Compendium of Total Ionizing Dose and Displacement Damage Results from NASA Goddard Spaceflight Center

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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

NASA spacecraft are subjected to harsh space environments that include exposure to various types of ionizing and non-ionizing radiation. Long-term exposure to radiation has been known to affect the function of the spacecraft electronics. As a result, flight parts must be tolerant to radiation-induced total ionizing dose (TID) and displacement damage (DD) effects or be mitigated by shielding or other methods to reduce TID and DD effects. Hence, the effects of TID and DD need to be evaluated by test in order to determine risk to spaceflight applications.

The test results presented here were gathered to establish the sensitivity of candidate spacecraft electronics to TID and/or DD damage. Proton-induced degradation, dominant for most NASA missions, include both ionizing total dose and non-ionizing displacement damage effects. For similar results on single event effects (SEE), a companion paper has also been submitted to the 2016 IEEE NSREC Radiation Effects Data Workshop entitled: "Compendium of Current Single Event Effects Results From NASA Goddard Space Flight Center" by M. O'Bryan, et al. [1]

II. 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.

TABLE I
LIST OF PRINCIPAL INVESTIGATORS

Abbreviation	Principal Investigator (PI)
DC	Dakai Chen
RL	Raymond Ladbury
MC	Megan Casey
MJC	Michael J Campola

- *Test Method*

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

- *Test Source – TID*

TID testing was performed using a high energy gamma ray source. Dose rates used for testing were between 0.05 and 30 rad(Si)/s.

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TABLE II
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 III
Summary of TID and DD Test Results

Part Number	Manufacturer	LDC	Device Function	Technology	PI	Results	App. Spec (Y/N)	Dose Rate (rad(Si))	Degradation Level (krad (Si)) or Proton Fluence
Operational Amplifiers									
HA2-2640	Intersil	14-086; 0539	Op-Amp	Bipolar	MC	One unbiased part exceeded the input bias current specification at 2.5 krad(Si). One unbiased part exceeded the input offset current specification at 1 krad(Si),	N	0.01	<1
MSA0670	Avago	15-008; 1301	Op-Amp	BiCMOS	MC	Two unbiased parts exceeded the input offset current specification at 3 krad(Si). One unbiased part exceeded the specification for negative input bias current at 4.5 krad(Si). All unbiased parts exceeded the positive input bias current specification at 7.5 krad(Si).	N	0.01	<3
THS4131	Texas Instruments	14-083; 1349	Op-Amp	Bipolar	MC	All measured parameters remained within specification to 5 krad(Si).	N	0.01	>5
OPA128	Texas Instruments	14-087	Op-Amp	Bipolar	MC	Power gain was outside the specification for all dose points, including pre-rad. All other parameters remained within specification to 50 krad(Si).	N	0.01	>50
SFT 5094	Analog Devices	15-077; 0928	Op-Amp	Bipolar	RL	For HDR, hfe2 fails pre-rad spec~65krad(Si) For LDR, hfe2 fails pre-rad spec~30 krad(Si) and hfe3 fails pre-rad spec~55 krad(Si); hfe2 goes to 0 by 100 krad(Si)	N	0.1	HDR~65 LDR~30
CMOS									

Part Number	Manufacturer	LDC	Device Function	Technology	PI	Results	App. Spec (Y/N)	Dose Rate (rad(Si))	Degradation Level (krad (Si)) or Proton Fluence
MAX9180	Maxim	15-030; 1421	LVDS Repeater	CMOS	MJC	No degradation in recorded parameters	Y	50-300	>30
MCI0EL31	ON Semiconductor	15-033; 1309	Logic	CMOS	RL	No significant degradation; input currents increased slightly (~10%) but remained within specifications	N	50	>100
54AC258	E2V	16-001; 301451	Multiplexer	CMOS	DC	Parts remained within specification limits up to the maximum tested total dose level of 30 krad(Si).	Y	50	>30
Bipolar									
SFT 5094	Analog Devices	15-077; 0928	Op-Amp	Bipolar	RL	For HDR, hfe2 fails pre-rad spec~65krad(Si) For LDR, hfe2 fails pre-rad spec~30 krad(Si) and hfe3 fails pre-rad spec~55 krad(Si); hfe2 goes to 0 by 100 krad(Si)	N	0.1	HDR~65 LDR~30
MAT-01	Analog Devices	15-034; 1324	Matched Xstr Pair	Bipolar	RL	Gains started out below "typical" values; hfe1, the only gain with a minimum pre-rad specification started above, but fell below by 10 krad(Si); Collector to Emitter leakage current and Collector to Base leakage current exhibited bimodal response for unbiased parts, but remained within specifications	N	0.05	<10
2N5434	Siliconix	12-029; S1124	JFET	Bipolar	MJC	Increasing IGSS stays in specification	Y	50	>75
AD96687	Analog Devices	15-035; 1422	Comparator	Bipolar	RL	No failures or significant degradation seen.	N	0.05	>100
UC1823A	TI	15-062; 1345	Pulse Width Modulator	Bipolar	DC	Parts remained within specification limits up to the maximum tested total dose level of 30 krad(Si).	Y	0.01	>30

Table IV
Ongoing Low Dose Rate tests:

Part Number	Manufacturer	LDC	Device Function	Technology	PI	Results	App. Spec (Y/N)	Dose rate (rad(Si)) or	Degradation Level (krad (Si))
Operational Amplifiers									
LM124 (Ceramic DIP-14)	National Semiconductor	JM0591182	Operational Amplifier	Bipolar	DC	Parameters within specification.	Y	1	>100
								0.5	>80
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	$40 < I_B \leq 60$
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	$40 < I_B \leq 60$
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	>70
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

Part Number	Manufacturer	LDC	Device Function	Technology	PI	Results	App. Spec (Y/N)	Dose rate (rad(Si)) or	Degradation Level (krad (Si))
Transistors									
2N2222	Semicoa	1001	NPN	Bipolar	DC	Minimal degradation. All	N	10	>100

(Engineering Samples)			Transistor			parameters within specification. [43]		1	>40
								0.5	>20
2N3811JS	Semicoa	1456	NPN Transistor	Bipolar	DC	No bias dependence. Two devices exceeded specifications after 30 krad(Si).	N	50 rad(Si)/s	$30 < H_{FE} < 50$
								10	$60 < H_{FE} \leq 70$
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	$50 < H_{FE} < 70$
								10	$20 < H_{FE} \leq 30$
2N2222AJSR	Semicoa	1364	NPN Transistor	Bipolar	DC	LDR EF = 3.9 after 100 krad(Si).	N	10	$35 < H_{FE} < 45$
								5	$65 < H_{FE} < 90$
								1	>40
								0.5	>30
2N2907	Semicoa	0932	PNP Transistor	Bipolar	DC	Low dose rate testing in progress. LDR EF = 1.78 after 100 krad(Si).	N	10	$40 < H_{FE} < 50$
2N2857	Semicoa	1008	NPN Transistor	Bipolar	DC	All parameters within specification up to 100 krad(Si). Minimal LDR sensitivity.	N	50	>100
								10	> 100
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	$5 < H_{FE} < 28$
								1	$30 < H_{FE} < 40$
								0.5	>20
2N3700UBJV	Semicoa	J1935	NPN Transistor	Bipolar	DC	Dose rate effect not evident at this stage.	N	10	$10 < H_{FE} < 20$
								1	$15 < H_{FE} < 30$
Part Number	**Manufacturer**	**LDC**	**Device Function**	**Technology**	**PI**	**Results**	**App. Spec (Y/N)**	**Dose rate (rad(Si)) or**	**Degradation Level (krad (Si))**
2N5153	Semicoa	1013	PNP Transistor	Bipolar	DC	Minimal LDR EF.	N	1	>50
2N5154	Semicoa	1023	PNP Transistor	Bipolar	DC	Minimal LDR EF.	N	1	>50
Voltage Reference/Voltage Regulators									

LM136AH2.5QMLV (3-LEAD TO-46)	National Semiconductor	200746K019	Voltage Reference	Bipolar	DC	Exhibits no LDR enhancement.	N	5, 1 0.5	> 100 >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 0.5	> 100 > 70
LT1009IDR	Texas Instruments	0606	Internal Reference	Bipolar	DC	Parameters within specification. Parts exhibit minimal LDR enhancement.	N	5, 1 0.5	> 100 > 70
RHFL4913ESY332 (TO257)	StMicroelectronics	30828A	Voltage Regulator	Bipolar	DC	All parameters within specification. Minimal dose rate sensitivity.	N	10, 5, 1 0.5	>100 > 60
RHFL4913KP332 (Flat-16)	StMicroelectronics	30814B	Voltage Regulator	Bipolar	DC	All parameters within specification. Minimal dose rate sensitivity.	N	10, 5, 1 0.5	>100 > 60
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 1 0.5	>100 $30 < V_{OUT} < 40$ > 70
Miscellaneous									
LM139AWRQMLV	National Semiconductor	JM046X13	Comparator	Bipolar	DC	Parameters within specification.	Y	0.5	$I_B > 75$

III. 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. SFT5094 from Solid State Devices, Inc

The SFT5094 is a 500 V PNP transistor manufactured by Solid State Devices, Inc. This transistor was assessed for TID sensitivity using a 1.1 MeV gamma ray source. A total of twelve transistors were characterized in two test groups. Five devices were tested at an average dose rate of 10 rad (Si)/s and five were tested at a lower average dose rate of 0.06 rad (Si)/s, with two held in reserve as controls. The devices were irradiated incrementally up to 100 krad (Si). Parametric and functional degradation were measured following each dose step. Transistor performance was assessed to determine device functionality using the following parameters:

Table IV
Parametric Characteristics Used for SFT5094 PNP Transistor Assessment

Electrical Characteristics	Condition:
Collector-Emitter Breakdown Voltage	Min: 350 V
Collector-Base Breakdown Voltage	Min: 450 V
Emitter-Base Breakdown Voltage	Min: 6 V
Collector Cut-Off Current	Max: 1.0 μA
DC Current Gain: h_{FE1} $I_c = 1$ mA, $V_{CE} = 10$ V	20 – 250
DC Current Gain: h_{FE2} $I_c = 25$ mA, $V_{CE} = 10$ V	40 - 300
DC Current Gain: h_{FE3} $I_c = 100$ mA, $V_{CE} = 10$ V	20 - 250
Collector-Emitter Saturation Voltage	Max: 500 mV
Base-Emitter Saturation Voltage	Max: 1.0 V

In the lower dose rate test, DC Current Gain h_{FE1} fell below the required minimum specification value of 20 following the 100 krad (Si) dose step with an average value of 7.23. For both the higher and lower dose rate tests, the DC Current Gain h_{FE2} value fell below the minimum specification value of 40 during testing. Fig. 1 and Fig. 2 present the DC Current Gain results as a function of total accumulated dose:

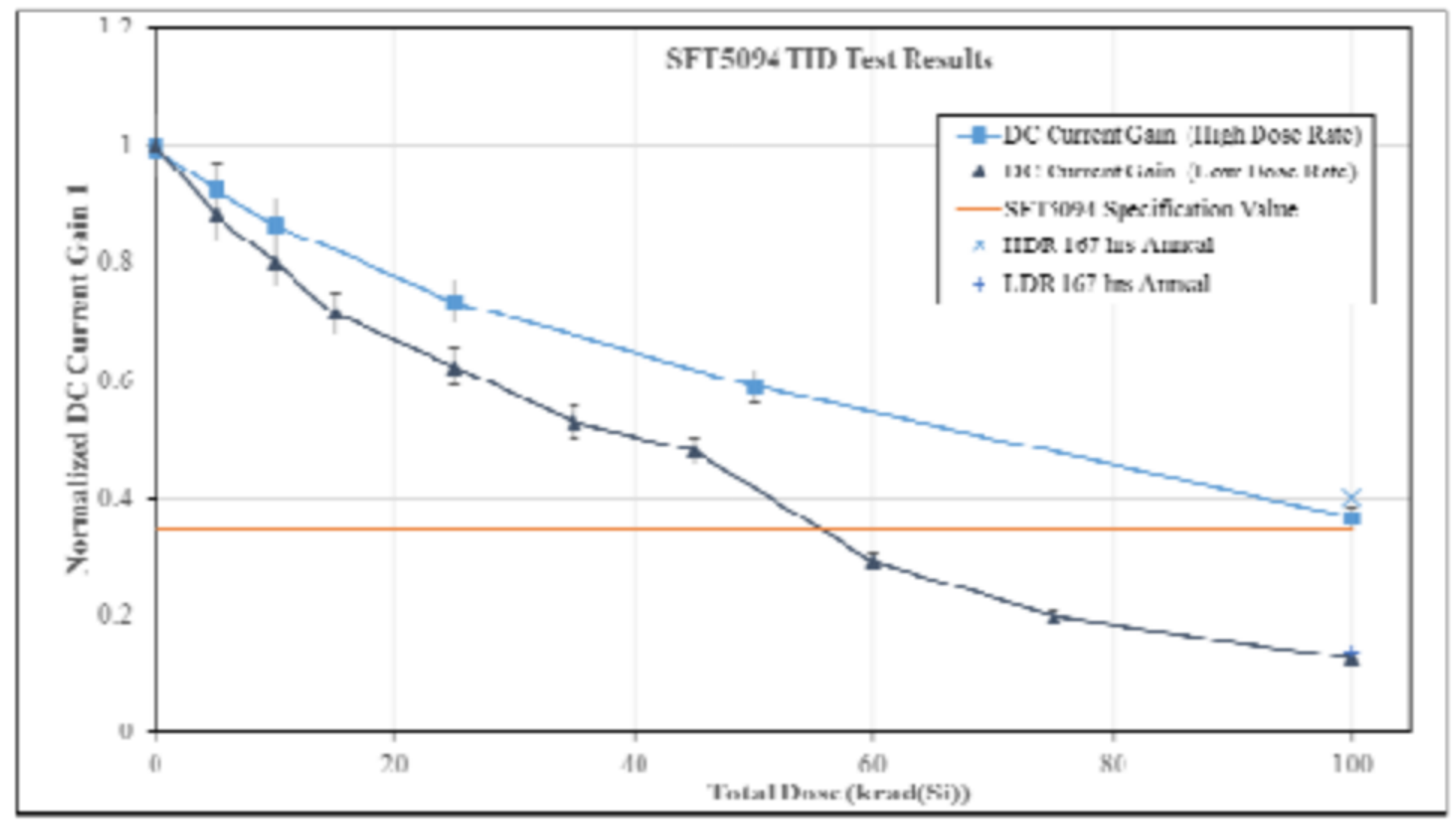

Fig. 1: DC Current Gain vs. Total Dose for SFT5094; I_c = 1 mA, V_{CE} = 10 V

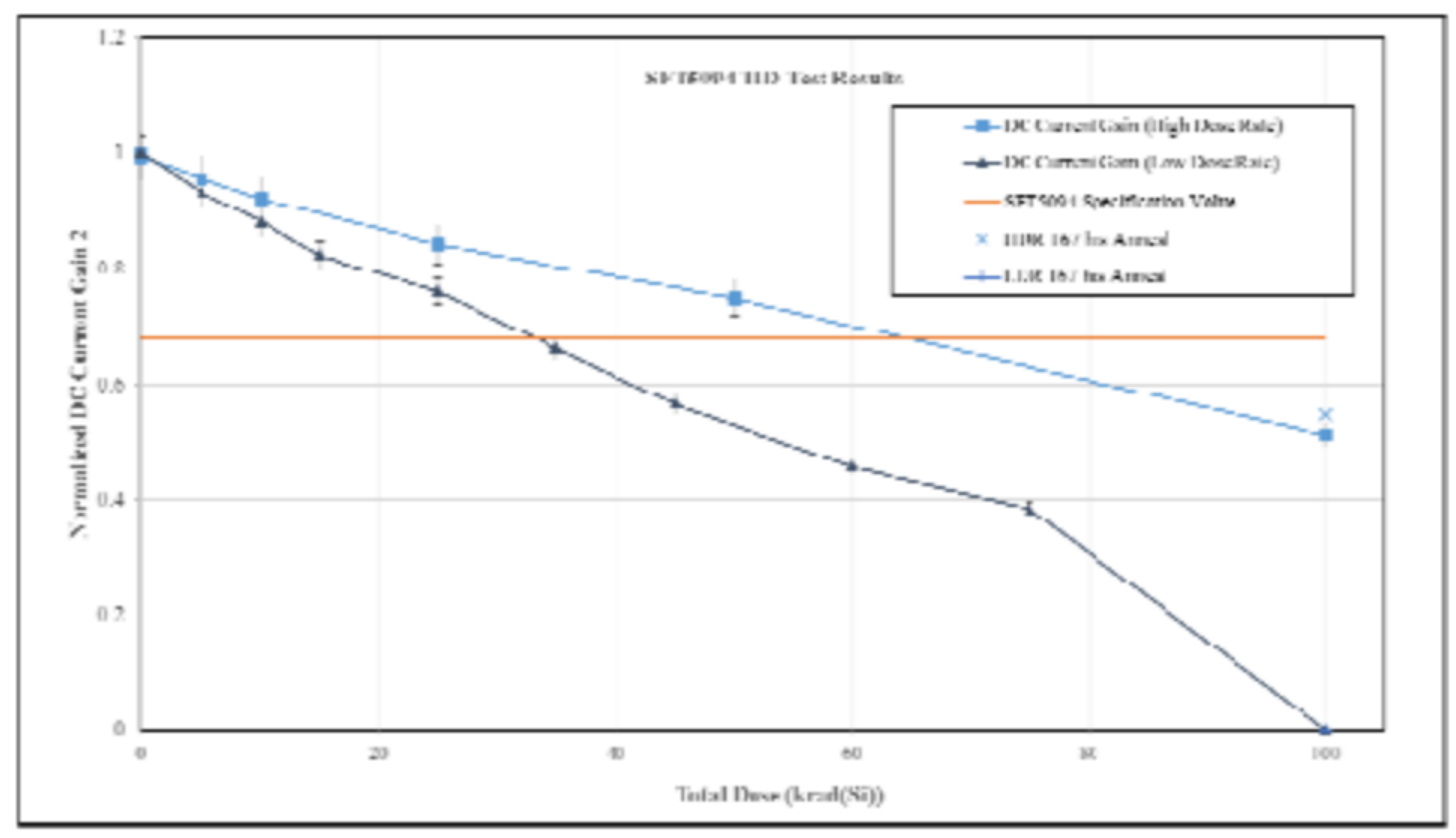

Fig. 2: DC Current Gain vs. Total Dose for SFT5094; I_C = 25 mA, V_{CE} = 10 V

In the above figures, the error bars represent the standard deviation of values across measured devices, indicating part-to-part variability. The results demonstrate enhanced degradation for current gain for both conditions at the lower tested dose rate. This low dose rate (LDR) sensitivity has been previously observed for several discrete bipolar junction transistors [5]. For the SFT5094 test, the h_{FE1} low dose rate enhancement factor (LDR EF)—the ratio of Δh_{FE}^{-1} at lower dose rate to that at the higher dose rate—was calculated and found to be 3.19 at 100 krad (Si). This enhancement factor is among the higher documented values of LDR EF for the transistor gain of discrete bipolar junction transistors [5],[6]. The behavior of the DC current gain 2 ($h_{FE2)}$ here is atypical; following the 100 krad (Si) dose step, the gain value fell to 0. With the exception of the low-dose rate h_{FE2} value, a slight increase in performance was observed for h_{FE1} and h_{FE2} values following a 167-hr annealing period at both higher and lower dose rates.

B. Ultra ELDRS for 2N2222

The ongoing test results for low dose rate sensitivity are coming to a stopping point in the near future. The results shown in Fig 3 show the 1/Δhfe over dose. While there is some low dose rate sensitive of the part, the lowest dose rate show a worse response at 1 mrad(Si) per second. This supports the idea that the TO package of this transistor does not have a pronounced effect at very low dose rate testing. The ground based measurements at higher dose rates are representative of the device response with caution as to proper margins.

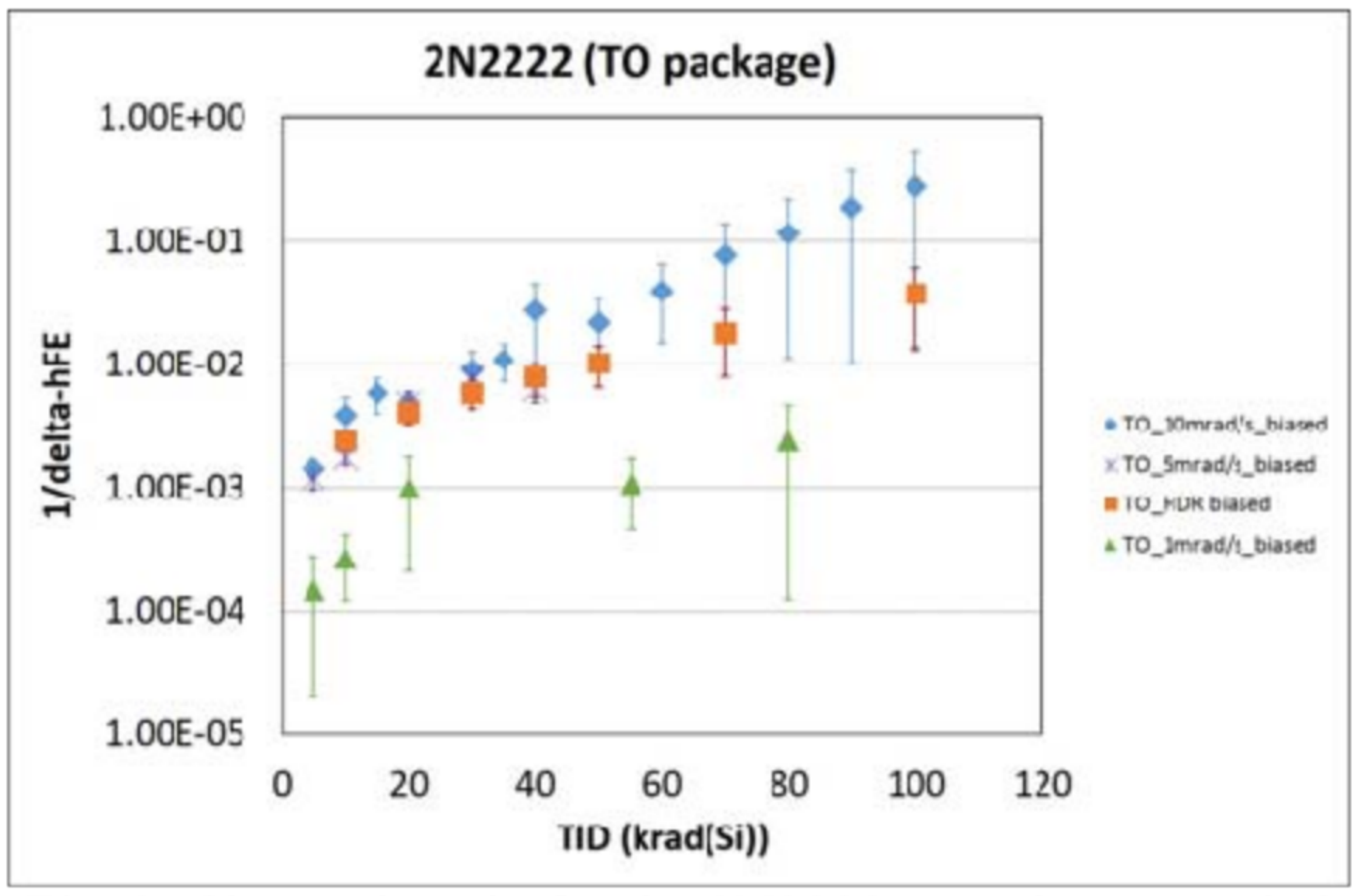

Fig. 3: Change in gain for the 2N2222 over dose at varied dose rates

C. 2N5434 from Siliconix

The 2N5434 JFET is used on multiple programs and the testing was required for a new flight light to meet shortages of previously tested lots. This particular lot from the manufacturer performed well showing degradation, but remaining in specification through 75 krad.

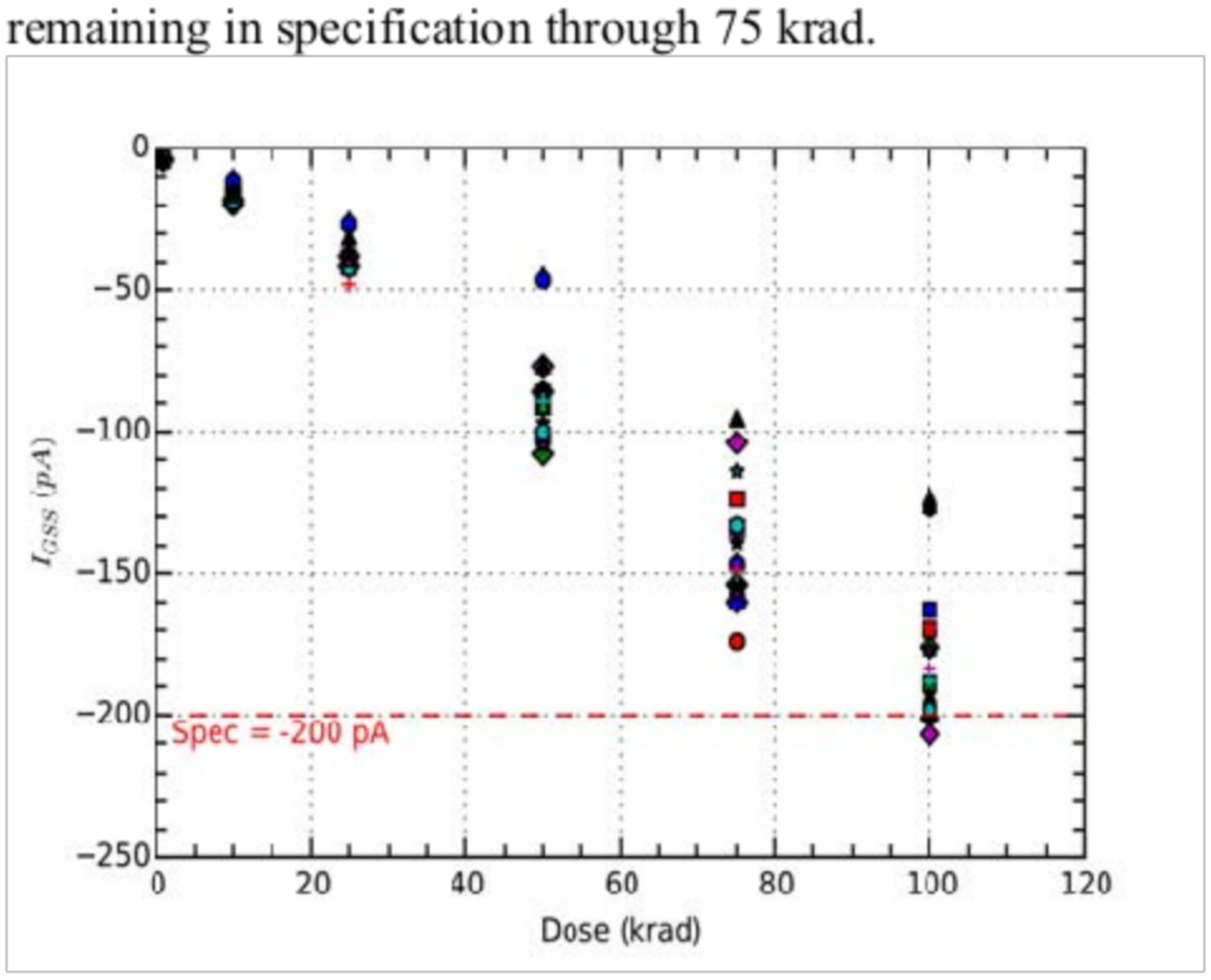

Fig. 4: I_{GSS} over dose for the 2N5434 JFET

D. MAX9180 from MAXIM

The LVDS repeater from MAXIM was tested to 30krad, one device dropped out at 20krad. No parametric degradation was recorded on the parts that survived. Careful considerations were taken into account for different clocking speeds in the part's application for clean signal outputs.

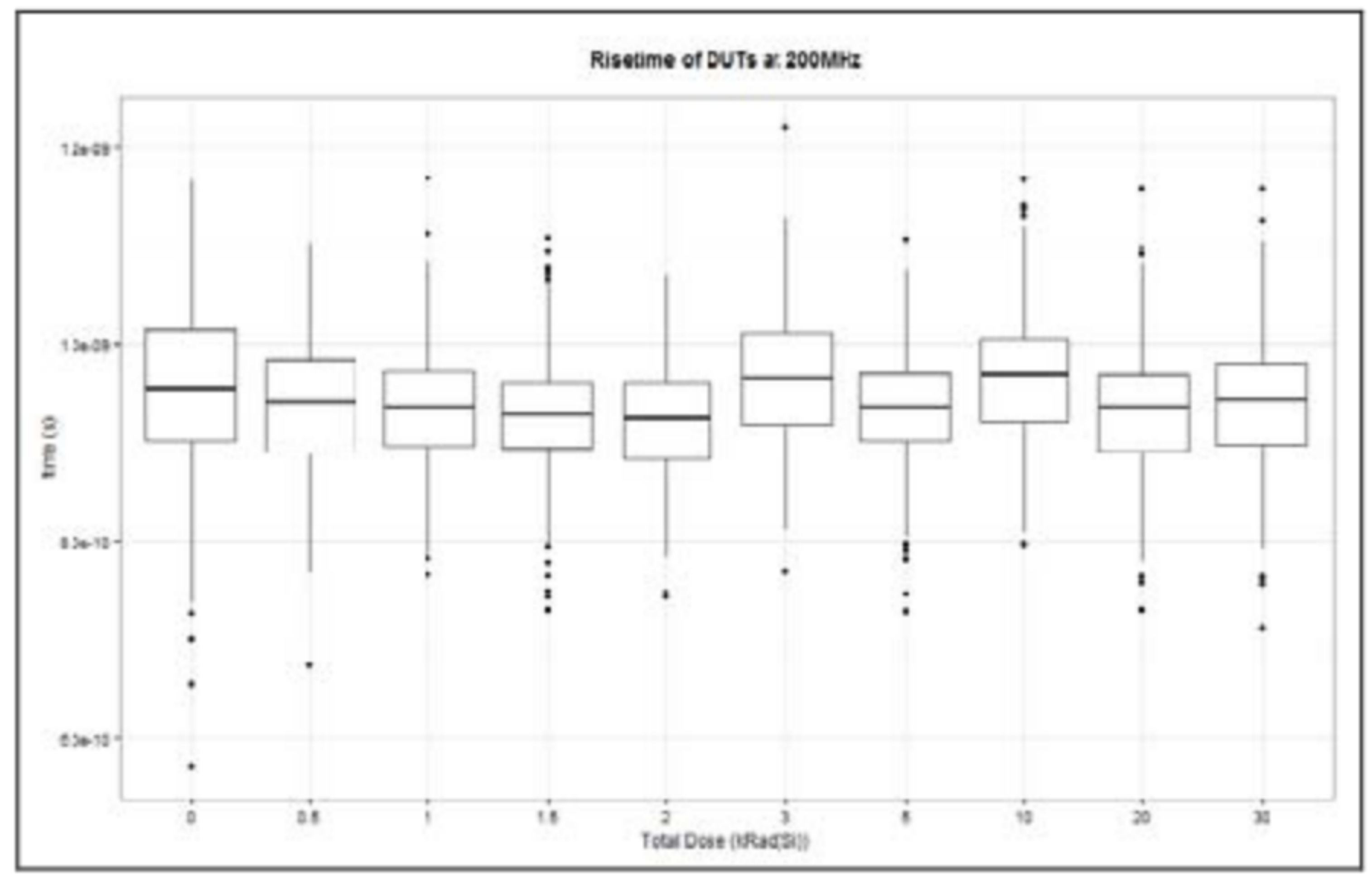

Fig. 5: Rise-time over dose, MAX9180

IV. Summary

We have presented data from recent TID 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.

V. Acknowledgment

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VI. 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.