Investigation of Application-Specific Bias Conditions and Dose Rate Dependency in Total Ionizing Dose (TID) Response

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Abstract--**This paper investigates flight circuit application bias and irradiation dose rate dependencies ("test as you fly" conditions) in the total ionizing dose (TID) response of various electronic components considered for use in a space radiation environment.**

I. INTRODUCTION

THE complexity and feature size of electronic components for space missions is constantly evolving. As a result, it is essential for the radiation effects community to advance from historical test methods, based on military standards, to focus on more rigorous total ionizing dose (TID) device characterization, with emphasis on the complexities of the space radiation environment, part technology, and the impact of flight application-specific circuit design conditions [1]. In terms of radiation hardness assurance (RHA), this approach is known as "test as you fly." It is a critically important strategy to implement when designing a spacecraft intended to survive the stresses of the space radiation environment.

It has been documented in the past, dose rate and application-specific irradiation bias can have a significant impact on the TID response for different device technologies (i.e. CMOS, bipolar linear, and BiCMOS). From a hardness assurance perspective, these factors must be carefully considered when performing radiation testing. Total dose data should be evaluated with respect to the applicability of the part performance in the radiation environment as well as the flight circuit application(s) of interest [2]. As a result, deviations from military standard total dose test methods may be necessary in order to ensure radiation survivability, especially for non-standard circuit designs, which may differ from the recommended operating conditions specified in the manufacturer's datasheet.

This paper investigates application-specific bias conditions as well as dose rate dependency for various part types, which could potentially induce (or mitigate) significant TID degradation. In fact, irradiation bias, which can significantly impact a worst case total dose response, has also been shown to be directly correlated to dose rate [3]. The intent of this paper is to show the importance of considering this correlation on a case-by-case basis, and to emphasize that standard historical TID test generalities and methodology do not always apply.

Several devices, under consideration for use on the NASA Europa Clipper mission, were irradiated based on flight application circuit conditions at varying mission-specific dose rates (which may or may not encompass the MIL-STD dose rates). Post irradiation, trends in critical circuit parameters are analyzed and the impact to radiation hardness assurance is assessed. All total dose testing was performed by the Jet Propulsion Laboratory (JPL).

The results presented herein have been compared to generic characterization data and test methodologies. Based on these findings, overall radiation hardness assurance recommendations are provided on specific bias and dose rate conditions to consider when performing radiation lot acceptance testing (RLAT) on these part types. Circuit design guidelines and mitigations are also proposed.

II. DEVICE DESCRIPTION

The devices characterized for the total dose environment are identified in Table I. Two of the part types were traditional bipolar linear operational amplifiers (one bulk CMOS process and another analog bipolar). There are also two digital-to-analog converters (DACs), an analog-to-digital converter (ADC), and a digital isolator.

III. EXPERIMENTAL PROCEDURE

All total ionizing dose irradiations were done using the Cobalt-60 sources on site at the Jet Propulsion Laboratory in Pasadena, CA. TID irradiation as well as pre- and post-irradiation electrical characterization was performed at ambient room temperature (25°C). Where specified, parts were operated under biased, and in some cases, unbiased, test conditions during irradiation. A step-stress model was implemented and electrical parametric characterization was performed pre-rad and after each intermediate dose point, out to an accumulated exposure of 300 krad(Si).

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Selected dose rates include 42 mrad(Si)/s for bipolar linear and BiCMOS components as well as 100 mrad(Si)/s for bulk CMOS. These target dose rates were derived from the environmental profile specific to the Europa Clipper mission [4-5]. One of the goals of this paper is to compare the results at these mission-specific dose rates to generic data at the standard MIL-STD-883 dose rates, in order to highlight any dependencies in the TID response.

Irradiation bias conditions and parametric test conditions were intended to bound part performance and replicate the flight circuit applications of these devices. A minimum sample size was identified as five parts per wafer/diffusion lot per test condition. All test samples were pulled from the procured flight lot.

TABLE I. PART INFORMATION FOR TID TEST DEVICES

Generic Part No.	**Manufacturer**	**Part Description**	**Process Technology**
RHR61, RHR64	ST Micro	Operational amplifier	CMOS
RH1013	Analog Devices	Operational amplifier	Bipolar linear
DAC5675	Texas Instruments	DAC	BiCMOS (0.6 µm)
DAC121 S101	Texas Instruments	DAC	CMOS (submicron CMOS7)
RHF1201	ST Micro	ADC	CMOS (0.25 µm)
IL815T	NVE	Digital Isolator	CMOS

IV. TEST RESULTS AND DISCUSSION

A. ST Micro RHR61 (5962R1620401VXC) and RHR64 (5962R1620501VXC)

The ST Micro RHR61 and RHR64 are bulk CMOS single and quad, rail-to-rail operational amplifiers, respectively. These devices are rated to 100 krad(Si) at high dose rate (HDR) per the ST Micro datasheet [6]. Separate TID RLATs were performed by JPL in 2018 using off-specification/application-specific bias conditions.

Ten samples (plus two controls) of the RHR61 and RHR64 were irradiated to an accumulated dose of 300 krad(Si) at an exposure rate of 100 mrad(Si)/s. Five devices were biased in a generic voltage follower (unity gain), op-amp configuration (common case) per the manufacturer recommended bias circuit. The other five devices were left unbiased, with all leads shorted to ground, during irradiation. For the parametric testing, Vin was set to 1.8V, 3.3V and 5V. Parametric failures of the supply current (I_{CC}) and input offset voltage (V_{IO}) were first observed starting at 100 krad(Si).

The data for Vin=5V was worst case. Severe parametric failures of the RHR64 were observed at 200 krad(Si), where several devices-under-test (DUTs) began producing anomalous parametric readings. A biased, room temp 168-hour anneal was performed post 300 krad(Si). Several DUTs did not recover back in spec following the anneal. In some cases, the spec limits were exceeded by tens of millivolts as well as hundreds of microamps for critical parameters. As expected with bulk CMOS devices, the biased parts performed much worse than the unbiased devices.

In a separate test, a different lot of RHR64 samples were TID characterized in a comparator bias configuration. The bias circuit applied a 2.5V input voltage differential using 5V supply (comparator output low 0V). The DUTs were biased during irradiation and three devices were grounded. The test was performed at a high dose rate of ~38 rad(Si)/s.

Under these bias conditions, significant parametric and functional failures were observed for the biased samples, and the test was stopped at 200 krad(Si). The functional failure was defined by an inability to measure the V_{OUT+} parameter, which implies the comparator was not producing an output signal. Other out of spec parameters include input offset current, bias current, supply current, offset voltage, slew rate, and open loop gain. An unbiased 168 hour room temperature anneal was performed after test completion. No recovery of functionality in any of the three failed test devices was observed (which were biased during irradiation). The unbiased parts, however, met the manufacturer datasheet limits up to and including 200 krad(Si).

To continue to assess the TID response with the comparator bias, another follow-on pathfinder test was performed on additional RHR64 samples. The intent was to gain better visibility into when the output gets stuck low, and how the input offset voltage changes with radiation. The input differential voltage was varied on the bias to include measurements for 0V, 0.5V, 1.0V, and 2.0V. The test was run at room temperature with a higher dose rate of ~40 rad(Si)/s.

Three of the op-amps in the RHR64 quad device were biased as voltage followers while the other op-amp was biased as a comparator. Functional failures were first observed starting at 150 krad(Si) for the voltage follower configuration. Under bias, as a comparator, with varying input voltage differential, functional failures occurred at 62 krad(Si). It was noted, as the input differential voltage is increased, the results get worse until saturation is reached. An unbiased 168 hour room temperature anneal was performed after the test completion. No recovery of functionality in any of the failed test devices was observed.

From a design perspective, it is not recommended to use standard rail-to-rail op-amps in a comparator circuit configuration. In general, for these types of parts, the output stage is designed as a current mirror with bipolar transistors or MOSFETs to keep the output current constant regardless of loading. When the part is operated open loop, the internal second stage will attempt to increase the current drive to close the loop, but it cannot, which results in an increase in supply current. As a result, the sustained input differential voltages can cause the part's supply current to increase drastically. Overall, these op-amps are typically not designed to handle the levels of current that would result from the part being used as a comparator.

B. Analog Devices RH1013 (5962R8876003VHA)

The RH1013 is a dual, radiation hardened, rail-to-rail operational amplifier manufactured by Analog Devices Inc. (ADI) on a 7 µm bipolar process. Two separate TID RLATs were performed on this part to 300 krad(Si) at a dose rate of 42 mrad(Si)/s. During one RLAT, the parts were biased as a traditional voltage follower with unity gain, while the other test implemented a comparator configuration.

The part was previously characterized by the manufacturer to 100 krad(Si) (using a traditional op-amp bias) at a low dose rate of 10 mrad(Si)/s. Per this test report, all parts remained within the datasheet limits out to 100 krad(Si) [7].

Specifically, for the Europa Clipper test campaign, a total of 10 samples were Co-60 gamma irradiated (5 biased and 5 unbiased during irradiation) at low dose rate of 42 mrad(Si)/s to an accumulated exposure of 300 krad(Si). An additional eleventh sample was used as a control, which was not irradiated. Parametric characterization was performed to the specifications and test conditions provided in the standard microcircuit drawing (SMD), 5962-88760, Rev G, Table I. The part was biased during irradiation at ±15V and the parametric tests were performed at a supply voltage of ±15V and +5V.

After accumulated exposure up to 300 krad(Si), this device continued to meet all SMD specification limits with minimal parametric degradation and no functional failures. As expected, in most cases, the unbiased parts performed worse than the biased devices, indicating bias dependency in the TID response. The most sensitive parameter appeared to be the offset voltage with the largest recorded delta shifts out to 300 krad(Si). Although, all measured parameters were very stable throughout the duration of the test.

For the RH1013 RLAT in the comparator configuration, the following bias conditions were implemented: V_{CC} = 5V, V_{EE} = 0V. Channel A: -input = 0V, +input = 2.5V, with the output forced to a high state. Channel B: -input = 2.5V, +input = 0V, with the output forced to a low state. Parametric testing was performed at supply voltages of ±15V and +5V. Similar to the op-amp configuration, the input offset voltage was the only parameter that changed significantly, as plotted in Figure 1. The SMD spec limit is exceeded at levels >200 krad(Si). There was minimal dependency on supply voltage in the TID response.

Overall, these rail-to-rail op-amps performed much better than the RHR64 bulk CMOS devices. However, Figure 2 shows the comparator bias did induce more parametric degradation in the RH1013 in comparison to the op-amp configuration. Looking specifically at the offset voltage parameter, the low dose rate enhancement is worse for the comparator configuration, however, the worst case measured supply current as a function of radiation was nearly identical under both bias conditions (see Figure 3).

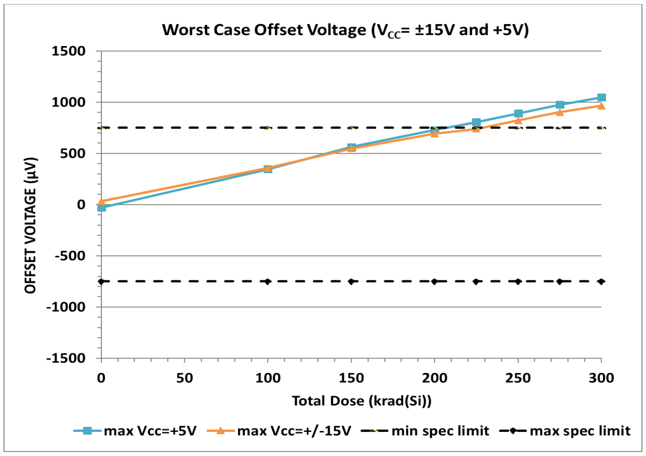

Fig. 1. RH1013 comparator bias – worst case input offset voltage as a function of total dose (VCC = +5V and ±15V).

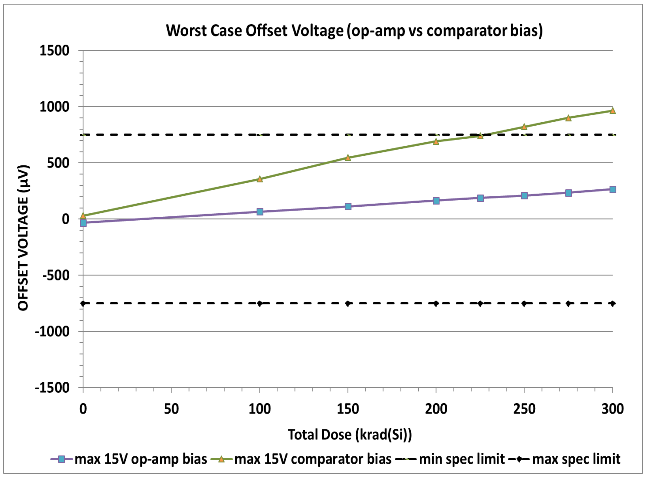

Fig. 2. RH1013 comparator versus op-amp bias – worst case offset voltage as a function of total dose (VCC = ±15V).

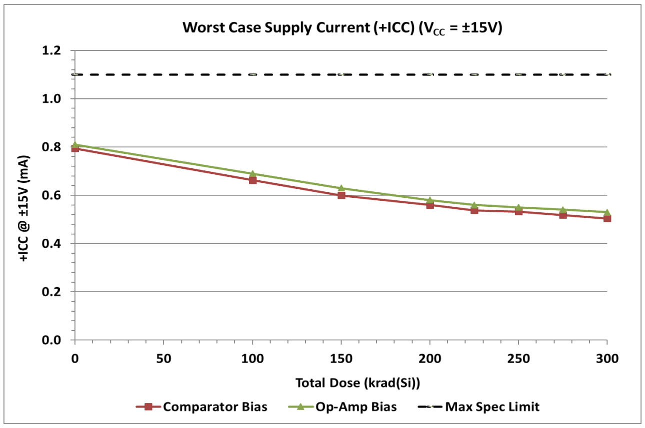

Fig. 3. RH1013 comparator versus op-amp bias – worst case supply current as a function of total dose (VCC = ±15V).

C. Texas Instruments DAC5675A-SP (5962-0720401VXC)

The DAC5675 is a 14-bit resolution, high-speed, 400-Msps, digital-to-analog converter. It is manufactured on Texas Instruments advanced high-speed mixed-signal 0.6 µm BiCMOS process. A preliminary TID characterization test was performed on five parts biased and five parts unbiased to 200 krad(Si) using a dose rate of 150 mrad(Si)/s. At 150 krad(Si), functional failures were first observed.

Furthermore, Texas Instruments performed a TID test to 150 krad(Si) per reference [8]. The sample size was five and the dose rate was medium at 2.53 rad(Si)/s. All devices remained in spec throughout the duration of the test and were functional post 150 krad(Si). Total current as a function of TID exposure is shown in Figure 4.

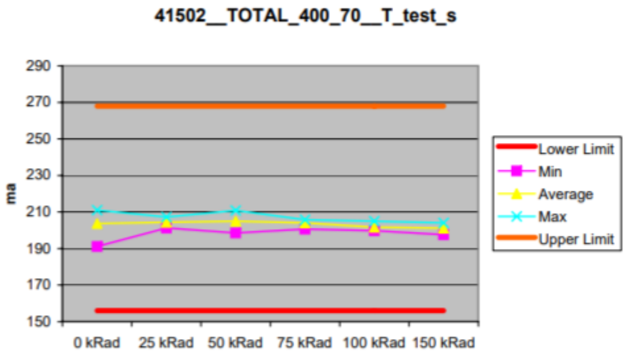

Fig. 4. DAC5675 total current as a function of total dose (2.53 rad/s) [6].

In 2019, JPL performed a static-biased TID RLAT at 10 mrad(Si)/s to explore dose rate dependency on five biased devices plus one unirradiated control sample. During parametric testing, post 35 krad(Si), functional failure was first observed on two of the DUTs. As shown in Table II, the automated test equipment no longer returned integral nonlinearity (INL) or differential nonlinearity (DNL) values for serial numbers 3 and 8. Serial number 7 functionally failed at 40 krad. A follow-up measurement was made on the RLAT parts with an oscilloscope. It was confirmed that the devices failed to provide an analog output when the digital input was changed, validating the lack of a reading from the automated tester. Also to note, JPL directly tested the internal reference voltage. Whereas, the external V_{REF} was measured by applying a voltage source to I_{BIAS} and then measuring the DAC's full scale output voltage. It did not appear the internal reference was the failure point in this device.

TABLE II. DAC5675 INTEGRAL NONLINEARITY (INL) MEASUREMENTS AS A FUNCTION OF TOTAL DOSE (10 MRAD(SI)/S)

INL- @ CODE 15872	**Total Dose [krad(Si)] at 10 mrad(Si)/s**					
Serial Number (Biased)	**0**	**25**	**30**	**30.2**	**35**	**40**
C302	-2.409	-2.290	-2.519	-2.541	-2.093	-2.145
1	-2.895	-1.546	-1.377	-1.438	-1.621	-2.347
2	-2.322	-1.982	-2.190	-2.256	-2.312	-2.548
3	-0.935	-1.024	-	-0.988	🟥	🟥
7	-1.079	-1.902	-1.679	-1.746	-1.973	🟥
8	-1.973	-1.696	-1.792	-2.204	🟥	🟥
MIN	**-2.895**	**-1.982**	**-2.190**	**-2.256**	**-2.312**	**-2.548**
MEAN	**-1.841**	**-1.630**	**-1.561**	**-1.726**	**-1.969**	**-2.448**
MAX	**-0.935**	**-1.024**	**-0.769**	**-0.988**	**-1.621**	**-2.347**
STDEV	**0.831**	**0.380**	**0.530**	**0.533**	**0.346**	**0.142**

The last pass level was 30 krad(Si). However, it should also be noted, the actual TID threshold of this device has not been established due to the statistically low sample size of five devices. The low-side tail of the log-normal distribution may extend below 30 krad(Si).

Comparing the two datasets (the manufacturer characterization data versus the JPL results), a significant low dose rate dependency was identified for this part. For applications with environments below 30 krad(Si), a test-to-failure, using a larger sample size of parts, at the application-specific dose rate (as determined by the radiation transport analysis), is recommended to demonstrate that the Probability of Success (Ps) is sufficiently high. The low dose rate enhancement factor is so significant, it is recommended to TID RLAT this device at an appropriate dose rate <10 mrad(Si)/s to bound the worst case performance for the specific mission environment.

D. Texas Instruments DAC121S101 (5962R0722601VZA)

The DAC121S101 is a 12-bit voltage-output digital-to-analog converter (DAC) that can operate from a single 2.7V to 5.5V supply. It is manufactured on the heritage National Semiconductor submicron CMOS process (CMOS7) with active parasitic bipolar PNP transistors and the 5V cell library [9]. Degradation of these PNP transistors can impact the DAC accuracy parameters, including INL and DNL, as well as full scale error [9].

Per the Texas Instruments radiation report [9], the space grade version of this device, DAC121S101WGRQV (type -02), is qualified for low dose rate environments to a TID level of 100 krad(Si). When the DUTs are biased during irradiation with 5.5V, many electrical parameters significantly exceed the manufacturer specification limits post 100 krad(Si) as dose rate is increased. After a biased room temperature anneal of 1008 hours, all electrical parameters recovered to within spec limits. Per MIL-STD-883, the product is qualified to 100 krad(Si) for environments with dose rates of 27 mrad(Si)/s or lower [9].

JPL performed the TID RLAT to 300 krad(Si) at a dose rate of 100 mrad(Si)/s on the -01 version of this device. The DUTs were irradiated biased and unbiased. Parametric failures were observed starting at 100 krad(Si). Significant failures occurred between 150 and 200 krad(Si) as evident in the INL (see Figure 5), DNL, and zero code output (see Figure 6) measurements. Post 300 krad(Si), a biased, room temperature anneal was performed for 168 hours. No measurable recovery occurred. The biased parts performed much worse than the unbiased DUTs.

Again, the out of spec performance at 100 krad(Si), indicates a potential measurable bias dependency in the TID response. For applications with total dose requirements >100 krad(Si), RLAT is recommended to be performed at the mission-specific dose rate, under flight application-specific bias conditions, in order to ensure a representative TID-induced response in the device.

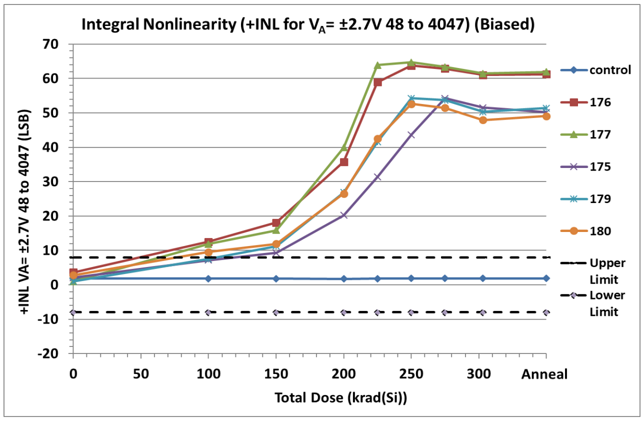

Fig. 5. DAC121S101 integral nonlinearity (INL) as a function of total dose (biased during irradiation, 100 mrad(Si)/s).

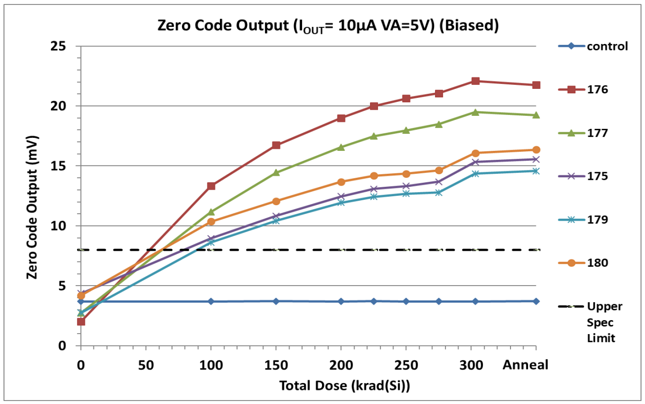

Fig. 6. DAC121S101 zero code output as a function of total dose (biased during irradiation, 100 mrad(Si)/s).

E. ST Micro RHF1201KSO-01V (5962F0521701VXC)

The RHF1201 is a 12-bit, 50 Msps sampling frequency analog-to-digital converter fabricated on bulk CMOS 0.25 µm technology. This device is guaranteed to 300 krad(Si) at high dose rate per the SMD radiation hardness rating.

Preliminary pathfinder testing, under various flight application-specific bias conditions, showed measurable dependence on the sample frequency, polarization resistance (Rpol), input voltage, and supply voltage in the TID response. This also included exercising the devices, during irradiation, statically and dynamically as well as in single-ended and differential mode. The pathfinder results showed as sample frequency and Rpol are increased, the TID degradation is worst case. Due to a potential inherent noise issue with this part, operating at higher frequency, Rpol, and supply voltage can result in signal integrity issues and degraded output waveforms that can be misinterpreted as radiation-induced.

From a hardness assurance perspective, in order to minimize total dose effects, it is recommended to operate these parts in differential mode using the minimum Rpol value per the manufacturer datasheet. For any flight application-specific off-spec use cases of this part, it is highly recommended to perform a TID RLAT under the applicable operating conditions. Parametric degradation has been observed as early as 100 krad(Si), specifically for the integral and differential nonlinearity.

F. NVE IL815T

IL815T is a bulk CMOS, high speed, digital isolator manufactured by NVE (Spintronic Giant Magneto Resistive or GMR technology). Previous cobalt-60 TID testing, by NRL on the IL715T (same process as the 815), indicated functional failures starting at 120 krad(Si) at an extremely accelerated dose rate of 240 rad/s [8]. The supply voltages were set at V_{DD} = 5V and V_{DD} = 3.3V for the NRL test. The supply current, output currents as well as functionality were measured after each irradiation dose point. Post 120 krad(Si), two of the ten DUTs failed functional testing with V_{DD} = 5V. For V_{DD} = 3.3V, seven of the ten test samples were no longer functioning. By 150 krad(Si), nearly all DUTs functionally failed, regardless of supply voltage [10]. This data would indicate the last pass level is 100 krad(Si) at a very high dose rate.

In 2019, JPL performed the TID RLAT on the IL815T to 300 krad(Si) at a dose rate of 100 mrad(Si)/s. Post irradiation, a one week, room temperature, biased anneal was performed. The RLAT began with V_{DD1} = V_{DD2} = 5.0V and three different TID bias configurations: 1. sync and output enable pins both grounded (through 1 kΩ resistor), 2. sync pulled high and output enable pin grounded, and 3. both sync and output enable pin pulled high to 5V. Parametric measurements were performed at V_{DD} = 3.3V and V_{DD} = 5.0V.

Post 100 krad(Si), significant parametric and functional failures were observed based on the supply currents (I_{OH} and I_{OL}) and timing parameters for bias condition 2. In the flight application, the signal to the sync pin is intermittent, sent whenever the state of the device wants to be changed. During radiation exposure, a 1 Hz signal with 50% duty cycle was applied to the sync pin to simulate this application-specific bias configuration.

For bias condition 1, several parametric non-conformances were observed post anneal, and the parts did not fully recover back in spec. Failing parameters include I_{CCH}, I_{CCL}, and I_{IH} as well as some timing parameters. Figure 7 is a plot of the supply current as a function of total dose for bias condition 1 with both pins grounded. The spec limit is exceeded prior to 100 krad(Si) and the degradation is significant by 150 krad(Si).

The hardness assurance recommendation is to ensure the sync pin and output enable are both grounded in flight applications. Bias condition 3 was also worst case for TID-induced parametric degradation (where sync = output enable = 5V).

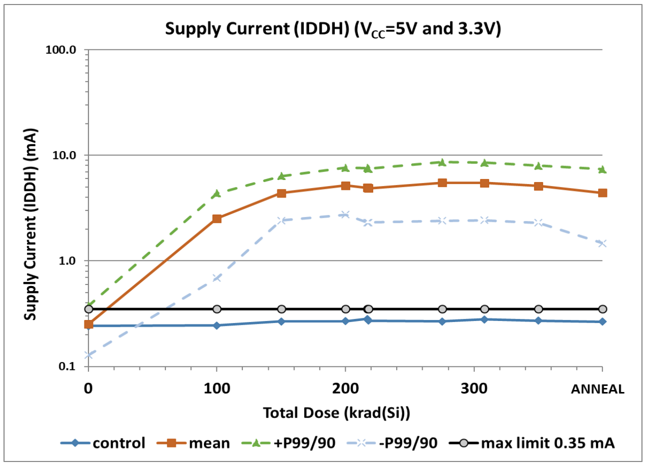

Fig. 7. NVE IL815T supply current as a function of total dose.

V. Conclusion

Overall, we have shown the total ionizing dose response for several different part types (covering a range of process technologies) is entirely dependent on the applied irradiation bias configuration and dose rate. In some cases, these two variables are directly correlated, and must be considered together when bounding the worst case TID performance.

The intent of this paper was to summarize the observed functional and parametric failure mechanisms due to radiation degradation as a function of irradiation bias and dose rate. As part of a radiation hardness assurance campaign, it is critical to identify root causes and recommend potential design strategies to mitigate the amount of TID degradation for different application-specific use cases.

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