SINGLE EVENT EFFECT TEST RESULTS FOR CANDIDATE SPACECRAFT ELECTRONICS

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Abstract

We present both heavy ion and proton single event effect (SEE) ground test results for candidate spacecraft electronics. A variety of digital, analog, and fiber optic devices were tested, including DRAMs, FPGAs and fiber links.

I. Introduction

As spacecraft and spacecraft designers increasingly utilize increasing number of commercial technology devices as opposed to the more traditional radiation hardened (RH) components in order to meet stringent spacecraft requirements in areas such as volume, weight, power, cost and schedule, SEE ground testing has become a key in many spaceflight programs.

The objective of this study was to determine the Linear Energy Transfer (LET) threshold (the minimum LET value to cause an effect at a fluence of 1E7 particles/cm^2) and saturation cross section of candidate spacecraft electronics for Single Event Upset (SEU) and Single Event Latchup (SEL) due to protons and heavy ions.

II. Test Techniques and Setup

A. Test Facilities

All tests were performed between February 1996 and February 1997. Heavy Ion experiments were performed at the Brookhaven National Laboratories (BNL) Single Event Upset Test Facility (SEUTF), and at the Texas A&M University (A&M) Cyclotron. The SEUTF uses a tandem Tandem Van De Graaf accelerator, while the Texas A&M facility uses a 88" Cyclotron. Both are suitable for providing various ions and energies for testing.

At both facilities, test boards containing the device under test (DUT) are mounted inside a vacuum chamber. Testing was performed with LET values ranging from 1.1-120 MeV*cm^2/mg, fluences from 1E5-1E7 particles/cm^2, and fluxes from 1E2 -1E5 particles/cm^2/sec, all depending on device sensitivity. Ions used are listed in Table 1. Intermediate LETs were obtained by changing the angle of incidence of the DUT to the ion beam, thus changing the path length of the ion through the DUT. Energies and LETs varied slightly due to multiple test dates over the calendar year.

Table 1 Test Ions

Facility	Ion	Energy, MeV	LET, MeV*cm2/mg
BNL	C-12	98	1.45
	F-19	140	3.45
	Si-28	186	7.88
	Cl-35	210	11.4
	Ni-58	278	26.2
	Br-79	286	37.2
	I-127	320	59.7
	Au-197	350	82.3
A&M	Ne-20	298	2.5
	Ar-40	599	7.4

Proton SEE testing was performed at both the University of California at Davis (UCD) and the University of Indiana at Bloomington (IUCF) cyclotron facilities. Test energies ranged from 26.6 to 63 MeV at UCD, and 54 to 197 MeV at IUCF. Typically, fluence was 1E10-1E11 particles/cm^2, and flux was 1E8 particles/cm^2/sec.

<u>B. Test Method</u>

Three test modes were used, depending on the DUT:

***dynamic* - actively exercise a DUT during beam exposure while counting errors, generally by comparing DUT output with a reference device or other expected output. Devices may have several dynamic test modes, such as *Read/Write* and *Read Only*, depending on their**

function

static **- load device prior to beam irradiation, then retrieve data post-run, counting errors**

biased (SEL only) **- DUT is biased and clocked while I_{cc} (power consumption) is monitored for latchup**

Devices were monitored for both SEU (*transients*, *bit flips*, *control errors*, *etc.*, as defined on a device-by-device basis) and SEL (both *destructive* _ I_{cc} above specified maximum for the device _ and *microlatch* _ a self-limiting latchup localized to an area of the device; I_{cc} is above normal operating current, but below specified maximum for the device, requiring a power reset to clear), along with any destructive conditions.

All tests were performed at room temperature, unless noted.

III. Test Results and Discussion

Table 2 summarizes the devices tested for SEE and the test results, using the following conventions:
HI = heavy ion test
P = proton test
SEU = SEU LET_{th} (MeV*cm^2/mg)
SEL = SEL LET_{th} (MeV*cm^2/mg)
σ = cross section (cm^2/device, unless specified as cm^2/bit)

Device-by-device descriptions of test procedures and results follow Table 2. This paper is a summary of results; complete test reports are available online at: http://flick.gsfc.nasa.gov/radhome.htm [1]

Table 2 Summary of Test Results

DEVICE	FUNCTION	MANUF.	TEST RESULTS	NOTES
RAM (Random Access Memory)				
0116400J1D Luna-ES2	4Mx4 DRAM	IBM	*P* bit, block errors, σ ~ 1.45E-15/bit (bit, 5V), 1.45E-15/bit (bit, 3.3V) *H* SEU < 3.38 (bit), 3.9 (block) SEL > 11.5	3.3 V, 5 V devices
KM48V8100AS-16	8Mx8 DRAM	Samsung	*P* bit errors, σ ~ 1.03E-14/bit	3.3 V
UPD4216400-60	4Mx4 DRAM	NEC	*P* bit errors, σ ~ 7.76E-12/bit	5V
TMS416400DJ-60	4Mx4 DRAM	TI	*P* bit errors, σ ~ 5.42E-12/bit	5V

			H SEU < 2.5 (bit) SEL > 65	
88130L45PC	128kx8 SRAM	Hitachi/ EDI	*P* bit errors, σ ~ 1.7E-13/bit	5V
MT5C1008CW-25	128kx8 SRAM	Micron	*P* bit errors, σ ~ 3E-7	5V
FPGAs (Field Programmable Gate Arrays)				
CLAy-31	RAM-based FPGA	NSC	*P* data, reconfig. errors *H* SEU 5 (data), 11 (reconfig./snapback) SEL > 90	anomalous current change
A14100A	FPGA	Actel	*P* S-, I/O-mod errors *H* SEU 8 (S-, I/O-mod), 28 (C mods) SEL > 80	[2]
A1460A	FPGA	Actel	*P* S-, I/O-mod errors *H* SEU 6-8 (S-, I/O-mod), 25-30 (C mods) SEL > 80	[2]
Data Transmission				
UT63M147-BPC	1553 Transceiver	UTMC	*H* SEU 11 SEL > 35	
DR1773	1773 Transceiver	Boeing	*P* σ ~ 1.4E-10 (bit-RX), < 2E-11 (bit-TX)	attenuation-, angle-dependent [3,4]
2706T	Fibre Channel Link Transmitter	Force, Inc.	*P* bit, burst errors	[5]
2706R	Fibre Channel Link Receiver	Force, Inc.	*P* bit, burst, sync errors	[5]
ATTDA204B	Fibre Channel Link Transmitter	AT&T	*P* bit, burst errors	[5]
ATTDA205B	Fibre Channel Link Receiver	AT&T	*P* bit, burst, sync errors	[5]
AM7968	TAXI Transmitter	AMD	*P* σ ~ 5.27E-10(data), 6.6E-10(sync) *H* SEU < 3.39(data, sync) SEL > 53.2	sync errors required power reset
AM7969	TAXI Receiver	AMD	*P* σ ~ 5.27E-10(data), 6.6E-10(sync) *H* SEU < 3.39 SEL > 53.2	sync errors required power reset

Other				
5690R-D15	**DC-DC Converter**	**MDI**	***H* SEU 26.6 (LM139)** **SEB/SEGR 30.7**	**multi-chip module**
M67204EV-50	**4kx9 FIFO**	**Matra**	***P* σ ~ 8.58E-14(bit), 8.3E-13(pointer), 2E-12(control)** ***H* SEL 37.1**	
CS5012A	**12-bit ADC**	**Crystal Semi.**	***H* SEU 3.4-4.8** **SEL 11.4**	**laser test for SEL**
AD570	**8-bit ADC**	**Analog Devices**	***H* SEU 7** **SEL > 52.5**	
DAC8800	**Octal 8-bit DAC**	**Analog Devices**	***H* SEU > 80** **SEL > 80**	
AD630	**Balanced Modulator**	**Analog Devices**	***H* SEU 3.38 (short), 7.4 (medium, long)** **SEL > 65**	
AD652	**Voltage/Frequency Converter**	**Analog Devices**	***H* SEU 7.4** **SEL > 65**	
LM136	**Voltage Reference**	**NSC**	***H* SEU 3.38 (short only)** **SEL > 52.5**	
TI7770-5	**Power Supervisor**	**TI**	***H* SEU 7.5-11.6** **SEL > 65**	
TI7705	**Power Supervisor**	**TI**	***H* SEU 3.38-4.5, 20 (hard error)** **SEL > 30**	

A. RAM (Random Access Memory)

1. DRAMs (Dynamic RAM)

These DRAMs were tested in three modes (dynamic, static, refresh only) and two access methods (byte, page), always with a checkerboard pattern, all with no impact to the results.

DUTs were monitored for *bit, block* (a single ion strike induces a partial or full address column or row to be in error), and *control* errors. Figure 1 shows proton test data for the following DRAMs.

a. 0116400J1D Luna-ES2

Both the 3.3 V and 5 V versions of this device were tested. The 3.3 V version was also tested at 3.0 and 2.75 V, and the 5 V version was also tested at 4.5 V.

Proton **_ *Bit* errors were seen. σ for the 3.3 V devices was 4.20E-15 cm^2/bit at 3.3 V, increasing to 1.08E-15 cm^2/bit at 2.75 V. σ for the 5 V devices was 1.14E-15 cm^2/bit at 5 V, increasing to 1.20E-15 cm^2/bit at 4.5 V. Occasional *block* errors were seen in both devices. No variance between modes of operation was observed.**

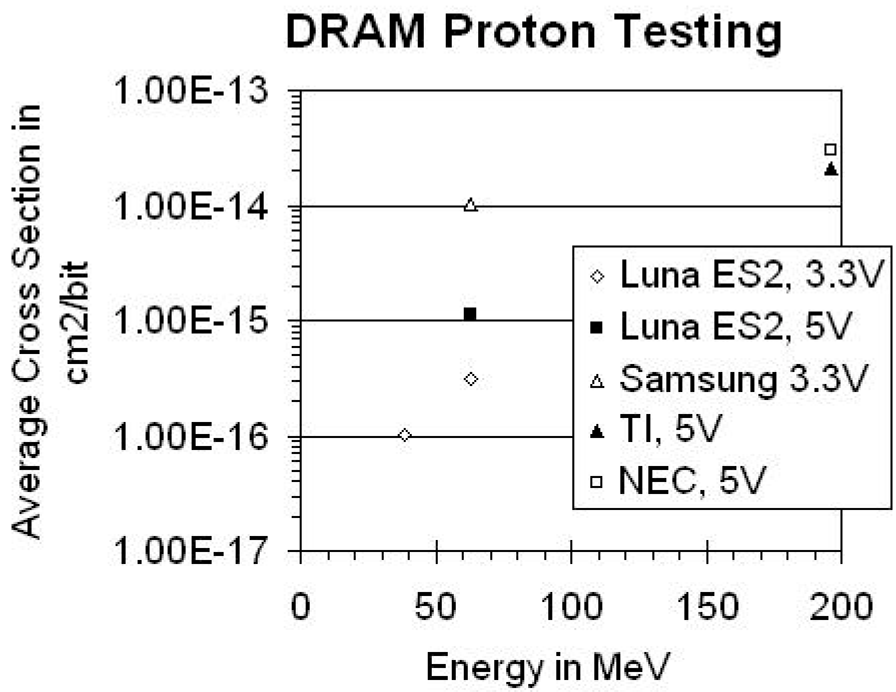

Figure 1

Heavy ion **_ Only the 5 V devices were tested for heavy ion, at the full 5 V. Both *bit* and *block* errors were seen, with LET_{th} of < 3.38 (bit) and 3.9 (block).**

b. KM48V8100AS-16

This 3.3 V device was tested for proton effects only. Note that this is not the EDO version of this device. SEU tests were performed with V_{cc}s of 3.0 and 3.3 V.

Only *bit* errors were observed, with σ ~ 1.03E-14 cm^2/bit at 3.3 V and 1.23E-14 cm^2/bit at 3.0 V. No variance between modes of operation was observed. I_{cc} increase was noted at ~ 10 kRad (Si) of proton exposure, but no functional failures were observed.

c. UPD4216400-60

This 5 V device was tested for proton effects only. Only *bit* errors were observed, with σ ~ 3.03E-14 cm^2/bit. No variance between modes of operation was noted.

d. TMS416400DJ-60

Proton **_ Only *bit* errors were observed, with a measured σ ~ 2.12E-14 cm^2/bit. No variance between modes of operation was noted.**

Heavy Ion **_ Only *bit* errors were observed, in all test modes, starting at the minimum tested LET of 2.5; σ for all modes was ~ 3 cm^2/device, or ~ 1.8E-4 cm^2/bit for this 16Mbit device. SEL was not observed, up to a maximum tested LET of 65.**

2. SRAMs (Static RAM)

SRAM proton test data is shown in Figure 2.

a. 88130L45PC

These 5 V devices were tested for proton effects only, with test patterns of all 1's and all 0's. No pattern dependence was seen. σ for all modes was ~ 9.77E-15 cm^2/bit for *single-bit* SEUs, and 5.66e-17 cm^2/bit for *double-bit* SEUs.

b. MT5C1008CW-25

These 5 V devices were tested for proton effects only, with test patterns of all 1's and all 0's. Results showed a strong pattern dependence: σ for *single-bit* SEUs was ~ 1.77E-14 cm^2/bit for all 1's, and 4.77e-17 cm^2/bit for all 0's. *Double-bit* SEUs were seen only with an all 1's pattern, with σ ~ 9.54E-17 cm^2/bit.

B. <u>FPGAs (Field Programmable Gate Arrays)</u>

1. CLAy-31

This device is a RAM-based gate array, programmed with a 3022-stage shift register. 8k out of 64k of configuration RAM was used. It was clocked at 1 MHz for testing. In addition to room-temperature testing, SEL tests were performed at 70° C. Devices were monitored for *data* and *reconfiguration* errors.

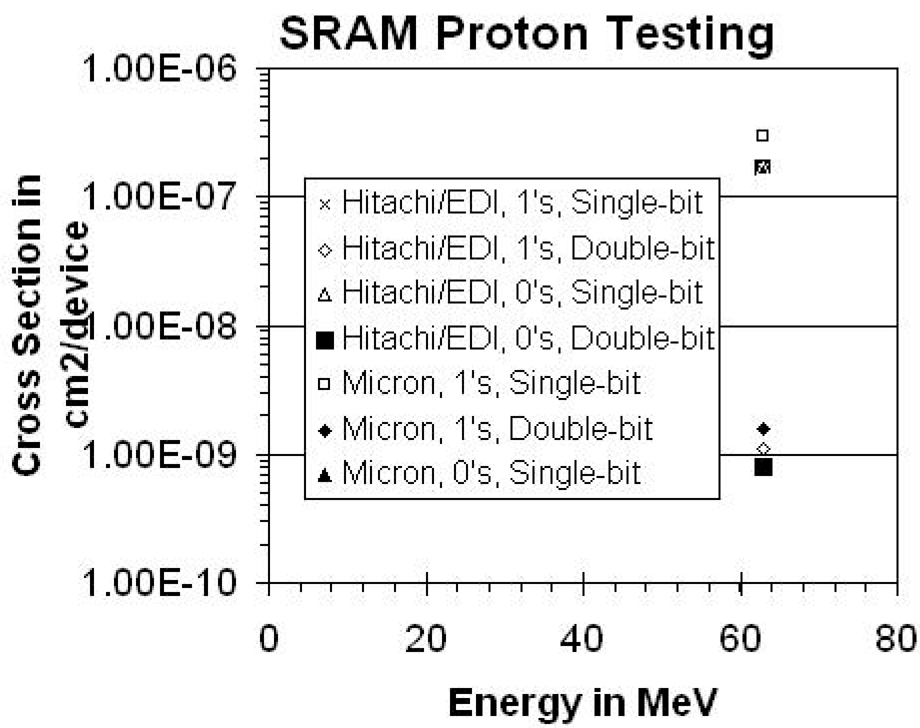

Figure 2

Data **and** ***reconfiguration*** **errors were observed, both with LET_{th} ~ 5. In addition, an anomalous condition was observed, with an LET_{th} of 11: I_{cc} would increase stepwise from the typical operating level of 22 mA, occasionally past the SEL current limit of 80 mA, while the device continued to operate normally. Then, if the devices were reloaded with the proper configuration without removing device power, I_{cc} would return to normal. This condition was most likely either a reconfiguration (with output drivers in conflict) or snapback.**

2. A14100A, A1460A

These FPGAs are part of Actel's ACT3 product line, with 10000 and 6000 gates, respectively. The devices were tested for ***S-module, C-module,*** **and** ***IO-module*** **errors. In addition to the SEU data which follows, several lots of these devices have also been tested for total dose, with the results being foundry- dependent. Technical data, along with complete test procedures and results are available elsewhere [2].**

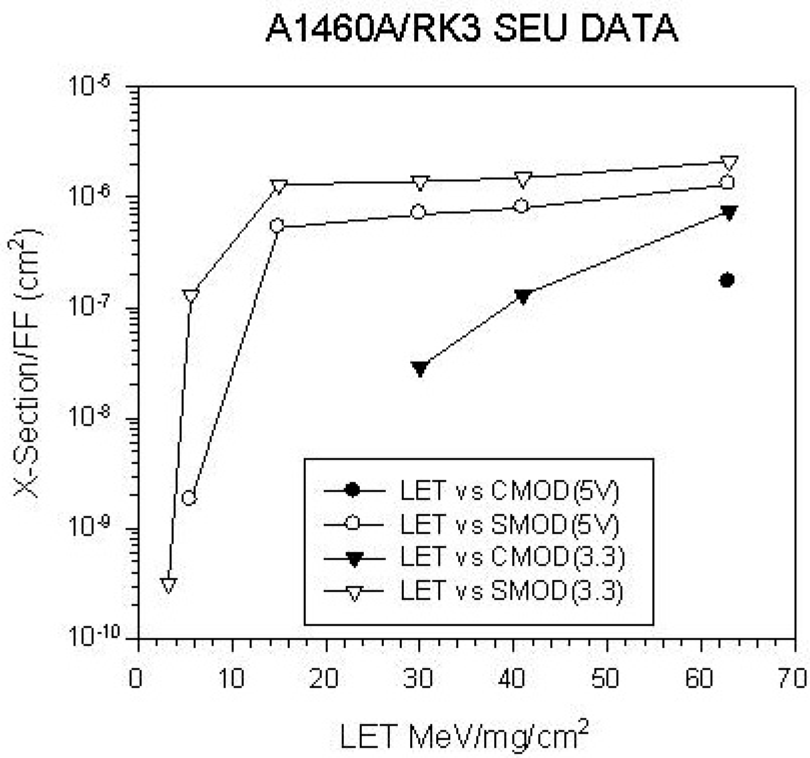

Figure 3

***Proton* _ Both the *S-modules* and *IO-modules* saw errors, with σ ~ 1.29E-13 cm^2/module and 2.82E-14 cm^2/module respectively.**

***Heavy ion* _ All three types of module saw errors. LET_{th} values for *S-* and *IO-modules* were 8 (A14100A), and 6-8 (A1460A), while LET_{th} for *C-modules* was ~ 28 for both devices. Figure 3 shows heavy ion data.**

C. <u>Data Transmission</u>

1. UT63M147-BPC

This device is a monolithic bipolar 1553 transceiver, running at 471 kbps (variable with delay). Errors include bad data, and invalid Manchester encoding or parity. It was tested for heavy ion effects only; threshold for SEUs was ~ 11.4.

2. DR1773

This device is a radiation-hardened dual-rate (1 Mbps, 20 Mbps) transceiver, operating at a 1300 nm wavelength. Proton testing was performed on both the transmitter and receiver components, at both rates, with several levels of optical attenuation: -8 dB, -17 dB, -23 dB, and -25 dB.

The transmitter experienced only a single error during testing, while it was operating at 20 Mbps, for a limiting $\sigma \sim$ 2E-11 cm^2. The receiver experienced errors only while operating at 20 Mbps, with a worst-case (-25 dB) $\sigma \sim$ 1.0E-7. When the device was tested as in a typical application, (-17 dB), sporadic errors were seen on only one test run, with $\sigma <$ 1.4E-10 cm^2. No angle dependence was observed. Complete test procedures and results are available elsewhere [3,4].

3. Fiber Optic Data Links

Proton testing was performed on two fiber optic data links. The 2706T and 2706R fibre channel link uses an InGaAs Laser and diode, along with CMOS ICs, running at a data rate of 125-531 Mbps. The ATTDA204B and ATTDA205B are integrated silicon bipolar devices, mostly ECL, with some TTL components. They provide a 1.0625 Gbps serial data link, with user-selectable 8B10B (8 bit to 10 bit) coding. Complete technical data, along with test procedures and results are available [5].

During testing, a serial bit stream was fed through the receiver back to the transmitter, producing an output bit stream identical to the input. Bit error rate equipment was used to characterize any errors in the link. *Bit* and *burst* errors were observed, along with loss of synchronization (*LOS*) errors requiring either a toggle of a control line (word synchronization enable - WDSYNCEN), or a device reset and full initialization of the link.

a. 2706T, 2706R

Testing on these devices was performed at a data rate of 500 MHz. The transmitter saw no errors, but the receiver saw *bit* errors, with $\sigma \sim$ 5.99E-9.

b. ATTDA204B, ATTDA205B

Table 3 below summarizes σ for the various types of errors observed with the ATTDA204B and ATTDA205B [5]:

7. AM7968, AM7969 TAXI Chipset

The TAXI transmitter/receiver pair was tested using a commercial evaluation board. Testing was performed in local mode, with 8 bits of checkerboard data and 4 command lines, at the maximum rated serial speed of 125 MHz. The devices were monitored for both *data* errors, where incorrect data is sent or received, and *sync* errors, where the transmitter and receiver lose synchronization.

a. AM7968 TAXI Transmitter

***Proton* - Both *sync* (requiring several power resets to recover) and *data* SEUs were seen, with $\sigma \sim$ 6.60E-10 (*sync*) and 5.27E-10 (*data*).**

***Heavy ion* - Both *sync* (requiring several power resets to recover) and *data* SEUs were seen**

at the lowest tested LET of 3.39. Figure 4 displays *sync* data; saturation was not reached, but the maximum measured receiver σ was 4.75E-4 cm^2. Because *sync* errors caused inaccurate *data* counts, *data* errors could not be accurately tallied. Neither device experienced SEL during any test run, up to a maximum tested LET of 53.2.

b. AM7969 TAXI Receiver

Proton **- Both *sync* (requiring several power resets to recover) and *data* SEUs were seen, with σ ~ 3.00E-10 (*sync*) and 2.56E-10 (*data*).**

Table 3 Summary of ATTDA204B, ATTDA205B Test Results

	RX _ 8B10B on	RX _ 8B10B off	TX _ 8B10B on	TX _ 8B10B off
Bit Error	5.1E-7	3.4E-7	7.4E-7	1.2E-6
Burst Error	1.6E-8	1.0E-8	4.3E-9	4.8E-9
LOS w/ WDSYNCEN	1.0E-8	n/a, required reset	n/a	n/a, required reset
LOS w/ Reset	3.9E-9	3.8E-9	4.7E-10	n/a

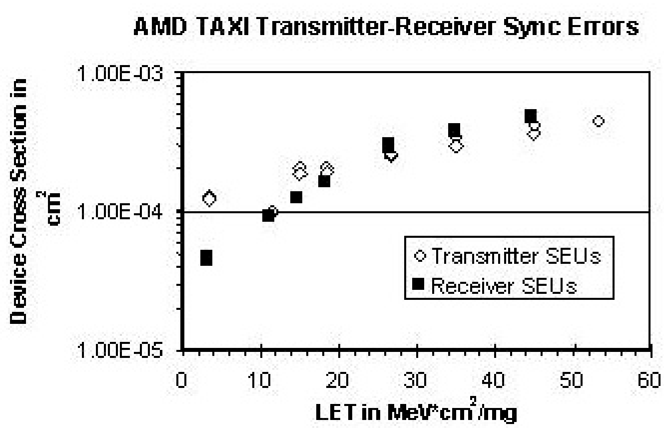

Figure 4

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Heavy ion **- Both *sync* (requiring several power resets to recover) and *data* SEUs were seen at the lowest tested LET of 3.39. Figure 4 displays *sync* data; saturation was not reached, but the maximum measured receiver σ was 4.75E-4 cm^2. Because *sync* errors caused inaccurate *data* counts, *data* errors could not be accurately tallied. Neither device**

experienced SEL during any test run, up to a maximum tested LET of 53.2.

D. <u>Other</u>

1. 5690R-D15

This hybrid DC/DC converter was monitored for *step* (a change in V_{out}) and *reset* (device self-resets) errors. It was redesigned from an earlier version, with an added RC filter for *reset* protection. Only *reset* errors were seen, with LET_{th} between 23-26.6. A destructive condition was also seen at LET 52.6.

2. M67204EV-50

This device is a 4k x 9 RAM cell-based FIFO. During testing, it was pre-loaded with alternating 9 bit patterns of 00H, 11H, AAH, 55H; while being irradiated, the device is read/rewritten on a byte-by-byte basis. *Bit*, *pointer* (the FIFO's internal pointer is no longer at the appropriate location, requiring a reset to recover), and *control* errors (constant errors, often requiring a reset to recover) were monitored.

***Proton* _ Proton testing was performed at two energy levels: at 196 MeV, *bit*, *pointer*, and *control* errors were all seen, with σ ~ 8.58 E-14 cm^2/bit (*bit*), 8.3 E-13 cm^2/bit (*pointer*), 2.0E-12 cm^2/device (*control*, requiring reset), and 1.3 E-12 cm^2/device (*control*, not requiring reset). However, at 63 MeV, only bit errors were seen, with σ ~ 5.57E-14 cm^2/bit.**

***Heavy Ion* - During SEL only tests, latchup was observed on several tests runs at an LET of 64.7, and again on the following test run at an LET of 37.1 (possibly related). No other runs at LET 37.1 exhibited latchup.**

3. CS5012A

This 12-bit Analog-to-Digital Converter (ADC) was tested using an evaluation board from Crystal Semiconductor. The evaluation board provided a bipolar power supply of ±5 V, and the device was clocked at 2 MHz. During testing, the DUT was sent a DC level of ~4 V, for a full-scale/all high output, while monitoring the output.

LET_{th} for SEU was between 3.4-4.8; σ could not be measured, due to the onset of SEL. SEL threshold was ~11.4, with σ ~1.5E-3. Almost all latchups occurred on the -5 V supply, although this may have been caused by circuitry on the evaluation board, rather than by the ADC itself.

4. AD570

This 8-bit analog-to-digital ADC was input with a 100Hz sine wave, varying between 0-7.2 V. Conversions occurred at a frequency of 5 kHz. A difference in output from a reference device greater than 80 mV was counted as an SEU. LET_{th} for SEU was 7, with σ ~ 3E-4. SEL was not observed, up to a maximum tested LET of 52.5.

5. DAC8800

The DAC8800 is an octal, 8-bit Digital-to-Analog Converter (DAC). During testing, the DUT was sent serial data selecting the output channel and voltage level, typically channel 1@0 V or channel 8@5 V. The analog output was monitored by an oscilloscope, which was set to trigger on glitches. The device was tested with a unipolar power supply at 12V, and reference voltage of 5V. Clock speed was 2 MHz. No effects of any kind were seen, up to a maximum tested LET of 80.

6. AD630

This demodulator was tested with a signal input at 9 kHZ, 20 V_{p-p}, and a carrier input at 250 kHZ, 5 V_{p-p}. DUT output was compared to a reference output, with mismatches of greater than 1V counted as SEUs according to duration: *short* (< 20 μ s), *medium* (20-100 μ s), or *long* (> 100 μ s). Heavy ion testing was begun at the A&M, and completed at BNL, with some discontinuities in the results. LET_{th} for *short* SEUs was ~ 3.38, at both BNL and A&M. However, LET_{th} for *medium* SEUs was ~ 17 at BNL, and 7.4 at A&M. *Long* SEUs were seen only at A&M, also starting at LET 7.4. No SEL was observed, up to a maximum tested LET of 65.

7. AD652

This voltage-to-frequency converter was tested with an input voltage of 10 V, and a conversion rate of 250 kHz. During testing, 14 output bits are continuously captured and compared to a reference output. Mismatches are counted as SEUs according to the number of the 14 output bits in error (*single-*, *double-*, or *multiple-bit*). LET_{th} for all SEUs was ~ 7.4, with σ ~ 3E-3 for *single-bit* SEUs, 6E-5 for *double-bit* SEUs, and 1E-4 for *multiple-bit* SEUs. No SEL was observed, up to a maximum tested LET of 64.7.

8. LM136

This zener diode was tested with a 5 V input and 2.5 V output. DUT output was compared with a reference output, with a difference greater than 0.35 V counted as an SEU according to duration: *short* (< 1μ s), *medium* (1-10 μ s), or *long* (> 10 μ s). LET_{th} for *short* SEUs was ~ 3.38, with σ ~ 1.5E-3; Figure 5 shows σ vs. LET. No *medium* SEUs, *long* SEUs, or SEL were observed, up to a maximum tested LET of 52.5.

9. TI7770-5

This power supervisor was tested by providing an input which constantly switched between 4 V and 5 V. The reset line went low when the input voltage reached 4V, and returned to high ~ 500 ns after the input voltage was switched to 5V, with an SEU counted if the reset line was still low after 600 ns. LET_{th} for SEU was between 7.5-11.6, with a maximum observed σ ~ 1E-4; Figure 5 shows σ vs. LET for both power converters tested. Although device current rose as each test run progressed, SEL was not observed, up to a maximum

tested LET of 65.

10. TI7705

This power supervisor was tested by providing an input which constantly switched between 4 V and 5 V. The reset line went low when the input voltage reached 4 V, and returned to high ~ 300 ns after the input voltage was switched to 5 V, with an SEU counted if the reset line was still low after 600 ns. LET_{th} for SEU was between 3.38-4.5, with a maximum observed σ ~ 8E-5; Figure 5 shows σ vs. LET for both power converters tested. Although device current rose as each test run progressed, SEL was not observed, up to a maximum tested LET of 30. A hard error, possibly total dose-related, was observed at LET 20, with the device's reset line stuck low.

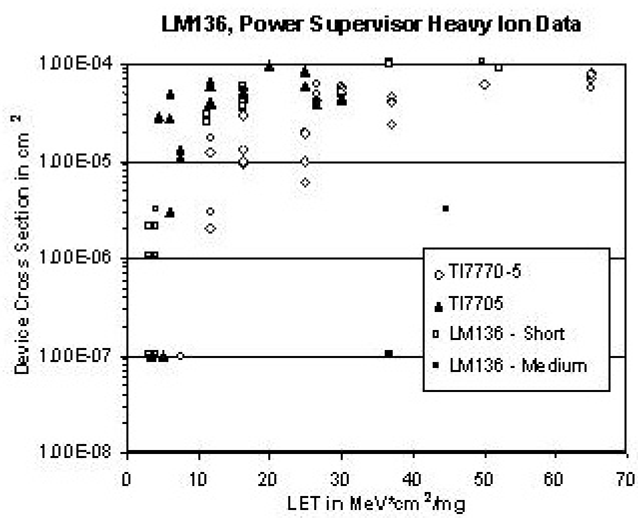

Figure 5

Recommendations

Following heavy ion and proton testing , devices generally are categorized into one of four categories for recommendation to the flight project of interest, as seen in Table 4:

Category 1 **- relatively hard or immune to SEEs and recommended for spaceflight**

Category 2 **- somewhat susceptible to SEEs; may need some error detection and correction (EDAC) when used in an application**

Category 3 **- fairly soft, and very susceptible to SEEs; use with great caution, if at all. Intensive EDAC schemes may be necessary as these devices have potentially high error rates.**

Category 4 **- not recommended for spaceflight. Destructive conditions, such as latchup, total**

dose failure or burnout, were seen in these devices at low LETs.

Table 4 Summary of Test Results

Category 1	Category 2	Category 3	Category 4
	Random Access Memory (RAM)		
	0116400J1D, KM48V8100AS-16, UPD4216400-60, TMS416400DJ-60, MT5C1008CW-25	88130L45PC	
	Field Programmable Gate Arrays (FPGAs)		
	A14100A (Category 2/3), A1460A (Category 2/3)	CLAy-31	
	Data Transmission		
DR1773	UT63M147-BPC, 2706T (more testing), 2706R (more testing)	ATTDA204B, ATTDA205B, AM7968, AM7969	
	Other		
DAC8800	AD570, AD630, AD652, LM136	5690R-D15, M67204EV-50, CS5012A,TI7770-5, TI7705	

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References

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