Recent Radiation Test Results at JPL

Bruce E. Pritchard, *Member, IEEE*, Bernard G. Rax, and Steven S. McClure

***Abstract* - This paper documents recent TID (including ELDRS) and proton damage test results obtained by JPL. Unusual test results, such as abnormally low or high failure levels or unusual failure or response mechanisms, are emphasized.**

***Keywords* - Total ionizing dose, ELDRS, proton damage, displacement damage**

I. Introduction

THIS paper documents selected, recent TID (total ionizing dose), ELDRS (Enhanced Low Dose Rate Sensitivity), and proton damage radiation test results obtained by the Jet Propulsion Laboratory (JPL). This paper is not a full compendium, as it only covers the past three years of testing. More data and discussion re devices tested for ELDRS are provided in [1], and compendia of ELDRS test data have also been published by others [2], [3]. Also, the emphasis in this paper is on unusual test results, such as exceptionally low or high TID failure levels or unusual failure or response mechanisms. Space limitations do not allow for presentation of complete data sets, and actual reports should be checked for full data and discussion of individual test results. (Some parts not included herein are addressed in more detail in [1].)

II. Discussion

A significant number of semiconductor and photonic devices have been tested at JPL over the past few years. Table I provides a tabular summary of the parts tested, the conditions of the test, and the principal results. Parts are listed by manufacturer number (with any military prefixes omitted; see reports for more details). Note that the table only provides average (mean) dose or fluence levels, not "worst-case" values. Definitions of "worst case" vary, but the one normally preferred is 99/90, which is defined as 90% confidence (based on the number of samples tested) that the survival probability of the lot is ≥99% at the specified dose or fluence. (Of course, for most parts, the term "lot" does not refer to wafer lot, but merely date code.) Individual test reports and data must be examined to determine "worst case." Unless otherwise noted, TID testing was performed at either JPL's High- and/or Low-Dose Rate Cobalt-60 gamma ray facilities, and proton testing was performed at UC Davis. In the following section, a number of parts that have been tested are briefly discussed. Additional data may be obtained through JPL's RadNet website [4] or by contacting the authors. Other organizations also provide data through websites, including the Defense Threat Reduction Agency (DTRA) [5], NASA-Goddard Space Flight Center (GSFC) [6], the European Space Agency (ESA) [7], [8], and certain private companies [9], [10].

There has been considerable discussion among radiation community members and organizations regarding the relative value of existing test data. Some believe that existing data cannot be relied upon and that RLAT (Radiation Lot Acceptance Testing) is always necessary, while others believe that once a part has been tested, its hardness level is settled. Some organizations have developed guidelines for derating radiation test results based on the age, part category, and other factors. However, several factors must be considered, including the age of the parts tested, the methods used to test, and whether the part's manufacturing process or design have been changed, or whether normal lot-to-lot variations may have adversely impacted hardness. (Of course, data on a part from one manufacturer is not applicable for one made by another manufacturer. This is because, even though they may share the same device name and electrical characteristics, the designs and processes are different, and in general, their hardness characteristics will also be different.) In general, digital parts tend to evolve very rapidly, making frequent testing more necessary. Linear parts tend to evolve more slowly, due to their nature. Generally, once designed and built, the designs are often not changed thereafter (although process changes can still occur). However, there have been exceptions to this, as manufacturers transfer foundry operations to other locations or else they may merge and consolidate foundry operations.

However, one factor involving any TID assessment for a space application is the relative scarcity of appropriate ELDRS data for bipolar ICs (or BiCMOS). In many cases, there is no ELDRS data at all. Even when there is data, in many cases, the dose rate is not low enough (i.e., preferably 5 mrads/s, and no higher than 10 mrads/s), or there is no data taken on unbiased parts (which is often the worst case, and very important for space systems that often employ unpowered (cold), redundant, backup systems).

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Bruce E. Pritchard is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (telephone: 818-393-6895, e-mail: bruce.e.pritchard@jpl.nasa.gov).

Bernard G. Rax is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA (telephone: 818-354-9799, e-mail: bernard.g.rax@jpl.nasa.gov).

Steven S. McClure was with the Jet Propulsion Laboratory, but is now with Northrop Grumman Space Technology, Redondo Beach, CA 90278 (telephone: 310-812-7147, e-mail: Steve.McClure@ngc.com).

III. Test Results

A. 1N5665A Zener Diode (Microsemi)

This JANTX1N5665A is a 200-V transient absorption zener diode. It was tested unbiased with 63-MeV protons at UC Davis to a fluence of 1.19 x 10^{11} p/cm^2 (corresponding to a dose of 16 krads in silicon). The purpose was to determine whether displacement damage would cause significant changes to occur in breakdown voltage, leakage current, or dynamic impedance in such a high-voltage device. All changes were very minor. The largest percentage change was a 3% reduction in breakdown voltage. Leakage current remained within specifications, typically only rising ~10 nA.

B. 2N2222A NPN Transistor (Semicoa)

These parts were provided in chip form (no diffusion lot information) and packaged at JPL. They were tested with V_{CB} = 50 V. As shown in Fig. 1, they performed within specification up to 30 krads, with h_{FE} at low-current (0.1 mA) falling below specification at 60 krads. High-current h_{FE} remained within specification up to 300 krads. I_{CBO} and $V_{CE(sat)}$ did not change significantly up to the highest test level of 300 krads.

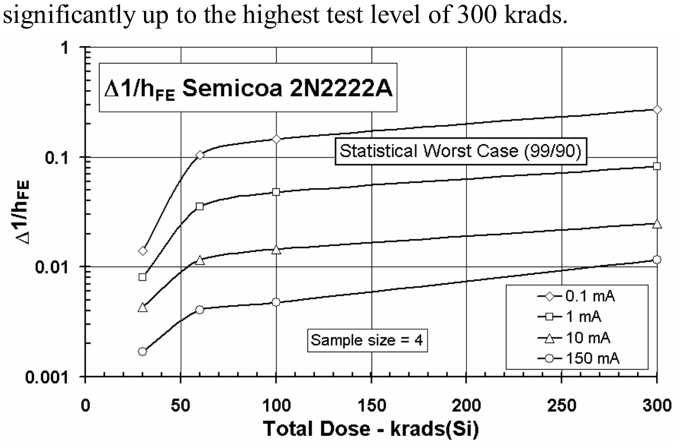

Fig. 1. Change in Reciprocal Beta ($\Delta 1/h_{FE}$) for the Semicoa 2N2222A Transistor During Biased Irradiation

C. 2N2484 NPN Transistor (Motorola)

This JANS2N2484 NPN transistor was tested with V_{CB} = 48 V. As shown in Fig. 2, they performed within specification up to 100 krads. I_{CBO} increased by 90 pA at 200 krads and $V_{CE(sat)}$ only increased by 10 mV at 200 krads.

D. 2N2857A NPN Transistor (Semicoa)

This 2N2857A NPN transistor made by Semicoa was tested with V_{CB} = 15 V (six samples tested). As shown in Fig. 3, they performed within specification up to 100 krads. At 300 krads, h_{FE} at 6 V and 2 mA was only slightly below the pre-radiation specification limit, and $V_{CE(sat)}$ increased only slightly (20 mV).

E. 2N2907A PNP Transistor (Semicoa)

These parts were provided in chip form (no diffusion lot information) and packaged at JPL. They were tested with V_{CB} = 50 V. They performed within specification up to 60 krads, with low-current h_{FE} falling below specification above 60 krads. High-current h_{FE} remained within specification up to 300 krads, although I_{CBO} and $V_{CE(sat)}$ exceeded specification values at 300 krads.

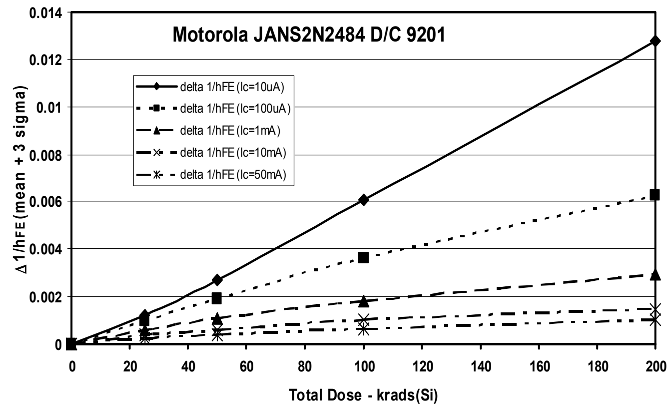

Fig. 2. Change in Reciprocal Beta ($\Delta 1/h_{FE}$) for the Motorola JANS2N2484 Transistor During Biased Irradiation (worst-case)

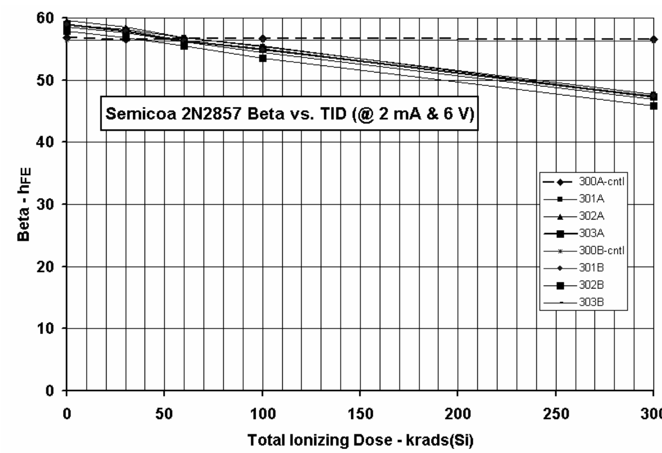

Fig. 3. Change in h_{FE} for the Semicoa 2N2857A Transistor During Biased Irradiation (worst-case)

F. 2N3637 PNP Transistor (Semicoa)

These parts were tested, due to similarity with previously tested high voltage bipolar transistors that had exhibited extreme sensitivity of gain at low current (i.e., 2N3700 discussed below). They were tested with V_{CB} = -80 V and V_{BE} = +2 V. As shown in Fig. 4, all devices performed within specification for h_{FE} to greater than 50 krads. Devices began to fail the minimum specification for h_{FE} at 0.1 and 1.0 mA at 100 krads with values of 33 and 65, respectively (versus minimum specifications of 55 and 90 at these currents). All parts remained within specification for h_{FE} at 10 mA at 100 krads, the highest dose level tested.

G. 2N3700 NPN Transistor (Semicoa)

These parts were tested due to extreme sensitivity of gain at low current observed in parts from previously tested manufacturers [11]. They were tested with V_{CB} = 80 V and V_{BE} = -2 V.

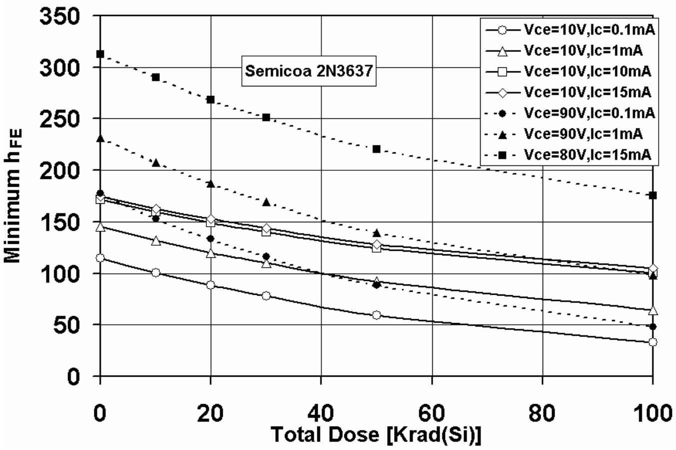

Fig. 4. Change in Beta (h_{FE}) for the Semicoa 2N3637 Transistor During Biased Irradiation

Fig. 5 (below) shows the 2N3700 devices remaining within specification for h_{FE} up to 10 krads. Devices began to fail the minimum specification for h_{FE} of 50 for I_C = 0.1 mA at 20 krads, with h_{FE} values of 41 to 47 at that dose. However, h_{FE} at 10 mA remained above the specification of 90 beyond 50 krads, and only dropped below specification at 100 krad, with values as low as 80.

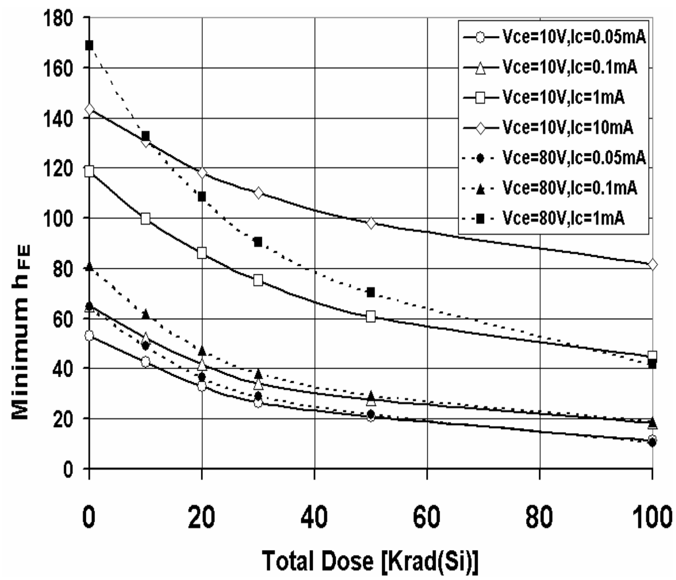

Fig. 5. Change in Beta (h_{FE}) for the Semicoa 2N3700 Transistor During Biased Irradiation

H. 4N49 Optocoupler (Micropac)

This JANTX4N49 optocoupler was tested unbiased with 50-MeV protons at UC Davis. Two date code lots were irradiated up to a fluence of 3.4 x 10^{10} protons/cm^2. The current-transfer ratio (CTR) of the more sensitive lot dropped below the required value of 0.47 at a worst-case fluence of 2.3 x 10^{10} p/cm^2.

I. AD768 D/A Converter (Analog Devices)

This 16-bit digital-to-analog converter (DAC) is a Bipolar/ CMOS part. Four samples were tested biased at high dose rate and performed within specifications up to 50 krads. Between 50 and 100 krads, V_{ref} (Fig. 6) and integral nonlinearity (INL) were out of specification. However, the part continued to function with somewhat degraded parameters up to 200 krads. (It is not known whether this part is susceptible to ELDRS.)

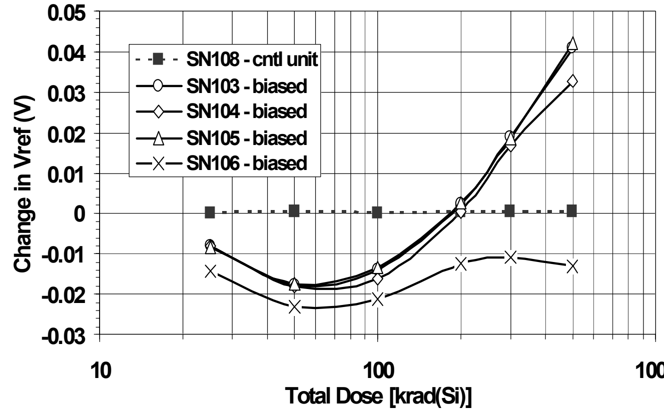

Fig. 6. Change in V_{ref} vs. Total Dose for the AD768 Irradiated in the Biased Condition at High Dose Rate

J. AD829 Video Op Amp (Analog Devices)

This high-speed video op amp is manufactured using Analog Devices' complementary bipolar (CB) dielectrically isolated process and was procured as a military grade hermetic part. Since the PNP transistors are high-f_T (600 MHz) and therefore not lateral, the part was expected to have little susceptibility to Enhanced Low Dose Rate Sensitivity (ELDRS), and low dose rate testing (at 0.01 rads/s) of both biased and unbiased parts up to 30 krads confirmed this.

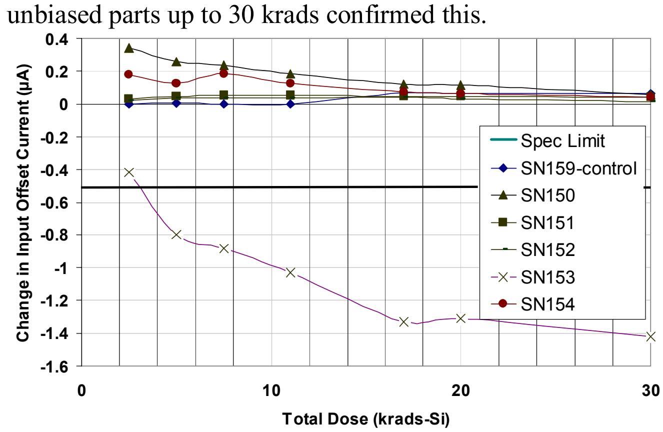

Fig. 7. Change in Input Offset Current (@±15V) vs. Total Dose for the AD829 Irradiated in the Biased Condition at Low Dose Rate

As seen in Fig. 7, all of the biased devices (with the exception of one anomalous part) continued to meet specification to the highest tested level of 30 krads. (There was a one biased device failure, which marginally exceeded specification for input offset current and power supply rejection ratio starting at 5 krads. This single anomalous failure may be due to latent ESD damage to the device input, though this was not verified since the failure was marginal.)

As shown in Fig. 8, all of the unbiased devices met specifications to 20 krads and failed marginally at 30 krads for both positive and negative I_B. In general, the device exhibited marginal bias effects with the change in I_B being roughly twice as large for the unbiased group as that of the biased group.

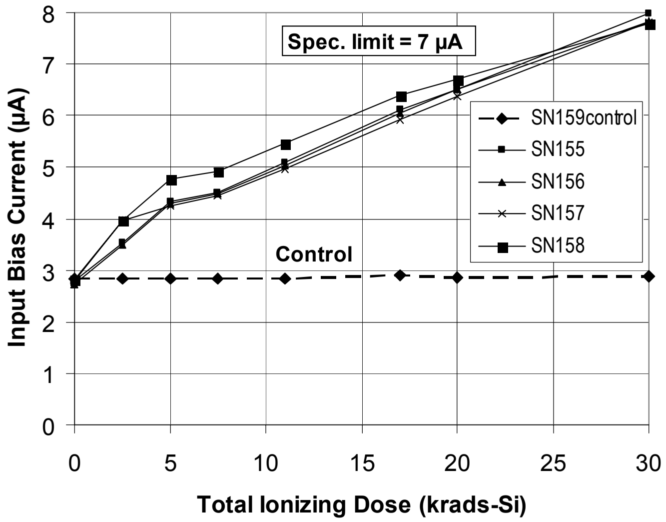

Fig. 8. Input Bias Current (@±15V) vs. Total Dose for the AD829 Irradiated in the Unbiased Condition at Low Dose Rate

K. ADC1175 A/D Converter (National)

This 8-bit analog-to-digital converter (ADC) is a CMOS part. It was tested biased at high dose rate and performed well up to 50 krads. Above that dose, its supply currents went out of specification, although it continued to function with degraded parameters up to 175 krads. (Fig. 9 shows the digital supply current.)

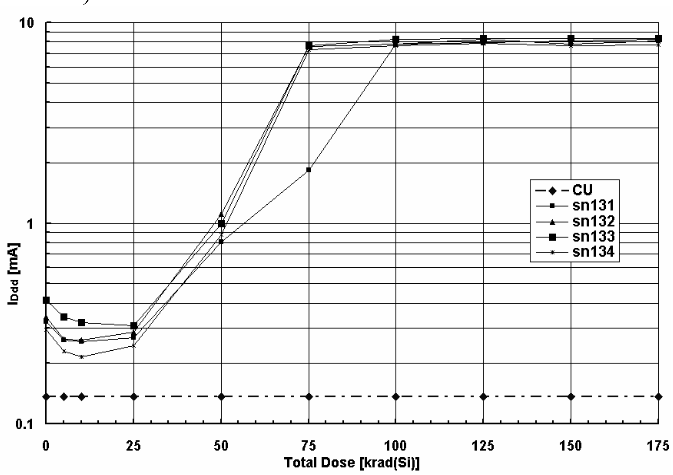

Fig. 9. Digital supply current (I_{Ddd}) for ADC1175 CMOS A/D Converter

L. AMA2805D, AMF2805D, ARH2803.3S, & ARH2805S DC-to-DC Converters (Advanced Analog/Lambda)

Four hybrid DC-to-DC converter part types made by Lambda/Advanced Analog Inc. (now owned by International Rectifier) were tested in 2001. Tested types included the AMA2805D and AMF2805D radiation-tolerant devices and the ARH2803.3 and ARH2805S radiation-hardened devices. Testing was performed at both high and intermediate dose rates of 25 and 0.05 rads/s, respectively. (The rad-hard types were only tested at high dose rate.) All parts met the manufacturer's respective radiation specifications for total ionizing dose, with the ARH2800 series working efficiently up to a tested level of 300 krads (high dose rate only), and the AMA2805D and AMF2805D failing at about 40 krads. (While the ARH-series parts are specified to work up to 500 krads, testing was not extended to that level.) While this exceeded the manufacturer's specification of 30 krads for the AMF2800 and AMA2800 family, it should be noted no unbiased parts were tested, and the dose rate tested was not low enough to meet the current standard for low dose rate (i.e., ≤10 mrads/s, and ideally 5 mrads/s).

At the lower (i.e., intermediate) dose rate, both rad-tolerant types survived to approximately 10 krads higher (44 and 47 krads for the AMA and AMF types, respectively) than their high dose rate failure points (33 and 40 krads). Thus, it cannot be concluded from this data whether these types are susceptible to ELDRS or not.

M. DG406 Multiplexer (Maxim)

Three samples of the Maxim DG406 multiplexer were exposed (biased) in a single step to a total dose 5 krads. All three failed functionally. The leakage current on channel 16 was over range (failed), and appeared to be stuck on. All other channels failed to turn on. (Channel 16 was in the on condition during irradiation.)

N. Emcore 8585-8323 VCSEL

The Emcore 8585-8323 Vertical Cavity Surface-Emitting Laser (VCSEL) with monitor photodiode were irradiated unbiased with 51-MeV protons. Four samples were tested. No significant degradation was observed (<2% fluctuation) for the laser up to a fluence of 3.28×10^{11} p/cm^2, for which the corresponding dose was 40 krads(GaAs). However, significant degradation of the monitor photodiode was observed. At a VCSEL forward current of 5 mA, the average loss in monitor diode responsivity was 4 percent after 5 krads (4.10×10^{10} p/cm^2). At 40 krads, the average loss was 10 percent. Fig. 10 shows data of a representative test sample.

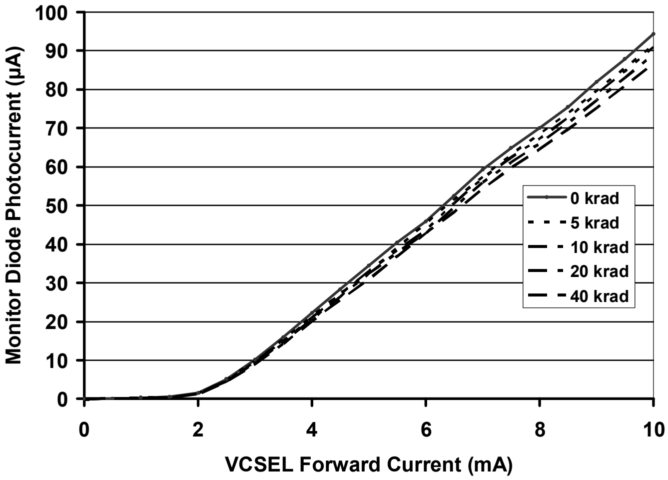

Fig. 10. Change in Emcore 8585-8323 VCSEL Monitor Diode Photocurrent vs. Total Dose from Protons

O. HFE4083-322 VCSEL (Honeywell)

The HFE4083-322 VCSEL with monitor photodiode made by Honeywell was irradiated unbiased with 51-MeV protons. No significant degradation was observed (<2% fluctuation) for the laser in the VCSEL up to the maximum tested fluence of 3.28 x 10^{11} p/cm^2 [40 krads(GaAs)]. However, degradation of the monitor photodiode was again observed. At a VCSEL forward current of 5 mA, the loss in monitor responsivity after 5 krads ranged from 24 to 29 percent among the five samples tested. After 40 krads, the average loss was 49 percent. Fig. 11 shows data from a representative test sample.

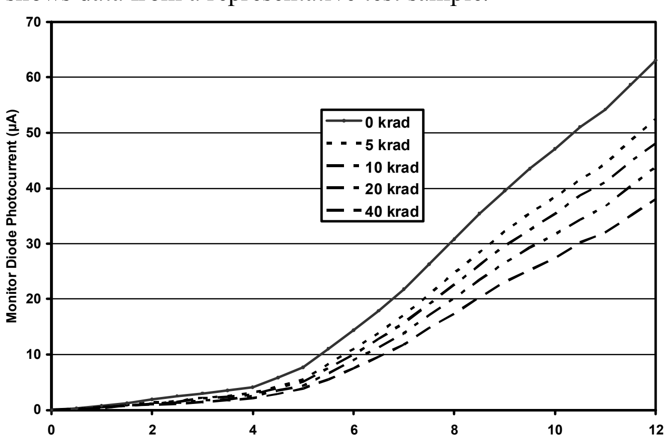

Fig. 11. Change in Honeywell HFE4083-322 VCSEL Monitor Diode Photocurrent vs. Total Dose from Protons

P. IRFMG40 Power MOSFET (International Rectifier)

This is a 1000-V, N-channel MOSFET. For an unhardened device, its total dose capability was respectable. Tests were performed at high, low, and room temperatures, with parts exposed in two bias modes: (1) gate at 5 V, drain at 0; and (2) drain at 800 V, gate at 0. (Extended temperature testing was only performed pre-rad and after 16 krads to minimize annealing.) Figs. 12, 13, and 14 show changes observed at differ-

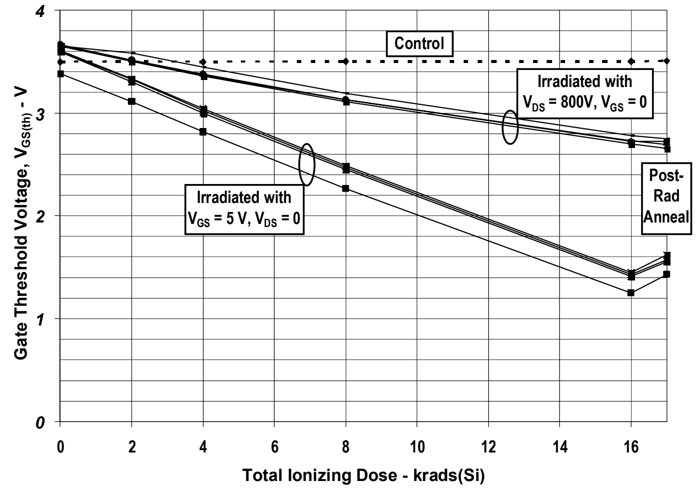

Fig. 12. Gate Threshold Voltage vs. Total Dose for the IRFMG40 MOSFET Irradiated in Various Bias Conditions (room temp.).

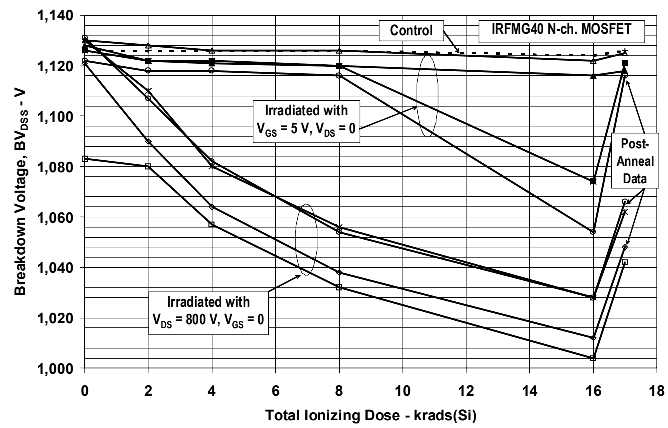

Fig. 13. Breakdown Voltage vs. Total Dose for the IRFMG40 MOSFET Irradiated in Various Bias Conditions (room temp.).

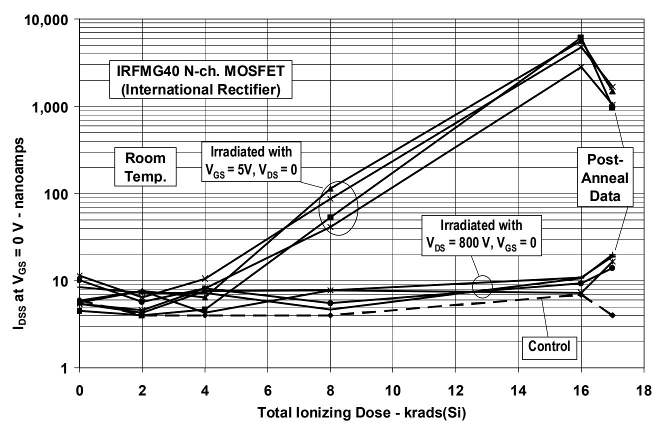

Fig. 14. Leakage Current vs. Total Dose for the IRFMG40 MOSFET Irradiated in Various Bias Conditions (room temp.)

ent exposure bias conditions for gate-threshold voltage, drain-source breakdown voltage, and drain-source leakage current, respectively.

The most marginal parameter (not shown) was breakdown voltage at -55°C, which just barely exceeded the 1000-V pre-rad specification. After 16 krads, this declined to ~930 V, but this should not be a problem for a properly derated part. Other parameters remained within specification or usable ranges throughout the testing up to the maximum of 16 krads.

Q. LF2802A RF Power MOSFET (M/A-Com)

This is an RF, N-channel, DMOS FET. It was tested in various bias modes: unbiased, and gate biased at 5 V or 20 V. The unbiased parts remained in specification up to 25 krads, but the gate-biased parts went out of specification for gate threshold voltage after 5 krads (Fig. 15). Changes in gate or drain-to-source leakage currents were negligible up through 50 krads.

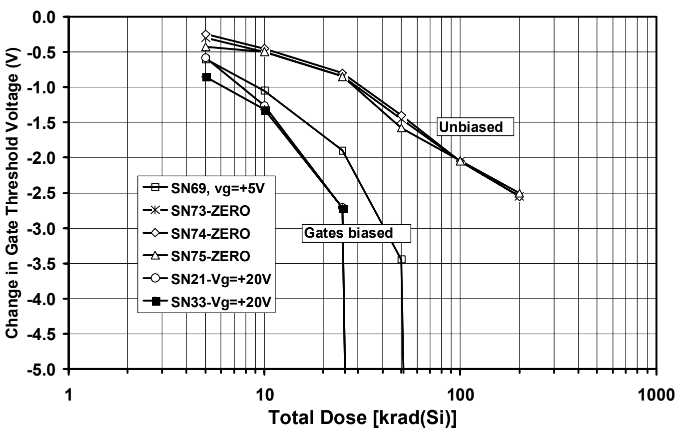

Fig. 15. Change in Gate-Threshold Voltage vs. Total Dose for the M/A-Com LF2802A RF MOSFET

R. LM124A Op Amp (National)

This bipolar IC is a quad, low-power, op amp that was built at National's Grenock, Scotland facility. It was tested at various bias modes and dose rates to characterize ELDRS behavior. As shown in Fig. 16, the input bias current (I_B) of both the biased and unbiased parts went out of specification (50 nA) at approximately 3 to 4 krads at low dose rate.

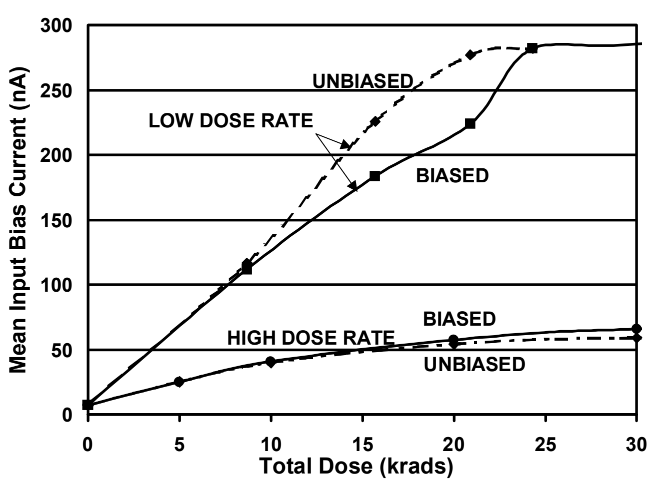

Fig. 16. Mean Input Bias Current for National LM124A Op Amp

At high dose rates, the offset voltage (V_{OS}) of both the biased and unbiased parts went out of specification (2 mV) at approximately 5 krads. However, with appropriate parametric derating, these parts can be used at levels up to 30 krads.

S. LT1006A Op Amp (Linear Technology)

This bipolar op amp was tested at both high and low dose rates (biased and unbiased samples exposed at 25 rads/s and 0.01 rads/s, respectively). The part performed functionally to greater than 10 krads(Si), although input bias current exceeded the manufacturer's specification at approximately 5 krads. Parametric performance was worst for the low-dose-rate groups at 5 and 10 krads. However, the biased, high-dose-rate group failed functionally 15 krads, while both of the low-dose-rate groups continued to function at 24 krads (the highest level tested). The part is considered acceptable for use up to 10 krads, depending on application parametric requirements. Both the biased and unbiased high-dose-rate groups met the manufacturer's specifications following 5 krads and had marginal parametric failures after 10 krads. However, as shown in Fig. 17, at 15 krads, V_{OS} increased significantly to greater than 600 µV (well above the specification of 180 µV), whereas other parameters, such as CMRR (common-mode rejection ratio), PSRR (power-supply rejection ratio), and A_{VOL} (open-loop voltage gain) failed marginally.

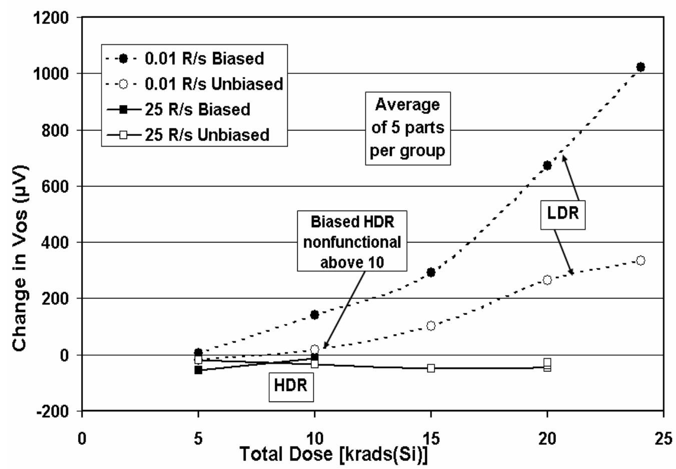

Fig. 17. Input Offset Voltage Degradation for LT1006A Op Amp

At 20 krads, the high-dose-rate groups failed functionally. Significant annealing was observed after 1 and 3 hours of biased annealing. Though neither of the low-dose-rate groups failed functionally to the highest level tested (24 krad), these groups exhibited enhanced parametric degradation in comparison to the high rate groups, with the input bias and offset currents marginally exceeding the specification at 5 krads. V_{OS} began failing the specification at 10 krads (Fig. 9), and other parameters exceeded the specification beginning at 15 krads. Fig. 18 shows the degradation of I_B.

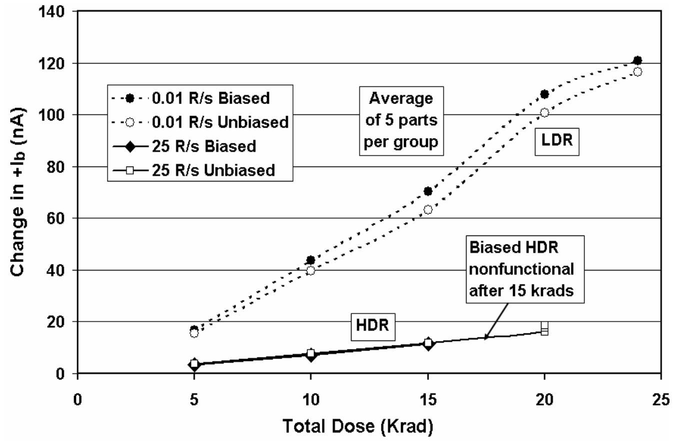

Fig. 18. Input Bias Current Degradation for LT1006A Op Amp

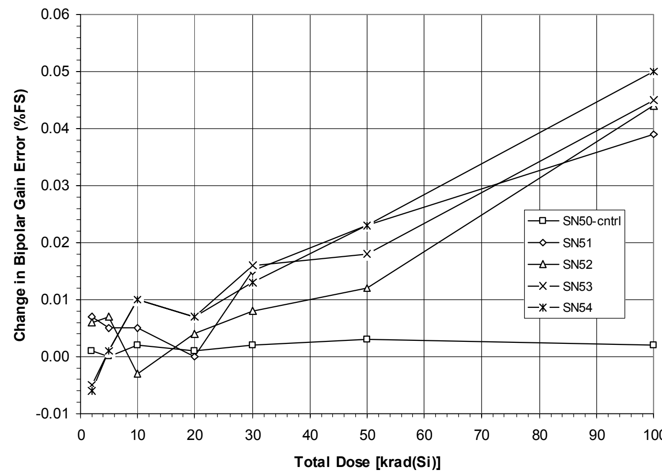

Fig. 20. Change in Bipolar Gain Error vs. Total Dose for the LTC1604.

T. LTC1157 MOSFET Driver (Linear Technology)

This part is a CMOS MOSFET driver. All test samples remained within manufacturer's specification to 2.5 krads(Si). Onset of parametric failure began at 3 krads, with a decrease in V_{gate} and a significant increase in I_{CCL} (not shown). (The minimum specification for V_{gate} is 7.5 V above supply, which for the 5.5-V test supply is 13.0 V.) Decrease in V_{gate} is probably due to degradation of the internal charge pump. Significant increases in supply currents above 3 krads are likely due to internal threshold voltage shifts. Statistical worst-case (lower 99/90 limit) for V_{gate} is shown in Fig. 19.

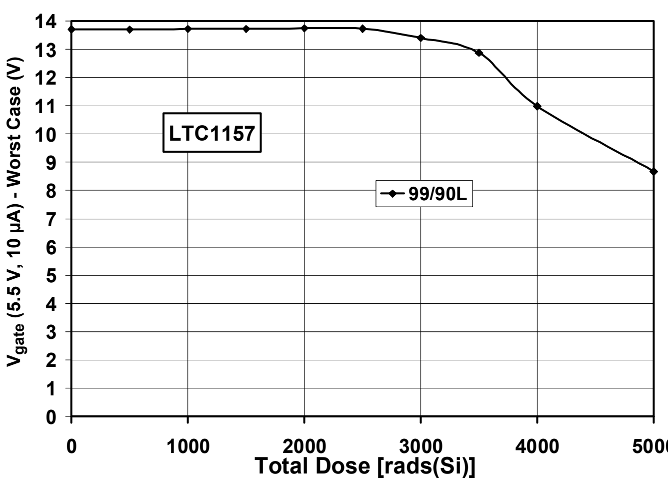

Fig. 19. V_{gate} Voltage Decrease for LTC1157 MOSFET Driver

U. LTC1604AIG A/D Converter (Linear Technology)

This is a CMOS, 16-bit, analog-to-digital converter. All device parameters remained within the manufacturer's pre-radiation specification for test levels up to 100 krads(Si) with the exception of bipolar gain error. This parameter fell only slightly out of manufacturer's specification at 100 krad for one sample. The remaining parameters were not affected. The behavior of bipolar gain error is shown in Fig. 20.

V. MAX306 Multiplexer (Maxim)

This 16-channel multiplexer (CMOS) was initially tested biased at high dose rate with address pins high. However, all three parts failed functionally at the first step of 1 krad. A second test was then performed at low dose rate and with address pins rolling dynamically (corresponding to application usage). As shown in Fig. 21, degradation started at 1.5 krads with $I_{D(on)}$ exceeding the 20-nA specification. It reached 300 nA at 3 krads, but the part continued to function up to 5 krads with $I_{D(on)}$ increasing to a microampere.

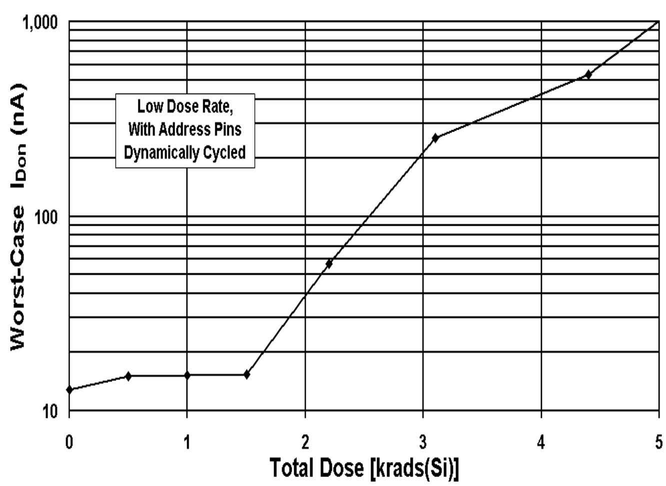

Fig. 21. I_{Don} Leakage Current for Maxim MAX306 Multiplexer

W. MAX539 D/A Converter (Maxim)

This 12-bit, CMOS DAC was tested biased at high dose rate, and while minor parametric degradations were noted, the devices performed within specifications up to 10 krads. Between 10 and 20 krads, severe degradations occurred for many parameters, such as linearity and supply currents.

X. OPA687 Wide-Band Op Amp (Burr Brown/Texas Inst.)

The OPA687 is a wide-band op amp made by Burr Brown (now part of Texas Instruments) that is built with a very high speed, complementary bipolar process. However, no schematic was available; therefore samples of this part were tested in both biased and unbiased conditions at low dose rate only (0.01 rads/s). The device exhibited no significant degradation for either bias condition up to the highest test level of 30 krads.

Y. PSS-QP50-6-SM Quadrant Photodiode (Pacific Silicon Sensor)

The PSS-QP50-6-SM quadrant photodiode is a large-area silicon type made by Pacific Silicon Sensor. It was irradiated unbiased with 51-MeV protons up to a maximum test fluence of 2.4×10^{11} p/cm^2 [40 krads(Si)]. Fig. 22 shows the average degradation for the samples tested. While the average output degraded approximately 50 percent at 15 krads, 20% of the degradation occurred after 1 krad(Si).

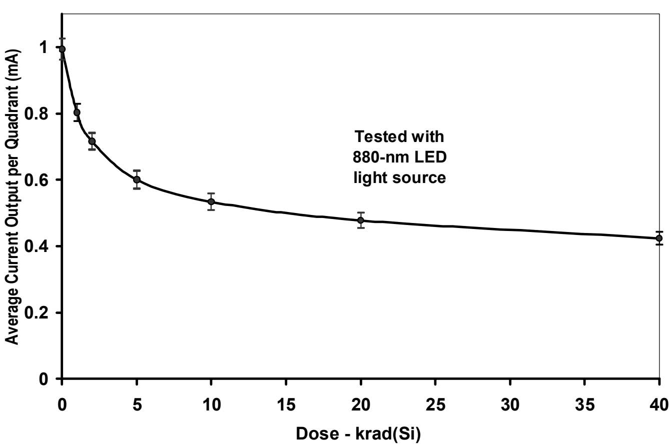

Fig. 22. Change in Output of PSS-QP50-6-SM Quadrant Photodiode vs. Total Dose from Protons.

Z. UC1717 Stepper Motor Driver (Texas Instruments)

This bipolar IC is made by the Unitrode division of Texas Instruments. Biased and unbiased samples were tested at low dose rate (0.01 rads/s). All devices remained within specifications up to 10 krads. At 16 krads and above, most devices had marginal failures in comparator threshold voltages for the 19% and 60% current conditions. All other parameters remained within specification to 30 krads (the highest level tested). Also, the output waveform for all devices was observed in an application circuit, but no significant changes were noted in the waveform to 30 krads for the biased case. However, waveforms for the unbiased case indicated that the chopper frequency was about doubled at 30 krads.

IV. Summary

This paper provides summary test results for most parts tested for total ionizing dose and proton damage at JPL over the past few years (although in many cases, the parts tested were often made several years earlier than the test dates). These data are only intended to be used as a guide for consideration in space applications with various radiation requirements. Since only average data is generally discussed in this summary, individual test reports should be reviewed for more detail. Also, since modern parts tend to evolve, "improve," or otherwise change processes frequently, radiation lot acceptance testing is highly recommended, especially when previously tested parts have older date codes.

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VI. Disclaimer

VII. References

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TABLE I. Summary of Recent TID/DD Test Results at the Jet Propulsion Laboratory

Part Type	Description	Tech.	Mfr.*	Date Code	Sample Size	Dose Rate (rad/s)	Bias During Exposure	Failure Parameter	Spec. Limit	Pre-Rad Value	Av. Dose/ Fluence to Parm. Failure	Av. Dose/ Fluence to Func. Failure	Comments
1N5665A	Zener Diode	Diode, Si	Microsemi	0039A	5	Protons	Unbiased	BV, I_L			>1.2E11 p/cm²		Very minor changes
2N2222A	NPN Transistor	Si, NPN	Semicoa	Chip	6	50 (HDR)	Vcb = 40	h_{FE} @ 0.1mA			30 krads	300 krads	Usable with derating >60K
2N2484	NPN Transistor	Si, NPN	Motorola	9201	3	~50 (HDR)	Vcb = 48	h_{FE}			>100 krads	>200 krads	Good to 100 krads
2N2857A	NPN Transistor	Si, NPN	Semicoa	Chip	6	50 (HDR)	Vcb = 15	h_{FE}	50 @ 6 V & 2 mA	57	200 krads		
2N2907A	PNP Transistor	Si, PNP	Semicoa	Chip	6	50 (HDR)	Vcb = 45	h_{FE} @ 0.1mA			60 krads	300 krads	Usable with derating @ 100K
2N3637UB	PNP Transistor	Si, PNP	Semicoa	0022	10	25 (HDR)	Vcb = -80, Vbe = +2	h_{FE}	55 @ Ic = 0.1 mA	155	60 krads		
2N3700UB	NPN Transistor	Si, NPN	Semicoa	J392	11	25 (HDR)	Vcb = +80, Vbe = -2	h_{FE}	50 @ Ic = 0.1 mA	65	20 krads		
4N49, JANTXV	Optocoupler	GaAs LED, Si photo-transistor	Micropac	9810, 9838	5	Protons	Unbiased	CTR	0.47		2.5E10 p/cm²		
AD768AR	D/A Converter, 16-bit	BiCMOS	An. Dev.	9805, 9746	4	25 (HDR)	Biased	Vref,			50-100 krads	300-500 krads	BiCMOS part; not tested for ELDRS nor unbiased
AD829SE (5962-9312901M2A)	Op amp, video	Bipolar, DI	An. Dev.	0005	5 & 4	0.01 (LDR)	5 Biased, 4 Unbiased	I_B	7 µA	3 µA	~23 krads		Usable to >30 krads, if larger bias currents tolerable.
ADC1175	A/D Conv., 8-bit	CMOS	National	--	4	50 (HDR)	Biased	I_{Add}, I_{Ddd}			50 krads	>175 krads	
AMA2805D	DC/DC converter	Hybrid	Advanced Analog	127	1	25 (HDR)	Biased	Functional				33 krads	
AMA2805D	DC/DC converter	Hybrid	Advanced Analog	127	1	0.05 (LDR)	Biased	Functional				44 krads	
AMF2805D	DC/DC converter	Hybrid	Advanced Analog	124	1	25 (HDR)	Biased	Functional				40 krads	
AMF2805D	DC/DC converter	Hybrid	Advanced Analog	124	1	0.05 (LDR)	Biased	Functional				47 krads	
ARH2803.3S	DC/DC converter	Hybrid	Advanced Analog	129	2	25 (HDR)	Biased	Functional				>300 krads	
ARH2805S	DC/DC converter	Hybrid	Advanced Analog	129	3	25 (HDR)	Biased	Functional				>300 krads	
DG406	Multiplexer, 16-channel	CMOS	Maxim	9918	3	? (HDR)	Biased, static	Functional	--	--	--	<5 krads	
Emcore 8585-8323	VCSEL with monitor diode	GaAs	Emcore		4	Protons	Unbiased	Monitor diode responsivity		90 µA	>3.28E11 p/cm² [>40 krads (GaAs)]		Laser output unchanged up to 40 krads(GaAs). However, monitor diode responsivity degraded 4% @ 5 krads, & 10% @ 40 krads.
HFE4083-322	VCSEL with monitor diode	GaAs	Honey-well		5	Protons	Unbiased	Monitor diode responsivity		63 µA	~3.28E11 p/cm² [~40 krads (GaAs)]		Laser output unchanged up to 40 krads(GaAs). However, monitor diode responsivity degraded ~27% @ 5 krads, & ~50% @ 40 krads.

TABLE I. SUMMARY OF RECENT TID/DD TEST RESULTS AT THE JET PROPULSION LABORATORY (CONT'D.)

Part Type	Description	Tech.	Mfr.*	Date Code	Sam-ple Size	Dose Rate (rad/s)	Bias During Exposure	Failure Parameter	Spec. Limit	Pre-Rad Value	Av. Dose/ Fluence to Parm. Failure	Av. Dose/ Fluence to Func. Failure	Comments
IRFMG40	MOSFET, 1000V	N-channel	Int. Rect.	0032	8	25 (HDR)	Gate or drain biased	BVds, I_{DSS}, & $V_{G(th)}$	various		~14 krads	>16 krads	Usable to ~16 krads with some parameter derating @ high/low temperatures
LF2802A	MOSFET, RF	N-channel	M/A-Com	01F15	6	50 (HDR)	Various biases	$V_{G(th)}$	various		5 krads	5-10 krads	Usable to >5 krads with $V_{G(th)}$ derating
LM124A	Op amp, quad	Bipolar	National	HODO110 B	3	50 (HDR)	Biased	V_{OS}	2 mV		5 krads	>30 krads	Scotland foundry
LM124A	Op amp, quad	Bipolar	National	HODO110 B	3	50 (HDR)	Unbiased	V_{OS}	2 mV		5 krads	>30 krads	Scotland foundry
LM124A	Op amp, quad	Bipolar	National	HODO110 B	3	0.01 (LDR)	Biased	I_{B+}	50 nA		3-4 krads	>30 krads	Scotland foundry
LM124A	Op amp, quad	Bipolar	National	HODO110 B	3	0.01 (LDR)	Unbiased	I_{B+}	50 nA		3-4 krads	>30 krads	Scotland foundry
LT1006A	Op Amp	Bipolar	Lin. Tech.	9626A	5 per group	HDR & LDR	Biased & Unbiased	V_{OS}	180 µV	<50 µV	12 krads (LDR, biased)	10-15 krads (HDR, biased)	Generally OK to 10 krads; RLAT recommended
LTC1157CS8	MOSFET driver	CMOS	Lin. Tech.	819	5	25 (HDR)	Biased	Voh, Iccl	--	--	3 krads		OK to 2.5 krads
LTC1604AIG	A/D converter, 16-bit	CMOS	Lin. Tech.		4	25 (HDR)	Biased	Bipolar Gain Error					Bipolar gain error slightly out of specification at 100 krads
MAX306EWI	Multiplexer, 16-channel	CMOS	Maxim	0143	3	25 (HDR)	Biased	Functional	--	--	--	<1 krad	Address lines high
MAX306EWI	Multiplexer, 16-channel	CMOS	Maxim	0143	4	0.01 (LDR)	Biased (see comment)	ID(on)	300 nA	20 nA	3 krads	5 krads	Address lines cycled continuously
MAX539	D/A Converter, 12-bit	CMOS	Maxim	GF008	4	25 (HDR)	Biased, clocked	Linearity, supply currents			>10 krads	<20 krads	Minor parametric changes within spec. at 10 krads
OPA687N	Op Amp, wide-band	Bipolar, very high speed, com-plementary	Tex. Instr. (Burr Brown)	0231	5 per group	0.01 (LDR)	Biased & Unbiased	No significant changes after 30 krads	'--		>30 krads	>30 krads	
PSS-QP50-6-SM	Quadrant photo-diode (Si)	Si diode	Pacific Silicon Sensor	0123	8	Protons	Unbiased	Responsivity		1 mA	2.4E11 p/cm² [~40 krads(Si)]		Responsivity degraded ~20% @ 1 krad, & ~50% @ 15 krads.
UC1717J (5962-9474601MEA)	Stepper-motor driver	Bipolar IC	Tex. Instr. (Unitrode)	0144A	5 & 4	0.01 (LDR)	5 Biased, 4 Unbiased	Comparator threshold voltage	--	--	--	~16 krads	

* Note: Where a second name is given in parentheses, it is a previous name due to merger, acquisition, sale, spin-off, etc.