Total Ionizing Dose Results and Displacement Damage Results for Candidate Spacecraft Electronics for NASA

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Abstract– We present data on the vulnerability of a variety of candidate spacecraft electronics to total ionizing dose and displacement damage. Devices tested include optoelectronics, digital, analog, linear bipolar devices, hybrid devices, Analog-to-Digital Converters (ADCs), and Digital-to-Analog Converters (DACs), among others.

I. INTRODUCTION

Commercial and emerging technology devices have established themselves in the space flight community as a means to meet the needs for higher performance, cost savings, and scheduling demands. With this dramatic increase in the use of these devices, the importance of ground testing for the effects of total ionizing dose (TID) and proton-induced degradation (also known as displacement damage (DD)) to qualify the devices for flight, has increased due to the often uncertain nature of such devices.

The results of testing presented here were done to establish the sensitivity of the devices selected as candidate spacecraft electronics to TID and proton damage (both ionizing and non-ionizing). This testing serves to determine the limit to which a candidate device may be used or if it may not be used at all.

The work presented is sponsored by NASA Electronic Parts and Packaging (NEPP) Program's Electronics Radiation Characterization (ERC) Project, Defense Threat Reduction Agency (DTRA) under IACRO 02-40391, and NASA Flight Projects.

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For single event effects (SEE) results, see a companion paper submitted to the 2003 IEEE NSREC Radiation Effects Data Workshop entitled: "Single Event Effects Results for Candidate Spacecraft Electronics for NASA" by M. O'Bryan, et al.[1]

II. TEST TECHNIQUES AND SETUP

A. Test Facilities - TID

TID testing was performed using a Co-60 source at the Goddard Space Flight Center Radiation Effects Facility (GSFC REF). The source is capable of delivering a dose rate of up to 0.5 rads(Si)/s, with dosimetry being performed by an ion chamber probe.

Testing performed at Naval Surface Warfare Center Division (NAVSEA) used the Shepherd Model 484 Cobalt-60 Tunnel Irradiator Test Facility. The source is capable of delivering dose rates between 0.8 rads(Si)/s and 49.5 rads(Si)/s.

Testing performed by JAYCOR was done at four facilities: The Salk Institute (Salk Inst.) Gammabeam 150-C Co-60 Irradiator, the Sandia National Laboratories (SNL) Gamma Irradiation Facility (GIF), the Defense Microelectronics Activity (DMEA) Science and Engineering Gamma Irradiation Test (SEGIT) Facility using a J.L. Shepherd & Assoc. Model 81 Co-60 irradiator, and Titan Corp. Pulse Sciences Division (PSD) Cs-137 irradiator. TID facilities are summarized in Table I.

Table I: Gamma Ray TID Test Facilities

Goddard Space Flight Center Radiation Effects Facility (GSFC REF) Co-60
Naval Surface Warfare Center Division (NAVSEA) Shepherd Model 484 Cobalt-60 Tunnel Irradiator Test Facility
JAYCOR: Salk Institute, Sandia National Laboratories, Defense Microelectronics Activity, (Co-60), Titan Corp. (Cs-137)

B. Test Facilities – Proton Damage

Proton DD/TID tests were performed at two facilities: The University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) that has a 76" cyclotron (maximum energy of 63 MeV), and the Indiana University Cyclotron Facility (IUCF) that has an 88" cyclotron (maximum energy of 205 MeV). The proton damage test facilities and energies used on the devices are shown in Table II.

Table II: Proton Damage Test Facilities

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

C. Test Method

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

1) TID Testing

TID testing was performed to the MIL-STD-883 1019.5 test method [2].

2) Proton Damage Testing

Proton damage tests were performed on biased devices with functionality and parametrics being measured either continually during irradiation (in-situ) or after step irradiations (for example, every 10 krad(Si), or every $1x10^{10}$ protons).

III. Test Results Overview

Abbreviations and conventions are listed in Table III. Abbreviations for principal investigators (PIs) and test engineers are listed in Table IV. Definitions for the categories are listed in Table V. TID results are summarized in Table VI. Displacement Damage testing results are presented in Table VII. 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. Please note that these test results can depend on operational conditions. Complete test reports are available online at http://radhome.gsfc.nasa.gov [3].

Table III: Abbreviations and Conventions:

ADC – analog to digital converter
CTR = current transfer ratio
DAC – digital to analog converter
DD = displacement damage
DNL = differential non-linearity
GPS = global positioning system
GSFC REF = Goddard Space Flight Center Radiation Effects Facility
H_{fe} = collector to base current gain
I_b = input bias current
I_{dd}, I_{cc} = power supply current
INL = integral non-linearity
Krads(Si) = kilorads(Si)
ksps = kilosamples per second
LDC = lot date code
LET = linear energy transfer (MeV•cm^2/mg)
MEMS = Microelectromechanical System
MeV = Mega Electron Volt
N/A = not available
op amp = operational amplifier
P = proton test
P/cm^2 = protons/cm^2
PI = Principal Investigator
RH = radiation hard
RS = Reed Solomon
SEFI = single event functional interrupt
SEL = single event latchup
TID = total ionizing dose
V_{io} = input offset voltage
V_{ol} = output saturation voltage
σ = cross section (cm^2/device, unless specified as cm^2/bit)
σ_{SAT} = saturation cross section at LET_{max} (cm^2/device, unless specified as cm^2/bit)

Table IV: List of Principal Investigators

Abbreviation	Principal Investigator (PI)
SB	Steve Buchner
MC	Marty Carts
JH	Jim Howard
SK	Scott Kniffin
RL	Ray Ladbury
PM	Paul Marshall
CP	Christian Poivey
MX	Mike Xapsos

TABLE VI: SUMMARY OF TID TEST RESULTS

Part Number	Manufacturer	LDC	Function	Facility Date/P.I (*Co-60 source unless otherwise noted*).	Dose rate (rads(Si)/s)	Summary of Results	Degradation Level (krads(Si))	Reference
SG7805	Linfinity (Microsemi)	9439	Positive Fixed Linear Voltage Regulator	GSFC02OCT – SB	~0.28	No parametric failures were observed up to 20 krads(Si)	>20	[4]
SG7815	Linfinity (Microsemi)	0039	Positive Fixed Linear Voltage Regulator	GSFC02SEP – SB	~0.28	No parametric failures were observed up to 20 krads(Si)	>20	[5]
SG7915	Linfinity (Microsemi)	0207	Negative Fixed Linear Voltage Regulator	GSFC02OCT – SB	~0.28	No parametric failures were observed up to 20 krads(Si)	>20	[6]
LP2953	National Semiconductor	0208A	Voltage regulator	GSFC02DEC – CP	0.1 to 0.47	Voltage output and dropout out of specification limits after 2.5 krads(Si) Significantly degraded after 5 krads(Si)	<2.5	[7]
LM193	National Semiconductor	Flight lot	Dual voltage comparator	GSFC02OCT – CP	0.06 to 0.4	I_b out of specification limits after 7 krads(Si) V_{io} out of specification limits after 15 krads(Si) Functional after 65 krads(Si) (maximum test dose)	<7	[8]
OP27ARC	Analog Devices	0128A	Op amp	GSFC03JAN – CP	0.08 to 0.14	all parameters within specification limits up to 25 krads(Si)	>25	[9]
OP97	Analog Devices	0133A	Op amp	GSFC02OCT – SB	~0.15	No parametric failures were observed up to 20 krads(Si)	>20	[10]
OP221	Analog Devices	0127	Op amp	GSFC02SEP – SB	~0.08	No parametric failures were observed up to 20 krads(Si)	>20	[11]
OP296	Analog Devices	0048	Op amp	GSFC02SEP –SK	~0.01	Devices failed functionally at 1.8 krads(Si)	<1.8	[12]
AD743	Analog Devices	0110	Op amp	GSFC02SEP – SB	~0.28	No parametric failures were observed up to 20 krads(Si)	>20	[13]
AD822	Analog Devices	0211	Op amp	GSFC02SEP – SB	~0.28	No parametric failures were observed up to 20 krads(Si)	>20	[14]
AD625	Analog Devices	0204	Instrument Amplifier	GSFC02OCT – SB	~0.28	No parametric degradation up to 20 krads(Si).	>20	[15], [16]
AD5334	Analog Devices	0011	Quad 8-bit DAC	GSFC02SEP – JH	~0.11	Parametric and functional failure at 20 krads(Si)	15<x<20	[17]

Part Number	Manufacturer	LDC	Function	Facility Date/P.I *(Co-60 source unless otherwise noted).*	Dose rate (rads(Si)/s)	Summary of Results	Degradation Level (krads(Si))	Reference
P140	Leach International	0121	Power Controller	GSFCOCT02 - SB	0.17	Functional failure between 20 and 40 krads(Si)	20<x<40	[18]
TPS9103	Texas Instruments	N/A	Power Supply for GaAs power amplifier	GSFC02AUG – CP	0.06 to 0.14	I_{cc} standby and Ron out of specification limits after 9 krads(Si), Significantly degraded after 12 krads(Si)	<9	[19]
CULPRiT RS Encoder	AMI	N/A	RS Encoder	GSFC02JUL – MX	~0.44	No degradation of performance at 100 krads(Si)	>100	[20], [21]
LM139	National Semiconductor	0139	Voltage regulator	NAVSEA02 – CP	0.295	Output saturation voltage out of specification limit and significantly degraded after 5 krads(Si)	<5	[22]
LTC1657CGN	Linear Technology	0105	Parallel 16-bit DAC	NAVSEA02 – CP	0.9	INL out of specification limit after 2.5 krads(Si), significantly degraded after 7.5 krads(Si), functional failure after 20 krads(Si)	<2.5	[23]
LP2951	National Semiconductor	0128A-0221A	Voltage regulator	JAYCOR02 – CP (DMEA)	~0.1	All parameters within specification at 50 krads(Si)	>50	[24], [25]
MIC29302	Micrel	0124	Low dropout voltage regulator	JAYCOR02 – CP (DMEA)	~0.1	Line regulation out of specification limits after 5 krads(Si)	<5	[26]
LM2651MTC-ADJ	National Semiconductor	Flight lot	Switching regulator	JAYCOR02 – CP (Titan Corp.) (Cs-137 used)	~0.1	Functional failure between 10 and 20 krads(Si)	10<x<20	[27]
ADG452	Analog Devices	0129	Analog Switch	JAYCOR02 – CP (SNL)	~0.1	I_{dd} out of specification limits after 2.5 krads(Si). Significant degradation after 10 krads(Si).	<2.5	[28]
MAT02	Analog Devices	0235	Matched dual NPN transistors	JAYCOR03 – CP (Salk Inst.)	~0.5 to 1	h_{FE} slightly out of specification limits at 10 krads(Si)	<10	[29]
MAT03	Analog Devices	0235	Matched dual PNP transistors	JAYCOR02 – CP (Salk Inst.)	~0.5 to 1	h_{FE} out of specification limits at 5 krads(Si) significantly degraded at 10 krads(Si)	<5	[30]
LM6144	National Semiconductor	0148	Op amp	JAYCOR02 – CP (DMEA)	~0.1	Aol out of specification limits after 5 krads(Si)	<5	[31]
ADC1175CIJM	NSC	N/A (marked EJ03AB)	8-bit DAC (20 MHz)	JAYCOR02 – CP (Salk Inst.)	0.5 to 1	I_{dd} out of specification limits between 5 and 10 krads(Si)	5<x<10	[32]

TABLE VII: SUMMARY OF DISPLACEMENT DAMAGE RESULTS

Part Number	Manufacturer	LDC	Function	Facility Date/P.I.	Summary of Results	Degradation Level (krads(Si))	Reference
HV583	Supertek	N/A	Serial to parallel converter	UCD02APR – SB	TID degradation at 50 krads(Si)	50	[33]
MRX8501	Emcore	A1 312-12	Fiber Optic Receiver	UCD02FEB – MC	Not sensitive to TID/DD up to ~103 krads(Si) at fluence of 7.16×10^{11} p/cm^2	>103	[34]
MTX8501	Emcore	A1 233-01	Fiber Optic Transmitter	UCD02FEB – SB/PM	Not sensitive to TID/DD up to 28.8krads(Si)	>28.8	[34]
MI66099	Micropac	Custom	Optocoupler	UCD02APR – SB	Observed anomalous decay of CTR	<5	[35]
MI66099	Micropac	Custom	Optocoupler	IUCF02JUN – SB	Observed anomalous decay of CTR	<5	[36]
CO-566	Vectron	0142	Oscillator	IU02JUNE – JH	TID: > 1 Mrad(Si); DD: > 3.23×10^{13} p/cm^2	>1000	[37]
CO-718S	Vectron	0143	Oscillator	IU02JUNE – JH	TID: > 1 Mrad(Si); DD: > 2.72×10^{13} p/cm^2	>1000	[38]
AD7664	Analog Devices	0110	16-bit ADC (570 ksps)	IU03FEB – JH	Devices failed due to proton TID at 21.7 ± 1.1 krads(Si)	21.7	[39]
ColdFire	Motorolla	0120	Microprocessor	IU02JUNE – JH	Dose failure occurred at ~62 krads(Si).	~62	[40]
SH-4	Hitachi	N/A	Microprocessor (Commercial version of RH microprocessor)	IU02JUNE – JH	Hard failure occurred after ~ 11 krads(Si) (1.91×10^{11} p/cm^2) Could not determine whether latchup or dose failure was reason for hard failure. Device also tested for SEFI and SEL.	11	[41]
GP2021	Zarlink Semiconductor	9617A	GPS 12-Channel correlator	IU02JUNE – JH	Hard failure occurred after ~49 krads(Si) (8.3×10^{11} p/cm^2)	49	[42]

IV. TID TEST RESULTS AND DISCUSSION

1) AD5334

The AD5334 quad 8-bit DAC from Analog Devices was tested to 50 krads(Si) at a dose rate of ~0.11 rads(Si)/s. Tests were performed at the NASA GSFC REF Co-60 facility. The devices were biased statically. After 15 krads(Si), all devices began to deviate from the nominal values in DNL, INL, gain error, offset error, and supply current. See Figures 1 and 2 for DNL & INL results. After 20krads(Si), the above parameters began to degrade very significantly with DNL and INL having degraded to well outside 8-bit performance.

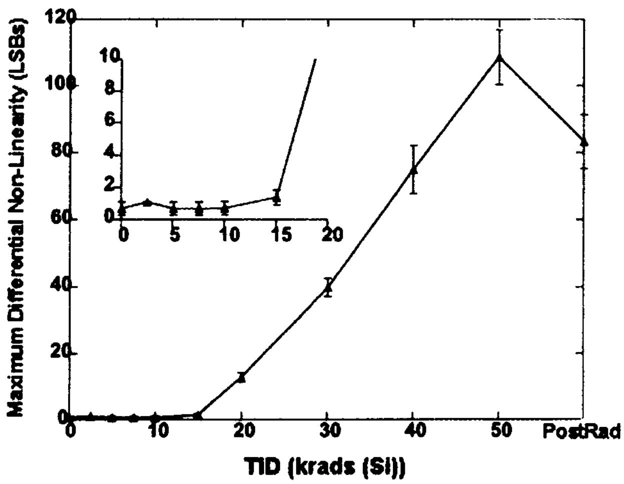

Fig. 1. AD5334 Maximum DNL as a function of TID.

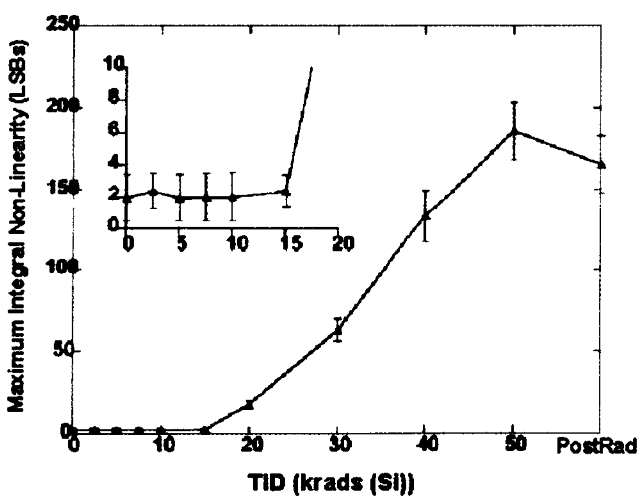

Fig. 2. AD5334 Maximum INL as a function of TID.

After 30 krads(Si), the device lost monotonicity and the output voltage became oscillatory across the entire range of the DAC. Annealing at 100°C for one week did not provide significant recovery.

2) ADG425

The ADG425 analog switch from Analog Devices was tested to 50 krads(Si) at an average dose rate of ~0.19 rads(Si)/s. Tests were performed by JAYCOR. Six devices were statically biased and total current was monitored during testing. Two devices were unbiased during testing. After 2.5 krads(Si), the biased devices were out of specification in I_{DD}, I_{SS}, $I_{S\ off}$ +10V, and $I_{S\ off}$ -10V. The degradation between 10 and 20 krads (Si) was significantly enough that the timing and high/low threshold readings could not be made and the devices would not change from state to state. Annealing at room temperature for 1 week resulted in no observed recovery. The unbiased devices show some degradation at 30 and 50 krads(Si). Annealing the unbiased devices resulted in no significant recovery.

3) LM193

The LM193 quad low power voltage comparator from National Semiconductor was tested to 65 krads(Si) at an average dose rate of ~0.25 rads(Si)/s. Tests were performed at the NASA GSFC REF Co-60 facility. Four devices were statically biased and two devices were unbiased during testing. After 7 krads(Si), both I_b+ and I_b- in all devices (biased and unbiased) were well above the specification limits. After 15 krads(Si), V_{IO} were above the specification limit for the four biased devices; one unbiased device went above the specification limit after 35 krads(Si). All other parameters stay within specification limits up to the maximum test dose level of 65 krads(Si) (see Fig. 3.). Annealing at room temperature for 1 week resulted in no significant annealing.

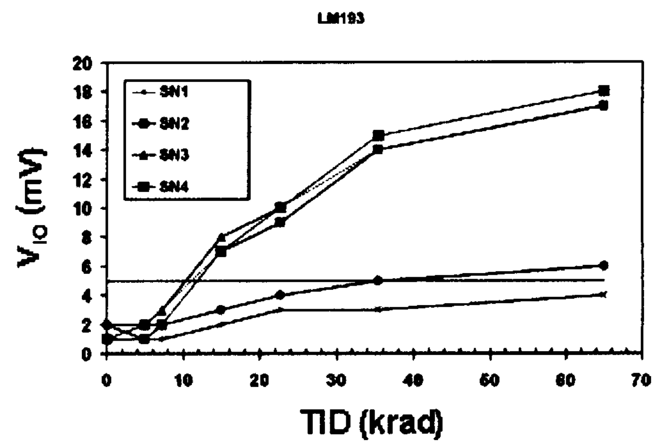

Fig. 3: Variation of V_{IO} with TID in the LM193.

4) LM139

The LM139 (M38510/11201BDA) quad low power voltage comparator from National Semiconductor was tested to 50 krads(Si) at an average dose rate of 0.295 rads(Si)/s. NAVSEA Crane Division performed the total dose testing at their Co-60 tunnel irradiator. Six devices were statically biased, two unbiased. Results of the total dose testing indicated:

- Both unbiased devices failed to operate properly between 5 krads(Si) and 10 krads(Si) as evidenced by output saturation voltage (V_{OL}) increasing well above specification (See Fig. 4.).
- All statically biased devices failed to operate properly between 10 krads(Si) and 20 krads(Si) as evidenced by output saturation voltage (V_{OL}) increasing well above specification (See Fig. 4).

- All devices began showing power supply current decrease after 5.0 krads(Si).

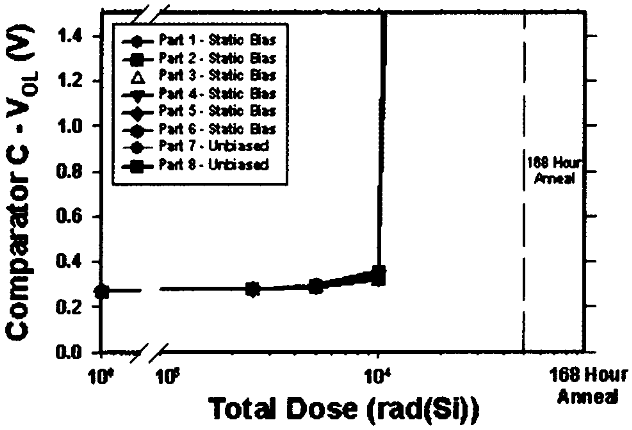

Fig. 4. TID induced V_{OL} failure of the LM139.

5) MRX8501/MTX8501

The MTX8501/MRX8501 12 x 1.25 Gbps parallel array transmitter and receiver modules from Emcore were tested for DD and TID effects with 63 MeV protons at UC Davis, CNL cyclotron. The first receiver was exposed to a total fluence of 7.16×10^{11} protons/cm^2; equivalent to 103 krads(Si). Following this exposure, there was no change in the functioning of the device, or in the current supplied to the board. The second receiver was exposed to a TID of 30.7 krads(Si) and no change was observed. The transmitter was exposed to a fluence of 2×10^{11} protons/cm^2; equivalent to a TID of 28.8 krads(Si) and no change in error rate or operating parameters was observed. These devices were also tested for SEE, those results are also in the test report and are presented in "Single Event Effects Results for Candidate Spacecraft Electronics for NASA" accepted for publication in IEEE NSREC 2003 Data Workshop, July, 2003.

6) OP296

The OP296 micropower, rail-to-rail input and output operational amplifier from Analog Devices was tested to 1.8krads(Si) at a dose rate of 0.01 rads(Si)/s. Tests were performed at the NASA GSFC REF Co-60 facility. The devices were biased statically. The devices failed functionally at 1.8 krads(Si) and no recovery was observed after annealing for one week at room temperature.

7) AD7664

The AD7664 16-bit ADC from Analog Devices was tested with protons at IUCF. While performing other tests, the devices were left in the beam until TID failure. The devices failed at a TID of 21.7 +/-1.1 krads(Si). The devices were also tested for proton induced SEL and heavy ion induced SEL see [1] for more details on those tests.

V. Summary

We have presented data from recent TID and proton-induced damage tests on a variety of primarily 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.

VI. 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) under IACRO 02-4039I.

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