nsrec07_W26: To be presented by Christian Poivey at the IEEE Nuclear and Space Radiation Effects Conference (NSREC), July 23-27, 2007 and to be published in the 2007 IEEE Radiation Effects Data Workshop, Sept. 2007 and on http://rahome.gsfc.nasa.gov

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

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Abstract-- Sensitivity of a variety of candidate spacecraft electronics to total ionizing dose and displacement damage is studied. Devices tested include optoelectronics, digital, analog, linear bipolar devices, and hybrid devices.

Index Terms- Displacement Damage, optoelectronics, Proton Damage, Total Ionizing Dose, and Single Event Effects.

I. INTRODUCTION

In order to meet the cost, performance, and schedule demands imposed by the space flight community, commercial and emerging technology devices have assumed a prominent role in meeting these needs. Thus, the importance of ground based testing for the effects of total ionizing dose (TID) and proton displacement damage to qualify such devices for flight is paramount. The novel ways in which some of these devices are used also highlights the need for application specific testing to ensure their proper operation and ability to meet mission goals.

The test results presented here were gathered to establish the sensitivity of the devices selected as candidate spacecraft electronics to TID and proton damage. Proton-induced degradation is a mix of ionizing (TID) and non-ionizing damage. This non-ionizing damage is commonly referred to as displacement damage (DD). This testing serves to determine the limit to which a candidate device may be used in space applications. For single event effects (SEE) results, see a companion paper submitted to the 2007 IEEE NSREC Radiation Effects Data Workshop entitled: "Compendium of Current 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

B. TID testing was performed using a Co-60 source at the Goddard Space Flight Center Radiation Effects Facility (GSFC REF), Table I. The source is capable of delivering a dose rate in excess of 30 rads(Si)/s, with dosimetry being performed using a chamber probe.

C. Test Facilities – Proton

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). Table II lists the proton damage test facilities and energies used on the devices.

This work was supported in part by the NASA Electronic Parts and Packaging Program (NEPP), NASA Flight Projects, and the Defense Threat Reduction Agency (DTRA).

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Table I: Proton Test Facilities

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

D. *Test Methods*

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 1019.7 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 10krads(Si), or every $1x10^{10}$ protons).

III. Test Results Overview

Abbreviations for principal investigators (PIs) are listed in Table II.. Abbreviations and conventions are listed in Table III. Table IV provides a summary of TID and DD test results. 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 II: List of Principal Investigators

Abbreviation	Principal Investigator (PI)
SB	Steve Buchner
JH	Jim Howard
TO	Timothy Oldham
CP	Christian Poivey
AS	Anthony Sanders

Table III: Abbreviations and Conventions:

ACRONYM/ DEFINITION	ACRONYM/ DEFINITION
ADC = analog to digital converter	LDC = Lot Date Code
ASIC = application specific integrated circuit	LED = Light emitting diode
CCD = charge coupled device	I_{cc} = power supply current
CMOS = complementary metal oxide semiconductor	MeV = Mega electron volt
DAC = digital to analog converter	N/A = not applicable
DD = displacement damage	Op amp = operational amplifier
DNL = differential non-linearity	P/cm^2 = $protons/cm^2$
FET = field effect transistor	PI = Principal Investigator
I_b = bias current	PT = photo transistor
I_c = collector current	TID = total ionizing dose
I_f = forward current	VOL = output saturation voltage
I_{OS} = offset current	V_{out} = output voltage
I_{STDBY} = standby current	V_{cc} = collector emitter voltage

TABLE IV: SUMMARY OF TID AND DD TEST RESULTS

Part Number	Manufacturer	LDC	Function	Facility Date/P.I (*Co-60 source unless otherwise noted).*	Summary of Results [Test Report]	Dose rate (rads(Si)/s)	Degradation Level (krads(Si))	Appl Spec
Data Converters								
AD565	Analog Devices	0013F	12-bit DAC	GSFC06JUL/SB	All parts passed functional testing up to 100 krad(Si) at low dose rate. All parametric values were within specifications up to 40 krad(Si). One part failed differential nonlinearity at 50 krad(Si) and 6 parts failed at 75 krad(Si).	0.02	50 to 75	N
AD670	Analog Devices	044A	8-bit ADC	GSFC06OCT/SB	One part failed functionally between 5 and 10 krad(Si). Two parts failed functionally between 10 and 15 krad(Si) and one part failed functionally between 15 krad(Si) and 20 krad(Si).	0.02	5 to 20	N
LTC1419	Linear Tech	0118	ADC	GSFC06OCT/SB	Some parametric values for some parts were out of specification before exposure to ionizing radiation. Some of the results lacked consistency as evidenced by the fact that their values were out of specification at low doses and within specification at higher doses. These results should be carefully vetted before deciding to use them.	2	inconclu-sive	N
Discretes								
IMEC 65nm test Transistors	IMEC	n/a test samples	65 nm test structures, N and P MOSFETS	GSFC06NOV/CP	No degradation up to 150 krad(Si).	LDR: 0.1 HDR: 4	>150	N
JANS2N2222	Analog Devices	0315	Transistors	GSFC06OCT/SB	The four parts tested passed Vce (saturation voltage) and Vbe up to a total dose of 40 krad(Si). The forward current transfer ration went out of specification for two devices between 30 and 40 krad(Si).	0.02	30 to 40	N
JANS2N3501	Analog Devices	0002	Transistors	GSFC06AUG/SB	The four parts tested passed all parametric and functional tests up to a total dose of 40 krad(Si).	0.02	>40	N
Linear - Amplifiers								
OP200	Analog Devices	0237A	Op Amp	GSFC06AUG/SB	The input bias current went out of specification for all three parts between 20 and 30 krad(Si).	0.02	21 to 40	N
OP400	Analog Devices	0349F	Op Amp	GSFC06AUG/SB	The supply current and input offset voltage remained within specifications up to 50 krad(Si). The input bias current went out of specification between 6 and 11 krad(Si).	0.02	6 to 11	N
AD524	National Semiconductor	0502A and 0606	Instrument Op Amp	GSFC06NOV/SB	The input bias current went out of specification at a total dose of less than 5 krad(Si). The input offset voltage went out of specification at 40 krad(Si). One device failed the specification for output offset voltage between 5 and 10 krad(Si).	0.02	5 to 10	N
OP27A	Analog Devices	0448	Op Amp	GSFC06JAN/SB	Input bias current and input offset current go out of specification between 20 and 30 krad(Si).	0.02	20 to 30	N
OP11	Analog Devices	0412F	Op Amp	GSFC05DEC/SB	Testing was done for a specific application that was different from used to generate the data in the data sheet. Therefore no comparison with the specifications could be made.	0.02	18-20	Y
OP42	Analog Devices	0223A	Op Amp	GSFCTBD/SB	Supply current and input bias current exceeded parametric values between 5 and 10 krad(Si). Input offset voltage went	0.02	5-10	N

Part Number	Manufacturer	LDC	Function	Facility Date/P.I *(Co-60 source unless otherwise noted).*	Summary of Results [Test Report]	Dose rate (rads(Si)/s)	Degradation Level (krads(Si))	Appl Spec
					out of specification between 0 and 5 krad(Si).			
LT1037	Linear Tech	9846B	Op Amp	GSFC06APR/CP	All parts passed 7krad(Si), Ib is out of specification limits for all parts at 15 krad(Si).	<1	7	N
Logic Devices								
54ACTQ14	National Semiconductor	0545A	HEX Inverter with Schmitt Trigger	GSFC06JUL/SB	All the parametric values were within specifications! I up to a total ionizing doese of 100 krad(Si).	2	>100	N
54ACTQ244	National Semiconductor	0548B	Quiet Series Octal Buffer/Line Driver	GSFC06AUG/SB	All parametric values were within specifications after being exposed to 50 krad(Si) followed by a one week anneal except for the supply current which exceeds specifications after 20 krad(Si) and Tristate Output Leakage Current which exceeds specifications after a total dose of 50 krad(Si).	2	20 to 50	N
54ACTQ16244	National Semiconductor	0435 and 0548	16-bit Buffer/Line Driver	GSFC06AUG/SB;	All parts passed all functional tests up to a TID of 50 krad(Si).	2	>50	N
Linear Other								
SG1526	Micro-Semi		Pulse Width Modulator	GSFC06AUG/SB	The input bias current went out of specification between 10 and 20 krad(Si). No other parameters changed with TID up to 40 krad(Si).	0.02	10-20	N
UC1708	Texas Instruments	0224B	Non-inverting high speed power driver	GSFC06DEC/SB	All parts passed all parametric tests up to a TID of 40 krad(Si).	2	>40	N
LP2951	National Semiconductor	0610A	Micro-Power Adjustable Voltage Regulator	GSFC06NOV/SB UCD06OCT/SB	Passed all parametric tests up to a TID of 40 krad(Si).	0.02	5 to 10	N
Memory								
NAND01GW3BZAN6E	ST Microelectronics	0604	NAND Flash	GSFC06MAY/TO; IUCF06JUL/TO	All passed at 30 krad(Si). All failed at 100 krad (Si).	25	30-100	N
AMD29LV256	Spansion	0606	Flash NVM (256M)	GSFC06MAY/TO	Program/erase modes failed at 10-20 krad(Si), rad only mode failed at 30-50 krad(Si).	25	10-20	N
K9F4G08U0A	Samsung	0624	NAND Flash	GSFC07JAN/TO	All passed at 100 krad(Si). All failed at 200 krad(Si).	25	100-200	N
TC58FVM7B2ATG-65	Toshiba	0539	NOR Flash (128M)	GSFC06MAY/TO	Program/erase modes failed <10 krad(Si), read only mode failed 20-40 krad(Si).	25	40	N
Programmable Devices								
AT22V10	Atmel	0437A	EEPLD	GSFC06SEP/CP	All parts passed 8krad(Si). All parts failed functionally at 15 krad(Si).	~1	>7	Y
Voltage References, Regulators & Comparators								
TL431	Texas Instruments	n/a - test chips	Prog Shunt Regulator	GSFC06JUL/SB	All parts passed all functional and parametric electrical tests up to a total dose of 20 krad(Si).	0.02	>50	N
AD584	Analog Devices	0042A	Voltage Reference	GSFC06JUL/SB	The AD584 meets all specifications after exposure to TID of 40 krad(Si).	0.02	>40	N
AD589	Analog Devices	1050	Voltage Reference	GSFC06JUL/SB	All devices met specifications for output voltage up to a total dose of 50 krad(Si).	0.02	>50	N
OMH3075	Optek Technology	M0551	Optek Hall Effects Sensor	GSFC07JAN/AS	Meets all specifications for supply current and output saturation voltage up to a TID of 40 krad(Si).	0.02	>40	N

Part Number	Manufacturer	LDC	Function	Facility Date/P.I *(Co-60 source unless otherwise noted).*	Summary of Results [Test Report]	Dose rate (rads(Si)/s)	Degradation Level (krads(Si))	Appl Spec
Displacement Damage								
HCPL-6751	Agilent Technologies	0251	Power MOSFET optocoupler	IUCF06NOV/JH	Very little change in dc characteristics, even to 1×10^{12} protons/cm^2; very little change in CTR value, except at lower drive currents.	n/a	n/a	N

IV. Test Results and Discussion

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 [3] describing in further detail, test method, TID conditions/parameters, test results, and graphs of data.

1) National Semiconductor LP2951 Micro-Power Adjustable Voltage Regulator

The LP2951WG/883 (5962-3870501MXA), micro-power adjustable voltage regulator was tested for its sensitivity to TID and DD. The part was manufactured by National Semiconductor and had a lot/date code of 0610A. Because the technology is bipolar, the part was tested for enhanced low dose rate sensitivity (ELDRS) The part was packaged in a 10-lead ceramic surface mount package.

Four parts were irradiated under bias and one part was reserved as a control. During irradiation, all four devices were biased so that their outputs were at 15 V. The devices were exposed to the following total ionizing doses: 0, 5, 10, 15, 20, 30, 40 krad(Si). Fig. 1 shows the circuit used to test the device.

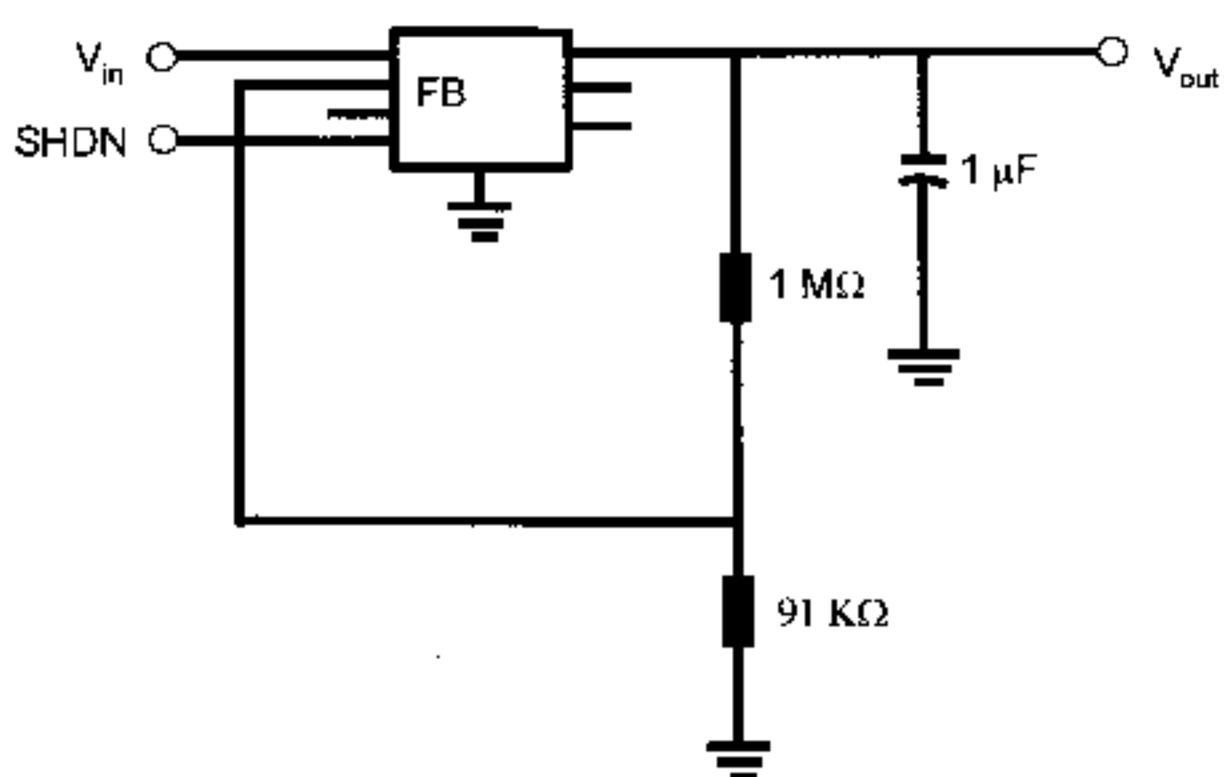

Figure 1. Test setup used for measuring the parametric values.

The devices begin to fail at relatively low doses, as evidenced by the fact that the ground current for one of the devices exceeds the specified value in the data sheet at 5 krad(Si). By 10 krad(Si), the ground current for the 100 mA load exceeds the specified value for all four devices. In addition the load regulation on two of the devices was out of specification, as was the dropout voltage. At higher doses, other electrical parameters also failed.

The part was also tested with 63 MeV protons at UCD-CNL. Parts were unbiased when exposed to the protons. The proton fluence levels were 1×10^{10}, 3×10^{10}, 6×10^{10}, 1.6×10^{11}, 3.6×10^{11} protons/cm^2. All five parts were irradiated to the first level, then one part was removed and the remaining four were irradiated. This process was repeated until only the final part was exposed to the maximum fluence. In this case as well, the ground current and load regulation went out of specification after the initial fluence of 1×10^{10} protons/cm^2.

In summary, this part fails to operate properly at a total ionizing dose of less than 5 krad(Si) and a proton fluence of 1×10^{10} protons/cm^2.

2) Analog Devices AD654 voltage-to-frequency converter

The AD654 is a voltage-to-frequency converter from Analog Devices that was previously total dose tested and found to exceed the full scale error at 18 krad(Si) and the input bias current at 8 krad(Si) [1]. The part was tested at a dose rate of 20 mrad(Si)/s (because of time constraints) in the configuration that will be used for flight, which was different from that specified in the data sheet. Very little change was observed in the nonlinearity of the frequency as a function of input voltage or in the input current. Figure 2 shows a small decrease in frequency (0.6%) after a dose of 35 krad(Si) for an input of 7 volts, which is well within the requirements for the application.

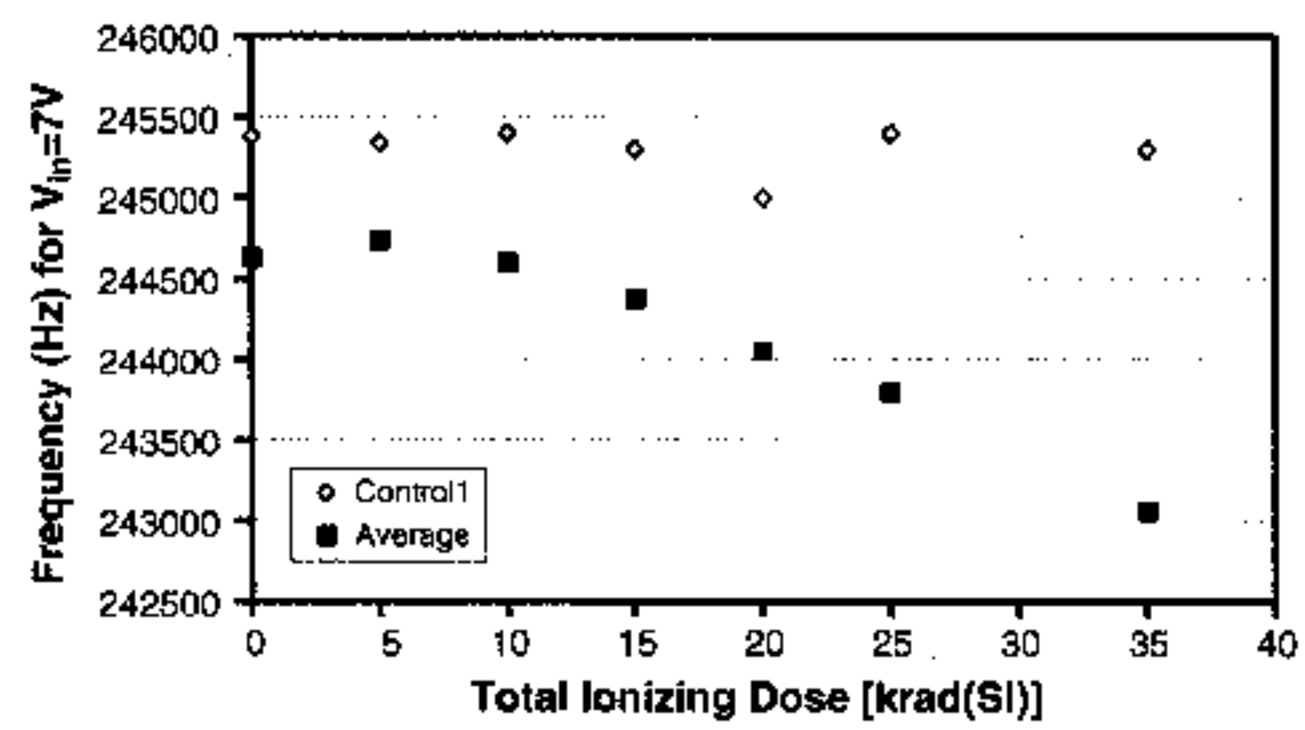

Figure 2. Average output frequency for eight parts as a function of TID and for one control device.

3) Analog Devices AD670 8-bit Analog-to-Digital Converter

The AD670 is an 8-bit Analog-to-Digital Converter from Analog Devices. The part was tested at a dose rate of 20 mrad(Si)/s. One part failed functionally between 5 and 10 krad(Si). Two parts failed functionally between 10 and 15 krad(Si) and one part failed functionally between 15 krad(Si) and 20 krad(Si). The functional failure manifested itself as a complete failure to convert so that the digital output did not change with changes in input voltage.

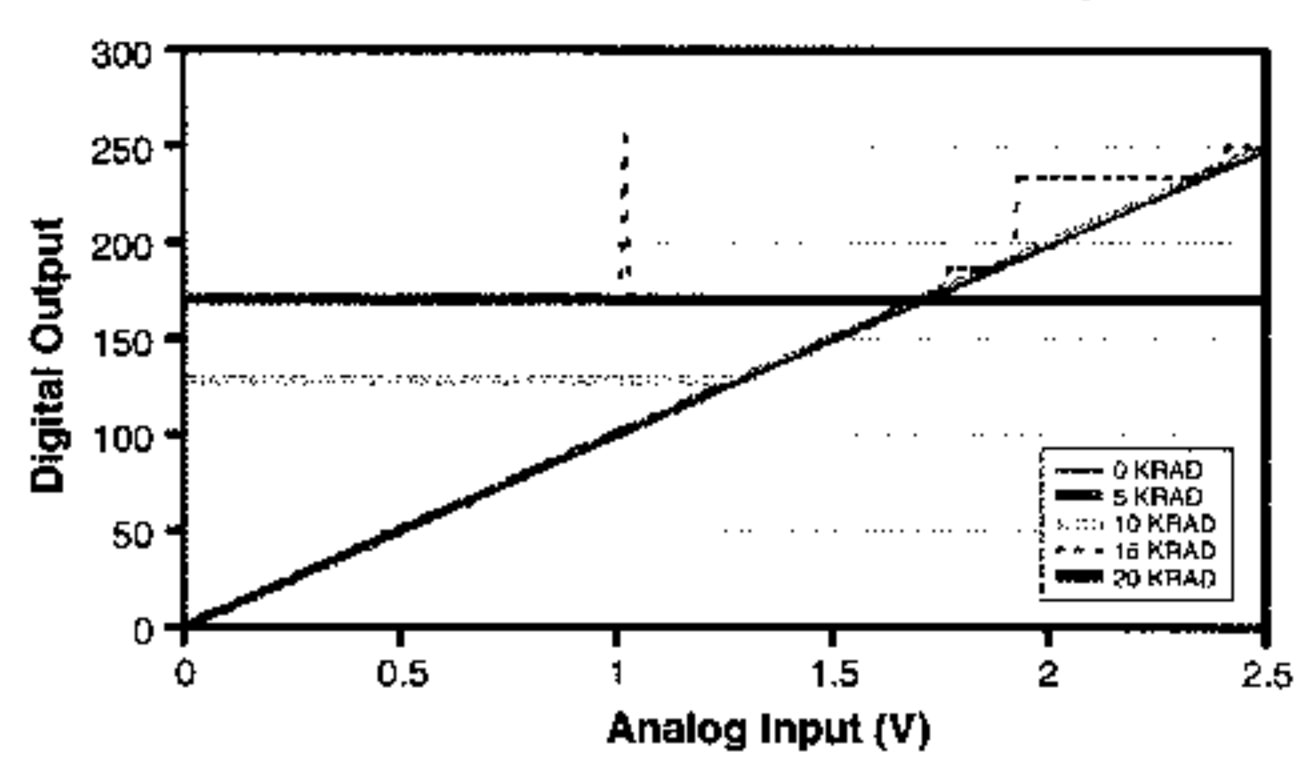

Figure 3. Digital output as a function of analog input for one AD670 at five different TID levels.

4) Analog Dedices AD589 1.2 Volt Reference

The AD589 is a 1.2 Volt reference manufactured by Analog Devices. The part was irradiated to 50 krad(Si) at a dose rate of 20 mrad(Si)/s. The output voltage was measured as a function of input current after each exposure. Figure 4 shows that the output voltage changed with dose but remained within specifications (1.2V to 1.25V) up to the final dose of 50 krad(Si).

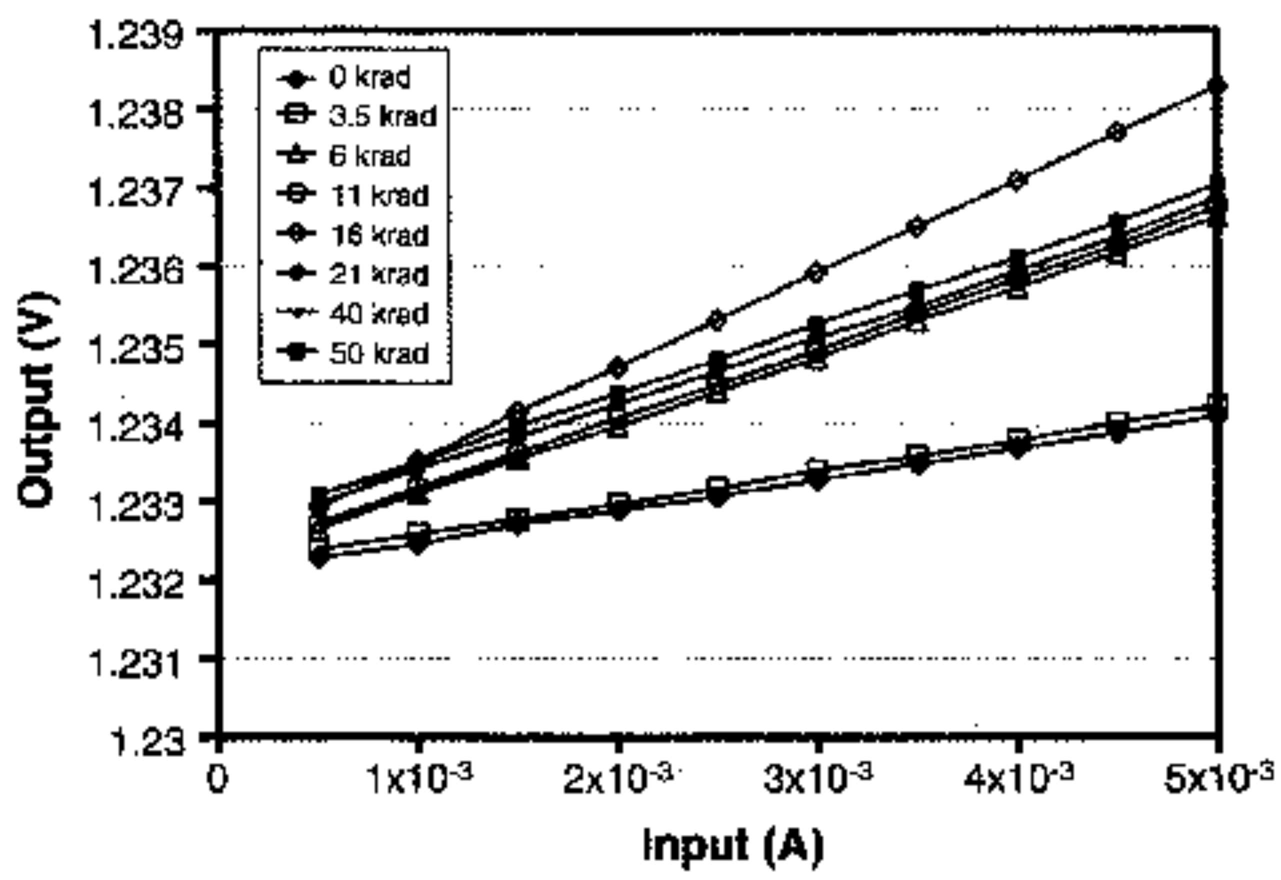

Figure 4. Output Voltage as a function of input current for one AD589 exposed to 8 different total dose levels.

5) Texas Instruments TL431 Three-Terminal Adjustable Voltage Regulator

The TL431 is a three-terminal adjustable voltage regulator from Texas Instruments. The part was tested to a total dose of 20 krad(Si) at a dose rate of 20 mrad(Si)/s. All parts passed all parametric tests up to a total dose of 20 krad(Si). Figure 5 shows the output reference voltage as a function of total dose. Data for both the average of 7 parts and the control device are included. The error bars show the standard deviation for the measurements.

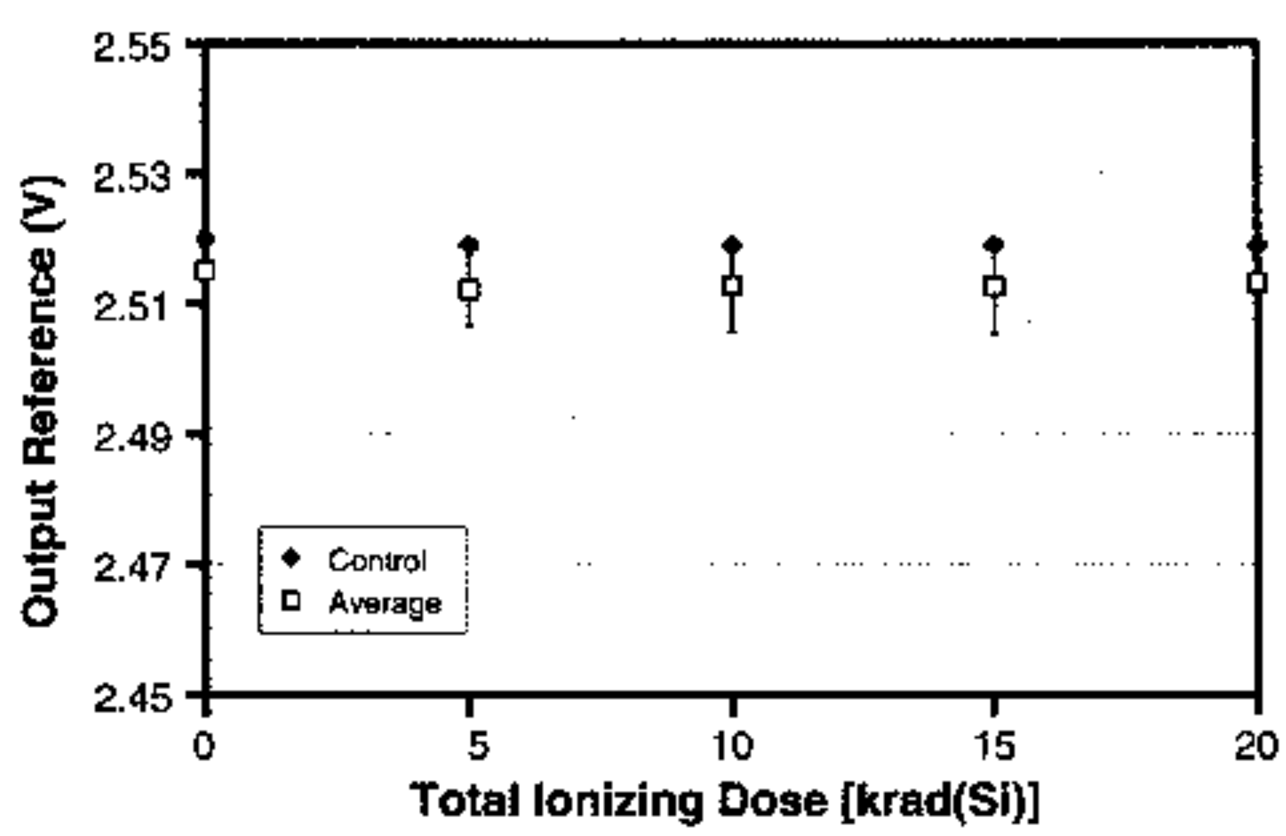

Figure 5. Output reference voltage for the TL431 voltage regulator.

6) K9F4G08U0A NAND Flash Memory – Samsung

Figure 6 shows the TID response for five NAND flash memories, the STMicroelectronics 1Gb, Micron 2Gb and 4Gb, Hynix 4Gb, and Samsung 4Gb, and also for two NOR flash memories, Toshiba 128Mb and Spansion 256Mb. During exposures, the parts were biased, but not actively exercised. Between exposures, the parts were written, read, and erased multiple times, in a total of four patterns, to verify full functionality. The patterns were checkerboard, checkerboard complement, all zeroes, and all ones. The orange bars indicate the highest dose at which all tested parts were still fully functional. For the Micron 4Gb, one of four samples failed at 100 Krad (SiO2), and all passed at 75 Krad (SiO2). For the Samsung 4Gb, eight of eight parts passed at 100 Krad (SiO2), and seven of eight parts passed at 150 Krad (SiO2). None of the other parts tested as well as the Samsung 4Gb. The result is encouraging for many space applications.

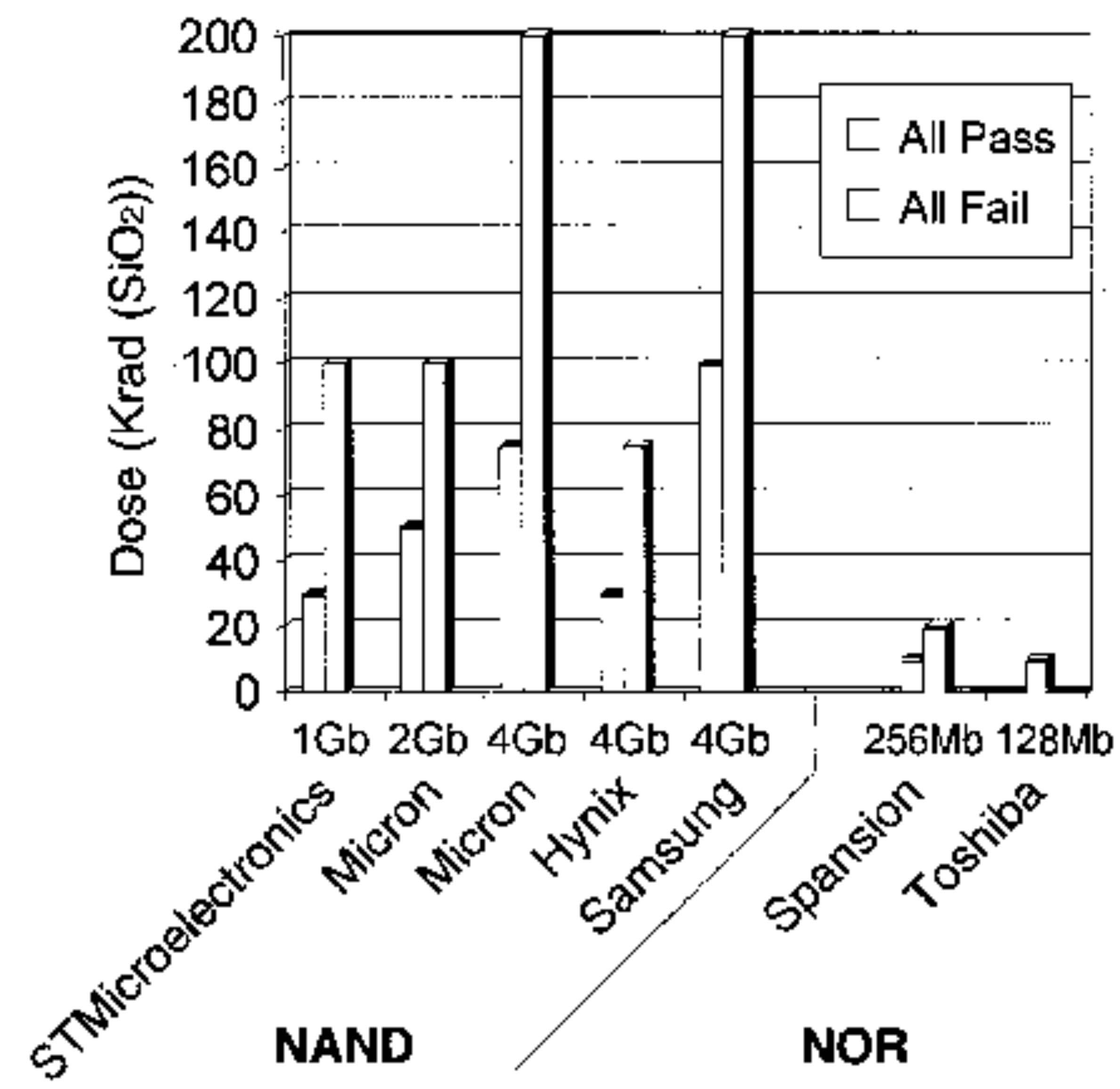

Figure 5. Total dose response of selected NAND and NOR flash memories.

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 lot and application specific testing be performed on any suspect or commercial device.

VI. Acknowledgment

The authors would like to acknowledge the sponsors of this effort: the NASA Electronic Parts and Packaging (NEPP) program, NASA Flight Projects and the Defense Threat Reduction Agency (DTRA) under IACRO #07-42071. The authors thank members of the Radiation Effects and Analysis Group who contributed to the test results presented here, Craig Stauffer, Hak S. Kim, Anthony M. Dung-Phan, Donald K. Hawkins, Martin A. Carts, James D. Forney, Tim Irwin, Christina M. Seidleck, Stephen R. Cox, and Mark Friendlich.

VII. References

[1] M. O'Bryan, et al., Compendium of Current Single Event Effects Results for Candidate Spacecraft Electronics for NASA" submitted to the 2007 IEEE NSREC Radiation Effects Data Workshop.
[2] Department of Defense "Test Method sTANDARD Microcircuits," MIL-STD-883 Test Method 1019.7 Ionizing radiation (total dose) test procedure, September 30, 2006, http:/www.dscc.dla.mil/downloads/MIL-STD-883/std883.pdf
[3] NASA/GSFC Radiation Effects and Analysis home page, http://radhome.gsfc.nasa.gov.