CR 114364
AVAILABLE TO NASA HQRS & CENTERS ONLY

CASE FILE COPY

WALTER V. STERLING, INC.

CORPORATE OFFICE: CLAREMONT, CALIFORNIA
ENGINEERING OFFICES: LOS ALTOS, CALIFORNIA
ARLINGTON, VIRGINIA

RADIATION EFFECTS ON ELECTRONIC PARTS

Revision A

June 18, 1971

TECHNICAL AND MANAGEMENT CONSULTANTS TO INDUSTRY AND GOVERNMENT

FACILITY FORM 602

N72-17762	
(ACCESSION NUMBER)	(THRU)
159	G3
(PAGES)	(CODE)
CR-114364	24
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

RADIATION EFFECTS ON ELECTRONIC PARTS

Revision A

June 18, 1971

Prepared for

R&QA Branch
NASA-Ames Research Center
Moffett Field, California
NAS 2-4398

By

W. S. Johnson
Walter V. Sterling, Inc.

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
	Glossary	2
II.	TYPES OF RADIATION	4
	A. Near and Solar Space	4
	B. Nuclear Reactor Radiation	5
III.	RADIATION HARDNESS OF ELECTRONIC PARTS	7
	A. Passive Devices	7
	B. Semiconductors	9
	1. Diodes	9
	2. Bipolar Transistors	13
	3. Junction Field Effect Transistors	18
	4. Metal Oxide Semiconductor Field Effect Transistors	20
	C. Integrated Circuits	21
IV.	CONCLUSIONS	28
BIBLIOGRAPHY		37
APPENDIX		39

LIST OF TABLES

TABLE I	Descending Radiation Hardness by Part Category	7
TABLE II	Trends of Radiation Damage in Semiconductor Devices	12
TABLE III	Radiation Hardening vs Reliability	19
TABLE IV	Integrated Circuit Fabrication Techniques	25
TABLE V	General Damage Thresholds	26
TABLE VI	Estimate of Damage Thresholds of Pioneer Transistors	31
TABLE VII	Estimate of Damage Thresholds of Pioneer Integrated Circuits	34

Page

LIST OF FIGURES

FIGURE 1	Effects to be Expected from Different Types of Radiation	6
FIGURE 2	Estimated Effects of Radiation Environment on Resistors	8
FIGURE 3	Estimated Effects of Radiation Environment on Capacitors	10
FIGURE 4	Useful Range for Semiconductors Exposed to Space Radiation	11
FIGURE 5	Nomograph for Neutron Damage for Silicon Transistors	14
FIGURE 6	Nomograph for Proton Damage in Silicon Transistors	16
FIGURE 7	Gate Threshold Voltage vs Dose at 3 Different Drain Currents	22
FIGURE 8	Gate Threshold vs Dose with Two Biases	23
FIGURE 9	Gate Threshold vs Dose with Bias Change During Exposure	23
FIGURE 10	Typical Normalized Gate Threshold Voltage vs Dose with Gate Bias During Exposure Indicated	24
FIGURE 11	Typical Normalized Gate Threshold Voltage vs Proton Dose	24

I. INTRODUCTION

The purpose of this task has been to search existing literature regarding the long term effects of nuclear radiation on electronic parts. The intent was to gather data on parts used in the Pioneer Spacecraft which relates to the effects of long term, low intensity radiation fields such as would be encountered on deep space missions passing through planetary radiation belts and having RTGs on board.

The majority of the literature covers the effects of radiation damage due to nuclear blasts. Although blast effects are more severe than long term space radiation, some of the data can still be useful in predicting the radiation thresholds for Pioneer's electronic parts.

This report is divided into four parts. Section I is the introduction and also includes a glossary of terms used in the remainder of the report. Section II is a brief discussion of the various types of radiation the spacecraft will encounter. Section III is a discussion of radiation on electronic parts. Section IV contains conclusions and two tables giving an estimate of the damage threshold of the transistors and integrated circuits used on the Pioneer Spacecraft. An appendix is also included at the end of the report which contains copies of various tables and figures used in the literature that may be of further help in assessing the radiation damage of the Pioneer parts.

GLOSSARY OF RADIATION TERMS

Beta Rays - High energy electrons ejected from a nucleus.

Protons - Hydrogen nuclei.

Alpha Particles - Helium nuclei.

Gamma Rays (Photons) - Similar to x-rays, electromagnetic waves (packets of gamma rays which behave as particles).

Neutrons - Neutral particle with about the same mass as protons.

Roentgen - A quality of ionizing radiation which will produce 2.083 X 10^9 ion pairs per cubic centimeter of STP air or deposit 83.8 ergs per gram of STP air.

Roentgen Per Hour - The intensity of a field of ionizing radiation which will deliver one Roentgen per hour.

Rep - Roentgen equivalent physical (93 ergs per gram of tissue equivalent).

Rem - Roentgen equivalent mammal (that quantity of ionizing radiation which will produce biological damage equivalent to one Roentgen of x-rays).

Rad (M) - A unit of absorbed energy (100 ergs per gram of material M).

Ergs/Gram (Carbon) - The preferred measurement of absorbed dose (a standard ionization chamber is used which is made of carbon and carbon dioxide).

Neutron Flux (nv) - Neutrons of energy E crossing a sphere of unit cross-sectional area per second (neutrons per square centimeter per second).

nvt - The time integral of neutron flux (neutrons per square centimeter).

Flux - The flow of radiation.

Dose - Absorbed energy.

Dose Rate - The rate of radiation or intensity.

Mev - Million electron-volts.

Fluence - The number of particles that enter a sphere of unit cross-sectional area (particle/cm^2).

Cosmic Rays - Very high energy particles which permeate space.

Van Allen Belts - Trapped particles found in two zones about the earth's geomagnetic axis - the lower maximum consists of protons and electrons, the upper maximum is apparently only electrons.

RADIATION TERM CONVERSION CHART

TO CONVERT	TO	MULTIPLY BY
Rads	ergs/gr	100
ev/gr	ergs/gr (c)	1.6×10^{-12}
Roentgen	erg/gr (c)	87.7
Rep	erg/gr (c)	84.6
Rad (Tissue)	erg/gr (c)	90.9
Rad (H_2O)	erg/gr (c)	90.0
MeV/cm^2	erg/gr (c)	4.5×10^{-8}
Photons/cm^2	erg/gr (c)	4.5×10^{-8}
Rad/hr	Neutrons/cm^2/sec	8.3×10^{4}

II. TYPES OF RADIATION AND THEIR EFFECTS

Electronic equipment which is designed to be sent into space will be exposed to several radiation environments. Basically, these environments fall into two classes, (1) near and solar space, and (2) radiation from on-board nuclear reactors. The types of penetrating radiation associated with each class will be discussed briefly in this section.

A. Near and Solar Space - The penetrating nuclear radiation of near and solar space may be divided into cosmic radiation, trapped radiation (planetary radiation belts) and solar flares. Of less importance are solar winds, solar x-rays and neutrons. Electromagnetic radiation (photons) is also of some concern.

Cosmic rays consist of about 90% protons (hydrogen nuclei) and 10% alpha particles (helium nuclei). The ionization dose rates attributable to cosmic rays are low but become a factor on long duration flights.

Planetary radiation belts consist of a large number of electrons and protons of various kinetic energies which are trapped by a planet's magnetic field. Protons are the most penetrating type of radiation because of their high average energy and mass. The average energy of electrons in the belts allows shielding but the secondary radiation these electrons create is very troublesome. Medium energy electrons expend their energy by ionizing materials. This results in a secondary dose of ionization. High energy electrons produce x-rays and gamma rays. This type of radiation is more penetrating than electrons and causes high ionization doses inside the vehicle.

Proton radiation in space is produced by solar flares and solar winds. Solar flares, which occur about twice a year and last approximately 50 hours, produce large fluxes of energetic protons. Solar winds expose a spacecraft to a constant stream of charged particles (proton and electrons) emanating from the sun. The effect of charged particle radiation is damaging both from ionization and atomic displacement.

Another type of radiation in space which affects materials is photons; electromagnetic radiation. The primary source of this radiation is the sun and the radiation intensity varies inversely as the square of the distance from the sun. The effect of photon radiation is damage due to ionization.

B. Nuclear Reactor Radiation - Nuclear reactors produce two types of radiation, neutrons and gamma rays. Energetic electrons are also present, and should be considered since they are formed by the interaction of gamma rays with matter.

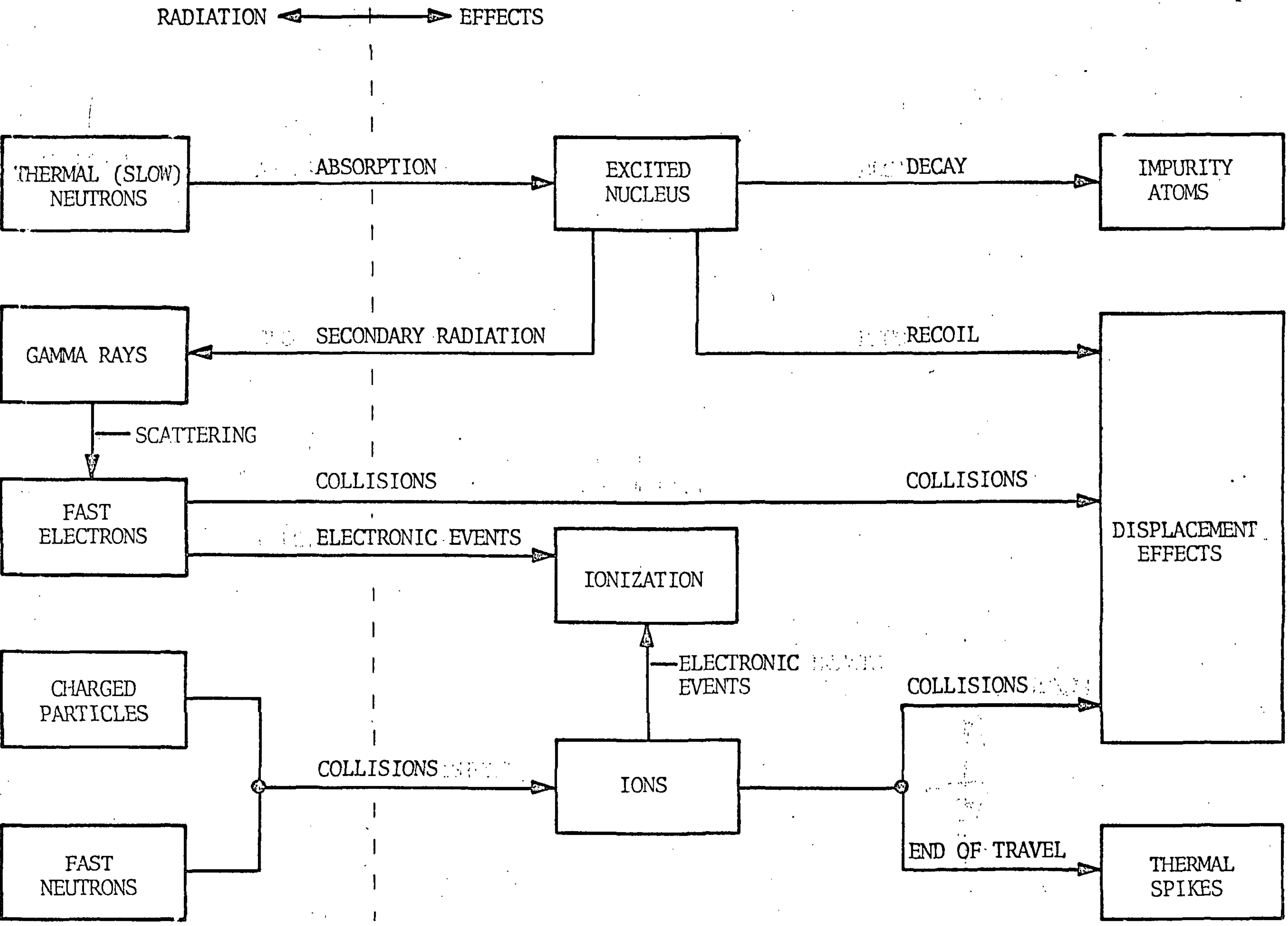
Gamma rays are massless pockets of energy (photons) which speed through a material and free the orbiting electrons of the atom through which they pass. These ionized electrons flow in the irradiated material as an electric current until recombination takes place. The higher the gamma application rate, the higher the current flow. Gamma flux, or gamma dose rate, is the effect of interest insofar as electronic equipment is concerned.

Neutrons have a large mass and a neutral charge. The neutral charge prevents energy loss due to electrical particle interaction. Neutrons penetrate a material unimpeded until they contact the nucleus of an atom. This collision results in a dislocation of the atom from its position in the crystal lattice. The dislocation incurred may be permanent or temporary, depending upon the energy level of the neutron. The total damage inflicted in a material is directly proportional to the total number of bombarding particles. For this reason, neutron fluence is of greater importance in electronic equipment than neutron flux.

Figure 1 illustrates the types of radiation and their effects on materials which are exposed to them.

FIGURE 1

EFFECTS TO BE EXPECTED FROM DIFFERENT TYPES OF RADIATION



III. RADIATION HARDNESS OF ELECTRONIC PARTS

A survey of the published information on radiation hardness indicates that passive devices are relatively insensitive to radiation damage when compared to semiconductor devices. For this reason, the major emphasis of this section will be on radiation effects on semiconductors. Table I lists the important part categories in order of the radiation hardness. Resistors and capacitors will be covered only briefly to point out the relative hardness of the various types within the two categories.

TABLE I

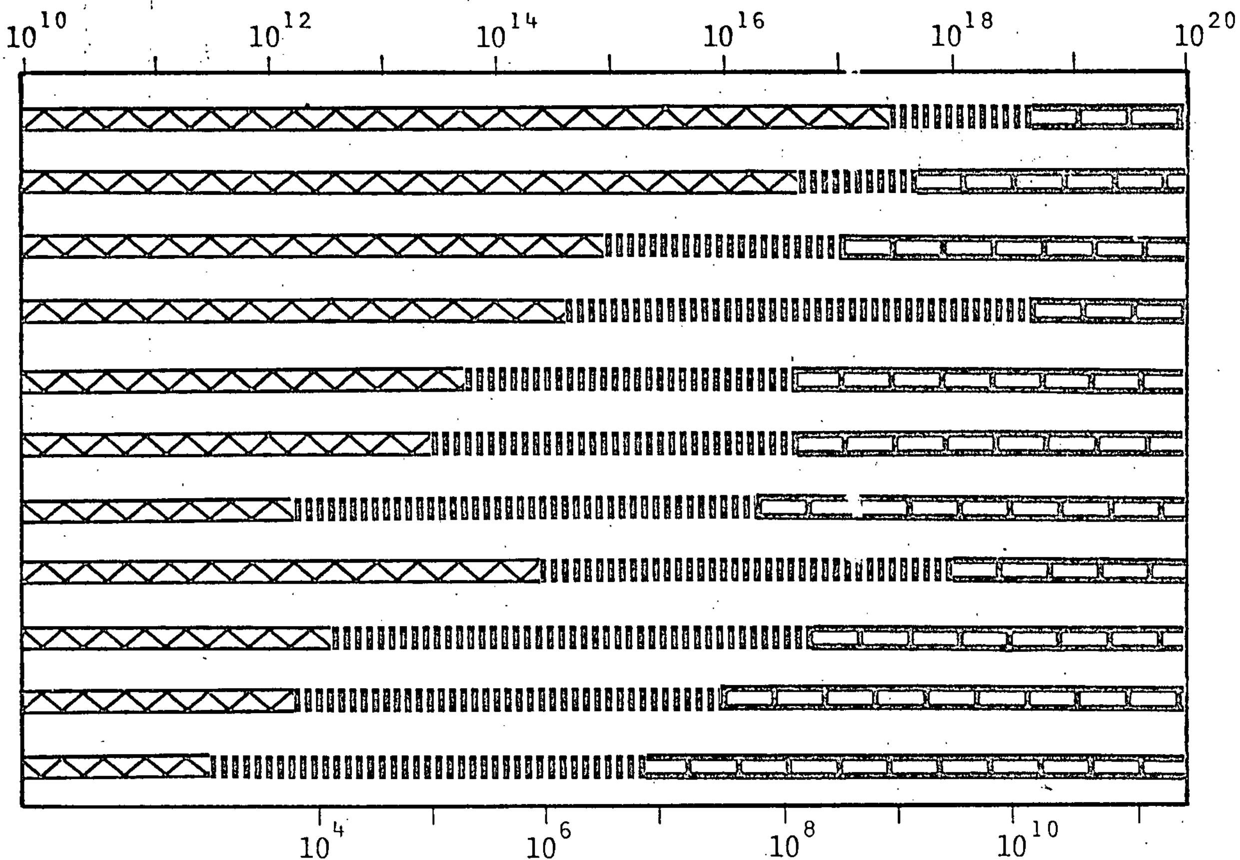
Descending Radiation Hardness by Part Category

1. Resistors
2. Capacitors
3. Diodes
4. Switching Transistors
5. Digital Integrated Circuits
6. Power Transistors
7. Linear Transistors
8. Linear Integrated Circuits

A. Passive Devices - Resistive elements can withstand large dosages of radiation in comparison to semiconductors. The effects of radiation are an increase in resistance for carbon elements and a decrease for metal elements. Metal oxide elements, such as used in RL and RLR style MIL-SPEC resistors, are the least radiation resistant of all resistor types and their resistance either increases or decreases in accordance with the type of radiation exposure. All resistors suffer insulation damage with prolonged exposure to radiation. Figure 2 shows the various types of resistors and their radiation thresholds for producing permanent damage.

FIGURE 2

ESTIMATED EFFECTS OF RADIATION ENVIRONMENT ON RESISTORS



PRECISION WIREWOUND (CERAMIC BOBBIN)

METAL FILM

CARBON FILM

PRECISION WIREWOUND (EPOXY BOBBIN)

CARBON COMPOSITION (FILM)

CARBON COMPOSITION (SLUG)

OXIDE FILM

VARIABLE WIREWOUND RESISTOR

VARIABLE FILM RESISTOR

PRECISION FILM POTENTIOMETER

PRECISION WIREWOUND POTENTIOMETER

LEGEND:

NO MEASURABLE DAMAGE

MILD TO MODERATE DAMAGE

SEVERE DAMAGE

The radiation effects on capacitors are usually an increase in dissipation factor and leakage current and a change in capacitance. Some types, such as plastic and electrolytic, also suffer seal and case damage. Figure 3 shows the various capacitor types and their relative radiation resistance.

B. Semiconductors - Semiconductors are more susceptible to radiation damage and are more widely used than any other part in electronic systems used in space. Figure 4 shows, in a general manner, the radiation resistance of various types of discreet devices. Table II lists the trends of radiation damage for these devices.

1. Diodes

In general, diodes are much more resistant to radiation damage than other semiconductor devices. Thin-base, high speed computer and power diodes show very slight degradation at radiation doses where other semiconductors are unusable. Thick-based diodes and diodes using highly doped material show considerable increase in forward voltage drop with radiation and use of such devices should be avoided.

Zener diodes exhibit slight changes in V_Z with exposure to gamma radiation. The application determines whether or not the change will be significant. Voltage reference zeners are temperature-compensated with a built-in forward biased diode. If the compensating diode is not a hard diode, as mentioned above, the reference voltage could change considerably. Since reference zeners are used in critical applications, this could present a serious design problem. The reference voltage variation can be held almost to that of a conventional zener diode by careful selection of the reference zener, or by making a temperature-compensated reference zener using a conventional zener in series with a high-speed computer diode.

Tunnel diodes are relatively radiation resistant. They exhibit an increase in valley current at large radiation doses and could be useful in application requiring operation after exposure to large amounts of radiation.

FIGURE 3

ESTIMATED EFFECTS OF RADIATION ENVIRONMENT ON CAPACITORS

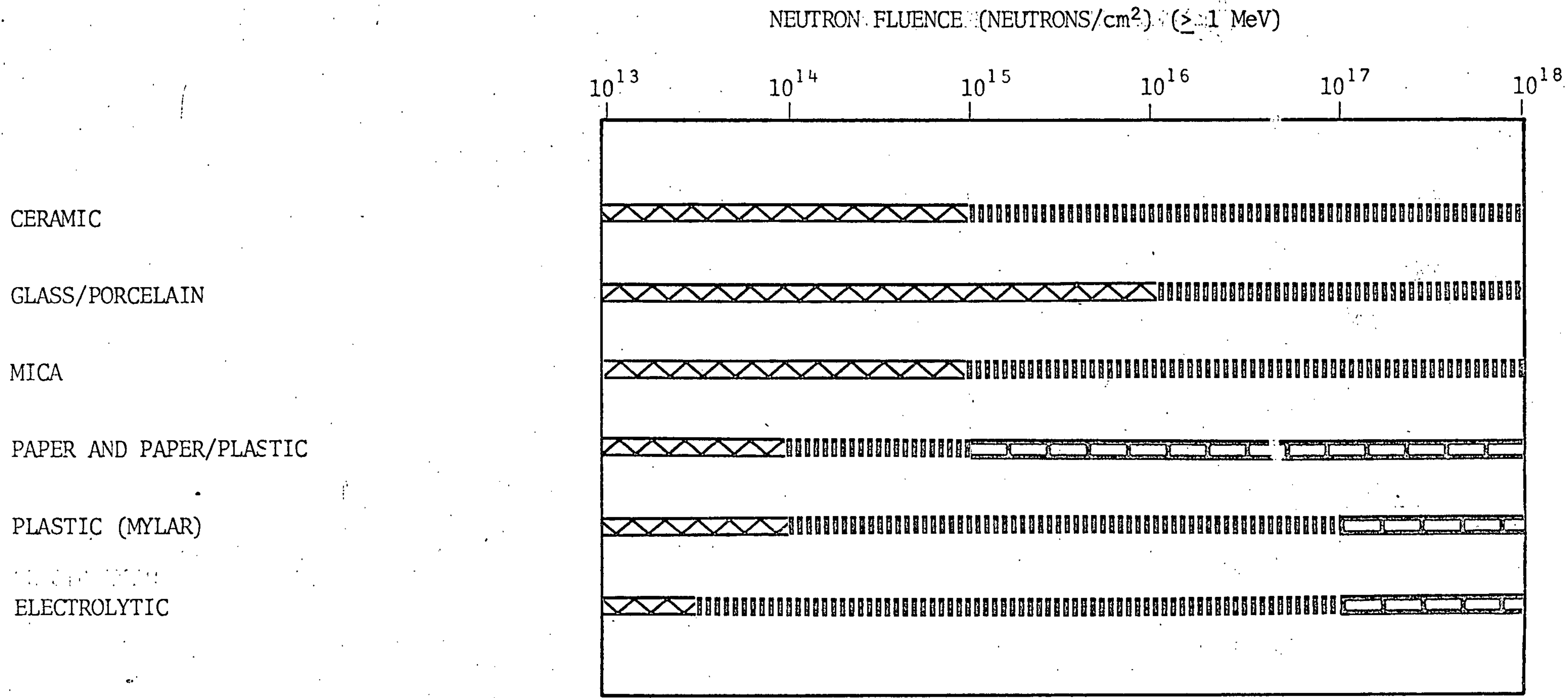


FIGURE 4

USEFUL RANGE FOR SEMICONDUCTORS EXPOSED TO SPACE RADIATION

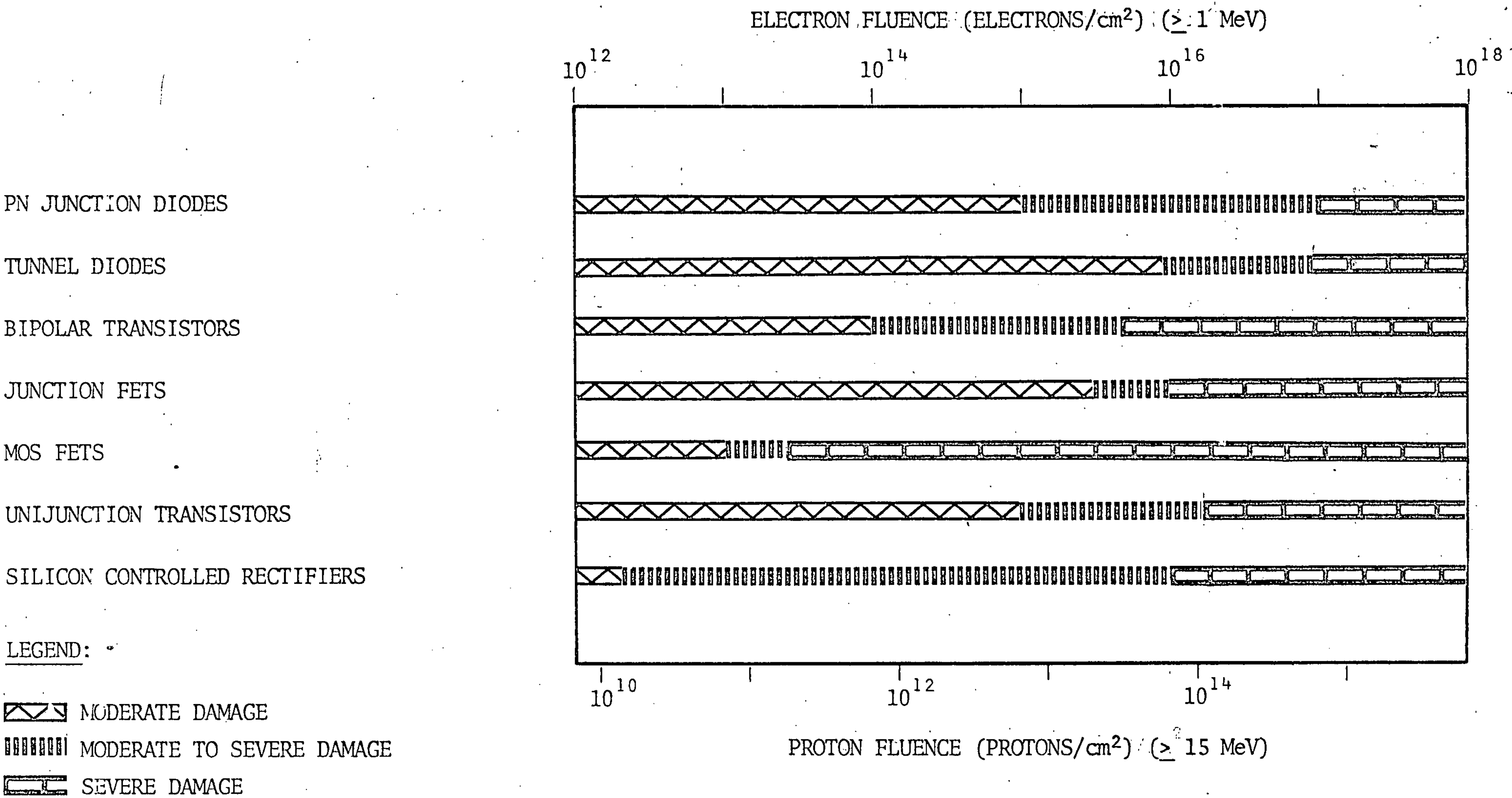


TABLE II

TRENDS OF RADIATION DAMAGE IN SEMICONDUCTOR DEVICES

Device Type	Operating Parameter	Parameter Change With Increasing Fluence	Comments
DIODES, PN Junction	Forward Voltage (V_F) Reverse Breakdown Voltage (V_R) Reverse Leakage Current (I_R) Rise Time (T_R) Storage Time (T_S)	Increase Slight Increase Increase Increase Decrease	Fast diodes with low breakdown voltages are less sensitive to permanent effects because of doping profiles.
DIODES, Tunnel	Peak Current (I_P) Valley Current (I_V)	Slight Decrease Increase	Because of high doping, this device is not affected until relatively high dose levels.
TRANSISTORS, Bipolar	Current gain (h_{FE}) Reverse Leakage Current (I_{co}) Saturation Voltage (V_{CE}) (sat)	Decrease Increase Increase	High-frequency, low-breakdown voltages, characteristics of epitaxial devices, provide better radiation resistance. Some manufacturers advertise radiation-resistant devices incorporating these features.
TRANSISTORS, Junction Field Effect	Transconductance, (g_m) Drain Current with $V_{gs} = 0$ (I_{DSS}) Pinch-Off Voltage (V_p)	Decrease Decrease Decrease	Gain parameter (transconductance) is not appreciably degraded until relatively high radiation dose levels, making the device less sensitive than comparable bipolar devices.
TRANSISTORS, MOS Field Effect	Transconductance, (g_m) Threshold Voltage (V_r) Channel Resistance (r_{DS})	Decrease Increase Increase	Very easily degraded in an ionizing radiation environment via charge storage in the oxide layer.
TRANSISTORS, Unijunction	Interbase Resistance (R_{BB}) Valley Current (I_V) Valley Voltage (V_V) Intrinsic Standoff Ratio	Increase Decrease Increase Remains Same	Interbase resistance very sensitive to neutron-induced permanent radiation damage due to doping concentrations.
SILICON - Controlled	Gate Current for Triggering (I_{GF}) Gate Voltage required for I_{GF} (V_{GF})	Increase Increase	New device design, employing selective current gains in the analog of the device, claim greatly increased radiation tolerance.

2. Bipolar Transistors

Bipolar transistors are among the more sensitive semiconductor devices because their gain is critically dependent on minority carrier lifetime. The lifetime is the period during which the carrier injected from the emitter can exist in the base region before combining with an impurity. When exposed to radiation, the number of impurities in the base material is increased and the carrier lifetime is shortened.

Particle collisions also change the base material's conductivity. Except in very-high-frequency transistors, this effect is much less drastic than the effect on minority carrier lifetime. The two effects are nearly equal and opposite in VHF and fast switching transistors, making them more radiation resistant than other bipolar transistor types.

Gain degradation has been found to be proportional to neutron fluence as expressed by the following equation:

$$h_{FE} = \frac{h_{FE_o}}{1 + h_{FE_o} t_b K \phi}$$

Where:

h_{FE} = Initial current gain.

t_b = Average base transit time

K = Damage factor dependent on device parameters. K is also a function of emitter current, neutron energy, and device temperature.

ϕ = Neutron fluence, n/cm^2.

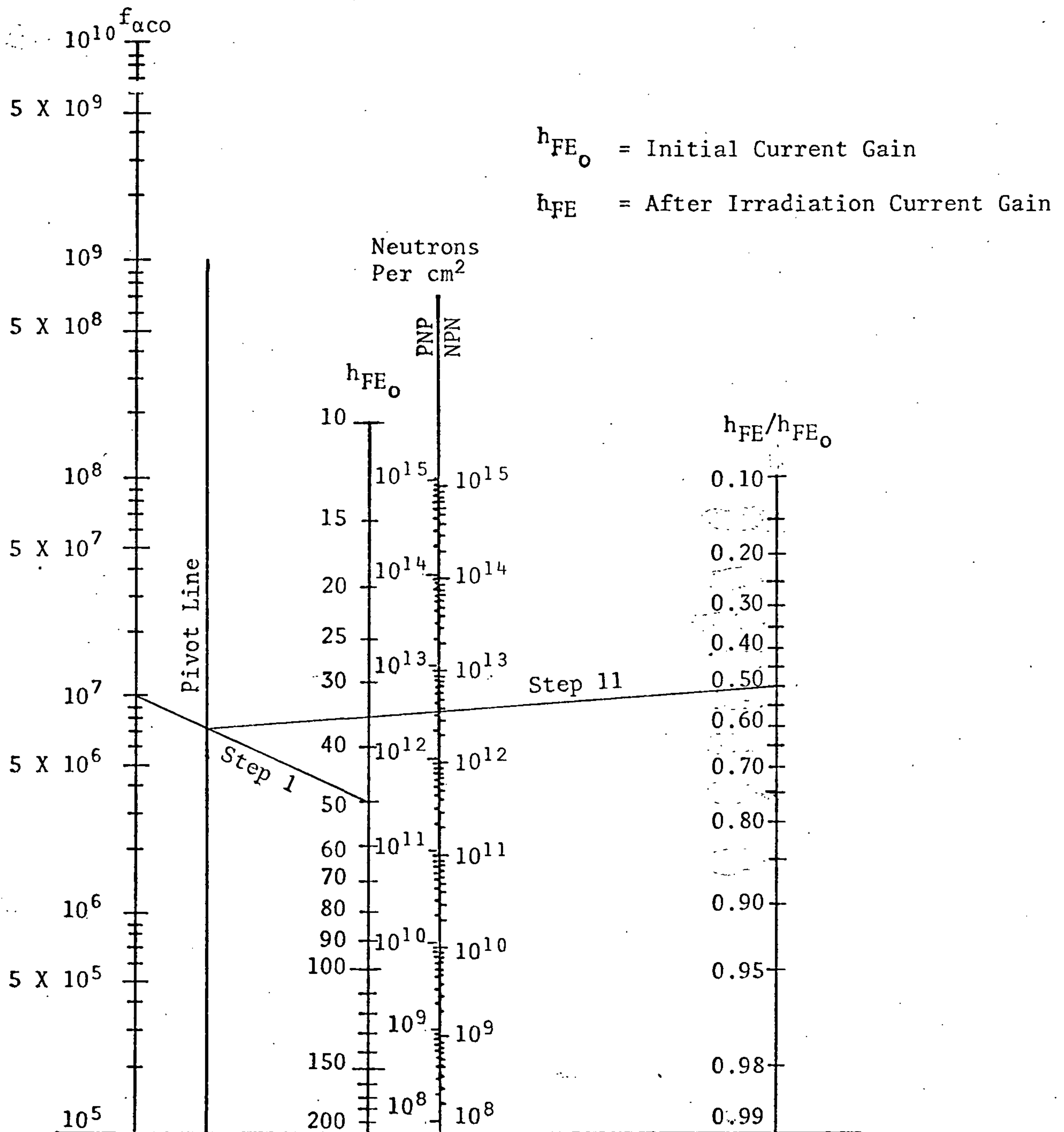
It should be noted that t_b can be related to alpha cutoff frequency ($f_{\alpha CO}$) by the equation;

$$f_{\alpha CO} \simeq \frac{1}{t_b}$$

and $f_{\alpha CO}$ is a parameter more readily available by standard test methods.

Assuming a given fission spectrum, such as that for the RTG's, K can be considered a constant with respect to energy. Further, if it is assumed that the device is operating at 25°C and near its h_{FE} vs. I_C peak, then a first order estimate of neutron damage can be made using the nomograph in Figure 5.

FIGURE 5 - Nomograph For First Order Neutron Damage Estimate for Silicon Transistors. Note: Assumes Fission Spectrum, 25°C, and Device Operating at h_{FE} vs I_C Peak.



To use the nomograph, place a straight edge through the frequency and initial gain of the device as shown in Step 1, then pass the straight edge through the intersection of Step 1, with the pivot line and through the neutron of interest.

Proton effects are somewhat similar to the damage caused by neutrons. The proportionality of gain degradation due to proton fluence can be expressed using the same equation as given for neutrons, with the exception that K should be converted to the equivalent proton damage constant as follows:

For 8-17 MeV protons; $K_{proton} = 33\ K_{neutrons}$

For 100 MeV protons; $K_{proton} = 8\ K_{neutrons}$

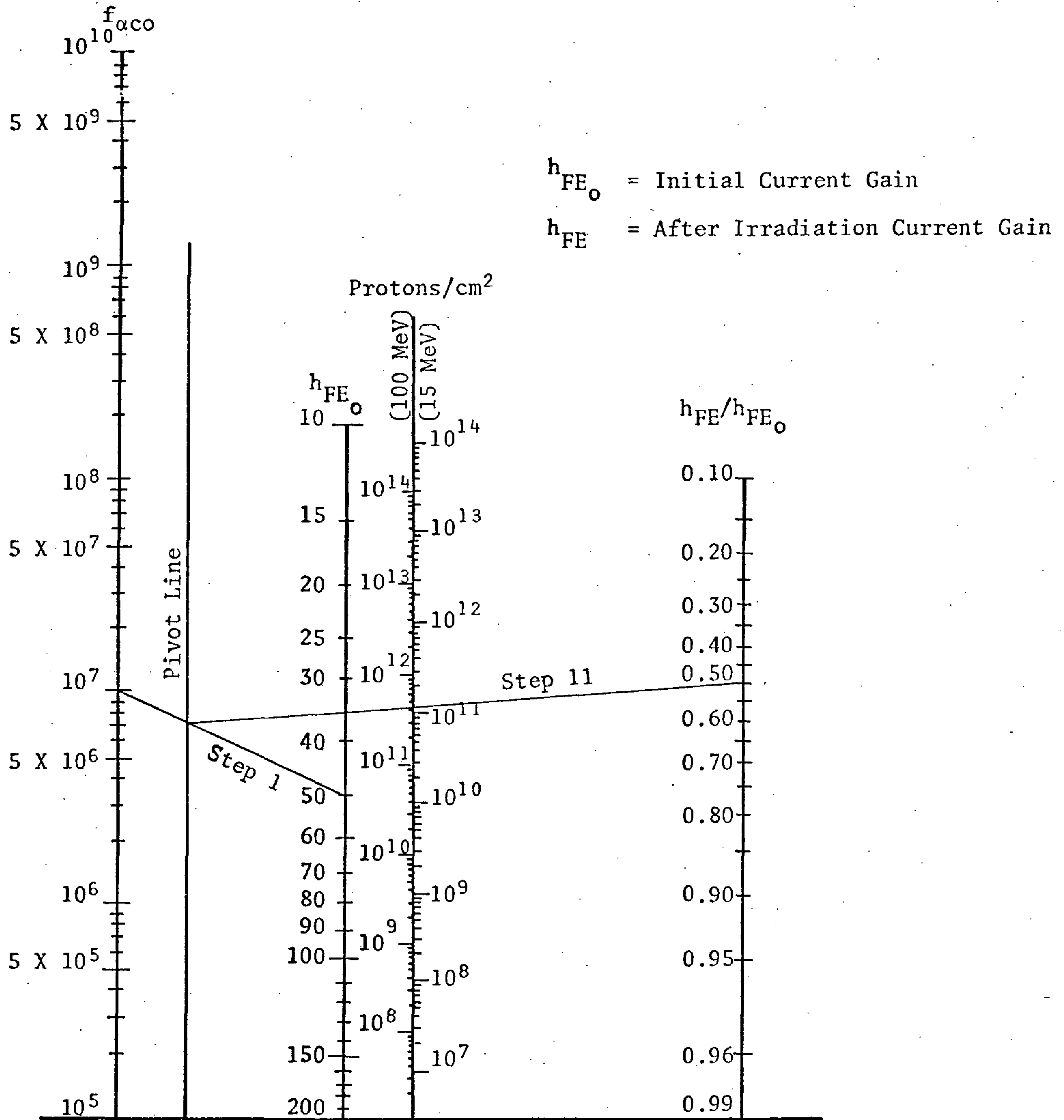
The nomograph in Figure 6 can be used to estimate the displacement damage caused by proton fluence. Again it should be assumed the transistor is operating at 25°C and near its h_{FE} vs I_C peak.

Significant surface damage can also result, in addition to displacement damage, because protons are ionized. Surface damage is not readily predictable because it is dependent on the operating conditions of the transistor during irradiation.

Gamma rays produce both ionization and displacement in bipolar transistors. The displacement damage, however, is low compared to that produced by neutrons and protons. Ionization therefore, is the most significant effect for gamma irradiation levels at or below about 10^6 rads (Si), with the exception of low frequency power devices.

When the surface of the transistor is ionized by gamma rays a positive charge accumulates within and on the surface of the oxide layer. These positive charges cause changes in the surface potential at the silicon surface, thus affecting the surface recombination characterisitcs. If a bias is applied to the transistor during irradiation, the charge accumulation is influenced. For NPN devices, the charge accumulation is influenced in such a way as to degrade h_{FE}. Tests have shown that evacuating the transistor cans greatly reduces the bias dependence of surface ionization damage.

FIGURE 6 - Nomograph For Making First Order Estimate of Proton Damage in Silicon Transistors. Note: Assumes 25°C and Device Operating at h_{FE} vs I_C Peak.



To use the nomograph, place a straight edge through the frequency and initial gain of the device as shown in Step 1, then pass the straight edge through the intersection of Step 1, with the pivot line and through the neutron of interest.

The consensus, based on the collected information, is that the desired radiation resistant device must have the following:

High f_t	f_t is the best indicator of base transit time.
High h_{FE}	For a given transistor family, the higher the h_{FE}, the higher the f_t and the more h_{FE} can change before reaching the circuit design minimum.
Low LV_{CEO}	The higher the starting resistivity, the more significant the change, e.g., increasing the LV_{CEO} from 70 to 100 volts halved the radiation resistance of transistors having identical geometries and diffusions.
Small Geometries	The smaller the geometry and the shallower the device, the smaller the diffusion volume and thus, the less susceptible to transient radiation.
Low V_{CE} (Sat)	The lower saturation voltage essentially requires epilaxial collector construction. The change in resistivity in the collector will make the $V_{CE(sat)}$ increase drastically and possibly cause the transistor to come out of saturation.
Operate at or near the h_{FE} vs. I_C peak.	In general, the low current gain will decrease at a much faster rate than will the gain at h_{FE}, which is quite susceptible to various radiation effects.

Selecting hard devices that can be functional in a radiation environment often requires measures that conflict with standard High Reliability practices. Table III shows the areas where these conflicts exist.

3. Junction Field Effect Transistors - Unfortunately, data on JFET's is very scarce. The available data indicates that they are comparable to high frequency bipolar transistors in radiation resistance. The sensitive parameters for displacement damage are the transconductance (g_m), the drain to source current (I_{DSS}), and the pinch off voltage (Vp). It has been observed that n-channel devices are more resistant to displacement damage than p-channel devices.

The gate to source leakage current (I_{GS}) is the most sensitive parameter for ionization damage, and it usually increases very rapidly above 10^6 rads. In the case of ionization damage, p-channel devices are more resistant than n-channel units.

As stated earlier, the effect of neutron exposure is atomic displacement. Since JFET's are majority carrier devices, the effect of the displacements on device operation is carrier removal in the channel region. This results in a decrease in g_m.

Empirical thresholds have been established for neutron damage in presently available JFET's and it is found that they are able to withstand doses in the order of 10^{13}n/cm^2 with very little degradation but show significant effects at 10^{14}n/cm^2 and are completely destroyed at 10^{15}n/cm^2.

Protons cause both displacement and ionization damage. It is therefore expected that proton fluence will produce changes in g_m, I_{GS}, I_{DSS} and Vp. The data shows that Vp degrades at fluence two orders of magnitude less than g_m or I_{DSS}. The early change in Vp is probably due to the ionization effect. Protons have been observed to cause significant damage to g_m and I_{DSS} in JFETs. Generally, these parameters were degraded 30 percent by a fluence of 10^{12} - 10^{13}P/cm^2 (22 MeV).

TABLE III

Radiation Hardening Versus Reliability

PARAMETER	RADIATION REQUIREMENT	RELIABILITY REQUIREMENT
Voltage	High doping levels limit the effect of irradiation on material resistivity. Selection of the lowest useable voltage rating allows the use of low resistivity, highly doped materials.	Derating factors above operating voltages are recommended for all components in a high reliability system. Operating a device at too low a voltage level may cause marginal propagation times.
Current	Maximum current density is recommended in the radiation environment.	Minimum current, properly derated, is recommended for high reliability systems.
Frequency	The maximum f_t available in a device has been found to correlate well with the device hardness level. Gain-bandwidth products greater than 1 GHz are recommended.	For power devices, a high f_t unit is more likely to be unreliable because it is more vunerable to secondary breakdown.
Masking	Use of the smallest possible geometries is required to minimize device response to both neutron and transient gamma environments. Both area and volume should be minimized.	The smaller the volume and area of device's construction, the greater the chance of a positioning or diffusion depth error. Thus reliability and yield may be reduced.
Base Width	Minimum base width reduces the area in the base which contributes to the forward biasing exhibited in the base emitter junction during transient radiation. Also, the narrow base region will aid post neutron beta, since there is less chance for electron recombination before attaining the collector region.	Base widths on the order of 0.3 microns have been constructed. The danger of punch-through in a base of this magnitude is increased. In addition, the use of thin base regions in power devices increases the threat of secondary breakdown by limiting current fanout.
Internal Base Resistance	At some level of transient gamma radiation, the transient current thru the internal base resistance will develop sufficient voltage to forward bias the base-emitter junction and turn the device on. Low values of resistance will thus increase the radiation failure threshold.	The base doping, which determines the internal base resistance, also affects the doping level of the emitter and collector. In some cases, the lowest value of base resistance may not allow optimum doping for collector and emitter regions.
Bonding	Use of aluminum bonding is recommended.	Full strength of aluminum bonds may be somewhat less than that of other techniques presently used. In addition, ball bonding is not useable. Whether these effects are significant to device reliability remains to be determined.
Materials	Changes in packaging, packaging materials, and bonding may be required.	Existing materials have established reliability records.

The primary effect of gamma radiation and electron radiation is ionization damage. The gate leakage current (I_{GS}) is the parameter most affected by ionization. This is attributed to the build-up of inversion layers on the high resistivity p-type material of the n-channel devices due to charge accumulation in the oxide passivation layer. These inversion layers cause channel formations over the junction, which result in leakage paths. The charge cannot accumulate in the oxide of the p-channel devices due to the low resistivity p-type silicon source and drain and thereby is less effective at inverting the p-channel JFETs. For this reason, p-channel devices are less subject to channel formation. The I_{GS} changes are bias dependent and, if the bias is removed, JFETs show considerable annealing.

Surface effects are not readily predictable, but a general threshold for damage has been observed to be about 10^6 rads (Si). Above 10^6 rads (Si), the leakage currents degrade very rapidly. For applications requiring high input impedance, the threshold should be lowered to about 10^5 rads (Si).

4. Metal Oxide Semiconductor Field Effect Transistors (MOSFET)

Ionization damage is the most important degradation mechanism in MOSFETs. Although displacement damage can be present, the device sensitivity to ionization effects in the oxide makes the displacement effects of only secondary importance.

The parameter most sensitive to radiation in MOSFETs is the gate threshold voltage (V_{GT}). It has been reported that V_{GT} shifts several volts when exposed to 10^4 to 10^5 rads (Si). The exact amount of degradation is a function of applied gate bias during irradiation. The degradation of V_{GT} can be attributed to the accumulation of trapped charge within the oxide insulation layer and/or the introduction of surface states at the oxide silicon interface.

Because the effects of radiation on MOSFETs are almost entirely due to ionization, the important radiation environments are gamma rays, electrons, and protons. Figures 7 through 11 are from a GSFC report and are quite representative of V_{GT} degradation in p-channel MOSFETs due to these three types of radiation.

Figure 7 is a plot of V_{GT} vs gamma dose at three different drain currents; 10 μa, 50 μa and 100 μa. The curves indicate a strong dependence of gate threshold voltage on dose.

Figures 8 and 9 illustrate that the rate of gate threshold change with radiation is influenced by the operating voltage of the gate during exposure. For all remaining curves, the V_{GT} is defined at a drain current of 10 μa.

Figure 10 is representative of the degradation using a 2 MeV electron source. The four curves are the result of biasing the gate at 6.6v, 10 v, 15 v, and 20 v during exposure. Two dependency relationships can be noted. The first is the increase in V_{GT} with dose. These curves are very similar to the Co^{60} data. The second effect is the dependence of damage rate on gate bias during exposure. This is also similar to the Co^{60} data shown in Figure 8.

Figure 11 shows the degradation of V_{GT} as a result of exposure to 22 MeV protons. The V_{GT} increases with dose and there is also a dependence of V_{GT} damage rate on gate bias.

C. Integrated Circuits - Integrated circuits exhibit the same degradation characteristics as bipolar transistors plus changes in resistor value as a result of neutron and proton environments. Ionization is the major effect producing circuit failure. This is because all reverse-biased junctions produce photocurrents that can cause a change in state or overload, or even complete failure.

The amount of degradation due to irradiation of microcircuits depends on the interaction of circuit components and the fabrication technique employed by the manufacturers. Table IV lists these various major fabricating techniques. Semiconductor manufacturers are currently fabricating microcircuits combining the use of almost all the techniques listed.

FIGURE 7

GATE THRESHOLD VOLTAGE vs DOSE AT 3 DIFFERENT DRAIN CURRENTS

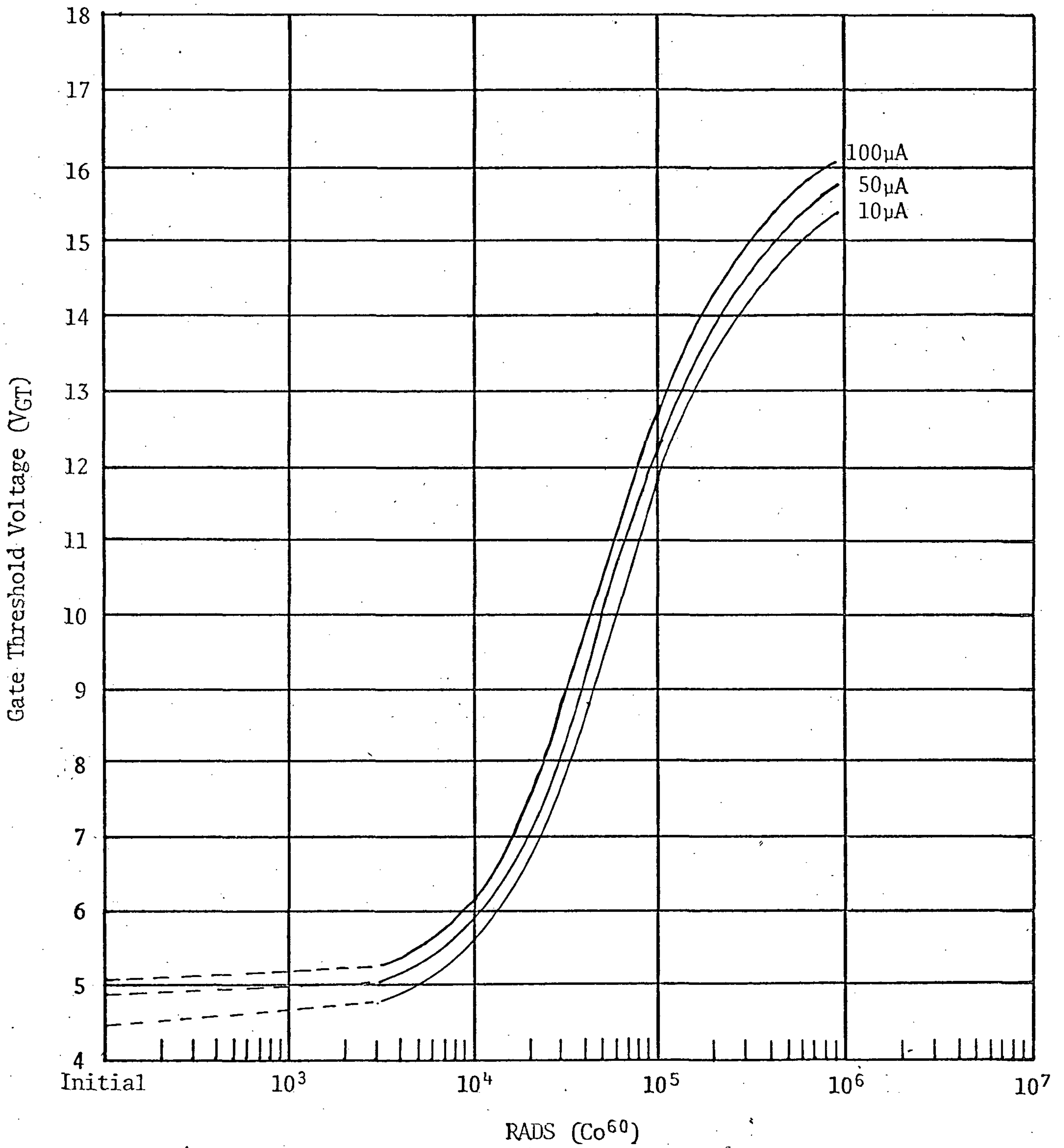


FIGURE 8

GATE THRESHOLD vs DOSE WITH TWO BIASES

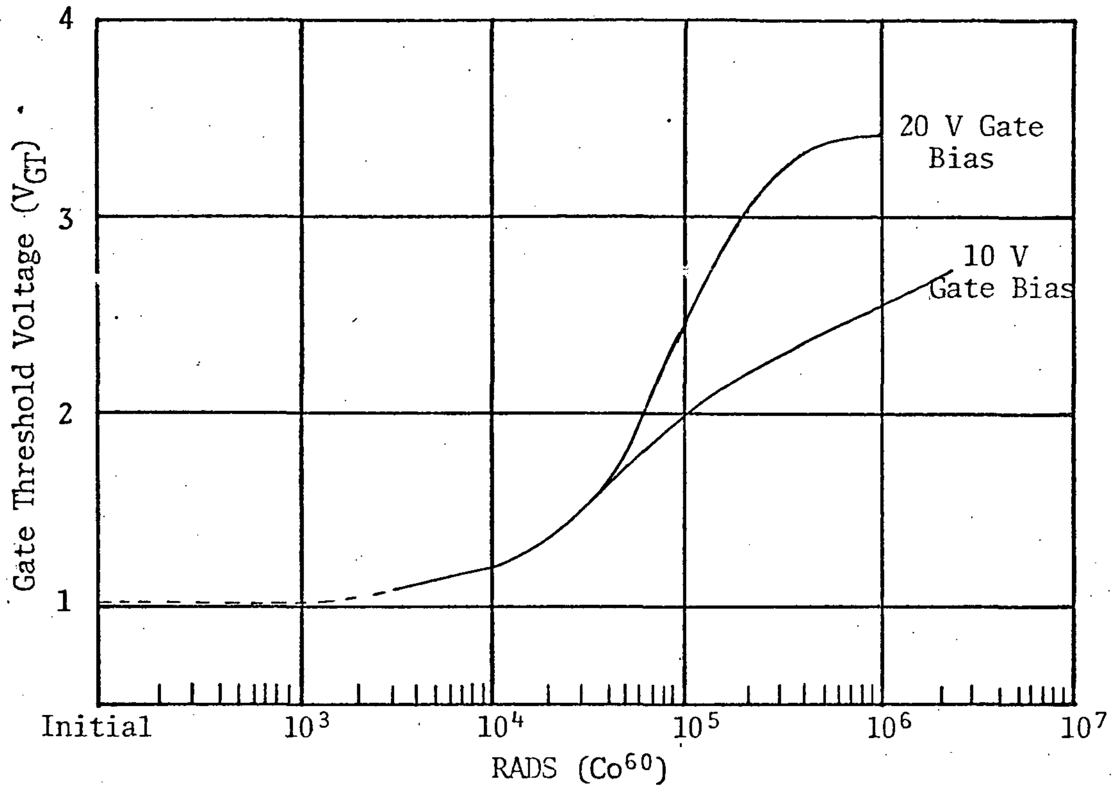


FIGURE 9

GATE THRESHOLD vs DOSE WITH BIAS CHANGE DURING EXPOSURE

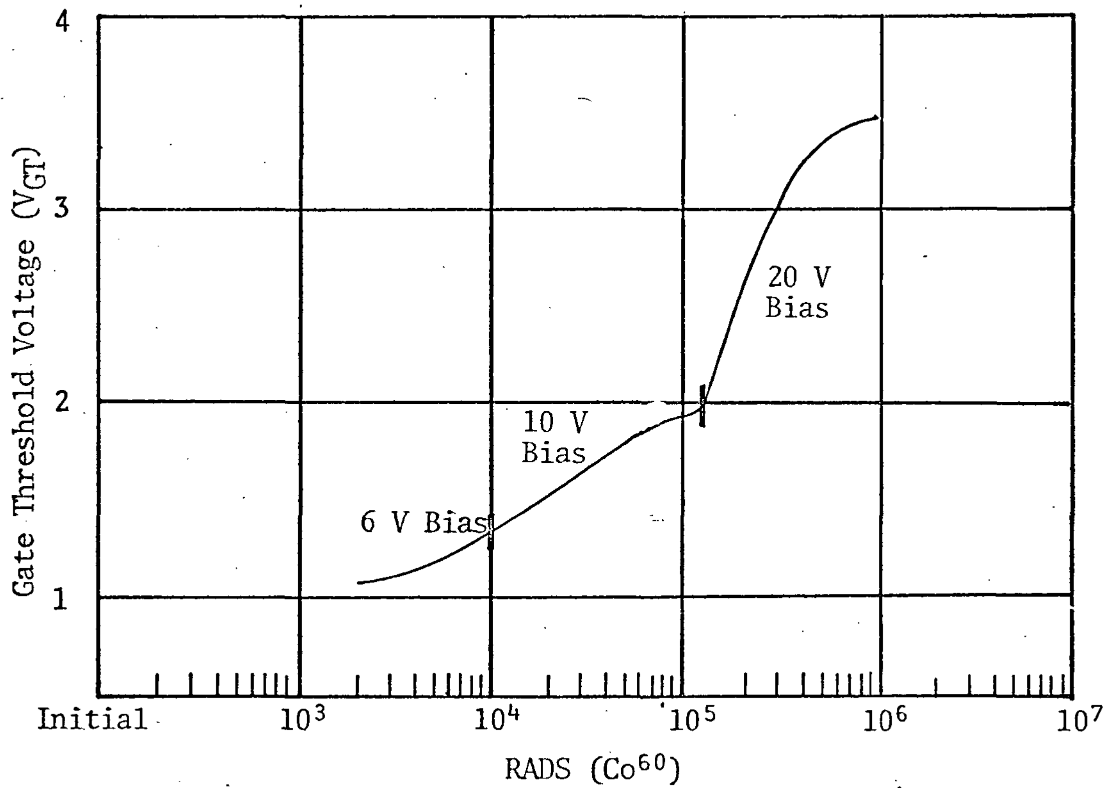


FIGURE 10

TYPICAL NORMALIZED GATE THRESHOLD VOLTAGE vs DOSE WITH GATE BIAS DURING EXPOSURE INDICATED

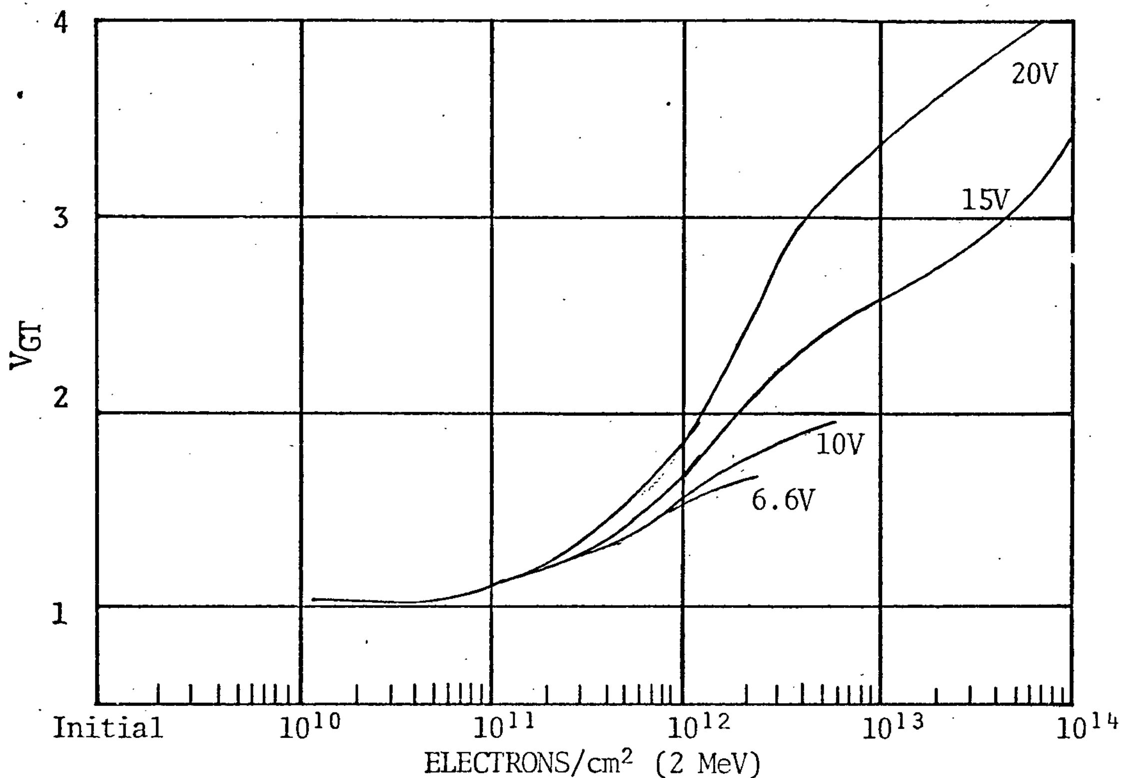


FIGURE 11

TYPICAL NORMALIZED GATE THRESHOLD VOLTAGE vs PROTON DOSE

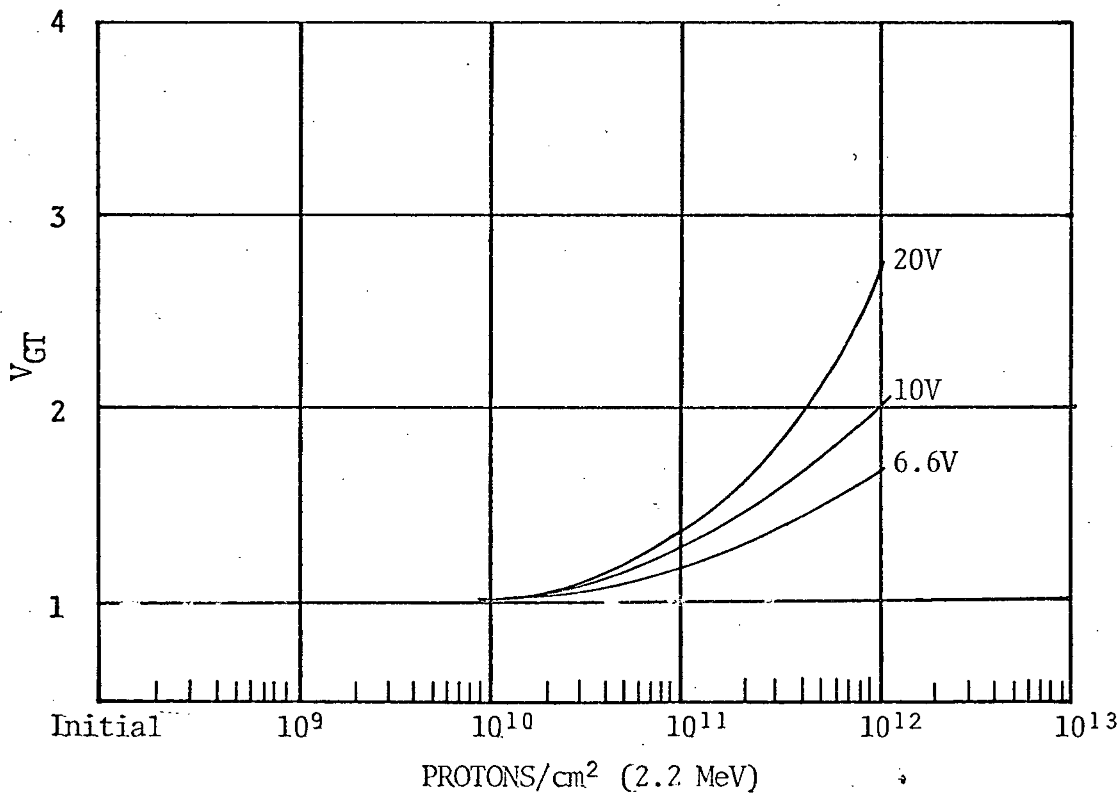


TABLE IV

INTEGRATED CIRCUIT FABRICATION TECHNIQUES

Component Type	Fabrication Techniques	
Transistors	Bipolar NPN and PNP	FET
Isolation	Diffused	Dielectric
Resistors	Diffused	Thin Film
Capacitors	Junction Collector Base/Emitter Base	MOS

Conventional IC's are constructed using diffused isolation, whereas "hardened" IC's use dielectric isolation. It has been found that the dielectric isolation eliminates photocurrents created by transient irradiation. However, it does little to counteract the effects of displacement type radiation (permanent damage). The difference between diffused and thin-film resistors is that thin-film resistors do not change value during neutron irradiation whereas diffused resistors decrease in resistance. For permanent damage conditions, the junction capacitor is best, while for ionizing radiation the MOS-type capacitor is more desirable.

Hardened microcircuits should have the following design characteristics:

- Dielectric isolation between the components in the circuit. This eliminates the primary source of photocurrents, and the occurrence of latch-up is greatly reduced.
- Small geometry transistor structure, shallow diffusion depth and low resistivity materials, which greatly reduce the effects of radiation on the active devices in the circuit.

- Thin-film resistors should be used rather than diffused resistors.
- High frequency; high gain bipolar transistor elements should be used and circuit operation must be relatively insensitive to transistor gain degradation.

Most of the major manufacturers offer various types of hardened circuits using the above techniques. Use of such hardened devices should be considered.

Because of the large number of integrated circuit types now available, it is not practical to list parameter degradation factors for each. Rather, general thresholds for broad circuit categories are presented in Table V.

TABLE V

GENERAL DAMAGE THRESHOLDS

Radiation Type	Circuit Type* (Bipolar Transistors)	General Region for Significant Damage or Circuit Failure
Neutron	Digital	10^{13} to 10^{15} n/cm^2
	Linear	~10^{12} to 10^{14} n/cm^2**
Proton (22 MeV)	Digital	~10^{11} to 10^{13} P/cm^2
	Linear	~10^{10} to 10^{13} P/cm^2**
Gamma (Co-60)	Digital	>10^6 rads
	Linear	10^5 to 10^7 rads (Si)
Electron (3 MeV)	Digital	10^{15} to 10^{17} e/cm^2
	Linear	~10^{13} to 10^{15} e/cm^2*

* There is insufficient data in the literature to specify MOS circuits; however, limited testing has indicated that Digital MOS circuitry can survive 10^6 to 10^7 rad (Si).

** Estimated.

Digital circuits are by nature more radiation resistant than linear circuits. This is because digital circuits are usually composed of high speed switching transistors which are not required to operate in their linear region. The main problem encountered in using digital circuits in a radiation environment is latch-up or a change in memory state. A good design criterion is to limit the fan-out to as low as practical when using the devices in a radiation environment.

Linear circuits, on the other hand, are very dependent on transistor gain and in most cases must operate throughout their linear region. To further complicate matters, differential operational amplifiers require the characteristics of the input transistors to be closely matched. During irradiation these characteristics shift but not always to the same degree in both transistors. This causes a shift in offset voltage giving a false output. Because of susceptibility to damage and drift, linear integrated circuits should be used very cautiously.

When using microcircuits of any kind, it should be remembered that the environment levels at which their parameters become significantly affected are a strong function of the type of environment and the circuit design.

IV. CONCLUSIONS

An analysis of the radiation theshold of the electronic parts used in the Pioneer Spacecraft shows that passive devices and diodes have thresholds sufficiently high to pose no problems to the Jupiter Orbiter mission. On the other hand, transistors and integrated circuits will experience some degradation during the mission. The amount of damage, as stated earlier, is highly dependent on the type of device and the circuit application.

Since transistors and integrated circuits are the parts most likely to degrade during the mission, an estimate was made of the damage threshold of the devices used in Pioneer. The results of the estimate are presented in Tables VI and VII.

Table VI lists the transistors being used and gives their respective damage thresholds. The estimate was made assuming the transistors are operating at their optimum operating point and the dc current gain can degrade 50% before being considered a failure. The exact levels of radiation which will cause degradation are highly dependent upon the circuit application, therefore the levels listed in the table are only a first order approximation and should not be considered as absolute values.

Transistors used in circuits requiring the following characteristics will have the highest degradation and are the most difficult to evaluate.

- Low collector currents.
- High transistor gain.
- Matched transistor gains.
- Low noise levels.

The radiation damage threshold of devices used in this manner can only be assessed by actual test.

On the other hand, transistors used in the following applications are inherently hard:

- Switching circuits employing high frequency transistors.
- Transistors used in circuits operating at or near their h_{FE} vs I_C peak.
- Circuits using degenerative feed-back so circuit functions are not dependent upon transistor gain.
- Circuits using high gain transistors in low gain applications.

Transistors used in the above categories will be in line with the threshold listed in the table.

Table VII lists the approximate damage thresholds of the integrated circuits used in Pioneer. The values again are only estimates taken from data gathered by various investigators working in the radiation effects field.

It can be seen from the thresholds listed in the two tables, that there are five transistors and three ICs that may present a hazard to the success of the mission. The four Germanium transistors used in the power subsystem and the Unijunction transistor used in the CDU are types of devices most researchers do not recommend using in a radiation environment. The ICs that may cause problems are the three MOSFET Gates used in the DTU. The use of these devices should be investigated very closely to insure that their use will not degrade the mission.

PIONEER USAGE CODE FOR TABLES VI AND VII

1. Communications
   a. Transmitter Driver
   b. Receiver Number 1
   c. Receiver Number 2
   d. Con-Scan S/P

2. Antenna

3. Data Handling
   a. DTU
   b. DSU
   c. DDU

4. Attitude Control
   a. CEA
   b. SRA

5. Electronic Distribution
   a. CDU

6. Power
   a. Battery
   b. PCU
   c. Inverter
   d. Central TRF

TABLE VI

ESTIMATE OF DAMAGE THRESHOLDS OF PIONEER TRANSISTORS

PT4-	DEVICE	TYPE	f_t MHz	h_{FEo}	DAMAGE THRESHOLD (h_{FE}/h_{FEo} = 50%) NEUTRONS/cm²	PROTONS/cm² 15 MeV	PROTONS/cm² 100 MeV	ELECTRONS cm² (≥ 1 MeV)	GAMMA RADS	PIONEER USAGE	NOTES
7157	2N2920	Dual NPN	60	30	3.5×10^{13}	1×10^{12}	4×10^{12}		Note 6	1-ab, 3-ac, 4-b, 5-a, 6-bcd	1
7158	2N2369A	NPN	500	40	1.2×10^{14}	6×10^{12}	2.5×10^{13}		Note 6	1-a	
7159	2N3838	Comp.Pair	200	100	3×10^{13}	1×10^{12}	4×10^{12}		Note 6	5-a	2
7162	2N2484	NPN	60	175	4×10^{12}	4×10^{11}	1.1×10^{11}		Note 6	1-bc, 3-ab, 4-b, 5-a, 6-b	
7163	2N2222A	NPN	300	100	5×10^{13}	1.5×10^{12}	5.5×10^{12}		Note 6	1-abc, 4-ab, 5-a, 6-abc	
7164	2N2907	PNP	200	100	3×10^{13}	1×10^{12}	4×10^{12}		Note 6	1-abc, 3-a, 4-a, 6-abcd	
7165	2N2851	NPN	30	40	1.5×10^{13}	4×10^{11}	1.5×10^{12}		Note 6	6-abcd	
7169	2N2857	NPN	1600	50	5×10^{14}	1.2×10^{13}	5×10^{13}		Note 6	1-bc	
7170	2N918	NPN	600	30	3.4×10^{14}	1×10^{13}	4×10^{13}		Note 6	1-abc	
7174	2N3137	NPN	800	30	5×10^{14}	1.5×10^{13}	5.5×10^{13}		Note 6	1-a	
7178	2N3501J	Power NPN	150	100	1.5×10^{13}	7.5×10^{11}	3×10^{12}		Note 6	4-a, 6-cd	
7179	2N2912	Power PNP (Ge)	10	670	1.5×10^{12}				Note 6	6-a	3
7180	GA3262	PNP (Ge)	5	50	1×10^{13}				Note 6	6-a	3
7188	K5001-3	NPN	450	20	4×10^{14}	1.1×10^{13}	4.5×10^{13}		Note 6	1-bc	
7206	2N4025	Diff.Pair PNP	50	250	3×10^{11}	9×10^{9}	3.5×10^{10}		Note 6	1-d, 3-a, 4-b	1

TABLE VI

ESTIMATE OF DAMAGE THRESHOLDS OF PIONEER TRANSISTORS
(CONTD.)

PT4-	DEVICE	TYPE	f_t MHz	h_{FEo}	DAMAGE THRESHOLD (h_{FE}/h_{FEo} = 50%)					PIONEER USAGE	NOTES
					NEUTRONS/ cm^2	PROTONS/cm^2		ELECTRONS cm^2 ($\geq$ 1 MeV)	GAMMA RADS		
						15 MeV	100 MeV				
7207	2N3954	N-Channel J FET	-	-	1×10^{13}	1×10^{12}		1×10^{13}	1×10^{6}	1-bc, 3-c	4
7208	2N4041	NPN	300	60	8×10^{13}	2.5×10^{12}	9×10^{12}		Note 6	3-b	
7213	SWB2895	Dual NPN	500	40	2×10^{14}	7×10^{12}	2.8×10^{13}		Note 6	3-b	
7216	SSC4309	Dual NPN	250	100	4×10^{13}	1.1×10^{12}	5×10^{12}		Note 6	3-ab, 5-a	
7217	SSB2528	Dual PNP	200	100	3×10^{13}	1×10^{12}	4×10^{12}		Note 6	3-abc, 5-a	
7218	2N3964	PNP	50	250	2.8×10^{12}	1×10^{10}	4×10^{10}		Note 6	1-bc	
7229	244835	UNJ	-	-	1×10^{12}	5×10^{10}	1×10^{11}	1×10^{15}	5×10^{5}	5-a (3 used)	5
7271	2N5153	PNP	70	70	1.6×10^{13}	6×10^{11}	2×10^{12}		Note 6	6-b	
7272	2N5154	NPN	70	70	1.8×10^{13}	6×10^{11}	2×10^{12}		Note 6	5-a	
7281	V415,7	NPN	4000	30	$>10^{15}$	7×10^{13}	$>10^{14}$		Note 6	1-ab	
7290	2N5438	PNP (Ge)	.350	40	2×10^{12}	5×10^{8}			Note 6	6-bc	3
7291	2N5004	NPN Power	70	70	1.8×10^{13}	6×10^{11}	2×10^{12}		Note 6	6-bd	
7292	2N3599	NPN Power	30	50	1×10^{13}	3.5×10^{11}	1.5×10^{12}		Note 6	6-b	
7293	2N5005	PNP Power	70	70	1.6×10^{13}	6×10^{11}	2×10^{12}		Note 6	6-d	4
7296	2N5520 2N5515	P-Channel J FET	-	-	1×10^{13}	1×10^{12}		1×10^{13}	1×10^{6}	4-b	

TABLE VI NOTES

1. This is an estimate of damage to each transistor in the package and does not take into account the mismatch which may occur due to unequal degradation.

2. Mismatch will occur because of the different degradation factors of NPN and PNP transistors.

3. Germanium transistors are not recommended for use in a nuclear environment.

4. Same as one above, also degradation factors of FETs are highly dependent on bias conditions.

5. Unijunction transistors are not recommended for use in a nuclear environment.

6. Damage due to Gamma is very dependent on bias conditions, however, tests show they should withstand about 10^6 rads (Si).

TABLE VII

ESTIMATE OF DAMAGE THRESHOLD OF PIONEER INTEGRATED CIRCUITS

PT4-	DEVICE	TYPE	DAMAGE THRESHOLD					PIONEER USAGE	NOTES
			NEUTRONS/ cm^2	PROTONS/cm^2		ELECTRONS/ cm^2 ($\geq$ 1 MeV)	GAMMA (RADS) (Si)		
				15 MeV	100 MeV				
4048	SE424J	RCTL F.F.	1×10^{14}			1×10^{15}		3-a (19)	
4059	UD4037	Buffer Amp	1×10^{13}	5×10^{11}		1×10^{14}	1×10^{6}	1-d (2)	
4060	UD4036	Ladder Switch	1×10^{13}	5×10^{11}		1×10^{14}	1×10^{6}	1-d (2)	
4085	Special	Oscillator						3-a (2)	
4088	LPDTL9041	DTL Gates				8×10^{15}		5-a (28)	1
4132	SN54L04	TTL Inverter	3×10^{14}	1×10^{12}		1×10^{6}		1-d,3-abc,4-a,5-a (196)	
4133	SN54L10	TTL Gates	3×10^{14}	1×10^{12}		1.8×10^{16}		1-d,3-abc,4-a,5-a (187)	2
4134	SN54L20	TTL Gates	3×10^{14}	1×10^{12}		1.8×10^{16}		1-d,3-abc,4-a,5-a (78)	2
4135	SN54L30	TTL Gates	3×10^{14}	1×10^{12}		1.8×10^{16}		1-d,3-abc,4-a,5-a (89)	2
4136	SN54L54	TTL and/or Invert Gates	3×10^{14}	1×10^{12}		1.8×10^{16}		1-d (5)	2
4137	SN54L72	TTL, JK F.F.	3×10^{13}	1×10^{12}		1×10^{16}		1-d,4-a,5-a (29)	
4138	SN54L78	TTL, JK F.F.	3×10^{13}	1×10^{12}		1×10^{16}		1-d,3-b,4-a (10)	
4141	SN54L95	TTL/MSI Resistor						1-d,3-a,4-a,5-a (87)	
4142	SN54L93	TTL/MSI Shift Reg.						3-a,4-a,5-a (82)	
4143	SN54L91	TTL/MSI Shift Reg.						4-a,5-a (6)	
4144	SN54L00	TTL Gates	3×10^{14}			1.8×10^{16}		1-d,3-abc,4-a,5-a (309)	

TABLE VII

ESTIMATE OF DAMAGE THRESHOLD OF PIONEER INTEGRATED CIRCUITS (CONTD.)

PT4-	DEVICE	TYPE	DAMAGE THRESHOLD					PIONEER USAGE	NOTES
			NEUTRONS/ cm^2	PROTONS/ cm^2		ELECTRONS/ cm^2 ($\geq$ 1 MeV)	GAMMA (RADS) (Si)		
				15 MeV	100 MeV				
4145	NH0008	Hybrid Driver	1×10^{14}	1×10^{12}		1×10^{14}	1×10^{7}	4-a (18)	
4146	G1186	MOSFET Gates				1×10^{12}		3-a (65)	
4147	D123LG	Driver	1×10^{13}	5×10^{11}		1×10^{14}	1×10^{6}	3-a (9)	
4148	G119L	MOSFET Gates				1×10^{12}		3-a (17)	
4149	G124L	MOSFET Gates				1×10^{12}		3-a (21)	
4150	SN54L86	TTL Gates	3×10^{14}	1×10^{12}		1×10^{16}	1×10^{7}	1-d, 3-a (12)	
4151	SN54L71	TTL FF	3×10^{13}	1×10^{12}		1×10^{16}	1×10^{7}	3-bc (15)	
4152	SN54L51	TTL Gates	3×10^{14}	1×10^{12}		1×10^{16}	1×10^{7}	1-d, 3-ab (21)	
4153	SN54L73	TTL FF	3×10^{13}	1×10^{12}		1×10^{16}	1×10^{7}	1-d,3-abc,4-a,5-a (302)	
4154	SN5404	TTL Inverter	3×10^{14}	1×10^{12}		1×10^{16}	1×10^{7}	1-d,3-ac,5-a (16)	
5027	UA723	Diff Comp.	1×10^{12}	5×10^{11}		1×10^{14}	1×10^{5}	6-cd (42)	
5032	MC1590G	RF Amp.	1×10^{14}	1×10^{12}		1×10^{15}	1×10^{6}	1-bc (4)	
5033	UA735	Op. Amp.	1×10^{13}	5×10^{11}		1×10^{14}	1×10^{6}	1-bcd,3-ac,6-b (45)	
5034	MC1711F	Dual V. Comparator	1×10^{13}	5×10^{11}		1×10^{14}	1×10^{6}	3-b (12)	
5035	LM101A	Op. Amp.	3×10^{13}	5×10^{11}		1×10^{14}	5×10^{4}	1-d, 4-b (5)	

TABLE VII NOTES

1. Fan-out degrades to about 30% of pre-irradiation fan-out.

2. Fan-out degrades to about 50% of pre-irradiation fan-out.

3. Differential Amplifiers depend on matched transistors in the input circuit. Some mismatch will occur at levels slightly lower than those listed.

BIBLIOGRAPHY

Alvi, S. M. S., and Chechile, R. A., "Designing and Assuring Neutron Radiation Hardness in Integrated Circuits," IDEP Report Number 347.65.00.00-C1-CR3, October 1968.

Crittenden, J. R., "Basic Effects of Nuclear Radiation," Electronic Industries, January 1962.

Finnell, Joseph T., Jr., and Karpowich, Fred W., "Skipping the Hard Part of Radiation Hardening," Electronics, March 4, 1968.

Gardner, Dr. Leonard B., "Selecting Electronic Components for Space Radiation," Electromechanical Design, January 1963.

Heaton, E. C., Rotolante, R. A., and Fitch, S. H., "Radiation Hardness Assurance for Electronic Systems," IDEP Report No. 347.65.00.00-G1-18, 20 July 1970.

Hess, Wilmot N., "Earth's Radiation Environment," Space/Aeronautics, November 1964.

Hood, J. A., "Degradation of NPN Silicon Planar Transistors With Bombardment by High-Energy Neutrons," SCP and Solid State Technology, January 1965.

Hughes, Harold L., and Giroux, Ronald R., "Space Radiation Affects MOSFET's," Electronics, December 28, 1964.

Kaufman, Alvin B., "Field Effect Transistors Under Nuclear Radiation," Electronic Industries, March 1964.

Kircher, John F., and Bowman, Richard E., Effects of Radiation on Materials and Components, Reinhold Publishing Company, New York, 1964.

Klass, Phillip J., "Radiation-Hardened Avionics Gain Interest," Aviation Week & Space Technology, September 8, 1969.

Lowenhar, Herman, "Hardened Electronics," Space/Aeronautics, August 1969.

Messenger, G. C., "Radiation Hardening of Electronic Systems," IDEP Report No. 347.65.00.00-C1-09, 1 July 1969.

Olesen, Henning H. Lind, "Designing Against Space Radiation," Electronics, December 28, 1964 and January 11, 1965.

Olesen, Henning Lind, Radiation Effects on Electronic Systems, Plenum Press, New York, 1966.

Schmitz, Gary E., "The Facts and Failures of Radiation Hard Device Specs," Evaluation Engineering, September/October 1969.

Schmitz, Gary E., "Selection of Reliable Radiation Hard Components," Proceedings from the 1969 Annual Symposium on Reliability, January 21-23, 1969.

Wannemacher, Harry E., "Gamma, Electron, and Proton Radiation Exposures of P-Channel, Enhancement, Metal Oxide Semiconductor, Field Effect Transistors," Goddard Space Flight Center, August 1965.

"Hardened IC's for Radiation Environments," Application Report 100, Radiation, Inc., August 1969.

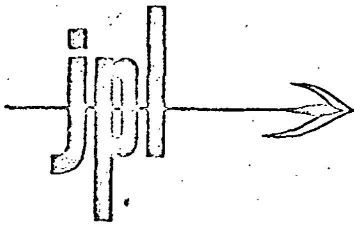
"Literature Search and Radiation Study on Electronic Parts," Report No. D2-126203-3, by the Boeing Company for JPL, May 1970

"Report on Radiation Test Series No. 15," IDEP Report No. 347.65.00.00-S6-13, October 21, 1968.

"TOPS Program," JPL Newsletters (1970 and 1971 issues).

"TREE Handbook," Battelle Memorial Institute, Columbus, Ohio, 1966.

APPENDIX



ELECTRONIC PARTS ENGINEERING

NEWSLETTER

JET PROPULSION LABORATORY, 4800 Oak Grove Drive, Padadena, Ca. 91103

ISSUE 13 MAY 1971

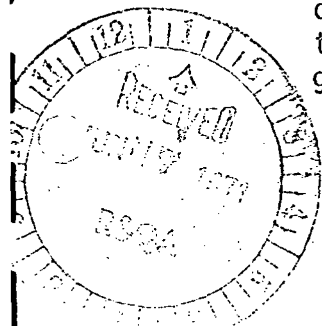
This newsletter is published monthly by Section 354. It is intended to provide electronic parts engineering information for JPL internal use. If you have any comments regarding this newsletter, please direct them to the editor - K. Martin, X3676.

PARTS INFORMATION PROGRAM (PIP)

PIP Sheet No. 19 discusses the results of qualification testing General Electric 3N86 silicon controlled switch. PIP Sheet No. 20 discusses qualification testing of high speed IN3892 rectifier diodes manufactured by Dickson Electronics and Motorola. Copies of these PIP's may be obtained by contacting J. Netzley, X5751.

SPECIAL RADIATION TEST

As part of the Section 354 special radiation tests in support of the TOPS program, twenty (20) each Motorola 2N2907A and twenty (20) each Motorola 2N930 transistors were exposed to Co-60 gamma radiation at a rate of approximately 5×10^5 rads/hr. Ten (10) of each device type were irradiated back biased (V_{CB}) and ten (10) each were irradiated nonbiased (open leads). The purpose was to evaluate bias conditions during irradiation in support of future test programs. At the TOPS test level of 10^5 rads, leakage current (ICBO) and saturation voltage $V_{CE}(sat)$ had increased but remained within the JPL screening specification limit for both device types. At 10^6 rads all of the 2N2907A back biased devices had exceeded the 10 nA limit. The highest device measured was 54 nA. The other devices remained within specification limits. Figure 1 compares the percent degradation of the back biased versus nonbiased 2N2907A groups. Figure 2 compares the 2N930 groups. Only the worst case


RECEIVED

(lowest) collector current gain (H_{FE}) measurements are outlined. The data presented here confirms previous test data indicating that back bias is the more degrading condition during irradiation. Additional details may be obtained by contacting C. Hunte, X5591, and requesting IOM A-27-71.

MAY PART FAILURES

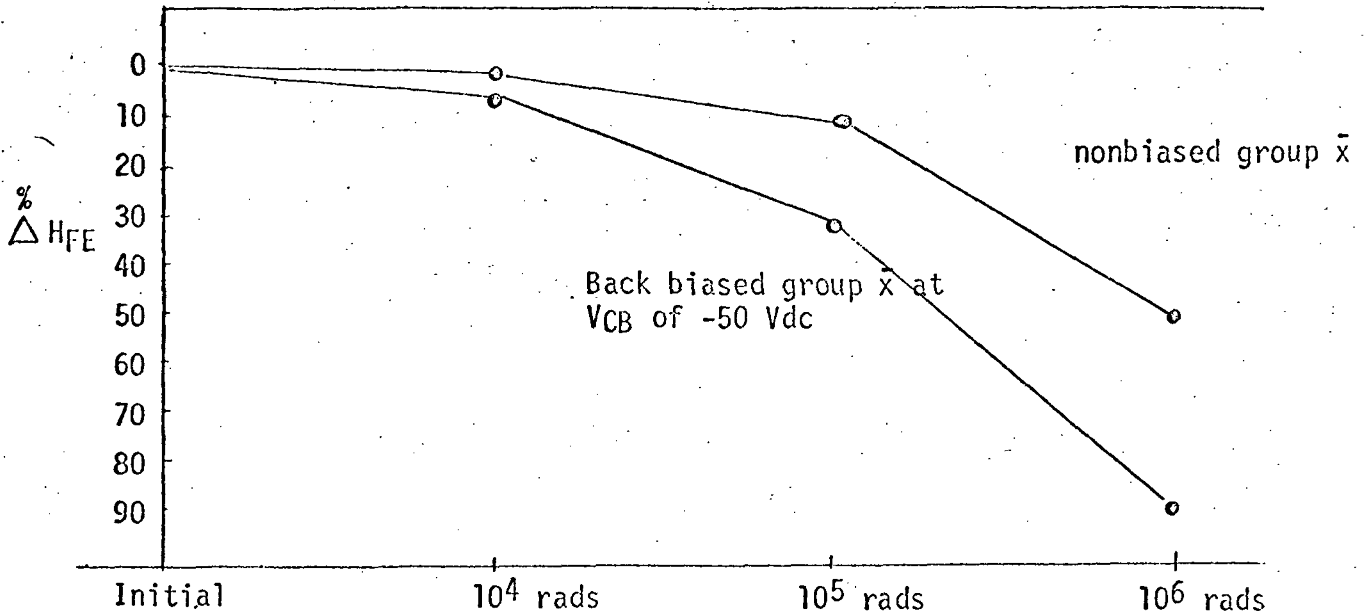
The following failures have been analyzed. Additional details may be obtained by requesting the desired log number from S. Hoyt, X5591.

Electronic Arrays, Type EA1204, 256 bit dynamic shift registers, Log 1352 - Five devices were exposed to 10^5 rads gamma followed by electron irradiation. During electron irradiation, the devices became nonoperational at approximately 6 x 10^{12} e/cm^2. The failures were attributed to the radiation environments.
TOPS Radiation Test.

National, Type SM54L00F1-1S and SM54L73F1-1S IC's, Log 1370 - Both devices in the same circuit were reported as failing under certain operating conditions. Investigation revealed that the problem was related to improper device application. The failure report discusses the application problem in detail.
Pioneer VH Magnetometer.

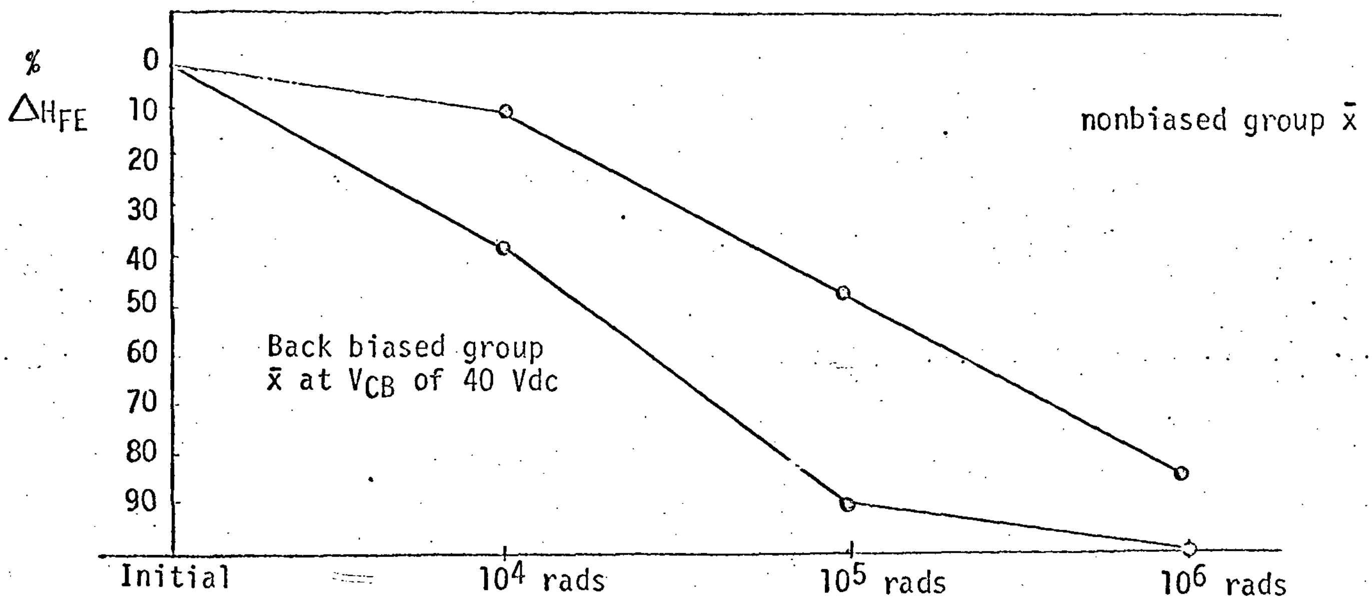
JFD Electronics Co., Type UY03471J, 470 pf. 300 Vdc fixed ceramic capacitor, Log 1374 - An entire lot of sixty (60) capacitors failed JPL screening visual inspection due to cracks in the glass outer encapsulant material. The problem was attributed to manufacturing defects.
Nimbus E Mixer Preamp Assembly.

Robert M. Hadley, Inc., Type 17046 transformer, Log 1381 - The reported short between leads 2 and 4 was verified. Failure was due to excessive solder internally bridging the two terminals.
MVM'73 TV.



Degradation of Group mean H_{FE} at 1.0 mA versus Co-60 gamma dose for 2N2907A devices

FIGURE 1



Degradation of group mean H_{FE} at 10 uA versus Co-60 gamma dose for 2N930 devices.

FIGURE 2

S/N 5350: Examination revealed fair workmanship with well formed bonds and no obvious defects.

Contact: R. Piety, X2298.

TOPS RADIATION TESTING

The TOPS microelectronics committee, considering projected Grand Tour requirements, has selected the following ten part types for the TOPS radiation program described in the September Newsletter:

Manufacturer	Type	Function
Texas Instrument	SN54L00T	Quad, 2 Input NAND Gate
" "	RSN54L00T(Hardened)	Quad, 2 Input NAND Gate
Solitron	2N2658	NPN Power Transistor
Texas Instrument	TIXL103	Optically Coupled Isolator
" "	2N2907A	PNP Transistor
" "	2N2222A	NPN Transistor
" "	MSX147	NPN Microwave Transistor
National Semiconductor	NH0001AF	Operational Amplifier
Microwave Semiconductor	MSC3005	NPN Microwave Power Transistor
Electronic Arrays Inc.	EA1204	256 Bit Shift Register

Contact: K. Martin, X3676.

OCTOBER PART FAILURES

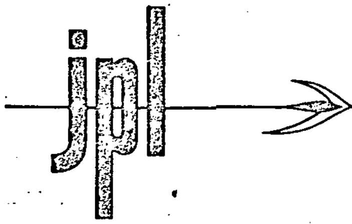
The following failures have been analyzed. Additional details may be obtained by requesting the desired report by log number from S. Hoyt, X5591.

Texas Instruments SN54L73T, IC, Log 1228 - The emitter input from pin 1 clock was found to be open.

National DM76L73F, IC, Log 1252 - The device failed to stay in an "0" state following a clear pulse.

Motorola MC1710G, IC, Log 1233 - The gain was erratic at normal room temperature operation.

US Capacitor Corp. Type 2021-004, Filter, Log 1223 - Shorted inductance.



ELECTRONIC PARTS ENGINEERING

NEWSLETTER

R&QA BRANCH ROUTING
DeMuth, F.
Asch, H.
Besbow, S.
Convertino, R.
Mulkern, J.
File: PERS - file

Jet Propulsion Laboratory 4800 Oak Grove Drive, Pasadena, Calif. 91103

ISSUE 9 JANUARY 1971

This newsletter is published monthly by Section 354. It is intended to provide electronic parts engineering information for JPL internal use. If you have any comments regarding this newsletter, please direct them to the editor - K. Martin, X3676.

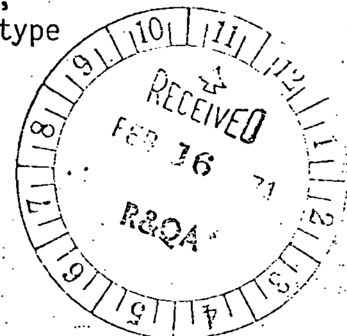
PARTS INFORMATION PROGRAM (PIP)

Two PIP sheets were released during January. Copies are available by contacting J. Netzley, X5751 and specifying the PIP number.

- PIP No. 16 specifies the new reliability classifications for parts previously listed with a "T" rating (undertest) in PD610-12A, Mariner Mars 1971 Electronic Parts Design Control List.
- PIP No. 17 outlines problems experienced in the handling and installation of heat sensitive miniature chip capacitors including methods to prevent part damage.

TOPS RADIATION TEST PROGRESS (Ref. Sept., Oct. 1970 Newsletter)

Ten each Texas Instruments (TI) SN54L00T and ten each RSN54L00T (hardened) quadruple two input NAND gates, and five each Electronic Arrays, Inc. (EA) EA1204, 256 bit dynamic shift registers were exposed to 10^5 rads of gamma rays from the Section 342 Co-60 source. The TI devices were quiescent (2 ea.), pulsed (3 ea.), and biased (5ea.), during radiation exposure. The parameter of interest was the output voltage low state (V_{OL}). The SN54 device V_{OL} increased an average of six millivolts (mv). The RSN54 (hardened) device increased an average of 2 mv. The magnitude of the increases are not considered of engineering significance, although the RSN54 device appeared harder to this level and type of radiation.



The EA1204 devices were all operated (pulsed at 50 kHz) during radiation exposure. During and upon completion of exposure, the output pulse level and shape remained stable for all devices. The measurement data are still being analyzed.

The devices are next scheduled to be exposed to a fluence of 1.4×10^{13} electrons/cm^2 from the Section 342 Dynamitron. For additional details contact K. Martin, X3676.

JANUARY PART FAILURES

The following failures have been analyzed. Additional details may be obtained by requesting the desired log number from S. Hoyt, X5591.

Texas Instruments, Type SNC54L20T, IC, Log 1302 - The device failed due to an open metallization stripe at a point where it passed over an oxide step.

National, Type DM75L72F, IC, Log 1306 - The device failed due to a manufacturing error in an emitter window cut. In addition, serious metallization etching problems were located (see Figures 1 and 2).

National, Type LM105 (2 each), IC, S/N AA84 and AA67, Log 1239 - S/N AA84 failed due to a wire corrosion problem. S/N AA67 failed due to improper chip bonding.

Texas Instruments, Type PEX4105, Photon coupled switch, Log 1271 - The following failures are from a special qualification program:

- S/N 202, 203 and 58 failed due to an internal lead contacting an improper bonding terminal.
- S/N 74 and 100 failed due to an open stitch bond from the cathode of the light emitting diode (LED).
- S/N 340 and 341 failed due to an open collector bond to the output photo transistor.
- S/N 318 failed due to a breakdown in the isolation between the LED cathode and photo transistor.
- S/N 330, 350 and 315 failed due to improper die attach.

Union Carbide, Type 2N4391, transistor, Log 1275 - The failure was due to a broken internal aluminum lead.

TABLE V.

TYPICAL POST-IRRADIATION TRANSISTOR PARAMETER VALUES FOR HIGH CURRENT SWITCHES & CORE DRIVERS.

Device	Product Type	Neutron Dosage (nvt)	$LV_{CEO}\phi$ $I_C = 10$ mA	$h_{FE}\phi$				
				$I_C =$ 10 mA $V_{CE} = 5$ V	100 mA 5 V	300 mA 5 V	500 mA 5 V	1 A 5 V
2N2222	NPN	3×10^{14}	40 V	15	20		10	
2N3303	NPN	3×10^{14}	> 20 V		12	12		
2N3725	NPN	3×10^{14}	65 V		15	10	8	6
2N3502	PNP	3×10^{14}	70 V		12		5	
2N4032	PNP	3×10^{14}	120 V		8		10	7

TABLE VI.

TYPICAL POST-IRRADIATION TRANSISTOR PARAMETER VALUES FOR AMPLIFIERS.

Device	Product Type	Neutron Dosage (nvt)	$LV_{CEO}\phi$ $I_C = 10$ mA	$h_{FE}\phi$				
				$I_C = 100\mu$A $V_{CE} = 5$ V	1 mA 5 V	10 mA 5 V	50 mA 5 V	100 mA 5 V
2N918 2N2616	NPN	1×10^{15}	20 V			12		
2N3137	NPN	3×10^{14}	35 V			10	15	
TO 115A	NPN	1×10^{15}	25 V	10		17		
TO 115B	NPN	1×10^{15}	25 V	7		12		
2N4251	NPN	1×10^{15}	20 V	7	12	20		17
FT 40	NPN	1×10^{15}	20 V		10	15		
2N4034-5	PNP	5×10^{14}	50 V		8	10	11	

TABLE VII.

TYPICAL POST-IRRADIATION TRANSISTOR PARAMETER VALUES FOR HIGH-SPEED SWITCHES.

Device	Product Type	Neutron Dosage (nvt)	$LV_{CEO}\phi$ $I_C = 10$ mA	$h_{FE}\phi$				
				$I_C =$ $V_{CE} =$	10 mA 5 V	30 mA 5 V		
2N2369A	NPN	1×10^{15}	20 V		10	11		
2N2894	PNP	5×10^{14}	25 V		11	10		
2N4207	PNP	5×10^{14}	12 V		10			

In general, it can be noted that we have used neutron irradiation as a method of specification. The disagreement within the ranks of radiation effects investigators and systems specification writers as to what to test, and how to test transient effects makes it impossible at the present time for a semiconductor manufacturer to completely test and specify all possible radiation environments. However, the Defense Atomic Support Agency through Rome Air Development Center has two simultaneous contracts with IBM and Boeing for the ultimate purpose of rectifying the confusion and specifying measurement methods and techniques. Therefore, within the next year many of these problems should be resolved.

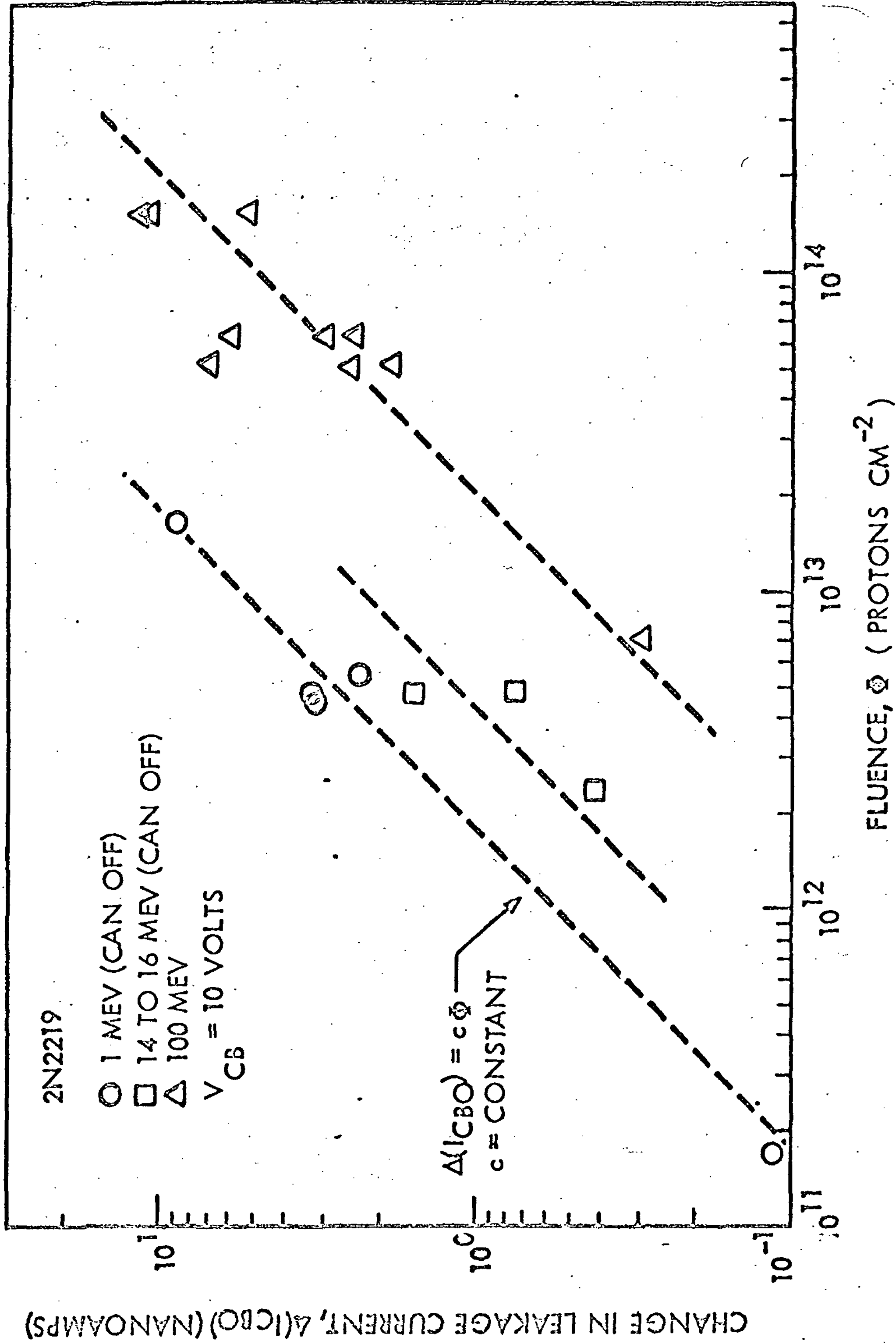


Figure 4.5 Dependence of $\Delta(I_{CBO})$ on Proton Fluence (2N2219)

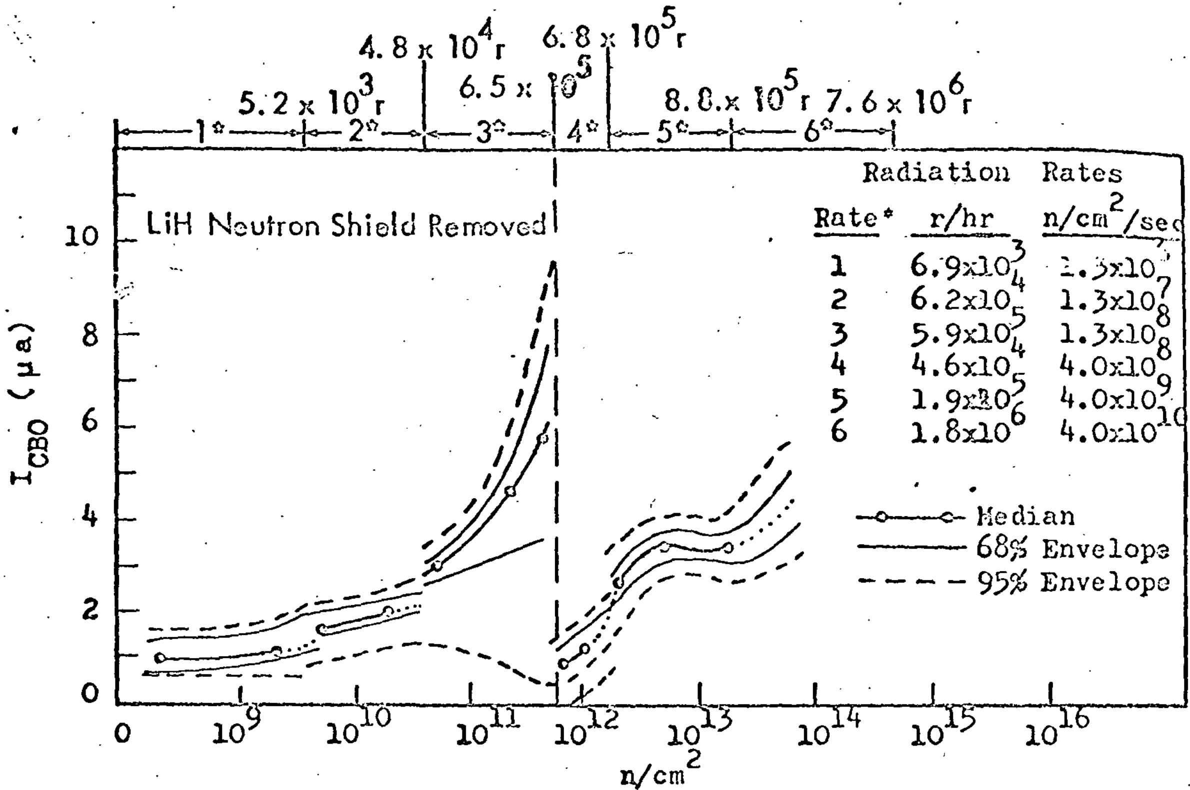


Figure 4.12A 2N2222, I_{CBO} Versus Integrated Neutron Flux at T = 37 - 0.5°C (14 Specimens). (Ref. 4.25A)

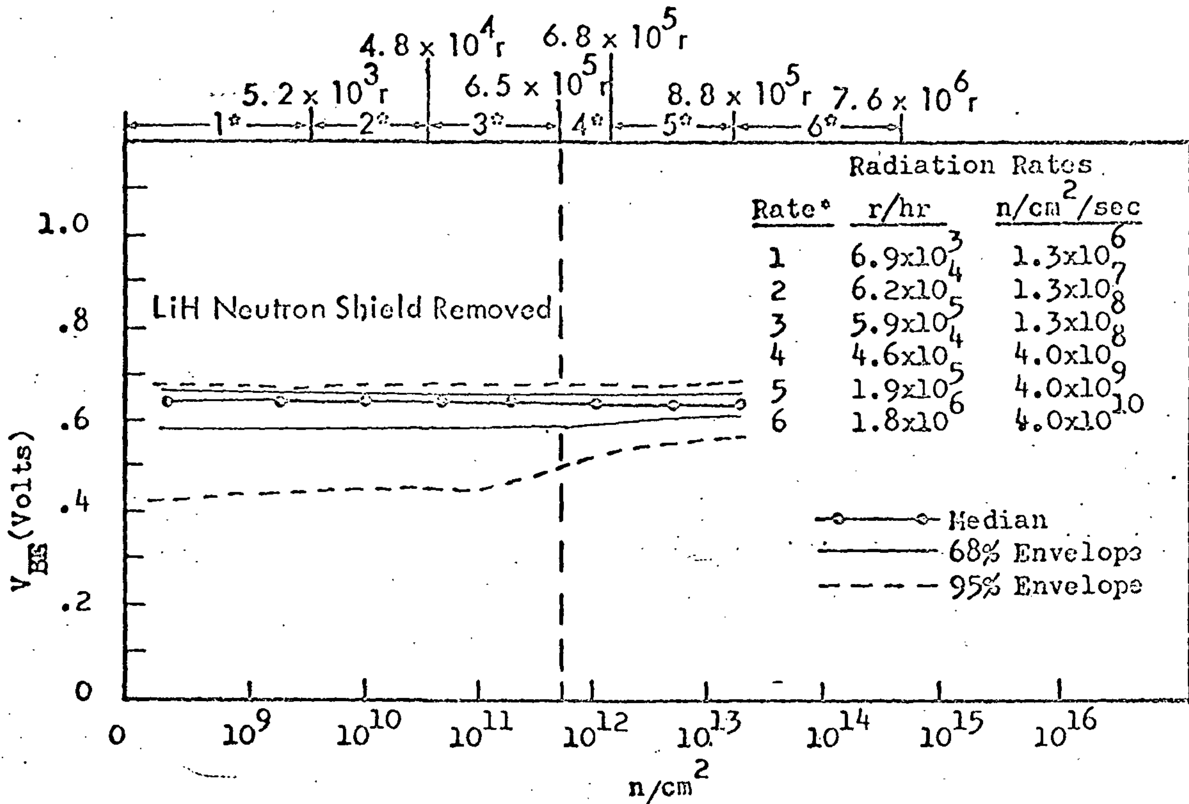


Figure 4.13A 2N2222, V_{BE} (I_C 10 ma Constant) Versus Integrated Neutron Flux at T = 37 - 0.5°C (13 Specimens) (Ref. 4.25A)

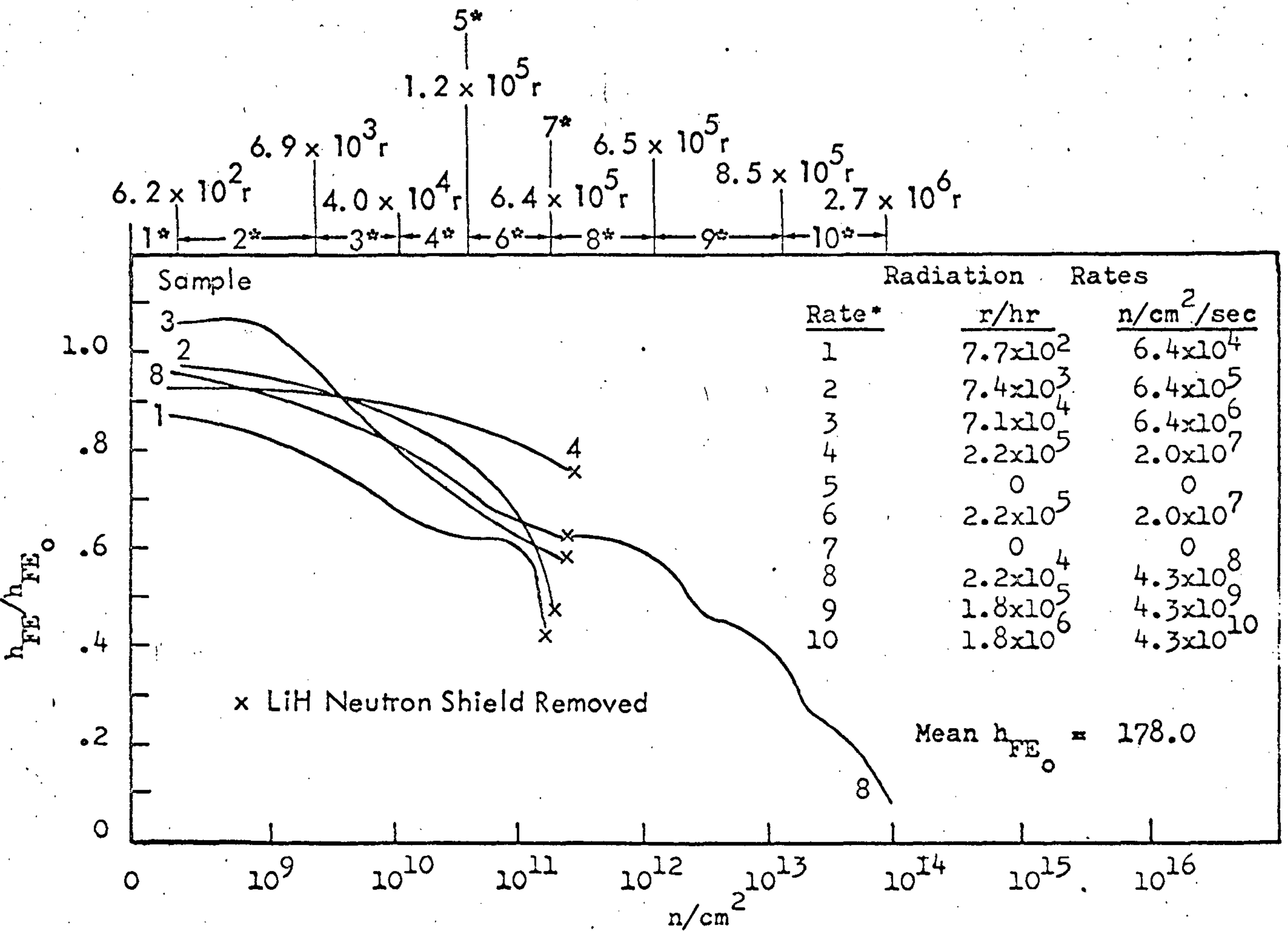


Figure 4.14A 2N2222, General Instrument, Inactive, Ambient, Normalized h_{FE} Versus Integrated Neutron Flux. (Ref. 4.26A)

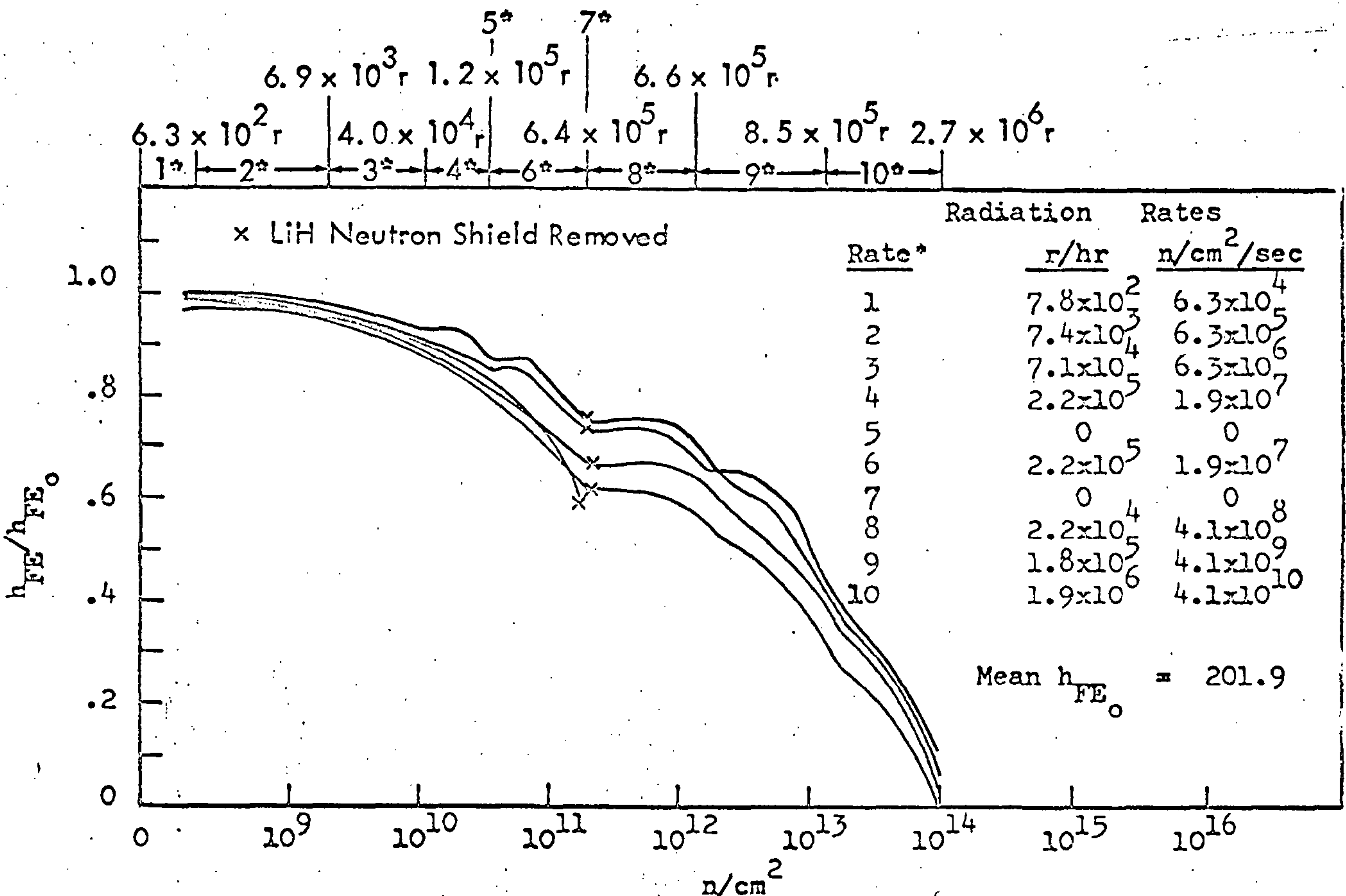


Figure 4.15A 2N2222, Texas Instruments, Inactive, Ambient, Normalized, h_{FE} Versus Integrated Neutron Flux. (Ref.4.26A)

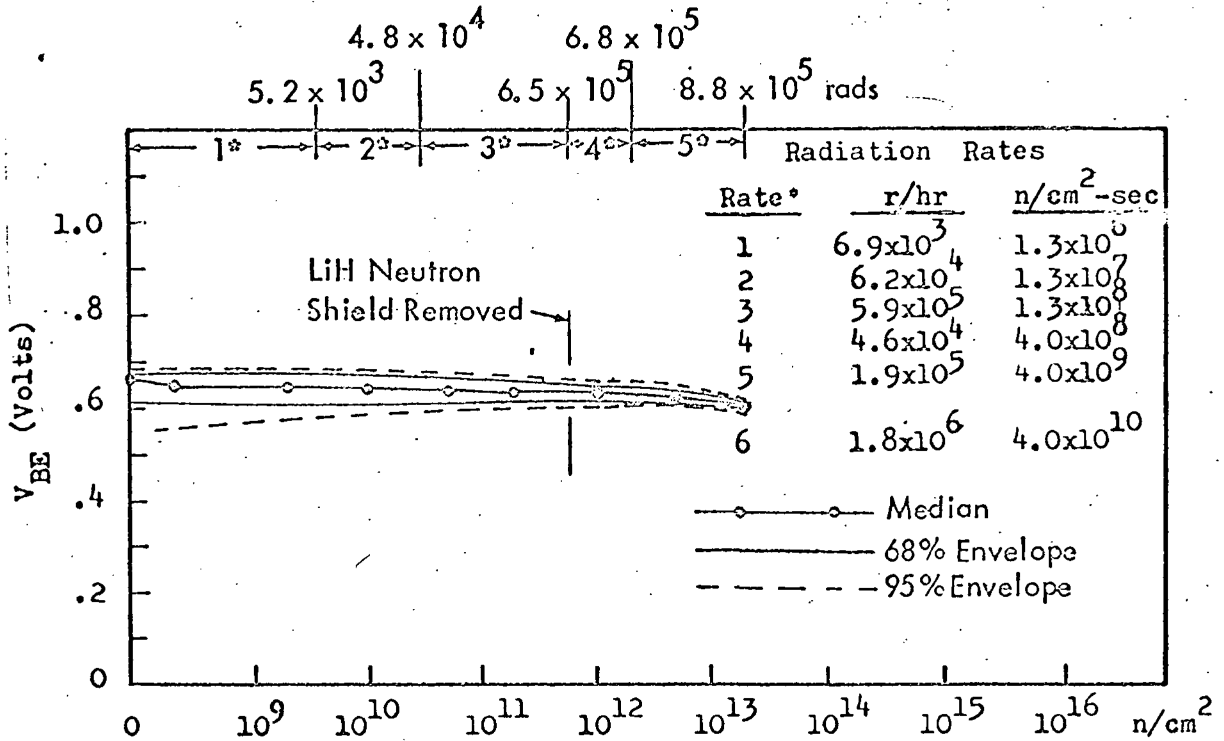


Figure 4.16A 2N2222, V_{BE} (I_B Constant, Mean I_C 10 ma) Versus Integrated Neutron Flux at T = 37°C (12 Specimens). (Ref. 4.25A)

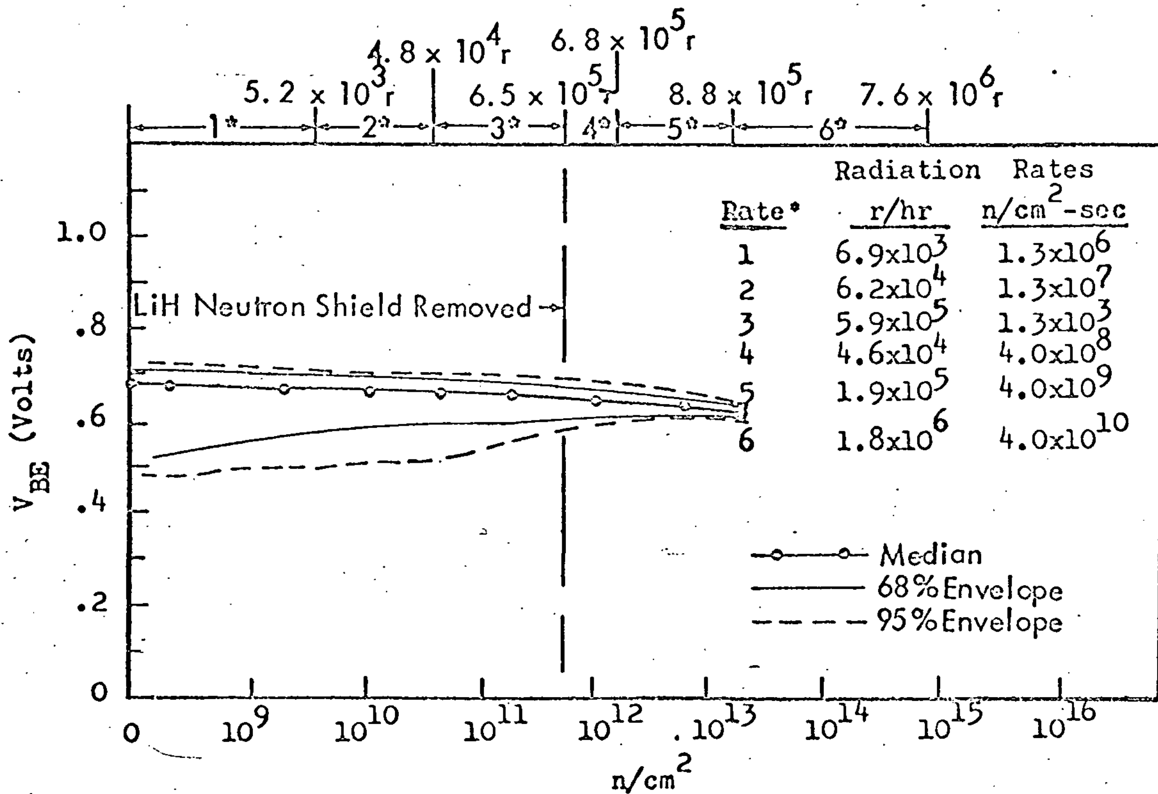


Figure 4.17A 2N2222 V_{BE} (I_B Constant, Mean I_C 20 ma) Versus Integrated Neutron Flux at T = 37° - 0.5°C (13 Specimens). (Ref. 4.25A)

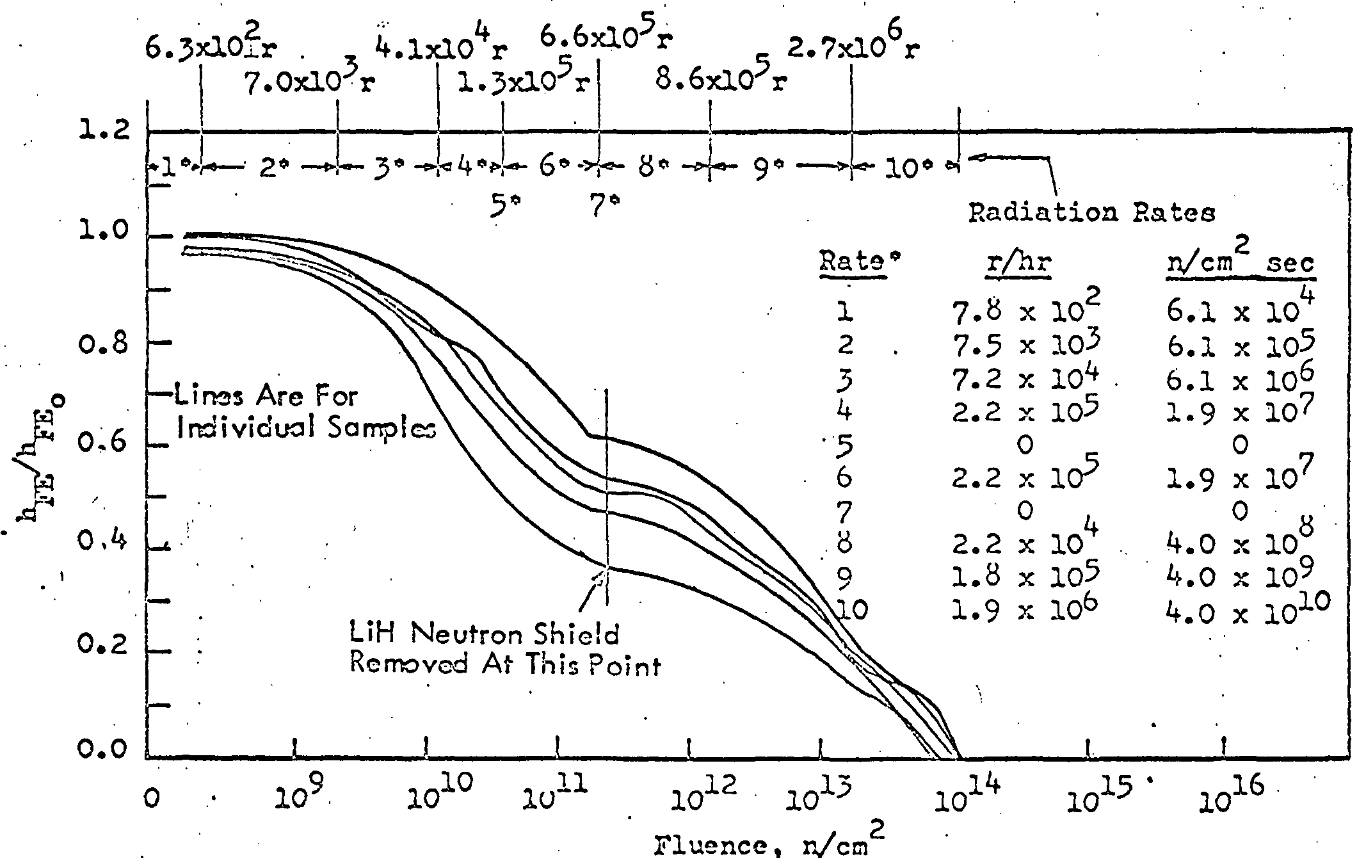


Figure 4.18A Normalized h_{FE} Versus Fluence for Active 2N2222 Transistor (Ref. 4.26A)

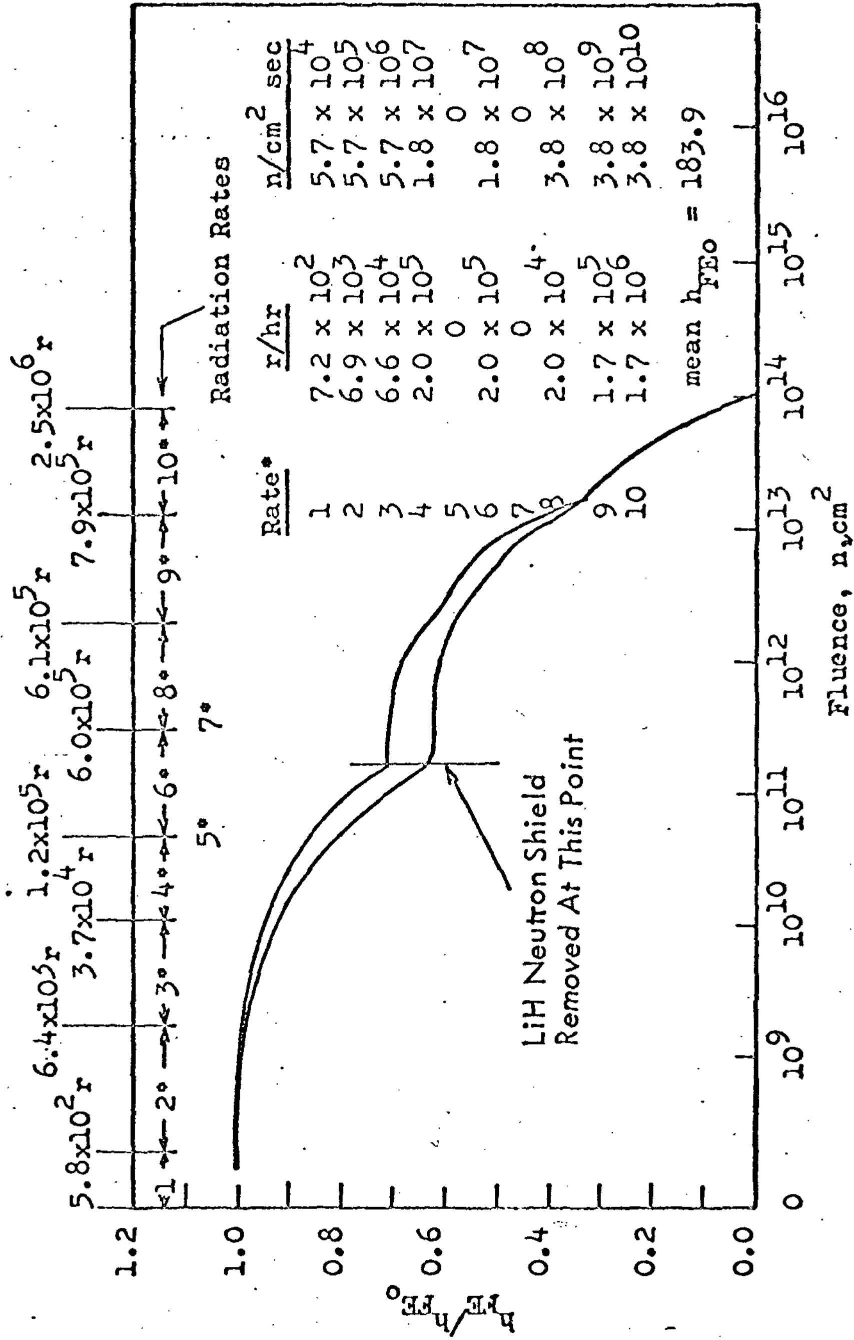


Figure 4.19A Normalized h_{FE} Versus Fluence for Active 2N2222 Transistors (Ref. 4.26A)

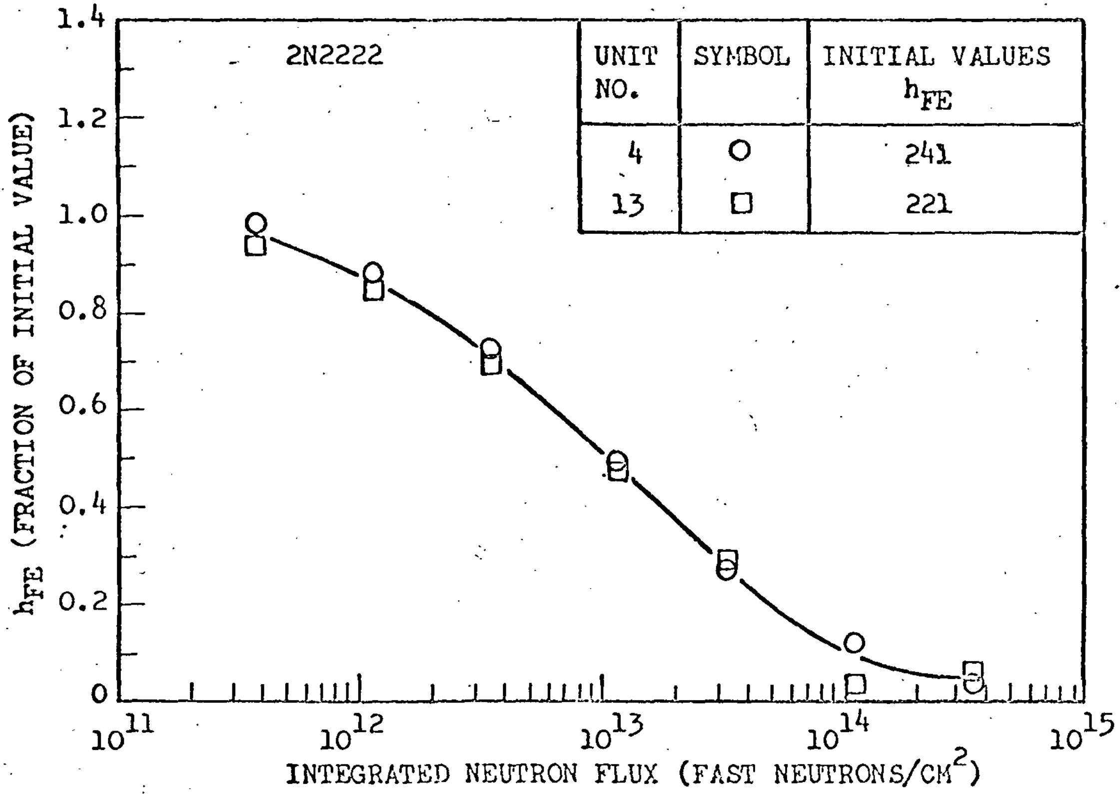


Figure 4.20A Transistor 2N2222 Neutron Dependence of h_{FE} (Ref. 4.21A)

Table 5.2 2N4448 N-Channel JFET (Ref. 5.76)

PARAMETER	UNIT NO.	DOSE IN RADS (SI)					
		0	10^4	10^5	10^6	8.3×10^6	3.7×10^7
R_{ON}	1	10.5	10.8	10.9	10.8	10.9	11.2
(ohms)	2	11.0	11.5	11.3	11.3	11.7	11.6
$V_{GS} = 0V$ &	3	8.4	8.7	8.6	8.8	9.0	9.1
$V_{DS} = .1V$	4	10.0	10.0	10.0	10.0	10.0	10.1
$V_{DS(ON)}$	1	.105	.108	.109	.108	.109	.112
(volts)	2	.110	.115	.113	.113	.117	.116
$V_{GS} = 0V$ &	3	.084	.087	.086	.088	.090	.094
$I_{DS} = 10ma$	4	.100	.100	.100	.100	.100	.101
$I_{DS(OFF)}$	1	<1	<1	1.5	500	570	1100
(na)	2	<1	<1	6.2	360	97	270
$V_{GS} = -10V$ &	3	<1	<1	1.0	3.0	17	26
$V_{DS} = 5V$	4	<1	<1	0.6	1.8	10	16
V_P	1	-8.7	-8.7	-8.7	-9.0	-8.7	-8.7
(volts)	2	-4.6	-4.6	-4.6	-4.9	-4.6	-4.6
$V_{DS} = 5V$ &	3	-5.2	-5.2	-5.2	-5.4	-5.2	-5.1
$I_{DS} = 3\ \mu a$	4	-2.8	-2.8	-2.8	-3.2	-2.8	-2.8
I_{GSS}	1	< .1	.17	2.8	90	1000	2700
(na)	2	< .3	.85	16	89	240	950
$V_{GS} = -15V$ &	3	< 1	.90	1.5	6.1	36	53
$V_{DS} = 0V$	4	< .1	.19	.70	4.0	18	29

Table 5.4 Degradation Factors for JFETs

Radiation Type	Parameter	Fluence	Degradation Factor	Fluence	Degradation Factor
Neutrons (fission)	g_m	10^{14} n/cm^2	-10 percent	10^{15} n/cm^2	-80 percent
	I_{DSS}	10^{14} n/cm^2	-25 percent	10^{15} n/cm^2	-90 percent
	V_p	10^{14} n/cm^2	-25 percent	10^{15} n/cm^2	———
Protons (22 MeV)	g_m	10^{13} P/cm^2	-15 percent	3×10^{13} p/cm^2	-50 percent
	I_{DSS}	10^{13} p/cm^2	-20 percent	3×10^{13} p/cm^2	-55 percent
	V_p	5×10^{10} p/cm^2	+100 percent	4×10^{11} p/cm^2	+400 percent
Electrons (1.5 MeV)	I_{GS}	10^{12} e/cm^2	+300 percent	10^{13} e/cm^2	+4000 percent
Gamma Radiation (Co-60)	I_{DSS}	10^5 rads(Si)	+250 percent	10^6 rads(Si)	approaching μamps
	V_p	10^5 rads(Si)	0 percent	10^6 rads(Si)	———
	I_{GS}	10^5 rads(Si)	>2800 percent	10^6 rads(Si)	approaching μamps

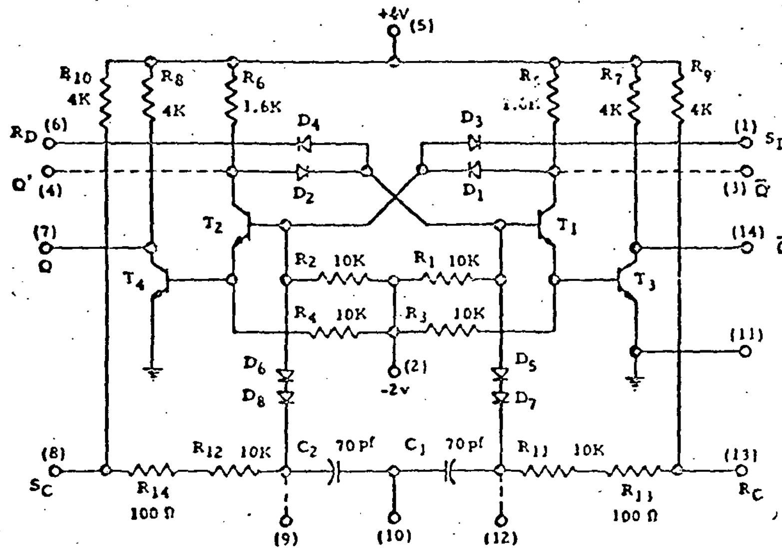


Figure 12.2 Signetics SE124 Monolithic Binary Element. (Ref. 12.73)

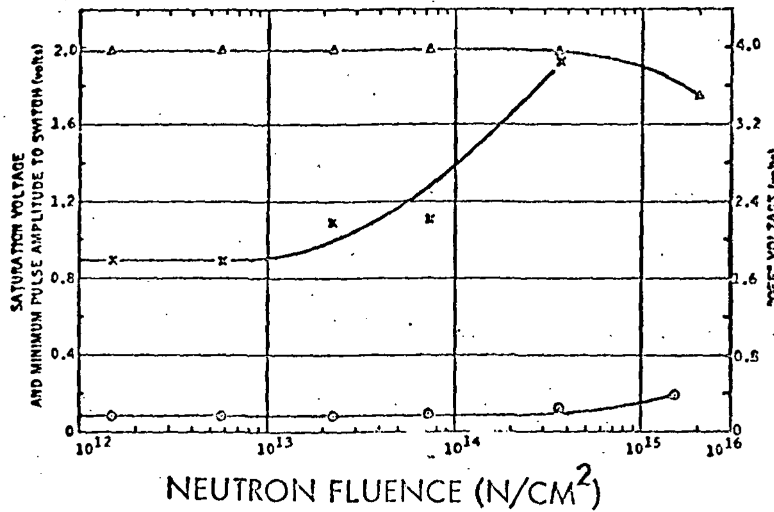


Figure 12.3 Neutron Degradation of SE124K-1 "off" Voltage, Saturation Voltage, and Minimum Pulse Amplitude to Switch Q Output. (Ref. 12.73)

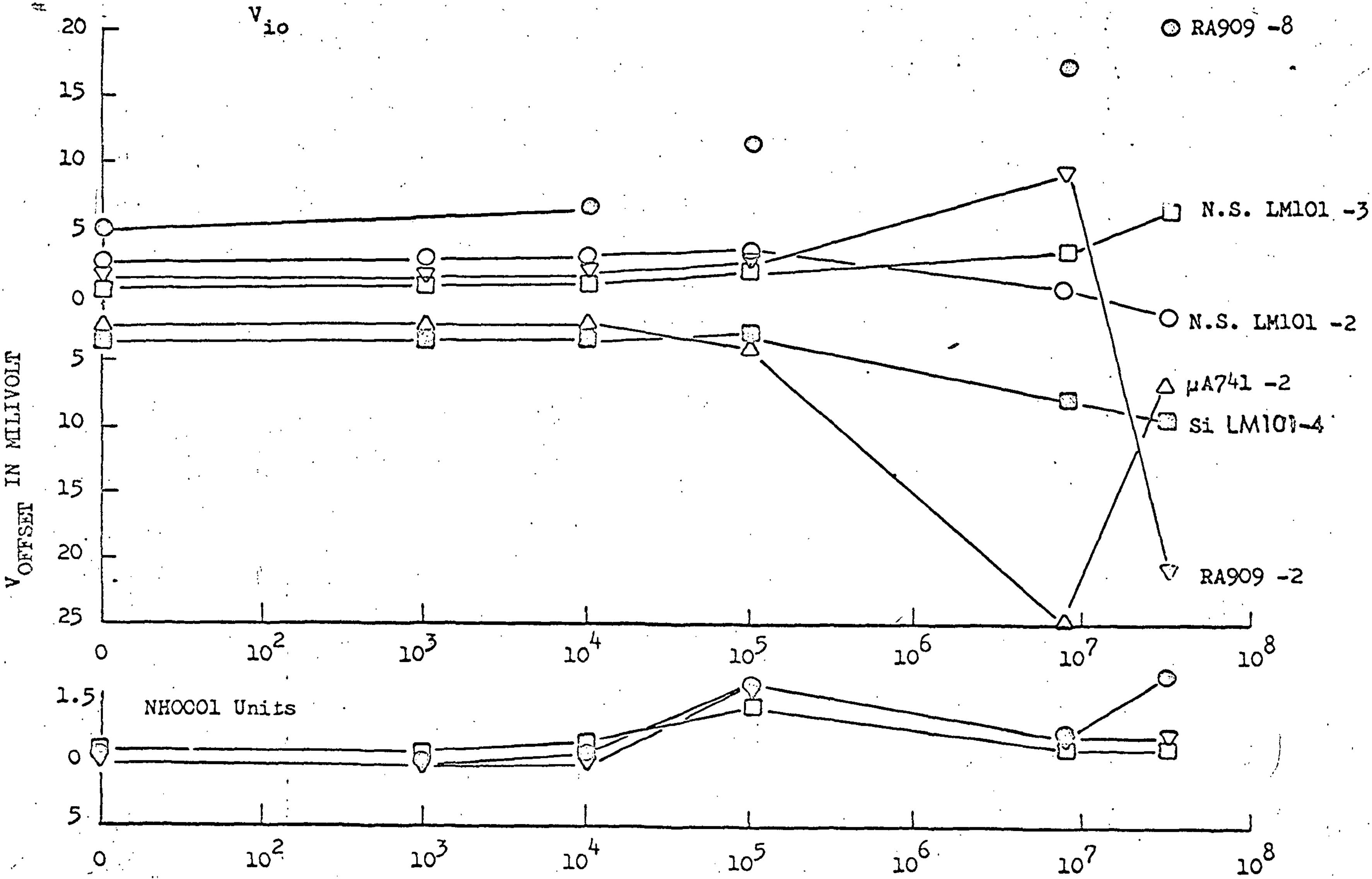


Figure 12.12 Illustrative V_{OFFSET} Variations Versus Co-60 Dose. (Ref. 12.76)

TABLE XVa

Voltage Gain in V/V Versus Radiation of μA702A Devices Measured at $V^+ = 12V$ and $V^- = -6V$, $R_L = 2K$.

DEVICE NO.	RADIATION LEVEL 0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	2000	1700			
2	1400	1100			
3	1700	1500			
4	1500	1300			
6	1700		1350		
7	2200		1600		
8	1700		1400		
9	1700		1300		
11	1600			1000	
12	2000			1000	
13	1200			500	
14	1900			950	
16	1300				100
17	1400				25
18	1900				150
19	2000				25

TABLE XVb

Voltage Gain in V/V Versus Radiation of μA709 Devices Measured at $V^+ = +15V$ and $V^- = -15V$ With No Load.

DEVICE NO.	RADIATION LEVEL 0	3×10^{12} nvt	10^{13} nvt	3×10^{13} nvt
1	45,000	45,000		
5	43,000	43,000		
7	43,000	43,000		
9	45,000	45,000		
4	44,000		43,000	
6	40,000		34,000	
8	43,000		43,000	
10	40,000		40,000	
13	44,000			30,000
14	44,000			40,000
15	45,000			40,000
19	45,000			43,000

TABLE XVc

Voltage Gain in V/V of μA710 Devices Versus Radiation Measured at $V^+ = +12V$, $V^- = -6V$ and No Load.

DEVICE NO.	RADIATION LEVEL 0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	1400	1200		
2	2000	1800		
3	1600	1500		
9	1800		1200	
11	1400		800	
12	1500		850	
17	1600			60
18	1800			65
19	1800			30

TABLE XVd

Voltage Gain in V/V of μA711 Devices Versus Radiation Measured at $V^+ = +12V$, $V^- = -6V$ and No Load.

DEVICE NO.	RADIATION LEVEL 0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	1400	1200		
2	1800	1500		
3	1800	1700		
4	1700	1500		
9	1700		800	
10	1800		800	
11	1800		900	
12	1800		1000	
19	2000			60
20	1400			40
21	1800			20
22	1700			60

TABLE XVIa

Input Bias Current in μA for the μA702A Devices Versus Radiation Measured at V+ = +12V and V− = −6V.

DEVICE NO.	RADIATION LEVEL 0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	3.4	3.7			
2	2.2	2.4			
3	3.1	3.2			
4	3.0	3.4			
6	5.4		6.3		
7	2.9		4.1		
8	3.8		4.8		
9	2.8		3.8		
11	1.7			5.8	
12	1.7			5.5	
13	8.8			16.0	
14	2.0			6.0	
16	9.0				44.0
17	4.5				19.5
18	1.8				22.5
19	2.3				19.5

TABLE XVIb

Input Bias Current in μA for the μA709 Devices Versus Radiation Measured at V+ = +15V and V− = −15V.

DEVICE NO.	RADIATION LEVEL 0	3 x 10^{12} nvt	10^{13} nvt	3 x 10^{13} nvt
1	0.12	0.14		
2	0.16	0.19		
3	0.15	0.18		
5	0.09	0.12		
4	0.15		0.27	
6	0.12		0.22	
8	0.07		0.13	
10	0.20		0.30	
13	0.13			0.30
14	0.13			0.32
15	0.21			0.40
16	0.11			0.29

TABLE XVIc

Input Bias Current in μA for the μA710 Devices Versus Radiation Measured at V+ = +12V and V− = −6V.

DEVICE NO.	RADIATION LEVEL 0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	29.0	31.2		
2	13.0	19.2		
3	11.0	14.5		
4	9.0	9.1		
9	23.0		66.7	
11	33.0		79.8	
12	29.0		79.6	
17	8.2			225
18	49.0			415
19	19.0			233
20	42.0			361

TABLE XVId

Input Bias Current in μA for the μA711 Devices Versus Radiation Measured at V+ = +12V and V− = −6V.

DEVICE NO.	RADIATION LEVEL 0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	16.5	19.1		
2	14.3	17.8		
3	12.5	14.6		
4	9.6	11.0		
9	12.7		27.8	
10	10.9		25.0	
11	11.0		27.2	
12	7.0		16.7	
19	9.1			74.0
20	21.4			87.3
21	24.9			100.0
22	14.9			84.6

TABLE XVIIa

Voltage Offset in mV Versus Radiation for μA702A Devices.

DEVICE NO.	RADIATION LEVEL 0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	+0.8	+0.7			
2	+2.8	+2.5			
3	+0.9	+0.9			
4	−0.8	−0.8			
5	−2.4	−2.0			
6	+0.1		+0.3		
7	+2.0		+1.9		
8	+2.6		+2.7		
9	−1.0		−1.0		
10	−0.6		−0.8		
11	−0.9			−1.4	
12	+0.9			+0.5	
13	−1.8			−3.4	
14	+0.6			+0.4	
15	−0.6			−1.2	
16	+2.0				−6.2
17	−0.4				−6.5
18	−2.9				−6.2
19	−0.2				−4.6
20	−1.8				−7.2

TABLE XVIIb

Voltage Offset in mV Versus Radiation for μA709 Devices.

DEVICE NO.	RADIATION LEVEL 0	3 x 10^{12} nvt	10^{13} nvt	3 x 10^{13} nvt
5	−0.3	−0.3		
7	+2.1	+2.2		
9	−0.6	−0.5		
2	−3.0	−3.0		
6	−0.2		−0.2	
8	−0.3		−0.2	
4	−0.4		−0.4	
11	−0.8		−0.8	
15	−1.0			−1.0
19	+1.8			+1.8
13	−1.5			−1.4
14	−0.6			−0.6

TABLE XVIIc

Voltage Offset in mV Versus Radiation for μA710 Devices.

DEVICE NO.	RADIATION LEVEL 0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	+6.2	+6.2		
2	+6.0	+6.0		
3	+3.6	+3.6		
4	−6.4	−6.3		
9	+5.7		+6.0	
11	+1.4		+1.3	
12	+5.9		+6.1	
17	+1.1			−1.3
18	+2.5			+4.6
19	+2.0			−1.5
20	−0.1			−7.6

TABLE XVIId

Voltage Offset in mV Versus Radiation for μA711 Devices.

DEVICE NO.	RADIATION LEVEL 0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	+1.2	+1.2		
2	+0.4	+0.4		
3	−0.2	−0.15		
4	−4.1	−4.1		
9	+0.6		+1.0	
10	−1.4		−1.0	
11	+0.5		+0.8	
12	+0.6		+1.2	
19	−0.2			+6.4
20	+0.8			+8.6
21	+2.2			Sat
22	−1.4			+0.2

TABLE XVIIIa

Input Offset Current in μA Versus Radiation for the μA702A Devices.

DEVICE	RADIATION LEVEL				
NO.	0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	0	+ .25			
2	+ .05	+ .35			
3	− .45	+ .35			
4	− .85	+ .25			
5	+ .65	+ .25			
6	−1.80		− .50		
7	+ .10		+ .15		
8	+1.80		+ .75		
9	−1.05		− .05		
11	+ .35			− .10	
12	− .05			+ .20	
13	−1.75			−1.00	
14	+ .45			+ .55	
16	+5.10				− .40
17	− .50				− .45
18	+ .30				−1.00
19	− .40				− .50

TABLE XVIIIb

Input Offset Current in nA Versus Radiation for the μA709 Devices.

DEVICE	RADIATION LEVEL			
NO.	0	3 x 10^{12} nvt	10^{13} nvt	3 x 10^{13} nvt
1	+80	+70		
5	0	0		
7	+90	+90		
9	+70	0		
6	−40		−40	
8	+20		+20	
4	−20		−20	
11	−10		+10	
15	0			0
19	+20			+ 40
13	−20			− 40
14	−90			−110

TABLE XVIIIc

Input Offset Current in μA Versus Radiation for the μA710 Devices.

DEVICE	RADIATION LEVEL			
NO.	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	+1.0	−1.5		
2	+1.0	−2.0		
3	0	− .5		
4	−3.0	+3.0		
9	+4.0		+6.5	
11	+2.0		+2.5	
12	+3.0		+6.5	
17	0			+2.5
18	+13.5			−19.5
19	+1.0			+4.0
20	−2.5			+11.6

TABLE XVIIId

Input Offset Current in μA Versus Radiation for the μA711 Devices.

DEVICE	RADIATION LEVEL			
NO.	0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	−1.0	−1.0		
2	−0.5	+1.0		
3	−1.5	−1.5		
4	−0.5	−1.0		
9	0		0	
10	0		0	
11	−0.5		0	
12	−1.0		−1.0	
19	+1.0			+5.0
20	0			+11.0
21	+1.0			Sat
22	−2.0			−1.5

TABLE XIXa

Positive Supply Current in mA Versus Radiation of the μA702A Devices Measured at V+ = +12V and V− = −6V.

DEVICE NO.	RADIATION LEVEL 0	10^{12} nvt	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	7.1	6.9			
2	8.4	6.8			
3	6.8	6.5			
4	7.6	6.7			
6	7.5		7.0		
7	8.5		6.7		
8	7.0		6.4		
9	7.2		6.1		
11	7.0			6.6	
12	7.2			6.7	
13	8.0			6.8	
14	7.8			6.8	
16	7.4				5.1
17	7.6				5.1
18	7.3				4.8
19	6.9				5.0

TABLE XIXb

Positive Supply Current in mA Versus Radiation of the μA709 Devices Measured at V+ = +15V and V− = −15V.

DEVICE NO.	RADIATION LEVEL 0	3 x 10^{12} nvt	10^{13} nvt	3 x 10^{13} nvt
1	3.45	3.53		
5	3.73	3.28		
7	4.25	4.31		
9	3.40	3.45		
6	3.41		3.48	
8	2.72		2.71	
4	4.16		4.28	
11	3.20		3.28	
15	3.64			3.83
19	4.05			4.18
13	3.45			3.51
14	3.07			3.08

TABLE XIXc

Power Dissipation in mW Versus Radiation of the μA710 Devices Measured at V+ = +12V and V− = −6V.

DEVICE NO.	RADIATION LEVEL 0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	94.2	94.5		
2	81.6	81.6		
3	83.4	85.1		
4	85.1	86.0		
9	109.0		107.5	
11	96.4		93.5	
12	99.0		96.5	
17	204.0			169.7
18	100.0			72.1
19	64.4			45.7
20	96.0			70.2

TABLE XIXd

Power Dissipation in mW Versus Radiation of the μA711 Devices Measured at V+ = +12V and V− = −6V.

DEVICE NO.	RADIATION LEVEL 0	10^{13} nvt	10^{14} nvt	10^{15} nvt
1	137	132		
2	143	129		
3	159	153		
4	109	100		
9	127		117	
10	133		133	
11	130		116	
12	120		105	
19	130			100
20	146			109
21	147			106
22	147			109

COMPARISON OF AMPLIFIER CHARACTERISTICS AT 25°C

AMPLIFIER DESIGNATION	LM101	μA741	RA909	NH0001
Type	Gen. Purpose	Gen. Purpose	Gen. Purpose	Gen. Purpose Low Power
Construction	Monolithic	Monolithic	Dielectric Isolation	Monolithic
Unity-Gain Compensation	Ext.-One 30 pf Capacitor	Internal	Internal	Ext.-One 39 pf & One 22 pf Capacitor
Offset Null	Requires a 5 MΩ pot plus a 5.1 M Resistor	Requires only a 10 K pot.	Requires a 200 K pot - only available in flatpack.	Not indicated on Mfr. spec sheet.
Standby Power Consumption	25 mw (typical) at ± 15V	85 mw (max.) at ±15V	75 mw (max.) at ±15V	2 mw (typ.) @ ±15V; .6 mw (typ.) at ±6V
Short Circuit Proof	Yes	Yes	No-Output current must be limited @ 50 ma.	Yes
Max. Diff. Input Voltage	±30V	±30V	±7V	±7V
Input Voltage Range	Equal to supply voltage but no greater than ±15V.	Equal to supply voltage but no greater than ±15V.	±12V	Equal to supply voltage.
Max. Supply Voltage	±22V	±22V	±25V	±20V
Large Signal Voltage Gain	50,000 (min)	50,000 (min)	25,000 (min)	25,000 (min)
Input Offset Voltage	5 mv (max) $R_S \leq 10K$	5 mv (max) $R_S \leq 10K$	5 mv (max) $R_S \leq 10K$	1 mv (max) $R_S \leq 5K$
Input Bias Current	500 nA (max)	500 nA (max)	300 nA (max)	100 nA (max)
Input Offset Current	200 nA (max)	200 nA (max)	150 nA (max)	20 nA (max)
Input Resistance	300 KΩ	300 KΩ	200 KΩ	No Data

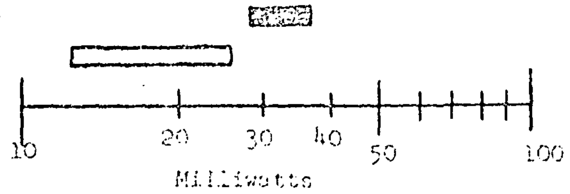
COMPARISON OF AMPLIFIER CHARACTERISTICS AT 25°C
(CONTD.)

AMPLIFIER DESIGNATION	LM101	μA741	RA909	NH0001
Output Resistance	No data	No data	150Ω (typical)	No data
Common Mode Rejection Ratio	70 db (min)	70 db (min)	80 db (min)	90 db (typ.)
Power Supply Rejection Ratio	70 db (min)	90 db (typ.)	80 db (min)	90 db (typ.)
Equivalent Noise Input	No data	No data	5 μV (rms) max R_S <10K, 10Hz to 1 KHz	No data
Slew Rate	No data	.5 v/μs (typ)	5 v/μs (typ)	No data
Unity Gain Bandwidth	600 KHz (typ)	800 KHz (typ)	7 MHz (typ)	1 MHz (typ)
Average Temperature Coefficient of Voltage Offset	6μv/°C (typ) $R_S \leq 10K$	No data	5 μv/°C (typ)	No data
Date of Spec Sheet	May 1967	May 1968	Jan. 1968	Mar. 1968

[illegible]

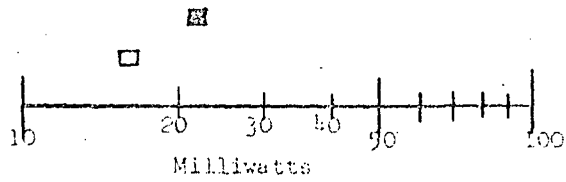
NATIONAL SEMICONDUCTOR LM101

Before
After 3.4×10^7 rads (Si)



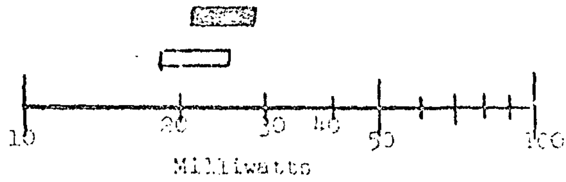
SILICONIX LM101

Before
After 3.4×10^7 rads (Si)



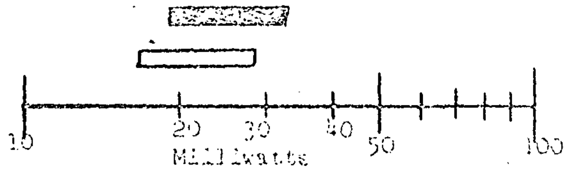
FAIRCHILD μA741

Before
After 3.4×10^7 rads (Si)



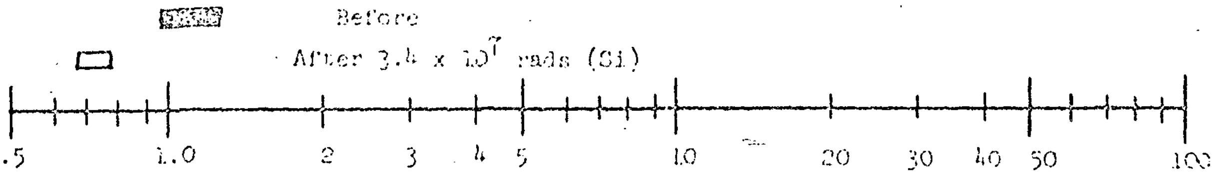
RADIATION INC. RA909

Before
After 3.4×10^7 rads (Si)



NATIONAL SEMICONDUCTOR NH0001

Before
After 3.4×10^7 rads (Si)



STANDBY POWER CONSUMPTION IN MILLIWATTS

FIGURE 4.

V_{OFFSET} IN MILLIVOLTS

DOSE IN RADS (Si)		0	10^3	10^4	10^5	8.1×10^6	3.4×10^7
NAT. SEMI. LM101	1	-1.94	-2.01	-2.11	-2.52	-6.69	-6.86
	2	+2.57	+2.62	+2.68	+3.00	<.01	-1.98
	3	+ .52	+ .47	+ .41	+1.67	+2.48	+5.68
	4	+1.78	+1.80	+1.82	+1.23	+2.88	- .29
SILICONIX LM101	1	+ .48	+ .48	+ .47	+ .40	-6.57	-6.63
	2	- .35	- .35	- .35	- .41	-1.93	-4.57
	3	- .18	- .19	- .20	- .28	-4.36	-5.09
	4	-3.40	-3.39	-3.42	-3.48	-8.62	-9.81
FAIRCHILD µA741	1	+ .45	+ .54	+ .59	-2.23	-22.02	-7.65
	2	-2.68	-2.67	-2.67	-3.75	-25.32	-7.22
	3	-1.04	-1.03	-1.02	-2.18	-22.03	-6.58
	4	- .31	- .28	- .25	- .60	-10.98	-4.57
	5	- .46	- .44	- .43	-1.11	-21.84	-5.97
RADIATION INC. RA909	1	+3.48	+3.54	+3.58	+4.12	+10.57	+13.81
	2	+ .87	+ .90	+1.02	+2.09	+8.27	-21.16
	3	+2.14	- NO DATA TAKEN -	+2.35	+3.13	+10.41	+13.68
	4	+1.67		+1.75	+2.56	+9.87	+13.63
	5	+4.08		+4.26	+5.13	+12.59	+16.30
	6	+3.10		+4.83	+10.06	+15.15	+19.59
	7	+1.96		+2.14	+2.91	+9.96	+13.34
	8	+5.04		+6.55	+11.15	+16.53	+19.41
NAT. SEMI. NH0001	1	-.070	-.010	-.010	+1.59	+ .51	+ .39
	2	-.062	-.050	+ .17	+1.64	+ .47	+1.79
	3	+.104	+.140	+ .41	+1.15	+ .33	+ .30

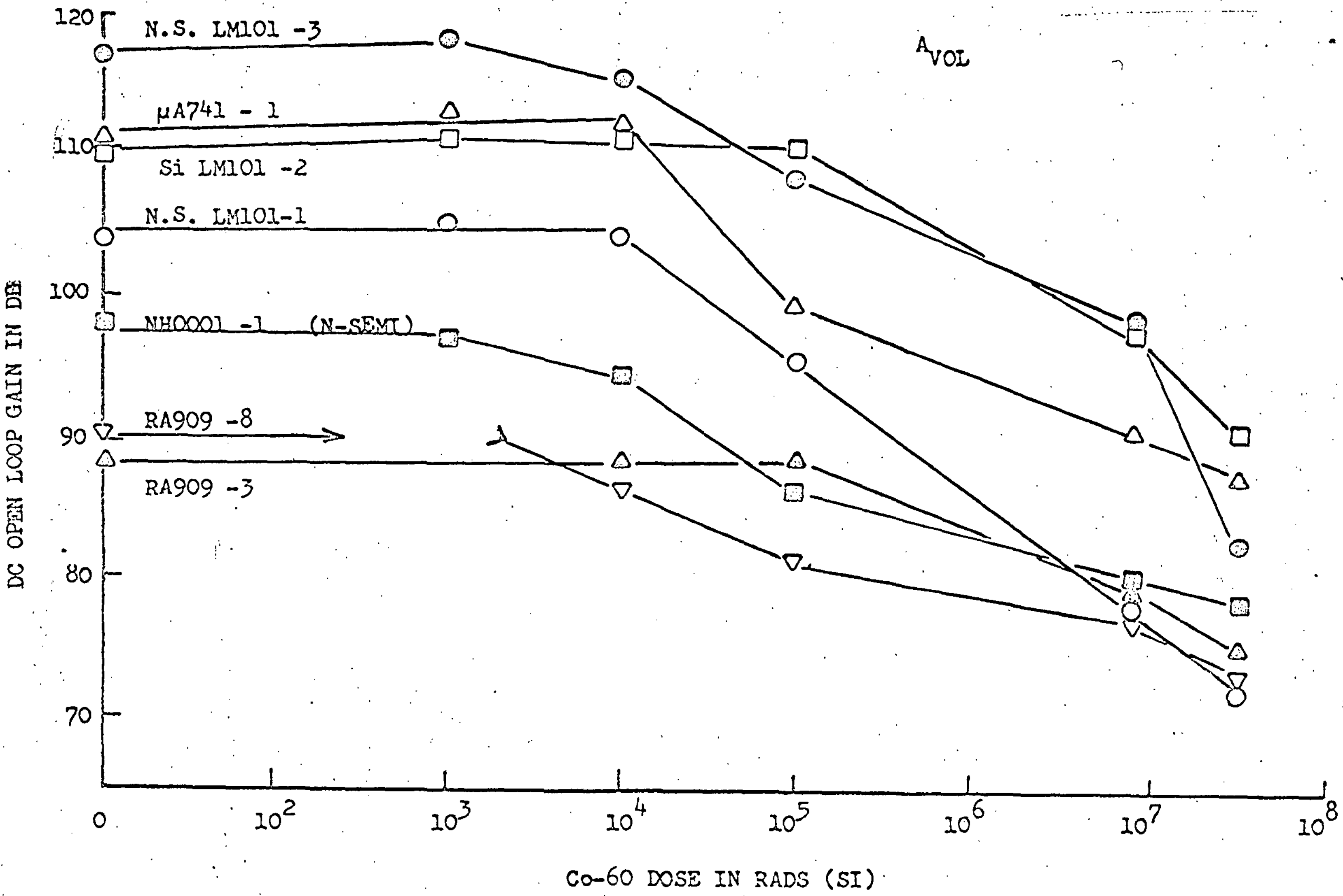


FIGURE 12.13 Illustrative Gain Degradation Versus Co-60 Dose. (Ref. 12.76)

DC OPEN LOOP GAIN (A_{VOL}) IN DB

DOSE IN RADS (Si)		0	10^3	10^4	10^5	8.1×10^6	3.4×10^7
NAT. SEMI. LM101	1	104	105	104	95	78	72
	2	101	102	99	95	78	73
	3	117	118	115	108	98	82
	4	115	116	115	107	97	83
SILICONIX LM101	1	113	113	112	110	90	87
	2	110	111	111	110	97	90
	3	113	112	112	110	92	89
	4	108	109	109	107	88	84
FAIRCHILD µA741	1	110	113	112	99	90	87
	2	108	111	110	105	88	88
	3	110	112	110	98	*	89
	4	111	113	111	105	*	*
	5	106	107	106	99	*	90
RADIATION INC. RA909	1	90	89	90	87	82	77
	2	90	90	90	90	82	72
	3	88	NO DATA TAKEN	88	88	79	75
	4	90		89	89	80	75
	5	90		90	88	80	75
	6	92		89	82	80	75
	7	91		91	90	81	77
	8	90		86	81	77	73
NAT. SEMI. NH0001	1	98	97	94	86	80	78
	2	101	100	97	89	79	77
	3	101	101	98	90	80	77

* Excessively noisy or unable to dc stabilize.

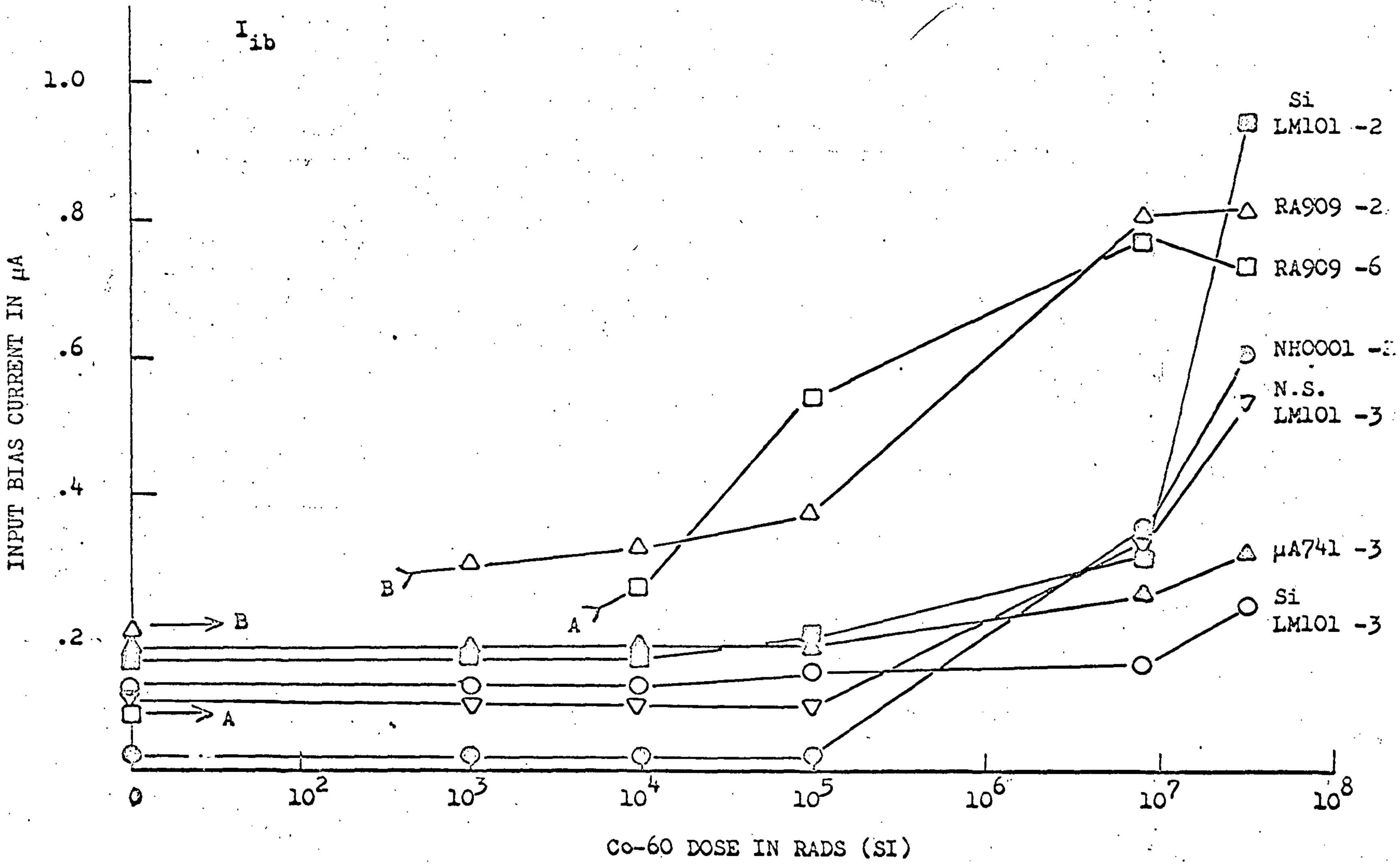


Figure 12.14 Illustrative Input Bias Current Variations Versus Co-60 Dose. (Ref. 12.76)

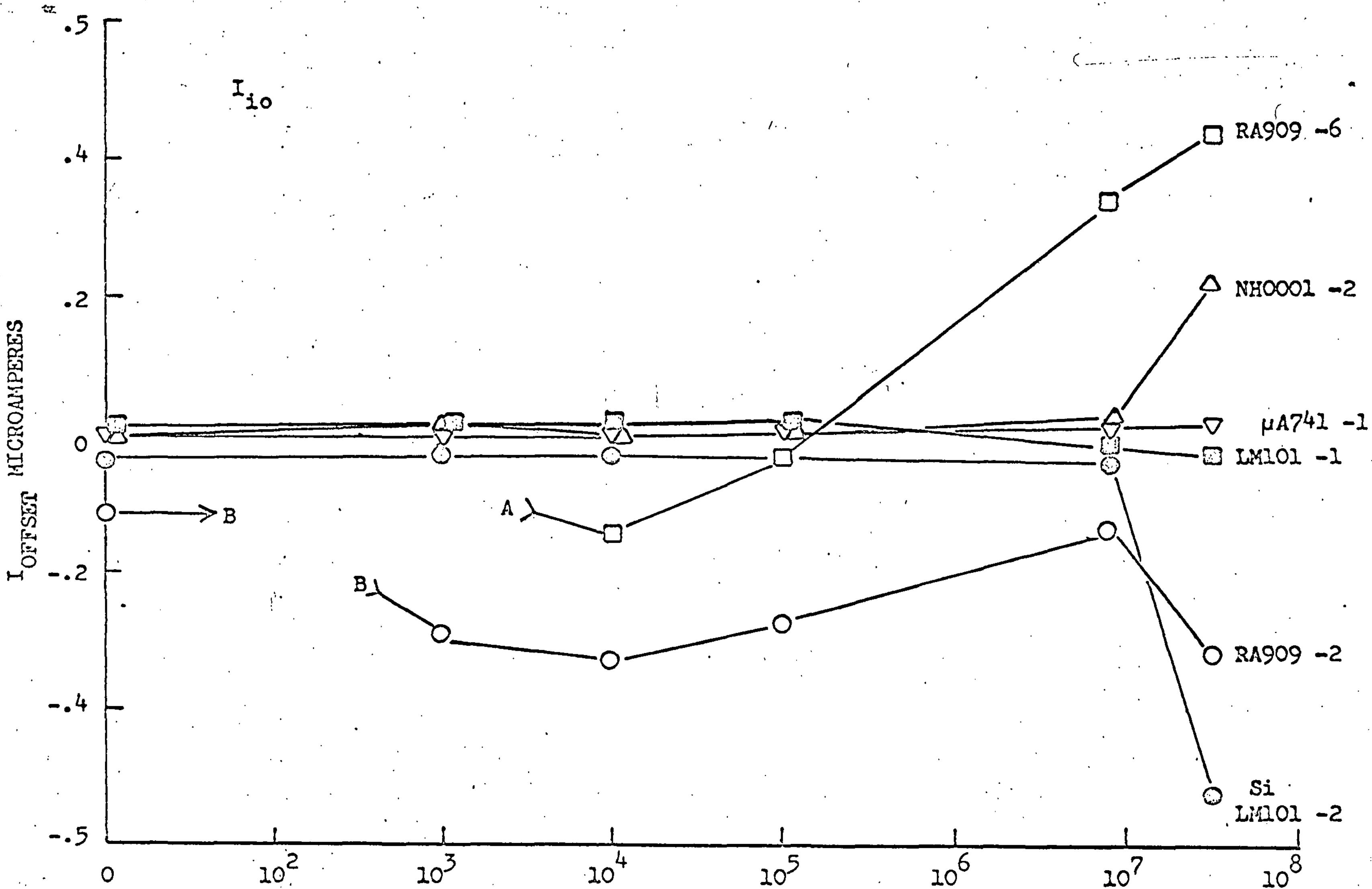


Figure 12.15 Illustrative I_{OFFSET} Variations Versus Co-60 Dose. (Ref. 12.76)

TABLE IV

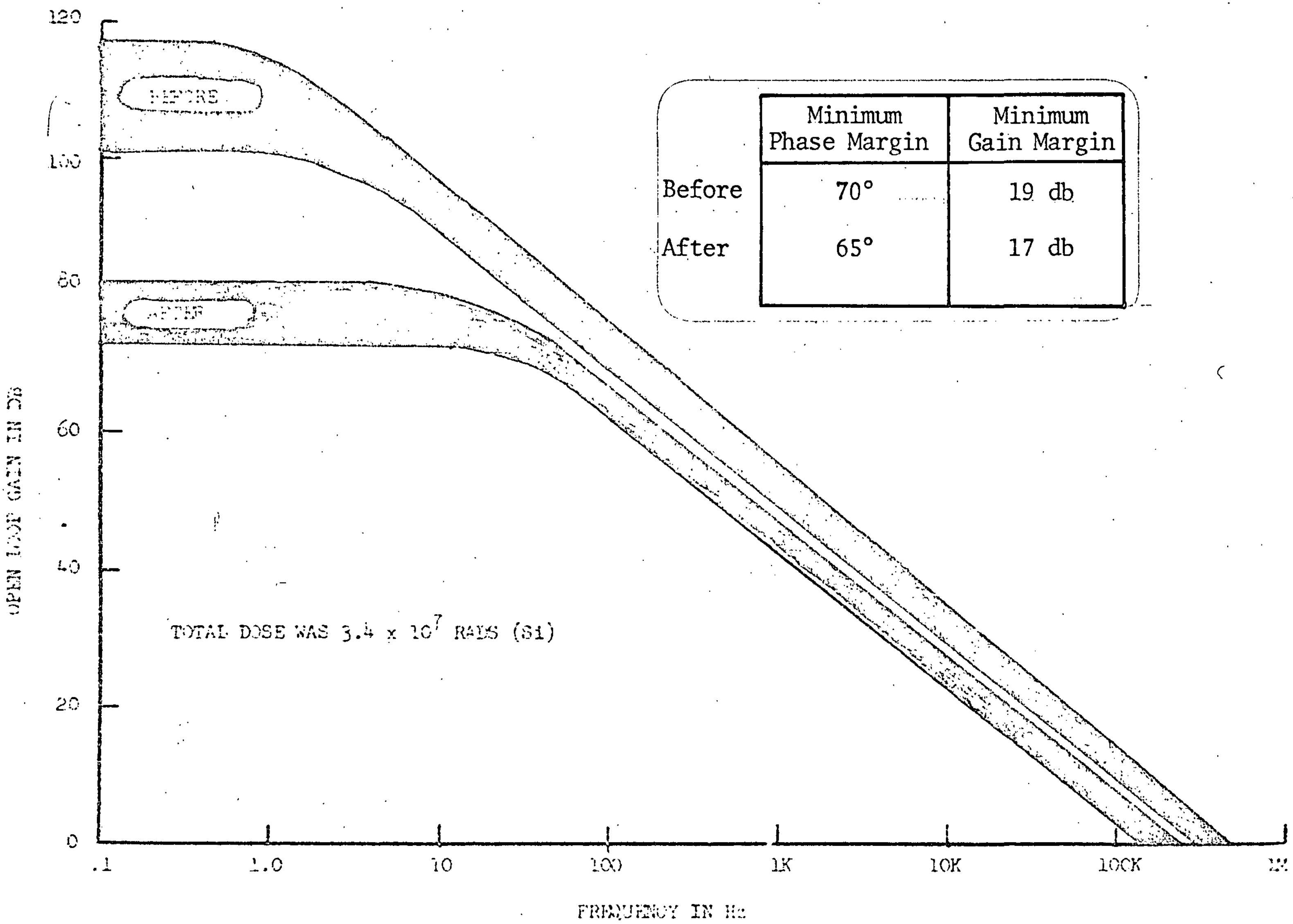
INPUT BIAS CURRENT IN nA

DOSE IN RADS (Si)		0	10^3	10^4	10^5	8.1×10^6	2.4×10^7
NAT. SEMI. LM101	1	72	67	66	71	325	527
	2	99	93	92	90	330	522
	3	92	76	77	81	245	265
	4	97	83	85	85	255	377
SILICONIX LM101	1	130	130	133	148	156	241
	2	156	156	160	182	306	920
	3	118	120	122	138	154	224
	4	180	180	181	197	257	[illegible]
FAIRCHILD μA741	1	137	127	136	147	201	[illegible]
	2	79	78	79	87	176	260
	3	172	167	166	172	256	316
	4	90	90	90	95	214	[illegible]
	5	154	152	154	157	227	302
RADIATION INC. RA909	1	140	208	218	147	576	566
	2	200	295	326	368	786	780
	3	48	NO DATA TAKEN.	105	137	384	420
	4	93		107	124	331	394
	5	49		92	121	330	394
	6	85		262	536	752	711
	7	111		197	248	567	642
	8	49		146	327	538	499
NAT. SEMI. NH0001	1	19	16	20	29	298	452
	2	19	17	19	26	302	588
	3	18	17	19	34	161	447

OFFSET CURRENT IN nA

DOSE IN RADS (Si)		0	10^3	10^4	10^5	8.1×10^6	2.4×10^7
NAT. SEMI. LM101	1	10	9	8	5	-24	[illegible]
	2	-26	-29	-26	-22	-23	-33
	3	-55	-36	-30	-24	-43	[illegible]
	4	3	11	11	10	-51	9
SILICONIX LM101	1	4	3	3	2	-12	-22
	2	-34	-34	-35	-39	-51	-529
	3	- 2	- 2	- 3	- 5	-12	-21
	4	- 5	- 3	- 4	- 8	-30	-36
FAIRCHILD μA741	1	-21	-23	-20	-32	-18	-32
	2	13	13	12	12	- 8	20
	3	11	13	13	7	-67	14
	4	- 3	- 5	- 4	- 4	1	< 1
	5	29	29	30	30	- 6	35
RADIATION INC. RA909	1	22	-106	-101	-32	-67	101
	2	-114	-294	-331	-280	[illegible]	-325
	3	- 5	NO DATA TAKEN.	-91	-90	9	94
	4	-95		-100	-80	-17	53
	5	2		-59	-60	21	104
	6	- 5		-147	-39	325	414
	7	- 3		-138	-127	34	140
	8	7		-56	-45	257	270
NAT. SEMI. NH0001	1	< 1	5	- 1	-13	-53	-24
	2	< 1	3	- 1	- 3	[illegible]	[illegible]
	3	- 1	1	- 2	-27	-17	11

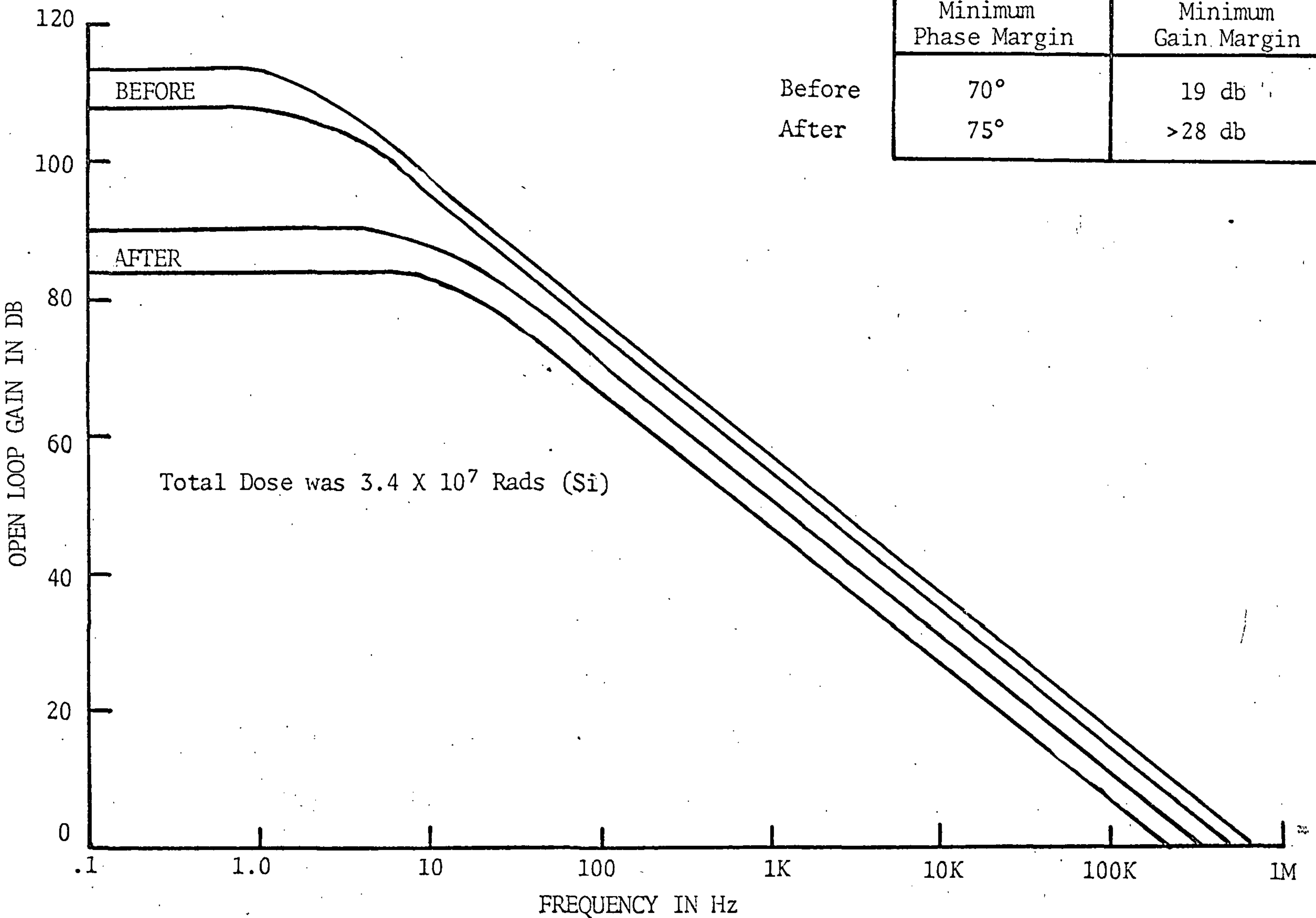
OPEN LOOP GAIN VS. FREQUENCY FOR NATIONAL SEMICONDUCTOR LM101 UNITS
BEFORE AND AFTER CO-60 IRRADIATION



	Minimum Phase Margin	Minimum Gain Margin
Before	70°	19 db
After	65°	17 db

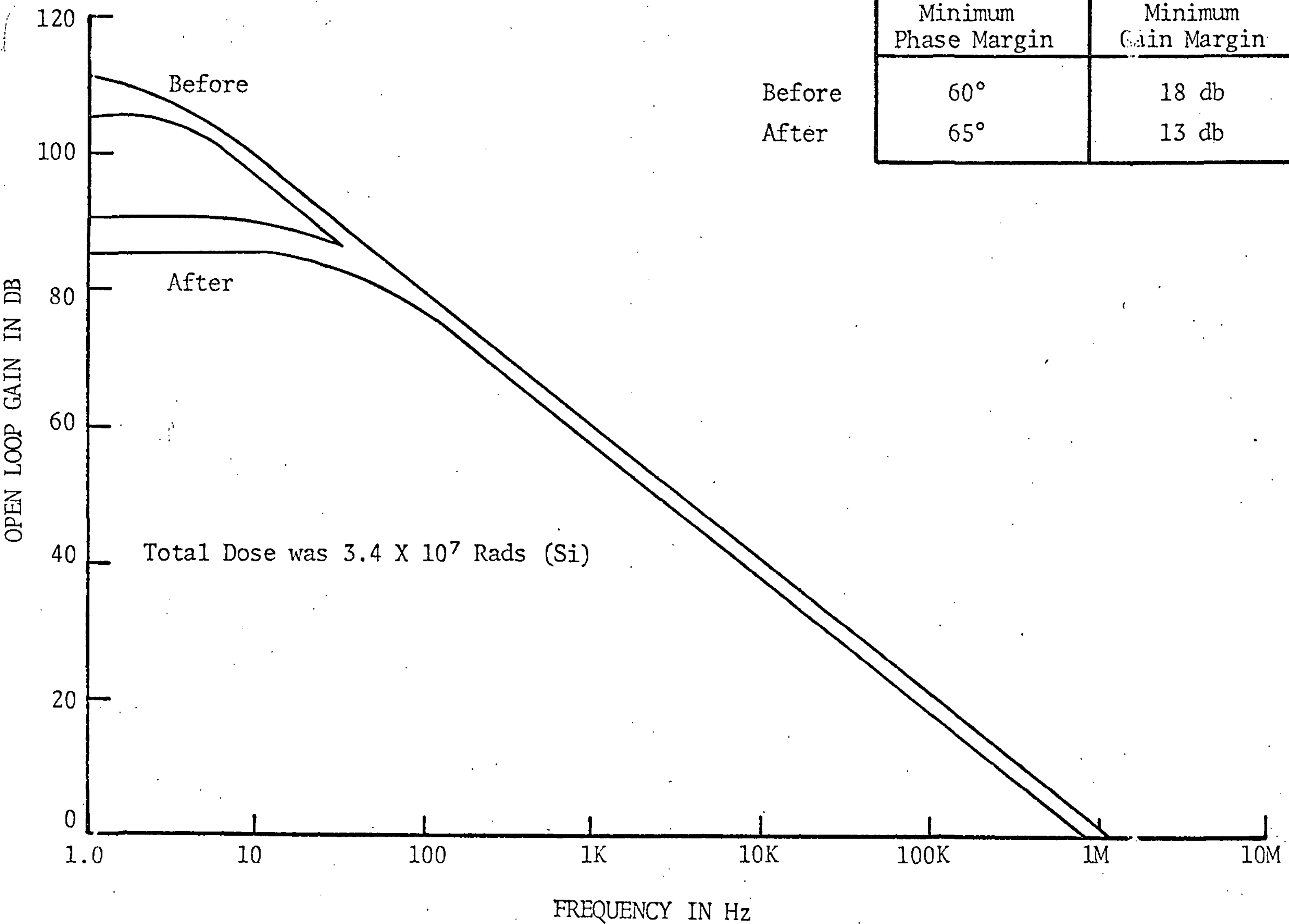
FIGURE 9.

OPEN LOOP GAIN vs FREQUENCY FOR SILICONIX LM101 UNITS
BEFORE AND AFTER CO-60 IRRADIATION



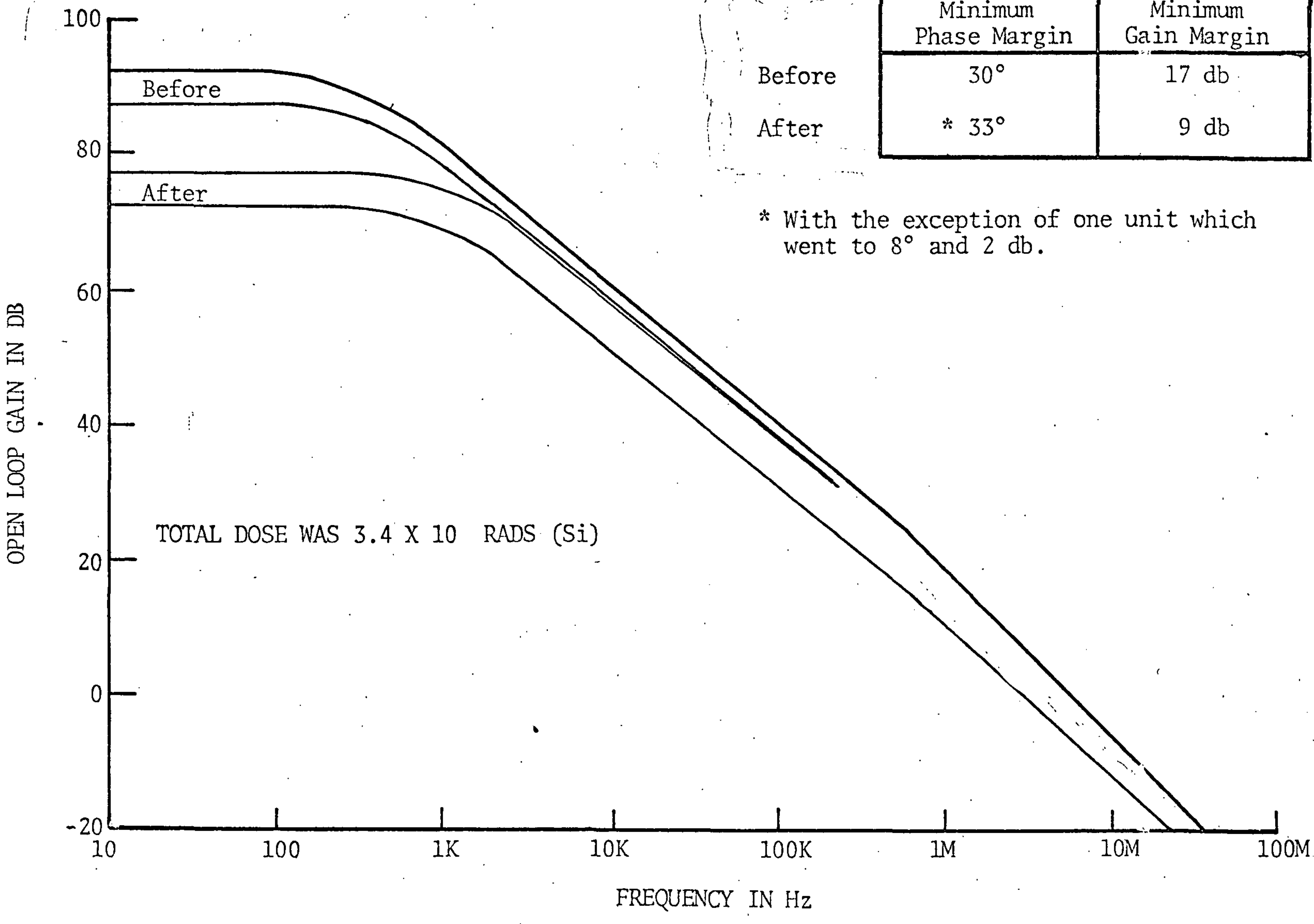
	Minimum Phase Margin	Minimum Gain Margin
Before	70°	19 db
After	75°	>28 db

OPEN LOOP GAIN vs FREQUENCY FOR FAIRCHILD μA741 UNITS
BEFORE AND AFTER CO-60 IRRADIATION



	Minimum Phase Margin	Minimum Gain Margin
Before	60°	18 db
After	65°	13 db

OPEN LOOP GAIN vs FREQUENCY FOR RAD. INC. RA909 UNITS
BEFORE AND AFTER CO-60 IRRADIATION



	Minimum Phase Margin	Minimum Gain Margin
Before	30°	17 db
After	* 33°	9 db

* With the exception of one unit which went to 8° and 2 db.

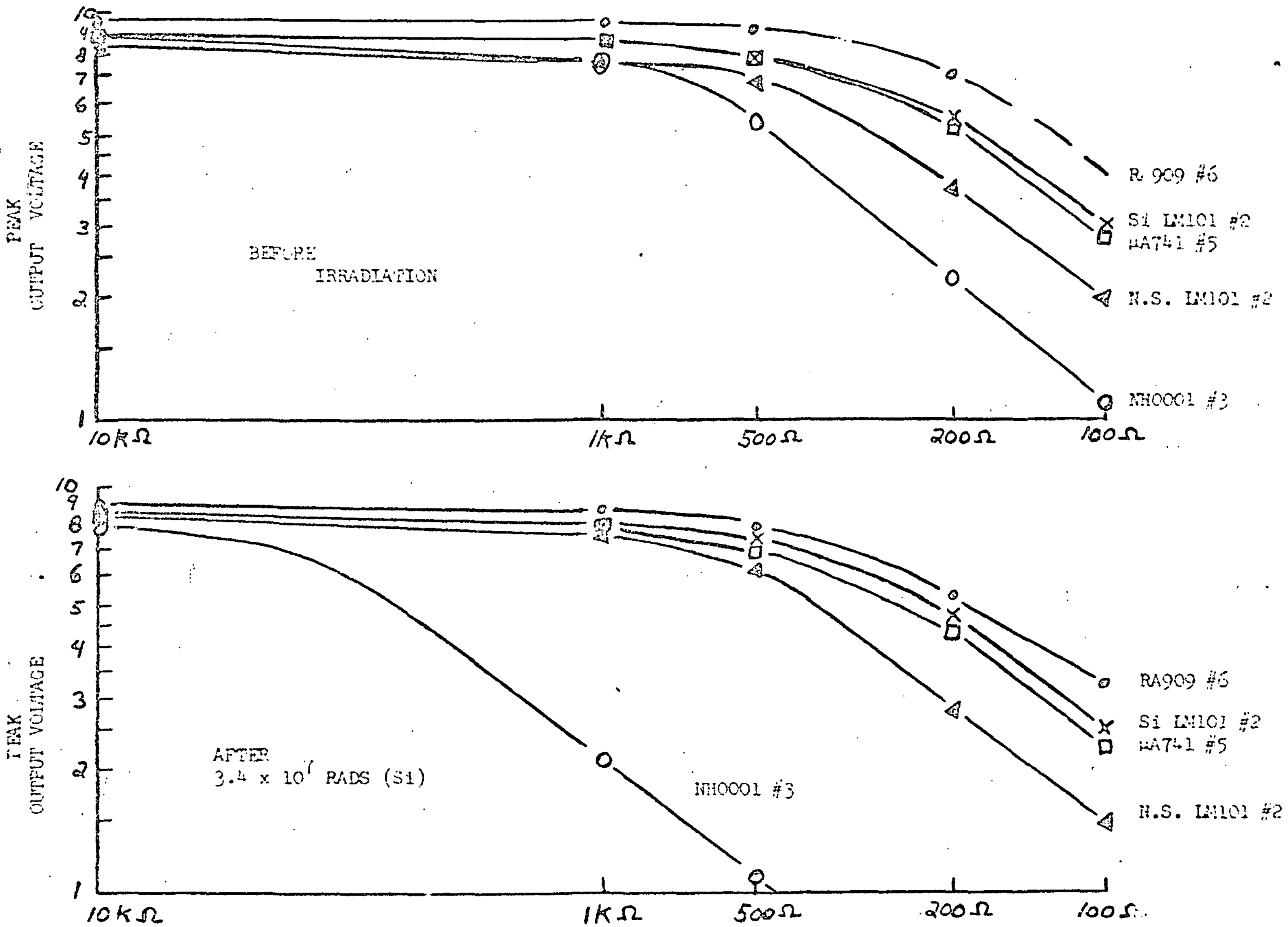


FIGURE 13.

DATA SHEET

		STANDBY POWER CONSUMPTION IN MW		SLEW RATE IN V/μs		EQUIV. INPUT NOISE μV(rms)/μV(Pk. to Pk)	
		BEFORE	AFTER 3.4 X 10^7 RADS	BEFORE	AFTER 3.4 X 10^7 RADS	BEFORE	AFTER 3.4 X 10^7 RADS
NAT. SEMI. LM101	1	29.6	13.2	.25	.12	1.0/5	7.5/50
	2	28.8	12.7	.25	.14	3.5/50	13/100
	3	36.6	26.6	.35	.20	1.0/5	15/100
	4	32.9	24.1	.45	.34	1.0/10	10/75
SILICONIX LM101	1	22.8	15.6	.65	.22	.7/4	2.5/20
	2	21.8	16.2	.65	.34	.7/4	2.0/15
	3	21.2	15.5	.55	.23	.7/4	2.0/.5
	4	22.0	15.8	.55	.22	.7/4	3.0/15
FAIRCHILD μA741	1	28.8	25.4	1.0	.90	1.0/5	40/100
	2	24.4	21.4	1.0	.80	.75/4	3.0/20
	3	27.4	24.4	1.0	.95	.75/4	10/100
	4	21.2	18.6	.86	.70	.75/4	2.0/15
	5	23.6	21.0	1.0	.82	.75/4	5.0/50
RADIATION INC. RA909	1	27.8	25.3	1.5	2.0	2/10	2/10
	2	31.6	28.7	1.8	2.0	2/10	2/10
	3	21.4	19.0	1.0	1.4	1.3/1.5	2.5/15
	4	21.4	18.6	1.0	1.3	1.0/1.5	2.5/15
	5	21.0	18.6	1.0	1.3	1.0/1.5	2.5/15
	6	28.0	20.0	.5	1.6	1.0/1.5	5.0/30
	7	28.2	24.8	1.5	1.8	1.0/1.5	2.5/15
	8	19.0	16.5	1.0	1.3	2.3/10	5.0/30
NAT. SEMI. NH0001	1	1.27	.67	.25	.20	1.5/20	10/100
	2	1.02	.76	.25	.19	3.5/15	20/100
	3	.98	.76	.23	.18	3/15	5/25

OPEN LOOP FREQUENCY RESPONSE AND STABILITY CHARACTERISTICS

		FREQ. (Hz) @ 3 db down		FREQ. (KHz) @ 0 db		PHASE MARGIN		FREQ. (MHz) @ 0° Phase		GAIN (db) MARGIN	
		BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
NAT. SEM. LM101	1	2.0	33	275	124	60°	75°	4.3	3.5	30	>33
	2	2.5	35	300	131	80°	80°	4.6	3.6	30	>32
	3	1.0	15	450	240	75°	70°	3.2	2.6	22	24
	4	1.5	25	600	370	70°	65°	3.2	2.2	19	17
SILICONIX LM101	1	1.5	10	700	232	70°	80°	4.5	4.6	19	31
	2	2.3	10	670	366	70°	75°	4.8	4.8	20	28
	3	1.6	9.2	560	247	70°	80°	4.6	5.1	20	34
	4	2.7	15	550	262	75°	80°	5.3	5.6	21	31
FAIRCHILD μA741	1	1.8	45	1100	1100	65°	70°	8.6	6.3	21	16
	2	2.5	55	1000	1000	70°	70°	7.4	5.7	20	15
	3	3.5	40	1100	1100	65°	68°	8.0	6.1	20	14
	4	2.0	22	900	900	60°	65°	5.5	4.1	19	13
	5	5.0	30	1000	1100	65°	65°	7.0	5.1	19	13
RADIATION INC. RA909	1	380	1080	4500	4400	40°	30°	25	12.5	19	24
	2	430	1230	5700	3100	40°	8°	20	3.7	13	2
	3	350	950	4100	4400	36°	34°	26	10.2	19	10
	4	280	840	3600	3500	40°	35°	20	8.6	18	10
	5	260	870	3500	3600	35°	33°	22	8.0	19	9
	6	280	870	5200	4300	36°	36°	26	11.0	17	10
	7	360	1100	5200	5000	37°	33°	25	12.5	17	11
	8	270	860	3700	3500	30°	36°	20	9.1	19	10

PEAK OUTPUT VOLTAGE vs LOAD RESISTANCE

LOAD RESISTANCE IN OHMS			BEFORE						AFTER 3.4 X 10^7 RADS (Si)					
			∞	10K	1K	500	200	100	∞	10K	1K	500	200	100
NAT. SEMI. LM101	1	+	9.4	9.2	8.3	6.8	4.0	2.1	9.4	9.2	5.0	2.9	1.2	.65
		-	8.5	8.5	7.8	6.8	4.0	2.1	8.7	8.6	7.6	6.3	3.1	1.6
	2	+	9.4	9.2	8.3	6.9	3.9	2.0	9.4	9.2	5.5	3.3	1.5	.75
		-	8.5	8.4	7.6	6.9	3.9	2.0	8.6	8.5	7.6	6.1	2.9	1.5
	3	+	9.4	9.2	8.6	7.4	4.3	2.2	9.4	9.3	8.3	6.9	3.6	1.9
		-	8.5	8.5	7.8	7.0	4.1	2.2	8.7	8.6	7.8	7.0	3.7	1.9
	4	+	9.5	9.2	8.4	7.2	4.1	2.1	9.4	9.3	8.0	6.6	3.2	1.7
		-	8.5	8.3	7.7	6.9	4.1	2.1	8.6	8.6	7.7	6.8	3.7	1.9
SILICONIX LM101	1	+	9.8	9.6	9.2	8.5	4.6	2.3	9.4	9.2	8.7	6.0	2.7	1.5
		-	9.3	9.2	8.6	7.9	5.6	3.1	8.8	8.7	8.0	7.3	4.9	2.6
	2	+	9.8	9.6	9.2	8.5	4.6	2.3	9.4	9.2	8.6	5.8	2.6	1.4
		-	9.3	9.2	8.6	7.9	5.5	3.0	8.7	8.7	8.0	7.3	4.8	2.5
	3	+	9.7	9.5	9.2	8.4	4.7	2.4	9.4	9.2	8.7	6.4	3.0	1.6
		-	9.3	9.2	8.6	7.9	5.5	3.1	8.8	8.7	8.0	7.3	4.8	2.5
	4	+	9.8	9.6	9.2	8.5	4.8	2.4	9.4	9.2	8.2	5.3	2.4	1.2
		-	9.2	9.1	8.5	7.9	5.5	3.0	8.8	8.7	8.0	7.4	4.7	2.5
FAIRCHILD μA741	1	+	9.8	9.7	9.4	8.6	4.5	2.2	9.4	9.3	8.9	8.0	4.3	2.2
		-	9.4	9.1	8.5	8.0	6.2	3.3	8.8	8.6	8.0	7.3	5.2	2.6
	2	+	9.8	9.6	9.2	8.4	4.0	2.1	9.4	9.3	8.8	7.8	3.7	1.9
		-	9.4	9.2	8.6	8.0	5.9	3.1	8.8	8.7	8.0	7.2	4.7	2.4
	3	+	9.8	9.6	9.2	8.6	4.4	2.1	9.4	9.3	8.9	8.0	3.9	2.0
		-	9.4	9.1	8.6	7.9	6.1	3.1	8.8	8.6	7.9	7.2	4.9	2.5
	4	+	9.8	9.7	9.2	8.1	3.8	1.9	9.4	9.3	8.7	7.3	3.3	1.7
		-	9.4	9.3	8.5	7.8	5.6	2.9	8.8	8.6	7.8	7.0	4.5	2.3
	5	+	9.8	9.6	9.2	8.2	3.8	1.9	9.4	9.3	8.8	7.5	3.6	1.8
		-	9.3	9.1	8.4	7.8	5.4	2.8	8.8	8.6	7.9	7.1	4.5	2.3

PEAK OUTPUT VOLTAGE vs LOAD RESISTANCE

(Continued)

LOAD RESISTANCE IN OHMS			BEFORE						AFTER 3.4 X 10^7 RADS (Si)					
			∞	10K	1K	500	200	100	∞	10K	1K	500	200	100
RADIATION INC. RA909	1	+	8.6	8.6	8.5	8.4	7.9	-- NO DATA TAKEN --	8.1	8.1	8.0	7.9	7.1	4.6
		-	9.7	9.6	9.5	9.3	7.9		9.2	9.1	9.0	8.7	6.6	4.1
	2	+	8.4	8.4	8.3	8.1	7.6		8.0	8.0	7.9	7.7	6.7	4.3
		-	9.8	9.7	9.6	9.8	7.7		9.2	9.1	8.9	8.4	6.1	3.7
	3	+	8.8	8.7	8.6	8.4	7.8		8.2	8.2	8.1	7.9	6.7	4.3
		-	9.7	9.6	9.5	9.2	7.4		9.1	9.1	8.8	8.1	5.3	3.2
	4	+	8.7	8.6	8.5	8.3	7.5		8.2	8.2	8.1	7.8	5.8	3.5
		-	9.8	9.7	9.5	9.2	7.2		9.1	9.1	8.8	8.0	5.0	3.0
	5	+	8.7	8.7	8.5	8.4	7.5		8.2	8.2	8.0	7.8	5.7	3.5
		-	9.8	9.7	9.4	9.2	7.2		9.1	9.1	8.8	8.0	5.1	3.0
	6	+	8.5	8.5	8.4	8.2	7.4		8.1	8.0	7.9	7.6	6.1	4.0
		-	9.8	9.7	9.5	9.2	7.2		9.1	9.0	8.7	8.0	5.4	3.3
	7	+	8.4	8.4	8.3	8.1	7.5		8.0	8.0	7.9	7.7	6.1	3.8
		-	9.8	9.7	9.5	9.3	7.6		9.1	9.0	8.8	8.2	5.5	3.3
	8	+	8.6	8.6	8.5	8.3	7.5		8.2	8.2	8.0	7.7	5.9	4.0
		-	9.8	9.8	9.5	9.2	7.2		9.1	9.0	8.8	8.0	5.2	3.1
NAT. SEMI. NH0001	1	+	8.1	7.8	7.1	6.6	4.2	2.3	7.9	7.3	3.2	1.7	.66	.34
		-	9.4	9.2	7.1	5.6	2.2	1.2	8.8	7.7	2.6	1.4	.54	.28
	2	+	8.4	8.1	7.4	6.8	3.5	1.9	8.3	7.7	2.1	1.1	.43	.22
		-	9.6	9.3	7.9	6.6	2.9	1.5	8.9	8.1	2.9	1.6	.62	.32
	3	+	8.5	8.3	7.6	6.9	3.5	1.9	8.3	7.7	2.3	1.2	.47	.24
		-	9.6	9.2	7.6	5.4	2.2	1.1	8.9	8.0	2.1	1.1	.44	.23

QUAD FET DATA

I_{GSS} IN nA

DOSE IN RADS	0	10^4	10^5	8.1×10^6	3.4×10^7
1-A	.007	.42	180	160	110
B	.046	.48	140	190	140
C*	.003	.15	2	18	14
D*	.015	.17	2	19	12
2-A	.012	.18	7.6	170	150
B	.016	.16	6.4	150	140
C*	.008	.08	1.2	14	8
D*	.010	.09	1.4	14	8
3-A	.030	.19	6.2	220	190
B	.035	.19	5.1	180	180
C*	.026	.08	.9	15	6
D*	.024	.07	.9	15	7
4-A	.022	.26	8.1	67	56
B	.017	.25	7.9	64	53
C*	.017	.10	1.2	13	10
D*	.024	.13	1.7	11	9

* Biased at I_{DS} = 10 ma during irradiation; all others biased at I_{DS} = 0.

V_P IN NEGATIVE VOLTS

DOSE IN RADS	0	10^4	10^5	8.1×10^6	3.4×10^7
1-A	3.30	3.31	3.32	3.33	3.33
B	3.25	3.28	3.29	3.29	3.30
C	3.33	3.35	3.35	3.35	3.35
D	3.09	3.10	3.12	3.11	3.11
2-A	4.33	4.34	4.34	4.34	4.35
B	4.93	4.93	4.94	4.94	4.95
C	4.23	4.24	4.24	4.24	4.23
D	4.13	4.14	4.14	4.14	4.14
3-A	4.92	4.93	4.93	4.93	4.94
B	3.90	3.89	3.89	3.90	3.90
C	4.75	4.76	4.76	4.76	4.77
D	5.06	5.04	5.04	5.06	5.05
4-A	5.09	5.11	5.11	5.16	5.17
B	5.14	5.16	5.18	5.23	5.24
C	4.96	4.97	4.98	4.98	4.97
D	5.53	5.54	5.55	5.56	5.54

R_{ON} IN OHMS

DOSE IN RADS	0	3.4 X 10	DOSE IN RADS	0	3.4 X 10
1-A	26.4	40.3	3-A	32.3	35.4
B	26.5	40.3	B	37.8	41.0
C	26.4	40.4	C	33.3	36.6
D	26.9	41.2	D	32.0	34.9
2-A	24.8	27.4	4-A	34.9	44.4
B	23.2	25.6	B	35.9	46.8
C	25.1	27.6	C	36.1	45.9
D	25.5	28.0	D	33.9	43.5

$I_{D(Off)}$ IN nA

DOSE IN RADS	0	10^4	10^5	8.1×10^6	3.4×10^7
1-A	.004	.26	150	70	49
B	.022	.26	110	70	49
C	.007	.06	.9	8	7
D	.009	.06	.9	9	7
2-A	.007	.11	4.9	67	63
B	.006	.10	4.4	63	62
C	.006	.04	.6	8	4
D	.006	.04	.7	7	4
3-A	.016	.09	3.7	81	79
B	.021	.08	3.5	55	63
C	.016	.03	.4	7	3
D	.013	.03	.4	7	3
4-A	.013	.14	5.6	32	28
B	.011	.14	5.1	31	27
C	.013	.05	.6	7	4
D	.017	.06	.9	5	4

DUAL PNP DATA

h_{FE} @ I_C = .1ma

DOSE IN RADS	0	10^4	10^5	8.1 X 10^6	3.4 X 10^7
1-A	116	115	100	17.5	13.7
1-B	116	112	100	17.5	13.5
2-A*	156	137	103	9.3	8.7
2-B	157	137	114	16.4	15.2
3-A*	125	116	91	8.6	6.7
3-B	128	118	100	15.6	13.5
4-A*	182	167	132	10.4	7.7
4-B	176	161	133	18.8	15.2
5-A	133	127	116	21.3	13.3
5-B	137	128	118	22.2	13.8

*Biased at I_C = 0 during irradiation; all others biased at I_C = .1 ma.

I_{CBO} IN nA @ V_{CB} = 10V

DOSE IN RADS	0	10^4	10^5	8.1 X 10^6	3.4 X 10^7
1-A	.10	.14	.90	17	14
1-B	.10	.17	.42	18	15
2-A	.11	.19	.44	37	48
2-B	.10	.17	.40	15	8
3-A	.05	.08	.28	15	12
3-B	.05	.07	.30	15	11
4-A	.18	.23	.44	15	14
4-B	.18	.24	.46	18	14
5-A	.13	.17	.34	18	21
5-B	.14	.18	.32	18	20

ΔV_C IN mV

DOSE IN RADS	0	10^4	10^5	8.1 X 10^6	3.4 X 10^7
1	-59	-60	-57 to -62	-65 to -67	-69 to -78
2	-10	-10 to -16	-12 to -15	+85 & decreasing	+70 & decreasing
3	+80	+74 to +80	+72 to +78	+80 to +85	+74 to +82
4	-105	-102 to -104	-104 to -107	-90 to -92	-97 to -100
5	+85	+79 to +83	+82 to +84	+84 to +86	+78 to +84

NOTE: $V_{BE(Offset)} = 6.2 \times 10^{-3}\ \Delta V_C$

Table 12.2 Changes in Parameters of a RCTL NOR Gate Due To Bombardment With 20-MeV Protons to an Integrated Flux of 1.7×10^{13} Protons/cm^2. (Ref. 12.75)

Symbols	Parameter		Average changes, percent
β	Transistor gain	$\phi_t = 1.5 \times 10^{12}$ P/cm^2	-50
		$\phi_t = 1 \times 10^{13}$ P/cm^2	-91
		$\phi_t = 1.7 \times 10^{13}$ P/cm^2	-95
$V_{CE}^{(sat)}$	Output saturation voltage		+272
$V_{min(one)}$	Input minimum Logical "one" Voltage	No load	+298
		Fan-out of 1	+296
		Fan-out of 5	+287
$V_{max(zero)}$	Input maximum Logical "zero" Voltage	No load	+184
		Fan-out of 1	+165
		Fan-out of 5	+99
I_L	Leakage Currents	Input	No significant changes
		Output	No significant changes
I_{IN}	Input drive current requirement		-4
I_{out}	Output driving current Capability	Input = 0 volt	+5 to 10
		Input = 0.5 volt	+5 to 8
V_f	Isolation diode Forward voltage		-9
R_L	Load resistor		+11
t_r	Rise time		Nonconclusive results Output pulses distorted
t_s	Storage time		
t_f	Fall time		
t_d	Delay time		

Table 12.3 Electron Fluence at First Failure For Gates Tested. (Ref. 12.77)

Failure Fluence, 10^{14} e/cm^2 (3 MeV)	Specified Typical Propagation Delay, ns	Logic Configuration	Function	Construction Method
7	150	RCTL	NOR	Diffused[b]
17	12	RTL	NOR	Epitaxial
25	40	RTL	NOR	Epitaxial
33	25	DTL	NAND	Diffused[b]
84	30	DTL	NAND	Diffused[b]
100	43	DTL	NAND	Epitaxial
130	6	ECL	NOR	Epitaxial
180	9	T^2L	NAND	Epitaxial

Table 12.4 Electron Fluence at First Failure For Flip-Flops Tested. (Ref. 12.77)

Failure Fluence, 10^{14} e/cm^2 (3 MeV)	Specified Typical Clock Rate, mc	Logic Configuration	Type	Construction Method
12	1.0	RCTL	RS	Diffused[b]
22	10.0	RTL	JK	Epitaxial
50	4.8	DTL	JK	Diffused[b]
55	14.0[a]	ECL	dcRS	Epitaxial
74	12.0[a]	DTL	RS	Diffused[b]
77	10.0	T^2L	RS	Epitaxial
93	8.5	RTL	D	Epitaxial
110	8.0	DTL	JK	Epitaxial

(a) Estimated.

(b) No epitaxial processing.

Table 12.5 Comparative Parametric Changes in Gate Circuits. (Ref. 12.77)

Description	RTL Epitaxial 12 ns	RTL Epitaxial 40 ns	DTL Epitaxial 43 ns	ECL Epitaxial 6.0 ns	DTL Diffused 30 ns	T^2L Epitaxial 9 ns	RCTL Diffused 150 ns	DTL Diffused 25 ns
Accumulated exposure (10^{14} e/cm^2) (3MeV)	43	34	120	200	85	180	7.8	35
	Average Percent Change of Static Test Units With Respect To Control Units							
Input threshold voltage	+9.6	+7.6	+4.5	+3.4	+5.5	+8.3	+88.9	--
Output drive current capability to ground	N. S.	N. S.	--	≠	--	N. S.	--	-70.0
Output drive current capability to positive supply	--	--	--	--	-70.8	-49.6	--	-41.0
Output saturation voltage	+38.4	+45.6	+91.3	--	--	--	+44.2	--
Storage time	-48.6	-18.8	-33.1	N. S.	-9.4	-50	N. S.	-40.0
Delay time	+7.2	N. S.	+8.9	-12.0	+9.4	+14	N. S.	+71
Rise time	+16.6	+20.4	+50.8	+26.0	+49.0	+63	+5.7	+102
Fall time	N. S.	N. S.	+1.7	+100.0	-5.2	+631	+8.2	+1
Transistor gain	-59.8	--	--	-85.0	--	--	-74.0	-107
Resistance	+1.0	+1.0	+2.6	+3.8	+1.6	--	+8.0	+0.8
Diode forward voltage	N. S.	-0.4	+0.9	--	-0.8	-1.2	-5.6	--

Note: N. S. = No significant change.
≠ = All units failed test.
-- = Data not taken or not conclusive.

Table 12.6 Comparative Parametric Changes in Flip-Flip Circuits. (Ref. 12.77)

Description	RTL Epitaxial 8 mc	RTL Epitaxial 8.5 mc	DTL Epitaxial 8 mc	ECL Epitaxial 12 ns	DTL Diffused 10 mc	T^2L Epitaxial 10 mc	RCTL Diffused 1.0 mc	DTL Diffused 4.8 mc
Accumulated exposure (10^{14} e/cm^2) (3 MeV)	92	110	110	140	78	130	17	39
	Percent Change in Static Test Units With Respect to Control Units							
Direct input threshold voltage	+13.2	+11.8	+5.4	--	+4.6	--	+60.2	✢
Clocked input threshold voltage	--	-7.6	+2.8	+6.2	N. S.	+1.1	-5.4	+82.0
Minimum clock-pulse amplitude width to trigger	+4.8	+7.0	N. S.	--	+1.4	N. S.	+15.0	-32.4
Minimum clock-pulse width to trigger	N. S.	+18.0	+18.4	--	N. S.	--	--	--
Output drive current capability to ground	N. S.	-3.5	N. S.	--	N. S.	-62.6	-9.9	-52.2
Output drive current capability to positive supply	-54.1	-59.3	-64.5	-3.3	-58.1	-46.5	--	-53.3
Output logical "one" voltage	+1.1	N. S.	N. S.	+10.8	N. S.	-0.5	N. S.	✢
Output saturation voltage	+35.8	--	--	--	--	--	--	--
Storage time	-27.1	-4.2	-15.0	N. S.	--	-27.2	+7.0	-38.0
Delay time	-25.2	-12.4	N. S.	-34.6	+3.6	-9.2	+3.7	N. S.
Rise time	+18.6	+38.4	+52.0	+18.6	+59.2	+102.8	+59.0	+135.6
Fall time	-8.2	-1.0	+5.6	N. S.	-2.7	+43.3	+2.2	+70.0
Transistor gain	--	--	--	-91.2	--	--	--	--
Resistance	-0.9	--	+0.8	+3.0	+1.49	--	+7.1	--
Diode forward voltage	N. S.	--	--	--	--	--	--	--

Note: N. S. = No significant change.
✢ = All units failed test.
-- = Data not taken or not conclusive.