Single Event Effects Results for Candidate Spacecraft Electronics for NASA

Martha V. O'Bryan, *Member, IEEE,* Kenneth A. LaBel, *Member, IEEE,*
Scott D. Kniffin, *Member, IEEE,* James W. Howard Jr., *Senior Member, IEEE,*
Christian Poivey, *Member, IEEE,* Ray L. Ladbury, *Member, IEEE,*
Stephen P. Buchner, *Member, IEEE,* Michael Xapsos, *Senior Member, IEEE,*
Robert A. Reed, *Member, IEEE,* Anthony B. Sanders, Christina M. Seidleck,
Cheryl J. Marshall, *Member, IEEE,* Paul W. Marshall, *Member, IEEE,*
Jeffrey Titus, *Senior Member, IEEE,* Dale McMorrow, Ken Li, Jody Gambles, Robert F. Stone,
Jeff Patterson, Hak S. Kim, Donald K. Hawkins, Martin A. Carts, James D. Forney,
Tim Irwin, Zoran Kahric, Stephen R. Cox, and Christopher Palor

***Abstract*-- We present data on the vulnerability of a variety of candidate spacecraft electronics to proton and heavy ion induced single event effects. Devices tested include digital, analog, linear bipolar, and hybrid devices, among others.**

I. Introduction

As spacecraft designers use increasing numbers of commercial and emerging technology devices to meet stringent performance, economic and schedule requirements, ground-based testing of such devices for susceptibility to single event effects (SEE) has assumed ever greater importance. The studies discussed here were undertaken to establish the sensitivities of candidate spacecraft electronics to heavy ion and proton-induced single event upsets (SEU), single event latchup (SEL), and single event transient (SET). Note: For proton displacement damage (DD) and total ionizing dose (TID) results please see a companion paper entitled "Total Ionizing Dose and Displacement Damage Results for Candidate Spacecraft Electronics for NASA" by Donna Cochran, et al. that is also being submitted to IEEE NSREC Data Workshop [1].

Manuscript received February 6, 2003. This work was supported in part by NASA Electronics Radiation Characterization (ERC) Project, a portion of NASA Electronic Parts and Packaging Program (NEPP), NASA Flight Projects, and the Defense Threat Reduction Agency (DTRA).

M. V. O'Bryan is with Martha V. O'Bryan, Raytheon Information Technology & Scientific Services (ITSS), c/o NASA Goddard Space Flight Center (GSFC), Code 561.4, Bldg. 22, Rm. 062A, Greenbelt, MD 20771 USA (telephone: 301-286-1412, fax: 301-286-4699, email: martha.obryan@gsfc.nasa.gov)

Kenneth A. LaBel is with NASA/GSFC, Code 561.4, Greenbelt, MD 20771 USA (telephone: 301-286-9936, e-mail: ken.label@gsfc.nasa.gov).

Ray L. Ladbury is with Orbital Sciences Corporation, c/o NASA/GSFC, Code 561.4, Greenbelt, MD 20771 USA (telephone: 301-286-1030, email: rladbury@pop500.gsfc.nasa.gov)

James W. Howard Jr. is with Jackson & Tull Chartered Engineers, c/o NASA/GSFC, Code 561.4, Greenbelt, MD 20771 USA (telephone: 301-286-1023, email: jihoward@pop500.gsfc.nasa.gov)

II. Test Techniques and Setup

A. Test Facilities

All SEE tests were performed between February 2002 and February 2003. Heavy Ion experiments were conducted at the Brookhaven National Laboratories' (BNL) [2] Single Event Upset Test Facility (SEUTF) and at the Texas A&M University Cyclotron (TAMU) [3]. The SEUTF uses a twin Tandem Van de Graaff accelerator while the TAMU facility uses an 88" cyclotron. Both facilities are suitable for providing a variety of ions over a range of energies for testing. At both facilities, test boards containing the device under test (DUT) were mounted in the test area. For heavy ions, the DUT was irradiated with ions with linear energy transfers (LETs) ranging from 1.2 to 120 MeV•cm^2/mg, with fluences from 7.6×10^4 to 1×10^7 particles/cm^2. Fluxes ranged from 5.2×10^2 to 3×10^5 particles/cm^2 per second, depending on the device sensitivity. Representative ions used are listed in Table I. LETs between the values listed were obtained by changing the angle of incidence of the ion beam on the DUT, thus changing the path length of the ion through the DUT. Energies and LETs available varied slightly from one test date to another.

Proton SEE tests were performed at two facilities: the University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) [4], and the Indiana University Cyclotron Facility (IUCF) [5]. Proton test energies incident on the DUT are listed in Table II. Proton SEE tests were performed analogously to heavy ion exposures in many regards. Exceptions include proton energy as opposed to LET, as well as differences in cumulative fluence and particle flux rates.

Laser SEE tests were performed at the pulsed laser facility at the Naval Research Laboratory (NRL) [6]-[7]. The laser light used had a wavelength of 590 nm that resulted in a skin depth (depth at which the light intensity decreased to 1/e - or about 37% - of its intensity at the surface) of 2 microns. A pulse rate of 100 Hz was chosen.

Charge collection testing was carried out at Sandia National Laboratory's (SNL's) Microbeam Facility [8]. For all tests the ion beam spot size was ~2 μm². The total area exposed during one sweep (or scan) was ~1600 μm². The step size was ~0.1 μm.

TABLE I
HEAVY ION TEST FACILITIES AND TEST HEAVY IONS

	Ion	Energy, MeV	LET in Si, MeV•cm²/mg	Normal Incidence Range in Si, μm
BNL	C^{12}	102	1.42	193
	F^{19}	140	3.4	77
	Cl^{35}	210	11.4	63
	Ni^{58}	280	26.3	44.3
	Br^{81}	278	37.5	36
	Ag^{107}	345	53	34.5
	I^{127}	320	59.7	31
	Au^{197}	333	81.4	28
TAMU	Ne^{20}	264-285	2.6-2.81	262-331
	Ar^{40}	496-561	8.05-8.9	174-244
	Cu^{63}	750	19.95	120
	Kr^{84}	912-953	28-29.3	116-122
	Ag^{107}	1200	42.85	100
	Xe^{129}	1291-1722	49.3-54	102-127
	*Kr^{84}	2050	20	300
	*Xe^{129}	2800	40.5	200
	†Ne^{20}	800	1.2	1648
	†Ar^{40}	1600	3.9	1000

* 25 MeV per nucleon tune
† 40 MeV per nucleon tune

TABLE II
PROTON TEST FACILITIES AND PARTICLES

Facility	Particle	Particle Energy, (MeV)
University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL)	Proton	26.6-63
Indiana University Cyclotron Facility (IUCF)	Proton	54-197

TABLE III
OTHER TEST FACILITIES

Naval Research Laboratory (NRL) Pulsed Laser SEE Test Facility Laser: 590 nm, 3 ps pulse width, beam spot size ~1.5 μm

B. *Test Method*

Unless otherwise noted, all tests were performed at room temperature and with nominal power supply voltages.

1) SEE Testing - Heavy Ion

Depending on the DUT and the test objectives, one or more of three SEE test methods were used:

Dynamic – the DUT was exercised continually while being exposed to the beam. The errors were counted, generally by comparing DUT output to an unirradiated reference device or other expected output. In some cases, the effects of clock speed or device modes were investigated. Results of such tests should be applied with caution because device modes and clock speed can affect SEE results.

Static – the DUT was loaded prior to irradiation; data were retrieved and errors were counted after irradiation.

Biased (SEL only) – the DUT was biased and clocked while I_{CC} (power consumption) was monitored for SEL or other destructive effects. In some SEL tests, functionality was also monitored.

In SEE experiments, DUTs were monitored for soft errors, such as SEUs and for hard errors, such as SEL. Detailed descriptions of the types of errors observed are noted in the individual test results.

SET testing was performed using a high-speed oscilloscope. Individual criteria for SETs are specific to the device being tested. Please see the individual test reports for details. [9]

Heavy ion SEE sensitivity experiments include measurement of the saturation cross sections and the Linear Energy Transfer (LET_{th}) threshold (the minimum LET value necessary to cause an effect at a fluence of $1x10^7$ particles/cm²).

2) SEE Testing - Proton

Proton SEE tests were performed in a manner similar to heavy ion exposures in many regards. Differences include measuring the SEE cross section as a function of proton energy as opposed to LET, as well as differences in cumulative fluence and particle flux rates.

3) Pulsed Laser Facility Testing

The DUT was mounted on an X-Y stage in front of a 100x lens that produced a spot size of about 1.5 microns. The X-Y stage could be moved in steps of 0.1 micron for accurate positioning of SEU sensitive regions in front of the focused beam. An illuminator together with a CCD camera and monitor were used to image the area of interest, thereby facilitating accurate positioning of the device in the beam. The pulse energy was varied with a neutral density filter and the energy was monitored by splitting off a portion of the beam and directing it at a calibrated energy meter.

4) Charge Collection Testing

A four probe Ion Beam Induced Charge Collection (IBICC) measurement was used to simultaneously measure the charge presented on the collector, emitter, base, and substrate terminal due to a series of ion strikes occurring in and around the transistor's area.

III. TEST RESULTS OVERVIEW

Abbreviations and conventions are listed in Table IV. Abbreviations for principal investigators (PIs) are listed in Table V. SEE test result categories are summarized in Table VI and SEE results are summarized in Table VII. These tables contain only a portion of the parts tested (over 30 parts were tested for SEE). The final data workshop publication will contain results for additional parts tested. Unless otherwise noted, all LETs are in MeV•cm^2/mg and all cross sections are in cm^2/device. This paper is a summary of results. Complete test reports are available online at http://radhome.gsfc.nasa.gov [9].

TABLE IV
ABBREVIATIONS AND CONVENTIONS

H = heavy ion test
P = proton test (SEE)
L = laser test
CC = Charge Collection
LET = linear energy transfer (MeV•cm^2/mg)
LET_{th} = linear energy transfer threshold (the minimum LET value for which a given effect is observed for a fluence of 1×10^7 particles/cm^2 – in MeV•cm^2/mg)
SEE = single event effects
SEU = single event upset
SEL = single event latchup
SET = single event transient
SEFI = single event functional interrupt
SEB = single event burnout
SEGR = single event gate rupture
< = SEE observed at lowest tested LET
> = No SEE observed at highest tested LET
σ = cross section (cm^2/device, unless otherwise specified)
σ_{SAT} = saturation cross section at LET_{max} (cm^2/device, unless specified as cm^2/bit)
LDC = Lot Date Code
DAC = Digital to Analog Converter
V_{dd} = Supply Voltage
EEPLD = Electronically Erasable Programmable Logic Device
FPU = Floating Point Units
HBT = Heterojunction Bipolar Transistor
ADC = Analog to Digital Converter
DAC = Digital to Analog Converter
CMOS = Complementary Metal Oxide Semiconductor
FPGA = Field Programmable Gate Array
GPS = Global Positioning System
UART = Universal Asynchronous Receiver Transmitter
R-S Encoder = Reed-Solomon Encoder
DUT = Device Under Test
N/A = Not Applicable
App. Spec. = Application Specific
V_{DS} = drain-to-source voltage
V_{GS} = gate to source voltage
Temp. Sensor = Temperature Sensor
Cat. = Category
P.I. = Principal Investigator

TABLE V
LIST OF PRINCIPAL INVESTIGATORS

Abbreviation	Principal Investigator (P.I.)
SB	Steve Buchner
JH	Jim Howard
SK	Scott Kniffin
RL	Ray Ladbury
PM	Paul Marshall
JP	Jeff Patterson
CP	Christian Poivey
RR	Robert Reed
AS	Anthony Sanders
JT	Jeff Titus
MX	Mike Xapsos

TABLE VI
LIST OF CATEGORIES

Category	Implications
1	Recommended for usage in all NASA/GSFC spaceflight applications.
2	Recommended for usage in NASA/GSFC spaceflight applications, but may require mitigation techniques.
3	Recommended for usage in some NASA/GSFC spaceflight applications, but requires extensive mitigation techniques or hard failure recovery mode.
4	Not recommended for usage in any NASA/GSFC spaceflight applications.
RTV	Research Test Vehicle - Please contact the P.I. before utilizing of this device for spaceflight applications.

TABLE VII
SUMMARY OF SEE TEST RESULTS

Part Number	Manufacturer	LDC	Device Function	Process	Particle: (Facility,Date) P.I.	Testing Performed	Test Results LET in MeV•cm²/mg σ in cm²/device, unless otherwise specified	SEE Cat.	Reference	Sample Size	Supply Voltage
[illegible]											
AD623	Analog Devices	0030	Op Amp	BiCMOS	H: (TAMU) RL	SET, SEL	SEL LET_{th} >85.7 SET LET_{th} ~ 1	3	[10] T100202_ AD623	2	5V
LM124	National Semiconductor	0010	Op Amp	Bipolar	H: (TAMU) CP	SET; SEL	SEL LET_{th} >66 SET LET_{th} ~3; $\sigma = 2x10^{-3}$	2	[11] TAMU02-03_LM124	3	±15
LM193	Texas Instruments	0145	Comparator	Bipolar	H: (TAMU) AS/ JH/RR	SET, SEL	SEL LET_{th} >98.6 SET LET_{th} ~2; σ = 1E–3 (low output) SET LET_{th} ~5; σ = 1E–4 (high output)	2	[12] T081102_ LM193A	2	±12
LMC6484	National Semiconductor	No LDC – marked XM106AB	Op Amp	CMOS	H: (BNL) CP (TAMU) CP L: (NRL) SB	SET; SEL	H: SEL LET_{th} >77; SET LET_{th} ~ 3; SET $\sigma > 1x10^{-4}$ L: Transient amplitude and duration increase with laser energy	2	[13] 2002_ LMC6484	1	+10/0
LT1128	Analog Devices	0050	Op Amp	Bipolar	H: (TAMU) CP	SET	SEL LET_{th} >66 SET LET_{th} ~3; $\sigma = 1.5x10^{-3}$	2	[14] T1202_ LT1128	2	±15
OP293	Analog Devices	0021	Op Amp	BiCMOS	H: (TAMU) RL L: (NRL) RL	SEE, SET	H: SEL LET_{th} >85; SET LET_{th} ~1 Transients >1ms are possible L: Long duration transients were observed	3	[15] T100202_ OP293	H: 2 L: 1	5V
OP42	Analog Devices	9750	Op Amp	Bipolar	H: (TAMU) JH	SET, SEL	SEL LET_{th} <57.8; SET LET_{th} ~3; σ_{SAT} ~6x10³	2	[16] T081102_ OP42	2	±6.5
OP727	Analog Devices	0137	Op Amp	BiCMOS	H: (TAMU) RL	SET, SEL	SEL LET_{th} >85.7; SET LET_{th} ~3-5	3	[17] T100202_ OP727	2	3.6V
OPA2347	Texas Instruments	No LDC - marked 26zzz	Op Amp	BiCMOS	H: (TAMU) RL	SET, SEL	SEL LET_{th} <11.95; σ_{SAT} ~2x10⁻⁴ SET LET_{th} ~1	4	[18] T100202_ OPA2347	3	3.6V
[illegible]											
HV583	Supertek	N/A	Serial to parallel converter	CMOS	P: (UCD) SB	SEU, SEL	No SELs observed at 63 MeV protons (cooled to 30K); SEL LET_{th} increases with decreasing temperature SEU observed at 63 MeV protons (cooled to 30K)	3	[19] D040402_ HV583	3	5V
LTC1149	Linear Technology	0101	Step-Down Switching Regulator	CMOS	H: (TAMU) JH	SET, SEL	SEL: LET_{th} >75; SET: LET_{th} >75	1	[20] T081102_ LTC1149	2	24V, 28V, 34V
MSK5042	National Semiconductor	0204	Switching Regulator	Hybrid	H: (BNL) CP	SET; SEFI	SET LET_{th} <3.38; SEFI LET_{th} <3.38	4	[21] B061702_ MSK5042	3	8.5V, 12V
CULPRiT R-S Encoder	Institute of Advanced Microelectronics	N/A	R-S Encoder	CMOS Ultra-Low Power Radiation Tolerant (CULPRiT)	L: (NRL) MX	SEU	SEL LET_{th} >60 SEU LET_{th} =18; σ_{SAT} =17 μm²/bit Shift register area susceptible to SEU	2	[22] NRL060702 _CULPRiT	1	0.5V
IRF640	International Rectifier	0045	N-channel power MOSFET	MOSFET	H: (BNL) JT/RL	SEE	SEB down to 22% of rated VDS for VGS=–1 (LET>52); VGS dependence not strong No SEGR observed; SEB σ_{SAT} ~ 5x10⁻²	4	[23] B053102_ IRF640	2	N/A
IRLL110	International Rectifier	0042	N-channel power MOSFET	MOSFET	H: (BNL) JT/RL	SEE	SEGR for V_{DS}>35% of rated value (at all LETs up to LET=60); Strong dependence on V_{GS} and LET SEGR σ_{SAT} ~ 2.5x10⁻²	3	[24] B053102_ IRL110	4	N/A

TABLE VII (CONT.)

Summary of SEE Test Results

Part Number	Manufacturer	LDC	Device Function	Process	Particle: (Facility,Date) P.I.	Testing Performed	Test Results LET in MeV•cm²/mg σ in cm²/device, unless otherwise specified	SEE Cat.	Reference	Sample Size	Supply Voltage
[illegible]											
ATF22V10	Atmel	0127	EEPLD	CMOS	P: (IU) MX/SK	SEE	No SEFI or SEL at 200 MeV protons Note: TID functional failures observed; Device failed destructive physical analysis (DPA) test	2	[25] B030402_ 22V10	2	5V
MCF5307	Motorola	0120	Coldfire Processor	CMOS	H: (TAMU) JH P: (IU) JH	SEE	SEL LET_{th} >107 SEU: Not measured (SEFI upsets dominant) SEFI: observed 2.8-28.9 ; $\sigma \sim 2.45 \times 10^{-11}$	3	[26] I060602_ TAMU_ MCF5307	H: 3 P: 1	8V
SG1525A	Linfinity	0126	Pulse Width Modulator controller	Bipolar	H: (TAMU) JH	SEE	SEL LET_{th} >61.3 SET LET_{th} >5; $\sigma \sim 1 \times 10^{-4}$	4	[27] T081102_ SG1525A	4	11.75 (app. spec.)
SH-4	Hitachi	N/A	Micro processor	CMOS	P: (IU) JH	SEE	SEFI: observed (address errors; FPU) SEU: Not measured (SEFI upsets dominant) SEFI $\sigma \sim 2.04 \times 10^{-10}$; SEL $\sigma \sim 5.2 \times 10^{-12}$	4	[28] I060602_ SH4	1	3.3V
[illegible]											
SPT7760	Signal Processing Technologies	H0123 H2	ADC	Bipolar	H: (TAMU) RL	SEU	SEU LET_{th} > 2.8, $\sigma = 1 \times 10^{-5}$	2	[29] T091202_ SPT7760	2	-5.2V
Test Sample	IBM	N/A	Transistor	5HP SiGe HBT	CC: (SNL) RR/PM	CC	SEU sensitive depending on operational conditions [ref Gofou Niu_tns03]	RTV	[23] SNL092302_ SiGe_HBT; [24] Gofou Niu_tns03	4	N/A
Test Sample	IBM	N/A	PRN	7HP SiGe HBT	P: (IU) RR/PM H: (TAMU) RR/PM	SEU	SEU sensitive depending on operational conditions [ref Reed_tns03]	3	[30] SNL092302_ SiGe_HBT; [32] Reed_tns03	2	N/A
Test Sample	IBM	N/A	Transistor	7HP SiGe HBT	CC: (SNL) RR/PM	CC	SEU sensitive depending on operational conditions [ref Reed_tns03]	RTV	[30] SNL092302_ SiGe_HBT; [32] Reed_tns03	1	N/A
AD8151	Analog Devices	N/A	Crossbar Switch	BiCMOS	L: (NRL) SB	SEE	SET Burst of upsets observed dependent on laser pulse energy (LET); SET Burst length dependent on dose rate Identified SEFI and SET sensitive areas on chip	3	[33] NRL092402_ AD8151	1	±3.3V
GP2021	Zarlink Semiconductor	9617A	GPS Correlator	CMOS	P: (IU) JH	SEE	SEU $\sigma \sim 1.3 \times 10^{-11}$ SEFI $\sigma \sim 1.7 \times 10^{-12}$ SEL $\sigma = 4.3 \times 10^{-13}$	3	[34] I060602_ GP20211G	4	5V
TPS9103	Texas Instruments	N/A	Power Supply for GaAs power amplifier	CMOS, MOSFET	H: (BNL) CP	SEL/SET	SEL: $LET_{th} \sim 8$; $\sigma \sim 1 \times 10^{-5}$ SET (Bat_out output): $LET_{th} \sim 4$; $\sigma = 4 \times 10^{-5}$; No SET was seen on the GATE_BIAS output	3	[35] B061702_ TPS9103	2	3.3V; Bat_{IN} 7V
KM48C8000	Samsung	N/A	64 Mbit DRAM	Memory	H: (TAMU) JP/RL	SEE	SEL LETth >46 SEU LETth <2; σ_{SAT} =3 μm²/bit SEFI, address errors and multibits also seen	3	[36] T0802_ KM48C8000	5	5V

TABLE VIII
SUMMARY OF SEL TEST RESULTS

Part Number	Manufacturer	LDC	Device Function	Process	Particle: (Facility,Date) P.I.	Testing Performed	Test Results LET in MeV•cm²/mg σ in cm²/device, unless otherwise specified	SEE Cat.	Reference	Sample Size	Supply Voltage
AD5334	Analog Devices	0011	DAC	CMOS	H: (TAMU) JH	SEL	SEL LET_{th} ~8; σ_{SAT} ~ 2 to $3x10^{-4}$ cm^2	4	[37] T031302_ AD5334	4	V_{DD} 5V; V_{SS} 0V
AD7414	Analog Devices	0049	Temp. Sensor	CMOS	L: (NRL) SK	SEL	SEL LET_{th} ~6; Power cycling required to recover device.	4	[38] NRL060702 _AD7414	1	3.3 & 5V
AD7664	Analog Devices	0110	ADC	CMOS	H: (TAMU) JH P: (IU) JH	SEL	H: SEL LET_{th} ~7; σ_{SAT} ~1.2 $x10^{-3}$ cm^2 P: No SEL observed at fluence of $1.8x10^{12}$ p/cm^2; SEL σ <$1.8x10^{-13}$	3/4	[39] T120202_ AD7664 [40] I021503_AD7664	H: 12 P: 5	5V
TMP36	Analog Devices	N/A	Temp. Sensor	BiCMOS	H: (BNL) RL	SEL	SEL LET_{th} >100	1	[41] B061702_ TMP36	2	3.3V, 5.5V
Test Sample	IBM	N/A	Ring Oscillator	5HP BiCMOS	H: (TAMU) RR	SEL	SEL LET_{th} >81	RTV	[42] T032802_ 5HP	1	N/A
CO566	Vectron	0142	Oscillator	Hybrid	P: (IU) JH	SEL	No SEL observed at 189.9 MeV protons SEL σ <$3.1x10^{-14}$	1	[43] I060602_ CO566	1	5V
CO718S	Vectron	0217	Oscillator	Hybrid	P: (IU) JH	SEL	No SEL observed at 189.9 MeV protons SEL σ <$3.7x10^{-14}$	1	[44] I060602_ CO718S	1	12V

I. SEE Test Results and Discussion of Featured Parts

As in our past workshop compendia of GSFC test results, each DUT has a detailed test report available online at http://radhome.gsfc.nasa.gov [1] describing in further detail, test method, SEE conditions/parameters, test results, and graphs of data. This section contains a summary of testing performed on a selection of featured parts.

A. Linear Devices:

1) LM124

National Semiconductor LM124 operational amplifier was tested for SET at TAMU and NRL (laser facility). The objective of these additional tests was to achieve a better understanding of the effect of bias conditions on SET sensitivity and transient characteristics.

The output of the DUT was monitored with a digital oscilloscope. As soon as the DUT output exceeded a preset trigger level (generally 500 mV), an SET was counted and the complete SET transient data was stored on a computer for future analysis.

Fig. 1 shows the SET cross section for the 14 different bias conditions investigated when the device was tested at TAMU. One remarkable result is that all bias conditions, except the inverting gain x10 application with a 10V input voltage, gave similar cross sections. The LM124 was not sensitive to SET when used as an inverting gain x10 amplifier with a 10Vinput voltage. When the nominal output voltage was close to the power supply rails, as was the case for the inverting gain x10 application, the SET sensitivity was significantly reduced. As noted previously [45], different bias conditions affect the characteristics of the transient waveforms. For more details see "Single Event Transient in LM124 operational amplifier – Heavy ion test report" [11]. Laser experiments demonstrated that the laser tool is a very useful tool to study the effects of bias conditions on transients' characteristics [46].

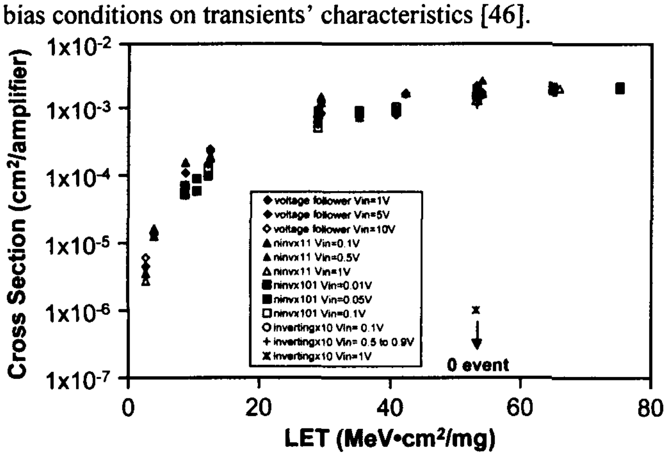

Fig 1. SET cross section curve for LM124.

2) LMC6484

National Semiconductor LMC6484 CMOS operational amplifier was tested for SET at TAMU and NRL (laser facility).

The output of the DUT was monitored with a digital oscilloscope. As soon as the DUT output exceeded a preset trigger level (generally 500 mV), an SET was counted and the complete SET transient data was stored on a computer for future analysis.

The part was not sensitive to SEL up to the maximum tested LET of 77 MeV•cm²/mg. Fig. 2 shows the SET cross section curve for the 6 different bias conditions investigated. The application and input bias conditions did not have an effect on the overall cross section curves, but they had a significant effect on the transient waveforms. Four different transient waveforms were observed. All transients, except the negative going transients, had a small amplitude of less than 2V. Fig. 3 shows typical negative going transients. The largest transient went down to the lower power supply rail. Laser experiments showed that the laser can reproduce the waveforms obtained with heavy ion beams [13].

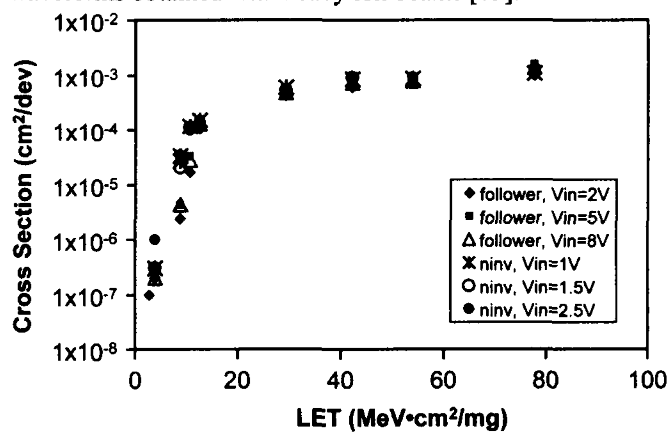

Fig. 2. LMC6484 SET cross section curve.

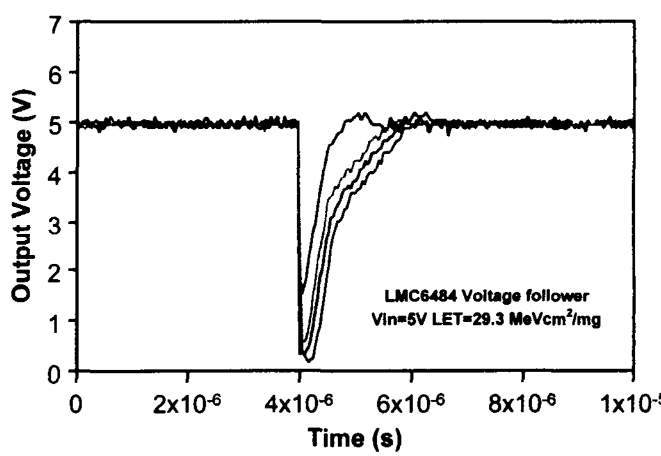

Fig. 3. LMC6484 typical negative going transients.

3) LT1128

Linear Technology LT1128 high speed operational amplifier was tested for SET at TAMU.

The output of the DUT was monitored with a digital oscilloscope. As soon as the DUT output exceeded a preset trigger level (generally 500 mV), an SET was counted and the complete SET transient data was stored on a computer for future analysis.

Fig. 4 shows the SET cross section curve for the 6 different bias conditions investigated. The application and input bias conditions did not have an effect on the overall cross section curves. The lower cross sections obtained for the highest input voltages, voltage follower application with an input voltage of 10V and non inverting gain with an input voltage of 1V, are due to a different trigger threshold setting on the oscilloscope. For these two conditions the trigger threshold was set to 1V instead of 500 mV for the other conditions.

The application, bias, and irradiation conditions had a significant effect on the transients' waveforms. Ten different waveforms were observed. Four of these waveforms represented a marginal part of the device's total response and three others had either a small amplitude (less than 1V) or a very short duration (less than 100 ns). Typical waveforms are shown in Figs. 5 to 7. The bipolar transient waveform shown in Fig. 5 was observed for all bias conditions and LET values. This waveform type was a significant part of the device's total response. The maximum amplitude was 5V, and the maximum duration is ~1 μs. The negative going transient waveform shown in Fig. 6 appears at an LET of 8.7 MeV•cm^2/mg. This type of waveform dominates the device's response for the non-inverting gain application, but was non-existent in the voltage follower application. The maximum amplitude was 5V, and the maximum duration was 2 μs. The positive going transient waveform shown in Fig. 7 appears at an LET of 8.7 MeV•cm^2/mg. This type of waveform dominated the device's response for voltage follower application, but was quasi non-existent in the non-inverting gain application. The maximum amplitude was 5V, and the maximum duration was 2 μs. For more details see "Heavy Ion Single Event Effect Test on the operational amplifier LT1128 from Linear Technology – Heavy ion test report" [14]

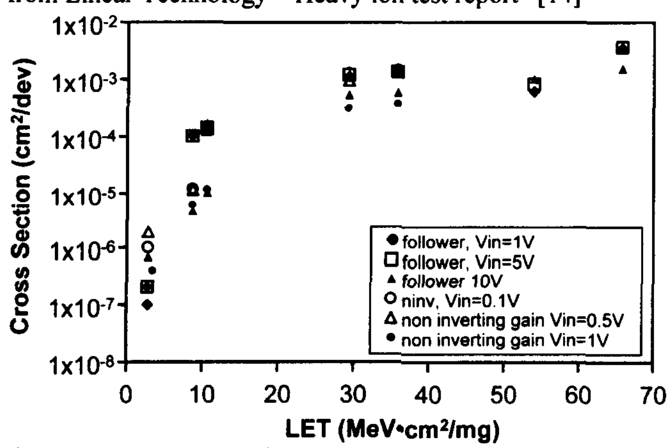

Fig. 4. LT1128 SET cross section curve.

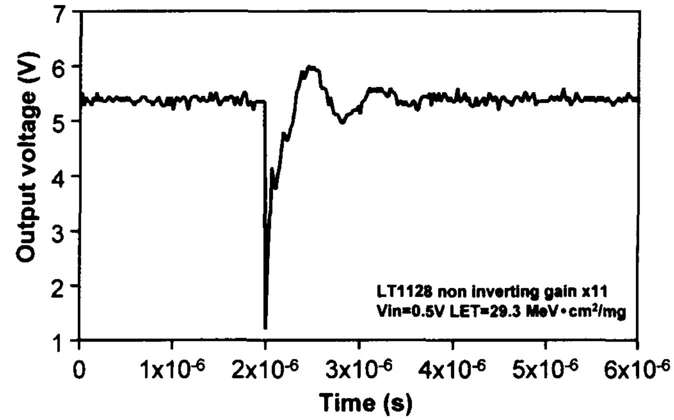

Fig. 5. LT 1128 typical bipolar transient.

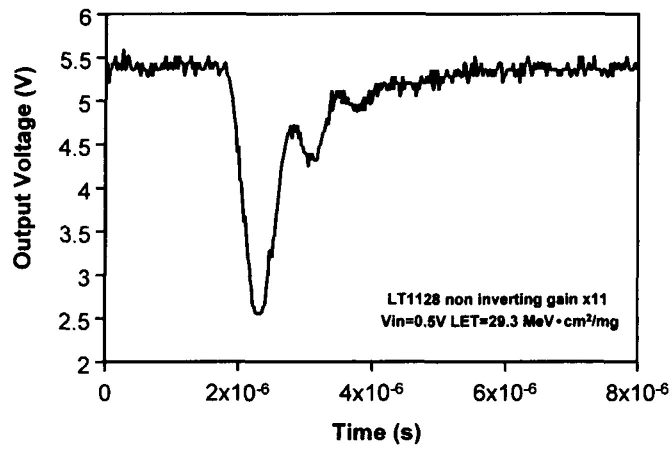

Fig. 6. LT1128 typical negative going transient.

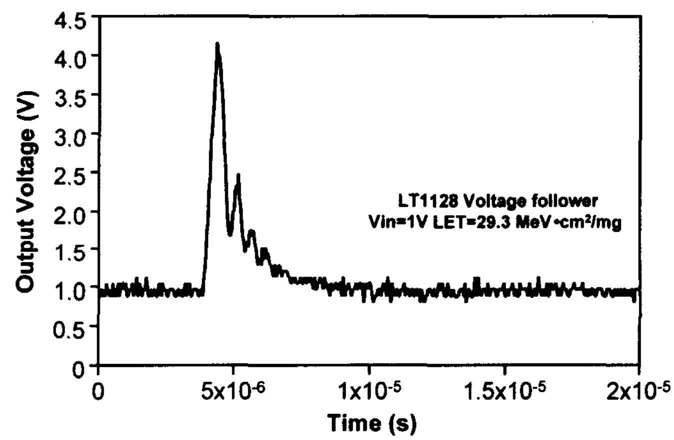

Fig. 7. LT1128 typical positive going transient.

4) OP293

The Analog Devices OP293 BiCMOS operational amplifier was tested for susceptibility to SEE at TAMU. No SEL susceptibility was observed up to an LET of 85 MeV•cm^2/mg. However, the op amp did exhibit a high degree of susceptibility to SETs, some lasting as long as 300 μs. Subsequent laser testing at NRL indicated that transients lasting longer than 1 ms could be possible with this device. These laser studies indicate that the transient duration is proportional to the difference between the supply rail for the part and the nominal output. The die area susceptible to these transients is large and does not correspond to any visible feature (transistor, capacitor, etc.) Fig. 8 shows a profile of a typical long-duration transient seen during heavy-ion testing. In addition to these long transients, shorter duration transients with durations on the order of 30 µs were also seen. Transients lasting longer than 100 µs were seen at the lowest test LET (7.8 MeV•cm²/mg). Transients lasting longer than 150 µs were seen for LET > 10 MeV•cm²/mg, and the longest duration transients were seen for LETs >16 MeVcm²/mg. Fig. 9 shows the cross section vs. LET curve for all transient durations [15].

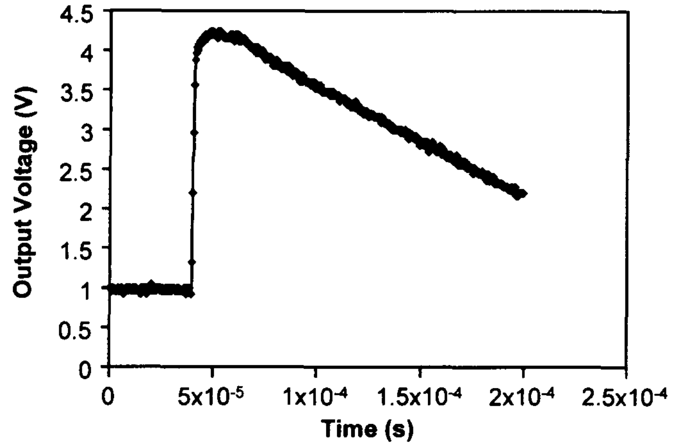

Fig. 8. Typical OP293 long duration transient.

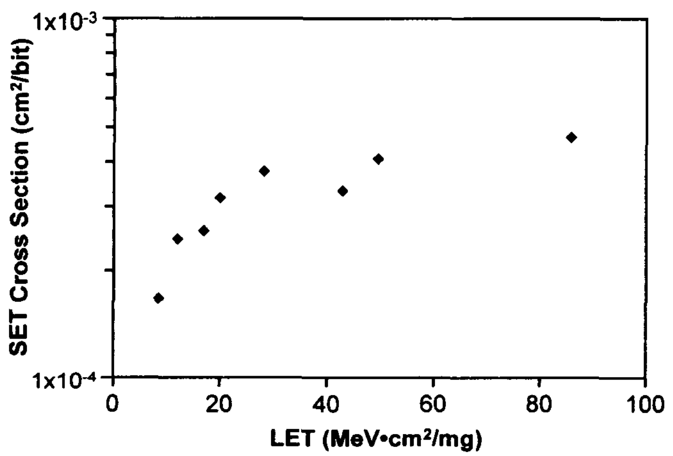

Fig. 9. Cross section vs. LET curve for OP293.

B. Power Devices:

1) CMOS Ultra-Low Power Radiation Tolerant (CULPRiT)

CMOS Ultra-Low Power Radiation Tolerant (CULPRiT) Reed-Solomon encoders were tested for SEE at BNL and the NRL laser facility. CULPRiT is a 0.35 µm 0.5 V CMOS/epi technology that is manufactured by AMI Semiconductor. A Single Event Radiation Technology (SERT) cell design developed at the University of Idaho was used for SEU mitigation. This is the fourth processing run of CULPRiT technology by AMI Semiconductor.

The SEE test board uses a UART interface for configuration and control and contains a Xilinx FPGA that exercises the RS encoder and signals miscompare errors and proper operation. A V_{dd} of 0.5 V was used during testing. P-channel and n-channel back-biases are used to control the low transistor threshold voltages. For testing, p-channel back-biases of 2.0 and 2.5 V were used, and n-channel back-biases of -1.4, -1.9 and -2.4 V were used. The p-channel and n-channel bias combination of 2.0 and -1.4 V gave optimal encoder performance. SEU results for this situation are shown in Fig. 10.

The SEU results show an angle or ion dependent effect, as seen in Fig. 10. The worst case Weibull fit shown gives an SEU threshold of 18 MeV•cm²/mg and a saturated cross section of 17 µm²/bit for this 2048 bit encoder. No latch-up was observed under any bias conditions for either the laser testing or for the heavy ion testing up to an LET of 60 MeV•cm²/mg. [15]

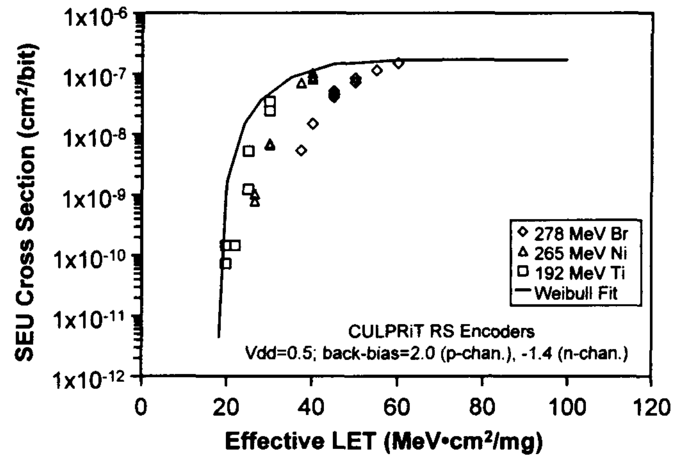

Fig. 10. CULPRiT SEU results.

2) IRF640 and IRLL110

The 200-volt IRF640 and 100-volt IRLL110 MOSFETs (both n-channel MOSFETs from International Rectifier) were tested for vulnerability to single-event burnout and single-event gate rupture at BNL. The IRF640 was found to be vulnerable to SEB for V_{DS} values as low as 22% of its rated value for LETs above about 37 MeV•cm²/mg, and as low as 25% of its rated value for LETs between 26 and 37 MeV•cm²/mg. The softness of the device (designed specifically for commercial applications) to SEB may be attributable to its shallow junction [47].

Although the IRLL110 was considered to be a SEGR risk because of its relatively thin gate oxide, for V_{GS}=0, the part exhibited not susceptibility to SEB or SEGR for LETs up to 59.9 MeV•cm²/mg. However, susceptibility to SEGR increased dramatically as V_{GS} decreased to more negative values. SEGR was observed at an LET of 59.9 MeV•cm²/mg at V_{DS}= 20V for V_{GS}=-7.5V [23].

C. Miscellaneous:

1) AD8151

The Analog Devices AD8151 crossbar switch device was SEE tested at NRL. The part was configured to switch data from a single input to a single output. SEFIs were generated when the laser was focused on the switches that contained data specifying the connections between input and output. Following a SEFI the device had to be reprogrammed for communications in order to restart. Bursts of errors in the transmitted data were generated when the laser light was focused on the switches themselves and on the drivers. Fig. 11 shows the average number of upset bits per burst as a function of both laser pulse energy and data rate for the case where the switches were irradiated. The figure shows that the average number of errors per burst was 14 when the data rate was 3 Gbps. This is identical with the maximum average number of errors per busts obtained with heavy ions. In general, the burst length increased with both laser pulse energy and data rate, confirming the trend observed when testing with heavy ions and protons [33], [48]-[51]. Details of the heavy ion and proton radiation test results of the AD8151 are submitted for publication to RADECS03 [52].

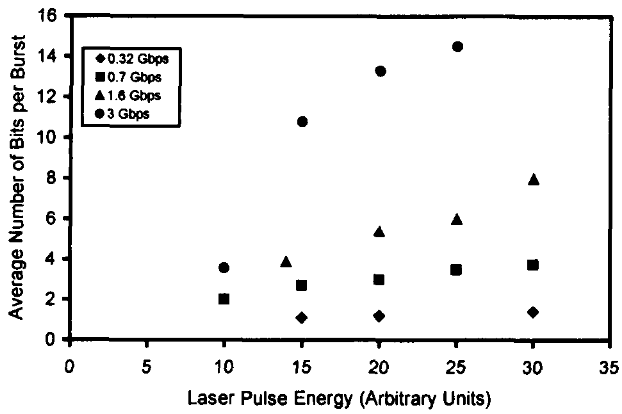

Fig. 11. Average number of errors per burst as a function of laser pulse energy for different data rates for the AD8151.

2) TPS9103

Texas Instruments TPS9103 Power Supply for GaAs power amplifier was tested for SEE at BNL. The test bias conditions are similar to the application conditions. An oscilloscope monitored the BATT_OUT and GATE_BIAS outputs during irradiation. As soon as one of the device outputs deviated by 500 mV from the nominal output voltage, an SET was counted. The power supply current was monitored during irradiation. When the current was larger than 5 mA, a SEL was counted. The device nominal power supply current was about 300 μA.

The part exhibited sensitivity to both SET and SEL. The cross section curves are shown in Fig. 12. The SEL LET_{th} was ~8 MeV•cm²/mg. The SEL cross-section at saturation is ~$1x10^{-5}$ cm²/device. The maximum latchup current is 50 mA. The SET LET_{th} for the BATT_OUT output is ~4 MeV•cm²/mg. Because of the SEL sensitivity, it was not possible to measure the SET cross section at an LET higher than 11.4 MeV•cm²/mg. The maximum measured cross section was $4x10^{-5}$ cm²/device. A typical transient waveform on the BATT_OUT output is shown in Fig. 13. No SETs were seen on the GATE_BIAS output [35].

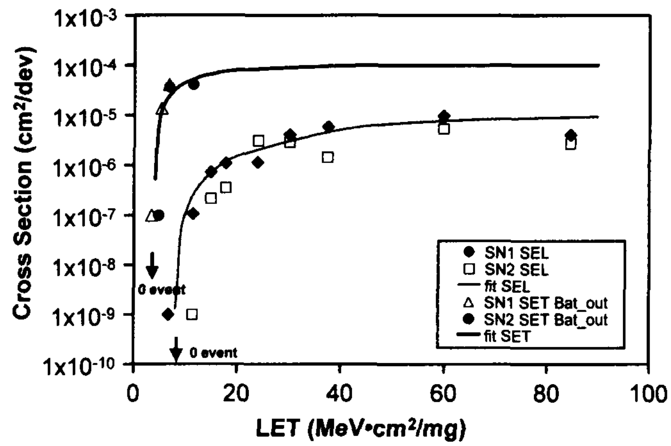

Fig. 12. TSP9103 SEL and SET Bat_out cross-section curves.

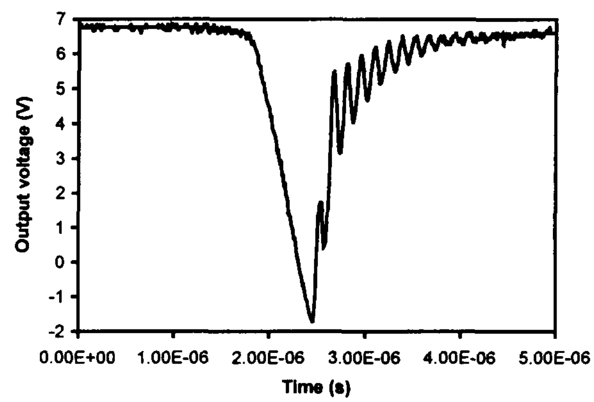

Fig. 13. TPS9103 Typical transient on Bat_out output.

II. Single Event Latchup Test Results and Discussion of Featured Parts

1) AD7664

The AD7664 ADC manufactured by Analog Devices, Inc. were tested at TAMU and UCD. At TAMU we measured the SEL cross section using ions covering a range of LETs from 8.7 to 53.9 MeV•cm²/mg. The LET_{th} for SEL is ~7 MeV•cm²/mg. The test configuration included the use of three power supplies. One was to supply power to the analog V_{dd}, a second to supply power to the digital V_{dd}, and finally a third was used to supply power to the latchup protection circuitry and the control lines on the DUT (the control logic lines place the device in a given operational state). When the power supply providing the control lines was current limited to 200 mA or less, all observed SELs were non-destructive, even with no current limiting on the analog or digital supplies. However, if the control line power is not limited, latchup events will be destructive. For both types of latchup events, the saturation cross section was approximately $1.2x10^{-3}$ cm². The complete cross section curve is given in Fig. 14, where the error bars represent 3 sigma deviation based on the number of observed events [39].

No proton-induced latchup events were observed for a total fluence of $1.8x10^{12}$ protons/cm² across all five devices tested at UCD. This implies a limiting cross section for proton induced latchup of less than $5x10^{-13}$cm² [40].

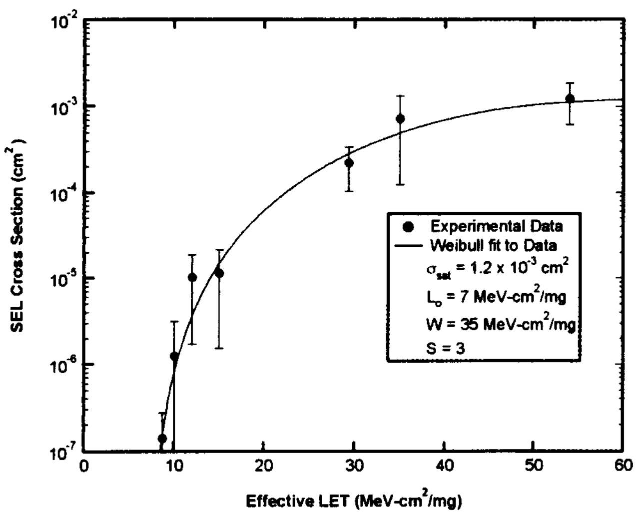

Fig. 14. AD7664 cross section curve.

III. SUMMARY

We have presented recent data from SEE on a variety of mainly 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. ACKNOWLEDGMENT

The Authors would like to acknowledge the sponsors of this effort: NASA Electronics Radiation Characterization (ERC) Project, a portion of NASA Electronic Parts and Packaging Program (NEPP), NASA Flight Projects, and the Defense Threat Reduction Agency (DTRA).

V. REFERENCES

[1] Donna Cochran, et al. "Total Ionizing Dose and Displacement Damage Results for Candidate Spacecraft Electronics for NASA" submitted for publication in IEEE NSREC03 Data Workshop, July 2003.
[2] M. Wiplich "Brookhaven National Laboratories' (BNL) Tandem Van de Graaf Accelerator Facility", http://tvdg10.phy.bnl.gov/index.html, July 2003.
[3] B. Hyman, "Texas A&M University Cyclotron Institute, K500 Superconducting Cyclotron Facility", http://cyclotron.tamu.edu/facilities.htm, July 2003.
[4] C. M. Castaneda, "Crocker Nuclear Laboratory (CNL) Radiation Effects Measurement and Test Facility," *IEEE NSREC01 Data Workshop*, pp. 77-81, July 2001.
[5] C. C. Foster, S. L. Casey, P. Miesle, N. Sifri, A. H. Skees, K. M. Murray, "Opportunities for Single Event and Other Radiation Effects Testing and Research at the Indiana University Cyclotron Facility," *IEEE NSREC96 Data Workshop*, pp. 84-87, July 1996.
[6] J. S. Melinger, S. Buchner, D. McMorrow, T. R. Weatherford, A. B. Campbell, adn H. Eisen, "Critical evaluation of the pulsed laser method for single event effects testing and fundamental studies," *IEEE Trans. Nucl. Sci.*, vol 41, pp. 2574-2584, Dec 1994.
[7] D. McMorrow, J. S. Melinger, and S. Buchner, "Application of a Pulsed Laser for Evaluation and Optimization of SEU-Hard Designs," *IEEE Trans. Nucl. Sci.*, vol 47, no. 3, pp. 559-565, June 2000.
[8] G. Vizkelethy, B. L. Doyle, F. D. McDaniel, P. Rossi, and P. E. Dodd, "High LET Radiation Effects Microscopy for ICs," *IEEE NSREC02 Data Workshop*, pp. 165-170, July 2001.
[9] NASA/GSFC Radiation Effects and Analysis home page, http://radhome.gsfc.nasa.gov
[10] R. Ladbury and H. Kim "Heavy Ion Latch-up and Transient Test Results for the Analog Devices AD623 Instrumentation Amplifier," http://radhome.gsfc.nasa.gov/radhome/papers/T100202_AD623.pdf, Oct. 2002.
[11] C. Poivey, K. LaBel, J. Forney, H. Kim, "Single Event Transient in LM124 operational amplifier – Heavy ion test report," http://radhome.gsfc.nasa.gov/radhome/papers/TAMU02-03_LM124.pdf, May 2003.
[12] A. Sanders, J. Howard, R. Reed, and J. Forney "Heavy Ion Transient and Latch-up Test Results for the Texas Instruments LM193", http://radhome.gsfc.nasa.gov/radhome/papers/T081102_LM193.pdf, Aug. 2002.
[13] C. Poivey, Jim Howard, Hak Kim, Jim Forney, Steve Buchner, D. McMorrow, "Heavy Ion Single Event Effect Test on the CMOS operational amplifier LMC6484 from National Semiconductors – Heavy ion test report," http://radhome.gsfc.nasa.gov/radhome/papers/2002_LMC6484.pdf, Feb 2002.
[14] C. Poivey, Ken LaBel, Hak Kim, "Single Event Transient in LT1128 operational amplifier – Heavy ion test report," http://radhome.gsfc.nasa.gov/radhome/papers/T1202_LT1128.pdf, Dec 2002.
[15] R. Ladbury and H. Kim, "Heavy Ion Latch-up and Transient and Laser Transient Test Results for the Analog Devices OP293 Operational Amplifier," http://radhome.gsfc.nasa.gov/radhome/papers/T100202_OP293.pdf, Oct. 2002.
[16] A. Sanders, J. Howard, R. Reed, and J. Forney, "Heavy Ion Transient and Latch-up Test Results for the Analog Devices OP42 Operational Amplifier," http://radhome.gsfc.nasa.gov/radhome/papers/T081102_OP42.pdf, Aug. 2002.
[17] R. Ladbury and H. Kim, "Heavy Ion Latch-up and Transient Test Results for the Analog Devices OP727 Operational Amplifier," http://radhome.gsfc.nasa.gov/radhome/papers/T100202_OP727.pdf, Oct. 2002.
[18] R. Ladbury and H. Kim, "Heavy Ion Latch-up and Transient Test Results for the Texas Instruments OPA2347 Operational Amplifier," http://radhome.gsfc.nasa.gov/radhome/papers/T100202_OPA2347.pdf, Oct. 2002.
[19] S. Buchner, H. Kim, C. Zincke, R. Hu, and D. Rapchun, "Proton Testing of the Supertex HV583 128-Channel Serial-to-Parallel Converter with Push-Pull Outputs," http://radhome.gsfc.nasa.gov/radhome/ papers/D040402_HV583.pdf, Apr. 2002
[20] J. Howard, Z. Kahric, H. Kim, and T. Irwin, "Single Event Transient and Destructive Single Event Effects Testing of the Linear Technology LTC1149 Step-Down Switching Regulator," http://radhome.gsfc.nasa.gov/radhome/papers/T081102_LTC1149.pdf, Aug. 2002.
[21] C. Poivey and Z. Kahric, "Heavy ion Single Event Effects test of 4A Adjustable Switching regulator MSK5042 from M. S. Kennedy," http://radhome.gsfc.nasa.gov/radhome/papers/B061702_MSK5042.pdf Jun. 2002.
[22] K. Li, R. Stone, M. Xapsos, and S. Buchner, "Laser Testing of CULPRiT RS Encoder and USES Compression Chips," http://radhome.gsfc.nasa.gov/radhome/papers/NRL060702_CULPRiT.pdf, Jun. 2002.
[23] J. Titus and R. Ladbury, "NAVSEA Crane Radiation Test Report Test Report No.: NSWC C6054-IRF640-0001-SEGR," http://radhome.gsfc.nasa.gov/radhome/papers/B053102_IRF640.pdf, May 2002.
[24] J. Titus and R. Ladbury, "NAVSEA Crane Radiation Test Report Test Report No.: NSWC C6054-IRL110-0001-SEGR," http://radhome.gsfc.nasa.gov/radhome/papers/B053102_IRL110.pdf, May 2002.
[25] S. Kniffin, C. Palor, and M. Xapsos, "Heavy Ion Single Event Effects Test Results for Three Candidate 22V10 Reprogrammable Logic Devices," http://radhome.gsfc.nasa.gov/radhome/papers/B030402_22V10.pdf, Mar. 2002.
[26] J. Howard, A. Lanham, L. Dougherty, L. Nguyen, J. Roman, and T. Irwin, "Proton and Heavy Ion Single Event Effects Testing of the Motorola ColdFire (MCF5307) Processor," http://radhome.gsfc.nasa.gov/radhome/papers/I060602_TAMU_MCF5307.pdf, Jun. 2002.
[27] J. Howard, M Carts, J. Forney, and T. Irwin, "Single Event Transient and Destructive Single Event Effects Testing of the Linfinity SG1525A Pulse Width Modulator Controller," http://radhome.gsfc.nasa.gov/radhome/papers/T081102_SG1525A.pdf, Aug. 2002.

[28] J. Howard, L. Nguyer, L. Dougherty, A. Lanham, J. Roman, and T. Irwin, "Proton Testing of the Hitachi SH-4 Processor," http://radhome.gsfc.nasa.gov/radhome/papers/I060602_SH4.pdf, Jun. 2002.

[29] R. Ladbury, R. Reed, and H. Kim, "Agile-Input Single Event Upset Testing of the SPT7760 Analog to Digital Converter from Signal Processing Technologies," http://radhome.gsfc.nasa.gov/radhome/papers/T091202_SPT7760.pdf, Sept. 2002.

[30] R. A. Reed, P. W. Marshall, G. Niu, J. Cressler, G. Vizkelethy, P. Dodd, R. Krithivasan, and N. Shah, "Trip Report on Microbeam Testing of SiGe Heterojunction Bipolar Transistors (HBTs) Fabricated in IBM 5HP, 6HP and 7HP," http://radhome.gsfc.nasa.gov/radhome/papers/SNL092302_SiGe_HBT.pdf, Sept. 2002.

[31] M. Varadharajaperumal, G. Niu, R. Krithivasan, J. D. Cressler, R. A. Reed, P. W. Marshall, G. Vizkelethy, P. E. Dodd and A. J. Joseph, "3D Simulation of Heavy-Ion Induced Charge Collection in SiGe HBTs," accepted for publication *IEEE Trans. on Nucl. Sci.*, Dec 2003.

[32] R. Reed, P. W. Marshall, J. Pickel, M. A. Carts, T. Irwin, G. Niu, J. Cressler, R. Krithivasan, K. Fritz, P. Riggs, J. Prairie, B. Randall, B. Gilbert, G. Vizkelethy, P. Dodd, K. LaBel, "Broad Beam and Ion Microprobe Studies of Single-Event Upsets in High Speed 0.18mm Silicon Germanium Heterojunction Bipolar Transistors and Circuits," accepted for publication *IEEE Trans. on Nucl. Sci.*, Dec 2003.

[33] S. Buchner, M. Carts, and D. McMorrow, "Results of Pulsed Laser Testing of the AD8151 Crossbar Switch," http://radhome.gsfc.nasa.gov/radhome/papers/NRL092402_AD8151.pdf

[34] J. Howard, L. Dougherty, J. Roman, A. Lanham, L. Nguyen, and T. Irwin, "Proton Testing of the Zarlink Semiconductor GP2021 GPS 12-Channel Correlator," http://radhome.gsfc.nasa.gov/radhome/papers/I060602_GP2021IG.pdf, Jun. 2002.

[35] C. Poivey and J. Forney, "Heavy ion Single Event Effects test of Power Supply for GaAs power amplifier TPS9103 from Texas Instruments," http://radhome.gsfc.nasa.gov/radhome/papers/B061702_TPS9103.pdf, Jun. 2002.

[36] J. Patterson "SEE testing of the Samsung KM48C8000 64 Mbit DRAM," http://radhome.gsfc.nasa.gov/radhome/papers/T0802_KM48C8000.pdf, 2002.

[37] J. Howard, M. Carts, and H. Kim, "Single Event Latchup Testing of the AD5334 Analog Devices Digital to Analog Converter," http://radhome.gsfc.nasa.gov/radhome/papers/T031302_AD5334.pdf, Mar. 2002

[38] S. Kniffin, Z. Kahric, S. Buchner, "Laser Single Event Effects Test Results for Analog Devices AD7414 Temperature Sensor," http://radhome.gsfc.nasa.gov/radhome/papers/NRL060702_AD7414.pdf, Jun. 2002.

[39] J. Howard, M. Carts, and H. Kim, "Single Event Latchup Testing of the AD7664 Analog Devices Analog to Digital Converter," http://radhome.gsfc.nasa.gov/radhome/papers/T120202_AD7664.pdf, Dec. 2002.

[40] J. Howard, J. Forney, Tim Irwin and H. Kim, "Proton Single Event Latchup Testing of the AD7664 Analog Devices Analog to Digital Converter, http://radhome.gsfc.nasa.gov/radhome/papers/I021503_AD7664, Feb. 2003.

[41] C. Poivey, H. Kim, "Heavy ion Single Event Effects test of the temperature sensor TMP36 from Analog Devices," http://radhome.gsfc.nasa.gov/radhome/papers/B061702_TMP36.pdf, Jun. 2002.

[42] R. Reed, C. Palor, "Single Event Latchup Test Results IBM 5HP CMOS Ring Oscillator," http://radhome.gsfc.nasa.gov/radhome/papers/T032802_5HP.pdf, Mar. 2002.

[43] J. Howard, L. Dougherty, J. Roman, A. Lanham, and L. Nguyen, "Proton Testing of the Vectron CO-566 Oscillator," http://radhome.gsfc.nasa.gov/radhome/papers/I060602_CO566.pdf, Jun. 2002

[44] J. Howard, L. Dougherty, J. Roman, A. Lanham, and L. Nguyen, "Proton Testing of the Vectron CO-718S Oscillator," http://radhome.gsfc.nasa.gov/radhome/papers/I060602_CO718S.pdf, Jun. 2002.

[45] C. Poivey, J. Howard, S. Buchner, K. LaBel, J. Forney, H. Kim, A. Assad, "Development of a test methodology for single event transients (SET) in linear devices," *IEEE Trans. on Nucl. Sci.*, vol. 48, pp. 2180-2186, Dec 2001.

[46] S. Buchner, D. McMorrow, C. Poivey, J.W. Howard Jr., R.L. Pease, M. Savage, L. Massengill, and Y. Boulghassoul, "Comparison of Single Event Transients Induced in an Operational Amplifier (LM124) by Pulsed Laser Light and a Broad Beam of Heavy Ions," submitted for publication to European Conference on Radiation and its Effects on Components and Systems (RADECS), Sept 2003.

[47] Milton J. Boden, International Rectifier, El Segundo, CA, personal communication, 2003.

[48] S. Buchner, J. Howard, and M. Carts, "Heavy-Ion Testing of the AD8151 Cross-Point Switch," http://radhome.gsfc.nasa.gov/radhome/papers/T031502_AD8151.pdf, Mar. 2002.

[49] S. Buchner, J. Howard, M. Carts, and K. LaBel "Single-Event Testing of the AD8151 Digital Crosspoint Switch," http://radhome.gsfc.nasa.gov/radhome/papers/T031502_AD8151_paper.pdf, Mar. 2002.

[50] P. W. Marshall, M. Carts, and S. Buchner, "Proton Testing of the AD8151 Cross-Point Switch," http://radhome.gsfc.nasa.gov/radhome/papers/D013102_AD8151.pdf, Jan. 2002.

[51] Martha V. O'Bryan, et al., "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics," IEEE NSREC 2002 Data Workshop, pp. 82-105, July, 2002.

[52] S. Buchner, M. Carts, D. McMorrow, H. Kim, P. Marshall and K. LaBel, "Characteristics of Single-Event Upsets in a Fabric Switch (AD8151)," submitted for publication to European Conference on Radiation and its Effects on Components and Systems (RADECS), Sept 2003.