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

Donna J. Cochran, Scott D. Kniffin, Stephen P. Buchner, Kenneth A. LaBel, Martha V. O'Bryan, Raymond Ladbury, Anthony B. Sanders, Donald K. Hawkins, Stephen R. Cox, Christian F. Poivey, Timothy Oldham, Hak Kim, Tim L. Irwin, Mark Friendlich, Anthony M. Dung-Phan, Martin A. Carts, Melanie Berg, Christina M. Seidleck, and James D. Forney

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, Total Ionizing Dose, and Single Event Effects.

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Donna J. Cochran, MEI Technologies Inc., c/o NASA Goddard Space Flight Center (GSFC), Code 561.4, Bldg. 22, Rm. 062A, Greenbelt, MD 20771 (USA), phone: 301-286-8258, fax: 301-286-4699, email: dcochran@pop700.gsfc.nasa.gov

Scott D. Kniffin, Martha V. O'Bryan, Christian F. Poivey, Hak Kim, Tim L. Irwin, Mark Friendlich, Anthony Dung-Phan, Martin A. Carts, Melanie Berg, Christina M. Seidleck, and James D.Forney, MEI Technologies Inc., c/o NASA/GSFC, Code 561.4, Greenbelt, MD 20771 (USA), phone: 301-286-1185 (Kniffin), 301-286-1412 (O'Bryan), 301-286-2128 (Poivey), 301-286-5587 (Kim), 301-286-2014 (Irwin), 301-286-3327 (Friendlich), 301-286-1239 (Phan), 301-286-2600 (Carts), 301-286-2153 (Berg), 301-286-1009 (Seidleck), 301-286-9855 (Forney), email: Scott.D.Kniffin.1@gsfc.nasa.gov, vobryan@pop700.gsfc.nasa.gov, cpoivey@pop500. gsfc.nasa.gov, hkim@pop700.gsfc.nasa.gov, tirwin@pop500.gsfc.nasa.gov, Mark.R.Friendlich.1@gsfc.nasa.gov, Anthony.M.Dung-Phan.1@gsfc.nasa.gov, mcarts@pop500.gsfc.nasa.gov, Melanie.D.Berg.1@gsfc.nasa.gov, cseidlec@ pop700.gsfc.nasa.gov, and jforney@pop700.gsfc.nasa.gov ,

Kenneth A. LaBel, Ray L. Ladbury, Anthony B. Sanders, Donald K. Hawkins, and Stephen R. Cox, NASA/GSFC, Code 561.4, Greenbelt, MD 20771 (USA), phone: 301-286-9936 (LaBel), 301-286-1030 (Ladbury), 301-286-1151 (Sanders), 301-286-4789 (Hawkins), 301-286-7721 (Cox), email: Kenneth.A.Label@nasa.gov, Raymond.L.Ladbury @nasa.gov, Anthony.B.Sanders@ nasa.gov, Donald.K.Hawkins@nasa.gov, and Stephen.R.Cox@ nasa.gov,

Stephen P. Buchner, and Timothy R. Oldham, QSS, c/o NASA/GSFC, Code 561.4, Greenbelt, MD 20771 (USA), phone: 301-286-5019 (Buchner), 301-286-5489 (Oldham), email: sbuchner@pop500.gsfc.nasa.gov, timothy.r.oldham@gsfc.nasa.gov

I. INTRODUCTION

In order to meet the demands of reduced cost, higher performance and more rapid delivery schedules imposed by the space flight community, commercial and emerging technology devices have assumed a prominent role in meeting these needs. With the skyrocketing increase in the use of such devices, 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 2006 IEEE NSREC Radiation Effects Data Workshop entitled: “Compendium of 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 in excess of 2 rads (Si)/s, with dosimetry being performed by an ion chamber probe.

B. 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 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)	26.6-63

C. 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 1019.6 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. Definitions for the categories are listed in Table III. Abbreviations and conventions are listed in Table IV. Table V 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
SK	Scott Kniffin
TO	Timothy Oldham
CP	Christian Poivey

TABLE III: LIST OF CATEGORIES

1	Not tested to failure
2	Degradation at >50krads(Si)
3	Degradation at 20-50krads(Si)
4	Degradation at 5-20krads(Si)
5	Degradation at 5krads(Si) or less
REV	Research Test Vehicle – Please contact the P.I. before utilizing this device for spacecraft applications.

TABLE IV: 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_{ce} = collector emitter voltage

TABLE V: SUMMARY OF TID AND DD 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))	Cat.
Amplifiers								
AD549LH	Analog Devices	0414	Op Amp	GSFC05APR/SK	0.04	All devices passed all tests to 5krads(Si). Degradation seen in +Ib and –Ib from 10 to 20krads(Si), returned to within specification limits after annealing. Two devices exceed the specification limit for Vos after 20krads(Si) and recovered to within 3µV of the specification limit after annealing.	10	4
PA10M	Apex Microtechnology Corp.	0437	Op Amp	GSFC05JUL/SK	0.06	All parts passed all tests up to 40krads(Si). After 50krads(Si), one DUT exceeded the specification limits for Io and +Ib, but recovered after annealing.	50	3
OP400	Analog Devices	0312	Op Amp	GSFC05APR/SK	0.097	+Ib and –Ib exceeded specification limits after 20krads(Si). Slew Rate fell well below specification limits after 20krads(Si) and is effectively non-existent after 40krads(Si). However, devices are still fully functional in DC mode through 100krads(Si).	20	3
OP200	Analog Devices	0245A	Op Amp	GSFC/SB	0.02	All parts passed all tests up to 30krads(Si). I_C exceeded specification limit after 40krads(Si). All other parameters remained within specifications up to 75krads(Si).	40	3
OP77	Analog Devices	0419	Op Amp	GSFC/SB	0.02	All parts passed all tests up to 10krads(Si). I_B exceeded specification limits after 15krads(Si).	15	4
OP97A	Analog Devices	0521	Op Amp	GSFC/SB	0.02	All parts passed all tests up to 5krads(Si). I_B exceeded specification limits after 10krads(Si).	10	4
HA2-5142	Intersil	9930	Op Amp	GSFC/SB	0.02	All parts passed all tests up to 5krads(Si). I_{OS} exceeded specification limits after 10krads(Si).	10	4
LM101	National Semi.	9931	Op Amp	GSFC/SB	0.02	No parametric degradation to 40krads(Si).	>40	1
LMH6702	Analog Devices	0432	Op Amp	GSFC/SB	0.02	No parametric degradation to 100krads(Si).	>100	1
LM6142	National Semi.	0428	Op Amp	GSFC/SB	2	No parametric degradation to 100krads(Si).	>100	1
AD524	Analog Devices	0502A	Instrument Amp.	GSFC/SB	0.02	I_C and V_{IO} exceeded specification limits after 10krads(Si).	10	4
AD585	Analog Devices	0307A	Samp. & Hold Amp	GSFC/SB	0.02	No parametric degradation to 40krads(Si).	>40	1
Converters								
AD650	Analog Devices	0518	Voltage Frequency Converter	GSFC05OCT/CP	0.14-1.4	No parametric degradation to 100krads(Si).	>100	1
MX7545A	Maxim	0503A	12-Bit DAC	GSFC05MAR/CP	0.78	No parametric degradation to 10krads(Si). After 15krads(Si) Offset Error exceeded specification limits. After 20krads(Si), INL and DNL exceeded specification limits.	10-20	4
AD1671	Analog Devices	0512	12-Bit ADC	GSFC/SB	0.02	No parametric degradation to 5krads(Si). After 10krads(Si) INL exceeded specification limits.	10	4

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))	Cat.
Voltage References, Regulators & Comparators								
AD580	Analog Devices	0419C	Voltage Ref	GSFC/SB	100 & 0.02	Slight degradation within specification limits seen up to 100krads(Si). No ELDRS effects seen.	>100	1
MAX6021	Maxim		Voltage Ref	GSFC/SB	0.02	All parts passed all tests to 11krads(Si). V_{Out} exceeded specification limits after 20krads(Si).	20	3/4
LM136	National Semi.	0134	2.5V Vref	GSFC/SB	0.02	No parametric degradation to 100krads(Si).	>100	1
LM111	National Semi.	0126A	Voltage Comparator	GSFC/SB	0.02	No parametric degradation to 40krads(Si).	>40	1
LM117	National Semi.	0433AP	Voltage Regulator	GSFC/SB	0.02	Degradation within specification limits seen up to 40krads(Si).	>40	1
LM119	National Semi.	0423B	Voltage Comparator	GSFC/SB	0.02	All parts passed all tests to 5krads(Si). I_B exceeded specification limits after 10krads(Si).	10	4
LM139	National Semi.	0302	Quad Comparator	GSFC/SB	0.02	No degradation in the measured parameters to 40krads(Si)	>40	1
Logic Devices								
MT29F2G08B	Micron	0524	NAND Flash Memory	GSFC05OCT/TO	7.01	Isolated errors that could be cleared by reset from 10 to 30krads(Si). Functional failure from 50 to 75krads(Si). Complex error modes, see report.	10-30	4
54ACTQ04	National Semi.	0518A	HEX inverter	GSFC/SB	2	No parametric degradation up to 100krads(Si).	>100	1
54ACTQ14	National Semi.	0248A	HEX Schmitt Trigger	GSFC/SB	2	All parameters remained within specification up to 100krads(Si) except I_C that was larger by 25% than the specification limit for measurements made at 20 and 40krads(Si) only. After 100 hour anneal, all parameters within specification limits.	20-100	1/3
54ACTQ14	National Semi.	0312	HEX Schmitt Trigger	GSFC/SK	0.12	Icch and Iccl exceed specification limits from 20-80krads(Si). Icch within specification limits after 100krads (Si), Iccl continued to degrade. No change after annealing. No functional failures.	20-100	3
54AC2525	National Semi.	0527	Minimum skew clock distributor	GSFC/SB	100	No parametric degradation up to 100krads(Si).	>100	1
54ACTQ16244	National Semi.	0423	16-bit Buffer/Line Driver	GSFC/SB	100	No parametric degradation up to 100krads(Si).	>100	1
DS26F31	National Semi.	0230A	Quad diff. Line driver	GSFC/SB	100	No parametric degradation up to 100krads(Si).	>100	1
SG1644	Linfinity	0432	Dual High Speed Driver	GSFC/SB	2	No parametric degradation up to 100krads(Si).	>100	1
Other Devices								
2N2222	Microsemi	0315	Transistor	GSFC05SEP/SB	0.02	No parametric degradation to 20krads(Si). One device fell below the specification limit for H_{FE} after 30krads(Si) and its reading degraded further after annealing.	30	3
2N2907	Microsemi	0331	Transistor	GSFC05AUG/SB; GSFC05SEP/SB	0.02	No parametric degradation to 30krads(Si).	>30	1
SW06	Analog Devices	0202	Analog Switch	GSFC/SB	100	No parametric degradation to 40krads(Si)	>40	1

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))	Cat.
UC1825	TI	0303A	Pulse Width Modulator	GSFC/SB	100	One functional failure after 10krads(Si) (first step). V_{REF} exceeded specification limit from 30krads(Si) on. No recovery after annealing.	10	4
SG1524	Linear Tech.	0430	Pulse Width Modulator	GSFC/SB	0.02	All parts passed all tests up to 10krads(Si). After 20krads(Si), devices exceeded the specification limit for V_{REF} and continued to degrade through 100krads(Si). The devices did not recover after annealing.	20	4
S3590-02	Hamamatsu	N/A	PiN photodiode	GSFC/SK	6.6	No degradation seen at 15.4krads(Si).	>15.4	1
RP21005D0-100	DDC	0348	Power Controller	GSFC/SK	0.09	No parametric degradation to 15krads(Si).	>15	1
RP21005D0-160K	DDC	0343	Power Controller	GSFC/SK	0.09	No parametric degradation to 15krads(Si).	>15	1
LTZ1000A & AD845	Linear Tech	0415 & 0413	Precision Vref and Op Amp	GSFC/SK	0.01	Tested as a complete circuit due to critical nature of output voltage to mission. All measurements remained within specification limits to 30krads(Si).	>30	1
Research Test Vehicle								
G FLX RAM249	LSI Logic	0528	SRAM	GSFC05SEP/CP	0.14-1.4	No parametric degradation to 300krads(Si).	>300	RTV
G FLX RAM187	LSI Logic	0528	SRAM	GSFC05SEP/CP	0.14-1.4	No parametric degradation to 300krads(Si).	>300	RTV
G FLX L9A0443	LSI Logic	0528	0.11 µm CMOS	GSFC05NOV/CP	1.54	No parametric degradation to 300krads(Si).	>300	RTV
Nano-Crystal Memory	Freescale Semi.	RTV	90nm non-volatile memory	GSFC/TO	10	No degradation or slight improvement in number of bad bits to 100krads(Si). After 150 and 200krads(Si), many thousands of bad bits observed.	150	RTV
Displacement Damage								
53272	Micropac	0444	Power MOSFET optocoupler	UCD/SB		I_F required to turn MOSFET on increases by 8mA from initial to $7x10^{11}$p/cm^2, no other changes noted.		1
HCPL-6731	Agilent	9631	Optocoupler	UCD/SK		CTR degradation noted, however still within specificaiton to $1x10^{12}$p/cm^2		1
HCPL-520K	Agilent	0227	Optocoupler	UCD/SK		No degradation to $1x10^{12}$p/cm^2		1
HCPL-655K	Agilent	0507	Optocoupler	UCD/SK		CTR degradation noted, however still within specificaiton to $1x10^{12}$p/cm^2		1
HCPL-553K	Agilent	0408	Optocoupler	UCD/SK		CTR degradation noted, however still within specificaiton to $1x10^{12}$p/cm^2		1
LTZ1000A	Linear Tech	0415	Precision Vref	UCD/SK		Some change within specification limits was seen in the Vref measurement after $1x10^{12}$p/cm^2.		1
STAR1000	Fill Factory	No LDC	CMOS Image Sensor	UCD/CP		No degradation to $8x10^{10}$p/cm^2 (10.8krads(Si)).		1
ADV202	Analog Devices	0351	Video Compressor	DD & TID: UCD05MAY/CP		No parametric degradation to 70krads(Si) with 63MeV protons.	>70	1

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) RAM187 and RAM249 from LSI Logic (PI:CP)

The RAM187 (high density module) and RAM249 (high speed module) are 4Mbit Gflx SRAMs in a 512kx8 structure from LSI Logic. The process is 0.11mm bulk CMOS and there were three different structures of each type. The structure types were labeled Standard, Buried Layer 1 and Buried Layer 2. The buried layer formats were designed for SEL immunity. Four samples of each structure per device type (3 for test + 1 control each, 18 for test + 6 controls total) were tested to 300krads(Si) at dose rates between 500 and 5000rads(Si)/hour. All devices were from LDC 0528. All devices were subjected to a battery of tests to determine device functionality as follows:

Table VI. Parametric Characteristics (Vcore=1.2V, VI/O=2.5V)

Parameter	Condition
Functional test1	All 0 pattern, 10MHz
Functional test2	55 pattern, 10 MHz
Functional test3	AA pattern, 10 MHz
Functional test4	All 1 pattern, 10 MHz
Vdd core Power supply standby current1	All 0 pattern
Vdd core Power supply standby current2	55 pattern
Vdd core Power supply standby current3	AA pattern
Vdd core Power supply standby current4	All 1 pattern
VI/O Power supply standby current1	All 0 pattern
VI/O Power supply standby current2	55 pattern
VI/O Power supply standby current3	AA pattern
VI/O Power supply standby current4	All 1 pattern

Test results on both memory designs and all processes did not show any functional failure or degradation of electrical parameters up to the maximum test dose of 300krads(Si). Figures 1 and 2 show the memory core standby current in function of total dose. Memory core standby current showed the most variation due to TID.

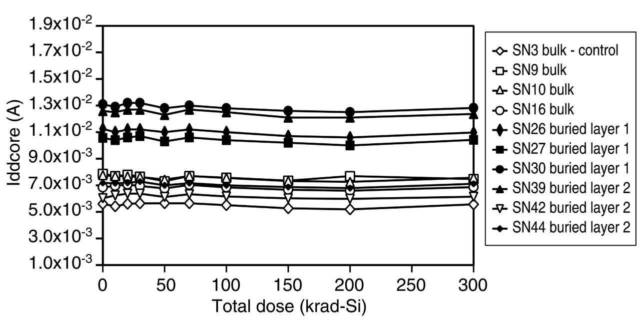

Fig. 1. RAM249 Idd core standby current versus TID

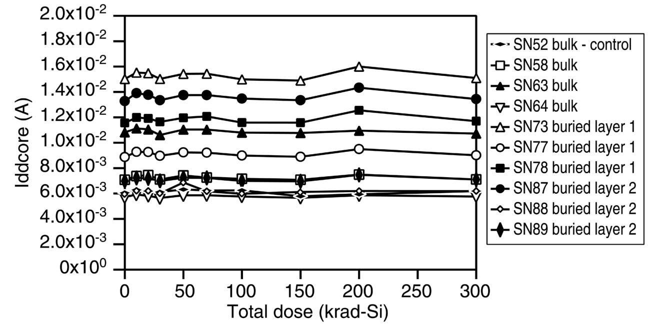

Fig. 2. RAM187 Idd core standby current versus TID

2) MT29F2G08 from Micron (PI:TO)

The MT29F2G08 is a 2Gbit non-volatile memory using a floating gate NAND flash cell. A total of 6 devices were irradiated in two test groups at an average dose rate of 7.01rads(Si)/s. In the first group, four devices were characterized. Two devices (A &B) were only read, in both cache & non-cache mode. The other two devices (C&D) tested all device functions, read, write & erase, using multiple patterns (FF AA 55 & 00) in both cache & non-cache mode. These first four devices were characterized at a test frequency of 10 MHz (100 ns cycle time). Later, a second group of two additional devices (I and J) was characterized in a similar manner, except that the test frequency was 33 MHz (30 ns cycle time). One additional test was also performed on these last two devices, a continuous Read/Erase/Write cycle, where the tests are performed block-by-block, instead of reading the whole memory, erasing the whole memory, etc. The commands to read, erase, write, and move to the next block were given under automatic computer control, rather than manually, as in the first set of tests. The purpose of this test was to investigate apparent timing changes in the control circuitry that were observed after annealing in the first set of exposures.

In all cases, functional failure occurred between 50 and 100krads(Si). There were a number of errors at several dose steps that could be cleared by resetting the device. What was unusual, was that a number of the errors observed were "1" turning to "0"; the opposite of what is usually expected in TID testing. Further adding to the intrigue of these devices, was the discovery that when the devices were tested manually after annealing, they appeared to function normally; however, when tested dynamically (Read, Write, Erase under computer control), the devices were completely non-functional.

3) 2N2222 from Microsem (PI:SB)

The 2N2222 is an NPN switching transistor commonly used for space flight. A total of 5 devices were tested (4 irradiated + 1 control). The devices were irradiated to 30krads(Si) at an average dose rate of 0.019rads(Si)/s. All devices passed all tests up to 20krads(Si). After 30krads(Si), one device fell below the specification limit for one Gain measurement (hfe2). After annealing, this particular device continued to degrade as expected in a bipolar device of this nature. All other parts passed all test. See Figure 3 for the details of the gain measurements.

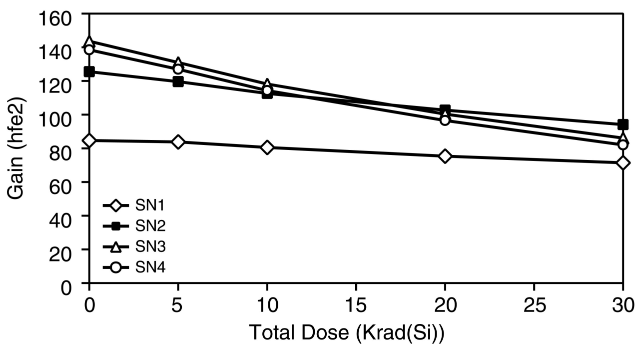

Fig. 3 Gain (hfe2: Vce = 10V, Ic = 1mA) as a function of total dose

4) HCPL-6731, HCPL-520K, HCPL-655K, and HCPL-553K from Agilent (PI:SK)

Four types of HCPL series optocouplers from Agilent were tested for DD effects at UCD. Each device was tested by sweeping IF from 0mA to the specification sheet maximum, for each 1V step of VCE (VCE = 6V to 18V for HCPL-6731, HCPL-520K and VCE = 0V to 18V for HCPL-655K, and HCPL-553K). While there was degradation of CTR (HCPL-6731, HCPL-655K, and HCPL-553K) or the logic switch point (HCPL-520K), especially for IF below the specification sheet minimum for each given part type, once an appropriate IF was reached, all devices performed within specification limits for all tests to a total test fluence of $1x10^{12}p/cm^2$.

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.

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References

[1] M. O'Bryan, et al., Compendium of Single Event Effects Results for Candidate Spacecraft Electronics for NASA" submitted to the 2006 IEEE NSREC Radiation Effects Data Workshop.

[2] Department of Defense Test Method Microcircuits, MIL-STD-883 Test Method Standard, Microcircuits, MIL-STD-883 Test Method 1019.6, Dated: 07 March 2003, File name: std883not5.pdf, http://www.dscc.dla.mil/Downloads/MilSpec/Docs/MIL-STD-883/std883not5.pdf

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