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

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***Abstract*-- Vulnerability 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, Single Event Effects, and Total Ionizing Dose.

I. Introduction

Long-term radiation induced failure modes play a significant role in determining space system reliability. As such, the effects of total ionizing dose (TID) needs to be evaluated in order to determine risk to space projects.

The test results presented here were gathered to establish the sensitivity of candidate spacecraft electronics to TID. This testing serves to determine the appropriateness of a candidate device which may be used in space applications. For similar results on single event effects (SEE), a companion paper has also been submitted to the 2010 IEEE NSREC Radiation Effects Data Workshop entitled: "Current Single Event Effects Compendium of Candidate Spacecraft Electronics for NASA" by M. O'Bryan, et al [1].

II. Test Techniques and Setup

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

A. *Test Methods – TID*

TID testing was performed according to the MIL-STD-883 1019.8 test method unless otherwise noted. [2]

B. *Test Methods – Proton*

Proton damage tests were performed on biased devices. Functionality and parametrics were measured either continually during irradiation (in-situ) or after step irradiations (for example: every 10krad(Si), or every $1x10^{10}$ protons/cm^2). Table I lists the proton damage test facilities and energies used on the devices.

TABLE I
PROTON TEST FACILITIES

Facility	Proton Energy, (MeV)
University of California at Davis Crocker Nuclear Laboratory (UCD-CNL)	~ 63

III. Test Results Overview

Abbreviations for principal investigators (PIs) are listed in Table II. Abbreviations and conventions are listed in Table III. 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	Stephen Buchner
MaC	Martin Carts
MiC	Michael Campola
DC	Dakai Chen
HK	Hak Kim
KL	Kenneth LaBel
CM	Cheryl Marshall
TO	Timothy Oldham
JP	Jonathan Pellish
AS	Anthony Sanders
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TABLE III
ABBREVIATIONS AND CONVENTIONS

ACRONYM/ DEFINITION	ACRONYM/ DEFINITION
A = amp ASIC = application specific integrated circuit CMOS = complementary metal oxide semiconductor DD = Displacement Damage DIP = dual inline package DNL = Differential Non-Linearity ELDRS = Enhanced Low Dose Rate Sensitivity FET = field effect transistor I_b = bias current I_c = collector current I_{cc}= power supply current I_f = forward current INL = Integral Non-Linearity I_{os} = offset current I_{out} = output current I_{STDBY} = standby current IUCF = Indiana University Cyclotron Facility LDC = lot date code MeV = mega electron volt mA = milli amp op amp = operational amplifier	P+ = protons N/A = not available NMRC = National Microelectronics Research Centre PI = principal investigator ROIC = Read Out Integrated Circuit SEE - single event effects Spec = specifications TID = total ionizing dose V_{bias} = bias voltage V_{cc} = power supply voltage V_{ce} = collector emitter voltage VCO = voltage-controlled oscillator V_{do} = dropout voltage V_{ENABLE} = enable voltage V_{os} = offset voltage VOL = output saturation voltage V_{out} = output voltage V_{ref} = reference voltage V_z = reverse breakdown voltage

TABLE IV
SUMMARY OF TID AND DD TEST RESULTS

Part Number	Manufacturer	LDC	Technology/ Device Function	Date/PI	Summary of Results	App. Spec. Test (Y/N)	Dose rate (rads(Si)/s)	Deg. Level (krads (Si))
Data Converters								
AD667	Analog Devices	0629A	Digital to Analog Converter/Bipolar	MAY09/SB	Differential Non-Linearity (DNL) exceed specs for two parts between 10 & 20 krad(Si). Integral Non-Linearity (INL) exceeded specs for three parts between 20 and 30 krad(Si).	N	0.01	10<DNL<20 20<INL<30
Linear								
PA10	Apex	60024	Power Amplifier/ Linear Bipolar	APR09/SB	Input offset voltage for two parts exceeded specifications.	N	0.01	$30< V_{os}<40$
LM317	Texas Instruments	39600	Voltage Regulator/ Linear Bipolar	APR09/MiC	Tested to verify operation over elevated temperature (30ºC, 55ºC, 75ºC), part's supply current, adjust current, and output voltage stayed within specification.	Y	10	>100
LT1009IDR	Texas Instruments	0606	2.5V internal reference/ Linear Bipolar	JUNE09/DC	V_z degrades with TID. Parameters within specification for all dose rates. (on-going)	N	0.005	$V_z >100$
							0.001	$V_z >100$
							0.0005	$V_z >100$
LM317KTTR	Texas Instruments	0608	Positive volt reg 3-terminal/ Linear Bipolar	JUNE09/DC	V_{out} shows dose rate enhancement. (on-going)	N	0.005	$V_{out} >80$
							0.001	$V_{out} >20$
							0.0005	$V_{out} >15$
LM117HRQMLV (TO-39 metal can)	Natl Semi	7D5867L019	Comparator/ Linear Bipolar	JUNE09/DC	V_{out} shows dose rate enhancement. (on-going)	N	0.005	$V_{out} <20$
							0.001	Vref <15
							0.0005	Vref <10
LM158AJRLQMLV (8-lead CERDIP)	Natl Semi	7W4453G019	Op Amp/ Linear Bipolar	JUNE09/DC	I_b shows dose rate dependence. (on-going)	N	0.01	$I_b >100$
							0.005	$60 < I_b <70$
							0.001	$I_b >30$
							0.0005	$I_b >15$
LM136 (3-lead TO-46)	Natl Semi	200746K019	Voltage Reference 2.5/Linear Bipolar	JUNE09/DC	V_z degrades with TID. Within specification for all dose rates. (on-going)	N	0.005	$V_z >100$
							0.001	$V_z >20$
							0.0005	$V_z >10$
RH1013MH (TO5 metal can)	Linear Technology	0329A/9513A	Dual precision op-amp/Linear Bipolar	JUNE09/DC	I_b degrades with TID.Parameters within specification for different dose rates and package types. (can and DIP). (on-going)	N	0.005	$I_b >80$
RH1013MJ8 (Ceramic DIP)		0305A/0337A					0.005	$I_b >80$
RH1021CMW-5 (Flatpack)	Linear Technology	0123A	Precision 5V Reference/Linear	JUNE09/DC	5 mrad(Si)/s show enhanced degradation to V_z relative to 8 mrad(Si)/s. (on-going)	N	0.005	$V_z >90$
							0.001	$V_z >20$
							0.0005	$V_z >10$

Part Number	Manufacturer	LDC	Technology/ Device Function	Date/PI	Summary of Results	App. Spec. Test (Y/N)	Dose rate (rads(Si)/s)	Deg. Level (krads (Si))
RH1021CMH-5 (TO-5 can)	Linear Technology	9783A	Precision 5V Reference/Linear Bipolar	JUNE09/DC	Flatpacks show less degradation for V_z than TO cans. (on-going)	N	0.005 0.001 0.0005	$80 < V_z < 90$ $V_z > 20$ $V_z > 10$
RH1009MW (Flatpack)	Linear Technology	0649A	2.5V Reference/ Linear Bipolar	JUNE09/DC	Enhanced degradation for V_z relative to high dose rate. (on-going)	N	0.005 0.001 0.0005	$100 < V_z < 120$ $V_z > 20$ $V_z > 10$
RH1009MH (TO-46 can)	Linear Technology	0829H	2.5V Reference/ Linear Bipolar	JUNE09/DC	Enhanced degradation for V_z relative to high dose rate. (on-going)	N	0.005 0.001 0.0005	$80 < V_z < 90$ $V_z > 20$ $V_z > 10$
RHFL4913ESY332 (TO257)	ST Microelectronics	30828A	Voltage Regulator/ Linear Bipolar	JUNE09/DC	We have observed negligible degradation. Parameters within specification. (on-going)	N	0.001 0.0005	$V_{out} > 10$ $V_{out} > 13$
RHFL4913KP332 (Flat-16)	ST Microelectronics	30814B	Voltage Regulator/ Linear Bipolar	JUNE09/DC	We have observed negligible degradation. Parameters within specification. (on-going)	N	0.01 0.001	$V_{out} > 10$ $V_{out} > 13$
Memory								
K9F4G08UOA-PCB0	Samsung	0840	CMOS/ 4Gb NAND Flash	MAY09/TO/AS	No errors @100 krad (Si), errors but functional @125 krad(Si), functional failure @150 krad(Si).	N	12	>100
K9F4G08UOA-PCB0	Samsung	0843	CMOS/ 4Gb NAND Flash	MAY09/TO/AS	No errors @ 100 krad(Si), errors but functional @ 125 krad(Si), functional failure @ 150 krad(Si).	N	12	>100
K9F4G08UOA-PCB0	Samsung	0846	CMOS/ 4Gb NAND Flash	MAY09/TO/AS	No errors @ 125 krad(Si), errors but functional @ 150 krad(Si), functional failure @ 175 krad(Si).	N	12	>125
K9F4G08UOA-PCB0	Samsung	0901	CMOS/ 4Gb NAND Flash	MAY09/TO/AS	No errors @ 125 krad(Si), errors but functional @ 150 krad(Si), functional failure @ 175 krad(Si).	N	12	>125
K9F4G08UOA-PCB0	Samsung	0907	CMOS/ 4Gb NAND Flash	MAY09/TO/AS	No errors @ 125 krad(Si), errors but functional @ 150 krad(Si), functional failure @ 225 krad(Si).	N	12	>125
N/A	N/A	N/A	90 nm CMOS/ Phase Change Non-Volatile Memory	NOV09/KL/HK	A commercial sample of a 90nm CMOS phase change non-volatile memory was tested for TID tolerance using a nominal 30 rads(Si)/sec dose rate at room temperature. Samples were biased during irradiation and tested in step dose level increments then tested for functional operation (read, write, erase with checkerboard and inverse checkerboard patterns). No degradation was noted to the maximum tested level of 300 krad(Si).	N	30	>300

Part Number	Manufacturer	LDC	Technology/ Device Function	Date/PI	Summary of Results	App. Spec. Test (Y/N)	Dose rate (rads(Si)/s)	Deg. Level (krads (Si))
Miscellaneous								
Complex 45nm Processor	N/A	N/A	45 nm CMOS/ Processor	09/KL/MaC	Complex 45nm processor was tested for TID tolerance using a nominal 30 rads/sec dose rate at room temperature. Samples were biased during irradiation and tested in step dose level increments then shipped via dry ice to an off-site test organization for full parametric characterization within a 48 hour period. Functionality was checked on these devices prior to shipping. No degradation was noted to the maximum tested level of 1 Mrad(Si).	N	30	>1000
Complex 65nm Processor	N/A	N/A	65 nm CMOS/ Processor	08/KL/MaC	Complex 65nm processor was tested for TID tolerance using a nominal 30 rads/sec dose rate at room temperature. Samples were biased during irradiation and tested in step dose level increments then shipped via dry ice to an off-site test organization for full parametric characterization within a 48 hour period. Functionality was checked on these devices prior to shipping. No degradation was noted to the maximum tested level of 1 Mrad(Si).	N	30	>1000
RadFET	NMRC	201	Field Effect Transistor/CMOS	APR09/MiC	Tested to verify annealing at cold temperature (-55C). Threshold voltage shift, no failure.	Y	10	<100
N/A	N/A	N/A	0.5 µm CMOS ReadOut Integrated Circuit (ROIC)	SEPT08/CM	ROIC imaging during exposure. No significant degradation at 40 K for bias currents and voltages, dark current, noise, photo-response and base line levels.	N	85	>35 at 40K
N/A	N/A	N/A	InGaAsP QWIP & 0.5 µm CMOS/ Quantum Well Infrared Photo-detector (QWIP) Array & ROIC	CNL/08NOV/ CM	* Proton test performed: No significant degradation in ROIC parameters that respond to TID and DD for bias currents and voltages, dark current, noise, photo-response and base line levels. An increase in hot pixels was observed in 1 DUT but room temperature annealing was very effective. Transient study for ROIC and QWIP performed at 9 MeV and 63 MeV. Large positive-going transients were seen to occur with the probability of ~10-6 per incident 63.3 MeV proton, corresponding to the approximate probability for a proton nuclear reaction event. Resulting single event functional interrupt may require power cycle.	N	85	~15

Part Number	Manufacturer	LDC	Technology/ Device Function	Date/PI	Summary of Results	App. Spec. Test (Y/N)	Dose rate (rads(Si)/s)	Deg. Level (krads (Si))
Power								
TL750L05CDR	Texas Instruments	0605	LDO positive voltage reg 5V/ Linear Bopolar	JUNE09/DC	Functional failures (V_{out}) show dose rate dependence. (on-going)	N	0.005	V_{out} <40
							0.001	V_{out} <15
							0.0005	V_{out} <10
TL750M05CKTRR	Texas Instruments	0707	LDO positive voltage reg 5V/ Linear Bopolar	JUNE09/DC	V_{out} degrades with TID. Parameters within specification for I_{out} = 10 mA. (on-going)	N	0.005	V_{out} >80
STPSC806D	ST Microelectronics	0818	Power Diode/ SiC Substrate	NOV09/DC	Minimal change in forward I-V, reverse I-V, and capacitance-voltage characteristics after 9000 krad(Si).	N	6-17	>9000
STPSC1006D	ST Microelectronics	0830	Power Diode/ SiC Substrate	NOV09/DC	Minimal change in forward I-V, reverse I-V, and capacitance-voltage characteristics after 9000 krad(Si).	N	6-17	>9000
Test Parts								
Test Transistors	Texas Instruments	N/A	65nm test transistors/CMOS	MAR09/MX/JP	No degradation observed.	N	3.3	>300
IBM 5AM SiGe HBT 0.5x5 μm^2	IBM	Test Vehicle	5AM SiGe/ BiCMOS	JUL09/JP	Unexpected collector current shift during TID. [4]	N	3.3	>1000

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.

A. STPSC1006D/ ST Microelectronics/Power Diode

The ST Microelectronics power diode STPSC1006D was tested for TID tolerance using a Co60 source. The power diodes are robust against TID up to highest tested level of 9 Mrad(Si). The reverse current showed slight increase from approximately 120 V to 250 V. The forward current-voltage and capacitance-voltage characteristics remain unchanged after irradiation. Thus there were minimal degradation to the diode's physical and electrical properties, including the Schottky contact, doping concentration, and series resistance.

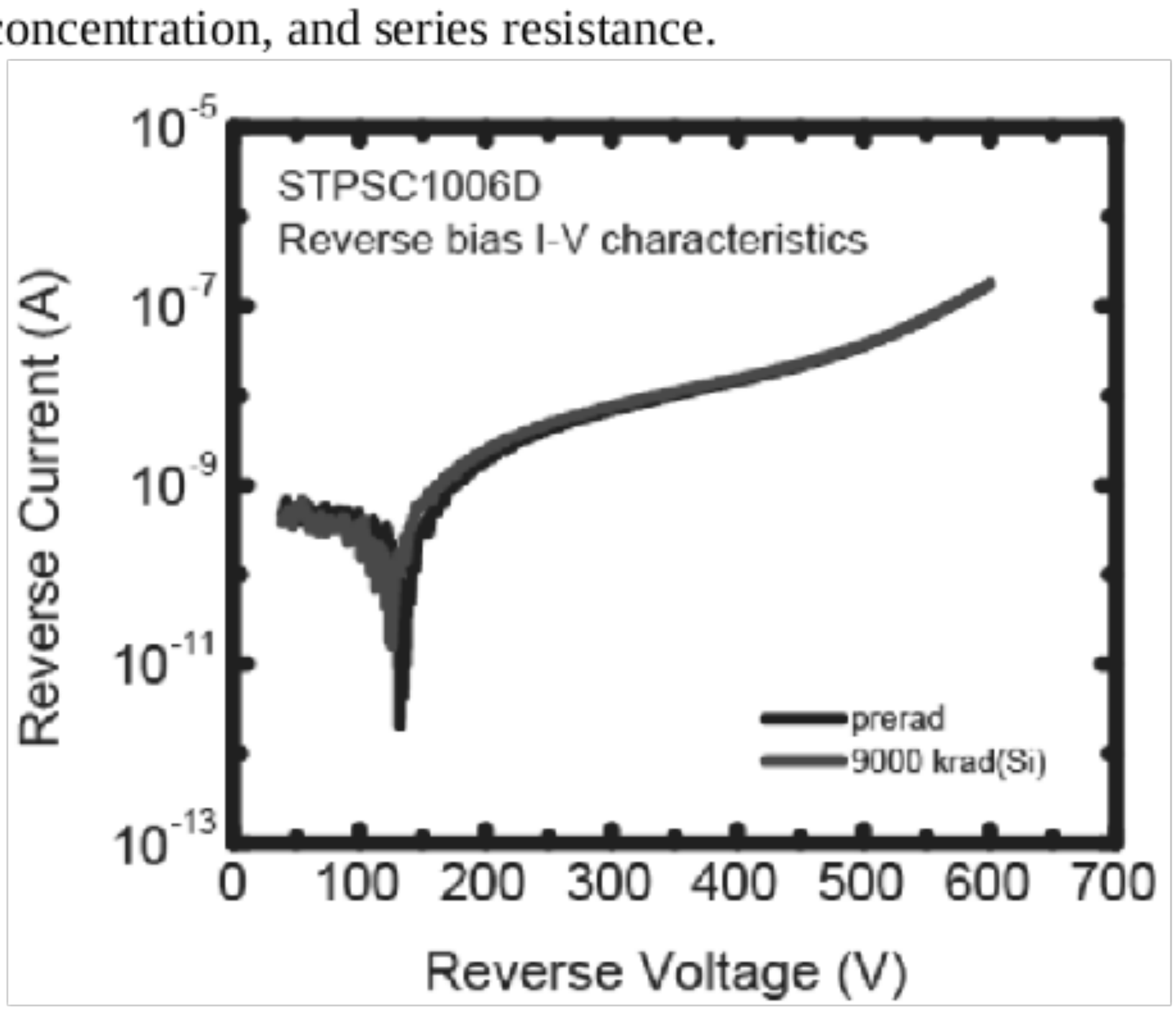

Fig. 1. Reverse bias I-V characteristics for the STPSC1006D power diode pre-irradiation and after 9 Mrad(Si).

B. 4G NAND Flash/ Samsung

TID results for the Samsung 4G NAND Flash are presented in Fig. 2. Twenty five samples were tested, five each from five different LDCs. Parts were exposed in a Co-60 source at the rate of 12 rad(Si)/sec. Nominal bias for these parts is 3.3 V, but testing was done at nominal VDD+10% (per TM 1019.8), or 3.6 V. Parts were biased , but not actively exercised during exposures. There were no errors in any part from any LDC at less than 100 krad(Si), which is sufficient for many NASA missions. At higher doses, there were some errors, which could be reset, however, the parts worked properly after being reset, until functional failure occurred, at 150-225 krad(Si), depending on LDC. The differences between LDCs were not large but measurable indicating one source of uncertainty when dealing with unhardened commercial technology. When functional failure occurred, it was due to the erase function failing in all cases. Although these parts represent unhardened commercial technology, we note that their radiation tolerance is dramatically better than the nearest commercial equivalent parts from ten or fifteen years ago, making them promising candidates for most NASA missions.

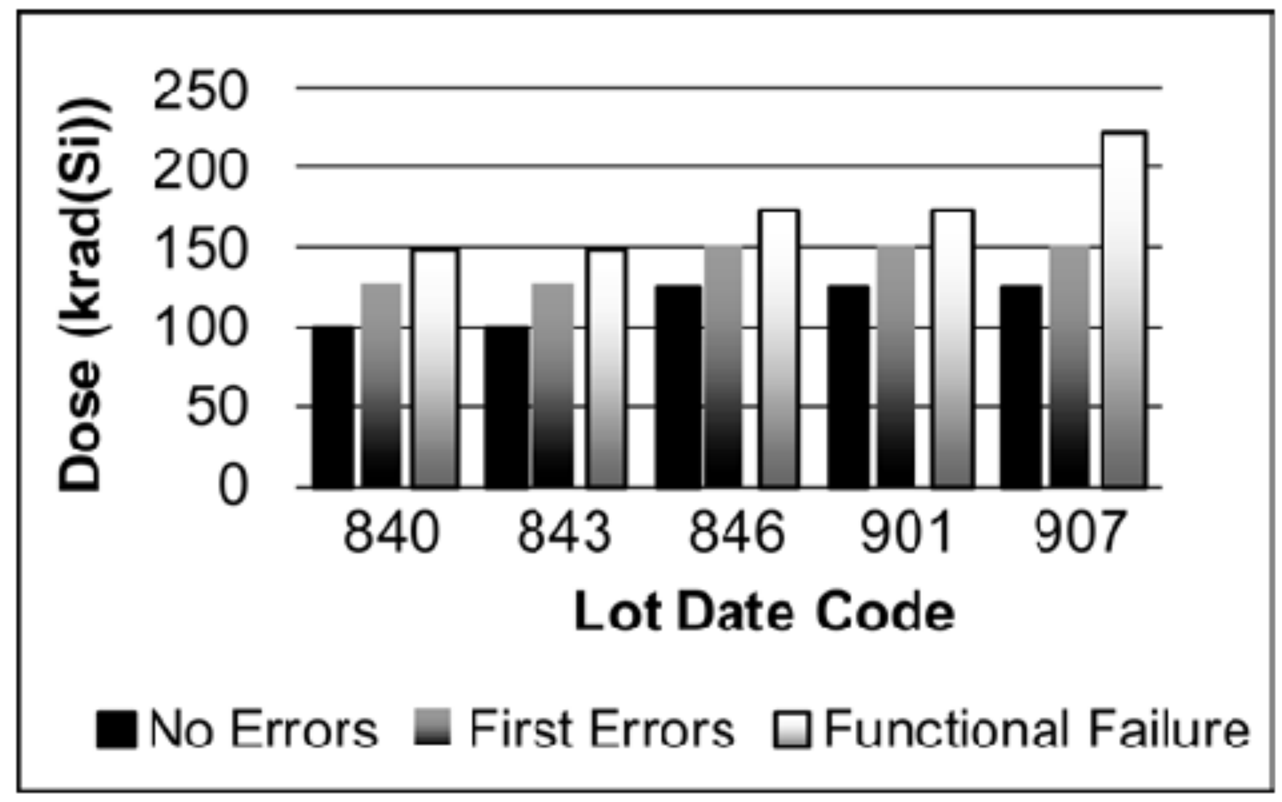

Fig. 2. Samsung 4G NAND Flash TID Results.

C. TL750L05CDR/ Texas Instruments/Voltage Regulator

The TL750L05CDR is a commercial low-dropout voltage regulator manufactured by Texas Instruments tested for extreme enhanced low dose rate sensitivity (ELDRS) as research. Detailed description of the results for this part and other parts in the ELDRS study can be found in [5]. Fig. 3 shows average output voltage (from 4 parts at each dose rate) vs. TID. We observe distinct dose rate dependence for functional failures of the Vout. The initial failures occur after 40, 20, and 10 krad(Si) for the 5, 1, and 0.5 mrad(Si)/s parts, respectively. In the 5 mrad(Si)/s case, one part each failed after 40 and 50 krad(Si). Two parts failed after 80 krad(Si). In the 1 mrad(Si)/s case, two parts failed after 20 krad(Si), while two parts remain functional. In the 0.5 mrad(Si)/s case, two parts failed after 10 krad(Si), while two parts remain functional. The device failures are characterized by the functional failure of the output voltage. The parts failed abruptly, without gradual degradation to V_{out} or any other measured parameter.

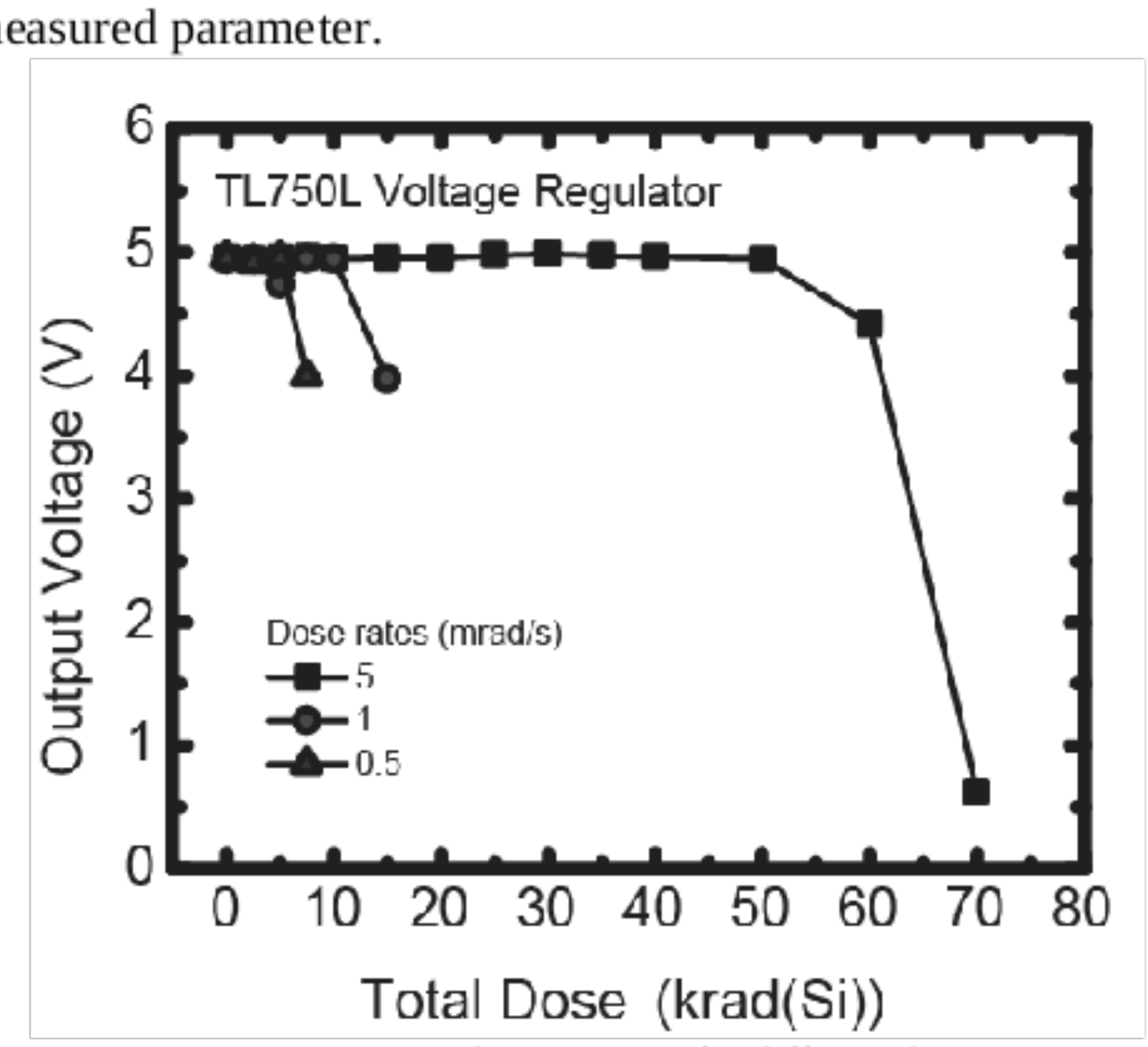

Fig. 3. Average output voltage vs. TID for different dose rates for the TL750L voltage regulator, irradiated with all pins grounded.

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

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VII. References

[1] Martha V. O'Bryan, et al., "Current Single Event Effects Compendium of Candidate Spacecraft Electronics for NASA," submitted for publication in IEEE NSREC10 Data Workshop, July 2010.

[2] Department of Defense "Test Method Standard Microcircuits," MIL-STD-883 Test Method 1019.8 Ionizing radiation (total dose) test procedure, September 30, 2006, http://www.dscc.dla.mil/Downloads/MilSpec/Docs/MIL-STD-883/std883_1000.pdf

[3] NASA/GSFC Radiation Effects and Analysis home page, http://radhome.gsfc.nasa.gov.

[4] P. E. Cheng et al., IEEE TNS, vol. 56, no. 6, p. 3318, Dec. 2009.

[5] Dakai Chen, et al., "The Effects of ELDRS at Ultra-low Dose Rates," submitted for publication in IEEE NSREC10 Data Workshop, July 2010.