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Recent Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics

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Abstract-- We present data on the vulnerability of a variety of candidate spacecraft electronics to proton and heavy-ion induced single-event effects and proton-induced damage. Devices tested include optoelectronics, digital, analog, linear bipolar, hybrid devices, Analog-to-Digital Converters (ADCs), Digital-to-Analog Converters (DACs), and DC-DC converters, 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) and proton-induced damage 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), single event transient (SET), and proton damage (ionizing and non-ionizing).

II. TEST TECHNIQUES AND SETUP

A. Test Facilities

All SEE and proton-induced damage tests were performed between February 2000 and February 2001. Heavy-Ion experiments were conducted at the Brookhaven National Laboratories Single-Event Upset Test Facility (SEUTF) and at Texas A&M University Cyclotron (TAMU). The SEUTF uses a twin Tandem Van De Graaf accelerator while the TAMU facility uses a 88" Cyclotron. Both facilities are suitable for providing various ions and energies for testing. At both facilities, test boards containing the device under test (DUT) were mounted in the test chamber. For heavy ions, the DUT was irradiated with ions with linear energy transfers (LETs) ranging from 1.1 to 120 MeV·cm²/mg, with fluences from 1x10⁵ to 1x10⁷ particles/cm². Fluxes ranged from 1x10² to 1x10⁵ particles/cm² 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 ion beam onto 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 and damage tests were performed at three facilities: the University of California Davis (UCD) Crocker Nuclear Laboratory (CNL), TRI-University Meson Facility (TRIUMF), and the Indiana University Cyclotron Facility (IUCF). Proton test energies incident on the DUT are listed in Table II. Typically, the DUT was irradiated to a fluence from 1×10^{10} to 1×10^{11} particles/cm², with fluxes on the order of 1×10^{8} particles/cm² per second.

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The pulsed-laser facility at the Naval Research Laboratory was used to generate single-event transients in integrated circuits. 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 of its intensity at the surface) of 2 microns. A pulse rate of 100 Hz was chosen. The DUT was mounted on a 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.

Table I: Heavy Ion Test Facilities
Facility
Brookhaven National Laboratories (BNL) Single-Event Upset Test Facility (SEUTF)
Texas A&M University Cyclotron (TAMU)

	lon	Energy, MeV	LET in Si, MeV•cm²/mg	Range in Si, µm
BNL	C ¹²	102	1.42	193
	O ¹⁶	131	2.53	145
	F ¹⁹	145	3.31	126
	Si ²⁸	203	7.55	85.3
	Cl ³⁵	224	11.1	68.5
	Ti ⁴⁸	253	18.1	53.2
	Ni ⁵⁸	280	26.3	44.3
	Br ⁷⁹	305	36.9	38.7
	I ¹²⁷	370	60.1	34.3
TAMU	Ne ²⁰	298	2.5	331.0
	Ar ⁴⁰	599	7.4	243.7
	Kr ⁸⁴	1260	25.1	154
	Xe ²⁹	1935	47.1	127
	Au ¹⁹⁷	390	84.1	30.2
	* O ¹⁶	880	0.59	3607
	* Ar ⁴⁰	1980	3.0	1665
		* 55 Me	V per nucleon tun	e

Table	III:	Proton	Test	Facilities	and	Particles

Facility	Particle	Particle Energy, (MeV)
University of California at Davis (UCD) Crocker Nuclear Laboratory	Proton	26.6-63
TRI-University Meson Facility (TRIUMF)	Proton	50-500
Indiana University Cyclotron Facility (IUCF)	Proton	54-197

Table IV: 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	
Goddard Space Flight Center Radiation Effects Facility (GSFC REF)	

B. Test Method

Unless otherwise noted, all tests were performed at room temperature and 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 was 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.

Heavy ion SEE sensitivity experiments include measurement of the saturation cross sections and the Linear Energy Transfer (LET) threshold (the minimum LET value to cause an effect at a fluence of 1x107 particles/cm2).

2) SEE Testing - Proton

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.

SEE 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. [1]

3) Proton Damage Testing

Proton damage tests were performed on biased devices with functionality and parametrics being measured either continually during irradiation or after step irradiations (for example, every 10 krad (Si), or every 1×10^{10} protons).

Displacement damage test guidelines are currently under development. Optocoupler characterization approaches used in this study are found in [1]

4) Pulsed-Laser Facility Testing

The pulsed-laser facility at the Naval Research Laboratory was used to generate single-event transients integrated circuits. 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 of its intensity at the surface) of 2 microns. A pulse rate of 100 Hz was chosen. The DUT was mounted on a X-Y stage in front of a 100X lens that produced a spot size of about 1.5 microns.

5) TID Testing

TID testing was performed using a Co-60 source at the Radiation Effects Facility at Goddard Space Flight Center. The source is capable of delivering dose rates from 0.003-1.1 Rad(Si)/s, with dosimetry being performed by an ion chamber probe.

III. TEST RESULTS OVERVIEW

Abbreviations and conventions are listed in Table III. Abbreviations for principal investigators are listed in Table IV. SEE test results are summarized in Table V. Unless otherwise noted, all LET_{th}s are in (MeV•cm²/mg) and all cross sections are in cm²/device. This paper is a summary of results. Complete test reports are available online at http://radhome.gsfc.nasa.gov [1].

TABLE V: ABBREVIATIONS AND CONVENTIONS: H = heavy ion test P = proton test (SEE) LET = linear energy transfer (MeV·cm²/mg) LET_{th} = linear energy transfer threshold (the minimum LET value for which a given effect is observed for a fluence of 1x10⁷ particles/cm² - in MeV·cm²/mg) LET_{max} = highest tested LET $LET_{eff} = effective LET$ SEU = single event upset SEL = single event latchup SET = single event transient SEFI = single event functional interrupt DD = displacement damage < = SEE observed at lowest tested LET > = No SEE observed at highest tested LET TID = total ionizing dose $\sigma = cross section (cm²/device, unless specified as cm²/bit)$ σ_{SAT} = saturation cross section (cm²/device, unless specified as cm²/bit) LDC = lot date code CTR = current transfer ratio DAC = digital to analog converter ADC = analog to digital converter LED = light emitting diode DRAM = dynamic random access memory SRAM = static random access memory MOSFET = metal oxide semiconductor field emitter PAL = Programmable array logic device ALU = Arithmetic Logic Unit Vs = Supply voltage IF = Forward current V_F = Forward voltage V_{IN} = Input voltage

TABLE VI: LIST OF PRINCIPAL INVESTIGATORS

Principal Investigator (PI)	Abbreviation
Kenneth LaBel	KL
Robert Reed	RR
Jim Howard	JH
Ray Ladbury	RL
Scott Kniffin	SK
Tony Sanders	TS

TABLE VII: LIST OF CATEGORIES

Category	Implications
1	Relatively hard or immune to SEEs; recommended for spaceflight
2	Somewhat susceptible to SEEs; may need some error detection and correction (EDAC) when used in an application
3	Fairly soft devices that are very susceptible to SEEs; use with great caution. Intensive EDAC may be necessary
4	Not recommended for spaceflight. Destructive conditions, such as latchup, total dose failure, or burnout were seen in these devices at low dose levels.

	TABLE VII: SUMMARY OF SEE TEST RESULTS						
Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results	Cat a at	
ADCe	an an ann an	n an an an an an an Albertan	n an	e <u>i i i i i i i i i i i i i i i i i i i</u>	an a	A3453	
AD1674	ADC	Analog Devices	H: (BNL) JH/RR	SEU; SEL	SEL LET _{th} >37, σ_{sat} <1x10 ⁻⁷ . For positive input: SEU LETth<2.6 σ_{sat} <1.6x10 ⁻³ . For negative input: SEU LET _{th} =5.2 σ_{sat} =2.2x10 ⁻⁴	2	
AD6640	ADC	Analog Devices	H:(BNL) JH/RL/RR	SEU; SEL	SEUs LET _{th} < 1; $\sigma \sim 1-2x10^{-3}$ cm ² per device; $\sigma \sim 1-2x10^{-4}$ cm ² per bit; SEFIs observed; 26.2 < LET _{th} <37; $\sigma \sim 1x10^{-5}$ cm ² per device; No SELs observed; SEL LET _{th} >37	2	
DC-DC Converters				in any in Ny INSEE dia			
AFL12005SX/CH	DC-DC	Lambda	H: (BNL) JH/RR	SET	For Cl(LET=11.4) No transients seen. Saw destructive failure under low-voltage, high-load conditions during irradiation of sector 2. Sectors 1,3,4 not tested.	3	
AFL12012DX/CH	DC-DC	Lambda	H: (BNL) JH/RR	SET	For Br(LET=37) No transients or destructive events seen for high voltage low load. Saw destructive failure under low-voltage, high-load conditions during irradiation of sector 1.	3	
AFL12015DX/CH	DC-DC	Lambda	H: (BNL) JH/RR	SET	For Br(LET=37) No transients seen. No failure in sectors 1,3,4. Failure at low-voltage high-load in sector 2 led to a destructive event.	3	
DVHF2803R3SF	DC/DC	Virginia Power Technology	H:(BNL) JH	SET/DD	For Br(LET=37) No Destructive events seen. Destructive event at LET=60 and full loading. Small SETs observed at low rate.	2	
LCM-120	DC-DC	Interpoint	H:(BNL) JH/RR Laser:(NRL) JH TID:(GSFC-REF)TS	SET; SEL; TID	HI: SET LETth <2.6, $\sigma_{sat} \sim 10^{-3}$ SETs 50-100 µs in duratiion P: No SETs observed to σ <3x10 ⁻¹² P: (UCD) TID failure observed at proton doses of ~ 20 and 25 krads (Si)	2	
MDI3051RES05ZF	DC-DC	Modular Devices Inc.	H:(BNL) JH/RR	SET	For Cl(LET=11.4) No transients seen. Sector 2: failure at low-voltage high-load led to a destructive event.	3 •	
MDI3051RES12ZF	DC-DC	Modular Devices Inc.	H:(BNL) JH/RR	SET	For CI(LET=11.4) No transients or failures. For Ni(LET=28) no SETs in Sector 2: failure at 120 volts high- load led to a destructive event.	3	
MDI3051RES15ZF	DC-DC	Modular Devices Inc.	H:(BNL) JH/RR	SET	For CI(LET=11.4) No transients or failures. For Ni(LET=28) no SETs observed. Sector 2: failure at 120 volts moderate-load led to a destructive event.	3	

Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results	Cat
Linear Bloolar		ing she sugerservite and the set of the set				-
LM-124	Op Amp	National Semiconductor	Laser:(NRL) JH	SET	Several SETs observed, see poster [2] for application specific test results	2
LM-139	Comparator	National Semiconductor	H: (BNL) JH	SET	Transients observed; depended on input differential voltage, see poster [2]	2
HS-139	Comparator	Harris/Intersil	H:(BNL) JH	SET	Transients observed; depended on input differential voltage, see poster [2]	2
LM-148	Op Amp	Fairchild	P:(CNL) SK/RR	SET;SEU	HI: No SEL to I(LET=60); SET LET _{th} <2.6, σ_{sat} =2x10 ⁻⁵ ; Various pulse height and width P: No SETs observed, no SEUs observed; no performance degradation to 7.44x10 ¹¹ protons/cm ²	2
Board Tests			A THE REAL PROPERTY.	A BARAN		
Pentium III	Processor	Intel	P:(IU) JH H: (TAMU) JH	SEE; TID;	SEL: No SELs observed to LET>20; No SELs observed for 200 MeV proton; SEU: non-fatal errors were observed, SEFI: were observed. See poster [3]	3
AMD K7	Processor	Advanced Micro Devices	P:(IU) JH H: (TAMU) JH	SEU/SEL	No SELs observed; SEU: non-fatal errors were observed, SEFI: were observed. See poster [3]	4
Meccillanacousta						
IL710	DAC	Non Volatile Electronics	H:(BNL) RR	SEL; SET	No SEL seen LET _{th} >60, SETs observed beginning near LET=11, σ_{sat} =2.5x10 ⁻⁵	2
Mii42142	Power Op Amp	Micropac	H:(BNL) RR/SK P:(CNL) RR/SK	SET; SEGR	HI:SET _{th} <11.4 (dependent on bias) conditions; SEGR _{th} <37 (application specific) P: No SETs obseved	4
Mii53124	Power MOSFET Optocoupler	Micropac	H:(BNL) RR/SK	SET; SEGR	No SET; SEGR at LET=60	3
Mii53250	Relay	Micropac	H:(BNL) RR/SK	SET; SEGR	No SET; SEGR at LET _{th} >60	3
Mii53253	Power MOSFET Optocoupler	Micropac	H:(BNL) RR/SK	SEGR	No SET; SEGR at LET=60	3
Mii53258	Relay	Micropac	H:(BNL) RR/SK	SET; SEGR	No SET; SEGR at LET=60	3
SPT7760	ADC 1 GSPS	Signal Processing Tech.	H:(TAMU)RR	SEU; SEFI Functional Failure	Functional failure occurred at LET=84, power cycle was required to recover. σ =2x10 ⁻² for functional failure. No functional failure at LET=50 to a fluence of 1x10 ⁷ p/cm ² LET _{th} <1.8, σ _{set} ~2x10 ⁻³ cm ² /device	2
6651	Optocoupler	Agilent (Hewlett Packard)	P:(UCD) SK	SET	SETs observed with angular dependence	3

TABLE VII	(CONT.):	SUMMARY O	F SEE	TEST	RESULTS
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Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results
Displacement Dan	nage Test Res	alts:	in the second seco	NALATION IN A CONTRACTOR OF A C	
OD800	LED	optodiode	P:(CNL) SK/RR	DD	Output power showed 20% degradation at 6.6x10 ¹⁰ p/cm ²
P2824	Optocoupler	Hamamatsu	P:(UCD) SK	DD	CTR degradation observed at 1x10 ¹⁰ p/cm ² (flight lot)
66099	Optocoupler	Micropac	P:(UCD) SK	DD	CTR degradation observed at 2.5x10 ¹¹ p/cm ² (non flight lot)
4N49 (LDCs 9803 & 9819)	Optocoupler	Micropac	P:(UCD) SK	DD	No V_{CE} degradation to 5×10^{10} p/cm ² . Some V_{CE} degradation was seen for some conditions at 1×10^{11} p/cm ²
4N49	Optocoupler	Micropac	P:(UCD) SK	DD	CTR degradation observed at 3x10 ¹⁰ p/cm ² (non flight lot)
4N49S	Optocoupler	Micropac	P:(UCD) SK	DD	Some CTR degradation observed at 1x10 ¹² p/cm ² (flight lot)
6N134	Optocoupler	Micropac	P:(UCD) SK	DD	CTR degradation observed at 1×10^{12} p/cm ² (non flight lot)
6N140	Optocoupler	Micropac	P:(UCD) SK	DD	CTR degradation observed at 7.5×10^{11} p/cm ² (flight lot); and at >1x10 ¹² (non flight lot)
Mii42142	Power Op Amp	Micropac	P:(CNL) RR/SK	DD	No SET/SEGR to 7.44x10 ¹² p/cm ² ; 18% drop in output current after 7.44x10 ¹² p/cm ²
Mii53124	Power MOSFET Optocoupler	Micropac	P:(CNL) RR/SK	DD	No SET, no significant degradation to 1x10 ¹² p/cm ²
Mii53250	Relay	Micropac	P:(CNL) RR/SK	DD	No SET, no significant degradation to 1x10 ¹² p/cm ²
Mii53253	Power MOSFET Optocoupler	Micropac	P:(CNL) RR/SK	DD	No SET, no significant degradation to 1x10 ¹² p/cm ²
Mii53258	Relay	Micropac	P:(CNL) RR/SK	DD	No SET, no significant degradation to 1x10 ¹² p/cm ²

TABLE VIII: SUMMARY OF DISPLACEMENT DAMAGE (DD) TEST RESULTS

Part Number	Function	Manufacturer	Particle: (Facility)P.I.	Testing Preformed	Summary of Results**	Cat
Linear Bipolar	Devices:			and and a second se Second second second Second second	And a loss and a state of the s	Alva Y.
CMP402	Comparator	Analog Devices	H:(BNL) RL/RR	SEL	No SEL seen up to LET _{eff} =119.8	1
OP16	Op Amp	Analog Devices	H:(BNL) JH/RL	SEL	No SEL seen up to LET _{eff} =37.3	1
OP37	Op Amp	Analog Devices	H:(BNL) JH/RL	SEL	No SEL seen up to LET _{eff} =59.9	1
OP42	Op Amp	Analog Devices	H:(BNL) JH/RL	SEL	No SEL seen up to LET _{eff} =37.3	1
ADC/DAC:	مېر مېر يېمېرېنې ورو . مېره د ورومې ورو	an a	e en la companya de la companya de la companya de la comp de la companya de la c	1973 - 1995 -		34
AD7535	DAC	Analog Devices	H:(BNL) JH/RR	SEL	No SEL to LET _{eff} =74.6	1
AD7564	DAC	Analog Devices	H:(BNL) RL/RR	SEL	No SEL to LET _{eff} =59.9	1
AD7664	ADC	Analog Devices	H:(BNL) JH	SEL	SEL LET _{th} ~ 8-10, $\sigma = 2-3 \times 10^{-4}$	3
AD7854	ADC	Analog Devices	H:(BNL) RL/RR	SEL	SEL 6.7 <let<sub>th<11.4, σ_{sat} <1x10⁻³.</let<sub>	4
AD7858	ADC	Analog Devices	H:(BNL) RL/RR	SEL	SEL LET _{th} 11.4-22.8, $\sigma_{sat} < 1 \times 10^{-3}$.	4
AD7888	ADC	Analog Devices	H:(BNL) RL/RR	SEL	SEL LET _{th} 16.7-22.8, σ _{set} <1.3x10 ⁻⁵ .	4
Miscellaneous					Providence in the second s	5.51
ADG704	Multiplexer	Analog Devices	H:(BNL) RL/RR	SEL	SEL LET _{th} ~16, σ _{sat} <1.1x10 ⁻⁴ .	1
AMP01	Inst. Amp	Analog Devices	H:(BNL) RL/KL/JH	SEL	Hard Failure LET _{th} >32.7; more likely at normal incidence	3
					Susceptible to SET [4]	ļ
INA117	Diff. Amp	TI/Burr-Brown	H:(BNL) RL	SEL	No SEL seen up to LET _{eff} =119.8	1
MAX313	Switch	Maxim	H:(BNL) JH/RR	SEL	No SEL seen up to LET _{eff} =59.9	1
MAX4503	CMOS switch	Maxim	H:(BNL) JH	SEL	No SEL seen up to LET _{eff} =119.8	2
MAX4528	CMOS analog switches	Maxim	H:(BNL) RL/RR	SEL	No SEL seen up to LET _{eff} =59.9	1
MAX4583	CMOS analog switches	Maxim	H:(BNL) RL/RR	SEL	No SEL seen up to LET _{eff} =59.9	1
MAX4617	MUX	Maxim	H:(BNL) RL	SEL	No SEL seen up to LETeff=119.8	1
MAX584	Vref	Maxim	H:(BNL) RR	SEL	No SEL seen up to LET _{eff} = 37.3	1

Note: * Rating applies only for SEL not for other SEE concerns.

** All parts tested to a minimum fluence of 1.0 x 10⁷ particles/cm²

IV. SEE TEST RESULTS AND DISCUSSION

A. ADCs:

1) AD1674

The Analog Devices AD1674 analog-to-digital converter (ADC) was tested for SEU and SEL at Brookhaven National Laboratory using ions with effective LETs ranging from 2.6 MeV·cm2/mg (Oxygen) to approximately 56 MeV·cm²/mg (Bromine at 45 degrees). No SEL events were observed for normal incidence Br up to a fluence of 1×10^7 ions/cm², or for a fluence of 8x10⁵ ions/cm² Br ions incident at 45 degrees. To investigate SEUs in the AD1674, the output of the device under test (DUT) was compared to that of a reference chip located outside the beam and given an identical input to that of the DUT. Device upset cross section vs. LET was measured for both positive and negative inputs to the ADCs. For all tests, the lowest two significant bits were masked off to avoid counting noise as upsets.

For positive device input, the threshold LET was about 2-3, and the limiting cross section was approximately $1.6 \times 10^{-3} \text{ cm}^2$. For negative input, the threshold LET for upset was found to be about 5-8, with a limiting cross section of about 2.2x10⁻⁴cm², about an order of magnitude lower than for positive input. This indicates that the mechanisms underlying upsets under conditions of positive input and negative input are probably distinct. For additional information refer to the GSFC radiation group website. [1]

The hardware setup for this testing is show via a block diagram pictured in Figure 1. The data taken for the case of 4 masked bits versus 2 bits is featured in Figure 2. [5 ref B080100.pdf]



Figure 1. Block diagram of the experimental setup for testing the AD1674 ADC.



2) AD6640

The Analog Devices AD6640 12-bit ADC was tested for single-event upset (SEU), single-event latchup (SEL) and single-event functional interrupt (SEFI). The AD6640 is a 65 MHz, 12-bit ADC fabricated in Analog Devices XFCB dielectrically isolated bipolar process. Because of the high speed required in this test (15-40 MHz), noise was a concern, and several steps were taken to ensure that noise was kept to a minimum. Even so, several least significant bits had to be masked off to avoid triggering on noise. The number of masked bits varied from 3 at the lowest frequencies up to 5 at the higher frequencies. SEUs were seen even for carbon ions, which have LET=1.44 MeV·cm²/mg, indicating that the LET threshold is less than 1 MeV·cm²/mg. The limiting cross section for SEU was seen to be about 1-2x10⁻³cm² per device. When the cross sections were calculated per bit, based on the number of bits available to cause upsets (that is 12 - the number of masked bits), these per bit cross sections gave a fairly tight distribution with limiting value on the order of 1- $2x10^{-4}$ cm² per bit.

Single-event functional interrupts were also observed. These events caused every conversion to be in error after they occurred until they were reset by cycling power to the device. The threshold LET for these SEFIs was between 26.2 and 37 MeV•cm²/mg, and the limiting cross section was on the order of 1×10^{-5} cm² per device. No evidence of SEL was observed up to a fluence of 2×10^{6} ions/cm² for Br⁷⁹. [6 ref B111600a.pdf]

B. DC-DC Converters:

1) AFL12005SX/CH

The AFL12005SX/CH Advanced Analog Lambda, Inc. DC/DC Converter was tested for susceptibility to destructive single event effects and single-event transients at Brookhaven National Laboratory using Cl^{35} ions with an LET of 12.

The DC/DC converter was tested under bias conditions of 126 volts with a load of approximately 7.7 watts and 113 volts with a load of approximately 56.4 watts. The DC/DC converter was de-lidded and the active device area divided into four circular regions. With the active section of the converter in the left half of the device, the four regions, numbered 1 through 4. Region #2 contained the power MOSFETs.

For the first of the conditions (high voltage and low loading), no single event transients were observed at the output voltage port and no destructive events were observed for any of the four regions. However, the device experienced a destructive event when region #2 was exposed under the second set of conditions. That event resulted in the output dropping to zero volts and a loss of functionality that was not recovered after a power cycle. No indication was seen of any transient event, the device's first event was destructive. This indicates that the device is susceptible to destructive errors with a threshold LET less than or equal to 12 with a cross section that cannot be determined from the current study. [7 ref B080100a.pdf]

2) AFL12012DX/CH

The AFL12012DX/CH Advanced Analog Lambda, Inc. DC/DC Converter was tested for single event destructive and transient susceptibility at Brookhaven National Laboratory using Br^{79} ions with an LET of 37.

The DC/DC converters were tested under bias conditions of 120 and 126 volts with a load of approximately 7.7 watts and 116 volts with a load of approximately 57.6 watts. The DC/DC converter was de-lidded and the active device area divided into four circular regions. With the active section of the converter in the left half of the device, the four regions, numbered 1 through 4, start in the upper left hand corner and proceed clockwise. The power MOSFETs were primarily located in region #2, but may have overlapped into region #1. For the first of the conditions (high voltage and low load), no single event transients were observed at the output voltage port and no destructive events were observed for any of the four regions. However, the device did experience a destructive event when region #1 was exposed under the second set of conditions. That event resulted in the output dropping to zero volts and functionality being lost. Cycling power did not return the device to functionality. This

indicates that this device is susceptible to destructive failure with a threshold LET less than 37 and a cross section that cannot be determined from this study. The susceptibility of the AFL12005SX/CH) to destructive failure with threshold LET less than 12 may indicate that the threshold LET is substantially lower than 37. [8 ref B080100b.pdf]

3) AFL12015DX/CH

The AFL12015DX /CH Advanced Analog Lambda, Inc. DC/DC Converter was tested for single event destructive and transient susceptibility at Brookhaven National Laboratory using ions with an LET of 37 (Br^{79}).

The DC/DC converters were tested under bias conditions of 126 volts with a load of approximately 7.8 watts and 116, 117, and 113 volts with a load of approximately 55.6 to 58.5 watts. The DC/DC converter was de-lidded and the active device area divided into four circular regions. With the active section of the converter in the left half of the device, the four regions, numbered 1 through 4, start in the upper left hand corner and proceed clockwise. Region #2 contained the power MOSFETs.

For the first of the conditions (high voltage and low load), no single event transients were observed at the output voltage port and no destructive events were observed for any of the four regions. However, the device did experience a destructive event when region #2 was exposed under bias conditions of 116, 117, and 113 volts at a loading of approximately 55.6 to 58.5 watts. That event resulted in a loss of device functionality and a drop of the device output to zero volts. Functionality could not be restored by cycling power. No indication was seen of any transient event; the device's first event was destructive. This result indicates that the device is susceptible to a destructive failure with a threshold LET less than or equal to 37, and with a cross section that cannot be determined from the current study. The fact that another AFL part (AFL12005SX/CH) exhibited a similar destructive failure at an LET of 12 suggests that the threshold LET could be considerably lower than 37. [9 ref B080100c.pdf]

4) DVHF2803R3SF

The DVHF2803R3SF/HBM DC/DC Converters from Virginia Power Technology, Inc. were tested to determine their susceptibility to destructive single event effects and single-event transients at Brookhaven National Laboratory using ions with LETs of 37 (Br^{79}) and 59.8 (I^{127}).

The DC/DC converters were tested under bias conditions of 28 and 35 volts with loads of approximately 1.65 and 9.9 watts. The DC/DC converter was de-lidded and the active device area was divided into three circular regions. With the device as shown in Figure 3X, region 1 contains the power devices and is located near the upper right-hand corner, region 2 is the upper left-hand side and region 3 the lower left-hand side. The lower right contained only passive devices.



Figure 3. Photograph of a de-lidded DVHF2803R3SF converter.

For these converters both destructive events and transients were observed, albeit at high LET values. Because the destructive events may be of greater concern, they will be discussed first. DUTs 1 and 2 were test with Bromine ions (LET = 37) at low and high load conditions and with both nominal (28 volts) and high (35 volts) input conditions. Under all of these conditions, no destructive events were observed. For runs with Iodine ions (LET = 59.8), destructive events were observed. However, these events occurred only when the device was operated at full load. Both DUTs passed at Iodine under low-load conditions. Additionally, DUT 2 passed one run with input voltage 28 volts and high load with lodine, but failed on the next run when the input voltage was raised to 35 volts. The location of the power devices and the structures surrounding them made it impossible to irradiate the parts at angles other than normal incidence, so effective LETs between the nominal ion LETs could not obtained. Therefore, the threshold LET for destructive events is between 37 and 59.8. For the two destructive events observed, the average cross section for the event is approximately 2 x 10⁻⁶ cm², although the low statistics and uncertainties in the final fluence dictate large error bars for this number.

Transient errors were also observed as positive pulses of magnitude up to 500 mV superimposed on the output voltage. Transient durations were on the order of a microsecond, although the exact duration could not be determined because of limitations on the timescales of the digitizing scope. Transients were observed on both devices (although DUT 2 was approximately an order of magnitude more sensitive) at both LET = 37 and 59.8 MeV \cdot cm²/mg. This indicates that the threshold LET for these events is less than 37. No lower bound can be determined from the current data. However, cross sections were small (10⁻⁷ to 10⁻⁵ cm²), suggesting a fairly low event rate even for low LET thresholds. Moreover, the short duration of the transients suggests that they could be substantially mitigated by filtering. These considerations lowered the priority of exact determination of the LET threshold for these transients. [10 ref B111500a.pdf]

5) LCM-120

SET and SEL testing were performed on the Interpoint LCM-120 line conditioning module. This device was tested at

three facilities, Brookhaven National Laboratory, Naval Research Laboratory Plused Laser SEE test facility, and University of California Crocker Nuclear Laboratory.

Based on these test runs, it has been determined that the LCM-120 is susceptible to single event transients on the output of the device when exposed to heavy ions. The threshold for the transients is <2.6 (lowest LET used) and the saturation cross section is approximately 10^{-3} cm². The transients all lasted on the order of 50-100 microseconds. The transients took the form of voltage drops from the nominal output voltage of 24 volts, and they ranged from a volt to approximately 18 volts. The large voltage transients exhibited very rapid fall times, and because of limitations of the digital scope to capture such rapid events, it cannot be ruled out that the drop was all the way to ground.

Despite the very low threshold LET observed for heavy ions, proton testing at UCD did not reveal any proton induced SET sensitivity to a cross section of less than 3 x 10^{-12} cm². The sensitivity to proton-induced SETs at lower cross sections could not be evaluated due to the total dose restrictions of the LCM-120. Total dose failure was observed at the UCD facility at proton doses of approximately 20 and 25 krads for the two devices tested there [11 ref B080100d.pdf]. TID testing was performed on the LCM-120, the device performed within specifications up to 28Krads(Si) [12 ref G052200.pdf].



Figure 4. Plot of LCM-120 SET cross section as a function of the ion LET. Data for two Device s Under Test (DUT) are shown.



Figure 5. Photograph of the LCM-120 device with the four sensitive components circled in yellow.

6) MD13051RES05ZF

The MDI3051RES05ZF DC/DC Converter from Modular Devices, Inc. was tested for susceptibility to single-event induced transients and destructive events induced at the Brookhaven National Laboratory Single Event Effects Test Facility.

The DC/DC converter was tested under bias conditions of 126 volts with a load of approximately 7 watts, and 113 volts with a load of approximately 52.9 watts. The DC/DC converter was de-lidded and the active device area divided into two circular regions. With the active section of the converter in the upper left quadrant of the device, region 1 is in the upper left-hand corner and region two is to the immediate right of region 1. Region #2 contained the power MOSFETs.

For the first of the conditions (126 volts and a load of 7 watts), no single event transients were observed at the output voltage port and no destructive events were observed for either of the two regions. However, the device did experience a destructive event when region #2 was exposed under the second set of conditions (113 volts, 52.9 watts load). That event resulted in the output dropping to zero volts and the Functionality could not be device losing functionality. restored by cycling power. No indication was seen of any transient event, as the device's first event was destructive. This destructive condition occurred for the only LET ion used (LET = 12). These data indicate that the device is susceptible to a single-event induced destructive mechanism with threshold LET less than 12 and a cross section that cannot be determined from the current study. [13 ref B080100e.pdf]

7) MDI3051RES12ZF

The MDI3051RES12ZF DC/DC Converter from Modular Devices, Inc. was tested for susceptibility to single-event induced transients destructive events at the Brookhaven National Laboratory Single Event Effects Test Facility.

The DC/DC converters were tested with an input voltage of 120 volts and loads of approximately 7.8, 18.9, 37.1 and 55.5 watts using a beam of Cl ions (LET=12). Testing was also done at 120 volts and loads of approximately 8, 19.2, 37.6 and 56.3 watts for a beam of Ni ions (LET=26.7). The DC/DC converter was de-lidded and the active device area divided into two circular regions. With the active section of the converter in the upper left quadrant of the device, region 1 was in the upper left-hand corner and region two was to the immediate right of region 1. Region 2 contained the power MOSFETs.

No single-event transients were observed while irradiating region 2 with either ion for any test conditions. Previous testing had indicated that region 1 was not sensitive. No destructive events were observed for the high-load conditions. However, the device did experience a destructive event when region #2 was exposed to Ni when the input was 120 volts and the load was 56.3 watts. That event resulted in the output dropping to zero volts and the device losing functionality. Functionality could not be restored by cycling power. No

indication was seen of any transient event; the device's first event was destructive. This indicates that the device is susceptible to a destructive condition with a threshold LET between 12 and 28. The cross section for this destructive mechanism cannot be determined from this study. [14 ref B080100f.pdf]

8) MDI3051RES15ZF

The MDI3051RES15ZF DC/DC Converter from Modular Devices, Inc. was tested for susceptibility to single-event induced transients and destructive events at the Brookhaven National Laboratory Single Event Effects Test Facility.

The DC/DC converters were tested under conditions of 120 volts input and loads of approximately 8.2, 19.4, 38.3 and 56.6 watts for the Chlorine beam (LET=12). Testing was also done for 120 volts input and loads of approximately 8.2, and 38 watts and 75 volts input and 38.7 watts for the Nickel beam. The DC/DC converter was de-lidded and the active device area divided into two circular regions. With the active section of the converter in the upper left quadrant of the device, regions I was in the upper left-hand corner and region two was to the immediate right of region 1. Region 2 contained the power MOSFETs.

No single event transients were observed at the output voltage port for any of the conditions tested under irradiation by either ion. No destructive events were observed for region #2 under conditions of high load. (Other testing had indicated that region #1 was not sensitive). However, the device did experience a destructive event with a Nickel beam incident on region #2 while the input voltage was 120 volts and the load was 38 watts. That event resulted in the output dropping to zero volts and the device losing functionality. Functionality could not be restored by cycling power. No indication was seen of any transient event; the device's first event was destructive. These data indicate that this device is susceptible to a destructive mechanism with an LET threshold between 12 and 28. The cross section cannot be determined from this study. [15 ref B080100g.pdf]

C. Linear Bipolar Devices:

1) LM-124, LM-139, and HS-139

The National Semiconductor LM-124 Op Amp was tested for transient susceptibility at Naval Research Laboratory Plused Laser SEE test facility.

The National Semiconductor LM-139, and the Harris/Intersil HS-139 Comparators were tested for heavy ion induced transient susceptibility at the Brookhaven National Laboratory Single Event Effects Test Facility.

Transients were observed. For application specific test results see J.W. Howard et al., "Development of a Test Methodology for Single Event Transients (SETs) in Linear Devices," [2].

2) LM-148

The Fairchild LM148 (LDC9905) quad op amp was irradiated with 63MeV protons at UCD/CNL. The device was biased with $V_s = 15V$ and $I_L = 2mA$ and a 10kHz, 10V p-

p sine wave input. No SETs and no performance degradation were observed up to a fluence of $7.44 \times 10^{11} \text{ p/cm}^2$.

The Fairchild LM148 (LDC9905) quad op amp was irradiated with heavy ions at BNL to determine the SET/SEL characteristics of the device. The device was biased with V_s = 15V and I_L = 2mA with a 10kHz, 10V p-p sine wave input. No SELs were observed in testing. The SET LET_{th} = 3.7MeV·cm²/mg and σ_{sat} = 8x10⁻⁴cm². [16 ref D082400.pdf]



Figure 6. Heavy ion SET cross-section data for two LM148 devices.

D. Board Tests:

1) Pentium III

Intel Pentium III processors were tested for SEE and TID at TAMU, and at the IUCF. No SELs observed for LETs up to at least 20. No SELs observed for 200 MeV proton. Non-fatal SEU errors were observed and SEFIs were observed. See J.W. Howard et al., "Total Dose and Single Event Effects Testing of the Intel Pentium III (P3) and AMD K7 Microprocessors". [3] and [17 ref i062100.pdf]

2) AMD K7

AMD K7 processors were tested for SEU and SEL at TAMU and at the IUCF. No SELs were observed. Non-fatal SEU errors were observed and SEFI were observed. See J.W. Howard et al., "Total Dose and Single Event Effects Testing of the Intel Pentium III (P3) and AMD K7 Microprocessors". [3] and [17 ref i062100.pdf]

E. Miscellaneous:

1) IL710

The Non Volatile Electronics (NVE) IL710 digital isolator was tested at BNL to determine its sensitivity to heavy ion induced single-event effects (SEE). Two samples were tested, one manufactured using 1.2 μ m fabrication process and the other manufactured using a 0.6 μ m process.

During testing we observed that the SETs were typically 5ms in duration. Using an iris to modulate the beam size, we were able to focus the beam on the entire DUT or on either the output or the input side of the DUT. The SET cross section obtained when exposing the input side of the DUT are plotted at LET = 37 MeV·cm²/mg. No upsets were observed when exposing the output side to a fluence of 1×10^7 ions/cm². This clearly indicates that the input side of the device is more sensitive to SETs. Neither IL710 type experienced SELs for LETs up to 37. [18 ref B092600.pdf]

2) Mii42142

The Micropac Mii42142 power op amp was irradiated with heavy ions at BNL to determine device susceptibility to SET and other SEE. Irradiation took place under several bias conditions, including combinations of $V_s = 8V$ or 15V and $V_{IN} = 0.1V$, 0.6V or 1.3V. The SET_{TH} = 11.4 MeV•cm²/mg. The $\sigma_{sat} = 9x10^{-3}$ cm² for transients at $V_{IN} = 0.1V$ at both values of V_s (Figures 7 and 8). An SEGR occurred at LET=60 with $V_s = 8V$ and $V_{IN} = 0.1V$. No Proton SETs were observed. [19 ref D120400c.pdf]



Figure 7. Mii42142 SET Cross Section for the indicated input voltages at $V_s = 15V$.



Figure 8: Mii42142 SET Cross Section for the indicated input voltages and $V_s = 8V$.

3) Mii53124 and Mii53253

The Micropac Mii53124 \pm 90V/0.8A, and Mii53253 Dual 90V/0.8A power MOSFET optocoupler hybrids were irradiated with heavy ions at BNL to determine their susceptibilities to SET and other SEE. All devices showed some voltage fluctuations on the input that appeared to be precursors to SEGR. One Mii53124 device did have one current-based anomaly with the LED on. Cycling power reset the device. This anomaly occurred under irradiation with Br) (LET = 37.3) and was not seen under any other conditions. All devices experienced SEGR, which caused the output voltage to drop significantly. Resetting the device did not

return the device to functionality after SEGR. The onset of this effect occurred at 70V with LET = $60 \text{MeV} \cdot \text{cm}^2/\text{mg}$ for both device types. No SETs were observed for either device type. [20 D120400d.pdf]

4) Mii53250

The Micropac Mii53250 40V/10A(2A) optocoupler hybrid solid-state relay was irradiated with heavy ions at BNL to determine device susceptibility to SET and SEE. This device showed no SET or SEGR to a fluence of 1×10^7 particles/cm² with LET = 60MeV•cm²/mg at normal incidence and at 50° to the normal. The device was tested with V₀ = 40V and I₀ = 0.6A. This was deemed to be the worst-case condition as this represents the largest voltage drop from drain-to-source across the MOSFET. This device was also tested with the LED on to determine if there were any other effects; no anomalies were observed. [21 ref D120400e.pdf]

5) Mii53258

The Micropac Mii 53258 120VDC/5A(2A) optocoupler hybrid solid-state relay was irradiated with heavy ions at BNL to determine its susceptibility to SET and other SEE. SEGR occurred in one device under irradiation with iodine ions (LET = 59.9) at normal incidence while the device was biased at 120V (the maximum rated voltage for the part) and I_0 = 0.2A. No SETs were observed in this device. The other devices showed no SET or SEGR to a fluence of 1x10⁷particles/cm² with Br-81 (LET = 37 MeV•cm²/mg) at normal incidence and 50° to the normal with V₀ = 60V and 120V. Nor were SET or SEGR seen for these devices under irradiation with I-127 (LET = 60 MeV•cm²/mg) at normal incidence and 50° with V₀ = 60V with and I₀ = 0.2A in all cases. [21 ref D120400e.pdf]

6) SPT7760

The SPT7760 is an Emitter Coupled Logic (ECL) based 1Gsps (1 giga-sample per second) 8 bit + overflow flash analog-to-digital converter manufactured by Signal Processing Technologies, Incorporated. 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. It is de-multiplexed into two identical ports (labeled ports A and B) each with 9 bits (8 + overflow) plus clock at a maximum output rate of 500 Msps. The aggregate throughput is therefore 1 Gsps. The device is supplied in an 80 pin MQUAD package with the option of MIL-STD-883 screening.

The SPT7760 was tested for susceptibility to heavy ion induced SEUs at TAMU using beams of Ne, Kr and Xe ions. Because the input was a constant dc voltage, the output from the ADC was also constant unless an SEU occurred. As a result, SEUs were identified by comparing each conversion to the previous conversion. Any changes were recorded as SEUs and the data were stored on a PC for post-processing. [22 Ref --Robert's and Paul's RADECS paper 1999 RADECS, p188].

Figure 9 shows results from heavy-ion SEU tests at TAMU. The plot shows measured cross sections for the device for various dc input conditions (-2 to 0 volts), frequencies (10, 100 and 1000 MHz) and LETs (1.28, 20 and 50). No clear dependence of cross section on input voltage or frequency is evident in the data.

Functional failure occurred at LET=84 and a power cycle was required to recover. The cross section for functional failure was approximately $2x10^{-2}$ cm². No functional failures were observed up to LET=50 for a fluence of 1x107 p/cm². The threshold LET for SEU was less than 1.8 and the limiting cross section was on the order of about $2x10^{-3}$ cm².



Figure 9. Heavy Ion induced SEU testing on the SPT7760.

7) 6651

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The Agilent (Hewlett Packard) HCPL6651 (LDC0027) high-speed optocoupler was irradiated with 63MeV protons at UCD/CNL to determine the SET response of the device. The device was biased at $V_{CC} = 5V$, $V_F = 5V$, and I_F was selectable via eight input resistors. The devices were tested for SETs with three output configurations: passive filter, active filter and no output filter. The device channels with the passive filter showed no transients on the output. The device channel with the active filter showed only a very few output transients with an angle of incidence effect and a cross section on the order of $10^{-\overline{10}}$ cm². (1) The channels with no output filter showed a significant number of SETs with an angle of incidence effect and a maximum cross section of 5.4x10⁻⁷cm². (2) The devices showed no significant CTR degradation to a fluence of 1.36x10¹³p/cm². See Figures 10 and 11. [23 ref D120400a.pdf] and [24 Roberts SET Poster]



Figure 10. SET Cross Section vs. Angle of Incidence for the HCPL6651 with active SET filter (non-flight lot).



Figure 11. SET Cross Section vs. Angle of Incidence for the HCPL6651 with no SET filter (non-flight lot).

V.DISPLACEMENT DAMAGE TEST RESULTS AND DISCUSSION

1) OD800

The OD800 LED from Optodiode was irradiated with 63MeV protons at UCD/CNL to determine the radiation induced degradation in the output of the device. The device is a GaAs double heterojunction LED. The mean ratio of post-irradiation power to pre-irradiation power, P/P_{0} , for all bias conditions was approximately 0.80 for a single exposure to 6×10^{10} p/cm².

2) P2824

The Hamamatsu P2824 (manufactured 1997) optocoupler was irradiated with 63MeV protons at UCD/CNL to determine the CTR degradation of the device. The device was biased at $V_{CC} = 5V$, $V_F = 5V$, and I_F was selectable via eight input resistors. There was some degradation in CTR at 1×10^{10} p/cm² and significant degradation was seen by the time a fluence of 4×10^{10} p/cm² was reached. No SETs were observed. [23 ref D120400a.pdf]

3) 66099

The Micropac 66099 (LDC0048) optocoupler was irradiated with 63MeV protons at UCD/CNL to determine the

CTR degradation of the device. The device was biased at $V_{CC} = 5V$, $V_F = 5V$, and I_F was selectable via eight input resistors. The onset of CTR degradation occurred at 2.5×10^{11} p/cm² and device performance was unacceptable at 7.5×10^{11} p/cm². No SETs were observed. [23 ref D120400a.pdf]

4) 4N49 and 4N49S

The Micropac 4N49 (LDCs 9803 & 9819) was irradiated with 63MeV protons at UCD/CNL to determine the degradation of V_{CE} . No significant degradation in V_{CE} was observed to a fluence of 5×10^{11} p/cm². Degradation was seen for the worst-case bias condition of $V_{CC} = 34$ V, $V_{IN} = 3.6$ V at 1×10^{11} p/cm². The differing results indicate that different LEDs are being utilized in the two different devices. It is conjectured that the 4N49S uses a double hetrojunction LED, while the 4N49 uses a single hetrojunction LED.



Figure 12. Micropac 4N49 (LDCs 9803 & 9819) average V_{CE} results for the worst, nominal and best cases up to $5 \times 10^{10} \text{ p/cm}^2$ [25 Ref: D120400b.pdf].

The Micropac 4N49 (LDC 0048) optocoupler was irradiated with 63MeV protons at UCD/CNL to determine the CTR degradation of the device. The device was biased at $V_{CC} = 5V$, $V_F = 5V$, and I_F was selectable via eight input resistors. The onset of CTR degradation occurred at $5x10^{10}$ p/cm² and device performance was unacceptable at $1.5x10^{11}$ p/cm². No SETs were observed. [23 ref D120400a.pdf]



Figure 13. CTR degradation in 4N49S DUT 394 (Flight Lot)



Figure 14. CTR degradation in 4N49 DUT 941 (Non-Flight Lot)



Figure 15. Comparison of 4N49 CTR degradation flight lot to non-flight lot for $I_F=12.5mA$. CTR₀ for DUT 394 = 0.623 (flight 4N49S), CTR₀ for DUT 865 = 0.586 (non-flight 4n49).

The Micropac 4N49S (LDC 9736) optocoupler was irradiated with 63MeV protons at UCD/CNL to determine the CTR degradation of the device. The device was biased at $V_{CC} = 5V$, $V_F = 5V$, and I_F was selectable via eight input resistors. The onset of CTR degradation occurred at 1×10^{12} p/cm² and device performance was unacceptable at 4.5×10^{12} p/cm². No SETs were observed. [23 Ref: D120400a.pdf]

5) 6N134

The Micropac 6N134 (66123) (LDC0046) high-speed optocoupler was irradiated with 63MeV protons at UCD/CNL to determine the CTR degradation of the device. The device was biased at $V_{CC} = 5V$, $V_F = 5V$, and I_F was selectable via eight input resistors. The onset of CTR degradation occurred at $1.0x10^{12}$ p/cm² and device performance was unacceptable at $3.0x10^{12}$ p/cm². The SET test function did not operate correctly during testing, but SETs were expected. [23 Ref: D120400a.pdf]

6) 6N140

The Micropac 6N140 (66124) (LDC9724) optocoupler was irradiated with 63MeV protons at UCD/CNL to determine the

CTR degradation of the device. The device was biased at $V_{CC} = 5V$, $V_F = 5V$, and I_F was selectable via eight input resistors. The onset of CTR degradation occurred at 7.5×10^{11} p/cm² and device performance was unacceptable at 1.0×10^{12} p/cm². No SETs were observed.

The Micropac 6N140 (66124) (LDC0048) optocoupler was irradiated with 63MeV protons at UCD/CNL to determine the CTR degradation of the device. The device was biased at $V_{CC} = 5V$, $V_F = 5V$, and I_F was selectable via eight input resistors. The onset of CTR degradation occurred at $1.0x10^{12}$ p/cm² and device performance was unacceptable at $3.0x10^{12}$ p/cm². No SETs were observed. [23 Ref: D120400a.pdf]



Figure 16. CTR Degradation in 6N140 DUT 597 Channel 1 (Flight Lot)



Figure 17. CTR Degradation in 6N140 DUT 286 Channel 1 (Non-Flight Lot)



Figure 18. Comparison of 6N140 CTR degradation flight lot to non-flight lot for $I_F=5.71mA$

7) Mii42142

The Micropac Mii42142 power op amp was irradiated with 63MeV protons at UCD/CNL to determine device susceptibility to SET. The part showed no transients in its most sensitive configuration of $V_S = 8V$ and $V_{IN-} = 0.1V$. The device also showed no loss of output current in the most stressful condition of $V_S = 15V$ and $V_{IN-} = 1.3V$ up to $3x10^{12}$ protons/cm² and only an 18.5% loss of output current after 7.44x10¹² protons/cm². No SEGRs were observed. [19 ref D120400c.pdf]

8) Mii53124 and Mii53253

The Micropac Mii 53124 \pm 90V/0.8A, and Mii53253 Dual 90V/0.8A power MOSFET optocoupler hybrids were irradiated with 63MeV protons at UCD/CNL to determine device susceptibility to SET. The DUTs showed no evidence of SET. There was a nominal increase in the forward current threshold for the LED but the threshold remained below the minimum specification limit for operating the devices. There was also no pronounced change in the output currents of the devices. Each DUT was tested to a total fluence of 1x10¹² p/cm². [20 ref D120400d.pdf]

9) Mii53250 and Mii53258

The Micropac Mii53250 40V/10A(2A) and Mii53258 120VDC/5A(2A) optocoupler hybrid solid-state relays were irradiated with 63MeV protons at UCD/CNL to determine their susceptibility to SET. The devices exhibited no SETs. There was a nominal increase in the forward current threshold for the LED, but threshold remained below the minimum specification limit for operating the device. There was also no pronounced change in the output current of the device. The devices were tested to a total fluence of $1 \times 10^{12} \text{ p/cm}^2$. [21 ref D120400e.pdf]

VI. SEL TEST RESULTS AND DISCUSSION

A. Linear Bipolar Devices:

1) CMP402

Heavy-ion irradiations were conducted on the Analog Devices comparator-to ensure that they were not susceptible to SEL or any other SEE induced hard failure. No SELs were observed for a fluence of 1×10^7 Iodine ions/cm² incident at 60° to the normal (LET_{eff} = 119.8).

2) OP16, OP37, and OP42

Heavy-ion irradiations were conducted on three Analog Devices op amps-the OP42, OP37 and OP16-to ensure that they were not susceptible to SEL or any other SEE induced hard failure. All three parts survived irradiation to a fluence of 1×10^7 ions/cm² of Br at normal incidence (LET=37).

B. ADC/DAC:

1) AD7535

Heavy-ion irradiations were conducted at BNL to determine the SEL sensitivity of the Analog Devices AD7535. No SELs were observed for a fluence of 1×10^7 ions of Br incident at 60 to the normal (LET_{eff} = 74.6).

2) AD7564

Heavy-ion irradiations were conducted on the Analog Devices AD7564 comparator to ensure that they were not susceptible to SEL or any other SEE induced hard failure. No SELs were observed up to a fluence of 1×10^7 Iodine ions/cm² incident at 60° to the normal (LET_{eff} = 119.8).

3) AD7664

The Analog Devices AD7664 analog-to-digital converter (ADC) was tested for SEU and SEL at Brookhaven National Laboratory using ions with LETs ranging from 7.88 (Si) to 37.9 (Br). The Analog to Digital Converters were tested under the bias conditions of + 5 volts.

Testing was performed to determine the latchup threshold LET. Both devices tested showed the same threshold characteristics with an LET threshold of 8-10 MeV•cm²/mg. For all test conditions, the DUTs were exposed to the ion beam until latchup occurred. At this point the fluence was recorded. Typically 2 to 3 fluence reading were taken for each test condition, to allow for some statistics in calculating a cross section. This cross section data is shown in Figure 19.

Consider the cross section data in Figure 19. SEL did not occur for 5 x 10^6 ions/cm² of Si at normal incidence (LET=7.88). The two data points with the downward arrows for this LET value thus represent upper limits for the SEL cross section. SEL did occur for Si incident at 30° (LET=9.1), indicating an SEL threshold LET between these two values. Despite the considerable spread in the cross section data, the "best fit" curve through the data yields a reasonalble estimate of the saturation cross section, $\sigma_{sat} \approx 2$ to 3×10^4 cm².

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. [26 ref B030600.pdf]



Figure 19. The symbols show the cross section data as a function of Effective LET for the two DUTs. Note: Symbols with a downward arrow indicate that no latch occurred for that LET.

4) AD7854

The Analog Devices AD7854 is a CMOS single-channel, 200 KSPS 12 bit ADC. It was tested for SEL only and found to be susceptible to SEL with a threshold LET between 8 and 11 MeV•cm²/mg and with a limiting cross section between 1×10^{-4} and 1×10^{-3} cm². The device was susceptible for both 3.6 and 5 volt supply voltages. This device should be considered a category 4 device. [27 ref B092500a.pdf]

5) AD7858

The Analog Devices AD7858 is a CMOS 8 channel, 200 KSPS 12 bit ADC. It was tested for SEL only and found to be susceptible with a threshold LET between 11 and 22 MeV \cdot cm²/mg and a limiting cross section between 1x10⁻⁴ and 1x10⁻³ cm². The device was susceptible for both 3.6 and 5 volt supply voltages. This device should be considered a category 4 device. [28 ref B092500b.pdf]

6) AD7888

The Analog Devices AD7888 is a CMOS 8 channel, 125 KSPS 12 bit ADC. It was tested for SEL only and found to be susceptible with a threshold LET between 16 and 22 and a limiting cross section between 1×10^{-5} and 1×10^{-4} cm². The device was susceptible for both 3.6 and 5 volt supply voltages. This device should be considered a category 4 device. [29 ref B092500c.pdf]

C. Miscellaneous:

1) ADG704

The Analog Devices ADG704 is a low-voltage (1.8 to 5 Volts) quad CMOS multiplexer. It was tested for SEL only and found to be susceptible with a threshold LET of about 16 and with a limiting cross section between 1×10^{-5} and 1×10^{-4} cm². The device was tested only at the upper limit of its supply voltage range. This device should be considered a category 4 device. [30 ref B092700b.pdf]

2) AMP01

The AMP01 was tested to further characterize a destructive failure observed in 1998 SEE tests [4]. The new tests raised the lower limit on the LET threshold for failure to >32.7 $(1 \times 10^7 \text{ ions/cm}^2 \text{ of Ge at normal incidence})$. No dependence on temperature or device load were observed. The higher threshold LET and the fact that failure is more likely for normally incident ions imply that the failure rate for this mechanism will be low – for example, less than 1×10^{-10} failures per day per device in geostationary orbit. Because these devices are susceptible to single event transients (measured in previous tests) this device is considered a Category 3 [4].

3) INA117

The Texas Instruments/Burr-Brown INA117 is a differential amplifier. It was tested for SEL and other destructive mechanisms only. No destructive events were seen for an effective fluence of 1×10^7 ions/cm2 of Iodine incident at 60 degrees for an effective LET of 119.9.

4) MAX313

Testing was performed at BNL to determine the SEL susceptibility of the Maxim MAX313 Analog Switch. Supply current was monitored for an increase or decrease. No SELs were observed for the MAX313 up to a fluence of 1x107 ions/cm2 of iodine at normal incidence (LET=59.8). [31 ref B080100h.pdf]

5) MAX4503

The Maxim MAX4503 CMOS switch was tested for SEL susceptibility at BNL. Test conditions included the supply voltage set to 3.6 volts, the dc input to the switch of 2.15 volts. The switching voltage set to 3.3 volts and the frequency was 200 Hz. No SELs were observed up to LET of 37. At LET values of 37 and greater, transients on the output were beginning to appear. As this was only a latchup test, details of the transients were not investigated. However, with an LET threshold of 37, the event rate should be very small. [32 ref B111600c.pdf]

6) MAX4528 and MAX4583

SEL sensitivity tests were preformed at BNL on the Maxim MAX4528 and MAX 4583 CMOS analog switches. The power supply current was monitored for large increases, and the device functionality was verified after each SEL.

The MAX4528 exhibited no SEL events up to a fluence of 1×10^7 ions/cm² of iodine (LET=59.9). The MAX4583 exhibited no SEL events for a fluence of 1×10^7 ions/cm² of iodine incident at 60° (LET_{eff}=119.8). [33 ref B092700c.pdf]

7) MAX4617

The Maxim MAX4617 CMOS analog multiplexer was tested at BNL for sensitivity of SEL. The power supply was monitored for large increases. The MAX4617 exhibited no SEL events for a fluence of 1×10^7 ions/cm² of iodine incident at 60° (LET_{eff}=119.8). [34 ref B111700.pdf]

8) MAX584

Testing was performed at BNL to determine the SEL susceptibility of the Maxim MAX584 voltage reference. No SELs were observed up to a fluence of 1×10^7 ions/cm² of Br at normal incidence (LET_{ett}=37.3).

VII. SUMMARY

We have presented recent data from SEE, and protoninduced damage 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.

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