

ELDRS Characterization for a Very High Dose Mission

Richard D. Harris, *Member, IEEE*, Steven S. McClure, *Member, IEEE*, Bernard G. Rax,
Aaron J. Kenna, Dennis O. Thorbourn, Karla B. Clark, and Tsun-Yee Yan

Abstract— Evaluation of bipolar linear parts which may have Enhanced Low Dose Rate Sensitivity (ELDRS) is problematic for missions that have very high dose radiation requirements. The accepted standards for evaluating parts that display ELDRS require testing at a very low dose rate which could be prohibitively long for very high dose missions. In this work, a methodology for ELDRS characterization of bipolar parts for mission doses up to 1 Mrad(Si) is evaluated. The procedure employs an initial dose rate of 0.01 rad(Si)/s to a total dose of 50 krad(Si) and then changes to 0.04 rad(Si)/s to a total dose of 1 Mrad(Si). This procedure appears to work well. No change in rate of degradation with dose has been observed when the dose rate is changed from 0.01 to 0.04 rad(Si)/s. This is taken as an indication that the degradation due to the higher dose rate is equivalent to that at the lower dose rate at the higher dose levels, at least for the parts studied to date. In several cases, significant parameter degradation or functional failure not observed at HDR was observed at fairly high total doses (50 to 250 krad(Si)) at LDR. This behavior calls into question the use of dose rate trend data and enhancement factors to predict LDR performance.

I. INTRODUCTION

RADIATION poses a unique technical challenge for any potential mission to the moons of Jupiter since the spacecraft would spend a significant amount of time in the harsh Jovian radiation belts. The radiation dose level experienced by a mission to, say, Europa would be unprecedented for a NASA mission. Due to the very strong magnetic field of Jupiter, the radiation belt has a large flux of highly energetic electrons. Dose levels could easily be several Mrads behind 100 mil of aluminum shielding. Devices within electronic boxes could be subjected to as much as 300 to 1000 krad(Si).

This level poses a risk since many linear bipolar devices are not available as radiation hardened nor have been tested

to such a high level. In order to support such a mission scenario, we developed a test methodology for Enhanced Low Dose Rate Sensitivity (ELDRS) susceptible devices which addresses this high dose environment and performed initial tests on several bipolar linear devices.

During the course of testing this methodology, data has been acquired which shows functional or parametric failures at fairly high dose levels (50 to 150 krad(Si)) during low dose rate (LDR) irradiation only. Failure in these parts was not seen during high dose rate (HDR) irradiation up to 1 Mrad(Si), considerably higher than the LDR failure doses. This behavior rules out the use of trend data to extrapolate LDR performance using an enhancement factor on the HDR performance data. In other words, test methods must include LDR testing to levels greater than the mission dose in order to bound device performance.

II. TEST METHODOLOGY

The accepted standards for evaluating parts with ELDRS require testing at a very low dose rate which could be prohibitively long for very high dose missions. The dose rates used to determine if a specific part displays ELDRS are governed by Mil-Std-883, Method 1019 [1] and require comparing the degradation with irradiation under a high dose rate (HDR) of 50 – 300 rad(Si)/s with that under a low dose rate (LDR) of 0.01 rad(Si)/s. If there is an increased degradation per unit dose at the lower dose rate, the part is concluded to have ELDRS. Once this determination is made, all subsequent evaluation and qualification must be performed at the low dose rate. The difficulty for these very high dose scenarios is that the time required for testing to 300 to 1000 krad(Si) levels at the required LDR would take 1 to 3 years, much too long to comply with mission parts approval requirements.

Various methods have been proposed to accelerate the lengthy testing protocol for very high dose missions. These include irradiating at elevated temperature [2] and using trend data to predict LDR performance based on using an enhancement factor on the measured HDR data [3]. These procedures have not met with universal acceptance [4]. However, the challenges of very high dose missions make some sort of accelerated method necessary.

A reasonable potential mission could be at Europa for 3 months, after spending 3 months between reaching Jupiter

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The authors are with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (richard.d.harris@jpl.nasa.gov, (phone: 818-393-6872, fax: 818-393-4559); steven.s.mcclure@jpl.nasa.gov; bernard.g.rax@jpl.nasa.gov; aaron.kenna@jpl.nasa.gov; dennis.o.thorbourn@jpl.nasa.gov; karla.b.clark@jpl.nasa.gov; tsun-yeeyan@jpl.nasa.gov).

and achieving Europa orbit insertion. In such a scenario, almost the entire dose would be expected to be received during this 6 month portion of the mission. A total dose of 300 to 1000 krad(Si) received over a 6 month time period results in a time average dose rate of approximately 0.02 to 0.06 rad(Si)/s.

To address such a scenario, a test procedure was developed where parts are irradiated to at least 50 krad(Si) at 0.01 rad(Si)/s, the accepted low dose rate, then continued at an increased dose rate of 0.040 rad(Si)/s until a total dose of 1 Mrad(Si) was reached, or the parts failed, whichever came first. The initial low dose rate step serves three purposes: 1) it sets a baseline comparison to Mil-spec, 2) it provides a worst-case bound on performance for the dose received during the cruise stage, and 3) it is compatible with JPL's Juno mission to Jupiter. This third purpose permits the use of parts for which the NRE efforts are already completed and the initial data is already taken. The higher LDR step, 0.040 rad(Si)/s, is a compromise to address the 300 to 1000 krad dose level accumulated over the 6 months near Jupiter.

The parts selected for this initial testing were parts for which testing was already in progress for the ongoing Juno project. This project required LDR testing to 50 krad(Si) and HDR testing to 100 krad(Si). Testing was extended to 1 Mrad(Si) for the present study. Test devices evaluated to date are identified in Table I which includes the TID level reached to date.

III. EXPERIMENTAL DETAILS

A. Total Dose Facilities

Total dose irradiations for all devices were performed at the Co-60 HDR and LDR facilities at the Jet Propulsion Laboratory. The dose rate capability obtained by employing both sources spans from 0.001 to 50 rad(Si)/s. For all high dose rate exposures, a dose rate of 25 rad(Si)/s was used. Low dose rate exposures were carried out at 0.01 rad(Si)/s to a dose of at least 50 krad(Si) and 0.04 rad(Si)/s to 1 Mrad(Si) or to failure (or to the highest level reached at the time that this paper was submitted).

B. Electrical Tests

Electrical tests were performed on-site at JPL using one of two mixed signal testers; either an ETS-300 or an LTS-2020. In general, all parameters specified by the manufacturer were measured. Measurements were performed prior to the start of irradiation and following a variety levels throughout the irradiation. The levels included: 5, 10, 20, 30, 50, 75, 100, 150, 200, 250, 300, 500, 700, and 1000 krad(Si). Irradiation and measurements were made at room temperature.

C. Procedure

Samples of each device type were divided into four groups of four to five parts for each irradiation condition. These included HDR and LDR with parts both biased and unbiased at each rate. In all cases, all parts of a particular type were

from the same date code. The irradiation bias conditions for biased irradiations were in accordance with either the manufacturer's recommendation or the application condition. Parts in the unbiased groups had all leads shorted and grounded.

IV. EXPERIMENTAL RESULTS

Table II summarizes the failures observed to date. The failures listed here are divided into 3 categories: functional failures (where the part is no longer functional), extreme parametric failures (where the part is still functional but so far out of spec as to be unusable) and mild parametric failures (where the parameters are out of spec, but may still be useable if the parameter drift can be accounted for in the circuit design).

Selected parameters are discussed and their radiation dependence is plotted in the following sections. In all subsequent plots the average values of the parts irradiated under a particular condition are shown. In addition, the spec limits are shown.

A. AD537 Voltage to Frequency Converter

Parametric failures in the AD537 begin to appear in the input bias current at about 30 krad(Si) for all irradiation conditions, as shown in Fig. 1. There may be an ELDRS effect as the LDR unbiased case shows the most degradation at the lowest doses, but the effect is small. The more significant factor is the bias during irradiation with unbiased parts showing more degradation.

Parametric failures in the linearity error begin to appear at 100 krad(Si); (not shown) and become extreme by 150 krad(Si). There is no ELDRS effect in the failure as both LDR and HDR unbiased cases display the same behavior. Again, there is a significant bias effect.

Significant parametric shifts in the output frequency (not shown) appear above 75 krad(Si) for all but the biased HDR case. This degradation was most significant at higher input voltage values, indicating that device performance is improved by limiting the input voltage range.

These results indicate that this device is not usable beyond 150 krad(Si) unless it is used only in the biased condition with no unbiased units.

B. AD606 Logarithmic Amplifier

Extreme parametric failures were observed for the LDR unbiased irradiation condition at 150 krad(Si) for log slope (not shown), log conformance (Fig. 2), and the intercept point (not shown). Both HDR, and LDR biased conditions continued to be functional to the highest levels tested thus far. These results indicate that this device is not usable beyond 150 krad(Si) unless it is used only in the biased condition with no unbiased units. All parameters fail above about 700 krad for the LDR biased.

C. AD652 Voltage to Frequency Converter

The voltage reference of the AD652 degraded very rapidly with extreme parametric degradation setting in by 10 krad(Si) as shown in Fig. 3. As a result, this part must be used with an external reference. ELDRS and bias effects are readily apparent with the LDR unbiased irradiation condition being the worst case. As a result, this part must be used with an external reference.

Other parameters in this part remain well behaved

D. AD667 12-bit Analog to Digital Converter

The integral non-linearity (INL, Fig. 4) and differential non-linearity (DNL, not shown) of the AD667 both shown gradual degradation beginning by 10 krad(Si). The low dose rate unbiased case performed the worst the change in INL was up to about 2 LSB by 250 krad(Si). The degradation appears to saturate at this point.

Both unipolar zero offset (UZE, not shown) and bipolar zero offset (BZE, not shown) demonstrated a significant spike around 300 krad(Si) for the HDR biased case. This behavior appears to be a real effect as it occurred in all the devices. This behavior, or at least the recovery after 300 krad(Si), may be due to the timing of tests. Test levels up to 300 krad(Si) were done rapidly within the first day of testing, then devices were left on bias overnight with no irradiation. The remaining tests were performed the next day and were likely not performed as quickly after irradiation leaving open the possibility that the observed spike was due to an effect that is relatively fast annealing. This interpretation is somewhat speculative at this time, and more investigation will be necessary to be sure. Unbiased LDR indicated saturation in the damage occurring at about 100 krad(Si) with recovery at higher doses.

The reference voltage for this device indicated no significant degradation to the highest levels tested. All devices continue to work at the highest level tested thus far and remain usable provided the parametric degradation can be tolerated in the application

E. RH117 Regulator

Only two (2) parts were available for the RH117 resulting in only LDR unbiased irradiations being performed. The degradation of the reference voltage is shown in Fig. 5. This parameter falls out of spec above 150 krad(Si) and then begins a precipitous fall after 300 krad(Si).

The dropout voltage is out of spec above 200 krad(Si) (not shown). Similar behavior is also observed for V_{REG} and V_{OUT} (not shown).

F. AD574 12-bit Analog to Digital Converter

Functional failures in the AD574s began to appear in INL and DNL in unbiased LDR devices at 50 krad(Si). By 100 krad(Si), all devices had failures. The INL behavior is depicted in Fig. 6. Prior to the functional failure there was no indication of ELDRS with all groups performing similarly.

Mild parametric failures began to appear in INL and DNL at 30 krad(Si) for all bias and dose rate conditions, and the HDR and biased LDR parts continued in this mild degraded state to the highest doses tested. This includes the biased LDR group which performed very well beyond 300 krad(Si) and is still functional at 1 Mrad(Si).

The general behavior of the bipolar zero error (not shown) is quite similar to that of INL. Functional failure is observed following about 75 krad(Si) for the LDR unbiased case. All other conditions continue to function.

These results indicate that use of this device beyond 30 krad(Si) would have to be limited to a biased condition with no unbiased units. If this were done, above about 400 krad(Si) the mild parametric failures would need to be tolerated by the circuit design.

G. AD648 Bi-FET Op-Amp

The input bias current on the AD648 exhibited mild parametric failure at the first irradiation step of 5 krad(Si) and increased to extreme parametric failure by 30 krad(Si), as shown in Fig. 7. AOL exhibits mild parametric failure beginning at 30 krad(Si) and increased to functional failure by 100 krad(Si). There does not appear to be any bias or dose rate dependence in the degradation rate. Other parameters also showed extremely poor performance.

As a result of the extreme nature of the poor performance, no graphs are included in this report.

H. AD8138 Differential ADC Driver

The parameters of the AD8138 show very little to no degradation with irradiation. During the HDR irradiation, the dose level was extended to 3 Mrad(Si) to see if the good performance would continue; it did. For the very little degradation seen, there is no apparent bias or dose rate dependence.

This part is fabricated with a complementary high speed process that is expected to be very radiation tolerant. These results support that expectation.

I. LM113 Voltage Reference

There were only a limited number of LM113 flight parts. As a result, the flight quality parts were only irradiated under LDR conditions. Most parameters were well behaved, including the reference voltage (not shown) which while showing a gradual degradation with increasing dose, is still well within spec at the present dose level (300 krad(Si)). The step at 133 krad(Si) is due to the irradiation being stopped at this point and then restarted after a 16 month anneal. It is interesting that after restarting, the degradation resumes its initial degradation curve.

The dynamic impedance, shown in Fig. 8, displays steady and rapidly increasing mild parametric degradation exceeding the spec value at about 50 krad(Si). The devices are still functional at the present level and remain usable provided the parametric degradation can be tolerated in the application.

The step seen at 133 krad(Si) in the referenced voltage is also seen in the dynamic impedance.

J. AD590 Temperature Comparator

Parametric degradation begins at the first irradiation level and results in failures in the temperature error for LDR after 20 krad(Si) and for HDR after 75 krad(Si) as shown in Fig. 9.

K. OP400 Operational Amplifier

Parametric degradation proceeds slowly until functional failure occurs for the OP400. The offset voltage, (not shown) fails for all cases except the LDR biased case below 100 krad(Si). The LDR biased case is still functional and in spec at 100 krad, the present level.

The input bias current degrades very rapidly, resulting in failure above 5 krad (Si) for all cases as shown in Fig. 10. I_{IO} and AVS show similarly rapid degradation and failures.

L. RH1078 Dual Operational Amplifier

Only a limited number of parts were available for the RH1078 resulting in only LDR irradiations being performed. The offset voltage, shown in Fig. 11, begins to exceed the spec limit above 250 krad(Si) for the LDR unbiased case. For the LDR biased case the parameter is still within spec, but is quickly approaching the limit.

The source current is not shown. For both bias cases the parameter is above the spec limit above ~ 250 krad(Si). Similar behavior is also observed for PSRR and slew rate.

M. RH1814 Quad Operational Amplifier

Only a limited number of parts were available for the RH1814 resulting in only LDR irradiations being performed. The only parameter which drifted out of spec is I_{SINK} shown in Fig. 12. This is an unusual and interesting case where the LDR biased values drift up out of spec at ~ 50 krad(Si), but then drift back down in spec and remain in spec at the present dose of 300 krad(Si).

N. PM139 Quad Voltage Comparator

Only a limited number of parts were available for the PM139 resulting in only LDR irradiations being performed. All parameters for the PM139 are still within spec at the present dose level of 300 krad(Si).

O. OP484 Quad Operational Amplifier

Only a limited number of parts were available for the OP484 resulting in only LDR irradiations being performed. The offset voltage (not shown) begins to degrade with the first irradiation level and exceeds the spec limit above 30 krad(Si) for the unbiased case. The biased case is still in spec at the present level of 50 krad(Si), but appears to also be approaching the limit.

The input bias current, shown in Fig. 13, degrades even more rapidly and begins to exceed spec above 10 krad(Si) for both bias cases.

V. DISCUSSION

An accelerated test method has been evaluated on a number of bipolar linear parts which appears to produce acceptable results. This method employs a LDR value of 0.01 rad(Si)/s until a dose of 50 krad(Si) is reached and then increases the LDR to 0.04 rad(Si)/s until 1 Mrad(Si) is reached. This decreases the total irradiation time from 3.2 years for a constant LDR of 0.01 rad(Si)/s to 0.9 years for the accelerated two rate method. With this accelerated method, the testing can be completed in a more manageable, albeit still long, time.

Several general observations can be made: 1) Significant parametric degradation or functional failure was observed at fairly high total dose levels (50 to 150 krad(Si)) for almost half of the parts studied. This behavior rules out the use of trend data to extrapolate LDR performance by using an enhancement factor on the HDR performance data. In other words, mission assurance test methods **must** include LDR testing to levels greater than the mission dose (with RDF) in order to bound device performance. 2) No obvious change in degradation rate is observed when LDR dose rate is increased from 0.01 to 0.04 rad(Si)/s. This is an indication that the test method might also provide a bounding test condition for high dose missions where the dose rate is even lower than the scenario imagined here. However, additional rate comparison testing would be required to verify this. 3) These results indicate the present extended test method would be a practical method for the characterization and RLAT testing for such an envisioned Europa mission. 4) Almost half of the linear bipolar devices tested are experiencing either parametric or functional failure in the unbiased condition at 50 to 150 krad(Si), while failure is not occurring for the biased condition. This indicates that leaving devices in a powered state is a mitigation strategy that should be considered

VI. CONCLUSIONS AND RECOMMENDATIONS

No previous work has addressed hardness assurance methods for assessing ELDRS for very high dose missions. Also, very little data exists for ELDRS evaluations beyond 100 krad(Si). This work has shown that, at least for the scenario used here, a practical test method can be developed. Further work is recommended to verify that this method bounds device performance for longer missions with lower dose rate requirements. Additional device tests including long term verification test condition at 0.01 rad(Si)/s to compare with the two dose rate test condition should be performed to determine how well the proposed test method bounds device performance.

ACKNOWLEDGMENT

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VII. REFERENCES

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TABLE I
DESCRIPTION OF TESTED PARTS AND THE CURRENT DOSE LEVEL

Generic P/N	Full Part Number	Description	MF	Date Code	HDR Level	LDR Level
AD537	AD537SH/883B	Voltage to Frequency Conv.	ADI	0719A/B	1 Mrad	1 Mrad
AD606	AD606JRZ-ND	Demodulating Log Amp	ADI	0650	1 Mrad	1 Mrad
AD652	AD652SQ/883B	Voltage to Frequency Conv.	ADI	0745	1 Mrad	1 Mrad
AD667	AD667-713F	12 bit ADC	ADI	0737	1 Mrad	1 Mrad
RH117	RH117H	Regulator	LTC	0750A	n/a	1 Mrad
AD574	5962R8512701VX	12 bit ADC	ADI	0622	100 krad	1 Mrad
AD648	5962-9753502VPA	Bi-FET Op-Amp	ADI	0629A	1 Mrad	700 krad
AD8138	AD8138ARMZ-ND	Differential ADC Driver	ADI	MAR 08	3 Mrad	499 krad
LM113	5962-9684302VXA	Voltage Reference	NSC	01A	1 Mrad	500 krad
AD590	5962R8757104VX	Temperature Comparator	ADI	0435A	1 Mrad	75 krad
OP400	5962-8777101VBA	Op-Amp	ADI	0502	1 Mrad	100 krad
RH1078	RH1078MW	Dual Op-Amp	LTC	0741A	n/a	300 krad
RH1814	RH1814MW	Quad Op-Amp	LTC	0414A	n/a	300 krad
PM139	5962R8773901VD	Quad Voltage Comparator	ADI	0046A	n/a	300 krad
OP484	5962R0051701VD	Quad Rail-to-Rail Op-Amp	ADI	0843A	n/a	55 krad

TABLE II
FAILURES OF TESTED PARTS AND FAILURE LEVEL

Generic P/N	Failing Parameters	Failure Type	Failure Condition	Failure Level
AD537	Linearity Error, Output Frequency	Extreme Parametric	HDR, LDR unbiased	150 krad
AD606	Log Conformance, Log Intercept, Slope	Extreme Parametric	LDR unbiased	150 krad
AD652	Voltage Reference	Mild Parametric	All	10 krad
AD667	INL, DNL, UZE, BZE	Mild Parametric	LDR unbiased	10 krad
RH117	Reference Voltage, Dropout Voltage	Mild Parametric	LDR unbiased	150 krad
AD574	INL, DNL, Bipolar Zero Error	Functional	LDR unbiased	50 krad
AD648	Input Bias Current, AOL	Extreme Parametric	All	5 krad
AD8138	None	-	-	-
LM113	Dynamic Impedance	Mild Parametric	LDR unbiased	50 krad
AD590	Temperature Error	Extreme Parametric	LDR both	20 krad
OP400	Offset Voltage Input Bias Current	Functional Extreme Parametric	HDR both, LDR unbiased All	25 krad 5 krad
RH1078	Offset Voltage, Source Current	Mild Parametric	LDR unbiased	250 krad
RH1814	Sink Current	Mild Parametric	LDR biased	50 krad but recovers
PM139	None	-	-	-
OP484	Offset Voltage, Input Bias Current	Mild Parametric	LDR both	10 krad

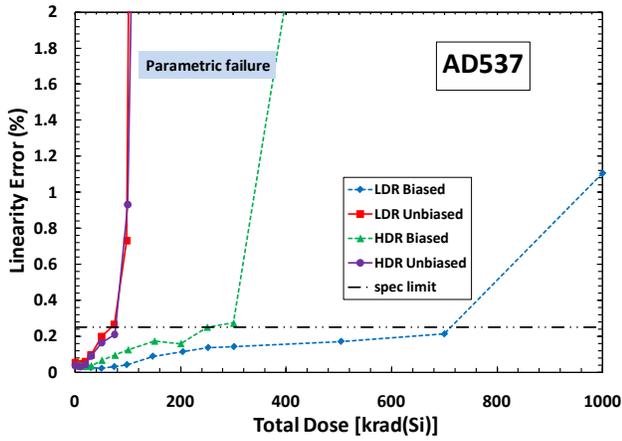


Fig. 1 - AD537 Linearity Error. Extreme parametric failure is observed above about 150 krad for both unbiased cases. To use part above 150 krad it must be kept in a biased state.

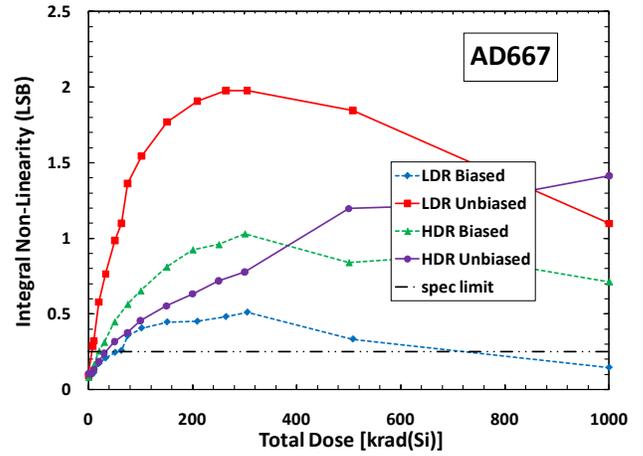


Fig. 4 - AD AD667 Integral Non-Linearity. Mild parametric degradation is observed beginning at about 10 krad. Degradation appears to saturate at about 250 krad

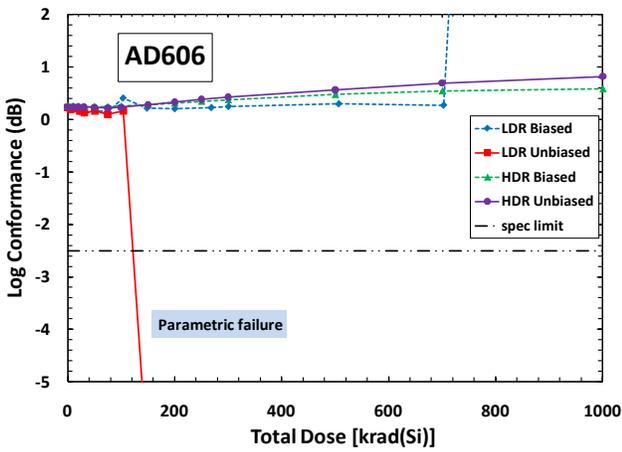


Fig. 2 - AD606 Log Conformance. Extreme parametric failure is observed above about 150 krad in the LDR unbiased condition. All parameters fail above 700 krad for LDR biased.

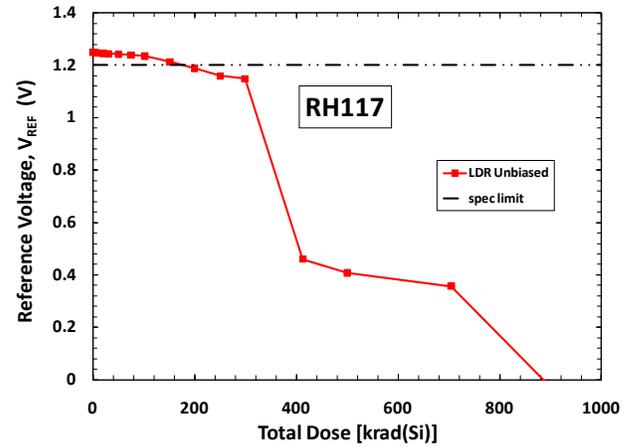


Fig. 5 - RH117 Regulator Reference Voltage. V_{REF} falls out of spec above 150 krad(Si) and then falls dramatically after 300 krad(Si).

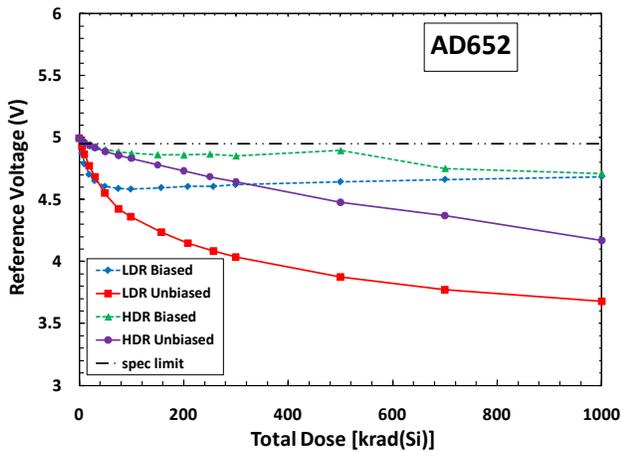


Fig. 3 - AD652 Reference Voltage. Extreme parametric failure is observed above about 10 krad. As a result, this part must be used with an external reference.

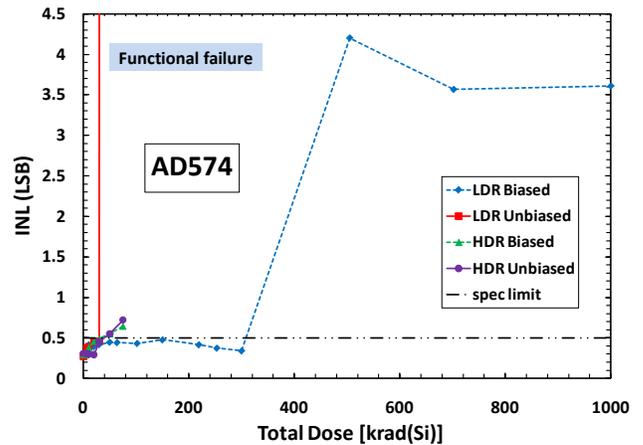


Fig. 6 - AD574 Integral Non-Linearity. Functional failure is observed above about 50 krad for the LDR unbiased case. To use this part above 50 krad it must be kept in a biased condition.

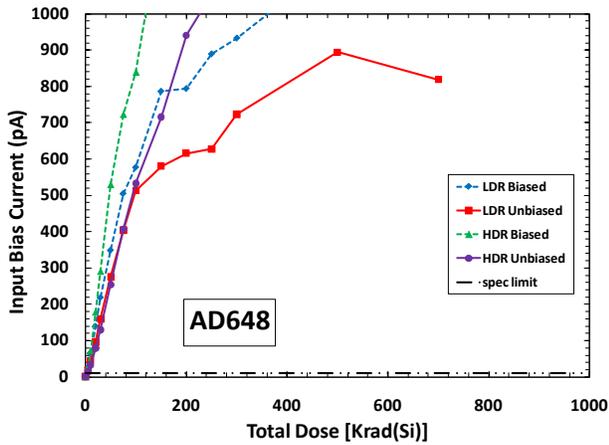


Fig. 7 - AD648 Input Bias Current. Mild parametric failure is observed at the first irradiation step of 5 krad increasing to extreme parametric failure by 30 krad.

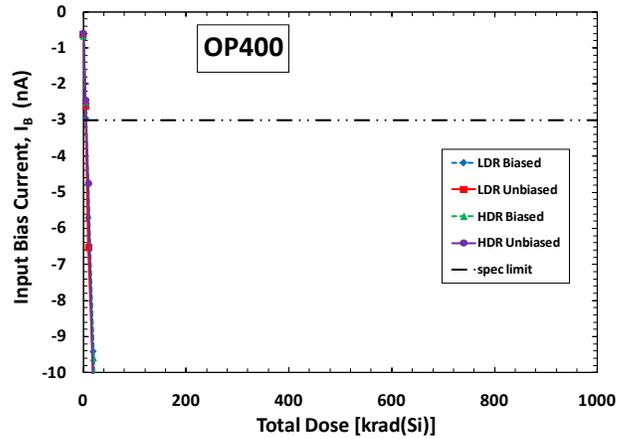


Fig. 10 - OP400 Input Bias Current. Very rapid degradation is observed resulting in failure above 5 krad(Si) for all cases.

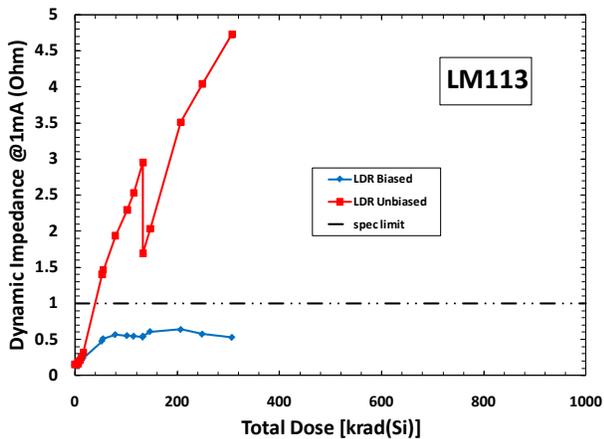


Fig. 8 - LM113 Dynamic Impedance. Mild parametric degradation begins at about 50 krad(Si). The devices are still functional at the present level and remain usable provided the application can tolerate the amount of degradation.

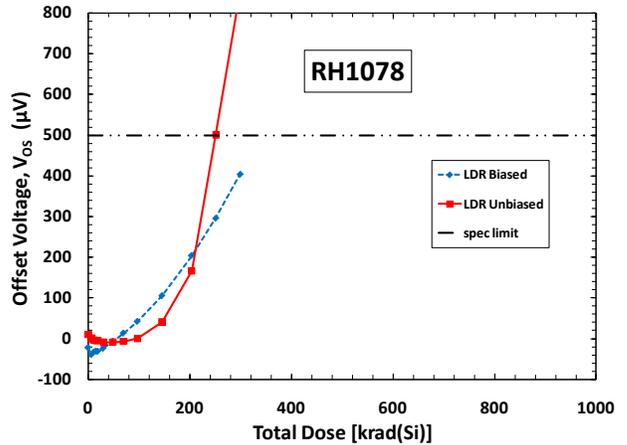


Fig. 11 - RH1078 Offset Voltage. Parametric degradation begins to exceed spec for the LDR unbiased case above 250 krad(Si). Based on extrapolating the LDR biased curve, the spec is expected to be exceeded above about 400 krad(Si).

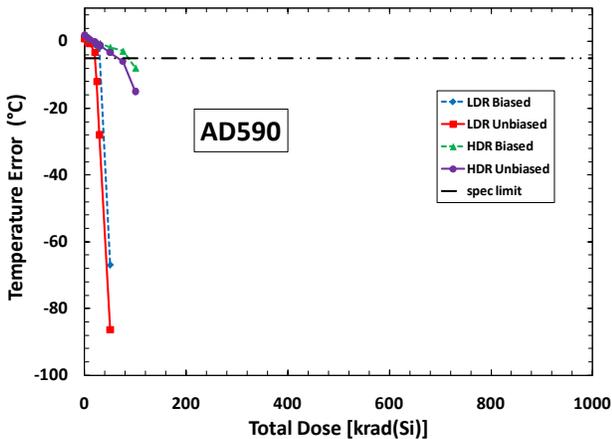


Fig. 9 - AD590 Temperature Error. Parametric failures observed after 20 krad(Si) at LDR and after 75 krad(Si) at HDR.

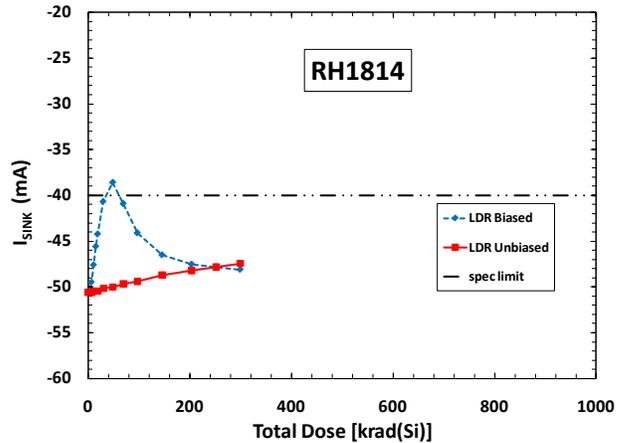


Fig. 12 - RH1814 Sink Current. This parameter drifts out of spec at about 50 krad(Si) and then immediately drifts back into spec for the LDR biased case. This is an unusual behavior.

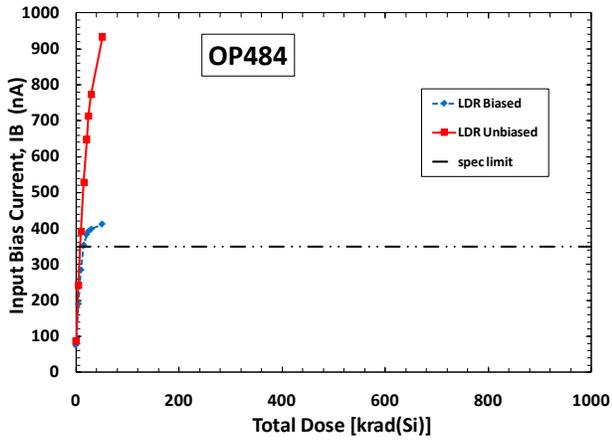


Fig. 13 - OP484 OpAmp Input Bias Current. Very rapid degradation is seen in I_B which exceeds spec above 10 krad(Si) for both bias cases.