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THE EFFECTS OF GAMMA AND NEUTRON IRRADIATIONS ON LINEAR INTEGRATED CIRCUITS AND POWER DEVICES

A Thesis

Presented for the

Master of Engineering

Degree

The University of Tennessee, Knoxville

David K. Su

March 1985

ACKNOWLEDGEMENTS

The author wishes to acknowledge the guidance and collaboration of Dr. E.J. Kennedy throughout this research. Special thanks go to Drs. T.V. Blalock and J.M. Rochelle for their participation on the thesis committee and for their invaluable advice. Dr. T.F. Williams and his assistants are acknowledged for providing the gamma irradiation facility.

This research was sponsored by the Department of Energy contract No. W-7405-ENG-26 to the Oak Ridge National Laboratory, and Subcontract No. 7685 to the University of Tennessee, Knoxville.

ABSTRACT

A variety of linear integrated circuits and power devices were irradiated with gamma rays and neutrons to determine total dose effects. Several operational amplifiers, voltage comparators, buffers, voltage references, power bipolar transistors, voltage rectifiers, transistor arrays, and monolithic breadboard components were identified with radiation hardness exceeding one megarad and $5X10^{13}n/cm^2$. The linear integrated circuits and power devices tested were separated into four categories depending on their radiation tolerance. The changes in the electrical parameters of the devies were examined. In general, the bipolar devices demonstrated greater radiation hardness than devices utilizing either JFET, MOS, or CMOS circuitry.

TABLE OF CONTENTS

PAGE

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

FIGURE		PAGE

CHAPTER 1

INTRODUCTION

Radiation-hardened electronics have wide applications in nuclear reactor instrumentation, space probes, and military requirements. Instruments in such radioactive environments must be able to withstand the total accumulated dose of both gamma and neutron irradiations over their required operating life span. With adequate shielding the instantaneous dose rate has little effect on the device performance, if kept below 10^5 rad/min[1]. Much work has been performed on the effects of both gamma and neutron irradiations for discrete devices, and in recent years on integrated circuits[1-5]. In this research, the radiation effects on a variety of integrated semiconductors are investigated.

1.1 Purpose of Study

According to current literature, there are two major categories of radiation-tolerant components[5]. The first category contains components that were specifically designed to operate in radiation environment. Very limited number of devices in this category is commercially available. The second category covers standard commercial electronics that are more radiation-tolerant because of their design and fabrication processes. Included in this category is a wide variety of devices and circuits that are readily available at low commercial prices. However, care must be exercised when using these devices because the radiation tolerance of such devices can vary from lot to lot if changes were made in the manufacturing processes.

The purpose of this research is to identify radiation-hardened semiconductors among commercially available linear integrated circuits that can withstand a total gamma dosage of 1 megarad and a total neutron dosage of 10^{13} n/cm^2[6]. Selected operational amplifiers, voltage comparators, buffers, voltage references, voltage regulators, timers, rectifiers, MOS power transistors, and bipolar power transistors were tested both before, and after, exposure to gamma and neutron irradiations to determine their radiation tolerances.

1.2 Scope of Work

This thesis describes the testing and evaluation of several semiconductor devices and their characteristics before, and after, being irradiated. The arrangement of the thesis is as follows:

Chapter 2 is an overview of the effects of gamma and neutron irradiations on semiconductors as described in the current literature.

Chapter 3 outlines the experimental setup and testing procedures for the evaluation of the radiation effects.

Chapter 4 summarizes the test results.

Chapter 5 states some general conclusions from the experimental results and offers suggestions for further work.

The experimental data for all the devices are given in the appendices.

CHAPTER 2

AN OVERVIEW OF RADIATION EFFECTS

2.1 Introduction

This chapter is a survey of the current literature on radiation effects in silicon semiconductors. The emphasis is on the effects under low dose rates of gamma and neutron irradiations as related to this research. This overview serves as the basis for the subsequent chapters.

2.1.1 Gamma Rays [3,7]

Gamma rays are electromagnetic radiations that are emitted by nuclei and in nuclear reactions. As a nucleus undergoes radioactive decay, it is often left in an excited state. For a nucleus to return to the ground state, gamma rays are often emitted. The energy of the gamma ray is directly proportional to the difference in energy between the excited and the ground states.

Gamma photons have no rest mass and no electrical charge. They are not stopped as easily as alpha and beta particles. The absorption of gamma rays by a material can occur in three basic ways: photoelectric absorption, Compton-type collision, and pair production. All of these are ionizing processes in which free electrons, positively-ionized atoms, and positrons may be produced.

The unit for absorbed gamma radiation is the rad (radiation absorbed dose)[4]. One rad is equivalent to 100 ergs or 10^{-5} joules of absorbed energy per gram of material. Silicon will be the referenced material throughout this thesis. Therefore:

1 rad(Si) = 100 ergs/g of silicon = 10^{-2} J/kg of silicon.

The radiation dose rate is usually given in rads(Si) per unit time.

2.1.2 Neutron Irradiation [3,4]

Neutrons are neutral atomic particles with rest mass of about 1 atomic mass unit. They are emitted by the nuclei of the atoms during nuclear fission and fussion processes.

A free neutron interacts with the nuclei of a material by scattering and absorption processes. In scattering collisions, a silicon atom may be displaced from its normal position in the lattice generating a vacancy and an interstitial. In absorptions, the neutron is absorbed by the nucleus of an atom (such as gold) to form an excited compound nucleus. The excited nucleus in turn may emit atomic particles such as protons, alpha, beta and gamma rays. The emitted particles, the scattered neutrons, and the re-coil atoms can cause ionization and further collisions.

The total dose of a neutron irradiation is typically given by the number of incident neutrons per cm^2 of the material.

2.2 Basic Radiation Effects

The two fundamental radiation effects on semiconductors are displacements and ionizations. For most devices, since the absorption lengths of the incident radiation are much larger than the dimensions, uniform dose rates can be assumed throughout the devices[8].

2.2.1 Displacement Damage

Displacement is the process by which an atom is displaced from its normal lattice position by the incident radiation creating a vacancy and an interstitial defect in the crystal lattice. Such damages are primarily caused by fast neutrons. Electrons generated from gamma ray ionization are less effective in causing displacement damage[3].

Vacancies and interstitial defects in the crystal lattice act as acceptors, donors, and recombination centers with energy levels within the forbidden gap of semiconductors[4]. Such defects cause:[3]

(i) a decrease in the majority carrier density. Carriers (electrons in the conduction band and holes in the valence band) are trapped at the energy states in the forbidden gap.

(ii) a decrease in the mobility of the majority carriers. Mobility of a semiconductor is determined by the frequency of lattice and impurity scattering[9]. Introduction of the additional ionized acceptors and donors by the radiation effects causes more impurity scattering and thus a reduction in carrier mobility.

(iii) a decrease in the minority carrier lifetime. Minority carrier lifetime is inversely proportional to the density of recombination centers. As the number of recombination centers increases with radiation damage, minority carrier lifetime decreases.

In general, displacement damage in silicon tends to make the semiconductor more intrinsic[3]. A summary of the effects of displacement damage on some discrete devices is given in Table 2-1.

Table 2-1 Summary of displacement damage to semiconductors.

	DISPLACMENT DAMAGE
CAUSE	Fast neutrons with energy > 1 Mev Energetic electrons with energy > 250 kev
RESULTS	Vacancies and interstitial atoms that act as acceptors, donors, and recombination centers.
PRIMARY EFFECTS	1. Decrease in carrier density 2. Decrease in carrier mobility 3. Decrease in minority carrier lifetime
SECONDARY EFFECTS	1. Decreased bipolar current gain 2. Increased bipolar turn-on time 3. Decreased bipolar storage time 4. Increased bipolar saturation voltage 5. Increased bulk resistance 6. Increased junction dynamic "ON" resistance 7. Increased junction breakdown voltage 8. Increased junction "ON" voltage 9. Increased channel resistivity (FETs) 10. Increased junction leakage current 11. Decreased transconductance (FETs) 12. Shifted V-I characteristics (Unijunctions)

2.2.2 Ionization Damage

Ionization is the process of removing electrons from their parent atoms and thereby producing positive ions plus free electrons [3]. Photon interactions due to gamma rays are the dominant ionization processes. Ionization is also produced as a secondary effect of neutron irradiation. The damage due to ionization can be classified into two groups:

(i) Transient damage due to photocurrent effects.

(ii) Surface damage in silicon-silicon dioxide interfaces.

2.2.2.1 Photocurrent Effects

Transient damage due to ionization occurs in the biased p-n junctions of semiconductors as photocurrents[3]. Excess carriers are generated uniformly throughout the semiconductor by the ionization process. These excess carriers in the depletion region of a p-n junction are swept out of the junction by electric fields to form drift currents. Any excess carriers generated within a few diffusion lengths of the junction diffuse to the junction to form diffusion currents. Drift and diffusion currents due to the generated carriers are referred to as the primary photocurrents and are directly proportional to the dose rate and the geometry of the p-n junction.

For bipolar transistors, if the base of the transistor is effectively an open circuit, primary photocurrent in the base will be amplified by the current gain of the bipolar transistor. Secondary photocurrent refers to the sum of the primary photocurrent and any additional current due to the current-multiplication action of the transistor. These photocurrents can be minimized by keeping the transistor in the off-state during a radiation pulse with a compensation diode across the base-emitter junction[3]. Another way to reduce secondary photocurrent is to keep the resistance at the base of a transistor low so that the primary photocurrent will be removed through the base resistance instead of the base-emitter junction[8].

Effects of photocurrents can be made negligible at low radiation dose rates with careful design. Furthermore, this is a transient effect that decays rapidly after the radiation pulse is removed. The effects of the photocurrents on the performances of analog and digital microcircuits can be predicted by computer simulations using primary photocurrent generators[8].

2.2.2.2 Silicon Silicon-Dioxide Interface Damage

This ionization effect is important in the gate oxides of MOS devices and in the passivation layers of bipolar devices[1]. Compared to the photocurrent effects, interface damages are much more stable and could persist indefinitely after a radiation source has been removed. Two mechanisms are involved in this process:

(i) buildup of positive charges in the silicon dioxide layer of the interface, and

(ii) creation of surface states at the interface.

During ionization processes, holes and electrons are generated uniformly throughout an oxide layer. Electrons, being highly mobile, are swept out of the oxide layer by any applied electric field such as an external applied bias or the barrier potential of an p-n junction near the oxide[2,3]. Because of their lower mobility in the oxide, the holes drift toward the interface at a much slower speed. While most of the holes recombine with electrons, a fraction of them are captured by traps that exist within a few hundred angstroms of the interface[2]. This action results in a net buildup of trapped positive charge.

The position and the magnitude of trapped positive charges within the oxide depends on the location and nature of the traps, thickness of the oxide, applied oxide electric field, and total gamma radiation dosage[1,2]. Magnitude of the positive charge is maximum when the applied electric field causes holes to move toward the interface. For doses less than 10^5 to 10^6 rad(Si), the amount of excess positive charge buildup increases linearly with total dosage. At higher doses the damage effects begin to saturate[1].

At high total doses, surface (interface) states are generated within a few angstroms of silicon-silicon dioxide interfaces [1]. These interface states are induced energy states in the forbidden gap that act like a high-density layer of recombination centers located at the interface[10]. Density of interface states depend on the presence of bias voltage, oxide thickness, irradiation temperature, and processing techniques used during fabrication [1,3,11]. Negatively-charged interface states tend to compensate for the positive charges trapped in an oxide layer by repelling electrons from the interface[3]. There are numerous proposed mechanisms to explain the introduction of these interface states and their occupations by trapped electrons[1,2,10,11].

Unlike neutron damage, surface effects are harder to predict because of their high dependency on the processing techniques. Table 2-2 summarizes the surface damage effects of ionization on semiconductor devices.

2.2.3 Annealing Effects

The time dependent response of an irradiated device is an important phenomenon known as annealing[1]. Changes in the device

Table 2-2 Summary of surface damage due to ionization in semiconductors.

	IONIZATION (SURFACE DAMAGES)
CAUSES	Gamma rays Fast neutrons
RESULTS	1. Positive charge buildup 2. Negative interface states
EFFECTS	1. Decreased bipolar current gain 2. Increase junction leakage current 3. Increased bulk resistance 4. Decreased junction breakdown 5. Negative shift in MOS threshold voltage 6. Increased channel propagation delays (MOSFETs) 7. Decreased transconductance (FETs) 8. Increased drain-source "ON" resistance 9. Decreased saturation drain current (JFETs)

parameters immediately following an irradiation can be substantially greater than that measured at some later time. Radiation defects due to displacements and ionizations may disappear through vacancy-interstitial recombination, trapped hole and electron recombination and migration of defects to a free surface[3]. These processes are strong functions of temperature. At elevated temperatures, due to the increased mobility of defects and free electrons, the annealing process is accelerated and enhanced.

Annealing is usually described in two phases: short-term and long-term. Short-term annealing due to displacement damage, or an impulse of ionizing radiation, occurs in a few milliseconds to a few seconds[1,3]. At a fixed temperature, the long-term annealing of displacement damage is complete after about 30 minutes[3]. However if the temperature is increased, further annealing may occur. Annealing of ionizing radiation effects is primarily due to thermal untrapping of holes. The magnitude of ionization damage generally decreases as the logarithm of time depending on ambient temperature [1].

Besides ambient temperature, rate of annealing is also affected by the presence of radiation and applied bias. Enhanced rates of annealing during re-irradiation of both planar bipolar and MOS transistors were observed after removal of the applied bias[1]. This could be attributed to the injection of free electrons from the silicon into the oxide to neutralize existing trapped holes in the absence of a bias voltage.

2.3 Effects of Radiation on Semiconductor Devices

For low dose rates, the major radiation effects are due to displacement damage and surface damages at the silicon-oxide interface. The following is a brief summary of radiation effects on semiconductor devices.

2.3.1 Bipolar Transistors

The most prominent radiation effect of bipolar transistors is a reduction in transistor current gain. This reduction can be caused by both displacement and surface damage. As described earlier, displacement damage causes a decrease in the minority carrier lifetime and thereby results in a reduction of transistor gain[4]. In ionization, degradation of current gain is a direct interaction of carriers with interface states and the indirect effect of positive charge buildup[10]. Interface states act as a high-density layer of recombination centers that increases base currents and degrades transistor gain. Positive charges deposited near the emitter-base junction change the equilibrium carrier densities below the oxide layer and thereby alter recombination statistics for the interface states and nearby bulk recombination centers.

Besides transistor gain degradation, several other secondary effects can be observed in bipolar devices. Junction leakage currents are increased by both displacement and surface damage[2,4]. Displacement can also result in increased collector-emitter saturation voltage, increased breakdown voltage, increased turn-on time, increased bulk resistance, and decreased storage time[4]. Surface damage due to ionization tends to increase the bulk emitter and collector resistances, increase junction capacitance, and decrease junction breakdown voltage[2].

2.3.2 Metal-Oxide-Semiconductor (MOS) Devices

The threshold voltages of MOS transistors are very sensitive to surface damage of ionizing radiation. Positive trapped charge in the gate oxide induces a negative shift in threshold voltages of both the n-channel and p-channel devices[2]. The positive charge trapped in the gate oxide induces a negative charge below the oxide by attracting electrons. As a result, less positive applied gate voltage is needed to turn-on and-off the n-channel and p-channel devices, respectively. In n-channel devices that are operated with a positive gate bias, trapped oxide charges are repelled by the gate and therefore lie much nearer to the interface. A much greater change in the gate bias is needed to neutralize the trapped charges in the n-channel MOSFETs since it is located closer to the interface. Thus, the worst-case condition for a n-channel MOSFET is a static ON bias. Similarly, the worst-case condition for a p-channel MOSFET is a static OFF bias.

The buildup of interface states at high dosage can decrease the channel mobility and increase propagation delays[1]. Occupancy of these interface states by electrons can also compensate for the positive charge buildup and reverse the shift in the threshold voltages.

The shift in the threshold voltage is usually accompanied by an increase in the gate leakage current. In addition, the transconductance of a MOS transistor is decreased due to a decrease in carrier mobility. Similarly, other conduction factors such as drain-source ON resistance are also degraded[2].

Displacement damage on MOS devices is not as severe a problem[3]. Displacement damage reduces the density of the majority carriers in the substrate making it easier to form the channel between the source and the drain. That is, less voltage is needed to form the channel. In addition, the defects in the channel region act as scattering centers that reduces the carrier mobility and increases the drain-source ON resistance.

2.3.3 Junction Field-Effect Transistors (JFETs)

JFETs have the potential of being more resistant to radiation than either bipolar or MOS devices[4]. JFETs are relatively insensitive to effects of ionizing radiations[2,4]. Gate leakage can increase due to an increase in interface states. The transconductance and saturation drain current tend to decrease due to a reduction in the carrier mobility in the channel[2].

Displacement damage on JFETs are mainly due to the reduction in the channel doping. This results in a decrease in the transconductance, pinch-off voltage, and pinch-off current[4].

2.3.4 Linear Integrated Circuits

The radiation effects on linear integrated circuits have been extensively studied[5,12-17]. Much of this work was concentrated on general-purpose operational amplifiers, such as the LM108. All data indicated that both gamma and neutron irradiatons would cause decreases in the open-loop gain, slew rates, and gain-bandwidth products. Increases in offset voltages, input and offset currents, and reductions in output current drive were also observed.

CHAPTER 3

EXPERIMENTAL SETUP AND TESTING PROCEDURES

3.1 Introduction

Several semiconductor devices were irradiated with both gamma rays and neutrons. These devices included operational amplifiers, voltage comparators, buffer/drivers, voltage references, voltage regulators, timers, power bipolar transistors, power MOSFETs, rectifiers, transistor arrays, and monolithic breadboard components. A listing of all the devices tested are given in Tables 3-1 through 3-10. These devices were evaluated prior to and following the irradiations to determine their radiation tolerances.

For a typical radiation-hardened system, low-power devices such as operational amplifiers, buffers, voltage comparators, timers, transistor arrays, monolithic breadboard components are candidates for signal processing, control and communications. Voltage regulators and references are needed for power supply designs. The power transistors and rectifiers are needed for the switched-mode power supply and servo-amplifers. Two types of power MOSFETs were tested. These devices could be utilized for off-line switches in dc-dc converters. The 200V breakdown devices would be suitable for bridge converters, while 400V breakdown devices would be required for flyback-type converters. From the discussion in Chapter 2, bipolar transistors are more tolerant to gamma rays, however not as tolerant to high neutron irradiation. On the other

Table 3-1 A listing of the operational amplifiers tested.

Device Name	Descriptions
CA3140(RCA)	MOSFET input(BiMOS); 4.5MHz GBW
HA2505(Harris)	Bipolar; 12MHz GBW; Dielectric Isolation
HA2525(Harris)	Bipolar; 20MHz GBW; Dielectric Isolation; Av>3
HA2539(Harris)	Bipolar; 600MHz GBW; Dieletric Isolation; Av>10
HA2540(Harris)	Bipolar; 400MHz GBW; Dieletric Isolation; Av>5
HA2625(Harris)	Bipolar; 100MHz GBW; Dieletric Isolation; Av>5
HA4640(Harris)	Quad; Bipolar; Dieletric Isolation; High Temp(>250^{o}C)
HA5084(Harris)	Quad; JFET input(BiFET); Dieletric Isolation; 4MHz GBW
HA5135(Harris)	Bipolar; Superbeta input; Precision; 2.5MHz GBW; Dielectric isolation
ICL7621(Intersil)	Dual; low-power CMOS
LF351(National)	FET input(BiFET); General purpose; 4MHz GBW
LF353(National)	Dual; FET input(BiFET); General purpose; 4MHz GBW
LT1012(Linear Tech)	Bipolar; Low-power
LT1037(Linear Tech)	Bipolar; Low-noise; Precision; Av>5
NE5534(Signetics)	Bipolar; Low-noise; General purpose; Av>3
OP11(PMI)	Quad; Bipolar; 741-type; General purpose
OP15(PMI)	JFET input(BiFET); General purpose; 6MHz GBW
OP16(PMI)	JFET input(BiFET); General purpose; 8MHz GBW
OP17(PMI)	JFET input(BiFET); 30MHz GBW; Av>5
OP22(PMI)	Bipolar; Programmable; Low-power; Single or dual power supplies
OP27(MPS)	Bipolar; Precision; Low-noise; 8MHz GBW
OP27(PMI)	Bipolar; Precision; Low-noise; 8MHz GBW
OP32(PMI)	Bipolar; Programmable; Low-power; Single or dual power supplies; Av>10
OP37(PMI)	Bipolar; Precision; Low-noise; 63MHz GBW; Av>5
OP215(PMI)	Dual; JFET input(BiFET); General Purpose; 6MHz GBW
OPA111(Burr Brown)	JFET; Precision; Low-noise; I_B<1pA; Dielectric isolation
TLC251(Texas Instr)	CMOS
1344(Philbrick)	JFET input(BiFET);100MHz GBW; Dielectric isolation; Av>10

Table 3-2 A listing of the voltage comparators tested.

Device Name	Descriptions
CMP01(PMI)	Bipolar; ton<150ns; TTL output; LM311 equivalent
CMP04(PMI)	Quad; Bipolar; LM339 equivalent
CMP05(PMI)	Bipolar; ton<40ns; +5V P.S.; TTL output; uA710 equivalent
LM311(National)	Bipolar; Standard Comparator; open-collector output

Table 3-3 A listing of the buffer/drivers tested.

Device Name	Descriptions
BUF03(PMI)	JFET input(BiFET); 250 V/us; 60MHz; 70 mA output
HA5033(Harris)	Bipolar; 1V/ns; 250MHz; 100mA output
TSC428(Teledyne)	MOS driver; 1.5A output

Table 3-4 A listing of the voltage references tested.

Device Name	Descriptions
AD584 (Anal Dev)	Bipolar; Programmable(2.5V-10V); Precision; 15ppm/^oC
ICL8069(Intersil)	Bipolar; 1.22V bandgap; Precision; 20ppm/^oC
LM336Z(National)	Bipolar; 2.5V bandgap; Precision; 20ppm/^oC
TL430(Texas Instr)	Bipolar; 2.5V bandgap; shunt regulator; 100ppm/^oC

Table 3-5 A listing of the voltage regulators tested.

Device Name	Descriptions
LM317(National)	Bipolar; Adjustable positive regulator; 1.5A(+1.2V to +37V)
LM337(National)	Bipolar; Adjustable negative regulator; 1.5A(-1.2V to -37V)
MC7812(Motorola)	Bipolar; +12V regulator; 1A output
MC7912(Motorola)	Bipolar; -12V regulator; 1A output
UA7912(Fairchild)	Bipolar; -12V regulator; 1A output

Table 3-6 A listing of the timers tested.

Device Name	Descriptions
ICM 7555(Intersil)	CMOS timer
L555(Exar)	CMOS timer
TLC555(Texas Instr)	CMOS timer
UA555(Fairchild)	Bipolar timer

Table 3-7 A listing of the bipolar power transistors tested.

Device Name	Type	BV_{CEO}	$f_T(I_C)$	I_C at $H_{FE}(max)$	Remarks
LT1839(TRW)	NPN	70V	1.3GHz(50mA)	--	Med-power RF (2.5W)
MRF531(MOT)	NPN	100V	800MHz(50mA)	--	Med-power RF (2.5W)
D44C11(GE)	NPN	80V	50MHz(20mA)	150mA	Power bipolar (30W)
D45C8(GE)	PNP	60V	40MHz(20mA)	150mA	Power bipolar (30W)
D44H11(GE)	NPN	80V	50MHz(500mA)	1A	Power bipolar (50W)
D45H11(GE)	PNP	80V	40MHz(500mA)	1A	Power bipolar (50W)
MJ4237(MOT)	PNP	120V	75mHz(800mA)	1A	Power bipolar (90W)
MJ4247(MOT)	NPN	120V	75MHz(800mA)	1A	Power bipolar (90W)
MJ13080(SOL)	NPN	400V	--	1A	Power bipolar (150W)
MJE5221(MOT)	NPN	80V	--	1.3A	Power bipolar (83W)
MJE5231(MOT)	PNP	80V	--	1.3A	Power bipolar (83W)
MPSU05(MOT)	NPN	60V	150MHz(250mA)	100mA	Power bipolar (10W)
MPSU55(MOT)	PNP	60V	100MHz(250mA)	100mA	Power bipolar (10W)
2N6338(MOT)	NPN	100V	40MHz(1A)	--	Power bipolar (200W)
2N6339(SOL)	NPN	120V	40MHz(1A)	--	Power bipolar (200W)
2N6436(MOT)	PNP	80V	40MHz(1A)	2A	Power bipolar (200W)
2N6438(MOT)	PNP	120V	40MHz(1A)	2A	Power bipolar (200W)
2N6385(MOT)	NPN	80V	---	4A	Darlington (100W)
2N6385(RCA)	NPN	80V	---	4A	Darlington (100W)
2N6650(RCA)	PNP	80V	---	4A	Darlington (100W)

Table 3-8 A listing of the enhancement-mode power MOS transistors tested.

Device Name	Type	BV_{DS}	R_{ON}(max) in ohm	I_D (cont.)	Remark
IRF250(IRC)	N-ch	200V	0.085	30A	Power MOSFET (150W)
IRF250(MOT)	N-ch	200V	0.085	30A	Power MOSFET (150W)
IRF250(SIL)	N-ch	200V	0.085	30A	Power MOSFET (150W)
IRF430(MOT)	N-ch	500V	1.5	4.5A	Power MOSFET (75W)
IRF450(IRC)	N-ch	500V	0.4	13A	Power MOSFET (150W)
IRF450(SIL)	N-ch	500V	0.4	13A	Power MOSFET (150W)
MTM15N45(MOT)	N-ch	450V	0.5	15A	Power MOSFET (250W)
RFP3N45(RCA)	N-ch	450V	3	--	Power MOSFET
VN0600D(SIL)	N-ch	60V	0.12	18A	Power MOSFET (75W)

Table 3-9 A listing of the rectifiers tested.

Device Name	Descriptions
CTB34(Sanken)	Dual Schottky, 30V, 10A.
MBR745(MOT)	Schottky barrier rectifier; 45V, 7.5A.
MR854(MOT)	Fast recovery rectifier; 400V, 3A.

Table 3-10 A listing of the transistor arrays and monolithic breadboard components tested.

Device Name	Descriptions
CA3127E(RCA)	Bipolar; 5 NPNs; 1200MHz, BV_{CEO}=15V
CA3146(RCA)	Bipolar; 5 NPNs; 600MHz, BV_{CEO}=40V
CA3183(RCA)	Bipolar; 5 NPNs; 300MHz, BV_{CEO}=40V
SL3145C(Plessey)	Bipolar; 5 NPNs; 2500MHz, BV_{CEO}=8V
MO-003A(Interdesign)	Bipolar; 4 lateral PNPs
MO-004(Interdesign)	Bipolar; 2 small NPNs + 2 large NPNs
MO302B(Interdesign)	Bipolar; 5 NPNs + substrate PNP for RTL circuits
MO415(Interdesign)	CMOS; 2 N-channels + 2 P-channels
MO417(Interdesign)	CMOS; N-channel Driver + zener + p-resistors

hand, MOS devices are more suitable for neutron irradiation but less useful in high gamma dose applications. A wide range of bipolar power transistors (up to 400V collector-emitter breakdown) were tested. These bipolar devices could possibly be used for dc-dc converters if the MOS devices fail to meet the required radiation-hardness.

3.2 Radiation Test Setups

3.2.1 Gamma

The effect of the total accumulated gamma dose has been demonstrated to be independent of the dose rate for rates less than 10^5 rad/min[1]. A cobalt-60 source can thus be used to simulate the effect of the total gamma dose of the devices over their life-spans in a few hours.

The gamma radiation was provided by a Gammacell 200 Cobalt-60 source located at the Chemistry Department, UTK. The stainless steel test chamber is cylindrical with a height of 7.3 inches and a diameter of 3.5 inches. The central dose at the geometric center of the test chamber was certified by the Atomic Energy of Canada, Ltd. on September 14, 1971 to be $4.63 \times 10^5 \pm 0.24\%$ rads/hr decreasing by about 25% at the sides of the chamber[2]. Assuming a simple exponential time decay factor with a half-life of 5.3 years and allowing for a 25% variation within the chamber, the minimum dose rate on July 11, 1984 through August 31, 1984 was approximately 6.3×10^4 rad/hr. To obtain a minimum total dose of 1 megarad, 16 hours of gamma irradiation time was needed[18].

All the test samples were placed inside a cylindrical aluminum container with a diameter of 2.5 inches and a height of seven inches. Since the absorption of gamma rays by aluminum is low, very little shielding effect was introduced. All devices (with the exception of the power MOSFETs) were irradiated passively with all leads shorted with aluminum foil. To simulate the worst-case conditions for power n-channel MOSFETs, a positive gate bias voltage was applied from a 9V battery. Power supply connections to the devices being irradiated was possible through a spiraling access tube(I.D. 5/16 inch). The required length for the connecting wire was 8 feet. A twisted pair of polyvinyl chloride (PVC) insulated Alpha type B wire was used because of its resistance to gamma rays[2].

After irradiation, to minimize the thermal annealing effects devices were stored in a refrigerator at about 35°F.

All devices were irradiated for at least 2 megarads. Promising devices such as the OP27 operational amplifier were irradiated up to a total of 4 megarads.

3.2.2 Neutron

In the neutron tests, tolerance of different devices to a total of 10^{13}n/cm^2 were determined. The annealing factor between the irradiation and testing of devices was estimated to be approximately five[5]. Therefore, a total dose of $5X10^{13}$n/cm^2 was chosen.

The neutron irradiation was performed at the Bulk Shielding Reactor (BSR) at the Oak Ridge National Laboratory. The devices were irradiated in the D3-2 hole at the BSR, which is a 3-1/4-inch I.D. dry tube approximately 25 inches from the neutron source. With the Bulk Shielding Reactor at full power (2 megawatts), the anticipated dose rate of the D3-2 source is as follows:[19].

(i) fast neutron flux of $2.3X10^9 n/cm^2/sec$,

(ii) thermal neutron flux of $1X10^{12} n/cm^2/sec$,

(iii) gamma dose rate of $3.3X10^2$ rads/sec.

For the experiment the reactor was operated at 1 megawatt (half power). Devices to be irradiated were placed in polyethelene bottles having a diameter of 2 inches and a height of 5 inches. After allowing about 15 minutes for the reactor to stabilize, the bottles were exposed to the neutron source for 100 seconds to give a total dose of $5X10^{13} n/cm^2$.

Due to the interaction of neutrons with the devices, beta- and gamma-rays were emitted from the devices. The decay of the radiation occurred in two phases. The fast decay had a half-life of about 10 minutes while the half-life of the slow decay was approximately 1 day. The devices were kept in a storage cell (at 25^0F) for about one week until the radiation had decayed to a non-hazardous level before post-irradiation evaluations were conducted.

3.3 Evaluation of Device Performances

The evaluation of the characteristics of the semiconductor devices were made prior to and after irradiations. The following is a description of the testing procedures used.

3.3.1 Operational Amplifiers

The data were primarily obtained utilizing the Tektronix 577 curve tracer and the 178 linear IC test fixture. The power supplies for all devices were set at ±15V except for CMOS operational amplifiers ICL7621 and TLC251 which utilized ±8V power supplies.

The various steps to obtain offset voltages, input currents, gains, CMRRs, PSRRs, and supply currents were outlined in the 557 User's Manual[20]. The horizontal and vertical display for each test mode for the linear IC test fixture are summarized in Table 3-11. The sweep rate for the display was adjusted to be slow enough to eliminate phase shift effects. The sweep rate was typically set at approximately 0.05Hz. This test fixture was designed for testing unity-gain stable devices. However, due to the presence of stray capacitances, devices such as the OP17, OP37, HA2525, and OP32 were marginally stable without any compensation. For devices without an external compensation pin (such as the HA2539 and HA2540), a 0.1uF capacitor was used between the two inputs. This capacitor together with the resistance internal to the test fixture formed a lag-compensation network to ensure stability.

Table 3-11 Summary of vertical and horizontal displays of the linear IC test fixture

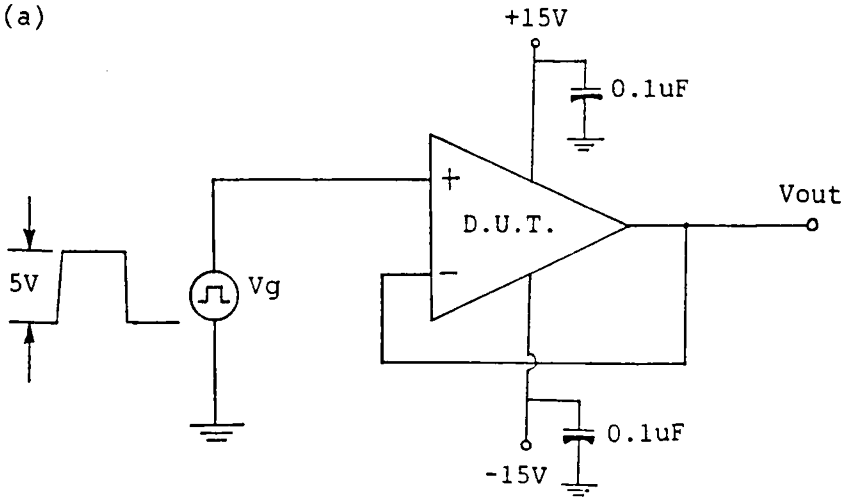
Function	Vertical Display	Horizontal Display
Offset Voltage	Differential Input Voltage	Output Voltage
Input Currents	Input Bias Currents	Common-mode Input Voltage
Gain	Change in differential Input Voltage*	Output Voltage
CMRR	Change in differential Input Voltage*	Common-mode Input Voltage
PSRR	Change in differential Input Voltage*	Supply Voltages
Supply Currents	Supply Currents	Supply Voltages

*Relative change in voltage only - no indication of absolute d.c. voltage level.

Photographs of the curve tracer displays were taken. The various dc characteristics were obtained from these photographs. The accuracies of the measurements were typically better than 10% except for large gains, CMRRs and PSRRs greater than 140dB, and for small currents less than 50pA.

The dynamic testing of slew-rates and gain-bandwidth products were performed using circuits shown in Fig. 3-1. The slew-rates were measured at either unity-gain or the minimum gain required to ensure stability. The gain-bandwidth product was

(a)



*All resistors in ohms.

(b)

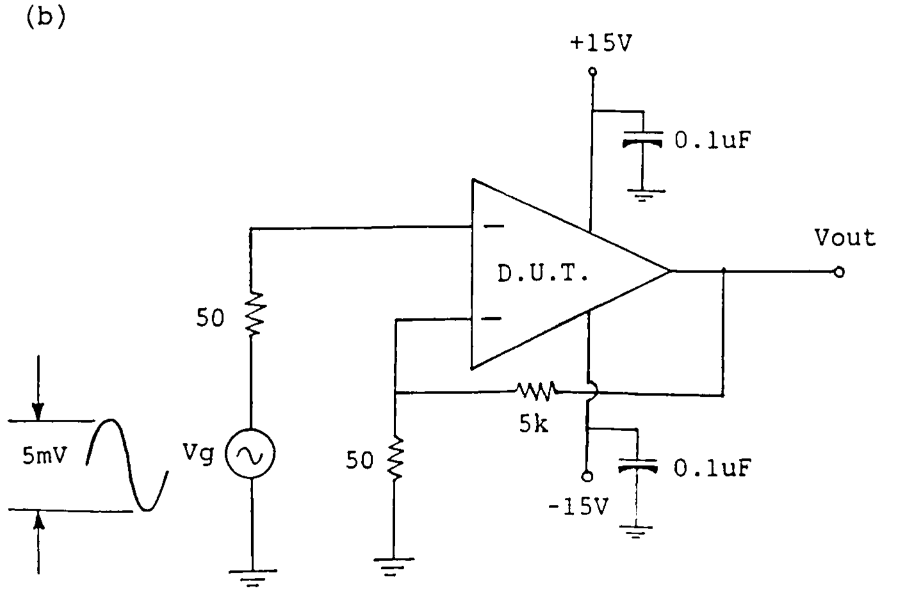


Fig. 3-1 Typical test circuits for measuring (a)slew-rates and (b)gain-bandwidth products of operational amplifiers.

obtained from the product of the -3db frequency corner and the circuit gain. The gain of the circuits were varied from 100 to 1000 to keep the frequency corner below 300KHz. The frequency corners were determined using a HP5614A frequency counter and a HP3400A RMS meter with verification from an oscilloscope. All the dynamic tests were wired on a protoboard with significant stray capacitances. Therefore, the measured slew-rate and bandwidth for some high-performance devices were lower than expected, but since the same test setups were utilized both before and after irradiations, changes due to radiation could be observed.

3.3.2 Comparators

Comparators CMP01 and LM311 were operated with $\pm$15V power supplies during testing while $\pm$5V power supplies were used for the CMP04 and CMP05 units. External pullup resistors were needed for the CMP04 and LM311 devices to provide a passive-pullup for their open-collector outputs.

The dc characteristics of the comparators, namely offset voltages, input currents, and supply currents were obtained using the Tektronix 577 curve tracer and the 178 linear IC test fixture in basically the same way as operational amplifiers. For measuring offset voltages, the connection of the inverting and non-inverting inputs to the test fixture were reversed. This resulted in a positive-feedback Schmitt-trigger type circuit. The magnitude of the offset voltage was given by the distance of the vertical axis intercept from the origin.

The test circuit for measuring response-time, rise-time, and output saturation voltages is shown in Fig. 3-2. The response-time was defined as the time from the zero-crossing of the input signal to 10% of the final output voltage. Due to the presence of stray capacitance and the finite rise-time of the input test signal, the measured parameters for some high-speed comparators were lower than expected but, as for the operational amplifier tests, the same circuit degradation was present both before and after irradiations.

3.3.3 Buffers/Drivers

The input currents, PSRRs, and supply currents of the buffers were obtained using the Tektronix 577 linear curve tracer and the 178 linear IC test fixture in the same manner as operational amplifiers. The dynamic characterisitcs of the buffers were obtained using the test circuit shown in Fig. 3-3. The propagation delay was measured from the 10% crossing of the input signal to 10% of the output signal.

3.3.4 Voltage References

The voltage references were measured using the Tektronix 577-177-D1 curve tracer as described in the operator's manual[21]. The TL430 adjustable shunt regulator was also tested using the circuit shown in Fig. 3-4 to give a nominal output of 24.75V. The programmable voltage references AD584 were tested at the four modes of operations to give 2.5V, 5.0v, 7.5V, and 10.0V outputs.

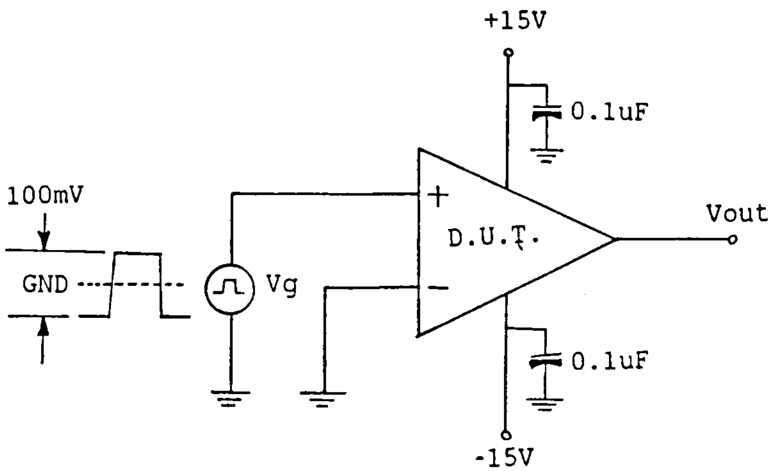


Fig. 3-2 Typical test circuit for measuring the characteristics of comparators.

*All resistors in ohms.

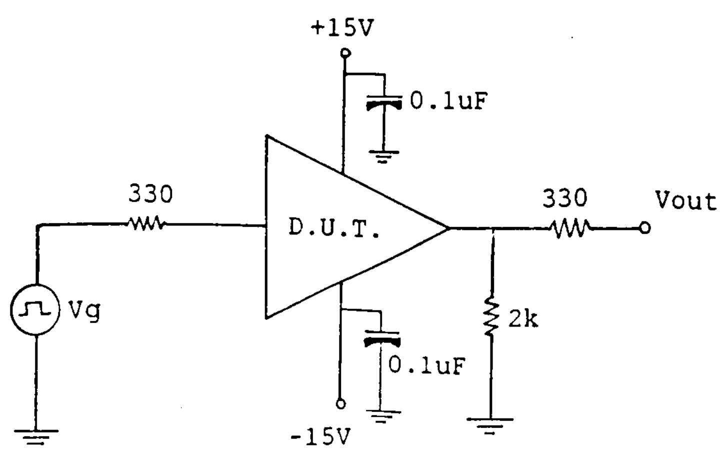


Fig. 3-3 Typical test circuit for measuring the characteristics of buffer/drivers.

3.3.5 Voltage Regulators

The regulators were tested for their line and load regulations. Line regulations were conducted using 30V, 25V, 20V, and 15V input voltages, and the load regulations were tested with 68 ohms, 110 ohms, 1.5 kohms, 2 kohms, and open loads. In addition, the adjustable regulators LM317 and LM337 were checked with test configurations for output voltages of 1.3V, 3.4V, 5.3V, 11V, and 22V.

3.3.6 Timers

The timers were tested with the circuit shown in Fig. 3-5. This circuit was designed to give a TTL-compatible output with a 45%-55% duty cycle at a nominal frequency of 100KHz. A 1 k-ohm pullup resistor and a 200 pF capacitor were used as the output load.

3.3.7 Power Transistors and Other Discrete Devices

The power bipolar and MOS transistors, transistor arrays, and monolithic breadboard components were tested using the Tektronix 577-177-D1 curve tracer as outlined in the User's Manual [21]. Photographs of the curve tracer displays were taken before and after irradiations. The current gains and other characteristics were obtained from these photographs.

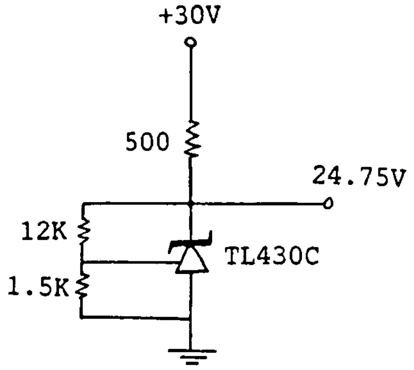


Fig. 3-4 Test circuit for TL430 adjustable shunt regulator to give a nominal output of 24.75V.

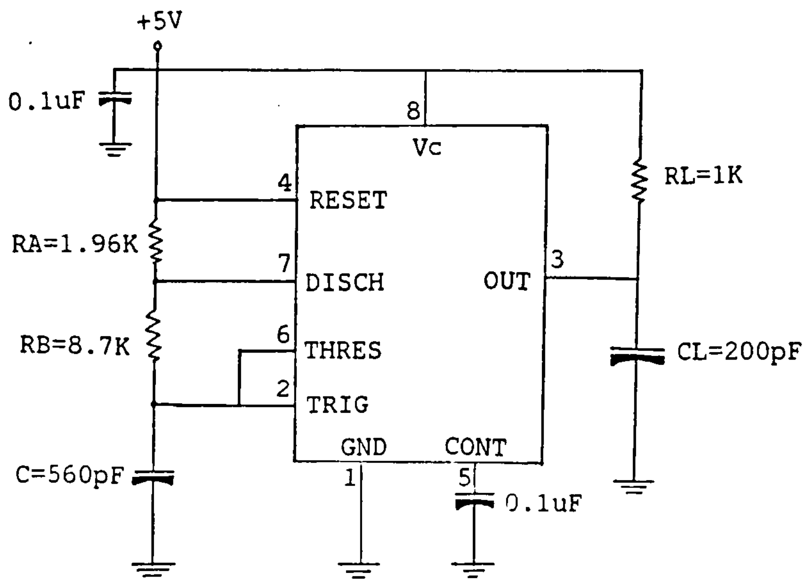


Fig. 3-5 Test circuit for timers to give a TTL-compatible output with a nominal frequency of 100kHz.

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 Introduction

This chapter presents the experimental results for the radiation tests performed on the various semiconductor devices. The major emphasis of the discussion will be on the effects of the gamma irradiations. Detailed experimental data for all the devices are provided in Appendix A.

4.2 Operational Amplifiers

A total of 28 types of operational amplifiers from a total of eleven manufacturers were tested. The sample size for each device varied from two to six. These operational amplifiers included bipolar, BiFET, FET, BiMOS, and CMOS devices using both dielectric isolation and junction isolation processes. These devices were first irradiated with gamma rays from a Cobalt-60 source at 1 megarad increments for up to 4 megarads total dose. The same devices were then subjected to a neutron irradiation dose of $5X10^{13}n/cm^2$.

The bipolar devices demonstrated good radiation tolerance. The bipolar operational amplifiers from Harris with dielectric isolation were shown to be radiation hard to several megarads without significant changes. Devices from Precision Monolithic Inc. also indicated no drastic changes. This is possibly due to the silicon-nitride layer in their triple passivation process[22].

However, both the LT1012 and LT1037 operational amplifiers from Linear Technology suffered drastic failures after 1 megarad of gamma dose, and these devices supposedly had similar passivation. Hence, clear-cut conclusions are difficult to obtain.

As anticipated, all the CMOS and BiMOS devices failed without exception after one megarad of gamma irradiation. The JFET input devices showed significant changes, especially in offset voltages after irradiations.

The following is a survey of the radiation effects on various parameters of the operational amplifiers.

4.2.1 Offset Voltage

The offset voltage of an operational amplifier is due to the mismatch in the two dc gain paths, from the inverting and non-inverting inputs to the output. Predominant sources of offset error for a typical device are the mismatches in the two differential input transistors and the load impedance of the differential stage. If a cascade of two or more differential stages were used, the mismatch due to the first stage is usually dominant (except for differential-cascode configurations). This is because the offset contribution of the second stage is divided by the voltage gain of the first stage.

The changes in magnitude of the offset voltages for the various operational amplifiers tested are plotted in Figs. 4-1 through 4-4. Only the averages of the samples are shown in the figures. In general, the offset voltages increased with radiation

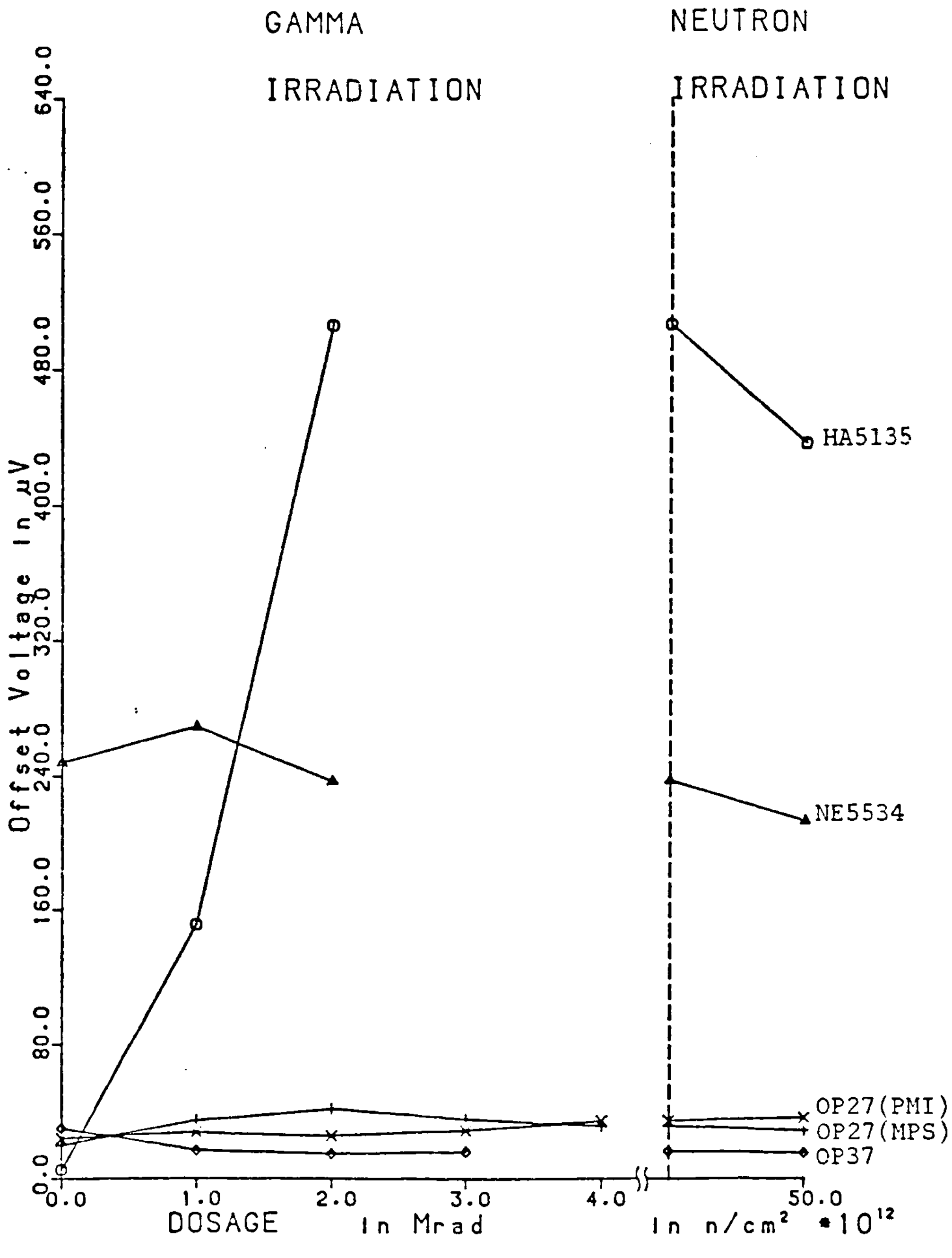


Fig. 4-1 Plot of average offset voltage versus radiation dosage for precision bipolar input operational amplifiers.

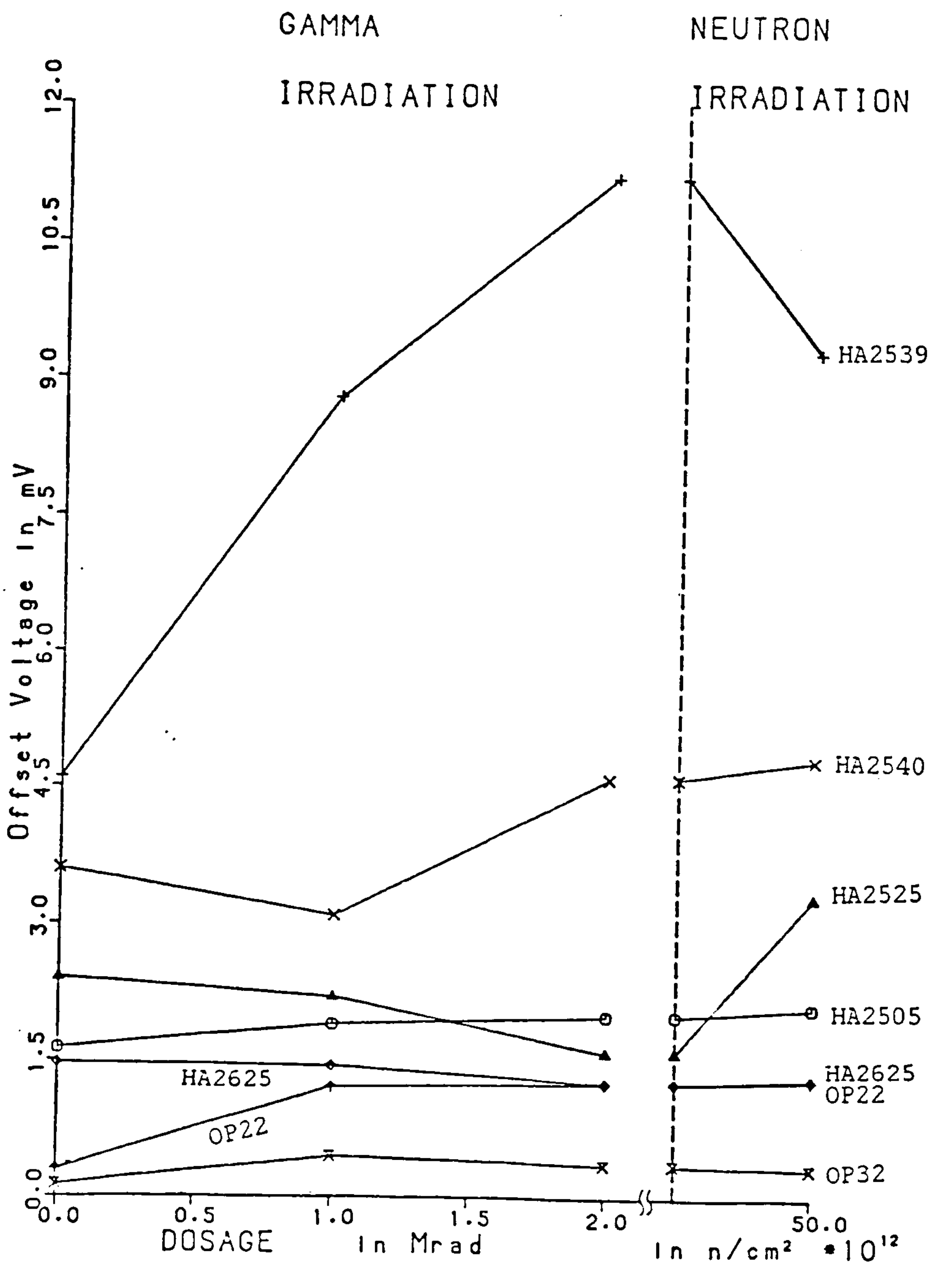


Fig. 4-2 Plot of average offset voltage versus radiation dosage for general-purpose and high-frequency bipolar input operational amplifiers.

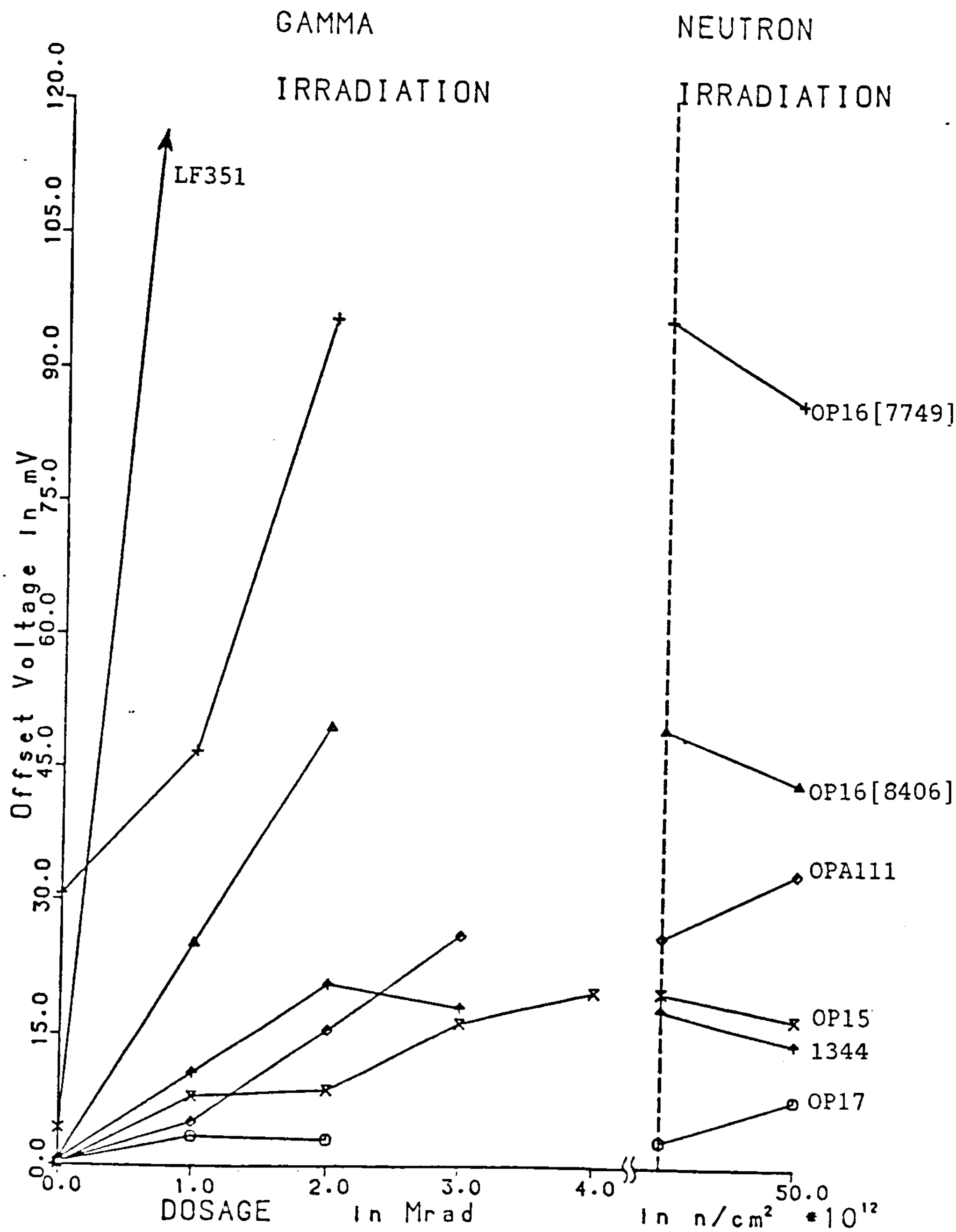


Fig. 4-3 Plot of average offset voltage versus radiation dosage for operational amplifiers with JFET inputs.

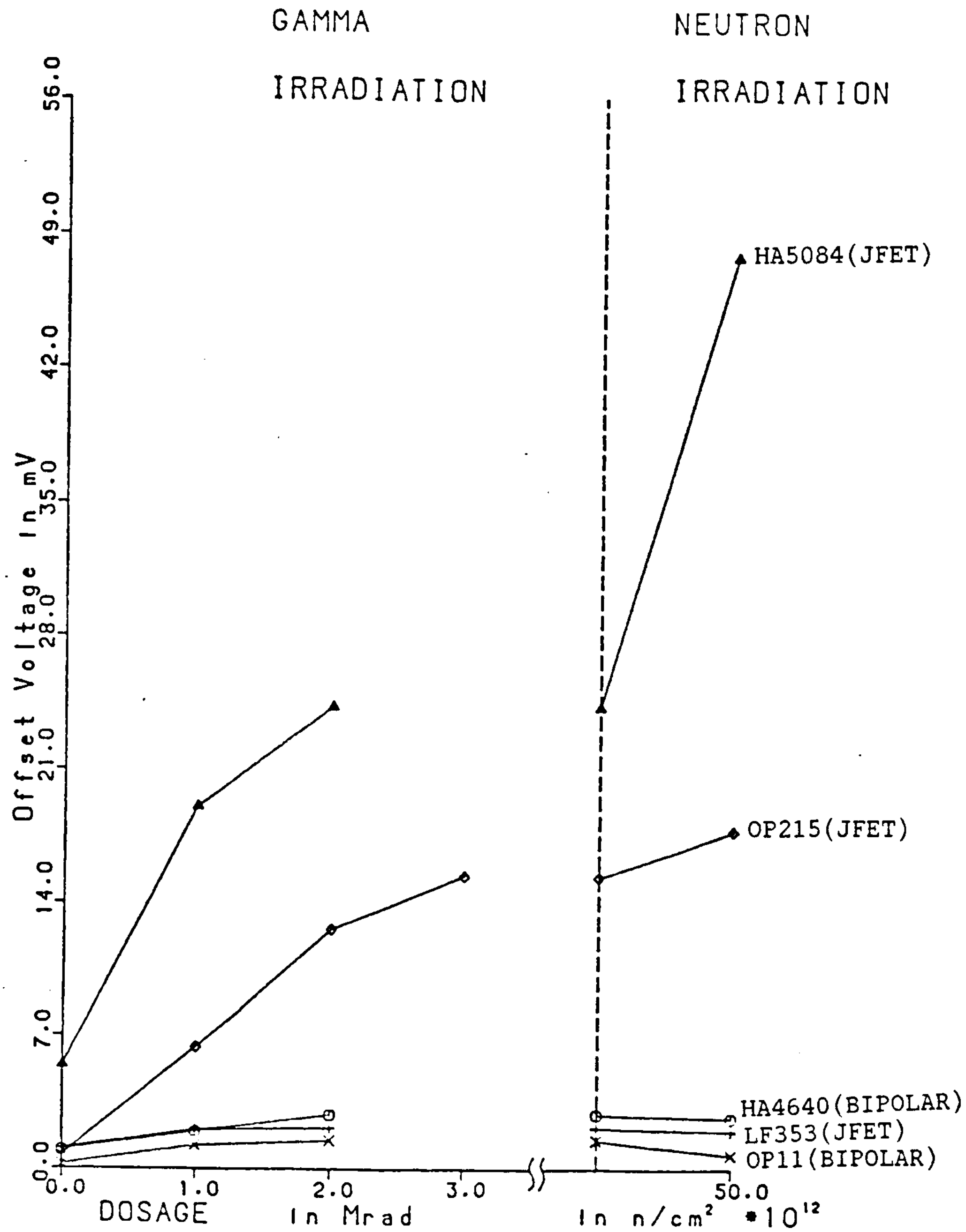


Fig. 4-4 Plot of average offset voltage versus radiation dosage for dual and quad operational amplifiers.

damages. Decreases in the offset voltages due to neutron irradiations can probably be attributed to thermal annealing effects.

Devices having the least shift in offset voltage were found to be low-noise, precision bipolar input devices with resistive collector loads for the input differential stages, such as the OP27, OP37, and NE5534. These three operational amplifiers showed no significant changes and no definite direction of change in the offset voltages. Conversely, operational amplifier HA5135 with a superbeta bipolar input stage and an active collector load showed an increase from 5 microvolts to about 500 microvolts after 2 megarads of gamma irradiation.

The offset voltage of general-purpose and high-frequency bipolar devices, as shown in Fig. 4-2, were typically below 5 mV after irradiations, with the HA2625 device changing by less than 10%. The HA2539 and HA2540 operational amplifiers gave the largest absolute increase, but their offset voltages after 2 megarad and $5x10^{13}n/cm^2$ were still below the pre-radiation maximum specification of 15 mV. The offset voltages of these bipolar devices should not be the major constraint for a radiation-hardened design.

The devices with JFET inputs shown in Fig.4-3 gave the largest changes in offset voltage among those devices that were still functioning. The JFET input operational amplifiers did not show any saturation effects with increasing dosage. In fact, for these devices the rate-of-change actually increased for the second megarad of gamma dose. The LF351 gave an increase of over 150 mV after the first megarad of gamma dose. With the exception of the OP17 operational amplifier, the offset voltages of all the other devices with JFET inputs were over 10mV after irradiations. In addition, during post-irradiation testing the offset voltages were observed to drift by several tens of millivolts with the self-heating of the JFET op amps. These devices are definitely not ideal for a radiation-hardened system.

Similar behaviors were observed for the dual and quad operational amplifiers in Fig. 4-4. Devices with JFET inputs such as the HA5084 and OP215 showed drastic increases while smaller changes were observed for bipolar devices such as the OP11 and HA4640.

In summary, the experimental results allow the following conclusions regarding changes in offset voltages with radiations:

(i) Devices with JFET inputs gave the largest change.

(ii) Significant changes were observed for bipolar devices with active collector loads for the input stages.

(iii) Bipolar devices with resistive collector loads for the input stages indicated negligible variations with irradiations.

4.2.1.1 A comparison of the changes in offset voltages due to gamma rays for bipolar and JFET input stages.

The equivalent circuits for the bipolar and JFET input stages of typical operational amplifiers are shown in Fig. 4-5 where V_{OS} is the equivalent input offset voltage.

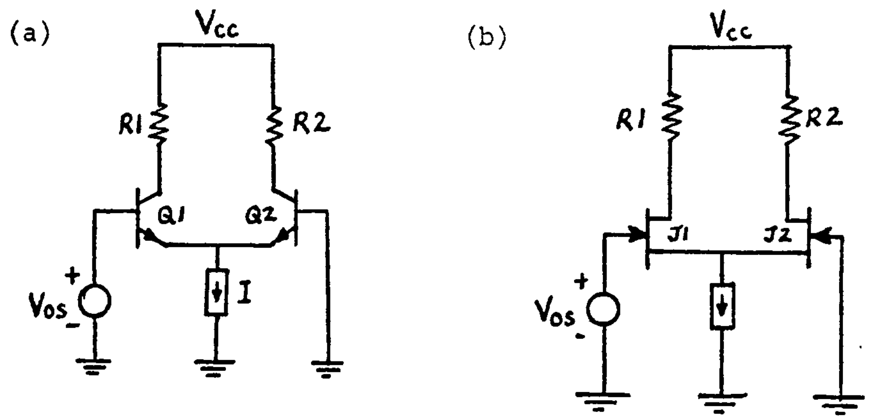


Fig. 4-5 Equivalent circuits for (a) bipolar and (b) JFET input stages.

For bipolar input stages, summing voltages around the inputs gives

$$V_{OS} = V_{BE_1} - V_{BE_2}, \tag{4-1}$$

but $$I_c \approx I_s\, e^{\frac{V_{BE}}{V_T}}, \tag{4-2}$$

where $V_T = kT/q$ and I_s is the reverse saturation current. Therefore, solving for V_{BE} from Eq.(4-2) and substituting into Eq.(4-1) gives

$$V_{OS} \approx V_T \left[\ell n\left(\frac{I_{c1}}{I_{c2}}\right) + \ell n\left(\frac{I_{s1}}{I_{s2}}\right) \right] . \tag{4-3}$$

Now, make the following assumptions:

$$\Delta I_c = I_{c1} - I_{c2},\ I_c = \frac{I_{c1} + I_{c2}}{2},$$

$$\Delta I_s = I_{s1} - I_{s2}, I_s = \frac{I_{s1} + I_{s2}}{2}, \tag{4-4a}$$

$$I_{c1} = I_c + \frac{\Delta I_c}{2}, I_{c2} = I_c - \frac{\Delta I_c}{2},$$

or

$$I_{s1} = I_s + \frac{\Delta I_s}{2}, I_{s2} = I_s - \frac{\Delta I_s}{2}, \qquad (4\text{-}4b)$$

and $\qquad \Delta I_c << I_c, \quad \Delta I_s << I_s.$

Using a Taylor series expansion, from Eq.(4-3) we obtain

$$V_{OS}(\text{Bipolar}) \approx V_T \left[\frac{\Delta I_c}{I_c} - \frac{\Delta I_s}{I_s} \right]. \qquad (4\text{-}5)$$

Thus, the input offset voltage is a function of the mismatches in collector currents and physical device parameters such as base doping concentration, base width, collector doping concentration, and base-emitter area[23].

From Eq.(4-5), assuming perfectly matched load resistors and identical base-collector voltages, the collector currents will be identical. Then the offset voltage due to the input transistors reduces to

$$\left| V_{OS} \right| \approx V_T \left| \frac{\Delta I_s}{I_s} \right|. \qquad (4\text{-}6)$$

For a graded-base transistor, the saturation current is given by[23]

$$I_s = \frac{q D_n n_i^2}{Q_B} A_{EB}, \qquad (4\text{-}7)$$

where D_n is the mean electron diffusion constant,

n_i is the intrinsic carrier concentration,

Q_B is the total charge in the base,

and A_{EB} is the base-emitter area.

Assuming a square base-emitter area of d^2,

$$I_s = \left[\frac{q D_n n_i^2}{Q_B} \right] d^2 . \tag{4-8}$$

The primary effect of ionizing radiation is the buildup of trapped charges and interface states. These trapped charges in the oxide can alter the shape of the emitter, base, and collector [1] by attracting electrons to the p-n junction under the oxide. Thus one of the dominant changes in I_s is due to the change in the base-emitter area (Note that hereafter the symbol Δ refers to a mismatch in the two transistors while the symbol δ refers to the change in the parameter due to irradiations).

From Eq. (4-8) we can now write the change in I_s due to ionizing radiation as

$$\delta I_s = 2 \left[\frac{q D_n n_i^2}{Q_B} \right] d \cdot \ \delta d \cdot \ \left(\frac{d}{d} \right) , \tag{4-9}$$

or

$$\frac{\delta I_s}{I_s} = 2 \, \frac{\delta d}{d} . \tag{4-10}$$

If the two input transistors were perfectly matched prior to irradiation, then the initial offset voltage and the initial mismatch in Is were

$$V_{OS}(\text{initial}) = 0 ,$$
$$\Delta I_s(\text{initial}) = 0 . \tag{4-11}$$

Assuming that the I_s of one transistor was changed by δI_s after irradiation, the mismatch in I_s became

$$\Delta I_s(\text{final}) = \delta I_s . \tag{4-12}$$

From Eqs.(4-6) and (4-12), for $\delta I_s << I_s$ the offset voltage after irradiation is

$$V_{OS}(\text{final}) \approx V_T \left| \frac{\delta I_s}{I_s} \right| , \qquad (4\text{-}13)$$

Therefore using Eqs.(4-10) through (4-13), the change in offset voltage of a bipolar input stage due to ionizing radiation is

$$\delta V_{OS}(\text{Bipolar}) = V_{OS}(\text{final}) - V_{OS}(\text{initial}) \approx (0.026)\left(2\,\frac{\delta d}{d}\right). \qquad (4\text{-}14)$$

For the JFET input stage in Fig. 4-5(b), summing voltages around the input gives

$$V_{OS} = V_{GS1} - V_{GS2}\,. \qquad (4\text{-}15)$$

Assuming square-law characteristics for the JFET's,

$$V_{GS} = V_p\left(1 - \sqrt{\frac{I_D}{I_{Dss}}}\right), \qquad (4\text{-}16)$$

where V_p is the pinch-off voltage,

I_D is the drain current,

and I_{Dss} is the drain saturation current.

As before let us assume

$$\begin{aligned} I_{D1} &= I_D + \frac{\Delta I_D}{2}\,, \quad I_{D2} = I_D - \frac{\Delta I_D}{2}\,, \\ I_{Dss_1} &= I_{Dss} = \frac{\Delta I_{Dss}}{2}\,, \quad I_{Dss_2} = I_{Dss} - \frac{\Delta I_{Dss}}{2}\,, \qquad (4\text{-}17) \\ V_{p1} &= V_p + \frac{\Delta V_p}{2}\,, \quad V_{p2} = V_p - \frac{\Delta V_p}{2}\,. \end{aligned}$$

Substituting Eqs.(4-16) and (4-17) into Eq.(4-15) and simplifying gives[23]

$$V_{OS} \approx \Delta V_p - V_p \sqrt{\frac{I_D}{I_{Dss}}}\left(\frac{\Delta I_D}{2I_D} - \frac{\Delta I_{Dss}}{2I_{Dss}} + \frac{\Delta V_p}{V_p}\right). \qquad (4\text{-}18)$$

The offset voltage of a JFET device is the sum of two components: the mismatch of pinch-off voltages alone, and a combination of the mismatches in drain currents, pinch-off voltages, and drain saturation currents. For most operational amplifiers, drain currents of the input stages are low. Therefore the second term in Eq.(4-18) is negligible, so that the offset voltage is approximately given by the mismatch in pinch-off voltage of the two transistors[23], or

$$V_{OS} \approx \Delta V_p . \tag{4-19}$$

The square-law characteristics of a JFET are well-approximated by a step junction[23]. For a step junction, the pinch-off voltage is given by [9]

$$V_p = \left(\frac{qN_D}{8\varepsilon} a^2 - \psi_0 \right), \tag{4-20}$$

where a is the zero-bias channel thickness,

N_D is the channel doping concentration,

ε is the permittivity of free space,

q is the charge of an electron,

and Ψ_0 is the built-in barrier voltage of the gate-channel junction.

The buildup of positive charges in the oxide above the gate can alter the zero-bias channel thickness. The change in V_p due to changes in the channel thickness a is

$$\delta V_p = \frac{2q N_D}{8\varepsilon} a \cdot \delta a \cdot \frac{a}{a}, \tag{4-21}$$

or

$$\delta V_p = 2 \left[V_p + \psi_0 \right] \frac{\delta a}{a} . \tag{4-22}$$

Again, assume perfect matching in Vp prior to irradiation with the initial offset voltage and the initial mismatch in the pinch-off voltage given by

$$V_{OS}(\text{initial}) = 0 \,,$$
$$\Delta V_p(\text{initial}) = 0 \,. \qquad (4\text{-}23)$$

When the pinch-off voltage of one of the transistors changes by δV_p, the offset voltage becomes

$$V_{OS}(\text{final}) = \Delta V_p(\text{final}) \approx \delta V_p \,. \qquad (4\text{-}24)$$

Then the change in the offset voltage is

$$\delta V_{OS} = V_{OS}(\text{final}) - V_{OS}(\text{initial}) \approx 2 \left[V_p + \psi_o \right] \frac{\delta a}{a} \,. \qquad (4\text{-}25)$$

Now, using a reasonable value for a BiFET process of $V_p + \psi_o = 2V$, the change in offset voltage of a JFET input stage due to irradiation is given by

$$\delta V_{OS}(\text{JFET}) \approx 4 \frac{\delta a}{a} \,. \qquad (4\text{-}26)$$

From Eqs.(4-14) and (4-26), the changes in the base-emitter junction length and the zero-bias channel width are both due to surface damages. For similar processing techniques, these changes are probably in the same order of magnitude. With this assumption, the changes in input offset voltages due to ionization should be about 80 times more severe in JFETs than bipolars. The actual change in offset voltages may not be as severe as indicated by this qualitative analysis, depending on the processing techniques and the correlation between changes in the two input transistors. However, the larger absolute change induced in the JFET defines a greater probability for JFETs to give larger offset voltages after gamma irradiations. This conclusion is supported by the experimental data given in Figs. 4-1 through 4-4.

4.2.1.2 A comparison of the changes in offset voltages due to gamma rays for bipolar input stages with and without active loads.

The offset voltage for a bipolar input stage was derived in the preceding section and is given by Eq.(4-5). The component of the offset due to the collector load is

$$\left| V_{OS} \right| \approx V_T \left| \frac{\Delta I_c}{I_c} \right| . \tag{4-27}$$

Fig. 4-6 shows typical equivalent circuits for bipolar input stages with, and without, active loads. For resistive collector loads, assuming identical base-collector junction voltages,

$$R_1 I_{c1} = R_2 I_{c2} , \tag{4-28}$$

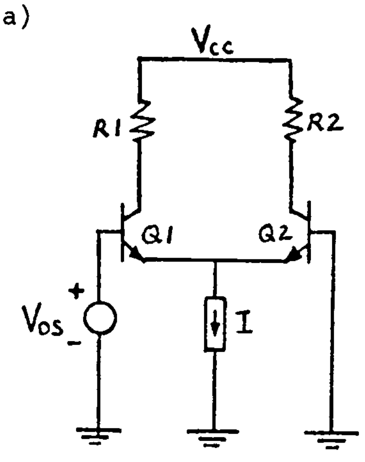
or

$$\frac{I_{c1}}{I_{c2}} = \frac{R_2}{R_1} . \tag{4-29}$$

Assuming

$$R_1 = R + \frac{\Delta R}{2} , R_2 = R - \frac{\Delta R}{2} ,$$
$$I_{c1} = I_c + \frac{\Delta I_c}{2} , I_{c2} = I_c - \frac{\Delta I_c}{2} . \tag{4-30}$$

(a)



(b)

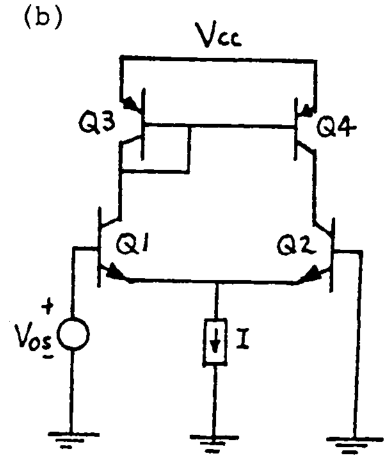


Fig. 4-6 Equivalent circuits for bipolar input stages with (a) resistive loads and (b) active loads.

Substituting Eq.(4-30) into Eq.(4-29) and simplifying gives

$$\frac{\Delta I_c}{I_c} \approx \frac{\Delta R}{R} . \qquad (4\text{-}31)$$

Thus, for resistive loads, Eqs.(4-27) and (4-31) give

$$V_{OS} \approx V_T \frac{\Delta R}{R} . \qquad (4\text{-}32)$$

In a monolithic integrated circuit operational amplifier, a resistor is determined by the sheet resistivity $R_\square$ specified in ohms-per square) and the length-to-width ratio of the resistor, L/W. Thus, in the circuit of Fig. 4-6 the collector resistor value is

$$R = \left| \frac{L}{W} \right| R_\square . \qquad (4\text{-}33)$$

Both length L and width W are surface parameters that change with positive trapped charges in the oxide. The changes are most probably correlated since positive trapped charges in the oxide should cause both the length L and width W of a p-type diffused resistor to decrease by attracting electrons to the p-n junction beneath the oxide. The sheet resistivity $R_\square$ is a non-linear function of the doping and junction depth. Unlike the length and width of the resistor, both the doping and the junction depth are bulk parameters and probably weak functions of surface damages due to ionization at low dose rates. Therefore, the sheet resistivity $R_\square$ is not expected to change significantly with ionizing radiations. The change in resistance after irradiation can thus be reasonably correlated as

$$\delta R = R_{\square} \frac{W\delta L - L\delta W}{W^2} , \tag{4-34}$$

or from Eqs.(4-33) and (4-34),

$$\frac{\delta R}{R} = \frac{\delta L}{L} - \frac{\delta W}{W} . \tag{4-35}$$

If the two collector resistors were perfectly matched with $\Delta R = 0$ before irradiation and one of the resistors changed by δR, then from Eq.(4-32) the change in offset voltage due to resistive collector loads is

$$\delta V_{OS} \approx V_T \frac{\delta R}{R} , \tag{4-36}$$

or

$$\delta V_{OS} \approx V_T \left| \frac{\delta L}{L} - \frac{\delta W}{W} \right| . \tag{4-37}$$

For a simple active load configuration, as shown in Fig. 4-6(b), summing the voltages around the emitters of transistors Q3 and Q4 gives

$$V_{BE_3} = V_{BE_4} . \tag{4-38}$$

Using Eq.(4-2), we obtain

$$\frac{I_{c3}}{I_{c4}} \approx \frac{I_{s3}}{I_{s4}} . \tag{4-39}$$

Assuming very large current gains,

$$I_{c1} \approx I_{c3} ,$$

and $$I_{c2} \approx I_{c4} .$$

Now, let $$\Delta I_{sL} = I_{s3} - I_{s4} , I_{sL} = \frac{I_{s3} + I_{s4}}{2} , \tag{4-40}$$

or $$I_{s3} = I_{sL} + \frac{\Delta I_{sL}}{2} ,$$

$$I_{s4} = I_{sL} - \frac{\Delta I_{sL}}{2} .$$

Then
$$\frac{\Delta I_c}{I_c} \approx \frac{\Delta I_{sL}}{I_{sL}} . \tag{4-41}$$

Substituting Eq.(4-41) into Eq.(4-27) gives

$$V_{OS} \approx V_T \frac{\Delta I_{sL}}{I_{sL}} . \tag{4-42}$$

The saturation current is a function of the base-emitter junction area. Assuming a junction length L_E and junction width W_E, then from Eq.(4-7)

$$I_s \approx K(L_E \cdot W_E) , \tag{4-43}$$

where K is a constant of proportionality. Taking appropriate changes, we have

$$\frac{\delta I_s}{I_s} \approx \frac{\delta L_E}{L_E} + \frac{\delta W_E}{W_E} . \tag{4-44}$$

Thus, for perfectly-matched active loads prior to irradiation, the changes in offset voltage due to the active loads is, from Eqs.(4-42) and (4-44),

$$\delta V_{OS} \approx V_T \left[\frac{\delta L_E}{L_E} + \frac{\delta W_E}{W_E} \right] . \tag{4-45}$$

Let us compare Eqs. (4-37) and (4-45). First, changes in the lengths and widths should be correlated. That is, they should either be both increasing or decreasing. Assuming the same order of magnitude change in the dimensions, the change in offset voltage due to a resistive load would be smaller because of possible cancellation effect of the relative changes in its length and width. Secondly, the dimension of a typical resistor is larger than that of the base-emitter junction. Smaller relative changes in length and width for the resistive load are therefore expected.

Any one or both of the above reasons could be the cause of the smaller changes observed in offset voltages of operational amplifiers with resistive loads for their input stages.

4.2.2 Input Bias Current

The input bias currents for the operational amplifiers are shown in Figs. 4-7 and 4-8. The input currents in all cases increased with irradiations. A slight thermal annealing was observed for most devices during the neutron irradiations. However, the changes due to the annealing were negligible compared to the total change in input currents. The offset currents also increased with the radiation dosage. Devices with and without base current cancellation networks showed no notable difference. On the other hand, the changes between devices with bipolar and JFET inputs, and those with dielectric and junction isolations, were significantly different.

For bipolar devices, the increases in base current can be directly attributed to the decreases in current-gain h_{FE} of the input transistors. Most base current cancellation networks involve both standard NPN and lateral PNP transistors. The surface damage due to ionization would cause a significantly greater decrease in the current-gain of lateral PNP transistor[13,14], which would thereby make the base current cancellation scheme ineffective. Because of the lower current-gain of lateral PNP transistors, devices with PNP inputs generally gave higher input currents and showed larger changes due to radiation damages.

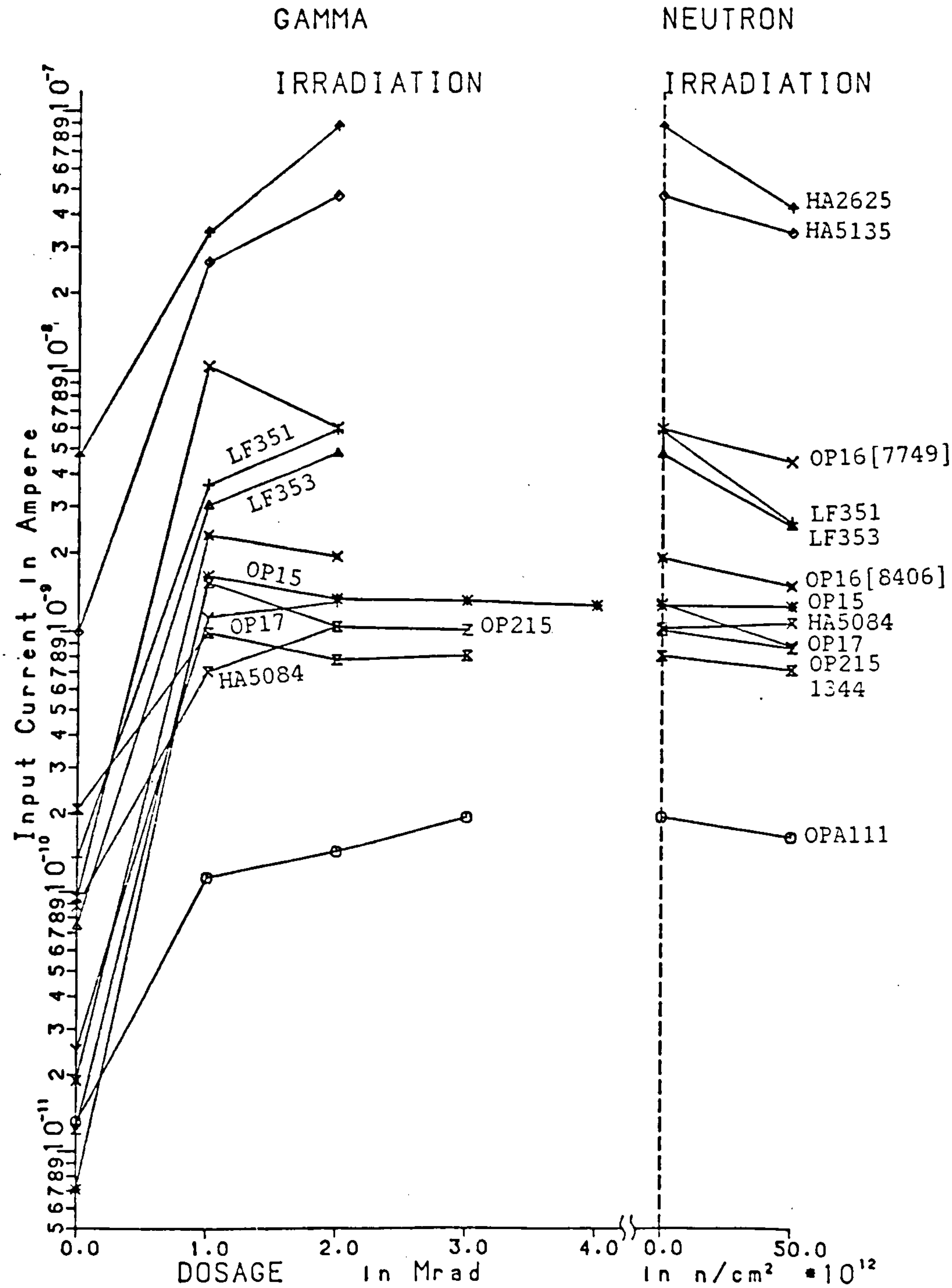


Fig. 4-7 Plot of input bias current versus radiation dosage for operational amplifiers with low input currents.

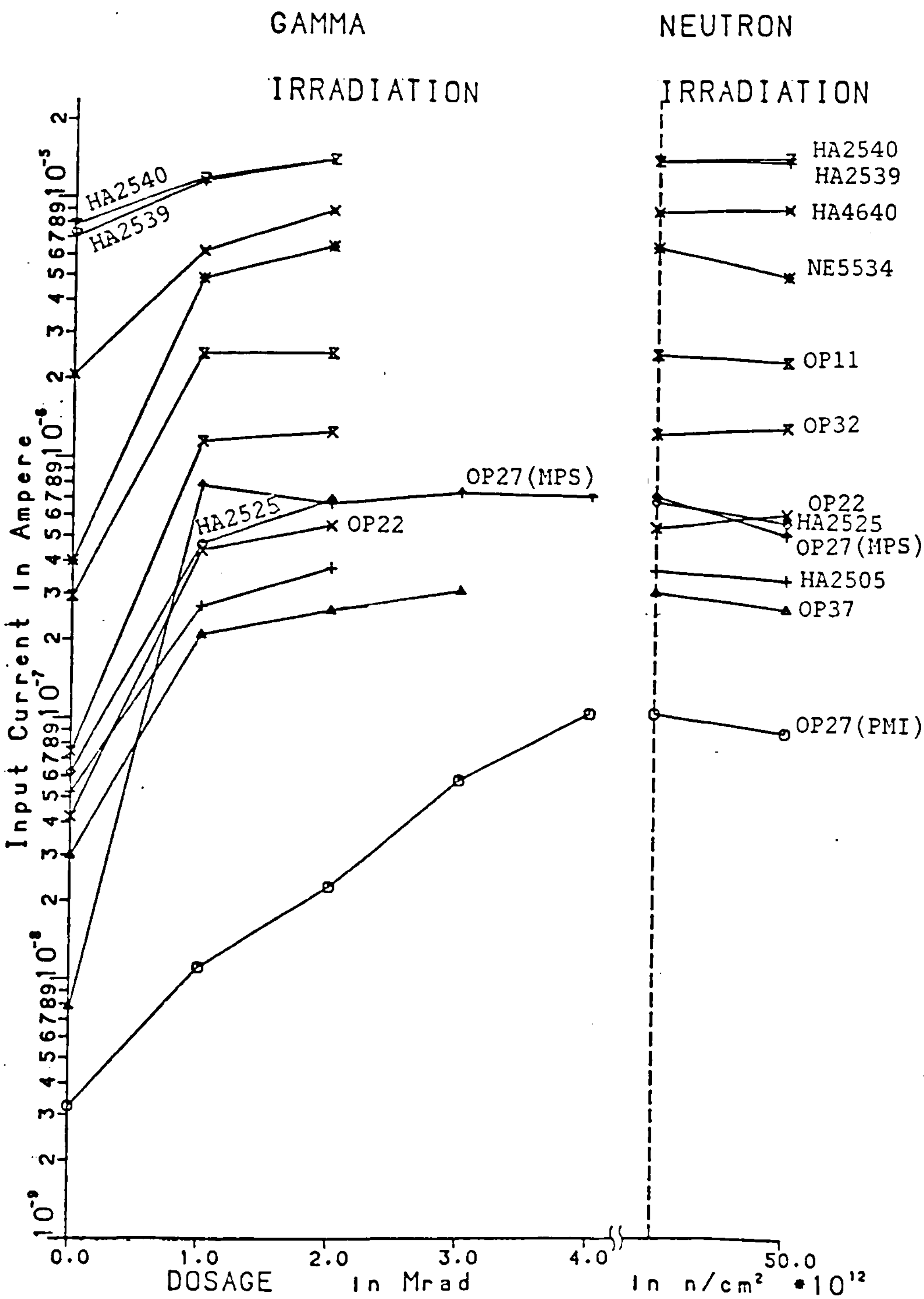


Fig. 4-8 Plot of input bias current versus radiation dosage for operational amplifiers with high input currents.

For devices with JFET input stages, the increases in junction leakage currents were the primary cause of higher input currents. The increases were probably due to the surface damages near the reversed-biased gate to channel junctions. The input currents for most of the devices with JFET inputs showed an increase of 1 to 3 nanoamperes.

The fabrication processes of the devices had definite impacts on changes in the input currents. The OP27 op amps from MPS showed an increase of about 10 times larger than those from PMI. Devices with dielectric isolation also gave less increase. The Harris bipolar devices showed slightly smaller relative increases. The OPA111 op amp with a dielectrically-isolated JFET input gave the least change. Its input bias current after 3 megarads was less than 200pA, while all other junction-isolated JFET devices had input currents of over 1 nA after one megarad.

Despite the larger percentage increases in input currents showed by the JFETs, their absolute input currents after irradiations were below 10nA, while their bipolar counterparts had input currents of over 100nA. The strong temperature dependencies of the input currents of JFETs might make the bipolars the better choice in most applicatons, particularly when the smaller increase in input offset voltage of the bipolar devices are also considered.

Based on the experimental results, except for special low current applications, the input bias currents should not pose a major design constraint.

4.2.3 Supply Currents

The supply currents of all the devices were observed to decrease after irradiations. The supply current for a typical operational amplifier is established by a reasonably supply-independent biasing network. The set current of the biasing network is reflected to the rest of the circuit via current mirrors. Due to the lack of information regarding the exact nature of the biasing network from the manufacturers' data books, the radiation hardness of various biasing network designs could not be compared.

Devices that gave less than 15% change in supply currents included the OP17, OP27 from PMI, OP37, OPA111, HA2505, HA2525, HA2539, HA2540, HA2625, HA4640, and HA5084. With the exception of the three devices from PMI, all the others were dielectrically isolated. The OP27 op amps from PMI and MPS showed a decrease of 7% and 20% respectively. The change in supply current due to irradiation was obviously a strong function of processing techniques used during fabrications.

For the programmable operational amplifiers OP22 and OP32 with supply-dependent biasing networks, drastic reductions in the supply currents were observed when the same value of set resistors were used before and after irradiations. For low initial set currents, the devices were not functioning after irradiation due to decreases in the supply currents. This was probably caused by severe damages in the two lateral PNP's used in the biasing network.

The supply currents tended to reach a saturation limit after the first megarad of gamma dose. This could be explained by the saturation effects of surface damage.

For most operational amplifiers, the drop in supply current was the cause for many other changes in the device performances, such as open-loop gain, gain-bandwidth product, and slew-rate.

4.2.4 Open-Loop Gain

As shown in Figs. 4-9 and 4-10, the open-loop gain for all the devices dropped after irradiations. The OP16 with a date code of 7749 showed questionable performances before irradiation; its result is therefore ignored in the following analysis.

For all devices except the OP16 and LF353, the open-loop gains were rather constant with output drive for a 50 k-ohm load. However, for 2 k-ohm loads most low-power devices showed a nonlinear behavior which could probably be attributed to the substrate PNP output transistors.

The primary gain stage of a typical operational amplifier is in the form of a common-emitter stage. Therefore the open-loop gain is a linear function of the bias current of the gain stage. The supply currents for most of the operational amplifiers dropped after irradiations. This decrease in the bias current due to radiation damage is the potential cause of the decrease in open-

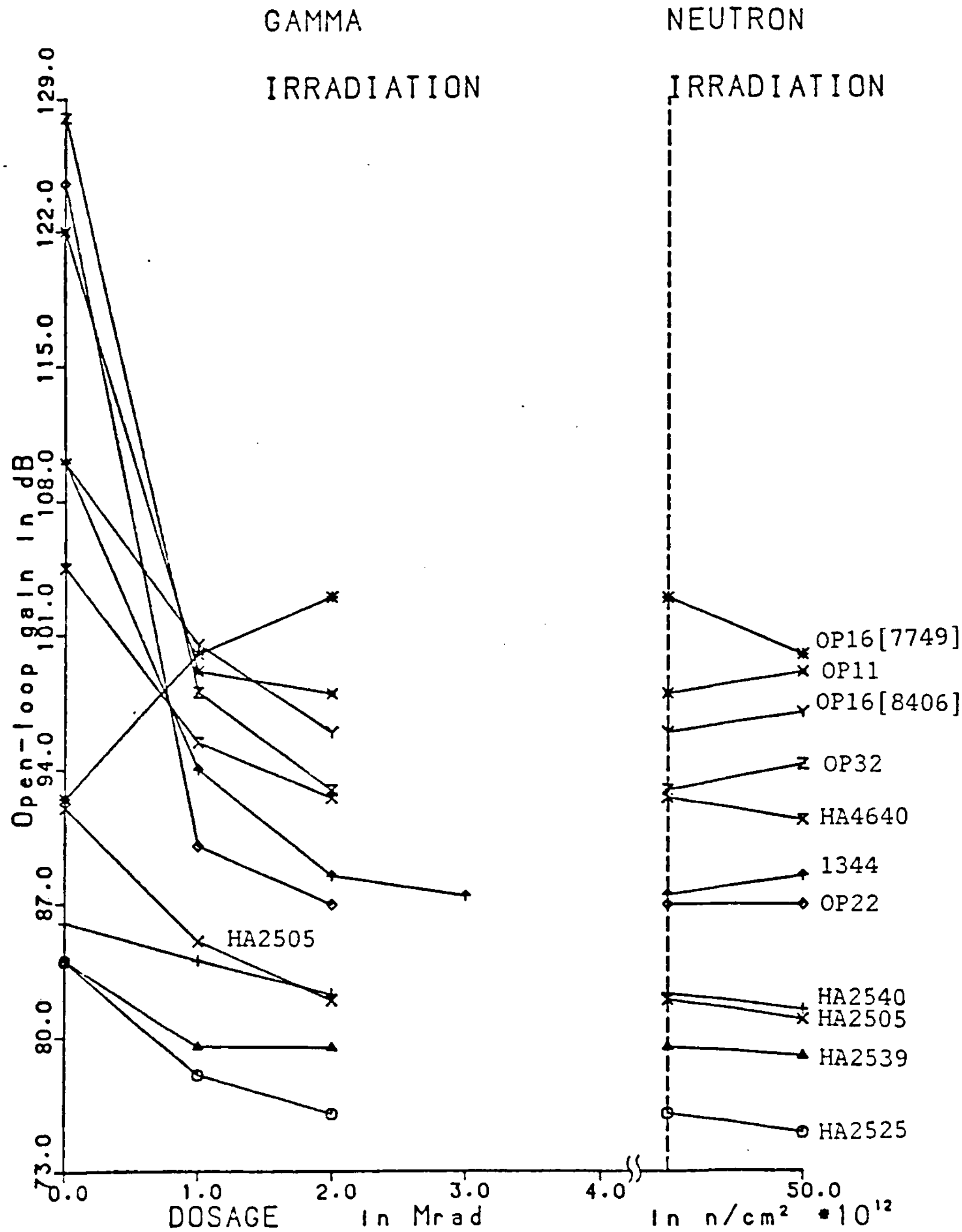


Fig. 4-9 Plot of open-loop gain versus radiation dosage for operational amplifiers with low inital gain.

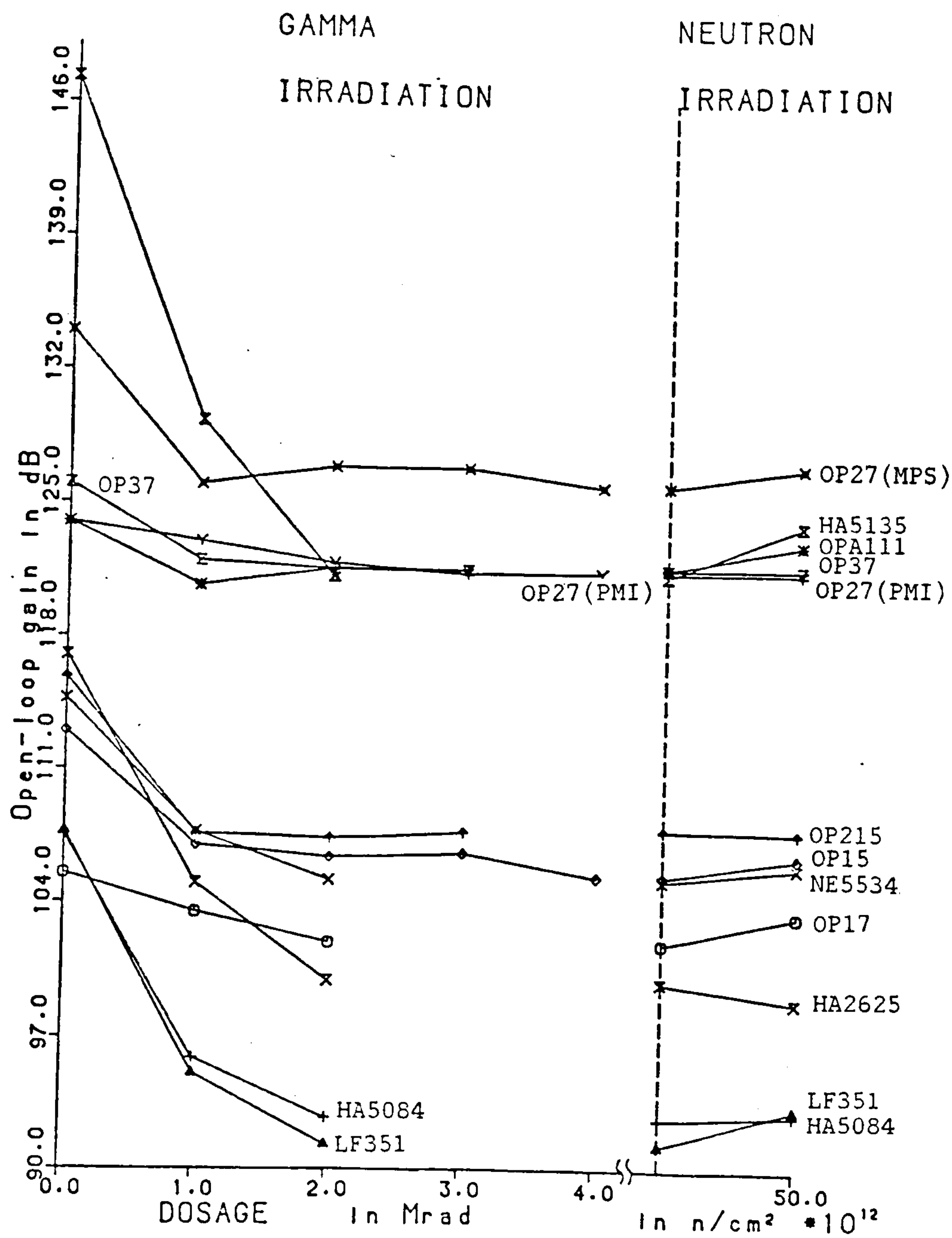


Fig. 4-10 Plot of open-loop gain versus radiation dosage for operational amplifiers with high initial gain.

loop gain. This assumption is supported by the corresponding sharp decrease in supply currents in devices that exhibited a large drop in their open-loop gain. In addition, devices without emitter feedback resistors to lower their gain dependency on bias currents (such as OP11, OP22, and OP32) showed reductions of over 10 dB more than the other devices.

The reductions in the open-loop gains were also partially due to the decrease in current-gain of the transistors, thereby resulting in a smaller load resistance for the gain stages. Therefore, devices with better processing techniques (with a smaller change in the transistor current gains) should give a smaller drop in the open-loop gain.

In all cases the open-loop gain of the devices after irradiations were over 70dB. The assumption of an infinitely high open-loop gain can still be applied for most general-purpose applications.

4.2.5 Gain-Bandwidth Product

The gain-bandwidth product (GBW) of the operational amplifiers before-and-after irradiations are given in Figs. 4-11 and 4-12. In most cases distinct declines in gain-bandwidth products were found.

The gain-bandwidth product of a typical operational amplifier is approximately equal to the product of the transconductance gm of the input device times the inverse of the

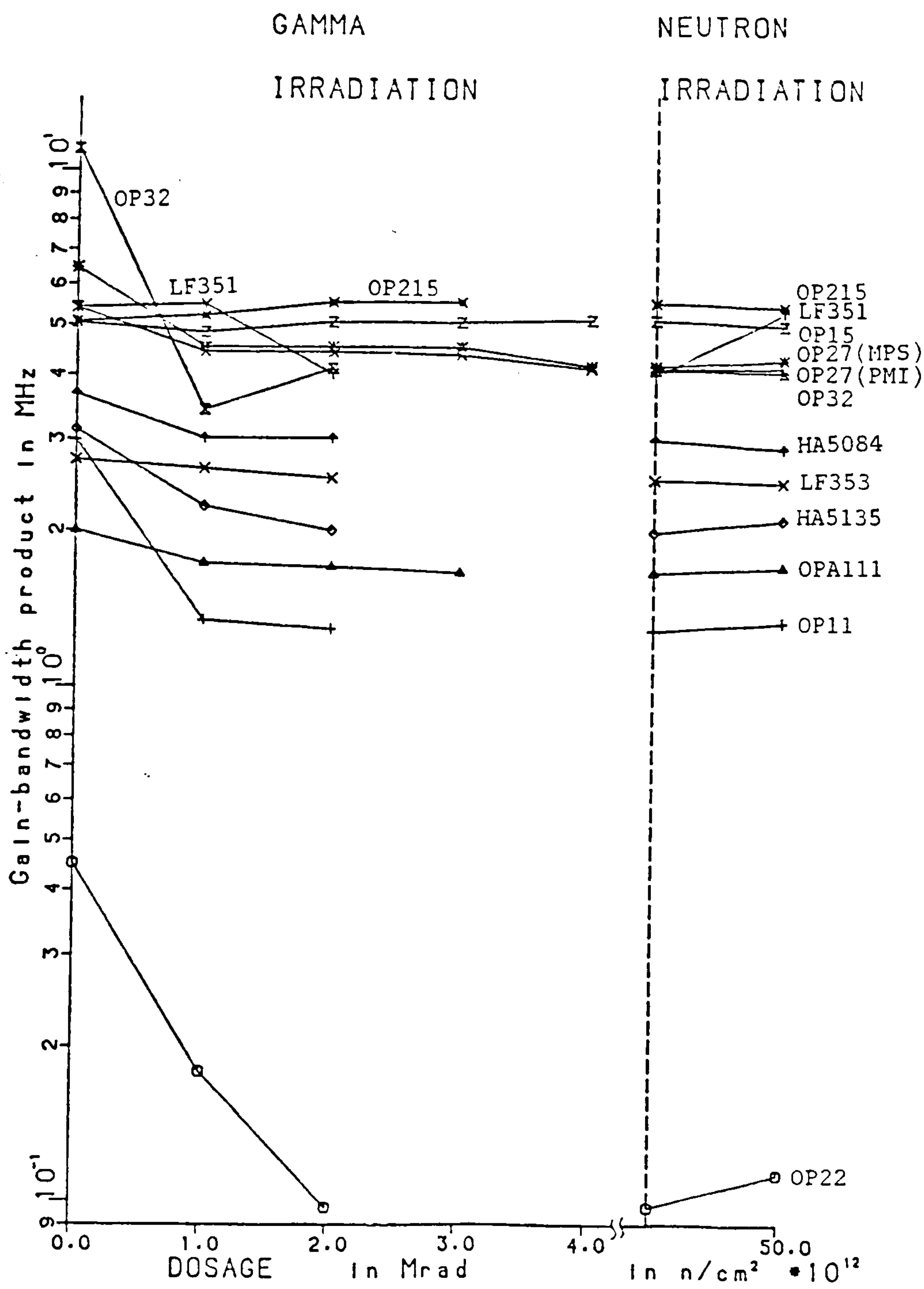


Fig. 4-11 Plot of gain-bandwidth product versus radiation dosage for operational amplifiers with low values of gain-bandwidth products.

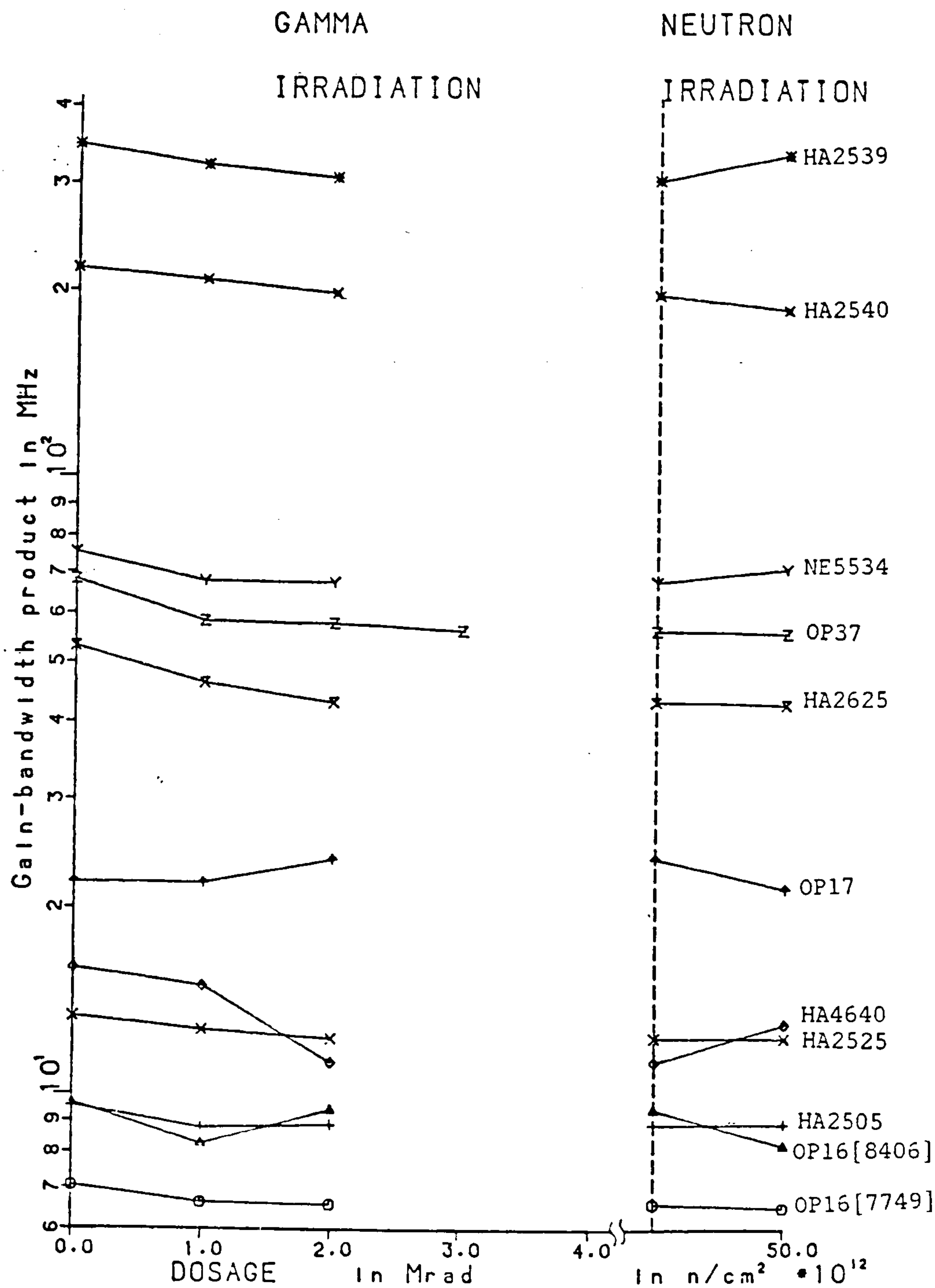


Fig. 4-12 Plot of gain-bandwidth product versus radiation dosage for operational amplifiers with large values of gain-bandwidth products.

capacitance at the dominant node C_f, or

$$GBW \approx \frac{gm}{2\pi C_f} . \qquad (4\text{-}46)$$

Also, the gain-bandwidth product can be expressed as a function of the capacitance at the dominant node C_f, the resistance at the dominant node of the circuit, and the open-loop gain. For most cases, the change in the critical frequency was probably not as severe as that of the open-loop gain because the change in the gain-bandwidth product corresponded with the drop in the open-loop gain. The largest decreases in the gain bandwidth were observed for the OP11, OP22, and OP32 devices; these units also showed the greatest drop in their open-loop gains.

With the exception of the above three devices, the radiation damage on the gain-bandwidth products of the devices were not significant enough to render special attention for most applications.

4.2.6 Slew Rates

The slew rates of the devices also decreased after irradiations. The slew rate is a function of the available current and the capacitance at the dominant node C_f used, and is dependent on the ratio of current I and transconductance gm of the input stage and the gain-bandwidth product GBW, as indicated by Eq.(4-47).

$$SR \approx \frac{I}{C_f} \approx \frac{2\pi I}{gm} GBW . \qquad (4\text{-}47)$$

This relationship was observed in all the devices tested; the percentage decrease in the slew rates were closely related to that of the change in supply currents and the gain-bandwidth products.

4.2.7 Miscellaneous Parameters

The CMRR and PSRR of operational amplifiers are complex functions of the open-loop gain and other parameters. During testing the CMRR and PSRR of many devices varied with the output voltage drive making an accurate determination of these parameters difficult. In many devices rapid annealing was observed during the testing of CMRR. This was probably because both input terminals of the devices were driven between the positive and negative power supply voltages. The devices with large decreases in CMRR and PSRR usually had corresponding large drops in their open-loop gains. In addition (with the exceptions of OP27 from PMI, OP37, and NE5534), devices with dielectric isolations showed much less change than those with junction isolations.

No significant changes in the output drive of the devices were observed for 50 k-ohm loads. At 2 k-ohm loads, the OP22, OP32, LF351, and HA4640 units all showed noticeable drops in their output drive capabilities. In general, a device that showed no noticeable change in the maximum output voltage swing when driving a 50 k-ohm or a 2 k-ohm load during initial testing would be less likely to give drastic change in its drive capability after irradiations.

4.3 Voltage Comparators

Four types of bipolar voltage comparators from PMI and National Semiconductor Incorporated were tested. The sample size ranged from one for the LM311 comparator to four for the CMP05 comparator. All devices were subjected to a total of 2 megarads of gamma dose and $5X10^{13}n/cm^2$ of neutron dose.

Good radiation tolerance was observed for all the devices tested with the possible exception of the CMP01 comparator. One unit of the CMP01 comparator was damaged during pre-irradiation testing while two additional units were damaged during testing after the neutron irradiation. In both cases, the output of the comparator was latched to the +15V power supply. The failure of these CMP01 units could be due to damages in the output circuitry that generates TTL-compatible signals. The latches at the outputs of all the CMP05 comparators were damaged after 1 megarad of gamma irradiation but all the other characteristics of the devices indicated no significant change. Therefore the CMP05 device can be used in a radiation-hardened system only when its output-latch capability is not needed. The following is a survey of the radiation effects on the device characteristics of the comparators.

As expected, the offset voltage of the comparators increased with irradiations as shown in Fig. 4-13. The CMP01 and CMP05 devices with resistive collector load impedances for their differential input stages showed considerably less increases than

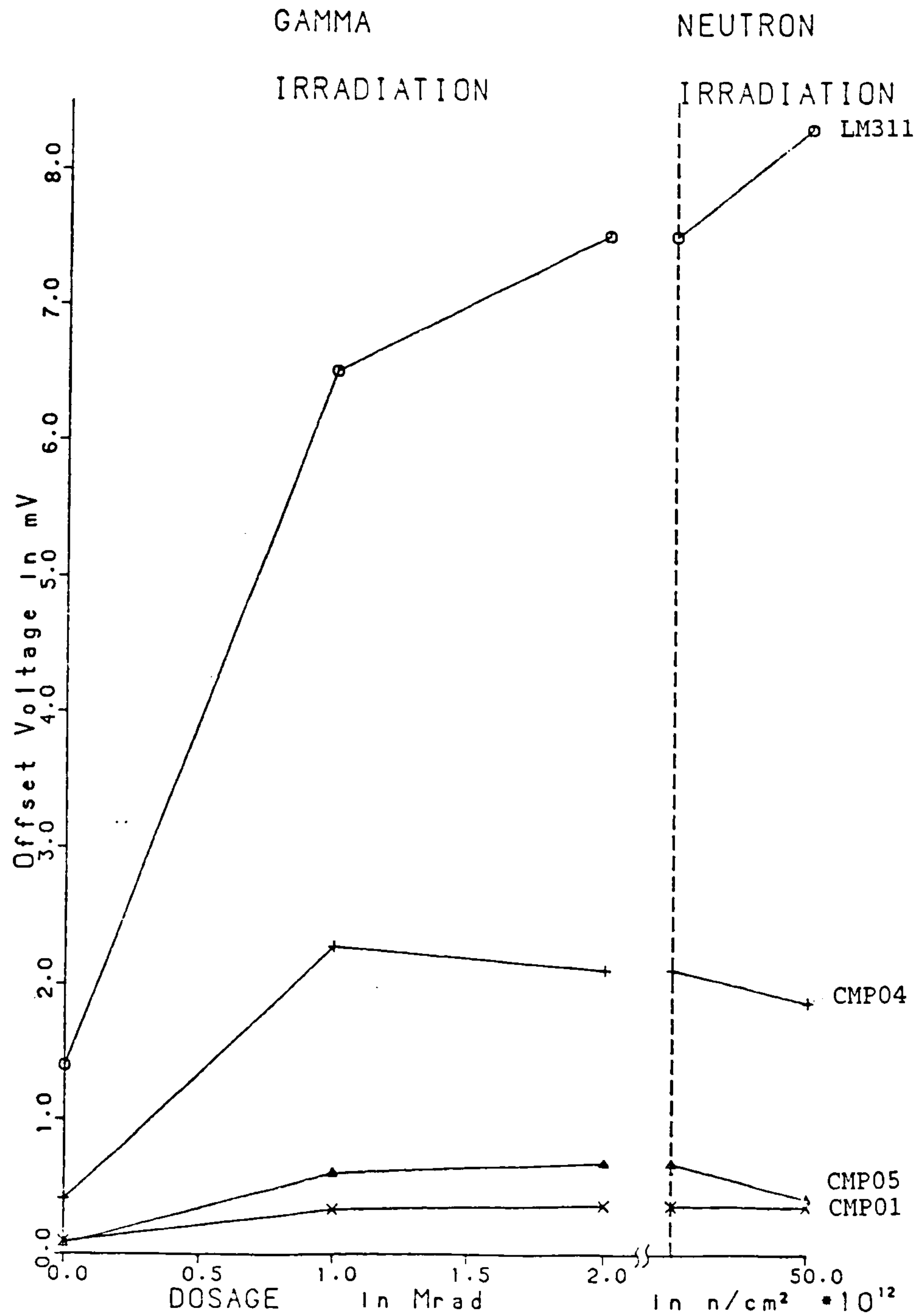


Fig. 4-13 Plot of average offset voltages versus radiation dosage for voltage comparators.

the CMP04 comparator with active collector loads. The large increase for the LM311 could possibly be attributed to the different processing technique used during fabrication. Thermal annealing was probably the cause for decreases in the offset voltages after the neutron irradiation.

As in the case of operational amplifiers, the accumulations of the positive charges in the oxide was the cause of increased surface recombination currents that contributed to the increases in input bias currents of the devices. The averages of the input bias currents before-and-after the irradiations are given in Fig. 4-14. The LM311 and CMP04 comparators with initial input currents of under 100nA showed increases of one to two microamperes after 1 megarad of gamma dose. Further irradiations did not induce any significant changes showing saturation effects of the surface damages. The CMP01 device had an initial input current of about 0.6 microampere. Its input current of about 1.6 microamperes after 1 megarad of gamma dose was comparable to those of the LM311 and CMP04 devices. The CMP05 comparator gave a pre-irradiation input current of over 1.5 microamperes and increased to over 6 microamperes after irradiations. The higher input bias currents could be due to the larger input-stage collector currents. The input offset currents also increased proportionally with the bias currents except for the LM311 device which showed an increase in the offset current of about 1 microampere.

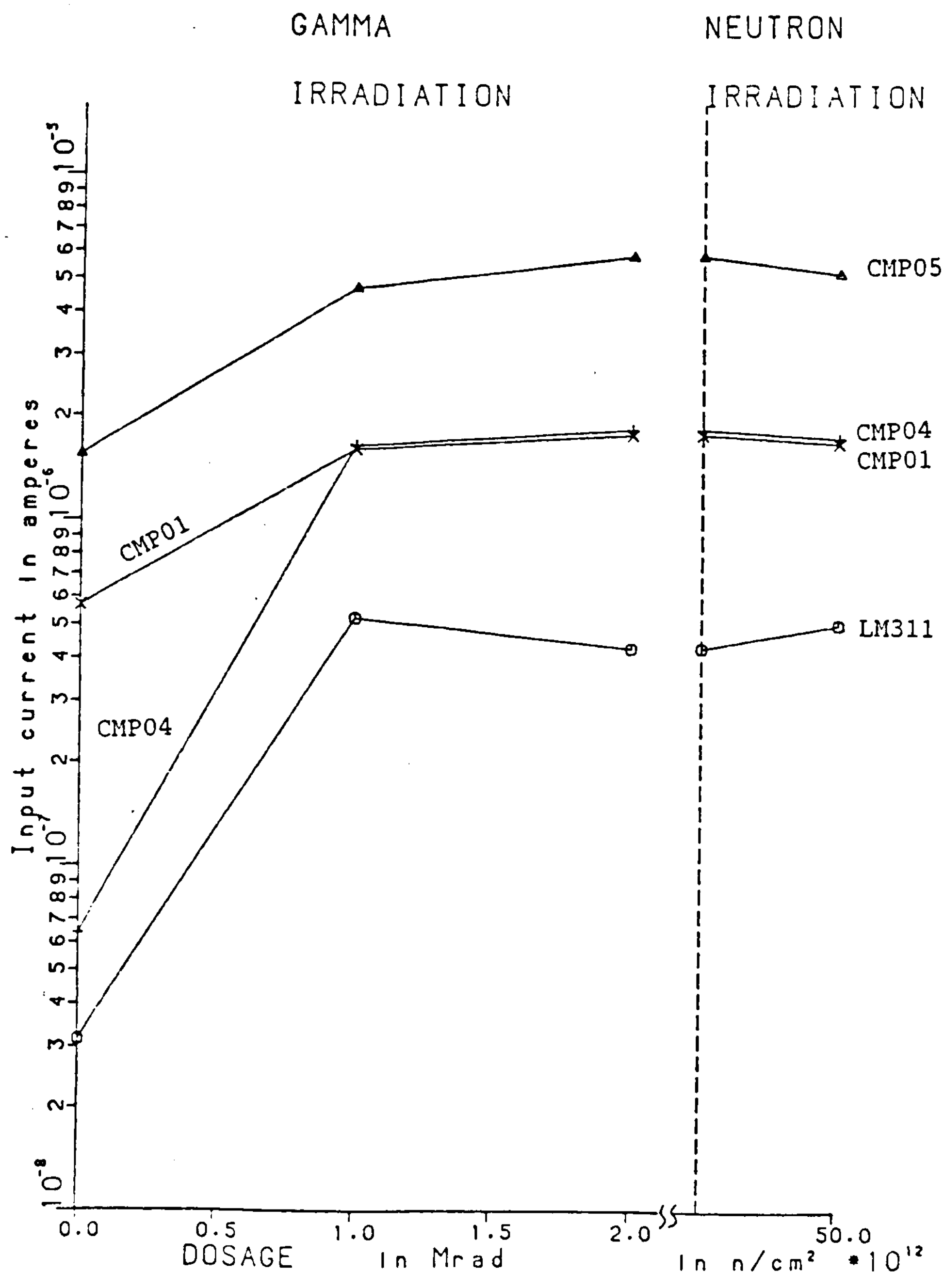


Fig. 4-14 Plot of average input bias currents versus radiation dosage for voltage comparators.

The output saturation voltages of all the devices increased with radiation damages. The increases could be explained by the degradation in the current-gain h_{FE} of the output transistors. For the output transistor to be saturated, the product of h_{FE} and base current must be larger than the collector current[5]. As the current-gain h_{FE} degraded, with the same base current the transistor became less saturated causing the output saturation voltage to increase. Only minor increases in the output saturation voltages were observed. All the output signals were still TTL-compatible.

The rise and fall times of comparators are expected to increase with radiation-induced degradations in the transistor current-gains[5]. However, from the experiment results increases in the rise times were observed for the LM311 and CMP05 devices while decreases were noted in the CMP01 and CMP04 devices. On the other hand, the response times of all the devices decreased with irradiation. The response time was probably the only parameter of the comparator that showed an apparent improvement after irradiations. The response time is primarily influenced by the storage time of the transistor. With the degradation of current-gains, the transistors became less saturated. The time needed for these transistors to come out of saturation was reduced. The storage time should therefore decrease when the current-gain degraded[5]. Thus the decreases in the response time after irradiation was not unexpected.

With the possible exception of the LM311 device, the other three comparators showed little change with irradiations and could be employed in most radiation-hardened systems.

4.4 Voltage Buffer/Followers

Three types of voltage buffers from three different manufacturers were tested. Two of the buffers were bipolar devices while the other was CMOS. The bipolar units were functional after a total dose of 2 megarads and $5X10^{13}n/cm^2$ while the CMOS device failed after 1 megarad of gamma dose.

As anticipated, increases in input currents were observed for the two bipolar buffers. The BUF03 device showed an increase from about 150 pA to over 5 nA after 1 megarad. The HA5033 gave an increase from about 5uA to over 15uA. The larger base currents of the HA5033 was most probably due to its larger input stage collector current.

The BUF03 buffer showed a drastic drop in its supply current from about 20 mA to below 10 mA while no significant change occurred in the HA5033 device. Both buffers were high-performance devices. The presence of stray capacitance in the test circuits makes an accurate determination of the slew-rates and propagation delays difficult. No significant change in these characteristics were observed for both buffers. The rise time of the BUF03 device increased slightly for the first megarad and then showed a decrease of over 100% after the neutron irradiation instead of increasing as predicted from the current-gain

h_{FE} degradation[5]. The HA5033 buffer showed no notable change in the rise-time.

The power supply rejection ratios of both devices remained unchanged with irradiations. Small changes in the voltage and current drives of the devices were observed but the peak voltage and current drives after irradiations were still over 10 V and 50 mA respectively.

4.5 Voltage References

Four types of voltage references were tested. These devices were irradiated with up to a total of 2 megarads of gamma dose and $5X10^{13}$ n/cm^2 of neutron dose. All four devices gave no drastic change after the irradiations.

Two units of AD584 programmable voltage reference from Analog Devices Incorporated were evaluated. The output voltages and the bandgap voltages showed changes of less than 2% with a 20 k-ohm load. However with a 1 k-ohm load, the 10.0V output of one unit dropped to about 3 volts indicating a drastic reduction in its output current drive capability. Therefore the output load of this device must be much larger than 1 k-ohm when used in a radiation environment.

The ICL8069 bandgap reference indicated radiation hardness of over 2 megarads. The forward voltage drop and the minimum reverse current showed no significant change. The 1.2V bandgap voltage changed by less than 1% after 2 megarads of gamma dose.

After the neutron irradiation, an increase of about 40 mV was observed. This device is a prime candidate for a radiation-hardened power supply design.

The 2.7V output voltage of the TL430 programmable voltage reference from Texas Instruments increased by less than 60 mV after the irradiations. The reference terminal input current showed a jump of 5 microamperes from about 2 microamperes. The minimum operating current increased by less than 0.06 mA from 0.4 mA, while the maximum operating current dropped by about 20 mA from 130 mA. No change was observed in the difference between the reference voltage at minimum and maximum currents. The output voltage for a 24.75V nominal voltage configuration increased by about 5%. This device was in good functioning condition after gamma and neutron irradiations.

The LM336 from National Semiconductor Incorporated is a 2.4V voltage reference. It did not show the same radiation hardness of the ICL8069 and TL430. The reference voltage changed by about 4% but the minimum and maximum operating currents were altered by 20% and 50%, respectively. In addition, the difference between the reference voltage at the minimum and maximum operating currents changed by over 200 mV. Although the LM336 device was still functioning after the radiation tests, its use in a radiation-hardened system should be limited.

4.6 Voltage Regulators

Three types of fixed voltage regulators (the MC7812, MC7912, and UA7912) and two types of adjustable voltage regulators (LM317 and LM337) were tested. Although all the regulators were bipolar devices, their radiation hardness was less than satisfactory.

The fixed +12V regulator MC7812 was the only regulator that was still functioning after the irradiations. The device showed an increase of 5% in the output voltage. Thermal annealing was also observed with the self-heating of the device. In addition, the load regulation deteriorated significantly. Post-irradiation testing with 68-ohm and 110-ohm loads showed a drop in the output voltage of over 0.5V from the no-load condition. Care must be exercised when using this device in a radiation environment.

The fixed -12V regulators, MC7912 and UA7912, showed deteriorations in both the line and load regulations after 1 megarad of gamma dose. After 2 megarads, upon initial power-on with a 110-ohm load the output of the MC7912 was at -5.1V instead of -12V, probably due to its inability to supply the necessary current. With thermal annealing due to the self-heating of the device, normal operation was restored. The UA7912 suffered the same failure upon power-on but did not recover its operation with self-heating. The deterioration in the load regulation could be attributed to the decrease in the current drive capability of the devices. Both devices are not suitable for a radiation-hardened design.

The LM317 adjustable regulators showed significant drop in the line regulation after 1 megarad of gamma dose due to an increase in the drop-out voltage of about 3 volts. The load regulation was also degraded but to a lesser extent. Thermal annealing with self-heating of the device was prominent. After 2 megarads, severe degradation in both the line and load regulations made the device useless for any practical applications.

The LM337 adjustable regulators indicated even poorer radiation tolerance. Both units of the device gave outputs of less than -1 volt for an 11-volt configuration.

Additional testing is to be performed on other types of voltage regulators. In the event that no suitable voltage regulators can be found, a discrete design would have to be implemented.

4.7 Timers

Four types of timers were tested including three CMOS devices and one bipolar device. The L555 and TLC555 CMOS timers failed after one megarad with their output latched to the power supply voltage. The ICM 7555 CMOS devices from Intersil were still functioning after 1 megarad of gamma dose but with significantly degraded performances including changes in the frequency. After the second megarad of irradiation the device completely failed.

The 555 bipolar unit from Fairchild showed much poorer radiation hardness than anticipated. The output was latched to the power supply after 1 megarad dose. About 2 to 3 minutes after power-on, due to thermal annealing the device began to function with a slow drift in the frequency. The same performance was observed after the second megarad of gamma dose. This device is definitely not suitable for instrumentation in a radiation environment.

4.8 Power Devices

4.8.1 Power Bipolar Transistors

A total of twenty different types of power bipolar transistors including devices from five manufacturers were tested. These devices ranged from 2.5W medium-power RF transistors to 200W power devices and 100W Darlington pairs. Varying amounts of gamma and neutron doses were applied to these devices. Most of the transistors were irradiated with gamma rays prior to the neutrons. All bipolar power devices had been chosen for testing based on good high-frequency characteristics, and it was therefore anticipated that these devices would perform well after irradiation[5,6,24].

The general trend for all these devices was a decrease in dc current-gain h_{FE} after both gamma and neutron doses. Thermal annealing could be the cause of smaller decreases, and even inreases, in h_{FE} of some devices after the neutron irradiations. The average values of the current-gains before-and-after the irradiations are plotted in Figs. 4-15 through 4-17.

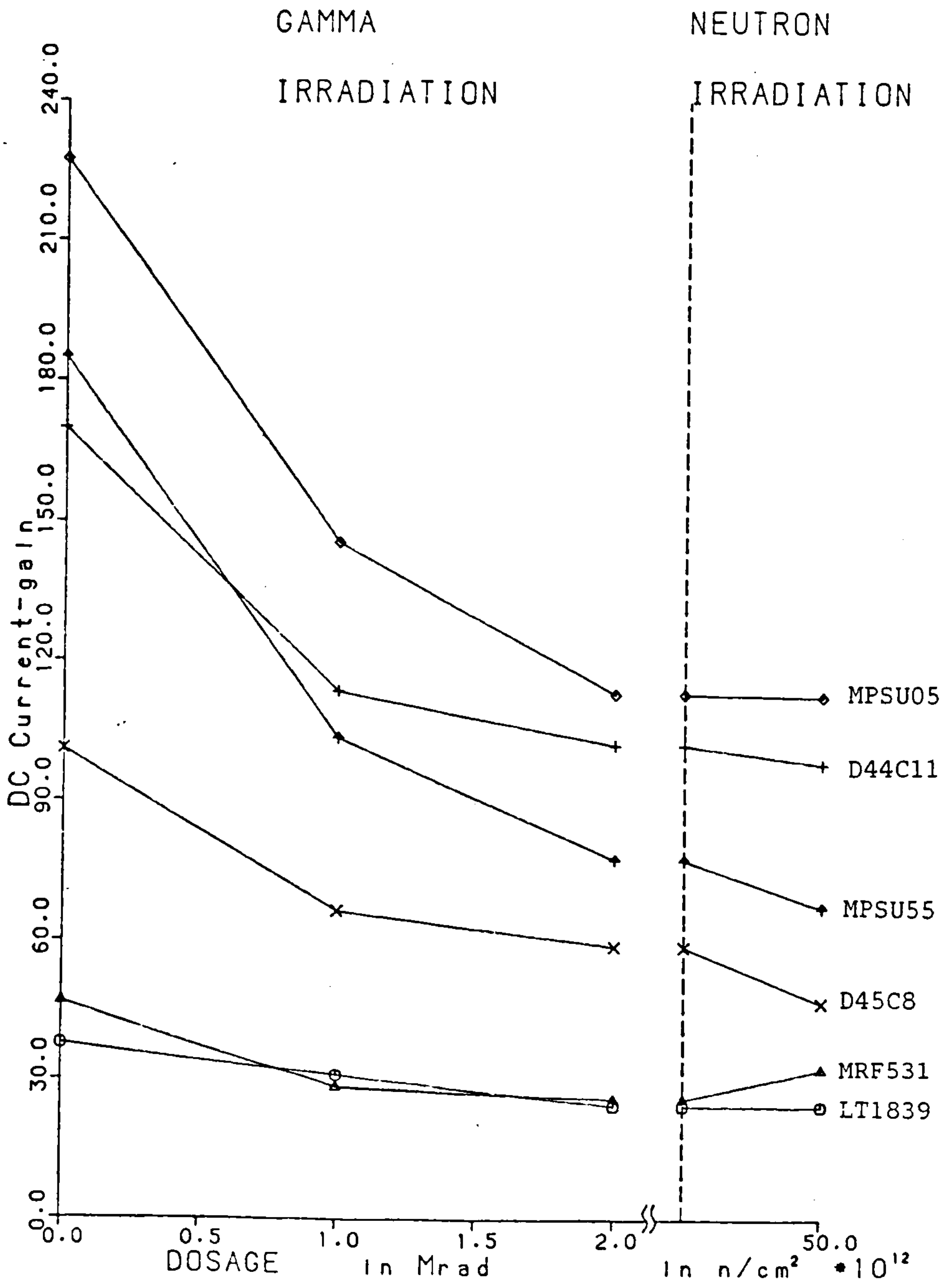


Fig. 4-15 Plot of average dc current-gain versus radiation dosage for medium-power bipolar transistors.

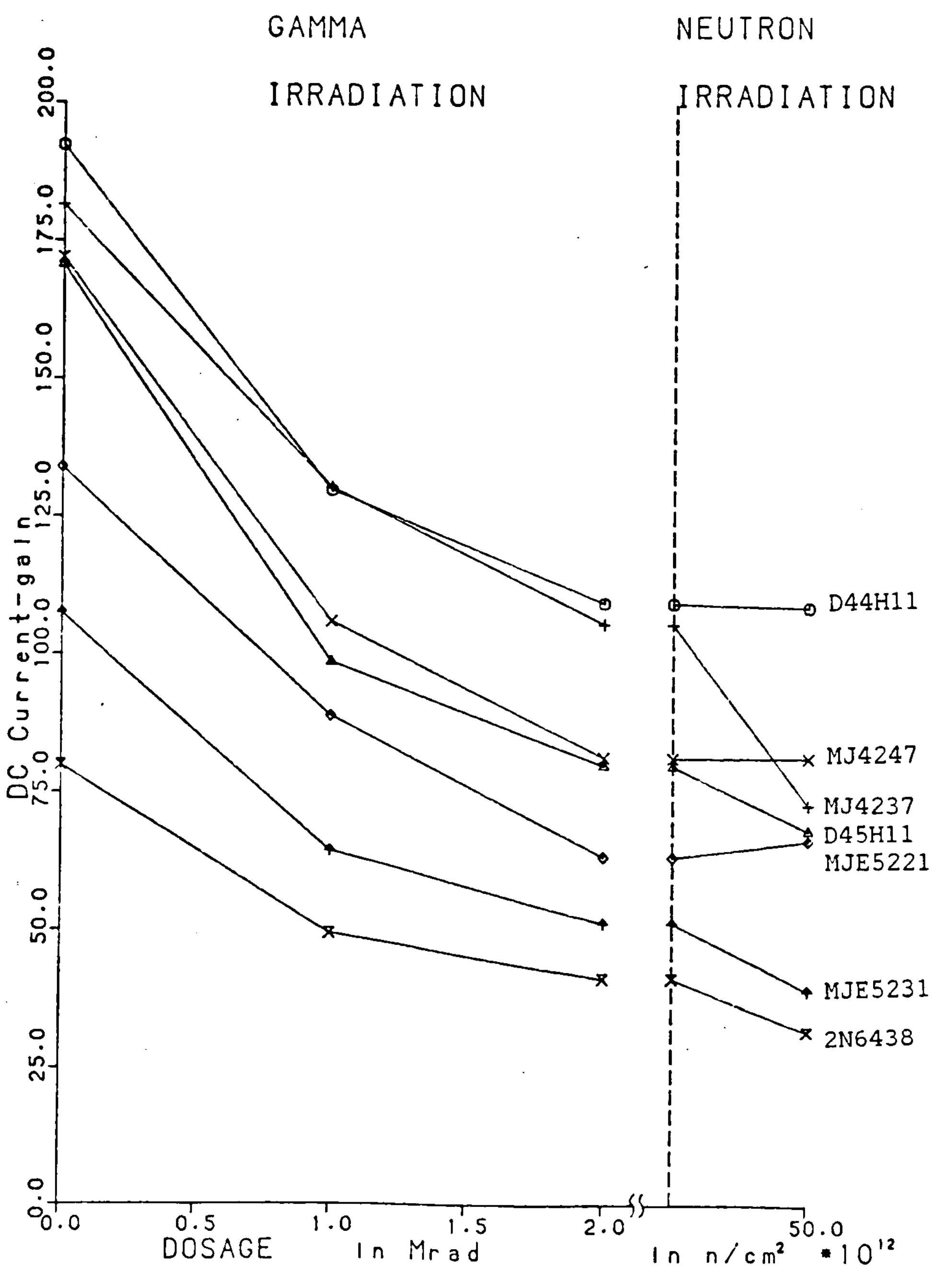


Fig. 4-16 Plot of average dc current-gain versus radiation dosage for power bipolar transistors.

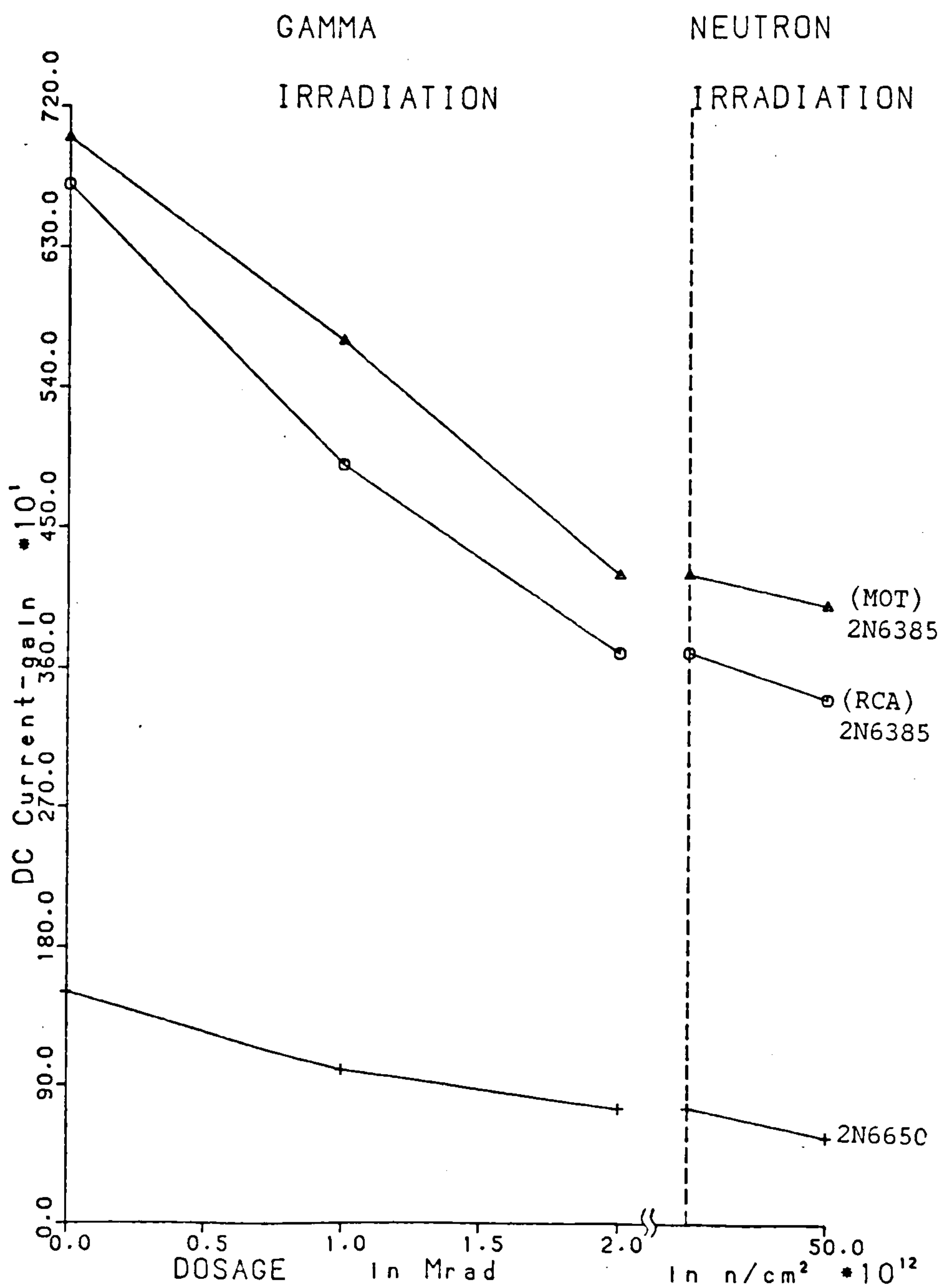
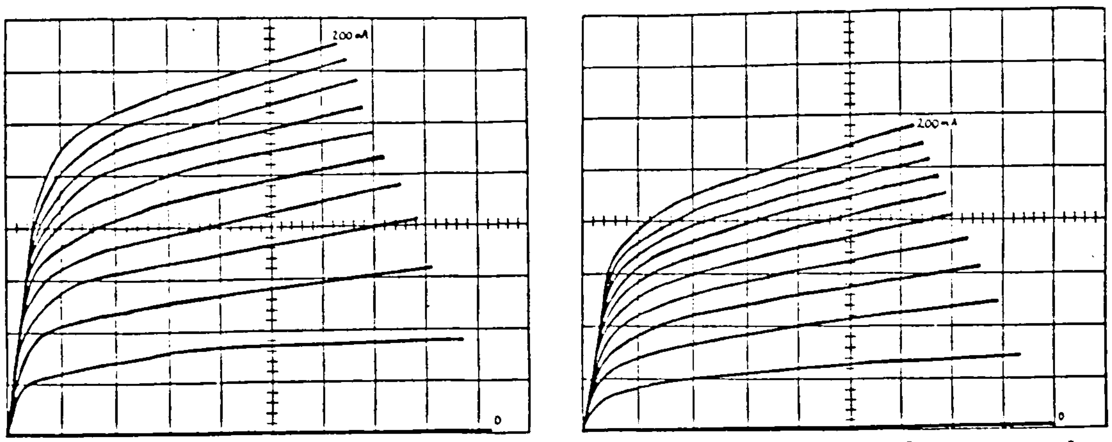


Fig. 4-17 Plot of average dc current-gain versus radiation dosage for bipolar Darlington transistors.

After one megarad of gamma dose, the average value of h_{FE} decreased by about 30%. After a total dose of 2 megarads and $5X10^{13}n/cm^2$, decreases in current-gains ranging from 30% to 60% were observed. The majority of the devices showed current-gain degradations of about 50%. The decreases in current-gain after the gamma and the neutron irradiations were due to two phenomena. The ionization effects of gamma irradiations resulted in the buildup of positive charges in the oxide and interface states at the oxide-silicon junction. This, in turn, caused increased surface recombination currents and decreases in the transistor current-gain[10]. The gain degradation due to neutron bombardments could be attributed to the decreases in the minority carrier lifetime caused by the displacement damages[5].

The common-emitter static characteristics of typical NPN and PNP power transistors are given in Figs. 4-18 and 4-19. Although significant changes in transistor current-gain were observed, all the bipolar devices were still functional. The gain degradation could be compensated easily by careful design[5]. No drastic changes in the linearities of these devices were observed.

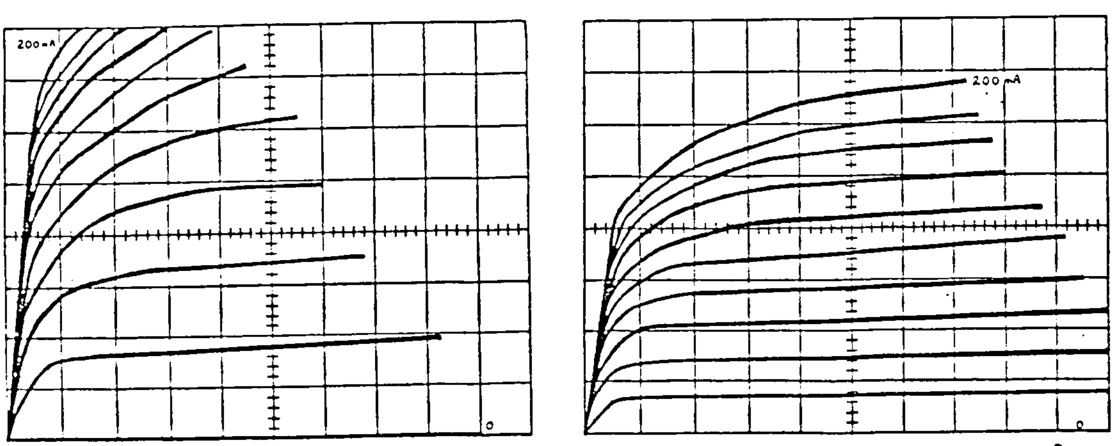
For switching applications, the power transistors are operated in basically two modes: saturated and cut-off states. With decreases in current-gains, larger base currents will be needed to keep the transistors in saturation. For applications in radiation environments, the base currents of the switching transistors should be kept at least 2 or 3 times larger than that



(a) BEFORE IRRADIATION (b) AFTER $5X10^{13}n/cm^2$ + 1.5Mrad

VERTICAL: Collector Current (0.5A/div)
HORIZONTAL: Collector-emitter Voltage (0.5V/div)
STEP: Base Current (20mA/step)

Fig. 4-18 The effects of gamma and neutron irradiations on a typical NPN power bipolar transistor, MJ13080[Solitron].



(a) BEFORE IRRADIATION (b) AFTER 2 Mrad + $5X10^{13}n/cm^2$

VERTICAL: Collector Current (1A/div)
HORIZONTAL: Collector-emitter Voltage (-0.5V/div)
STEP: Base Current (20mA/step)

Fig. 4-19 The effects of gamma and neutron irradiations on a typical PNP power bipolar transistor, 2N6438[Motorola].

required to achieve saturation prior to irradiations. This would ensure proper operations even after the h_{FE} degraded by about 50%. If the above requirement resulted in unusually high base-current drive for the control circuitry, a cascade of transistors in the Darlington configuration could be employed.

4.8.2 Power MOS Transistors

Six different types of power n-channel MOS transistors from six different manufacturers were tested for their gamma radiation tolerances. The primary change was observed in the threshold voltages of the devices. The threshold voltages of MOS devices were known to shift with ionizing radiations[5,25,26]. The threshold voltage of a n-channel MOS transistor is given by[23]

$$V_T(n-\text{channel}) = \left| 2\phi_F \right| + \phi_{ms} + \left| \frac{Q_B}{C_o} \right| - \left| \frac{Q_{ss}}{C_o} \right| , \qquad (4\text{-}48)$$

where ϕ_F is the Fermi potential,

ϕ_{ms} is the metal-semiconductor work function difference,

Q_B is the charge density in the depletion region,

Q_{ss} is the positive charge density in the oxide at the silicon interface,

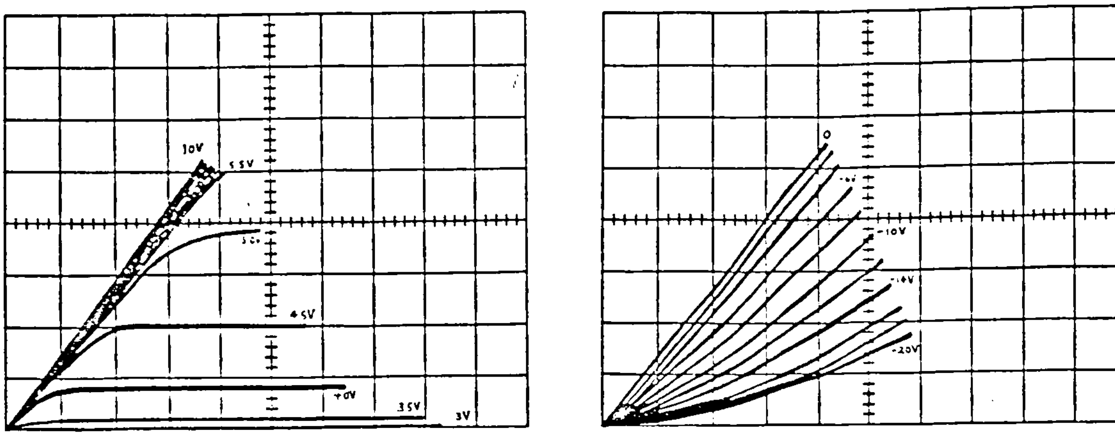
C_o is the capacitance per unit area of oxide layer.

With the buildup of positive charges in the oxide due to irradiations, the increases in Q_{ss} would result in a negative shift in threshold voltage.

This experiment reinforced the above theory. All the n-channel enhancement-mode devices were converted to their depletion-mode counterparts after irradiation. Typical common-source static characteristics prior to and after gamma irradiations for 500V and 200V devices are given in Figs. 4-20 and 4-21. In contrast to the bipolar devices in Figs. 4-18 and 4-19, the MOS transistors showed drastic changes in the overall performances of the devices after 1 megarad of gamma dose. Large changes in the threshold voltages made these devices unsuitable for any switching applications. Devices that could be turned off by a TTL low-level signal were found to conduct several amperes of current, even with gate voltages of -20 volts. For such devices to operate in a radiation environment, the gate control voltages would have to change by over 50 volts. To obtain such large gate control voltage swing, special voltage drive circuitry using probably power bipolar devices would have to be employed. This obviously negates the use of power MOS transistors. Thus the use of these power MOS transistors in a radiation-hardened design appeared to be impractical. Power bipolar devices should be used instead.

4.8.3 Voltage Rectifiers

All three voltage rectifiers tested showed radiation hardness of well above 2 megarad and $5 \times 10^{13} n/cm^2$ doses. In fact, as evident from Fig. 4-22, no significant change in the device characteristics before-and-after irradiations could be distinguished. The applications of these devices in a radiation-hardened system should not require any circuit modifications.

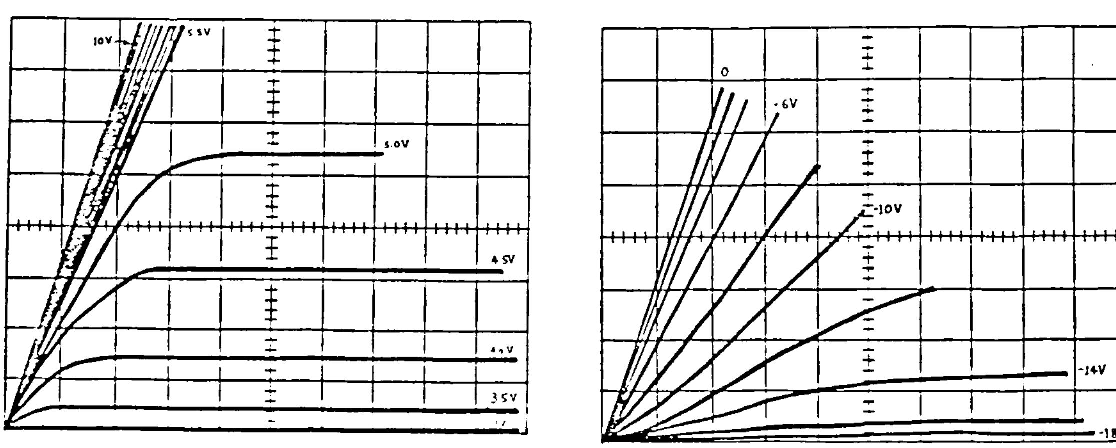


(a) BEFORE IRRADIATION

(b) AFTER 1 Mrad OF IRRADIATION

VERTICAL: Drain Current (2A/div)
HORIZONTAL: Drain-source Voltage (1V/div)
STEP: Gate-source Voltage (as indicated)

Fig. 4-20 The effects of gamma irradiations on a typical 500V n-channel MOSFET, IRF450[Siliconix].

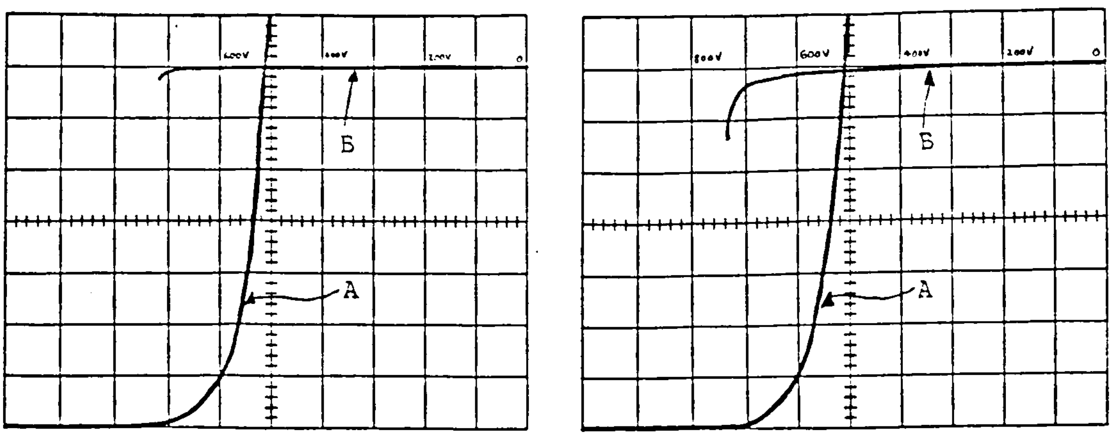


(a) BEFORE IRRADIATION

(b) AFTER 1 Mrad OF IRRADIATION

VERTICAL: Drain Current (2A/div)
HORIZONTAL: Drain-source Voltage (0.5V/div)
STEP: Gate-source Voltage (as indicated)

Fig. 4-21 The effects of gamma irradiations on a typical 200V n-channel MOSFET, IRF250[Siliconix].



(a) BEFORE IRRADIATION

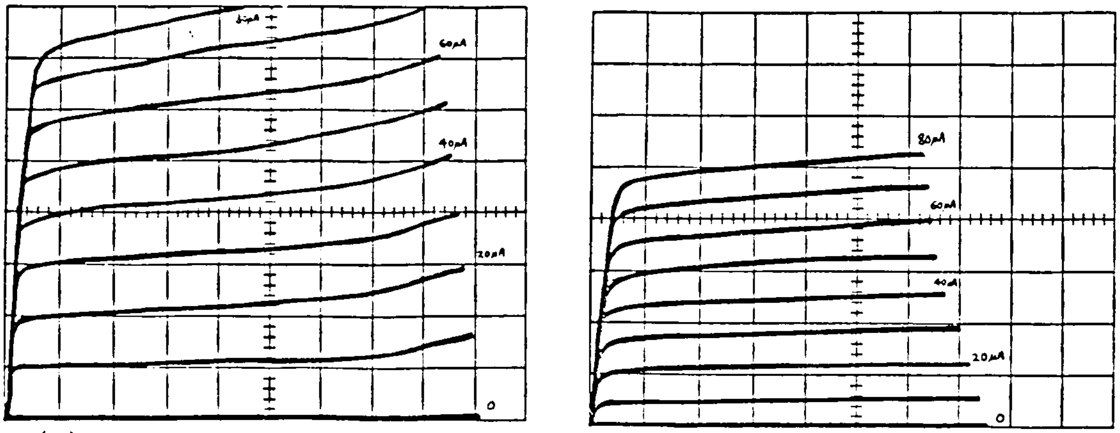
(b) AFTER 2Mrad + $5X10^{13}n/cm^2$

Trace A - VERTICAL: Forward Current(0.5A/div)
HORIZONTAL: Forward Voltage (0.2V/div)
Trace B - VERTICAL: Reverse Current (10uA/div)
HORIZONTAL: Reverse Voltage (100V/div)

Fig. 4-22 The effects of gamma and neutron irradiations on the forward and reverse V-I characterisitics of a typical fast recovery voltage rectifier, MR854[Motorola].

4.9 Transistor Arrays

Four types of NPN transistor arrays were tested. Fig. 4-23 indicates a typical common-emitter static characteristic of an RCA CA3127 array before and after irradiation. Despite a typical overall drop of 50% in current-gain, the devices showed little change in the linearity and general shape of the voltage-current curves. As seen from Fig. 4-24, these transistor arrays showed radiation tolerance equivalent to that of the high-frequency power bipolar transistors. The transistor arrays were irradiated with one megarad of gamma dose followed by a neutron dose of $5X10^{13}$ n/cm^2, and then an additional 1.5 megarads. Decreases of about 45% were observed after the first megarad of gamma dose. Increases



(a) BEFORE IRRADIATION

(b) AFTER 2.5Mrad + $5X10^{13}n/cm^2$

VERTICAL: Collector Current (1mA/div)
HORIZONTAL: Collector-emitter Voltage (2V/div)
STEP: Base Current (10uA/step)

Fig. 4-23 The effects of gamma and neutron irradiations on a typical transistor array, CA3127[RCA] .

after the neutron irradiation were most probably caused by thermal annealing effects. The additional 1.5 megarads of gamma dose induced further degradations in the h_{FE}. A minimum h_{FE} of about 45 was maintained which is adequate for most general-purpose applications. Therefore, with minor circuit design alterations these transistor arrays could readily be used in a radioactive environment.

4.10 Monolithic Breadboard Components

The radiation hardness of five monolithic breadboard components from Interdesign were evaluated. These devices were tested with a total of 2.5 megarad of gamma dose and $5X10^{13}n/cm^2$ of neutron dose. The devices tested included small and large

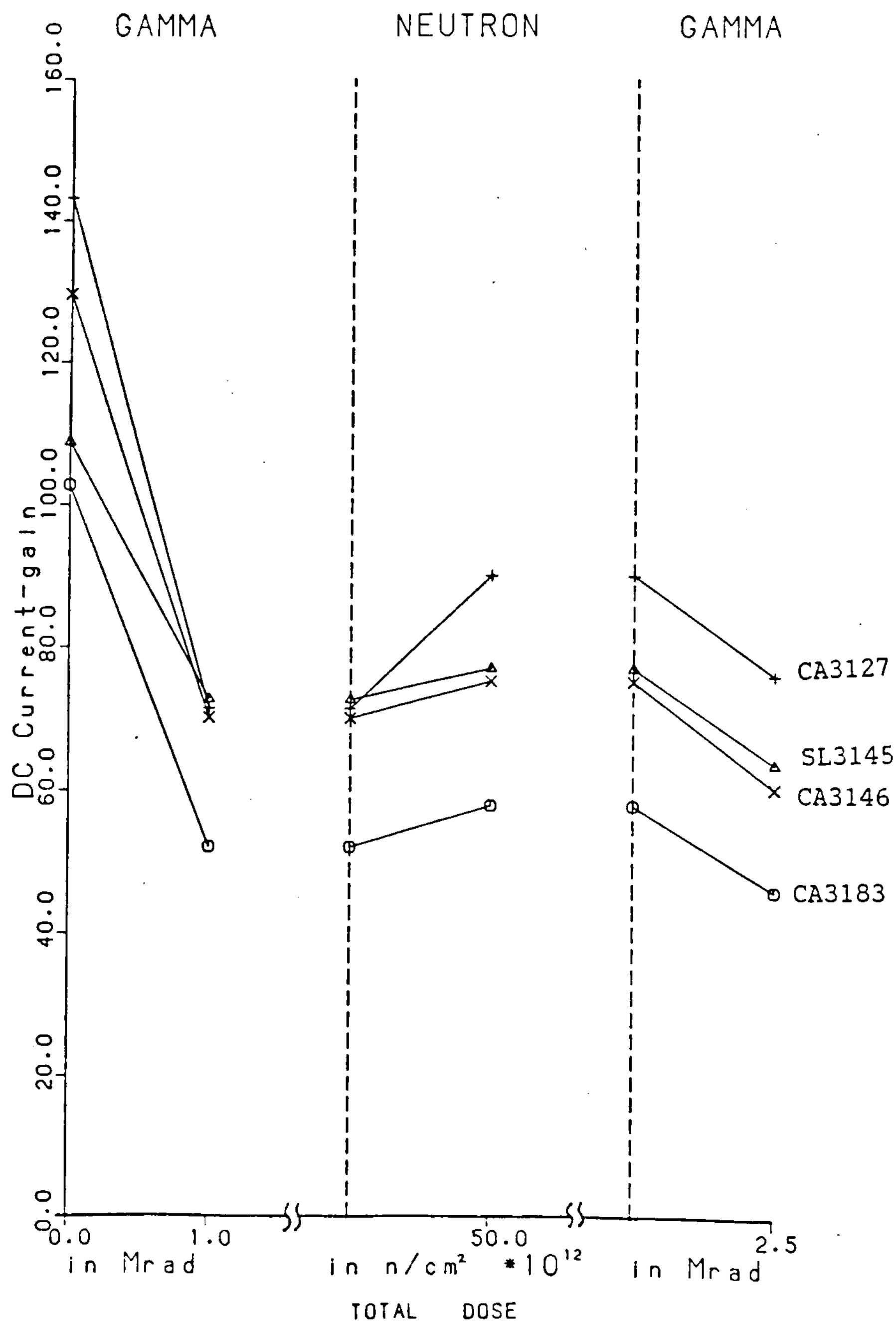


Fig. 4-24 Plot of dc current-gain versus radiation dosage for transistor arrays.

signal NPNs, lateral and substrate PNPs, n and p-channel MOSFETs, zeners, and p-type diffused resistors.

The NPN bipolar transistors showed decreases in h_{FE} ranging from about 30% for the M0302B to 47% for the large signal NPNs of the M0004. Lateral PNPs of the M0003A showed a drop in current-gain of over 75% from 43 to 10. The large drop was not unexpected because of the sensitivity of lateral PNPs to surface damages[13]. The substrate PNP of the M0417 also gave large changes in h_{FE}, showing a drop of over 90%. Special care should be exercised when using any monolithic PNP bipolar transistors.

Unlike the power MOS devices, the n and p-channel MOSFETs showed good radiation hardness. The n-channel showed decreases in threshold voltages of less than 0.5V while threshold voltages of the p-channel increased from -0.84V to -5.4V. The smaller changes in threshold voltages of these MOSFETs could be due to the fact that they were irradiated passively instead of the worst-case static bias[3]. Also, these were aluminum gate (older technology) devices, whereas most modern power MOSFETs use silicon-gate construction, which generally is less radiation resistant[5].

No significant changes were observed in the p-type diffused resistors and the Zener diode.

CHAPTER 5

CONCLUSIONS

5.1 Summary

The devices tested showed varying degrees of radiation hardness. The following summarizes the test results. The devices are grouped into four categories according to their feasiblities in applications requiring a total radiation hardness of 1 megarad and $5X10^{13}n/cm^2$:

Group I: RECOMMENDED. These devices were in good-functioning condition after 2 megarads and $5X10^{13}n/cm^2$ dose. They could be used with very little special attention.

Group II: USE WITH CARE. These devices were usable after 2 megarads and $5X10^{13}n/cm^2$ dose but showed significant changes in their characteristics. They should only be used when no suitable Group I substitute is available. To ensure correct operations after irradiations, special attentions must be given to the device parameters indicated in the following tables.

Group III: UNSUITABLE. Although they were functional after 1 megarad of irradiations, these devices either failed or were too far out of specifications to be useful after an additional megarad dose. Such devices could conceivably be used in applications requiring a lower total dose.

Group IV: UNSUITABLE. These devices either failed or suffered drastic changes after 1 megarad of gamma irradiation. Consisted of primarily MOS devices, the Group IV devices have very limited applications in a radiation environment.

5.1.1 Operational Amplifiers

In general, the irradiations of operational amplifiers with gamma rays and neutrons resulted in the overall degradation of the device performance. Increases in input offset voltage, bias and offset currents, and decreases in supply currents, open-loop gain, gain-bandwidth product, slew rate, CMRR, PSRR, and output current drive capability were observed. However, the primary cause of failure for the operational amplifiers appeared to be a combination of large increases in the input offset voltage and drastic reduction in the output drive capabilities.

The different processing techniques indicated varying degrees of radiation hardness. The CMOS devices suffered drastic failures and were not functional. Although the devices with JFET inputs gave smaller input currents, large increases in the offset voltages were observed. The operational amplifiers with bipolar superbeta transistors and active collector loads for the input stages also showed larger increases in the offset voltages than regular bipolar devices. In addition, devices with dielectric isolation processes and those with the triple passivation process from PMI indicated significantly higher radiation tolerance. Table 5-1 summarizes the test results for the operational amplifiers. The devices are arranged according to their radiation hardness into the four categories described previously. The worst-case parameters are indicated in the table.

5.1.2 Voltage Comparators

The irradiation of voltage comparators resulted in increases in input offset voltages, bias and offset currents, output saturation voltages, and decreases in response times. All the voltage comparators tested were bipolar devices. The devices with active collector loads for the input stages demonstrated larger increases in the offset voltages than those with resistive loads. All devices were functional after the irradiations. Table 5-2 summarizes the test results showing the worst-case parameters for each device.

5.1.3 Voltage Buffers

The major effects of gamma and neutron irradiations on the voltage buffers are increases in input currents accompanied by decreases in supply currents and rise-times. The CMOS device suffered drastic failures after irradiations while the bipolar units were functional. The test results are summarized in Table 5-3.

5.1.4 Voltage References

All voltage references tested were in good functioning conditions after the irradiations. Only minor changes in the

Table 5-1 Summary of test results for operational amplifiers.

Group	Device Name	Total Gamma Dose (megarad)	Total Neutron Dose ($X10^{13}n/cm^2$)	Major Radiation Effects
I	OP27(PMI)	4	5	Input current of about 100nA.
	OP37(PMI)	3	5	Input current of about 400nA.
	HA2505(HAR)	2	5	Input current of 500nA, open-loop gain of 80dB.
	HA2525(HAR)	2	5	Input current of 1µA, open-loop gain of 74dB.
	HA2625(HAR)	2	5	Input current of 100nA.
	HA2539(HAR)	2	5	Input current of 21µA, open-loop gain of 79dB.
	HA2540(HAR)	2	5	Input current of 23µA, open-loop gain of 79dB.
	HA4640(HAR)	2	5	Input current of 10µA, reduction in drive at 2K load,
II	NE5534(SIG)	2	5	Input current of about 7µA.
	HA5135(HAR)	2	5	Input offset voltage of 0.6mV and input current of 100nA.
	OP27(MPS)	4	5	Input current of about 1µA.
	OP17(PMI)	2	5	Input offset voltage of 15mV and input current of 1nA.
	LF353(NAT)	2	5	Input offset voltage of 5mV, large reduction in output drive of one unit, input current of 5nA.
	OP11(PMI)	2	5	Input offset voltage of 3mV, input current of 3µA, slew rate of 0.5V/µs, GBW of 1MHz.
	OP15(PMI)	4	5	Input offset voltage of 40mV and input current of 2nA
III	OPA111(BB)	3	5	Input offset voltage of 50mV and input current of 300pA.
	1344(TEL)	3	5	Input offset voltage of 20mV and input current of 1nA.
	HA5084(HAR)	2	5	Input offset voltage of 85mV and input current of 1nA.
	OP215(PMI)	3	5	Input offset voltage of 65mV with no correlation between devices on the same chip, input current of 1nA.
	OP16(PMI) [8406]	2	5	Input offset voltage of 170mV and input current of 3nA.
	OP22(PMI)	2	5	Not functional for 20Mohm set resistor. Drastic reduction in drive, slew rate, GBW.
	OP32(PMI)	2	5	Not functional for 20Mohm set resistor. Drastic reduction in drive, slew rate, GBW.
IV	OP16(PMI) [7749]	2	5	Input offset voltage of 200mV. Had questionable performance before any irradiation.
	LF351(NAT)	2	5	Input offset voltage of 800mV and drifted by 100mV during poweron after irradiation.
	TLC251(TI)	2	-	Input offset voltage drifted wildly. Drastic reduction in output drive.
	CA3140(RCA)	1	-	Failed.
	ICL7621(IN)	1	-	Failed.
	LT1012(LT)	1	-	Failed.
	LT1037(LT)	1	-	Failed.

Table 5-2 Summary of test results for voltage comparators.

Group	Device Name	Total Gamma Dose (megarad)	Total Neutron Dose ($X10^{13} n/cm^2$)	Major Radiation Effects
I	CMP05(PMI)	2	5	Offset voltage of 1mV, input current of 6uA, output latch damaged.
II	CMP04(PMI)	2	5	Offset voltage of 6mV, input current of 2uA.
	CMP01(PMI)	2	5	Input current of 2uA, two units failed during testing after neutron irradiation.
	LM311(NAT)	2	5	Offset voltage of 10mV, input current of 1uA.

Table 5-3 Summary of test results for voltage buffers.

Group	Device Name	Total Gamma Dose (megarad)	Total Neutron Dose ($X10^{13} n/cm^2$)	Major Radiation Effects
I	BUF03 (PMI)	2	5	Input current as high as 7nA.
II	HA5033 (HAR)	2	5	Input current as high as 40uA.
IV	TSC428 (TEL)	1	-	Failed.

device characteristics such as reference voltage were observed. The results are given in Table 5-4.

Table 5-4 Summary of test results for voltage references.

Group	Device Name	Total Gamma Dose (megarad)	Total Neutron Dose ($X10^{13} n/cm^2$)	Major Radiation Effects
I	TL430 (TI)	2	5	Reference voltage changed by 2%, reference input current of 7uA, maximum operating current of 110mA.
	AD584 (AD)	2	5	Reference voltage changed by 2% except for 1k-ohm load.
	ICL8069 (INT)	2	5	Reference voltage changed by 3%.
II	LM336 (NAT)	2	5	Reference voltage changed by 4%, large change in minimum and maximum operating currents,

5.1.5 Voltage Regulators

The voltage regulators showed large changes with drastic reductions in the output current drive as shown in Table 5-5.

5.1.6 Timers

All the timers tested were not suitable for applications in a radiation environment as indicated in Table 5-6.

Table 5-5 Summary of test results for voltage regulators.

Group	Device Name	Total Gamma Dose (megarad)	Total Neutron Dose ($X10^{13}n/cm^2$)	Major Radiation Effects
II	MC7812 (MOT)	2	5	5% change in output voltage, decrease in current drive
III	MC7912 (MOT)	2	5	Drastic reduction in output current drive.
	UA7912 (FCH)	2	-	Drastic reduction in output current drive.
	LM317 (NAT)	2	-	Drastic reduction in output current drive.
IV	LM337 (NAT)	1	-	Failed.

Table 5-6 Summary of test results for timers.

Group	Device Name	Total Gamma Dose (megarad)	Total Neutron Dose ($X10^{13}n/cm^2$)	Major Radiation Effects
III	ICM7555 (INT)	2	-	Large change in frequency, failed after 2 megarad.
IV	UA555 (FCH)	2	5	Output latched to +5V PS after irradiations but recovered with self-heating.
	L555 (EXAR)	1	-	Failed.
	TLC555 (TI)	1	-	Failed.

5.1.7 Power Devices

Degradations in dc current gain h_{FE} after both gamma and neutron irradiations were the major change observed in the power bipolar transistors. All the power MOS transistor failed showing large shift in threshold voltages. The voltage rectifiers showed no significant change indicating good radiation tolerance. The important results are summarized in Table 5-7.

5.1.8 Transistor Arrays and Monolithic Breadboard Components

Although the NPN transistor arrays showed significant decreases in their dc current gains, they were functional after the irradiations. The monolithic breadboard components from Interdesign were also operational showing decreases in dc current-gains for the bipolar devices and negative shifts in threshold voltages for the MOSFETs. A summary of the experimental results is given in Table 5-8.

This concludes the summary of the test results. The tables above could be used as a selection guide for instrumentation in a radiation environment. Group I devices should be used whenever possible. After the devices for a given radiation-hardened system have been elected and assembled, the entire system should be "burned in" for at least 100 hours to eliminate any infant mortality failures.

Table 5-7 Summary of test results for power devices.

Group	Device Name	Total Gamma Dose (megarad)	Total Neutron Dose ($X10^{13} n/cm^2$)	Major Radiation Effects
I	CTB34 (Sanken)	2	5	Rectifier; no change
	MBR745(MOT)	2	5	Rectifier; no change
	MR854(MOT)	2	5	Rectifier; no change
II	LT1839(TRW)	2	5	h_{FE}(min)=24
	MRF531(MOT)	2	5	h_{FE}(min)=25
	D44C11(GE)	2	5	h_{FE}(min)=73
	D45C8(GE)	2	5	h_{FE}(min)=47
	D44H11(GE)	2	5	h_{FE}(min)=89
	D45H11(GE)	2	5	h_{FE}(min)=62
	MJ4237(MOT)	2	5	h_{FE}(min)=70
	MJ4247(MOT)	2	5	h_{FE}(min)=81
	MJ13080(SOL)	1.5	5	h_{FE}(min)=15
	MJE5221(MOT)	2	5	h_{FE}(min)=53
	MJE5231(MOT)	2	5	h_{FE}(min)=37
	MPSU05(MOT)	2	5	h_{FE}(min)=104
	MPSU55(MOT)	2	5	h_{FE}(min)=66
	2N6338(MOT)	2.5	5	h_{FE}(min)=44
	2N6339(SOL)	-	5	h_{FE}(min)=43
	2N6436(MOT)	2.5	5	h_{FE}(min)=28
	2N6438(MOT)	2	5	h_{FE}(min)=29
	2N6385(MOT)	2	5	h_{FE}(min)=4000
	2N6385(RCA)	2	5	h_{FE}(min)=3400
	2N6650(RCA)	2	5	h_{FE}(min)=520
IV	IRF250(IRC)	1	-	Failed.
	IRF250(MOT)	1	-	Failed.
	IRF250(SIL)	1	-	Failed.
	IRF430(MOT)	1	-	Failed.
	IRF450(IRC)	1	-	Failed.
	IRF450(SIL)	1	-	Failed.
	MTM15N45 (MOT)	1	-	Failed.
	RFP3N45 (RCA)	1	-	Failed.
	VN0600D (SIL)	1	-	Failed.

Table 5-8 Summary of test results for transistor arrays and monolithic breadboard components.

Group	Device Name	Total Gamma Dose (megarad)	Total Neutron Dose ($X10^{13} n/cm^2$)	Major Radiation Effects
II	CA3127(RCA)	2.5	5	$h_{FE}(min) = 58$
	SL3145(PLY)	2.5	5	$h_{FE}(min) = 61$
	CA3146(RCA)	2.5	5	$h_{FE}(min) = 57$
	CA3183(RCA)	2.5	5	$h_{FE}(min) = 45$
	M0004	2.5	5	$h_{FE}(min) = 143$
	M0302B	2.5	5	$h_{FE}(min) = 47$
	M0003A	2.5	5	$h_{FE}(min) = 10$
III	M0417	2.5	5	$V_T(n\text{-}ch) = 0.44V$
	M0415	2.5	5	$V_T(n\text{-}ch) = 0.86V$
				$V_T(p\text{-}ch) = -5.4V$

5.2 Future Work

Although an enormous amount of literature is now available regarding the radiation effects on semiconductors, much work has yet to be performed. The following is a list of possible future work directly related to this research.

1. A literature search revealed the lack of fundamental studies on the radiation effects of physical device parameters such as device dimensions, doping levels, doping profiles.
2. A detail comparison of:
   (i) different processing techniques,
   (ii) different design techniques for linear integrated circuits

such as JFET and bipolar input stages, active and resistive loads for the input stages, supply-independent biasing circuits could be performed.

3. The effect of the neutron irradiations in this experiment was in most cases over-shadowed by the thermal annealing effects of gamma irradiations. To obtain the true effects of the neutron dose, a similar set of experiments need to be conducted with devices without any prior gamma dose.
4. An automated test setup should be developed to measure the device parameters during the irradiations and to obtain correlations between passive and active (with the devices operating) irradiations.

LIST OF REFERENCES

LIST OF REFERENCES

1. Nichols, D.K., "A Review of Dose Rate Dependent effects of Total Ionizing Dose (TID) Irradiations," IEEE Transactions on Nuclear Science, Vol. NS-27, No. 2, April 1980.

2. Orrick, H.P., The Effects of Gamma Radiation on Semiconductor Devices for High Temperature Electronics, ORNL/Sub-7685/12, University of Tennessee, Knoxville, 1981.

3. Gover, J.E., "Basic Radiation Effects in Electronics Technology," IEEE 1981 Annual Conference on Nuclear and Space Radiation Effects, Tutorial Short Course, Seattle, Washington, July 1981.

4. Larin, F., Radiation Effects in Semiconductor Devices, John Wiley & Sons, New York, 1968.

5. Harrell, J.A.,et al, "The Application of Remote Electronics in a Nuclear Fuel Reprocessing Environment: Radiation Effects and Design Guidelines," Sandia National Laboratories Report SAND 82-2151, January 1983.

6. Kennedy, E.J., private communications.

7. Bueche, F.J., Introduction to Physics for Scientists and Engineers, 2nd ed., McGraw-Hill, New York, 1975.

8. Raymond, J.P., "Analysis and Testing of Radiation-Induced Transient Effects in Complex Microcircuits," IEEE 1981 Annual Conference on Nuclear and Space Radiation Effects, Tutorial Short Course, Seattle, Washington, July 1981.

9. Grove, A.S., Physics and Technology of Semiconductor Devices, John Wiley & Sons, New York, 1967.

10. Hart, A.R., Smyth Jr., J.B., van Lintt, V.A.J., Snowden, D.P., Leadon, R.E., "Hardness Assurance Considerations for Long-term Ionizing Radiation Effects on Bipolar Structures," IEEE Transactions on Nuclear Science, Vol. NS-25, No.6, December 1978.

11. Grunthaner, F.J., Lewis, B.F., Zamini, N., and Maserjian, J., "XPS Studies of Structure-Induced Radiation Effects at the Si/SiO_2 Interface," IEEE Transactions on Nuclear Science, Vol. NS-27, No.6, December 1980.

12. Palkuti, L.J., "Process Investigations of Total-Dose Hard, Type-108 Op Amp," IEEE Transactions on Nuclear Science, Vol. NS-23, No. 6, December 1976.

13. Johnston, A.H. and Lancaster, C.A., "A Total Dose Homogeneity Study of the 108A Operational Amplifier," IEEE Transactions on Nuclear Science, Vol. NS-26, No. 6, December 1979.

14. Johnston, A.H., "The Application of Operational Amplifiers to Hardened Systems," IEEE Transactions on Nuclear Science, Vol. NS-24, No.6, December 1977.

15. Stanley, A.G. and Gauthier, M.K., "SEM Analysis of Ionizing Radiation Effects in Linear Integrated Circuits," IEEE Transactions on Nuclear Science, Vol. NS-24, No.6, December 1977.

16. Johnston, A.H., "Hand Analysis Techniques for Neutron Degradation of Operational Amplifiers," IEEE Transactions on Nuclear Science, Vol. NS-23, No.6, December 1976.

17. Gauthier, M.K. and Nichols, D.K., "A Comparison of Radiation Damage in Linear ICs from Cobalt-60 Gamma Rays and 2.2 MeV Electrons," IEEE Transactions on Nuclear Science, Vol. NS-30, No. 6, December 1983.

18. Williams, T.F., private communications.

19. Operations Manual for the Bulk Shielding Reactor, April 1983, ORNL/TM-2676/R1.

20. Tektronix 577-178-D1 Linear IC Curve Tracer Instruction Manual, Tektronix Inc., Beaverton, Oregon, 1973.

21. Tektronix 577-177-D1 or D2 Operator's Instruction Manual, Tektronix Inc., Beaverton, Oregon, 1973.

22. PMI 1984 Data Book: Linear and Conversion Products, Precision Monolithics Incorporated, 1984.

23. Gray, P.R., and Meyer, R.G., Analysis and Design of Analog Integrated Circuits, 2nd ed., John Wiley & Sons, New York, 1984.

24. Cooper, M.S. and Retzler, J.P., "Combined Neutron and Thermal Effects on Biipolar Transistor Gain," IEEE Transactions on Nuclear Science, Vol. NS-26, No.6, December 1979.

25. Mitchell, J.P. and Wilson, D.K., "Surface Effects of Radiation on Semiconductor Devices," The Bell System Technical Journal, Vol. XLVI, No.1, Jan. 1967.

26. "Radiation Resistance of HEXFETs," HEXFET Data Book, International Rectifier, El Segundo, California, 1982.

APPENDICES

APPENDIX A

EXPERIMENTAL DATA

The experimental data obtained from the radiation tests are presented in this appendix. The arrangement of the data is as follow:

OPERATIONAL AMPLIFIERS PAGE

VOLTAGE COMPARATORS PAGE

VOLTAGE BUFFERS PAGE

VOLTAGE REFERENCES PAGE

VOLTAGE REGULATORS PAGE

TIMERS PAGE

POWER BIPOLAR TRANSISTORS PAGE

POWER BIPOLAR TRANSISTORS(Continued) PAGE

POWER MOS TRANSISTORS PAGE

VOLTAGE RECTIFIERS PAGE

TRANSISTOR ARRAYS AND MONOLITHIC BREADBOARD COMPONENTS PAGE

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (RCA) CA3140T
Sample Size: 2
Date code: 614

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	7.5mV			
	(2)	-11.5mV			
Output Saturation Voltage (50K load) (+)	(1)	12.9V			
	(2)	12.9V			
(-)	(1)	-14.9V			
	(2)	-14.7V			
Output Saturation Voltage (2K load) (+)	(1)	12.9V			
	(2)	12.9V			
(-)	(1)	-14.7V			
	(2)	-14.7V			
Input Current (+)	(1)	20pA			
	(2)	14pA			
(-)	(1)	23pA			
	(2)	8pA			
Gain (for 50k load)	(1)	92dB	BOTH DEVICES STOPPED FUNCTIONING AFTER 1 MRAD OF GAMMA IRRADIATION		
	(2)	101dB			
CMRR at Vcm = 0V	(1)	78dB			
	(2)	90dB			
PSRR: At +P.S. (+Min)	(1)	100dB(3V)			
	(2)	91dB(3V)			
At -P.S. (-Max)	(1)	78dB(1V)			
	(2)	88dB(1V)			
Supply Current at (+)&(-) P.S.	(1)	3.8mA			
	(2)	3.6mA			
Slew rate (+)	(1)	7.7V/us			
	(2)	7.7V/us			
(-)	(1)	12V/us			
	(2)	11V/us			
Gain-bandwidth Product	(1)	4.8MHz			
	(2)	5.8MHz			

Remark:
1. Gain varies with output swing.
2. This BiMOS operational amplifier was damaged by irradiation of 1Mrad. Output was latched to -P.S.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Harris) HA2-2505-5
Sample Size: 3
Date code: 8249

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	0.4mV	1.3mV	1.2mV	1.2mV
	(2)	2.8mV	3.3mV	3.6mV	3.5mV
	(3)	-1.7mV	-1.1mV	-1.1mV	-1.5mV
Output Saturation Voltage (50K load) (+)	(1)	11.5V	11.6V	11.4V	11.8V
	(2)	12.0V	12.0V	12.0V	12.0V
	(3)	12.0V	12.8V	12.0V	12.0V
(-)	(1)	-11.5V	-11.2V	-11.0V	-11.0V
	(2)	-11.5V	-11.3V	-11.3V	-11.6V
	(3)	-11.5V	-12.0V	-11.3V	-11.5V
Output Saturation Voltage (2K load) (+)	(1)	11.2V	11.2V	11.2V	11.7V
	(2)	11.6V	11.6V	11.7V	11.7V
	(3)	11.8V	12.4V	11.5V	11.6V
(-)	(1)	-10.8V	-10.7V	-10.6V	-10.6V
	(2)	-11.0V	-10.8V	-10.8V	-11.2V
	(3)	-11.0V	-11.6V	-11.0V	-11.0V
Input Current (+)	(1)	100nA	443nA	515nA	495nA
	(2)	27nA	185nA	300nA	260nA
	(3)	31nA	188nA	330nA	285nA
(-)	(1)	96nA	415nA	493nA	465nA
	(2)	27nA	188nA	300nA	261nA
	(3)	29nA	175nA	322nA	287nA
Gain (2K load and 50K load)	(1)	92dB	86dB	83dB	82dB
	(2)	93dB	84dB	81dB	80dB
	(3)	92dB	84dB	82dB	81dB
CMRR at Vcm = 0V	(1)	101dB	101dB	101dB	101dB
	(2)	98dB	97dB	96dB	97dB
	(3)	98dB	97dB	97dB	97dB
PSRR: At +P.S. (+Min)	(1)	95dB(3V)	92dB(4V)	90dB(4V)	90dB(4V)
	(2)	114dB(3V)	102dB(3V)	98dB(3V)	96dB(3V)
	(3)	105dB(3V)	100dB(3V)	101dB(3V)	98dB(3V)
At -P.S. (-Max)	(1)	94dB(4V)	89dB(4V)	86dB(4V)	85dB(4V)
	(2)	96dB(3V)	87dB(3V)	84dB(3V)	83dB(3V)
	(3)	95dB(3V)	86dB(3V)	84dB(3V)	82dB(3V)
Supply Current at (+)&(-) P.S.	(1)	5.4mA	5.4mA	5.4mA	5.3mA
	(2)	4.3mA	4.2mA	4.1mA	4.1mA
	(3)	4.4mA	4.2mA	4.1mA	4.1mA
Slew rate (+)	(1)	40V/us	40V/us	42V/us	42V/us
	(2)	30V/us	30V/us	30V/us	32V/us
	(3)	30V/us	32V/us	31V/us	31V/us
(-)	(1)	33V/us	40V/us	39V/us	40V/us
	(2)	29V/us	29V/us	28V/us	29V/us
	(3)	29V/us	30V/us	29V/us	29V/us
Gain-bandwidth Product	(1)	12MHz	11MHz	11MHz	11MHz
	(2)	8.6MHz	7.7MHz	7.9MHz	7.7MHz
	(3)	8.0MHz	7.6MHz	7.9MHz	7.9MHz

Remark:

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Harris) HA2-2525-5
Sample Size: 3
Date code: 8319

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
Offset Voltage	(1)	-2.3mV	-1.5mV	-1.9mV	-4.0mV
	(2)	-0.7mV	1.3mV	0.9mV	1.8mV
	(3)	4.2mV	3.7mV	-2.0mV	4.2mV
Output Saturation Voltage (50K load) (+)	(1)	11.6V	11.6V	11.6V	11.8V
	(2)	12.0V	12.0V	12.0V	12.0V
	(3)	12.0V	12.0V	12.0V	12.1V
(-)	(1)	-11.2V	-11.2V	-11.2V	-11.2V
	(2)	-11.2V	-11.2V	-11.2V	-11.5V
	(3)	-11.5V	-11.2V	-11.2V	-11.5V
Output Saturation Voltage (2K load) (+)	(1)	11.3V	11.5V	11.5V	11.7V
	(2)	11.8V	11.8V	11.6V	11.8V
	(3)	11.8V	11.8V	11.8V	11.8V
(-)	(1)	-11.0V	-11.0V	-11.0V	-10.9V
	(2)	-11.0V	-11.0V	-10.5V	-11.0V
	(3)	-11.0V	-11/0V	-11.0V	-11.1V
Input Current (+)	(1)	68nA	385nA	560nA	470nA
	(2)	64nA	730nA	1.02uA	830nA
	(3)	54nA	280nA	470nA	375nA
(-)	(1)	68nA	375nA	560nA	468nA
	(2)	65nA	750nA	1.06uA	880nA
	(3)	51nA	270nA	470nA	370nA
Gain (2K load and 50K load)	(1)	84dB	82dB	76dB	75dB
	(2)	83dB	76dB	74dB	74dB
	(3)	84dB	77dB	77dB	77dB
CMRR at Vcm = 0V	(1)	109dB	109dB	107dB	108dB
	(2)	100dB	94dB	94dB	95dB
	(3)	92dB	91dB	108dB	91dB
PSRR: At +P.S. (+Min)	(1)	large(3V)	93dB(3V)	94dB(3V)	94dB(3V)
	(2)	91dB(3V)	84dB(3V)	83dB(4V)	83dB(3V)
	(3)	90dB	87dB(3V)	102dB(3V)	84dB(3V)
At -P.S. (-Max)	(1)	85dB(3V)	81dB(3V)	76dB(3V)	77dB(3V)
	(2)	88dB(3V)	78dB(3V)	76dB(4V)	77dB(3V)
	(3)	86dB	80dB(4V)	78dB(3V)	78dB(3V)
Supply Current at (+)&(-) P.S.	(1)	6.0mA	6.0mA	5.8mA	5.8mA
	(2)	5.6mA	5.2mA	5.0mA	5.0mA
	(3)	5.0mA	4.8mA	5.8mA	4.6mA
Slew rate (+)	(1)	100V/us	100V/us	97V/us	103V/us
	(2)	86V/us	86V/us	79V/us	87V/us
	(3)	80V/us	80V/us	79V/us	83V/us
(-)	(1)	100V/us	100V/us	94V/us	100V/us
	(2)	94V/us	83V/us	75V/us	82V/us
	(3)	80V/us	80V/us	75V/us	80V/us
Gain-bandwidth Product	(1)	14MHz	14MHz	14MHz	14MHz
	(2)	14MHz	13MHz	12MHz	12MHz
	(3)	12MHz	11MHz	11MHz	11MHz

Remark: 1. Offset voltage can change by as much as 3mV during initial poweron after irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Harris) HA1-2539-5
Sample Size: 2
Date code: 8405

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
Offset Voltage	(1)	-4.9mV	-6.5mV	-9.4mV	-6.6mV
	(2)	-4.3mV	-11mV	-13mV	-12mV
Output Saturation Voltage (50K load) (+)	(1)	12.4V	12.4V	12.2V	12.5V
	(2)	12.5V	12.5V	12.5V	12.6V
(-)	(1)	-13.0V	-12.6V	-12.6V	-12.8V
	(2)	-12.5V	-12.5V	-12.5V	-12.5V
Output Saturation Voltage (2K load) (+)	(1)	12.4V	12.4V	12.2V	12.4V
	(2)	12.0V	12.0V	12.5V	12.3V
(-)	(1)	-13.0V	-12.6V	-12.6V	-12.8V
	(2)	-12.0V	-12.0V	-12.5V	-12.3V
Input Current (+)	(1)	-4.2uA	-6.5uA	-7.6uA	-6.9uA
	(2)	-8.8uA	-13uA	-16uA	-15uA
(-)	(1)	-5.9uA	-9.4uA	-11uA	-12uA
	(2)	-9.1uA	-17uA	-21uA	-21uA
Gain (2K load and 50K load)	(1)	84dB	79dB	79dB	79dB
	(2)	84dB	80dB	80dB	79dB
CMRR at Vcm = 0V	(1)	72dB	72dB	72dB	72dB
	(2)	73dB	73dB	73dB	72dB
PSRR: At +P.S. (+Min)	(1)	73dB(2V)	70dB(2V)	69dB(2V)	70dB(3V)
	(2)	72dB(2V)	70dB(2V)	69dB(3V)	69dB(3V)
At -P.S. (-Max)	(1)	82dB(3V)	79dB(3V)	86dB(3V)	85dB(3V)
	(2)	84dB(3V)	90dB(3V)	103dB(4V)	107dB(3V)
Supply Current at (+)&(-) P.S.	(1)	17.5mA	17.5mA	17.5mA	17.5mA
	(2)	20.0mA	19.5mA	19.5mA	20.0mA
Slew rate (+)	(1)	670V/us	670V/us	600V/us	600V/us
	(2)	500V/us	630V/us	670V/us	670V/us
(-)	(1)	800V/us	670V/us	600V/us	600V/us
	(2)	500V/us	660V/us	670V/us	710V/us
Gain-bandwidth Product	(1)	332MHz	300MHz	300MHz	320MHz
	(2)	360MHz	340MHz	310MHz	350MHz

Remark: 1. Both devices tend to oscillate if input voltage exceeds -13.0V.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Harris) HA1-2540-5
Sample Size: 4
Date code: (1)&(2) 8219
(3)&(4) 8408

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	3.9mV	0.45mV	-0.75mV	-2.0mV
	(2)	2.9mV	-0.08mV	-1.1mV	-1.6mV
	(3)	-3.5mV	-5.2mV	-7.4mV	-7.2mV
	(4)	-4.1mV	-6.8mV	-9.0mV	-8.5mV
Output Saturation Voltage (50K load) (+)	(1)	12.9V	12.5V	12.5V	12.5V
	(2)	13.0V	12.8V	12.7V	12.8V
	(3)	12.5V	12.5V	12.5V	12.5V
	(4)	12.5V	12.5V	12.2V	12.5V
(-)	(1)	-12.3V	-12.5V	-12.5V	-12.8V
	(2)	-13.0V	-12.8V	-12.7V	-12.8V
	(3)	-12.5V	-12.1V	-12.5V	-12.5V
	(4)	-12.5V	-12.5V	-12.5V	-12.5V
Output Saturation Voltage (2K load) (+)	(1)	12.8V	12.2V	12.2V	12.3V
	(2)	12.8V	12.5V	12.3V	12.5V
	(3)	12.1V	12.1V	12.3V	12.4V
	(4)	12.5V	12.5V	12.2V	12.3V
(-)	(1)	-12.3V	-12.0V	-12.5V	-12.5V
	(2)	-12.5V	-12.5V	-12.3V	-12.3V
	(3)	-12.1V	-12.1V	-12.3V	-12.0V
	(4)	-12.5V	-12.5V	-12.5V	-12.3V
Input Current (+)	(1)	-12.3uA	-17.0uA	-19.0uA	-17.5uA
	(2)	-5.7uA	-9.0uA	-10.5uA	-10.8uA
	(3)	-5.8uA	-9.0uA	-11.5uA	-12.0uA
	(4)	-6.5uA	-9.2uA	-11.3uA	-11.8uA
(-)	(1)	-13.5uA	-19.5uA	-21.5uA	-23.0uA
	(2)	-5.4uA	-9.5uA	-11.5uA	-12.5uA
	(3)	-6.4uA	-10.2uA	-13.0uA	-13.0uA
	(4)	-6.8uA	-10.8uA	-13.5uA	-13.5uA
Gain (2K load and 50K load)	(1)	82dB	81dB	78dB	79dB
	(2)	90dB	86dB	84dB	84dB
	(3)	86dB	85dB	83dB	82dB
	(4)	86dB	84dB	84dB	81dB
CMRR at Vcm = 0V	(1)	78dB	71dB	71dB	71dB
	(2)	72dB	72dB	72dB	72dB
	(3)	71dB	70dB	71dB	70dB
	(4)	71dB	71dB	71dB	72dB
PSRR: At +P.S. (+Min)	(1)	75dB(2V)	72dB(2V)	70dB(2V)	70dB(2V)
	(2)	72dB(2V)	70dB(2V)	68dB(2V)	68dB(2V)
	(3)	72dB(3V)	70dB(3V)	69dB(3V)	66dB(3V)
	(4)	73dB(3V)	71dB(2V)	70dB(3V)	69dB(3V)
At -P.S. (-Max)	(1)	77dB(2V)	77dB(2V)	78dB(2V)	79dB(3V)
	(2)	84dB(2V)	94dB(3V)	100dB(3V)	97dB(3V)
	(3)	78dB(2V)	81dB(2V)	82dB(3V)	66dB(3V)
	(4)	78dB(2V)	81dB(3V)	83dB(3V)	84dB(3V)
Supply Current at (+)&(-) P.S.	(1)	18.0mA	18.0mA	18.0mA	18.0mA
	(2)	17.5mA	17.5mA	18.0mA	18.0mA
	(3)	20.0mA	20.0mA	20.0mA	21.0mA
	(4)	19.0mA	19.0mA	19.0mA	19.0mA
Slew rate (average of + & - slope)	(1)	250V/us	250V/us	250V/us	250V/us
	(2)	250V/us	270V/us	260V/us	250V/us
	(3)	450V/us	470V/us	440V/us	440V/us
	(4)	400V/us	420V/us	420V/us	410V/us
Gain-bandwidth Product	(1)	160MHz	160MHz	150MHz	150MHz
	(2)	160MHz	160MHz	150MHz	140MHz
	(3)	300MHz	260MHz	250MHz	240MHz
	(4)	250MHz	250MHz	240MHz	220MHz

Remark: 1. All devices tend to oscillate for inputs exceeding -13.0V.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Harris) HA2-2625-5
Sample Size: 3
Date code: 7814

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	-2.0mV	-2.4mV	-2.1mV	-2.2mV
	(2)	1.9mV	1.4mV	1.4mV	1.3mV
	(3)	-0.51mV	-0.56mV	-0.24mV	-0.44mV
Output Saturation Voltage (50K load) (+)	(1)	12.2V	11.8V	11.9V	12.0V
	(2)	12.5V	12.3V	12.2V	12.2V
	(3)	12.0V	11.8V	12.2V	12.2V
(-)	(1)	-12.8V	-13.0V	-13.0V	-12.2V
	(2)	-13.5V	-13.2v	-13.3V	-13.3V
	(3)	-13.2V	-13.6V	-13.2V	-13.3V
Output Saturation Voltage (2K load) (+)	(1)	11.8V	11.7V	11.7V	11.8V
	(2)	12.2V	12.0V	12.0V	12.0V
	(3)	11.8V	11.6V	12.0V	11.9V
(-)	(1)	-12.7V	-12.7V	-12.8V	-12.0V
	(2)	-13.1V	-12.8V	-13.0V	-12.8V
	(3)	-13.0V	-13.2V	-12.8V	-13.0V
Input Current (+)	(1)	9nA	-1nA	-16nA	-50nA
	(2)	8.8nA	1.5nA	-95nA	-48nA
	(3)	-3.8nA	-34nA	-60nA	-100nA
(-)	(1)	3.4nA	30nA	32nA	9.5nA
	(2)	0.5nA	34nA	35nA	-13nA
	(3)	2.5nA	105nA	113nA	34nA
Gain (2K load and 50K load)	(1)	122dB	117dB	106dB	104dB
	(2)	112dB	98dB	96dB	95dB
	(3)	117dB	100dB	98dB	98dB
CMRR at Vcm = 0V	(1)	98dB	102dB	102dB	101dB
	(2)	110dB	106dB	103dB	108dB
	(3)	104dB	102dB	104dB	102dB
PSRR: At +P.S. (+Min)	(1)	108dB(3V)	100dB(3V)	108dB(3V)	108dB(3V)
	(2)	100dB(3V)	100dB(3V)	98dB(3V)	98dB(3V)
	(3)	109dB(3V)	100dB(3V)	108dB(3V)	111dB(3V)
At -P.S. (-Max)	(1)	99dB(3V)	98dB(3V)	95dB(2V)	95dB(2V)
	(2)	101dB(3V)	104dB(2V)	109dB(2V)	105dB(2V)
	(3)	110dB(2V)	100dB(2V)	100dB(2V)	98dB(2V)
Supply Current at (+)&(-) P.S.	(1)	3.6mA	3.2mA	3.1mA	2.9mA
	(2)	2.5mA	2.1mA	2.0mA	1.9mA
	(3)	2.5mA	2.1mA	2.1mA	2.0mA
Slew rate (+)	(1)	25V/us	24V/us	23V/us	24V/us
	(2)	17V/us	17V/us	15V/us	16V/us
	(3)	17V/us	17V/us	16V/us	17V/us
(-)	(1)	20V/us	20V/us	19V/us	20V/us
	(2)	14V/us	14V/us	12V/us	13V/us
	(3)	14V/us	14V/us	13V/us	14V/us
Gain-bandwidth Product	(1)	67MHz	60MHz	57MHz	56MHz
	(2)	45MHz	39MHz	35MHz	35MHz
	(3)	47MHz	40MHz	37MHz	37MHz

Remark:

TEST RESULTS FOR QUAD OPERATIONAL AMPLIFIERS

Device Name: (Harris) HA1-4640-1
Sample Size: 2
Date code: 8239

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1A)	0.28mV	0.92mV	1.9mV	1.7mV
	(1B)	1.0mV	1.7mV	2.8mV	2.6mV
	(1C)	0.58mV	1.4mV	2.8mV	2.5mV
	(1D)	0.87mV	-0.25mV	0.6mV	0.43mV
	(2A)	0.27mV	1.7mV	2.5mV	2.4mV
	(2B)	0.90mV	2.3mV	3.0mV	2.8mV
	(2C)	1.3mV	3.0mV	3.9mV	3.8mV
	(2D)	2.5mV	4.2mV	5.0mV	5.0mV
Output Saturation Voltage (50K load) (+)	(1)	12.7V	12.5V	12.5V	12.7V
	(2)	12.2V	12.5V	12.5V	12.6V
(-)	(1)	-13.5V	-13.0V	-12.8V	-13.2V
	(2)	-13.0V	-13.0V	-13.0V	-13.0V
Output Saturation Voltage (2K load) (+)	(1)	12.0V	12.0V	12.0V	12.0V
	(2)	12.0V	12.0V	12.0V	12.0V
(-)	(1)	-12.7V	-7.7V	-5.0V	-4.7V
	(2)	-12.4V	-6.5V	-4.2V	-4.0V
Input Current (+)	(1A)	-2.0uA	-5.8uA	-8.2uA	-8.8uA
	(1B)	-2.1uA	-6.6uA	-9.4uA	-9.4uA
	(1C)	-2.8uA	-6.7uA	-9.6uA	-9.0uA
	(1D)	-1.9uA	-5.7uA	-8.4uA	-8.7uA
	(2A)	-2.0uA	-5.9uA	-8.4uA	-9.0uA
	(2B)	-2.0uA	-6.5uA	-9.6uA	-9.2uA
	(2C)	-2.0uA	-6.7uA	-9.6uA	-9.0uA
	(2D)	-1.7uA	-6.2uA	-8.6uA	-9.1uA
(-)	(1A)	-2.1uA	-5.9uA	-8.6uA	-9.0uA
	(1B)	-2.1uA	-6.6uA	-9.4uA	-9.6uA
	(1C)	-1.9uA	-6.1uA	-9.0uA	-9.0uA
	(1D)	-2.2uA	-6.1uA	-8.8uA	-9.1uA
	(2A)	-1.9uA	-5.8uA	-8.6uA	-9.2uA
	(2B)	-2.2uA	-6.4uA	-9.4uA	-9.5uA
	(2C)	-2.0uA	-6.2uA	-9.0uA	-8.9uA
	(2D)	-2.0uA	-5.5uA	-8.0uA	-8.4uA
Gain (50K load)	(1A)	105dB	96dB	93dB	92dB
	(1B)	105dB	96dB	93dB	92dB
	(1C)	105dB	96dB	93dB	92dB
	(1D)	105dB	96dB	93dB	92dB
	(2A)	104dB	95dB	93dB	91dB
	(2B)	103dB	95dB	92dB	91dB
	(2C)	106dB	95dB	92dB	91dB
	(2D)	103dB	94dB	92dB	90dB
CMRR at Vcm = 0V	(1A)	109dB	110dB	115dB	119dB
	(1B)	104dB	106dB	109dB	103dB
	(1C)	104dB	106dB	109dB	112dB
	(1D)	118dB	116dB	109dB	112dB
	(2A)	101dB	103dB	102dB	104dB
	(2B)	107dB	112dB	114dB	114dB
	(2C)	104dB	108dB	109dB	109dB
	(2D)	102dB	106dB	106dB	106dB

TEST RESULTS (Continued)

Device Name: (Harris) HA1-4640-1

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
PSRR: At +P.S.	(1A)	103dB(3V)	97dB(3V)	93dB(3V)	92dB(3V)
(+Min)	(1B)	103dB(3V)	97dB(3V)	93dB(3V)	92dB(3V)
	(1C)	101dB(3V)	96dB(3V)	93dB(3V)	91dB(3V)
	(1D)	103dB(3V)	96dB(3V)	93dB(3V)	92dB(3V)
	(2A)	98dB(3V)	94dB(3V)	92dB(3V)	92dB(3V)
	(2B)	102dB(3V)	95dB(3V)	92dB(3V)	92dB(3V)
	(2C)	103dB(3V)	95dB(3V)	92dB(3V)	92dB(3V)
	(2D)	100dB(3V)	94dB(3V)	91dB(3V)	90dB(3V)
At -P.S.	(1A)	109dB(2V)	118dB(2V)	124dB(2V)	118dB(2V)
(-Max)	(1B)	106dB(2V)	110dB(2V)	120dB(2V)	120dB(2V)
	(1C)	103dB(2V)	107dB(2V)	109dB(2V)	110dB(2V)
	(1D)	114dB(2V)	111dB(2V)	107dB(2V)	106dB(2V)
	(2A)	98dB(2V)	100dB(2V)	103dB(2V)	104dB(2V)
	(2B)	110dB(2V)	120dB(2V)	114dB(2V)	112dB(2V)
	(2C)	104dB(2V)	108dB(2V)	116dB(2V)	120dB(2V)
	(2D)	104dB(2V)	107dB(2V)	111dB(2V)	114dB(2V)
Supply Current	(1)	7.0mA	6.8mA	6.6mA	6.6mA
at (+)&(-) P.S.	(2)	6.4mA	6.3mA	6.0mA	6.0mA
Slew rate (+)	(1A)	5.9V/us	5.9V/us	5.9V/us	6.3V/us
	(1B)	6.3V/us	5.9V/us	5.9V/us	5.6V/us
	(1C)	5.9V/us	5.9V/us	5.9V/us	5.0V/us
	(1D)	5.9V/us	5.9V/us	5.9V/us	5.0V/us
	(2A)	5.3V/us	5.6V/us	5.6V/us	5.0V/us
	(2B)	5.3V/us	5.6V/us	5.6V/us	5.0V/us
	(2C)	5.3V/us	5.6V/us	5.6V/us	5.0V/us
	(2D)	5.3V/us	5.6V/us	5.6V/us	5.0V/us
(-)	(1A)	5.9V/us	5.4V/us	5.3V/us	5.0V/us
	(1B)	5.9V/us	5.4V/us	5.3V/us	5.0V/us
	(1C)	5.7V/us	5.4V/us	5.3V/us	4.5V/us
	(1D)	5.7V/us	5.3V/us	5.3V/us	4.5V/us
	(2A)	5.3V/us	4.8V/us	4.8V/us	4.2V/us
	(2B)	5.0V/us	4.8V/us	4.8V/us	4.2V/us
	(2C)	5.0V/us	4.8V/us	4.8V/us	4.2V/us
	(2D)	5.0V/us	4.8V/us	4.8V/us	4.2V/us
Gain-bandwidth	(1A)	17.2MHz	16.0MHz	12.2MHz	14.1MHz
Product	(1B)	17.3MHz	16.0MHz	12.6MHz	14.0MHz
	(1C)	16.3MHz	15.8MHz	12.1MHz	13.4MHz
	(1D)	16.3MHz	15.7MHz	11.8MHz	13.5MHz
	(2A)	15.7MHz	14.3MHz	10.4MHz	12.4MHz
	(2B)	15.1MHz	13.9MHz	10.3MHz	12.0MHz
	(2C)	15.0MHz	14.0MHz	10.3MHz	12.0MHz
	(2D)	14.6MHz	14.0MHz	10.3MHz	12.2MHz

Remark: 1. Gain at 2K load is about 10dB lower.

TEST RESULTS FOR QUAD OPERATIONAL AMPLIFIERS

Device Name: (Harris) HA1-5084-5
Sample Size: 3
Date code: 8224

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1A)	-7.5mV	26mV	45mV	85mV
	(1B)	5.4mV	48mV	61mV	78mV
	(1C)	1.2mV	46mV	57mV	85mV
	(1D)	3.4mV	-16mV	22mV	50mV
	(2A)	2.8mV	4.4mV	5.8mV	28mV
	(2B)	8.3mV	13mV	14mV	28mV
	(2C)	10mV	17mV	18mV	35mV
	(2D)	1.5mV	5.0mV	6.2mV	34mV
	(3A)	-10mV	-1.6mV	7.8mV	20mV
	(3B)	-4.6mV	28mV	29mV	64mV
	(3C)	-3.0mV	22mV	22mV	50mV
	(3D)	-6.8mV	-1.1mV	2.7mV	15mV
Output Saturation Voltage (2K load) (+)	(1)	11.2V	11.0V	11.2V	11.2V
	(2)	11.0V	11.0V	11.2V	11.8V
	(3)	11.1V	11.0V	11.2V	11.2V
(-)	(1)	-11.2V	-11.0V	-11.0V	-11.0V
	(2)	-11.0V	-11.0V	-11.0V	-11.2V
	(3)	-11.1V	-11.0V	-11.0V	-11.2V
Input Current (+)	(1A)	125pA	914pA	1.1nA	1.2nA
	(1B)	114pA	920pA	1.1nA	1.3nA
	(1C)	100pA	840pA	1.1nA	1.2nA
	(1D)	130pA	860pA	1.1nA	1.3nA
	(2A)	90pA	800pA	1.3nA	1.1nA
	(2B)	85pA	760pA	1.2nA	1.0nA
	(2C)	85pA	800pA	1.2nA	1.3nA
	(2D)	80pA	800pA	1.1nA	0.85nA
	(3A)	56pA	540pA	1.1nA	1.1nA
	(3B)	66pA	580pA	1.1nA	1.1nA
	(3C)	60pA	600pA	1.0nA	1.1nA
	(3D)	68pA	600pA	1.0nA	1.3nA
(-)	(1A)	125pA	720pA	0.90nA	0.93nA
	(1B)	80pA	700pA	0.90nA	1.0nA
	(1C)	118pA	820pA	1.0nA	1.2nA
	(1D)	110pA	780pA	1.0nA	1.2nA
	(2A)	90pA	600pA	0.94nA	0.83nA
	(2B)	100pA	640pA	0.94nA	0.80nA
	(2C)	84pA	760pA	1.1nA	1.3nA
	(2D)	86pA	760pA	1.0nA	0.80nA
	(3A)	58pA	420pA	0.90nA	0.83nA
	(3B)	64pA	430pA	0.90nA	0.87nA
	(3C)	68pA	570pA	1.0nA	1.1nA
	(3D)	76pA	580pA	1.0nA	1.2nA
Gain (50K load)	(1A)	108dB	96dB	93dB	94dB
	(1B)	108dB	96dB	93dB	93dB
	(1C)	104dB	96dB	93dB	92dB
	(1D)	106dB	96dB	93dB	93dB
	(2A)	111dB	98dB	94dB	94dB
	(2B)	111dB	98dB	94dB	94dB
	(2C)	111dB	98dB	94dB	94dB
	(2D)	111dB	96dB	94dB	94dB
	(3A)	104dB	94dB	91dB	92dB
	(3B)	105dB	94dB	91dB	92dB
	(3C)	106dB	94dB	91dB	92dB
	(3D)	105dB	94dB	91dB	92dB
CMRR at Vcm = 0V	(1A)	94dB	88dB	86dB	84dB
	(1B)	90dB	86dB	87dB	88dB
	(1C)	84dB	77dB	84dB	78dB
	(1D)	97dB	74dB	83dB	75dB
	(2A)	100dB	99dB	112dB	88dB
	(2B)	107dB	97dB	100dB	98dB
	(2C)	94dB	93dB	86dB	79dB
	(2D)	92dB	91dB	98dB	103dB
	(3A)	87dB	87dB	81dB	80dB
	(3B)	94dB	89dB	84dB	86dB
	(3C)	96dB	90dB	87dB	85dB
	(3D)	92dB	87dB	91dB	84dB

TEST RESULTS (Continued)

Device Name: (Harris) HA1-5084-5

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
PSRR: At +P.S.	(1A)	101dB(2V)	108dB(3V)	105dB(2V)	102dB(2V)
(+Min)	(1B)	101dB(2V)	109dB(3V)	108dB(3V)	108dB(3V)
	(1C)	101dB(2V)	103dB(3V)	103dB(2V)	101dB(3V)
	(1D)	101dB(2V)	108dB(3V)	108dB(3V)	96dB(3V)
	(2A)	108dB(3V)	103dB(2V)	99dB(2V)	101dB(2V)
	(2B)	108dB(3V)	109dB(2V)	108dB(2V)	110dB(2V)
	(2C)	114dB(3V)	102dB(2V)	99dB(2V)	107dB(2V)
	(2D)	119dB(3V)	120dB(3V)	106dB(2V)	110dB(2V)
	(3A)	108dB(3V)	100dB(2V)	96dB(2V)	95dB(2V)
	(3B)	107dB(3V)	99dB(2V)	98dB(2V)	98dB(2V)
	(3C)	118dB(3V)	105dB(2V)	98dB(2V)	99dB(2V)
	(3D)	107dB(3V)	98dB(2V)	97dB(2V)	95dB(2V)
At -P.S.	(1A)	91dB(4V)	79dB(3V)	82dB(2V)	93dB(3V)
(-Max)	(1B)	86dB(4V)	88dB(3V)	96dB(3V)	91dB(3V)
	(1C)	86dB(4V)	86dB(3V)	82dB(2V)	79dB(3V)
	(1D)	110dB(4V)	80dB(3V)	78dB(3V)	74dB(3V)
	(2A)	110dB(4V)	92dB(3V)	98dB(3V)	95dB(3V)
	(2B)	91dB(4V)	102dB(6V)	95dB(3V)	107dB(3V)
	(2C)	86dB(4V)	94dB(3V)	91dB(3V)	84dB(3V)
	(2D)	80dB(4V)	90dB(3V)	94dB(3V)	95dB(3V)
	(3A)	88dB(4V)	89dB(3V)	87dB(3V)	82dB(2V)
	(3B)	96dB(4V)	80dB(3V)	80dB(3V)	79dB(2V)
	(3C)	102dB(4V)	83dB(3V)	81dB(3V)	80dB(2V)
	(3D)	112dB(4V)	90dB(3V)	89dB(3V)	81dB(2V)
Supply Current	(1)	6.8mA	6.0mA	5.0mA	5.3mA
at (+)&(-) P.S.	(2)	7.2mA	6.0mA	4.4mA	5.6mA
	(3)	5.6mA	5.2mA	4.2mA	4.4mA
Slew rate (+)	(1A)	16V/us	11V/us	12V/us	11V/us
	(1B)	16V/us	11V/us	12V/us	11V/us
	(1C)	15V/us	11V/us	11V/us	10V/us
	(1D)	14V/us	11V/us	11V/us	10V/us
	(2A)	16V/us	12V/us	12V/us	12V/us
	(2B)	16V/us	12V/us	12V/us	12V/us
	(2C)	16V/us	12V/us	12V/us	11V/us
	(2D)	16V/us	12V/us	12V/us	11V/us
	(3A)	15V/us	11V/us	10V/us	10V/us
	(3B)	14V/us	10V/us	9.8V/us	9.3V/us
	(3C)	15V/us	11V/us	10V/us	10V/us
	(3D)	15V/us	11V/us	10V/us	10V/us
(-)	(1A)	17V/us	11V/us	12V/us	11V/us
	(1B)	17V/us	11V/us	12V/us	11V/us
	(1C)	17V/us	11V/us	11V/us	11V/us
	(1D)	16V/us	11V/us	11V/us	10V/us
	(2A)	13V/us	11V/us	11V/us	11V/us
	(2B)	13V/us	12V/us	12V/us	11V/us
	(2C)	14V/us	12V/us	12V/us	11V/us
	(2D)	14V/us	12V/us	12V/us	11V/us
	(3A)	15V/us	10V/us	10V/us	9.8V/us
	(3B)	15V/us	10V/us	10V/us	9.6V/us
	(3C)	15V/us	11V/us	10V/us	9.8V/us
	(3D)	15V/us	10V/us	9.9V/us	9.5V/us
Gain-bandwidth	(1A)	3.7MHz	3.1MHz	3.0MHz	2.9MHz
Product	(1B)	3.7MHz	3.1MHz	3.1MHz	3.0MHz
	(1C)	3.6MHz	3.0MHz	3.0MHz	2.9MHz
	(1D)	3.7MHz	2.9MHz	3.0MHz	2.8MHz
	(2A)	3.7MHz	3.1MHz	3.1MHz	3.0MHz
	(2B)	3.8MHz	3.2MHz	3.1MHz	3.0MHz
	(2C)	3.8MHz	3.2MHz	3.2MHz	3.1MHz
	(2D)	3.9MHz	3.2MHz	3.2MHz	3.1MHz
	(3A)	3.5MHz	2.9MHz	2.9MHz	2.7MHz
	(3B)	3.5MHz	2.9MHz	2.9MHz	2.7MHz
	(3C)	3.6MHz	2.8MHz	2.9MHz	2.8MHz
	(3D)	3.5MHz	2.8MHz	2.8MHz	2.7MHz

Remark:
1. Offset voltage changes by as much as 30mV during initial poweron after irradiation.
2. Gain at 2K load varies with negative output swing and is lower by about 20dB.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Harris) HA2-5135-5
Sample Size: 3
Date code: 8345

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
Offset Voltage	(1)	1uV	-260uV	-600uV	-560uV
	(2)	7uV	-178uV	-620uV	-520uV
	(3)	8uV	-20uV	-300uV	-230uV
Output Saturation Voltage (50K load) p (+)	(1)	12.5V	13.5V	13.2V	13.3V
	(2)	13.0V	13.0V	13.0V	13.0V
	(3)	13.0V	13.0V	13.0V	13.0V
(-)	(1)	-12.3V	-13.2V	-12.9V	-12.8V
	(2)	-12.8V	-12.8V	-13.0V	-12.8V
	(3)	-12.8V	-12.8V	-13.0V	-12.8V
Output Saturation Voltage (2K load) (+)	(1)	12.1V	13.0V	13.0V	12.8V
	(2)	12.8V	12.8V	13.0V	13.0V
	(3)	12.8V	12.8V	13.0V	13.0V
(-)	(1)	-12.0V	-13.2V	-12.6V	-12.5V
	(2)	-12.5V	-12.8V	-12.8V	-12.6V
	(3)	-12.3V	-12.6V	-12.5V	-12.6V
Input Current (+)	(1)	0.18nA	-20nA	-22nA	-23nA
	(2)	3.0nA	-7.6nA	12nA	6.2nA
	(3)	0.8nA	-20nA	-23nA	-19nA
(-)	(1)	-0.18nA	29nA	60nA	40nA
	(2)	0.8nA	56nA	100nA	76nA
	(3)	0.95nA	26nA	66nA	40nA
Gain (2K load and 50K load)	(1)	150dB	128dB	120dB	123dB
	(2)	146dB	128dB	120dB	123dB
	(3)	146dB	132dB	124dB	126dB
CMRR at Vcm = 0V	(1)	134dB	120dB	114dB	115dB
	(2)	134dB	118dB	109dB	112dB
	(3)	134dB	126dB	116dB	119dB
PSRR: At +P.S. (+Min)	(1)	137dB(3V)	120dB(3V)	114dB(3V)	118dB(3V)
	(2)	144dB(3V)	120dB(3V)	114dB(3V)	115dB(3V)
	(3)	136dB(3V)	127dB(3V)	118dB(3V)	120dB(3V)
At -P.S. (-Max)	(1)	145dB(2V)	116dB(2V)	110dB(2V)	111dB(2V)
	(2)	144dB(2V)	114dB(2V)	108dB(3V)	110dB(2V)
	(3)	140dB(2V)	124dB(2V)	114dB(2V)	115dB(2V)
Supply Current at (+)&(-) P.S.	(1)	0.80mA	0.64mA	0.60mA	0.61mA
	(2)	1.1mA	0.85mA	0.78mA	0.80mA
	(3)	1.0mA	0.85mA	0.76mA	0.80mA
Slew rate (+)	(1)	0.9V/us	0.7V/us	0.6v/us	0.6V/us
	(2)	1.0V/us	0.7V/us	0.7V/us	0.6V/us
	(3)	1.0V/us	0.9V/us	0.8V/us	0.8V/us
(-)	(1)	0.7V/us	0.6V/us	0.5V/us	0.5V/us
	(2)	0.8V/us	0.7V/us	0.6V/us	0.5V/us
	(3)	0.9V/us	0.9V/us	0.7V/us	0.7V/us
Gain-bandwidth Product	(1)	2.7MHz	1.9MHz	1.7MHz	1.8MHz
	(2)	3.2MHz	2.1MHz	1.9MHz	2.0MHz
	(3)	3.5MHz	2.7MHz	2.4MHz	2.5MHz

Remark: 1. Offset Voltage changes by about 1 mV during initial poweron after irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Intersil) ICL7621DCPA
Sample Size: 2
Date code: 8001

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1A)	-2.2mV			
	(1B)	0.13mV			
	(2A)	0.38mV			
	(2B)	0.70mV			
Output Saturation Voltage (50K load) (+)	(1)	7.9V			
	(2)	7.8V			
(-)	(1)	-7.9V			
	(2)	-7.8V			
Output Saturation Voltage (2K load) (+)	(1)	7.2V			
	(2)	---			
(-)	(1)	-2.4V			
	(2)	---			
Input Current (+)	(1A)	3pA	OUTPUT OF DEVICE (1) WAS +3.5V D.C. FOR ANY INPUT		
	(1B)	2pA			
	(2A)	4pA			
	(2B)	4pA			
(-)	(1A)	5pA			
	(1B)	2pA	OUTPUT OF DEVICE (2) WAS -8V D.C. FOR ANY INPUT		
	(2A)	5pA			
	(2B)	5pA			
Gain (for 50k load)	(1)	104dB			
	(2)	106dB			
CMRR at Vcm = 0V	(1A)	99dB			
	(1B)	100dB			
	(2A)	100dB			
	(2B)	100dB			
PSRR: At +P.S. (+Min)	(1A)	97dB(0.4V)			
	(1B)	110dB(0.4V)			
	(2A)	97dB(1V)			
	(2B)	99dB(1V)			
At -P.S. (-Max)	(1A)	large(2V)			
	(1B)	100dB(2V)			
	(2A)	100dB(2V)			
	(2B)	99dB(2V)			
Supply Current at (+)&(-) P.S.	(1A)	0.36mA			
	(1B)	0.28mA			
	(2A)	0.37mA			
	(2B)	0.27mA			
Slew rate (+)	(1A)	0.38V/us			
	(1B)	0.38V/us			
	(2A)	0.36V/us			
	(2B)	0.36V/us			
(-)	(1A)	0.2V/us			
	(1B)	0.2V/us			
	(2A)	0.25V/us			
	(2B)	0.22V/us			
Gain-bandwidth Product	(1A)	345KHz			
	(1B)	347KHz			
	(2A)	355KHz			
	(2B)	350KHz			

Remark: 1. This dual CMOS operational amplifier was damaged by 1Mrad of gamma irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (National) LF351N
Sample Size: 3
Date code: 915

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
Offset Voltage	(1)	4.2mV	180mV	355mV	496mV
	(2)	-3.6mV	37mV	390mV	502mV
	(3)	-4.8mV	275mV	620mV	843mV
Output Saturation Voltage (50K load) (+)	(1)	14.2V	14.0V	14.0V	14.2V
	(2)	13.8V	13.8V	14.0V	14.2V
	(3)	14.0V	14.0V	--	14.1V
(-)	(1)	-14.2V	-14.0V	-13.2V	-13.4V
	(2)	-13.2V	-13.2V	-13.3V	-13.0V
	(3)	-13.2V	-13.0V	--	-13.0V
Output Saturation Voltage (2K load) (+)	(1)	13.6V	9.6V	7.0V	9.0V
	(2)	13.6V	8.0V	5.6V	7.5V
	(3)	13.2V	9.0V	--	10.5V
(-)	(1)	-13.8V	-12.6V	-12.5V	-13.0V
	(2)	-13.0V	-12.7V	-12.8V	-12.7V
	(3)	-12.8V	-12.5V	--	-12.5V
Input Current (+)	(1)	50pA	3.0nA	5.8nA	2.4nA
	(2)	28pA	3.1nA	6.0nA	2.6nA
	(3)	35pA	4.2nA	5.3nA	2.5nA
(-)	(1)	75pA	3.6nA	6.8nA	2.6nA
	(2)	580pA	3.6nA	6.2nA	2.8nA
	(3)	45pA	4.4nA	5.4nA	2.8nA
Gain (50K load)	(1)	109dB	99dB	96dB	97dB
	(2)	108dB	94dB	90dB	92dB
	(3)	106dB	92dB	88dB	91dB
CMRR at Vcm = 0V	(1)	86dB	78dB	82dB	84dB
	(2)	86dB	74dB	73dB	60dB
	(3)	90dB	67dB	55dB	58dB
PSRR: At +P.S. (+Min)	(1)	87dB(1V)	90dB(1V)	78dB(1V)	78dB(1V)
	(2)	89dB(2V)	78dB(2V)	75dB(2V)	66dB(1V)
	(3)	112dB(2V)	69dB(2V)	67dB(1V)	66dB(1V)
At -P.S. (-Max)	(1)	91dB(4V)	78dB(4V)	90dB(4V)	80dB(4V)
	(2)	91dB(5V)	90dB(3V)	68dB(3V)	67dB(3V)
	(3)	97dB(6V)	64dB(3V)	58dB(4V)	61dB(4V)
Supply Current at (+)&(-) P.S.	(1)	2.2mA	1.5mA	1.4mA	1.4mA
	(2)	2.2mA	1.6mA	1.4mA	1.4mA
	(3)	2.2mA	1.6mA	1.4mA	1.4mA
Slew rate (+)	(1)	14V/us	9.7V/us	7.4V/us	7.1V/us
	(2)	13V/us	11V/us	8.3V/us	8.0V/us
	(3)	38V/us	17V/us	12V/us	12V/us
(-)	(1)	14V/us	15V/us	12V/us	12V/us
	(2)	13V/us	15V/us	12V/us	12V/us
	(3)	29V/us	33V/us	25V/us	24V/us
Gain-bandwidth Product	(1)	4.0MHz	4.0MHz	3.4MHz	3.5MHz
	(2)	3.7MHz	3.6MHz	3.5MHz	3.5MHz
	(3)	8.5MHz	8.9MHz	5.2MHz	8.9MHz

Remark:
1. Offset voltage drifted by as much as 100mV for all three devices during initial poweron after irradiation.
2. Gain at 2K load was about 8dB lower.
3. Device (3) was marginally stable at unity gain

TEST RESULTS FOR DUAL OPERATIONAL AMPLIFIERS

Device Name: (National) LF353N
Sample Size: 4
Date code: P212

Type of Irradiation				GAMMA		NEUTRON
Parameters		S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Offset Voltage		(1A)	1.2mV	3.1mV	5.0mV	5.0mV
		(1B)	-0.20mV	-1.7mV	-2.0mV	0.16mV
		(2A)	0.42mV	-0.80mV	-0.75mV	-0.68mV
		(2B)	1.4mV	2.8mV	3.2mV	3.4mV
		(3A)	-0.94mV	0.09mV	0.90mV	1.4mV
		(3B)	-2.9mV	2.7mV	3.4mV	4.2mV
		(4A)	0.88mV	3.1mV	0.13mV	-0.60mV
		(4B)	0.42mV	1.8mV	1.6mV	-0.32mV
Output Saturation Voltage (50K load)	(+)	(1A&B)	14.2V	14.2V	14.0V	14.2V
		(2A)	14.2V	9.0V	6.2V	6.0V
		(2B)	14.2V	14.0V	14.0V	14.1V
		(3A&B)	14.0V	14.0V	14.2V	14.1V
		(4A&B)	14.2V	14.1V	14.0V	14.1V
	(-)	(1A&B)	-12.8V	-13.0V	-13.0V	-12.9V
		(2A)	-13.9V	-13.0V	-13.0V	-13.0V
		(2B)	-13.9V	-13.2V	-13.0V	-13.0V
		(3A&B)	-13.1V	-13.0V	-13.4V	-13.0V
		(4A&B)	-13.1V	-13.1V	-13.2V	-13.0V
Output Saturation Voltage (2K load)	(+)	(1A&B)	13.9V	13.9V	13.6V	13.7V
		(2A)	13.9V	5.0V	2.5V	2.5V
		(2B)	13.9V	13.8V	13.8V	13.7V
		(3A&B)	13.8V	13.8V	14.0V	13.7V
		(4A&B)	13.9V	13.9V	13.8V	13.8V
	(-)	(1A&B)	-12.5V	-12.4V	-12.3V	-12.7V
		(2A)	-12.5V	-12.5V	-12.5V	-12.5V
		(2B)	-12.5V	-12.5V	-12.6V	-12.5V
		(3A&B)	-12.7V	-12.7V	-13.0V	-12.5V
		(4A&B)	-12.7V	-12.7V	-12.6V	-12.5V
Input Current	(+)	(1A)	95pA	3.4nA	5.4nA	2.7nA
		(1B)	100pA	3.6nA	6.0nA	2.7nA
		(2A)	70pA	2.8nA	5.2nA	2.9nA
		(2B)	65pA	3.1nA	4.8nA	2.4nA
		(3A)	55pA	2.5nA	4.0nA	2.2nA
		(3B)	55pA	2.6nA	4.2nA	2.3nA
		(4A)	75pA	3.3nA	5.0nA	2.6nA
		(4B)	55pA	3.0nA	4.3nA	2.4nA
	(-)	(1A)	90pA	3.3nA	5.2nA	2.7nA
		(1B)	110pA	3.4nA	5.4nA	2.7nA
		(2A)	75pA	2.9nA	5.2nA	3.0nA
		(2B)	70pA	3.2nA	4.8nA	2.4nA
		(3A)	60pA	2.5nA	4.0nA	2.2nA
		(3B)	60pA	2.6nA	4.2nA	2.4nA
		(4A)	85pA	3.4nA	5.0nA	2.6nA
		(4B)	65pA	3.1nA	4.4nA	2.4nA
Gain (2K load and 50K load)		(1A)	--	106dB	102dB	103dB
		(1B)	--	106dB	102dB	103dB
		(2A)	--	97dB	90dB	90dB
		(2B)	--	110dB	104dB	104dB
		(3A)	--	108dB	101dB	103dB
		(3B)	--	108dB	102dB	104dB
		(4A)	--	114dB	110dB	110dB
		(4B)	--	114dB	110dB	110dB

TEST RESULTS (Continued)

Device Name: (National) LF353N

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
CMRR at Vcm = 0V	(1A)	107dB	103dB	100dB	103dB
	(1B)	106dB	108dB	110dB	101dB
	(2A)	113dB	104dB	100dB	102dB
	(2B)	124dB	103dB	106dB	106dB
	(3A)	98dB	106dB	103dB	98dB
	(3B)	100dB	104dB	94dB	100dB
	(4A)	126dB	101dB	114dB	130dB
	(4B)	121dB	108dB	96dB	98dB
PSRR: At +P.S. (+Min)	(1A)	102dB(2V)	100dB(2V)	100dB(1V)	102dB(1V)
	(1B)	113dB(1V)	105dB(1V)	103dB(1V)	95dB(1V)
	(2A)	107dB(2V)	112dB(1V)	120dB(3V)	large(7V)
	(2B)	118dB(2V)	103dB(1V)	102dB(1V)	99dB(1V)
	(3A)	124dB(1V)	106dB(2V)	105dB(1V)	107dB(2V)
	(3B)	124dB(1V)	102dB(2V)	102dB(1V)	110dB(1V)
	(4A)	108dB(2V)	95dB(2V)	112dB(2V)	106dB(1V)
	(4B)	120dB(1V)	104dB(1V)	91dB(1V)	90dB(1V)
At -P.S. (-Max)	(1A)	108dB(6V)	101dB(7V)	99dB(7V)	100dB(7V)
	(1B)	109dB(7V)	110dB(7V)	107dB(7V)	106dB(7V)
	(2A)	126dB(7V)	99dB(7V)	91dB(7V)	92dB(7V)
	(2B)	124dB(7V)	110dB(7V)	104dB(7V)	105dB(6V)
	(3A)	107dB(7V)	113dB(7V)	101dB(8V)	111dB(7V)
	(3B)	120dB(7V)	116dB(7V)	111dB(8V)	107dB(7V)
	(4A)	111dB(7V)	100dB(7V)	118dB(7V)	115dB(6V)
	(4B)	127dB(7V)	104dB(7V)	109dB(7V)	102dB(7V)
Supply Current at (+)&(-) P.S.	(1A)	3.9mA	2.4mA	2.8mA	2.7mA
	(1B)	3.9mA	2.4mA	2.7mA	2.6mA
	(2A)	4.2mA	3.0mA	3.0mA	2.9mA
	(2B)	5.0mA	3.3mA	2.8mA	2.9mA
	(3A)	3.1mA	2.0MA	2.1mA	2.1mA
	(3B)	3.1mA	2.0mA	2.1mA	2.1mA
	(4A)	4.0mA	2.0mA	2.2mA	2.2mA
	(4B)	4.0mA	2.0mA	2.1mA	2.3mA
Slew rate (+)	(1A)	12V/us	11V/us	8.3V/us	7.8V/us
	(1B)	13V/us	11V/us	8.3V/us	8.2V/us
	(2A)	12V/us	5.7V/us	3.3V/us	3.1V/us
	(2B)	12V/us	11V/us	10V/us	7.4V/us
	(3A)	11V/us	9.2V/us	6.7V/us	6.5V/us
	(3B)	11V/us	9.4V/us	6.8V/us	6.6V/us
	(4A)	8.0V/us	8.6V/us	7.0V/us	6.0V/us
	(4B)	7.7V/us	7.1V/us	5.5V/us	5.1V/us
(-)	(1A)	12V/us	12V/us	9.4V/us	8.4V/us
	(1B)	13V/us	11V/us	9.7V/us	8.7V/us
	(2A)	12V/us	10V/us	8.5V/us	8.0V/us
	(2B)	12V/us	11V/us	8.8V/us	8.0V/us
	(3A)	11V/us	9.1V/us	7.7V/us	6.9V/us
	(3B)	11V/us	9.4V/us	8.2V/us	7.1V/us
	(4A)	8.0/us	8.6V/us	6.3V/us	6.3V/us
	(4B)	7.7V/us	7.1V/us	6.0V/us	5.3V/us
Gain-bandwidth Product	(1A)	3.0MHz	3.0MHz	2.8MHz	2.7MHz
	(1B)	3.2MHz	3.1MHz	2.9MHz	2.8MHz
	(2A)	3.1MHz	2.9MHz	2.8MHz	2.7MHz
	(2B)	3.1MHz	2.9MHz	2.8MHz	2.9MHz
	(3A)	2.7MHz	2.6MHz	2.5MHz	2.4MHz
	(3B)	2.8MHz	2.6MHz	2.5MHz	2.5MHz
	(4A)	2.0MHz	2.1MHz	2.0MHz	1.9MHz
	(4B)	2.0MHz	1.9MHz	1.9MHz	1.9MHz

Remark:

1. Offset voltages drift by about 2mV during initial poweron after irradiation.
2. The gain for all four devices varies with output drive due thermal effects during the pretest before any irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Linear Technology) LT1012CH
Sample Size: 3
Date code: 344

Type of Irradiation	S/N	Pretest	GAMMA 1Mrad	GAMMA 2Mrad	NEUTRON $5X10^{13} n/cm^2$
Offset Voltage	(1)	4uV			
	(2)	18uV			
	(3)	17uV			
Output Saturation Voltage (50K load) (+)	(1)	14.2V			
	(2)	14.0V			
	(3)	14.0V			
(-)	(1)	-13.9V			
	(2)	-14.0V			
	(3)	-13.6V			
Output Saturation Voltage (2K load) (+)	(1)	13.0V			
	(2)	12.4V			
	(3)	12.6V			
(-)	(1)	-12.5V			
	(2)	-12.7V			
	(3)	-12.3V			
Input Current (+)	(1)	15pA			
	(2)	50pA			
	(3)	60pA			
(-)	(1)	15pA			
	(2)	60pA			
	(3)	110pA			
Gain (50K load)	(1)	128dB			
	(2)	128dB			
	(3)	125dB			
CMRR at Vcm = 0V	(1)	144dB			
	(2)	140dB			
	(3)	135dB	THE OUTPUT VOLAGE OF DEVICE (1) WAS -8.2VD.C.		
PSRR: AT +P.S. (+Min)	(1)	132DB(1V)			
	(2)	130dB(1V)			
	(3)	121dB(1V)			
At -P.S. (-Max)	(1)	133dB(1V)	THE OUTPUT VOLTAGE OF DEVICE (2) WAS -8.0VD.C.		
	(2)	133dB(1V)			
	(3)	128dB(1V)			
Supply Current at (+)&(-) P.S.	(1)	0.38mA	THE OUTPUT VOLTAGE OF DEVICE (3) WAS -9.0VD.C.		
	(2)	0.40mA			
	(3)	0.40mA			
Slew rate (+)	(1)	0.15V/us			
	(2)	0.15V/us			
	(3)	0.15V/us			
(-)	(1)	0.18V/us			
	(2)	0.17V/us			
	(3)	0.18V/us			
Gain-bandwidth Product	(1)	560KHz			
	(2)	540KHz			
	(3)	560KHz			

Remark: 1. The gain at 2K load varies with negative output swing.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Linear Technology) LT1037CH
Sample Size: 3
Date code: 321

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
Offset Voltage	(1)	53uV			
	(2)	-15uV			
	(3)	5uV			
Output Saturation Voltage (50K load) (+)	(1)	13.8V			
	(2)	14.0V			
	(3)	14.0V			
(-)	(1)	-14.0V			
	(2)	-14.0V			
	(3)	-14.0V			
Output Saturation Voltage (2K load) (+)	(1)	13.4V			
	(2)	14.0V			
	(3)	13.7V			
(-)	(1)	-14.0V			
	(2)	-13.6V			
	(3)	-13.7V			
Input Current (+)	(1)	8.5nA			
	(2)	10nA			
	(3)	8.0nA			
(-)	(1)	8.1nA	ALL DEVICES STOPPED FUNCTIONING AFTER 1 MRAD OF GAMMA IRRADIATION		
	(2)	9.2nA			
	(3)	6.8nA			
Gain (50K load)	(1)	150dB			
	(2)	150dB			
	(3)	151dB			
CMRR at Vcm = 0V	(1)	113dB			
	(2)	113dB			
	(3)	111dB			
PSRR: At +P.S. (+Min)	(1)	112dB(3V)			
	(2)	112dB(3V)			
	(3)	111dB(2V)			
At -P.S. (-Max)	(1)	140dB(3V)			
	(2)	140dB(3V)			
	(3)	136dB(3V)			
Supply Current at (+)&(-) P.S.	(1)	2.6mA			
	(2)	2.5mA			
	(3)	2.6mA			
Slew rate	(1)	11.6V/us			
	(2)	11.0V/us			
	(3)	11.7V/us			
Gain-bandwidth Product	(1)	49MHz			
	(2)	44MHz			
	(3)	50MHz			

Remark: 1. The gain at 2K load varies with negative output swing.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (SIG) NE5534N
Sample Size: 3
Date code: (1) 7921
(2) 8009
(3) 7851

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	240uV	240uV	330uV	330uV
	(2)	-74uV	50uV	210uV	245uV
	(3)	-430uV	520uV	170uV	-65uV
Output Saturation Voltage (50K load) (+)	(1)	14.2V	14.1V	14.0V	14.2V
	(2)	14.2V	14.3V	14.0V	14.0V
	(3)	14.2V	14.0V	14.0V	14.3V
(-)	(1)	-13.1V	-13.1V	-13.0V	-13.4V
	(2)	-13.4V	-14.2V	-13.2V	-13.3V
	(3)	-13.2V	-13.2V	-13.2V	-13.3V
Output Saturation Voltage (2K load) (+)	(1)	14.1V	14.0V	13.8V	14.0V
	(2)	14.2V	13.9V	13.7V	13.9V
	(3)	14.1V	13.8V	13.8V	14.0V
(-)	(1)	-13.1V	-13.1V	-12.8V	-13.0V
	(2)	-13.4V	-13.9V	-13.0V	-13.1V
	(3)	-13.2V	-13.1V	-13.0V	-13.2V
Input Current (+)	(1)	0.3uA	4.2uA	5.1uA	4.1uA
	(2)	0.44uA	4.6uA	6.8uA	5.3uA
	(3)	0.47uA	5.6uA	7.4uA	5.5uA
(-)	(1)	0.3uA	4.2uA	5.2uA	4.1uA
	(2)	0.44uA	4.9uA	7.1uA	5.5uA
	(3)	0.44uA	5.6uA	7.4uA	5.4uA
Gain (50K load)	(1)	114dB	108dB	106dB	106dB
	(2)	119dB	108dB	104dB	106dB
	(3)	111dB	107dB	106dB	106dB
CMRR at Vcm = 0V	(1)	110dB	110dB	112dB	112dB
	(2)	118dB	120dB	120dB	122dB
	(3)	115dB	115dB	120dB	123dB
PSRR: At +P.S. (+Min)	(1)	102dB(3V)	103dB(3V)	102dB(2V)	103dB(1V)
	(2)	118dB(2V)	112dB(2V)	112dB(2V)	118dB(1V)
	(3)	108dB(3V)	106dB(2V)	99dB(2V)	98dB(2V)
At -P.S. (-Max)	(1)	100dB(2V)	103dB(2V)	105dB(2V)	107dB(2V)
	(2)	117dB(2V)	118dB(2V)	113dB(2V)	112dB(2V)
	(3)	108dB(2V)	109dB(2V)	103dB(2V)	104dB(2V)
Supply Current at (+)&(-) P.S.	(1)	5.8mA	4.6mA	3.8mA	3.4mA
	(2)	4.0mA	3.3mA	2.9mA	2.8mA
	(3)	6.2mA	5.2mA	4.8mA	4.4mA
Slew rate (average of + & -)	(1)	20V/us	19V/us	16V/us	17V/us
	(2)	17V/us	14V/us	13V/us	13V/us
	(3)	22V/us	22V/us	19V/us	20V/us
Gain-bandwidth Product	(1)	72MHz	68MHz	68MHz	70MHz
	(2)	61MHz	54MHz	54MHz	58MHz
	(3)	93MHz	81MHz	80MHz	85MHz

Remark: 1. The gain at 2K load was about 10dB lower.

TEST RESULTS FOR QUAD OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP11FY
Sample Size: 2
Date code: 8405

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1A)	0.28mV	0.80mV	0.66mV	0.24mV
	(1B)	0.01mV	1.5mV	1.4mV	0.72mV
	(1C)	0.02mV	0.95mV	1.1mV	0.19mV
	(1D)	0.17mV	0.30mV	0.36mV	-0.32mV
	(2A)	0.19mV	1.4mV	2.4mV	1.1mV
	(2B)	0.12mV	0.80mV	1.6mV	0.4mV
	(2C)	0.50mV	1.5mV	1.6mV	0.9mV
	(2D)	0.50mV	2.4mV	2.7mV	2.0mV
Output Saturation Voltage (50K load) (+)	(1)	14.3V	14.3V	14.0V	14.1V
	(2)	14.2V	14.0V	14.0V	14.1V
(-)	(1)	-13.4V	-13.2V	-13.0V	-13.2V
	(2)	-13.6V	-13.2V	-13.2V	-13.0V
Output Saturation Voltage (2K load) (+)	(1)	14.0V	13.8V	13.8V	13.8V
	(2)	13.8V	13.8V	13.5V	13.6V
(-)	(1)	-12.9V	-12.9V	-12.8V	-13.0V
	(2)	-13.2V	-13.0V	-13.0V	-12.8V
Input Current (+)	(1A)	-265nA	-2.5uA	-2.5uA	-2.3uA
	(1B)	-310nA	-2.5uA	-2.5uA	-2.3uA
	(1C)	-290nA	-2.8uA	-2.9uA	-2.4uA
	(1D)	-340nA	-2.5uA	-2.8uA	-2.4uA
	(2A)	-268nA	-2.4uA	-2.6uA	-2.5uA
	(2B)	-300nA	-2.5uA	-2.7uA	-2.3uA
	(2C)	-291nA	-2.6uA	-2.5uA	-2.3uA
	(2D)	-335nA	-2.5uA	-2.4uA	-2.3uA
(-)	(1A)	-280nA	-2.5uA	-2.6uA	-2.4uA
	(1B)	-290nA	-2.2uA	-2.2uA	-2.1uA
	(1C)	-290nA	-2.8uA	-2.9uA	-2.6uA
	(1D)	-290nA	-2.4uA	-2.6uA	-2.4uA
	(2A)	-298nA	-2.4uA	-2.4uA	-2.4uA
	(2B)	-270nA	-2.6uA	-2.6uA	-2.4uA
	(2C)	-291nA	-2.4uA	-2.4uA	-2.3uA
	(2D)	-275nA	-2.0uA	-1.9uA	-2.0uA
Gain (50K load)	(1A)	124dB	98dB	98dB	99dB
	(1B)	124dB	102dB	101dB	102dB
	(1C)	124dB	101dB	100dB	102dB
	(1D)	124dB	98dB	98dB	99dB
	(2A)	120dB	100dB	98dB	98dB
	(2B)	120dB	96dB	94dB	96dB
	(2C)	120dB	97dB	96dB	97dB
	(2D)	120dB	101dB	99dB	100dB
CMRR at Vcm = 0V	(1A)	128dB	100dB	98dB	98dB
	(1B)	122dB	113dB	104dB	104dB
	(1C)	124dB	97dB	97dB	94dB
	(1D)	118dB	106dB	104dB	103dB
	(2A)	115dB	95dB	95dB	96dB
	(2B)	128dB	95dB	95dB	96dB
	(2C)	112dB	99dB	95dB	97dB
	(2D)	108dB	97dB	95dB	96dB

TEST RESULTS (Continued)

Device Name: (PMI) OP11FY

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
PSRR: At +P.S.	(1A)	124dB(1V)	99dB(2V)	99dB(1V)	102dB(2V)
(+Min)	(1B)	128dB(1V)	96dB(2V)	93dB(1V)	96dB(2V)
	(1C)	140dB(1V)	93dB(2V)	93dB(1V)	96dB(2V)
	(1D)	114dB(1V)	large(2V)	93dB(1V)	120dB(2V)
	(2A)	119dB(1V)	92dB(2V)	70dB(1V)	92dB(2V)
	(2B)	128dB(1V)	93dB(2V)	70dB(1V)	95dB(2V)
	(2C)	116dB(1V)	94dB(2V)	93dB(1V)	95dB(2V)
	(2D)	136dB(1V)	94dB(2V)	91dB(1V)	95dB(2V)
At -P.S.	(1A)	128dB(2V)	98dB(2V)	106dB(2V)	106dB(2V)
(-Max)	(1B)	116dB(2V)	94dB(2V)	92dB(2V)	96dB(2V)
	(1C)	116dB(2V)	98dB(2V)	90dB(2V)	113dB(2V)
	(1D)	128dB(2V)	106dB(2V)	97dB(2V)	109dB(2V)
	(2A)	114dB(3V)	97dB(2V)	91dB(2V)	93dB(2V)
	(2B)	118dB(2V)	97dB(2V)	91dB(2V)	96dB(2V)
	(2C)	132dB(2V)	94dB(2V)	94dB(2V)	96dB(2V)
	(2D)	111dB(2V)	93dB(2V)	94dB(2V)	92dB(2V)
Supply Current at (+)&(-) P.S.	(1A)	2.9mA	1.8mA	1.9mA	1.8mA
	(1B)	3.4mA	1.8mA	1.9mA	1.9mA
	(1C)	3.4mA	1.8mA	1.9mA	1.9mA
	(1D)	4.0mA	1.8mA	1.9mA	1.9mA
	(2A)	2.7mA	1.6mA	1.5mA	1.6mA
	(2B)	3.3mA	1.6mA	1.5mA	1.6mA
	(2C)	3.3mA	1.6mA	1.5mA	1.6mA
	(2D)	3.8mA	1.6mA	1.5mA	1.6mA
Slew rate (+)	(1A)	1.2V/us	0.54V/us	0.55V/us	0.50V/us
	(1B)	1.2V/us	0.57V/us	0.55V/us	0.50V/us
	(1C)	1.2V/us	0.55V/us	0.55V/us	0.52V/us
	(1D)	1.2V/us	0.60V/us	0.58V/us	0.55V/us
	(2A)	1.1V/us	0.40V/us	0.40V/us	0.37V/us
	(2B)	1.1V/us	0.40V/us	0.39V/us	0.36V/us
	(2C)	1.1V/us	0.40V/us	0.41V/us	0.38V/us
	(2D)	1.1V/us	0.50V/us	0.48V/us	0.42V/us
(-)	(1A)	1.2V/us	0.52V/us	0.51V/us	0.53V/us
	(1B)	1.2V/us	0.54V/us	0.51V/us	0.53V/us
	(1C)	1.2V/us	0.55V/us	0.51V/us	0.48V/us
	(1D)	1.2V/us	0.55V/us	0.51V/us	0.48V/us
	(2A)	1.1V/us	0.40V/us	0.35V/us	0.37V/us
	(2B)	1.1V/us	0.40V/us	0.32V/us	0.34V/us
	(2C)	1.1V/us	0.40V/us	0.35V/us	0.36V/us
	(2D)	1.1V/us	0.50V/us	0.41V/us	0.43V/us
Gain-bandwidth Product	(1A)	3.1MHz	1.5MHz	1.5MHz	1.4MHz
	(1B)	2.9MHz	1.5MHz	1.5MHz	1.4MHz
	(1C)	3.1MHz	1.5MHz	1.5MHz	1.5MHz
	(1D)	3.1MHz	1.6MHz	1.6MHz	1.6MHz
	(2A)	2.9MHz	1.1MHz	1.0MHz	1.1MHz
	(2B)	2.9MHz	1.1MHz	1.0MHz	1.1MHz
	(2C)	3.0MHz	1.1MHz	1.1MHz	1.2MHz
	(2D)	2.9MHz	1.3MHz	1.1MHz	1.3MHz

Remark:

1. Gain at 2K load varies with negative output swing.
2. Offset voltage varies by about 0.3mV during initial poweron after irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP15FJ
Sample Size: 4
Date code: 8402

Type of Irradiation			GAMMA				NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	3Mrad	4Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	0.3mV	14mV	-0.64mV	0.48mV	--	1.05mV
	(2)	0.06mV	17mV	16mV	25.5mV	--	26mV
	(3)	-0.08mV	-0.11mV	-0.84mV	-1.36mV	-5.2mV	-5.5mV
	(4)	0.04mV	-0.12mV	-16.5mV	-38mV	-34.5mV	-35mV
Output Saturation Voltage (2K load) (+)	(1)	12.7V	12.8V	12.9V	12.6V	--	12.7V
	(2)	12.5V	12.8V	13.1V	12.8V	--	12.9V
	(3)	11.6V	11.6V	11.4V	12.5V	12.9V	12.5V
	(4)	11.8V	11.8V	11.8V	12.9V	13.0V	13.1V
(-)	(1)	-12.5V	-12.2V	-12.3V	-12.5V	--	-12.5V
	(2)	-12.5V	-12.4V	-12.9V	-12.4V	--	-12.5V
	(3)	-12.5V	-12.7V	-12.5V	-12.5V	-12.3V	-12.5V
	(4)	-12.0V	-12.6V	-12.2V	-12.3V	-12.2V	-12.6V
Input Current (+)	(1)	-9.5pA	1.8nA	1.8nA	1.6nA	--	1.35nA
	(2)	-4pA	1.1nA	1.5nA	1.25nA	--	1.24nA
	(3)	-5pA	1.3nA	0.85nA	0.86nA	1.04nA	0.96nA
	(4)	-3pA	2.2nA	1.2nA	1.5nA	1.5nA	1.43nA
(-)	(1)	-13pA	2.0nA	1.8nA	1.8nA	--	1.42nA
	(2)	-7pA	1.1nA	1.4nA	1.2nA	--	1.18nA
	(3)	-10pA	1.1nA	0.8nA	0.8nA	1.0nA	0.92nA
	(4)	+5pA	2.4nA	1.3nA	1.55nA	1.55nA	1.48nA
Gain (for 2k load and 50K load)	(1)	113dB	106dB	106dB	106dB	--	106dB
	(2)	113dB	108dB	106dB	107dB	--	107dB
	(3)	114dB	108dB	108dB	108dB	106dB	108dB
	(4)	112dB	106dB	106dB	106dB	105dB	105dB
CMRR at Vcm = 0V	(1)	106dB	86dB	80dB	98dB	--	102dB
	(2)	90dB	79dB	88dB	88dB	--	88dB
	(3)	102dB	107dB	89dB	97dB	84dB	83dB
	(4)	88dB	77dB	100dB	78dB	83dB	84dB
PSRR: At +P.S. (+Min)	(1)	94dB(2V)	95dB(6V)	95dB(7V)	96dB(9V)	--	96dB(8V)
	(2)	92dB(2V)	94dB(2V)	94dB(2V)	94dB(2V)	--	93dB(2V)
	(3)	98dB(2V)	96dB(2V)	95dB(2V)	96dB(2V)	95dB(2V)	95dB(2V)
	(4)	94dB(2V)	94dB(5V)	89dB(9V)	91dB(7V)	90dB(9V)	91dB(9V)
At -P.S. (-Max)	(1)	96dB(3V)	96dB(4V)	83dB(3V)	130dB(4V)	--	119db(6V)
	(2)	94dB(3V)	79dB(4V)	86dB(3V)	86dB(3V)	--	86dB(4V)
	(3)	96dB(3V)	88dB(3V)	92dB(5V)	86dB(5V)	83dB(4V)	82dB(4V)
	(4)	94dB(4V)	79dB(4V)	87dB(4V)	80dB(4V)	86dB(4V)	88dB(4V)
Supply Current at (+)&(-) P.S.	(1)	4.0mA	1.7mA	1.6mA	1.6mA	--	1.6mA
	(2)	4.0mA	2.0mA	1.9mA	1.8mA	--	1.8mA
	(3)	3.6mA	2.3mA	2.1mA	2.0mA	1.9mA	1.9mA
	(4)	3.0mA	3.4mA	1.6mA	1.5mA	1.5mA	1.5mA
Slew rate (+)	(1)	11V/us	13V/us	13V/us	14V/us	--	14V/us
	(2)	14V/us	10V/us	10V/us	11V/us	--	11V/us
	(3)	12V/us	13V/us	14V/us	13V/us	14V/us	14V/us
	(4)	12V/us	13V/us	14V/us	14V/us	13V/us	14V/us
(-)	(1)	22V/us	18V/us	17V/us	18V/us	--	18V/us
	(2)	24V/us	21V/us	20V/us	19V/us	--	21V/us
	(3)	18V/us	20V/us	23V/us	20V/us	19V/us	21V/us
	(4)	17V/us	17V/us	17V/us	15V/us	17V/us	17V/us
Gain-bandwidth Product	(1)	4.9MHz	4.9MHz	5.2MHz	5.2MHz	--	5.2MHz
	(2)	4.5MHz	4.7MHz	4.7MHz	4.6MHz	--	4.6MHz
	(3)	5.5MHz	5.0MHz	5.3MHz	5.3MHz	5.2MHz	5.2MHz
	(4)	5.3MHz	4.8MHz	5.1MHz	5.2MHz	5.1MHz	5.0MHz

Remark:
1. Offset Voltage may change during intial poweron after irradiation by as much as 20 mV.
2. Devices (1) and (2) were subjected to a maximum of 3Mrads of gamma irradiation before the neutron irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP16FJ
Sample Size: 2
Date code: 7749

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	60mV	75mV	3mV	-2.1mV
	(2)	-1.1mV	18.3mV	-188mV	-170mV
Output (+) Saturation	(1)	13.0V	13.0V	--	13.0V
	(2)	12.5V	12.8V	12.6V	12.7V
Voltage (-) (2K load)	(1)	-13.0V	-13.0V	--	-13.0V
	(2)	-13.5V	-12.8V	-13.0V	-13.0V
Input (+) Current	(1)	60pA	10nA	6nA	4.5nA
	(2)	140pA	8.5nA	5.6nA	4.2nA
(-)	(1)	100pA	14nA	6.5nA	4.8nA
	(2)	80pA	9.5nA	7.0nA	4.4nA
Gain (for 50k load)	(1)	81dB	102dB	100dB	97dB
	(2)	104dB	98dB	106dB	103dB
CMRR at Vcm = 0V	(1)	77dB	84dB	--	82dB
	(2)	94dB	94dB	84dB	79dB
PSRR: At +P.S.	(1)	60dB(1V)	74dB(2V)	61dB(2V)	59dB(2V)
(+Min)	(2)	98dB(2V)	91dB	88dB(2V)	88dB(3V)
At -P.S.	(1)	68dB(3V)	70dB(3V)	62dB(3V)	62dB(3V)
(-Max)	(2)	94dB(3V)	86dB	74dB(4V)	81dB(5V)
Supply Current at (+)&(-) P.S.	(1)	12mA	7.6mA	6.4mA	6.0mA
	(2)	12mA	6.0mA	4.6mA	4.8mA
Slew rate (+)	(1)	12V/us	13V/us	12V/us	11V/us
	(2)	13V/us	15V/us	14V/us	15V/us
(-)	(1)	13V/us	42V/us	40V/us	42V/us
	(2)	20V/us	50V/us	50V/us	51V/us
Gain-bandwidth Product	(1)	6.7MHz	6.5MHz	6.2MHz	6.1MHz
	(2)	7.4MHz	6.8MHz	7.0MHz	6.9MHz

Remark:

1. A total of 6 OP16 operational amplifiers were tested. Only two of these devices had a date code of 7749.
2. The offset voltage varies during poweron after irradiation by as much as 100mV for device (2)
3. The gain for 2K load is less than that for 50K load.
4. These devices has questionable performance before any irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP16FJ
Sample Size: 4
Date code: 8406

Type of Irradiation				GAMMA	NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	-0.9mV	-13.7mV	-17mV	-21mV
	(2)	0.5mV	85mV	-173mV	-140mV
	(3)	0.7mV	0.46mV	-2.2mV	-2.0mV
	(4)	-0.6mV	-0.8mV	-6.0mV	-10.5mV
Output Saturation Voltage (2K load) (+)	(1)	12.6V	11.8V	13.0V	13.0V
	(2)	12.7V	--	12.7V	13.0V
	(3)	12.8V	12.8V	12.8V	12.4V
	(4)	12.8V	12.5V	12.8V	12.6V
(-)	(1)	-12.3V	-12.0V	-12.0V	-11.0V
	(2)	-12.5V	--	-12.2V	-12.2V
	(3)	-12.4V	-12.2V	-11.6V	-11.5V
	(4)	-12.5V	-12.7V	-12.5V	-12.6V
Input Current (+)	(1)	-10pA	2.0nA	1.5nA	1.22nA
	(2)	-29pA	3.4nA	2.9nA	2.0nA
	(3)	-25pA	2.4nA	1.85nA	1.5nA
	(4)	-2.0pA	1.3nA	1.35nA	1.24nA
(-)	(1)	-17pA	2.4nA	2.1nA	1.49nA
	(2)	-33pA	2.9nA	1.9nA	1.3nA
	(3)	-30pA	2.4nA	2.0nA	1.6nA
	(4)	-6pA	1.9nA	1.85nA	1.65nA
Gain (for 50k load)	(1)	113dB	102dB	103dB	104dB
	(2)	109dB	94dB	74dB	75dB
	(3)	110dB	102dB	103dB	105dB
	(4)	108dB	104dB	104dB	104dB
CMRR at Vcm = 0V	(1)	87dB	72dB	81dB	73dB
	(2)	95dB	36dB	38dB	38dB
	(3)	94dB	100dB	69dB	71dB
	(4)	106dB	96dB	83dB	81dB
PSRR: At +P.S. (+Min)	(1)	93dB(2V)	97dB(4V)	98dB(3V)	104dB(3V)
	(2)	98dB(2V)	36dB	34dB(2V)	34dB(2V)
	(3)	100dB(2V)	100dB(3V)	91dB(3V)	90dB(3V)
	(4)	87dB(2V)	97dB(5V)	102dB(7V)	101dB(8V)
At -P.S. (-Max)	(1)	100dB(5V)	75dB(5V)	82dB(5V)	72dB(5V)
	(2)	88dB(3V)	48dB	46dB(3V)	47dB(3V)
	(3)	96dB(4V)	92dB(4V)	72dB(4V)	72dB(4V)
	(4)	91dB(3V)	108dB(5V)	82dB(4V)	82dB(4V)
Supply Current at (+)&(-) P.S.	(1)	3.7mA	1.7mA	1.9mA	2.0mA
	(2)	3.8mA	0.8mA	0.8mA	0.8mA
	(3)	4.2mA	1.8mA	2.0mA	2.0mA
	(4)	6.8mA	3.0mA	2.8mA	2.7mA
Slew rate (+)	(1)	13V/us	17V/us	14V/us	14V/us
	(2)	13V/us	6.3V/us	6.3V/us	6.0V/us
	(3)	21V/us	20V/us	19V/us	18V/us
	(4)	50V/us	50V/us	45V/us	48V/us
(-)	(1)	15V/us	17V/us	16V/us	17V/us
	(2)	19V/us	15V/us	15V/us	13V/us
	(3)	23V/us	20V/us	17V/us	19V/us
	(4)	66V/us	62V/us	59V/us	56V/us
Gain-bandwidth Product	(1)	5.9MHz	5.4MHz	5.8MHz	5.1MHz
	(2)	6.7MHz	2.1MHz	5.1MHz	3.6MHz
	(3)	6.8MHz	6.6MHz	5.7MHz	5.1MHz
	(4)	19MHz	19MHz	21MHz	19MHz

Remark:

1. Out of the total 6 op16's tested, four of them had a date code of 8406.
2. Device (2) was severely damaged by irradiated.
3. Device (3) had visible cross-over distortion after neutron irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP17FJ
Sample Size: 2
Date code: (1) 7751
(2) 8350

Type of Irradiation			GAMMA		NEUTRON
Paramaters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	-0.23mV	2.1mV	-0.5mV	-0.34mV
	(2)	0.32mV	-4.6mV	5.4mV	15mV
Saturation (+) Voltage	(1)	12.0V	12.0V	13.0V	12.5V
(for 50K load)	(2)	13.0V	13.2V	13.2V	13.4V
(-)	(1)	-13.8V	-13.2V	-13.7V	-13.8V
	(2)	-13.8V	-13.8V	-13.7V	-14.0V
Saturation (+) Voltage	(1)	--	11.2V	12.8V	12.0V
(2K load)	(2)	12.8V	12.8V	12.9V	13.0V
(-)	(1)	--	-12.8V	-12.8V	-12.9V
	(2)	-12.8V	-12.5V	-12.5V	-12.7V
Input (+) Current	(1)	50pA	1.0nA	1.0nA	0.72nA
	(2)	10pA	1.25nA	1.55nA	1.0nA
(-)	(1)	30pA	0.95nA	1.0nA	0.74nA
	(2)	10pA	1.3nA	1.6nA	1.06nA
Gain (for 2k load and 50K load)	(1)	103dB	102dB	100dB	101dB
	(2)	108dB	105dB	104dB	106dB
CMRR at Vcm = 0V	(1)	84dB	86dB	86dB	89dB
	(2)	102dB	90dB	92dB	82dB
PSRR: At +P.S. (+Min)	(1)	84dB(3V)	95dB(3V)	94dB(3V)	91dB(3V)
	(2)	92dB(2V)	104dB(2V)	104dB(2V)	102dB(2V)
At -P.S. (-Max)	(1)	80dB(4V)	83dB(4V)	83dB(4V)	85dB(4V)
	(2)	98dB(4V)	94dB(4V)	94dB(4V)	84dB(4V)
Supply Current at (+)&(-) P.S.	(1)	8.0mA	7.0mA	5.6mA	4.8mA
	(2)	4.1mA	3.5mA	3.2mA	3.1mA
Slew rate (+)	(1)	48V/us	42V/us	70V/us	69V/us
	(2)	40V/us	42V/us	43V/us	50V/us
(-)	(1)	63V/us	67V/us	71V/us	77V/us
	(2)	58V/us	67V/us	63V/us	65V/us
Gain-bandwidth Product	(1)	24MHz	24MHz	26MHz	23MHz
	(2)	20MHz	20MHz	22MHz	20MHz

Remark:

1. Offset voltage varies during initial poweron after irradiation by about 2 mV.
2. The testing equipment is incapable of measuring bias current of less than 20pA accurately.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP22FJ
Sample Size: 2
Date code: 8416

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	-0.31mV	-1.8mV	-1.4mV	-1.5mV
	(2)	-0.28mV	-0.6mV	-1.1mV	-1.1mV
Output Saturation Voltage (50K load) (+)	(1)	13.8V	13.8V	13.7V	14.0V
	(2)	14.0V	14.0V	13.8V	14.0V
(-)	(1)	-14.1V	-11.2V	-13.3V	-13.0V
	(2)	-14.0V	-11.0V	-7.6V	-11.5V
Output Saturation Voltage (2K load) (+)	(1)	13.8V	--	4.0V	4.5V
	(2)	14.0V	--	1.1V	1.2V
(-)	(1)	-8.8V	--	-1.0V	-1.0V
	(2)	-13.6V	--	-0.2V	-0.35V
Input Current (+)	(1)	-42nA	-0.34uA	-0.47uA	-0.57uA
	(2)	-42nA	-0.50uA	-0.60uA	-0.64uA
(-)	(1)	-42nA	-0.40uA	-0.54uA	-0.60uA
	(2)	-42nA	-0.51uA	-0.59uA	-0.64uA
Gain (for 50k load)	(1)	124dB	94dB	91dB	91dB
	(2)	125dB	86dB	83dB	83dB
CMRR at Vcm = 0V	(1)	110dB	103dB	106dB	105dB
	(2)	116dB	110dB	106dB	106dB
PSRR: At +P.S. (+Min)	(1)	122dB(2V)	78dB(3V)	84dB(3V)	80dB(3V)
	(2)	111dB(2V)	74dB(3V)	73dB(3V)	71(5V)
At -P.S. (-Max)	(1)	114dB(1V)	120dB(1.5V)	108dB(1V)	116dB(1V)
	(2)	118dB(1V)	94dB(1V)	90dB(1V)	89dB(1V)
Supply Current (+)	(1)	400uA	180uA	200uA	185uA
	(2)	400uA	150uA	140uA	135uA
(-)	(1)	370uA	150uA	160uA	155uA
	(2)	390uA	115uA	110uA	105uA
Slew rate (average of + & - slope)	(1)	0.17V/us	0.11V/us	0.07V/us	0.07V/us
	(2)	0.17V/us	0.04V/us	0.04V/us	0.04V/us
Gain-bandwidth Product	(1)	450KHz	271KHz	110KHz	143KHz
	(2)	450KHz	88KHz	84KHz	82KHz

Remark:
1. This programmable operational amplifier was set with a 180K resistor from pin 8 to ground. The device stopped functioning for a set resistor of 20M after irradiation.
2. The gain varies with output swing after irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (MPS) OP27FJ
Sample Size: 2
Date code: 8321

Type of Irradiation			GAMMA				NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	3Mrad	4Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	16uV	43uV	56uV	38uV	44uV	33uV
	(2)	-24uV	-27uV	-27uV	-33uV	-19uV	-24uV
Saturation (+) Voltage (50K load)	(1)	13.5V	14.0V	14.0V	14.0V	14.0V	14.1V
	(2)	13.8V	14.0V	14.0V	13.8V	14.0V	14.0V
(-)	(1)	-13.8V	-14.0V	-13.8V	-14.0V	-14.2V	-14.0V
	(2)	-14.2V	-14.2V	-14.2V	-14.0V	-14.2V	-14.0V
Saturation (+) Voltage (2K load)	(1)	13.2V	13.6V	13.6V	13.6V	13.6V	13.8V
	(2)	13.4V	13.5V	13.6V	13.2V	13.5V	13.5V
(-)	(1)	-13.2V	-12.7V	-12.6V	-13.0V	-12.8V	-12.8V
	(2)	-13.7V	-13.0V	-13.2V	-13.0V	-13.0V	-13.0V
Input Current (+)	(1)	-0.6nA	0.80uA	0.70uA	0.80uA	0.80uA	0.53uA
	(2)	13nA	0.90uA	0.78uA	0.80uA	0.79uA	0.52uA
(-)	(1)	-3.0nA	0.75uA	0.67uA	0.81uA	0.80uA	0.54uA
	(2)	14nA	0.64uA	0.52uA	0.54uA	0.50uA	0.45uA
Gain (for 2k load and 50K load)	(1)	134dB	128dB	128dB	128dB	126dB	128dB
	(2)	134dB	124dB	126dB	126dB	126dB	126dB
CMRR at Vcm = 0V	(1)	130dB	133dB	131dB	133dB	132dB	132dB
	(2)	130dB	140dB	140dB	140dB	128dB	138dB
PSRR: At +P.S. (+Min)	(1)	131dB(3V)	133dB(3V)	133dB(3V)	135dB(3V)	150dB(2V)	131dB(2V)
	(2)	129dB(3V)	130dB(2V)	130dB(2V)	131dB(2V)	134dB(2V)	128dB(2V)
At -P.S. (-Max)	(1)	128dB(2V)	130dB(2V)	130dB(2V)	129dB(2V)	125dB(2V)	133dB(2V)
	(2)	134dB(2V)	124dB(2V)	126dB(2V)	126dB(2V)	121dB(2V)	129dB(2V)
Supply Current at (+)&(-) P.S.	(1)	3.0mA	2.4mA	2.3mA	2.3mA	2.2mA	2.3mA
	(2)	3.0mA	2.4mA	2.4mA	2.3mA	2.2mA	2.3mA
Slew rate (Average +&-)	(1)	2.0V/us	1.6V/us	1.5v/us	1.5V/us	1.6V/us	1.6V/us
	(2)	2.5V/us	1.7V/us	1/7V/us	1.7V/us	1.7V/us	1.7V/us
Gain-bandwidth Product	(1)	6.2MHz	4.4MHz	4.4MHz	4.4MHz	4.1MHz	4.2MHz
	(2)	6.7MHz	4.7MHz	4.7MHz	4.7MHz	4.3MHz	4.4MHz

Remark: 1. Op 27's from both MicroPower Systems and Precision Monolithic Incorporated were tested.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP27FJ
Sample Size: 2
Date code: 8113

Type of Irradiation			GAMMA				NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	3Mrad	4Mrad	$5X10^{13}n/cm^2$
Offset Voltage	(1)	-13uV	-8uV	-4uV	-12uV	-9uV	-8uV
	(2)	35uV	48uV	47uV	46uV	60uV	64uV
Output Saturation Voltage (50K load) (+)	(1)	14.0V	14.0V	13.8V	13.8V	13.8V	14.0V
	(2)	13.8V	14.0V	13.9V	14.0V	13.9V	14.0V
(-)	(1)	-14.0V	-14.0V	-14.0V	-14.0V	-14.0V	-14.0V
	(2)	-14.0V	-14.2V	-14.2V	-14.0V	-14.2V	-14.0V
Output Saturation Voltage (2K load) (+)	(1)	13.8V	13.8V	13.4V	13.5V	13.5V	13.7V
	(2)	13.6V	13.7V	13.5V	13.6V	13.5V	13.8V
(-)	(1)	-13.5V	-13.5V	-13.4V	-13.0V	-12.9V	-13.0V
	(2)	-13.7V	-13.6V	-13.8V	-13.5V	-13.8V	-13.8V
Input Current (+)	(1)	-3nA	-3nA	19nA	66nA	130nA	120nA
	(2)	4nA	17nA	15nA	34nA	66nA	28nA
(-)	(1)	-5nA	6nA	29nA	79nA	140nA	130nA
	(2)	1nA	18nA	27nA	53nA	84nA	74nA
Gain (for 2k load and 50K load)	(1)	124dB	123dB	121dB	121dB	121dB	121dB
	(2)	124dB	123dB	123dB	122dB	122dB	122dB
CMRR at Vcm = 0V	(1)	119dB	118dB	118dB	118dB	119dB	119dB
	(2)	129dB	129dB	129dB	130dB	129dB	130dB
PSRR: At +P.S. (+Min)	(1)	large(3V)	140dB(3V)	133dB(2V)	131dB(3V)	128dB(2V)	128dB(2V)
	(2)	large(3V)	large(3V)	large(3V)	138dB(3V)	150dB(2V)	150dB(2V)
At -P.S. (-Max)	(1)	128dB(2V)	129dB(2V)	129dB(2V)	131dB(2V)	130dB(2V)	130dB(2V)
	(2)	126dB(2V)	121dB(2V)	121dB(2V)	121dB(2V)	120dB(2V)	121dB(2V)
Supply Current at (+)&(-) P.S.	(1)	2.8mA	2.6mA	2.5mA	2.4mA	2.3mA	2.3mA
	(2)	3.1mA	2.9mA	2.7mA	2.7mA	2.6mA	2.6mA
Slew rate	(1)	1.8V/us	1.7V/us	1.6V/us	1.5V/us	1.4V/us	1.5V/us
	(2)	1.9V/us	1.8V/us	1.7V/us	1.7V/us	1.7V/us	1.7v/us
Gain-bandwidth Product	(1)	5.2MHz	4.3MHz	4.3MHz	4.2MHz	3.9MHz	3.9MHz
	(2)	5.6MHz	4.6MHz	4.6MHz	4.6MHz	4.4MHz	4.4MHz

Remark: 1. Op 27's from Precision Monolithic Incorporated and Micro-Power Systems were tested.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP32FZ
Sample Size: 3
Date code: 8351

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	-0.225mV	-0.45mV	-0.48mV	-0.44mV
	(2)	0.068mV	-0.70mV	-0.40mV	-0.42mV
	(3)	-0.10mV	-0.17mV	-0.20mV	0.125mV
Output Saturation Voltage (50K load) (+)	(1)	13.7V	14.0V	14.0V	14.3V
	(2)	14.0V	14.0V	14.1V	14.1V
	(3)	14.0V	14.0V	14.2V	14.2V
(-)	(1)	-14.2V	-14.0V	-14.0V	-14.0V
	(2)	-14.1V	-14.0V	-14.0V	-14.0V
	(3)	-14.0V	-14.0V	-14.0V	-14.0V
Output Saturation Voltage (2K load) (+)	(1)	13.7V	--	7.0V	7.0V
	(2)	13.0V	--	3.0V	5.1V
	(3)	14.0V	--	6.5V	6.2V
(-)	(1)	-13.5V	--	-3.0V	-3.0V
	(2)	-13.0V	--	-2.2V	-3.1V
	(3)	-13.0V	--	-2.5V	-3.0V
Input Current (+)	(1)	-40nA	-0.9uA	-1.05uA	-1.15uA
	(2)	-104nA	-1.2uA	-1.35uA	-1.4uA
	(3)	-78nA	-1.2uA	-1.3uA	-1.33uA
(-)	(1)	-40nA	-1.0uA	-1.15uA	-1.20uA
	(2)	-104nA	-1.3uA	-1.35uA	-1.45uA
	(3)	-78nA	-1.22uA	-1.3uA	-1.29uA
Gain (for 50k load)	(1)	128dB	94dB	94dB	96dB
	(2)	128dB	92dB	91dB	93dB
	(3)	128dB	108dB	94dB	94dB
CMRR at Vcm = 0V	(1)	130dB	98dB	98dB	106dB
	(2)	116dB	108dB	110dB	117dB
	(3)	111dB	108dB	108dB	111dB
PSRR: At +P.S. (+Min)	(1)	106dB(1V)	90dB(8V)	92dB(7V)	110dB(3V)
	(2)	104dB(1V)	91dB(2V)	82dB(7V)	84dB(4V)
	(3)	104dB(1V)	92dB(1V)	86dB(3V)	81dB(4V)
At -P.S. (-Max)	(1)	122dB(0.5V)	104dB(0.5V)	104db(0.5V)	97dB(0.5V)
	(2)	large(0.5V)	110dB(0.5V)	122dB(0.5V)	113dB(0.5V)
	(3)	112dB(0.5V)	102dB(0.5V)	105dB(0.5V)	99dB(0.5V)
Supply Current (+)	(1)	1.1mA	540uA	560uA	520uA
	(2)	1.2mA	480uA	480uA	500uA
	(3)	1.2mA	540uA	540uA	520uA
(-)	(1)	1.0mA	460uA	440uA	460uA
	(2)	1.0mA	400uA	360uA	420uA
	(3)	1.0mA	440uA	460uA	460uA
Slew rate	(1)	3.7V/us	1/8V/us	1.8V/us	1.8V/us
	(2)	3.6V/us	1.6V/us	1.6V/us	1.7V/us
	(3)	3.7V/us	1.6V/us	1.9V/us	1.8V/us
Gain-bandwidth Product	(1)	11MHz	3.8MHz	4.5MHz	4.3MHz
	(2)	11MHz	3.1MHz	3.6MHz	3.8MHz
	(3)	11MHz	3.4MHz	4.3MHz	4.1MHz

Remark:
1. The programmable operational amplifier was set by a 180K resistor between pin 8 and ground.
2. The device stopped functioning for a set resistor of 20M after irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP37FJ
Sample Size: 3
Date code: 8239

Type of Irradiation			GAMMA			NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	3Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	-20uV	-5uV	3uV	-1uV	1uV
	(2)	-40uV	-34uV	-32uV	-36uV	-39uV
	(3)	-30uV	-12uV	-10uV	-12uV	-6uV
Output Saturation Voltage (50K load) (+)	(1)	14.0V	14.0V	13.6V	14.0V	14.0V
	(2)	13.2V	13.9V	13.7V	14.0V	14.0V
	(3)	13.8V	13.8V	13.9V	14.0V	14.0V
(-)	(1)	-14.0V	-13.8V	-14.0V	-14.0V	-14.0V
	(2)	-14.0V	-14.0V	-14.0V	-14.0V	-14.0V
	(3)	-13.9V	-13.9V	-13.7V	-14.0V	-14.0V
Output Saturation Voltage (2K load) (+)	(1)	13.5V	13.5V	13.3V	13.8V	13.8V
	(2)	13.0V	13.6V	13.2V	13.4V	13.5V
	(3)	13.5V	13.4V	13.8V	13.7V	13.6V
(-)	(1)	-14.0V	-13.8V	-13.8V	-13.8V	-13.8V
	(2)	-13.8V	-13.8V	-13.8V	-13.4V	-13.5V
	(3)	-13.5V	-13.5V	-13.6V	-13.7V	-13.6V
Input Current (+)	(1)	48nA	18nA	9nA	70nA	84nA
	(2)	37nA	290nA	240nA	320nA	300nA
	(3)	14nA	330nA	460nA	520nA	410nA
(-)	(1)	53nA	-4nA	13nA	94nA	92nA
	(2)	15nA	280nA	380nA	380nA	300nA
	(3)	12nA	320nA	450nA	480nA	400nA
Gain (for 2k load and 50K load)	(1)	127dB	123dB	123dB	122dB	122dB
	(2)	125dB	120dB	120dB	120dB	120dB
	(3)	126dB	123dB	122dB	123dB	123dB
CMRR at Vcm = 0V	(1)	150dB	130dB	130dB	131dB	129dB
	(2)	124dB	122dB	123dB	124dB	123dB
	(3)	122dB	123dB	123dB	124dB	123dB
PSRR: At +P.S. (+Min)	(1)	124dB(3V)	124dB(2V)	124dB(2V)	124dB(2V)	123dB(2V)
	(2)	117dB(3V)	114dB(3V)	114dB(3V)	115dB(2V)	116dB(2V)
	(3)	134dB(3V)	130dB(3V)	130dB(3V)	131dB(2V)	130dB(2V)
At -P.S. (-Max)	(1)	135dB(2V)	121dB(2V)	120dB(2V)	120dB(2V)	123dB(2V)
	(2)	134dB(2V)	122dB(2V)	126dB(2V)	124dB(2V)	129dB(2V)
	(3)	134dB(2V)	126dB(2V)	124dB(2V)	124dB(2V)	124dB(2V)
Supply Current at (+)&(-) P.S.	(1)	3.5mA	3.2mA	3.1mA	3.1mA	3.1mA
	(2)	3.4mA	3.1mA	3.0mA	3.0mA	3.0mA
	(3)	3.8mA	3.6mA	3.5mA	3.4mA	3.5mA
Slew rate (Average of +&-)	(1)	17V/us	15V/us	14V/us	14V/us	14V/us
	(2)	18V/us	15V/us	14V/us	14V/us	14V/us
	(3)	20V/us	17V/us	16V/us	16V/us	16V/us
Gain-bandwidth Product	(1)	65MHz	56MHz	55MHz	54MHz	53MHz
	(2)	67MHz	57MHz	56MHz	54MHz	54MHz
	(3)	72MHz	62MHz	62MHz	60MHz	60MHz

Remark:

TEST RESULTS FOR DUAL OPERATIONAL AMPLIFIERS

Device Name: (PMI) OP215FJ
Sample Size: 5
Date code: 8345

Type of Irradiation				GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	3Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1A)	-0.5mV	0.3mV	8.4mV	23mV	16mV
	(1B)	-1.6mV	-2.4mV	12.8mV	9.1mV	9.0mV
	(2A)	-0.02mV	9.6mV	6.2mV	-11mV	-15mV
	(2B)	-1.2mV	1.2mV	3.0mV	-1.7mV	0.4mV
	(3A)	-0.3mV	34mV	66mV	65mV	65mV
	(3B)	-1.1mV	4.0mV	11mV	13mV	16mV
	(4A)	-0.5mV	2.9mV	-6.2mV	-3.5mV	--
	(4B)	-1.5mV	-0.05mV	-0.54mV	2.8mV	-1.0mV
	(5A)	-0.39mV	-5.0mV	7.8mV	-11mV	-22mV
	(5B)	-0.24mV	-3.8mV	-3.5mV	-13mV	-15mV
Output Saturation Voltage (2K load) (+)	(1A&B)	12.7V	12.6V	12.9V	13.0V	12.8V
	(2A&B)	12.2V	12.7V	12.5V	12.8V	12.8V
	(3A&B)	12.5V	12.6V	12.7V	12.7V	12.8V
	(4A&B)	12.8V	12.6V	12.8V	12.8V	12.6V
	(5A&B)	12.8V	12.8V	12.9V	12.7V	12.8V
(-)	(1A&B)	-12.2V	-12.4V	-12.2V	-12.7V	-12.3V
	(2A&B)	-12.5V	-12.4V	-12.3V	-12.3V	-12.3V
	(3A&B)	-12.6V	-12.2V	-12.4V	-12.4V	-12.2V
	(4A&B)	-12.5V	-12.6V	-12.2V	-12.4V	-12.6V
	(5A&B)	-12.3V	-12.2V	-12.2V	-12.4V	-12.3V
Input Current (+)	(1A)	10pA	2.2nA	0.80nA	0.80nA	0.70nA
	(1B)	5pA	1.2nA	1.3nA	1.3nA	1.0nA
	(2A)	10pA	1.3nA	0.84nA	0.86nA	0.70nA
	(2B)	5pA	2.7nA	1.5nA	1.4nA	1.0nA
	(3A)	7pA	1.6nA	1.5nA	1.2nA	1.1nA
	(3B)	10pA	1.7nA	1.4nA	1.6nA	1.3nA
	(4A)	15pA	1.1nA	0.91nA	0.86nA	--
	(4B)	16pA	1.8nA	0.68nA	0.70nA	0.60nA
	(5A)	1pA	1.3nA	0.95nA	0.86nA	0.80nA
	(5B)	6pA	1.1nA	0.90nA	0.80nA	0.71nA
(-)	(1A)	16pA	2.3nA	0.74nA	0.76nA	0.65nA
	(1B)	30pA	1.0nA	1.4nA	1.4nA	1.1nA
	(2A)	13pA	1.3nA	0.80nA	0.84nA	0.69nA
	(2B)	7pA	2.4nA	1.3nA	1.3nA	0.90nA
	(3A)	10pA	1.4nA	1.4nA	1.1nA	1.1nA
	(3B)	10pA	1.6nA	1.3nA	1.5nA	1.2nA
	(4A)	16pA	0.95nA	0.82nA	0.78nA	--
	(4B)	17pA	1.7nA	0.64nA	0.68nA	0.57nA
	(5A)	20pA	1.2nA	0.85nA	0.82nA	0.77nA
	(5B)	19pA	0.95nA	0.80nA	0.74nA	0.66nA
Gain (50K load)	(1A)	114dB	107dB	108dB	108dB	108dB
	(1B)	114dB	108dB	108dB	109dB	108dB
	(2A)	119dB	109dB	109dB	109dB	109dB
	(2B)	118dB	109dB	109dB	110dB	110dB
	(3A)	117dB	109dB	109dB	109dB	109dB
	(3B)	118dB	109dB	109dB	109dB	109dB
	(4A)	112dB	108dB	108dB	108dB	--
	(4B)	118dB	108dB	109dB	110dB	111dB
	(5A)	120dB	109dB	108dB	109dB	108dB
	(5B)	108dB	100dB	98dB	98dB	98dB
CMRR at Vcm = 0V	(1A)	94dB	96dB	79dB	78dB	79dB
	(1B)	92dB	89dB	79dB	80dB	82dB
	(2A)	111dB	85dB	87dB	82dB	83dB
	(2B)	104dB	100dB	88dB	80dB	80dB
	(3A)	92dB	76dB	73dB	73dB	74dB
	(3B)	94dB	91dB	85dB	84dB	87dB
	(4A)	98dB	90dB	86dB	85dB	--
	(4B)	108dB	105dB	110dB	94dB	97dB
	(5A)	91dB	78dB	86dB	84dB	83dB
	(5B)	92dB	90dB	89dB	88dB	91dB

TEST RESULTS (Continued)

Device Name: (PMI) OP215FJ

Type of Irradiation			GAMMA			NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	3Mrad	$5X10^{13}$ n/cm^2
PSRR: At +P.S. (+Min)	(1A)	87dB(3V)	90dB(2V)	88dB(2V)	86dB(2V)	84dB(2V)
	(1B)	87dB(2V)	88dB(2V)	86dB(4V)	84dB(4V)	84dB(4V)
	(2A)	93dB(2V)	94dB(2V)	91dB(2V)	92dB(2V)	90dB(2V)
	(2B)	94dB(2V)	95dB(2V)	93dB(2V)	92dB(3V)	92dB(3V)
	(3A)	92dB(2V)	92dB(2V)	88dB(2V)	88dB(2V)	84dB(2V)
	(3B)	96dB(2V)	96dB(4V)	93dB(5V)	92dB(6V)	90dB(6V)
	(4A)	93dB(2V)	92dB(2V)	95dB(2V)	96dB(2V)	--
	(4B)	95dB(2V)	94dB(2V)	93dB(2V)	93dB(2V)	91dB(2V)
	(5A)	82dB(2V)	82dB(2V)	81dB(2V)	81dB(2V)	78dB(2V)
	(5B)	83dB(2V)	83dB(2V)	83dB(2V)	82dB(3V)	79dB(3V)
At -P.S. (-Max)	(1A)	84dB(4V)	86dB(4V)	74dB(4V)	75dB(4V)	75dB(4V)
	(1B)	90dB(4V)	large(4V)	76dB(4V)	76dB(4V)	77dB(4V)
	(2A)	88dB(4V)	84dB(3V)	81dB(4V)	78dB(5V)	78dB(4V)
	(2B)	94dB(4V)	88dB(5V)	82dB(3V)	78dB(3V)	77dB(4V)
	(3A)	94dB(4V)	71dB(4V)	71dB(4V)	71dB(4V)	70dB(3V)
	(3B)	88dB(4V)	84dB(4V)	82dB(4V)	82dB(4V)	81dB(3V)
	(4A)	89dB(3V)	85dB(4V)	82dB(4V)	82dB(4V)	--
	(4B)	95dB(4V)	98dB(4V)	92dB(4V)	87dB(4V)	87dB(4V)
	(5A)	87dB(3V)	92dB(4V)	88dB(7V)	87dB(10V)	84dB(3V)
	(5B)	86dB(5V)	87dB(5V)	85dB(6V)	84dB(6V)	80dB(4V)
Supply Current at (+)&(-) P.S.	(1A)	5.4mA	3.0mA	2.6mA	2.5mA	2.4mA
	(1B)	6.2mA	2.5mA	2.4mA	2.3mA	2.3mA
	(2A)	5.0mA	3.6mA	3.2mA	3.0mA	2.9mA
	(2B)	4.0mA	3.6mA	3.5mA	3.0mA	3.0mA
	(3A)	4.6mA	3.6mA	2.7mA	2.6mA	3.2mA
	(3B)	4.5mA	4.6mA	2.4mA	2.4mA	2.4mA
	(4A)	4.2mA	3.4mA	3.2mA	3.1mA	--
	(4B)	4.0mA	3.9mA	3.2mA	3.1mA	3.0mA
	(5A)	4.4mA	3.4mA	3.1mA	3.0mA	3.0mA
	(5B)	3.8mA	3.7mA	3.5mA	3.0mA	3.0mA
Slew rate (+)	(1A)	13V/us	13V/us	13V/us	14V/us	14V/us
	(1B)	10V/us	10V/us	9.5V/us	11V/us	9.8V/us
	(2A)	13V/us	13V/us	14V/us	13V/us	13V/us
	(2B)	10V/us	13V/us	12V/us	10V/us	12V/us
	(3A)	14V/us	15V/us	16V/us	15V/us	15V/us
	(3B)	15V/us	11V/us	9.5V/us	10V/us	10V/us
	(4A)	13V/us	12V/us	13V/us	13V/us	--
	(4B)	22V/us	13V/us	12V/us	11V/us	10V/us
	(5A)	13V/us	13V/us	13V/us	13V/us	12V/us
	(5B)	14V/us	12V/us	12V/us	9.2V/us	8.7V/us
(-)	(1A)	15V/us	14V/us	15V/us	14V/us	14V/us
	(1B)	15V/us	15V/us	15V/us	13V/us	13V/us
	(2A)	20V/us	22V/us	22V/us	20V/us	18V/us
	(2B)	15V/us	20V/us	18V/us	14V/us	16V/us
	(3A)	25V/us	22V/us	23V/us	21V/us	18V/us
	(3B)	20V/us	18V/us	18V/us	13V/us	16V/us
	(4A)	13V/us	19V/us	21V/us	20V/us	--
	(4B)	17V/us	16V/us	17V/us	13V/us	15V/us
	(5A)	21V/us	21V/us	22V/us	20V/us	20V/us
	(5B)	18V/us	17V/us	16V/us	14V/us	14V/us
Gain-bandwidth Product	(1A)	5.0MHz	5.3MHz	5.5MHz	5.5MHz	5.5MHz
	(1B)	4.9MHz	5.1MHz	5.3MHz	5.3MHz	5.3MHz
	(2A)	4.9MHz	5.3MHz	5.5MHz	5.4MHz	5.5MHz
	(2B)	5.0MHz	5.2MHz	5.5MHz	5.3MHz	5.3MHz
	(3A)	5.7MHz	5.7MHz	6.1MHz	5.8MHz	5.9MHz
	(3B)	5.8MHz	5.8MHz	5.9MHz	5.7MHz	5.8MHz
	(4A)	4.8MHz	4.8MHz	5.3MHz	--	--
	(4B)	4.9MHz	4.8MHz	5.3MHz	5.3MHz	5.4MHz
	(5A)	4.7MHz	5.0MHz	5.4MHz	5.7MHz	5.0MHz
	(5B)	5.0MHz	5.3MHz	5.7MHz	6.0MHz	5.3MHz

Remark:

1. Heatsink was used during testing after 2Mrad of gamma irradiation and thereafter. Without heatsinks, the input bias current increases rapidly with self-heating.
2. Gain at 2K load was about 5dB lower and varies with output swing.
3. Device 4(A) failed during testing after 3Mrad irradiation.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (BB) OPA111AM
Sample Size: 3
Date code: 8407

Type of Irradiation			GAMMA			NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	3Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	0.64mV	1.1mV	0.34mV	7.4mV	9.5mV
	(2)	0.01mV	0.70mV	24mV	26mV	43mV
	(3)	0.24mV	13mV	22mV	45mV	47mV
Output Saturation Voltage (50K load) (+)	(1)	13.8V	13.5V	13.2V	13.2V	13.2V
	(2)	13.8V	13.0V	13.1V	13.1V	13.3V
	(3)	13.6V	13.0V	13.2V	13.2V	13.3V
(-)	(1)	-14.2V	-13.7V	-14.0V	-14.0V	-14.2V
	(2)	-14.6V	-14.0V	-14.1V	-14.0V	-14.1V
	(3)	-14.8V	-14.0V	-14.1V	-14.0V	-14.0V
Output Saturation Voltage (2K load) (+)	(1)	13.6V	13.2V	12.7V	13.1V	13.0V
	(2)	13.4V	12.8V	12.9V	12.9V	13.0V
	(3)	13.4V	12.9V	13.0V	13.1V	13.1V
(-)	(1)	-13.8V	-13.4V	-13.6V	-13.5V	-13.8V
	(2)	-14.0V	-13.6V	-13.5V	-13.4V	-13.5V
	(3)	-14.0V	-13.6V	-13.7V	-12.5V	-13.5V
Input Current (+)	(1)	15pA	66pA	65pA	100pA	95pA
	(2)	15pA	64pA	110pA	160pA	135pA
	(3)	10pA	200pA	245pA	300pA	200pA
(-)	(1)	15pA	54pA	61pA	100pA	95pA
	(2)	15pA	64pA	115pA	165pA	145pA
	(3)	10pA	230pA	258pA	340pA	295pA
Gain (2K load and 50K load)	(1)	125dB	122dB	121dB	120dB	121dB
	(2)	123dB	118dB	122dB	122dB	123dB
	(3)	124dB	122dB	122dB	123dB	125dB
CMRR at Vcm = 0V	(1)	large	140dB	130dB	128dB	126dB
	(2)	122dB	115dB	115dB	115dB	114dB
	(3)	115dB	110dB	123dB	140dB	110dB
PSRR: At +P.S. (+Min)	(1)	105dB(3V)	101dB(3V)	98dB(3V)	98dB(3V)	98dB(3V)
	(2)	104dB(2V)	98dB(2V)	97dB(3V)	96dB(3V)	96dB(3V)
	(3)	128dB(3V)	129dB(2V)	121dB(2V)	105dB(2V)	95dB(3V)
At -P.S. (-Max)	(1)	104dB(5V)	99dB(5V)	98dB(5V)	97dB(5V)	98dB(5V)
	(2)	106dB(4V)	99dB(4V)	98dB(4V)	97dB(4V)	97dB(4V)
	(3)	113dB(5V)	118dB(4V)	117dB(4V)	104dB(4V)	95dB(4V)
Supply Current at (+)&(-) P.S.	(1)	2.2mA	2.1mA	2.1mA	2.1mA	2.1mA
	(2)	2.5mA	2.4mA	2.4mA	2.4mA	2.4mA
	(3)	2.4mA	2.2mA	2.2mA	2.2mA	2.3mA
Slew rate (+)	(1)	5.4V/us	5.4V/us	5.4V/us	5.5V/us	5.5V/us
	(2)	5.7v/us	5.7V/us	5.7V/us	6.1V/us	6.0V/us
	(3)	5.7V/us	5.7V/us	5.7V/us	5.0V/us	4.9V/us
(-)	(1)	2.5V/us	1.7V/us	1.7V/us	1.7V/us	1.7V/us
	(2)	2.5V/us	2.2V/us	2.1V/us	2.0V/us	2.1V/us
	(3)	2.4V/us	1.9V/us	1.9V/us	2.0V/us	2.0V/us
Gain-bandwidth Product	(1)	1.9MHz	1.6MHz	1.6MHz	1.5MHz	1.5MHz
	(2)	2.0MHz	1.8MHz	1.8MHz	1.7MHz	1.8MHz
	(3)	2.1MHz	1.8MHz	1.7MHz	1.8MHz	1.8MHz

Remark: 1. The testing equipment is incapable of measuring bias current of less than 20pA accurately.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (TI) TLC251CP
Sample Size: 3
Date code: A406

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	1.3mV	-46mV	---	---
	(2)	0.7mV	-30mV	---	---
	(3)	-0.1mV	-18mV	---	---
Output Saturation Voltage (50K load) (+)	(1)	6.0V	5.4V	---	---
	(2)	6.8V	5.6V	---	---
	(3)	6.8V	5.6V	---	---
(-)	(1)	-7.6V	-7.8V	---	---
	(2)	-7.6V	-7.8V	---	---
	(3)	-7.6V	-7.8V	---	---
Output Saturation Voltage (2K load) (+)	(1)	5.2V	---	---	---
	(2)	5.9V	4.4V	---	---
	(3)	---	---	---	---
(-)	(1)	-6.8V	-7.5V	---	---
	(2)	-6.8V	-7.5V	---	---
	(3)	---	---	---	---
Input Current (+)	(1)	<0.1nA	10nA	---	---
	(2)	0.3nA	80nA	---	---
	(3)	0.6nA	100nA	---	---
(-)	(1)	<0.1nA	10nA	---	---
	(2)	0.3nA	40nA	---	---
	(3)	0.6nA	60nA	---	---
Gain (50K load)	(1)	99dB	66dB	---	---
	(2)	99dB	68dB	---	---
	(3)	97dB	68dB	---	---
CMRR at Vcm = 0V	(1)	99dB	---	---	---
	(2)	99dB	---	---	---
	(3)	97dB	---	---	---
PSRR: At +P.S. (+Min)	(1)	90dB(3V)	---	---	---
	(2)	103dB(2V)	---	---	---
	(3)	89dB(2V)	---	---	---
At -P.S. (-Max)	(1)	104dB(+0.5V)	---	---	---
	(2)	106dB(+1V)	---	---	---
	(3)	100dB(+0.5V)	---	---	---
Supply Current at (+)&(-) P.S.	(1)	1.0mA	2.8mA	---	---
	(2)	0.73mA	2.1mA	---	---
	(3)	0.88mA	2.1mA	---	---

Remark:
1. Pin 8 was connected to -8V power supply for high bias configuration during all testing.
2. The input current for devices (2)&(3) increased rapidly for positive input voltages during pretest.
3. For 2K load, the gain varied drastically with negative swing during pretest.
4. After 1Mrad of gamma irradiation, the gain at 50K load varied with positive swing.
5. After 2Mrad of gamma irradiation, device (1) was latched to +P.S.; the offset voltage of device (2)&(3) drifted wildly between -80mV to +20mV. In addition, the output drive was curtailed at about +2V to +6V.
6. After neutron irradiation, the devices were still not functioning.

TEST RESULTS FOR OPERATIONAL AMPLIFIERS

Device Name: (Teledyne Philbrick) 1344
Sample Size: 2
Date code: 8413

Type of Irradiation				GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	3Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1)	-0.8mV	-11mV	-21mV	-19mV	-14mV
	(2)	-0.4mV	-10mV	-20mV	-17mV	-14mV
Output Saturation Voltage (50K load) (+)	(1)	11.2V	12.0V	12.0V	11.9V	11.5V
	(2)	11.2V	12.0V	12.0V	11.9V	11.5V
(-)	(1)	-11.7V	-11.7V	-11.7V	-11.7V	-11.8V
	(2)	-11.7V	-11.7V	-11.7V	-11.0V	-11.8V
Output Saturation Voltage (2K load) (+)	(1)	11.4V	11.4V	11.4V	11.2V	11.0V
	(2)	11.4V	11.4V	11.4V	11.2V	11.0V
(-)	(1)	-11.0V	-10.8V	-8.1V	-8.2V	-11.0V
	(2)	-11.0V	-10.8V	-10.8V	-10.8V	-11.0V
Input Current (+)	(1)	210pA	0.45nA	1.0nA	0.8nA	0.7nA
	(2)	440pA	1.4nA	0.5nA	0.7nA	0.6nA
(-)	(1)	-160pA	0.80nA	0.9nA	0.75nA	0.65nA
	(2)	20pA	1.3nA	0.7nA	1.0nA	0.9nA
Gain (2K load and 50K load)	(1)	111dB	93dB	86dB	88dB	89dB
	(2)	109dB	95dB	91dB	87dB	88dB
CMRR at Vcm = 0V	(1)	94dB	83dB	80dB	79dB	80dB
	(2)	83dB	79dB	77dB	78dB	78dB
PSRR: At +P.S. (+Min)	(1)	100dB(4V)	78dB(4V)	74dB(3V)	74dB(3V)	74dB(3V)
	(2)	100dB(4V)	80dB(4V)	74dB(3V)	74dB(3V)	74dB(3V)
At -P.S. (-Max)	(1)	98dB(3V)	74dB(3V)	70dB(3V)	72dB(3V)	72dB(3V)
	(2)	84dB(3V)	74dB(3V)	71dB(3V)	70dB(3V)	70dB(3V)
Supply Current at (+)&(-) P.S.	(1)	6.0mA	5.0mA	4.6mA	4.5mA	4.6mA
	(2)	7.3mA	6.0mA	5.4mA	5.3mA	5.4mA
Slew rate	(1)	71V/us	---	---	---	---
	(2)	91V/us	---	---	---	---
Rise time (gain of 10)	(1)	65ns	---	---	---	---
	(2)	50ns	---	---	---	---

Remark:

TEST RESULTS FOR VOLTAGE COMPARATORS

Device Name: (PMI) CMP01EJ
Sample Size: 3
Date Code: 8406

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	-20uV	-24uV	17uV	60uV
	(2)	200uV	520uV	570uV	580uV
	(3)	-73uV	460uV	500uV	420uV
Output Saturation Voltage	(1)	0.163V	0.166V	0.166V	0.2V
	(2)	0.161V	0.163V	0.170V	0.2V
	(3)	0.167V	0.172V	0.175V	0.171V
Maximum Output Voltage (no load)	(1)	6.35V	6.28V	6.26V	--
	(2)	6.22V	6.23V	6.18V	--
	(3)	6.37V	6.27V	6.21V	6.25V
Maximum Output Voltage (20K load)	(1)	5.0V	4.95V	4.92V	4.90V
	(2)	5.0V	5.0V	4.95V	4.92V
	(3)	5.0V	5.0V	5.0V	4.95V
Maximum Output Voltage (5K load)	(1)	--	--	--	3.50V
	(2)	3.55V	3.55V	3.55V	3.52V
	(3)	3.62V	3.61V	3.60V	3.55V
Input Current (+)	(1)	0.66uA	1.95uA	2.25uA	2.00uA
	(2)	0.54uA	1.20uA	1.40uA	1.35uA
	(3)	0.56uA	1.95uA	1.98uA	1.86uA
(-)	(1)	0.51uA	1.35uA	1.50uA	1.50uA
	(2)	0.56uA	1.16uA	1.40uA	1.30uA
	(3)	0.57uA	1.95uA	2.11uA	2.00uA
Supply Current at +P.S. (+)	(1)	6.6mA	3.5mA	3.5mA	6.2mA
	(2)	6.8mA	3.5mA	3.5mA	6.4mA
	(3)	6.8mA	3.5mA	6.4mA	6.4mA
at -P.S. (-)	(1)	-1.8mA	-1.2mA	-1.2mA	-1.3mA
	(2)	-1.6mA	-1.2mA	-1.2mA	-1.3mA
	(3)	-1.5mA	-1.2mA	-1.3mA	-1.2mA
Response Time	(1)	100ns	65ns	66ns	--
	(2)	110ns	65ns	66ns	--
	(3)	100ns	60ns	60ns	55ns
Rise Time (10-90%)	(1)	400ns	330ns	350ns	--
	(2)	350ns	340ns	320ns	--
	(3)	400ns	340ns	300ns	310ns

Remark:
1. No external pullup resistor was used at the output.
2. The response time was measured from the zero-crossing of the input signal to 10% of the final output voltage.
3. Devices (2) & (3) failed during testing after neutron irradiation.

TEST RESULTS FOR VOLTAGE COMPARATORS

Device Name: (PMI) CMP04FY
Sample Size: 2
Date Code: 8337

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	(1A)	0.20mV	1.8mV	1.7mV	1.7mV
	(1B)	0.34mV	2.0mV	1.4mV	1.6mV
	(1C)	-0.31mV	1.0mV	0.2mV	0.6mV
	(1D)	0.30mV	0.9mV	1.1mV	1.1mV
	(2A)	0.44mV	4.6mV	5.1mV	3.7mV
	(2B)	-0.30mV	6.0mV	5.3mV	4.4mV
	(2C)	0.68mV	1.1mV	1.4mV	1.2mV
	(2D)	-0.70mV	-0.8mV	-0.6mV	-0.63mV
Output Saturation Voltage (Referenced to -P.S.)	(1A)	0.125V	0.193V	0.180V	0.175V
	(1B)	0.127V	0.197V	0.177V	0.178V
	(1C)	0.131V	0.193V	0.177V	0.175V
	(1D)	0.125V	0.189V	0.173V	0.171V
	(2A)	0.115V	0.177V	0.165V	0.158V
	(2B)	0.116V	0.186V	0.161V	0.163V
	(2C)	0.116V	0.186V	0.164V	0.162V
	(2D)	0.116V	0.181V	0.160V	0.159V
Maximum Output Voltage (no load) (+)	(1)	4.8V	4.4V	4.6V	4.6V
	(2)	4.6V	4.5V	4.6V	4.6V
(-)	(1)	-4.9V	-4.5V	-4.8V	-4.8V
	(2)	-4.9V	-4.8V	-4.8V	-4.8V
Input Current (+)	(1A)	-66nA	-1.7uA	-1.9uA	-1.7uA
	(1B)	-65nA	-1.8uA	-1.9uA	-1.8uA
	(1C)	-71nA	-1.7uA	-1.8uA	-1.8uA
	(1D)	-54nA	-1.5uA	-2.0uA	-1.8uA
	(2A)	-47nA	-1.6uA	-1.9uA	-1.7uA
	(2B)	-65nA	-1.5uA	-1.8uA	-1.6uA
	(2C)	-66nA	-1.5uA	-1.8uA	-1.6uA
	(2D)	-70nA	-1.9uA	-1.9uA	-1.6uA
(-)	(1A)	-68nA	-1.7uA	-1.8uA	-1.7uA
	(1B)	-68nA	-1.8uA	-2.0uA	-2.0uA
	(1C)	-78nA	-1.7uA	-2.0uA	-2.0uA
	(1D)	-64nA	-1.6uA	-1.9uA	-1.9uA
	(2A)	-45nA	-1.4uA	-1.6uA	-1.6uA
	(2B)	-61nA	-1.3uA	-1.5uA	-1.4uA
	(2C)	-62nA	-1.6uA	-1.7uA	-1.7uA
	(2D)	-64nA	-1.8uA	-1.9uA	-1.7uA
Supply Current without external pullup resistor.	(1)	1.0mA	0.46mA	0.42mA	0.44mA
	(2)	0.95mA	0.42mA	0.46mA	0.41mA
Response Time	(1A)	350ns	280ns	270ns	250ns
	(1B)	350ns	300ns	265ns	275ns
	(1C)	350ns	310ns	270ns	280ns
	(1D)	345ns	280ns	260ns	260ns
	(2A)	350ns	280ns	255ns	242ns
	(2B)	345ns	290ns	245ns	258ns
	(2C)	345ns	310ns	265ns	265ns
	(2D)	340ns	290ns	260ns	258ns
Rise Time (10-90%)	(1A)	350ns	280ns	240ns	250ns
	(1B)	300ns	260ns	243ns	240ns
	(1C)	320ns	270ns	240ns	245ns
	(1D)	320ns	270ns	240ns	250ns
	(2A)	300ns	270ns	230ns	240ns
	(2B)	300ns	260ns	240ns	230ns
	(2C)	320ns	250ns	235ns	240ns
	(2D)	320ns	270ns	240ns	245ns

Remark:

1. A 5.1Kohm external pullup resistor was used during testing.
2. The response time was measured from the zero-crossing of the input signal to 10% of the final output voltage.
3. With a 5.1K pullup resistor, the supply current is about 1mA higher.

TEST RESULTS FOR VOLTAGE COMPARATORS

Device Name: (PMI) CMP05FJ
Sample Size: 4
Date Code: 8417

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Offset Voltage	(1)	-50uV	800uV	550uV	500uV
	(2)	-25uV	400uV	1.1mV	650uV
	(3)	150uV	850uV	800uV	350uV
	(4)	-85uV	350uV	230uV	150uV
Output Saturation Voltage	(1)	0.110V	0.145v	0.150V	0.151V
	(2)	0.113V	0.134V	0.150V	0.141V
	(3)	0.123V	0.155V	0.161V	0.161V
	(4)	0.113V	0.128V	0.138V	0.138V
Maximum Output Voltage (no load)	(1)	3.22V	3.48V	3.48V	3.48V
	(2)	3.17V	3.43V	3.46V	3.47V
	(3)	3.11V	3.43V	3.45V	3.43V
	(4)	3.09V	3.27V	3.30V	3.33V
Maximum Output Voltage (20K load)	(1)	3.05V	3.30V	3.30V	3.30V
	(2)	2.90V	3.32V	3.30V	3.28V
	(3)	2.82V	3.25V	3.25V	3.25V
	(4)	2.86V	3.05V	3.10V	3.12V
Maximum Output Voltage (5K load)	(1)	2.85V	3.10V	3.10V	3.10V
	(2)	2.75V	3.12V	3.10V	3.10V
	(3)	2.70V	3.05V	3.05V	3.05V
	(4)	2.70V	2.86V	2.90V	2.95V
Input Current (+)	(1)	1.17uA	4.25uA	4.80uA	4.50uA
	(2)	1.48uA	4.60uA	7.20uA	6.15uA
	(3)	1.68uA	6.60uA	7.20uA	6.56uA
	(4)	1.85uA	3.30uA	3.90uA	3.76uA
(-)	(1)	1.15uA	4.70uA	4.80uA	4.45uA
	(2)	1.44uA	3.80uA	6.80uA	5.60uA
	(3)	1.69uA	6.75uA	7.80uA	6.56uA
	(4)	1.85uA	3.40uA	3.90uA	3.76uA
Supply Current at +P.S. (+)	(1)	8.0mA	6.5mA	10mA	10mA
	(2)	9.0mA	6.2mA	10mA	9.5mA
	(3)	9.0mA	7.0mA	10mA	10mA
	(4)	8.5mA	6.6mA	9.5mA	9.5mA
at -P.S. (-)	(1)	-10mA	-9mA	-9mA	-9.5mA
	(2)	-11mA	-10mA	-9.5mA	-9.5mA
	(3)	-12mA	-10mA	-10mA	-10mA
	(4)	-10mA	-10mA	-9.5mA	-10mA
Response Time	(1)	32ns	26ns	32ns	26ns
	(2)	31ns	25ns	32ns	28ns
	(3)	30ns	25ns	32ns	27ns
	(4)	30ns	26ns	33ns	26ns
Rise Time (10-90%)	(1)	19ns	24ns	25ns	25ns
	(2)	18ns	18ns	22ns	20ns
	(3)	18ns	20ns	22ns	20ns
	(4)	18ns	20ns	25ns	21ns

Remark:
1. No external pullup resistor was used at the output.
2. The response time was measured from the zero-crossing of the input signal to 10% of the final output voltage.
3. For all devices, the output latch-enable capability was destroyed after 1Mrad of gamma irradiation.

TEST RESULTS FOR VOLTAGE COMPARATORS

Device Name: (National) LM311N
Sample Size: 1
Date Code: P222

Type of Irradiation		GAMMA		NEUTRON
Parameters	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Offset Voltage	1.4mV	6.5mV	7.5mV	8.3mV
Output Saturation Voltage	5.0mV	126mV	131mV	132mV
Maximum Output Voltage (50K load)	13.6V	13.0V	13.6V	13.5V
Maximum Output Voltage (2K load)	4.3V	4.0V	4.2V	4.2V
Input (+) Current (-)	-34nA -29nA	-1.0uA -37nA	-0.86uA -1.9nA	-1.0uA -3.0nA
Supply Current at +P.S. (+) & -P.S. (-)	6.0mA -1.8mA	5.8mA -1.8mA	6.0mA -1.6mA	5.8mA -1.6mA
Response Time	165ns	120ns	130ns	124ns
Rise Time (10-90%)	660ns	700ns	800ns	670ns

Remark:

1. The response time was measured from the zero-crossing of the input signal to 10% of the final output voltage.
2. The pullup resistor used for testing was 5.1Kohms except for output saturation voltage, response time, and rise time measurements which used a 10Kohm pullup resistor.

TEST RESULTS FOR VOLTAGE FOLLOWERS/BUFFERS

Device Name: (PMI) BUF03AJ
Sample Size: 3
Date Code: 8339

Type of Irradiation		GAMMA			NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Input Current	(1)	200pA	3.0nA	1.3nA	0.64nA
	(2)	150pA	6.8nA	1.4nA	-2.0nA
	(3)	100pA	6.0nA	0.84nA	-0.2nA
PSRR: At +P.S. (Min)	(1)	74dB(4V)	74dB(4V)	75dB(4V)	76dB(4V)
	(2)	74dB(4V)	73dB(4V)	74dB(4V)	75dB(4V)
	(3)	74dB(4V)	72dB(4V)	75dB(4V)	75dB(4V)
At -P.S. (Max)	(1)	78dB(4V)	68dB(4V)	76dB(3V)	78dB(4V)
	(2)	78dB(4V)	68dB(4V)	74dB(3V)	74dB(3V)
	(3)	78dB(4V)	69dB(4V)	74dB(3V)	73dB(3V)
Supply Current at P.S. (+) & -P.S. (-)	(1)	17.5mA	16.5mA	10.0mA	9.0mA
	(2)	20.0mA	17.5mA	8.5mA	8.5mA
	(3)	18.4mA	16.0mA	8.0mA	8.0mA
Slew rate	(1)	300V/us	300V/us	300V/us	300V/us
	(2)	220V/us	270V/us	300V/us	300V/us
	(3)	280V/us	250V/us	300V/us	310V/us
Propagation Delay	(1)	15ns	15ns	15ns	14ns
	(2)	15ns	15ns	15ns	14ns
	(3)	14ns	14ns	15ns	14ns
Rise time (10-90%)	(1)	90ns	90ns	68ns	34ns
	(2)	90ns	90ns	50ns	33ns
	(3)	90ns	115ns	68ns	32ns
Maximum Voltage Drive(2k load)	(1)	23Vp-p	23Vp-p	23Vp-p	24Vp-p
	(2)	23Vp-p	23Vp-p	22Vp-p	24Vp-p
	(3)	23Vp-p	23Vp-p	22Vp-p	24Vp-p
Maximum Current Drive (peak current)	(1)	60mA	50mA	58mA	62mA
	(2)	59mA	52mA	54mA	56mA
	(3)	62mA	49mA	60mA	50mA

Remark:
1. Heat sink was used during testing after 2Mrad of gamma and neutron irradiations.
2. The rise time of test generator was about 20ns.

TEST RESULTS FOR VOLTAGE FOLLOWERS/BUFFERS

Device Name: (Harris) HA3-5033-5
Sample Size: 3
Date Code: 8420

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Input Current	(1)	-2.8uA	-6.5uA	-6.6uA	-4.6uA
	(2)	-3.8uA	-11uA	-17uA	-15uA
	(3)	8.0uA	-25uA	-40uA	-28uA
PSRR: At +P.S. (Min)	(1)	77dB(2V)	77dB(2V)	76dB(2V)	77dB(2V)
	(2)	74dB(2V)	75dB(2V)	75dB(2V)	75dB(2V)
	(3)	74dB(2V)	74dB(2V)	74dB(2V)	75dB(2V)
At -P.S. (Max)	(1)	76dB(2V)	76dB(2V)	75dB(2V)	75dB(1V)
	(2)	74dB(2V)	75dB(2V)	74dB(2V)	74dB(2V)
	(3)	74dB(2V)	75dB(2V)	74dB(2V)	74dB(2V)
Supply Current at P.S. (+) & -P.S. (-)	(1)	22.0mA	21.0mA	21.0mA	21.0mA
	(2)	23.0mA	22.0mA	22.0mA	21.0mA
	(3)	22.0mA	21.0mA	20.5mA	21.0mA
Slew rate	(1)	1.7V/ns	2.0V/ns	1.8V/ns	1.5V/ns
	(2)	1.7V/ns	2.0V/ns	2.0V/ns	1.6V/ns
	(3)	1.6V/ns	2.0V/ns	2.0V/ns	1.6V/ns
Propagation Delay	(1)	9ns	9ns	9ns	9ns
	(2)	10ns	9ns	8ns	9ns
	(3)	11ns	9ns	9ns	9ns
Rise time (10-90%)	(1)	25ns	24ns	23ns	24ns
	(2)	23ns	22ns	23ns	24ns
	(3)	18ns	23ns	22ns	24ns
Maximum Voltage Drive(2k load)	(1)	28Vp-p	25Vp-p	25Vp-p	26Vp-p
	(2)	28Vp-p	25Vp-p	25Vp-p	25Vp-p
	(3)	28Vp-p	25Vp-p	25Vp-p	26Vp-p
Maximum Current Drive (peak current)	(1)	78mA	88mA	88mA	92mA
	(2)	80mA	92mA	92mA	93mA
	(3)	83mA	92mA	90mA	93mA

Remark: 1. The rise time of test generator was about 20ns.

TEST RESULTS FOR VOLTAGE FOLLOWERS/BUFFERS

Device Name: (Teledyne) TSC428
Sample Size: 2
Date Code: 8413

Type of Irradiation		GAMMA			NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Input Current	(1)	---	---	BOTH DEVICES FAILED AFTER 1 MRAD OF GAMMA IRRADIATION	
	(2)	---	---		
Supply Current at P.S. (+) & -P.S. (-)	(1)	0.1mA	0.5mA		
	(2)	0.1mA	0.6mA		
Slew rate	(1)	---	---		
	(2)	---	---		
Propagation Delay	(1)	---	---		
	(2)	---	---		
Rise time (10-90%)	(1)	25ns	---		
	(2)	25ns	---		

Remark: 1. After 1Mrad of gamma irradiation, with an input of 0-5V no output was observed.

TEST RESULTS OF VOLTAGE REFERENCES

Device Name: (AD) AD584KH
Sample Size: 2
Date Code: 8345

Type of Irradiation			GAMMA			NEUTRON
Test Conditions		S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
No loading: All pins open	pin 1	(1)	10.002V	10.128V	10.140V	10.132V
		(2)	10.001V	10.176V	10.201V	10.190V
	pin 2	(1)	4.997V	5.037V	5.039V	5.037V
		(2)	5.001V	5.058V	5.060V	5.059V
	pin 3	(1)	2.500V	2.497V	2.493V	2.493V
		(2)	2.500V	2.498V	2.489V	2.493V
Pin 1 & 2 shorted	pin 1&2	(1)	4.998V	5.059V	5.070V	5.066V
		(2)	5.001V	5.073V	5.087V	5.081V
	pin 3	(1)	2.500V	2.507V	2.507V	2.507V
		(2)	2.500V	2.506V	2.503V	2.504V
Pin 1 & 3 shorted	pin 1&3	(1)	2.500V	2.513V	2.516V	2.516V
		(2)	2.500V	2.510V	2.510V	2.510V
	pin 2	(1)	2.498V	2.511V	2.516V	2.516V
		(2)	2.499V	2.508V	2.510V	2.510V
Pin 2 & 3 shorted	pin 1	(1)	7.505V	7.603V	7.617V	7.611V
		(2)	7.501V	7.628V	7.653V	7.642V
	pin 2&3	(1)	2.500V	2.502V	2.500V	2.500V
		(2)	2.500V	2.502V	2.497V	2.499V
Voltage at pin 1 with 20K load		(1)	10.002V	10.127V	10.135V	10.130V
		(2)	10.001V	10.172V	10.200V	10.189V
Voltage at pin 1 with 1K load		(1)	10.001V	10.103V	10.099V	10.093V
		(2)	10.000V	3.483V	3.108V	3.198V
Band-gap voltage		(1)	1.231V	1.216V	1.223V	1.224V
		(2)	1.239V	1.227V	1.221V	1.216V

Remark: 1. The input dc voltage during testing was +15.0V.

TEST RESULTS FOR VOLTAGE REFERENCES

Device Name: (Intersil) ICL8069 CCSQ
Sample Size: 2
Date Code: 8319

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Foward voltage drop at 200uA	(1)	0.63V	0.63V	0.63V	0.63V
	(2)	0.64V	0.63V	0.60V	0.60V
Reverse breakdown voltage at 400uA	(1)	1.2346V	1.2340V	1.2347V	1.2725V
	(2)	1.2340V	1.2315V	1.2412V	1.2652V
Minimum reverse current	(1)	29uA	29uA	30uA	29uA
	(2)	24uA	24uA	25uA	24uA

Remark:

TEST RESULTS FOR VOLTAGE REFERENCES

Device Name: (TI) TL430C
Sample Size: 2
Date Code: TIE 749

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Reference input voltage at 10mA	(1) (2)	2.656V 2.660V	2.707V 2.703V	2.711V 2.720V	2.717V 2.714V
Reference input current	(1) (2)	1.6uA 1.8uA	5.6uA 5.7uA	6.7uA 7.9uA	7.0uA 7.3uA
Minimum operating current	(1) (2)	0.38mA 0.41mA	0.42mA 0.44mA	0.44mA 0.44mA	0.44mA 0.44mA
Maximum operating current	(1) (2)	130mA 130mA	112mA 115mA	110mA 110mA	110mA 110mA
Change in reference voltage between minimum and maximum current	(1) (2)	220mV 220mV	220mV 220mV	220mV 220mV	220mV 220mV
Output voltage (24.75V nominal)	(1) (2)	23.8V 23.8V	24.2V 24.2V	24.6V 24.7V	24.6V 24.6V

Remark:

TEST RESULTS FOR VOLTAGE REFERENCES

Device Name: (National) LM336Z
Sample Size: 3
Date Code: 810

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Reverse breakdown voltage at 2mA	(1) (2) (3)	2.40V 2.41V 2.42V	2.45V 2.43V 2.45V	2.48V 2.43V 2.45V	2.45V 2.40V 2.42V
Minimum reverse current	(1) (2) (3)	230uA 270uA 260uA	210uA 250uA 240uA	190uA 240uA 210uA	195uA 240uA 220uA
Maximum reverse current	(1) (2) (3)	34mA 19mA 29mA	32mA 18mA 28mA	12mA 17mA 15mA	21mA 18mA 22mA
Change in reverse voltage between minimum and maximum current	(1) (2) (3)	< 10mV < 10mV < 10mV	160mV 60mV 100mV	240mV 100mV 240mV	200mV 70mV 240mV

Remark:

TEST RESULTS FOR VOLTAGE REGULATORS

Device Name: (National) LM317T
Sample Size: 2
Date Code: 841

Type of Irradiation			GAMMA			NEUTRON
Test conditions		S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Reference Voltage		(1)	1.233V	1.172V	0.995V	---
		(2)	1.238V	1.184V	0.53V	---
Adjustment pin input current		(1)	114uA	452uA	36uA	---
		(2)	94uA	45uA	3.8uA	---
Voltage adjustment						
(a) R2=27ohms	Iinput	(1)	5.3mA	5.8mA	5.1mA	---
		(2)	6.2mA	5.9mA	2.8mA	---
	Voutput	(1)	1.38V	1.33V	1.16V	---
		(2)	1.38V	1.33V	0.65V	---
(b) R2=500ohms	Iinput	(1)	6.2mA	7.4mA	6.4mA	---
		(2)	7.9mA	7.4mA	2.9mA	---
	Voutput	(1)	3.83V	3.69V	3.18V	---
		(2)	3.85V	3.69V	0.71V	---
(c) R2=750ohms	Iinput	(1)	8.7mA	8.3mA	7.1mA	---
		(2)	8.8mA	8.3mA	3.0mA	---
	Voutput	(1)	5.15V	4.93V	4.26V	---
		(2)	5.18V	4.93V	1.80V	---
(d) R2=1.8K	Iinput	(1)	12.4mA	11.8mA	10.0mA	---
		(2)	12.5mA	11.8mA	3.0mA	---
	Voutput	(1)	10.72V	10.22V	8.73V	---
		(2)	10.78V	10.22V	2.59V	---
(e) R2=3.9K	Iinput	(1)	19.7mA	18.4mA	12.7mA	---
		(2)	19.8mA	18.3mA	2.9mA	---
	Voutput	(1)	21.61V	20.13V	14.01V	---
		(2)	21.71V	20.15V	3.27V	---
Line Regulation						
(a) Input Voltage of +30V	Iinput	(1)	12.4mA	11.8mA	10.1mA	---
		(2)	12.5mA	11.8mA	---	---
	Voutput	(1)	10.73V	10.23V	7.76V	---
		(2)	10.78V	10.23V	---	---
(b) Input Voltage of +25V	Iinput	(1)	12.4mA	11.7mA	9.3mA	---
		(2)	12.5mA	11.7mA	---	---
	Voutput	(1)	10.72V	10.15V	7.14V	---
		(2)	10.77V	10.16V	---	---
(c) Input Voltage of +20V	Iinput	(1)	12.4mA	11.5mA	7.2mA	---
		(2)	12.5mA	11.5mA	---	---
	Voutput	(1)	10.72V	10.04V	5.50V	---
		(2)	10.77V	10.03V	---	---
(d) Input Voltage of +15V	Iinput	(1)	12.4mA	11.0mA	4.4mA	---
		(2)	12.5mA	10.1mA	---	---
	Voutput	(1)	10.71V	9.60V	3.35V	---
		(2)	10.76V	8.79V	---	---

TEST RESULTS FOR VOLTAGE REGULATORS (Continued)

Device Name: (National) LM317T

Type of Irradiation			GAMMA			NEUTRON
Test conditions			Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Load Regulation						
(a) no load	Iinput	(1)	5.3mA	5.0mA	4.3mA	---
		(2)	5.3mA	5.0mA	---	---
	Voutput	(1)	10.73V	10.31V	7.83V	---
		(2)	10.78V	10.29V	---	---
(b) 2K load	Iinput	(1)	10.7mA	10.1mA	8.7mA	---
		(2)	10.7mA	10.1mA	---	---
	Ioutput	(1)	5.4mA	5.1mA	3.9mA	---
		(2)	5.4mA	5.1mA	---	---
	Voutput	(1)	10.73V	10.29V	7.78V	---
		(2)	10.78V	10.27V	---	---
(c) 1.5K load	Iinput	(1)	12.4mA	11.8mA	10.1mA	---
		(2)	12.5mA	11.8mA	---	---
	Ioutput	(1)	7.2mA	6.8mA	5.2mA	---
		(2)	7.2mA	6.8mA	---	---
	Voutput	(1)	10.73V	10.28V	7.78V	---
		(2)	10.78V	10.26V	---	---
(d) 110 ohm load	Iinput	(1)	103mA	98mA	85mA	---
		(2)	104mA	98mA	---	---
	Ioutput	(1)	97mA	93mA	71mA	---
		(2)	98mA	93mA	---	---
	Voutput	(1)	10.71V	10.24V	7.78V	---
		(2)	10.78V	10.22V	---	---
(e) 68 ohm load	Iinput	(1)	164mA	155mA	130mA	---
		(2)	165mA	155mA	---	---
	Ioutput	(1)	157mA	150mA	114mA	---
		(2)	159mA	150mA	---	---
	Voutput	(1)	10.70V	10.19V	7.78V	---
		(2)	10.75V	10.19V	---	---
Dropout Voltage at no load		(1)	1.36V	3.2V	5.0V	---
		(2)	1.50V	4.3V	---	---

Remark:

1. Voltage adjustment range was tested with an input voltage of +30V, R1=240 ohms, and a load of 1.5K and 1uF.
2. Line regulation was measured with a 1.5Kohm and 1uF load and with R1=240 ohms and R2=1.8K.
3. Load regulation was measured with an input voltage of +30V and with R1=240 ohms and R2=1.8K.
4. After 1Mrad of gamma irradiation, the reference voltage of device (2) increased with self-heating.
5. After 2Mrad of gamma irradiation, the output voltage of both devices increased with self-heating. However, normal operatons were not restored. Both devices were damaged.

TEST RESULTS FOR VOLTAGE REGULATORS

Device Name: (National) LM337T
Sample Size: 2
Date Code: 820

Type of Irradiation				GAMMA		NEUTRON
Test conditions		S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Reference Voltage		(1)	1.251V	0.173V	---	---
		(2)	1.257V	0.181V	---	---
Adjustment pin input current		(1)	63uA	28nA	---	---
		(2)	64uA	380nA	---	---
Voltage adjustment (a) R2=27ohms	Iinput	(1)	5.7mA	---	---	---
		(2)	5.9mA	---	---	---
	Voutput	(1)	-1.27V	---	---	---
		(2)	-1.34V	---	---	---
(b) R2=500ohms	Iinput	(1)	7.6mA	---	---	---
		(2)	7.9mA	---	---	---
	Voutput	(1)	-3.41V	---	---	---
		(2)	-3.92V	---	---	---
(c) R2=750ohms	Iinput	(1)	8.8mA	---	---	---
		(2)	8.8mA	---	---	---
	Voutput	(1)	-5.25V	---	---	---
		(2)	-5.27V	---	---	---
(d) R2=1.8K	Iinput	(1)	12.6mA	---	---	---
		(2)	10.7mA	---	---	---
	Voutput	(1)	-10.94V	-0.71V	---	---
		(2)	-10.98V	-0.72V	---	---
(e) R2=3.9K	Iinput	(1)	20.0mA	---	---	---
		(2)	20.1mA	---	---	---
	Voutput	(1)	-22.02V	---	---	---
		(2)	-22.14V	---	---	---
Line Regulation (a) Input Voltage of -30V	Iinput	(1)	12.6mA	---	---	---
		(2)	12.6mA	---	---	---
	Voutput	(1)	-10.95V	---	---	---
		(2)	-10.98V	---	---	---
(b) Input Voltage of -25V	Iinput	(1)	12.6mA	---	---	---
		(2)	12.6mA	---	---	---
	Voutput	(1)	-10.95V	---	---	---
		(2)	-10.98V	---	---	---
(c) Input Voltage of -20V	Iinput	(1)	12.6mA	---	---	---
		(2)	12.6mA	---	---	---
	Voutput	(1)	-10.94V	---	---	---
		(2)	-10.97V	---	---	---
(d) Input Voltage of -15V	Iinput	(1)	12.6mA	---	---	---
		(2)	12.6mA	---	---	---
	Voutput	(1)	-10.94V	---	---	---
		(2)	-10.96V	---	---	---

TEST RESULTS FOR VOLTAGE REGULATORS (Continued)

Device Name: (National) LM337T

Type of Irradiation				GAMMA		NEUTRON
Test conditions			Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Load Regulation						
(a) no load	Iinput	(1)	5.3mA	---	---	---
		(2)	5.3mA	---	---	---
	Voutput	(1)	-10.95V	---	---	---
		(2)	-10.98V	---	---	---
(b) 2K load	Iinput	(1)	10.8mA	---	---	---
		(2)	10.8mA	---	---	---
	Ioutput	(1)	5.5mA	---	---	---
		(2)	5.5mA	---	---	---
	Voutput	(1)	-10.95V	---	---	---
		(2)	-10.98V	---	---	---
(c) 1.5K load	Iinput	(1)	12.6mA	---	---	---
		(2)	12.6mA	---	---	---
	Ioutput	(1)	7.3mA	---	---	---
		(2)	7.3mA	---	---	---
	Voutput	(1)	-10.95V	---	---	---
		(2)	-10.98V	---	---	---
(d) 110 ohm load	Iinput	(1)	107mA	---	---	---
		(2)	106mA	---	---	---
	Ioutput	(1)	100mA	---	---	---
		(2)	100mA	---	---	---
	Voutput	(1)	-10.98V	---	---	---
		(2)	-11.00V	---	---	---
(e) 68 ohm load	Iinput	(1)	168mA	---	---	---
		(2)	168mA	---	---	---
	Ioutput	(1)	162mA	---	---	---
		(2)	162mA	---	---	---
	Voutput	(1)	-10.99V	---	---	---
		(2)	-11.04V	---	---	---
Dropout Voltage at no load		(1)	1.37V	---	---	---
		(2)	1.35V	---	---	---

Remark:

1. Voltage adjustment range was tested with an input voltage of -30V, R1=240 ohms, and a load of 1.5K and 1uF.
2. Line regulation was measured with a 1.5Kohm and 1uF load and with R1=240 ohms and R2=1.8K.
3. Load regulation was measured with an input voltage of -30V and with R1=240 ohms and R2=1.8K.
4. After 1Mrad of gamma irradiation, both devices were severely damaged.

TEST RESULTS FOR VOLTAGE REGULATORS

Device Name: (MOT) MC7812CT
Sample Size: 2
Date Code: QQ 8327

Type of Irradiation			GAMMA			NEUTRON
Test conditions		S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Line Regulation						
(a) Input Voltage of +30V	Iinput	(1)	12.1mA	12.1mA	12.0mA	12.0mA
		(2)	12.8mA	12.8mA	12.7mA	12.7mA
	Voutput	(1)	11.84V	12.07V	12.16V	12.15V
		(2)	12.23V	12.51V	12.62V	12.59V
(b) Input Voltage of +25V	Iinput	(1)	12.0mA	11.9mA	11.9mA	11.9mA
		(2)	12.7mA	12.7mA	12.6mA	12.6mA
	Voutput	(1)	11.84V	12.06V	12.15V	12.15V
		(2)	12.22V	12.50v	12.61V	12.58V
(c) Input Voltage of +20V	Iinput	(1)	11.9mA	11.8mA	11.8mA	11.8mA
		(2)	12.6mA	12.6mA	12.5mA	12.5mA
	Voutput	(1)	11.84V	12.06V	12.13V	12.14V
		(2)	12.22V	12.50V	12.58V	12.55V
(d) Input Voltage of +15V	Iinput	(1)	11.8mA	11.7mA	11.7mA	11.7mA
		(2)	12.5mA	12.4mA	12.3mA	12.4mA
	Voutput	(1)	11.83V	12.05V	12.10V	12.10V
		(2)	12.22V	12.49V	12.57V	12.51V
Load Regulation						
(a) no load	Iinput	(1)	4.2mA	4.0mA	4.0mA	3.8mA
		(2)	4.7mA	4.5mA	4.4mA	4.3mA
	Voutput	(1)	11.84V	12.06V	12.16V	12.08V
		(2)	12.23V	12.51V	12.62V	12.60V
(b) 2K load	Iinput	(1)	10.2mA	10.0mA	10.0mA	9.8mA
		(2)	10.8mA	10.7mA	10.7mA	10.6mA
	Ioutput	(1)	5.9mA	6.0mA	6.1mA	6.0mA
		(2)	6.1mA	6.3mA	6.3mA	6.3mA
	Voutput	(1)	11.84V	12.06V	12.15V	12.07V
		(2)	12.23V	12.51V	12.62V	12.60V
(c) 1.5K load	Iinput	(1)	12.1mA	11.9mA	12.0mA	11.7mA
		(2)	12.8mA	12.7mA	12.7mA	12.6mA
	Ioutput	(1)	7.9mA	8.0mA	8.1mA	8.0mA
		(2)	8.2mA	8.3mA	8.4mA	8.4mA
	Voutput	(1)	11.84V	12.06V	12.15V	12.06V
		(2)	12.23V	12.52V	12.62V	12.61V
(d) 110 ohm load	Iinput	(1)	113mA	113mA	117mA	112mA
		(2)	118mA	117mA	120mA	120mA
	Ioutput	(1)	108mA	110mA	108mA	107mA
		(2)	111mA	113mA	111mA	110mA
	Voutput	(1)	11.86V	12.07V	11.82V	11.75V
		(2)	12.27V	12.47V	12.23V	12.19V
(e) 68 ohm load	Iinput	(1)	180mA	180mA	180mA	176mA
		(2)	186mA	187mA	188mA	177mA
	Ioutput	(1)	174mA	177mA	170mA	171mA
		(2)	181mA	182mA	177mA	176mA
	Voutput	(1)	11.86V	12.05V	11.57V	11.60V
		(2)	12.28V	12.37V	12.06V	12.00V
Dropout Voltage at no load		(1)	0.90V	0.9V	0.75V	0.86V
		(2)	0.90V	1.4V	0.9V	0.89V

Remark:

1. Line regulation was measured with a 1.5Kohm and 1uF load.
2. Load regulation was measured with an input voltage of +30V.
3. The device characteristics changes with self-heating.
4. The input current of the devices after 2Mrad gamma and after neutron irradiation fluctuated by about 10mA.

TEST RESULTS FOR VOLTAGE REGULATORS

Device Name: (MOT) MC7912CT
Sample Size: 1
Date Code: QQ 8026

Type of Irradiation		GAMMA		NEUTRON
Test conditions	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Line Regulation (1.5Kohm and 1uF load)				
(a) Input voltage of -30V				
Input current	13.5mA	13.2mA	12.2mA	12.4mA
Output voltage	-12.11V	-12.10V	-11.41V	-11.72V
(b) Input voltage of -25V				
Input current	13.5mA	13.2mA	11.8mA	12.3mA
Output voltage	-12.11V	-12.05V	-10.99V	-11.61V
(c) Input voltage of -20V				
Input current	13.5mA	13.1mA	9.8mA	12.1mA
Output voltage	-12.11V	-12.00V	-8.89V	-11.47V
(d) Input voltage of -15V				
Input current	13.5mA	13.0mA	6.2mA	11.8mA
Output voltage	-12.11V	-11.91V	-4.69V	-11.26V
Load Regulation (Input voltage of -30V)				
(a) no load				
Input current	5.4mA	4.9mA	4.4mA	4.7mA
Output current	0mA	0mA	0mA	0mA
Output voltage	-12.11V	-12.20V	-11.81V	-11.92V
(b) 2K load				
Input current	11.5mA	11.0mA	10.6mA	10.4mA
Output current	6.1mA	6.1mA	5.8mA	6.0mA
Output voltage	-12.11V	-12.17V	-11.65V	-11.91V
(c) 1.5K load				
Input current	13.5mA	12.9mA	12.5mA	12.3mA
Output current	8.1mA	8.1mA	7.6mA	7.9mA
Output voltage	-12.11V	-12.16V	-11.63V	-11.90V
(d) 110 ohm load				
Input current	117mA	114mA	113mA	112mA
Output current	111mA	109mA	108mA	105mA
Output voltage	-12.18V	-12.00V	-11.88V	-11.59V
(e) 68 ohm load				
Input current	186mA	178mA	174mA	171mA
Output current	179mA	175mA	172mA	170mA
Output voltage	-12.19V	-11.90V	-11.72V	-11.63V
Dropout Voltage at no load	0.60V	0.64V	0.60V	0.64V

Remark:
1. The device characteristics changes with self-heating.
2. Upon initial poweron, the output voltage was -11.4V without load and -5.1V with a 110 ohm load. With self-heating of the device, normal operation of the device was restored.

TEST RESULTS FOR VOLTAGE REGULATORS

Device Name: (FCH) UA7912UC
Sample Size: 1
Date Code: F8222

Type of Irradiation	GAMMA			NEUTRON
Test conditions	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Line Regulation (1.5Kohm and 1uF load)				
(a) Input voltage of -30V				
Input current	9.9mA	9.7mA	10.0mA	---
Output voltage	-12.285V	-12.079V	-12.49V	
(b) Input voltage of -25V				
Input current	9.9mA	9.7mA	10.0mA	---
Output voltage	-12.286V	-12.052V	-12.49V	
(c) Input voltage of -20V				
Input current	9.9mA	9.6mA	10.0mA	---
Output voltage	-12.285V	-12.012V	-12.47V	
(d) Input voltage of -15V				
Input current	9.9mA	9.6mA	10.0mA	---
Output voltage	-12.284V	-11.96V	-12.41V	
Load Regulation (Input voltage of -30V)				
(a) no load				
Input current	1.7mA	1.4mA		
Output current	0mA	0mA	---	---
Output voltage	-12.293V	-12.22V		
(b) 2K load				
Input current	7.8mA	7.6mA		
Output current	6.1mA	6.1mA	---	---
Output voltage	-12.29V	-12.19V		
(c) 1.5K load				
Input current	9.9mA	9.6mA		
Output current	8.2mA	8.1mA	---	---
Output voltage	-12.29V	-12.19V		
(d) 110 ohm load				
Input current	120mA	112mA		
Output current	112mA	110mA	---	---
Output voltage	-12.27V	-12.16V		
(e) 68 ohm load				
Input current	184mA	180mA		
Output current	180mA	178mA	---	---
Output voltage	-12.26V	-12.14V		
Dropout Voltage				
(a) at no load	0.53V	0.43V	---	---
(b) at 1.5K load	0.75V	0.71V	---	---

Remark:
1. The device characteristics changes with self-heating.
2. The device was damaged after 2Mrad of gamma irradiation. Upon initial poweron, the output voltage was -4.0V. With annealing induced by self-heating, marginally operation was observed. However with a 68 ohm load, the severe self-heating caused the output voltage to drop to -8.7V even without a load.

TEST RESULTS FOR TIMERS

Device Name: (Intersil) ICM7555 IPA
Sample Size: 3
Date code: 8307

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
Frequency	(1)	106.5KHz	92.6KHz	---	---
	(2)	103.7KHz	103KHz	6.1kHz	---
	(3)	103.9KHz	163KHz	---	---
Rise time (10-90%)	(1)	116ns	330ns	---	---
	(2)	120ns	297ns	4.2us	---
	(3)	133ns	200ns	---	---
Fall time (10-90%)	(1)	72ns	260ns	---	---
	(2)	78ns	320ns	2.3us	---
	(3)	90ns	325ns	---	---
Time interval for logic 0	(1)	4.4us	4.3us	---	---
	(2)	4.6us	3.4us	17.6us	---
	(3)	4.6us	3.2us	---	---
Time interval for logic 1	(1)	4.9us	6.4us	---	---
	(2)	4.9us	6.3us	144us	---
	(3)	4.9us	2.9us	---	---

Remark:

1. The test circuit was a typical 555 timer circuit to give a 45%-55% duty-cycle and a nominal frequency of 100KHz. A 1K pullup resistor and a 200pF capacitive load were used.
2. After 1Mrad of irradiation, the frequency of the CMOS timer drifted by about 1KHz with self-heating.
3. After 2Mrad of irradiation, device (1)&(3) stopped operating and the output saturation voltage of device (2) was about 1V. The frequency of device (2) also drifted with self-heating.

TEST RESULTS FOR TIMERS

Device Name: (EXAR) L555CP
Sample Size: 3
Date code: (1) 602
(2)&(3) 7831

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
Frequency	(1) (2) (3)	89.32KHz 89.39KHz 85.45KHz	AFTER 1 MRAD OF GAMMA IRRADIATION, THE OUTPUT WAS LATCHED TO +5V D.C.		
Rise time (10-90%)	(1) (2) (3)	250ns 260ns 265ns			
Fall time (10-90%)	(1) (2) (3)	125ns 85ns 100ns			
Time interval for logic 0	(1) (2) (3)	5.2us 5.2us 5.4us			
Time interval for logic 1	(1) (2) (3)	5.9us 5.9us 6.1us			

Remark:

1. The test circuit was a typical 555 timer circuit to give a 45%-55% duty-cycle and a nominal frequency of 100KHz. A 1K pullup resistor and a 200pF capacitive load were used.
2. All three CMOS timers failed after 1Mrad of irradiation.

TEST RESULTS FOR TIMERS

Device Name: (TI) TLC 555CP
Sample Size: 4
Date code: X406

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	5×10^{13} n/cm^2
Frequency	(1)	115.3KHz			
	(2)	114.1KHz			
	(3)	114.7KHz			
	(4)	113.4KHz			
Rise time (10-90%)	(1)	74ns			
	(2)	76ns			
	(3)	74ns			
	(4)	74ns			
Fall time (10-90%)	(1)	16ns	AFTER 1 MRAD OF GAMMA IRRADIATION, THE OUTPUT WAS LATCHED TO +5V D.C.		
	(2)	16ns			
	(3)	16ns			
	(4)	15ns			
Time interval for logic 0	(1)	4.0us			
	(2)	4.0us			
	(3)	4.0us			
	(4)	4.0us			
Time interval for logic 1	(1)	4.6us			
	(2)	4.7us			
	(3)	4.7us			
	(4)	4.7us			

Remark:
1. The test circuit was a typical 555 timer circuit to give a 45%-55% duty-cycle and a nominal frequency of 100KHz. A 1K pullup resistor and a 200pF capacitive load were used.
2. All four CMOS timers failed after 1Mrad of irradiation.

TEST RESULTS FOR TIMERS

Device Name: (FCH) UA555TC
Sample Size: 4
Date code: F8222

Type of Irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	5X10^{13} n/cm^2
Frequency	(1)	93.8KHz	102.5KHz	105.6KHz	106.3KHz
	(2)	91.6KHz	103.5KHz	101.8KHz	105.0KHz
	(3)	93.3KHz	103.0KHz	106.6KHz	107.9KHz
	(4)	93.7KHz	102.5KHz	102.2KHz	105.8KHZ
Rise time (10-90%)	(1)	780ns	295ns	320ns	420ns
	(2)	870ns	370ns	280ns	380ns
	(3)	780ns	310ns	300ns	420ns
	(4)	780ns	320ns	270ns	390ns
Fall time (10-90%)	(1)	130ns	285ns	245ns	245ns
	(2)	130ns	250ns	340ns	320ns
	(3)	140ns	300ns	295ns	280ns
	(4)	125ns	270ns	280ns	280ns
Time interval for logic 0	(1)	4.6us	4.2us	4.2us	4.1us
	(2)	4.6us	4.2us	4.3us	4.1us
	(3)	4.6us	4.3us	4.1us	4.0us
	(4)	4.6us	4.3us	4.3us	4.0us
Time interval for logic 1	(1)	6.0us	5.4us	5.2us	5.2us
	(2)	6.2us	5.4us	5.4us	5.3us
	(3)	6.0us	5.4us	5.2us	5.2us
	(4)	6.0us	5.4us	5.4us	5.2us

Remark:

1. The test circuit was a typical 555 timer circuit to give a 45%-55% duty-cycle and a nominal frequency of 100KHz. A 1K pullup resistor and a 200pF capacitive load were used.
2. After 1Mrad, the output voltage was initially latched to +5V. About 2 minutes after poweron, the device started functioning. The frequency increased at the rate of about 1KHz per hour.
3. After 2Mrad, the output voltage was again latched to +5V. The devices resumed operation about 3 minutes after poweron.

TEST RESULTS FOR HIGH-VOLTAGE MEDIUM-POWER BIPOLAR TRANSISTORS

Device Name: (TRW) LT1839
Date Code: 8421
Sample Size: 2
Type: NPN, 70V, 2.5W, RF

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE} at I_C = 40mA, V_{CE} = 30V	(1)	36	31	24	25
	(2)	40	31	25	24
BV_{CBo} at 10uA	(1)	136V	120V	120V	--
	(2)	124V	122V	122V	--

TEST RESULTS FOR HIGH-VOLTAGE MEDIUM-POWER BIPOLAR TRANSISTORS

Device Name: (MOT) MRF531
Date Code: 8403
Sample Size: 2
Type: NPN, 100V, 2.5W, RF

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE} at I_C = 40mA, V_{CE} = 40V	(1)	50	32	25	34
	(2)	44	25	27	31

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (GE) D44C11
Date Code: (1) 8417
(2) 8410
Sample Size: 2
Type: NPN, 80V, 30W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
h_{FE} at I_C = 0.8A V_{CE} = 10V	(1)	210	143	131	123
	(2)	130	84	73	73

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (GE) D45C8
Date Code: 8415
Sample Size: 2
Type: PNP, 60V, 30W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
h_{FE} at I_C = 0.8A V_{CE}= -10V	(1)	99	67	56	47
	(2)	103	66	62	47

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (GE) D44H11
Date Code: 8418
Sample Size: 3
Type: NPN, 80V, 50W

Type of Irradiation			GAMMA		NEUTRON
parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}$ n/cm^2
h_{FE} at I_C = 0.8A V_{CE} = 10V	(1)	232	152	128	127
	(2)	154	105	89	89
	(3)	191	133	111	110

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (GE) D45H11
Date Code: (1) 8414
(2)&(3) 8415
Sample Size: 3
Type: PNP, 80V, 50W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE} at I_C = 0.8A, V_{CE} = -10V	(1)	186	103	81	70
	(2)	188	107	86	73
	(3)	138	86	73	62

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) MJ4237
Date Code: 8052
Sample Size: 2
Type: PNP, 120V, 90W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE} at I_C = 0.8A, V_{CE} = -10V	(1)	168	123	103	70
	(2)	195	138	108	76

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) MJ4247
Date Code: 8126
Sample Size: 2
Type: NPN, 120V, 90W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE} at I_C = 0.8A, V_{CE} = 10V	(1)	160	107	82	82
	(2)	184	105	81	81

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (SOL) MJ13080
Date Code: 8426
Sample Size: 3
Type: NPN, 400V, 150W

Type of Irradiation			NEUTRON	GAMMA
Parameter	S/N	Pretest	$5X10^{13} n/cm^2$	1.5Mrad
h_{FE}	(1)	22	21	18
at I_C = 2A	(2)	20	18	15
V_{CE} = 2V	(3)	25	22	17

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) MJE5221
Date Code: 8339
Sample Size: 2
Type: NPN, 80V, 83W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE}	(1)	100	73	53	56
at I_C = 2A	(2)	168	105	74	77
V_{CE} = 2V					

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) MJE5231
Date Code: 8339
Sample Size: 2
Type: PNP, 80V, 83W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE}	(1)	105	63	51	37
at I_C = 2A	(2)	110	66	52	42
V_{CE} = -2V					

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) MPSU05
Sample Size: 2
Type: NPN, 60V, 10W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE} at I_C = 80mA V_{CE} = 10V	(1)	220	131	107	104
	(2)	235	160	119	121

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) MPSU55
Sample Size: 2
Type: PNP, 60V, 10W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE} at I_C = 80mA V_{CE} = -10V	(1)	160	104	82	69
	(2)	210	103	73	66

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) 2N6338
Date Code: 7952
Sample Size: 2
Type: NPN, 100V, 200W

Type of Irradiation			GAMMA	NEUTRON	GAMMA
Parameter	S/N	Pretest	1Mrad	$5X10^{13} n/cm^2$	2.5Mrad
h_{FE} at I_C = 4A V_{CE} = 2V	(1)	114	62	62	50
	(2)	85	65	57	44

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (SOL) 2N6339
Date Code: 8330
Sample Size: 3
Type: NPN, 120V, 200W

Type of Irradiation			NEUTRON
Parameter	S/N	Pretest	$5X10^{13} n/cm^2$
h_{FE} at I_C = 8A V_{CE} = 2.5V	(1)	74	70
	(2)	46	43
	(3)	100	92

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) 2N6436
Date Code: 7952
Sample Size: 2
Type: PNP, 80V, 200W

Type of Irradiation			GAMMA	NEUTRON	GAMMA
Parameter	S/N	Pretest	1Mrad	$5X10^{13} n/cm^2$	2.5Mrad
h_{FE} at I_C = 4A V_{CE} = -2V	(1)	63	45	33	28
	(2)	70	50	38	32

TEST RESULTS FOR POWER BIPOLAR TRANSISTORS

Device Name: (MOT) 2N6438
Date Code: 8426
Sample Size: 2
Type: PNP, 120V, 200W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13} n/cm^2$
h_{FE} at I_C = 4A V_{CE} = -2V	(1)	77	55	44	35
	(2)	83	44	39	29

TEST RESULTS FOR POWER DARLINGTON BIPOLAR TRANSISTORS

Device Name: 2N6385
Date Code: (1) RCA [7948]
(2) MOT [8226]
Sample Size: 2
Type: NPN, 80V, 100W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
h_{FE} at I_C = 4A V_{CE} = 4V	(1) (2)	6700 7000	4900 5700	3700 4200	3400 4000

TEST RESULTS FOR POWER DARLINGTON BIPOLAR TRANSISTORS

Device Name: (RCA) 2N6650
Date Code: (1) 8202
(2) 8210
Sample Size: 2
Type: PNP, 80V, 100W

Type of Irradiation			GAMMA		NEUTRON
Parameter	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
h_{FE} at I_C = 4A V_{CE} = 10V	(1) (2)	1540 1480	1100 910	760 730	600 520

TEST RESULTS FOR MOS POWER TRANSISTORS

Device Name: IRF250
Date Code: (1)&(2) IRC [8419]
(3)&(4) SIL [8420]
(5)&(6) MOT [8426]
Sample Size: 6
Type: N-ch, 200V, .085ohm, 20A

Parameters	S/N	Pretest	1Mrad of gamma irradiation
Threshold	(1)	2.97V	At V_{GS}=-30V & V_{DS}=2V, I_D=10A
Voltage	(2)	3.03V	At V_{GS}=-30V & V_{DS}=2V, I_D=10A
at I_D = 1mA	(3)	2.48V	At V_{GS}=-18V & V_{DS}=2V, I_D=5mA
V_{DS} = 10V	(4)	2.54V	At V_{GS}=-18V & V_{DS}=2V, I_D=300mA
	(5)	3.10V	At V_{GS}=-20V & V_{DS}=1V, I_D=16A
	(6)	3.08V	At V_{GS}=-20V & V_{DS}=1V, I_D=16A

TEST RESULTS FOR MOS POWER TRANSISTORS

Device Name: (MOT) IRF430
Date Code: 8326
Sample Size: 1
Type: N-ch, 500V, 1.5ohm, 4.5A

Parameters	Pretest	1Mrad of gamma irradiation
Threshold Voltage at I_D = 1mA V_{DS} = 10V	3.69V	At V_{GS}=-20V & V_{DS}=5V, I_D=4A

TEST RESULTS FOR MOS POWER TRANSISTORS

Device Name: IRF450
Date Code: (1)&(2) IRC [8427]
(3)&(4) SIL [8419]
Sample Size: 4
Type: N-ch, 500V, .4ohm, 13A

Parameters	S/N	Pretest	1Mrad of gamma irradiation
Threshold	(1)	3.02V	At V_{GS}=-20V & V_{DS}=2.5V, I_D=7A
Voltage	(2)	3.27V	At V_{GS}=-20V & V_{DS}=2.5V, I_D=7A
at I_D = 1mA	(3)	2.73V	At V_{GS}=-20V & V_{DS}=5V, I_D=2A
V_{DS} = 10V	(4)	2.65V	At V_{GS}=-20V & V_{DS}=5V, I_D=3A

TEST RESULTS FOR MOS POWER TRANSISTORS

Device Name: (MOT) MTM15N45
Date Code: 8413
Sample Size: 2
Type: N-ch, 450V, .5ohm, 15A

Parameters	S/N	Pretest	1Mrad of gamma irradiation
Threshold Voltage at I_D = 1mA V_{DS} = 10V	(1)	3.11V	At V_{GS}=-20V & V_{DS}=2V, I_D=4A
	(2)	2.59V	At V_{GS}=-20V & V_{DS}=2V, I_D=4A

TEST RESULTS FOR MOS POWER TRANSISTORS

Device Name: (RCA) RFP3N45
Date Code: 8315
Sample Size: 2
Type: N-ch, 450V

Parameters	S/N	Pretest	1Mrad of gamma irradiation
Threshold Voltage at I_D = 1mA V_{DS} = 10V	(1)	2.97V	At V_{GS}=-10V & V_{DS}=2.5V, I_D=0.5A
	(2)	2.54V	At V_{GS}=-10V & V_{DS}=2.5V, I_D=1A

TEST RESULTS FOR MOS POWER TRANSISTORS

Device Name: (SIL) VN0600D
Sample Size: 2
Type: N-ch, 60V, 0.12ohm, 18A

Parameters	S/N	Pretest	1Mrad of gama irradiation
Threshold Voltage at I_D = 1mA V_{DS} = 10V	(1)	3.34V	At V_{GS}=-10V & V_{DS}=2V, I_D=4A
	(2)	3.39V	At V_{GS}=-10V & V_{DS}=2V, I_D=6A

TEST RESULTS FOR RECTIFIERS

Device Name: (MOT)MR854
Date Code: 8424
Sample Size: 2

Type of irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
Forward Voltage at I=2A	(1) (2)	0.94V 1.0V	0.94V 0.92V	0.93V 0.92V	0.93V 0.92V
Leakage Current at 500V reverse voltage	(1) (2)	0.5uA 0.5uA	0.5uA 0.5uA	0.5uA 1uA	1uA 1uA
Reverse Voltage at 10uA leakage current	(1) (2)	>700V >700V	>700V 750V	730V 730V	720V 700V

TEST RESULTS FOR RECTIFIERS

Device Name: (Sanken)CTB34

Type of irradiation			GAMMA		NEUTRON
Parameters	S/N	Pretest	1Mrad	2Mrad	$5X10^{13}n/cm^2$
Forward Voltage at I=2A	(A) (B)	0.73V 0.73V	0.74V 0.74V	0.73V 0.73V	0.73V 0.73V
Leakage Current at 30V reverse voltage	(A) (B)	0.15mA 0.15mA	0.15mA 0.15mA	0.15mA 0.1mA	0.1mA 0.1mA
Reverse Voltage at 0.5mA leakage current	(A) (B)	42V 35V	42V 37V	41V 37V	47V 40V

TEST RESULTS FOR RECTIFIERS

Device Name: (MOT) MBR745
Date Code: 8336
Sample Size: 2

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameters	S/N	Pretest	1Mrad	$5X10^{13}n/cm^2$	2.5Mrad
Forward Voltage at I=4A	(1) (2)	0.50V 0.54V	0.56V 0.56V	0.51V 0.54V	0.52V 0.55V
Leakage Current at 40V reverse voltage	(1) (2)	10uA <10uA	20uA <10uA	15uA <10uA	20uA 10uA
Reverse Voltage at 50 uA leakage current	(1) (2)	47V 52V	45V 49V	47V 50V	46V 50V

TEST RESULTS FOR TRANSISTOR ARRAYS

Device Name: (RCA) CA3127E
Date Code: (1) 8127
(2) 8406
Sample Size: 2
Description: 5 NPNs

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13} n/cm^2$	2.5Mrad
h_{FE} at I_C = 4mA V_{CE} = 10V	(1Q1)	110	69	73	65
	(1Q2)	109	63	68	58
	(1Q3)	105	63	71	60
	(1Q4)	105	63	68	58
	(1Q5)	108	69	74	65
	(2Q1)	182	94	108	88
	(2Q1)	175	94	113	90
	(2Q3)	175	98	105	98
	(2Q5)	180	100	110	90
	(2Q4)	183	100	113	90

TEST RESULTS FOR TRANSISTOR ARRAYS

Device Name: (RCA) CA3146AE
Date Code: 8414
Description: 5 NPNs

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13} n/cm^2$	2.5Mrad
h_{FE} at I_C = 8mA V_{CE} = 9V	(Q1)	137	76	80	61
	(Q2)	133	72	77	60
	(Q3)	125	69	73	57
	(Q4)	123	65	72	57
	(Q5)	130	69	75	67

TEST RESULTS FOR TRANSISTOR ARRAYS

Device Name: (RCA) CA3183AE
Date Code: 8301
Description: 5 NPNs

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13} n/cm^2$	2.5Mrad
h_{FE} at	(Q1)	106	56	58	47
I_C = 25mA	(Q2)	102	50	57	47
V_{CE} = 8V	(Q3)	101	51	58	45
	(Q4)	102	51	58	45
	(Q5)	103	53	59	46

TEST RESULTS FOR TRANSISTOR ARRAYS

Device Name: (Plessey) SL3145C
Date Code: 8044
Description: 5 NPNs

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13} n/cm^2$	2.5Mrad
h_{FE} at	(Q1)	110	75	78	64
I_C = 8mA	(Q2)	108	71	78	64
V_{CE} = 9V	(Q3)	110	76	78	61
	(Q4)	108	70	75	61
	(Q5)	108	72	77	69

TEST RESULTS FOR MONOLITHIC BREADBOARD COMPONENTS

Device Name: (Interdesign) M0003A
Date Code: 8347
Description: 4 lateral PNPs

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13}n/cm^2$	2.5Mrad
h_{FE} at $I_C = 0.4mA$ $V_{CE} = -10V$	(Q1)	43	14	14	10
	(Q2)	43	13	13	10
	(Q3)	43	14	13	10
	(Q4)	43	15	14	10

TEST RESULTS FOR MONOLITHIC BREADBOARD COMPONENTS

Device Name: (Interdesign) M0004
Date Code: 8310
Description: 2 small NPNs (N1,N4)
2 large NPNs (N2,N3)

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13}n/cm^2$	2.5Mrad
h_{FE} at $I_C = 4mA$ $V_{CE} = 10V$	(N1)	228	166	168	143
	(N4)	253	170	175	148
h_{FE} at $I_C = 40mA$ $V_{CE} = 10V$	(N2)	300	200	200	160
	(N3)	293	185	189	152

TEST RESULTS FOR MONOLITHIC BREADBOARD COMPONENTS

Device Name: (Interdesign) M0302B
Date Code: 8118
Description: 5 NPNs + subs. PNP

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13}n/cm^2$	2.5Mrad
h_{FE} at $I_C = 5mA$ $V_{CE} = 3V$	(Q1)	66	54	54	47
	(Q2)	66	54	54	47
	(Q3)	67	52	56	50
	(Q4)	102	80	77	66
	(Q5)	101	76	79	68
h_{FE} at $I_C = 0.4mA$ $V_{CE} = -5V$	Subs. PNP	0.06	0.09	0.09	---

TEST RESULTS FOR MONOLITHIC BREADBOARD COMPONENTS

Device Name: (Interdesign) M0415
Date Code: 8342
Description: 2 N-ch + 2 P-ch

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13}n/cm^2$	2.5Mrad
Threshold Voltage at V_{DS}= 10V I_D = 1uA	(N1) (N2) (P1) (P2)	1.07V 1.07V -0.84V -0.84V	0.79V 0.79V -2.75V -2.75V	0.60V 0.71V -2.95V -2.95V	0.86V 0.86V -5.4V -5.4V

Remark: 1. The MOS devices were irradiated without an applied gate voltage. The leads were shorted.

TEST RESULTS FOR MONOLITHIC BREADBOARD COMPONENTS

Device Name: (Interdesign) M0417
Date Code: 8327
Description: 2 N-ch drivers, zener, p-resistor, subs. PNP.

Type of irradiation			GAMMA	NEUTRON	GAMMA
Parameter	No.	Pretest	1Mrad	$5X10^{13}n/cm^2$	2.5Mrad
Threshold Voltage at V_{DS}= 10V I_D = 1uA	(N1) (N2)	0.90V 0.90V	0.22V 0.22V	0.41V 0.41V	0.44V 0.44V
Zener Voltage (0.5mA)		6.6V	6.6V	6.6V	6.6V
Resistor (0-20V)	(8R) (4R)	130K 50K	140K 70K	130K 70K	140K 70K
Substrate PNP h_{FE} at I_C = 20mA V_{CE} = 4V	(E1) (E1+E2)	476 571	76 68	73 66	49 44

Remark: 1. The MOS devices were irradiated without an applied gate voltage. The leads were shorted.

APPENDIX B

PLOTTING PROGRAMS

The program listings for the Calcomp plotting programs are given below:

B.1 Plotting program: LINEAR (Linear axis)

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c                                                                  c
c                    PROGRAM NAME:   LINEAR                        c
c                                                                  c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
c                                                                  c
c   This program plots the results of 3, 4, or 5 values for        c
c   gamma irradiation and 2 values for neutron irradiation         c
c   using the Calcomp Plotter at UT Computing Center.              c
c                                                                  c
c   The number of graphs to be plotted on the same set of axis     c
c   is given an input variable, ILINE.                             c
c                                                                  c
c   Each set of input data must be in the following format:        c
c     NPTS      [ Number of data points for gamma irradations]     c
c     YG(1)  YG(2)  YG(3)  YG(4)  YG(5)                            c
c     YN(1)  YN(2)                                                 c
c                                                                  c
c (A) To execute this program do:                                  c
c          .DO CALCOM LINEAR [LINEAR is the filename]              c
c     or   .EX LINEAR,/SEARCH FOR:CALCOM.REL                       c
c                                                                  c
c (B) To view the plot on a tektronics terminal, do:               c
c    .R PRECAL                                                     c
c    and answer the questions with                                 c
c    FOR01,  4010 or 4025 or etc.,  30,  C                         c
c                                                                  c
c (C) To obtain a copy of the plot from the Calcomp Plotter, do:   c
c     .PLOT IBMjobname=FOR01.PLT/PEN:01                            c
c                                                                  c
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
      DIMENSION DX(4),DY(4),XG3(5),XG4(6),XG5(7),XN(4),YG(7),YN(4)
      DOUBLE PRECISION FILNAM
      DATA DX/4.5,4.5,0.0,1.0/,DY/0.0,8.0,0.0,1.0/
      DATA XG3/0.0,1.0,2.0,0.0,1.0/,XG4/0.0,1.0,2.0,3,0.0,1.0/,
     1 XG5/0.0,1.0,2.0,3,4,0.0,1.0/
      DATA XN/4.5,5.5,0,1/
      DATA FIRST/0/,DELTA/1.0/,YLEN/8.0/
      YWORD=YLEN+0.3
      YN(3)=FIRST
      YN(4)=DELTA
```

```
C
C Input the filename for the data
C
      WRITE(5,1)
1     FORMAT('0 INPUT FILENAME:- extension of filename must be .DAT')
      READ(5,2) FILNAM
2     FORMAT(A10)
       OPEN (UNIT=20,DEVICE='DSK',ACCESS='SEQIN',
     +  MODE='ASCII',FILE=FILNAM)
C
C Initialize plotting routines - Result is stored in FOR01.PLT
C
      CALL PLOTS(0,0,1)
C
C Plot axis and labels
C

      CALL DASHS(DX,DY,2,1,0.1,0.05,-1,1,-1,1)
      CALL IAXIS(0.0,0.0,17HDOSAGE    in Mrad,-17,4.0,0.0,0.0,1.0,1)
      CALL IAXIS(4.5,0.0,12H     in n/cm,-12,1.0,0.0,0.0,5.0E13,1)
      CALL IAXIS(0.0,0.0,20HOffset Voltage in mV,20,YLEN,
     1 90.0,FIRST,DELTA,1)
      CALL SYMBOL(1.5,YWORD,.15,5HGAMMA,0.0,5)
      CALL SYMBOL(1.5,YLEN,.15,11HIRRADIATION,0.0,11)
      CALL SYMBOL(4.5,YWORD,0.15,7HNEUTRON,0.0,7)
      CALL SYMBOL(4.5,YLEN,0.15,11HIRRADIATION,0.0,11)
C
C Input number of lines to be plotted
C
      WRITE(5,11)
11    FORMAT(' HOW MANY LINES ARE TO BE PLOTTED?')
      READ(5,*) ILINE
C
C Do loop to plot the lines
C
      DO 99 IDO=1,ILINE
        IS=IDO
        READ(20,*) NPTS
        READ(20,*) (YG(I), I=1,NPTS)
        READ(20,*) (YN(I), I=1,2)
        YG(NPTS+1)=FIRST
        YG(NPTS+2)=DELTA
      IF (NPTS .EQ. 3) CALL LINE(XG3,YG,NPTS,1,1,IS,1)
      IF (NPTS .EQ. 4) CALL LINE(XG4,YG,NPTS,1,1,IS,1)
      IF (NPTS .EQ. 5) CALL LINE(XG5,YG,NPTS,1,1,IS,1)
      CALL LINE(XN,YN,2,1,1,IS,1)

99    CONTINUE
      CALL PLOT(0,0,999)
      CLOSE(UNIT=20)
      STOP
      END
```

B.2 Plotting program: SEMI.LOG (Semi-log axis)

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                   C
C                    PROGRAM NAME: SEMI.LOG                         C
C                                                                   C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                                   C
C   This program plots the results of 3, 4, or 5 values for        C
C   gamma irradiation and 2 values for neutron irradiation using   C
C   the Calcomp Plotter at UT Computing Center.                    C
C                                                                   C
C   The number of graphs to be plotted on the same set of axis     C
C   is given by an input variable, ILINE.                           C
C                                                                   C
C   Each set of input data must be in the following format:        C
C     NPTS     [ Number of data points for gamma irradations]      C
C     YG(1)  YG(2)  YG(3)  YG(4)  YG(5)                             C
C     YN(1)  YN(2)                                                  C
C                                                                   C
C (A) To execute this program do: [LOG is the filename]            C
C           .DO CALCOM SEMI.LOG                                     C
C     or    .EX SEMI.LOG,/SEARCH FOR:SCIEN.REL,CALCOM.REL           C
C                                                                   C
C (B) To view the plot on a tektronics terminal, do:               C
C    .R PRECAL                                                      C
C    and answer the questions with                                  C
C    FOR01,  4010 or 4025 or etc.,  30,  C                          C
C                                                                   C
C (C) To obtain a copy of the plot from the Calcomp Plotter, do:   C
C     .PLOT IBMjobname=FOR01.PLT/PEN:01                             C
C                                                                   C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      DIMENSION DX(4),DY(4),XG3(5),XG4(6),XG5(7),XN(4),YG(7),YN(4)
      DOUBLE PRECISION FILNAM
      DATA DX/4.5,4.5,0.0,1.0/,DY/0.0,8.75,0.0,1.0/
      DATA XG3/0.0,1.0,2.0,0.0,1.0/,XG4/0.0,1.0,2.0,3,0.0,1.0/,
     1 XG5/0.0,1.0,2.0,3,4,0.0,1.0/
      DATA XN/4.5,5.5,0,1/
      DATA FIRST/6/,DELTA/0.21/,YLEN/8.0/
      YWORD=YLEN+0.3
      YN(3)=FIRST
      YN(4)=DELTA
C
C Input the filename for the data
C
      WRITE(5,1)
1     FORMAT('0 INPUT FILENAME:- extension of filename must be .DAT')
```

```
      READ(5,2) FILNAM
 2    FORMAT(A10)
       OPEN (UNIT=20,DEVICE='DSK',ACCESS='SEQIN',
     + MODE='ASCII',FILE=FILNAM)
C
C Initialize plotting routines - Result is stored in FOR01.PLT
C
      CALL PLOTS(0,0,1)
C
C Plot axis and labels
C

      CALL DASHS(DX,DY,2,1,0.1,0.05,-1,1,-1,1)
      CALL IAXIS(0.0,0.0,17HDOSAGE    in Mrad,-17,4.0,0.0,0.0,1.0,1)
      CALL IAXIS(4.5,0.0,12H     in n/cm,-12,1.0,0.0,0.0,5.0E13,1)
      CALL LGAXS(0.0,0.0,29HGain-bandwidth product in MHz,29,YLEN,
     1 90.0,FIRST,DELTA)
      CALL SYMBOL(1.5,YWORD,.15,5HGAMMA,0.0,5)
      CALL SYMBOL(1.5,YLEN,.15,11HIRRADIATION,0.0,11)
      CALL SYMBOL(4.5,YWORD,0.15,7HNEUTRON,0.0,7)
      CALL SYMBOL(4.5,YLEN,0.15,11HIRRADIATION,0.0,11)
C
C Input number of lines to be plotted
C
      WRITE(5,11)
11    FORMAT(' HOW MANY LINES ARE TO BE PLOTTED?')
      READ(5,*) ILINE
C
C Do loop to plot the lines
C
      DO 99 IDO=1,ILINE
        IS=IDO
        READ(20,*) NPTS
        READ(20,*) (YG(I), I=1,NPTS)
        READ(20,*) (YN(I), I=1,2)
        YG(NPTS+1)=FIRST
        YG(NPTS+2)=DELTA
      IF (NPTS .EQ. 3) CALL LGLIN(XG3,YG,NPTS,1,1,IS,1)
      IF (NPTS .EQ. 4) CALL LGLIN(XG4,YG,NPTS,1,1,IS,1)
      IF (NPTS .EQ. 5) CALL LGLIN(XG5,YG,NPTS,1,1,IS,1)
      CALL LGLIN(XN,YN,2,1,1,IS,1)

99    CONTINUE
      CALL PLOT(0,0,999)
      CLOSE(UNIT=20)
      STOP
      END
```

VITA

David Kouchieh Su was born in Kuching, Malaysia on September 16, 1961. He graduated from Kuching High School in December 1978. The following September he entered The University of Tennessee, Knoxville, and in December 1982 he received a Bachelor of Science degree in Electrical Engineering. In the summer of 1983 he began study toward a Master's degree. During the course of study he worked as a teaching and research assistant for the Electrical Engineering Department. He received the Master of Engineering degree with a major in Electrical Engineering in March 1985.

The author is a member of Phi Eta Sigma, Tau Beta Pi, and Eta Kappa Nu.