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ABSTRACT

The total ionizing dose response of fourteen IC types from eight manufacturers has been measured using Co-60 gamma rays and 2.2-MeV electrons for exposure levels of 100 to 20,000 Gy(Si). Key parameter measurements were made and compared for each device type. The data show that a Co-60 source may not be a suitable simulation source for some systems because of the generally more damaging nature of electrons as well as the unpredictable nature of the individual device response to the two types of radiations used here.

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I. INTRODUCTION

Comparisons of the total ionizing dose (TID)[1] responses of fourteen linear IC types of various functions and technologies have been made using the Jet Propulsion Laboratory (JPL) and Boeing Radiation Effects Laboratory (BREL) cobalt-60 gamma ray sources and Dynamitron electron accelerators. The cobalt-60 sources provide 1.33- and 1.17-MeV gamma rays with a component of low-energy secondary electrons; the Dynamitrons provide a continuous 2.2-MeV electron beam at the IC chip.

It is well known that gamma rays produce radiation damage via the creation of Compton electrons, which cause charge deposition at the oxide-semiconductor interface and the nearby oxide layer. Electrons also generate ionizing electrons, but those electrons with energies greater than a few tenths of an MeV have the capability of inducing substantial permanent damage via displacement of the lattice atoms.

The work to be presented in this paper will help to define the conditions for which the permanent damage from electrons becomes significant for selected MSI ICs. It is anticipated that this body of data will alert future system designers to the need to consider carefully the adequacy of cobalt-60 tests for simulating trapped electron charge in Earth and Jovian radiation belts as well as nuclear radiation environments. In particular, it was a goal of this effort to establish whether there exists a low-dose environment where electron-induced bulk damage was not significant in comparison to the surface damage effects introduced by both types of radiation.

II. BACKGROUND

An extensive characterization of transistors and integrated circuits to total ionizing dose has been conducted by JPL (see Reference 1) for Project Galileo in order to qualify parts for the relatively high-energy electron radiation environment surrounding Jupiter. Some forty-five types of bipolar transistors (with up to a dozen lots per device type) and fifty-seven ICs were included among the data. During the course of this testing, it was found that the electron radiation response of some ICs could not be accurately simulated by using cobalt-60 gamma rays. However, most transistors showed no difference in response to gammas or to 2.2-MeV electrons at equal radiation dose. Since cobalt-60 tests are more convenient, it is necessary to establish what conditions permit the use of cobalt-60 gamma rays to simulate the space electron environment for both transistors (see Reference 2) and integrated circuits.

[1]Definitions of abbreviations used in this paper may be found following the References list.

III. EXPERIMENTAL PROCEDURE

A. RADIATION SOURCES, DOSIMETRY, AND DOSE ENHANCEMENT

1. Dynamitron

The Dynamitron accelerators at both JPL and BREL provide a 2.5-MeV electron beam with beam currents ranging from 10^8 to 10^{10} electrons/cm^2/s. All tests described here were irradiated at each fluence level for exposure times between 5 and 20 minutes. The electron beam is brought out of the beam tube through a 0.05-mm titanium window, copper and aluminum scattering foils, and 0.9 m of air. After passage through all materials, including device lids, the energy of the electrons is degraded to 2.2 MeV at the chip. The beam has a uniformity of $\pm 10\%$ over the array of parts under test, which are confined within a 25-cm-diameter circle perpendicular to the direction of the beam. The beam is centered on a Faraday cup with a bending magnet prior to emplacement of the test samples, and the output from the Faraday cup is fed into a current integrator, which is calibrated against a standardized current source. The integrator is set to shut off the electron beam automatically when the desired fluence level is achieved.

2. Cobalt-60 Source

The cobalt-60 gamma ray source consists primarily of 1.17- and 1.33-MeV photons and secondary electrons arising from scattering and absorption. The gamma field is uniform within $\pm 10\%$ in the area where parts are exposed. Thermoluminescent dosimetry (TLD), using lithium fluoride/Teflon microrods, was used for uniformity checks. Calibration of the main source was performed with Landswerk ion chambers of $\pm 2\%$ accuracy, traceable to the National Bureau of Standards. Bimonthly dose rate computations were performed to account for the source decay. Exposure times were typically 5 to 20 minutes for each radiation level; maximum dose levels required 143 minutes at a dose rate of 70 Gy(Si)/min.

3. Dose Enhancement

No correction factors for possible dose enhancement effects have been applied to this data. Dose enhancement effects result from Hi-Z metallic overlays on the chip, or from Hi-Z materials in the package. In this series of tests, there were no known Hi-Z materials on or in the packages tested.

B. EXPERIMENTAL TEST

The seven functional groups of ICs shown in Table 1 were selected for test with a minimum of five devices, but usually ten devices were irradiated with Co-60 gamma rays and 2.2-MeV electrons. All lot samples of a given device type came from the same date code. All devices were irradiated to at least six different radiation levels ranging from

Table 1. Devices Tested

Function Group	Device Type	Package	Test Facility	Manufacturer
Op-amp (rad-hard)	LM101-RH	Can	JPL	NSC
	LM108-RH	Can	JPL	AMD, NSC, PMI
Op-amp (std. process)	LM101	Can	JPL	NSC
	LM108	Can	JPL	FSC, MOT, NSC
	OP21	Can	JPL	PMI
FET input op-amp	LF155	Can	JPL	MOT
	LF156	Can	JPL	NSC
	OP15	Can	JPL	PMI
	OPA100	Can	JPL	BUB
Low-power op-amp	HA5141	Can	JPL	HAR
Quad comparator	L161	DIP	BREL	SIL
	LM139	DIP	BREL	AMD, FSC, MOT, NSC, PMI
FET input switch-DPST(2)	DG154	DIP	JPL	SIL
FET input sample and hold	LF198	Can	BREL	AMD

100 Gy(Si)[2] to 20 kGy(Si). At each radiation level, measurements of key radiation sensitive parameters were taken.

The test set-up procedures were developed in accordance with the specifications of MIL-STD-883B (August 1977), method 1019.1. All tests were done at 25 ± 3°C, using low-noise power sources. Some tests were performed in situ, whereas others required remote testing.

For the in-situ tests, a matrix board switching system located outside of the irradiation chamber was used as a master control panel. The board interfaces up to six devices under test (DUT) to the power supplies and measurement equipment via a special fifteen-meter, double-shielded cable (see Figure 1). The matrix board was designed with very high insulation resistance so that very low current measurements (10-50 pA) could be made.

For the non-in-situ tests, the DUTs were removed from the site for approximately 20 minutes between each radiation level. A mobile

[2] The gray (Gy) is the new international standard for expressing radiation flux and fluence; 1 Gy(Si) = 100 rad (Si).

bias (battery) was applied to the device at all times except during parameter measurements taken with Tektronix 577/178 IC tester or a specialized tester.

Most devices were irradiated to six different radiation levels [750, 1500, 3000, 6000, 10,000, and 20,000 Gy(Si)] in each of the two sources, but a few device types were exposed to a lower series of dose levels. At each radiation level, parametric measurements were made under typical operating conditions.

A computer was used to process the data, and to calculate the mean, maximum, and minimum Δs. These data and the individual test procedures are on file at JPL.

IV. DISCUSSION OF RESULTS

The test results are divided into four main groupings of devices: (1) operational amplifiers, (2) comparators, (3) switch, and (4) sample and hold. The largest group was the operational amplifiers with ten different types of devices tested.

Devices which were known or expected to be rad-hard were irradiated to 750, 1500, 3000, 6000, 10,000, and 20,000 Gy(Si), while devices unknown or expected to be soft were irradiated to 100, 200, 300, 500, 750, 1500, 3000, and 6000 Gy(Si). When a device failed a measurement point, an asterisk (*) has been placed in Table 2 at the preceding measurement point. Failures may or may not be catastrophic. If a device parameter greatly exceeds its normal operating range, it may be considered a failure. For example: op-amp V_{OS} would be considered a failure above 125 mV and A_{VOL} would be considered a failure when the device can no longer drive its full output voltage into its normal test load.

It has been noted in previous research projects (see References 3 and 4) that the radiation effects on each transistor element in an IC chip are not the same and may vary by a factor of ten times or more. Therefore, large peaks or roll-offs that occur indicate there has been a major operational change taking place within the IC under test. Compensation networks, current sources, balanced networks, etc., have reached a maximum of their operating range and have saturated or cut off. Operating a device in this mode can be very dangerous, if not catastrophic to the system in which it has been placed. Many times this peak or roll-off can be seen in several parameters around the same total dose level. In some cases it has been noted that this peak or roll-off will be at different total dose levels depending on the irradiation source. In a few cases the peak may go positive when irradiated on one source and may go negative when irradiated with the other source. It is important that characterization tests for devices be conducted over a wide total dose range below and above the level of interest with the correct radiation source so that any anomalies in degradation may be noted. Device parameter failures usually appear in the electron irradiated devices one or two test levels before they appear in the Co-60 gamma ray irradiated devices (see Reference 5).

Table 2. Test Parameters and Irradiation Doses kGy(Si)

	ΔV_{OS} (mV)		ΔI_{OS} (nA)		ΔI_B (nA)		$\Delta A_{VOL}(+)$ (dB)		$\Delta A_{VOL}(-)$ (dB)	
Op-Amps	Elec	Co-60	Elec	Co-60	Elec	Co-60	Elec	Co-60	Elec	Co-60
LM101 Op-Amps										
NSC LM101	6	6	6	6	6	6	6	6	6	6
NSC LM101-RH	20	20	20	20	20	20	20	20	20	20
LM108 Op-Amps										
AMD LM108	20	20	20	20	20	20	20	20	6*	10*
FSC LM108	3*	6	3*	6	3*	6	1.5*	3*	1.5*	3*
MOT LM108	0.75*	1.5*	0.75*	0.75*	3*	3*	6	6	6	6
NSC (916) LM108	0.5*	0.75*	0.5*	0.75*	0.5*	0.75*	0.5*	1.5*	0.5*	1.5*
NSC (008) LM108	0.5*	0.75*	0.5*	0.75*	0.5*	0.75*	0.5*	0.75*	0.5*	0.75*
NSC LM108-RH	20	20	20	20	20	20	20	20	20	20
PMI (8224) LM108	20	20	20	20	20	20	20	20	20	20
PMI (E9774) LM108	20	20	20	20	20	20	6*	20	6*	20
FET Op-Amps										
NSC LF156	0.75*	3*	0.75*	3*	0.75*	3*	3*	6	3*	6
MOT LF155	6	6	6	6	6	6	6	6	6	6
BUB OPA100	20	20	20	20	20	20	20	20	20	20
PMI OP15(8150)	20	20	20	20	20	20	20	20	20	20
PMI OP15(8229)	20	20	20	20	20	20	20	20	20	20
Low-Power Op-Amp										
HARRIS HA5141A	6	3*	6	3*	6	3*	0.5*	1.5*	1.5*	3*

	ΔV_{OS} (mV)		ΔI_{OS} (nA)		ΔI_B (nA)		ΔI_{SK} (mA)	
Quad Comparators	Elec	Co-60	Elec	Co-60	Elec	Co-60	Elec	Co-60
MOT LM139	3*	20	3*	20	3*	20	3*	20
AMD LM139	20	20	20	20	20	20	20	20
NSC LM139	1.5*	3*	1.5*	3*	1.5*	3*	1.5*	3*
FSC LM139	1.5*	1.5*	1.5*	1.5*	1.5*	1.5*	1.5*	1.5*
PMI LM139	20	10*	1.5*	1.5*	3*	6*	3*	6*
SIL L161	0.75*	0.75*	0.75*	0.75*	0.75*	1.5*	0.75*	1.5*

FET Input Switch DPST(2)		I_D (nA)		I_S (nA)		$I_D + I_S$ (nA)		R_{DS} (ohms)	
		Elec	Co-60	Elec	Co-60	Elec	Co-60	Elec	Co-60
SIL DG154	ON	20	20	20	20	20	20	20	20
	OFF	20	20	20	20	20	20	20	20

	ΔV_{OS} (mV)		ΔI_B (nA)		ΔI_{SK} (mA)		ΔI_{SC} (mA)		$\Delta I_{CHG}(+)$ (mA)		$\Delta I_{CHG}(-)$ (mA)	
FET Input Sample & Hold	Elec	Co-60	Elec	Co-60	Elec	Co-60	Elec	Co-60	Elec	Co-60	Elec	CO-60
AMD LF198	10	10	10	10	10	10	10	10	10	10	10	10

* = Failure at next higher dose level.

Table 2 lists each device type tested by parameter and irradiation dose.

Figures 2 through 35 illustrate parametric degradation vs dose and source. They indicate the curves typical in this study.

Specific studies of postirradiation effects (PIE) were not made during this study, but it has been observed that devices with soft oxides indicate changes in PIE over the long term (minutes) more rapidly than those with hard oxides. It has also been seen that devices which are irradiated with Co-60 indicate changes in PIE more rapidly than those that have been irradiated with electrons. Because the radiation effects are not the same on each transistor element across the IC chip, the PIE are not the same, and some areas of the circuit will change faster than others. This may cause "reverses in the PIE" as well as other anomalous PIE effects.

A. OPERATIONAL AMPLIFIERS

There are five subgroups under Operational Amplifiers. They are LM101, LM108, OP21, FET input op-amps, and low-power op-amps.

1. LM101

There were two types of LM101 tested for this program, both manufactured by NSC. They are the standard process device and the radiation hard device (LM101-RH) developed for projects Voyager and Galileo.

a. ΔV_{OS} (Figure 2). The standard process devices, when electron irradiated, degrade very rapidly above 500 Gy(Si) while those Co-60 irradiated indicate little change. The rad-hard devices indicate little change to 3000 Gy(Si) where both test lots increase degradation. The electron irradiated devices degraded much more rapidly than the Co-60 irradiated devices.

b. ΔI_{OS} (Figure 3). The standard process devices indicate rapid degradation from electrons above 750 Gy(Si) while Co-60 irradiation causes a much slower degradation. The rad-hard process devices indicate small changes until 3000 Gy(Si) where the electron irradiated devices increase in current more rapidly than the Co-60 irradiated devices.

c. ΔI_B (Figure 4). Both device types indicate that electron irradiation increases the bias current about twice as fast as Co-60 irradiation.

d. ΔA_{VOL} (+) (Figure 5). Prior to degradation of those devices irradiated with electrons, devices irradiated with Co-60 indicated an initial increase in gain before degrading about three levels of magnitude. The standard process devices peak at a much higher (approximately 10 dB) level than the rad-hard devices. After their peak, all devices degrade very rapidly with the Co-60 irradiated devices degrading most rapidly. Large differences between devices irradiated with the two sources were measured at most test levels.

e. ΔA_{VOL} (-) (Figure 6). Devices irradiated with electrons peak and degrade sooner than when irradiated with Co-60. Large positive peaks were seen on both device types and with both sources. Large differences between devices irradiated with the two sources were measured at most test levels. Electron irradiated devices degraded more rapidly than those irradiated with Co-60.

2. LM108

The LM108 operational amplifier is a very popular device for space applications. Several companies make devices that are radiation hard to at least 1 Mrad(Si). Both standard process and special process devices were tested. A total of eight lots of devices were compared for this subgroup.

Two different date code lots were tested from NSC and PMI. The process differences between lots are very apparent. The NSC devices have very similar characteristics for V_{OS}, I_{OS}, and I_B, but have variations for A_{VOL} (+) and (-), while the PMI devices indicate large variations on all parameters, for all levels on both irradiation sources.

a. ΔV_{OS} (Figure 7).

AMD. Devices irradiated with Co-60 indicated very little change with dose while the devices irradiated with electrons indicated a small increase after 750 Gy(Si), then remained fairly constant for the rest of the test. The greatest degradation was caused by electrons.

FSC. There were large differences between sources to 750 Gy(Si). Devices irradiated with the electrons failed above 3000 Gy(Si).

MOT. Differences in radiation effects were first indicated at 200 Gy(Si). Electron irradiated devices failed above 750 Gy(Si) while Co-60 irradiated devices failed after 1500 Gy(Si).

NSC (d/c 916). Electron irradiated devices increased in V_{OS} rapidly after 300 Gy(Si) and failed after 500 Gy(Si). Co-60 irradiated devices did not start to degrade rapidly until 500 Gy(Si) and failed after 750 Gy(Si).

NSC(d/c 008). Same as NSC (d/c 916).

NSC-RH. Co-60 irradiated devices indicate little change in degradation while electron devices indicate an increase by 1500 Gy(Si); degradation continued to the maximum test level.

PMI (d/c 8224). Devices irradiated with Co-60 indicate little change in value until the 3000-Gy(Si) test level, then increase rapidly. The devices irradiated with electrons indicate initial change and continue to increase in degradation. The electron irradiated devices degrade more than the Co-60 irradiated devices.

PMI (d/c 9774). There is little difference in the degradation from the two sources except at the 6000-Gy(Si) measurement point where the Co-60 irradiated devices indicate approximately 50% more degradation. These devices reacted very differently than the 8224 date code devices.

b. ΔI_{OS} (Figure 8). The rad-hard devices indicate small changes up to 1500 Gy(Si). Overall changes are greater for electron irradiated devices than for devices that were irradiated with Co-60. Standard process devices indicate changes at much lower levels. The two NSC lots are very similar while the two PMI lots are very different in characteristics.

c. ΔI_B (Figure 9).

AMD. The AMD devices are ultralinear with little difference between sources below 6000 Gy(Si). The worst-case degradation was noted in devices irradiated with the Co-60.

FSC. Rapid degradation was indicated by both test lots. Electron irradiated devices peaked at 750 Gy(Si) and failed after 3000 Gy(Si) while Co-60 irradiated devices peaked at 3000 Gy(Si).

MOT. Rapid degradation was indicated by both test lots. Electron irradiated devices peaked at 500 Gy(Si) while the Co-60 irradiated devices peaked at 1500 Gy(Si). Both lots failed at 3000 Gy(Si).

NSC (d/c 916). Devices irradiated with electrons degrade much more rapidly than those irradiated with Co-60. The electron irradiated devices failed above 500 Gy(Si) while the Co-60 irradiated devices failed above 750 Gy(Si).

NSC (d/c 008). Same as NSC (d/c 916).

NSC-RH. Large changes between lots were noted between 750 and 3000 Gy(Si). Above 3000 Gy(Si) there was little difference between lots. Electron irradiated devices indicated the greatest change.

PMI (d/c 8224). Initially, the Co-60 irradiated devices indicated large shifts in bias current from 750 to 3000 Gy(Si). Above 6000 Gy(Si) the electron irradiated devices increased degradation more rapidly than the other lot of devices.

PMI (d/c E9774). These lots of devices indicate a greater degradation in electron irradiated devices than Co-60 irradiated devices until the total dose exceeded 10,000 Gy(Si). These devices reacted very differently than the 8224 date code devices.

d. ΔA_{VOL} (+) (Figure 10).

AMD. These devices indicated increased degradation when irradiated with Co-60.

FSC. The FSC devices failed above 1500 Gy(Si) when electron irradiated and above 3000 Gy(Si) when Co-60 irradiated.

MOT. The MOT devices which were electron irradiated indicated the greatest degradation.

NSC (d/c 916). The NSC (d/c 916) devices irradiated with electrons failed above 500 Gy(Si) while those irradiated with Co-60 peaked from 200 to 500 Gy(Si) before degrading and failing after 1500 Gy(Si).

NSC (d/c 008). The NSC (d/c 008) devices indicated little difference between sources except that the electron irradiated devices failed above 500 Gy(Si) while the Co-60 irradiated devices failed above 750 Gy(Si).

NSC-RH. The rad-hard process devices from NSC indicate very little difference between sources at 750 Gy(Si), but the electron irradiated devices degrade much more rapidly than the Co-60 irradiated devices above that level.

PMI (d/c 8224). Initially, there was a large difference with the electron irradiated devices increasing in gain and slowly rolling off to 3000 Gy(Si) before decreasing in gain, whereas the Co-60 irradiated devices slowly rolled off in gain. At 10,000 Gy(Si) both lots of devices are nearly the same.

PMI (d/c E9774). These devices react nearly identically to either source, except that the devices irradiated with electrons failed above 6000 Gy(Si). Degradation was greatest above 1500 Gy(Si) for the devices irradiated with the Co-60 source.

e. ΔA_{VOL} (-) (Figure 11).

AMD. These devices indicated increased degradation of the devices irradiated with Co-60. The electron irradiated devices failed above 6000 Gy(Si) and the Co-60 irradiated devices failed above 10,000 Gy(Si).

FSC. The FSC devices failed above 1500 Gy(Si) when electron irradiated, and above 3000 Gy(Si) when Co-60 irradiated.

MOT. The MOT devices, which were electron irradiated, indicated the greatest degradation.

NSC (d/c 916). The NSC (d/c 916) devices irradiated with electrons failed above 500 Gy(Si) while those irradiated with Co-60 failed after 1500 Gy(Si).

NSC (d/c 008). The NSC (d/c 008) devices indicated little difference between sources except that the electron irradiation devices failed above 500 Gy(Si) while the Co-60 irradiated devices failed above 750 Gy(Si).

NSC-RH. The electron irradiated devices degrade much more rapidly than the Co-60 irradiated devices.

PMI (d/c 8224). The lot of devices which was Co-60 irradiated indicated a sharp positive peak in gain at 6000 Gy(Si), then rapidly decreased. The lot of devices which was electron irradiated indicated a small peak at 3000 Gy(Si), then decreased.

PMI (d/c E9774). The devices irradiated with electrons failed after 1500 Gy(Si) while the devices that were Co-60 irradiated degraded very rapidly to 3000 Gy(Si), then indicated little additional change.

3. OP-21

Test results for the OP-21 by PMI are not presented herein because it is felt that the test results may be invalid. The electron portion of the test indicated typical op-amp results except for the fact that the A_{VOL} (+) test failed above 75 Gy(Si), while the A_{VOL} (-) test indicated no failures to the maximum test level of 6000 Gy(Si). The devices, which had been irradiated with the Co-60 source, failed above 100 Gy(Si) for V_{OS}, I_{OS}, and I_B. A_{VOL} (+) and (-) failed above 750 Gy(Si).

Although the OP-21 has been recently redesigned using an excessive number of lateral PNP transistors, and, therefore, should be very sensitive to surface effects, it is felt that confirmation of the test results is required. Follow-on tests of this device are planned for the near future.

4. FET Input Operational Amplifier

The four device types selected for this subgroup are similar in manufacture specifications, but are not identical, so large variations in parameter values can be expected. Two different date code lots of the PMI OP-15 were tested to look for lot-to-lot variations, and variations were found.

a. ΔV_{OS} (Figure 12).

BUB OPA-100. There is very little difference indicated between sources until 6000 Gy(Si), then the electron irradiated devices rapidly increase in degradation.

MOT LF155. There is little change in the V_{OS} until 500 Gy(Si). The electron irradiated devices indicated little overall change while the Co-60 irradiated devices first indicated a sharp peak at 1500 Gy(Si), then indicated an improvement in the parameter.

NSC LF156. The electron irradiated devices failed above 750 Gy(Si) while the Co-60 irradiated devices indicated a very rapid increase in V_{OS} above 1500 Gy(Si) and failure above 3000 Gy(Si).

PMI OP-15 (d/c 8150). The Co-60 irradiated devices indicated almost no change while the electron irradiated devices showed a large change above 1500 Gy(Si).

PMI OP-15 (d/c 8229). These devices indicated little change to 6000 Gy(Si). Above that the Co-60 irradiated devices degrade more rapidly.

b. ΔI_{OS} (Figure 13).

BUB OPA-100. These devices tracked very closely until the 20,000 Gy(Si) when the electron irradiated devices indicated an increased degradation.

MOT LF155. Little change was observed with the devices that were Co-60 irradiated. The electron irradiated devices indicated a sharp peak at 600 Gy(Si), then a rapid drop.

NSC LF156. The Co-60 irradiated devices failed above 750 Gy(Si) and the electron irradiated devices failed above 500 Gy(Si). Both lots of devices increased in degradation very rapidly before failure.

PMI OP-15 (d/c 8150). Inconsistent in degradation.

PMI OP-15 (d/c 8229). Devices irradiated with electrons indicated the greatest damage of all PMI OP-15 devices.

c. ΔI_B (Figure 14).

BUB OPA-100. Devices were similar in degradation from both sources up to 20,000 Gy(Si) where the degradation from the electron radiation starts increasing more rapidly.

MOT LF155. Nearly identical degradation from both sources.

NSC LF156. Electron irradiated devices indicated a very rapid increase in I_B after 200 Gy(Si) and failure after 750 Gy(Si). The Co-60 irradiated devices increased I_B very rapidly after 500 Gy(Si) and failed after 3000 Gy(Si).

PMI OP-15 (d/c 8150). Similar degradation was indicated to 600 Gy(Si) after which the electron irradiated devices degraded more rapidly.

PMI OP-15 (d/c 8229). These devices degraded very rapidly for both sources.

d. ΔA_{VOL} (+) (Figure 15).

BUB OPA-100. These devices degraded very rapidly for both sources.

MOT LF155. Inconsistent in degradation. Large negative peak at 3000 Gy(Si) for the electron irradiated devices.

NSC LF156. Little difference in degradation except for the failure above 3000 Gy(Si) for the electron irradiated devices.

PMI OP-15 (d/c 8150). Little difference in degradation to 3000 Gy(Si), then the electron irradiated devices indicated increased degradation.

PMI OP-15 (d/c 8229). These devices indicated little difference in degradation except for a small positive peak at 6000 Gy(Si) for the electron irradiated devices.

e. ΔA_{VOL} (-) (Figure 16).

BUB OPA-100. There is a negative peak indicated at 3000 Gy(Si) for the devices irradiated with Co-60. Worst-case degradation of these devices is when they are irradiated with electrons.

MOT LF155. Inconsistent in degradation. There is a positive peak at 3000 Gy(Si) for the devices irradiated with Co-60 and a negative peak at 3000 Gy(Si) for the devices irradiated with electrons.

NSC LF156. Devices irradiated with electrons failed above 3000 Gy(Si). Also, below 3000 Gy(Si) there were differences in the degradation between the two sources.

PMI OP-15 (d/c 8150). Similar degradation between the two sources. Electron irradiated devices indicated the greatest degradation.

PMI OP-15 (d/c 8229). Similar degradation between the two sources. Co-60 irradiated devices indicated the greatest degradation.

5. Low-Power Operational Amplifier

The Harris HA5141A low-power operational amplifier was the only device of this type to be tested in this group.

a. ΔV_{OS} (Figure 17). The devices irradiated with electrons indicated a larger change in degradation than those irradiated with Co-60. The electron irradiated devices peaked at 750 Gy(Si), followed by a negative peak at 3000 Gy(Si). The devices irradiated with Co-60 indicated no peaks, but did fail above 3000 Gy(Si).

b. ΔI_{OS} (Figure 18). Both lots of devices indicated peaks, both positive and negative. The devices irradiated with Co-60 indicated the greatest overall degradation including failure above 3000 Gy(Si).

c. ΔI_B (Figure 19). The electron irradiated devices indicated the greatest degradation up to 750 Gy(Si) with a sharp negative peak to 1500 Gy(Si). The devices irradiated with Co-60 increased to a peak at 1500 Gy(Si), then failed above 3000 Gy(Si).

d. ΔA_{VOL} (+) (Figure 20). The electron irradiated devices failed above 500 Gy(Si) while the Co-60 irradiated devices failed above 1500 Gy(Si).

e. ΔA_{VOL} (-) (Figure 21). The electron irradiated devices failed above 1500 Gy(Si) while the Co-60 irradiated devices failed above 3000 Gy(Si).

B. COMPARATORS

Two types of comparators from six manufacturers were tested in this group. LM139s from five different manufacturers and the L161 (Low-power Comparator) from Siliconix (SIL). The L161 is similar to, but not the same as, the LM139. Each device has four separate comparators per chip. It was noted during the data analysis that each separate comparator had its own characteristics with each source. In most cases, the degradation of the third comparator was about one-half that of the other three comparators. For the JPL analysis, the test results of the first comparator are reported herein.

1. ΔV_{OS} (Figure 22)

a. AMD. Devices irradiated with Co-60 indicated very little change while the devices irradiated with electrons degraded rapidly above 6000 Gy(Si).

b. FSC. Both lots of devices failed above 1500 Gy(Si) with electron degradation to the devices being much greater than Co-60 degradation.

c. MOT. Large differences were noted with a positive peak at 6000 Gy(Si) for the Co-60 irradiated devices and failure above 3000 Gy(Si) for the electron irradiated devices.

d. NSC. Both lots indicated very rapid increases in V_{OS} with failures of the electron irradiated devices above 1500 Gy(Si) and Co-60 irradiated devices above 3000 Gy(Si).

e. PMI. Differences in degradation increased above 3000 Gy(Si) with the Co-60 irradiated devices failing above 10,000 Gy(Si). The electron irradiated devices indicated the greatest degradation.

f. SIL. Large differences are indicated, with the electron irradiated devices increasing most rapidly. Both lots of devices failed above 750 Gy(Si).

2. ΔI_{OS} (Figure 23)

a. AMD. Electron irradiated devices indicated the greatest change.

b. FSC. There were very large differences in the two lots. Both lots failed above 1500 Gy(Si).

c. MOT. There were very large differences in the two lots. The electron irradiated devices failed above 3000 Gy(Si).

d. NSC. There were very large differences in the two lots. The electron irradiated devices failed above 1500 Gy(Si) while the Co-60 irradiated devices failed above 3000 Gy(Si).

e. PMI. There were very large differences in the two lots. The electron irradiated devices failed above 3000 Gy(Si).

f. SIL. There were very large differences in the two lots. Both lots failed above 750 Gy(Si).

3. ΔI_B (Figure 24)

a. AMD. Electron irradiated devices degraded nearly twice as fast as the Co-60 irradiated devices.

b. FSC. There were very large differences in the two lots. Both lots failed above 1500 Gy(Si).

c. MOT. There were very large differences in the two lots. The electron irradiated devices failed above 3000 Gy(Si).

d. NSC. Large differences in the two lots above 750 Gy(Si) were indicated in the test results. The devices irradiated with electrons failed above 1500 Gy(Si) while the Co-60 irradiated devices failed above 3000 Gy(Si).

e. PMI. Large differences in the two lots below 3000 Gy(Si) were indicated in the test results. The devices irradiated with electrons failed above 3000 Gy(Si) while the devices irradiated with Co-60 failed above 6000 Gy(Si).

f. SIL. Very large differences in the two lots were indicated in the test results. The devices irradiated with electrons failed above 750 Gy(Si) while the devices irradiated with Co-60 failed above 1500 Gy(Si).

4. ΔI_{SK} (Figure 25)

a. AMD. Some differences were noted in the test results with the electron irradiated devices degrading at a fast rate.

b. FSC. Very similar degradation between lots, with both failing above 1500 Gy(Si). Co-60 irradiated devices indicated slightly more degradation than the electron irradiated devices.

c. MOT. Very large differences in the two lots were indicated in the test results. The devices irradiated with electrons failed above 3000 Gy(Si).

d. NSC. The electron irradiated devices failed above 1500 Gy(Si) while the Co-60 irradiated devices failed above 3000 Gy(Si).

e. PMI. The electron irradiated devices failed above 3000 Gy(Si) while the Co-60 irradiated devices failed above 6000 Gy(Si).

f. SIL. The electron irradiated devices failed above 750 Gy(Si) while the Co-60 irradiated devices failed above 1500 Gy(Si).

C. SWITCH, DG154

The Siliconix DG154 is a DPST electronic switch with two devices in each package. This was the only device of this type to be tested in this group. No difference was seen between the two devices in the package, although very large total dose differences were seen within the same switch depending on the switch position, open or closed.

1. I_D (Figure 26)

When the switch was biased to ON, the electron irradiated devices degraded more rapidly and peaked at 10,000 Gy(Si). The Co-60 irradiated devices peaked at 20,000 Gy(Si). When the switch was biased OFF, the electron irradiated devices peaked at 1500 Gy(Si) then dropped off while the Co-60 irradiated devices continued to increase. At 10,000 Gy(Si) the difference between ON and OFF was over 1000 times.

2. I_S (Figure 27)

Similar to I_D above.

3. $I_D + I_S$ (Figure 26)

Large differences between the two lots for both ON and OFF conditions. Electron irradiated devices were degraded most.

4. $R_{DS(ON)}$ (Figure 29)

Overall little difference, although the electron irradiated devices indicated the lowest resistance.

D. SAMPLE-AND-HOLD, LF198

The AMD LF198 is a sample-and-hold. This device was tested to a maximum total dose of 10,000 Gy(Si).

1. ΔV_{OS} (Figure 30)

The electron irradiated devices indicated the highest degradation.

2. ΔI_B (Figure 31)

The electron irradiated devices indicated the highest degradation.

3. ΔI_{SK} (Figure 32)

The electron irradiated devices indicated the highest degradation.

4. ΔI_{SC} (Figure 33)

The Co-60 irradiated devices indicated a negative peak at 750 Gy(Si) and a positive peak at 6000 Gy(Si) while the electron irradiated devices indicated a peak at 3000 Gy(Si) before dropping negative very sharply. Co-60 irradiated devices indicated the maximum degradation.

5. $\Delta I_{CHG}(+)$ (Figure 34)

The electron irradiated devices indicated the highest degradation.

6. $\Delta I_{CHG}(-)$ (Figure 35)

Very little difference between test lots until 6000 Gy(Si) when the Co-60 irradiated devices rapidly increased their degradation.

V. CONCLUSIONS

The data reported here show that the cobalt-60 source may not be a suitable simulation source for electrons when characterizing the radiation damage of integrated circuits. At this time, the conditions cannot be established that permit the use of Co-60 gamma rays to simulate the space environment. Also, it was found that specific conditions for which permanent damage from electrons becomes significant for integrated circuits are device-, manufacturer-, geometry-, and process-dependent.

These conclusions are supported in part by previously published data (References 2, 6, and 7). In addition are noted the following general findings.

(1) The degradation of integrated circuit devices depends on the radiation source.

(2) Device degradation is geometry-and process-dependent.

(3) Each device parameter has its own unique degradation curve, which is radiation-source-dependent.

(4) 2.2-MeV electrons nearly always cause greater degradation in ICs than Co-60 gamma rays.

(5) Device failure is nearly always seen in electron irradiated devices before it is seen in Co-60 irradiated devices.

(6) Parameter damage rarely remains linear except over very limited ranges.

(7) Very small lot-to-lot variations seen on one source are no guarantee of similar small variations on a different source.

(8) Some devices indicate peaks and roll-offs that are radiation-source-dependent. Operation of these devices in the postpeak and roll-off ranges is not recommended.

(9) In general, devices that have radiation-softer oxides are more sensitive to Co-60 irradiation, while devices with harder oxides are more sensitive to electron irradiation.

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ABBREVIATIONS

AMD	Advance Micro Devices, Inc.
BUB	Burr-Brown Corp.
BREL	Boeing Radiation Effects Laboratory
dB	decibel
DIP	dual in-line package
DPST	double pole single throw
DUT	device under test
FSC	Fairchild Semiconductor Corp.
Gy(Si)	gray(silicon)
HAR	Harris Corp.
IC	integrated circuit
JPL	Jet Propulsion Laboratory
MeV	million electron volt
MSI	medium scale intergradation
MOS	metal-oxide semiconductor
MOT	Motorola, Inc.
NSC	National Semiconductor Corp.
pA	picoampere
PMI	Precision Monolithics, Inc.
PNP	p-types separated by n-type
RH	radiation hard
SEM	scanning electron microscope
SIL	Siliconix Corp
TID	total ionizing dose
TLD	thermoluminescent dosimetry

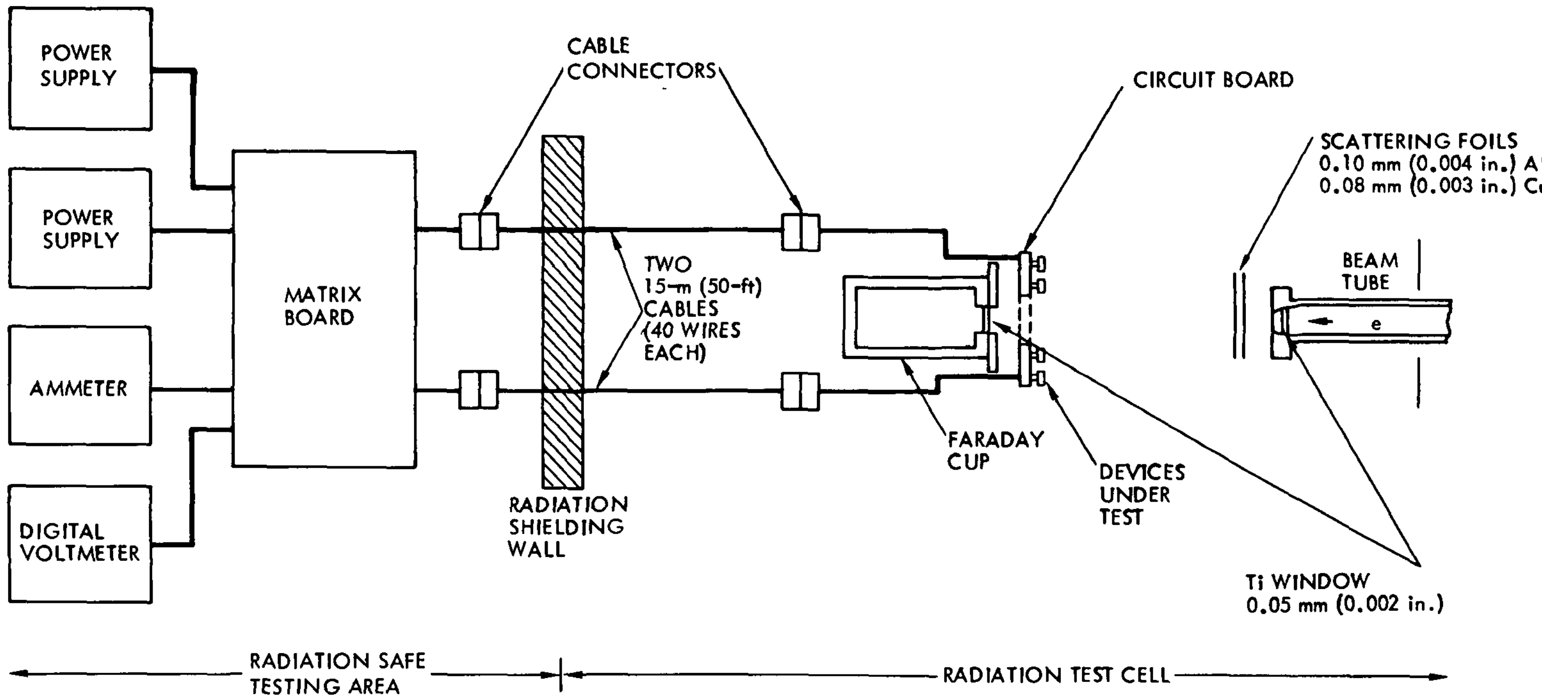

Figure 1. Experimental Test Setup

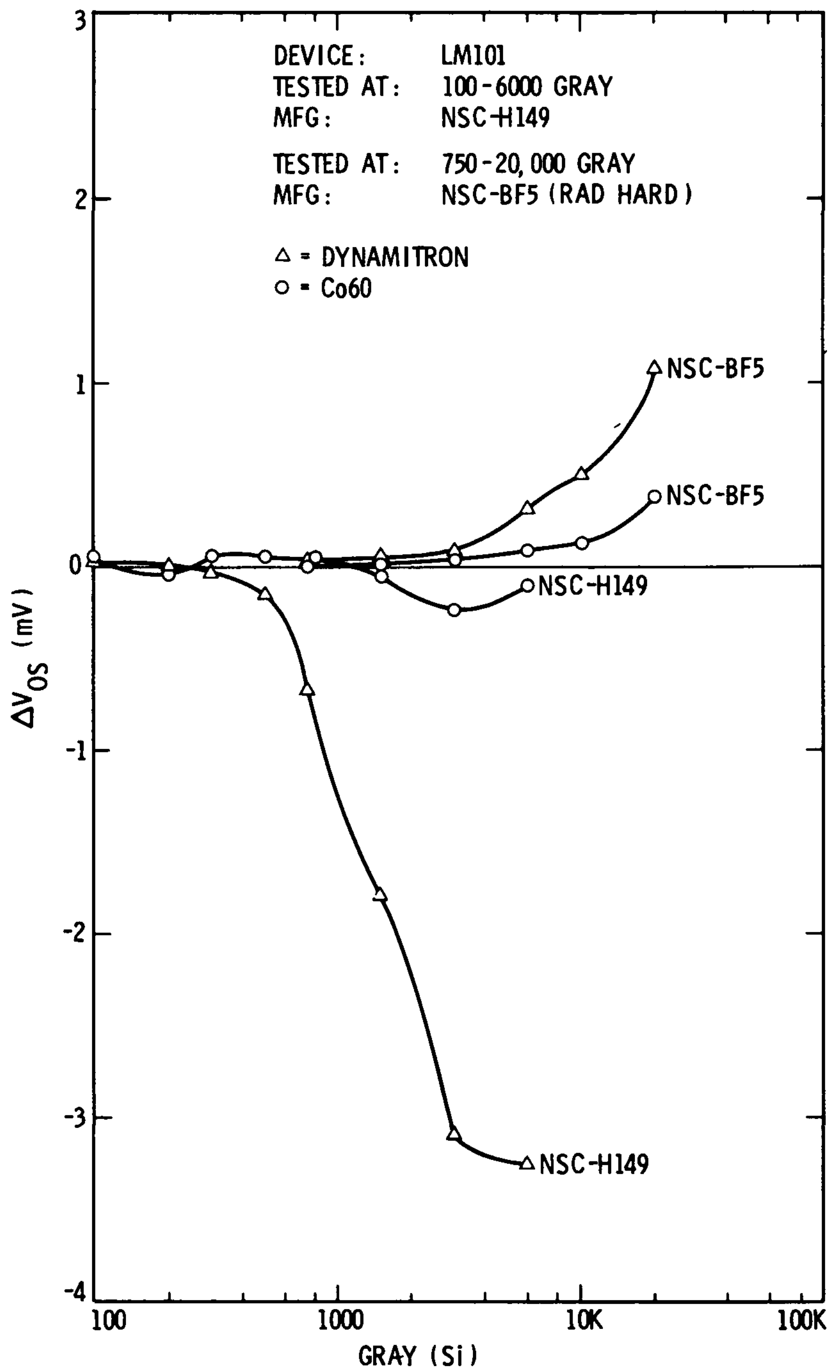

Figure 2. Comparisons of ΔV_{OS} Degradation, Standard vs Radiation-Hard LM101 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

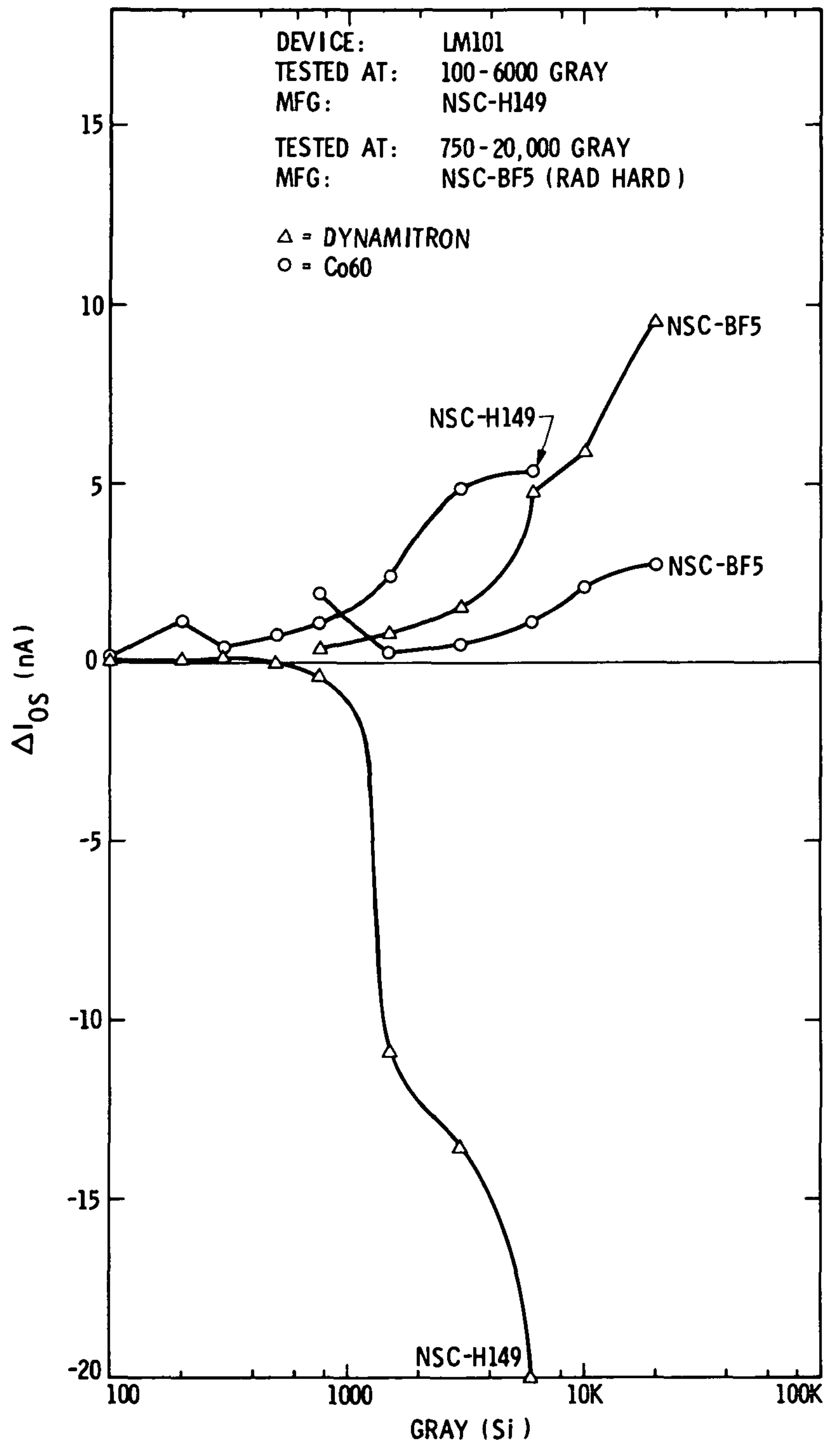

Figure 3. Comparisons of ΔI_{OS} Degradation, Standard vs Radiation-Hard LM101 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

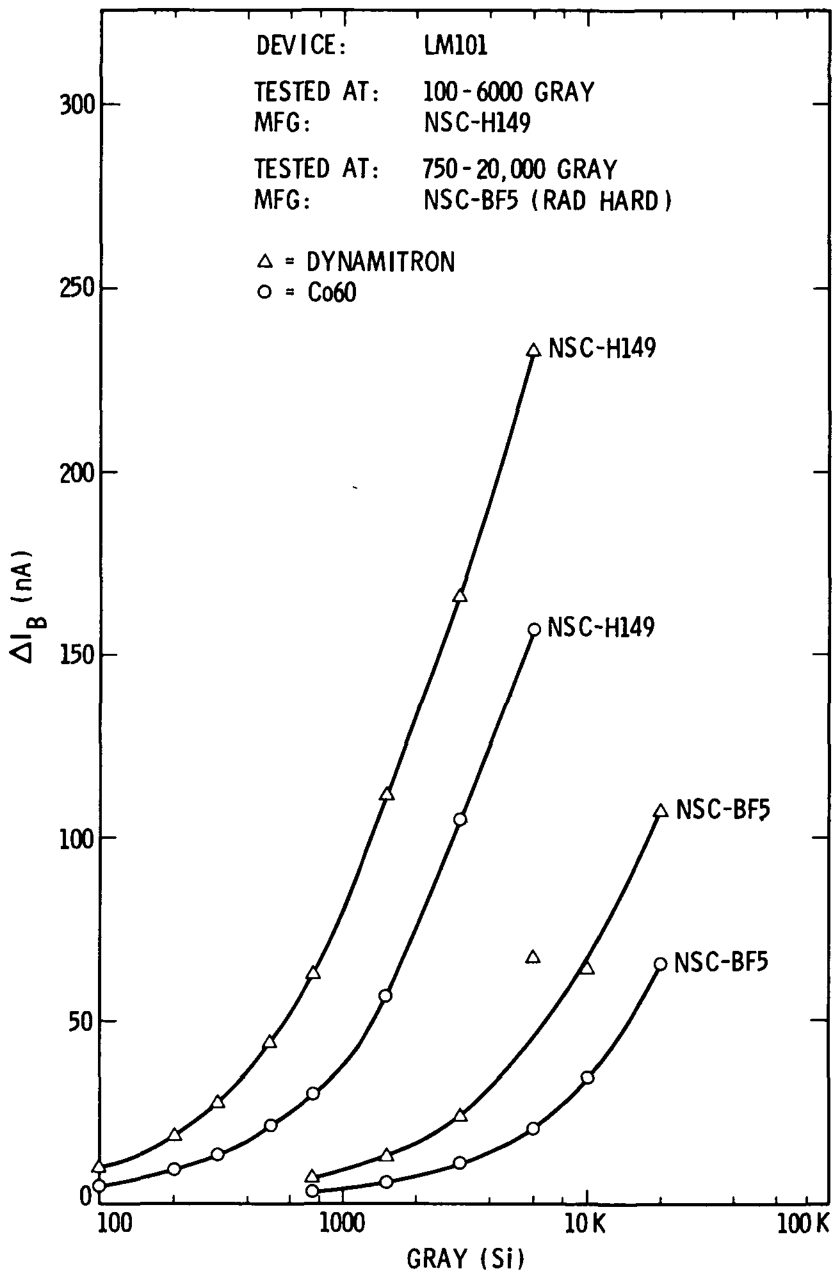

Figure 4. Comparisons of ΔI_B Degradation, Standard vs Radiation-Hard LM101 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

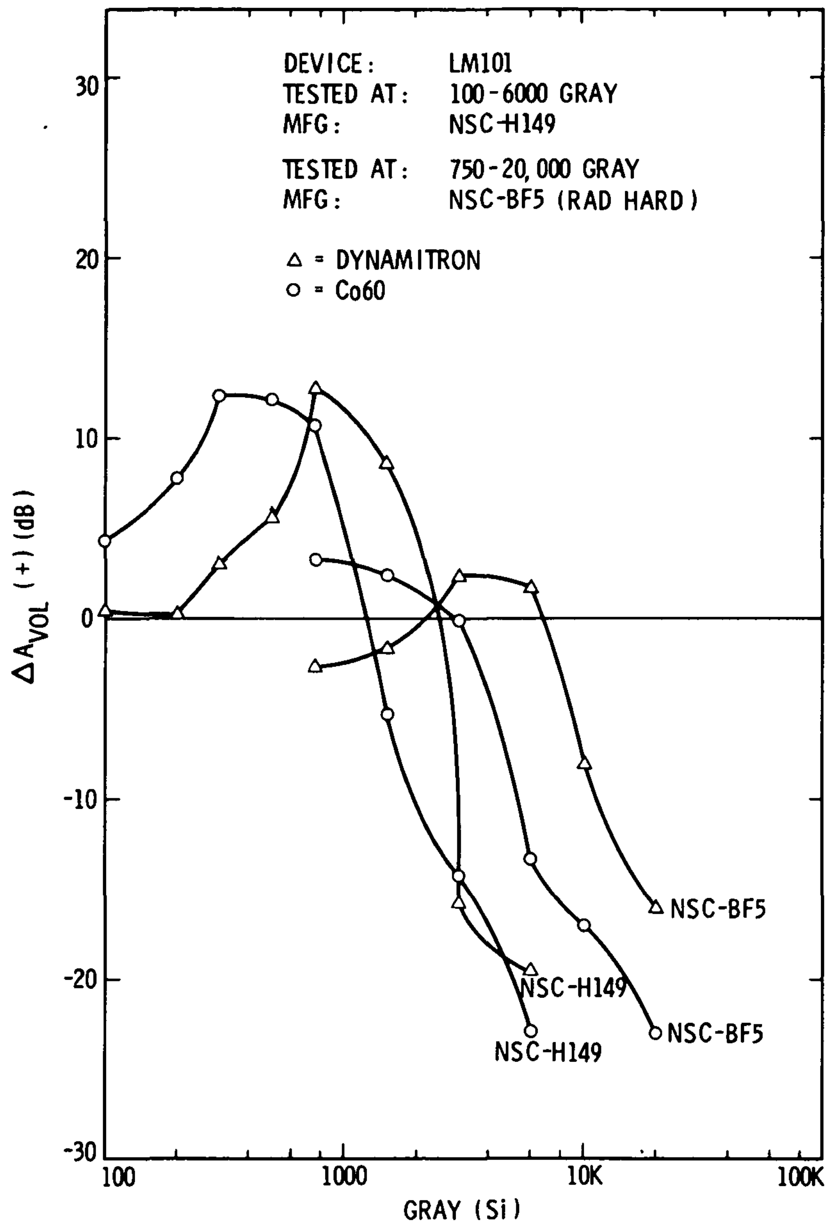

Figure 5. Comparisons of $\Delta A_{VOL}(+)$ Degradation, Standard vs Radiation-Hard LM101 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

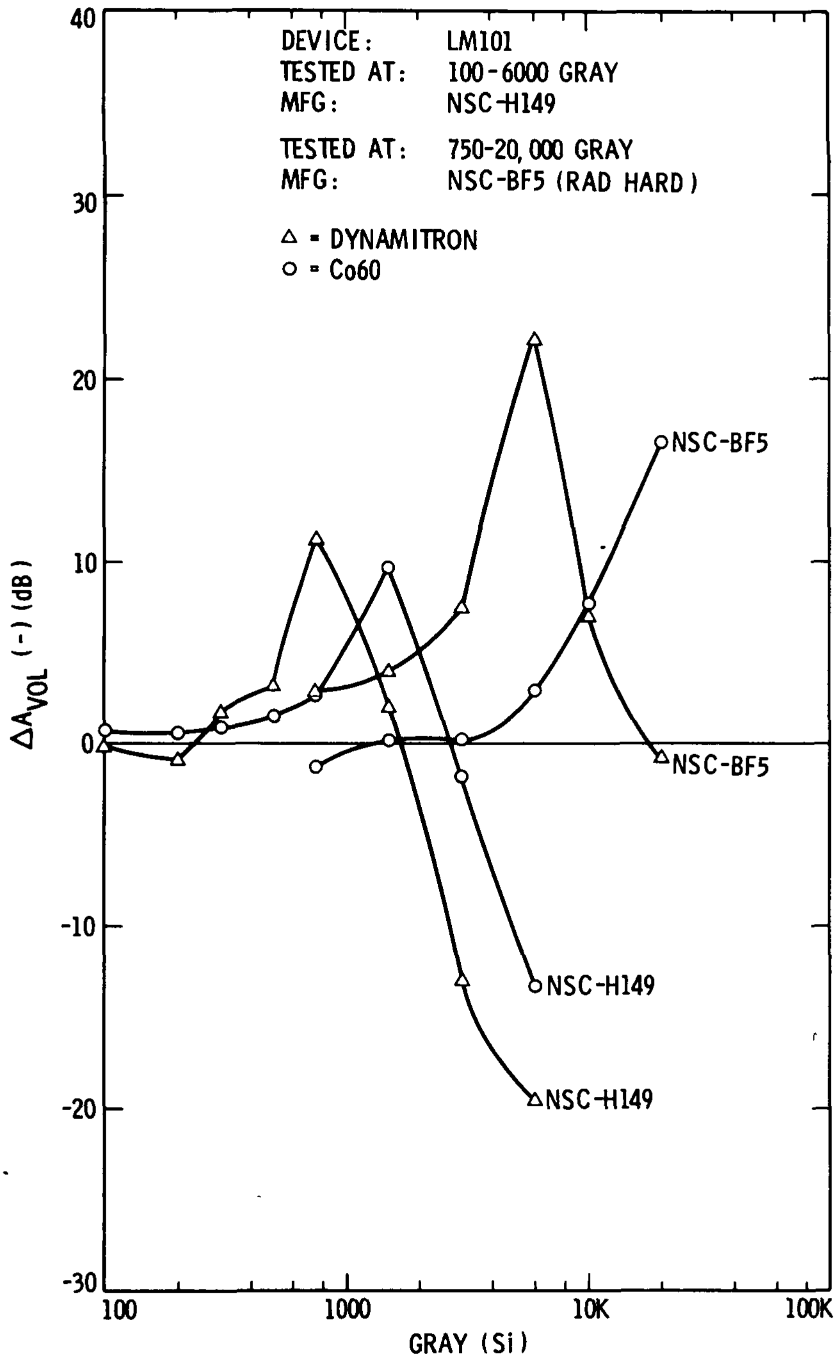

Figure 6. Comparisons of ΔA_{VOL}(-) Degradation, Standard vs Radiation-Hard LM101 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

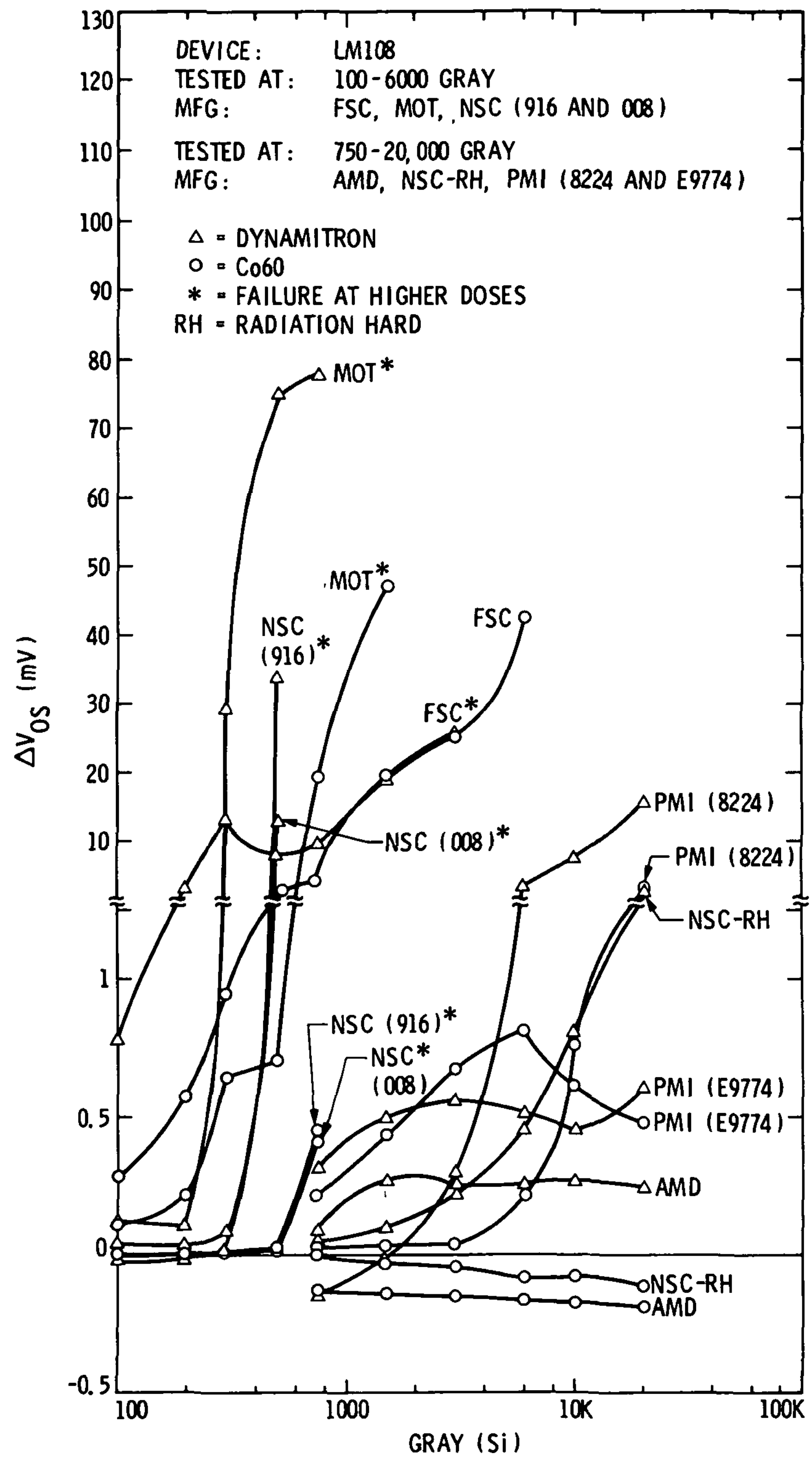

Figure 7. Comparisons of ΔV_{OS} Degradation, Standard vs Radiation-Hard LM108 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

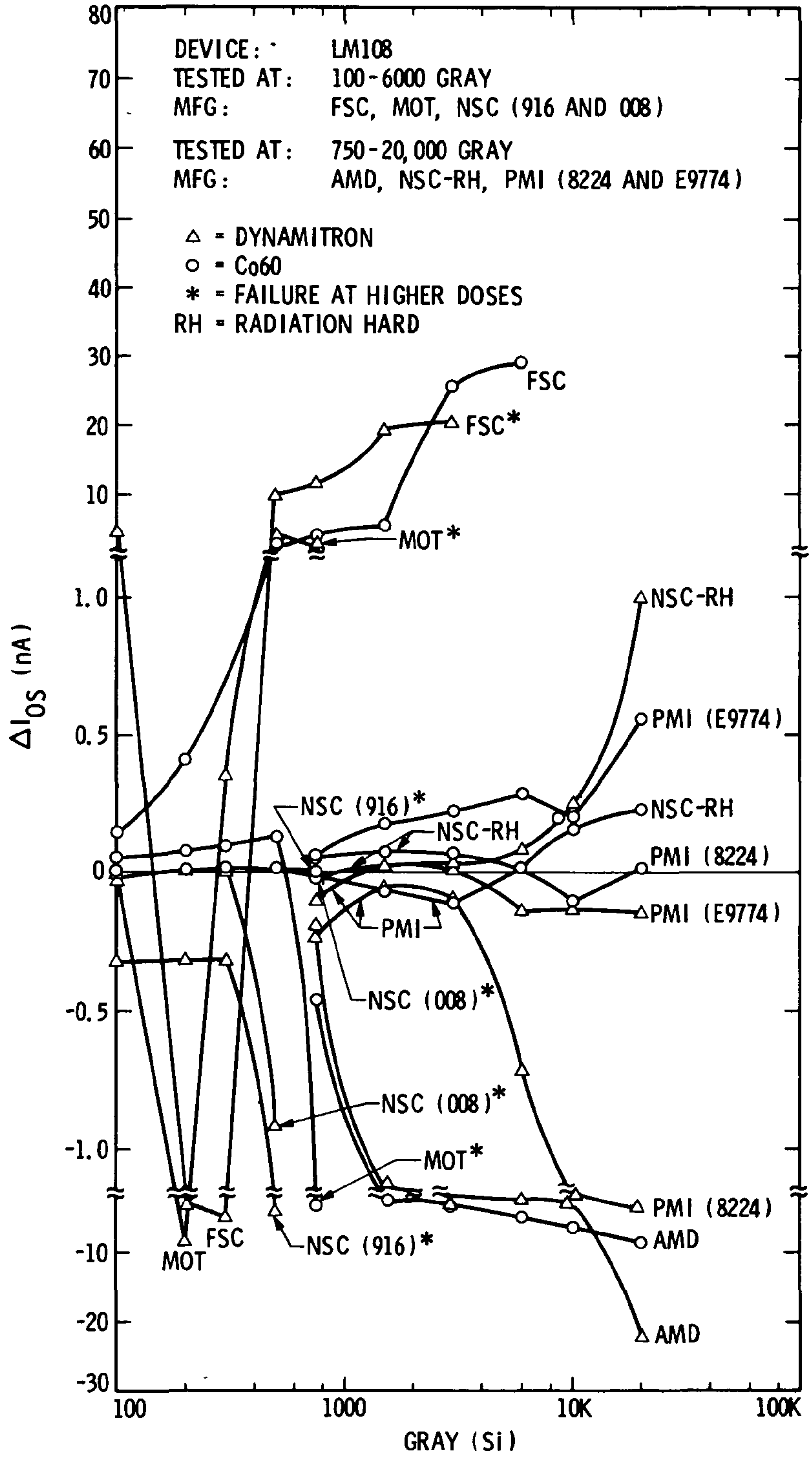

Figure 8. Comparisons of ΔI_{OS} Degradation, Standard vs Radiation-Hard LM108 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

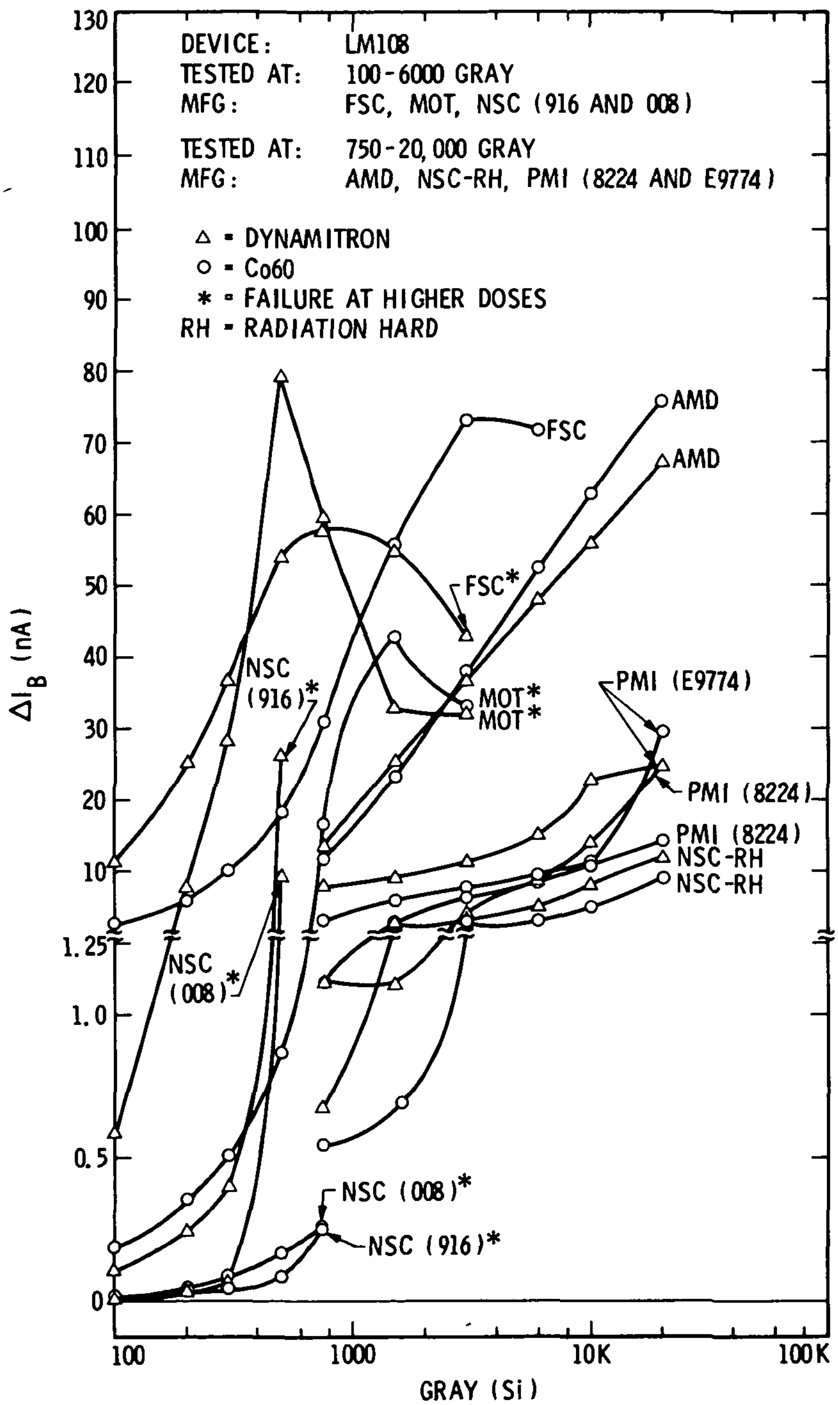

Figure 9. Comparisons of ΔI_B Degradation, Standard vs Radiation-Hard LM108 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

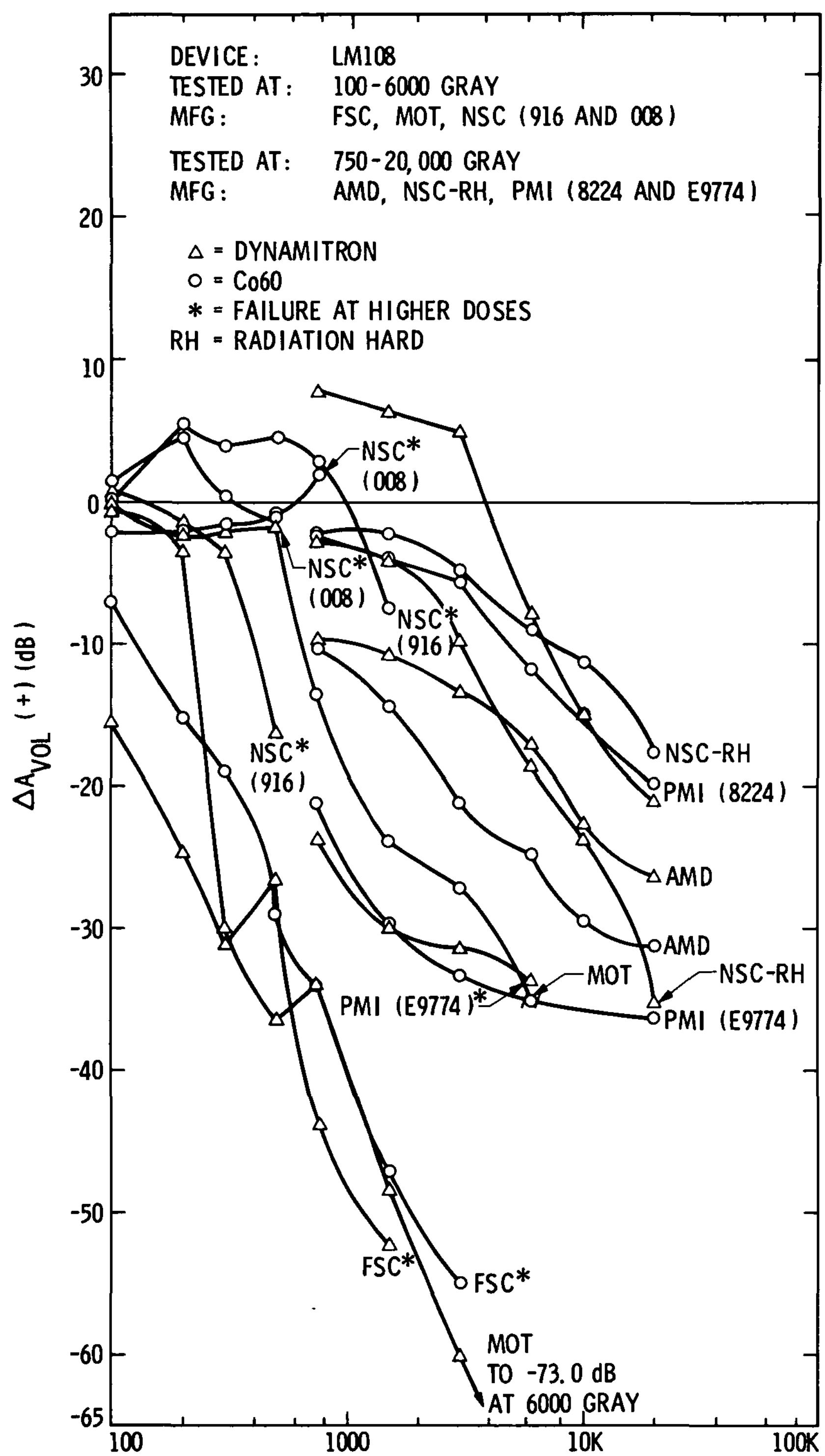

Figure 10. Comparisons of $\Delta A_{VOL}(+)$ Degradation, Standard vs Radiation-Hard LM108 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

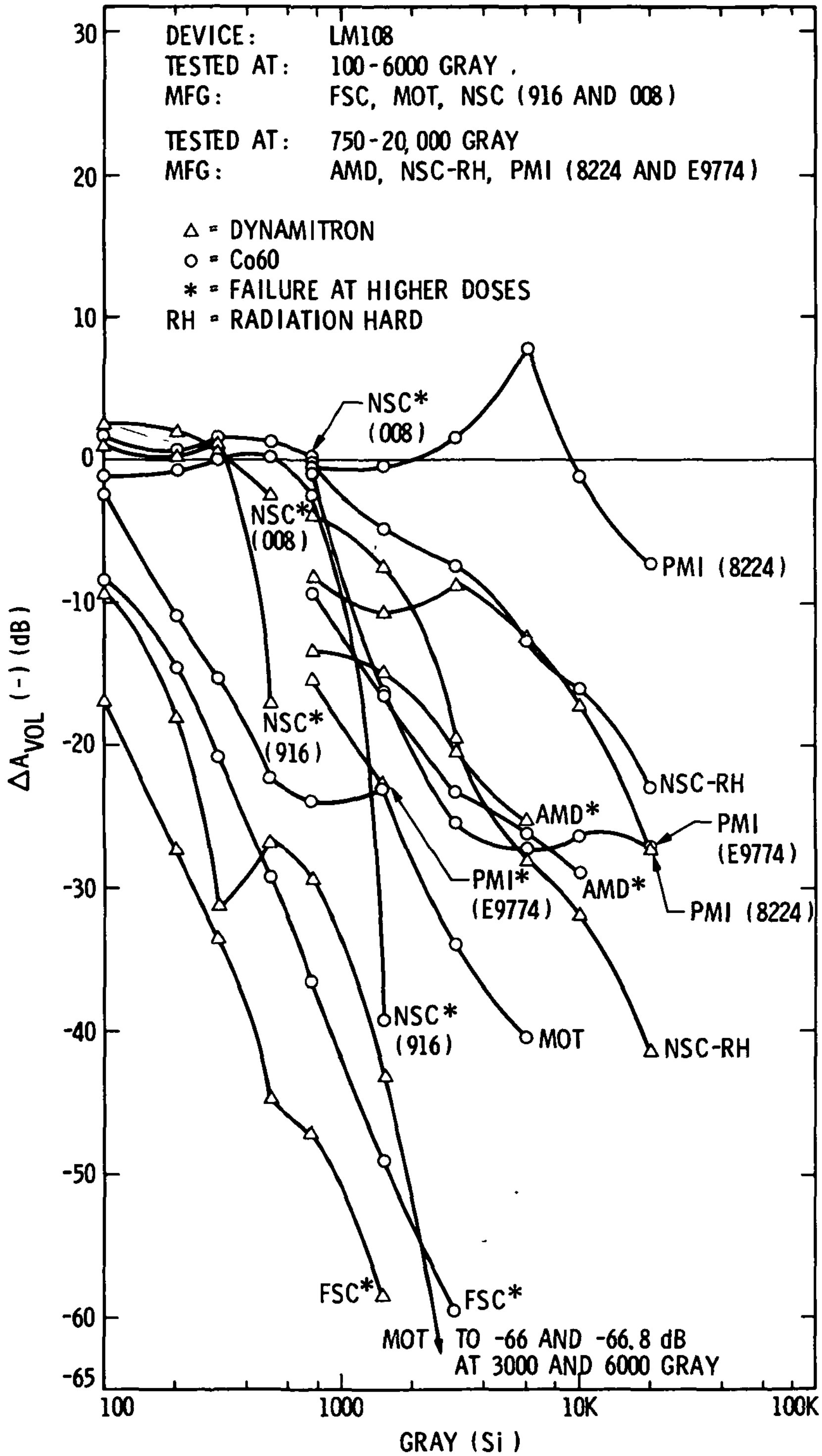

Figure 11. Comparisons of ΔA_{VOL}(-) Degradation, Standard vs Radiation-Hard LM108 Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

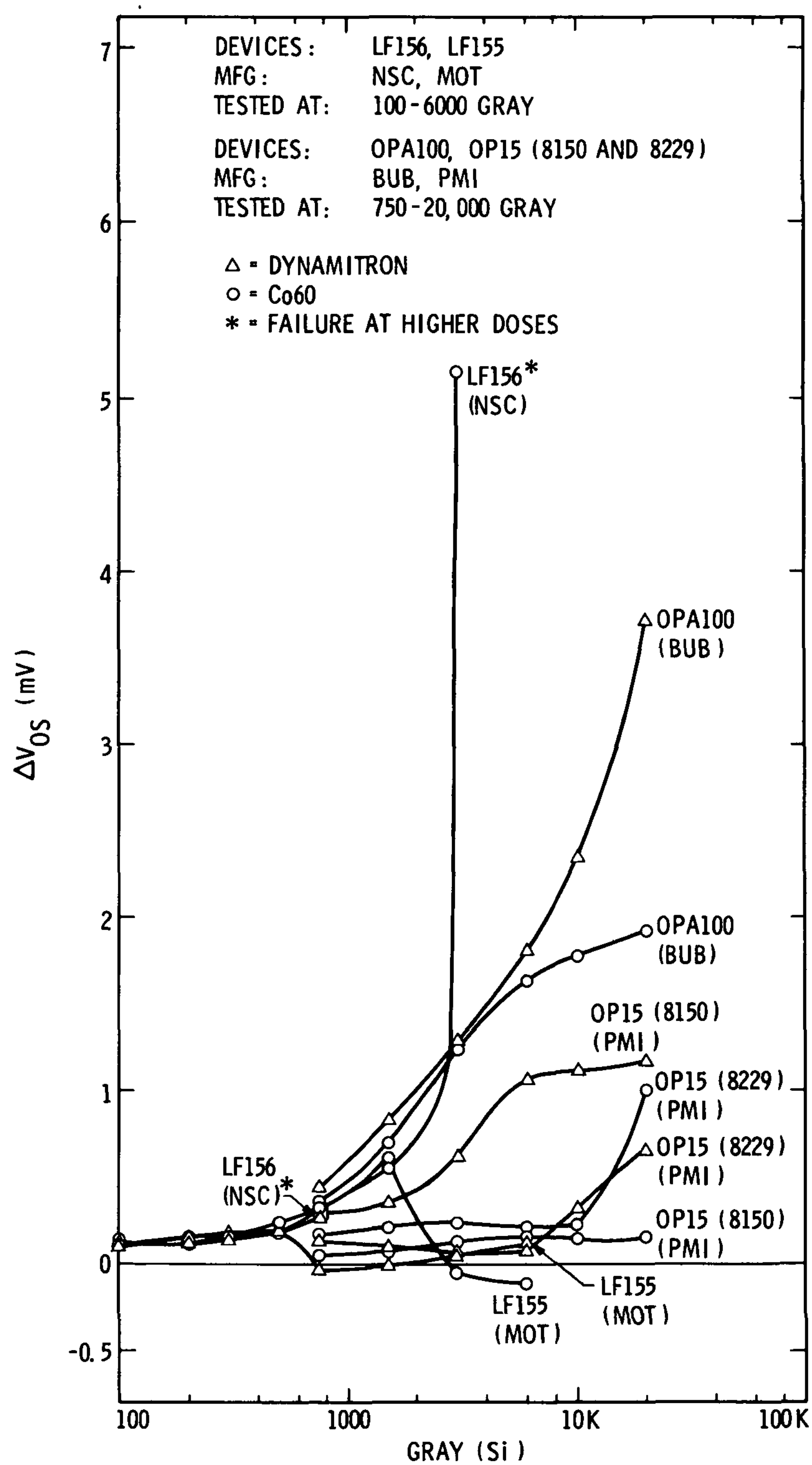

Figure 12. Comparisons of ΔV_{OS} Degradation, Standard Process FET Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

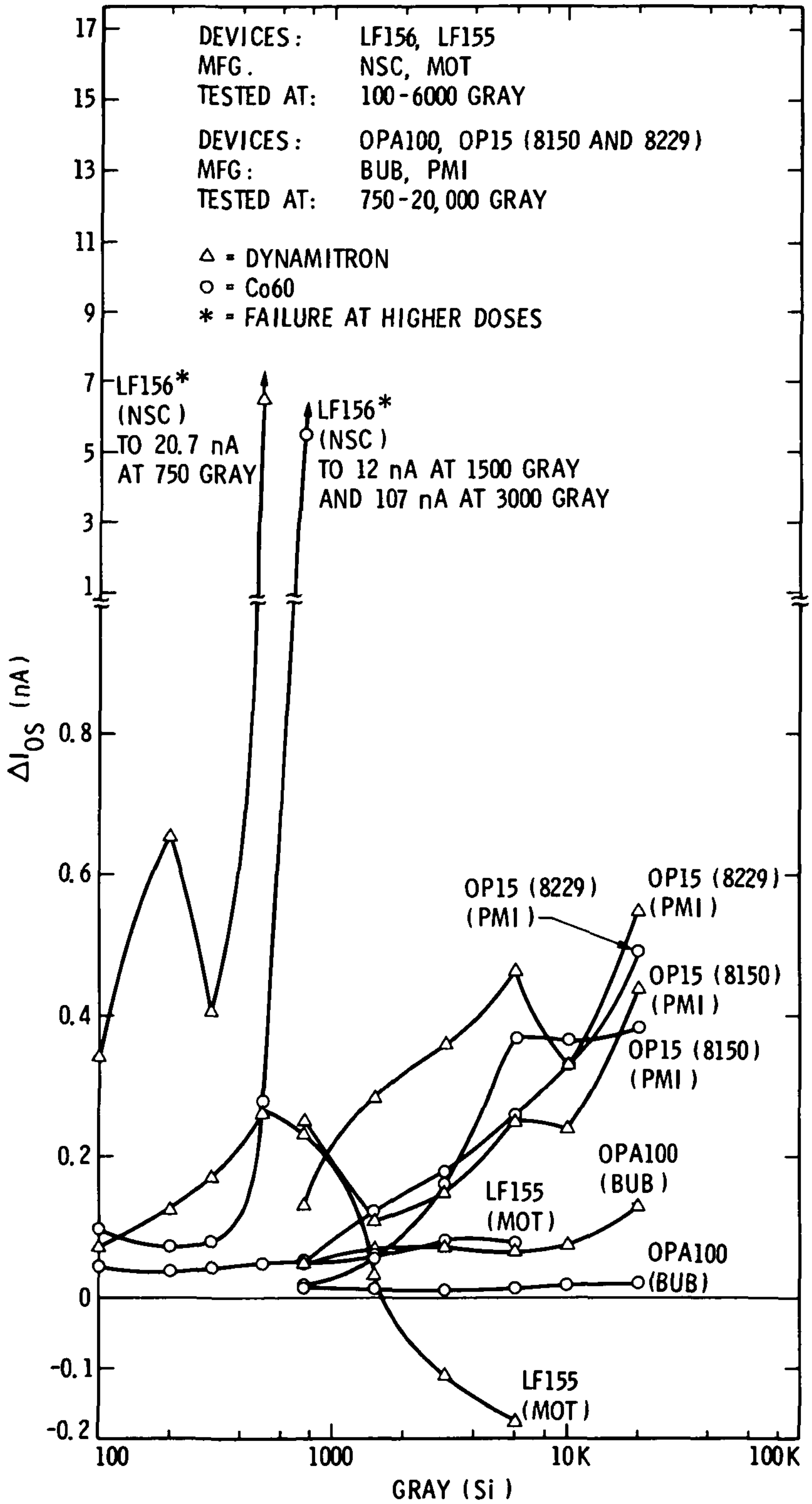

Figure 13. Comparisons of ΔI_{OS} Degradation, Standard Process FET Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

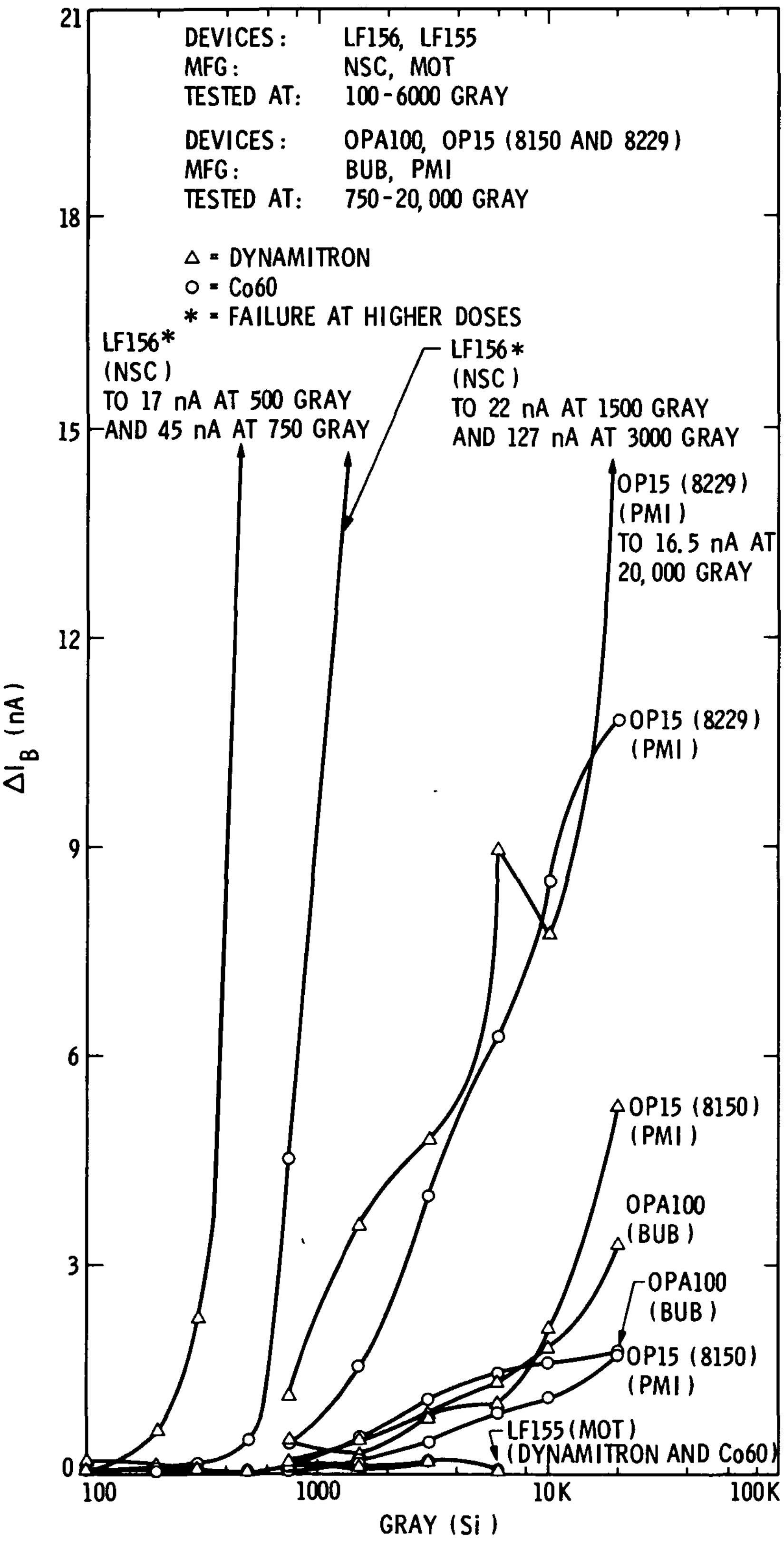

Figure 14. Comparisons of ΔI_B Degradation, Standard Process FET Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma rays

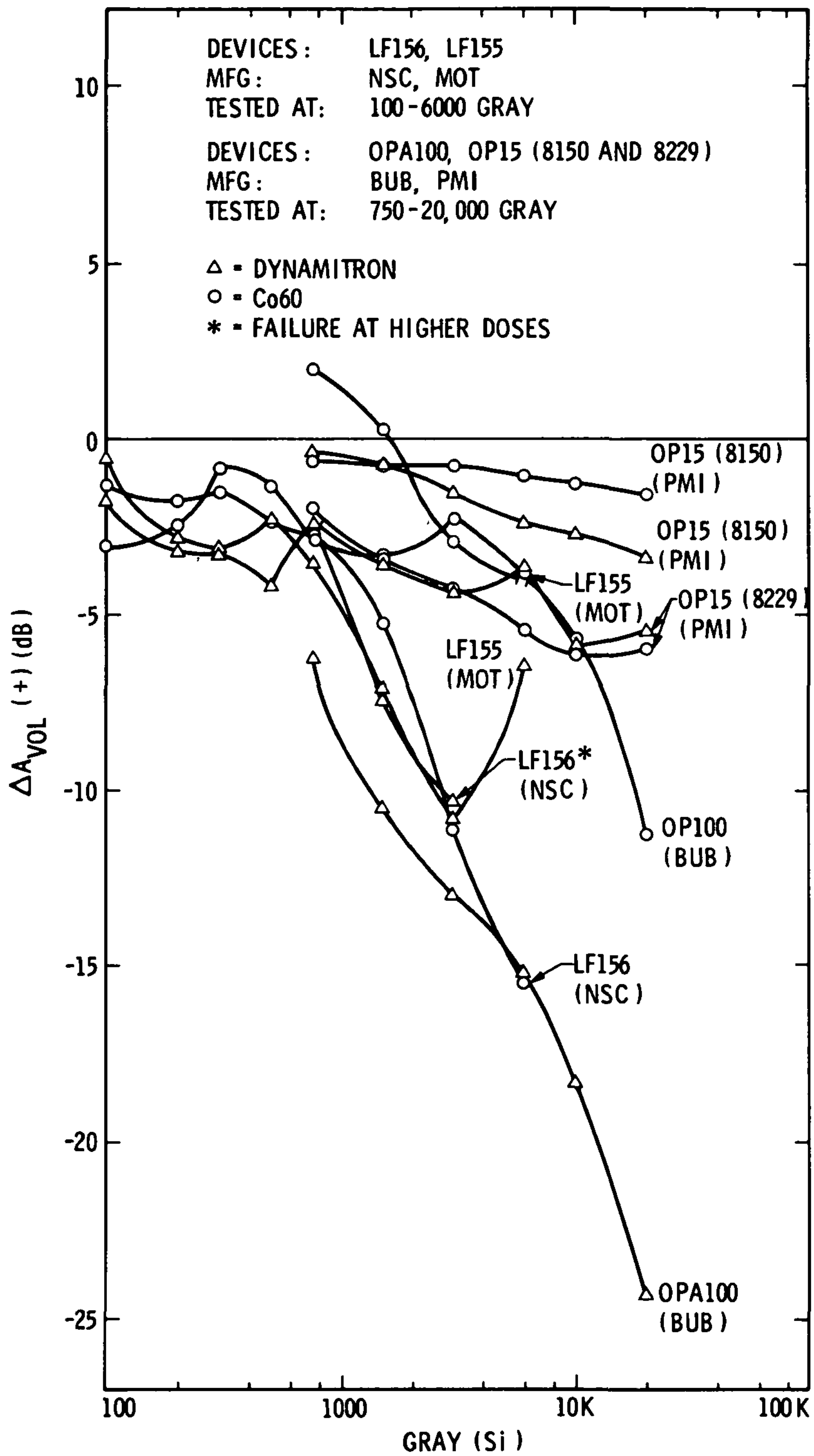

Figure 15. Comparisons of $\Delta A_{VOL}(+)$ Degradation, Standard Process FET Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

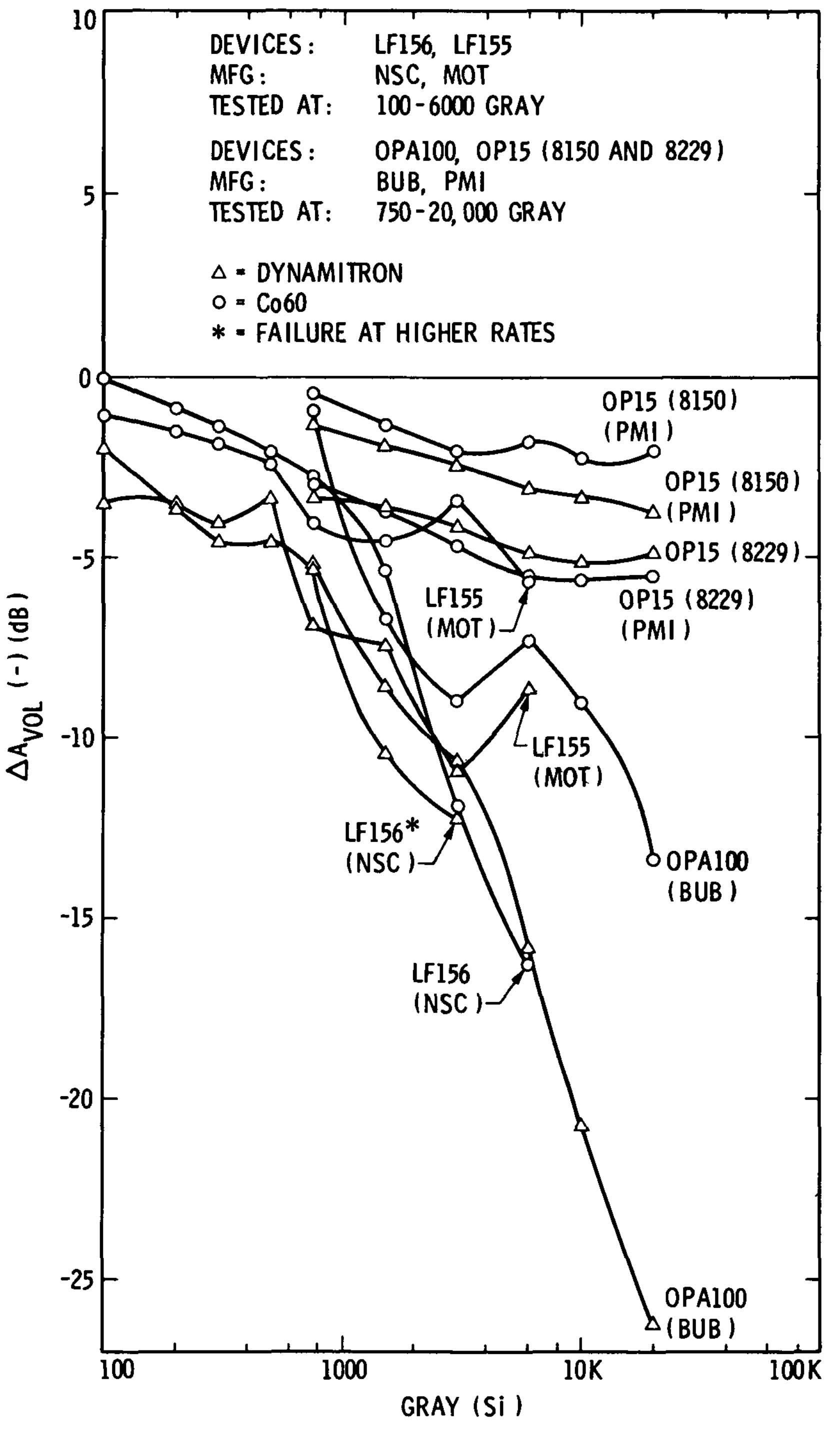

Figure 16. Comparisons of $\Delta A_{VOL}(-)$ Degradation, Standard Process FET Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

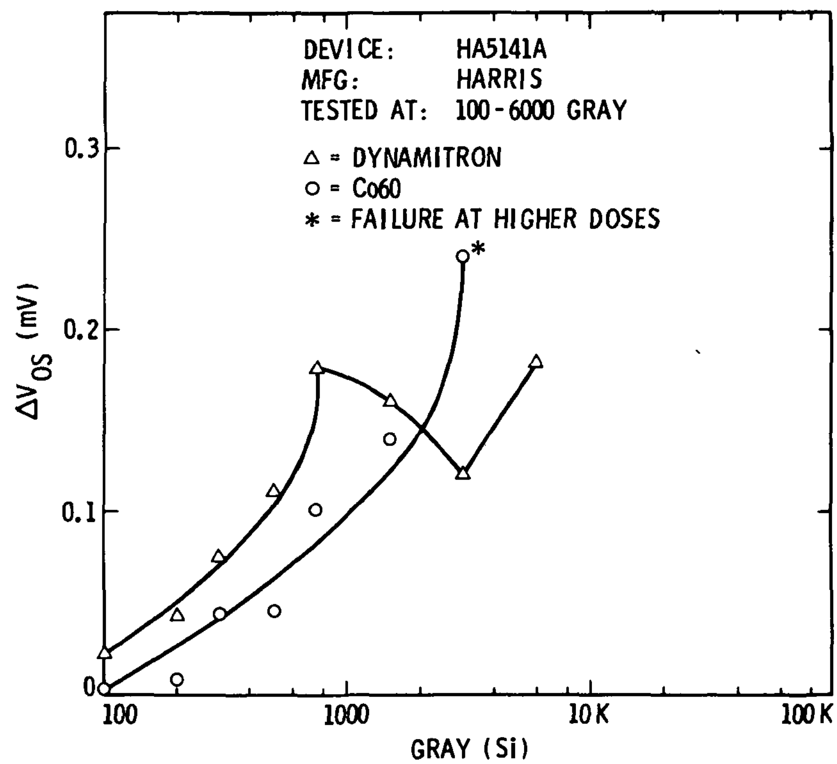

Figure 17. Comparison of ΔV_{OS} Degradation, HA5141A Low-Power Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

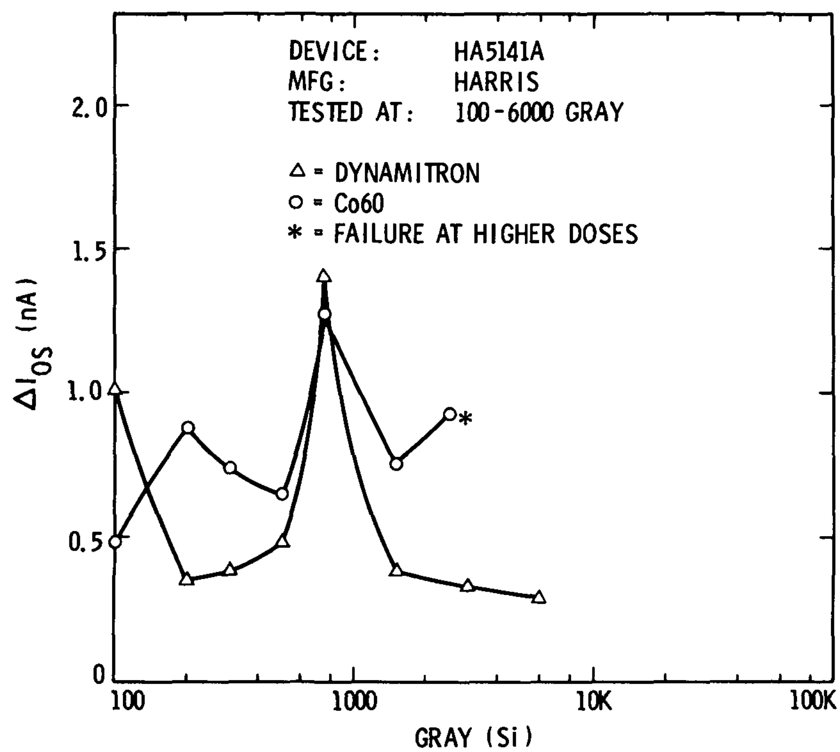

Figure 18. Comparison of ΔI_{OS} Degradation, HA5141A Low-Power Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

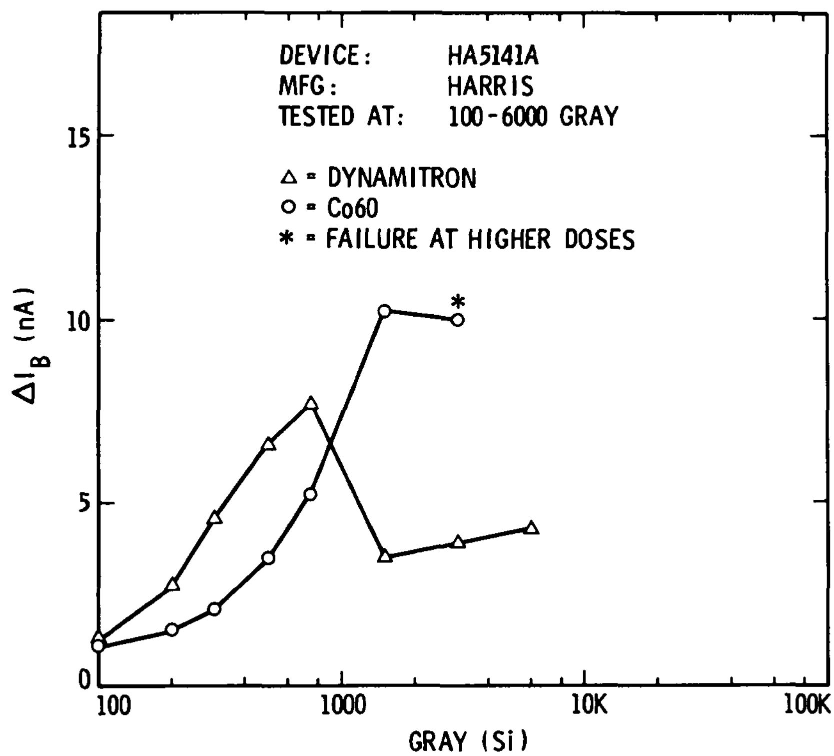

Figure 19. Comparison of ΔI_B Degradation, HA5141A Low-Power Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

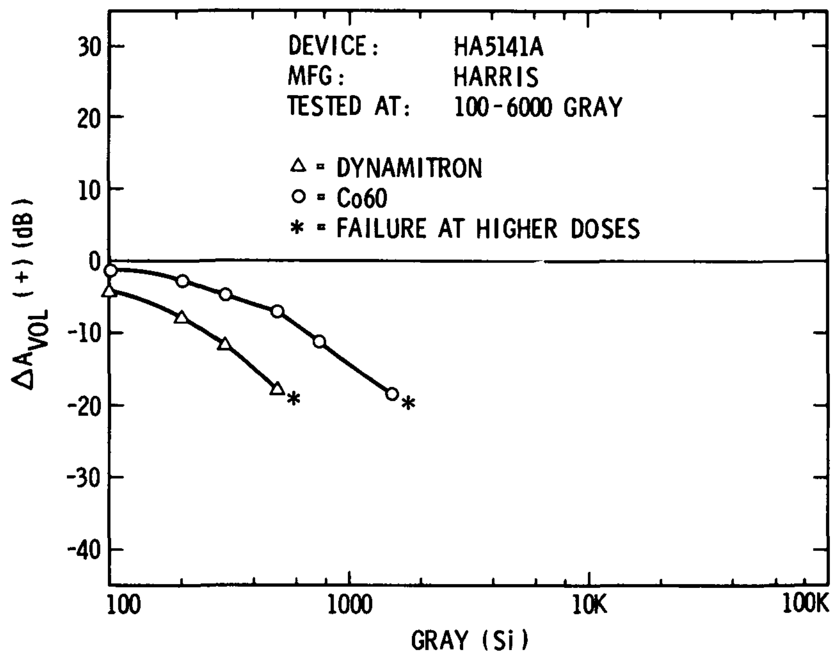

Figure 20. Comparison of $\Delta A_{VOL}(+)$ Degradation, HA5141A Low-Power Op-Amps; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

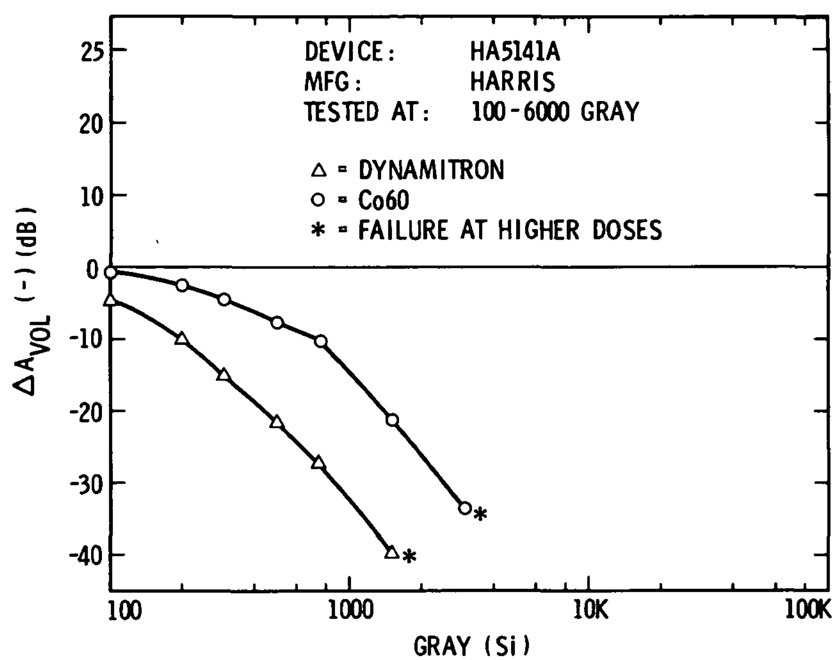

Figure 21. Comparison of $\Delta A_{VOL}(-)$ Degradation, HA5141A Low-Power Op-Amps; 2.2-MeV electrons vs Cobalt-60 Gamma Rays

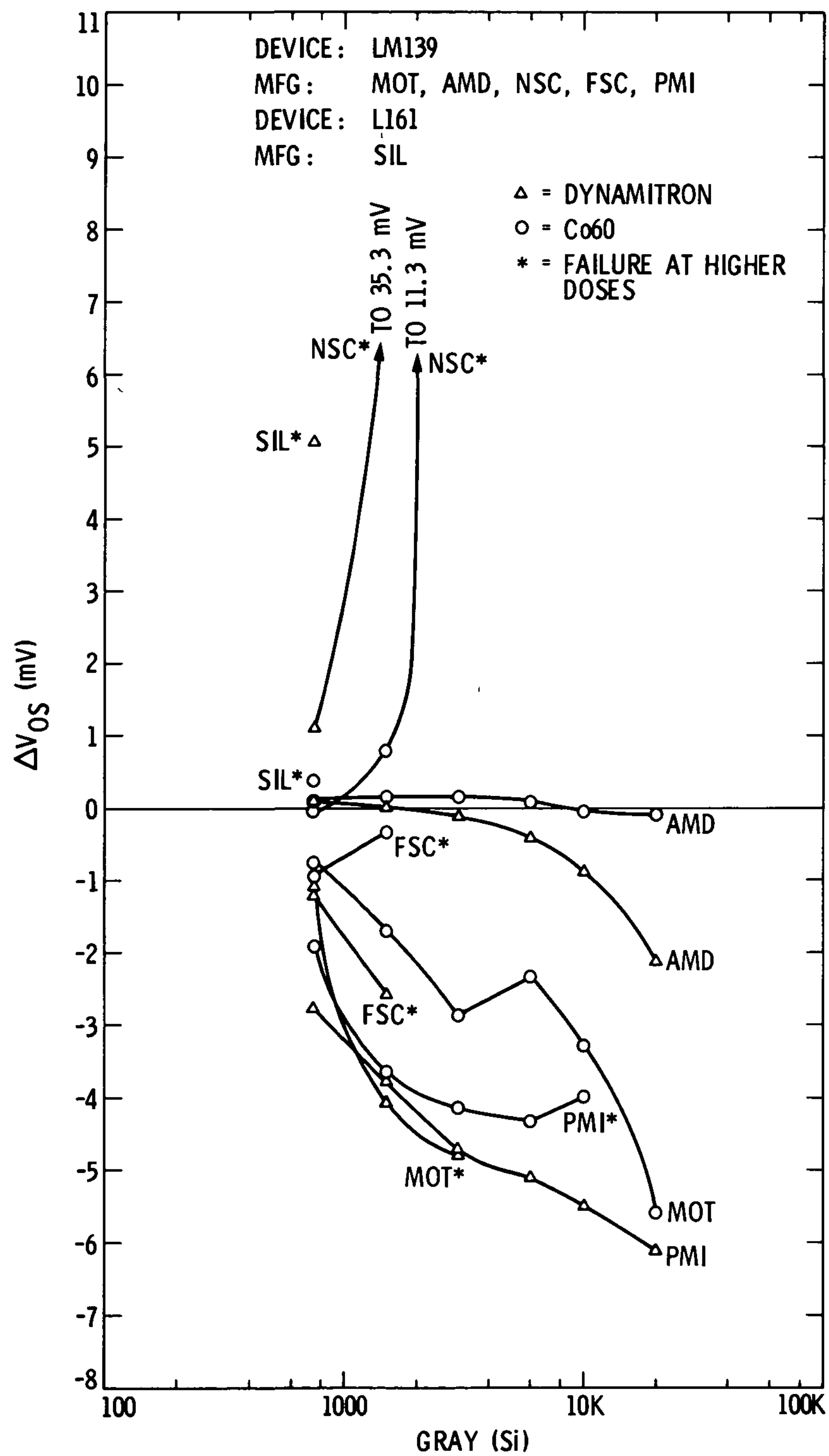

Figure 22. Comparisons of ΔV_{OS} Degradation, LM139 Quad Comparators and L161 Low-Power Quad Comparator; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

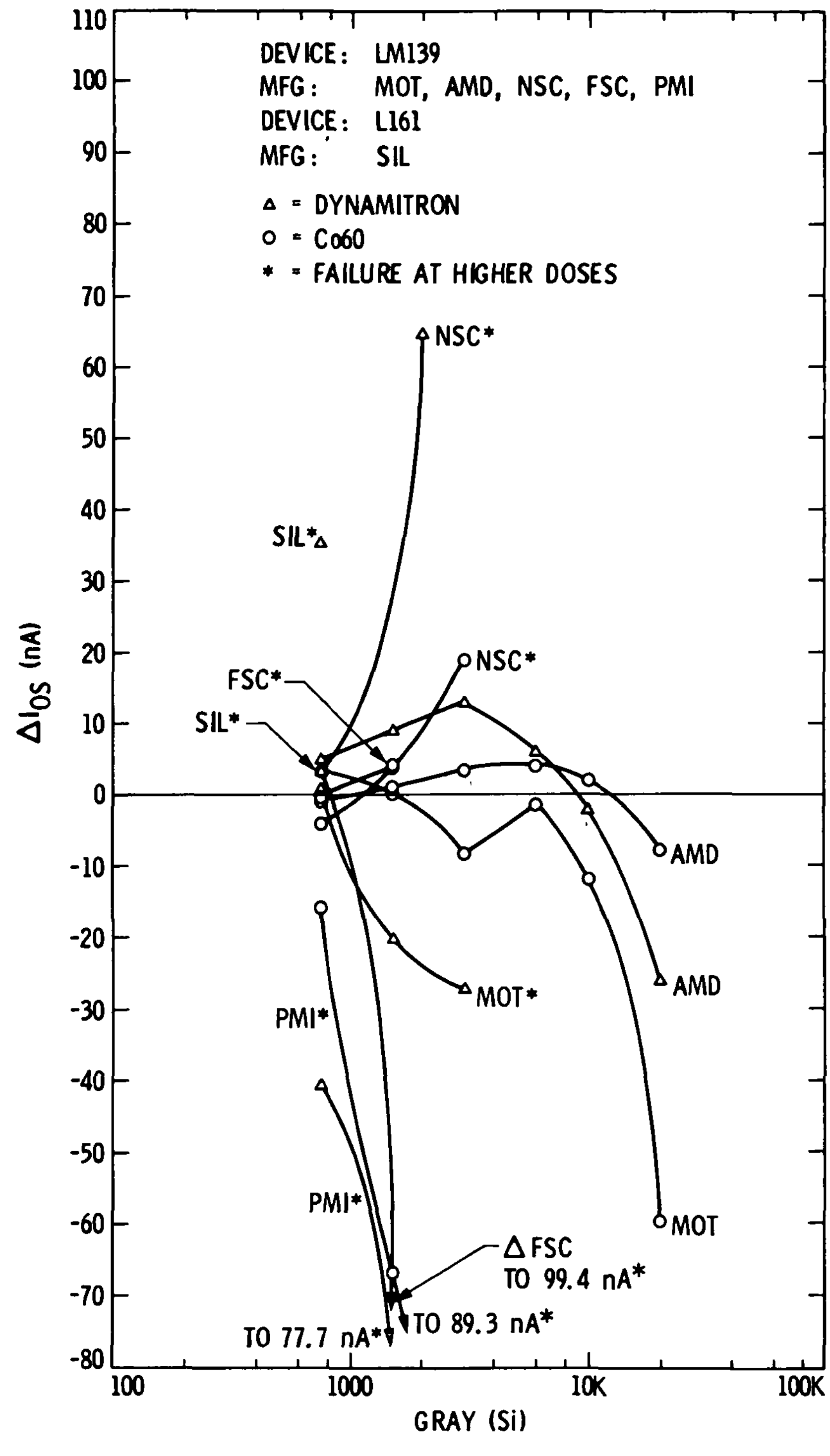

Figure 23. Comparisons of ΔI_{OS} Degradation, LM139 Quad Comparators and L161 Low-Power Quad Comparator; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

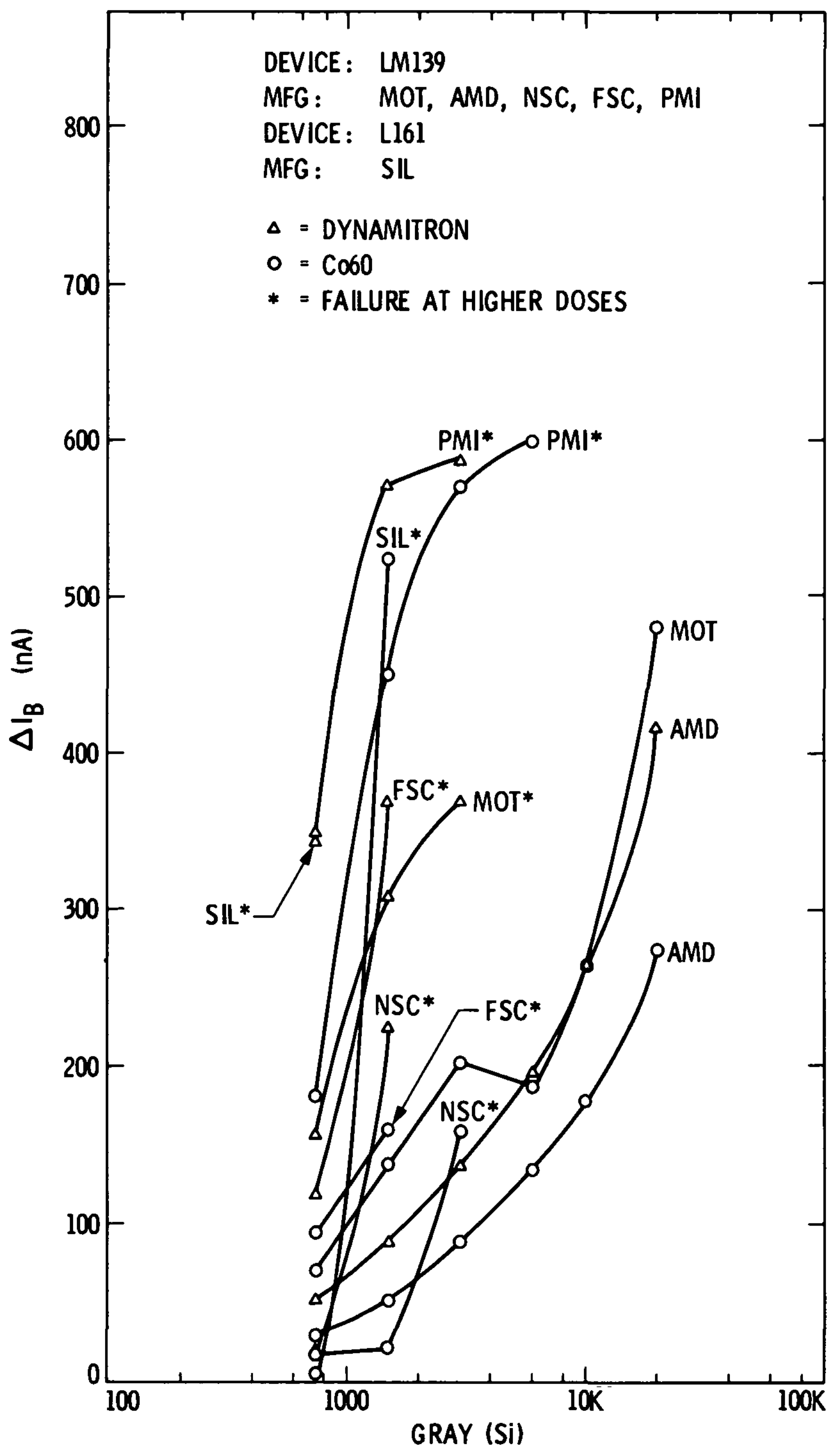

Figure 24. Comparisons of ΔI_B Degradation, LM139 Quad Comparators and L161 Low-Power Quad Comparator; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

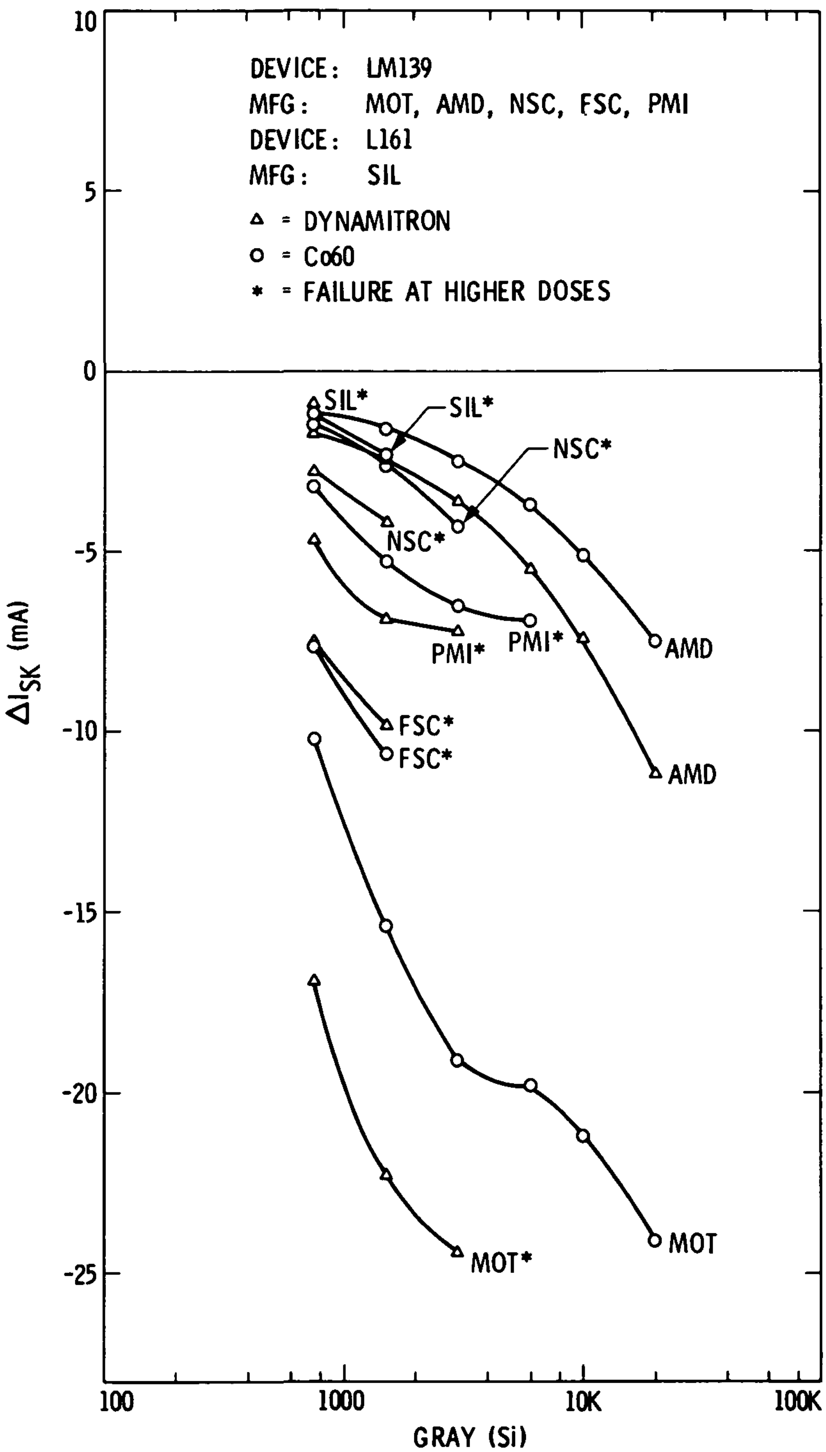

Figure 25. Comparisons of ΔI_{SK} Degradation, LM139 Quad Comparators and L161 Low-Power Quad Comparator; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

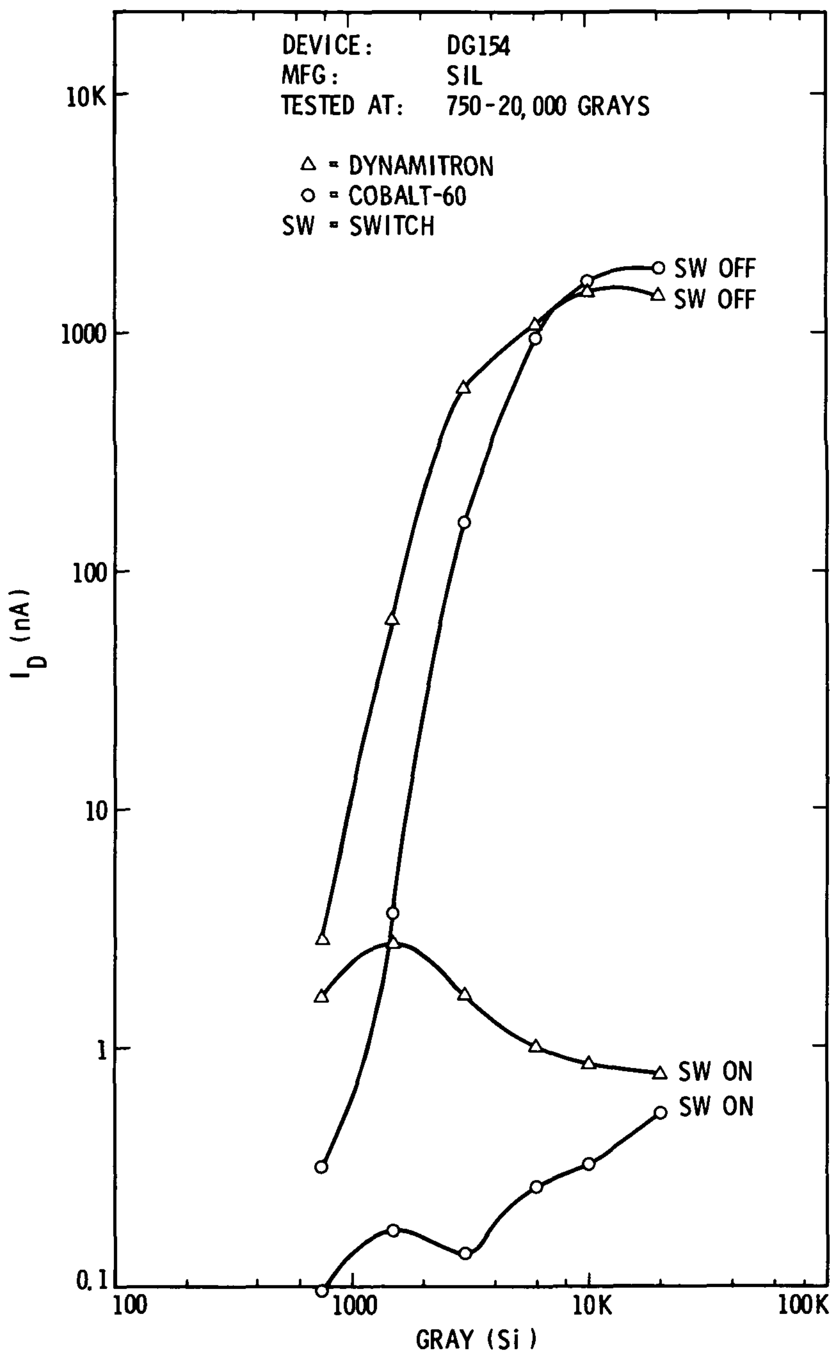

Figure 26. Comparison of I_D Degradation, DG154 FET Input Switch - DPST(2); 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

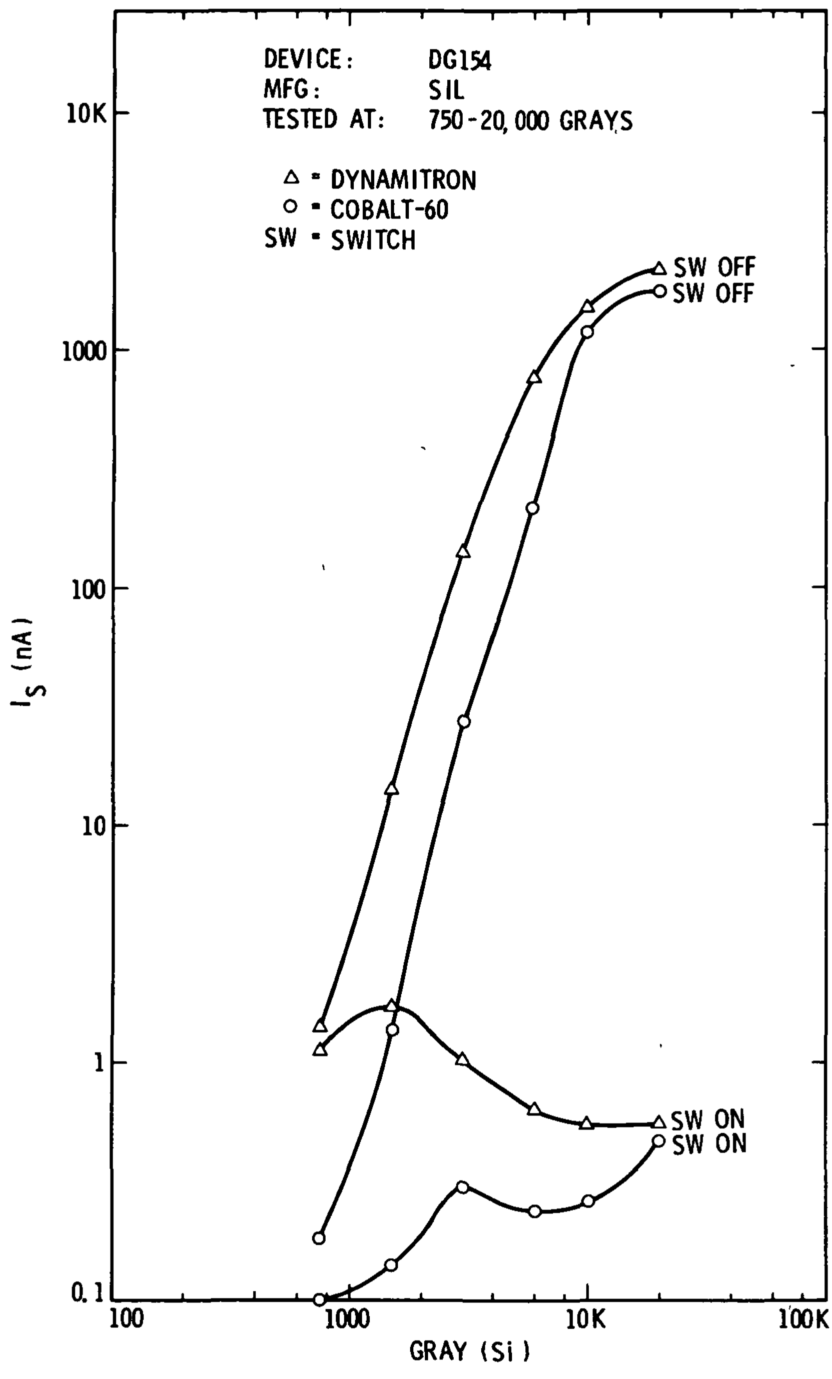

Figure 27. Comparison of I_S Degradation, DG154 FET Input Switch - DPST(2); 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

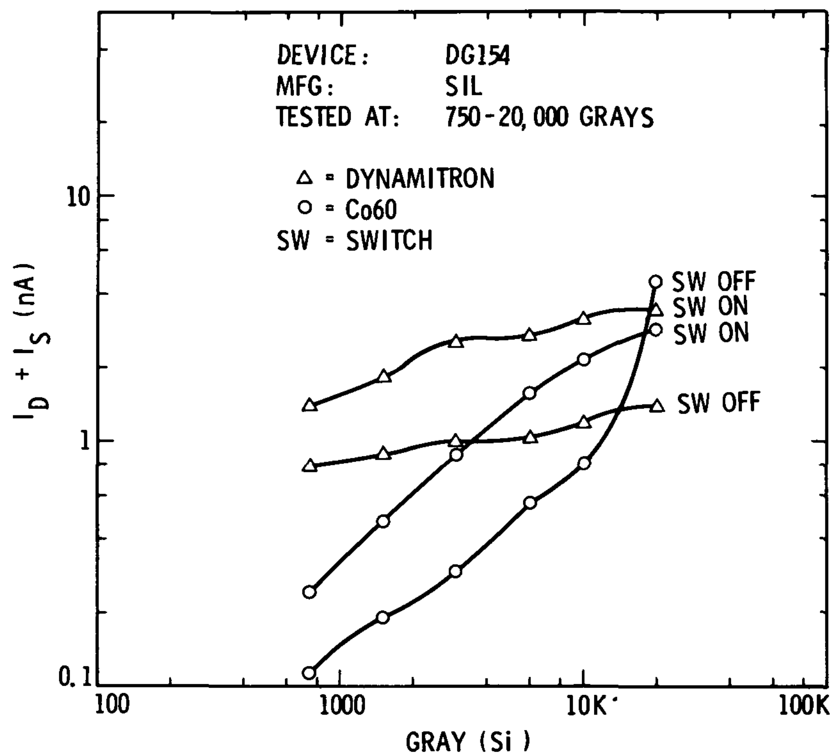

Figure 28. Comparison of $I_D + I_S$ Degradation, DG154 FET Input Switch - DPST(2); 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

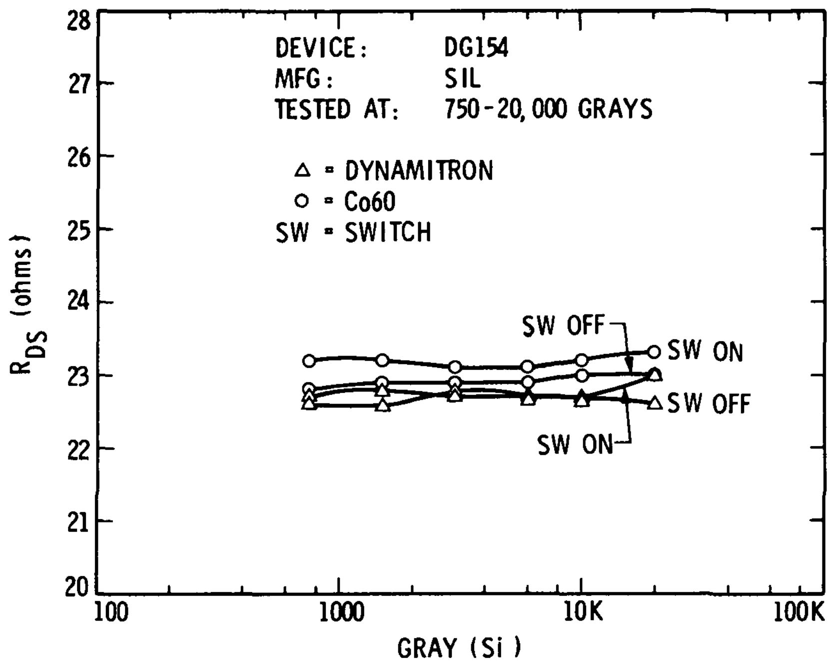

Figure 29. Comparison of R_{DS} Degradation, DG154 FET Input Switch - DPST(2); 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

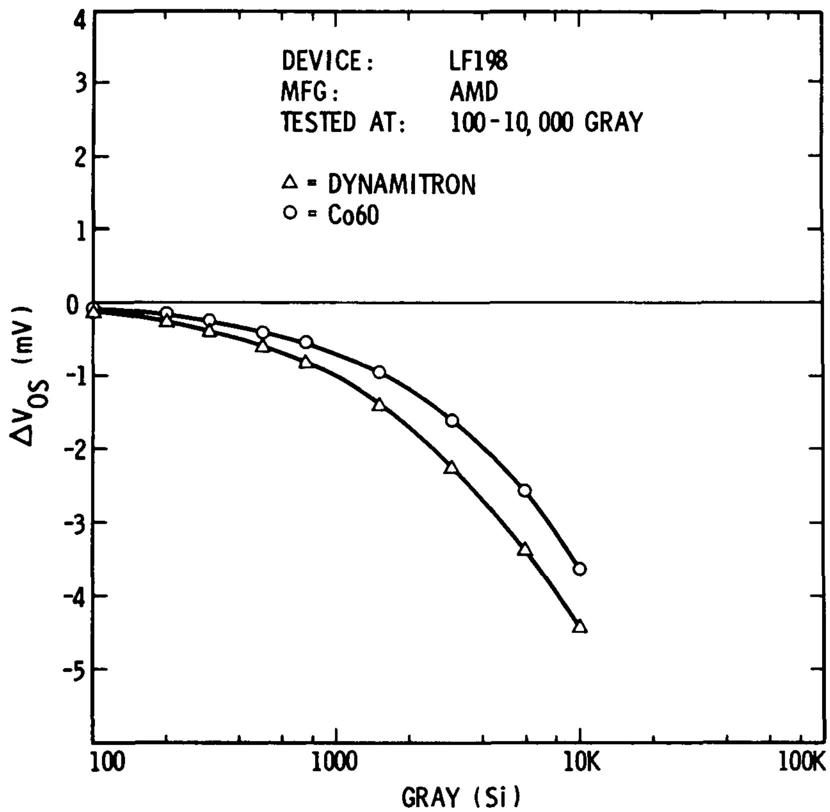

Figure 30. Comparison of ΔV_{OS} Degradation, LF198 FET Input Sample and Hold; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

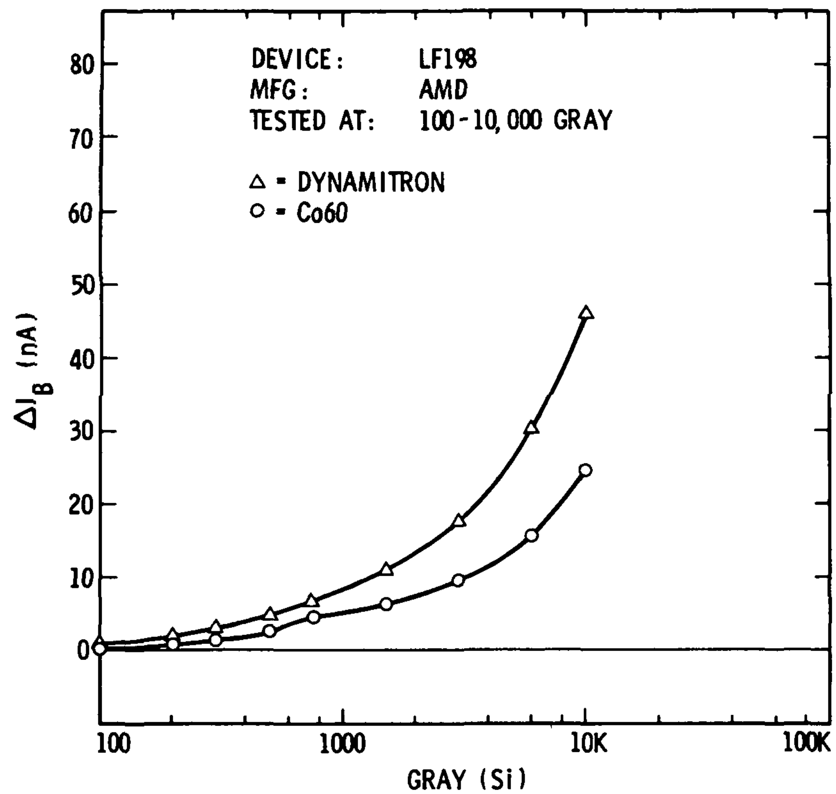

Figure 31. Comparison of ΔI_B Degradation, LF198 FET Input Sample and Hold; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

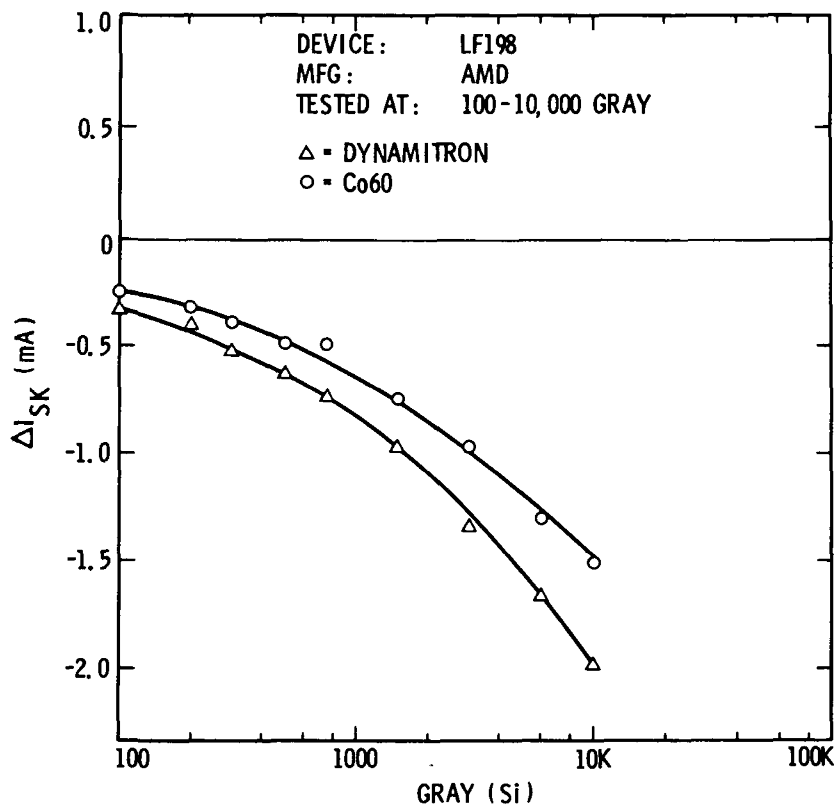

Figure 32. Comparison of ΔI_{SK} Degradation, LF198 FET Input Sample and Hold; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

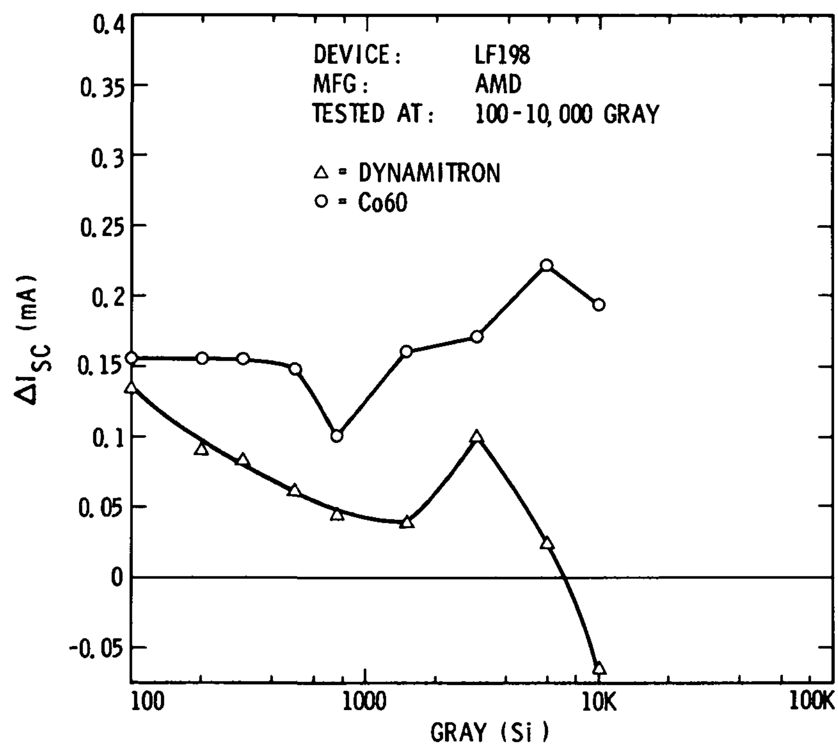

Figure 33. Comparison of ΔI_{SC} Degradation, LF198 FET Input Sample and Hold; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

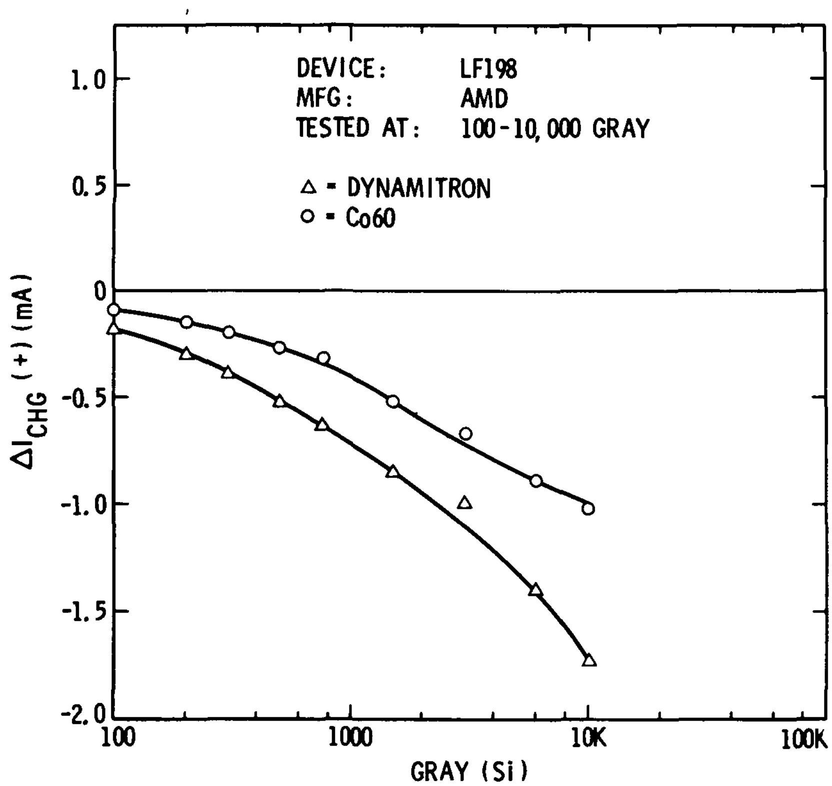

Figure 34. Comparison of $\Delta I_{CHG}(+)$ Degradation, LF198 FET Input Sample and Hold; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays

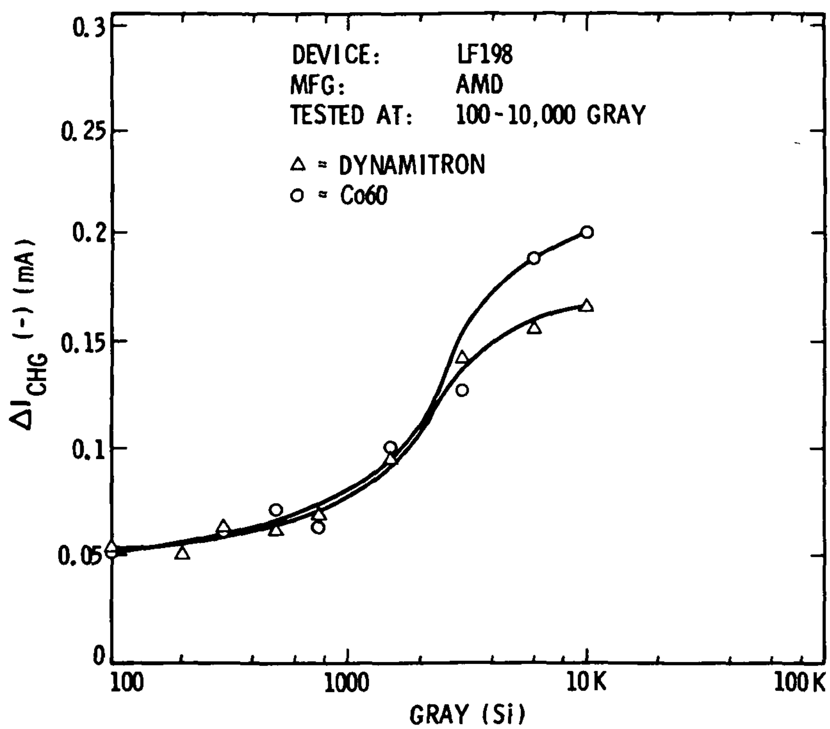

Figure 35. Comparison of $\Delta I_{CHG}(-)$ Degradation, LF198 FET Input Sample and Hold; 2.2-MeV Electrons vs Cobalt-60 Gamma Rays