

# The Rosetta Experiment: Atmospheric Soft Error Rate Testing in Differing Technology FPGAs - 90 Nanometer Update

Austin Lesea and Joe Fabula

**Abstract**—Results were previously presented [2] from real-time experiments that evaluated large FPGAs fabricated in different CMOS technologies (0.15 $\mu$ m, 0.13 $\mu$ m and 90 nanometer) for their sensitivity to radiation-induced single-event upsets. These results were compared to circuit simulation (Qcrit) studies, as well as to LANSCE neutron beam results and Crocker Nuclear Laboratory (U. C. Davis) cyclotron proton beam results. The latest data from two additional 90 nanometer technology studies have shown the simulation techniques used to be flawed, and have also shown that beam testing is not accurately predicting the real improvements that are being realized in the atmospheric testing

**Index Terms**—soft error, single event upset, cosmic rays, SRAM, FPGA, NSEU

## I. INTRODUCTION

“**R**osetta refers to the crucial breakthrough in the research regarding Egyptian hieroglyphs. It especially represents the “translation” of “silent” symbols into a living language, which is necessary in order to make the whole content of information of these symbols accessible.” [1]

Just as the Rosetta Stone enabled researchers to decode the unsolvable and mysterious Egyptian hieroglyphs by comparing them to the same text written in a known language, Xilinx’ Rosetta Experiments link two prior

known and well documented techniques of estimating atmospheric neutron single event upsets with the real effects of atmospheric neutrons on integrated circuits. The known techniques are accelerated testing in a neutron or proton beam and software simulation of the circuit to determine the critical charge a particular node or latch can handle before it changes state. In our experiment the actual upset rate of Xilinx’ FPGAs due to cosmic ray induced atmospheric neutron cascade is determined. Having a good understanding of the real effect(s) that these atmospheric neutrons are having on today’s integrated circuits enables us to validate the design and technology choices being used to mitigate these effects.

The prior article, published by the IEEE in the September 2005 Issue of Transactions on Device and Materials Reliability [2] detailed the results from simulation, beam testing, and atmospheric testing. In that article there was a decided discrepancy with respect to atmospheric flux predictions, and actual results. There was also an indication that the 90 nanometer technology node would show a somewhat less than twice improvement in resistance to upsets based upon the simulations and the beam testing.

In this paper we will concern ourselves with the solution to the atmospheric flux prediction issue which was arrived at in collaboration with the JEDEC89 committee, the realization that the simulation techniques we were using are clearly too simplified, and the observation that the actual results from 90 nanometer atmospheric testing has shown the improvements to be as much as a factor of thirty to one more than what is measured in the beam testing..

Predicting atmospheric neutron flux is not an exact science. In the JEDEC89 standard, there is a methodology which makes use of models and magnetic latitude data to predict the flux at any given location on the earth. The Rosetta results clearly did not agree with the JEDEC standard, and work was done by the JEDEC89 committee, in collaboration with Xilinx, to resolve this issue. Three corrections were made to JEDEC89 (now JEDEC89v0.4): realization that the proton flux is not insubstantial (it is approximately an additional 7% in San Jose, and as much as an additional 32% at Mauna Kea), that the attenuation by the building must be more accurately calculated (28% of

Manuscript received March, 2006. This work has benefited from the use of the Los Alamos Neutron Science Center at the Los Alamos National Laboratory. This facility is funded by the US Department of Energy under Contract W-7405-ENG-36. The authors would also like to thank the California Institute of Technology Submillimeter Observatory at Mauna Kea, Hawaii and the White Mountain Research Station at White Mountain, California operated by the University of California Office of Research in San Diego, California We would also like to thank the ASTEP group in Marseille, France for their generous contribution of three more atmospheric testing sites..

Austin Lesea is a Principal Engineer in the IC design group of the Advanced Products Group at Xilinx, San Jose California. (phone: 408-559-7778; fax: 408-559-7114; e-mail: austin@xilinx.com).

Joe Fabula is a High Reliability and Radiation Effects Engineer with the Military/Aerospace/Automotive Group at Xilinx, San Jose. (phone: 408-559-7778; fax: 408-559-7114; e-mail: joe.fabula@xilinx.com).

the flux is lost to the ground floor of a typical silicon valley two story ‘tilt-up’ concrete structure), and a more automated model can be developed to aid investigators (a new prototype web based tool):

<http://www.seutest.com/cgi-bin/FluxCalculator.cgi>

## II. EXPERIMENT

Each Rosetta experiment consists of multiple sets of 100 of Xilinx’ largest FPGAs of differing technologies and is located at seven different altitudes. All tested components were fabricated by UMC or Toshiba in their 300-mm sub-micron fabrication lines using standard logic CMOS processes and the new Triple Oxide Gate CMOS Process.

See Table I, below for locations, a Table II for the number of devices, and device hours at each location.

TABLE I  
LOCATIONS OF XILINX ROSETTA EXPERIMENTS

Facility	Location	Alt (ft)	Physical Placement
Xilinx SJ	San Jose, CA	0	Floor 1 of 2 in concrete slab “tilt-up” style
Xilinx ABQ	New Mexico	5,100	Floor 1 of 2 in concrete slab “tilt-up” style
WMRS	Barcroft Station	12,470	Top story of a Quonset hut building
CSO	Mauna Kea, HI	13,200	Bottom floor of observatory
L2MP	Marseille, France[7]	402	Floor 1 or steel roof machine shop
Rustrel	Rustrel, France[7]	-1500	500 meters below the summit
Pic de Bure	Pic de Bure, Fr[7]	8,171	Floor 1 of the microwave observatory

TABLE II  
DEVICES CURRENTLY UNDER TEST

Node (nm)	Die	Location	# DUTs	Device hours
150	2V6000	San Jose	100	1622200
		New Mexico	100	3110400
		White Mntn	100	1903200
		Mauna Kea	100	1338000
130	2VP50	L2MP+SJ	200	1983215
		Rustrel+NM	200	1906000
		Pic de Bure+WM	200	1885000
90	4VLX60/ 4VLX25	San Jose	200	1850000
		White Mntn	200	775435
90	S31500	San Jose	100	2212000
		Mauna Kea	100	365970

In the integrated circuit design of the Xilinx FPGAs, the individual memory cells (actually implemented as static latches) that are used for configuration, look-up tables, and block RAM were all simulated for their sensitivity to single event upsets.

In order to detect alpha contamination in packaging and assembly, we rotate the experimental groups through the three altitudes as well as make use of the underground facility at Rustrel, France [7]. If there were any evidence of a constant upset rate due to alpha particles, it would be observed as a non-altitude, non-latitude dependent factor in the resulting upsets, or measured directly at Rustrel.

Using the new JEDEC89v0.4 method to predict flux, we get for each location the values shown in Table III.

TABLE III  
ALTITUDE ACCELERATION FACTORS COMPARED WITH 0.15 UM DATA

	JEDEC89v0.4	Actual 0.15 um
San Jose	0.80	0.80 (baseline)
New Mexico	2.95	3.53
White Mountain	19.48	18.80
Mauna Kea	11.09	11.51

The one sigma error limits for each data group places all of these predictions of flux well within the expected uncertainty of the flux prediction itself.

TABLE IV  
ALTITUDE ACCELERATION FACTORS COMPARED WITH 0.13 UM DATA

	JEDEC89v0.4	Actual 0.13 um
San Jose	0.80	0.80 (baseline)
New Mexico	2.95	1.23
White Mountain	19.48	11.82

Clearly the 0.13 micron data does not fit cleanly. Even though we have roughly twice as many events as the 0.15 micron data, leading to better statistical confidence, the altitude acceleration factors do not fit well with the predictions from the tool.

Even more disturbing, is that both sets of 90 nanometer technology devices show an even greater disparity from sea level to altitude than do the 0.13 micron tests. In the case of 90 nanometers, the improvement at altitude is considerably greater than that which is predicted.

One explanation for this is presently being investigated: possible activation of the packaging materials when inspected by high energy X-ray machines or other inspection methods while being shipped. In collaboration with researchers at LANSCE, we are setting up an experiment to see if short term activation is occurring. The primary evidence for this was a period of upsets that began

immediately after the experiment started, and then ceased to occur after three months. At first this appeared to be alpha contamination. Upon closer inspection, this may have been a short term activation of materials in the device packaging which were all of a very short half life. The half life of any Pb-based alpha contamination would have been considerably longer.

The 0.13 micron data may also be showing this effect. For example, a six month running average of the San Jose data indicates an almost 2:1 trend of more upsets at the beginning of the experiment, as compared to later six month running intervals.

#### A. Atmospheric Test Results for 0.15 $\mu$

At the 0.15 $\mu$  technology node, the resulting data for the configuration cell is 401 FIT/Megabit, where 1 FIT is one bit flip in a billion hours. This does not include any SEUPI factor [5]. The BRAM is 364 FIT/Megabit.

This is based on 476 upsets and 118.51 giga-bit years of data. The 95% confidence interval is +/- 9%.

The error rate is either stated in Failures in Time per billion hours (FIT), or in Mean Time Between Events (MTBE) in hours, days, or years. A functional failure of the user data due to the single event upset rate then becomes Mean Time Between Functional Failure (MTBFF) in hours, days, or years. See the referenced [5] paper for a discussion of the relationship between configuration bit MTBF and MTBFF, which is exactly SEUPI.

BRAM upset will likely cause a functional failure in a user's design, so Virtex 4 included built in error check and correct (ECC) logic to remove a BRAM upset as a reliability consideration.

#### B. Atmospheric Test Results for 0.13 $\mu$

At 0.13 $\mu$ , the configuration cell is at 394 FIT/Megabit (without SEUPI), and the BRAM is at 525 FIT/Megabit. These results are based on 359 upsets and 68.31 giga-bit years of data. The 95% confidence interval is +/-10.5%.

#### C. Atmospheric Test Results for 90 Nanometers

At the 90 nanometer technology node, the first FPGA product produced was the Spartan 3. The second product is the Virtex 4. Virtex 4 utilizes 0.13 micron "mid" oxide transistors for the configuration memory and 90 nanometer transistors for the block RAM. There are 600 units under test at the San Jose location and 200 units at White Mountain.

The Spartan 3 data at this point is 107 FIT/MB (without SEUPI) for configuration with a 95% confidence interval from 43 to 220 FIT/Mb. BRAM is 581 FIT/Mb with a 95% confidence interval from 58 to 2,100 FIT/Mb. There are far too few BRAM bits in the Spartan 3 family to provide

enough events with time to achieve a tight confidence interval with the number of devices under test.

Virtex 4 data at this point is 51 FIT/Mb (without SEUPI) with a 95% confidence interval from 24 to 80 FIT/Mb. BRAM is 20 FIT/Mb with a 95% confidence interval from 0 to 73 FIT/Mb. Compare these values with those predicted by LANSCE: 164 FIT/Mb for configuration, and 380 FIT/Mb for BRAM. Obviously, LANSCE beam testing is not even a close indication of the actual improvements which IC designers have made to Virtex 4.

### III. RESULTS OF SIMULATIONS OF QCRIT

The Xilinx IC design group uses models and methods from our fabrication partners to estimate the potential sensitivity of the memory cells to upsets. These models and methods have been used in their production of standard products and ASICs. Their prediction of Qcrit to atmospheric upsets is used to compare with our observations in the Rosetta experiment.

The simulation results done by the methods chosen have shown increasing inaccuracy, starting with the 90 nanometer technology node. Work done by others has shown a much better correlation from simulation to beam testing [3,4]. Given that beam testing is also showing itself to be suspect, we question the use of more advanced simulation techniques, if these techniques are incapable of predicting atmospheric (actual) results.

TABLE V  
FIT/MB BASED ON QCRIT VS. TECHNOLOGY NODE

Qcrit/Node	Configuration	BRAM
0.15 $\mu$	101 FIT/Mb	105 FIT/Mb
0.13 $\mu$	106 FIT/Mb	114 FIT/Mb
90nm (S 3)	111 FIT/Mb	222 FIT/Mb
90nm (V 4)	61 FIT/Mb	222 FIT/Mb

Note that the simulation results are predicting roughly half the improvements of the actual atmospheric tests in 0.15 and 0.13 micron. In Spartan 3 and Virtex 4, the predictions are not even close to the atmospheric results even after "correction" by multiplying by two, nor close to the LANSCE beam predicted results by comparing cross section ratios from one device to another. Due to these issues, we are reviewing the methods we use for simulation, and also taking a look at how we use LANSCE results to verify our circuit design.

### IV. ACCELERATOR TESTS

Previously, we thought the best resource available to simulate atmospheric neutrons was the high-energy Neutron Testing Facility at the Los Alamos Neutron Science Center (LANSCE). At LANSCE, high-energy neutrons are produced by spallation. A linear accelerator

produces an 800-MeV pulsed proton beam that strikes a water cooled tungsten target. The impact produces a spectrum of neutrons whose energy distribution and intensity is precisely measured. The spectrum is very similar in shape to the atmospheric (Hess) spectrum. The flight path consists of a small building for the irradiation which also encloses the testing equipment, isolated from the beam by a substantial concrete barrier. The devices to be tested are placed in the neutron beam line (in air) in the irradiation building. The experimenters control the neutron beam by opening and closing a shutter external to the irradiation building, and the number of neutrons on the sample is continuously monitored and recorded. Corrections to flux for the  $1/R^2$  distance from the source must be included.

Given the great difference between in beam cross section results, and atmospheric cross section results, we are working with LANSCE researchers to identify the difference.

Newer facilities are also competing for the commercial vendor's attention, such as the quasi mono-energetic beam at TSL in Sweden. We are greatly concerned that other facilities will be used to test devices, and conclusions will be made without side by side actual atmospheric results. Any such tests must be seen for what they actually are: physics experiments which require a great deal of correlation, and further study to be of use.

Data from multiple visits is weighted based on the number of upset events recorded.

#### A. Results for Virtex-II

Virtex-II testing has been performed at LANSCE on seven different occasions. Each test utilized the 2V6000 devices. Median configuration cross-section is 2.63E-14, and median BRAM cross-section is 2.92E-14.

#### B. Results for Virtex-II Pro

Virtex-II Pro testing has been performed at LANSCE on four different occasions. Median configuration cross-section is 2.90E-14, and median BRAM cross-section is 4.41E-14.

#### C. Results for Spartan 3

Spartan 3 testing has been performed at LANSCE on four different occasions. Median configuration cross-section is 2.29E-14, and median BRAM cross-section is 4.82E-14.

#### D. Results for Virtex 4

Virtex 4 testing has been performed at LANSCE on four different occasions. Median configuration cross-section is 1.20E-14, and median BRAM cross-section is 3.34E-14.

#### E. Results for Spartan 3E

Spartan 3E 4 testing has been performed at LANSCE on two different occasions. Median configuration cross-section is 1.38E-14, and median BRAM cross-section is 1.45E-14. We have yet to acquire data from the Rosetta atmospheric arrays on Spartan 3E.

#### F. Conclusions from Recent Beam Testing

From the recent beam testing experiments, we have an immediate observation: due to beam fluctuations from one visit to the next, there are easily variations of +/-10% in results. Also, as we improve the hardness to atmospheric neutrons, we get fewer upsets in the beam testing, which will also affect the results, requiring longer beam exposures or resulting in lower statistical uncertainty. For example, in Spartan 3E, the configuration results have a 95% confidence interval of an additional +/- 20% beyond just the beam uncertainty.

Thus, unless the number of upsets is large, and we make repeated visits, it becomes difficult, if not impossible, to characterize the improvement from one technology to the next. To try to make some statement about foundry, process, voltage, or temperature effects is basically not possible without side by side experiments in the same beam, at the same time, with a few thousand upsets on each.

## V. CONCLUSION

Xilinx has presented updated data from the Rosetta Experiment from 0.15 and 0.13 micron, as well as new data on 90 nanometer Spartan 3 and 90 nanometer Virtex 4. The new data starting with 90 nanometer technology shows how the simulation methods we used were not effective. As well, beam test results are diverging from the actual atmospheric test results so much that it calls into question if the beam can be used to predict atmospheric device behavior, or whose use should be restricted to comparative measurements. Improvements in the JEDEC89 standard have provided a better means to estimate the atmospheric acceleration factors and local attenuation by building materials to a finer degree, but remain estimates, and must be treated as such.

## REFERENCES

[1] Ulrich Schade, Richard Wäsch, *The Stone of Rosette*. October 23, 1996.  
<http://www.ba.dlr.de/ne/pe/virtis/stone1.htm>  
 [2] Austin Lesea, Saar Drimer, Joseph Fabula, Carl Carmichael, and Peter Alfke, *The Rosetta Experiment: Atmospheric Soft Error Rate Testing in Differing Technology FPGAs*. IEEE Transactions on Device and Materials Reliability, Vol. 5, Number 3, September,

2005.  
 [3] Philippe Roche and Gilles Gasiot, *Impacts of Front-End and Middle-End Process Modifications on Terrestrial Soft Error Rate*. IEEE Transactions on Device and Materials Reliability, Vol. 5, Number 3, September, 2005.  
 [4] Karine Castellani, *3-D Modeling of Bulk and Multigate Transistors and SRAM*, (summary of research), Laboratoire Matériaux et Microélectronique de Provence (L2MP), UMR/CNRS  
 [5] Prasanna Sundararajan, Scott McMillan, Brandon Blodget, Carl Carmichael, Cameron Patterson, *Estimation of Single Event*

*Upset Probability Impact of FPGA Designs*. MAPLD 2003.

[http://klabs.org/richcontent/MAPLDCon03/presentations/p/p67\\_sundararajan\\_s.ppt](http://klabs.org/richcontent/MAPLDCon03/presentations/p/p67_sundararajan_s.ppt)

[6] *Xilinx Single Event Effects 1st Consortium Report Virtex-II Static SEU Characterization*, edited by Gary Swift, posted on the JPL web Site

[7] ASTEP, <http://www.l2mp.fr/astep/> Contact: Christophe Sudre, [christophe.sudre@l2mp.fr](mailto:christophe.sudre@l2mp.fr)

**Austin Lesea** (M'75) Austin received his Bachelor of Science in Electrical Engineering and Computer Sciences, University of California at Berkeley in 1975. In 1976 he received his Masters of Science in Electrical Engineering and Computer Sciences, University of California at Berkeley in optimization, control, and communications theory

He has spent the first year of his career teaching, and writing the book, *Microprocessor Interfacing Techniques* (1976, Sybex Publishing, Berkeley, California). He spent the next 13 years designing telecommunications transmission (copper, fiber optic, digital microwave), switching (PBX and ACD systems), and synchronization systems (building integrated timing systems). During that time, he spent eight years on the ATIS/ANSI T1 Committees helping write the SONET and TI CPE standards.

Mr. Lesea has spent the last six years at Xilinx where as a Principal Engineer in the IC design group where he has been part of the design efforts for five product families. Recent interest in radiation effects has led to the Rosetta study work, however he is also actively involved in the configuration design group with special emphasis on encryption and security. He holds 27 patents.

**Joseph J. Fabula** earned a Bachelor of Engineering (with Honors) degree, Stevens Institute of Technology, 1965 and a Masters of Business Administration (in Management), Fairleigh Dickenson University, 1981.

He started his career at RCA, holding various engineering and later management positions spanning 18 years there. He was a key contributor to the establishment of RCA's radiation tolerant and radiation hardened standard cell product lines, establishing production capabilities for radiation hardened bulk silicon and silicon on sapphire CMOS technologies. He is the co-inventor of and has several basic patents issued (to RCA Corporation) in the field of radiation hardening of channel oxides and in edge-defined guard banding for the control of radiation induced leakage currents. He was a recipient of the RCA Sarnoff Laboratories Achievement Award for his contributions in the field of radiation hardening. He also served as the Program Manager for several Air Force Avionics Laboratory and Air Force Materials Laboratory funded Manufacturing Technology Programs which established RCA's manufacturing capabilities for radiation hardened CMOS processes. Subsequently he joined the ITT Corporation for a period of 8 years, first serving as the Director of Semiconductor Process Engineering at ITT Semiconductors in Shelton CT. and later as the Director of Quality Assurance for ITT Power Systems in Tucson, AZ.

Mr. Fabula joined the Xilinx Corporation in 1991 as the Director of Quality Assurance, a position he held for eight years. He is currently supporting Xilinx terrestrial and deep space radiation testing efforts and providing customer applications and quality support for the Aerospace, Defense and Automotive products businesses at Xilinx Corporation, and holds patents issued there on radiation hardening of FPGA structures.