			100%	nb-poly-2	673.3	571.4
3. Vendor A, 256k x 4	$\alpha = 3.708 \times 10^{-12}$ cor=99%	$\beta = 7.693 \times 10^{-9}$	79%	n-free-2	980.6	1110
			99%	poly-2	4638.	4628
			73%	nb-poly-2	885.5	197.8
4. Vendor B, 256k x 4	$\alpha = 3.660 \times 10^{-13}$ cor=13%	$\beta = 3.406 \times 10^{-8}$	79%	novus-lead	340.5	431.8
			8%	n-free-2	1195.	1101
			67%	poly-2	672.5	673.3
5. Vendor C, 256k x 4	$\alpha = 1.511 \times 10^{-12}$ cor=98%	$\beta = 6.939 \times 10^{-18}$	6%	nb-poly-2	196.7	253.8
			8%	novus-lead	223.3	428.4
			100%	n-free-2	82.8	359
6. Atmel AT3864 8K x 8	$\alpha = 1.185 \times 10^{-14}$ cor=99%	$\beta = 3.050 \times 10^{-13}$	100%	poly-2	1909.	1866
			100%	nb-poly-2	202.9	58.57
			100%	novus-lead	216.7	139.7
6. Atmel AT3864 8K x 8	$\alpha = 1.185 \times 10^{-14}$ cor=99%	$\beta = 3.050 \times 10^{-13}$	26%	pbshtof	5.304	2.142
			46%	pbsheetfff	14.22	14.85
			98%	polyf	20.29	20.16

The most likely cause [8, 1, 10] of this observed strong thermal neutron upset rate is neutron interactions with ^{10}B in the SRAMs. The following section details the development of a methodology that attempts to model the effect of upsets from deposited charge due to recoils from both the silicon and boron atoms near the sensitive volume. The typical approach has been to relate the neutron upset rate to the burst generation rate (BGR) [11]. The burst generation rate is the macroscopic cross section for neutron-producing recoils with an energy greater than some specified threshold energy. Since elastic, inelastic and (n,p) reactions in silicon result in PKA recoil atoms of similar mass, the BGR method, still characterized by a recoil energy threshold, has been applied to the total reaction probability in silicon [12, 13, 14]. However, when we consider the upsets from alpha particles and from the ^7Li recoil particle from $^{10}\text{B}(n,\alpha)^7\text{Li}$ reactions, Figure 3 shows that the LETs from nuclei of equal recoil energy are not comparable. In order to put recoils from different nuclei on a comparable basis we modify the methodology by using the mass stopping power to convert a recoil energy of a specific mass nucleus into an LET. This modified methodology is similar to the traditional BGR method except that it corresponds to the macroscopic cross section for neutron producing recoils with an LET (rather than an energy) greater than some specified threshold value.

IV. METHODOLOGY

The neutron-induced upset is caused by the collected charge from the reaction products. We can model the ionization of neutron-induced reactions as:

$$D(E) = \sum_r \sigma_r(E) \int_0^\infty dE' \int_{-1}^1 d\mu f(E, \mu) g(E, E') \quad (1)$$

where D is the total ionization, E is the incident neutron energy, E' is the energy of the recoil particles, the summation r is over all reaction products and target atoms in the material of interest, μ is the cosine of the residual particle, g is the secondary energy ionization distribution, $\sigma_r(E)$ is the reaction cross section, and f is the angular distribution.

Since the range of charged particles is very short, a modified form of Equation 1 can be used to approximate the charge deposited in the sensitive region of a memory. This application of Equation 1 ignores the details of the geometry of the sensitive volume and the time response of the memory. Because different target atoms have a different geometric location relative to the sensitive volume, we can define a target-atom specific factor, C_A , and a charge-production factor that depends only on the recoil atom and recoil energy, $\xi_r(E')$. The form of this charge-production factor will be developed in the following paragraphs. Using the form of Equation 1, the number of neutron-induced upsets can be characterized as:

$$U(E) = \sum_{r,A} C_A \sigma_{r(A)}(E) \int_0^\infty dE' \int_{-1}^1 d\mu f(E, \mu) g(E, E') \xi_r(E') \quad (2)$$

where $U(E)$ is the upset rate, $\sigma_{r(A)}$ is the cross section for a reaction "r" on target atom "A". The LET of a recoil atom will vary with the media in which an atom deposits its energy. This paper will always consider that media to be silicon.

In general, if we know the upset threshold of a memory, Equation 2 can be used to model the relative probability of a particular neutron energy and particular interaction producing an upset. If the upset threshold is expressed in terms of a critical value, L_{crit} , for the LET of the recoil particles, we can relate the upset efficiency of different reactions on different target particles.

A number of assumptions need to be made if Equation 2 is to be simplified so that it can be used to represent the trends in experimental data. Figure 3 shows that a particle LET can increase as it slows down. If we are concerned about a threshold for upset then the maximum LET for any energy less than the incident energy should be considered rather than the LET for the specific recoil energy. In this paper we will designate the LET of a particle with an atomic number of Z and energy of E as $L_Z(E)$. The maximum LET of a particle for any energy less than E will be designated as $L'_Z(E)$. The probability that a neutron interaction produces a recoil particle with an LET exceeding L_{crit} as it downscatters will be designated as $\sigma_{LET}^Z(L'(E), L_{crit})$ and is given by:

$$\sigma_{LET}^Z(L'(E), L_{crit}) = \sum_r \sigma_{r(A)}(E) R'_r(E, L_{crit}) \quad (3)$$

where

$$R'_r(E, L_{crit}) = \int_0^\infty dE' \int_{-1}^1 d\mu f(E, \mu) g(E, E') L'_Z(E', L_{crit}) \quad (4)$$

From Equation 3 we see that the LET from different reaction particles are summed in this formalism. Since different recoil particles go in different spatial directions and have different ranges, their respective deposited charge may not be collected in the same sensitive volume, as is assumed in this methodology. The same methodology outlined here can be modified to incorporate the opposite assumption, that is that different recoil particles are treated as different reaction events. These two implementations can be expected to bracket how a real device would respond. A much more detailed device model that defines the spatial location of the sensitive collection volume and the location of any boron is required to make any more definitive statement about the applicability of these two limiting cases.

Figure 7 shows the neutron-energy dependent LET generation cross section, $\sigma_{\text{LET}}^Z(L'_Z(E), L_{\text{crit}})$, for ^{28}Si . Figure 8 shows $\sigma_{\text{LET}}^Z(L'_Z(E), L_{\text{crit}})$ for ^{10}B . The LET-generation cross section for ^{10}B has a $1/v$ shape and is independent of the L_{crit} for values less than $\sim 3 \text{ MeV}/(\text{mg}/\text{cm}^2)$.

To simplify Equation 2, we restrict our consideration to the silicon and boron target reactions. In the absence of specific device design and doping information, we can consider all outgoing particles from ^{10}B interactions with a given LET to have an equal probability of causing an upset. This assumption breaks down if upsets are caused by boron located in different geometric regions of the SRAM with different probabilities of passing through the chip's sensitive volume. We make the same assumption about silicon by modeling all outgoing particles from ^{28}Si interactions with a given LET as having equal upset probability. In the case of silicon this is, in effect, an averaging over the possible geometric paths from the recoil particles that deposit sufficient energy in the sensitive volume to cause an upset.

Figure 7: ^{28}Si LET Generation Cross Section

Figure 8: ^{10}B LET Generation Cross Section

In our reactor testing we can control and modify the thermal part of the spectrum by using cadmium or boron to absorb

thermal neutrons, but it is very difficult to make significant changes in the fast ($> 1 \text{ MeV}$) part of the fission spectrum. Since most low neutron energy upsets can be attributed to interactions with $^{10}\text{B}(n,\alpha)^7\text{Li}$ interactions, we will refer to the boron-induced upsets as thermal upsets. It is important to note that we are not just addressing actual thermal neutron interactions with a neutron energy near 0.025 eV , but low energy neutrons in the energy region where the $^{10}\text{B}(n,\alpha)$ cross section is the dominant mechanism. With this two component boron/silicon model, the spectrum-averaged neutron upset rate can be represented as:

$$U = \alpha \sigma_{B10} + \beta \sigma_{Si} \quad (5)$$

where α and β are the relative upset efficiencies for boron and silicon-induced reactions in the device, σ_{B10} is the neutron spectrum-averaged $\sigma_{\text{LET}}^Z(L'_Z(E), L_{\text{crit}})$ for the $^{10}\text{B}(n,\alpha)$ reaction in a silicon matrix, and σ_{Si} is the neutron spectrum-averaged LET cross section for a silicon reaction in a silicon matrix.

A linear least squares analysis of the experimentally observed reactor upset rates can be used to determine the device-dependent α and β coefficients for various values of L_{crit} . Table 2 shows the measured and modeled upset rates for six tested SRAMs when an LET threshold of $3 \text{ MeV}/(\text{mg}/\text{cm}^2)$ is assumed. The quality of the fit and the fitting coefficients were found to be relatively insensitive to the values used for the LET threshold when those values ranged from 0.3 to $3.0 \text{ MeV}/(\text{mg}/\text{cm}^2)$.

For this analysis we have found it convenient to use the concept of a critical charge, and hence a critical LET. The literature [15, 16] indicates that "the critical charge for a chip is not a single value, but can be affected by the pulse shape, circuit position on the chip, power supply voltages, temperature, and the manufacturing device parameter variations." The charge collection volume in a device is both process and neutron-energy-dependent and very little is experimentally known about the effective charge collection depth [17]. In a static RAM with active loads the outcome of a potential deposition event depends upon a race between the circuit feedback and the recovery time. Thus the collection time as well as the collection current is important. There is an extensive bibliography on this subject [18, 19], but for many devices, especially those with a large polysilicon load, the collection time is much less than the recovery time and it is proper to speak of a critical charge in the cell. The normal manufacturing process tolerances produce a 2X variation in a device critical charge [15] and modeling with the SEMM code [16] indicates that this may correspond to a 60X variation in soft error rates.

V. INTERPRETATION OF RESULTS

The first thing that should be seen from the Table 2 data is the dramatic difference between the upset rates between the "poly-2" and "nb-poly-2" neutron environments. Figure 9 converts the data to a "per neutron" basis and emphasizes the de-

pendence of the upset rate on neutron environment. Since these two neutron environments only differed by the presence of boron in the polyethylene downscatterer, the difference in upsets can only be attributed to the presence of thermal neutrons. This observation is confirmed by the comparison of the neutron spectra in Figure 1. To confirm this observation, the correlation between the experimentally-observed upset rate and the neutron fluence less than 1 eV was determined. This number is reported in column 2 of Table 2 as "cor =". In five of the six SRAMs the correlation was over 90%. Previous controversy over the importance of thermal neutron upset for COTS SRAMs is clearly answered, with thermal neutron upset being a very important consideration for reactor spectra.

Figure 9: Summary of Neutron Upset Rates in Reactor Fields

Before we can address the importance of thermal neutrons for other neutron environments, we had to apply the methodology detailed in Section IV to these data. The data in Table 2 represent the average over the number of parts tested, which ranged from one to five. The variation of the upset rate of a specific device in a given environment was generally small (within 50% for most cases, often less than 15% for high upset rate parts/environments). A portion of this variation can be attributed to the ionizing dose delivered to the part during the test sequence. The variation in the upset rates for a specific device type in a specific environment varied considerably with the manufacturer (typically greater than an order of magnitude).

The results in Table 2 correspond to the observed upset rate for a device voltage of 5 volts. A significant dependence of upset rate on device voltage was found during the testing. The 5-volt data is modeled in this paper since it was the voltage level where we gathered the most data. The strong variation in observed upset rates indicates that different upset coefficients should be applied to different device voltages. This may indicate a dependence on the variation in the collection efficiency of the device with voltage.

The agreement between the measured and modeled error rates in Table 2 is generally very good, especially when one considers the variation in upset rate between different parts from the same manufacturer. The importance of the boron in producing the upsets is illustrated in the Table 2 column 4 "Boron Upset Fraction." We emphasize again that this "Boron Upset" rate

does not just refer to the upsets produced by thermal neutrons with an energy near 0.025 eV. Boron interaction have a $1/v$ cross section energy dependence and are therefore important for neutron energies up to about 1 keV.

The Table 2 upset rates are a function of the reactor power. Table 3 provides the information to translate the upset rate to a "per neutron" basis. The α and β coefficients in Table 2 can be used to determine the upset rate in any other neutron environment. Table 3 gives the neutron spectrum characterization information needed to reproduce this work or to apply the methodology to other spectra. The table includes the conversion from MJ in the reactor to neutron fluence. This allows the Table 2 data to be interpreted in terms of neutron fluence rate per observed upset.

Table 3: Neutron Spectrum Characterization

Neutron Spectrum	Fluence (n/cm ² -MJ)	$\Phi(E > 3 \text{ MeV})$ (fraction)	$\sigma_{B10} (L_{crit}=3)$ (b)	$\sigma_{Si} (L_{crit}=3)$ (b)
n-free-2	3.24E12	0.083	73.31	0.0092
poly-2	9.43E11	0.050	1309.7	0.0069
nb-poly-2	4.67E11	0.112	82.95	0.01505
novus-lead	9.26E11	0.110	99.87	0.0125
atmospheric	---	0.25	66.04	0.0181

VI. UPSETS IN OTHER NEUTRON SOURCES

A. Reactor Spectra

The device performance in an untested neutron environment can be predicted by using the fitting coefficients from Table 2. The neutron spectrum-averaged modified BGR responses are calculated for silicon and boron in the reactor environment under consideration. Equation 5 is then used to predict the neutron-induced upset rate.

The neutron spectra used to derive the boron and silicon upset fitting coefficients were based on a fit to a fast fission spectrum (n-free-2), a down-scattered spectrum with a significant $1/E$ spectrum component but no thermal component (nb-poly-2), and a down-scattered spectrum with the $1/E$ component and a large thermal tail (poly-2). These spectra represent the range of neutron environments that can be readily produced from a typical reactor spectrum. If data are gathered from additional reactor spectra, the data can be used to improve the fidelity of the least squares determination of the fitting parameters. Data in a 14-MeV neutron environment and in a pure fission spectrum (without the $1/E$ scattering component) would improve the fidelity of the data fits. The SPR-III central cavity environment, depicted in Figure 1, is a reasonable representation of a clear fission spectrum.

B. Atmospheric Neutron Spectra

The neutron environment of most interest to commercial non-radiation hardened parts manufacturers is the atmospheric neutron environment [20, 21]. This environment is often referred to as the cosmic ray neutron environment. The cosmic rays in space are 92% protons, 6% alphas, and 2% heavier atomic nuclei. Direct knock-on reaction processes of cosmic ray with the atmosphere produces high energy (10 MeV - 1 GeV) neutrons while nuclear evaporation processes produce neutrons with energies in the 1-MeV region. These neutrons are down-scattered by subsequent collisions with air molecules. The most comprehensive experimental values for the sea-level neutron fluence rate comes from Reference 20. The atmospheric spectrum used in this paper comes from digitizing the 1030 g/cm² "Hess" spectrum from this reference.

For this atmospheric neutron source the boron upset rate can be important. Less than 0.05% of the atmospheric neutrons are at a thermal energy of 0.025 eV or below and only 18% have an energy less than 1 keV. The Table 3 neutron spectrum characterization data shows that the atmospheric neutron spectra parameters are not very different from some of the reactor spectra. When the Equation 3 formalism is applied to the SRAMs characterized in Table 2 for the atmospheric neutron spectrum with an L_{crit} of 3 MeV/(mg/cm²) ($\sigma_{B10} = 66.04$ b and $\sigma_{Si} = 0.0181$ b) we find that the six parts have a boron-induced upset fraction of 19%, 100%, 64%, 4%, 100%, and 99%, respectively¹. If an L_{crit} of 0.3 MeV/(mg/cm²) is used, the quality of the modeled upset for the Table 2 data is moderately degraded and three of the six neutron environments still show an upset rate predominately due to boron interactions. Thus the reactor testing data, when extended to the atmospheric neutron source, indicate that the boron-induced upset rate can be a significant contribution to the overall device SEU rate.

C. WNR Simulation Neutron Spectra

The WNR neutron spectrum is a very good representation of the atmospheric cosmic-ray induced neutron source for energies from 5 MeV to 500 MeV [22]. However, at a neutron energy of 1 MeV the differential number fluence differs by about a factor of 10 [22]. For lower energy neutrons (0.1 MeV to 1 MeV) the WNR spectrum is flat [3] and significantly underestimates the differential number neutron fluence seen in the atmospheric spectrum.

The authors have not been able to obtain detailed information on the WNR neutron spectra for energies less than 0.1 MeV. Extrapolating from the published WNR data, it appears that while the WNR neutron spectrum is an excellent facility to

test/simulate the silicon-induced upsets, it may not be the optimal facility to test the boron-induced upset component because of the significant under-representation of neutrons with an energy less than 0.1 MeV.

On a per neutron basis, the devices reported in Table 2 have a comparable upset rate to the devices tested at WNR and reported in Reference [23].

VII. CONCLUSION

Previous authors [8] have suggested that the thermal portion of the atmospheric neutron spectrum is responsible for a significant number of the observed upsets. This observation has been disputed by others [23]. This work has clearly indicated that low energy neutrons can be an important source of neutron upsets in COTS SRAMs. We have provided test data that shows the range of sensitivity of COTS memories to neutron-induced upset. These data have highlighted the importance of both thermal and fast neutrons in producing upsets in memories. A methodology has been provided that uses reactor test data to predict the upset rate of the memories from atmospheric neutron sources, threat neutron environments, and test environments.

Future work should be directed towards confirming the correlation of thermal upsets with the device boron content. The best approach would be to fabricate an identical device with various ¹⁰B enrichments of a boron dopant. In addition reactor upset rates should be measured in the SPR-III central cavity or in a ²⁵²Cf spontaneous fission environment. These environments have very hard fission spectra and will allow the fitting methodology to better discriminate between resonance energy and fast neutron upsets.

VIII. REFERENCES

- [1] T. R. Oldham, et al., "Single-Event Upset Induced by Thermal Neutrons". *J. of Rad. Eff. Research & Eng.*, Vol. 4, pp. 80-85, Winter 1985.
- [2] C. S. Guenzer, E. Wolicki, R. Allas, "Single Event Upset of Dynamic RAMs by Neutrons and Protons," *IEEE Trans. on Nucl. Sci.*, Vol. NS-26, pp. 5048-5052, Dec. 1979.
- [3] P. W. Lisowski, C. D. Bowman, G. J. Russell, S. A. Wender, "The Los Alamos National Laboratory Spallation Neutron Sources," *Nuclear Science and Engineering*, Vol. 106, pp. 208-218, 1990.
- [4] R. Velazco, et al., "Comparison Between Californium and Cyclotron S.E.U. Tests," *IEEE Trans. on Nucl. Sci.*, Vol. 36, pp. 2383-2387, Dec. 1989.
- [5] J. F. Ziegler, J. P. Biersack, U. Littmark, *The Stopping and Range of Ions in Solids, Volume 1 of The Stopping and Ranges of Ions in Matter*, Pergamon Press, New York, 2nd Edition, 1996.
- [6] ENDF-201, ENDF/B-VI Summary Documentation, edited by P. F. Rose, Brookhaven National Laboratory, Report BNL-NCS-1741, 4th Edition, October 1991.
- [7] R. E. MacFarlane, D. W. Muir, *The NJOY Nuclear Data Processing System*, Los Alamos National Laboratory, Report LA-12740-M, October 1994.

1. The cross sections and LET response functions used in this work are only characterized up to 20 MeV, the ENDF evaluation maximum energy. When we apply this work to a neutron spectrum with a component greater than 20 MeV, all higher energy neutrons were rebinned into the 20-MeV energy interval. The work in Reference [14] indicates that this is a conservative approach and overestimates the importance of the high energy neutron upsets.

- [8] R. Baumann, T. Hossian, S. Murata, H. Kitagawa, "Boron Compounds as a Dominant Source of Alpha Particles in Semiconductors," *Proceedings 1995 Int'l Reliability Physics Symposium*, p. 297, April 1995.
- [9] P. J. Griffin, J. G. Kelly, D. W. Vehar, Updated Neutron Spectrum Characterization of SNL Baseline Reactor Environments: Vol. 1: Characterization, SAND93-2554, Sandia National Laboratories, Albuquerque, New Mexico, 1994.
- [10] I. Arimura, C. Rosenberg, "Anomalous Damage Mechanism in the PNP Silicon Transistors Due to Thermal Neutrons," *IEEE Trans. on Nuclear Science*, Vol. NS-20, pp. 274-279, Dec. 1973.
- [11] J. F. Ziegler, W. A. Lanford, "Effect of Cosmic Rays on Computer Memories," *Science*, Vol. 206, pp. 776-788, Nov. 1979.
- [12] E. Normand, "Incorporation of ENDF-V Neutron Cross Section Data For Calculating Neutron-Induced Single Event Upsets," *IEEE Trans. on Nuclear Science*, Vol. 36, pp. 2349-2355, Dec. 1989.
- [13] B. Silberberg, C. Tsao, J. Letaw, "Neutron Generated Single-Event Upsets in the Atmosphere," *IEEE Trans. on Nuclear Science*, Vol. NS-31, pp. 1183-1185, Dec. 1984.
- [14] C. H. Tsao, R. Letaw, "A Comparison of Neutron-Induced SEU Rates in Si and GaAs Devices," *IEEE Trans. on Nuclear Science*, 1988.
- [15] L. B. Freeman, "Critical Charge Calculations for a Bipolar SRAM Array," *IBM Journal of Research and Development*, Vol. 40, pp. 119-129, Jan. 1996.
- [16] G. R. Srinivasan, P. C. Murley, H. K. Tang, "Accurate, Predictive Modeling of Soft Error Rate Due to Cosmic Rays and Chip Alpha Radiation," *32nd IEEE International Reliability Physics Proceedings*, pp. 12-16, 1994.
- [17] C. A. Gossett, B. W. Hughlock, M. Katoozi, G. S. LaRue, S. A. Wender, "Single Event Phenomena in Atmospheric Neutron Environments," *IEEE Trans. on Nuclear Science*, Vol. 40, pp. 1845-1852, Dec. 1993.
- [18] Z. M. Shanfield, W. M. Moriwaki, W. M. Digby, J. R. Sour, D. E. Campbell, "Characteristics of SEU Current Transients and Collected Charge in GaAs and Si Devices," *IEEE Trans. on Nuclear Science*, 1985.
- [19] K. O'Brien, H. A. Sandmeier, G. E. Hansen, J. E. Campbell, "Cosmic Ray Induced Neutron Background Sources and Fluxes for Geometries of Air Over Water, Ground, Iron, and Aluminum," *Journal of Geophysical Research*, Vol. 83, pp. 114-120, 1978.
- [20] W. Hess, H. W. Patterson, R. Wallace, "Cosmic-Ray Neutron Energy Spectrum," *Physical Review*, Vol. 116, pp. 445-457, Oct. 1959.
- [21] J. F. Ziegler, "Terrestrial Cosmic Rays," *IBM Journal of Research and Development*, Vol. 40, pp. 19-39, Jan. 1996.
- [22] W. R. McKee, H. P. McAdams, E. B. Smith, et al., "Cosmic Ray Neutron Induced Upsets as a Major Contributor to the Soft Error Rate of Current and Future Generation DRAM's," *34th IEEE International Reliability Physics Proceedings*, pp. 1-6, 1996.
- [23] E. Normand, "Single Event Upset at Ground Level," *IEEE Trans. on Nuclear Science*, Vol. 43, pp. 2742-2750, Dec. 1996.