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

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Abstract-- Total ionizing dose and displacement damage testing is performed to characterize and determine the suitability of candidate electronics for NASA spacecraft and program use.

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

I. INTRODUCTION

One of the many elements considered in the development of NASA flight hardware is the hazard posed by exposure to the space radiation environment, which includes both ionizing and non-ionizing radiation. Flight electronics can be directly affected by ionizing radiation in the form of total ionizing dose (TID) and single event effects (SEE), while displacement damage (DD) is a non-ionizing energy loss (NIEL) component of the incoming ionizing radiation. These effects could range from minor degradation to complete device failure and therefore threaten the overall mission. By characterizing and evaluating these devices through various types of testing, failure modes are better understood, and it becomes possible to determine the best method of mitigation to reduce the overall risk posed to mission success.

We provide recent TID and DD testing results for candidate electronics for various NASA missions and programs performed by the NASA Goddard Space Flight Center's Radiation Effects and Analysis Group (REAG). A companion REAG paper detailing recent SEE test results has also been submitted to the 2015 IEEE NSREC Radiation Effects Data Workshop, titled: "Compendium of Current Single Event Effects for Candidate Spacecraft Electronics for NASA" by M. O'Bryan, et al. [1].

II. TEST TECHNIQUES AND SETUP

A. *Test Source – TID*

TID testing was performed using a high energy gamma ray source. Dose rates used for testing were between 0.05 and 18 rad(Si)/s.

B. *Test Source – Proton*

Proton DD/TID tests were performed at the University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) using a 76" cyclotron (maximum energy of 64 MeV). Table I lists the proton damage test facilities and energies used on the devices. Unless otherwise noted, all tests were performed at room temperature and with nominal power supply voltages.

TABLE I: PROTON TEST FACILITIES

Facility	Incident Proton Energy, (MeV)
University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL)	6.5-64

III. TEST RESULTS OVERVIEW

Abbreviations for principal investigators (PIs) are listed in Table II. Abbreviations and conventions are listed in Table III. Summary of TID and DD test results are listed in Table IV and V.

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TABLE II
LIST OF PRINCIPAL INVESTIGATORS

Abbreviation	Principal Investigator (PI)
DC	Dakai Chen
RG	Robert Gigliuto
RL	Raymond Ladbury
JML	Jean-Marie Lauenstein
DV	Daniel Violette

TABLE III
ABBREVIATIONS AND CONVENTIONS

A = Amp
B_H = Magnetic Hysteresis
BiCMOS = Bipolar – Complementary Metal Oxide Semiconductor
B_{JT} = Bipolar Junction Transistor
B_{OP} = Magnetic Operating Point
B_{RP} = Magnetic Release Point
BV_{dss} = Breakdown Voltage
CMOS = Complementary Metal Oxide Semiconductor
CTR = Current Transfer Ratio
DAC = Digital to Analog Converter
DC-DC = Direct Current to Direct Current
DD = Displacement Damage
DDR = Double-Data-Rate (a type of SDRAM—Synchronous Dynamic Random Access Memory)
DIMM = Dual In-Line Memory Module
DNL = Differential Non-Linearity
DUT = Device Under Test
$DV_{out/}$ DI_{out} = Output Voltage Load Regulation
ELDRS = Enhanced Low Dose Rate Sensitivity
FET = Field Effect Transistor
FPGA = Field Programmable Gate Array
GaN = Gallium Phosphide
GSFC = Goddard Space Flight Center
HBT = Heterojunction Bipolar Transistor
H_{FE} = Forward Current Gain
I_b = Base Current
I_{bias} = Input Bias Current
I_c = Collector Current
I_{ce} = Output Current
IDD = Supply Current
I_f = Input Forward Current
IGaN = Indium Gallium Nitride
I_{GSS} = Gate Reverse Current
I_{os} = Offset Current
InGaP = Indium Gallium Phosphide
I_{OUT} = Output Current
JFET = Junction Field Effect Transistor
LCC = Leadless Chip Carrier
LDO = Low Dropout
LED = Light Emitting Diode
LDR = Low Dose Rate
LDR EF = Low Dose Rate Enhancement Factor
Loadreg = Load Regulation
MDAC = Multiplying Digital-to-Analog Converter
MeV = Mega Electron Volt
mA = milliamp
MLC = Multi-Level Cell
MOSFET = Metal Oxide Semiconductor Field Effect Transistor
Mrad = megarad
N/A = Not Available
NIEL = non-ionizing energy loss
Op-Amp = Operational Amplifier
PI = Principal Investigator
PSRR = Power Supply Rejection Ratio
R_{AP} = Analog Path Resistance Match
REAG = Radiation Effects & Analysis Group
SEE = Single Event Effects
SMART = Self-Monitoring, Analysis and Reporting Technology
Spec = Specification(s)
SSD = Solid State Device
SSDI = Solid State Devices, Inc.
TID = Total Ionizing Dose
TLC = Triple Level Cell
UCD-CNL = University of California at Davis – Crocker Nuclear Laboratory
V_{bias} = Bias Voltage
V_{ce} = Collector Emitter Voltage
V_{CEsat} = Collector-Emitter Saturation Voltage
VDD =Supply voltage
V_{IH} = High Level Input Voltage
V_{in} = Voltage In
V_{os} = Input Offset Voltage
VNAND = vertical-NAND
V_{oso} = Output Offset Voltage
V_{out} = Output Voltage
V_{ref} = Reference Voltage
V_{th} = Threshold Voltage
V_z = Reverse Breakdown Voltage

TABLE IV
SUMMARY OF TID AND DD TEST RESULTS

Part Number	Manufacturer	REAG ID; LDC	Device Function	Technology	PI	Results	App Spec	Dose rate (rad(Si)/s) or Proton Energy (MeV)	Degradation Level (krad(Si)) or Proton Fluence
Operational Amplifiers									
OP200	Analog Devices	3A0535E	Operational Amplifier	Bipolar	JML	Input bias current out of spec between 9.2 krad(Si) and 12 krad(Si). All other parameters remained within specification up to the maximum dose of 21.9 krad(Si).	N	0.009	$9.2 < I_b < 12$
Memory									
MZ7KE128BW (850 PRO)	Samsung	no LDC	Solid State Drive	MLC VNAND	DC	Parts irradiated with gamma rays and x-rays. Functional failure between 17 and 31 krad(Si). Functional failure accompanied by degradation in read or write speed. The functional failures are the result of radiation-induced parametric drift in the peripheral circuits, and/or the bit corruptions reaching the ECC threshold.	N	1.3 rad(Si)/s for gamma rays 210 rad(Si)/s for x-rays	$17 < FF \leq 31$
MZ-75E250 (850 EVO)	Samsung	no LDC	Solid State Drive	TLC VNAND	DC	Parts only irradiated with x-rays. Functional failure between 10 and 20 krad(Si). Similar degradation characteristics as MLC device described above.	N	210 rad(Si)/s x-rays	$10 < FF \leq 20$
Miscellaneous									
ARDUINO UNO R3 (ATMEGA 32G)	Arduino, ATMEL and Various Others	N/A	Microcontroller Board	Various	DV	Severe performance degradation observed at ~56 krad(Si), functional failure at 60 krad(Si).	N	30	56<FF<60
RASPBERRY Pi Model B, 512MB	Rasberry Pi Foundation, Broadcom, and Various Others	N/A	Single Board Computer	Various	DV	USB port failure at 50krad(Si), booted functionally through 150 krad(Si).	N	30	50<
MAX 367	Maxim Semiconductors	14-005; 0731	Signal-line Protector	BiCMOS	RL	Analog path resistance degradation between 2 and 3 krad(Si), with failure between 5 and 10 krad(Si).	N	5-10	ΔR(IN-OUT)
Transistors									
SFT5096	SSDI	1023	Transistor	Bipolar	JML	All measured parameters remained in spec up to the maximum dose of 20.2 krad(Si)	Y	0.01	20.2 <

Part Number	Manufacturer	REAG ID; LDC	Device Function	Technology	PI	Results	App Spec	Dose rate (rad(Si)/s) or Proton Energy (MeV)	Degradation Level (krad(Si)) or Proton Fluence
2N6351	Microsemi	0714	Transistor	Bipolar	JML	Biased samples: H_{FE} for I_C = 10 A, V_{CE} = 5 V out of spec between 5.6 krad(Si) and 8.7 krad(Si); other gain conditions (IC = 1 A, 5 A) remained in spec up to the max dose of 21.6 krad(Si). Saturation V_{CE} out of spec between 13 krad(Si) and 17.3 krad(Si). All other parameters remained within specification. Unbiased: all parameters remained within spec.	Y	0.01	$5.6 < H_{FE} < 8.7$ $13 < V_{CE\text{-}SAT} <= 17.3$
2N2484	Fairchild Semiconductor	0807	Transistor	Bipolar	DC	Current gain (I_C=2 mA) exceeded specification between 3 and 6 krad(Si) All current gains exceeded specification after 15 krad(Si); Device remained functional.	Y	0.01	$3 < FF \leq 6$
Displacement Damage									
NSPW500DS	Nichia	14-014; CAOS4E-90W	LED	GaN	RG	Exposures up to 1e12 p/cm2 yielded minimal visual damage. Exposures up to 5e13 p/cm2 yielded visual degradation to the epoxy resin encasing the LED – eventually turning the clear resin to a bright red. After several days at room temperature, annealing was observed.	N	63 MeV	P_{out} <1e12 p/cm^2

TABLE V
ONGOING LOW DOSE RATE TESTS:

Part Number	Manufacturer	LDC or Wafer #	Device Function	Tech-nology	PI	Results	App. Spec	Dose rate (mrad(Si)/s)	Degradation Level (krad(Si)) or Proton Fluence
Operational Amplifiers									
LM124 (Ceramic DIP-14)	National Semiconductor	JM0591182	Operational Amplifier	Bipolar	DC	Parameters within specification.	Y	1	> 100
								0.5	> 60
LM158AJRQMLV (Ceramic DIP-8)	National Semiconductor	JM084X27	Operational Amplifier	Bipolar	DC	Input bias current degradation shows dose rate sensitivity below 10 mrad(Si)/s. However parameters are within specification for all dose rates.	N	5, 1	> 100
								0.5	> 70
RH1013MH (TO-5 Metal Can)	Linear Technology	0329A	Operational Amplifier	Bipolar	DC	Small levels of dose rate sensitivity in the input bias current degradation. Parameters within specification.	Y	1	> 20
								0.5	> 20
RH1013MJ8 (Ceramic DIP)	Linear Technology	0305A	Operational Amplifier	Bipolar	DC	Small levels of dose rate sensitivity in the input bias current degradation. Parameters within specification.	Y	1	> 20
								0.5	> 20

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Part Number	Manufacturer	LDC or Wafer #	Device Function	Tech-nology	PI	Results	App. Spec	Dose rate (mrad(Si)/s)	Degradation Level (krad(Si)) or Proton Fluence
RH1078MH (TO-5)	Linear Technology	0741A	Operational Amplifier	Bipolar	DC	Parameters remain within post-irradiation specification.	Y	1	> 40
								0.5	> 30
RH1078W (Flatpack)	Linear Technology	0325A	Operational Amplifier	Bipolar	DC	Parameters remain within post-irradiation specification.	Y	1	> 40
								0.5	> 30
RHF310 (Ceramic Flat-8)	STMicroelectronics	30849A	Operational Amplifier	Bipolar	DC	Input bias current and input offset voltage within specification.	N	5	> 100
								1	> 80
								0.5	> 50
RHF43B (Ceramic Flat-8)	STMicroelectronics	30820A	Operational Amplifier	Bipolar	DC	Minimal dose rate sensitivity. Parameters within specification.	N	10	> 100
								1	> 50
								0.5	> 50
Transistors									
2N2222 (Engineering Samples)	Semicoa	1001	NPN Transistor	Bipolar	DC	Minimal degradation. All parameters within specification. [43]	N	10	>100
								1	>20
								0.5	>10
2N3811JS	Semicoa	1456	NPN Transistor	Bipolar	DC	No bias dependence. Two devices exceeded specifications after 30 krad(Si).	N	50 rad(Si)/s	30 < HFE < 50
								10	>15
2N3811UX	Semicoa	1994	NPN Transistor	Bipolar	DC	Flatpack devices show slightly worse degradation than TO can packaged devices in general.	N	50 rad(Si)/s	50 < HFE < 70
2N2222AJSR	Semicoa	1364	NPN Transistor	Bipolar	DC	LDR EF = 3.9 after 100 krad(Si).	N	10	35 < HFE < 45
								5	65 < HFE < 90
								1	>15
								0.5	>10
2N2907	Semicoa	0932	PNP Transistor	Bipolar	DC	Low dose rate testing in progress. LDR EF = 1.78 after 100 krad(Si).	N	10	40 < HFE < 50
2N2857	Semicoa	1008	NPN Transistor	Bipolar	DC	All parameters within specification up to 100 krad(Si). Minimal LDR sensitivity.	N	50	>100
								10	> 100

Part Number	Manufacturer	LDC or Wafer #	Device Function	Tech-nology	PI	Results	App. Spec	Dose rate (mrad(Si)/s)	Degradation Level (krad(Si)) or Proton Fluence
2N2369	Semicoa	1934	NPN Transistor	Bipolar	DC	All parameters within specification up to 100 krad(Si). Minimal LDR sensitivity.	N	50 rad(Si)/s	> 100
2N3700JV	Semicoa	1109	NPN Transistor	Bipolar	DC	Strong bias dependence. Biased devices show enhanced degradation than grounded devices.	N	10	20 < H_{FE} < 35
								5	25 < H_{FE} < 35
								1	>17
								0.5	>8
2N3700UBJV	Semicoa	J1935	NPN Transistor	Bipolar	DC	Dose rate effect not evident at this stage	N	10	10 < H_{FE} < 20
								1	>15
2N5153	Semicoa	1013	PNP Transistor	Bipolar	DC	Minimal LDR EF.	N	1	> 30
2N5154	Semicoa	1023	PNP Transistor	Bipolar	DC	Minimal LDR EF.	N	1	> 30
Voltage Reference/Voltage Regulators									
LM136AH2.5QMLV (3-LEAD TO-46)	National Semiconductor	200746K019	Voltage Reference	Bipolar	DC	Exhibits no LDR enhancement.	N	5, 1	> 100
								0.5	>70
LM317KTTR	Texas Instruments	0608	Positive Voltage Regulator	Bipolar	DC	Parameters within specification. Observed LDR sensitivity for parts irradiated at 0.5 and 1 mrad(Si)/s after 20 krad(Si).	N	5, 1	> 100
								0.5	> 70
LT1009IDR	Texas Instruments	0606	Internal Reference	Bipolar	DC	Parameters within specification. Parts exhibit minimal LDR enhancement.	N	5, 1	> 100
								0.5	> 70
RHFL4913ESY332 (TO257)	STMicroelectronics	30828A	Voltage Regulator	Bipolar	DC	All parameters within specification. Minimal dose rate sensitivity.	N	10, 5, 1	>100
								0.5	> 30
RHFL4913KP332 (Flat-16)	STMicroelectronics	30814B	Voltage Regulator	Bipolar	DC	All parameters within specification. Minimal dose rate sensitivity.	N	10, 5, 1	>100
								0.5	> 30
TL750M05CKTRR (TO263-3)	Texas Instruments	0707	LDO Positive Voltage Regulator	Bipolar	DC	One part irradiated at 1 mrad(Si) exceeded specification at 40 krad(Si). V_{out} specification for full temperature range. (Characterization performed in DC mode.) Minimal dose rate sensitivity.	N	5	> 100
								1	30 < V_{out} < 40
								0.5	> 70
Miscellaneous									
LM139AWRQMLV	National Semiconductor	JM046X13	Comparator	Bipolar	DC	Parameters within specification.	Y	0.5	> 30

IV. Test Results and Discussion

As in our past workshop compendia of GSFC test results, each device under test has a detailed test report available online at http://radhome.gsfc.nasa.gov [2] and at http://nepp.nasa.gov [3] describing in further detail the test method, conditions and monitored parameters, and test results. This section contains a summary of testing performed on a selection of featured parts.

A. MAX367/Signal-Line Circuit Protector/Maxim Semiconductor

The MAX367 is a CMOS signal line protector from Maxim Semiconductor. The device consists of 8 two-terminal paths intended to guard sensitive electronics against overvoltage and overcurrent when placed in series with them. Four parts were irradiated biased at 12 V and five parts were irradiated with all pins grounded at dose rates from 5-10 rad(Si)/s. All parts passed all parametric and functional measurements up to 2 krad(Si). At the 3 krad(Si) dose step, the biased parts exceeded the device specification for analog path resistance match (R_{AP}) (10 Ω), with average resistance equal to 12.2 Ω. This mismatch was due entirely to resistance change along the negative analog path, as the positive path resistance changed very little. It is also notable that there was very little difference in the values from part to part and across the eight channels within a part. Degradation of this parameter continued at subsequent dose steps. At 10 krad(Si), this parameter failed for the unbiased parts, averaging 15.5 Ω, and for all practical purposes, the biased parts ceased to function for negative voltages, as the fault-free analog signal range fell below specification. All other parameters remained within specifications for both bias conditions. Parametrics continued to degrade and exhibited no significant recovery during the one week of annealing at room temperature.

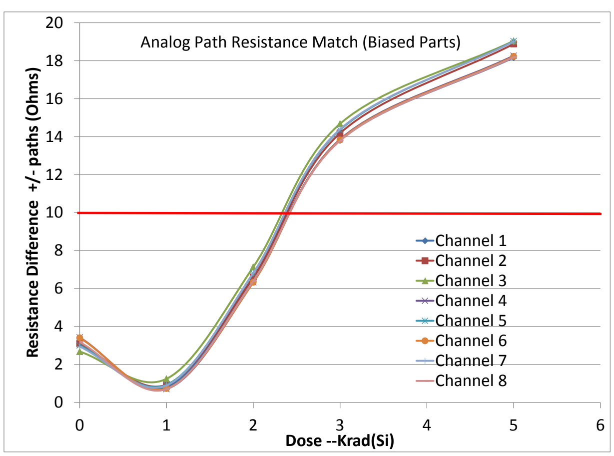

Fig. 1. Resistance difference between positive and negative outputs for all eight channels vs. Dose for MAX367 test parts in the biased condition.

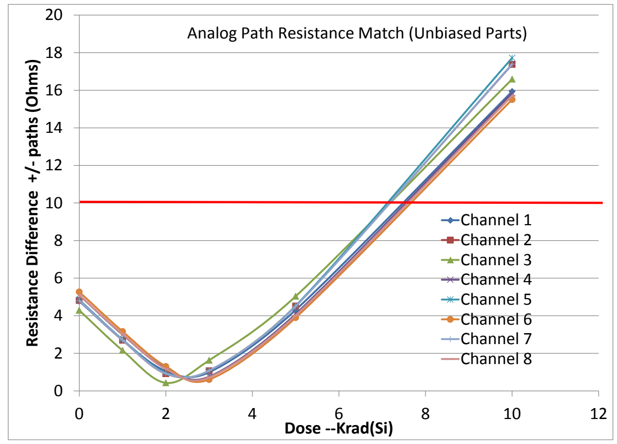

Fig. 2. Resistance difference between positive and negative outputs for all eight channels vs. Dose for MAX367 test parts in the unbiased condition.

B. Samsung 840 Pro/Solid State Drive (SSD)/Samsung

The 128 GB Samsung 840 Pro solid state drives (SSD) features the vertical-NAND (VNAND) flash. Two SSDs were irradiated with 1.1 MeV gamma rays with the test articles placed inside a Pb/Al filter box to minimize dose enhancement effects. The beam was collimated using lead bricks so that the two VNAND chips were exposed to the source while the other active components on the SSD were shielded. We performed dosimetry to measure the dose behind the shielding. We determined that the total dose at the collimated spots on the SSD drive ranged from approximately 1/18 to 1/3 of the dose at the (unshielded) DUT location. Therefore, degradation from other active components in addition to the VNAND may also play a role in the functional failures of the SSD.

An open source software called "Caine" was used as the diagnostic tool to perform read and write operations to the SSD allowing examination of the Self-Monitoring, Analysis and Reporting Technology (SMART) attributes, which includes a list of reliability parameters for the SSD. The following operation modes were evaluated: powered off, static on, continuous read, and continuous write/read. After initially writing a repeating pattern of AA the parts remained in standby mode throughout irradiation. Various operations were cycled at irradiation down points. The test procedure is as follows:

- Write pattern AA to entire SSD prior to irradiation
- Irradiate device with power on (standby mode)
- At irradiation down point, read the entire memory space and capture image
  - a) Perform a second read to examine whether some errors can be cleared
- Erase using the quick erase function
- Reprogram SSD to inverse checkerboard pattern (55)
- Obtain SMART attributes
- Irradiate to the next dose step
- Repeat from step 3 until device is nonfunctional

One part (DUT1) showed functional failure between 17 and 31 krad(Si). The other part (DUT2) showed partial functional failure between 22 and 26 krad(Si). Bit errors from the memory array were not recorded, however the SMART attributes showed increase in sector reallocation at the failure doses, which could be due to bit corruption. Tables V and VI show the SMART attributes for DUT1 and DUT2, respectively.

DUT1 showed degradation in the write speed after 31 krad(Si). Also, the SMART attributes from the write operation showed 5 reallocated sectors, and correspondingly, 5 program fails at which point the drive became inaccessible. DUT2 showed degradation in the read speed after irradiation to 26 krad(Si). The read operation revealed 1 reallocated sector and 7 uncorrectable errors before manual stoppage of the read operation due to the slow speed. The drive continued to show read access errors throughout. There were no program or erase fails, unlike DUT1, therefore the two drives showed distinct failure modes. The parts remained nonfunctional after 1 week of biased room temperature annealing and 1 additional week of unbiased annealing at 93ºC.

Table VI.
SMART attributes for DUT1.

SMART Attribute #	**5**	**179**	**181**	**182**	**183**	**187**	**195**	**241**
Total dose (krad(Si))	**Reallocated Sector Ct**	**Used Rsvd Blk Cnt Tot**	**Program Fail Cnt Total**	**Erase Fail Count Total**	**Runtime Bad Block**	**Reported Uncorrect**	**Hardware ECC Recovered**	**Total LBAs Written**
0	0	0	0	0	0	0	0	250069680
1.7	0	0	0	0	0	0	0	250069680
4.4	0	0	0	0	0	0	0	500139360
8.7	0	0	0	0	0	0	0	765463568
17.4	0	0	0	0	0	0	0	1015533248
30.5 before any operation	0	0	0	0	0	0	0	1015533248
After initial image read	0	0	0	0	0	0	0	1015533248
Write AA	5	5	5	0	5	0	0	1015533248

Table VII.
SMART attributes for DUT2.

SMART Attribute #	**5**	**179**	**181**	**182**	**183**	**187**	**195**	**241**
Total dose (krad(Si))	**Reallocated Sector Ct**	**Used Rsvd Blk Cnt Tot**	**Program Fail Cnt Total**	**Erase Fail Count Total**	**Runtime Bad Block**	**Reported Uncorrect**	**Hardware ECC Recovered**	**Total LBAs Written**
0	0	0	0	0	0	0	0	250069680
8.7	0	0	0	0	0	0	0	250069680
17.4	0	0	0	0	0	0	0	750209040
21.8	0	0	0	0	0	0	0	1000278720
26.1 before any operation	0	0	0	0	0	0	0	1000278720
Image read	1	1	0	0	1	7	7	1000278720
Badblocks read	2	2	0	0	2	2498	2498	1000278720
Test specific sector	2	2	0	0	2	2499	2499	1000278720

C. Nichia NSPW500DS White LEDs

A single lot of Nichia NSPW500DS White Light Emitting Diodes (LEDs) were exposed to a 64 MeV proton beam at UC Davis. Exposures up to 1E12 p/cm^2 yielded minimal visual damage – although a small percentage of the power output was observed. Continued exposures to 5E12 p/cm^2 and above resulted in a significant visual darkening of the LED epoxy resin (see Figure 3). Some annealing was observed after eighteen days at room temperature. The power output level is shown in Figure 4. Post-test analysis determined that the semiconductor material Indium Gallium Nitride (IGaN) was not measurably affected, rather, the measured degradation was a result of color centers in the epoxy resin of the LEDs.

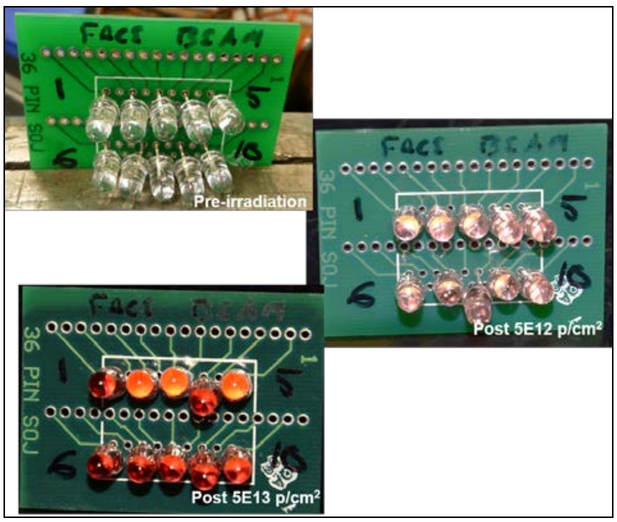

Fig. 3. Pre- and Post- Irradiated LEDs

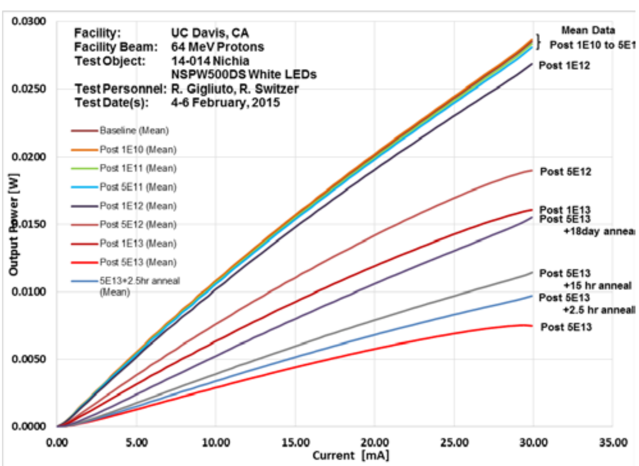

Fig. 4. Power Output measurements for Nichia NSPW500DS White LEDs as a function of radiation exposure.

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 due to many application/lot-specific issues. We also highly recommend that lot testing be performed on any suspect or commercial device.

VI. Acknowledgment

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VII. References

[1] Martha V. O'Bryan, et al., "Compendium of Current Single Event Effects for Candidate Spacecraft Electronics for NASA" to be submitted for presentation at IEEE NSREC 2015 Radiation Effects Data Workshop, July 2015.

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

[3] NASA Electronic Parts and Packaging Program home page, http://nepp.nasa.gov.