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Dose Rate and Bias Dependency of Total Dose Sensitivity of Low Dropout Voltage Regulators

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Abstract--**Total dose tests of six different low dropout voltage regulators show sensitivity to both dose rate and bias during exposure. All devices tested exhibited Enhanced Low Dose Rate Sensitivity (ELDRS) and performed worse for the unbiased irradiation condition. Behavior of critical parameters in different dose rate and bias conditions is compared and the impact to hardness assurance methodology is discussed.**

I. INTRODUCTION

In the past few years, low dropout voltage bipolar regulators have become increasingly popular for use in space systems. These devices replace the hybrid regulators used in the past, generally resulting in cost, space and weight reductions. However, a primary concern in the selection of these devices is their tolerance to the low dose rate, ionizing radiation environment in space. Enhanced low dose rate sensitivity (ELDRS), which results in increased degradation of bipolar linear integrated circuits when irradiated at low dose rates, has been observed and reported on extensively in the literature, see for example [1]-[4]. The physical mechanisms for this effect have been proposed [5]-[7]. Tests of a low dropout adjustable voltage regulator, the Micrel 29372, exhibited both an ELDRS effect as well as a significant bias dependency [8]. Parametric degradation for this device was most severe for the unbiased condition. This degradation was more severe for lower dose rates with maximum degradation occurring at dose rates near 0.01 rad(SiO^2)/s. The primary failure mechanism was found to be loss of pass transistor gain, which resulted in premature shutdown of the device.

In this work six different low dropout voltage regulators were tested at high [~ 50 rad(SiO^2)/s] and low [0.01 to 0.06 rad(SiO^2)/s] dose rates, with and without bias during exposure. The purpose of these tests was to determine if the devices were subject to degradation similar to the Micrel device and to assess suitability for use in space systems. The desire was to find regulators which were capable of functioning to greater than 100 krad and had minimal ELDRS effect. A further objective of these tests was to determine the environment and bias condition suitable for radiation lot acceptance testing. It should be noted, however, that these tests were not intended to bound device performance at low dose rates. In general, it is recommended to perform tests at several 'low' dose rates to determine if degradation continues to increase at even lower dose rates.

All devices exhibited enhanced degradation at low dose rate. The unbiased condition was found to be the worst case for most, but not all, parameters. For most parameters, the manufacturers pre-radiation specification was exceeded at much lower dose levels for the parts tested at low dose rate than for those tested at the higher dose rate.

II. DEVICE DESCRIPTIONS

Tested devices are identified in Table I. Four of the devices were positive regulators and two were negative. All devices were similar in function with over-current and thermal shutdown, internal band-gap reference, external shutdown control, and a dropout voltage below 500 mV. The internal pass transistors were lateral PNP's for the positive devices and NPN's for the negative devices. All of the devices were fabricated on standard bipolar processes, none were dielectrically isolated. All samples for each device type were procured from a single date code to ensure the validity of comparison data. Of the devices tested, only the LP2953 and the LT1175 were known to be in current use at the time. The remaining devices were proposed for use in several space applications.

III. EXPERIMENTAL DETAILS

A. Total Dose Facilities

Total dose irradiations for the LT1175, LT1528, and ADP3306 were performed at the Boeing Radiation Effects Laboratory, Seattle WA. At this facility, low and high dose rate irradiations were preformed using a Shepherd model 484 and a Gammacell 220 Co-60 irradiator respectively. Total

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TABLE I
IDENTIFICATION OF TESTED PART TYPES

Generic	Part Number	Date Code	Die Manufacturer	Description	Procured as
LP2953	5962-9233601QXA	9747	National Semiconductor	500 mA Positive Adjustable	Q-level ceramic
LT1528	LT1528CT	9611	Linear Technology	3A Positive Adjustable	Commercial plastic TO-220
AD3306	ADP3306-5	99xx[a]	Analog Devices	300 mA Positive Fixed 5V	Commercial plastic SO-8
LT1763	LT1763CS8	9918	Linear Technology	500 mA Positive Adjustable	Commercial plastic SO-8
LT1175	9R69-001FHA[b]	9728	Linear Technology	500 mA Negative Adjustable	Custom metal flat pack
LT1185	LT1185CT	9249	Linear Technology	3A Negative Adjustable	Commercial TO-220

[a] Engineering samples provided with no date code
[b] Commercial chips in hermetic flight package

dose irradiations for the LT1185, LT1763, and LP2953 were performed at the Raytheon Component Evaluation Center, El Segundo CA. At this facility, low and high dose rate irradiations were preformed using a Shepherd model 142 and a Gammacell 220 Co-60 irradiator respectively Dose rates for the high dose exposures ranged between 40 and 50 rad/s. Low dose rate exposures were carried out at between 0.01 to 0.06 rad/s. All sources were in compliance with MIL-STD-883, Method 1019, and have undergone dosimetry correlation [9].

B. Electrical Tests

All electrical tests, for parts tested at Raytheon in El Segundo, CA, were performed using an LTX automated test system. Electrical tests for parts tested at Boeing Radiation Effects Laboratory were preformed using a Tektronix S-3260 automated test system along with a Keithley Model 2400 Source Meter. Irradiations and electrical tests for each device type were performed at the same location. Electrical tests included all of the DC test parameters in the manufacturer's specification. One additional parameter, maximum output current, was added to determine the current at which the regulator went into shutdown mode. This parameter was measured by pulse testing with increasing load currents at an output voltage setting of 5 volts. Load current was increased until the output voltage dropped to 4.7 volts indicating that the device was beginning to shutdown. Beyond this point slight increases in load current result in the output going to a low voltage state. Maximum output current determines the functional failure limit of the device because when it is exceeded, the device fails to regulate.

Though not reported herein, for most cases, a phase margin test was also performed pre- and post-irradiation. This test was imposed to assess changes in device stability. Many of the devices tested were found to be marginally stable under some conditions prior to irradiation. It is recommended to perform a post irradiation stability test since the device phase margin can change.

C. Procedure

Twenty samples of each device type were divided into four groups with five parts each for biased and unbiased low rate as well as biased and unbiased high rate irradiations. After pre-irradiation electrical tests, the four groups underwent step level irradiation and test. The time between irradiation steps for electrical tests was between one to two hours. The outputs of the biased samples were periodically monitored on the bias circuit to ensure that the devices were stable while under irradiation. The time frame for group tests for each device type was maintained as short as possible; i.e. months did not pass between high and low dose rate tests. This was done to minimize any error due to equipment calibration changes. The irradiation bias conditions for biased irradiations are defined in Table II. Parts in the unbiased groups had all leads shorted.

TABLE II.
IRRADIATION BIAS CONDITIONS

Device	Input Voltage (V)	Output Voltage (V)	Output Current (mA)
LP2953	+6.0	+5.0	50
LT1528	+6.0	+5.0	100
AD3306	+6.0	+5.0	50
LT1763	+6.0	+5.0	50
LT1175	-6.0	-5.0	50
LT1185	-6.5	-5.0	100

IV. TEST RESULTS

A. LP2953

For the high dose rate groups, all parameters met the manufacturer's specification beyond 100 krad(Si) with little difference between the biased and unbiased cases. For the low dose rate groups, however, most parameters failed between 10 and 50 krad and, for most parameters, degradation was worse for the unbiased group. The maximum output current, Fig. 1, degrades to an unusable level at about 50 krad for the unbiased condition. .The high rate condition had very little degradation and no bias effect whatsoever. In contrast, the low dose rate case had a significant bias effect. Shown in Fig. 2, output voltage degraded very little for the high rate condition while at the low rate parts began to fail the specification limit below 20 krad. Reference voltage was found to degrade similarly indicating that reference voltage shift is primarily responsible for output voltage change. Unlike the other parameters, dropout voltage degrades most for the 'biased' low dose rate case as shown in Fig. 3.

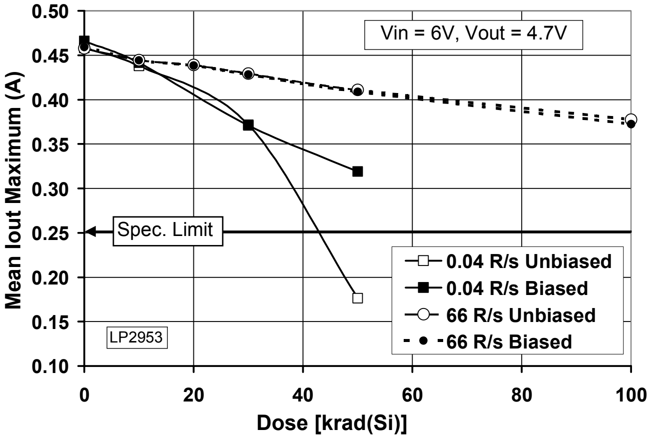

Fig. 1. Maximum output current for LP2953 degrades more for the unbiased low rate case. No bias effect seen for the high rate case.

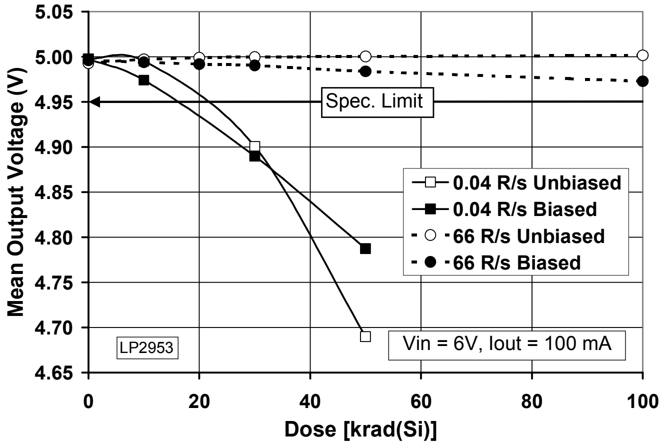

Fig. 2. Output voltage degrades rapidly at low dose rate while little degradation is seen for the high rate case.

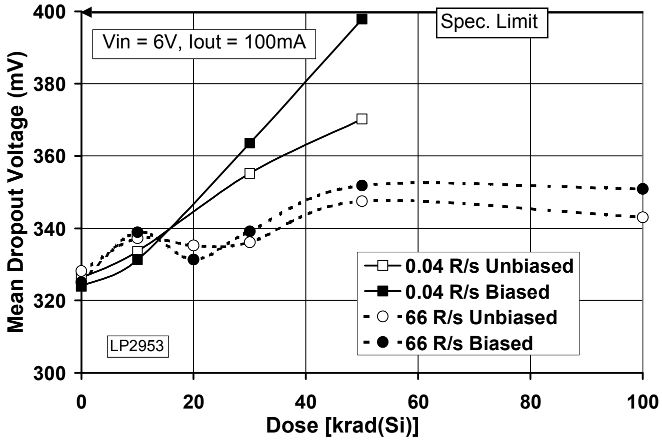

Fig. 3. Dropout voltage for the LP2953 degrades more for the 'biased' low dose rate condition than for the unbiased condition.

B. LT1528

A significant dose rate effect was found for both output current and output voltage as shown in Fig.s 4 and 5. For both cases no bias dependency was seen for the high dose rate condition. In contrast the biased and unbiased low rate conditions started to diverge at the higher dose levels. Change in the output voltage for the low and high rate condition drift in opposite directions.

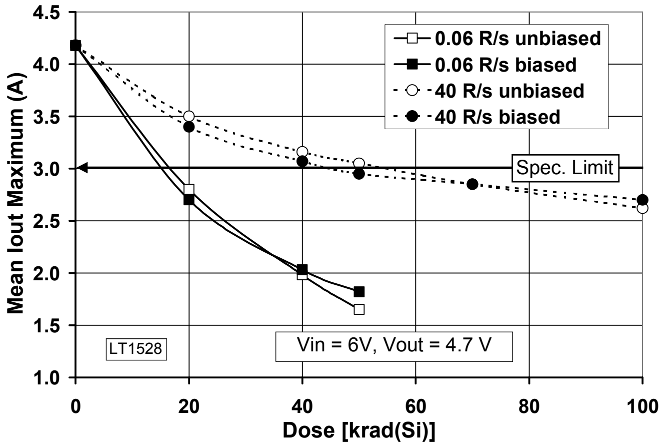

Fig. 4. .No bias effect seen for the LT1528 high dose rate cases. Biased and unbiased low rate cases appear to start diverging.

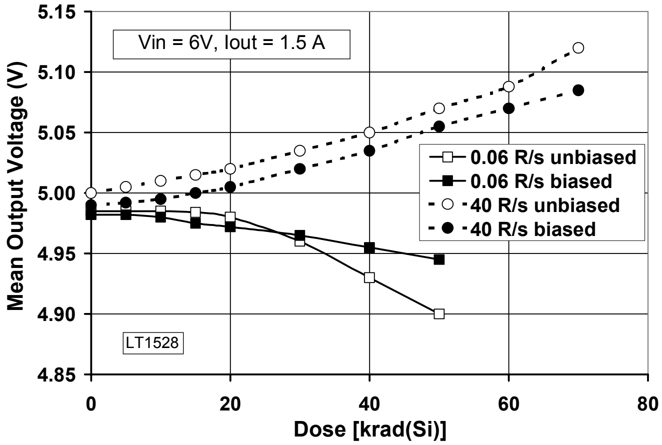

Fig. 5. .Change in output voltage for the LT1528 high and low dose rate cases is in opposite directions.

C. ADP3306

This device exhibited the least dose rate effect of the devices tested. However, as shown in Fig.s 6 and 7, both output current and voltage for the low rate unbiased group fail to the specification limit at half the dose level of the high rate groups. Bias effect is seen for the low rate group but not for the high rate group. Moreover, output current degradation of the biased low dose rate group appears to be less than that of the either of the high rate groups at the higher dose levels.

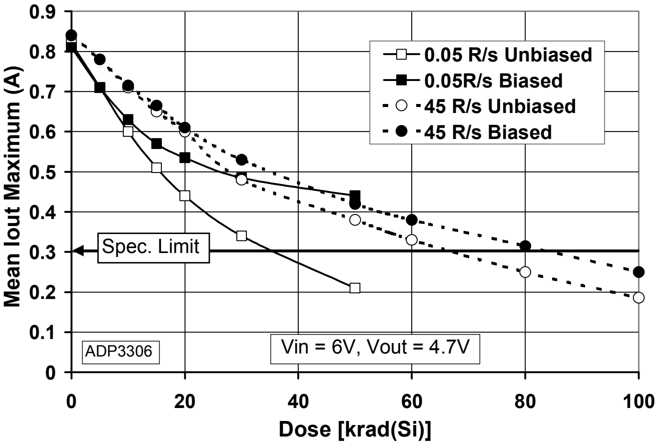

Fig. 6. .Maximum output current for the ADP3306 exhibited a bias effect for the low dose rate case. Degradation of the biased low dose rate group appears to be less than that of the high rate groups at higher dose levels.

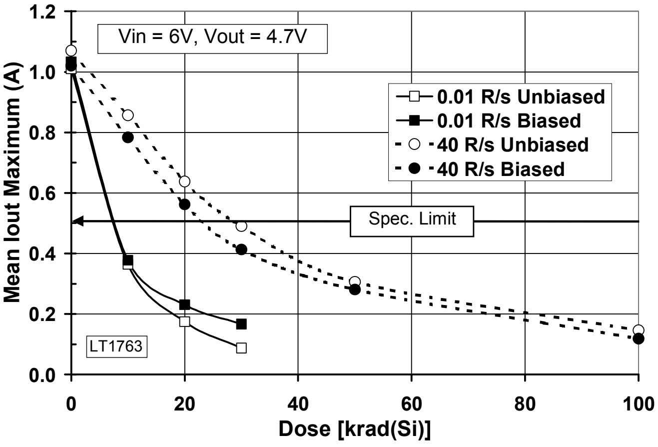

Fig. 8. .Maximum output current for the LT1763 shows a divergence in the biased and unbiased low dose rate groups.

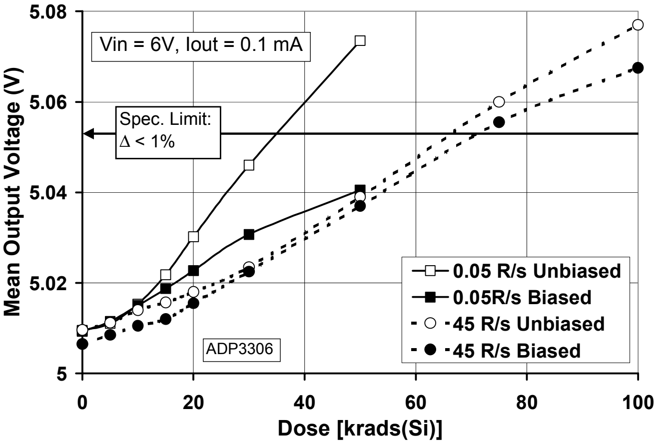

Fig. 7. .Output voltage for the ADP3306 exhibited a bias effect for the low dose rate case

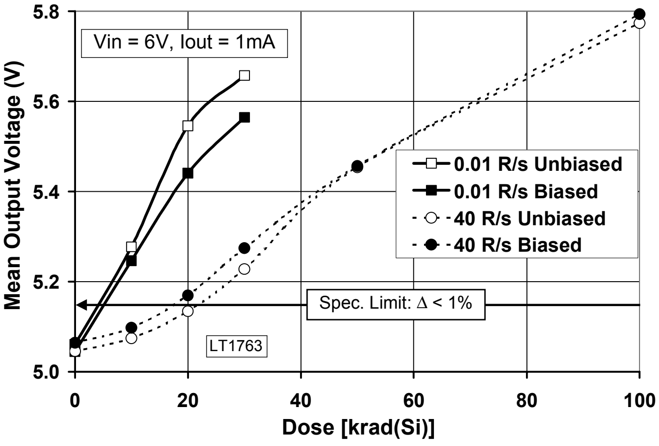

Fig. 9. .Output voltage drift for the LT1763 made the device unusable at about 10 krad.

D. LT1763

This device showed little bias dependency for the high dose rate groups. For the low rate groups, maximum output current and output voltage performed slightly better on the biased group as maximum output current degraded to near the irradiation bias current as shown in Fig.s 8 and 9. This slowing of degradation in the biased group may be due to the increase in the base-emitter voltage while the device loses gain during irradiation. The change in output voltage for this device was much worse than the other devices tested, making the device unusable at about 10 krad. Ground pin current degradation was found to track the change in the maximum output current indicating that loss of gain in the pass transistor of the device is the cause for the loss of output current. Increase in dropout voltage in this case was found to be worse for the unbiased low dose rate condition.

E. LT1185

The rapid loss of output current drive shown in Fig. 10 for the low dose rate unbiased condition was not expected since the device pass transistor is NPN. However, very little degradation was found for the ground pin current. Since the ground pin current is basically the base drive current in the pass transistor, the gain of this element was not affected. The decrease in output current is likely due to degradation in the current sense circuit which contains lateral PNP transistors. There was no similar degradation for the high dose rate groups. In fact, output current improved for the high dose rate groups. Degradation for the biased low rate group diverges strongly from the unbiased low rate group. This would lead to premature over-current shut down of the device. Output voltage , shown in Fig. 11, also exhibited bias and dose rate dependence. Reference pin current performance shown in Fig. 12 is significant since the reference pin is used to shut down the regulator. The shutdown function failed at 10 krad for the low dose rate cases. The change in reference current showed no bias dependency for either the high or low dose rate conditions.

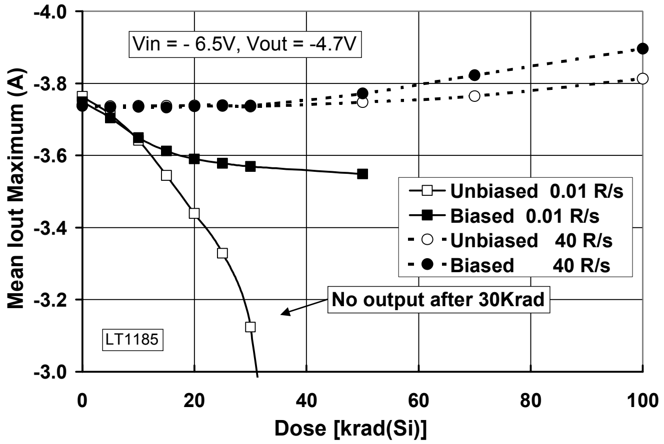

Fig. 10. .Loss of output current in the LT1185 at low dose rate was likely due to degradation of the over-current protection circuit. At high dose rate there was no degradation.

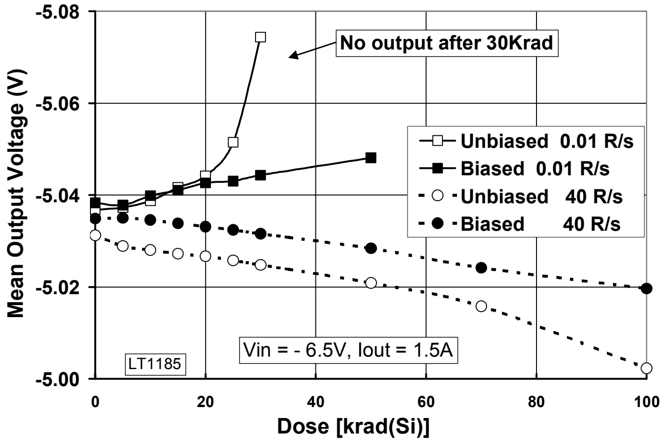

Fig. 11. .Output voltage for the LT1185 had a strong bias dependence at low dose rate. Reference voltage shift was in opposite directions for low and high dose rate.

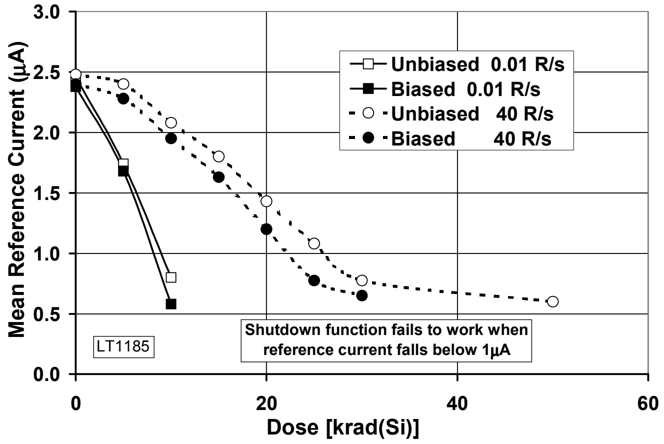

Fig. 12. .Loss of shutdown function on the LT1185 occurred earlier for the low dose rate cases.

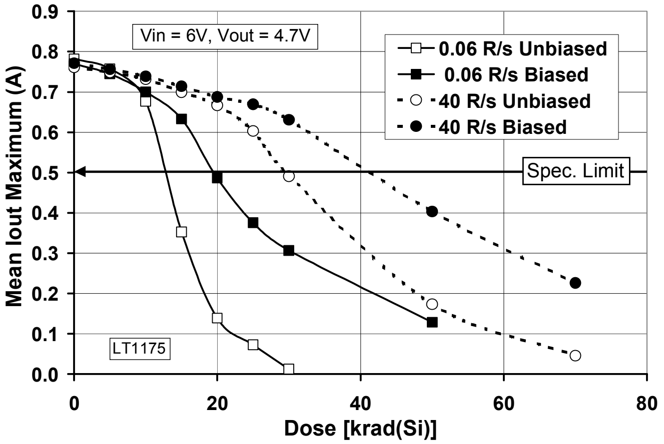

Fig. 13. .Maximum output current in the LT1175 exhibited both bias and dose rate dependence.

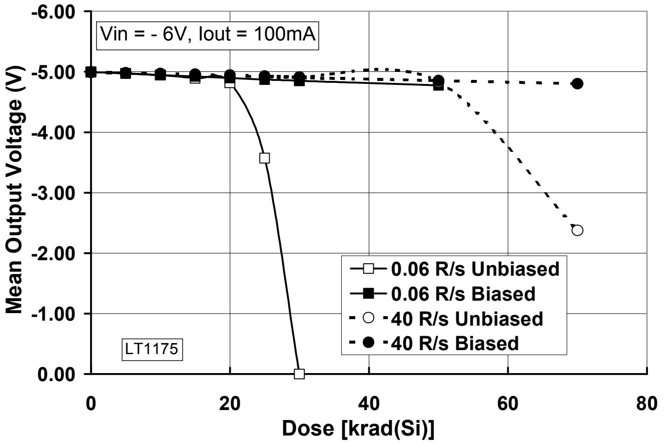

Fig. 14. .Loss of output voltage for the LT1175 occurred when the test condition exceeded the device output current capability

F. LT1175

Similarly to the LT1185 case, the significant dose rate effect for output current drive shown in Fig. 13 was unexpected since the device pass transistor is NPN. For this device as well there was very little change in ground pin current. Again indicating that there was little change in the pass transistor gain. Output current degradation shows both dose rate and bias dependence. Loss of output voltage shown in Fig. 14 is due to the inability of the device to drive the load current in the test. The external shutdown function of this device failed to work above 10 krad.

V. DISCUSSION

Common among the devices tested, both negative and positive, was a significant post-irradiation reduction in the maximum output current the device could supply. As total dose level increased each device went into over-current shut down at successively lower load currents. For the positive devices, this can be attributed to a reduction in pass transistor gain as indicated by significant increases in ground pin current (base drive to the PNP pass transistor). For the negative devices, however, gain of the NPN pass transistor was not significantly affected. For these, the likely cause of the decreased output current capability was degradation of the over-current shutdown circuit. In all cases, maximum output current exhibited ELDRS, with degradation at low dose rate being the worst case. Bias dependence was also more significant for the low dose rate condition. In some cases it was observed that the biased and unbiased low dose rate groups diverged at the higher dose levels.

For output voltage and reference voltage, the situation was more varied in both degree and direction of shift. For some cases, as with the LT1528 and LT1185, the output/reference voltage shift was in opposite directions for low and high dose rates. For the majority of other parameters the worst case irradiation condition was unbiased low dose rate.

VI. CONCLUSIONS

All of the devices tested exhibited both Enhanced Low Dose Rate Sensitivity and bias dependency. These results show that to adequately characterize devices of this type for space applications requires low dose rate testing. For applications where the device may be off for long periods of time, adequate characterization must include an unbiased test group. These comments apply as well to radiation lot acceptance testing. Additional testing beyond that in this study is recommended to determine if the observed ELDRS effect saturates or continues at even lower dose rates and to determine bias dependence with different load conditions.

VII. ACKNOWLEDGMENT

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