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RADIATION EFFECTS ON ADVANCED SEMICONDUCTOR TECHNOLOGIES

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Final Report

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14. ABSTRACT

Research grant was designed to investigate radiation effects particularly as they pertain to single event effects arising from strikes from galactic cosmic rays, protons, or neutrons. Our investigations considered both individually packaged microcircuits and stacks of microcircuits included within the same package.

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TABLE OF CONTENTS

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Summary

This was a three-year activity for a total dollar amount of approximately $450,000. The focus of this work was to investigate radiation effects on electronics related to space applications. A big portion of this work was related to testing modern electronics to determine changes in failure rates and other factors to help to determine which parts have the greatest possibility for future flight survivability.

Introduction

The University of New Mexico (UNM) proposed to conduct research related to analysis, modeling, simulation, and testing of radiation effects in advanced semiconductor technologies of potential interest for space applications. State of the art electronics employ design and fabrication techniques that can potentially degrade reliability in radiation environments either in natural space, or from an enhanced radiation environment resulting from nuclear weapon detonations, or from a combinations of the two. We proposed to investigate these effects particularly as they pertain to single event effects (SEE) arising from strikes from galactic cosmic rays, protons, or neutrons on selected packaged and stacked electronics. Our investigations considered both individually packaged microcircuits and stacks of microcircuits included within the same package. We also investigated synergistic effects due to SEE in microcircuits exposed to total ionizing dose and aging effects. We intended to quantify these effects and develop mathematical models of post-exposure performance as a function of time. This research provided the foundation for identifying advanced technologies that are suitable for space applications and for engineering modifications that may improve suitability.

The project was led by the researchers at the COSMIAC Research Center at UNM. COSMIAC is a Tier-2 research center at UNM that is devoted to the use of advanced digital and analog electronics in education, training and in satellite development. During 2014 to 2015, COSMIAC developed two instruments for investigating radiation effects in space environments. The Radiation Hazard Assessment Sensor (RHAS) instrument measures total dose effects from protons and electrons in a geosynchronous orbit. The Radiation Hardened Electronic Memory Experiment (RHEME) instrument measures single bit and multiple bit upsets in semiconductor memories as well as recording total ionizing dose from protons and electrons. Furthermore, RHEME can distinguish between dose from protons versus dose for electrons. RHEME-1 was launched to the ISS (International Space Station) in October, 2016, and subsequent missions (RHEME-2 & RHEME-3) are scheduled for a polar orbit and a geosynchronous orbit. Data from these instruments informed the research in this proposed activity.

We used the provided funds to complete five major goals:

1. Identify advanced analog and digital integrated circuits that are attractive candidates for space missions.
2. Develop test methodologies to reflect potential applications in space missions.
3. Conduct radiation tests to explore failure mechanisms and reliability degrading effects.
4. Develop and evaluate mathematical models of effects for simulating radiation degradation and effects on performance over mission life.
5. Report the results in the technical literature.

Methods, Assumptions and Procedures

The team made excellent advances during the period of performance. Radiation effects continue to develop as a dynamic and growing research rich field. The team has experimented with (and tested) a wide variety of different circuits. The assumption was made that all work that could be done should be done with what was considered state of the art materials and processes at the time of the project and that all testing was accomplished utilizing available equipment and standard analysis techniques.

Goal 1: Identify advanced analog and digital integrated circuits that are attractive candidates for space missions.

The goal of this activity was to identify those semiconductor technologies that have unique capabilities to support space missions but may be susceptible to degradation from the radiation environment. Priority will be given to devices that offer advantages in processing throughput, SWAP (size, weight, and power), and cost/availability.

The team created and flew two radiation hardened experiments called the Radiation Hardened Electronic Memory Experiment RHEME that has provided excellent results. RHEME-1 is on the International Space Station (ISS) and delivering data 24 hours a day and RHEME-2 was launched in the fall of 2018. RHEME-3 is currently being designed for an assigned launch.

As of the end of this grant's period of performance, RHEME-1 continues to operate perfectly on the ISS. RHEME-2 is going through initial on orbit check out. RHEME-3 and -4 are in the design phase. Each of these systems will deploy at a different orbit (apogee, perigee and inclination) and will therefore provide a wide and robust set of data points for future research.

Additionally, the team tested other systems (as well as components) for radiation robustness. In August 2016, COSMIAC tested analog to digital and digital to analog components in collaboration with the SpaceX Corporation and AFRL. This collaboration identified the need for a Cooperative Research and Development Agreement (CRADA) to fully expand this activity. The CRADA will allow companies to be able to pay for AFRL facilities through a UNM vehicle. This has increased the amount of information on robustness of cutting edge technology available to the federal government thus increasing mission part selection options. As more and more organizations are relying on commercial nanosatellite "systems" as compared to building their own items (such as power, propulsion and attitude control) more interest is being generated about how this affects radiation reliability. The team is constantly approached about performing radiation testing and with the CRADA as a catalyst, these opportunities will expand. Although not being swamped with requests, the team still has requests to use the CRADA for processing payments for radiation facility usage. Most recently the Northrop Grumman and Blue Origin companies have expressed interest.

The team as initiated the development of a long term strategy for the testing of electronics using local radiation facilities. Work during this period of performance has involved the creation of the strategy of testing electronics parts and larger systems for space applications. Three types of missions were identified: prime mission, intermediary mission and best efforts. This strategy and understanding of testing options is being staffed at the small satellite portfolio at AFRL currently.

Prime missions are multimillion dollar/multiyear activities with a strong military purpose. The missions will require either radiation hardened assets or parts testing to a very high degree of reliability. This could involve total dose testing as well as upset and beam testing. All technology levels within the system, including entire system, board and then chip level testing would be accomplished.

Intermediary missions are relatively short duration but still require a level of testing. In this area, simply testing for total dose and the use of parts that can be reset with a watchdog timer might be sufficient. In many cases, a known degree of radiation tolerance rather than strategic radiation hardened electronics are necessary for a successful mission.

Best effort missions are quick turn, short design time developments where the mission life is less than a year and the orbit is in a lower elevation. This type of mission would benefit from any radiation knowledge of the components being used and may result in only total dose testing of systems (at the most).

The team is now meeting monthly with the small satellite portfolio designers helping to identify specific parts for testing in each of the three satellite mission profiles.

Goal 2: Develop test methodologies to reflect potential applications in space.

For total ionizing dose (TID), a spectrum of energetic protons and electrons are the main constituents of the upper and lower Van Allen belts surrounding the earth and of the solar wind that emanates from the sun. The low energy portion of the spectrum can be attenuated with aluminum shielding. However, providing sufficient shielding to effectively attenuate the high energy portion of the spectrum is generally prohibitive because of limitations in weight and size. Also, bremsstrahlung radiation resulting from stopping electrons in the shielding material must be considered in the total dose budget. The benefits of TID hardening of memories can be clearly demonstrated by the dose depth curves as a function of shielding thickness for a variety of orbits. For example, memories used in a Global Positioning System (GPS) circular orbit at 20,200 km and 55° inclination with 100 mils of aluminum shielding experience 200 Krad(Si)/year. However, commercial DDR3 memories have been shown to exhibit “stuck bit” failures between 50 Krad(Si) – 100 Krad(Si), giving them a lifetime on orbit of 3 to 6 months without a significant increase in shielding. Clearly, national space assets require high performance memory with much greater hardness.

For single event effects, space electronics are bombarded by galactic cosmic rays (GCR) and protons from the natural environment. Protons are elements in the solar wind as well as being trapped in the Van Allen belts. The solar wind also includes alpha particles (He nuclei) and atomic nuclei from the sun's corona. GCRs are ions produced by super nova and other galactic events and include a relatively high abundance of ions up to iron (Fe) with a decreasing representation of ions above Fe. The flux of GCRs and protons is a function of orbit with the highest GCR flux occurring in orbits outside the magnetosphere, in upper MEO (medium earth orbit), and in polar orbits. Proton flux is most severe inside the Van Allen belts and within the South Atlantic Anomaly.

Ion strikes in the semiconductors can produce a variety of single event effects (SEE) including latch-up (SEL), upset (SEU), functional interrupts (SEFI), and transients (SET). The RHEME (Radiation Hardened Memory Experiment) memory must be hardened against these effects through the use of process modifications, memory cell design, redundancy, voting techniques, and EDAC (error detection and correction). Particular attention must be given to the design layout and arrangement of memory cells in a word to prevent a single ion strike from corrupting data in multiple bits.

During the period of performance of this grant, the team worked with the Defense Threat Reduction Agency (DTRA) to join AFRL in attendance of the DTRA Technical Working Group (TWG) that was held in December, 2016 as part of the Satellite Survivability Nuclear Standard (SSNS) development effort. The TWG involved many AFRL personnel active in the development of methods for radiation hardening and protecting electronics in the radiation environment of space. SSNS has many aspects such as testing of solar panels for displacement damage and it is believed that by presenting what was being accomplished under this grant that joint parts testing could be accomplished. We are still developing these activities as of the end of the period of performance.

The team also investigated power systems for satellites. COSMIAC has gained a great deal of experience and results by developing power systems for satellites over the past year. One particular focus area has been in the areas of solar parts and panel analysis. Of particular interest is the effect of flash x-rays on solar panel bypass diodes. COSMIAC has identified a potential failure point in orbit in the areas of bypass diode susceptibility in solar arrays during prompt radiation environments. The effects of gamma- and X-ray-induced transients on modern solar arrays is not well characterized. These transients must be evaluated in the context of the power system architecture including bypass and blocking diodes, filters associated with the electrical power system (EPS), and the mechanical structure of the array to account for parasitic capacitance and inductance. Transient damage concerns include burnout of the blocking/bypass diodes, damage to solar cell junction or metalization, and damage to the EPS due to overvoltage/overcurrent transients. Extensive testing was accomplished and papers submitted.

Goal 3: Conduct radiation tests to explore failure mechanisms and reliability degrading effects.

During the second quarter, the team created the detailed test plans that will be required to perform flash x-ray testing at Kirtland Air Force Base (KAFB). The team wanted to begin testing in late 2017. As of April, 2017, work continued in the area of bypass diode analysis. Parts were ordered to allow for future testing. Parts were ordered from the two major manufacturers of solar cell technology in the country for space applications: SolAero and Spectrolab. As of July, 2017, parts began to arrive for solar array testing. The plan was still to utilize the Kirtland Air Force Base (KAFB) Flash X-Ray (FXR) facility to perform a wide variety of different tests to include bypass and blocking diodes as well as solar cells and arrays of cells. The team developed a wide array of test boards that held the samples under test in the radiation environment. In October, 2017, the FXR facility at KAFB had critical parts failure and projections were that it would be down for more than a year. It was necessary to go to White Sands Missile Range (WSMR) in southern New Mexico to perform the radiation testing at their FXR facility. The team had never been to WSMR so a short trip was conducted to begin to make the plans necessary to perform this testing in the next quarter. Due to the remote location of the WSMR facility, the logistics necessary to support this testing grew substantially. Work was accomplished to develop all the test boards and fixtures for holding the test articles. The test articles were in house from the SolAero and Spectrolabs fabrication facilities.

As of January, 2018, significant tests were performed at WSMR. This was an excellent opportunity for students and faculty to perform real world testing in a radiation source. The students worked to perform modeling and simulation of the radiation effects as well as developing a sun emulator for illuminating the solar cells and arrays during the actual tests. The results of this solar emulator have been provided to the University Nanosatellite Program managers to share with the larger college community. At the end of the period of performance, the effects of a prompt dose on a variety of different diodes that can be used in power systems has begun to be better understood. There will be more testing in 2019 to further understand this phenomenon.

Goal 4: Develop and evaluate mathematical models of effects for simulating radiation degradation and effects on performance over mission life.

The team has developed a relationship between AFRL and the Defense Threat Reduction Agency (DTRA) related to modeling and simulation (M&S) for radiation in the natural and prompt environments. DTRA began teaching M&S for radiation effects workshops every other week at COSMIAC. The first tools to be investigated were the ASSIST package. ASSIST has a wide variety of different packages contained within it which provide the ability to do analyses on items such as the environment, RF scintillation and nuclear burst effects.

For almost a year, the team continued to learn and run M&S products related to the ASSIST software. The runs produced environmental effects that were then brought into other software packages for analysis such as RF scintillation. The team ran simulations on past COSMIAC satellite missions to obtain publishable data. The team also began work on modeling of radiation effects utilizing the Monte Carlo N-Particle eXtended (MCNPX) software. We used the MCNPX software for particle transport analysis through shielding to find effects in electronic systems in space. The students looked into effects such as ionizing and nonionizing profiles as well as nuclear activation resulting from particle interaction in materials.

The courses were terminated when the Aerospace Corporation that was running the weekly courses terminated his employment with Aerospace Corporation to take other work.

Goal 5: Report the results in the technical literature.

A paper on the diode testing was accepted and was presented in April, 2018. This resulted in both a poster and a paper being accepted.

Results and Discussions

The team achieved the original objectives as well as going into other areas of investigation that were of interest to the space community as more and more spacecraft activities are looking to use commercial parts for surviving the harsh radiation effects for satellite development in low earth orbit. The outcome is that excellent advances have been made in the areas of radiation effects study for space.

The team met established goals. There were no cost overruns on this activity.

Conclusions

The field of radiation effects study and mitigation has suffered extensively in the past decade from a continued decline in the number of US personnel working this area. More and more of them are retiring each year with a noticeable gap in the number of young people to take over. From a national perspective, this work was absolutely essential to help to develop the cadre of young engineers working in this field.

APPENDIX: RHEME Conference Paper

Single Event Upset Results from the Radiation Hardened Electronic Memory Experiment on the International Space Station

David Alexander, *Senior Member IEEE*, Alonzo Vera, *Senior Member IEEE*, Wesley Morris, James Christian,
David Gifford, Keith Avery, *Member IEEE*, Gabriel Urbaitis, Connie Li, Zack Daniels

***Abstract*-- Results are presented from the Radiation Hardened Electronic Memory Experiment (RHEME) performed on the International Space Station (ISS).**

I. INTRODUCTION

THE Radiation Hardened Electronic Memory Experiment (RHEME) was designed to investigate single event upsets (SEU) in semiconductor memories in terms of the rate of occurrence, the prevalence of upsets in adjacent bits, and the effectiveness of EDAC (error detection and correction) and scrubbing. The experiment consisted of four 16 Mbit memories and one, 72 Mbit memory composed of a stack of 18 Mbit memories. All memories were designed by Vorago Technologies. The 16 Mbit memories were fabricated and sold by Texas Instruments, and the 18 Mbit memories were fabricated by Global Foundries and sold by Vorago Technologies. Three flights of the experiment have been planned including: RHEME-1 on the ISS, RHEME-2 in a 500 km polar orbit, and RHEME-3 in a geosynchronous orbit. The data from RHEME-1 are presented here. RHEME-2 is scheduled for launch in the 3rd quarter of 2018, and RHEME-3 is scheduled for 2019.

II. EXPERIMENTAL DESIGN

As shown in Figure 1, the RHEME experiment consists of four 16 Mbit SRAMs (Texas Instruments SMV512K32-SP) configured on a common memory bus controlled by an M0 microcontroller (Vorago PA32KASA). The 72 Mbit stacked memory (Vorago SB018EA_B) communicates with the M0 over the SPI bus. These devices constitute the memory portion of the experiment. The 16 Mbit SRAMs have EDAC and scrubbing capability included in their design. The activation of EDAC and scrub rate are controlled by the M0. The 72 Mbit SRAM also has internal EDAC and write-back capability controllable by the M0. The controller and the memories are radiation hardened to prevent latch-up and exhibit total dose hardness in excess of 300 Krad(Si).

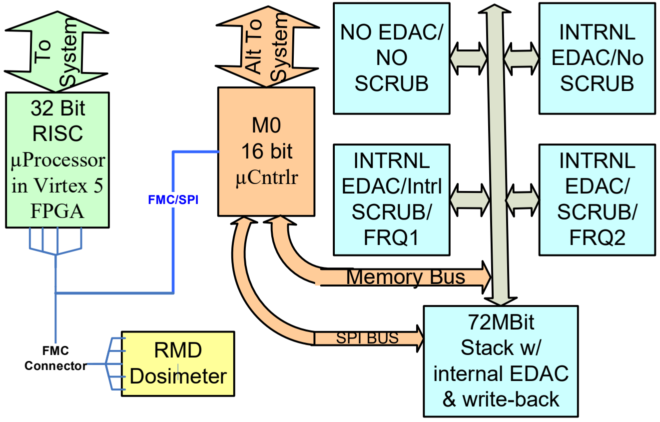

Fig. 1. RHEME block diagram

The primary communication to the space vehicle is performed by a VIRTEX 5 FPGA. It implements the communication interface protocol and monitors temperature sensors and general health and status monitors. RHEME also incorporates a dosimeter developed by Radiation Monitoring Devices that is capable of distinguishing electron dose from proton dose. Data formatting for the dosimetry data is also performed by the FPGA. Only the data from the memory experiments are presented in this paper.

Figure 2 shows the RHEME-1 instrument with the lid and back panel removed to show the configuration of the flight

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instrument. The M0 controller is located in the center of the board with the 16 Mbit memories placed in the four quadrants around it. The 72 Mbit stack is located on the right side of the board, and the RMD dosimeter is located near the right edge. The FPGA board and the power modules are located under the experiment board and communicate with it through an FMC (FPGA mezzanine connector). A single power connector is located on the left panel of the enclosure and provides a 28 V power line to the instrument. Internal power modules convert to the voltages required by the instrument electronics. The RHEME lid is 100 mils of aluminum that is thinned to 50 mils over the dosimeter. As deployed, the lid of the instrument faces the space environment.

Fig. 2. RHEME instrument with lid removed

The RHEME experiment was part of the NASA STP program that provides opportunities for space experiments to have access to the ISS. The specific mission assigned to RHEME was the STP-H5 mission, and Figure 3 shows the placement of that pallet with respect to the ISS configuration. Figure 4 shows the location for RHEME after full deployment.

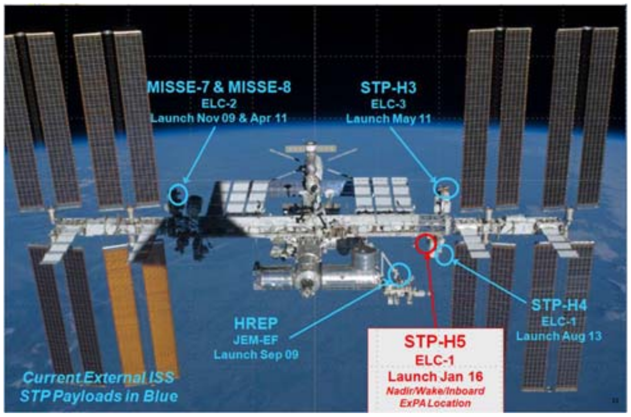

Fig. 3. Location of STP-H5 experiment pallet

The STP-H5 pallet included provisions for thermal management, and the RHEME-1 experiment monitored temperature with four thermal sensors. Figure 5 shows the thermal profile of the sensors over a period of 40 days. Over all sensor monitors, the temperature ranged between 11°C and 31°C. Because the temperature was so well controlled, no conclusions can be reached regarding the effect of temperature on upset.

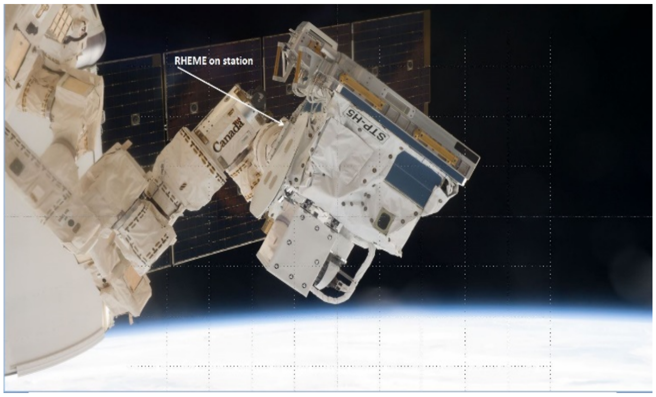

Fig. 4. RHEME location after deployment

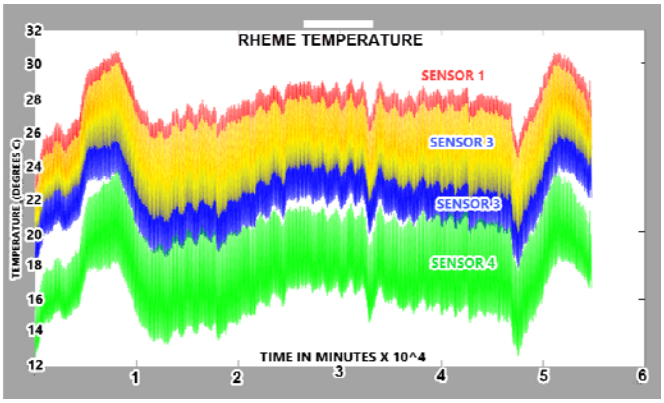

Fig. 5. Thermal profile of RHEME-1 sensors

When the temperature data from the RHEME sensors are mapped into the ISS orbital position at the time of the readings, a map of temperature versus orbit can be constructed as shown in Figure 6. The hotter temperatures are associated with the portion of the orbit under solar illumination and the colder temperatures occurred when shadowed by the earth.

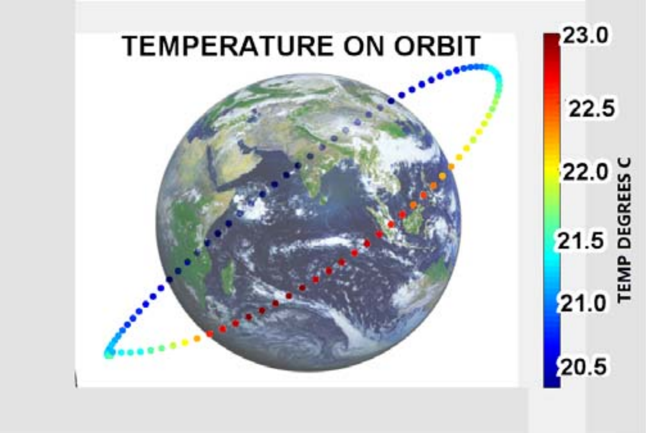

Fig. 6. RHEME thermal profile related to orbital position

III. 16 Mb SRAM Experimental Results

The 16 Mbit memories were tested at the Texas A&M cyclotron to determine their cross section as a function of

LET. As shown in Figure 7, the saturated cross section without EDAC was 5x10^{-8} cm^{-2}, and was reduced by a minimum of two orders of magnitude with EDAC turned on. With both EDAC and scrub, a cross section was not discernable.

Simulations with CRÈME96 for the ISS orbit using the Weibull fit to the cross section data gave an estimate of 2.98 upsets per device per day for the ISS orbit. [ref 1, 2,3] Thus, the 4 memories on RHEME were expected to experience an average of 12 upsets per day.

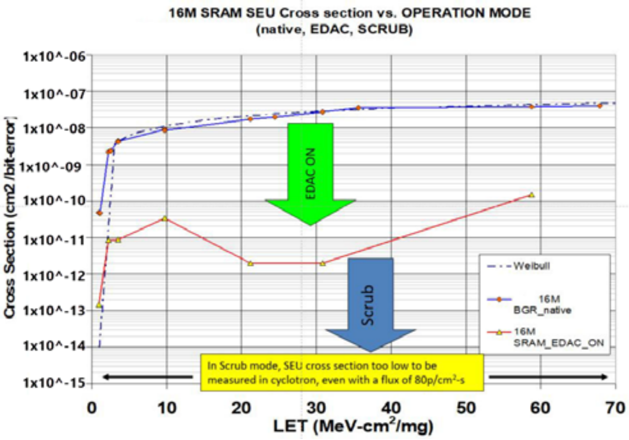

Fig. 7. 16 Mbit SRAM cross section

Data for the deployed RHEME without EDAC or scrubbing were available for 117 days in the period from 1 April 2017 until 15 January 2018. The cumulative number of errors detected in that period are shown in Figure 8. A total of 348 errors were detected with the average of 3 errors detected per day. Figure 9 shows the number of errors detected on a daily basis for the 4 SRAMs for those days when EDAC was not activated. While 3 was the average number of errors seen over the 117 days, as many as 8 upset were observed in one a day. There were also three days when no upsets were observed. Since the logical address to physical placement was known for the 16 Mbit SRAMs, the location of upsets could be determined. Figures 10 through 13 show the location of each of the upsets recorded in each of the memories. The red dots in the chip maps are centered on the physical location of each error. However, an ion strike at a shallow angle or a strike between adjacent bits could upset multiple bits. In examining the location of upsets, a small number of errors were detected in adjacent bits in three of the four 16 Mb SRAMs. Figure 14, shows the number of adjacent bits involved and the geometric orientation of the upsets.

The center grey colored columns in each of the memory figures represent the location of the bits used for EDAC. When the memories are not in EDAC mode, the bits in the grey regions are not observable. The location of the upset errors in each of the memories is randomly distributed throughout the chip. Thus, indicating that multiple errors were not generated from strikes on bit lines or word lines.

On July 20, 2017, EDAC was turned on for all four memories and was cycled off and on for a total active time of 53 days. During that time, no uncorrected errors were detected in any memory. In the EDAC mode, the correct data was written to each memory location after each read, which was performed hourly. This constituted an effective scrub rate of once per hour. Since EDAC with an hourly scrub rate was effective in eliminating any errors, evaluation of more frequent scrub rates was not performed. RHEME-2 and RHEME-3 will evaluate the effectiveness of scrubbing frequency in more stressful environments.

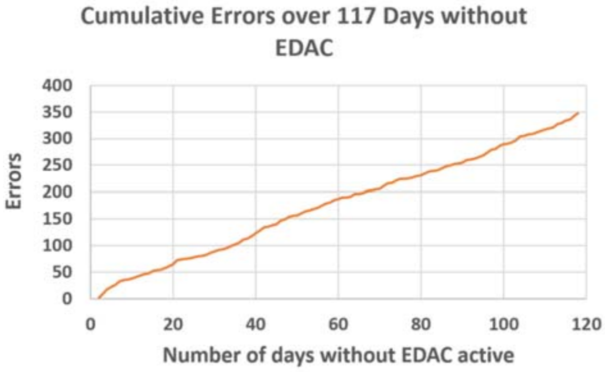

Fig. 8. Cumulative errors for 16 Mb SRAMs without EDAC

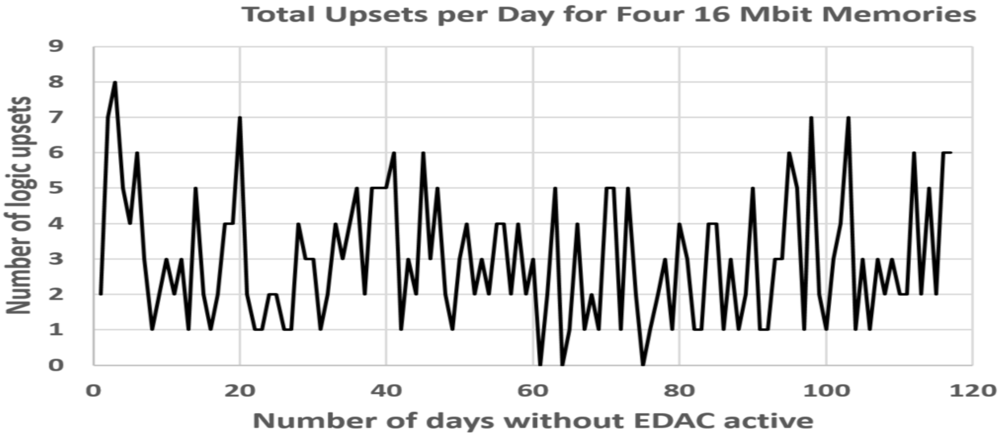

Fig. 9. 16 Mb Upsets observed on individual days without EDAC

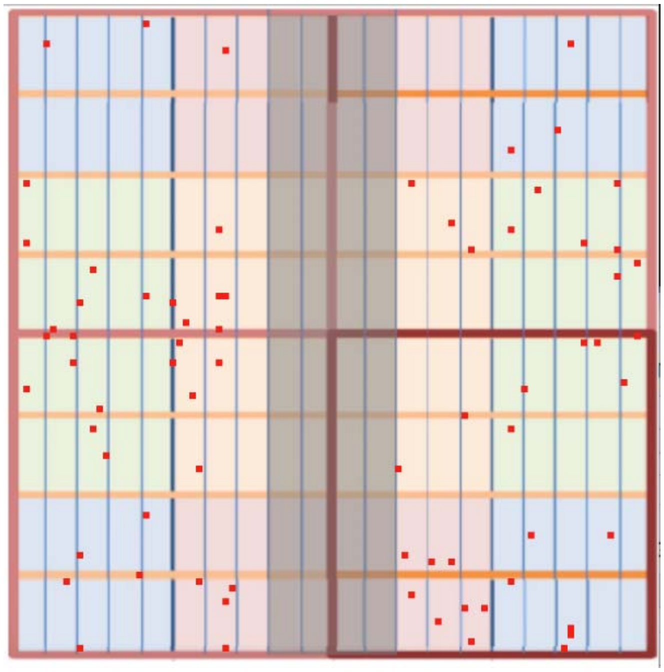

Fig. 10. Memory 0 error map

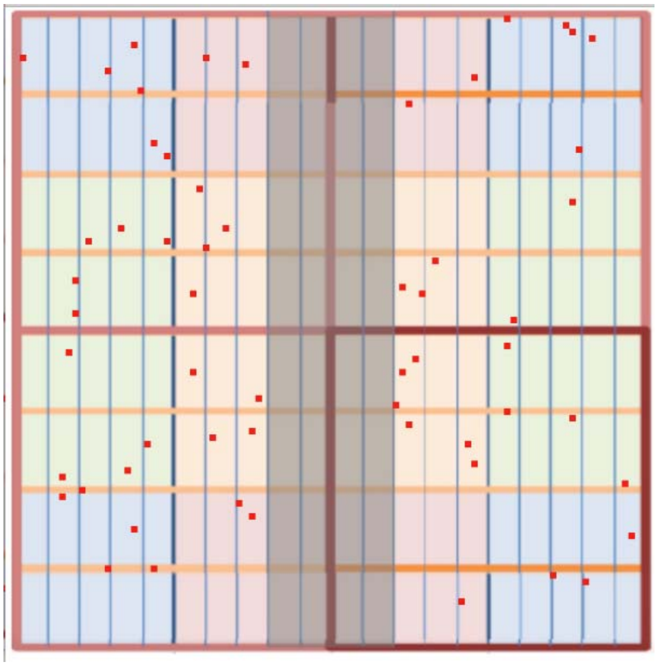

Fig. 11. Memory 1 error map

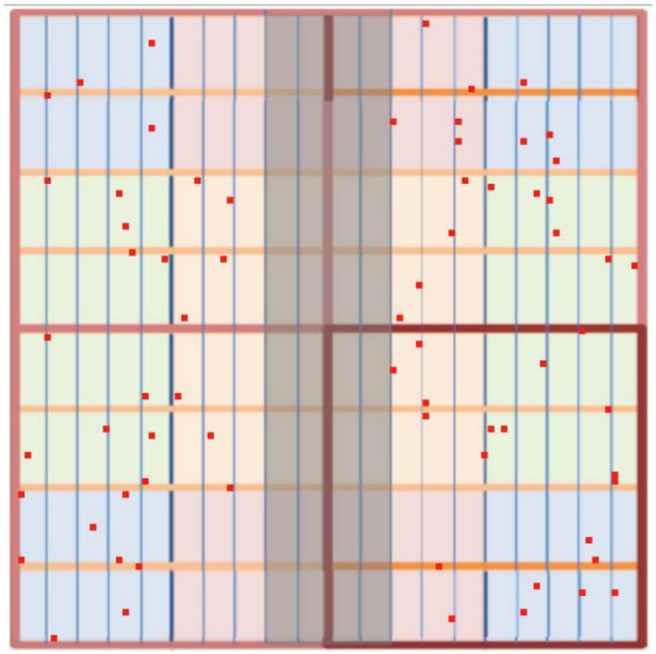

Fig. 12. Memory 2 error map

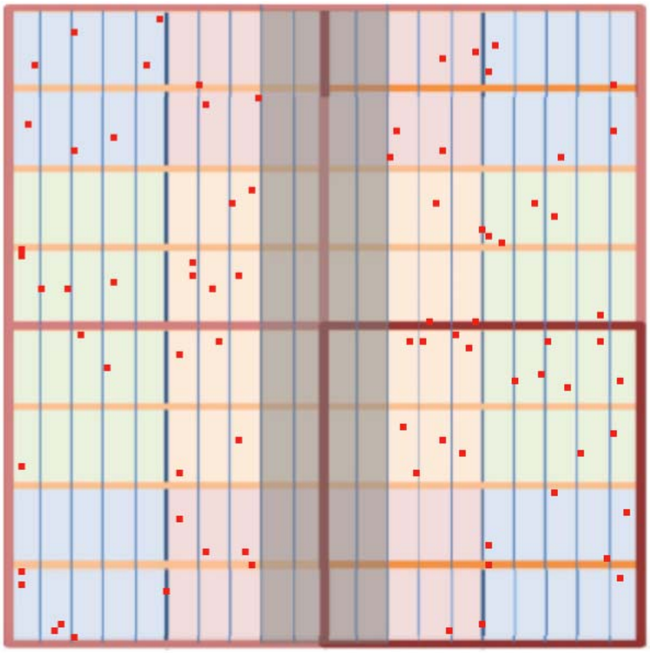

Fig. 13. Memory 3 error map

Adjacent Upsets

	MEM0	MEM1	MEM2	MEM3
Double	1	1	0	1
Triple	0	0	0	0

Orientation of Strike

8/13/2017 14:58:57

6/4/2017 14:20:05

10/31/2017 3:54:48

Fig. 14. Adjacent bit upsets in 16 Mb memories.

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IV. 72 MB SRAM EXPERIMENTAL RESULTS

The 18 Mbit memories that were stacked to create the 72 Mb were tested at the Texas A&M cyclotron to determine their cross section as a function of LET as shown in Figure 15. CREME96 analysis for these cross sections in the ISS orbit predicted 1.6 upsets/device/day without EDAC.

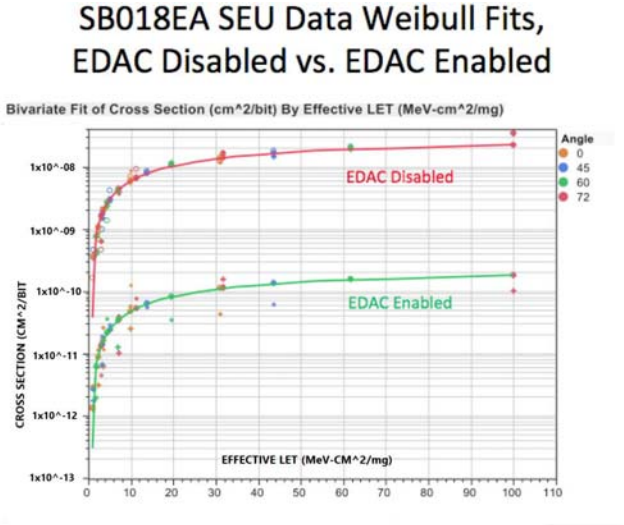

Fig. 15. Cross sections for 18 Mb SRAMs

Data for the deployed 72 Mb SRAMs without EDAC were available for 47 days from December 9, 2017 through February 19, 2018. The cumulative number of errors detected during that period are shown in Figure 16. A total of 161 errors were detected with an average of 3.4 errors per day for the stack or .85 upsets/device-layer/day. Figure 17 shows the number of errors detected daily on the 72 Mb stack. They range from a maximum of 10 errors/day to a minimum of 0 errors detected on two days during the period without EDAC.

Since the 72 Mb SRAM is a stack of four 18 Mb die, the top and bottom die in the stack might be expected to exhibit more errors than the two middle die. Figure 18 shows the location of the first 16 errors detected in the memory stack for one reporting period. Due to telemetry limitations, only the first 16 errors in one reporting sequence could contain position information. Of the 16 errors reported in this sequence, Figure 18 shows that two sets of errors involved bits on different layer that were in close proximity in their physical layout. The top and bottom layers accounted for 7 of the 16 errors.

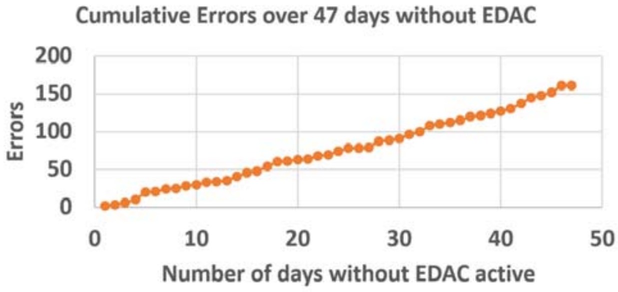

Fig. 16. Cumulative errors in the 72 Mb SRAM stack

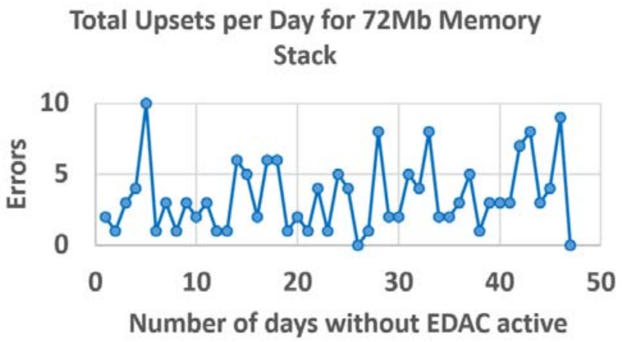

Fig. 17. 72 Mb upsets on individual days without EDAC

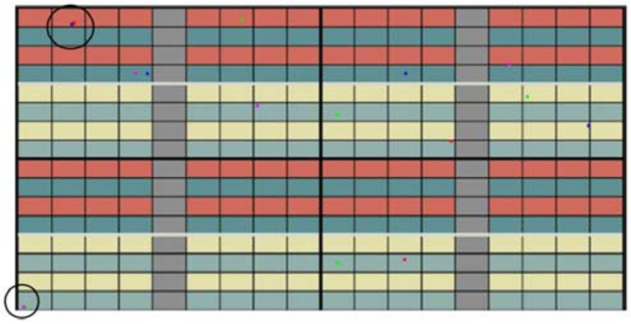

Fig. 18. 72 Mb memory map of sixteen error reports in on telemetry sequence (circled areas indicate multiple layer upsets)

V. SUMMARY

The first RHEME experiment has been performed in the ISS orbit and has provided a baseline for upsets in low earth orbits. This baseline will be used for comparison to future data to be acquired for a polar orbit and a geosynchronous orbit. CRÈME96 simulations were an upper bound on the observed upsets.

VI. REFERENCES

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List of Acronyms

AFRL – Air Force Research Laboratory
CRADA – Cooperative Research and Development Agreement
DTRA – Defense Threat Reduction Agency
EDAC – Error Detection and Correction
EPS – Electrical Power System
GCR – Galactic Cosmic Rays
GPS – Global Positioning System
ISS – International Space Station
M&S – Modeling and Simulation
MCNPX – Monte Carlo N-Particle eXtended (MCNPX)
MEO – Medium Earth Orbit
PCB – Printed Circuit Board
RHAS – Radiation Hazard Assessment Sensor
RHEME – Radiation Hardened Electronic Memory Experiment
SEE – Single Event Effects
SEFI – Single Event Fault Interrupt
SEL – Single Event Latch-up
SET – Single Event Transients
SEU – Single Event Upset
SSNS – Satellite Survivability Nuclear Standard
SWaP – Size, Weight and Power
TID – Total Ionizing Dose
TWG – Technical Working Group
UNM – University of New Mexico

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