RECENT RADIATION DAMAGE AND SINGLE EVENT EFFECT RESULTS FOR MICROELECTRONICS

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Abstract

We present heavy ion and proton single event effect (SEE) as well as radiation damage ground test results for candidate spacecraft electronics. Microelectronics tested include digital, analog, and hybrid devices.

I. Introduction

As spacecraft designers utilize increasing number of commercial and emerging technology devices in order to meet stringent spacecraft requirements such as volume, weight, power, cost and schedule, SEE and proton damage ground testing provide important inputs for many spacecraft programs.

The objectives of this study were to determine heavy ion SEE sensitivities including the Linear Energy Transfer (LET) threshold (the minimum LET value to cause an effect at a fluence of $1x10^7$ particles/cm^2) and saturation cross sections, of candidate spacecraft electronics for Single Event Upset (SEU) and Single Event Latchup (SEL), proton SEE sensitivities, and proton damage sensitivities (ionizing and non-ionizing).

II. Test Techniques and Setup

A. Test Facilities

All tests were performed between February 1998 and February 1999. Table 1 shows the test facilities utilized for this period. Heavy ion experiments were conducted at the Brookhaven National Laboratories (BNL) Single Event Upset Test Facility (SEUTF), Michigan Statue University (MSU) National Superconducting Cyclotron Laboratory (NSCL), and Tandem Accelerator Super-conducting Cyclotron (TASCC).
The SEUTF uses a tandem Tandem Van De Graaff accelerator, suitable for providing various ions with energies up to 6 MeV/amu for testing. 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 $1x10^5$-$1x10^7$ particles/cm^2, and fluxes from $1x10^2$ to $1x10^5$ particles/cm^2/s, 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.

Heavy ion measurements were performed in air at the TASCC facility at the Chalk River Laboratories of AECL Research, Canada. Table 1 shows the characteristics of each particle. The maximum flux used was $1x10^4 \pm 1x10^3$ p/cm^2/s.

The NSCL's cyclotron provides various ions with energies up to 60 MeV/amu. Test boards containing the DUT are mounted in air in front of an exit window. Testing was performed with LET values ranging from 0.8-40 MeV•cm^2/mg, fluences from $1x10^5$ to $1x10^7$ particles/cm^2, and fluxes from $1x10^2$ to $1x10^5$ particles/cm^2/s, depending on device sensitivity and beam delivery. Ions used are listed in Table 1. Intermediate LETs were obtained by placing beam degrades between the DUT and the exit window.

Table 1: Test Heavy Ions

Facility	Ion	Energy, MeV	LET, MeV•cm^2/mg	Range in Si microns
BNL	Cl-35	210	11.4	63.5
	Ti- 48	227	18.8	47.5
	Ni-58	278	26.2	41.9
	Br-79	286	37.2	39
	I-127	320	59.7	34
	Au-197	350	82.3	27.9
NSCL	Xe-129	7740	23.43	928
	Kr-84	5040	10.97	1205
	Ar-36	2160	2.83	1889
	Ne-20	1200	0.87	3319
	C-12	720	0.31	5534
	He-4	240	0.035	16598
TASCC	Br-79	540	33	67.4
	F-19	130	3.5	108

Table 2: Test Facilities and Particles

Facility	Particle
University of California at Davis (UCD)	Proton
TRI-University Meson Facility (TRIUMF)	Proton
Indiana University Cyclotron Facility (IUCF)	Proton
Brookhaven National Laboratories (BNL)	Heavy Ion
Michigan State University National Superconducting Cyclotron Laboratory (MSU/NSCL)	Heavy Ion
Tandem Accelerator Superconducting Cyclotron (TASCC)	Heavy Ion

Proton SEE and damage tests were performed at three facilities, the University of California at Davis (UCD), TRI-University Meson Facility (TRIUMF), and the Indiana University Cyclotron Facility (IUCF). Proton test energies ranged from 26.6 to 63 MeV at UCD, 50 to 500 MeV at TRIUMF, and 54 to 197 MeV at IUCF. Typically, fluence was $1x10^{10}$ to $1x10^{11}$ particles/cm^2, and flux was $1x10^8$ particles/cm^2/s.

B. Test Method

Three SEE test modes were typically used, depending on the device under test (DUT) and the test objectives:

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 or Program-Only, depending on their function. Clock speeds may also affect SEE results.

Static - load device prior to beam irradiation, then retrieve data post-run, counting errors.

Biased (SEL only) - DUT is biased and clocked while ICC (power consumption) is monitored for latch-up or other destructive conditions.

SEE DUTs were monitored for soft errors such as SEUs and hard errors such as SELs. Detailed descriptions of the types of errors observed will be noted in individual test results. Proton damage tests were preformed on biased devices with functionality and parametrics being measured either continuously during irradiation or after step irradiations (e.g., measurements every 10 krad(Si)).

Heavy ion SEE testing was performed with LET values ranging from 1.1-120 MeV•cm^2/mg.

All tests were performed at room temperature and nominal power supply voltages, unless otherwise noted.

III. Test Results and Discussion

Table 3 summarizes the devices tested and the test results, using the following conventions:

H = heavy ion test
P = proton test (SEE)
N = neutron test
SEU = SEU LET_{th} (MeV•cm^2/mg)
SEL = SEL LET_{th} (MeV•cm^2/mg)
SET = Single Event Transient
Destructive = Any destructive SEE LET_{th}
< = SEE observed at lowest tested LET
> = No SEE observed at highest tested LET
PD = Proton Damage (actually a mix of damage and ionizing dose)
TID = Total Ionizing Dose
σ = cross-section (cm^2/device, unless specified as cm^2/bit)
LDC = Lot Date Code
APL = Johns Hopkins Applied Physics Laboratory

All LET_{th}s discussed are in units of MeV•cm^2/mg; all σ_{sat}s discussed are in units of cm^2/device, unless otherwise noted.

Descriptions of test procedures for individual devices and results are summarized in Table 3. This paper is a summary of results, complete test reports are available online at:
http://flick.gsfc.nasa.gov/radhome.htm [1]

Table 3: Summary of Test Results

DEVICE #	FUNCTION	MANUF.	RESULTS	NOTES
Memories				
Not Available	4Mbit SRAM	SEI	H: SEU: LET_{th} <3	Low cross-section
AS5C4008DJ	4Mbit SRAM	Austin Semi w/ Samsung Die	H: SEU: LET_{th} <3	Low cross-section
WS512K8-XCX	4Mbit SRAM	White	H: SEU: LET_{th} <3	MBUs observed
Not Available	4Mbit SRAM	Electronic Designs Inc.	H: SEU: LET_{th} <3	Low cross-section
AM29LV800	Flash Memory	AMD	H: SEL: LETth > 37 SET: LET th <5, σ_{sat} ~$2x10^{-6}$	SETs are high current transients, possibly upset producing events

DEVICE #	FUNCTION	MANUF.	RESULTS	NOTES
Memories (Cont.)				
HM65656	SRAM	Matra	H: SEU: LET_{th} <3	No energy dependence
ISC DRAM Stack	DRAM	Irvine Sensor Corp/IBM	P; See Text (Section D)	
AT17C256	EEPROM	Atmel	H: SEL	
LMRH4Kx9 FIFO	4Kx9 FIFO	Lockheed-Martin	H: SEU: LET_{th} ~25-30	
Programmable Devices				
A1280A	FPGA	Actel	P: $\sigma \sim 1.3E^{-14}$ cm^2	S module
A1020	FPGA	Actel	H: SEU: LET_{th} >18	No energy dependence
DL5256	FPGA	Dynachip	H: SEU: LET_{th} <<37	
Processors				
RH21020	DSP	Lockheed-Martin	H: SEU: LET_{th} ~3	
Optocouplers				
3C91	Optocoupler	Mitel	PD: CTR degradation	
OLH5601	Optocoupler	Isolink	H: SET	
OLH249	Optocoupler	Isolink	H: SET	
4N48	Optocoupler	Optek	PD: CTR degradation	
4N49	Optocoupler	TI	PD: CTR degradation	
66088	Optocoupler	Micropac	PD: CTR degradation	
6651	Optocoupler	HP	H: SET	
66123	Optocoupler	Micropac	H: SET	
Converters				
M3G2805D	DC-DC Converter	Magnitude-3	H: SEL/SET LETth >82	
MHF2805S	DC-DC Converter	Interpoint	PD: functional failure	
MHF2815S	DC-DC Converter	Interpoint	PD: functional failure	
MHF2815d	DC-DC Converter	Interpoint	PD: functional failure	
MTR2805SF	DC-DC Converter	Interpoint	H: SEL: LET_{th} ~ 37.4 σ_{sat} ~1-2 x 10^{-7} cm^2 SET: LET_{th} > 82	
MTR2815SF	DC-DC Converter	Interpoint	H: SE destructive noted at worst-case condition @37.4 < LET <59.8	
ADC/DAC				
AD1672	ADC	Analog Devices	H: SEU LET_{th} <3	
MAX494	Op-Amp	MAXIM	H: SEL LET_{th} >59	
SPT7760	Analog to Digital Converter	Signal Processing Technology	P: See text (Section N)	Frequency and input sensitive
Analog				
AD780	Voltage Reference	Analog Devices	PD: 3 x 10^{11} p/cm^2	Majority of DUTs out of spec
CLC502	Op-Amp	COMLINEAR	H: SEL LET_{th} >59	
LT1021CCN8-5	Voltage Reference	Linear Technology	PD: 3 x 10^{11} p/cm^2	All of DUTs out of spec
LT1021CCN8-10	Voltage Reference	Linear Technology	PD: 3 x 10^{11} p/cm^2	All of DUTs out of spec
LT1153	Digital Circuit Breaker	Linear Technology	H: SEL LETth > 37	Heavy ion testing indicated a possible TID problem.

DEVICE #	FUNCTION	MANUF.	RESULTS	NOTES
Board Tests				
ZT-6500	CPCI Pentium Processor	Ziatech	P: SEU, SEL observed	
CPCI-100	Dual IP 3U Carrier	Greenspring	P: No events	
IP 1553	MIL-STD-1553 Interface	Greenspring	P: SEL	
Unknown	3U IP Carrier	Alphi	P: No events	
Unknown	3U IP Carrier	Alphi	P: No events	
CPCI-200	6U IP Carrier	Greenspring	P: No events	
CPCI-3603	CPCI PowerPC Processor	Force	P: SEU	
Unknown	IP Optocoupler Driver	Greenspring	P: SEU, displacement damage on optocoupler	
Unknown	HV-Unidig Driver	Greenspring	P: SEU	
Unknown	IP Serial Driver	Greenspring	P: SEU	
SCC-04	IP Serial Driver	Actis	P: SEU	
Unknown	GPS Correlator/Front-end	Plessey	P: SEU	
CMA-401A	STRONGARM Processor	Cogent Computers Inc	P: SEU	
Miscellaneous				
Honeywell ESN	ESN	Honeywell	H: op amp sensitivity	See text (Section T)
AD536	RMS-DC Converter	Analog Devices	H: SEL: $LET_{eff}th$ > 75 SET: LET th <1.4, σ_{sat} ~$5x10^{-3}$	
AMP01	Amplifier	Analog Devices	H: Destructive event noted	See text (Section V)
NYTEK 8002	Delay Line	NYTEK	H: SEL LET_{th} >59	
DAC8222	12-bit DAC	Analog Devices	H: SEL: $LET_{eff}th$ > 85 SET: LET_{th} ~40 hi inputs LET_{th} ~10 lo inputs σ_{sat} ~$1x10^{-3}$	
HI-509	Analog Mux/demux	Harris	H: SEL/SET: LET_{th} > 60	

A. <u>Commercial 4Mbit SRAM</u>

Four vendors of commercial 4 Mbit SRAMs were evaluated for SEE heavy ion characteristics. These four vendors are companies that repackage other die manufacturers' products for military and aerospace applications.

Testing was performed in a dynamic mode (1 Mhz operating rate) of read-modify-write using a logical checkerboard pattern. SEL was determined by a trip of device current limiting protection set at maximum operating current for the device. No single event functional interrupts (SEFIs) were noted.

Figure 1 compares the SEU response of two of the device types tested. It is clear that the die utilized by these two vendors are from different manufacturers. This figure shows the results for total bit errors observed. Figure 2 illustrates the multiple bit upset (MBU) results for this device. MBU counts are important input for determining the effectiveness of error detection and correction (EDAC) schemes in reliable system designs.

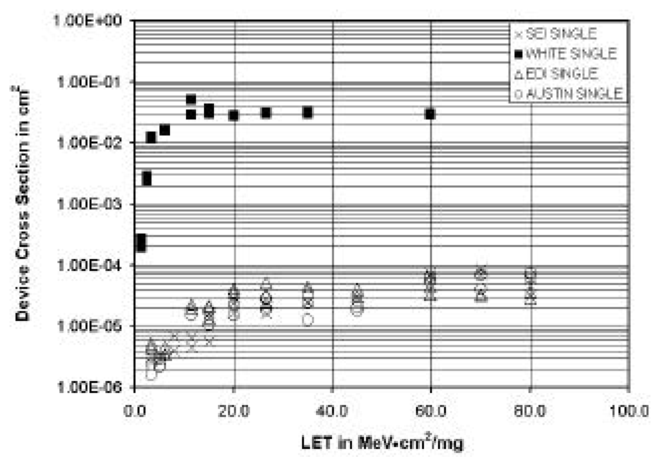

Figure 1: Commercial 4 Mbit SRAM Heavy Ion SEU comparison.

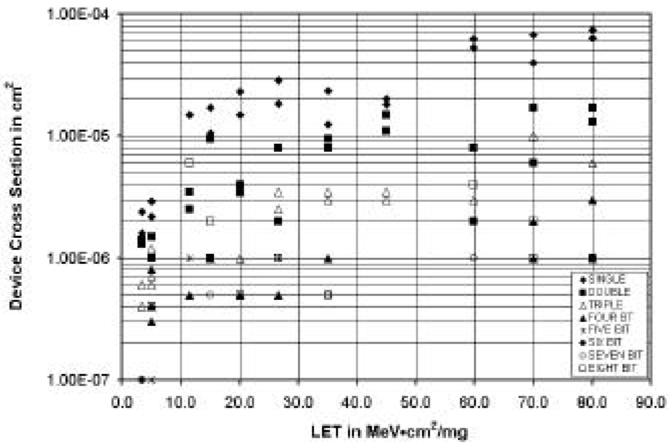

Figure 2: Commercial 4 Mbit SRAM Heavy Ion SEU and multiple bit upset comparison.

B. <u>AM29LV800</u>

The AM29LV800 Flash Memory devices were monitored for latchup induced high power supply currents. They were exposed to heavy ion beams at the MSU SEE Test Facility. Testing began with an LET of 11 MeV•cm^2/mg obtained with 2.4 GeV Kr-40. Following this, the cyclotron was tuned to 1.2 GeV Ne-20 and a 0.114 inch energy degrading foil was inserted resulting in a LET at the DUT of 5.0 MeV•cm^2/mg. Then Xe-129 beam at 7.74 GeV provided an incident LET of 27 MeV•cm^2/mg, and a 0.020 inch Al foil was used to increase the LET at the DUT to 37 MeV•cm^2/mg. At least two samples from the same lot and date code were tested under each set of conditions. The input voltage condition of 3.6 V was evaluated at four different values of LET.

No evidence of destructive latch-up was seen at an LET of 37 MeV•cm^2/mg and fluence of 10^7 ions/cm^2. Only one event was measured that required a power reset to clear. Single Event Transient high current conditions were measured which presumably correspond to loss of at least partial function during the event, but this was not verified by functional test. An approximate threshold LET for current transients of greater than 1 mA is less than 5 mA and an approximate cross section is 2 x 10^{-6} cm^2. Higher LET measurements do appear to correlate with longer recovery times, and some events lasted over 2 seconds at the highest LET of 37 MeV•cm^2/mg.

It would be reasonable to assume that the memory's contents were altered during the transient events. The manufacturer's data sheet points out that "The device electrically erases all bits within a sector simultaneously via Fowler-Nordheim tunneling. The data is reprogrammed using hot electron injection." We suggest the possibility that a single particle event could induce either of these processes.

C. <u>HM65656</u>

Heavy ion SEU testing was performed at NSCL, BNL and TAAS [2] to determine the energy dependence of SEU cross section. Figure 3 gives the results. We did not observe a strong energy dependence.

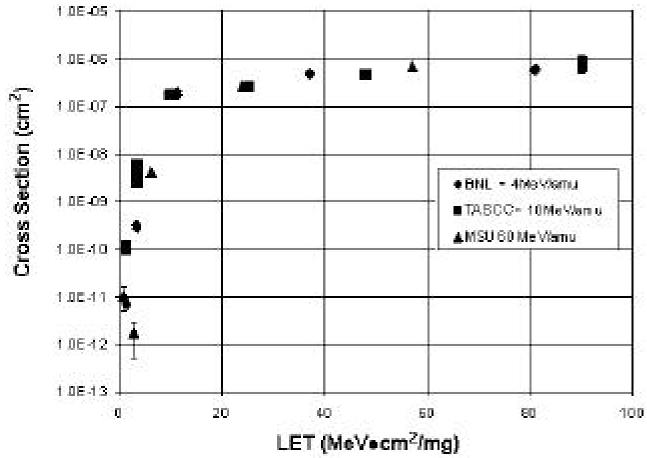

Figure 3: Matra HM65656 SEU testing results.

D. <u>ISC DRAM Stack, A1280A, and RH1020</u>

Proton irradiations for SEE were performed on Irvine Sensors Corporation (ISC) Stacked 320 Mbit DRAM Modules (die used: IBM Luna-ES Rev C – DD3 process), Actel A1280A Field Programmable Gate Array (FPGA) (die used: Matsushita Electronics (MEC) 1.0 um feature size), and Actel RH1020 (die used: Lockheed- Martin Federal Systems' TID-hardened CMOS). SEUs were observed with either high fluence levels (RH1020) or requiring multiple samples due to TID device limitations (A1280 and ISC Stack). Test method, data, and implications from these experiments are more fully described in reference [3]. Table 4 summarizes the results. Note that statistics are limited due to the low number of observed events for the RH1020.

Table 4: Summary of Test Results.

Device	**Cross-section in cm^2**	**Note**
ISC Stack	5.06E^{-13} cm^2 per IBM die	Failed column
	6.33E^{-13} cm^2 per IBM die	Weak column
	7.25E^{-13} cm^2 per IBM die	Temporary row error
	8.84E^{-13} cm^2 per IBM die	Temporary column error
	5.57E^{-17} cm^2 per bit	Single bit errors
	1.5E^{-20} cm^2 per nibble	Logical multiple bit upsets (MBUs)
	sporadic	Stuck bits (2 events observed in 100 die tested)
A1280A	1.36E^{-14} cm^2 per S-module	4.5V supply used
	1.25E^{-14} cm^2 per S-module	5.0V supply used
RH1020	~1.8E^{-18} cm^2 per C-module	4.5V and 5.0V supplies used

E. RH21020

The RH21020 is being developed by Lockheed Martin Federal Systems (LMFS) under sponsorship by Air Force Research Laboratory (AFRL) in an effort to build a total ionizing dose (TID) hardened commercially-compatible CMOS. The RH21020 is a Digital Signal Processor (DSP). This device is fully-compatible with the commercial ADSP21020 manufactured by Analog Devices. In support of this effort, GSFC provided heavy ion single event measurements.

Testing was performed using a custom test card and software that utilized dual RH21020 processors (reference and DUT) with a shared memory space between the two. The DUT was operated at 15 Mhz (50% derated) with a power supply voltage between 4.5 and 5.5V. Both static and dynamic tests were performed. The custom software suite include detailed testing of registers, memory input/ouput (I/O), functional applications (multiply, divide, etc.), interrupt tests, et al.

Table 5 notes the lowest LET values at which upsets were observed for the different areas monitored. Two types of SEUs were noted: those that caused errors such as data errors, and those that required a reset signal to recover. Figures 4 and 5 illustrate the results for these respective conditions.

Table 5: RH21020 Area Results

Type of Error	Lowest LET at which errors were observed
Data Address enerator (DAG) Registers	3.4
General Purpose Registers	3.4
Multiplier Registers	3.4
System Registers	11.4
Interrupt Registers	3.4
I/O errors	7.88

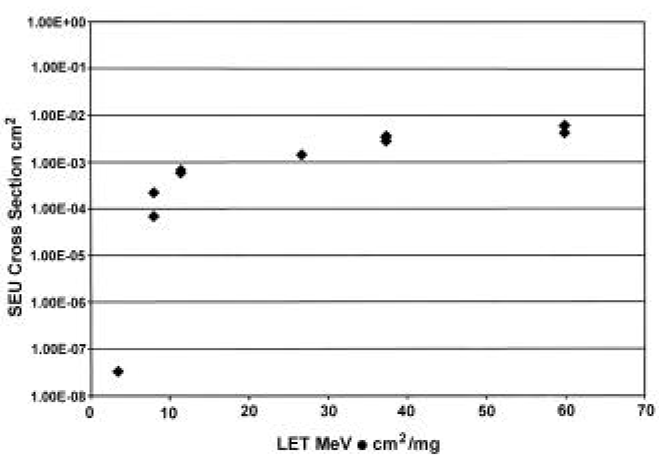

Figure 4: RH21020 error results.

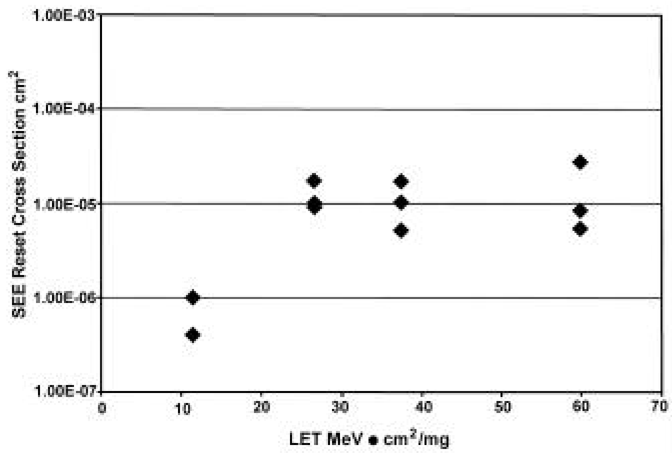

Figure 5: RH21020 reset results.

It should be noted that these results are consistent with results obtained and published in reference [4] for the ADSP21020 commercial device. Further proton SEE tests are planned due to the low LET_{th}s obtained.

F. AT17C256

Latch-up testing of the AT17C256-10SI was performed at the Michigan State University National Superconducting Cyclotron Facility using Kr-40 and Xe-129 ions at 60 MeV/amu. With degrading foils, the LET range varied from 11 MeV•cm^2/mg to 37 MeV•cm^2/mg. All tests were performed at a supply voltage level of 5.5 V. The latch-up protection circuit was set to trip at a level of 100 mA. During exposure, significant current fluctuations (both increases and decreases) were noted, but the 100 mA trip level was not seen. In some cases, the nominal current of about 7 mA was doubled and required power cycling to restore it to the 7 mA level. Figure 6 shows typical results for 24 MeV•cm^2/mg Xe-129 ions. The plot shows the current progression during a 41 second exposure to a fluence of 3.9 x 10^6 ions/cm^2. At higher LET values the switching between states occurred more frequently, and at the LET of 11 MeV•cm^2/mg the abrupt changes were rarely noted. No functional tests were performed.

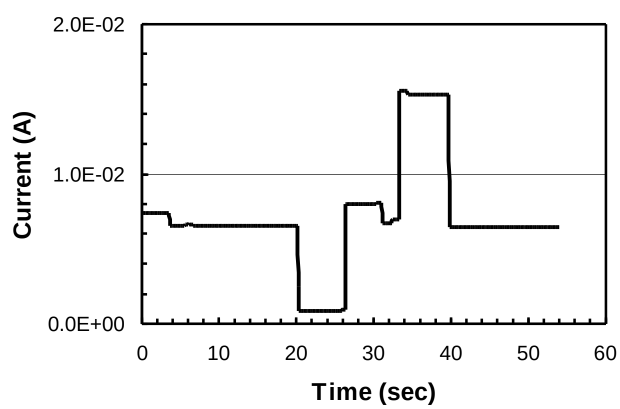

Figure 6: AT17C256 SEL data, Run 38, LET=24 MeV•cm^2/mg.

G. <u>LMRH4Kx9 FIFO</u>

This device was tested in a dynamic mode looking for bit (data) errors as well as control (pointer, JTAG) errors. Both types of errors were observed with an LET_{th} ~25-30. This was a preliminary test with further results to follow. [5]

H. <u>Actel A1020</u>

Heavy ion SEL testing was performed at BNL and MSU to compare the energy dependence on the SEL threshold. We did not observe a strong energy dependence for SEL. This data will be published in the 1999 NSREC proceedings [6].

I. <u>DL5256</u>

Two DynaChip DL5256 SRAM configured FPGAs were subject to a heavy ion SEL test at Brookhaven National Laboratory. These devices are produced on an IBM BiCMOS process and were packaged in a PG 208 in a cavity down configuration. The lot date code for both devices is 9749. No lookup tables (LUTs) are present in this architecture. Each module in the device consumes ~ 50-60 mW when used in a configuration and is controlled by the confiugration program loaded from an external memory.

Each device was subject to irradiation with Bromine at normal incidence, LET = 37 MeV•cm^2/mg and the supplies were set to nominal voltages. Prior to each irradiation, the configuration was loaded from an external serial PROM. Sample number 001 was irradiated twice and sample number 002 was irradiated once. Immediately after the beginning of each test, the device currents rapidly increased, tripping the limits on the power supply, set at 800 mA, corresponding to delta currents of over 300 mA per supply.

J. <u>Optocouplers</u>

Optocoupler performance in a radiation environment is degraded in two ways, SETs can occur on the output and/or the current transfer ratio (CTR) can degrade [7,8,9]. CTR is the ratio of the input drive current to the output current. Optocoupler response to radiation will depend on the type of LED, phototransistor, and coupling medium. The response also depends on how the optocoupler is being used in the circuit. The results given below are not general results. We recommend application specific testing.

1. Mitel 3C91

Proton-induced CTR degradation measurements for the Mitel 3C91C were performed at the Crocker Nuclear Laboratory. Measurements were made at room temperature. The Mitel 3C91C contains an amphoterical doped LED. Figure 7 shows insitu measurements made when irradiated with 63 and 31 MeV protons. The meausured CTR is normilized to the starting CTR for each DUT.

The drive current was 5 mA. V_{ce} was 5V. Notice that 31 MeV protons induce more degradation than 62 MeV protons at an equivalent fluence. Significant part to part variability was observed. Annealing measurements were not made.

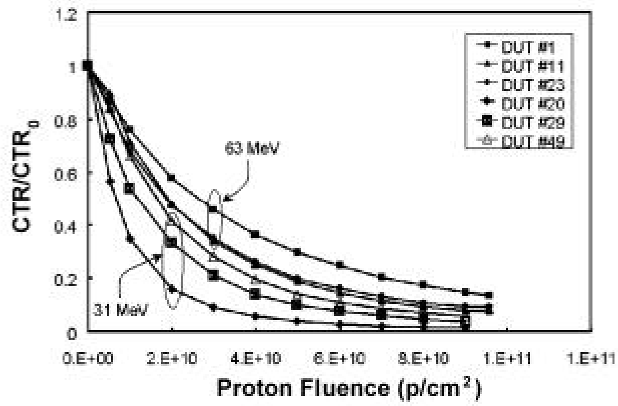

Figure 7: Proton Exposures of the Mitel 3C91C Optocoupler.

2. Isolink OLH5601 and OLH249

Heavy ion SET testing was performed at NSCL. We observed SETs on two Isolink optocouplers at an LET of 37 MeV•cm^2/mg for both devices. Cross sections were not computed. The test setup is given in [9].

3. Optek 4N48

Proton-induced CTR degradation measurements for the Optek 4N48 were performed at the Crocker Nuclear Laboratory. Measurements were made at room temperature. The measurements were application. The Optek 4N48 contains an amphoterically doped LED. Figure 8 gives insitu measurements of CTR made when irradiated with 63 MeV protons. The drive current was varied between 1.4 and 20.8 mA with initial CTR peaking between 1.4 and 3 mA. For this application, the collector current is saturated for drive currents greater than 2.5 mA. Operating a device in this mode leads to a more radiation tolerant application.

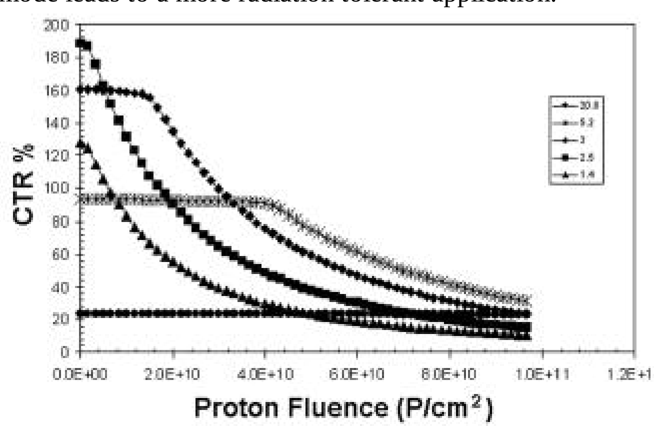

Figure 8: Application specific proton-induced CTR degradation measurements on the Optek 4N48 optocoupler

4. Texas Instruments 4N49

Proton-induced CTR degradation measurements for the TI 4N49 were performed at the Crocker Nuclear Laboratory. Measurements were made at room temperature. Figure 9 gives insitu measurements of CTR made when irradiated with 63 MeV protons. The drive current was varied between 1.2 and 11 mA. V_{ce} was fixed at 6V.

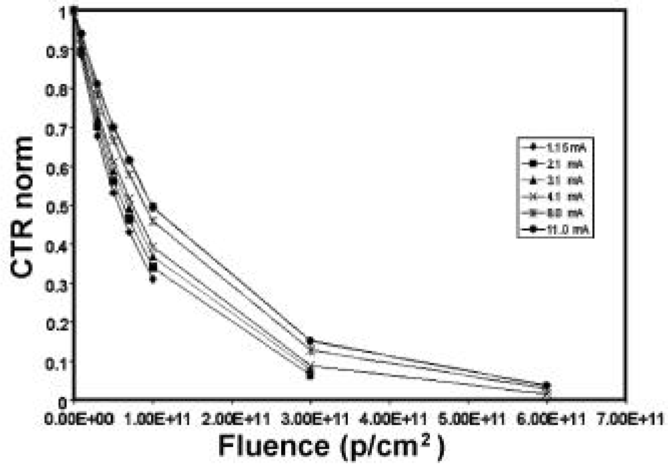

Figure 9: Proton-induced CTR degradation measurements on the Texas Insturments 4N49 optocoupler.

5. Micropac 66088

Proton-induced CTR degradation measurements for the Micropac 66088 were performed at the Crocker Nuclear Laboratory. Measurements were made at room temperature. These measurements were application specific. Figure 10 gives insitu measurements of CTR made when irradiated with 63 MeV protons. The drive current was varied between 4.1 and 19.7 mA.

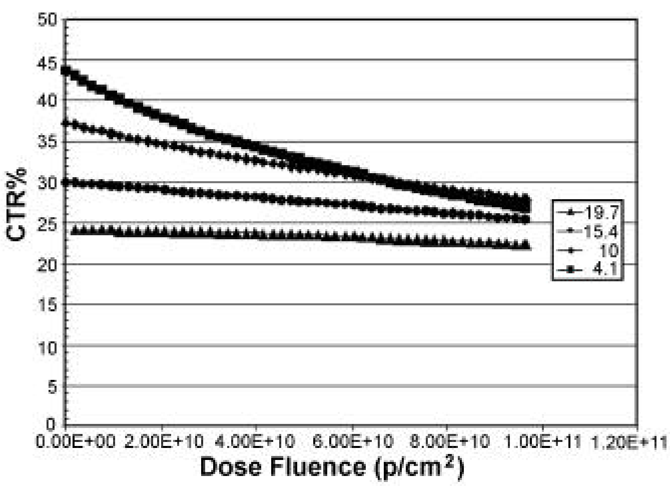

Figure 10: Application specific proton-induced CTR degradation measurements on the Micropac 66088 optocoupler.

6. HP HCPL6651

Proton SET testing was performed at TRIUMF and CNL. SETs were observed at various angle and energies. More details can be found in [9].

7. Micropac 66123

Proton SET testing was performed at TRIUMF. SETs were observed at various angles and energies. Figure 11 gives the results. The test setup is given in [9].

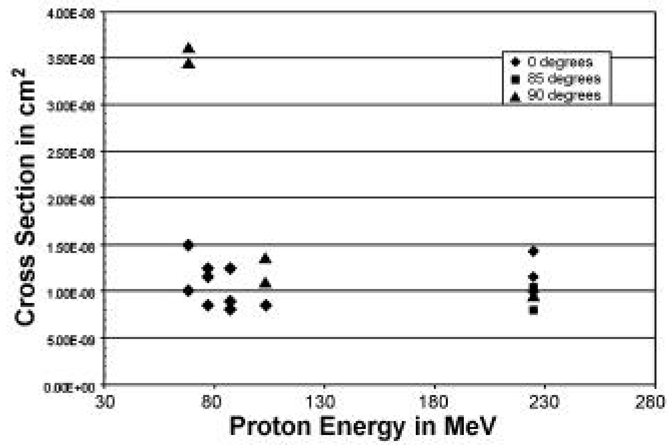

Figure 11: SET measurements over proton energy and angle of incidence on the output of the Micropac 66123.

K. Converters

1. M3G2805D Magnitude-3 DC/DC Converter

The M3G2805D DC/DC converters were monitored for transient interruptions in the output signal and for latchup induced high power supply currents. These devices were exposed to a Br and Au heavy ion beams (normal incident LETs of 37.4 and 82.3 MeV•cm^2/mg respectively) at the BNL SEE Test Facility. The converters were tested under bias conditions of 35 and 21 volts for both low (0.5 Amps) and high (3.0 Amps) load conditions. For all of these conditions, no single event induced transients or latchups were observed. The M3G2805D DC/DC Converter is considered to have an LET threshold for latchup and single event transients greater than 82 MeV•cm^2/mg.

2. Interpoint MHF2805S, MHF2815S and MHF2815D

Proton-induced degradation measurements of output on Interpoint's MHF2805S, MHF2815S and MHF2815D were performed at the Crocker Nuclear Laboratory using 63 MeV protons. Measurements were made at room temperature and at 15°C. The room temperature data was constant with the data presented in the 1998 Radiation Effects Data Workshop [10]. A coolant was used to decrease the temperature of the device. It was observed that the device could be brought back into specification during cooling.

3. MTR2805SF/MTR2815SF

The MTR2805SF/MTR2815SF Interpoint DC/DC converters were monitored for transient interruptions in the output signal and for latchup induced high power supply currents. They were exposed to a Ti, Ni, Br, and I heavy ion beams (normal incident LETs of 18.7, 26.6, 37.4, and 59.8 MeV•cm^2/mg, respectively) at the BNL SEE Test Facility [11]. The converters were tested under bias conditions of 21, 28 and 35 volts for both low (0.29 or 0.5 Amps) and high (1.5 Amps) load conditions.

For all of these conditions, no single event induced transients were observed at the output voltage port. The devices did experience a destructive event that resulted in high current conditions and loss of functionality. This destructive condition only occurred for the highest LET ion used (343.1 MeV I) biased with the worst case voltage (35 Volts) and at low load conditions. Since the failure did not occur with the 283.3 MeV Br beam, the approximate LET threshold for the condition is between 37.4 and 59.8 MeV•cm^2/mg. Based on approximate measurements on only two devices, the failure cross section at LET of 59.8 is estimated to be 1-2 x 10^{-7} cm^2. It is not possible at this time to determine the type of destructive failure. Single event gate rupture or latchup are the likely mechanisms.

L. Analog Devices AD1672 Analog to Digital Converter

Heavy ion-induced SEU testing at Brookhaven National Laboratory on the AD1672 resulted in the data shown in Figure 12. The devices were tested at room temperature. The input was swept from –2.5V to +2.5V. Vcc was 5V. The output was compared to output from a non-irradiated reference device.

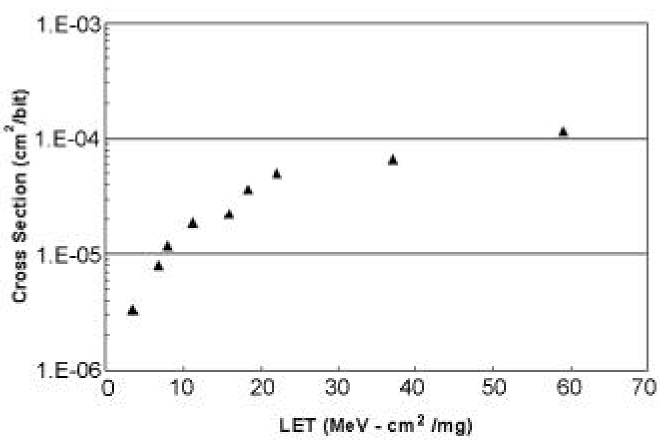

Figure 12: SEU cross section measurements on the Analog Devices AD1672 ADC.

M. MAXIM MAX494 Op Amp

The MAXIM MAX494 was monitored for SELs when exposed to a number of heavy ion beams at the Brookhaven National Laboratory Single Event Effects Test Facility. The device was exposed to Ni, Br, and I. The LETs were 27, 37 and 59 MeV•cm^2/mg. The devices were tested at room temperature. No SELs were observed on two devices tested under bias conditions of 7 volts at all ion LETs to a fluence of $1x10^7$ p/cm^2.

N. Signal Processing Technologies SPT7760 1Gsps ADC

Proton-induced SEU testing on the Signal Processing Technologies SPT7760 was performed at Crocker nuclear Laboratory using 63 MeV protons. The characterization was done for sample rates from 125 Msps to 1 Gsps.

The SPT7760 is an emitter coupled logic (ECL)-based 1Gsps (1 giga-sample per second) 8 bit + overflow flash analog-to-digital converter. It has an input range of 0 to –2 V and is fully parallel with 8 bits of resolution (256 values) plus an additional over-range bit. The analog input has a bandwidth of over 900 MHz and a capacitance of < 15 pF. The output byte-stream is at differential ECL levels and de-multiplexed into two identical ports (labeled ports A and B) each with 9 bits (8 + overflow) plus clock at a maximum output of 500 Msps. The aggregate throughput is therefore 1 Gsps. The DUT operates from a single –5.2 Vdc supply, nominally consuming 5.5 W. The manufacturer indicates that both a heat sink and a fan are required for operation. The device is supplied in an 80 pin MQUAD package with the option of MIL-STD-883 screening.

The high data rates associated with 1 Gsps operation preclude raw storage of the outputs and post-processing to evaluate SEE performance. This, plus additional complexities encountered when operating with dynamic input conditions, indicated the need for a pseudo-static test approach. The approach we adopted involved setting the analog input to a given level, capturing the output (in FIFO), and comparing the output during subsequent clock cycles (during irradiation) to flag changes that occurred as the result of a single event.

Figure 13 gives the measured cross section as a function of sample rate for various input levels. Test setup hardware limited data collection to less than 1 Gsps. The data is clearly nonlinear for all cases. However, for all cases tested, the cross section dips slightly near 500 Msps. For the given input levels, the variation with sample rate is less than a factor of three.

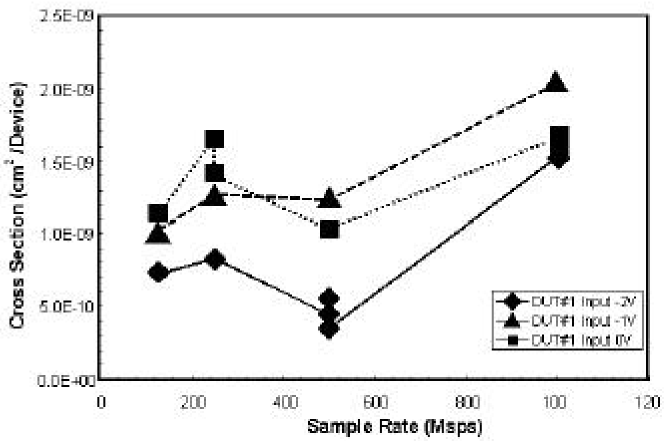

Figure 13: Cross section as a function of sample rate for various input levels.

O. AD780

The AD-780AN precision voltage references were monitored for displacement damage and total ionizing dose. The devices were exposed to a 193 MeV proton beam with a flux from 2.5 x 10^8 to 5 x 10^8 $p^+/cm^2/s$ at the Indiana University Cyclotron Facility. Five devices were exposed to a fluence of 3 x 10^{11} p^+/cm^2 with an output voltage of 2.5 ± 0.005 Volts. While the output current was not much affected, the reference voltage level did show change. With a ± 5 mV range, all but one of the devices indicated an end of life performance and the average reference voltage change of 4.6mV and a standard deviation of 4.8 mV. Annealing data were taken over the course of an hour with only random fluctuations about the end-of-exposure readings. Table 6 shows voltage reference sensitivity to 193 MeV Proton Fluence of 3.0 E+11 cm^{-2} Post-radiation Shifts in mV.

Table 6: Voltage Reference Sensitivity to 193 MeV Proton Fluence of 3.0 E+11 cm^{-2} Post-radiation Shifts in mV.

Manufacturer	Analog Devices	Linear Technology	Linear Technology
Device	AD-780AN	LT-1021CCN8-5	LT-1021CCN8-10
Output Accuracy	2.5000 V ± 0.005 V	5.000 V ± 0.0025 V	10.000 V ± 0.005 V
Run 1	0.4 mV	2.5 mV	-7.2 mV
Run 2	0 mV	3.8 mV	-11.5 mV
Run 3	0.1 mV	4.4 mV	-7.8 mV
Run 4	1.2 mV	4.6 mV	-10.4 mV
Run 5	0.6 mV	4.7 mV	-10.8 mV
Mean (1-5)	0.46 mV	4 mV	-9.5 mV
Std. Dev. (1-5)	0.48 mV	0.9 mV	1.9 mV

- AD-780 uses a compensated bandgap reference
- Both Linear Technology Devices use buried zener references

Here the compensated bandgap performed better, but the opposite was seen in: B.G. Rax, et al., [12] "Degradation of Precision Reference Devices in Space Environments, IEEE TNS, 44 (6), 1997.

P. COMLINEAR CLC502 Op Amp

The COMLINEAR CLC502 was monitored for SELs when exposed to a number of heavy ion beams at the Brookhaven National Laboratory SEE Facility. The device was exposed to Ni, Br, and I. The LET were 27, 37 and 59 MeV•cm^2/mg. The devices where tested at room temperature. No SELs were observed on two devices tested under bias conditions of 7 volts at all ion LETs to a fluence of 1x10^7 p/cm^2.

Q. LT1021CCN8-5 and LT1021CCN8-10

The LT-1021CCN8-5/10 precision voltage feferences were monitored for displacement damage and total ionizing dose. The devices were exposed to a 193 MeV proton beam with a flux from 2.5 x 10^8 to 5 x 10^8 $p^+/cm^2/s$ at the Indiana University Cyclotron Facility. Five devices of each type were exposed to a fluence of 3 x 10^{11} p^+/cm^2 with an output voltage of 5 ± 0.0025 Volts and 10 ± 0.005 Volts. While the output current was not much affected, the reference voltage level did show change. For the LT-1021CCN8-5 with a ± 2.5 mV range, all devices indicated an end of life performance and the average reference voltage change of 4.0 mV and a standard deviation of 0.9 mV. For the LT-1021CCN8-10 with a ± 5 mV range, all devices indicated an end of life performance and the average reference voltage change of –9.5 mV and a standard deviation of 1.9 mV. Annealing data was taken over the course of an hour with only random fluctuations about the end-of-exposure readings. Table 6 shows voltage reference sensitivity. Figure 14 shows voltage reference test results for LT-1021CCN8-10.

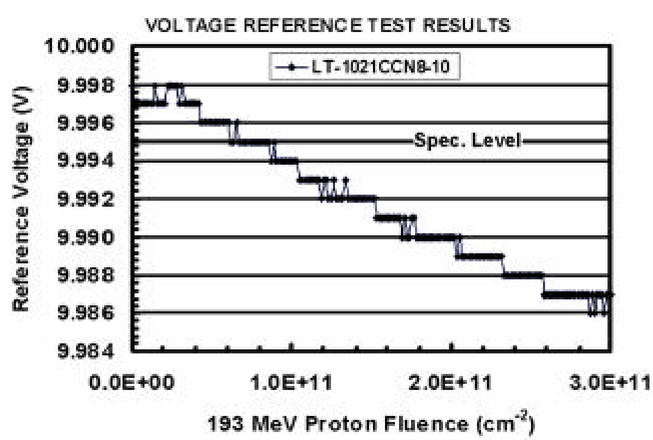

Figure 14: Voltage reference test results for LT-1021CCN8-10.

R. Linear Technology LTC1153 Electronic Circuit Breaker (ECB)

The LTC1153 ECBs were monitored for latchup induced high power supply currents at the MSU SEE Test Facility. Testing began with an LET of 11 MeV•cm^2/mg obtained with 2.4 GeV Kr-40. Following this, the Kr-40 beam was degraded in energy with a 0.037 inch thick Al foil with a resulting LET at the DUT of 30.6 MeV•cm^2/mg. The Xe-129 beam at 7.74 GeV provided an incident LET of 27 MeV•cm^2/mg, and then a 0.020 inch Al foil was used to increase the LET at the DUT to 37 MeV•cm^2/mg. The ECBs were tested under the bias conditions of +12 and +1 8 volts. There was no evidence of latchup at an LET of 37 MeV•cm^2/mg and fluence of 10^{07} ions/cm^2. An anomalous bimodal behavior in supply current was measured, but the circumstantial evidence suggests that DUT functionality may have been compromised by TID effects. TID testing with properly controlled conditions is strongly advised.

S. BOARD TESTS

Several commercial off-the-shelf (COTS) boards were proton irradiated to observed proton-induced SEEs as well as TID and displacement damage. Instead of performing Radiation Hardness Assurance (RHA) or Radiation Lot Acceptance Tests (RLATs) on piecepart devices, we are providing a "confidence" gathering process to increase the likelihood of mission success for COTS boards. Assuming that multiple copies of each board is being procured, the following test philosophy is utilized:

1. Perform proton irradiations on boards
2. Consider issues including particle, energy , fluence, flux, etc.
3. Attempt to isolate individual ICs during irradiations in order to determine sensitive components. This is difficult due to beam spread, double-sided boards, tight board layouts, etc.
4. Define a "martyr" board. Irradiate this board to a proton fluence N times greater than predicted mission fluence (mapping a multi-energy spectrum into a monoenergetic test) monitoring SEE and TID performance. If the "martyr" board passes, irradiate flight hardware boards to a low-level ("non-destructive") of proton fluence.

The martyr board is used for three reasons. These are:

- to pre-screen whether to irradiate flight hardware or not based on SELs, TID failure, etc.,
- to gain limited TID and displacement damage knowledge, and
- to gain confidence for flight SEU performance. For example, assuming a test fluence of 10X mission predicted levels and similarity between martyr and flight hardware, if no "events" were noted during martyr test, then the flight hardware has only a 1 in 10 chance of having an event during mission lifetime.

Table 7 summarizes the results observed in a qualitative manner. Full details on the test results as well as descriptions of the limitations of this method will be available in [13].

Table 7: Summary of Board Test Results.

Manufacturer	**Mfr. Part Number**	**Board Description**	**Test Date**	**Test Facility**	**Brief Results**	**Note**
Ziatech	ZT-6500	CPCI Pentium Processor	Sep-97	IUCF	SEU, SEL observed	
Greenspring	CPCI-100	Dual IP 3U Carrier	Sep-97	IUCF	No events	
Greenspring	IP 1553	MIL-STD-1553 Interface	Sep-97	IUCF	SEL	
Alphi	Unknown	3U IP Carrier	May-98	UCD CNL	No events	Martyr test
Alphi	Unknown	3U IP Carrier	Jun-98	IUCF	No events	Flight hardware test
Greenspring	CPCI-200	6U IP Carrier	May-98	UCD CNL	No events	
Force	CPCI-3603	CPCI PowerPC Processor	May-98	UCD-CNL	SEU	Flight hardware had different results than martyr
Force	CPCI-3603	CPCI PowerPC Processor	Jun-98	IUCF	SEU	Flight hardware had different results than martyr
Greenspring	Unknown	IP Optocoupler Driver	Jun-98	IUCF	SEU, Displacement damage on optocoupler	
Greenspring	Unknown	HV-Unidig Driver	Jun-98	IUCF	SEU	
Greenspring	Unknown	IP Serial Driver	Jun-98	IUCF	SEU	
Actis	SCC-04	IP Serial Driver	Jun-98	IUCF	SEU	
Plessey	Unknown	GPS Correlator/Front-end	Sep-98	UCD CNL	SEU	Loss of lock and SEFI
Cogent Computers Inc	CMA-401A	STRONGARM Processor	Sep-98	UCD CNL	SEU	Only 2 events in ~ 20 krad(Si) of protons

Table 8: ESN SEE Piecepart Summary.

Part Number	Manufac.	Description	LET_{th}** for SEL, SEGR, SEB	LET_{th}** for SEU or SET
UT75ER	UTMC	ASIC	No	~37
AMP01NBC	Analog Devices	Instrumentation Amp	>26	>4
AD574S	Analog Devices	12 Bit A/D Converter (resolution 60 mV)	>37	>37
OP77NBC	Analog Devices	Voltage Operational Amplifier	>59	>59
RH1009	Linear Tech.	2.5 V Shunt Regulator Diode	>55	>55
HSO-1840RH-Q	Harris	16 Ch. CMOS Analog Multiplexer	No	>120
HX6256	Honeywell SSEC	Static RAM CMOS 32K x 8	No	>120
HX6656	Honeywell SSEC	ROM	No	>120
MUX-28	Analog Devices	Dual 8 Ch. JFET Analog Multiplexer	No	> 85
FRC913OR	Harris	P-Ch. MOSFET	>37	N/A
FRC13OR	Harris	N-Ch MOSFET	>37***	N/A

** LETth is the threshold LET and is given in MeV•cm^2/mg
*** Derated

A. OP77NBC (U19), MUX-28 (U13), and AD574 (U15)

The Honeywell ESN was tested for SEU, SET, and single event parametric or functional failure, (e.g., single event latchup (SEL), single event gate rupture (SEGR), single event burnout (SEB)). The Honeywell Essential Services Node (ESN) contains several microelectronic devices. Table 8 gives the results for testing done at Brookhaven National Laboratory. The AMP01 instrumentation amplifier fails destructively below LETth of 37 MeV•cm^2/mg (see the section on the AMP01). The failure mechanism is unknown. The characteristics of the failure is a high current state of near 40 mA that is not recoverable on power cycle. The AMP01 also experiences SETs for LETs > 4 MeV•cm^2/mg.

B. AD536

The AD536 RMS-DC converters were monitored for transient interruptions in the output signal and for latchup induced high power supply currents. They were exposed to C, F, Cl, Ti, Br, and I heavy ion beams (normal incident LETs of 1.4, 3.4, 11.4, 18.7, 37.4, and 59.8 MeV•cm^2/mg, respectively) at the BNL SEE Test Facility. The converters were tested under bias conditions of +/- 8 volts. The devices had an input voltage source of a sine wave with frequency of 318 kHz and 10 volts peak-to-peak. For this condition, no single event induced latchups were observed in the part to an effective LET of 75 MeV•cm^2/mg. The device, however, did experience SETs. [14]

For the SETs, the cross section data shows a spread as a function of the ion species and its effective LET but a saturation cross section level was estimated at 5 x 10^{-3} cm^2. The LET threshold was never measured as transients were observed with an ion that has a normal-incidence LET of 1.4 MeV•cm^2/mg. The transients are mainly noise around the output signal of 3.3 volts with a sharp positive spike. The shape of the spike is a pulse of approximately few microseconds with peak heights of up to 2.5 volts above nominal. The noise surrounding this spike is approximately 200 mV on either side of the nominal output voltage. The AD536 is considered to have an LET threshold for latchup greater than 75 MeV•cm^2/mg. It has single event transients threshold of less than 1.4 MeV•cm^2/mg and a saturation cross section of 5 x 10^{-3} cm^2. It should be noted that for LET_{th} of 10 MeV•cm^2/mg or less, the possibility of sensitivity to proton-induced events exists. With a threshold of 1.4, this possibility is very likely but it is not addressed by this testing.

C. Analog Devices AMP01 Instrumentation Amplifier

Destructive Failure Testing:

Single Event Effects (SEEs) experimental data at Brookhaven National Laboratory has shown that the AMP01 can have a destructive failure when exposed to a heavy ion radiation environment. Test groups from GSFC and Sandia National Laboratory [15] have observed this failure independently. Table 9 describes the experimental results obtained by NASA/GSFC.

1. Notice that for DUTs 4 and 26 the failure occurred at LET = 59.8 MeV•cm^2/mg (I normal incident). Failure did not occur when testing these DUTs at effective LETs greater than 59 MeV•cm^2/mg (e.g., LET_{eff} = 73.0 MeV•cm^2/mg - Br at 60 degrees where the LET is 36.5 MeV•cm^2/mg).
2. For DUT 27 the effective cross section for failure is 1.74x10^{-6} cm^2/device for an LET_{eff} of 83.4 MeV•cm^2/mg (I at 45 degrees). Compare this to DUTs 3,4, and 26 where the cross section is greater than 1.3x10^{-5} cm^2/device at LET = 59.8 MeV•cm^2/mg (I at 0 degrees). The effective cross section for failure for DUT 27 is an order of magnitude lower that other DUTs when measure at a lower effective LET.

3. DUTs 1 and 2 show that the threshold LET is probably between 26.6 and 36.5 MeV•cm^2/mg.
4. The observed effect is independent of gain.

Points one and two can be explained by the either poor statistics, limited range of the ions, using HICUP calculation for RPP, or the RPP model may not be a valid prediction technique for this type of failure. A clear experimental data set and an understanding of the mechanism is required to define the valid explanation.

Table 9: Summary of Heavy Ion-Induced Failures for the Analog Devices AMP01.

DUT	LOT	Gain	Test Conditions Showing No Failure					Non-Recoverable Destructive Failure Conditions						
			ION	LET MeV-cm²/mg	ANG	LET_{eff} LET/cos(angle)	CS_{eff} CS/cos(angle)	ION	LET MeV-cm²/mg	ANG	LET_{eff}	CS_{eff}	I (mA) (+15V)	I (mA) (-15V)
3	ESN	100	Ni	26	0	26	$<1.1\times10^{-7}$	I	60	0	60	4.7×10^{-5}	34	39
4	ESN	1	Br	37	0	37	$<1.8\times10^{-7}$	I	60	0	60	1.3×10^{-5}	34	39
					52	60	$<1.0\times10^{-7}$							
					60	73	$<5.0\times10^{-8}$							
5	ESN	1	Did not test below LET of 37 MeV cm²/mg					Br	37	0	37	1.1×10^{-7}	34	39
7	ESN	100	Br	37	0	37	$<1.0\times10^{-7}$	Did not test above LET of 37 MeV cm²/mg						
10	ESN	1	Br	37	0	37	$<7.1\times10^{-9}$	Did not test above LET of 37 MeV cm²/mg						
1	IRAC	1	Ni	26	0	26	$<4.4\times10^{-8}$	Br	37	0	37	4.3×10^{-7}	21	24
2	IRAC	1000	Ni	26	0	26	$<4.0\times10^{-8}$	Br	37	0	37	3.5×10^{-8}	33	36
27	ESN	1	Br	37	0	37	$<6.4\times10^{-8}$	I	60	45	83	1.7×10^{-6}	34	36
					45	52	$<9.4\times10^{-8}$							
					60	73	$<1.3\times10^{-7}$							
26	ESN	1	Br	37	0	37	$<4.0\times10^{-8}$	I	60	0	60	3.5×10^{-5}	33	36
					45	52	$<5.6\times10^{-8}$							
					60	73	$<8.0\times10^{-8}$							

Note: CS = cross section = number of upsets per device/fluence
CS_{eff} = effective cross section = CS/cos(theta)= number of upsets per device/fluence/cos(theta)
LET_{eff} = effective LET = LET/cos(theta)

D. Nytek 8002 delay line

The Nytek 8002 was monitored for SELs when exposed to a number of heavy ion beams at the Brookhaven National Laboratory Single Event Effects Test Facility. The device was exposed to Ni, Br, and I. The LET were 27, 37 and 59 MeV•cm^2/mg. The devices where tested at room temperature. No SELs were observed on two devices tested under bias conditions of 7 volts at all ion LETs to a fluence of 1x10^7 p/cm^2.

E. Analog Devices DAC8222 Digital to Analog Converter

The DAC8222 Digital to Analog Converters were monitored for transient interruptions in the output signal and for latchup induced high power supply currents. They were exposed to a Ni, and I heavy ion beams (normal incident LETs of 26.6 and 59.8 MeV•cm^2/mg, respectively) at the BNL SEE Test Facility. The converters were tested under the bias condition of + 8 volts. Three cases were investigated to determine the sensitivity of SELs and SETs to the analog output conditions [16]. The digital input was adjusted until the three analog output voltages of –0.6, -2.5 and –4.2 volts were obtained. For these conditions, no single event induced latchups were observed in the part to an effective LET of 85 MeV•cm^2/mg. The device, however, did experience SETs.

The cross section data appears to have a saturation cross section level that is independent of the output analog condition (at a value of approximately 10^{-3} cm^2). The LET threshold, on the other hand, is significantly lower for the small analog output condition. The estimated LET threshold for the –2.5 and –4.2 volt outputs is 40 MeV•cm^2/mg and for the –0.6 volt output is 10 MeV•cm^2/mg. The transients are oscillatory in nature with an initial negative going portion. The shape and nature of the transients appears to also be independent of the output voltage condition. The initial negative going pulse is approximately 1 volt in peak and slightly less than 25 ns in duration. The follow-on positive peak is approximately 0.5 volts above nominal and lasts for about 25 ns. The oscillations continue with smaller peak voltages giving and overall transient duration of 100-150 ns.

The DAC8222 Analog Devices Digital to Analog

Converter is considered to have an LET threshold for latchup greater than 85 MeV•cm^2/mg. It has single event transients threshold for the –2.5 and –4.2 volt outputs of 40 MeV•cm^2/mg and for the –0.6 volt output of 10 MeV•cm^2/mg and a saturation cross section of 10^{-3} cm^2. It should be noted that for LET_{th} of 10 or less, the possibility of sensitivity to proton-induced events exists. This possibility is not addressed by this testing.

F. Harris HI-509 Analog Multiplexer

The Harris HI-509 Multiplexers were monitored for transient interruptions in the output signal and for latchup induced high power supply currents. They were exposed to a Ti, Br, and I heavy ion beams (normal incident LETs of 18.7, 37.4, and 59.8 MeV•cm^2/mg, respectively) at the BNL SEE Test Facility. The multiplexers were tested under bias conditions of +/- 9 and +/- 15 volts. For these conditions, no single event induced transients were observed at the output voltage port [17]. In addition, the devices were exposed to a fluence of 10^7 particles/cm^2 of the above ions with no latchup. The Harris HI-509 Analog Multiplexer is considered to have an LET threshold for latchup and single event transients greater than 60 MeV•cm^2/mg.

IV. Summary

We have presented recent data from SEE and proton damage tests on mostly commercial devices. It is the authors' recommendation that this data be used with caution. We also highly recommend that lot testing be performed on any suspect or commercial device.

IV. Acknowledgements

The Authors would like to acknowledge the sponsors of this effort: NASA's Office of the Chief Engineer.

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