LITERATURE SEARCH AND RADIATION STUDY ON ELECTRONIC PARTS

FINAL REPORT

JPL Contract No. 952565

MAY 1970

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-- Effects of Radiation
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Prepared by

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Literature Search and Radiation Study On Electronic Parts

Final Report

JPL Contract 952565

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MAY 1970

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ABSTRACT

A survey has been made of radiation effects literature pertinent to effects of low-level steady-state neutron, gamma, and proton environments on electronic components. A bibliography of over 300 references was compiled.

The data were scanned and an analysis made of the radiation effects state-of-the-art for electronic components on a deep space mission that might be exposed to planetary radiation belts and to on-board radioisotope thermoelectric generator environments.

Emphasis was placed on permanent parameter degradation, temporary parameter drifts, parameter degradation factors, hardening techniques, and screening techniques.

ACKNOWLEDGEMENTS AND KEY WORDS

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KEY WORDS

Radiation

Neutron

Gamma

Radioisotope thermoelectric generator

Proton

Electronic Components

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1.0 SUMMARY

1.10 The objective of this program was to perform a literature survey and to analyze data pertinent to radiation damage to electronic parts typical of those utilized in deep space missions. The radiation environments considered were: 1) that produced by radioisotope thermoelectric generators (RTGs), i.e.: low-level steady-state fission neutron and gamma spectra, and 2) high energy protons, both those generated during solar events and those trapped in planetary belts. Although it was beyond the scope of this program to consider electron effects, where data was readily available such effects were included.

During the course of the program the following facilities were utilized:

a. REIC (Radiation Effects Information Center, Battelle Memorial Institute).

b. NASA (computerized search performed by the Boeing Aerospace Technical Library).

c. DDC (Defense Documentation Center).

d. DASA (Defense Atomic Support Agency).

e. Boeing Aerospace Library containing the following tools:

  1) KWIC File Index citing Boeing research documentation.
  2) Engineering Index (Electronics Section)
  3) Physics Abstracts
  4) Electronics (an English Index)
  5) IDEP Files
  6) Plus the many personel reference books and documents of the Boeing Radiation Effects Group.

These searches resulted in hundreds of references of which about 260 were retained after screening for pertinent radiation environment and part types.

Analysis of the literature revealed that, in general, for most part types there are at least some neutron and gamma data but that for many types no proton data exist. The extent of the data coverage and its significance is discussed for each part type

in the report. Primarily the analysis was directed toward the determination of permanent degradation of parameters, temporary drifts of parameters, parameter degradation factors and hardening and screening procedures. Where appropriate, additional testing was recommended.

The relative sensitivities of components as determined from the analysis are summarized in Figures 1.1 thru 1.3. In general, SCRs and unijunction devices appear to be very vulnerable and SCR response is especially unpredictable. For this reason it is recommended that their usage be avoided where possible.

Power and low-frequency transistors appear to be the next most vulnerable group. Since their behavior is better understood, these devices can be used if sufficient gain margin is allowed or other concern is taken. It should be noted that in some cases shielding may be necessary.

Linear integrated circuits, reference diodes, and MOS devices also present a problem but if properly characterized, should be usable. In all three cases, in order to assure reliable performance, testing of statistical samples is recommended.

Resistors and capacitors, in comparison to the active semiconductor components, do not present a serious degradation problem, although it is not clear that the effects of low-level radiation exposures on long-term reliability has been fully evaluated for all cases (especially for resistors).

From the study, it can be concluded that: 1) for the present state of the art many active components will be seriously degraded by radiation during interplanetray missions, 2) in many cases data is inadequate to do more than make gross estimates of degradation of part type performance, 3) data evaluating proton damage is not available for many part types, 4) for most part types hardening and screening procedures are not known or are in a developmental stage, 5) although part degradation can be estimated for each environmental component, there is no data indicating how to assess the total degradation due to combined environments, and 6) using currently available data system reliability in a radiation environment would be difficult to assess, particularly for part types for which the radiation levels are near the threshold for damage. Even methods of assessing such damage needs to be more

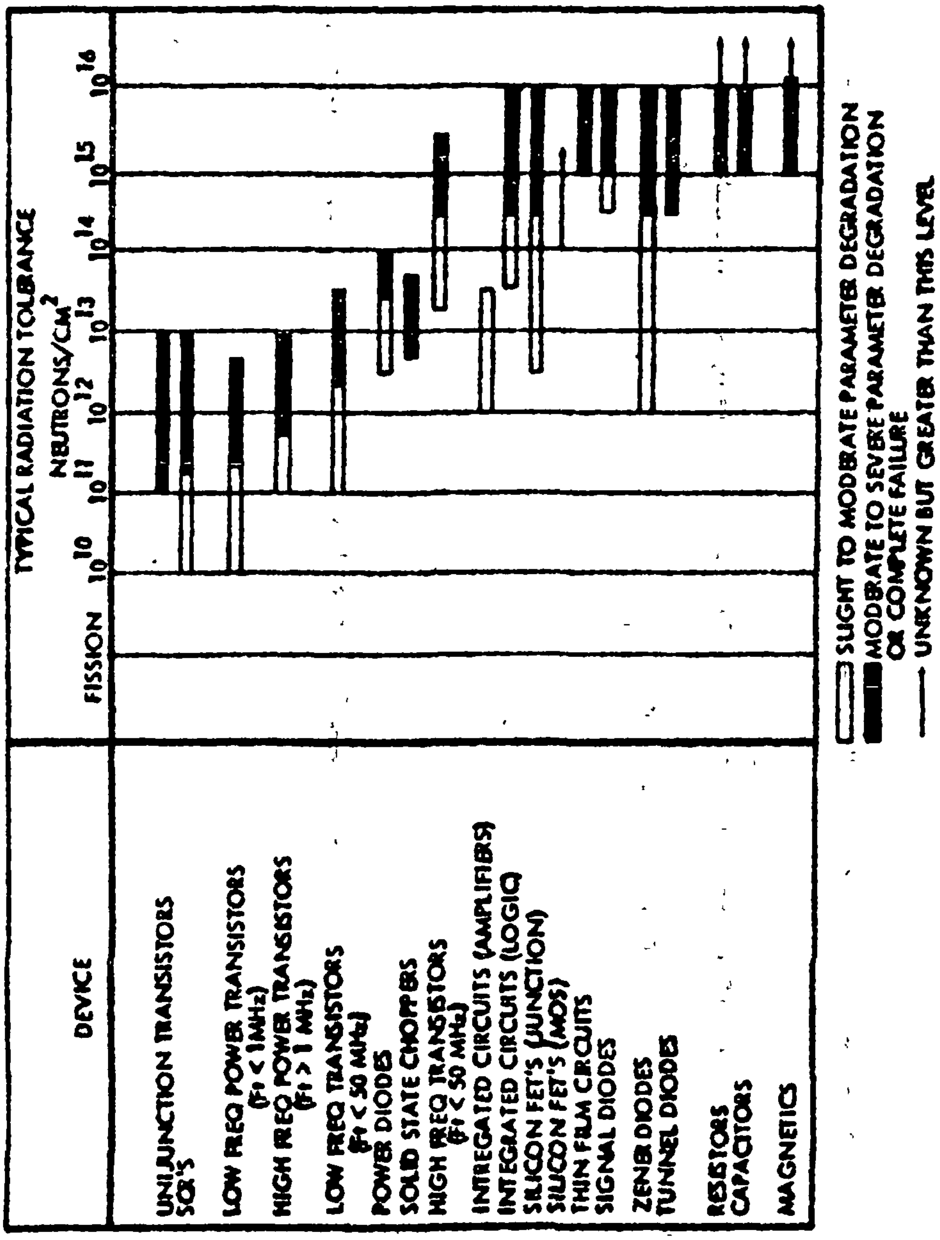


Figure 1.1 Survey of Component Neutron Degradation

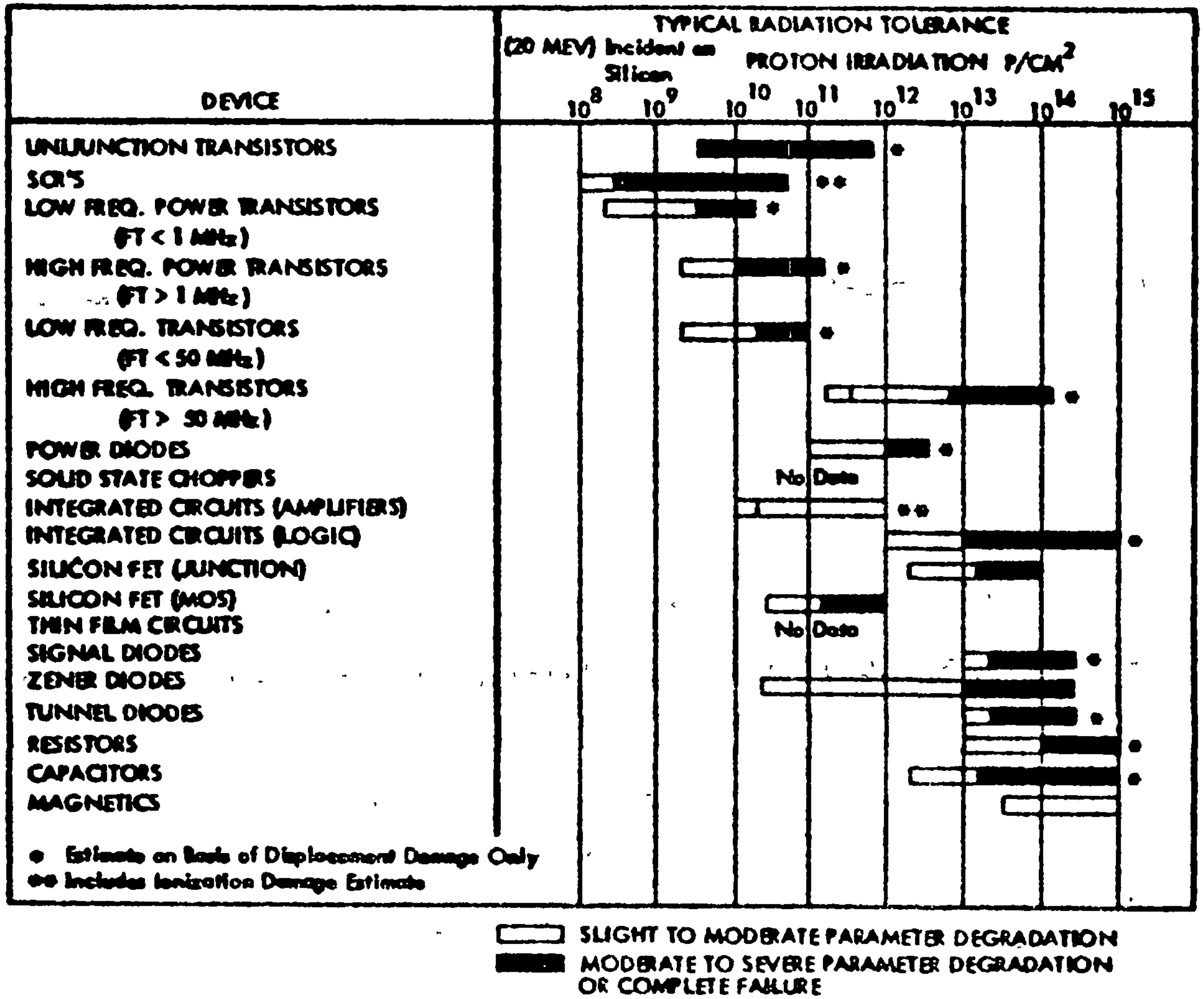


Figure 1.2 Survey of Component Proton Degradation

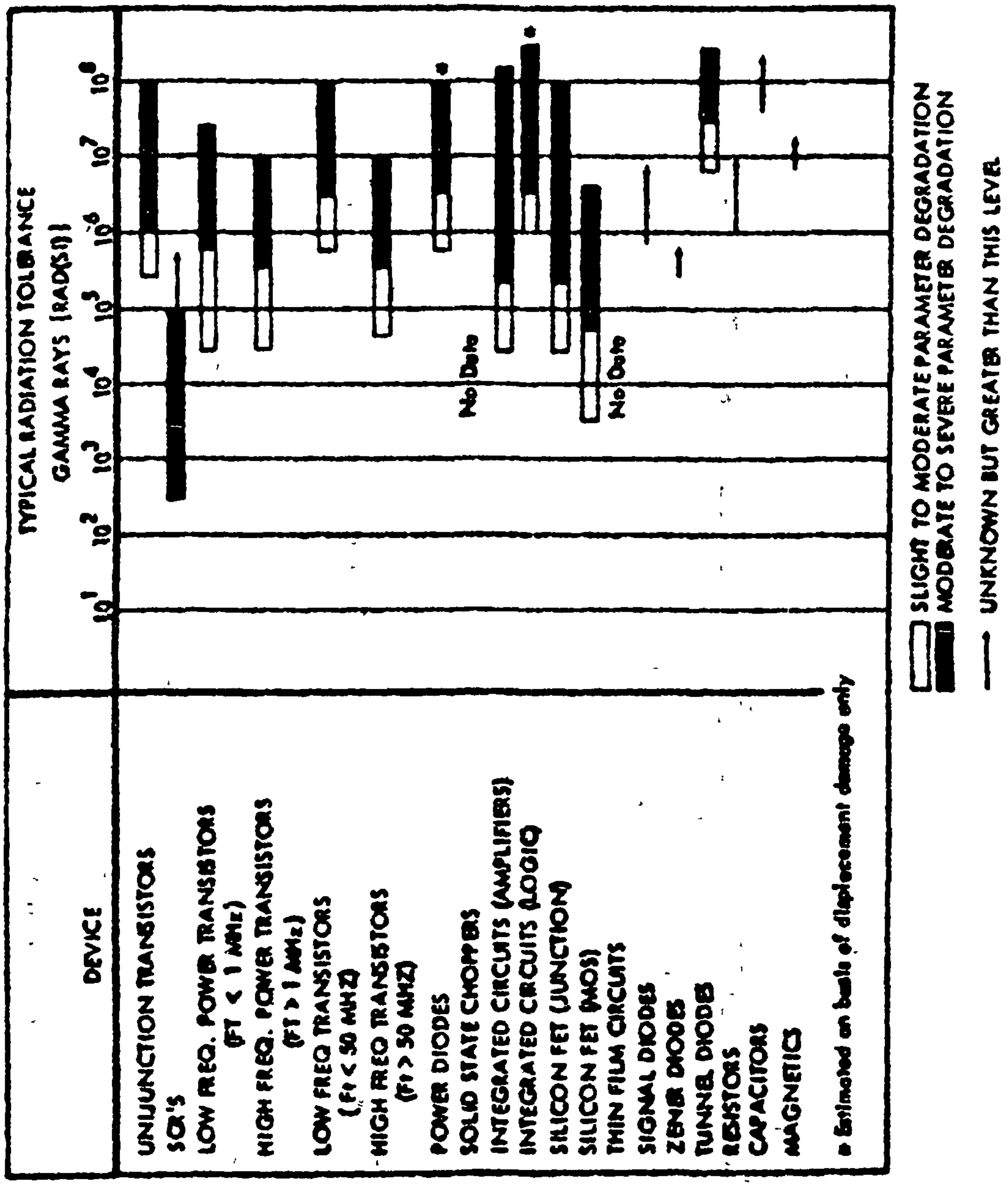


Figure 1.3 Survey of Component Gamma Degradation

fully explored.

It is recommended that; 1) evaluation testing be performed to obtain data on part types where no data exists and that lack of data is significant (these cases are noted in the report), 2) that testing in combined environments be performed to obtain insight into how to assess the total threat to parts in interplanetary missions, and 3) that methods of assessing reliability of irradiated components be more fully explored.

1.20 References

1.21 Bowman, W. C., et al, "Guide Book for AWACS Nuclear Radiation Survivability Study", Boeing Document D204-10317-1, August, 1969.

2.0 INTRODUCTION

The purpose of this program has been (a) to search existing industry and government literature regarding the long-term neutron, and gamma radiation exposure effects on electronic parts and, (b) to analyze the literature and information reviewed during the search with primary emphasis on the effects of plutonium 238 neutron and gamma radiation on electronic parts. Although it was not included in the scope of the contractual effort, data on charged particles such as protons and electrons were included when it was convenient to do so.

The effort has been limited 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 on board radioisotope thermoelectric generators. The analysis included the consideration of catastrophic failures, permanent degradation, temporary parameter drifting during radiation exposure, radiation levels in total integrated doses, degradation factors, and recommended testing.

The analyzed survey is presented in a form useful to persons having a knowledge of electronic parts but not necessarily familiar with radiation effects.

The program began on July 1, 1969 and the analysis was completed February, 1970.

3.0 GENERAL CONSIDERATIONS

Electronics to be used on board spacecraft during deep space missions encounter both particulate and electro-magnetic radiation. The particulate radiation consists of protons, electrons, and neutrons. The electromagnetic radiation consists of gamma and x-rays.

Protons are elementary nuclear particles with a positive electric charge equal numerically to the charge of an electron but whose mass is 1847 times the mass of an electron, or approximately one atomic mass unit. Protons are encountered in the vicinity of planets in the form of belts, i.e., charged particles trapped in the magnetic fields of planets. It is believed that the proton belts around Jupiter may be very intense. In interplanetary space, protons are encountered as a result of solar winds and solar flares, that is, protons are ejected by the sun and travel through space. Such protons have energies ranging from 1 Mev to 100 Mev. A typical spectrum is shown in Figure 3. 1.

Electrons are nuclear particles having unit negative charge and rest mass of 9.107×10^{-28} grams. These particles are many times less massive than protons and are much more penetrating. Energetic electrons in space are primarily found in the vicinity of planets as belts of charged particles trapped in the magnetic fields of planets.

Neutrons are atomic particles having zero charge and having mass approximately equivalent to that of a proton. Due to their lack of charge, neutrons are highly penetrating and when penetrating are attenuated by collisions with nuclei. In space missions, neutrons in significantly large numbers originate on board the spacecraft from radioisotope thermoelectric generators (RTGs).

Electromagnetic radiation encountered on spacecraft consists of gamma rays emanating from nuclear reactions in on board power supplies such as RTGs. X-rays are also generated by the stopping of energetic charged particles such as electrons and protons in dense materials; such radiation is called bremsstrahlung and can be

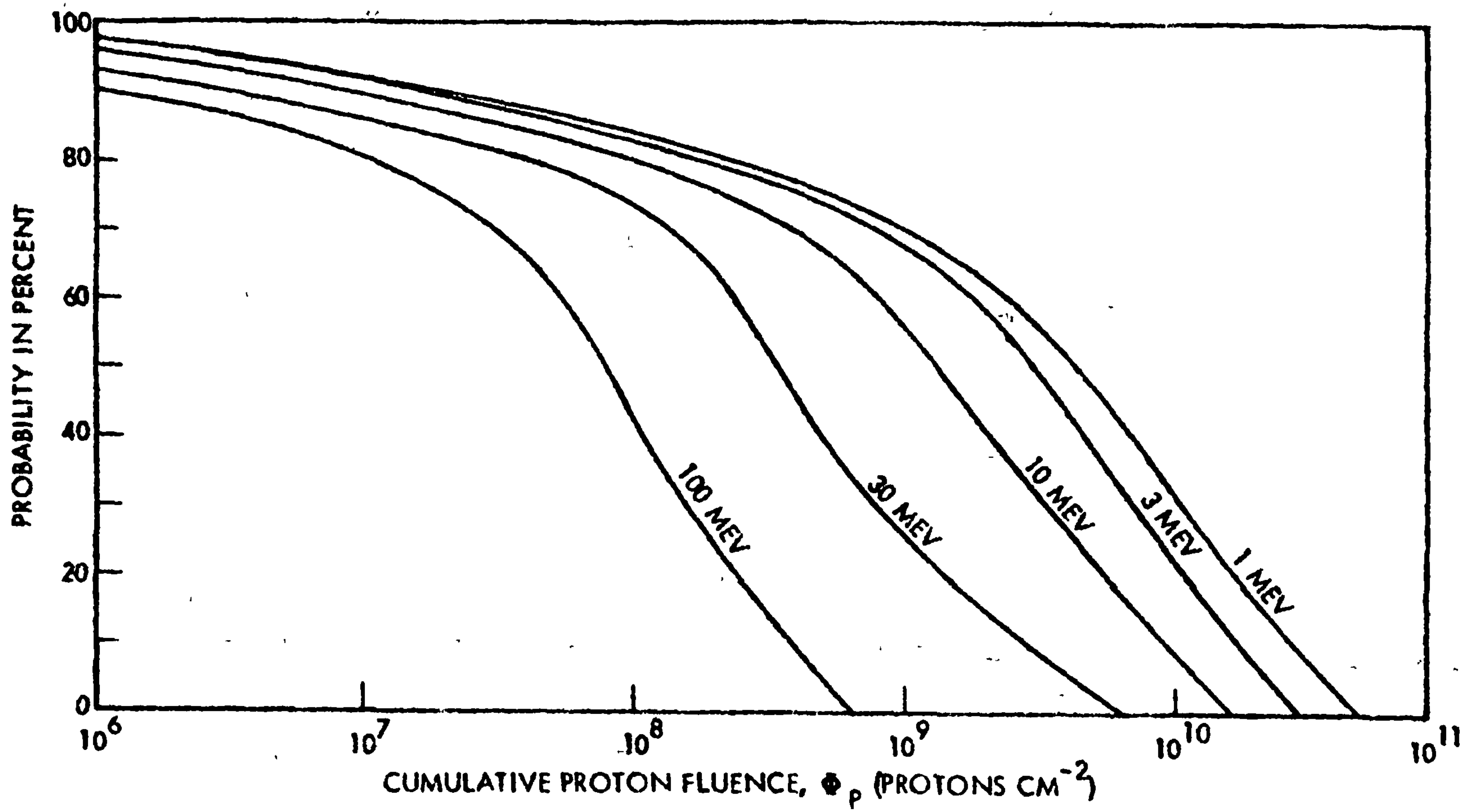


Figure 3.1 Probability for Solar Event Protons on an Earth-Mars Mission (200 Days)

significant in trapped planetary radiation belts.

Radiation is usually measured in two ways. Either in terms of absorbed energy (dose) or in terms of particles per square centimeter (Fluence). For absorbed dose, the most commonly used unit is the Rad. A Rad is defined as 100 ergs absorbed from the radiation field in one gram of irradiated material. It should be pointed out that the rad expresses absorbed dose in a specific material and the type of material is usually denoted by a suffix. For example, a Rad (Si) is 100 ergs of energy absorbed in one gram of silicon. Other common units are roentgen (R), and ergs. g^{-1}(C). In magnitude these units are fairly close. Conversions factors are listed below:

$$1 \text{ Rad(Si)} = 1.1 \text{ roentgen} = 96.4 \text{ ergs} \cdot g^{-1} \text{(C)}$$

$$1 \text{ roentgen} = 0.91 \text{ Rads(Si)} = 87.7 \text{ ergs} \cdot g^{-1} \text{(C)}$$

$$100 \text{ ergs} \cdot g^{-1} \text{(C)} = 1.037 \text{ Rads(Si)} = 1.141 \text{ roentgens}$$

For purposes of this report, since the objective is to establish approximate thresholds and relative sensitivities rather than absolute dosimetry, these units have been converted directly.

Particulate radiation such as electrons, protons, and neutrons are commonly expressed in fluence, or particles per centimeter square. Neutrons are also frequently expressed in nvt where n is neutrons per unit volume, v is velocity and t is time. This term has units of neutrons per centimeter square with the velocity expressing energy spectra. For this report, since only one fission energy spectrum from the RTG is involved, neutrons are expressed in fluence and the energy spectrum is understood to be a fission spectrum.

The effects of nuclear radiation on electronic materials can be grouped essentially into two types:

(1) Displacement effects,

(2) Ionization effects.

Displacement effects are the result of collisions between incident radiation particles and atomic nuclei of the material being bombarded. Displacement in a crystal lattice leaves a hole or vacancy in the lattice at the original site of the displaced atom. The displaced atom, in turn, comes to rest in some interstitial position in the lattice. These vacancy interstitial pairs, commonly called Frenkel defects, cause disruptions in the potential energy within the lattice creating new allowable electron energy levels in the forbidden band gap. In semiconductors, the new energy levels then act as recombination and generation sites and thus in an individual sense may act in the same manner as an impurity (dopant) atom. However, it has been observed that the net effect of displacements in silicon is very different from the controlled effect of donor and/or acceptors introduced for doping purposes. For instance, donor and/or acceptor levels increase the conductivity of the intrinsic crystal, whereas radiation-induced vacancy-interstitial pairs usually decrease the conductivity.

The introduction of vacancy-interstitial pairs, associated with the generation of new electron energy levels in the forbidden band gap, has an effect on quantities like electric and thermal conductivity, carrier mobility, and, especially, minority carrier lifetime. The most important changes for most purposes are the changes in conductivity and minority carrier lifetime.

Changes in conducitivity are usually referred to as a process called "carrier removal" and implies that majority carriers are removed and that the conductivity decreases. The decrease in conductivity occurs in both n- and p-type silicon.

Possibly the most important effect of displacement damage is the enhancement of recombination between conduction electrons and valence holes. Thus, vacancy-interstitial pairs can be thought of as trapping centers for minority carriers, leading to increased recombination with majority carriers.

An important question is what type of nuclear radiation gives rise to displacement damage. In order to displace an atom from its lattice site the bombarding particle must impart sufficient energy to the struck nucleus to overcome the displacement threshold value of the lattice. Since the energy transfer between the radiation particle and the nucleus is a function of their respective masses, the heavier radiation particles are more capable of displacement production than the lighter particles. The relative effectiveness of various particle types for producing displacement in silicon have been determined (Ref. 3. 1) are are presented in Table 3. 1.

The effectiveness of a given particle type to cause displacements is also a function of the particle energy. Figures 3. 2, 3. 3 and 3. 4 illustrate this for protons, electrons, and neutrons. As shown in Figure 3. 2 protons become more effective for causing displacement damage with decreasing energy. This fact has special significance when designing shielding for spacecraft. This significance will be discussed further in the following paragraphs.

When considering the effect of radiation on electronic components, one should consider the effect of shielding which may be inherent in the device packaging or spacecraft structural materials. The range of protons and electrons in aluminum is shown by the graphs in Figures 3. 5 and 3. 6. For shielding thicknesses that do not completely stop the radiation particles, the transmitted particles emerge with reduced energy. In the case of protons, the reduction in energy increases the efficiency for causing displacements.

Ionization effects occur when radiation passes through matter and interacts with atomic electrons within the material imparting sufficient energy to free the electrons from their atomic orbits. While it mightseem that only electrons, protons, and other charged particles can cause ionization, gamma and x-rays are quite effective in producing ionization and excitation; that is the generation of electron-hole pairs. When a gamma photon travels through matter, it generates photo electrons and compton electrons. In generation of photo electrons, all of the energy of the photon is lost, while in the compton process the photon imparts only part of its energy to the scattered electron and reappears as a lower energy photon. The compton scattered electrons, depending on the incident photon energy, generally receive sufficient energy to cause further "secondary" ionization along their path or even displace atoms creating Frenkel defects along their path. Thus, photons although they have zero mass, if sufficiently energetic can cause displacement

Table 3. 1. Equivalences of Particles for Displacement Production in Silicon Transistors (Ref. 3. 21)

Particle Type and Energy	Alpha* 5 MeV	Proton 15 MeV	Neutron TRIGA Reactor	Electron 1. 3 MeV	Gamma Rays Cobalt-60
Alpha* (5 MeV)	1	4.1	1.4×10^{2}	3.75×10^{3}	3.75×10^{5}
Proton 15 MeV	2.5×10^{-1}	1	3.3×10^{1}	9.0×10^{3}	9.0×10^{4}
Neutron (Reactor)	7.1×10^{-3}	3.1×10^{-2}	1	2.8×10^{1}	2.8×10^{3}
Electron 1. 3 MeV	2.7×10^{-4}	1.1×10^{-3}	3.6×10^{-2}	1	1.0×10^{2}
Gamma Rays Cobalt-60	2.7×10^{-6}	1.1×10^{-5}	3.6×10^{-4}	1.0×10^{-2}	1

*Transistor Cans off for 5 MeV Alpha Particles

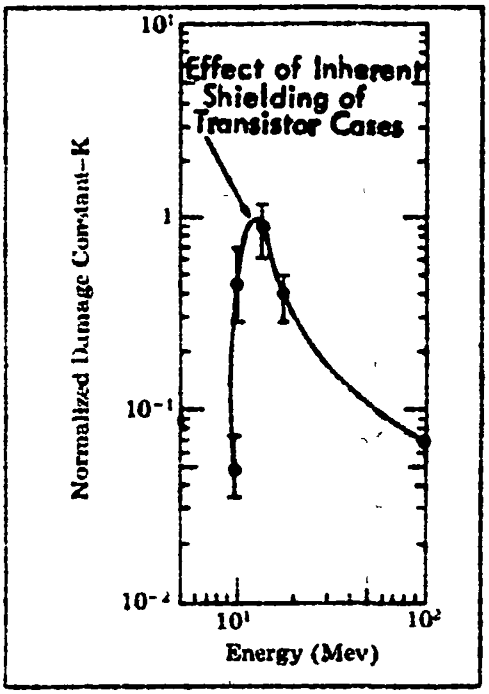


Figure 3.2

Normalized Proton Displacement Damage Constant, K (Ref. 3.22

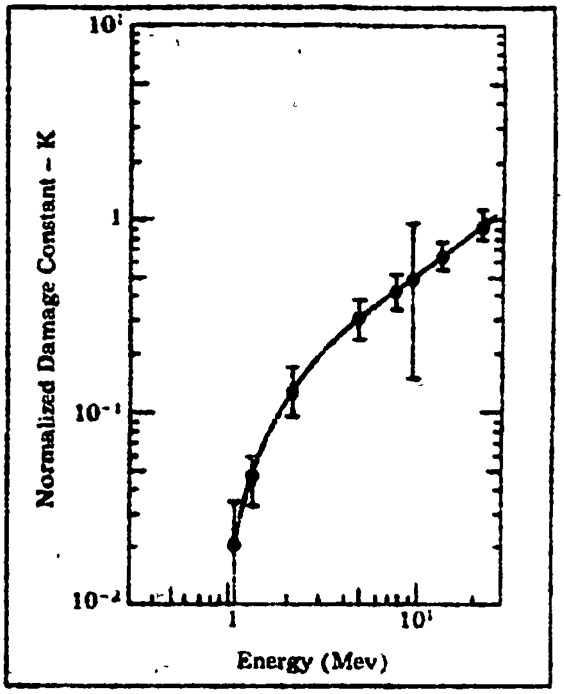
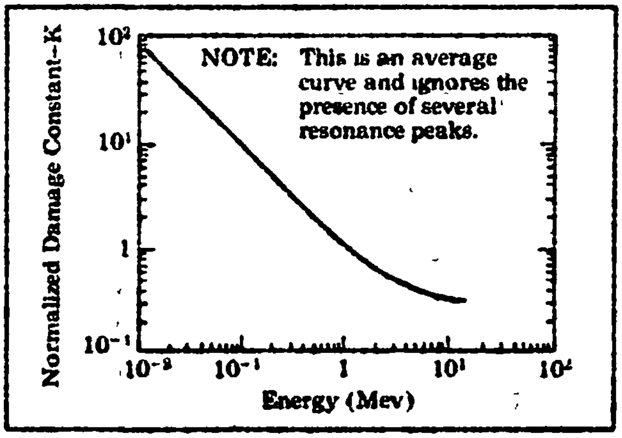


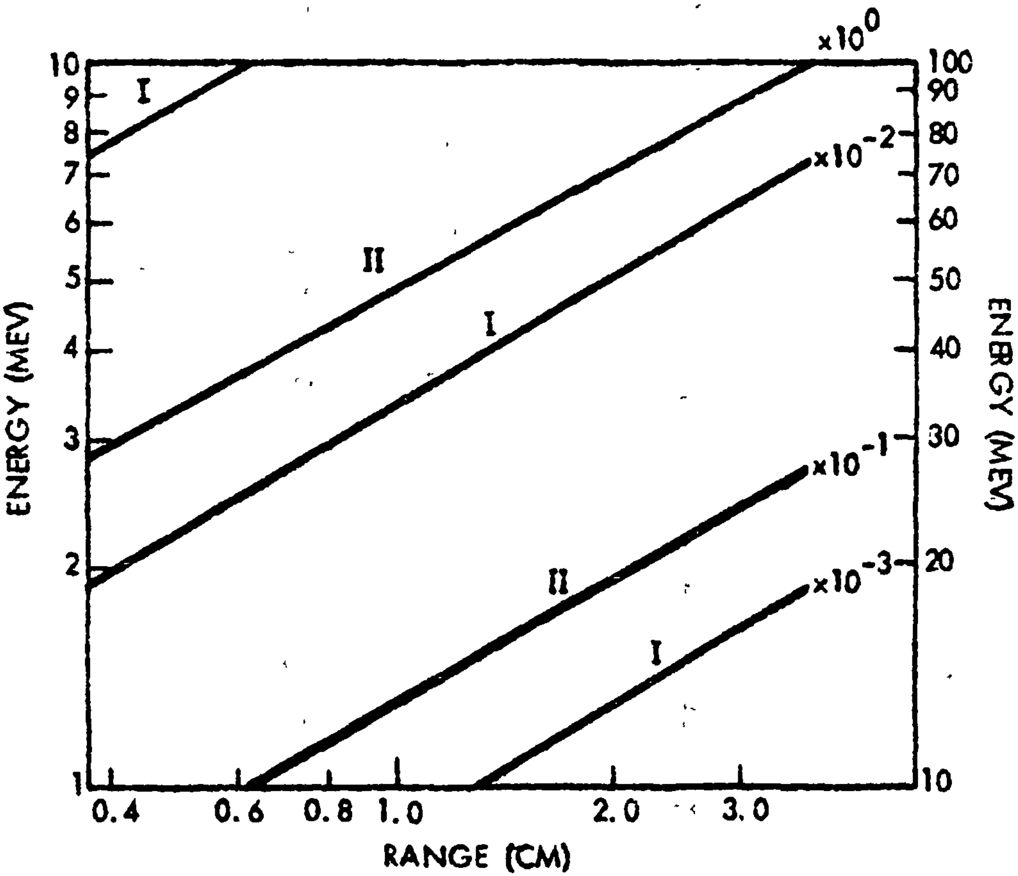
Figure 3.3

Normalized Electron Displacement Damage Constant, K (Ref. 3.22)



NOTE: This is an average curve and ignores the presence of several resonance peaks.

Figure 3.4 Normalized Average Neutron Displacement Damage Constant, K (Ref. 3.23)



Scale I: 1Mev E_p 10Mev

Scale II: 10Mev E_p 100Mev

Figure 3.5 Penetration Range of Protons in Aluminum (Ref. 3.24)

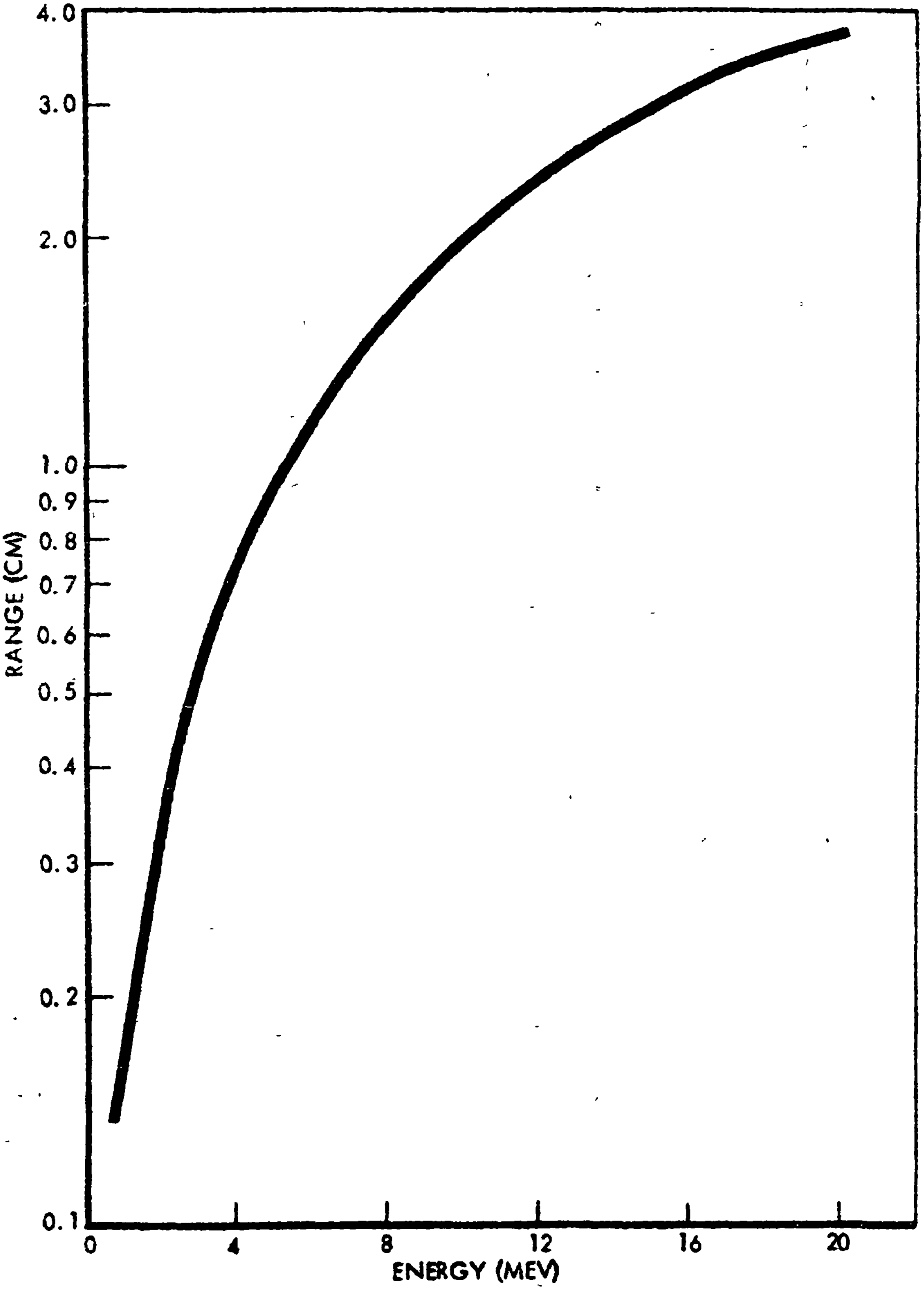


Figure 3.6 Penetration Range of Electrons in Aluminum (Ref. 3.25)

damage through secondary collisions between compton scattered electrons and nuclei.

The ionization process tends to raise the conductivity of insulating materials through the creation of electron-hole pairs in the irradiated materials. For pulsed, high intensity fields ionization induced currents become important; however, for low intensity steady-state fields such as those encountered in space vehicles the problem is less severe.

Further, ionization energy may act as a catalyst to cause chemical changes or molecular restructuring within materials. Also, in some cases, a net positive or negative charge may be left in the irradiated materials. In semiconductors, these changes usually manifest themselves at the surface of the material or within the oxide passivation layers of the silicon surfaces.

These general considerations of radiation effects and interactions should prepare the reader for the discussion of specific effects on electronic parts in subsequent sections.

3.2 References

3.21 Brown, R.R., Sivo, L.L., and Kells, K., "Radiation Induced Nonlinear Degradation of Transistor Gain", NASA Contract NAS5-10443, Boeing Document D2-125680-3, October, 1969.

3.22 Brown, R.R. and Horne, W.E., "Space Radiation Equivalence for Effects on Transistors", NASA Contract NAS5-9578, Final Report, November, 1966.

3.23 Messenger, G.C., "Radiation Effects on Microcircuits", IEEE Transactions on Nucl. Science, Vol. NS-13, No. 6, December, 1966.

3.24 Rich, Marvin, and Madey, Richard, "Range - Energy Tables", U.S. Atomic Energy Commission, UCRL-2301.

3.25 Nelms, Ann T., "Energy Loss and Range of Electrons and Positrons", National Bureau of Standards Circular 577, July 26, 1956.

4.0 BIPOLAR TRANSISTORS

4.10 Permanent Parameter Degradation

Bipolar transistors are one of the more radiation sensitive electronic components. In general, when transistors are irradiated, their current gain, h_{FE}, decreases while junction leakage currents, saturation voltage, $V_{CE(sat)}$, and breakdown voltage BV_{CBO}, all increase.

For passivated silicon transistors, the degradation of current gain is generally the most important effect.

4.11 Neutron Effects

Neutrons reduce transistor current gain primarily by two mechanisms, (1) the reduction of minority carrier lifetime in the base region and (2) the increase of recombination-generation currents in the emitter-base space charge region. Typically, for currents above a few milliamperes, the minority carrier lifetime effects in the base region are dominant. These effects have been observed to be proportional to the neutron fluence as expressed by equation 4. 1.

$$h_{FE} = \frac{h_{FE_o}}{1 + h_{FE_o} t_b K\Phi} \qquad \text{(Eq. 4. 1)}$$

h_{FE_o} = 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.

For first order damage evaluation, a number of simplifying assumptions can be made. For a given fission spectrum, such as that for radioisotope thermoelectric generators, RTG's, K can be considered a constant with respect to energy. Further, if one assumes a temperature of 25° C and that the device is operating near its h_{FE} vs. I_C peak, then an estimate of neutron damage can be made from the nomograph in

Figures 4.1 and 4.2. It is noted here that the cutoff frequency, $f\alpha_{CO}$, can be related to the base transit time by equation 4.2 at high currents.

$$f\alpha_{CO} \simeq \frac{1}{t_b} \qquad \text{(Eq. 4.2)}$$

In order to use the nomographs, one first aligns a straight edge so that it passes through the frequency and initial gain, h_{FE_o}, as shown on the nomographs as Step 1. One than starts at the intersection of Step 1 with the pivot line and places the straight edge through the neutron fluence of interest; as shown in Step 2, the intersection of the straight edge with the h_{FE} scale then indicates the final gain.

The above technique is only a first order estimate. If one is interested in a more accurate prediction, a detailed method which is the subject of a document by Frank and Taulbee (Ref. 4.71) can be used. Their method is not reproduced here because of its length. For applications that are particularly critical, if a device that is marginal by the above estimates must be used, actual radiation data should be obtained on a fairly large sample of the transistors in question.

Leakage currents are not so amenable to prediction since they are strongly influenced by surface effects. If the neutron fluence to ionization dose ratio is $> 10^8$ then the surface leakage current increases can (to a first approximation) be ignored and the leakage current predicted in the manner specified by Frank and Taulbee (Ref. 4.71), however, it should be noted that for an environment such as TOPS the ionization dose is enhanced by charged particle radiation. For this reason, leakage currents are not amenable to prediction for the TOPS environment and the rather detailed prediction technique is not included in this summary.

Saturation voltage, $V_{CE(sat)}$, increases due to gain reduction which tends to pull the transistor out of saturation and due to increases in the collector resistance. The complexity of parameters influencing $V_{CE(sat)}$ make it unpredictable at the present time.

4.12 Proton Effects

Proton effects include not only displacement damage somewhat similar to

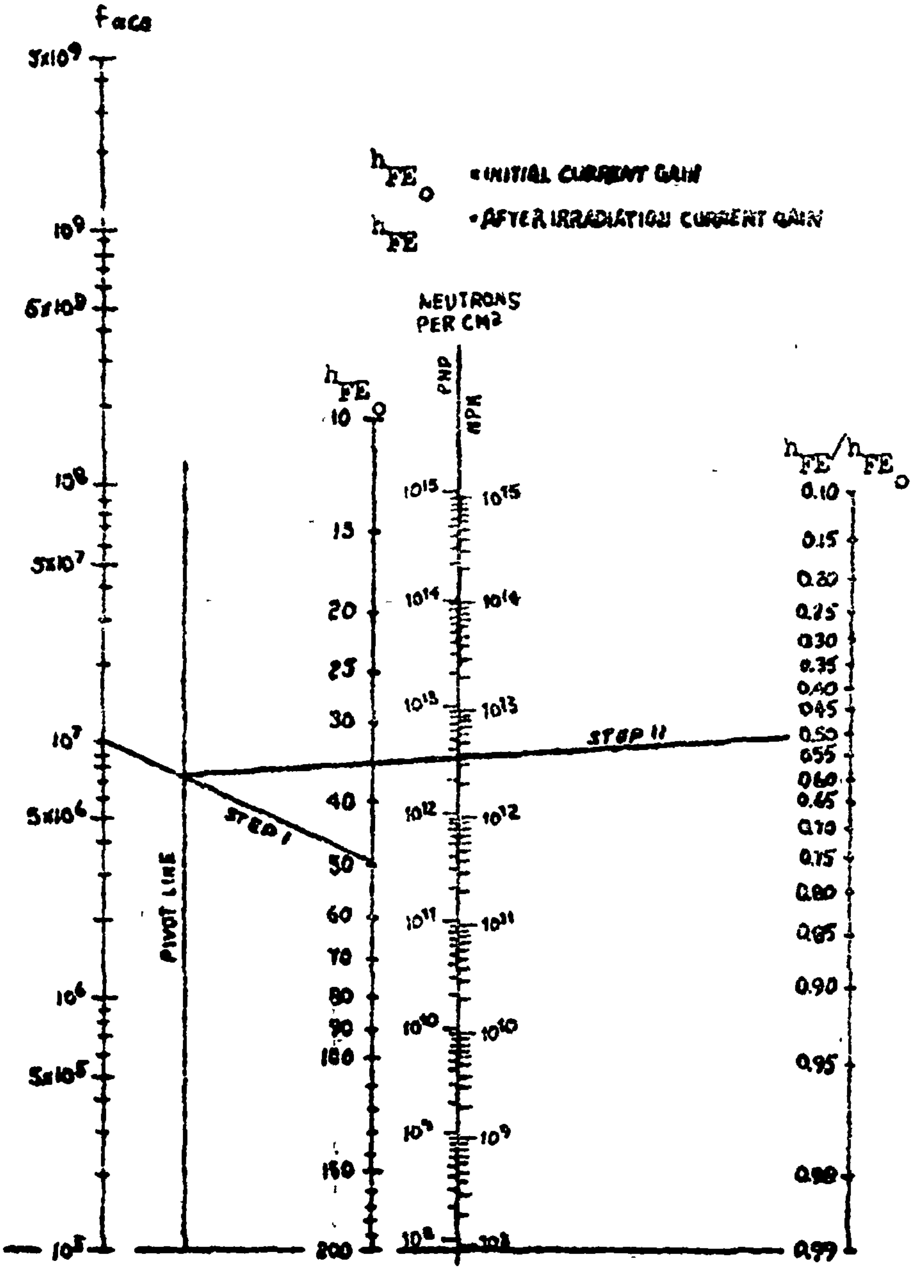


Figure 4.1 Nomograph For First Order Neutron Damage Estimate for Silicon Transistors. Note: Assumes Fission Spectrum, 25°C, and Device Operating at h_{FE} vs. I_C Peak.

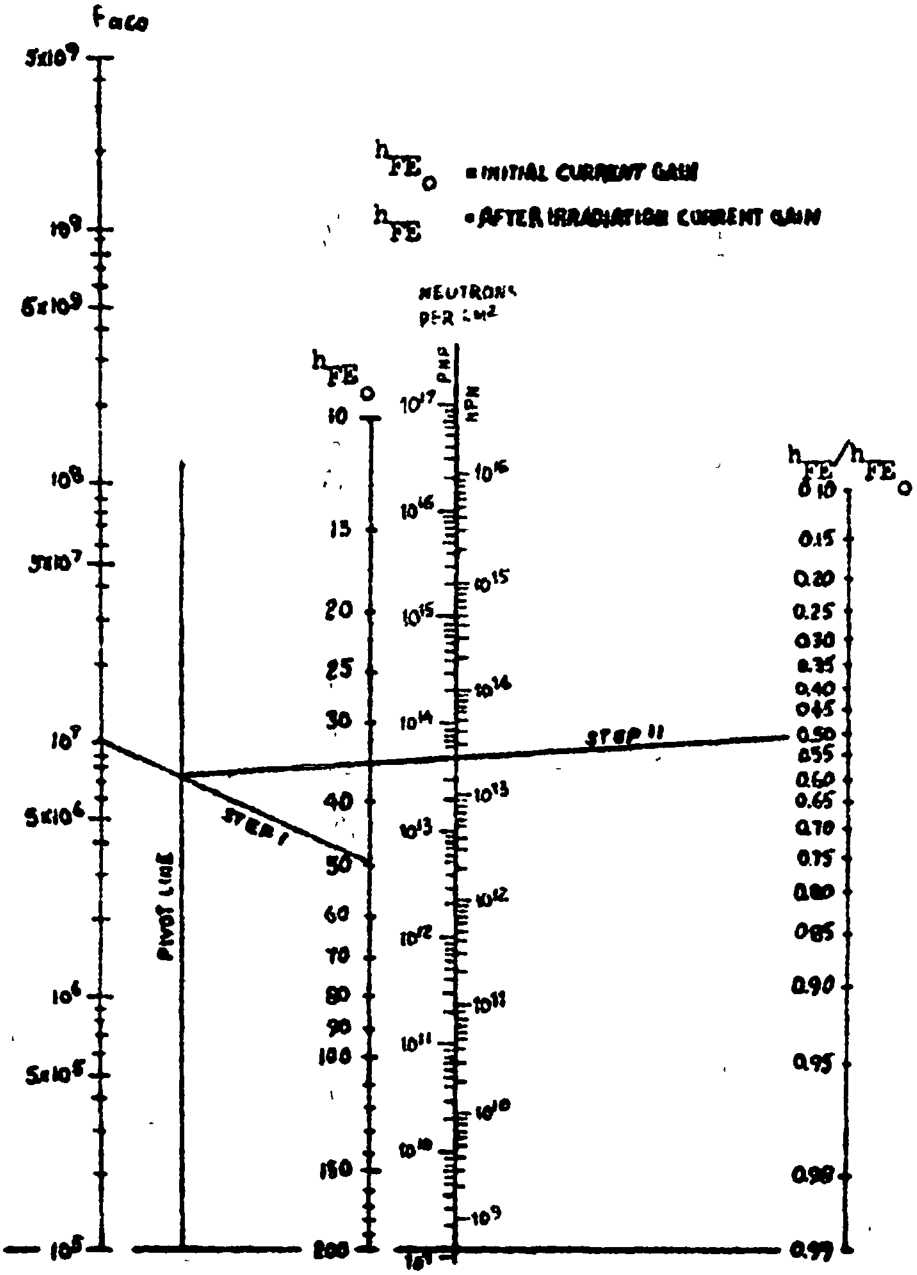


Figure 4.2 Nomograph for first order neutron damage estimate for Germanium transistors. Note: Assumes fission spectrum, 25° C, and device operating at h_{FE} vs. I_C peak.

neutrons, but, since protons are also heavily ionizing, significant surface damage can result which is not as readily predictable.

Bulk displacement damage due to protons can be estimated using the nomograph in Figure 4.3. It should be noted that this nomograph assumes the transistor to be operating near its h_{FE} vs. I_C peak at about 25°C. 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 fluence of interest. The intersection of Step 2, with the h_{FE} scale thus indicates the final gain. If more than a factor of 2 or 3 accuracy is required, one should use the detailed damage prediction technique referred to in Ref. 4.71 for neutrons; however, the damage constant should be converted to the equivalent proton damage constants as shown below:

8 - 17 MeV protons ———— $K_{proton} = 33\ K_{neutron}$

100 MeV protons ———— $K_{proton} = 8\ K_{neutron}$

where K = damage constant

In addition to the displacement damage due to protons, one also has an ionization dose which can be calculated approximately by

Dose — 5×10^{-7} rads/ (8-17 MeV on silicon chip) Protons/cm^2

Dose — 1×10^{-7} rads/ (100 MeV on silicon chip) Protons/cm^2

Ionization effects on current gain are dependent on the operating conditions of the transistor during irradiation. There have been some observations (Ref. 4.73) indicating that proton irradiation causes anomalously high damage in NPN transistors in comparison to an equivalent ionization dose incurred from electron or gamma radiation. These effects should be more fully investigated. Due to the observed anomalies described above, it is not practical to make estimates of proton ionization damage in NPN transistors at the present time. However, estimates of ionization induced gain degradation in PNP transistors can be made on the basis of absorbed dose (see gamma effects, Section 4. 13).

Further, the relative amount of ionization to displacements due to protons, make leakage current predictions unfeasible. However, for passivated silicon

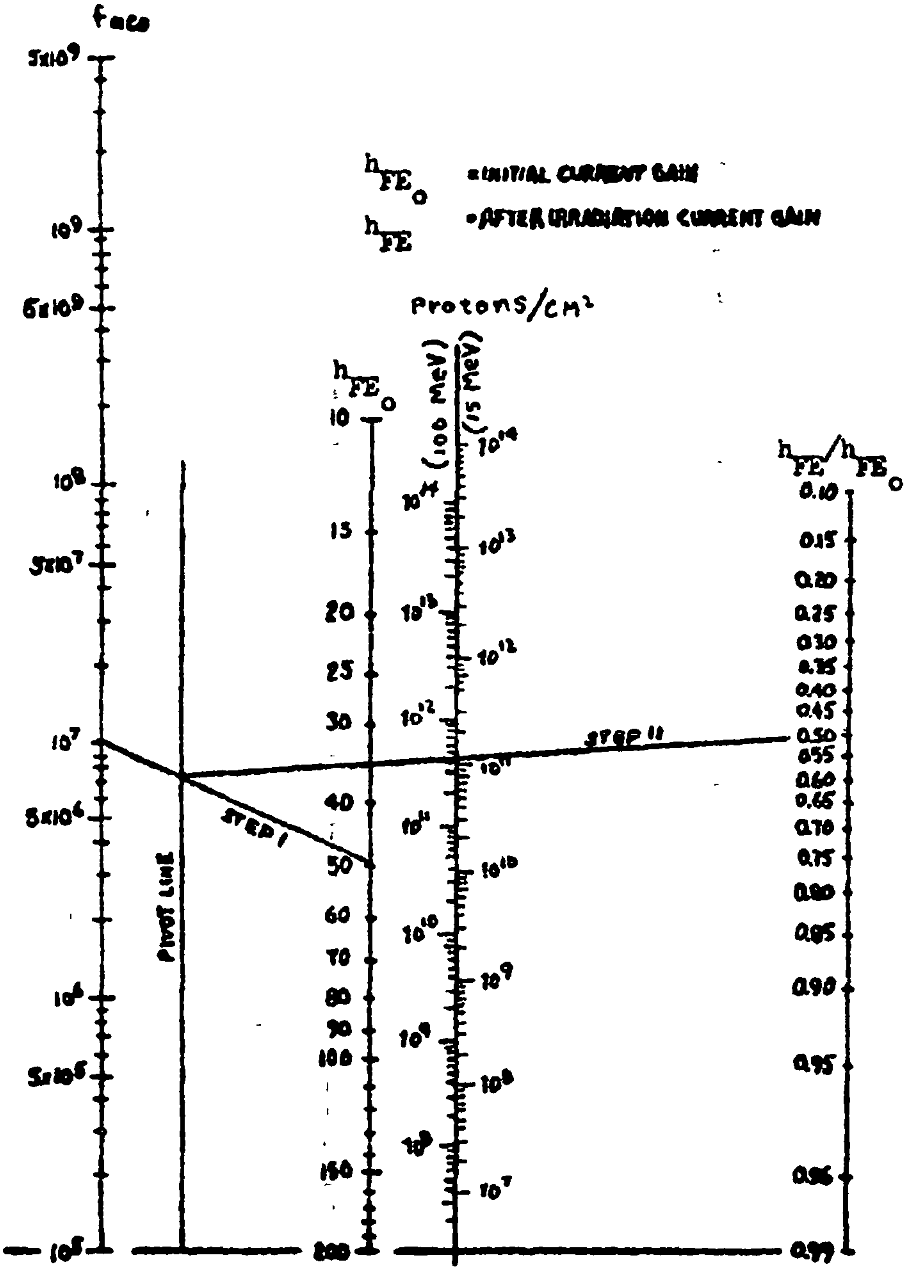


Figure 4.3 Nomograph For Making First Order Estimate of Proton Damage in Silicon Transistors. Note: Assumes 25°C and Device Operating at h_{FE} vs. I_C Peak.

devices, leakage current changes are generally unimportant compared to gain changes. Figures 4.4 and 4.5 show typical leakage current changes as a function of proton fluence.

4.13 Gamma Effects

Gamma rays produce both ionization and atomic displacements in silicon, however, their effectiveness for producing displacements is low compared to that of particutale radiation, such as neutrons and protons. The most significant effect for gamma irradiation in transistors is, therefore, ionization effects (the only exception being low frequency power devices) below exposure doses of about 10^6 rads(Si).

Although the exact mechanisms by which ionization affects transistor surfaces is not well understood, the effects have been well characterized and several models proposed to describe them. The present consensus seems to be that there are two basic ways in which ionization influences current gain, (1) ionization produces recombinarion sites and trapping centers at the interface of the silicon and silicon dioxide passivation layer. The mechanisms by which these states are produced are not well understood at this time; although it has recently been postulated that they may be caused by devitrification, or compaction, of the SiO_2 layer (4.74), (2) ionizing radiation ionizes the gas in the transistor can and the material in the silicon dioxide passivation layer on the device surface. As a result, positive charge accumulates within and on the surface of the oxide layer of the transistor. These positive charges then cause changes in surface potential at the silicon surface, thus affecting the surface recombination characteristics.

If an electrical bias is applied to the transistor during irradiation, then the charge accumulation is influenced. For NPN devices, the charge accumulation is influenced in such a way as to enhance gain degradation. It has been observed, (Ref. 4.73), that evacuating the transistor cans greatly reduces (if not eliminates) the bias dependence of surface ionization damage.

Since ionization damage is a surface effect, and is dependent on transistor operating conditions during irradiation, it is not possible at this time to make accurate predictions of the damage. However, from the observations of data on many

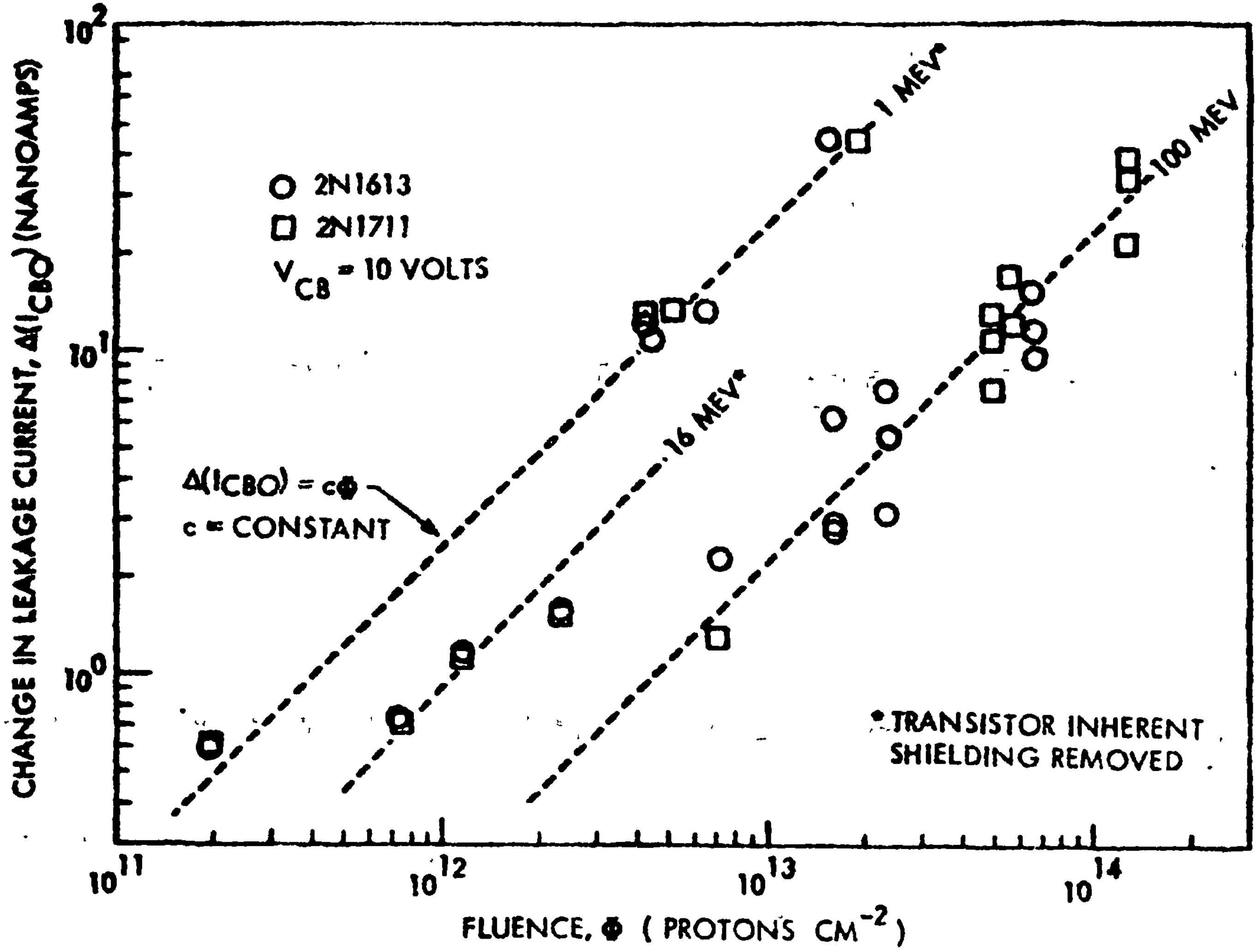


Figure 4.4 Dependence of $\Delta(I_{CBO})$ on Proton Fluence (2N1613 , 2N1711)

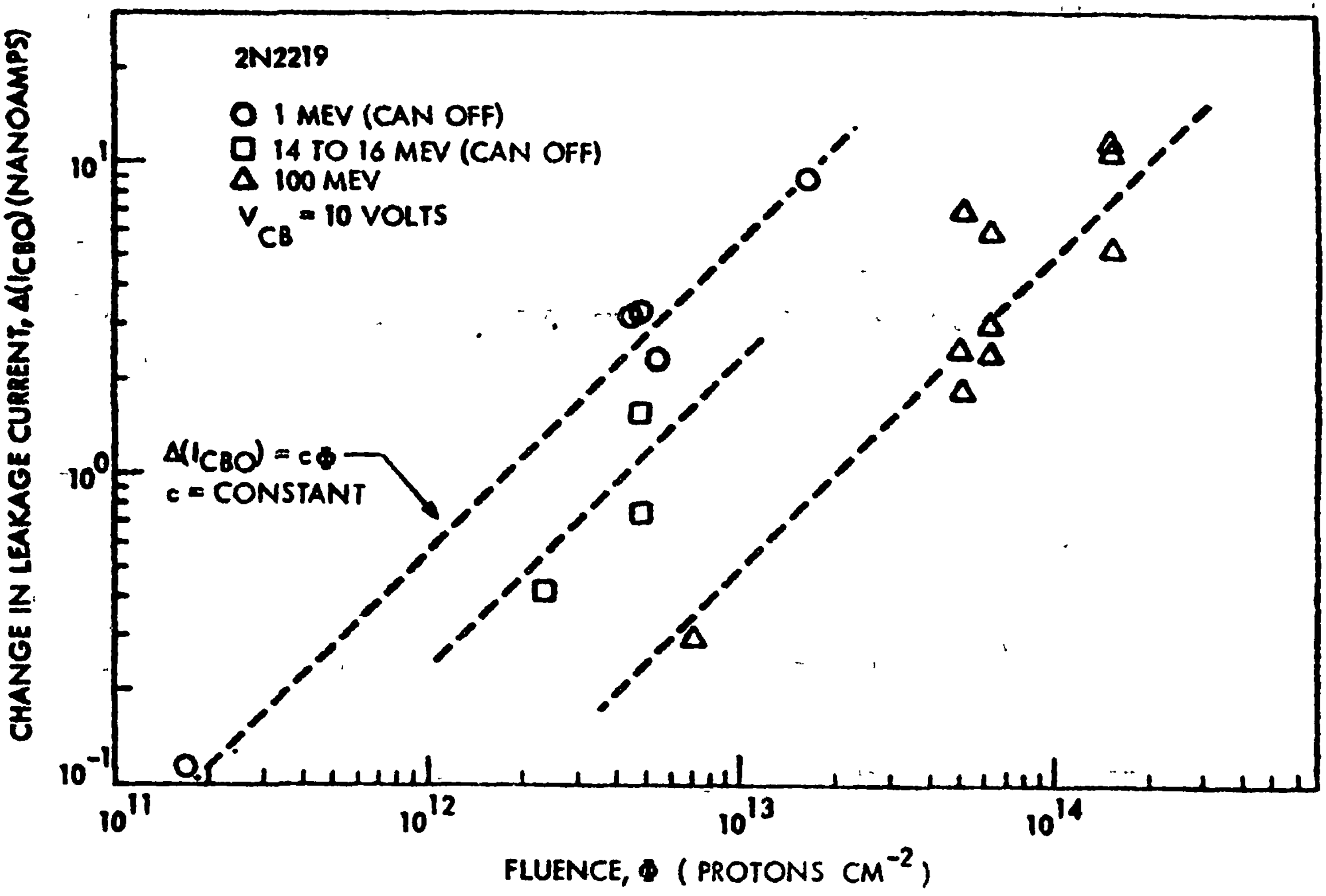


Figure 4.5 Dependence of $\Delta(I_{CBO})$ on Proton Fluence (2N2219)

devices, the nomograph in Figure 4.6 has been made to give an indication of typical effects of ionizing radiation on transistor gain. CAUTION - This should not be construed as a damage prediction, it is only a ballpark estimate and for NPN transistors is applicable only for those devices without bias applied during exposure.

The nomograph in Figure 4.7 provides an estimate of displacement effects of gamma radiation on transistors. The nomograph assumes the device to be operating near its h_{FE} vs. I_C peak at ~ 25°C.

The effects of gamma radiation on leakage current are unpredictable. In general, for passivated silicon devices, the leakage current changes are not as important as the gain changes; however, there are some devices that form surface channels and leakage becomes excessive. There is no well-proven method for detecting channel-prone devices, although a technique involving avalanche noise measurements has been proposed (Ref. 4.75). This technique will be discussed in a later section.

4.14 Electron Effects

Electron effects are very similar to gamma effects except that electrons are more effective for producing displacements than gamma rays. Figure 4.8 shows a nomograph for estimating electron displacement damage. The nomograph is based on a device operating near its h_{FE} vs. I_C peak at ~ 25°C.

The nomograph shown in Figure 4.6 can be used to make "ball park" estimates of typical gain degradation due to ionization effects of the electrons if the electron fluence is converted to an equivalent ionization dose using stopping powers. Note this is not a prediction technique and the text discussion of Figure 4.6 should be read before using the nomograph.

4.20 Temporary Parameter Drift

For long-term steady-state radiation effects, there is no evidence in the literature that parameters show drift other than the normal degradation already discussed. However, ionization damage does show some long-term annealing that usually occurs over several weeks at room temperature. For this reason, it has been

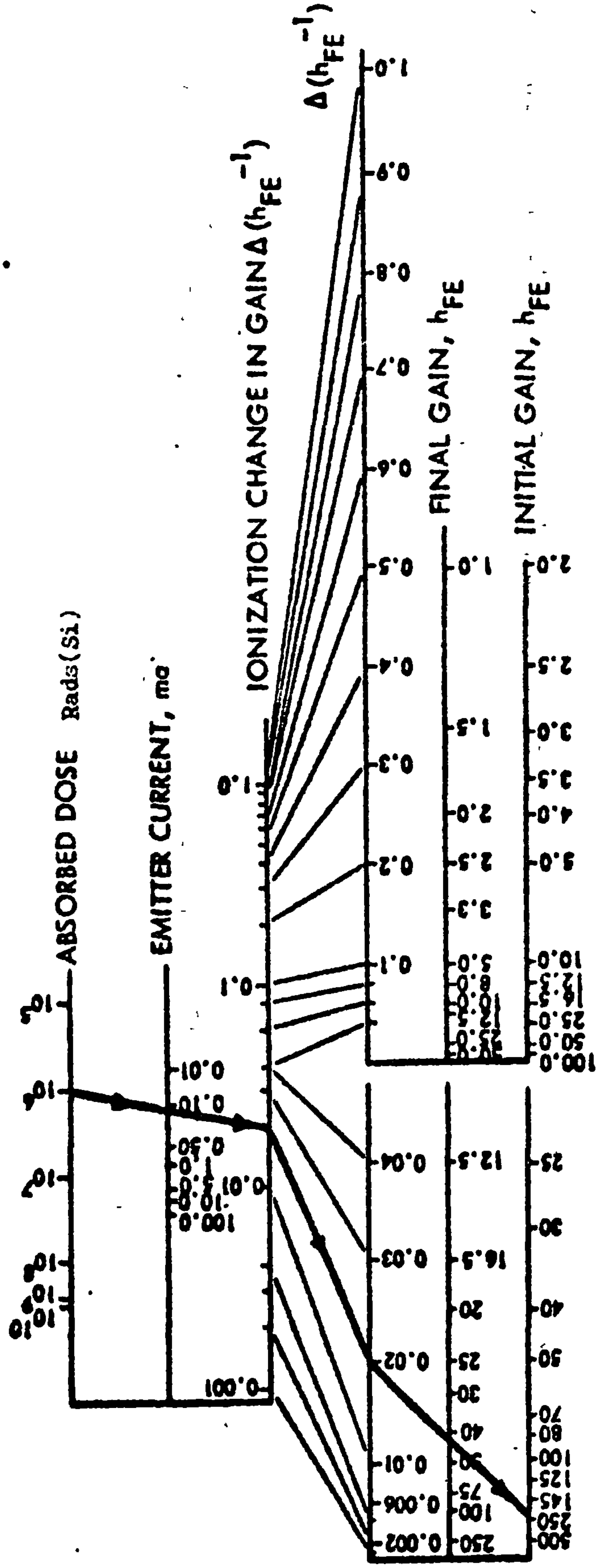


Figure 4.6 Nomograph For Estimating Average Ionization Degradation in Small Signal Silicon Transistors. Note: Assumes No Electrical Bias During Irradiation, 25°C, and 1 MeV Gamma Radiation.

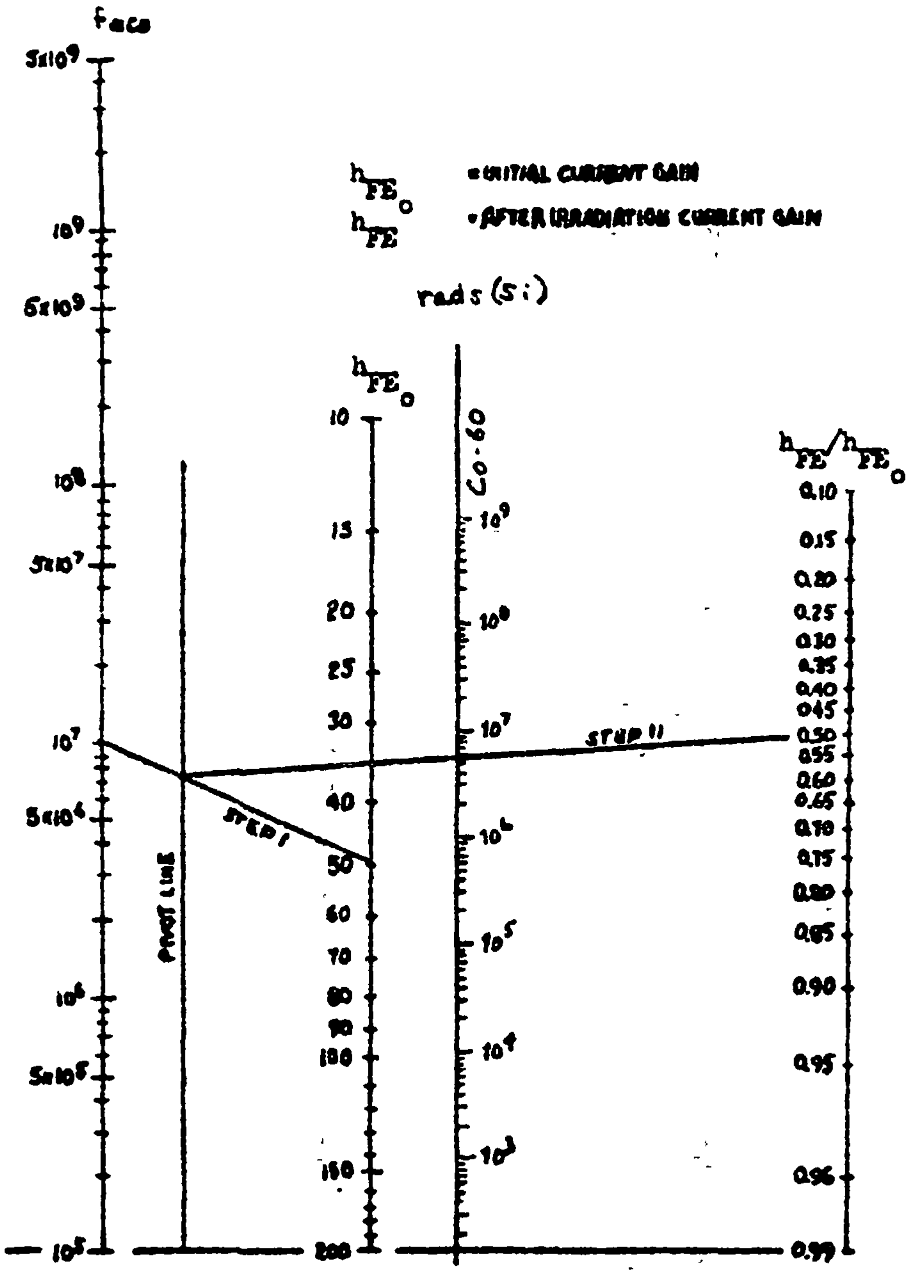


Figure 4.7 Nomograph For Making First Order Estimate of Displacement Damage in Silicon Transistors Due to 1 MeV Gamma Radiation. Note: Assumes 25°C and Device Operating at h_{FE} vs. I_C Peak.

suggested that ionization damage in low intensity ionizing environments may reach an equilibrium state where production rate equals annealing rate; however, there is no positive data to substantiate this. Furthermore, elevated temperature (i.e., 50°C) can accelerate surface damage recovery. Thus, circuits that are periodically exposed to radiation and operate above 25°C may show considerable drift in gain.

4.30 Parameter Degradation Factors

Due to the many different types of transistors, it is not practical to give generally applicable degradation factors for parameters at this point. After a device is selected, its specific derating factors should be determined from the estimation techniques outlined in the preceding sections. The parameters that should be derated are h_{FE}, I_{CBO}, and $V_{CE(sat)}$, although no specific estimating techniques are known for $V_{CE(sat)}$, or for ionization induced I_{CBO} changes. Fortunately, these parameters are not usually as significantly degraded as h_{FE}.

Data from the literature for specific devices on the TOPS parts list have been collected and are shown in the Appendix 4.A.

In general, damage thresholds for different categories are shown in Table 4.1.

Table 4.1 General Radiation Damage Thresholds For Bipolar Transistors

Transistor Category	Radiation Type	General Damage Threshold
Low Frequency Power	Fission neutrons	10^{10} to 10^{11} n/cm^2
	8-17 MeV Protons	5×10^8 to 5×10^9 P/cm^2
	Gamma Rays	10^4 to 10^5 rads(Si)
Med. frequency 50 MHz $< f\alpha_{CO} <$ 150 MHz	Fission neutrons	10^{12} to 10^{13} n/cm^2
	8-17 MeV Protons	5×10^9 to 5×10^{10} P/cm^2
	Gamma Rays	10^4 to 10^5 rads(Si)
High frequency $f\alpha_{CO} >$ 150 MHz	Fission neutrons	10^{13} to 10^{14} n/cm^2
	8-17 MeV Protons	5×10^{10} to 5×10^{11} P/cm^2
	Gamma Rays	10^4 to 10^5 rads(Si)

4.40 Radiation Hardening

Bipolar transistors can be hardened against radiation damage by: (1) keeping their effective base width as thin as possible, (2) designing them to operate near their h_{FE} vs. I_C peak, (3) keeping their emitter periphery as small as possible, (4) placing metallization on the oxide over the emitter base junction, (5) maintaining strict quality control over manufacturing processes to insure uniform surfaces, (6) evacuating the transistor cases, and (7) utilizing PNP construction.

Keeping the basewidth thin reduces displacement effects on h_{FE}. Operating near the h_{FE} vs. I_C peak reduces displacement effects and minimizes ionization effects.

Maier, (Ref. 4.75), has found that ionization effects on h_{FE} can be reduced by keeping the emitter-base periphery small and by placing metallization on the oxide over the emitter base junction. Since devices show such varied responses to surface damage, it is not practical to estimate the amount of improvement this gives.

The role of manufacturing quality control on surface effects is very important. Although one cannot estimate quantitatively the improvement, it is generally conceded that variations in manufacturer's processes result in the wide variations in transistor sensitivities to surface effects.

Evacuating Fairchild 2N1613 cans has been observed (Ref. 4.73) to reduce the bias dependence of surface damage, thus reducing the overall damage.

PNP devices have been found to be inherently harder to surface effects than NPN devices. They show almost no bias dependence for surface damage.

4.50 Recommended Testing

All devices to be used should be characterized in statistical samples for ionization effects. The dose ranges of interest are 10^4 to 10^6 rads(Si).

The anomalies observed for proton ionization damage (Ref. 4.73) as discussed in Section 4.12 should be investigated further. The parameters influenced are h_{FE} and I_C. The fluence range of interest is about 10^{13} p/cm^2 at 20 MeV.

Studies should be made of combined environmental effects to insure against synergistic effects and to determine how to evaluate total damage due to a mixed environment by considering its separate components, i.e., neutron, proton, gamma, and electrons.

4.60 Radiation Screening

Transistors to be used in a radiation environment should be screened by transit time or cutoff frequency measurements. Devices having abnormally low frequencies (or large transit times) should be eliminated. This should provide optimum devices for neutron and proton displacement damage resistance.

Several techniques have been studied for ionization screening. Perhaps the most thoroughly studied technique is one wherein the devices are irradiated in a Co-60 gamma environment and then, after observing their relative radiation sensitivities and eliminating the more sensitive devices, the remaining devices are annealed by baking at 150°C. The damage anneals completely, and the devices tend to retain their original radiation response characteristics. They have also been observed (Ref. 4.76) to be able to fulfill mil spec lifetesting requirements after such a screen.

Another technique (Ref. 4.75) which has not been fully tested on modern devices is the measurement of microplasma noise when a device is operating in the avalanche breakdown mode. Noisy NPN devices were observed to be more radiation resistant than quiet NPN devices while quiet PNP devices were more radiation resistant than noisy PNP units.

Further, considerable work (References 4.78, 4.79, 4.710, 4.711) has been done to study the effectiveness of the Weibull probability distribution for predicting radiation reliability and selecting reliable device types. This technique appears very promising, but needs further study.

4.70 References

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4.78 Poblenz, Frank W., "Analysis of Transistor Failure In a Nuclear Environment", IEEE Trans. on Nucl. Sci., Vol. NS-10, Jan. 1963.

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4.711 Horne, W. E. and Folsom, J. A., "Predicting Low-Dose Radiation Survival Probability For Transistors", Boeing Document D2-126230-1, Dec., 1969.

4.A APPENDIX

4.1A Radiation data from literature for JPL TOPS transistors.

4.2A References

4.21A The Boeing Company, "Analytical Methods and Fundamental Parameters for Predicting Responses of Electronic Circuits to Transient Nuclear Radiation, With Application to Hardened Circuit Design", AFWL TR-65-105, July 1965.

4.22A Magee, R. M., "Radiation Effects Parameters in NAP Applications", Final Report, BSR-988 WL-TDR-64-97, AD-609 302, N65-15990, Nov. 1964.

4.23A Lockheed-Georgia Co., "Components Irradiation Test No. 11, 2N1711, S2N 930, and 2N2501 Transistors", NASA-CR-57722 ER-7759 X65-13989, Jan., 1965.

4.24A Horne, W. E., The Boeing Co., unpublished data, 1969.

4.25A Lockheed-Georgia Co., "Components Irradiation Test No. 5 HPA-1002 and 1N1616 Diodes, S2N1724 and 2N2222 Transistors, 2N511 flip-flop Bistable Network", NASA-CR-60640, N65-17526, July, 1964.

4.26A Lockheed-Georgia Co., "Components Test No. 6 2N2222 Transistors and T1-257 Diodes", Final Report NASA CR-60417, ER-7564, X65-12050, Aug., 1964.

4.27A Can and Binder from FZM-12-6148-III, 18 October 1968, (SRD) Unclassified curve.

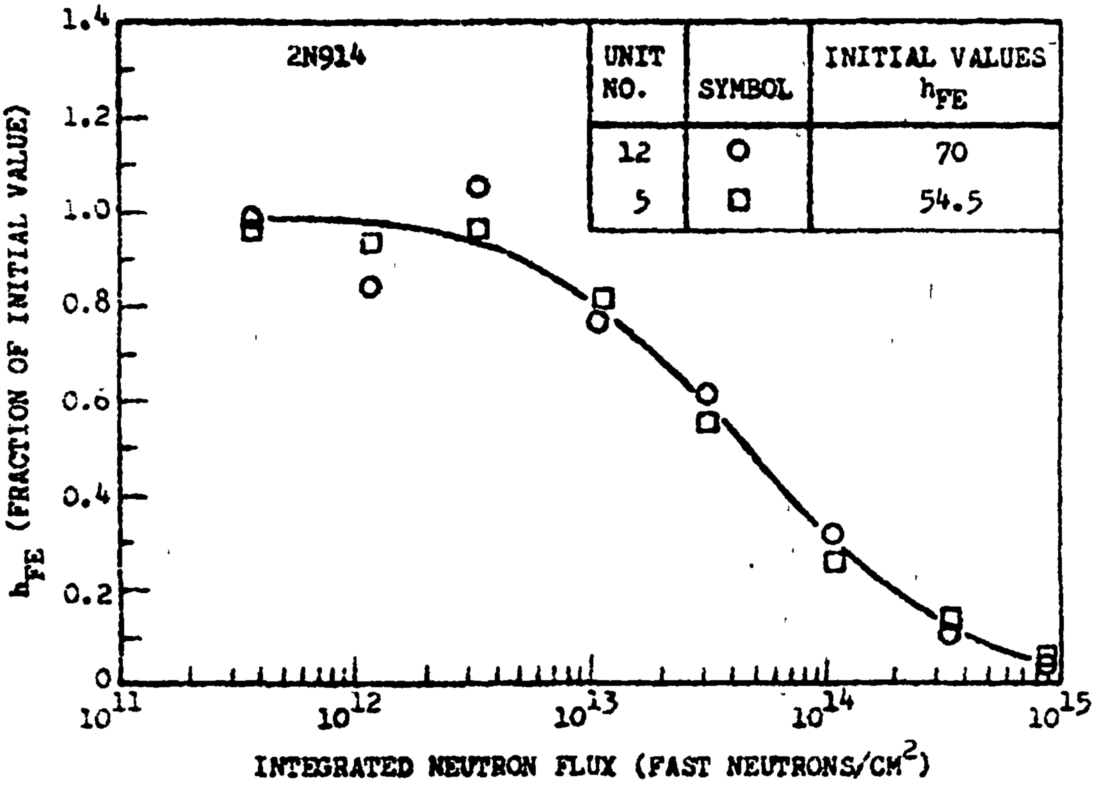


Figure 4.1A Transistor 2N914 Neutron Dependence of h_{FE} (Ref. 4.21A)

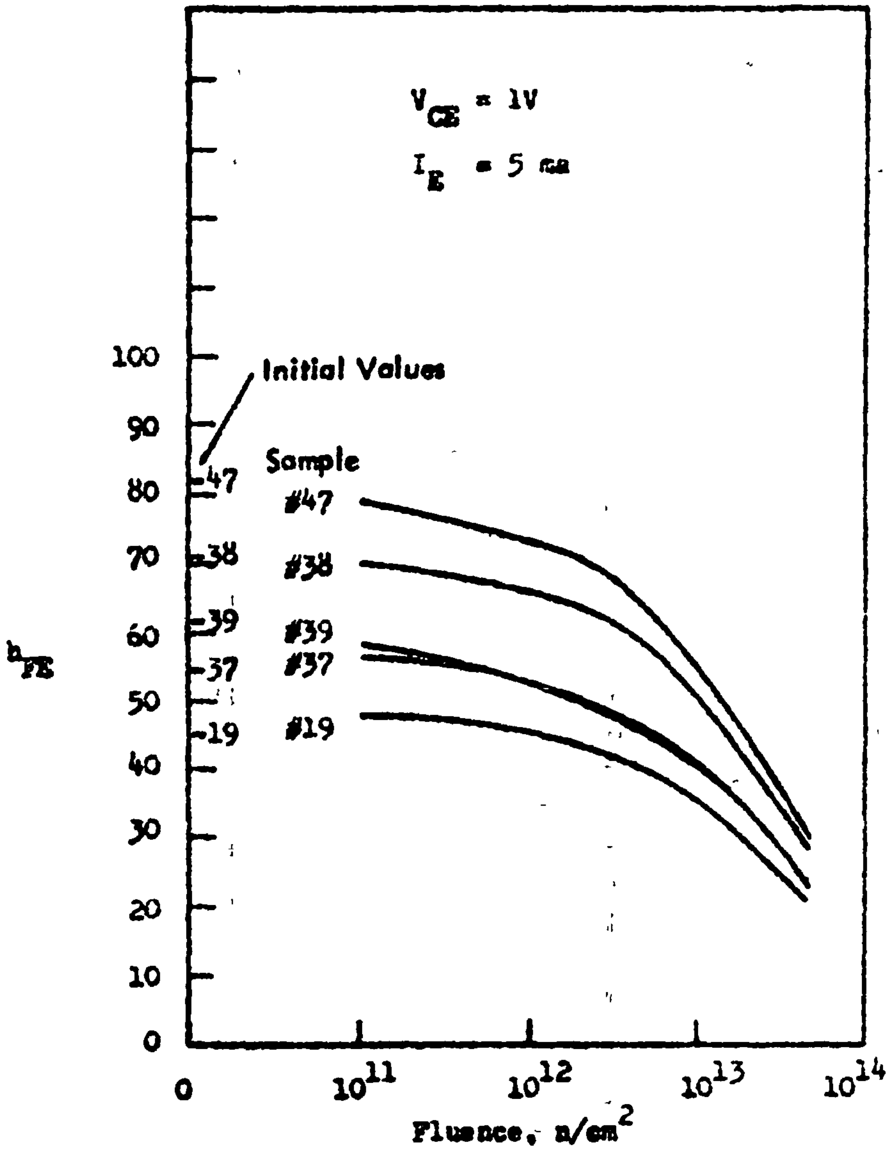


Figure 4.2A. h_{FE} Versus Fluence for 2N914 Transistors Data from Ref. 4.22A.

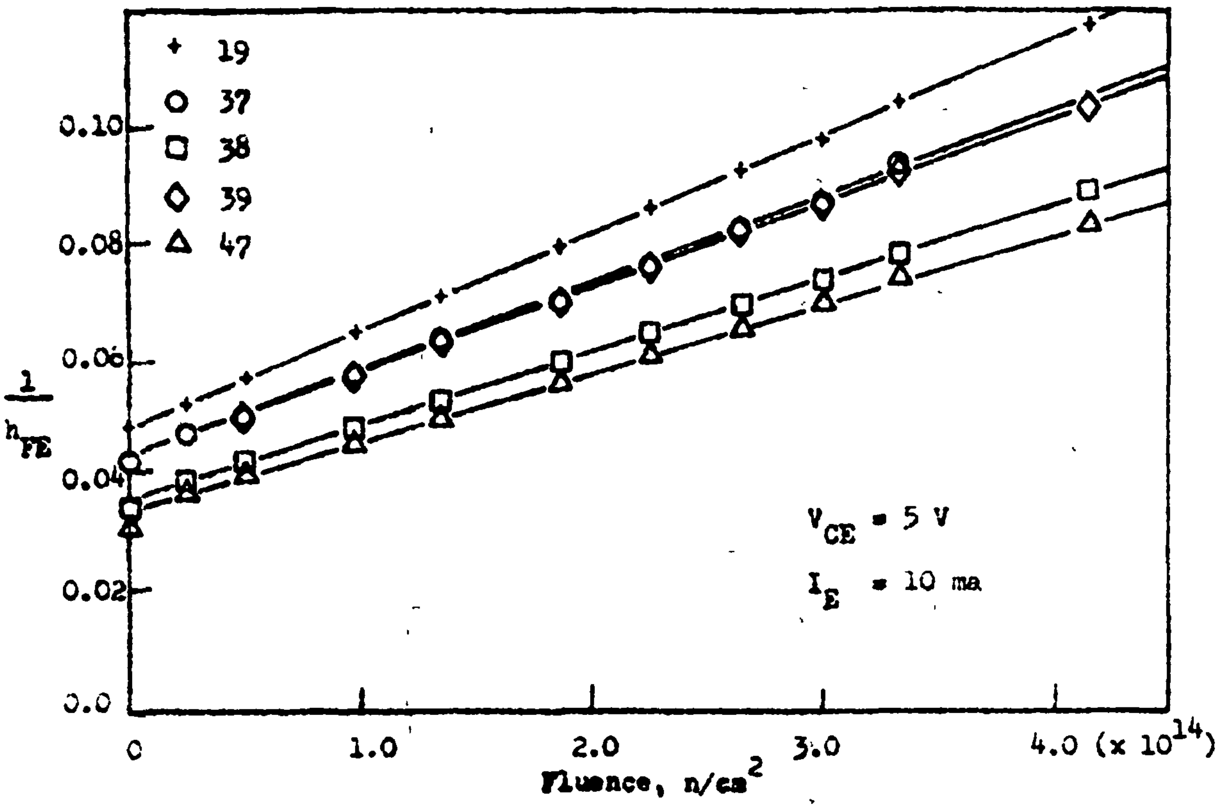


Figure 4.3A $1/h_{FE}$ Versus Fluence for 2N914 Transistor Data from Ref. 4.22A

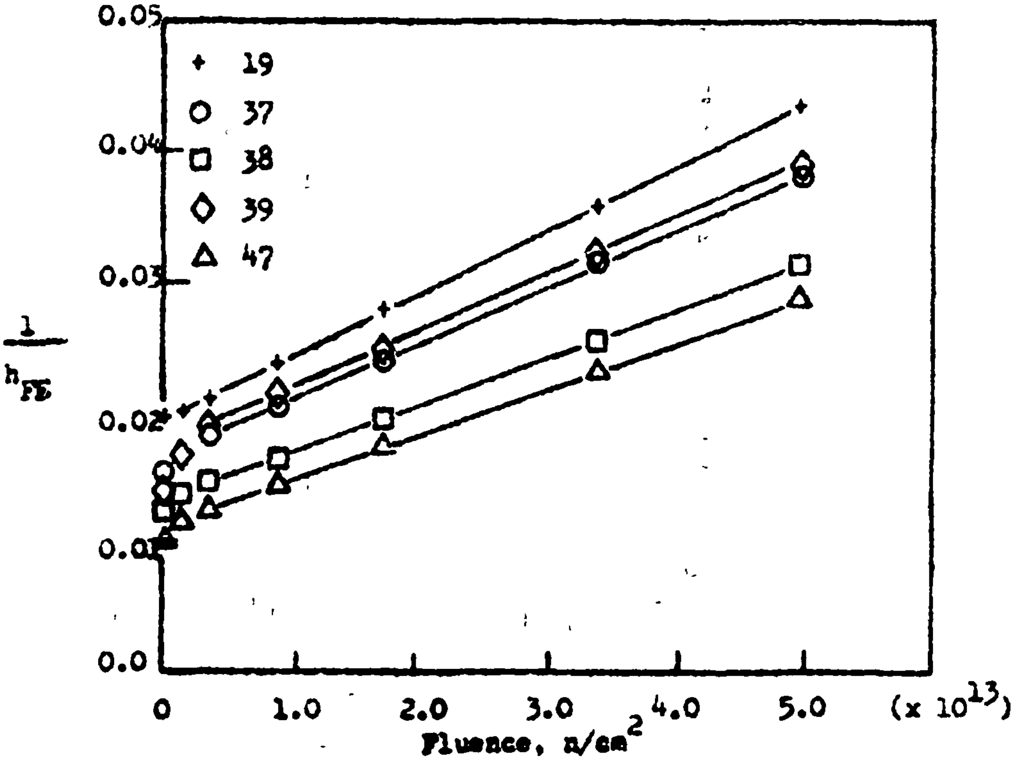
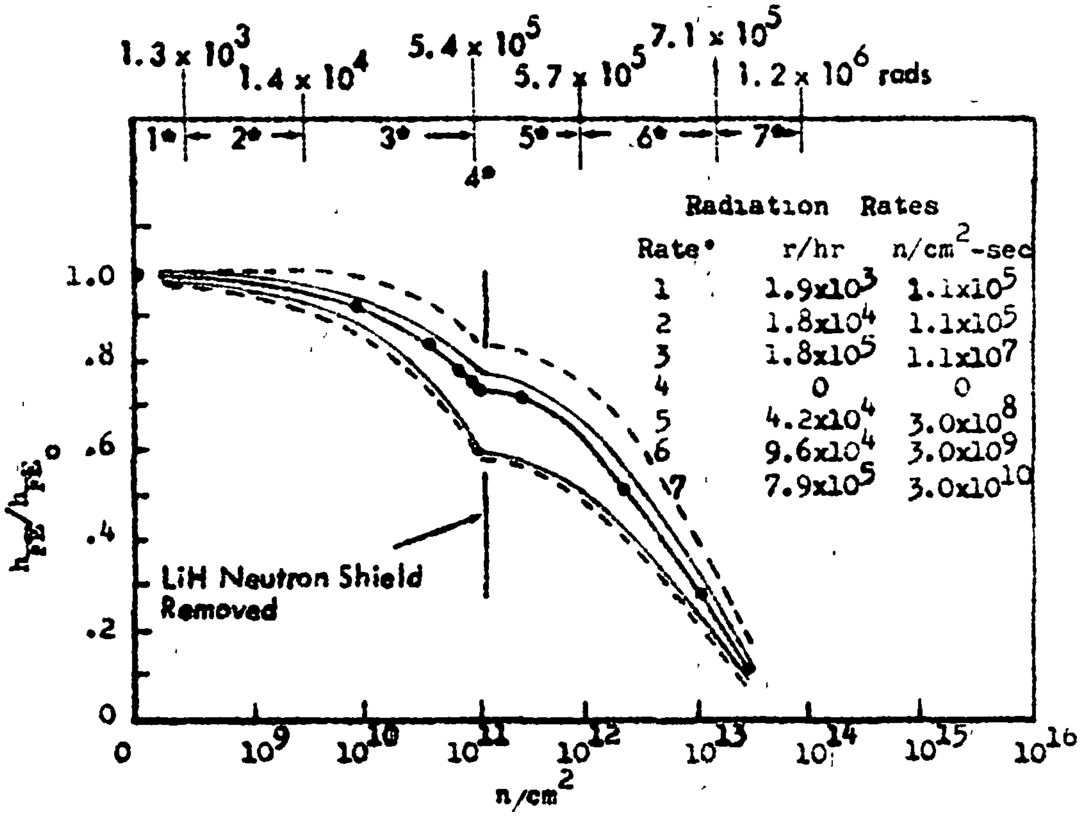


Figure 4.4A $1/h_{FE}$ Versus Fluence for 2N914 Transistors Data from Ref. 4.22A



Radiation Rates

Rate*	r/hr	n/cm²-sec
1	$1.9x10^3$	$1.1x10^5$
2	$1.8x10^4$	$1.1x10^5$
3	$1.8x10^5$	$1.1x10^7$
4	0	0
5	$4.2x10^4$	$3.0x10^8$
6	$9.6x10^4$	$3.0x10^9$
7	$7.9x10^5$	$3.0x10^{10}$

Figure 4.5A 2N930 Texas Instruments, 30°C, Normalized h_{FE} Versus Integrated Flux. (Ref. 4.23A)

—●—●— Median
——— 68% Envelope
– – – – 95% Envelope

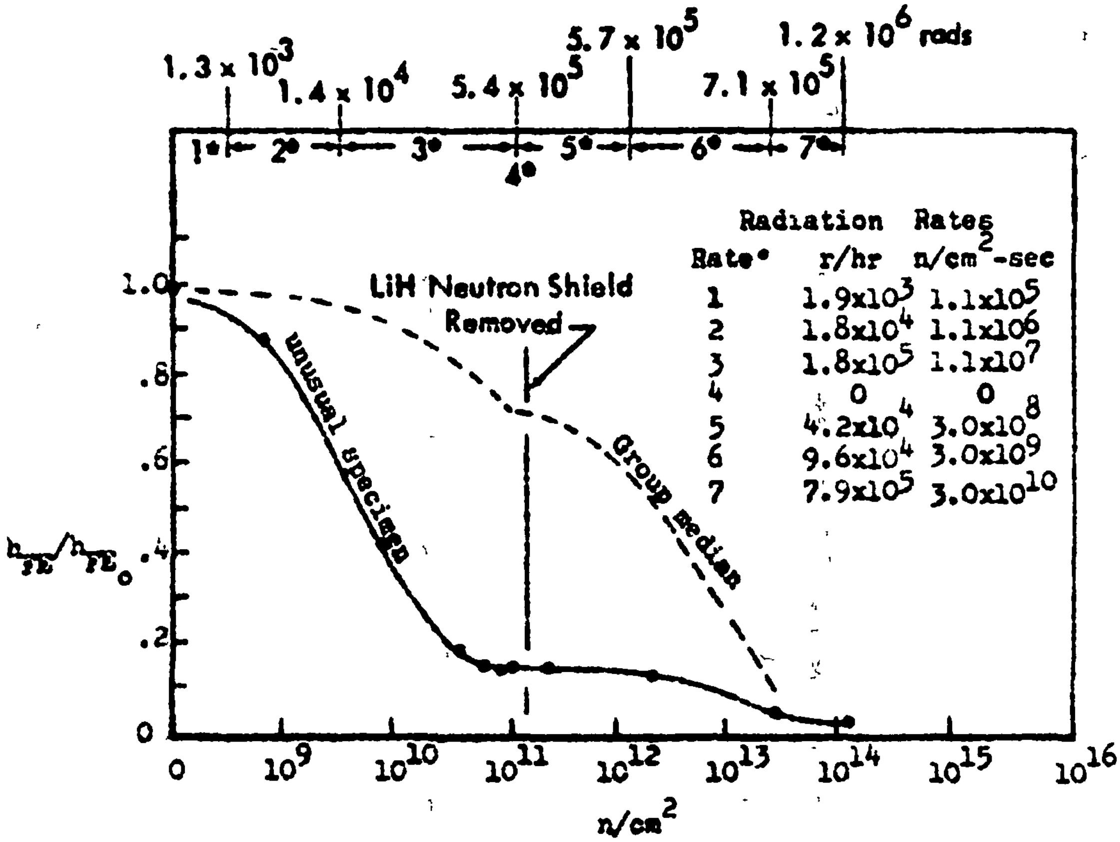


Figure 4.6A S2N930 Texas Instruments (one "unusual" specimen), 30°C, Normalized h_{FE} Integrated Neutron Flux. (Ref. 4.23A)

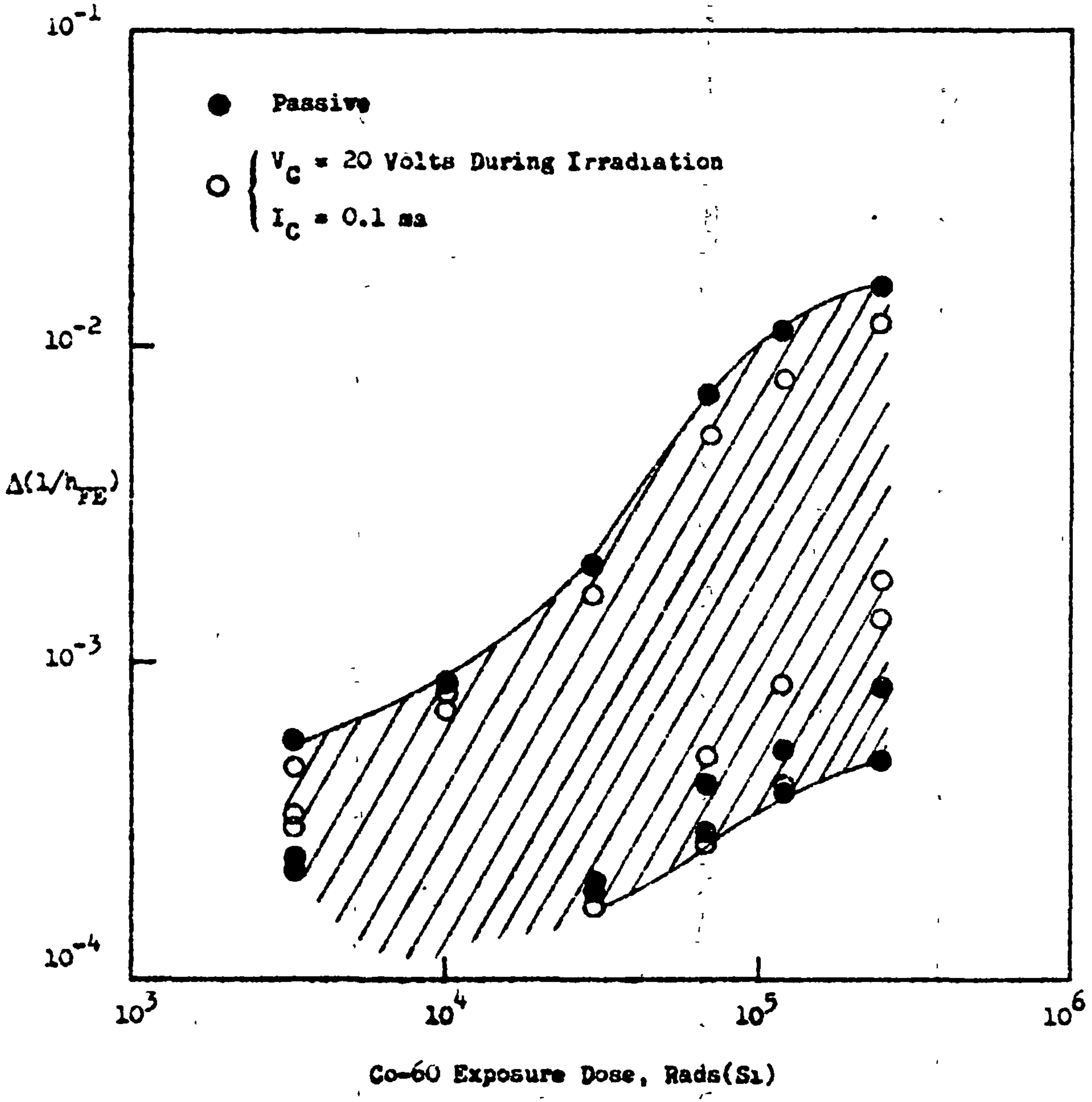


Figure 4.7A. Ionization Damage in Fairchild 2N930 Transistors at V_C = 20V, I_C = 1 ma Measurement Condition (Ref. 4.24A)

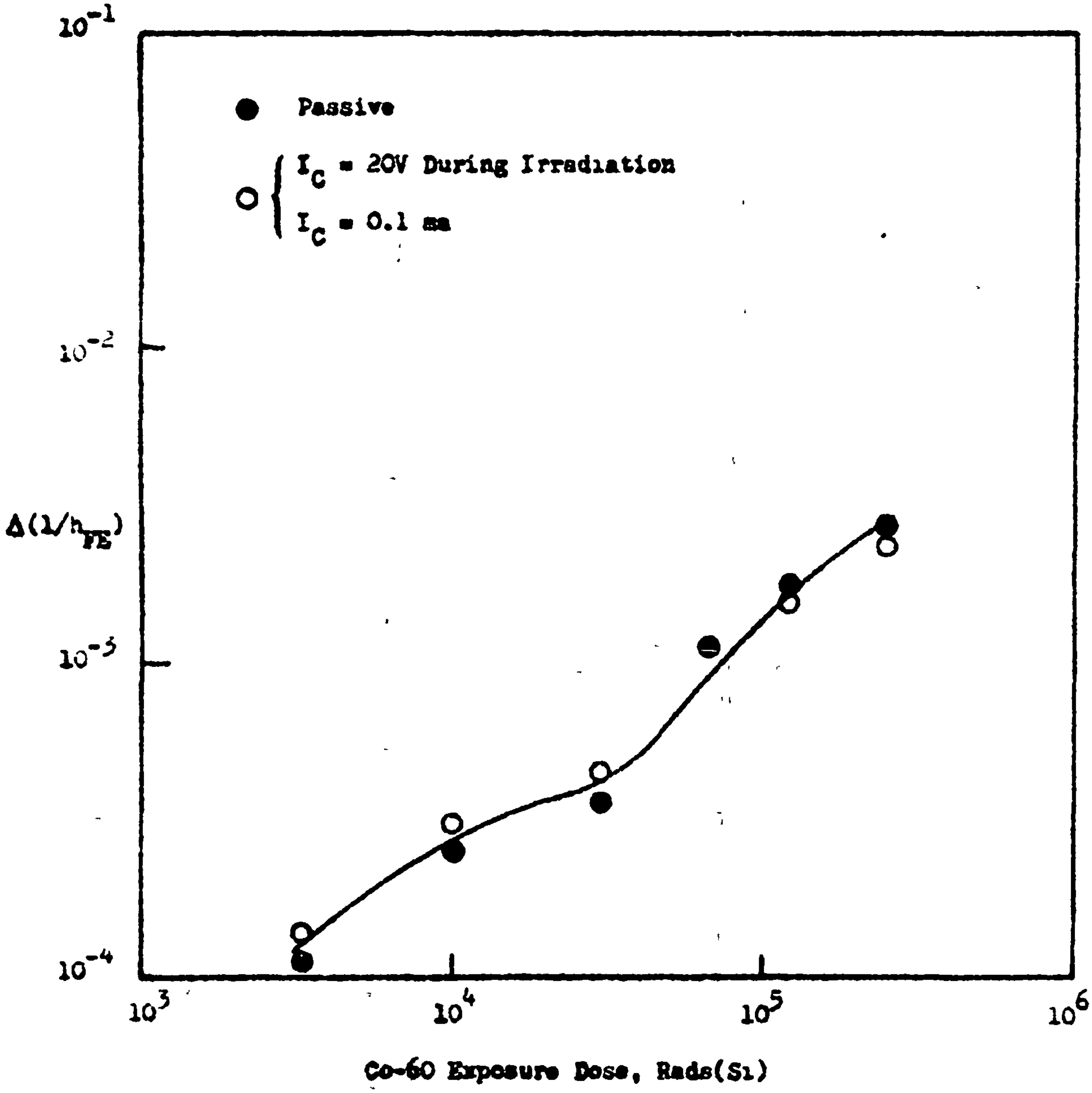


Figure 4.8A. Ionization Damage in Fairchild 2N930 Transistors at V_C = 20V, I_C = 10 ma Measurement Condition . (Ref. 4.24A)

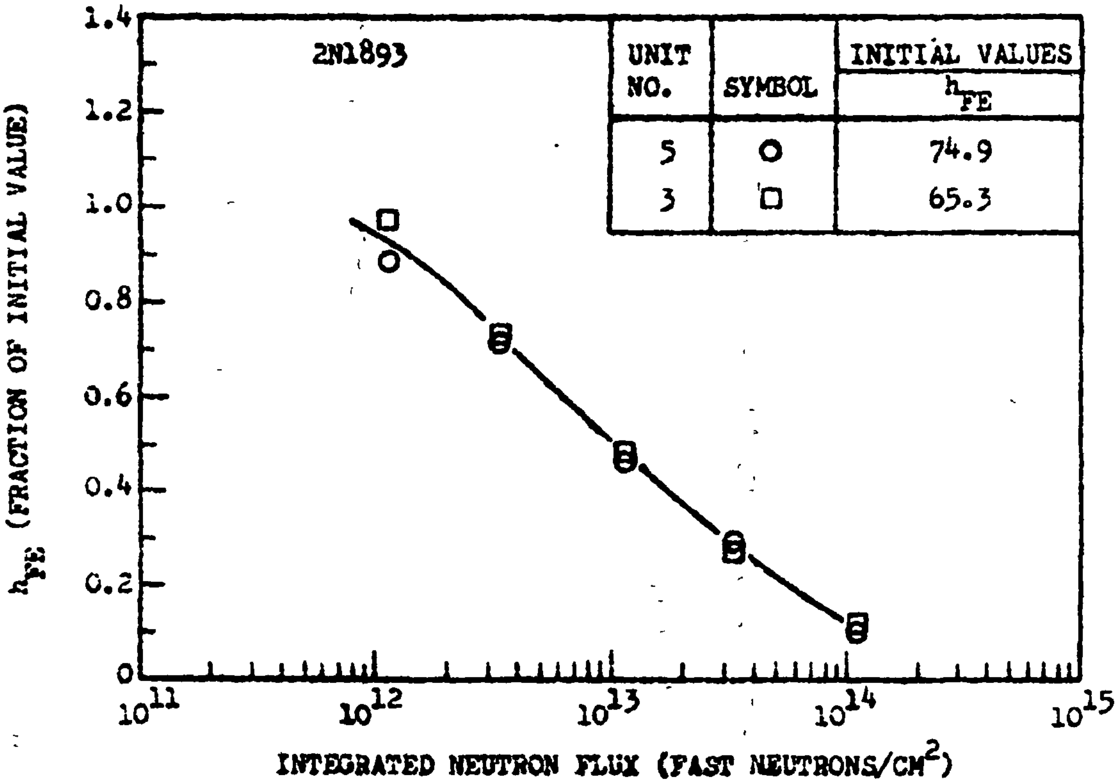


Figure 4.9A. Transistor 2N1893 Neutron Dependence of h_{FE}. (Ref. 4.21A)

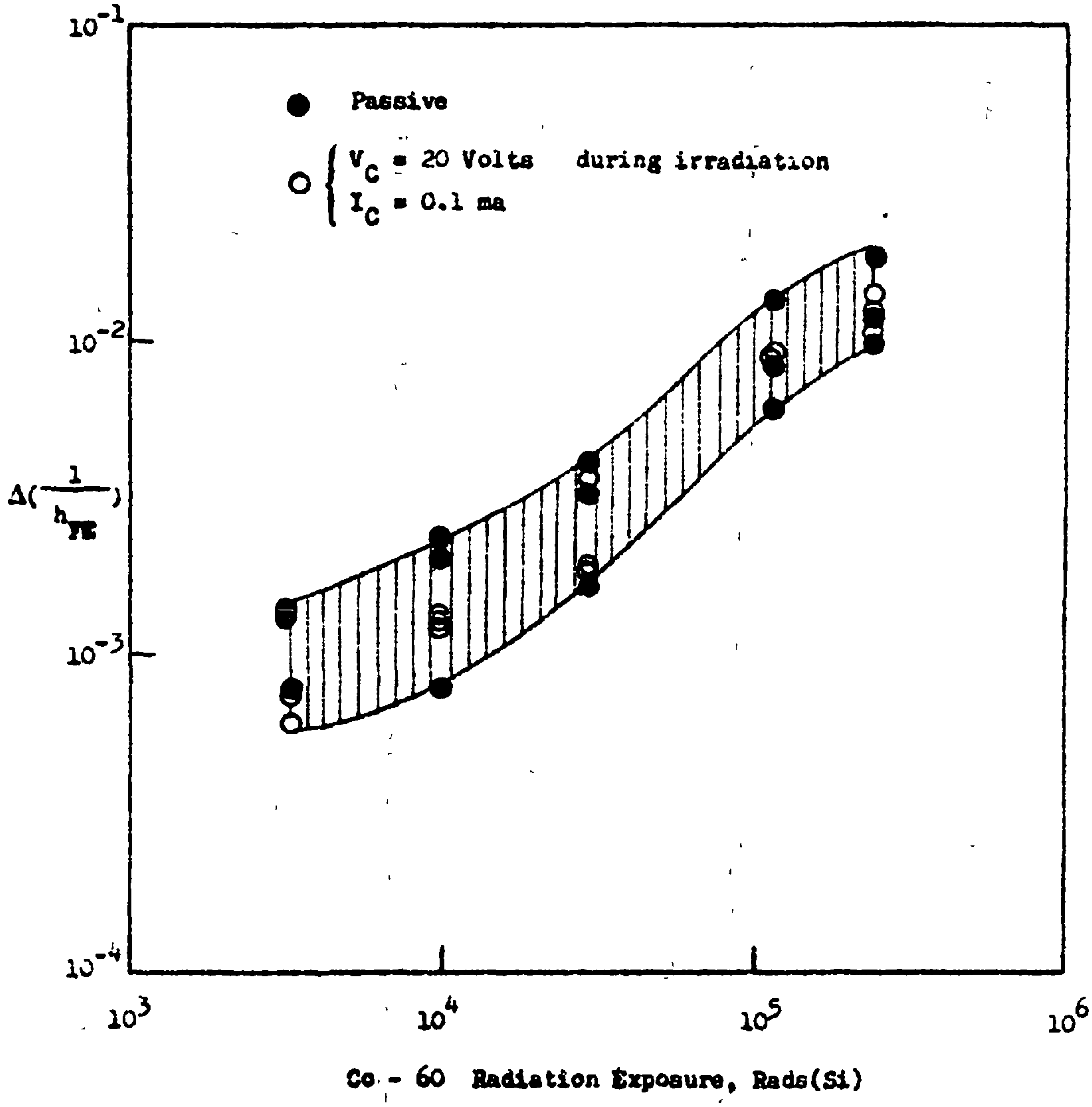


Figure 4.10A. Ionization Damage in Fairchild 2N1893 Transistors at V_C = 20 V, I_C = 1 ma Measurement Condition. (Ref. 4.24A)

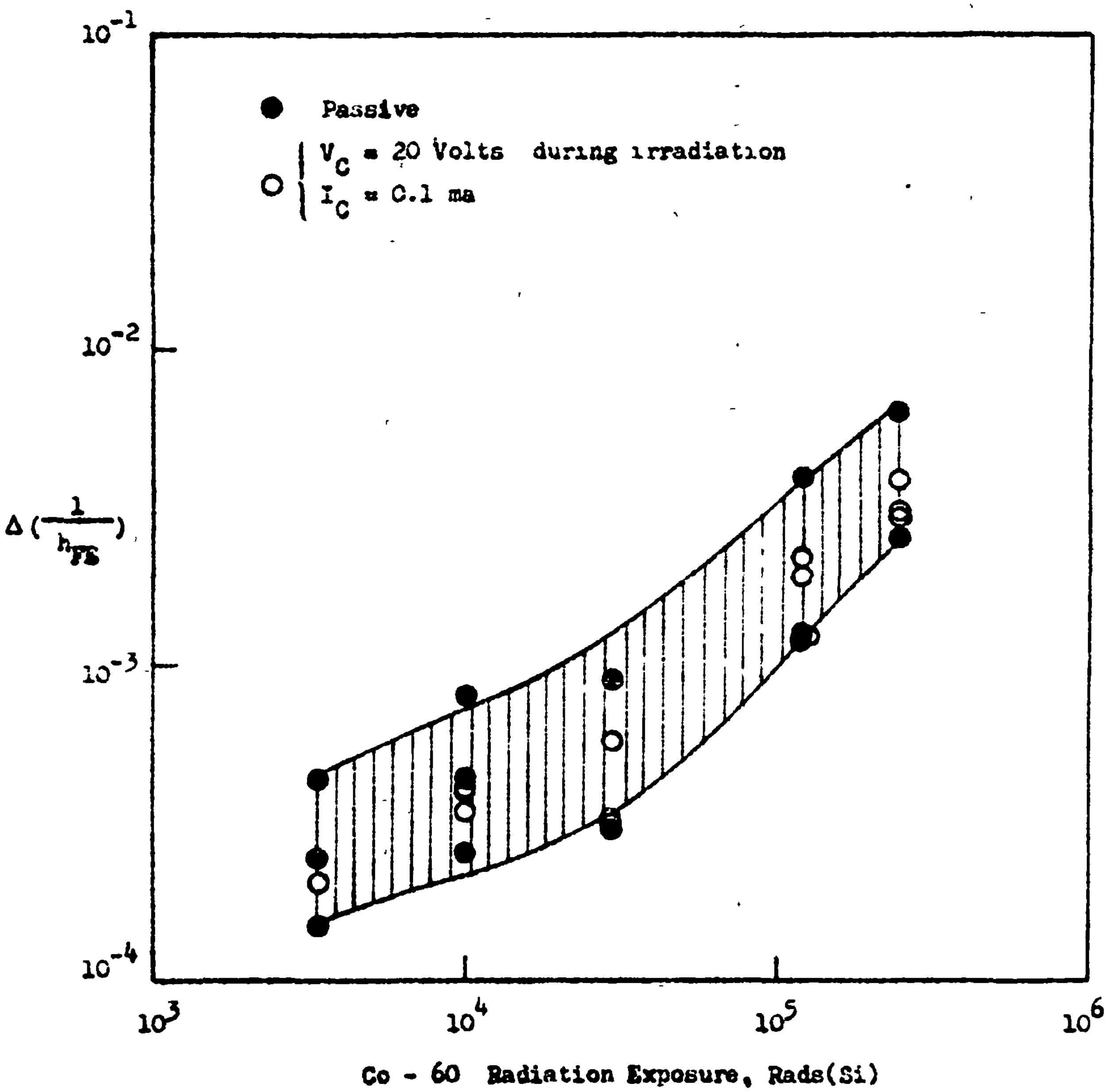


Figure 4.11A. Ionization Damage in Fairchild 2N 1893 Transistors at V_C = 20 V, I_C = 10 ma Measurement Condition. (Ref. 4.24A)

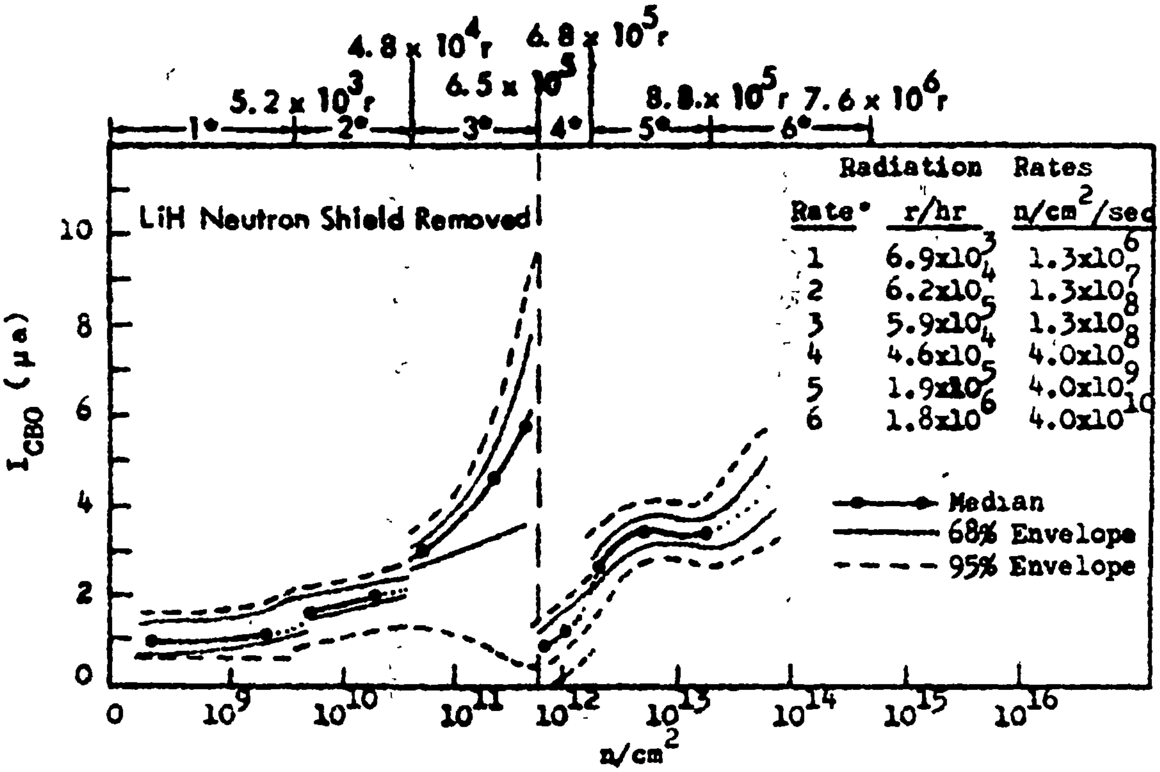


Figure 4.12A 2N2222, I_{CBO} Versus Integrated Neutron Flux at T = 37 - 0.5°C (14 Specimens). (Ref. 4.25A)

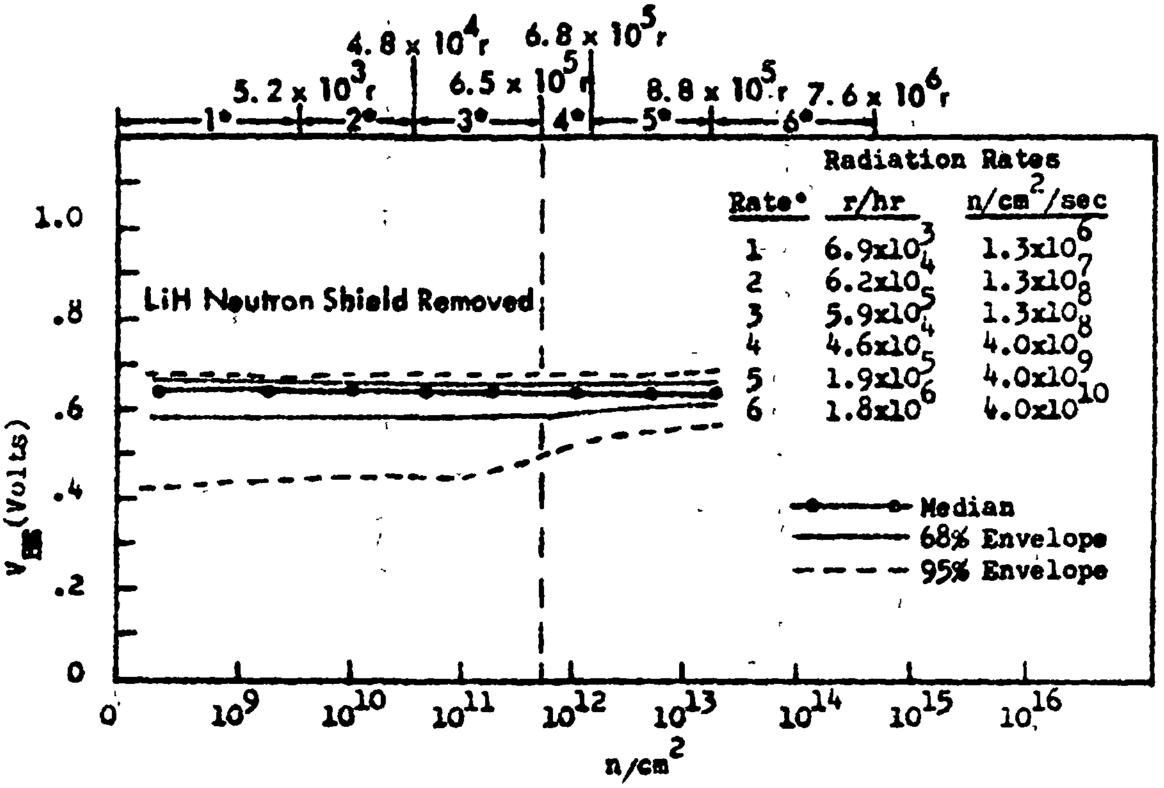
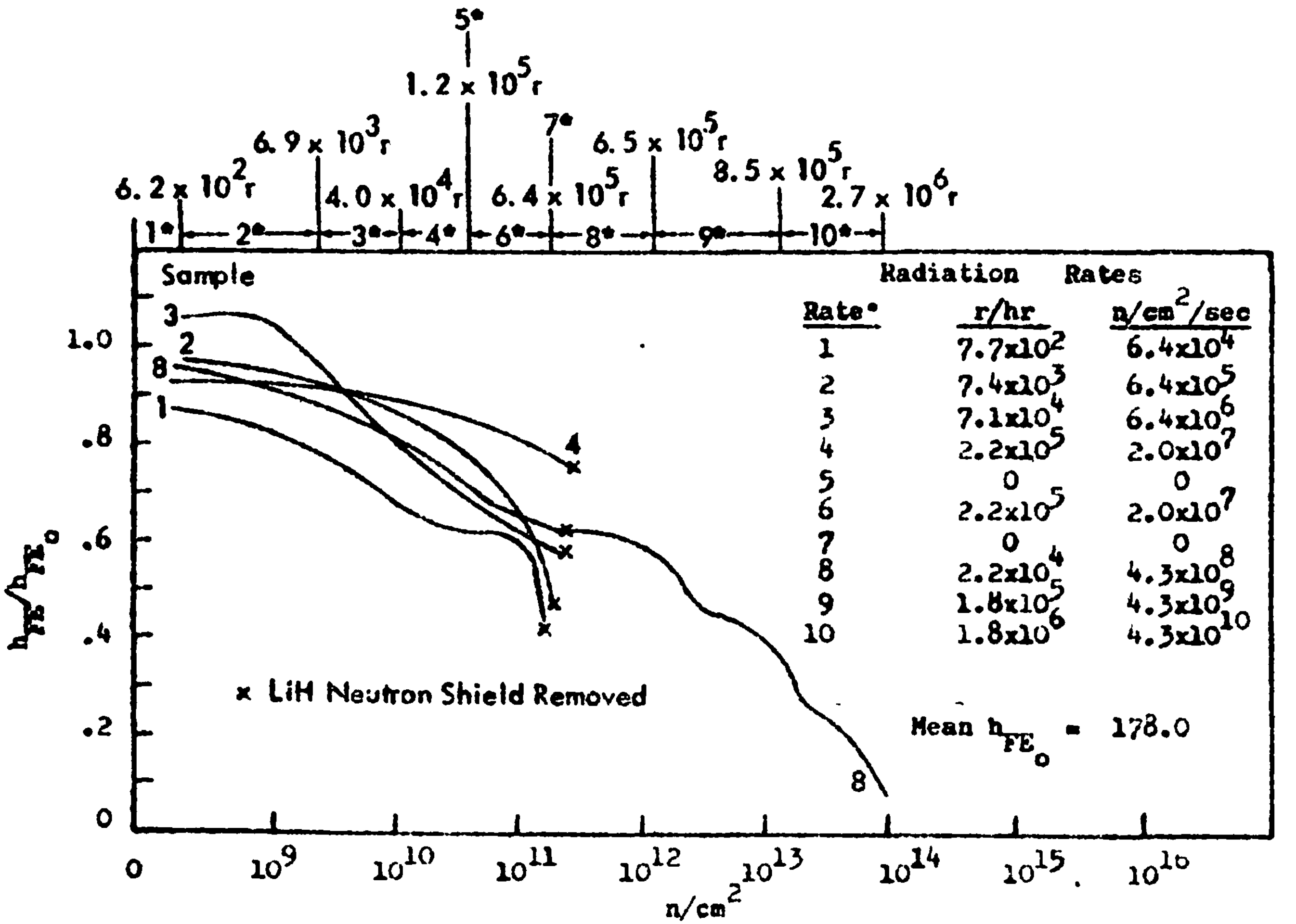


Figure 4.13A 2N2222, V_{BE} (I_C 10 ma Constant) Versus Integrated Neutron Flux at T = 37 - 0.5°C (13 Specimens) (Ref. 4.25A)



	Radiation	Rates
Rate*	r/hr	n/cm^2/sec
1	7.7x10^2	6.4x10^4
2	7.4x10^3	6.4x10^5
3	7.1x10^4	6.4x10^6
4	2.2x10^5	2.0x10^7
5	0	0
6	2.2x10^5	2.0x10^7
7	0	0
8	2.2x10^4	4.3x10^8
9	1.8x10^5	4.3x10^9
10	1.8x10^6	4.3x10^{10}

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

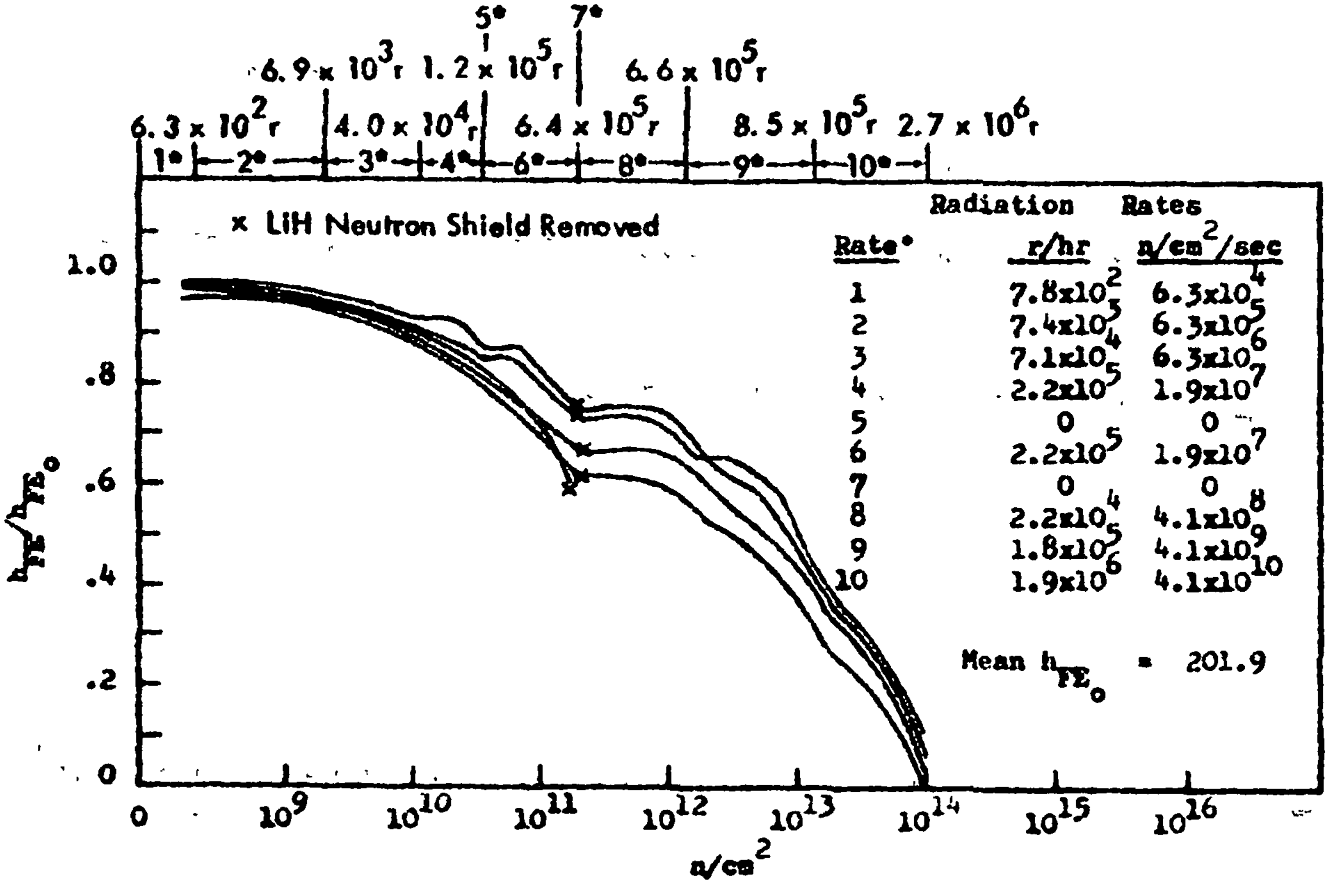


Figure 4.15A 2N2222, Texas Instruments, Inactive, Ambient, Normalized, h_{FE} Versus Integrated Neutron Flux. (Ref.4.26A)

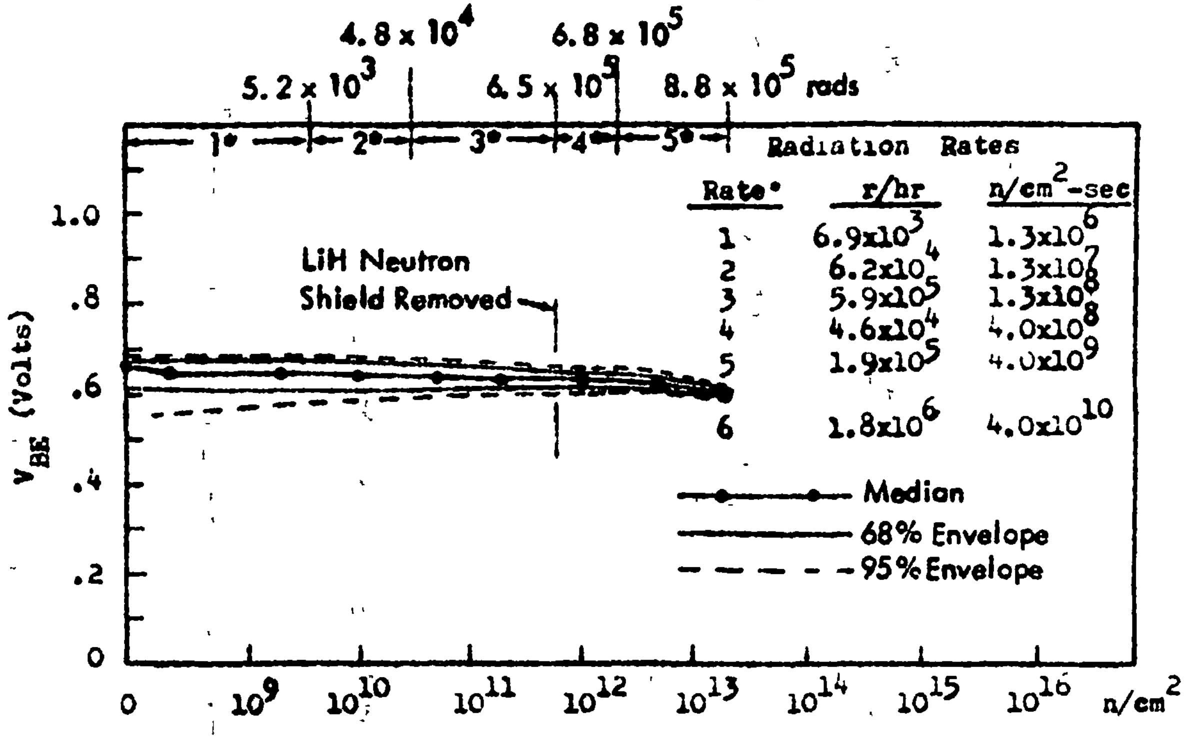


Figure 4.16A 2N2222, V_{BE} (I_B Constant, Mean I_C 10 ma) Versus Integrated Neutron Flux at T = 37°C (12 Specimens). (Ref. 4.25A)

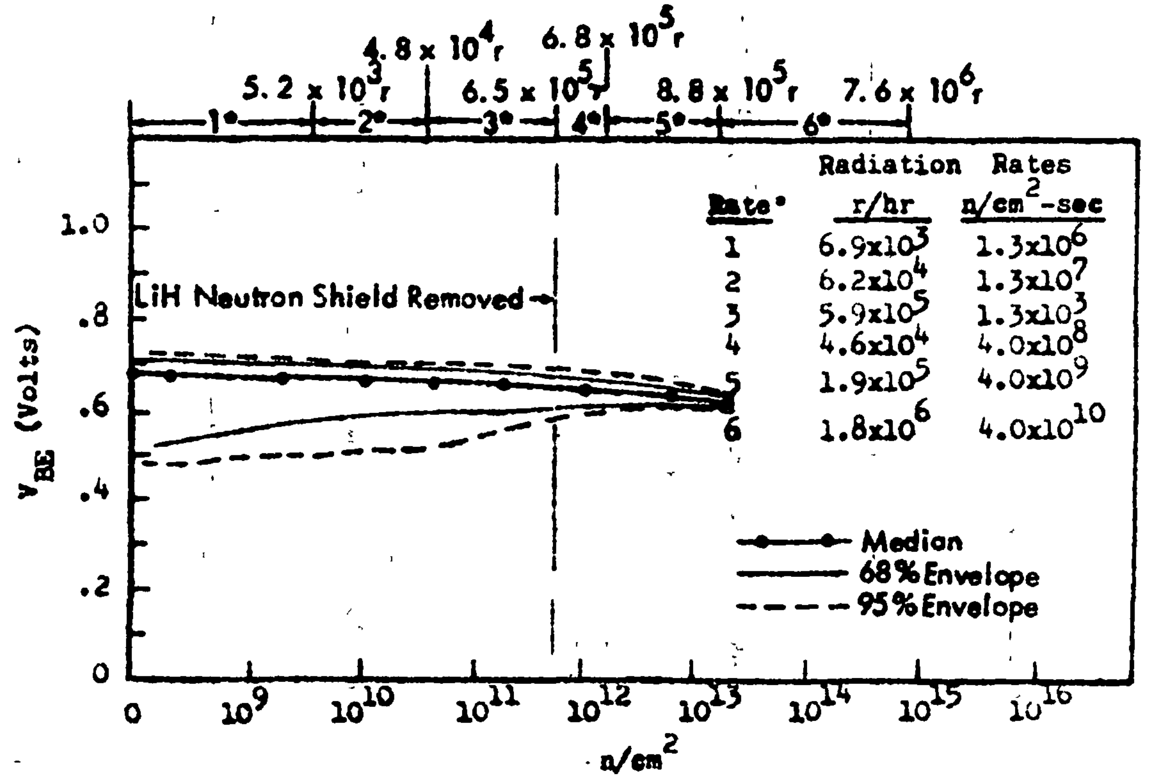


Figure 4.17A 2N2222 V_{BE} (I_B Constant, Mean I_C 20 ma) Versus Integrated Neutron Flux at T = 37° - 0.5°C (13 Specimens). (Ref. 4.25A)

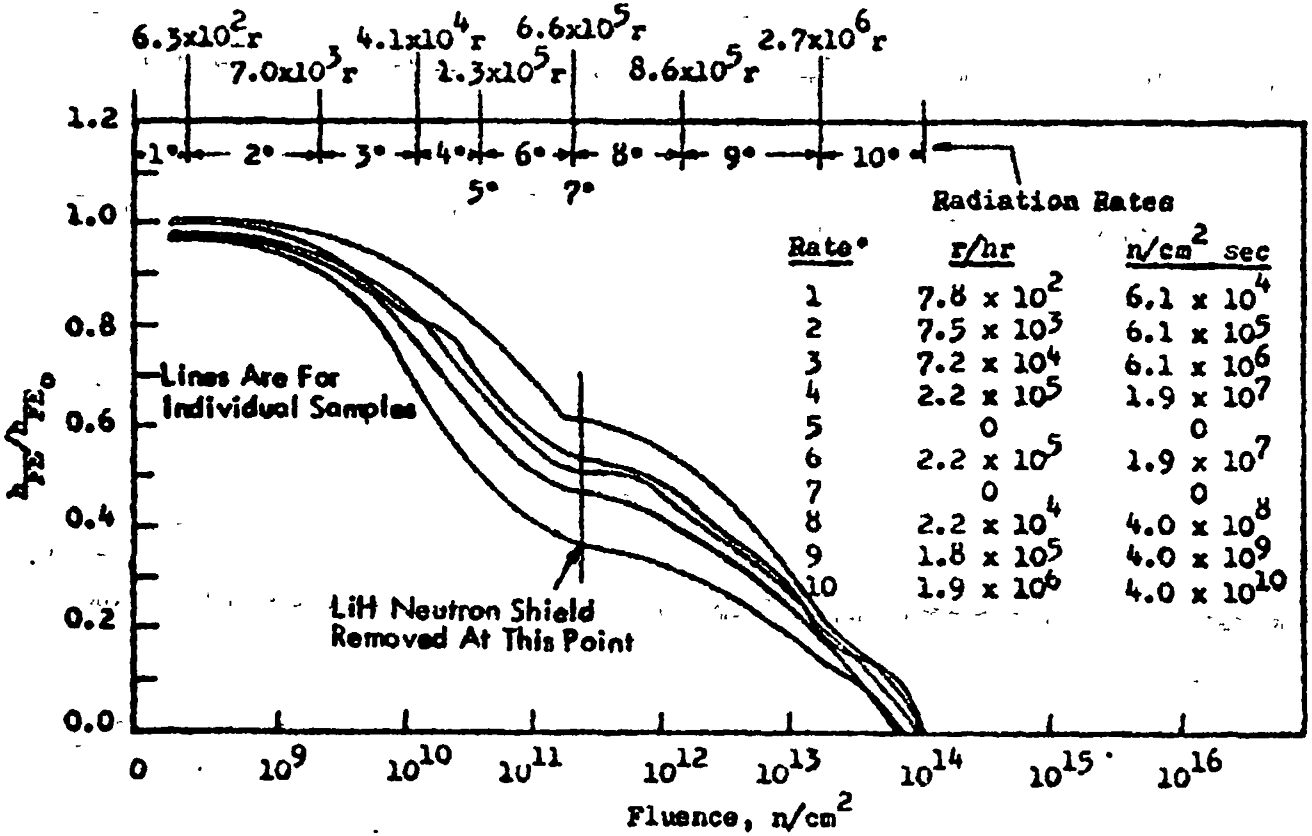
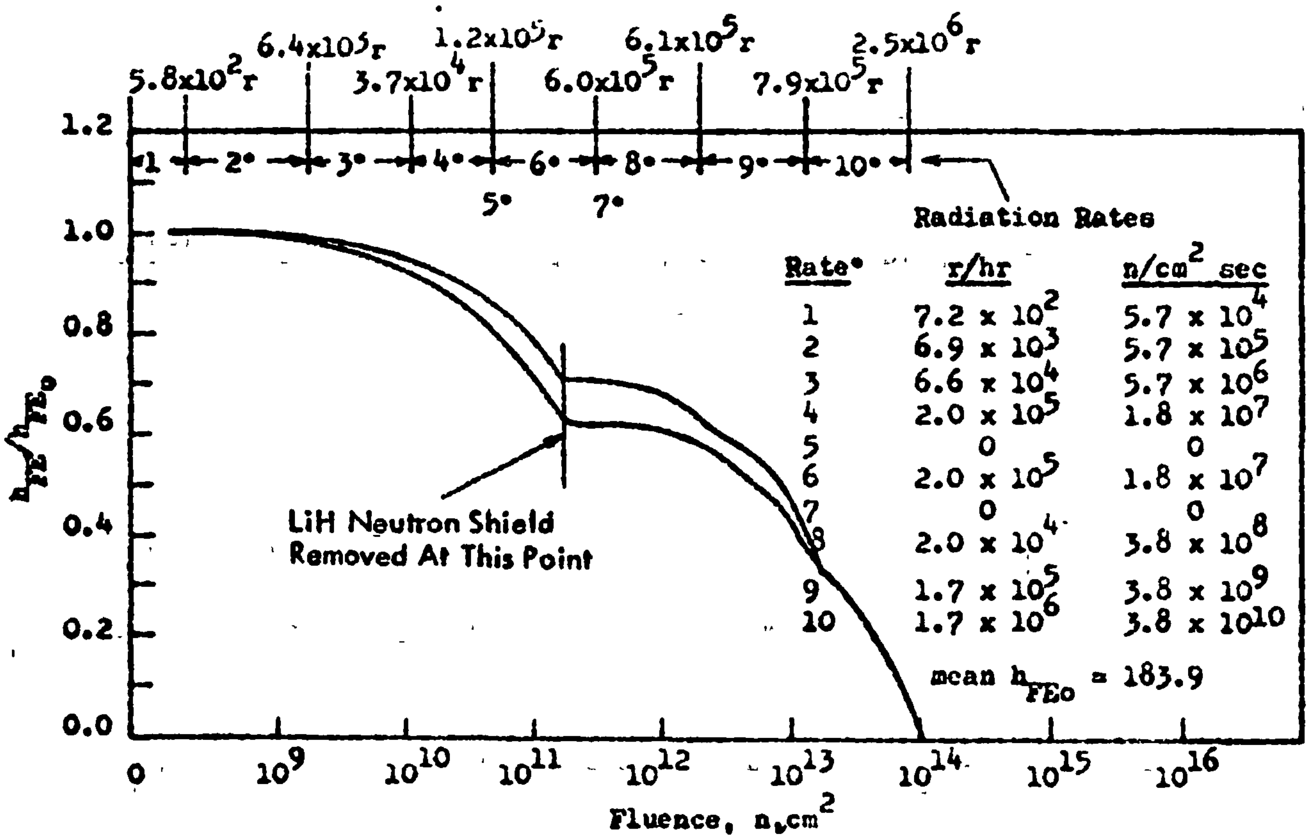


Figure 4.18A Normalized h_{FE} Versus Fluence for Active 2N2222 Transistor(Ref. 4.26A)



Rate•	r/hr	n/cm^2 sec
1	7.2×10^2	5.7×10^4
2	6.9×10^3	5.7×10^5
3	6.6×10^4	5.7×10^6
4	2.0×10^5	1.8×10^7
5	0	0
6	2.0×10^5	1.8×10^7
7	0	0
8	2.0×10^4	3.8×10^8
9	1.7×10^5	3.8×10^9
10	1.7×10^6	3.8×10^{10}

mean h_{FEo} = 183.9

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

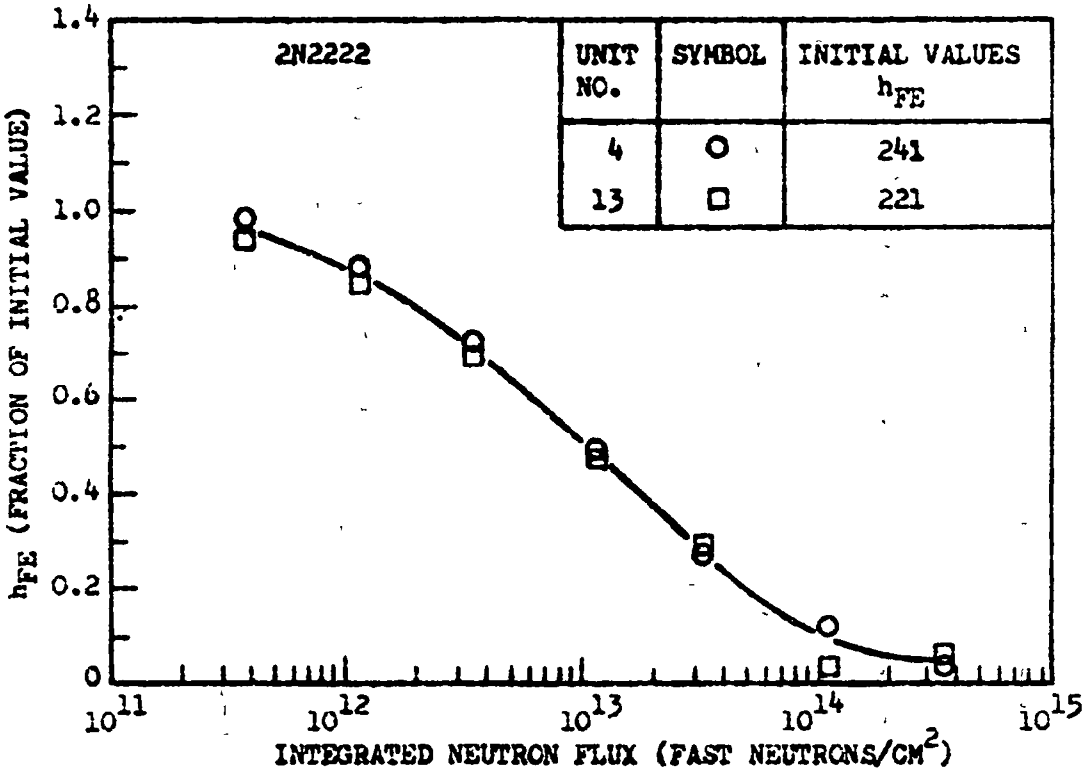


Figure 4.20A Transistor 2N2222 Neutron Dependence of h_{FE} (Ref. 4.21A)

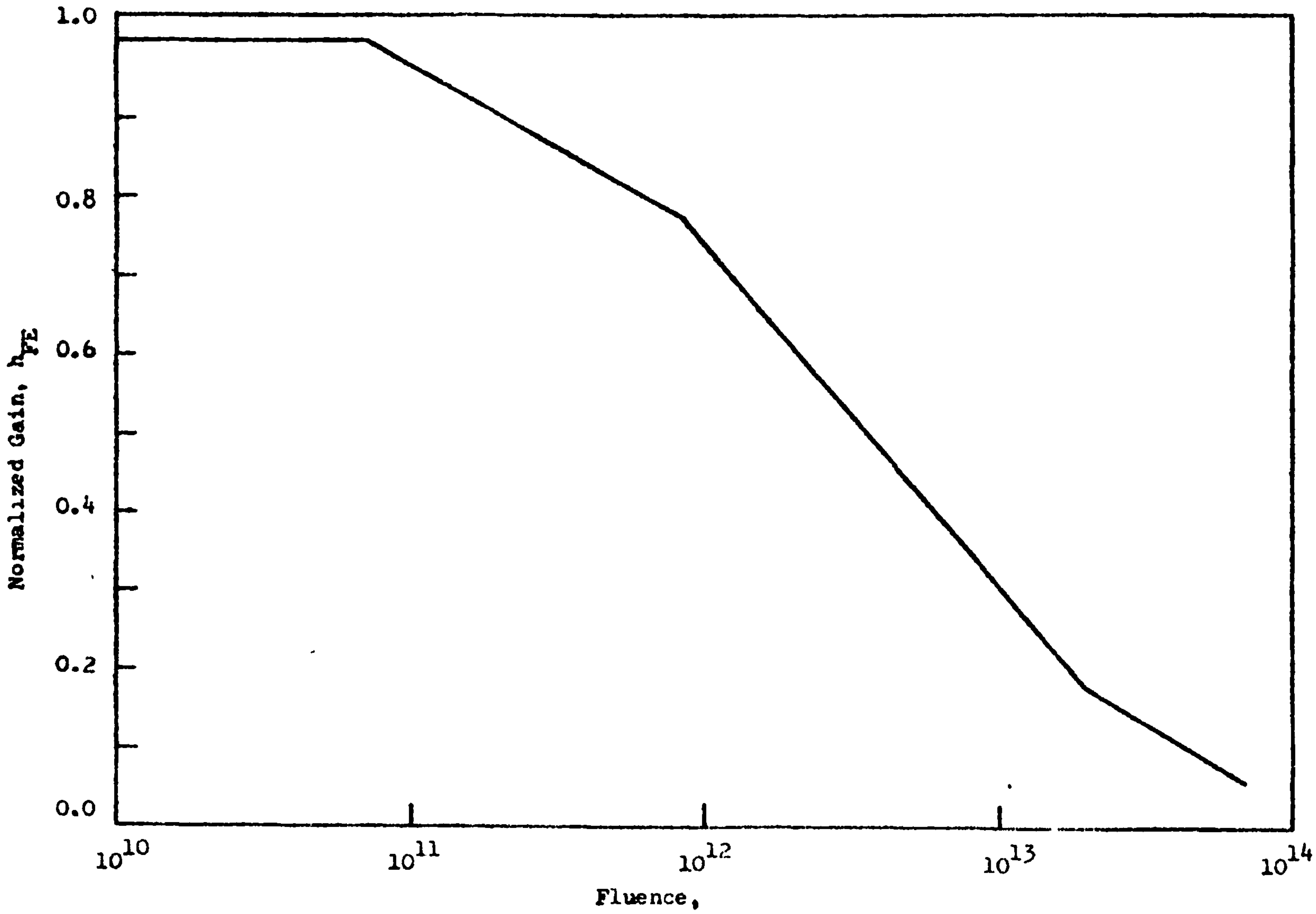


Figure 4.21A Normalized Gain Degradation for 2N2608 Transistor Data from Ref. 4.27A

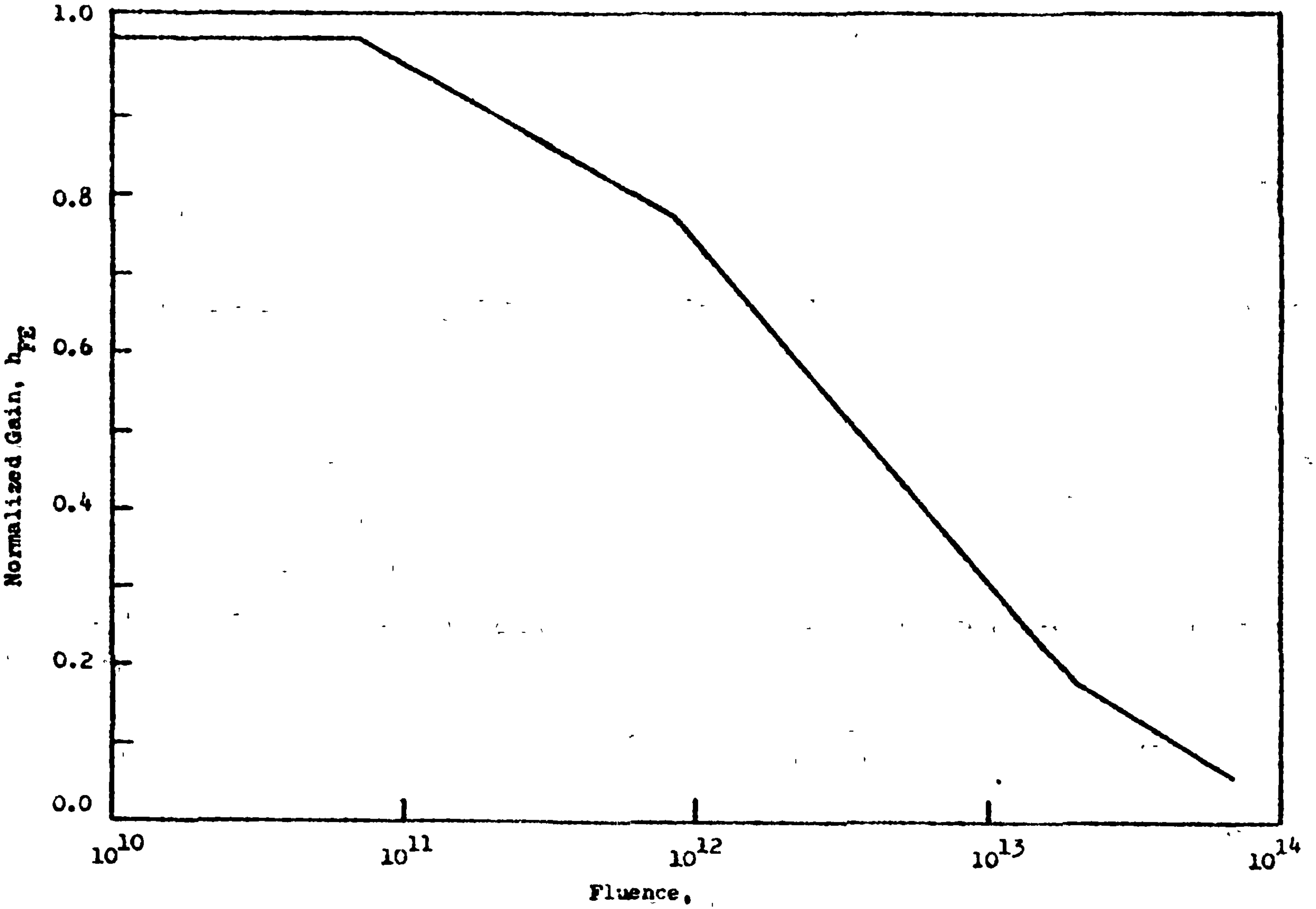


Figure 4.21A Normalized Gain Degradation for 2N2608 Transistor Data from Ref. 4.27A

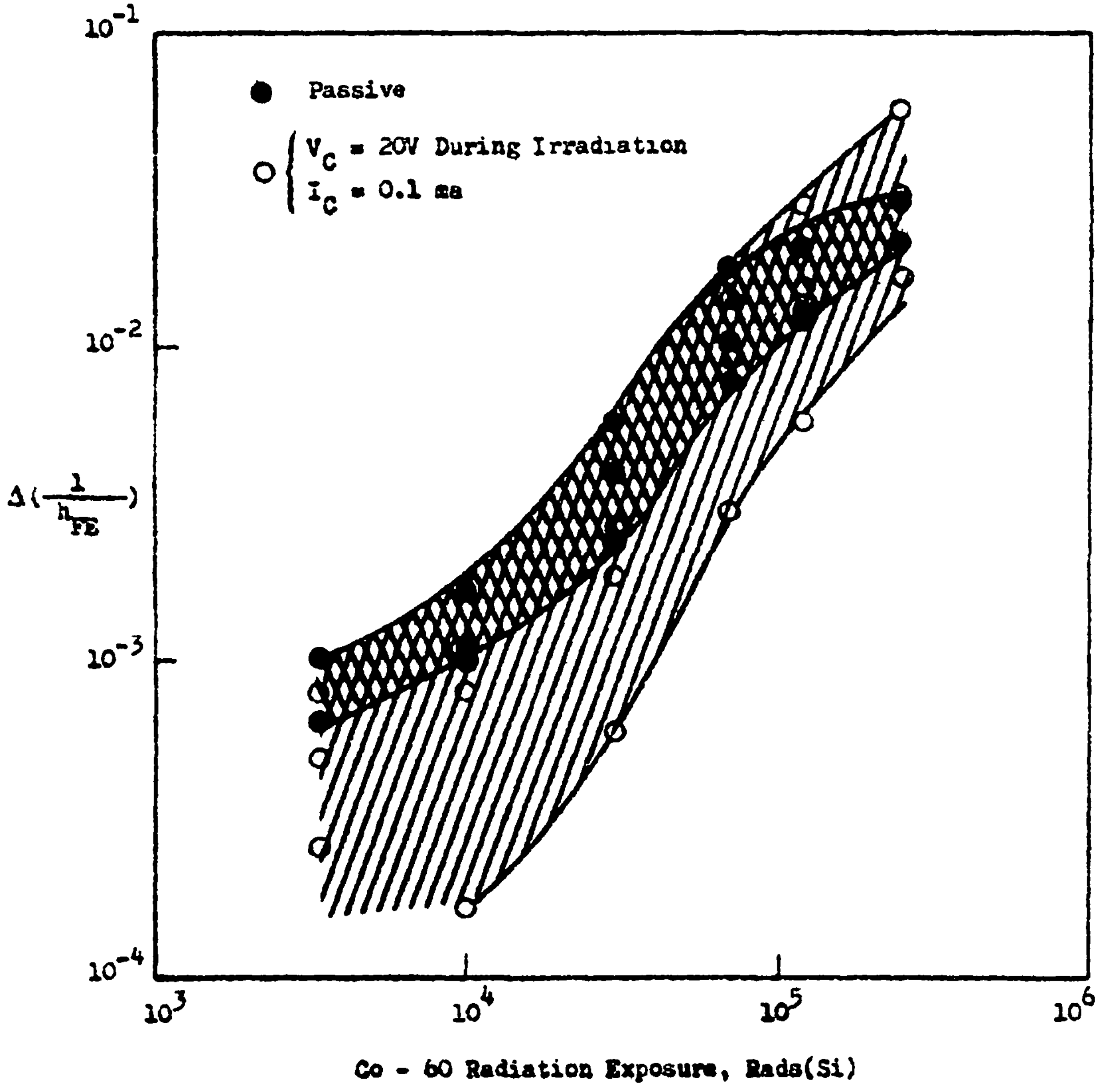


Figure 4.22A Ionization Damage in Fairchild 2N2946 Transistors at V_C = 20 V, I_C = 1.0 ma Measurement Condition. (Ref. 4.24A)

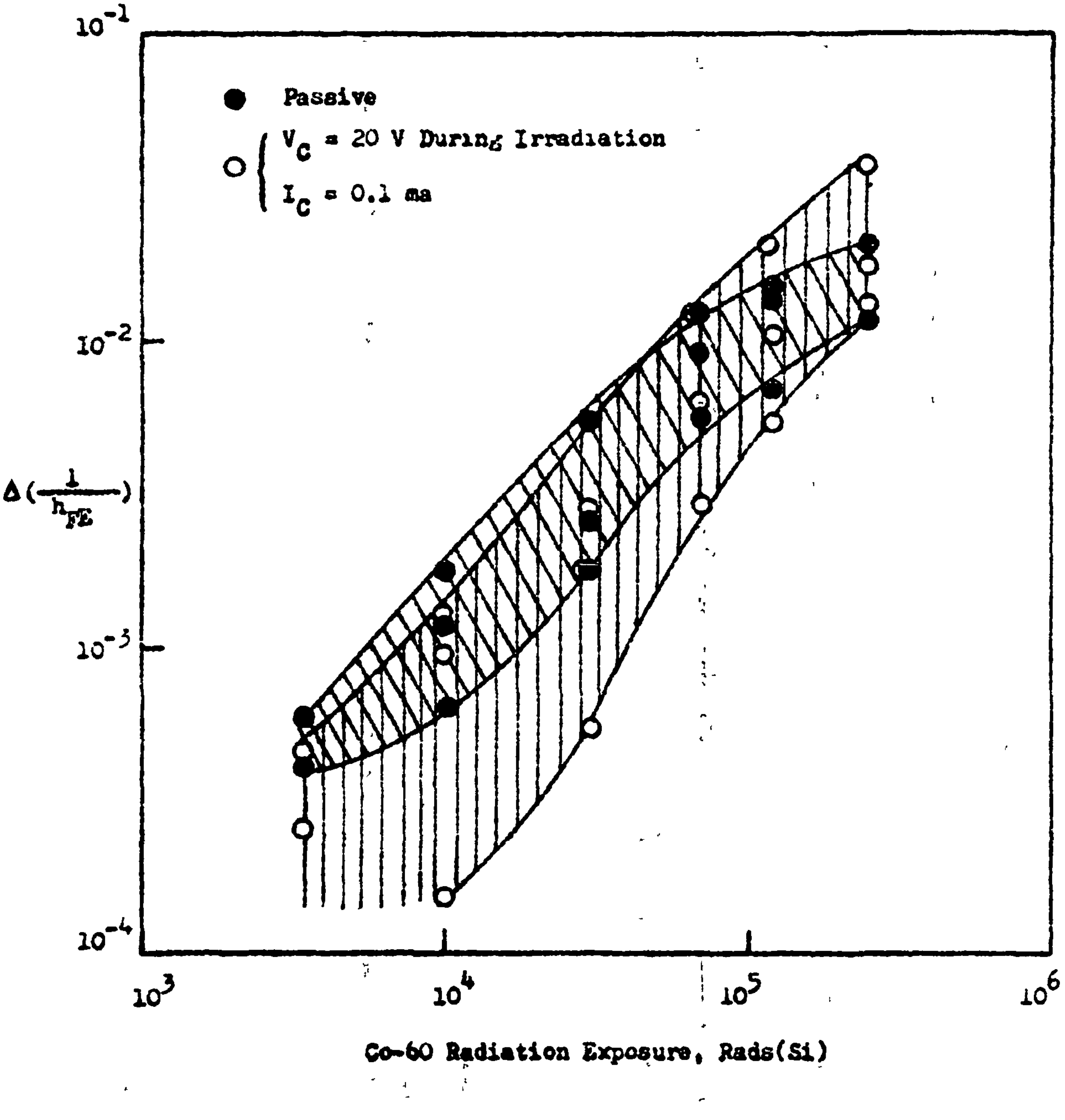


Figure 4.23A Ionization Damage in Fairchild 2N2946 Transistors at V_C = 20V, I_C = 10 ma Measurement Condition. (Ref. 4.24A)

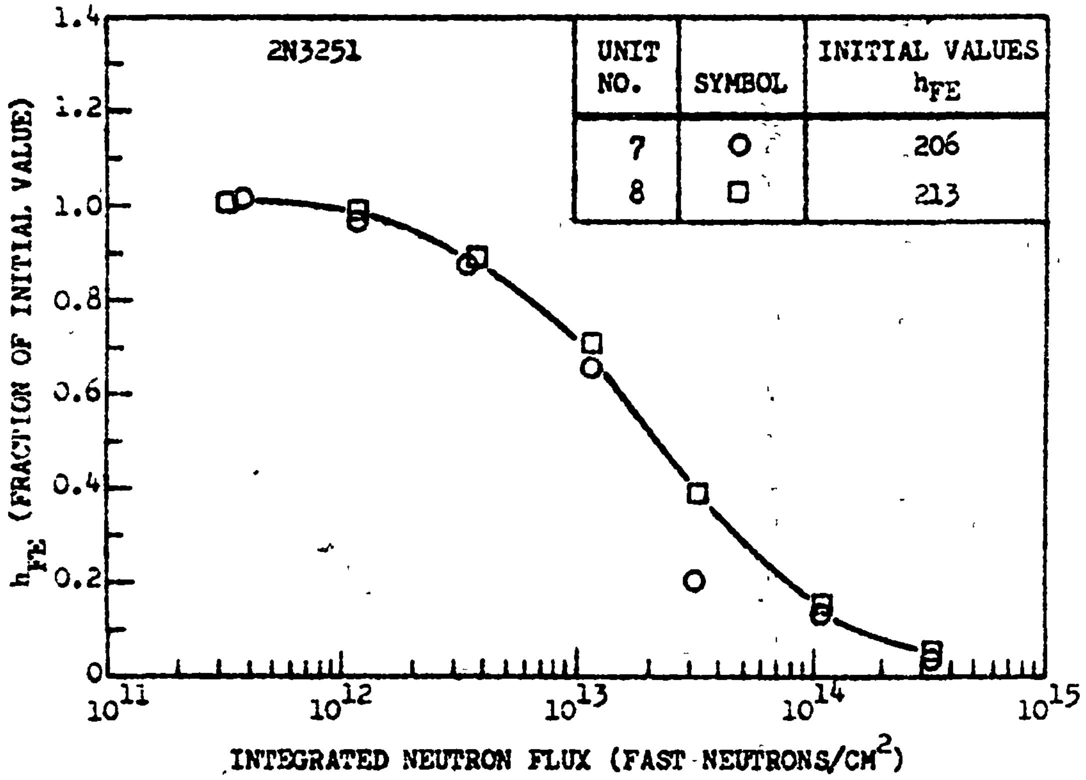


Figure 4.24A. Transistor 2N3251 Neutron Dependence of h_{FE}. (Ref. 4.21A)

5.0 JUNCTION FIELD EFFECT TRANSISTORS

5.10 Permanent Parameter Degradation

Presently available junction field effect transistors, JFETs, are comparable to high frequency (f_{aCO} > 150 MHZ) bipolar transistors in radiation sensitivity; however, recent studies have shown that, at least for displacement effects, they can possibly be made much harder.

For displacement damage, the transconductance, g_m, the drain to source current, I_{DSS}, and the pinch off voltages, V_P, are the sensitive parameters. Normally the devices show little degradation at fluences of the order 10^{13} n/cm^2, but show excessive damage between 10^{14} and 10^{15} n/cm^2. However, recent experimenters (Reference 5.71, 5.72) have fabricated special heavily doped devices which are able to withstand from 10^{15} to 10^{16} n/cm^2. It has also been observed that n-channel devices are more resistant to displacement damage than p-channel devices.

For ionization damage, the gate to source leakage current, I_{GS}, is the most sensitive parameter and it usually increases very rapidly beyond 10^6 rads. It has been observed (Reference 5.73) that p-channel JFET s are more resistant to ionizing radiation than n-channel units.

These observations indicate that a design tradeoff must be made in choosing n-channel or p-channel devices for radiation resistance after considering the environment to be encountered.

5.11 Neutron Effects

The predominant basic mechanism resulting from neutron exposure is the production of atomic displacements. Since JFET s are majority carrier devices, the most important effect of the displacements on device operation is carrier removal in the channel region. Shedd et al (Reference 5.72) have summarized the theory of permanent effects of neutrons in JFET s and presented the relation in equation 5.1 to express the degradation:

$$\frac{g_m(\Phi)}{g_{m_o}} = \exp\left(-\frac{\Phi}{K}\right) \qquad \text{(eq. 5.1)}$$

$g_m(\Phi)$ = transconductance at fluence Φ

g_{m_o} = initial transconductance

Φ = fluence, n/cm^2

$K = K_p = 398 P_o^{0.77}$ for a p-channel

$K = K_n = 93 N_o^{0.82}$ for a n-channel

P_o, N_o } Initial carrier concentrations

The important point to observe here is that theory predicts n-channel devices to be harder than p-channel devices. The full development of the theory is not presented here; however, it appears to be in good agreement with empirical observations. It should be noted, though, that the above relations have not been verified sufficiently on a statistical basis. Therefore, for the present, the relation should not be regarded as more than a semiquantitative estimate of neutron degradation.

Empirical thresholds have been established for neutron damage in presently available JFET s and it is found that they are generally able to withstand fluences of the order 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.

Further, some rate dependence has been reported (Reference 5.74) in the pinch off voltage, V_p, but the dependence appears to be significant only at rates greater than 3×10^{10} n/cm^2-sec plus 1×10^6 rads/hr (mixed environment). From the data it was not clear whether the rate dependence was due to the gamma field or the neutron field.

5.12 Proton Effects

Protons cause both displacement damage and ionization damage. Therefore, one would expect them to produce changes in g_m, I_{GS}, and V_p. Unfortunately, the only article located (Reference 5.75) dealing with proton effects did not report the effects of proton damage on I_{GS}. It is interesting to note that V_p showed degradation at a fluence two orders of magnitude less than g_m or I_{DSS}. This early change in V_p probably reflects proton ionization effects. Protons have been observed to cause significant damage to g_m and I_{DSS} in JFET s. Generally, the parameters g_m and I_{DSS} were degraded 30 percent by a fluence of 10^{12} - 10^{13} P/cm^2 (22 MeV).

A model was proposed for the degradation based on carrier removal in the channel region. The model yielded equation 5.2 and 5.3

$$I_{DSS} = I_{DSS_o} (1 + \gamma \Phi)^2 \qquad \text{(eq. 5.2)}$$

$$g_{mo} = g_{mo_o} (1 + \gamma \Phi) \qquad \text{(eq. 5.3)}$$

I_{DSS_o} = initial I_{DSS}

g_{mo} = g_m at zero gate voltage

g_{mo_o} = initial g_{mo}

Φ = proton fluence, P/cm^2

γ = *constant dependent on initial carrier concentration,* N_o, and initial carrier removal rate, $(dN/d\Phi)_o$, as expressed $\gamma = \dfrac{1}{N_o\,(dN/d\Phi)_o}$

The constant γ shows considerably variation between device types due to impurities in the materials. Examples of the variations observed in γ are shown in the equations 5.4 and 5.5 presented by Bryant (Reference 5.75) for two types of devices.

$$\text{Type 2N3070} \quad g_{mo}/g_{mo_o} = (1.0 - 0.148 \times 10^{-13}\,\Phi) \qquad \text{(eq. 5.4)}$$

$$\text{Type 2N2844} \quad g_{mo}/g_{mo_o} = 0.986(1.0 - 0.737 \times 10^{-14}\Phi) \qquad \text{(eq. 5.5)}$$

It should be noted that proton damage could probably be described by the neutron theory discussed in Section 5.11 which is not restricted to the condition of zero gate voltage as are the above relations.

5.13 Gamma Damage

Gamma radiation produces primarily ionization damage. Since semiconductor surfaces are altered by ionizing radiation, one would expect leakage currents to be the most sensitive JFET parameters to ionization damage. These expectations have been verified by experiment for both gamma and electron radiation (electrons cause heavy ionization). The gate leakage current, I_{GS}, is the parameter most affected. N-channel devices have been found more sensitive to ionization effects than p-channel devices. Stanley (Reference 5.73) has attributed this 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 formation over the junctions and, hence, leakage paths. The charge accumulation in the oxide of p-channel devices is less effective at inverting the low resistivity p-type silicon source and drain of the p-channel JFETs. For this reason, they are less subject to channel formation. As has been observed before, for similar oxide charge accumulation effects in bipolar and MOS devices, the I_{GS} changes are bias dependent and, if the bias is removed, show considerable annealing.

The 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 rad(Si), the leakage current degrades very rapidly. For applications requiring high input impedance, the threshold should be lowered to about 10^5 rads(Si).

5.20 Parameter Drift

The data indicate no significant parameter drift during irradiation other than the long term degradation discussed above. An exception being the enhancement of, and annealing of ionization damage by changing bias levels.

5.30 Parameter Degradation Factors

The extent of radiation degradation of various JFET parameters can be assessed from the data shown in Figures 5.1 through 5.6 and Tables 5.1 and 5.3 which are typical of the data located in this literature search. From the data

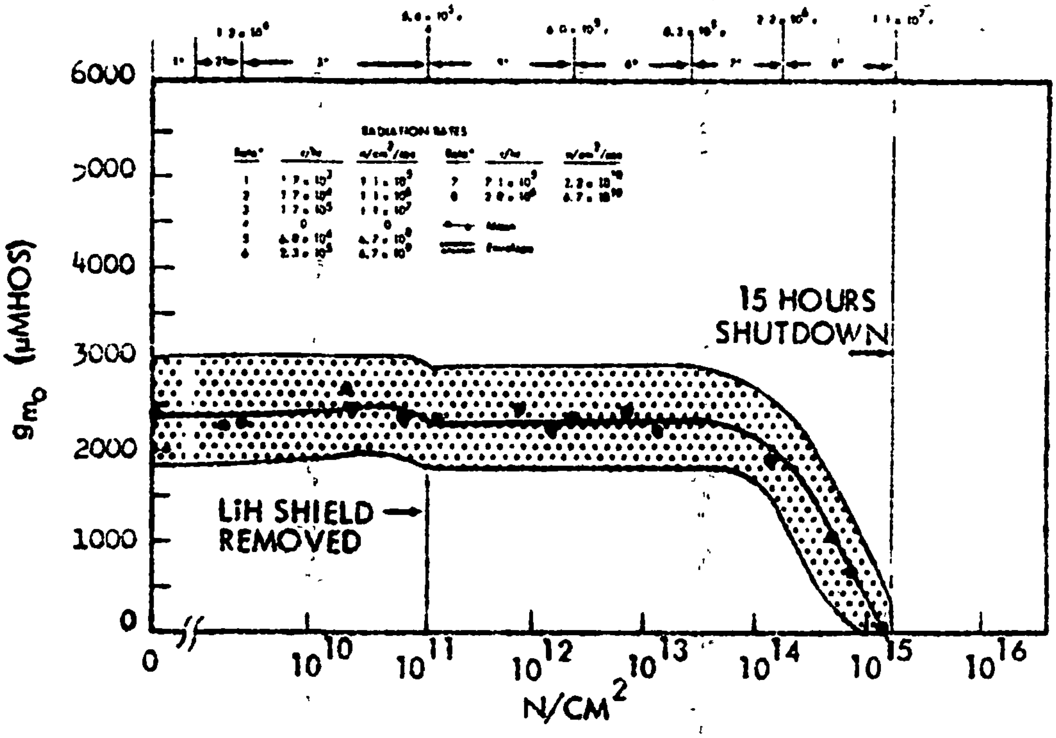


Figure 5.1 2N2498 Texas Instruments, 30°C, g_{m_o} Versus Integrated Neutron Flux (Ref 5.74)

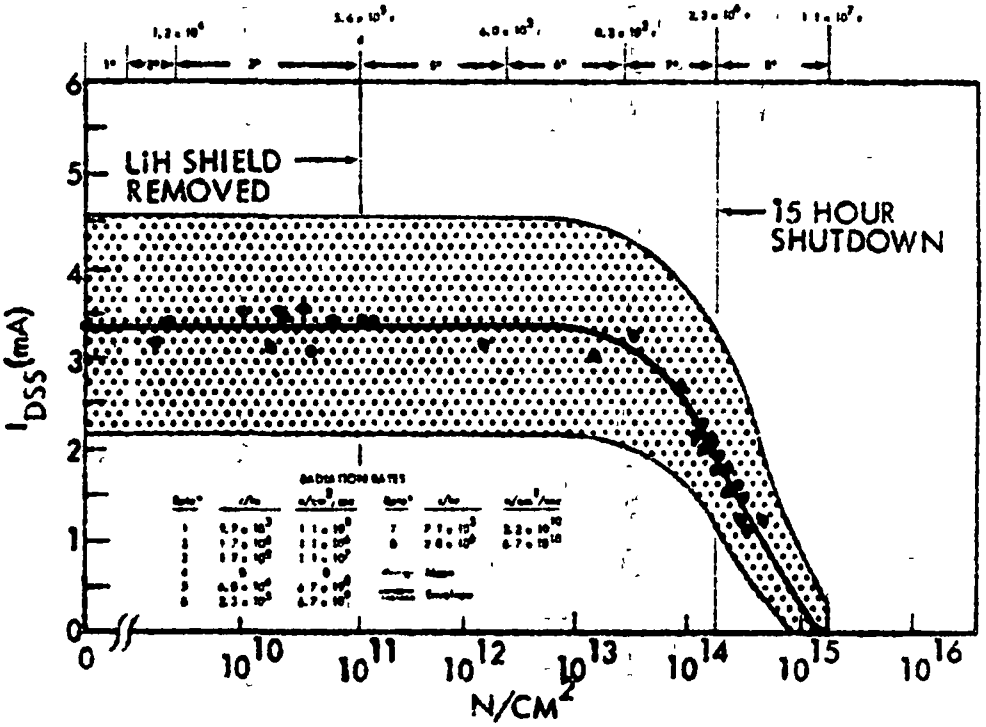


Figure 5.2 2N2498 Texas Instruments, 30°C, I_{DSS} Versus Integrated Neutron Flux (Ref 5.74)

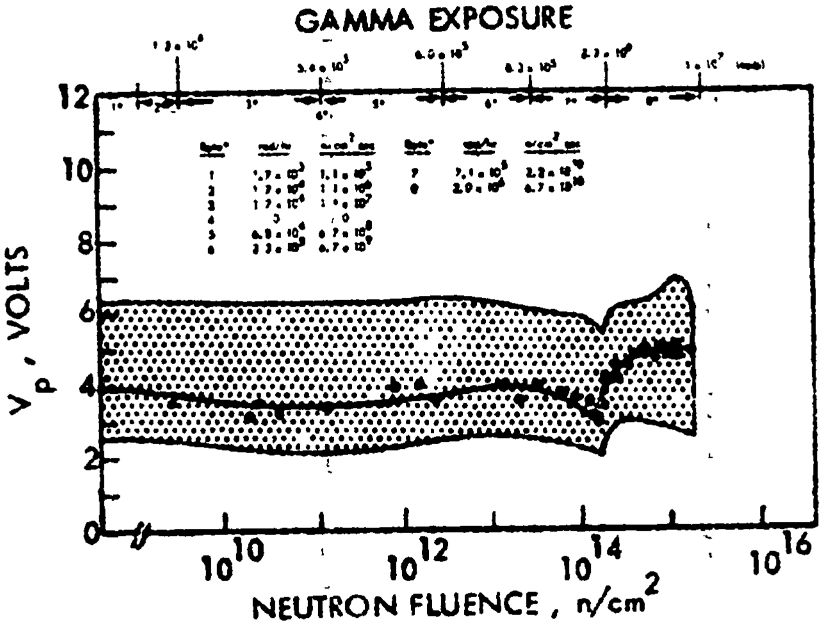


Figure 5.3 V_p Versus Neutron Fluence for Texas Instruments 2N2498 (30°) (Ref 5.74)

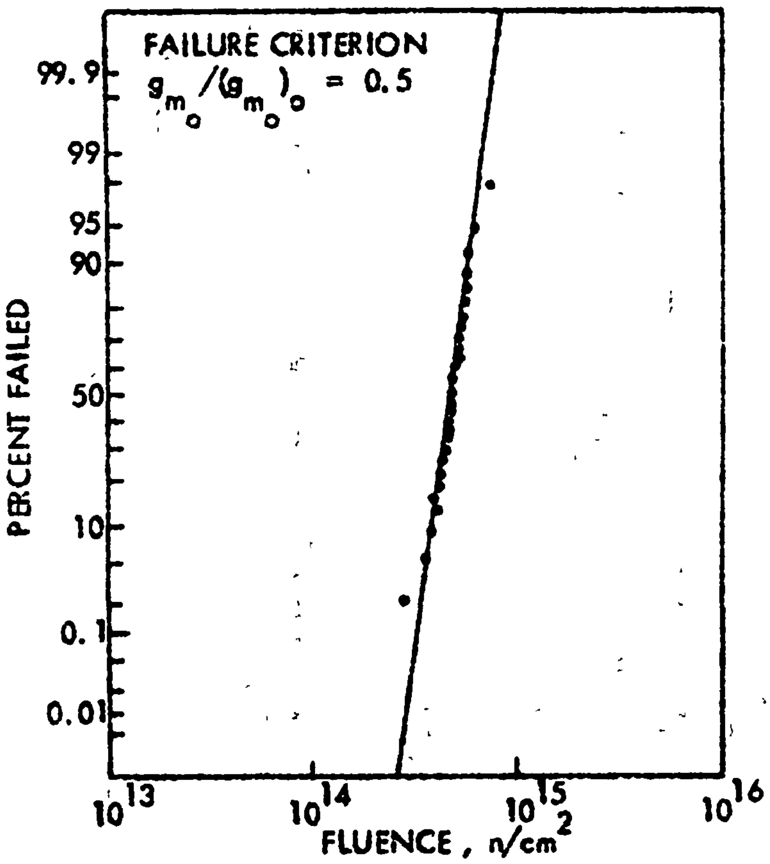


Figure 5.4 Percent Failed Versus Neutron Fluence for 2N2498 Texas Instruments Devices (30°) (Ref 5.74)

Table 5.1 Leakage Currents During Irradiation (Ref. 5.73)

Type	Unit	Irradiation Conditions		Initial	Leakage Current at Total Dose (e/cm^2)			
		Date	Bias		10^{12}	10^{13}	10^{14}	10^{15}
n-channel 175		9/16/65	V_{GS} = -6V V_{DS} = +12V		9.8×10^8	4.1×10^9	3.8×10^{10}	8.2×10^{11}
					Gate Current			
1				0.11 nA	0.35 nA	28.8 nA	5.2 A	
2				0.10 nA	0.48 nA	15.7 nA	3.8 A	
3				0.16 nA	0.63 nA	11.6 nA	5.0 A	9.9 A
4				0.28 nA	0.80 nA	11.5 nA	6.0 A	
5				0.29 nA	0.75 nA	1.9 nA	760 A	
6				0.26 nA	0.80 nA	3.2 nA	2.46 A	9.9 A
7				0.35 nA	1.10 nA	2.3 nA	562 nA	4.4 A
8				0.32 nA	0.90 nA	2.3 nA	920 nA	5.5 A

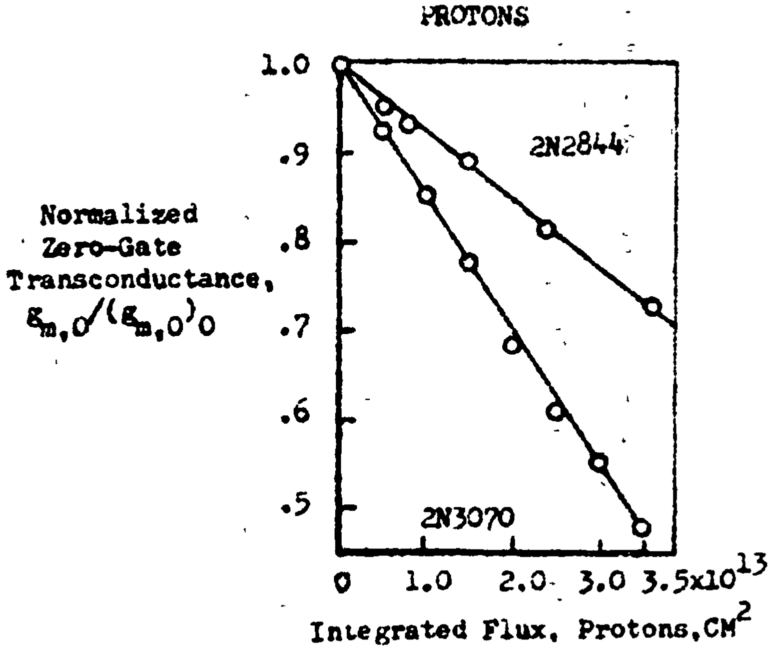


Figure 5.5 Normalized Zero-Gate Transconductance as a Function of 22-MeV Proton Flux. (Ref. 5.75)

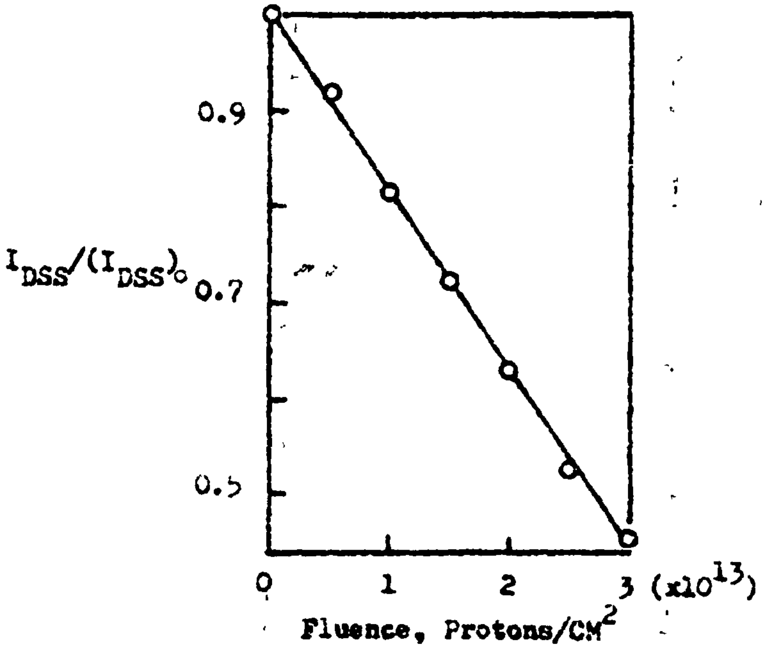


Figure 5.6 Normalized Zero-Gate Voltage Drain Current as a Function of 22-MeV Proton Fluence for Transistor Type 2N3067 (n-Channel). (Ref. 5.75)

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 μa	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 5.3 Brief Summary of 22-MeV Proton Irradiations (Ref. 5.75)

Transistor Type	Proton flux necessary to cause 30% degradation in I_{DSS}, protons/cm^2	Degradation at indicated flux, %	Proton flux necessary to cause 30 % degradation in g_m, protons/cm^2	Degradation at indicated flux, %
2N3067	$3.4 \pm 1.6 \times 10^{12}$	30	$4.5 \pm 2.5 \times 10^{12}$	30
2N3386	8×10^{12}	10 to 30	7×10^{12}	5 to 20
2N2344	$3.5 \pm 1.5 \times 10^{12}$	30	$5.3 \pm 1.8 \times 10^{12}$	30
2N3089	$5.0 \pm 3.0 \times 10^{12}$	30	$4 \pm 3 \times 10^{12}$	30
2N3070	$5.8 \pm 2.3 \times 10^{12}$	30	$5.8 \pm 2.1 \times 10^{12}$	30
2N3086	$6.6 \pm 1.4 \times 10^{12}$	12 to 16	8×10^{12}	8 to 12
2N3088	$5.0 \pm 2.0 \times 10^{12}$	30	$5.5 \pm 2.5 \times 10^{12}$	30
2N2497	$2.3 \pm 1.0 \times 10^{13}$	30	$5.3 \pm 0.2 \times 10^{13}$	30
2N3085	2×10^{13}	10 to 15	2×10^{13}	7 to 14

available in the literature, the general degradation factors (amount parameters are expected to degrade) presented in Table 5.4 are estimated. The degradation factors are defined as the percentage change expected in the parameter of interest.

5.40 Radiation Hardening

Recent studies (References 5.71, 5.72) have shown that JFET s can be made considerably harder than presently available devices by increasing the channel doping level. Techniques have also been developed in these studies to offset the deleterious effects of heavy doping in the channel region on breakdown voltage. These hardening procedures are effective against displacement damage (neutron, proton) only, however.

It has also been observed that n-channel devices are harder than p-channel units to displacement damage; however, n-channel devices are more susceptible to ionization damage than p-channel units. Thus, it can be seen that a choice must be made by the parts engineer depending on the displacement to ionization ratio of the environment in question.

5.50 Radiation Testing

It is recommended that JFET s be tested further in proton environments with more emphasis placed on observing the ionizing effects of protons on I_{GS}, I_{DSS}, and V_p. It is further recommended that any specific JFET type to be used in a radiation environment be characterized (on a statistical sample) in the environment in question.

5.60 Radiation Screening

At present there are no screening techniques for JFETs. Lockheed (Reference 5.74) as presented in Figure 5.4, has shown that the Weibull probability distribution may be useful in determining general component reliability.

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

5.70 References

5.71 George, W. L., "Optimization of the Neutron Tolerance of Junction Field Effect Transistors", IEEE Trans. Nucl. Sci. Vol. NS-16, No. 6, December, 1969.

5.72 Shedd, W., Buchanan, B., and Dolan, R., "Radiation Effects on Junction Field Effect Transistors", IEEE Trans. Nucl. Sci., Vol. NS-16, No. 6, December, 1969.

5.73 Stanley, A. G., "Effect of Electron Irradiation on Electronic Devices", Massachusetts Institute of Technology Lincoln Laboratory, Tech. Report 403, November 1965, AD-489617.

5.74 Lockheed-Georgia Co., "Components Irradiation Test", No. 15, NASA-CR-719271, June 1965.

5.75 Bryant, F. R., Fales, C. L., Jr., Breckenriage, R. A., "Proton Irradiation Effects In MOS and Junction Field-Effect Transistors and Integrated Circuits", RADC Physics of Failure in Electronics, Vol. 5, June 1967.

5.76 Partridge, "Report on Radiation Test Series No. 14 at the Martin Company", SOR-68-028 IDEP 347.65.00.00-56-10.

6.0 INSULATED GATE FIELD EFFECT TRANSISTORS

6.1 Permanent Parameter Degradation

At the present state of the art, ionization damage is the most important degradation mechanism in metal-oxide-semiconductor field effect transistors, MOSFET's. Although displacement damage can be present, the devices' sensitivity to ionization effects in the oxide, in particular, generally make the displacement effects only of secondary importance.

The parameter most sensitive to radiation is the gate threshold voltage, V_{GT}. For present, off-rhe-shelf units, V_{GT} often shifts several volts for radiation exposures between 10^4 and 10^5 rads(Si). The extent of degradation is a function of applied gate bias during irradiation. The proposed mechanisms for radiation degradation of V_{GT} are: (1) the accumulation of trapped charge within the oxide insulation layer, (2) the introduction of surface states at the oxide silicon interface.

As is the case with surface effects in transistors, MOSFET damage is not readily predictable at the present state of the art. Many studies have shown the damage to be highly dependent on processing techniques during manufacture and several processes (which will be discussed in Section 6.40) have proved promising for hardening MOSFET's in the laboratory, but these techniques have not generally reached commercial products yet. The best approach for estimating damage, at present, is to obtain actual data on a fairly large sample of devices. In general, for devices from identical production processes the radiation response is quite similar. For devices from the same lot but different chips the spread becomes greater; and for different lots from the same production line the spread in response is again increased. The extent of the different responses will be discussed in a later section.

Since the effects of radiation on MOSFET devices can be almost entirely due to ionization, it is not particularly valuable to discuss each particle type separately. Rather, it is shown in Figure 6.1 that if particle fluences are converted to ionization dose (rads) using stopping power tables* reasonable agreement can be established for damage from the different particle types.

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*Neutron dose was converted on the basis of accompanying gamma dose reported for the reactor type used and the ionization energy deposition by the neutrons.

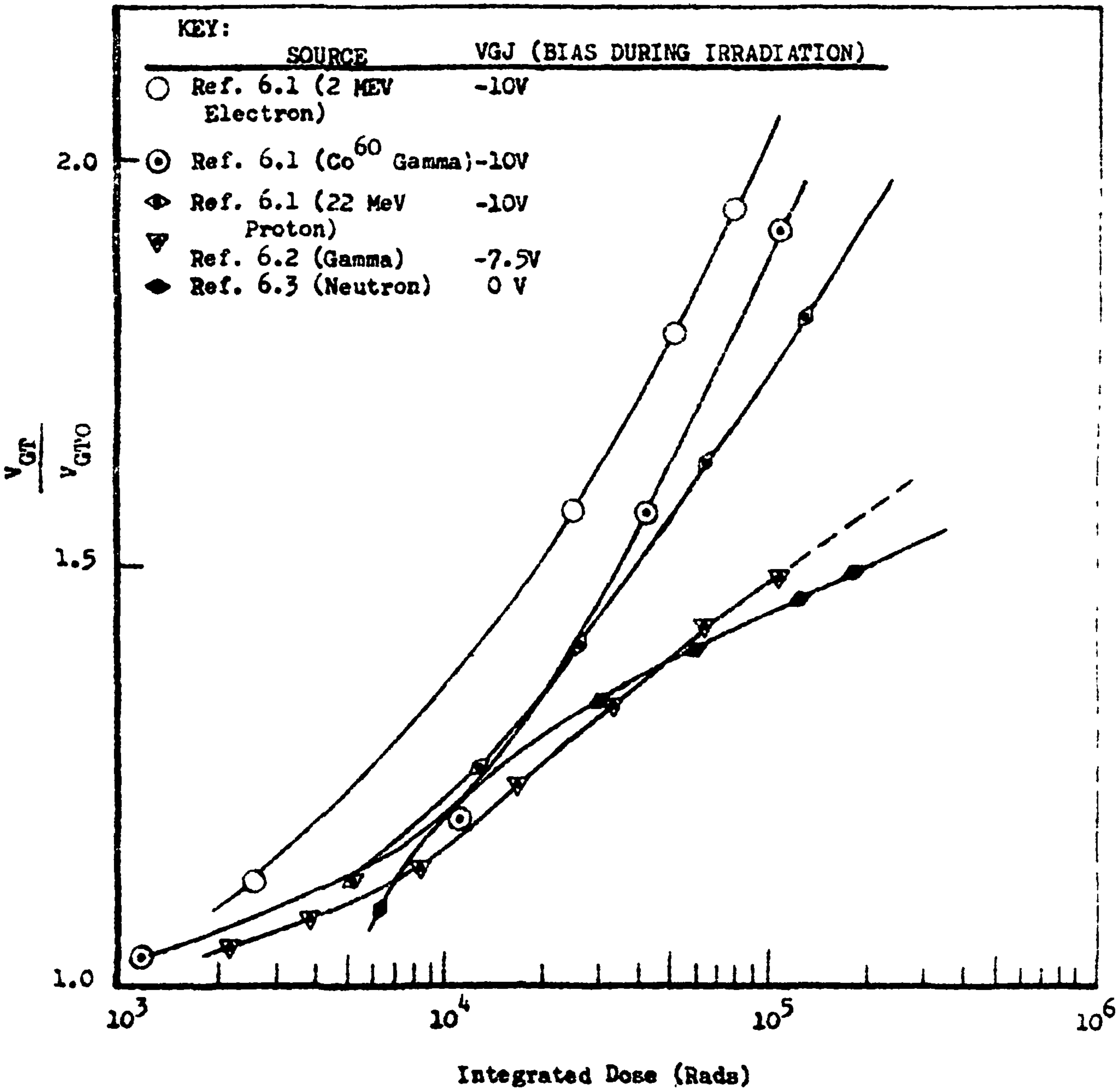


Figure 6.1 Comparison of Relative Effectiveness of Different Types of Radiation For Damage in MOS Devices

6.2 Temporary Parameter Drifts

Although some rather long term annealing is observed for MOSFETS, the damage is usually considered permanent at room temperature. Therefore, the drifts consist of normal degradation as discussed in the previous section. The degradation does have a tendency to reach a saturation level at high exposures ($> 10^6$ rads). This phenomenon is particularly true for biased units under radiation. Holmes-Siedle (Ref. 6.74) has observed that alternately biasing and unbiasing the devices during irradiation can cause the gate threshold voltage to oscillate as illustrated in Figure 6.2. He observed that the oscillations were bounded by the degradation curves of devices having no gate bias during irradiation and devices having a gate bias equal to the peak value of the cycled bias. He further observed that a device that is cycled on and off during irradiation with, for example, a square wave will experience a degradation curve at some median point between the zero bias condition and the maximum bias level that is proportional to the duty cycle. For example, if the bias alternated from zero to nine volts with a 50 percent duty cycle, the degradation curve would approximate that for a continuous bias of 4.5 volts.

6.3 Parameter Degradation Factors

Due to the heavy dependence on operating conditions, it is not practical to try to tabulate damage factors for MOS devices. Rather, typical degradation data is shown in Figures 6.3 through 6.12. Figure 6.3 shows typical bias dependence of the degradation.

Figure 6.4 shows the spread of radiation degradation curves for ten types of P-channel MOS transistor types irradiated with gamma rays. Figure 6.5 shows the spread in responses for devices irradiated with 22 MeV protons. Figures 6.6 through 6.11 show various degradation curves for Co-60, electron, and proton radiation. Figures 6.12 and 6.13 show the effect of an alternating bias during irradiation. As noted earlier, for such cases the bias dependence of the degradation seems to fall between that of zero bias and the peak of the alternating bias. The mean degradation curve is proportional to the duty cycle of the alternating bias.

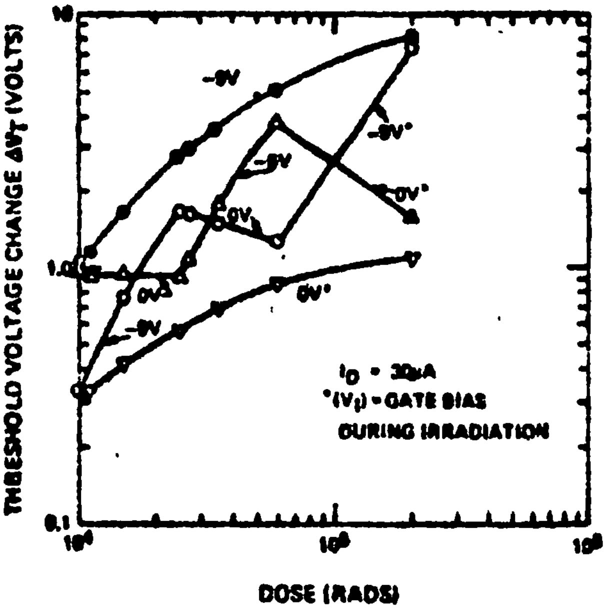


Figure 6.2 Threshold-Voltage Shift of TA5361 IC, Sample No. 3, P-Channel Cycled Over Long Time Intervals. (Ref. 6.74)

6.4 Radiation Hardening

Experimenters have found several fabrication techniques that seem to increase the radiation resistance of insulated gate devices. The results of many of these techniques are summarized in Figures 6.14 through 6.19.

It appears that the presence of phosphorous in the insulator tends to harden devices considerably. It is not fully understood why this is true. It is thought that the phosphorous may act as a getter for impurities in the oxide that may contribute to the charge trapping in the oxide.

It has also been found (Ref. 6.77) that the introduction of chromium into the silicon dioxide can reduce the formation of interface states between the oxide and silicon interface. This is explained by the fact that silicon dioxide alone under ionizing radiation tends to devitrify and undergo compaction or negative dilation. The contraction of the oxide parallel to the silicon interface breaks bonds between the two layers and the unsaturated silicon bonds cause the interface states. Thus, Hughes (Ref. 6.77) proposes that a composite structure utilizing a dielectric of silicon nitride and a chromium doped silicon dioxide may lead to a radiation resistant device.

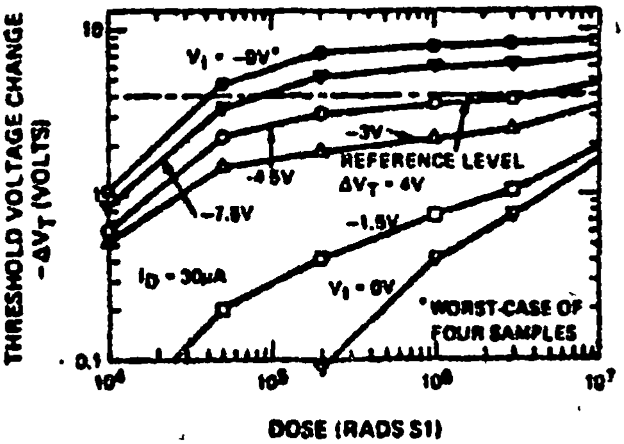


Figure 6.3 **Negative Threshold-Voltage Shift of TA6388, P-Channel Subelement Exposed to Cobalt-60 Gamma Rays. V_I is gate bias (i.e., oxide field) applied during irradiation.** (Ref. 6.74)

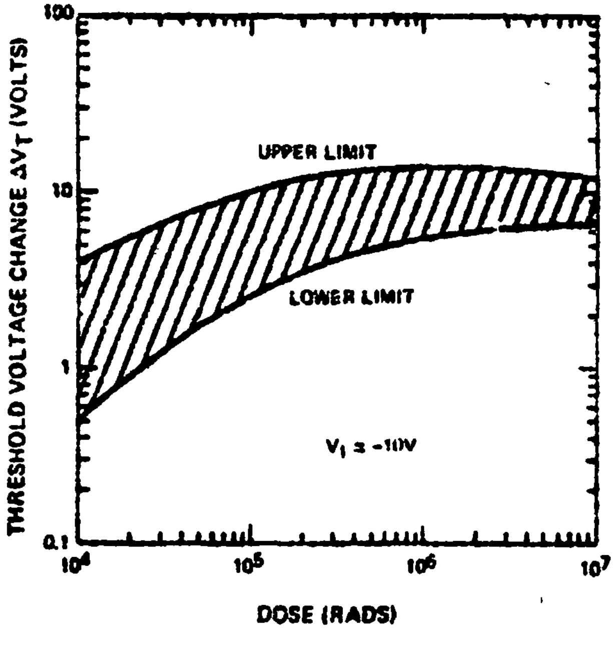


Figure 6.4 **Range of Threshold-Voltage Shift versus Radiation for Ten P-Channel, MOS Transistor Types with SiO_2 Insulators, from a Range of Different Production Lines between 1965 and 1968 (V_I = -10 Volts)** (Ref. 6.71)

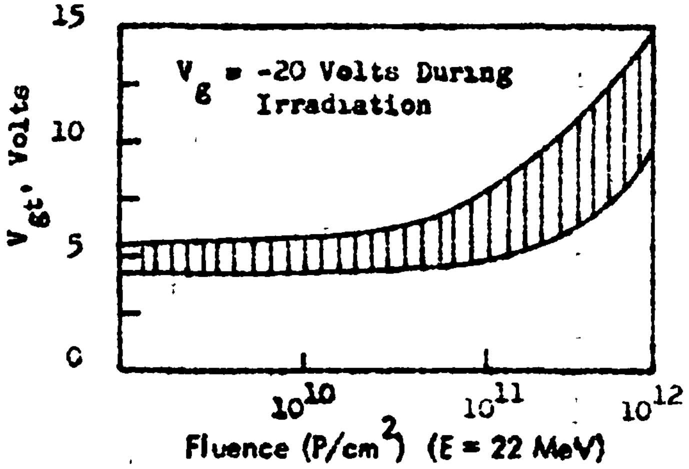


Figure 6.5 Shift and Spread 5 Each SC1128 (15 Individual Devices) Units as a Function of 22 MeV Proton Fluence. (Ref. 6.75)

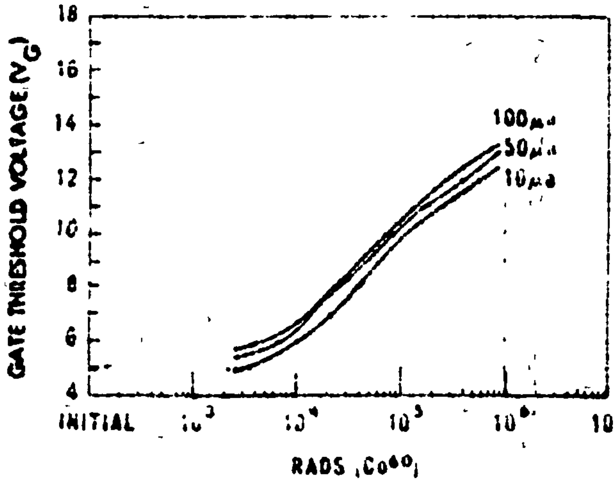


Figure 6.6 Unit A7 at 10 Volts Gate Bias 90 μa Drain Current During Exposure. (Ref. 6.71)

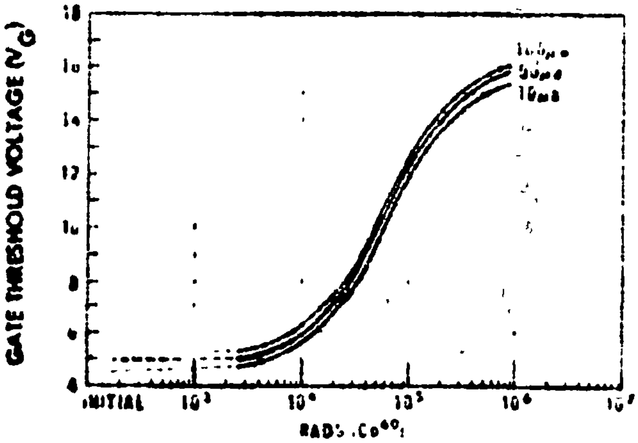


Figure 6.7 Unit A3 20 Volts Gate Bias 180 μa Drain Current During Exposure. (Ref. 6.71)

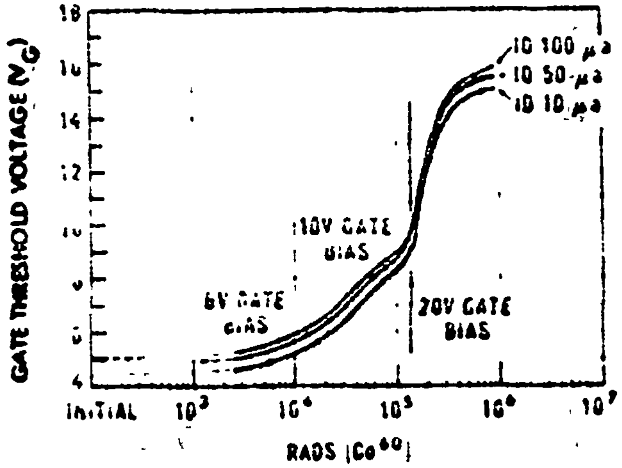


Figure 6.8 Unit A8 Voltage By Different Portions of Curve Indicate Bias During Exposure. (Ref. 6.71)

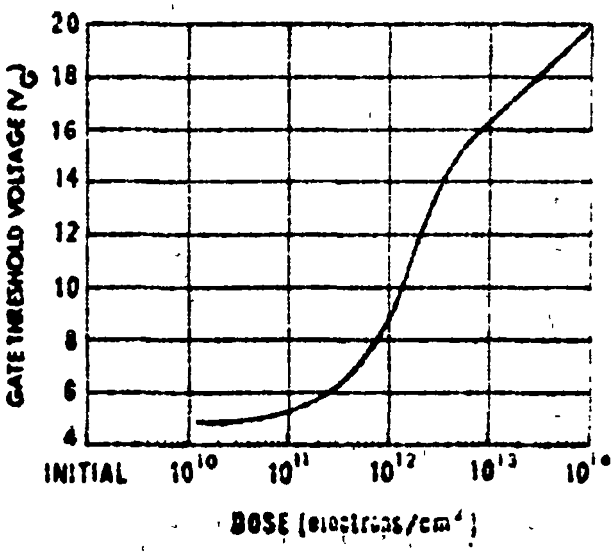


Figure 6.9 Unit B8 20 V Gate Bias During Exposure (100 μa Drain Current During Exposure. (Ref. 6.71)

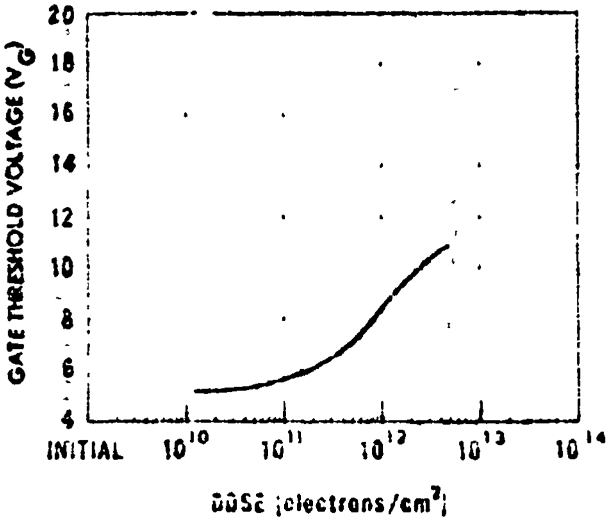


Figure 6.10 Unit B14 10 V Gate Bias During Exposure 100 μa Drain Current During Exposure. (Ref. 6.71)

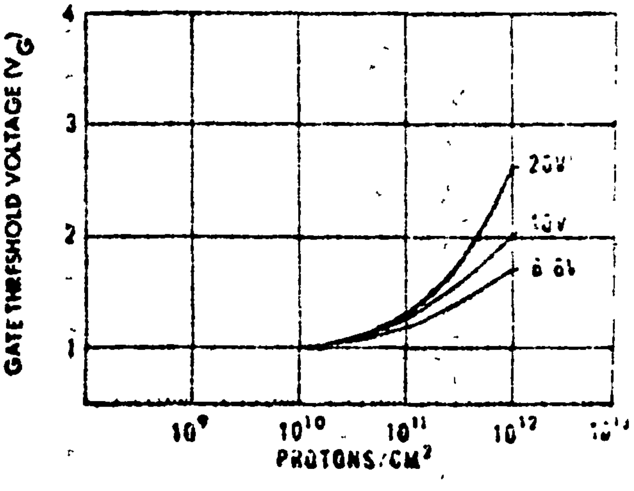


Figure 6.11 Typical Normalized Gate Threshold Voltage Vs. Proton Dose. (Ref. 6.71)

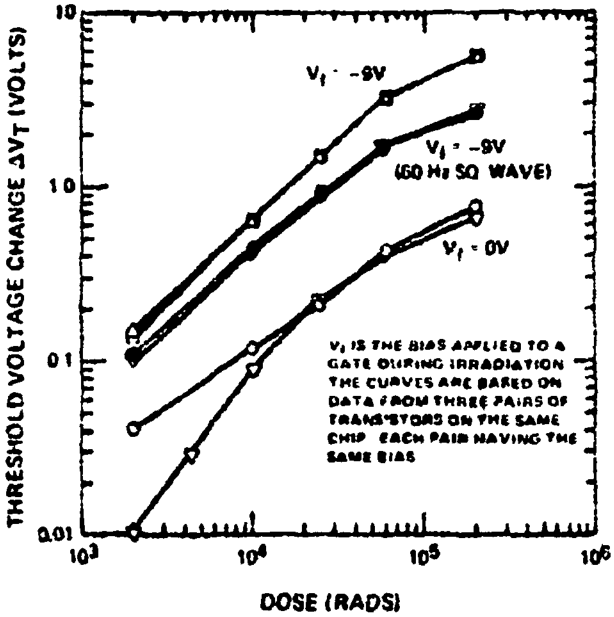


Figure 6.12 Threshold-Voltage Shift of TA5361 IC, P-Channel, Sample No. 11, Cycled with 60-Hertz Square Wave. (Ref. 6.74)

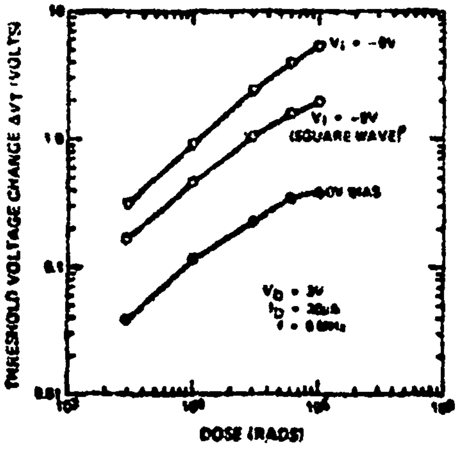


Figure 6.13 Threshold-Voltage Shift of CD4007D IC, P-Channel, Cycled with 5-MHz Square Wave. (Ref. 6.74)

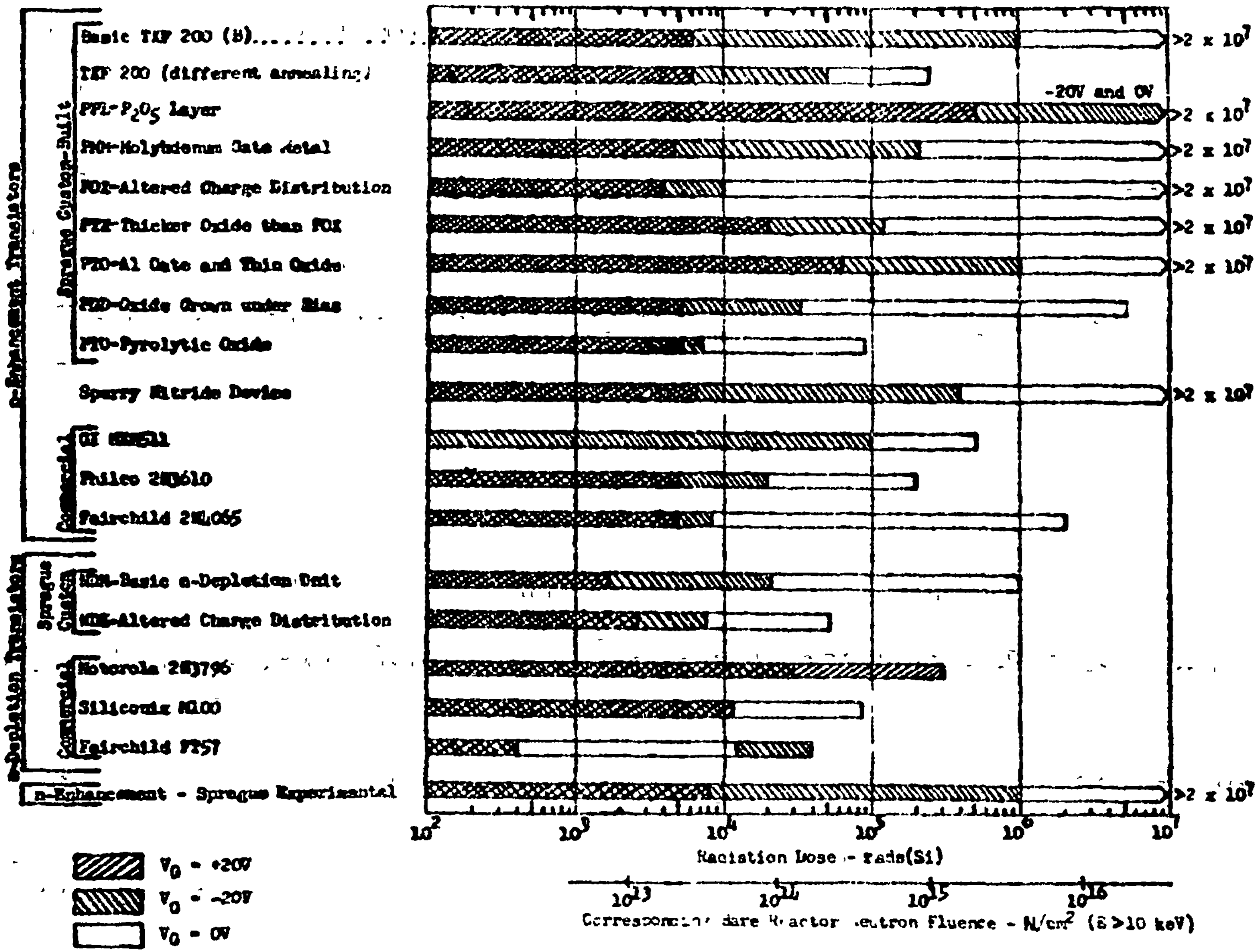


Figure 6.14 Radiation Exposure Required to Produce a Change of Three Volts in the V_T of MOS Transistors (Gate Bias = -20V, 0V, and +20V, Cobalt-60 Data) (Ref. 6.76)

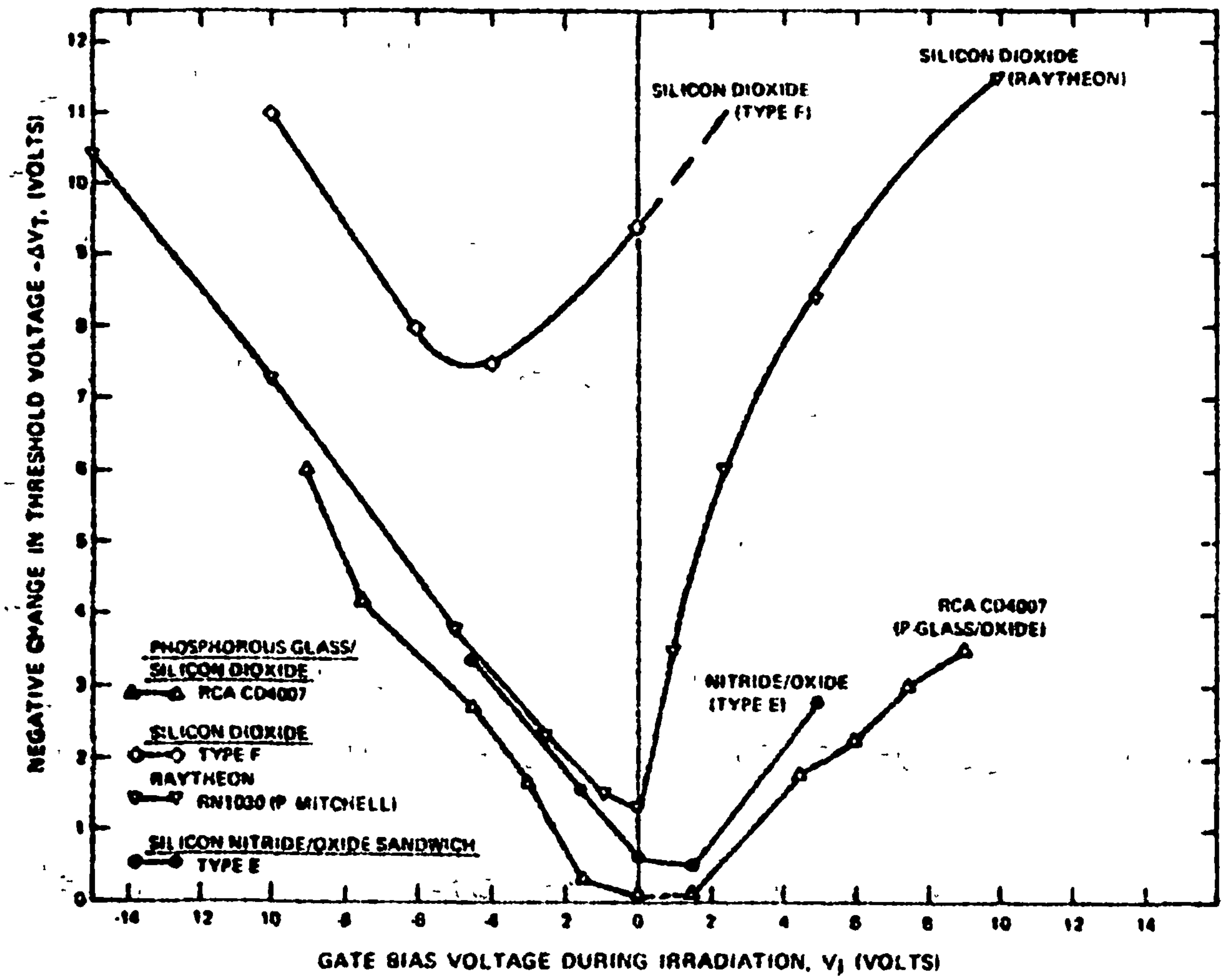


Figure 6.15 Dependence of Threshold-Voltage Shift (ΔV_T) on Gate Bias During Irradiation For Three Different MOS Channel Oxide Structures. The Total Dose for all Samples was 10^5 Rads(Si). (Ref. 6.74)

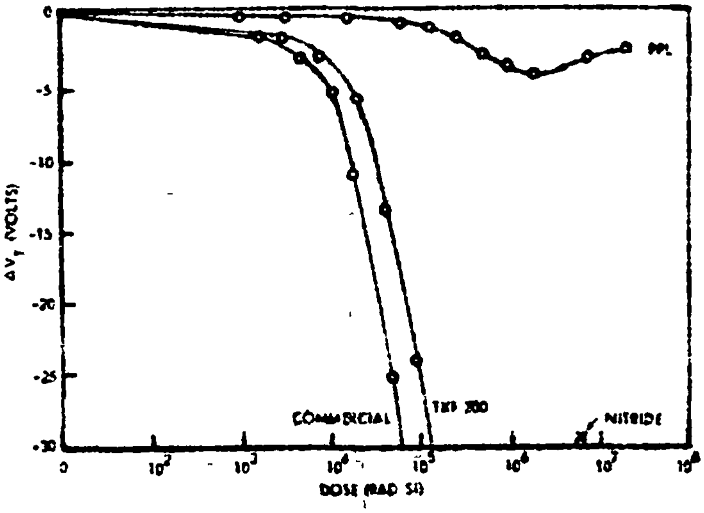


Figure 6.16

Change in V_T as a Function of Co-60 Dose (V_G = +20 V) (Ref. 6.76)

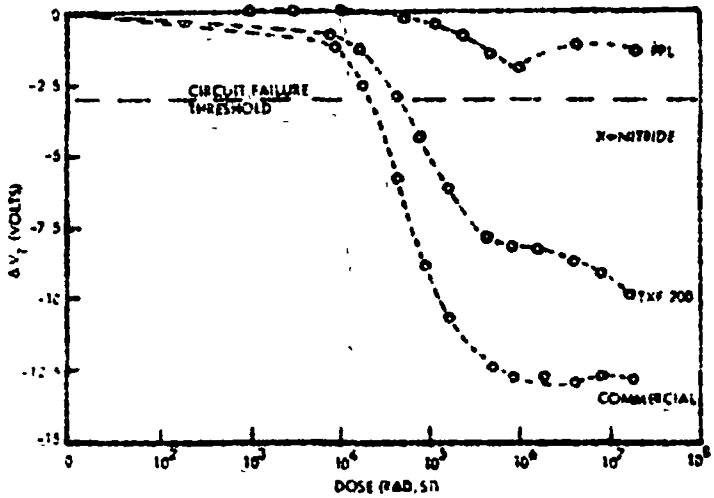


Figure 6.17

Change in V_T as a Function of Co-60 Dose (V_G = -20V) (Ref. 6.76)

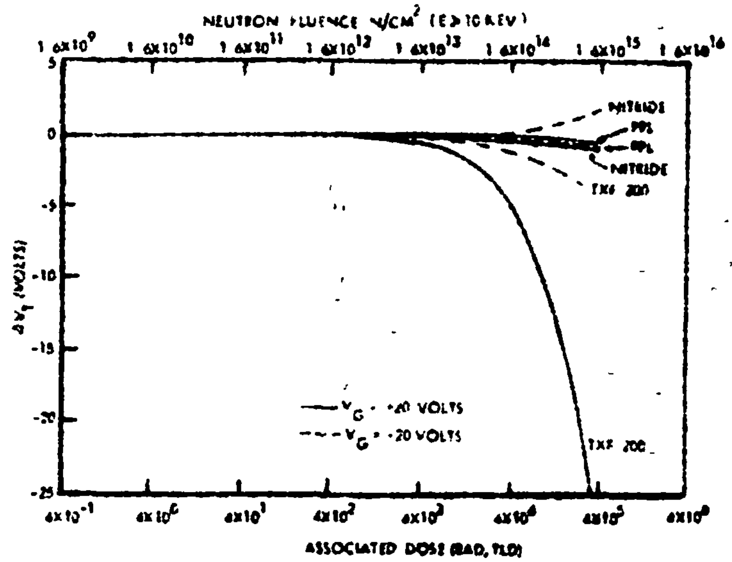
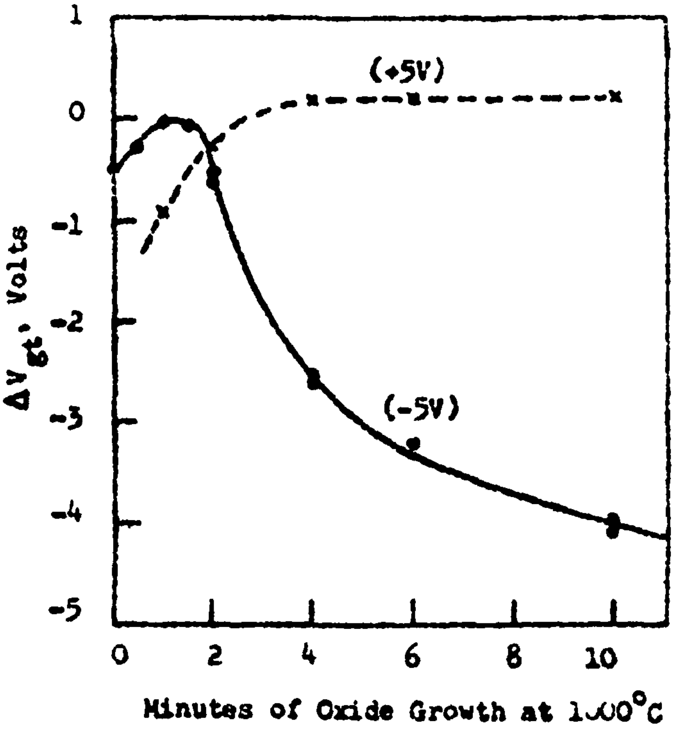


Figure 6.18

Change in V_T as a Function of Bare Reactor Exposure (Ref. 6.76)



Shifts in Threshold Voltage for MNOS Devices Versus Oxide Thickness (10 min = 280 Å) at 4 x 10^5 Rads(Si).

Figure 6.19 Shifts in Threshold Voltage for MNOS Devices Versus Oxide Thickness (10 min = 280 A) at 4 x 10^5 Rads(Si). (Ref. 6.78)

Another interesting technique is the use of a thin oxide layer over the silicon followed by a nitride layer under the gate metal. Figure 6.19 shows the effect of thickness of the oxide layer on the radiation response. The author (Ref. 6.78) comments that it appears that charge is trapped at the oxide-nitride interface and that the amount of charge is a function of the oxide thickness. The MNOS structures can withstand 10^6 rads exposure. This process does, however, tend to make the devices less temperature-voltage stable. The devices having 125 angstrom oxide layers were found usable between -40 to +35 volts gate bias. A feel for the relative state of the art in hardened MOS can be obtained by the following example: A production process which yielded hardened devices was reported by Long (Ref. 6.76). Later an attempt was made to reproduce the process and devices from both the original "hard" process and the second duplicate process were compared at The Boeing Laboratory (6.79). The second process yielded harder devices than other commercial processes, but did not produce the same degree of resistance as the original process. The results of the comparison are shown in Figure 6.20.

6.5 Recommended Testing

If a MOSFET device is to be used, it is recommended that a representative sample be given qualification testing to fully characterize its radiation response.

6.6 Screening

At the present time, (as for the case of surface effects in bipolar devices), there is no known technique for screening out hard, or soft, MOSFET's. The only procedure seemingly is to characterize the part type statistically.

6.70 References

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

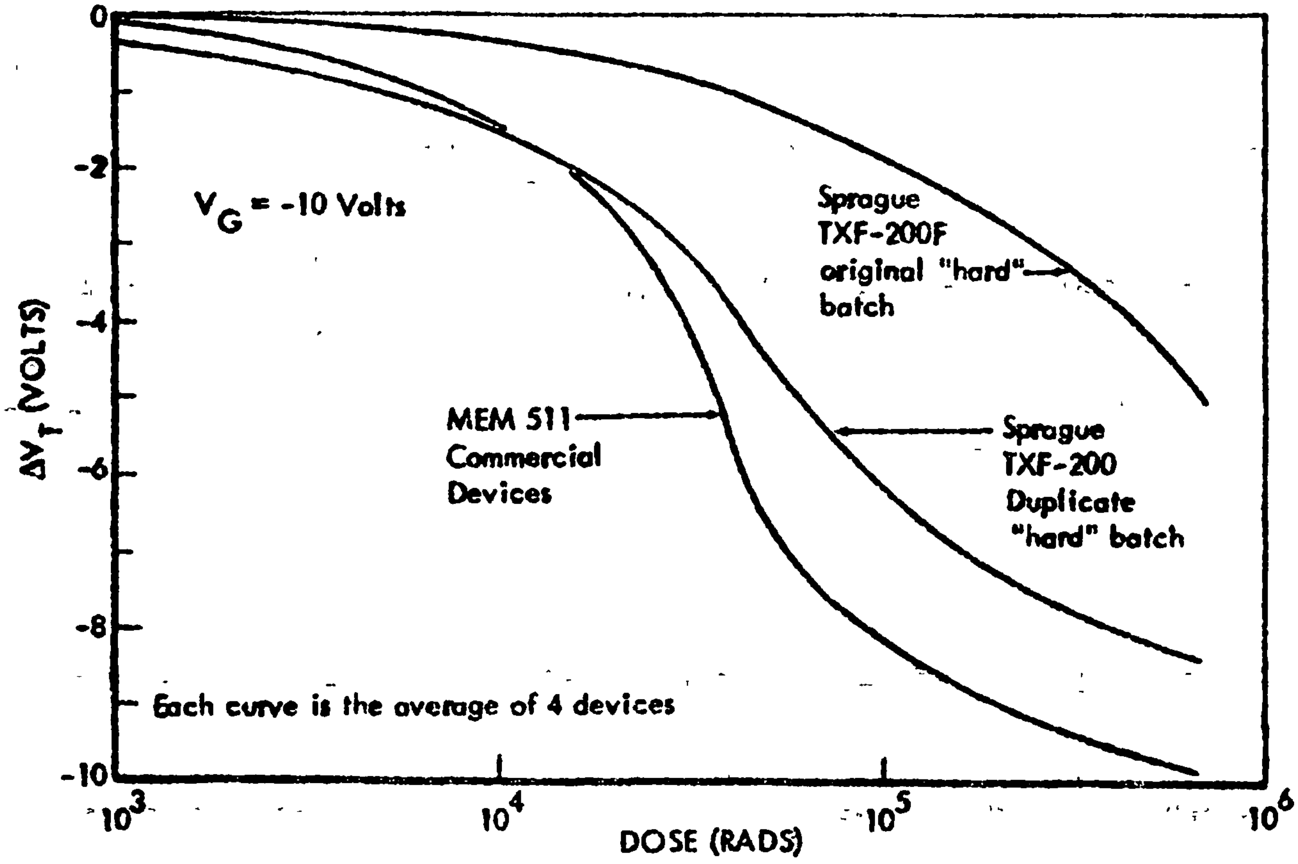


Figure 6.20 Comparison of Sprague TXF-200 MOSFETs from two different production lots and one commercial type device from General Instruments Corp. (Ref. 6.79)

6.72 Horne, W. E., Boeing data, (Unpublished) December, 1965.

6.73 Messenger, G. C., E. J. Steele, and M. Neustadt, "Displacement Damage in MOS Transistors", IEEE Trans. on Nuclear Science, Vol. NS-12, No. 5, October 1965.

6.74 Poch, W. and Holmes-Siedle, A. G., "Permanent Radiation Effects in Complementary-Symmetry MOS Integrated Circuits", IEEE Trans. on Nucl. Sci., Vol. NS-16, No. 6, Dec., 1969.

6.75 Gordon, F., Jr. and Wannemacher, H. E., Jr., "The Effects of Space Radiation on MOSFET Devices and Some Application Implications of Those Effects", IEEE Trans. Nucl. Sci., Vol. NS-13, No. 6, Dec. 1966.

6.76 Long, D. M. and Baer, R. D., "Radiation Effects on Insulated Gate Field Effect (MOS) Integrated Circuits", Tech. Report ECOM-01520-F, Dec., 1967.

6.77 Hughes, H. L., "Radiation-Induced Perturbations of the Electrical Properties of the Silicon-Silicon Dioxide Interface", IEEE Trans on Nucl. Sci., Vol. NS-16, No. 6, Dec. 1969.

6.78 Perkins, C. W., Aubuchon, K. G., and Dill, H. G., "Radiation Effects and Electrical Stability of Metal-Nitride-Oxide-Silicon Structures", Applied Physics Letters, Vol. 12, No. 11, June 1968.

6.79 Horne, W. E. and Folson, J. A., Boeing data, (unpublished), 1969.

7.0 UNIJUNCTION TRANSISTORS

7.1 Permanent Parameter Degradation

The negative resistance characteristic of the unijunction transistor depends on the conductivity modulation of a moderately high resistivity silicon bar by means of injected minority carriers from the rectifying emitter contact. It is, therefore, highly sensitive to radiation induced changes in minority carrier lifetime and resistivity. Figure 7.1 shows a typical unijunction characteristic. Failure is brought about by increasing Valley voltage, V_v, decreasing valley current, I_v, and decreasing peak point voltage, V_p.

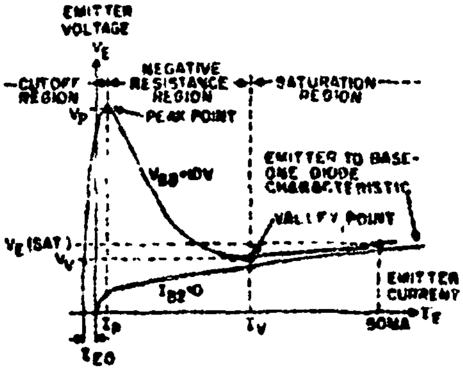


Figure 7.1 Static Emitter Characteristic Curve Showing Important Parameters (Ref. 7.71)

Failures are determined by the ratio of V_p to V_v that can be tolerated by the circuit application. Catastrophic failure can be considered as the point where $V_v = V_p$ and the negative resistance characteristic no longer exists. Typical failure thresholds are listed in Table 7.1

TABLE 7.1 Typical Radiation Failure Thresholds (i.e. $V_v = V_p$)

Neutron (Fission)	5×10^{11} ——— 5×10^{12} n/cm^2
Proton (17 - 20 MeV)	1.0×10^{10} ——— 1.0×10^{11} P/cm^2
Proton (100 MeV)	7×10^{10} ——— 7×10^{11} P/cm^2
Gamma (1 MeV)	$>4 \times 10^5$ rad (Si)

7.11 Neutron Effects

The primary effects of neutrons are the reduction of minority carrier lifetime by displacement defects in the bulk silicon of the base one region. Ruwe, (Reference 7.72) has developed an empirical equation for predicting neutron effects on unijunction transistors of the form

$$\ln R = (K_1 + K_2 + L_p) \ln I + K_3/L_p \qquad \text{(Eq. 7.1)}$$

R = saturation resistance of base 1 region

K_1, K_2, K_3 = empirically determined constants

L_p = diffusion length of holes in base 1.

He assumed that changes in the diffusion length of base 1 material was the only significant effect. He had some degree of success in predicting failure points for the specific devices (2N491) he studied; however, it is not clear that the equation is generally valid. Rather, it seems that the constants are dependent on device geometry and would have to be evaluated from test data on each device of interest.

7.12 Proton Effects

Protons should produce similar effects to those of neutrons with additional ionization effects. As pointed out earlier for bipolar transistors, protons are more effective than fission neutrons for causing displacement damage. One could apply the equivalence factors (Reference 7.73) 1 (8-17 MeV) Protons/cm^2 $\cong$ 33 n/cm^2 and 1 (100 MeV) Proton/cm^2 $\cong$ 7 n/cm^2 to compare neutron and proton damage thresholds but no data exists as to the ionizing effects of protons on unijunction transistors. Gamma radiation data indicate (Reference 7.73) that additional decreases in V_p may be incurred due to ionization effects. Also, if one uses the neutron damage thresholds for comparison, he should be aware that the estimate ignores the ionization effects of protons.

7.13 Gamma Effects

Gamma radiation will produce some displacement damage but it is much less effective than neutrons for displacement production. However, gamma radiation can cause considerable ionization. The effects of ionization on unijunction devices would result primarily in an increase of surface leakage currents with some changes in V_v and V_p at high dose levels. Measel (Reference 7.73) has tested unijunction devices in a cobalt-60 gamma environment and found them to survive with only small changes of all parameters for doses of 4×10^5 rads(Si). Flescher, (Reference 7.74) has found for 1.5 MeV electron radiation, which is highly ionizing, the peak voltage, V_p, is the most sensitive parameter as opposed to the Valley Voltage, V_v, for displacement damage.

7.20 Temporary Parameter Drifts

There is no evidence in the literature that any unusual parameter drifts occur in unijunction devices other than the permanent changes discussed in the preceding section. One might expect that the ionization effects might show some annealing over a period of time (perhaps weeks) similar to bipolar transistors, but this hasn't been verified.

7.30 Parameter Degradation Factors

The extent of effects of various radiation environments are shown in Figures 7.2 through 7.4 and in Table 7.2. Ruwe (Reference 7.72) has found that, for neutrons, unijunction devices experience catastrophic failure between 10^{12} and 10^{13} (fission) n/cm^2. Curves for electron irradiation are shown in Figure 7.2 through 7.4. Similar data were reported by Stanley (Reference 7.75). Data taken by Measel (Reference 7.73) for Co-60 gamma radiation are shown in Table 7.2.

From these data, the degradation factors listed in Table 7.3 are estimated. These degradation factors are determined from data on a few device types only and should not be construed as more than a "ballpark" estimate. The degradation factor is defined as the percentage the parameter may increase or decrease at a given radiation fluence.

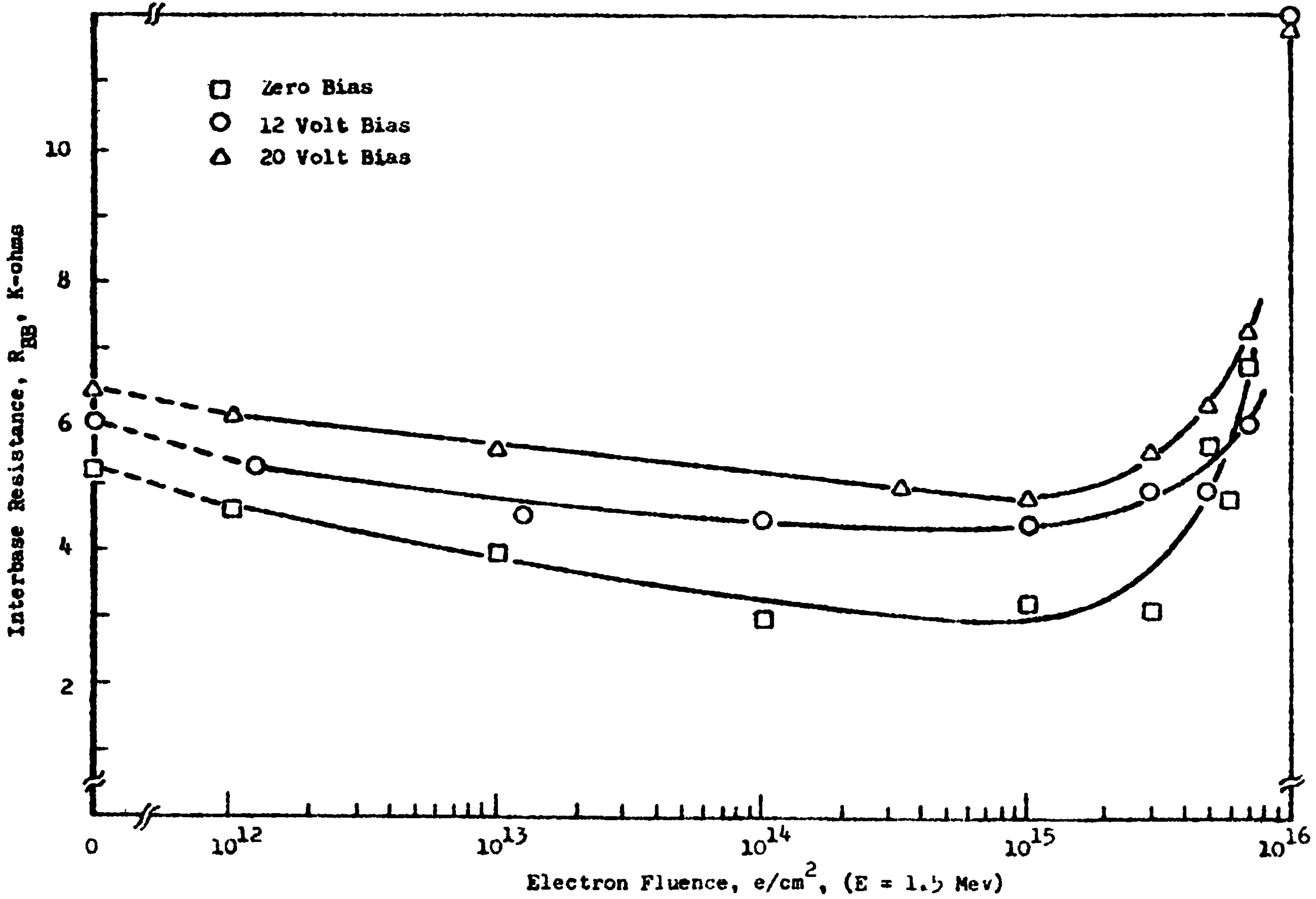


Figure 7.2. - Interbase Resistance (R_{BB}) Versus Electron Fluence for 2N3980

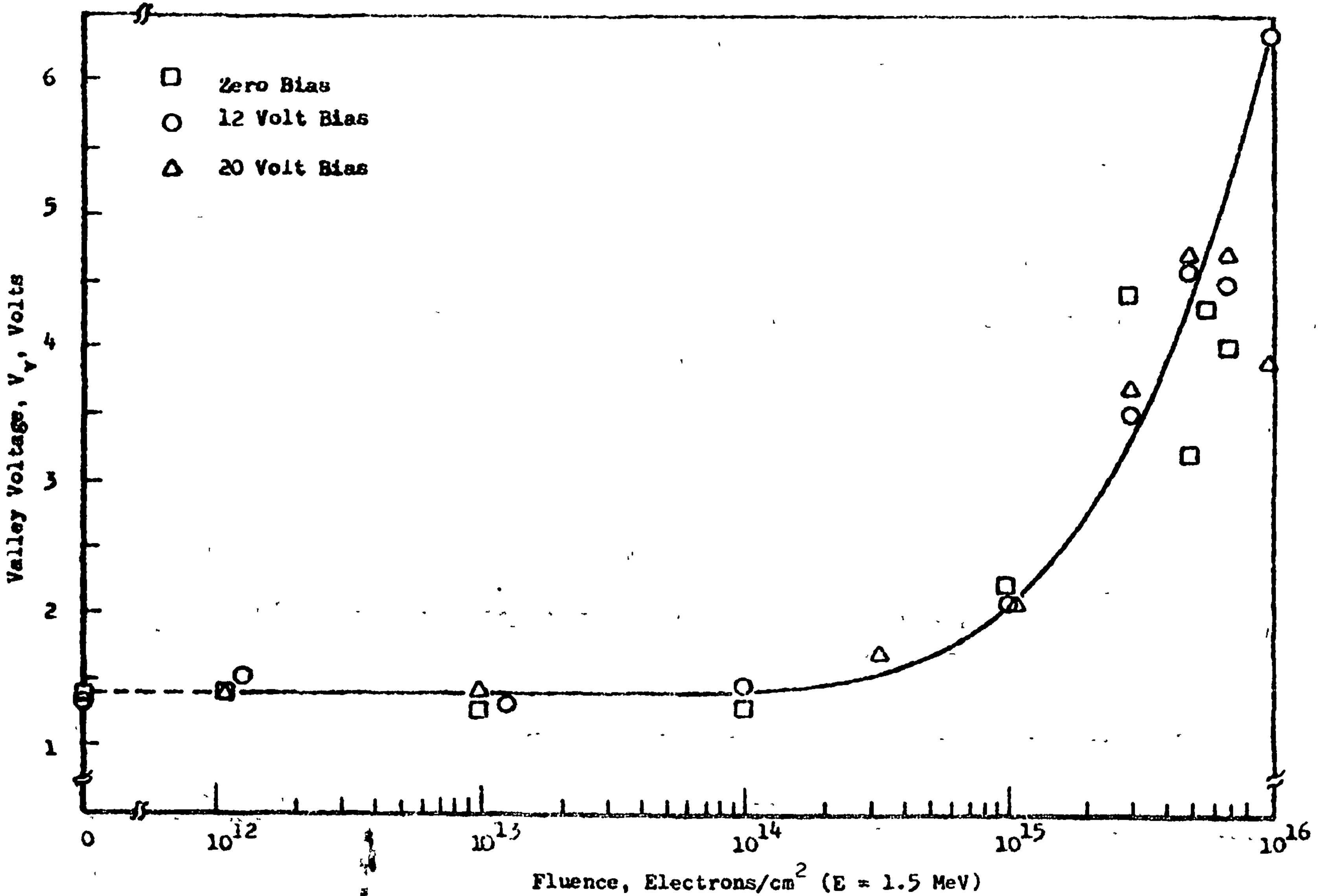


Figure 7.3 - Valley Voltage (V_v) Versus Electron Fluence For 2N3980 (Ref. 7.74)

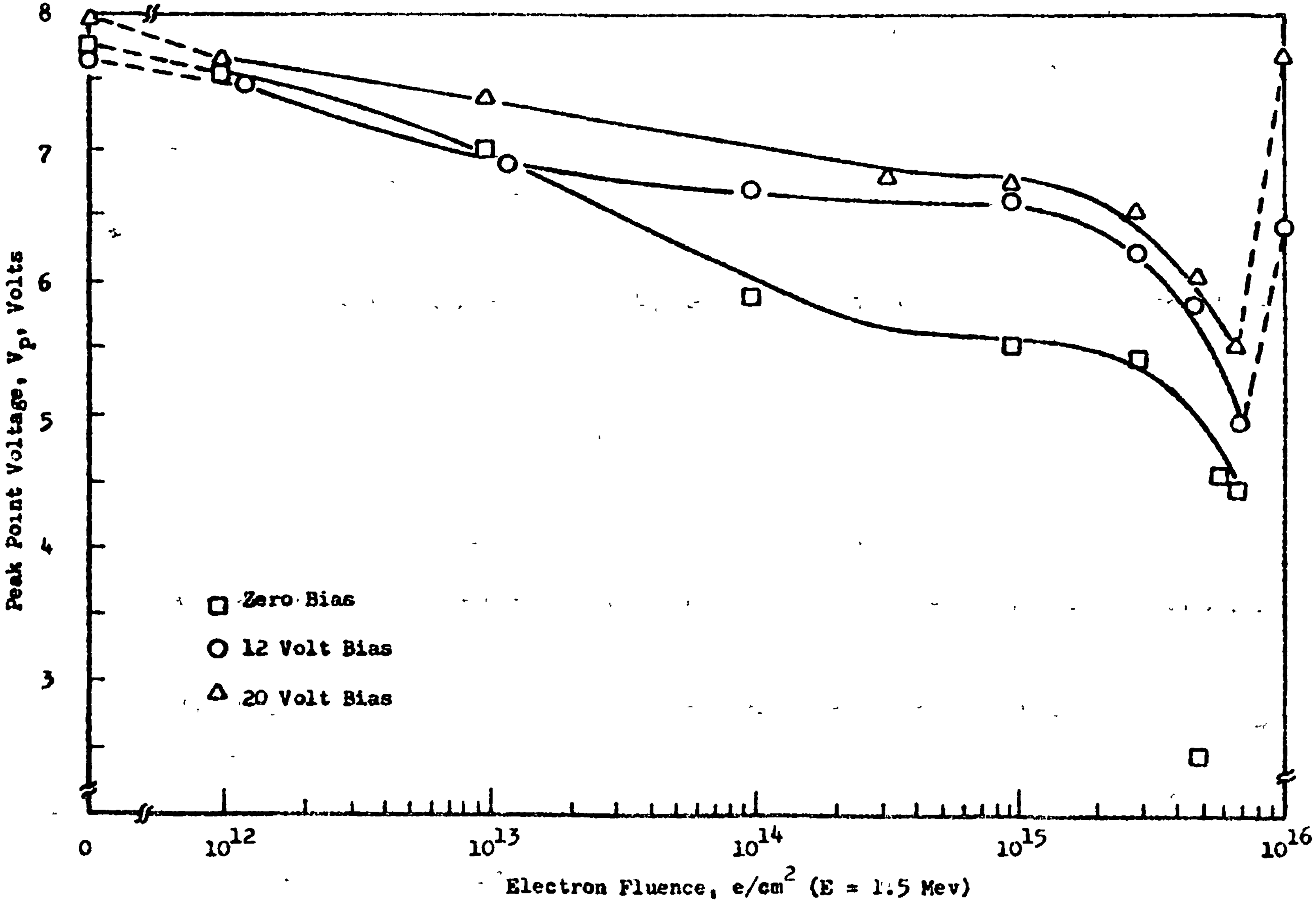


Figure 7.4 Peak Point Voltage (V_o) Versus Electron Fluence for 2N3980 Data from Ref. 7.74

TABLE 7.2 COBALT-60 EFFECTS IN 2N2646 U. J. T. (Ref. 7.73)

PRE-IRRADIATION						
UNIT NO.	η	R_{BB} (OHMS)	I_{B2mod} (ma)	I_{E_o} (amps)	V_V (volts)	I_V (ma)
1	.64	6×10^3	2.0	6.5×10^{-8}	1.20	4.5
2	.64	6×10^3	2.0	7.0×10^{-9}	1.47	6.0
3	.48	7.5×10^3	2.7	1.5×10^{-7}	1.02	2.5
4	.62	7.9×10^4	2.0	2.0×10^{-7}	1.40	5.0
POST-IRRADIATION 4×10^5 rad (Si)						
1	.62	5.5×10^3	2.7	8.0×10^{-9}	1.3	4.0
2	.59	5.2×10^3	2.6	6.0×10^{-9}	1.6	6.0
3	.49	5.7×10^3	3.3	1.1×10^{-9}	1.1	2.5
4	.56	6.3×10^3	2.5	2.5×10^{-9}	1.6	4.5

Table 7.3 Estimated Degradation Factors For Unijunction Transistors

Parameter	Radiation Type	Fluence	Degradation Factor
Interbase Resistance	Neutrons	2×10^{12} n/cm^2	+ 37 Percent
	Protons	——	——
	Electrons (1.5 MeV)	10^{14} e/cm^2	-26 Percent
	Gamma rays	4×10^5 rads (Si)	-16 Percent
Valley Voltage	Neutrons	10^{12} n/cm^2	+100 Percent
	Protons (8-17 MeV)	10^{11} n/cm^2	+100 Percent
	Electrons (1.5 MeV)	10^{15} e/cm^2	+100 Percent
	Gamma rays	4×10^5 rad (Si)	+10 Percent
Peak Point Voltage	Neutrons	——	——
	Protons (8-17 MeV)	——	——
	Electrons (1.5 MeV)	10^{14} e/cm^2	-18.7 Percent
	Gamma Rays	4×10^5 rads (Si)	-7.0 Percent

7.40 Radiation Hardening

Due to their construction, dependence on minority carrier lifetime, and requirements for moderately high resistivity material, unijunction transistors are very sensitive to radiation. Rather than suggest hardening techniques, researchers have generally concluded that unijunction devices are unsuitable for use in even low level radiation environments and should be avoided if possible.

7.50 Recommended Testing

If a unijunction device must be used, it is recommended that the specific device type to be used be radiation tested. It should be noted that the devices are sensitive to all components of the TOPS environment and that, for protons, the possible nonadditiveness of the effects of combined displacement and ionization damage have not been investigated.

7.60 Screening

There have been no screening techniques suggested in the literature.

7.70 References

7.71 Transistor Manual, General Electric Co., Copyright 1964.

7.72 Ruwe, V. W., "The Effect of Neutron Radiation on Unijunction Transistors and Silicon Controlled Rectifiers", Army Missile Command, AD-842-808, August 1968.

7.73 Measel, P. R., "Total Gamma Dose Effects on Several Types of Semiconductor Devices", Boeing Memo 2-7911-00-882, August 15, 1968.

7.74 Flescher, H. L., Szymkowiak, E. A., "Effects of Electron Radiation on Unijunction Transistors, NASA CR-526, N66-31669, July 1966.

7.75 Stanley, A. G., "Effect of Elecrron Irradiation on Electronic Devices", Mass. Inst. of Technology, Tech. Report - 403, November 1965.

8.0 DIODES

The following discussion is intended to cover switching diodes, rectifier diodes, and general purpose diodes. Where the discussion applies to only one of the three types, this is noted. It should also be noted that only limited data is available on general purpose diodes; however, it is felt that their behavior should be similar to the switching and rectifier types.

8.10 Permanent Parameter Degradation

The parameters that are affected by radiation are forward voltage, V_f, reverse leakage current, I_R, breakdown voltage, BV_{CO}, and the switching and storage times. The switching and storage times decrease while the breakdown voltage increases. Since these changes are not of great consequence in most applications, the discussion will deal only with changes in V_f and I_R.

8.11 Neutron Effects

The forward voltage, which is the most sensitive parameter to radiation in most cases, is influenced primarily by two effects, (1) minority carrier lifetime reduction and (2) carrier removal effects. Minority carrier lifetime degradation usually contributes to voltage changes at much lower fluences than carrier removal effects; however, carrier removal is generally the mechanism which causes ultimate device failure.

The degradation rate in diodes appears to be a function of the initial doping concentration, the junction area, the cross sectional area, and the base width. In general, the higher the doping level the less radiation sensitive the device. Thus, the lower the breakdown voltage of the diode (heavier doping) the more resistant it is. The junction and cross sectional area seems to play a fairly important role in switching diodes as indicated in Figure 8.1. (The current rating being an indirect indication of junction and cross sectional area). However, for rectifier diodes, the device area has not proved so important. The data indicate very little evidence of area dependence of damage in rectifier diodes. The data is too limited in the case of general purpose diodes to make any observations. Huth (Reference 8.81) has

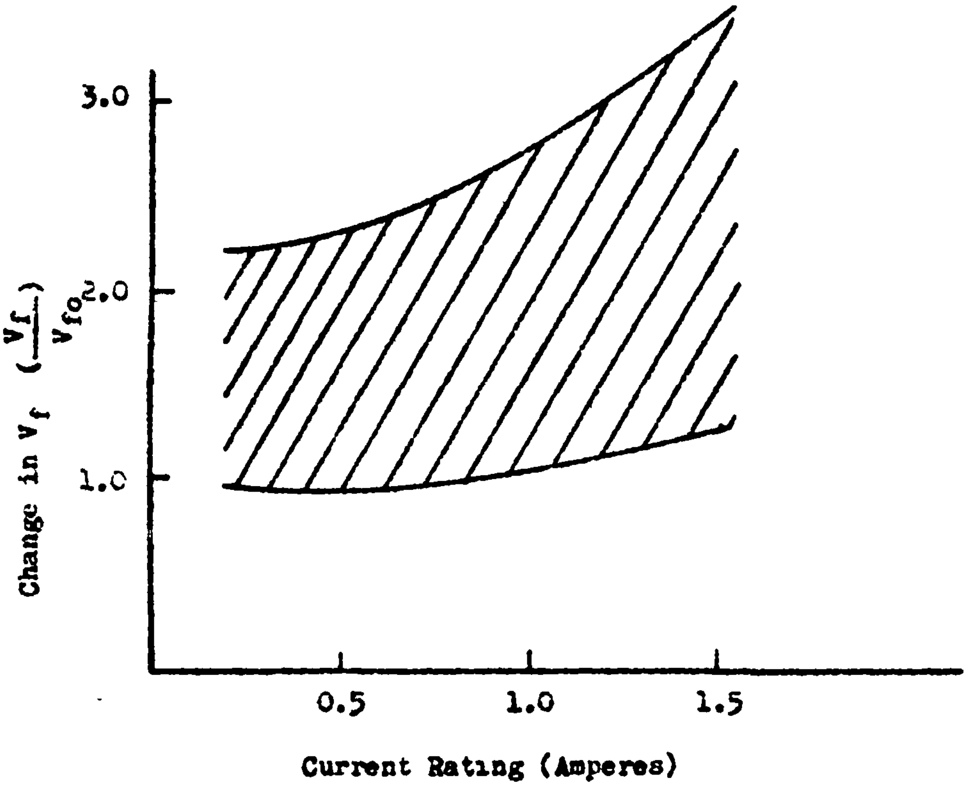


Figure 8.1 Comparison of Change in V_f Versus Current Rating for Switching Diodes at 5×10^{14} n/cm^2 (E > 10 kev)

shown that degradation in device forward voltage is a function of base width, i.e., the thicker the base, the greater the degradation for a given fluence.

Due to the many types of diodes, there has not been a general model developed to accurately express degradation as a function of radiation fluence for all types.

There have been two methods developed for estimating forward voltage changes as a function of neutron fluence. Manlief (Reference 8.82), has proposed a simplified model for rectifier diodes which neglects the effects of minority carrier lifetime degradation and assumes a simple step junction. Thus, based on the initial conductivity of the diode base region (or the reverse breakdown voltage which is inversely proportional to the conductivity), he suggests that one can obtain a semi-quantitative estimate of a diode's radiation sensitivity. Figure 8.2 indicates the correlation observed between neutron damage and breakdown voltage. In general, it appears that a device having a breakdown voltage of 100 volts or less should still be usable after exposures to neutron fluences greater than 10^{14} n/cm^2.

From Manlief's equations, one can develop equation 8.1 (See Appendix 8A for derivation) for obtaining a semiquantitative estimate of rectifier diode degradation in a neutron environment. Figure 8.3 shows a graph of R/N_o (for p on n junctions). Figures 8.4 and 8.5 show comparisons of predicted results and actual results. It should be pointed out again that this technique should be considered only a preliminary screen. The neglect of lifetime effects means that the estimate may be low for low fluences. If additional information is needed, one should obtain actual radiation data on the device type or, if this is not possible, obtain more parameter data from the manufacturer and use the estimation technique published by Frank and

$$\frac{V_f}{V_{f_o}} \overset{*}{\approx} e^{(R/N_o \Phi)} \qquad \text{(Eq. 8.1)}$$

where V_{f_o} = Initial forward voltage

* Semiquantitative estimate only

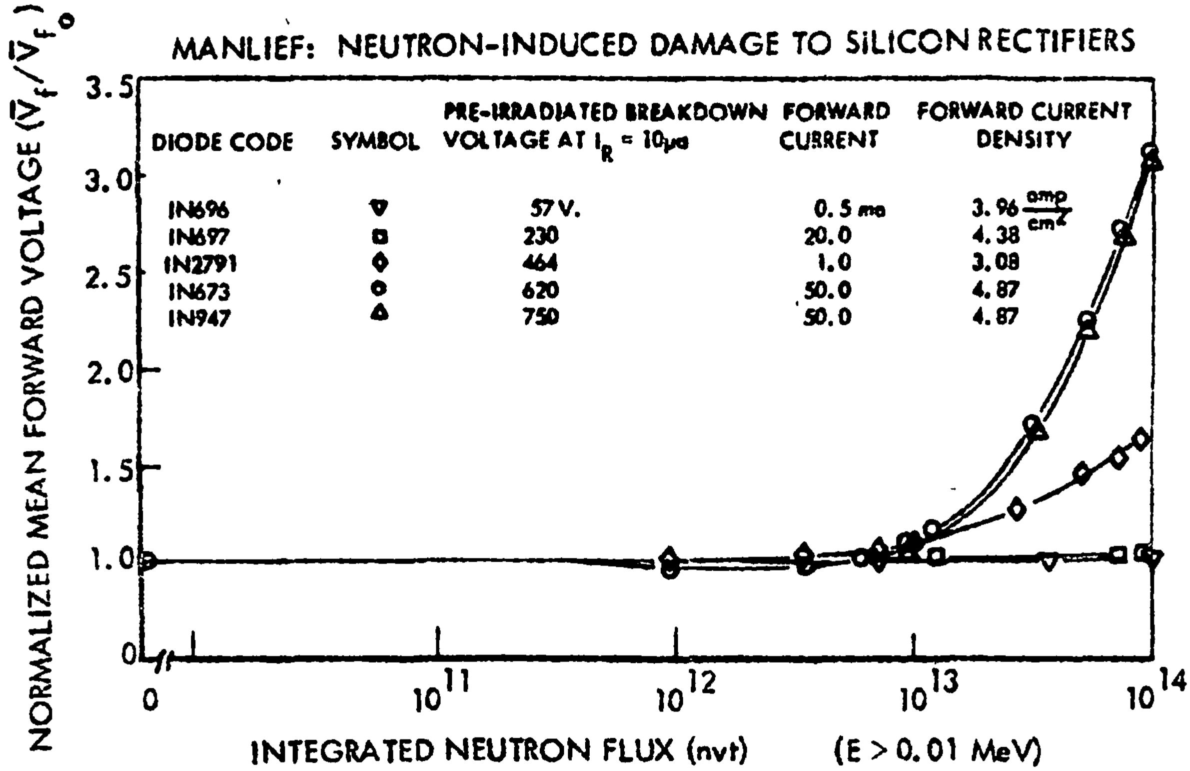


Figure 8.2 Relative Degradation of Forward Voltage Characteristics at Comparable Current Densities (Ref. 8.82)

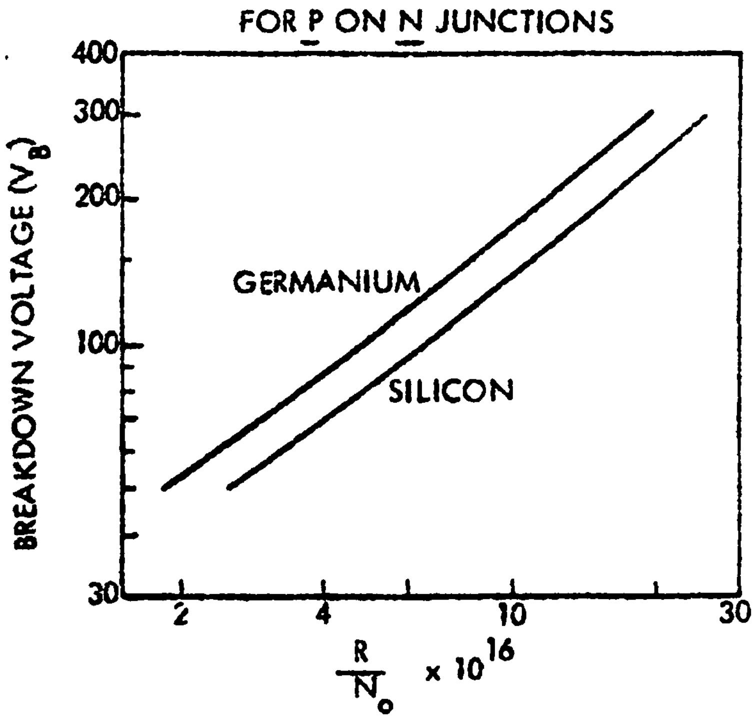


Figure 8.3 Breakdown Voltage Versus R/N_o

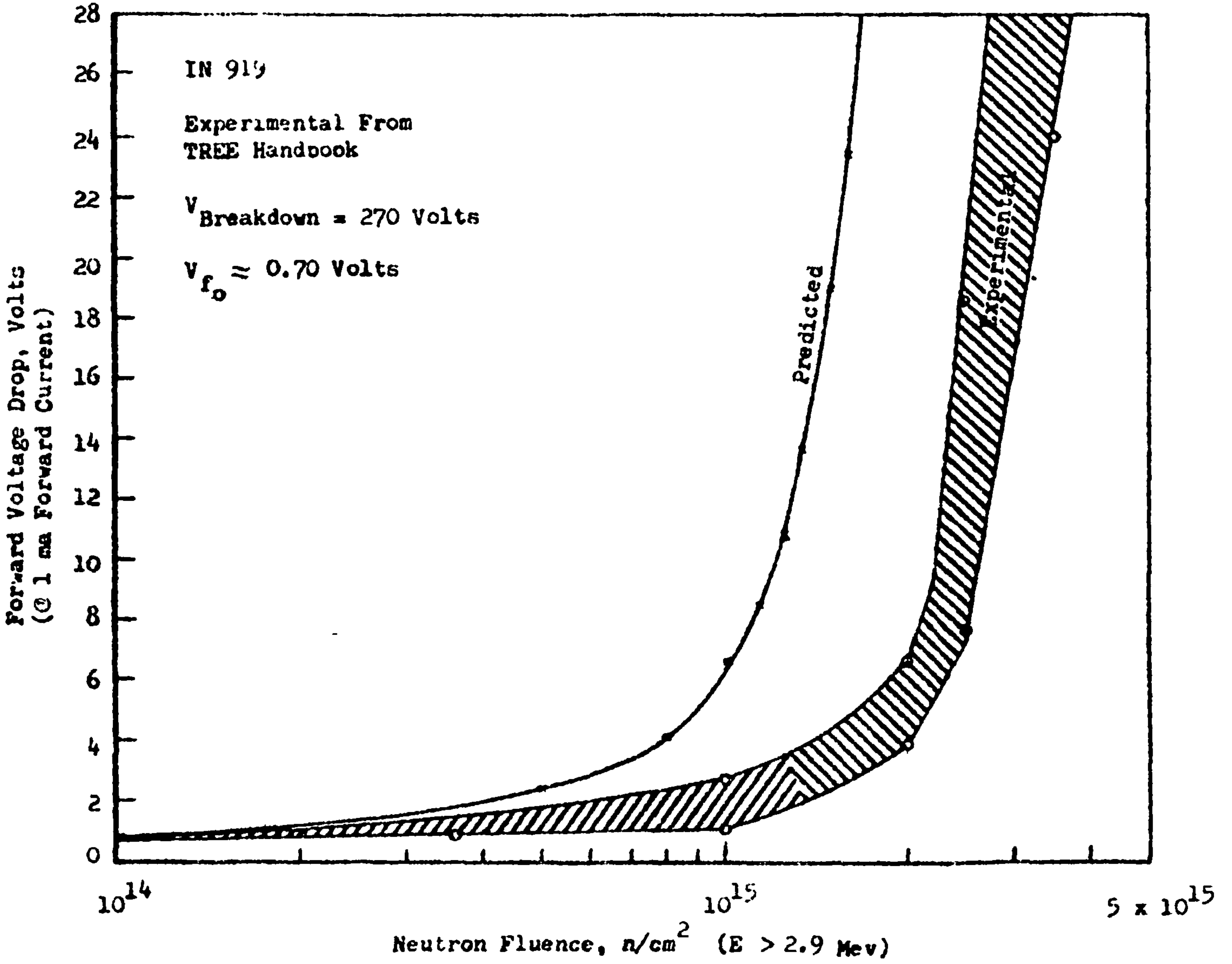


Figure 8.4 Comparison of Actual Diode Radiation Degradation to Predicted Degradation

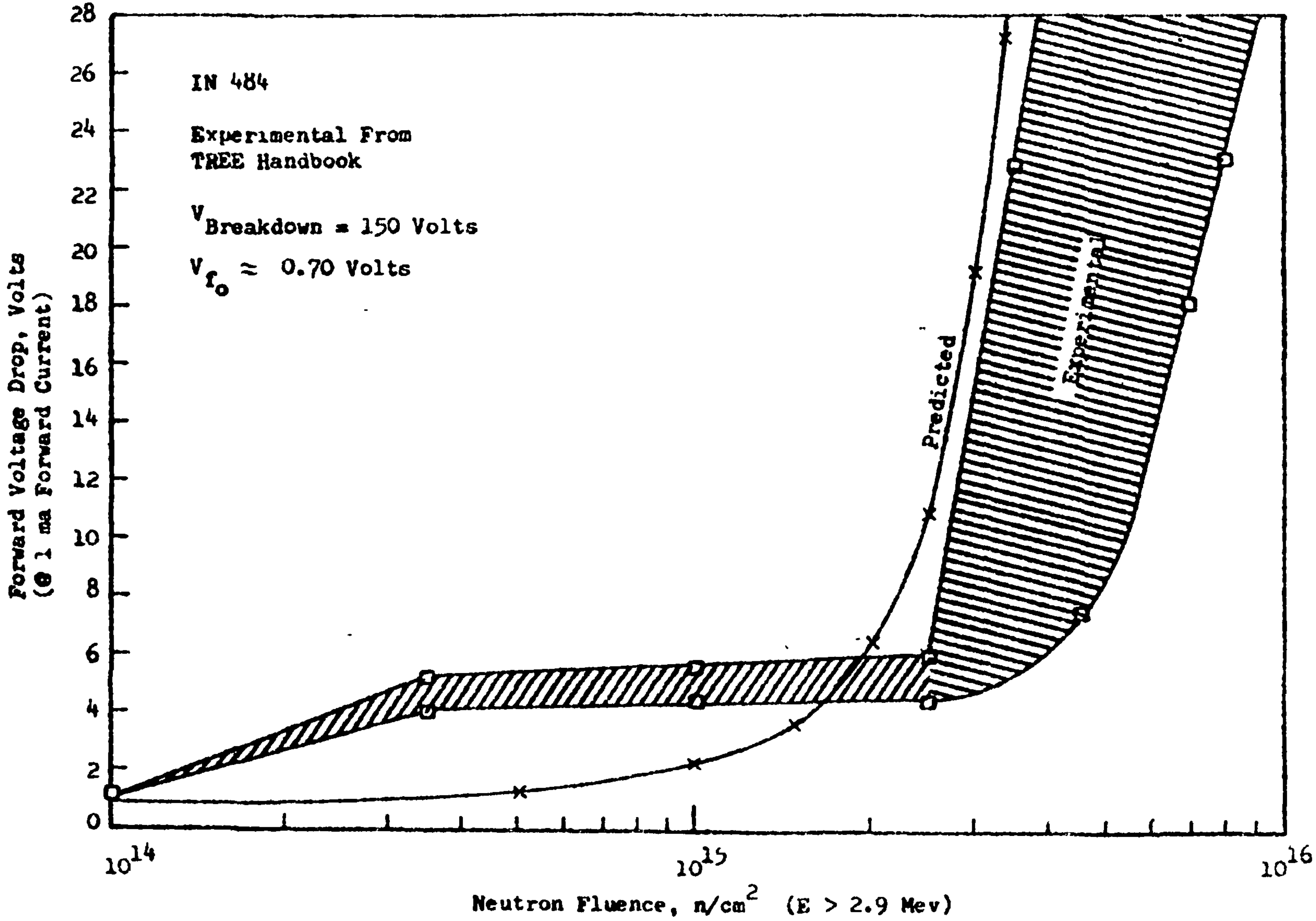


Figure 8.5 Comparison of Actual Diode Radiation Degradation to Predicted Degradation

Toulbee (Reference 8.83). Their technique is much more detailed and does consider lifetime changes, etc.

The effects on reverse leakage current are, in most cases, less important than the forward voltage changes. The changes in leakage current due to neutron radiation can be estimated by the method outlined for transistor junctions in Ref. 8.83 . The leakage current is affected by changes in the minority carrier lifetime. There are two components of leakage current, (1) the reverse-saturation current and (2) the carrier-generation current which is dependent on the minority carrier lifetime. Another component of leakage current arises at the surface and, as stated for transistors, is unpredictable. For the TOPS environment the extent of ionization present will probably result in the surface component being dominant. Thus, techniques for prediction of leakage currents are very questionable at the present state of the art.

8.12 Proton Effects

Proton effects on diodes are not so well documented as the effects of neutrons. In general, though, it should be possible to estimate proton damage in diodes using the neutron theory and experimentally determined equivalences, (Reference 8.84) between neutrons and protons. This technique ignores the ionizing effects of protons. However, in the case of diodes, since the major effect is carrier removal, the ionization effects on forward voltage are probably small. On the other hand, this may not be the case for reverse leakage currents, since ionization can cause channel formations over the junction regions. Unfortunately, to date there are no techniques for predicting channel formation. Forward voltage changes may be estimated semiquantitatively using Manlief's technique outlined in Section 8.11. In no case, should this be construed as final data. It is simply a "ball park" estimate and no more. For a more accurate estimate, one should consider the estimation technique outlined in Reference 8.83 for neutron damage. When using these techniques, the empirical equivalence factors listed in Table 8.1 should be used.

Table 8.1 Proton - Fission Spectrum Neutron Displacement Equivalances

1 (8-17 MeV) Protons/cm^2	$\approx$ 33 (fission spectrum) neutrons/cm^2
100 MeV Proton/cm^2	$\approx$ 8 (fission spectrum) neutrons/cm^2

If either of the above estimation processes indicate marginal performance for the part in question, the part should either be replaced by a more suitable type or actual data obtained on a reasonably large sample of devices.

It should be noted that no applicable data was found in the literature to verify the estimation techniques listed above.

No data was located to indicate leakage current effects, but one would expect the charged particles to induce surface leakage.

8.13 Gamma Effects

Gamma rays cause essentially the same effects in diodes as do protons but are much less effective. It is felt that if gamma damage produces significant effects in the TOPS environment, the effects will be due to channeling and increased leakage currents. As stated earlier, channel formation is not amenable to prediction at the present state of the art.

8.14 Combined Environments

At present, there are no data available indicating how to assess the effects of a combined environment. For the present state of the art, the most reasonable approach is to assess the effects of each individual environmental component and assume that the effects are additive on a one-to-one basis. For ionization effects on leakage currents, this is probably a worst-case assessment since ionization damage does appear to saturate with increasing dose.

8.20 Temporary Parameter Degradation

For the radiation intensities expected in the TOPS environment, there is no evidence in the literature that any abnormal drift in parameters will occur during irradiation other than the degradation discussed in the preceding section.

8.30 Parameter Degradation Factors

For diodes, the parameters to which degradation factors should be applied are forward voltage, reverse leakage current, and peak current capabilities.

Since the extent of radiation damage is highly dependent on device type, material, and construction, it is not feasible to list a universal degradation factor versus radiation level; however, using the damage estimation techniques outlined in Section 1, one can calculate reasonable degradation factors to be applied for a specific diode type. An example of such a calculation will be given for the IN645 diode. Using the sample prediction given in Ref. 8.83, it is estimatea that the forward voltage will be about 2.41 volts at $I_F = 100$ ma. The manufacturer data sheets lists 0.8 volts as typical for the device type before irradiation. Thus, the forward voltage at 100 ma will have to be uprated by +200 percent. The maximum allowable forward current at 25°C is listed by the manufacturer to be 400 ma. At 400 ma, a typical forward voltage is 1.0 volts. Thus, maximum power dissipation of 400 mW is established. The new maximum forward current must be derated sufficiently so that no more than 400 mW is dissipated in the device with the increased V_f. Thus, a reasonable derating factor would be calculated by the equation 8.2.

$$I_{f(max)} = \frac{400 \times 10^{-3}\ \mathrm{W}}{2.51\ \mathrm{volts}^{*}} = 160\ \mathrm{ma} \qquad \text{(eq. 8.2)}$$

* (0.1 volt was added to allow for increased current so that $I_{f(max)}$ should be derated by 60 percent at 7.2×10^{13} fission neutrons/cm^2.

Table 8.2 lists estimated average degradation factors for diode parameters.

8.60 Radiation Hardening

Diodes can be hardened by increasing their doping levels. In general, devices with low breakdown voltages have heavy doping and, thus, are relatively radiation resistant. One should, therefore, choose the lowest breakdown voltage unit that is in keeping with the application.

Further, it has been found (Reference 8.82) that gold doping tends to harden diodes to neutron radiation.

Table 8.2 Estimated Diode Degradation Factors

	Fluence	Fluence
Parameter	7.2×10^{13} Neutron/cm^2	2.2×10^{12} 8-17 MeV Proton/cm^2
	Degradation	Degradation
V_f at 100 ma	+ 200 percent	+200 percent
$I_{F(max)}$	-60 percent	-60.0 percent
I_R at 100 volts	Unpredictable due to Ionization* Damage	

* Leakage currents have been observed to change from 50 percent to 800 percent at a fluence of 10^{14} n/cm^2.

8.70 Radiation Screening

The only screening technique that has been suggested is preirradiation and annealing for ionization effects as described for transistors in Section 4.60.

8.80 References

8.81 Huth, G. C., "The Effect of Variation of the Width of the Base Region on the Radiation Tolerance of Silicon Diodes", Third Radiation Effects Symposium, Vol. 4, October, 1958.

8.82 Manlief, S. K., "Neutron-Induced Damage to Silicon Rectifiers", IEEE Trans. on Nucl. Sci., Vol. NS-11, Nov. 1964.

8.83 Frank, M., Taulbee, C. D., "Handbook for Predicting Semiconductor Device Performance in Neutron Radiation", AFWL-TR-67-54, AD818971, August, 1967.

8.84 Phillips, A. B., "Transistor Engineering", McGraw-Hill Book Company, New York, 1962.

APPENDIX 8A $\Delta(V_f)$ ESTIMATION TECHNIQUE

A method has been suggested (Ref. 8.82) for estimating the amount of neutron induced degradation in silicon rectifier diode performance. The method is outlined here and extended to yield a relation for normalized change in forward voltage. Although the method was developed for neutron damage, it should apply equally well to displacement damage caused by protons.

The estimation technique assumes a diode model of a silicon rectifier with a simple step junction. It is further assumed that the density of minority carriers is much less than the density of majority carriers, i.e., no conductivity modulation occurs. The above assumptions make the estimate semiquantitative as a general prediction technique.

The technique is developed mathematically starting with the relation for forward current presented in equation 8A.1.

$$I = I_s \left(\frac{qV_j}{e^{kt} - 1} \right) \qquad \text{(eq. 8A.1)}$$

$$I_s = qAN_p \left(\frac{D_n}{t_n} \right)^{1/2} \qquad \text{(eq. 8A.2)}$$

q = electronic charge

A = junction area

D_n = diffusion constant of electrons in the p-type material

K = Boltzmann's constant

T = absolute temperature

V_j = junction voltage

N_p = minority carrier density

t_n = minority carrier lifetime in the p-type material

I = diode current

and

$$V_b = \frac{IW}{A\,\sigma_p} \qquad \text{(eq. 8A.3)}$$

W = width of base region

σ_p = conductivity of the p-type base

Assumption - Primary effect is carrier removal in the p-type base region.

$$\sigma = \sigma_o \, e^{-a\Phi} \qquad \text{(eq. 8A.4)}$$

(over range of conductivities of interest).

σ = conductivity

σ_o = initial conductivity

a = constant

Φ = radiation flux

$$\frac{\sigma}{\sigma_o} = e^{-a\Phi} \qquad \text{(eq. 8A.5)}$$

$$\frac{\sigma_o}{\sigma} = e^{a\Phi} \qquad \text{(eq. 8A.6)}$$

$$\ln\left(\frac{\sigma_o}{\sigma}\right) = a\Phi \qquad \text{(eq. 8A.7)}$$

but the constant a can be related to σ_o by

$$a = -\frac{1}{\sigma_o} \left.\frac{d\sigma}{d\Phi}\right|_{\Phi \rightarrow 0} \qquad \text{(eq. 8A.8)}$$

but since $\sigma = P q\mu$ (eq. 8A.9)

P = impurity concentration

μ = mobility

then

$$a = +\frac{1}{\sigma_o} q\mu \left.\frac{dP}{d\Phi}\right|_{\Phi \rightarrow 0} \qquad \text{(eq. 8A.10)}$$

$$\left.\frac{dP}{d\Phi}\right|_{\Phi \rightarrow 0} = R \qquad \text{(eq. 8A.11)}$$

R = initial carrier removal rate

Thus $\sigma = + \frac{q\mu}{\sigma_o} R$ (eq. 8A. 12)

and ln $\left(\frac{\sigma_o}{\sigma}\right) = + \frac{q\mu}{\sigma_o} R\Phi$ (eq. 8A. 13)

But from (3)

$$\sigma = \frac{IW}{A\,V_b} \qquad \text{(eq. 8A. 14)}$$

So that

$$\ln\left(\frac{\frac{IW}{AV_{bo}}}{\frac{IW}{AV_B}}\right) = + \frac{q\mu}{\sigma_o} R\Phi \qquad \text{(eq. 8A. 15)}$$

or

$$\ln\left(\frac{V_b}{V_{bo}}\right) = + \frac{q\mu}{\sigma_o} R\Phi \qquad \text{(eq. 8A. 16)}$$

If one assumes that changes in μ are of secondary importance as Manlief suggests

$$\ln\left(\frac{V_b}{V_{bo}}\right) = + \quad K\,R\Phi \qquad \text{(eq. 8A. 17)}$$

or $\ln(V_b) = \ln V_{bo} + KR\Phi$ (eq. 8A. 18)

where $K = \frac{q\mu}{\sigma_o} = \frac{q\mu}{q\mu_o P_o} \approx \frac{1}{P_o}$ (eq. 8A. 19)

so that $\ln(V_b) \approx \ln V_{bo} + \frac{R}{P_o}\Phi$ (eq. 8A. 20)

or $\frac{V_b}{V_{bo}} = e^{\frac{R}{P_o}\Phi}$ for N on P diodes (eq. 8A. 21)

and $\frac{V_b}{V_{bo}} = e^{\frac{R}{N_o}\Phi}$ for P on N diodes (eq. 8A. 22)

If the initial conductivity of the base material is not known directly then it can be estimated from the curve in Figure 8A-1. R and N_o have been established from Manlief's curves of ϕ^* VS σ_o and N_o VS V_B and are plotted in the graph of Figure 8.3.

Plotted from Phillips (Page 76) Ref. 8.74 and Manlief (Fig. 2) Ref. 8.72.

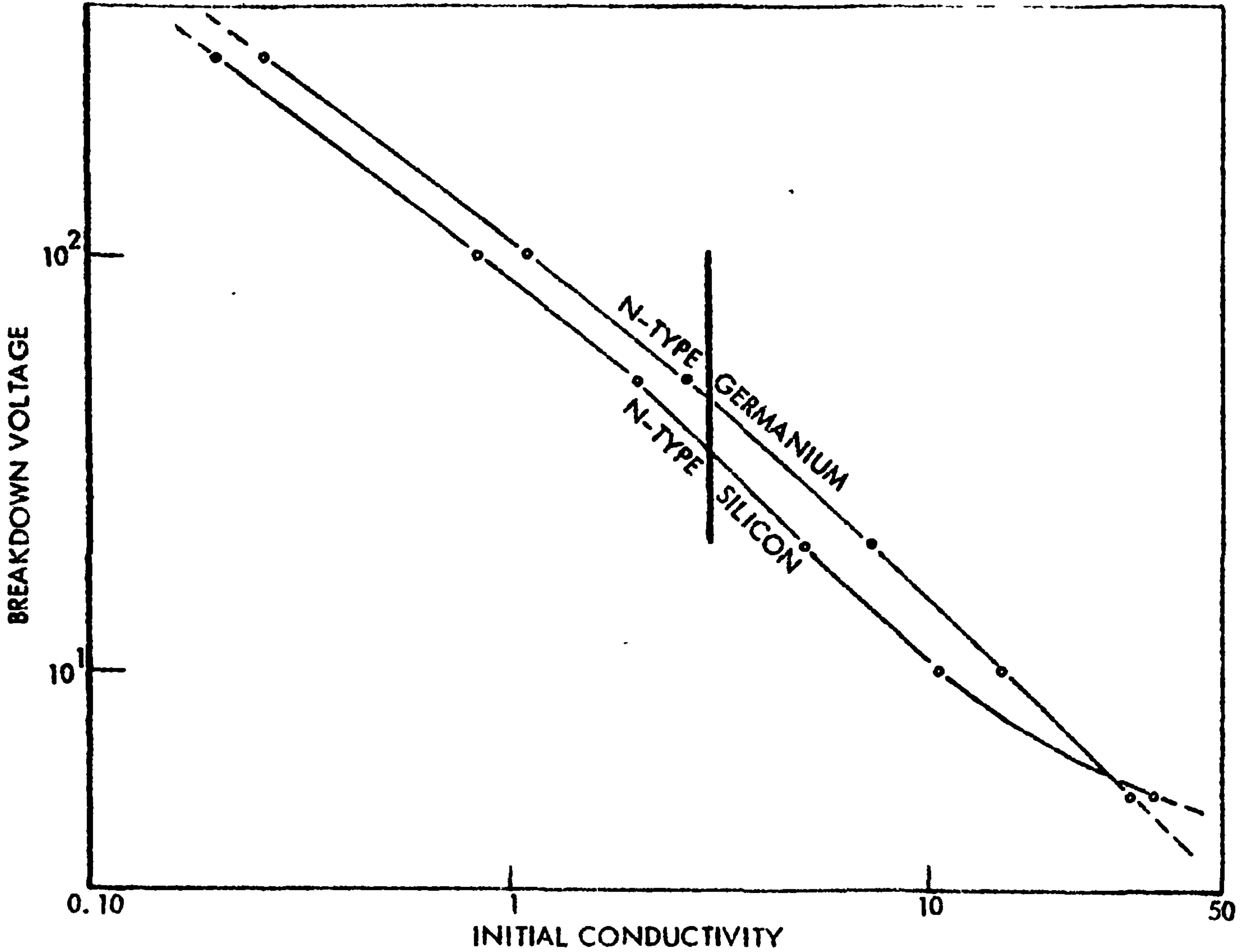


Figure 8A-1. Initial Conductivity Vs. Breakdown Voltage

9.0 ZENER DIODES

Due to close tolerances required by most zener diode applications, they must be considered as relatively radiation sensitive devices. They frequently show changes of from 2 to 4 percent in the reference voltage at neutron fluences of the order of 10^{12} n/cm^2 plus ionization doses of the order 10^6 rads.

9.10 Permanent Parameter Degradation

9.11 Neutron Effects

Thatcher (Reference 9.71) has made a survey of zener experiments through 1964 and his survey is reproduced in Table 9.1 with radiation units changed to conserve consistency in this report. In addition to the data presented in the Table, more recent tests (Reference 9.75) have shown that, even through zeners may, in some cases, show very little change with radiation at 25°C, the zener voltage versus temperature characteristics change with increasing radiation so that the device may show no change at 25°C, but show considerable change at higher or lower temperatures. This observation is illustrated in Figures 9.1 and 9.2.

9.12 Proton Effects

No data were found for proton effects on zener diodes, but the damage mechanisms should be similar to those for neutrons. However, it is noted that protons are relatively more damaging than neutrons. For example, 1 (15 MeV) proton/cm^2 does damage equivalent to that of about 33 (fission) neutrons/cm^2. (Ref. 9.76). This equivalence ignores the ionizing effects of protons.

9.13 Gamma Effects

The data for gamma effects on zener diodes, indicate that they appear to be altered very little by doses as high as 4×10^5 rads(Si) Co-60. Tests in combined environments of 10^6 rads and 10^{12} n/cm^2, however, show changes of from 2 to 4 percent in zener reference voltages.

9.20 Temporary Parameter Drift

The effects of radiation on zener diodes are permanent; however, they have

TABLE 9.1 RADIATION EFFECTS ON ZENER DIODES (Ref. 9.71)

Type Number	Mfg.	Material	Radiation Exposure $(nv_o)t$	$n\ cm^{-2}$	Rads	Effects	Reference
IN4308	--	Si	--	10^{16} (E > 0.3 Mev)	--	Showed slight decreases in voltage for various current levels up to 10^{15} $n\ cm^{-2}$. Above this level, voltages increased almost to initial values.	(30) 9.72
IN749A	MOTA	Si	--	4.8×10^{12} (E > 0.5 Mev)	7.1×10^5	Zener voltage change of 3.34 per cent.	(78) 9.73
IN753A	MOTA	Si	--	4.8×10^{12} (E > 0.5 Mev)	7.1×10^5	Zener voltage change of 2.5 per cent.	(78) 9.73
IN754A	MOTA	Si	--	4.8×10^{12} (E > 0.5 Mev)	7.1×10^5	Zener voltage change of 2.1 percent.	(78) 9.73.
IN821	--	Si	--	10^{16} (E > 0.3 Mev)	--	Slight decrease in voltage for various currents up to 10^{15} $n\ cm^{-2}$, then sharp decrease.	(30) 9.72
IN943	MOTA	Si	--	8×10^{15}	7.9×10^6	Zener voltage at 3×10^{15} $n\ cm^{-2}$ had decreased only 3 per cent. By end of test, Zener voltage had increased by 30 per cent. Dynamic resistance at end of test was over 1 k ohm.	9.74
IN943	MOTA	Si	--	5.6×10^{12}	2.6×10^7	Change in Zener voltage from 11.47 to 12 volts at about 5.6×10^{12}. Zener voltage measured at 10 ma.	9.74
IN992A	MOTA	Si	--	4.8×10^{12} (E > 0.5 Mev)	7.1×10^5	Zener voltage increase of 0.75 per cent.	(78) 9.73
IN1833A	HSO	Si	--	4.8×10^{12} (E > 0.5 Mev)	7.1×10^5	Zener voltage change of 1.2 per cent	(78) 9.73
CD3137	CDC	Si	--	6.8×10^{15}	8.8×10^5	Zener voltage at 100 μa showed a constant decrease of about 30 per cent. Zener voltage at 5 ma was relatively level until 1.35×10^{14} $n\ cm^{-2}$, then it decreased by at least 2.4 per cent. Zener voltage at 20 ma increased by as much as 5.6 per cent.	9.74
CD3147	CDC	Si	--	6.8×10^{15}	8.8×10^5	Zener voltage at 100 μa, 5 ma, and 20 ma increased by at least 5.8 per cent.	9.74
CD4113	CDC	Si	--	6.8×10^{15}	8.8×10^5	Zener voltage at 100 μa, 5 ma, and 20 ma decreased by at least 2.5 per cent	9.74
SV1004	TEC	Si	--	4.8×10^{12} (E > 0.5 Mev)	7.1×10^5	Zener voltage decrease of 2.0 percent	(78) 9.73

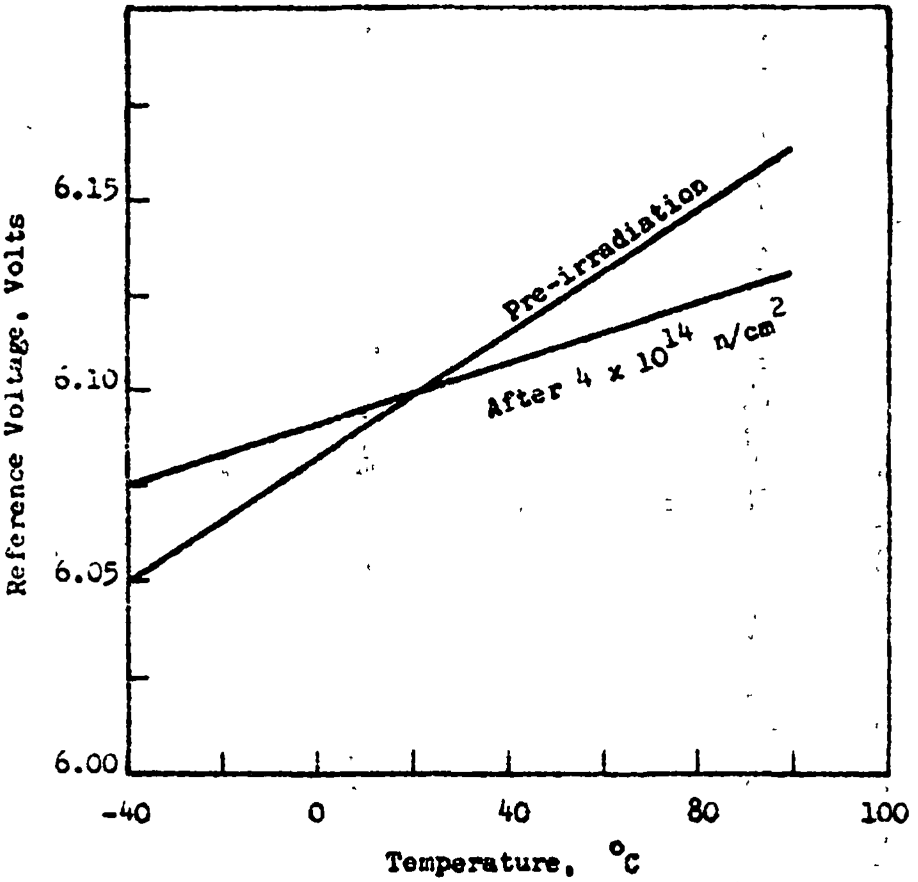


Figure 9.1 Voltage-Temperature Characteristics for 1N829 (9.75)

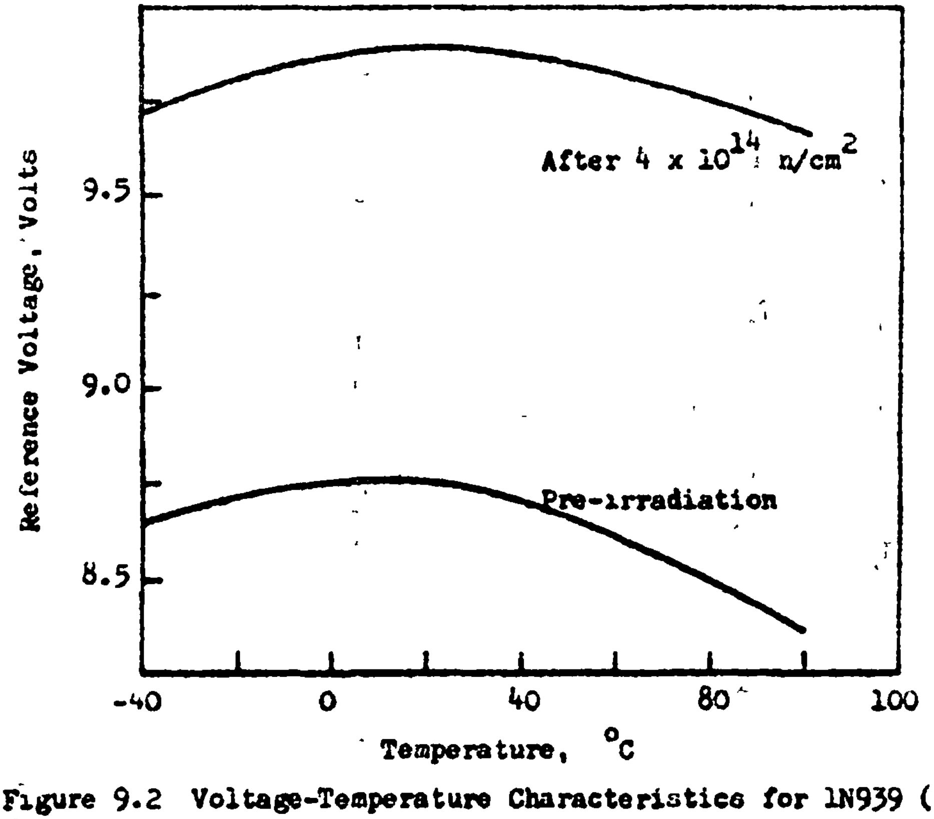


Figure 9.2 Voltage-Temperature Characteristics for 1N939 (9.75)

been observed to show both a decrease and a subsequent increase under radiation. For example, in one experiment (Reference 9.74) Motorola 1N943 devices were observed to decrease 3 percent at 3×10^{15} n/cm^2 and to then show an increase of ~ 30 percent by the end of the test (8×10^{15} n/cm^2).

9.30 Parameter Degradation Factors

Table 9.1 and Figures 9.1 and 9.4 summarize typical changes in zener reference voltages due to radiation. It is observed that zeners appear to change less than five percent at neutron fluences 10^{15} neutrons/cm^2. However, changes of from 2-4 percent occur at radiation levels as low as 5×10^{12} n/cm^2 plus 7×10^5 rads (C). The designer should note that these changes may be either increases or decreases with the pattern frequently being a gradual decrease in reference voltage followed by a rapid increase. It should also be noted that, as shown in Figures 9.1 and 9.2, the zener voltage versus temperature characteristics change with radiation.

9.40 Radiation Hardening

No techniques for hardening zener diodes were located in the literature.

9.50 Recommended Testing

It is recommended that any zener device type to be used in a critical application in a radiation environment be thoroughly characterized in the radiation environment of interest. The zener voltage should be tested both as a function of current and temperature.

9.60 Screening

No screening techniques for zener diodes were found in the literature.

9.70 References

9.71 Thatcher, R. K., Hamman, D. J., Chapin, W. E., Hanks, C. L. and

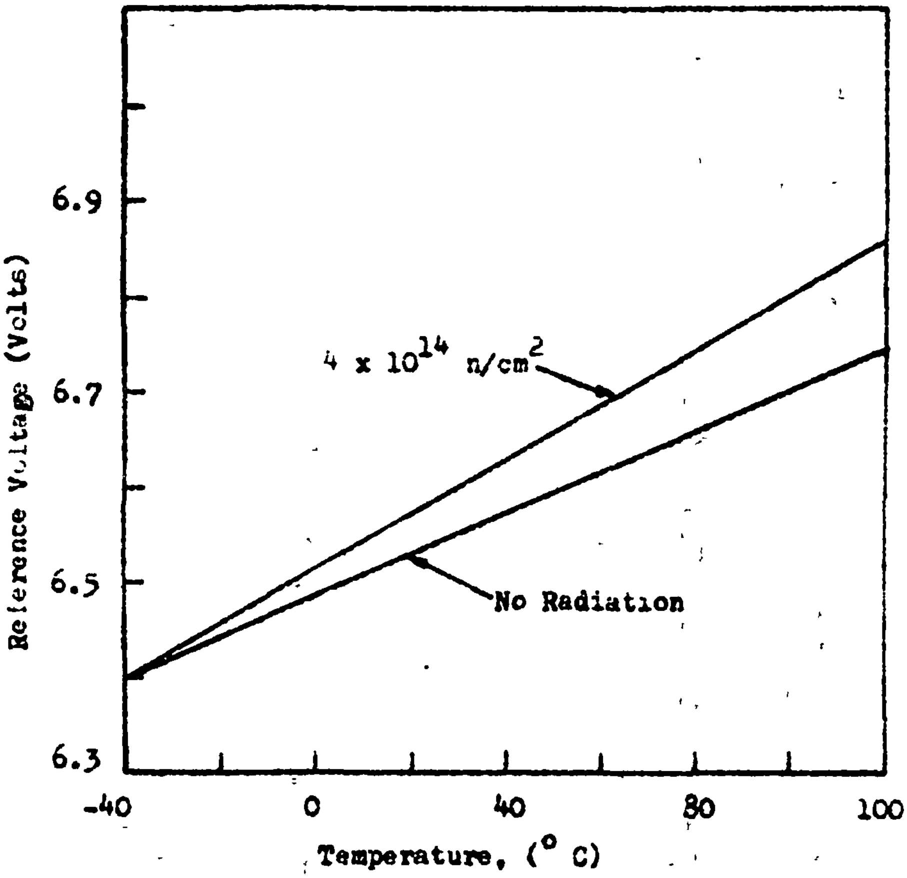


Figure 9.3 Voltage - Temperature Characteristics For IN745A (9.75)

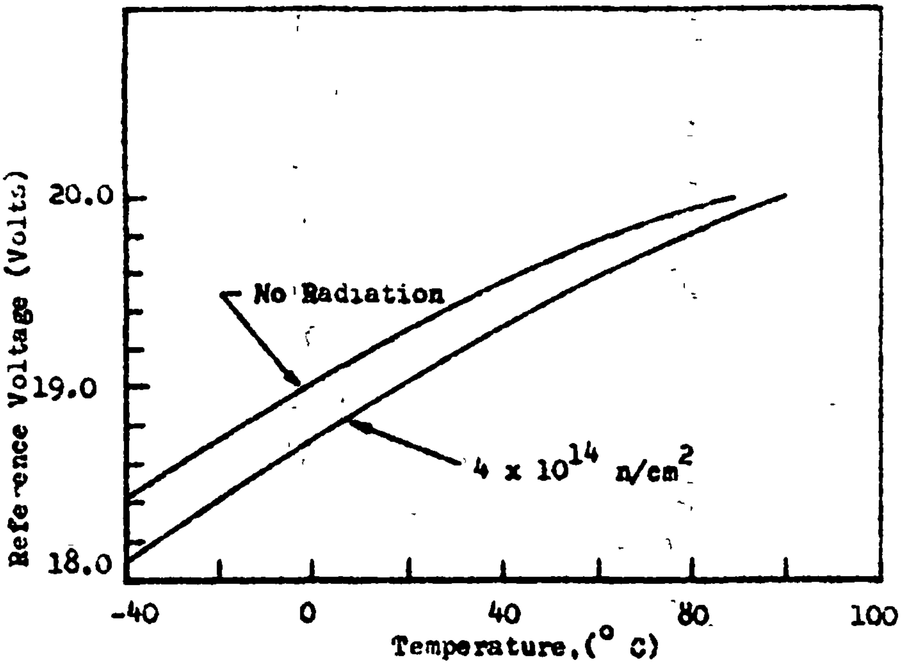


Figure 9.4 Voltage - Temperature Characteristics For IN968B (9.75)

Wyler, E. N., "The Effect of Nuclear Radiation on Electronic Components Including Semiconductors", REIC Report No. 36, October 1964.

9.72 Shorwir, R., and Montner, J., "Performance of Radiation-Resistant Magnetic Amplifier Controls Under Fast Neutron and Gamma Irradiation", Marquardt Corp., Report S-222, AF 33(616)-7857 (August, 1961).

9.73 Burnett, J. R., Azary, Z., and Sandifer, C. W., "Flashing Light Satellite System for SNAP Radiation Environments", Edgerton Germeshausen & Grier Inc., EGG-S-227-R, AF 19(628)-495 (January, 1963).

9.74 Armstrong, E. L., "Results of Irradiation Tests on Electronic Parts and Modules Conducted at Vallecitos Atomic Laboratory", Lockheed Aircraft Corp., Missiles and Space Division, AF 04(695)-136 (August, 1962).

9.75 Ruwe, V. W., "The Effect of Neutron and Temperature Environment on Sensistors, Stabistors, and Zener Diodes", Army Missile Command, Huntsville, Ala., RG-TR-67-20, AD 819 719, X67-23278, Aug. 15, 1967.

9.76 Brown, R. R., Horne, W. E., "Space Radiation Equivalence for Displacement Effects on Transistors", The Boeing Co., Seattle, Wash., D2-84088-2, Nov. 1966; NASA CR-804, July 1967.

10.0 TUNNEL DIODES

10.1 Permanent Parameter Degradation

Tunnel diodes are relatively resistant to radiation. This is true because they depend on the tunneling of electrons from the conduction band to the valence band for their operation. Thus, they are not dependent on minority carrier lifetime. Figure 10.1 shows a typical characteristic of a tunnel diode.

10.11 Neutron Effects

The primary effect of neutron radiation is to increase the excess current. This increase is believed to be brought about by the tunneling of electrons via defect energy states introduced by the radiation.

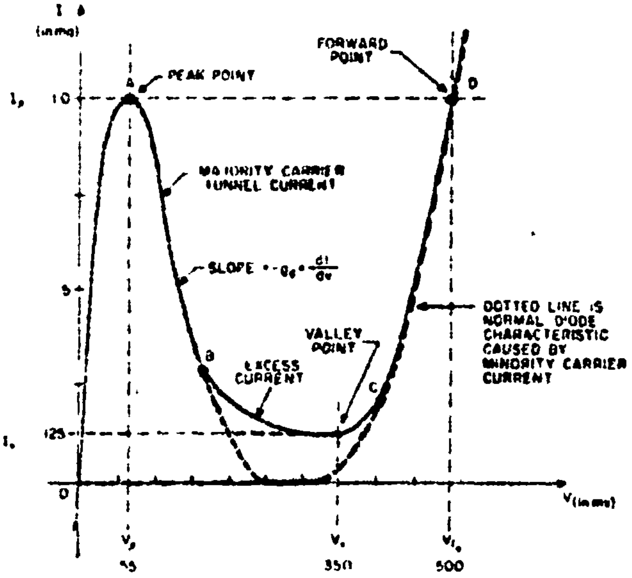


Figure 10.1 Static Characteristic Curve of Germanium Tunnel Diode (Ref 10.71)

Neutron damage has been characterized fairly well for tunnel diodes. However, although the damage has been theoretically described, there have been no models developed for making quantitative estimates of an individual device's sensitivity to radiation.

Thus, only ball park damage thresholds can be estimated from data in the literature. These estimates will be presented in Section 10.30.

10.12 Proton Effects

No data were located for proton effects on tunnel diodes; however, there are indications (from electron experiments) that ionization effects are relatively unimportant in these devices. If one neglects ionization effects, then damage thresholds should be related to neutron thresholds by the proton to neutron equivalence factors 1 (8-17 MeV) proton/cm^2 ≈ 33 (fission) neutron/cm^2. (Ref. 10.72)

10.13 Electron Effects

Although there is very little data on electron effects on tunnel diodes, early studies indicated that they could withstand very high levels (10^{17} to 10^{18} (1 MeV) electrons/cm^2). As in the case of neutron damage, the parameters that change are the excess current. The fluences are about the magnitude one would expect for displacement damage based on the equivalence factor (Reference 10.72) between fission neutrons and 1 MeV electrons.

10.14 Gamma Effects

The device's resistance to electron irradiation should indicate their response to gamma radiation which causes displacements primarily through compton scattered electrons. Therefore, one would expect them to be resistant to gamma radiation. Studies of n on p germanium diodes have indicated that they can operate in a properly designed circuit to 1.5×10^{16} n/cm^2 ($E > 0.3$ MeV) and 2.2×10^8 rads(C). Compared to other semiconductor devices, 2.2×10^8 rads is an extremely large ionization dose.

10.2 Temporary Parameter Drift

The data reviewed indicate no radiation induced parameter drift other than the permanent degradation discussed earlier.

10.3 Derating Factors

Based on available data, the derating factors listed in Table 10.1 are estimated. Figures 10.1 through 10.2 show typical degradation curves for tunnel diodes

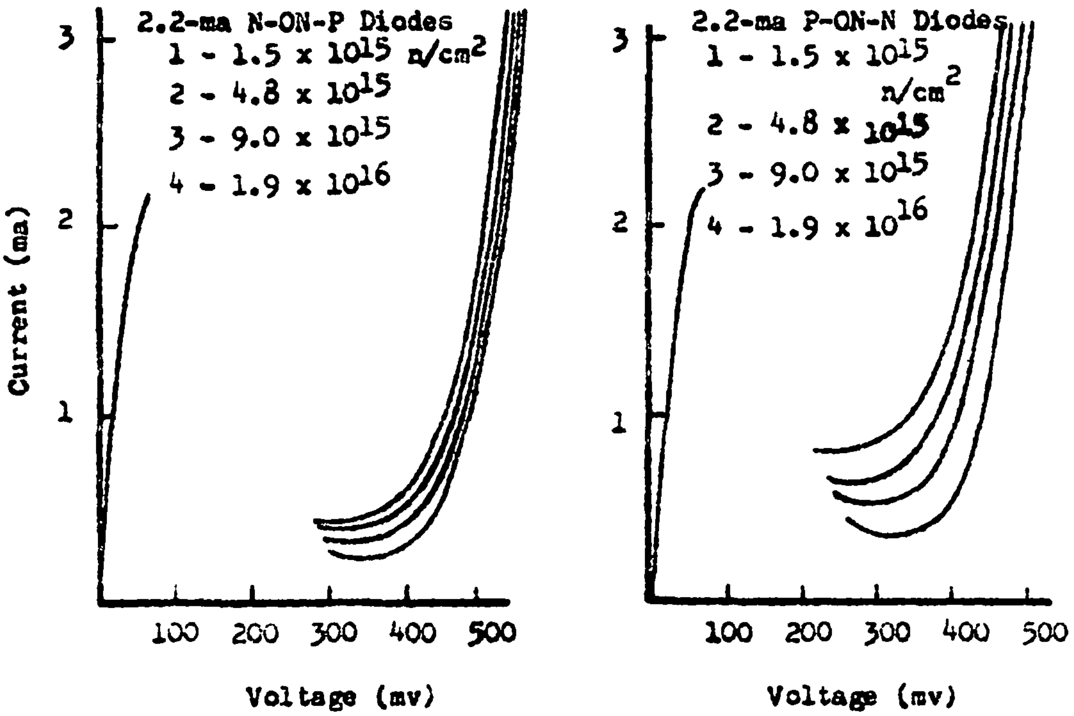


Figure 10.2 Degradation of 2.2-ma Tunnel Diode I-V Curves (Ref. 10.73)

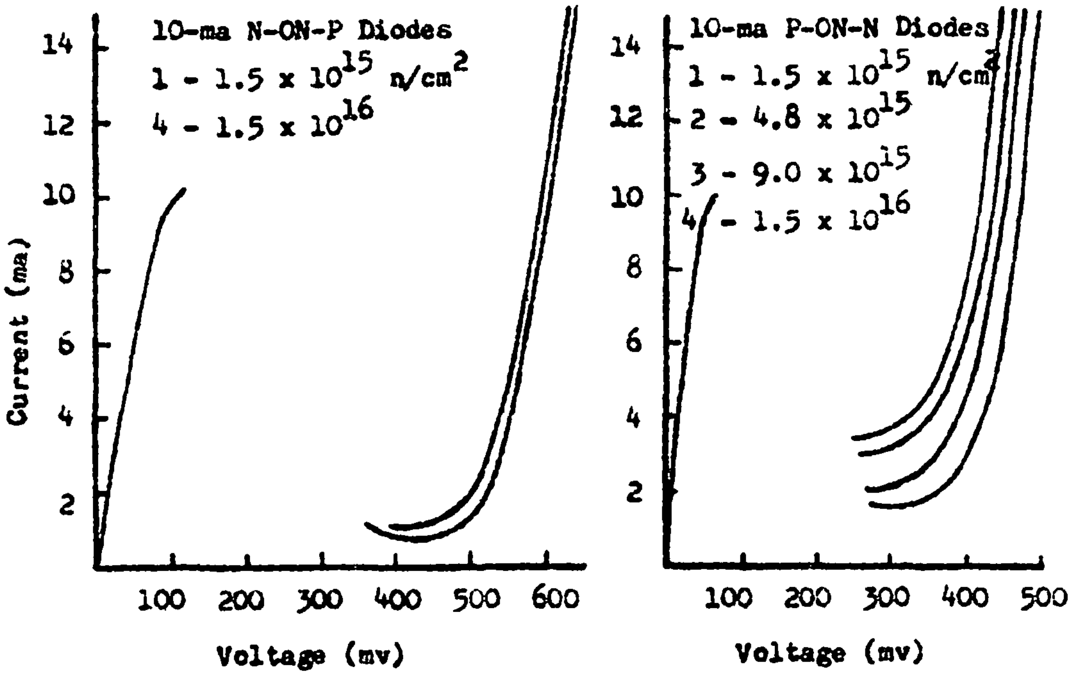


Figure 10.3 Degradation of 10-ma Tunnel Diode I-V Curves (Ref. 10.73)

from the literature.

Table 10.1 Degradation Factors For Germanium Tunnel Diodes

Radiation Type	Parameter	Fluence	Degrad.	Fluence	Degrad.
Neutrons	Excess current	1.0×10^{14} n/cm^2	+ 20	1×10^{15} n/cm^2	+ 90%
Proton (15 MeV)	Excess current	3×10^{12}, p/cm^2	+ 20	3×10^{13} p/cm^2	+ 90%
Electron (1 MeV)	Excess current	$> 10^{15}$ e/cm^2	+ 20	$> 10^{16}$ e/cm^2	- 90%
Gamma (Co-60)	Excess current	$> 10^{8}$ rads	+ 20	$> 10^{8}$ rads	+ 90%

10.4 Radiation Hardening

The only hardening suggestion noted in the literature was that of doping the devices to be used as heavily as is compatible with other requirements of the design.

10.5 Recommended Testing

All available data indicate that tunnel diodes are somewhat more radiation resistant than other semiconductor devices. No testing is felt to be necessary at this time, although it would be desirable to verify the effects of protons on tunnel diodes.

10.6 Screening

No screening techniques were noted in the literature.

10.7 References

10.71 Motorola Tunnel Diode Handbook, published by Motorola Inc.

10.72 Brown, R. R., Horne, W. E., "Space Radiation Equivalence for Displacement Effects on Transistors", The Boeing Company, Seattle, Washington, D2-84088-2, Nov. 1966, NASA CR-804, July, 1967.

10.73 Dowdey, J. E., Travis, C. M., "An Analysis of Steady-State Nuclear Radiation Damage of Tunnel Diodes", IEEE Trans. on Nuclear Science, Vol. NS-11, Nov. 1964, P. 55-59.

11.0 Silicon Controlled Rectifiers and Switches

11.1 Permanent Parameter Degradation

The operation of a four layer PNPN device is generally analyzed using the classic two transistor analogy (11.71, 11.72, 11.73) normally biased with a regenerative feedback loop (Fig. 11.1) where the alphas of each transistor (α_n & α_p) are strongly dependent on the total anode current.

Using the circuit of Fig. 11.1, the anode current through the device below breakdown is expressed by *Equation 11.1.*

$$I_A = \frac{M\,(I_{CO} + \alpha_{2n})}{1 - (\alpha_{1n} + \alpha_{2n})M}\; I_b \qquad \text{(Eq. 11.1)}$$

where: M is the multiplication factor at the center junction and Alpha (α) is defined as the emitter efficiency times the base transport factor for the corresponding transistor.

It may be seen from Equation (1) that the anode current is well defined as long as the demonimator does not equal zero. When (α_{1n} + α_{2n}) $M = 1$, the equation is undefined and I_A becomes unstable, switching from the nonconducting "off" state to the conducting or "on" state. The failure criteria is, therefore, defined as that point where (α_{1n} + α_{2n}) $M < 1$ and will not sustain I_A or when the surface leakage across the center reversed-biased junction increases to a level where (α_{1n} + α_{2n}) $M > 1$.

In general, forward breakover voltage (V_{BO}), gate firing current (I_{GE}) and gate firing voltage (V_{GF}) should all increase with bulk damage while the forward holding current (I_h) and reverse blocking current (I_R) will be sensitive to surface ionization.

11.11 Neutron Effects

The primary effect from neutron radiation is an increase in the recombination rate of the base region when trapping centers are created in the bulk silicon. These recombination and trapping centers not only increase the effective resistivity of the bulk by carrier removal, but most important they reduce the minority carrier lifetime. The reduction of the minority carrier lifetime decreases the alphas of the devices

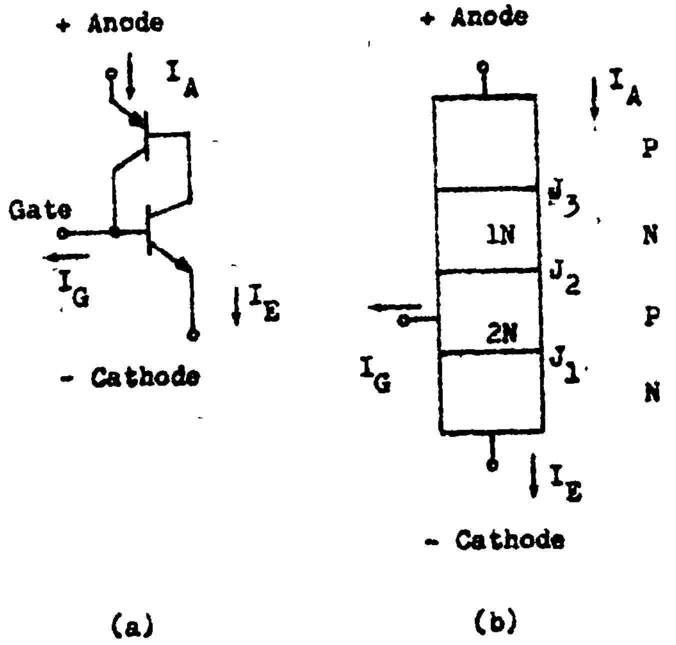


Figure 11.1 SCR Equivalent Circuit. (Ref. 11.72)

thereby increasing the saturation or breakover voltage. As the saturation voltage increases, a current much less than the rated value destroys the SCR by overheating. Fig. 11.2 shows a_{2n} vs. I_E as a function of integrated neutron fluence for a typical silicon-controlled rectifier.

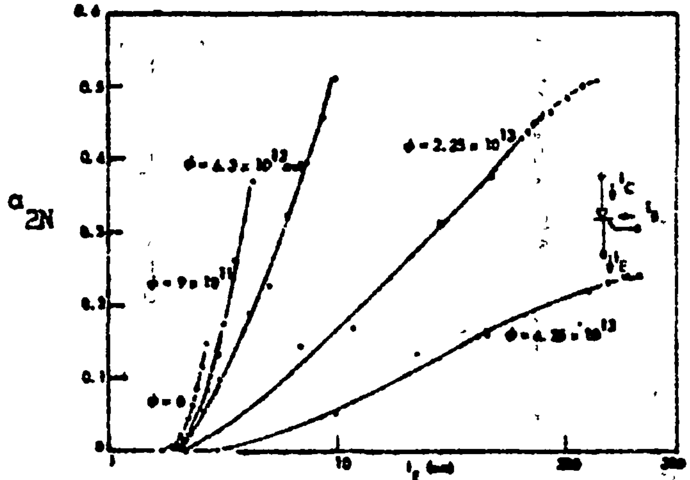


Figure 11.2 Alpha vs Emitter Current as a Function of Integrated Fast-Neutron Flux, ϕ (Ref. 11.7)

A secondary parameter of interest from neutron effects is the leakage current I_{CO}. Sah (11.74) et al., have shown that leakage currents generated in the space charge region or the center junction may be orders of magnitude greater than the normal diffusion leakage current. Since minority lifetime decreases under radiation and the generation rate is inversely proportional to the minority lifetime, it seems reasonable to expect that the leakage current will, therefore, increase.

11.12 Protons

No data has been published on SCR's for proton effects but as pointed out earlier for transistor etc., protons should produce similar effects to those of neutrons with additional ionization. Since protons are more effective than neutrons for displacement damage, one might expect a lower damage threshold.

11.13 Gammas

Surface ionization from gamma radiation produces a lowering of the switching characteristics by the generation of leakage currents or channeling across the center reversed biased junction. The turn-on characteristic of the SCR, neglecting recombination, depends basically on the number of majority carriers injected into specific regions, the transit time of the minority carriers in each base, emitter efficiency, and the base transport factor before regeneration can take place. As the regeneration process builds from ionization, the leakage current (I_{CO}) increases, thereby causing alpha to increase, a critical threshold is reached at $(\alpha_{2N} + \alpha_{1N})M=1$.

At this time the center junction has become slightly forward biased and causes the device to turn completely on. This phenomenon, observed by Stanley (11.72), Gwyn (11.75), and Measel (11.76), poses a serious radiation problem (failures as low as 10^3 rads (Si) for devices under electrical bias during irradiation).

11.2 Temporary Parameter Drifts

There has been no evidence in the literature to suggest a temporary drift in any of the parameters normally measured other than those mentioned in the preceding section on permanent damage.

11.3 Parameter Degradation Factor

The literature study has revealed that while in a radiation field all characteristics of a PNPN device appear to increase in magnitude, ranging from insignificant to orders of magnitude depending on the type of radiation and the particular parameter.

Tests conducted by the Georgia Nuclear Lab (11.77) 1964 (lockheed-Georgia Co.) revealed poor performance associated with SCR devices and the degradation factors are given in Table 11.1 and Figures 11.3 through 11.8 for the 2N1774.

Table 11.1 Degradation Factors for 2N1774

	Pre-Radiation		Degradation - Factor			
			2×10^{12} n/cm^2		4×10^5 Rad	
Parameter	Mean	% Dev.	Δmean%	max % Dev.	Δmean%	max%Dev.
V_{GF}	1.16 V	± 25	+ 26	+37 to -27	+11	+30 to -29
I_{GF}	5.0 ma	± 50	+ 64	+56 to -60	+ 20	+58 to -52
I_h	8.0 ma	+30 to -23	104*	+27* to -21	+ 28	+32 to -28
I_R	5.5 ma	+ 2	+ 0.1 ma	± 2	--	--

* Derating factors given for the single mode I_h condition only.

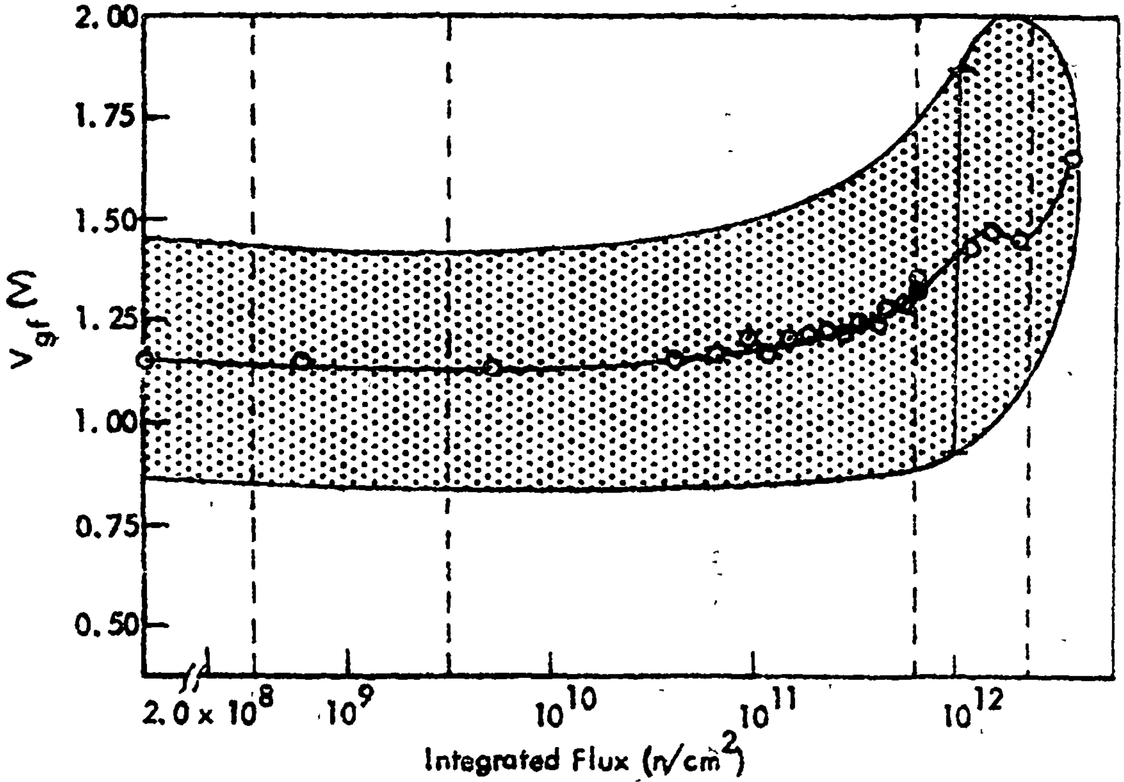


Figure 11.3 SCR 2N1774 - Mean Gate Firing Voltage Versus Integrated Flux

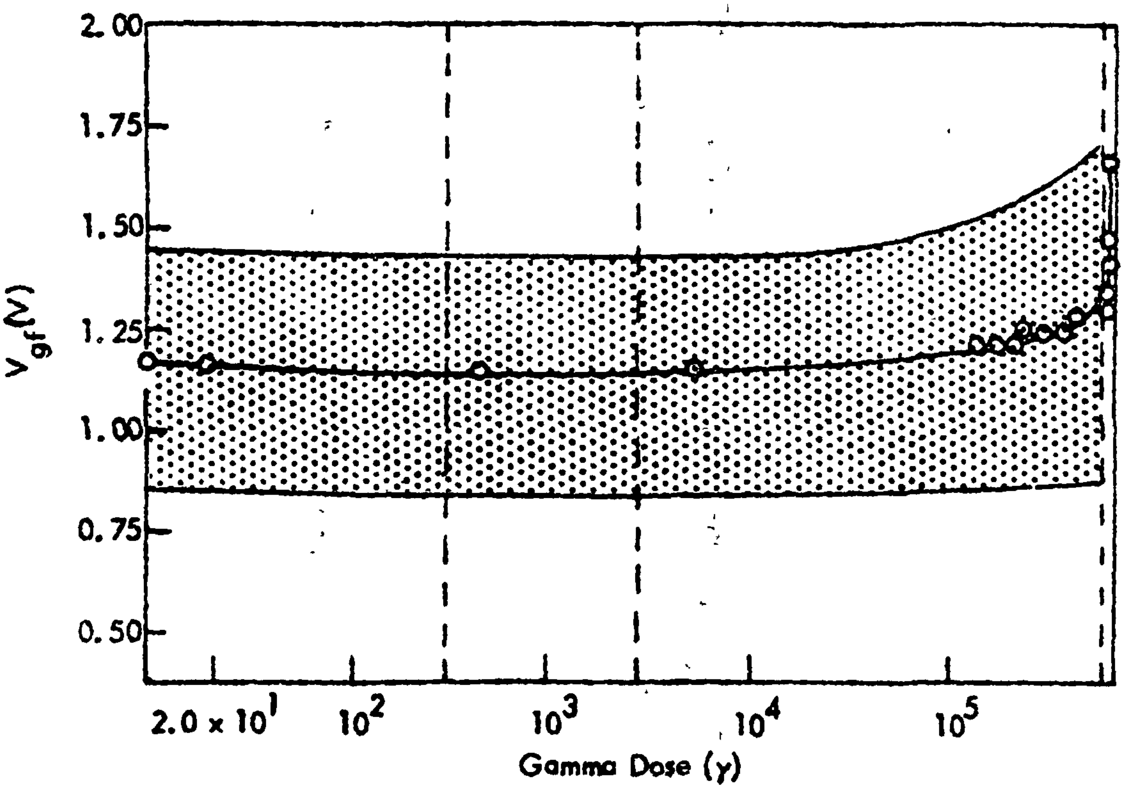


Figure 11.4 SCR 2N1774 - Mean Gate Firing Voltage Versus Gamma Dose

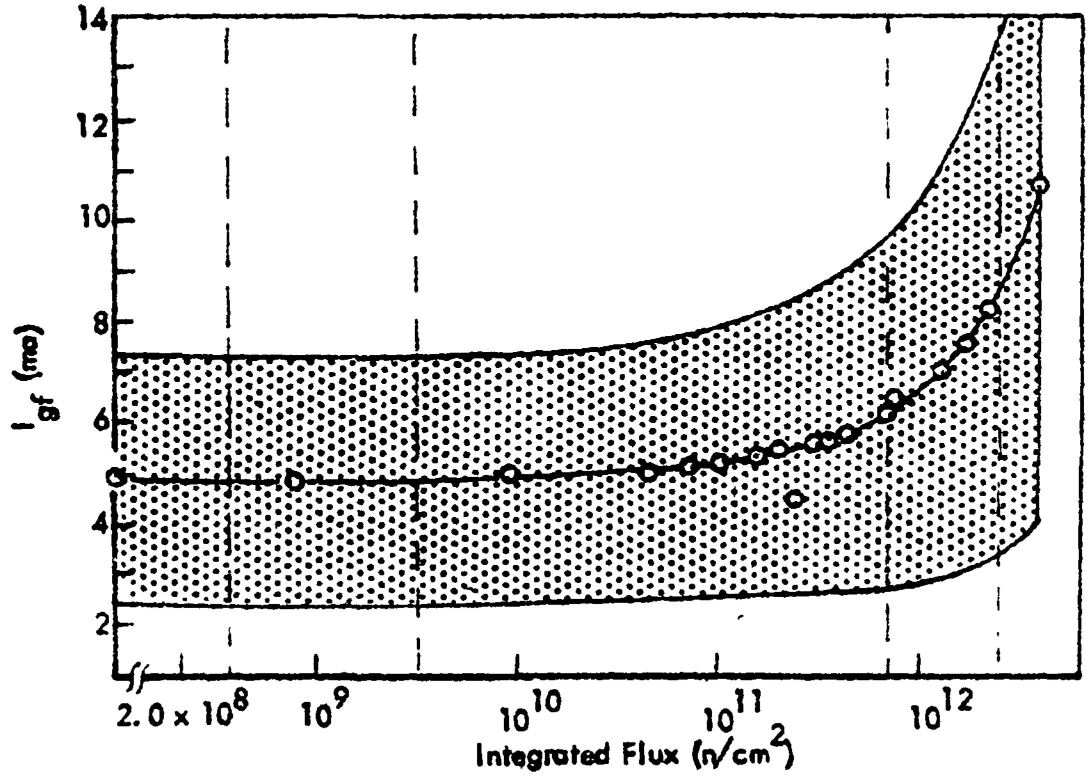


Figure 11.5 SCR 2N1774 - Mean Gate Firing Current Versus Integrated Neutron Flux (Ref. 11.77)

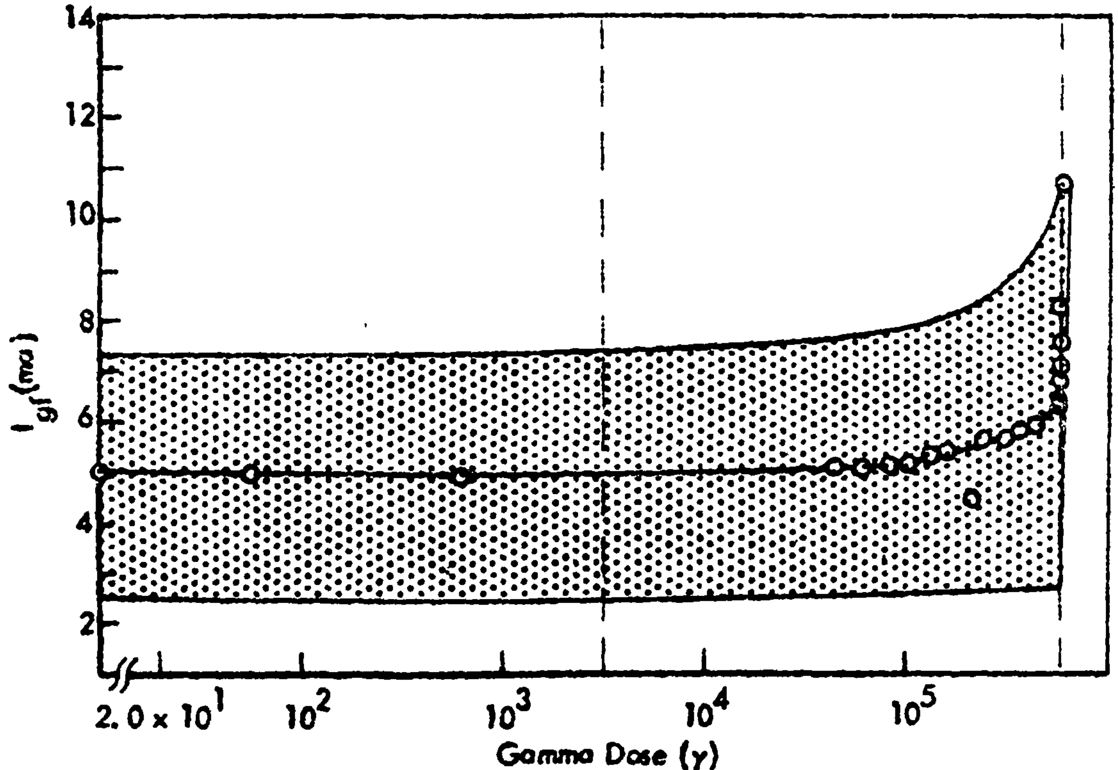


Figure 11.6 SCR 2N1774 - Mean Gate Firing Current Versus Gamma Dose (Ref. 11.77)

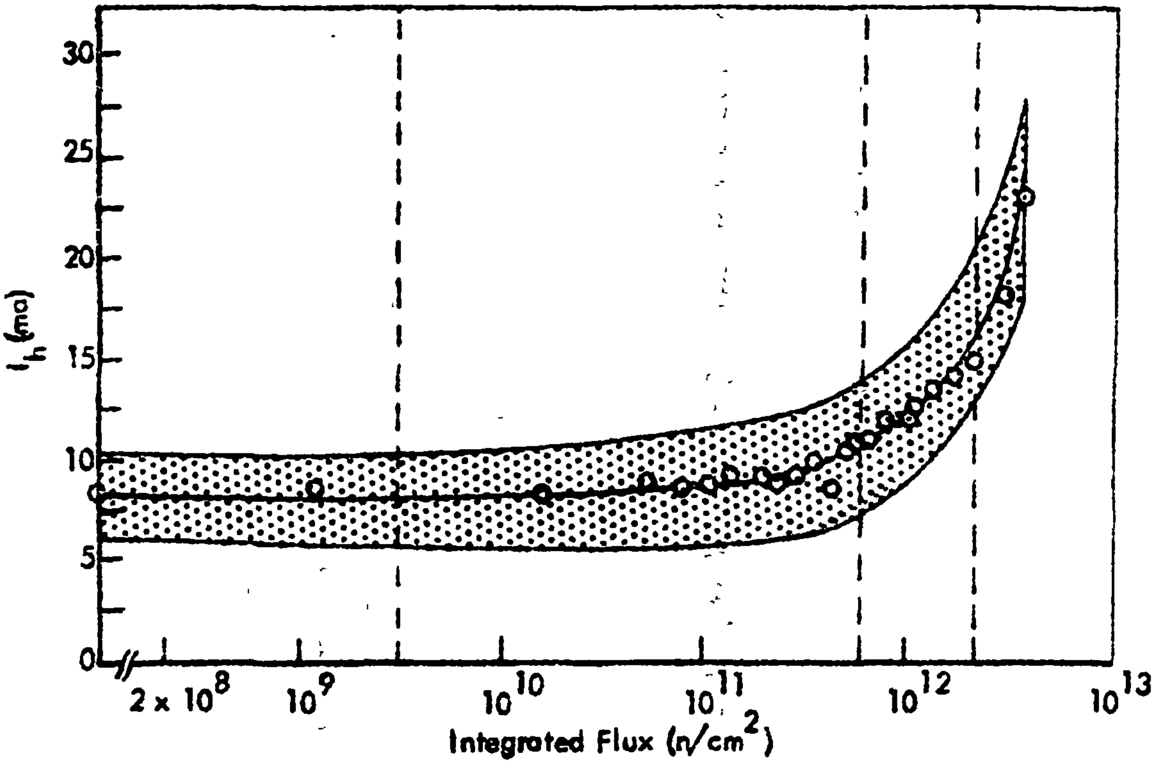


Figure 11.7 SCR 2N1774 - Holding Current (Specimens 1, 3, 4, 5, & 10) Vs. Integrated Flux (Ref. 11.77)

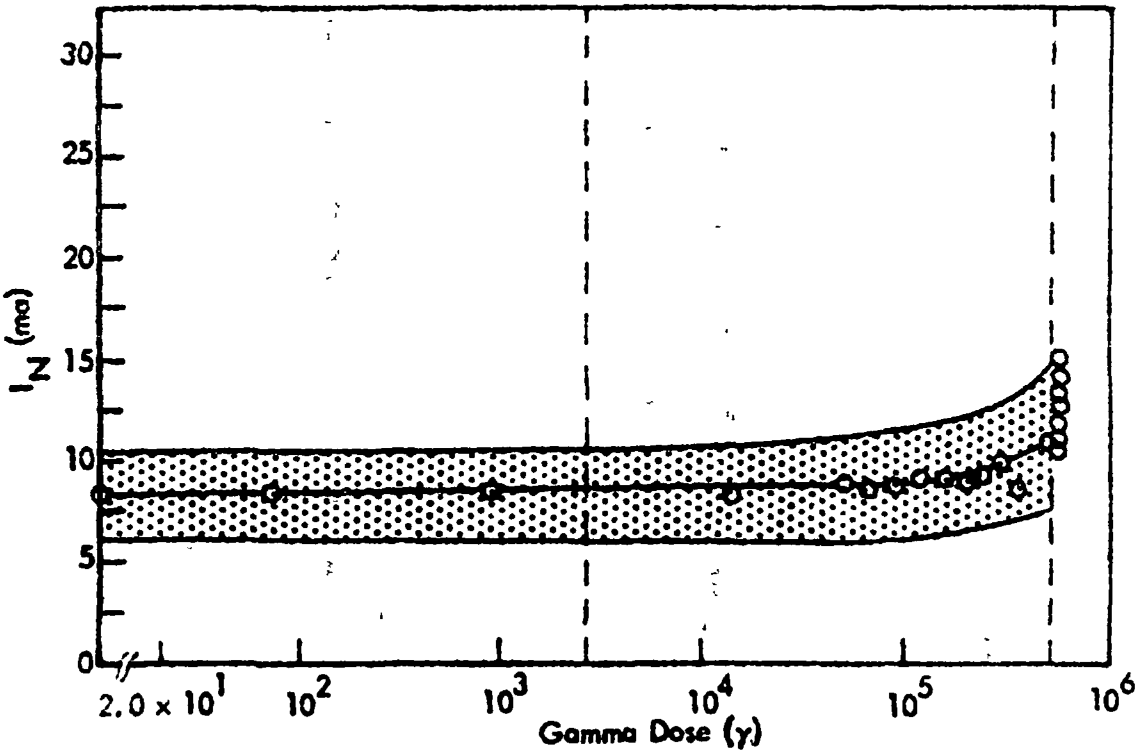


Figure 11.8 SCR 2N1774 - Holding Current (Specimens 1, 3, 4, 5, & 10) Vs. Gamma Dose (Ref. 11.77)

This poor radiation performance was further substantiated for neutron environments by Leith and Blair (11.73), December 1965. They concluded that SCR's are not well suited for use when subjected to an integrated fast neutron flux greater than 10^{13} n/cm^2.

In 1967, D. K. Wilson and H. S. Lee (11.71) conducted experiments on narrow base PNPN devices and concluded that SCR's are not only superior in performance in current switching and power handling but were more radiation resistant than bipolar transistors of comparable base widths. Table 11.2 gives the derating factors for the various structures tested and Fig. 11.9 through 11.10 show the forward "on" voltage vs. neutron fluence at two current levels. Fig. 11.11 and 11.12 show I_n and I_G, respectively. It is clear from the data of Wilson and Lee that the conventional triple diffused 2N1765 is severely damaged at 10^{13} n/cm^2 which agrees with previous investigators, whereas the narrow-based structure is relatively independent of neutron fluence at levels greater than 5×10^{14} n/cm^2. They also stated,

Table 11.2 Degradation Factors for Some SCRs

			Degradation Factor	
Parameter	Type	Base Width W_n (μ)	1×10^{13} n/cm^2	1×10^{14} n/cm^2
V_{GF}	2N1765	100	300 percent	
	35200 (WB)	50	± 10 percent	
	ZB1001 (WB)	20	± 10 percent	± 10 percent
	ZB1001 (NB)	15	± 10 percent	± 10 percent
I_{GF}	2N1765	100	Refer to Fig. 11.	
	352001 (WB)	50		
	ZB1001 (WB)	20		
	ZB1001 (NB)	15		
I_n	2N1765	100	Refer to Fig. 12.	
	352001 (WB)	50		
	ZB1001 (WB)	20		
	ZB1001 (NB)	15		

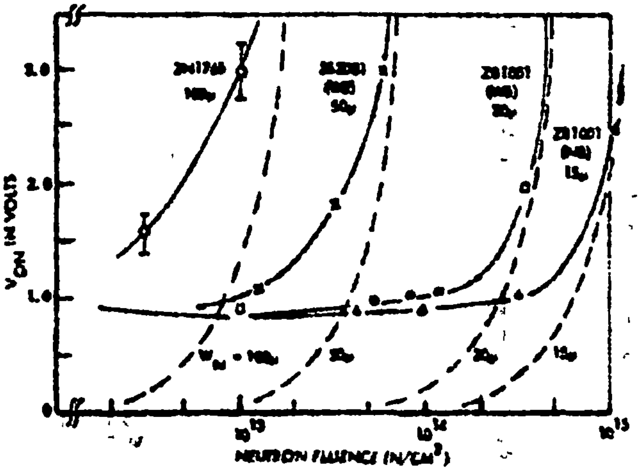


Figure 11.9 PNPN Forward "On" Voltage Versus Neutron Fluence (500 ma) (Ref. 11.71)

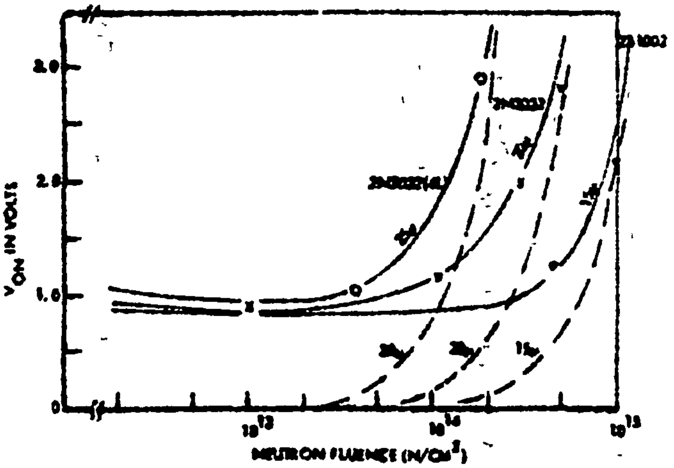


Figure 11.10 PNPN Forward Voltage Versus Neutron Fluence (100 ma) (Ref. 11.71)

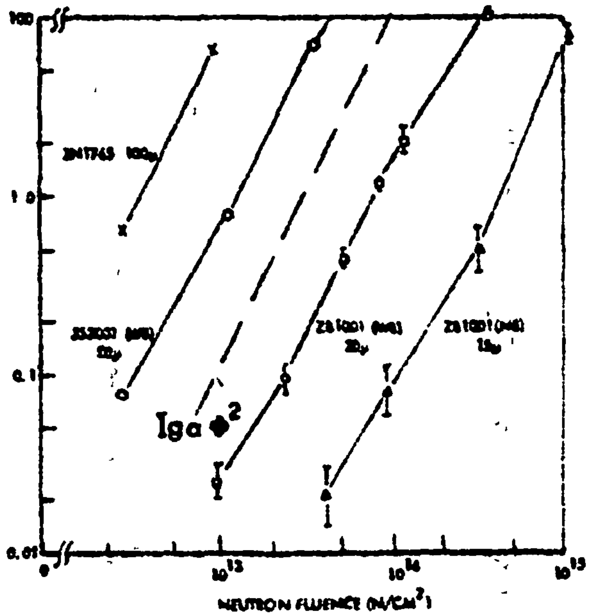


Figure 11.11 PNPN Gate Currents Versus Neutron Fluence (Ref. 11.71)

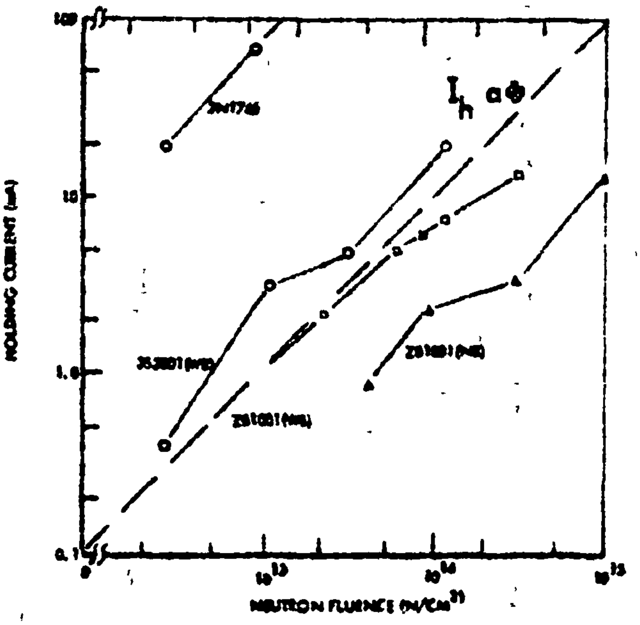


Figure 11.12 PNPN Holding Current Versus Neutron Fluence (Rgk = ∞) (Ref. 11.71)

for the narrow-base device, that it would be insensitive to transient ionization at dose rates greater than 10^9 rad/sec if the initial lifetime degraded to 3×10^{-10} sec. This value is apparently a design calculation since no experimental data were given by them to substantiate the estimate.

Following the work of Lee and Wilson on neutrons, A. G. Stanley (11.12) reported on bulk damage and ionization effects from electrons and the results are given in Table 11.4 and 11.5. Degradation factors could not be calculated from the data due to insufficient information. Bulk damage effects were assumed to predominate at a total electron dose of 5×10^{14} e/cm^2.

G. D. Smith (11.78) 1966 reported on PNPN devices using Cobalt 60 gamma radiation. The results of these tests and the degradation factors for the 2N688 are given in Fig. 11.13 through 11.17 and Table 11.3. C. W. Gwyn (11.5) reported on narrow base PNPN structures with a cathode-base region of 1.6μ width and an anode-base width of 10.6μ. This study did not give data for determining degradation factors, but showed that a rectangular radiation pulse with a peak dose rate or 6.4×10^8 rad(Si)/sec at 10 n.s. pulse width or a neutron exposure of 5×10^{13} n/cm^2 is required for device turn-on. Measel (11.76) also reported, using a Co-60 source, that turn-on was observed at doses of less than 10^3 rad if the devices were under operating bias during irradiation. Again, no factors could be calculated, but the results are shown in Table 11.6.

Table 11.3 Degradation Factors For SCR 2N688

Parameter	Degradation Factor	
	Percent/meg. rad	2×10^5 R
V_{GT}	+ 4.1	+ 5 - 8 percent
I_{GT}	+ 5	+ 10 percent
I_h	+ 6	+ 14 percent
I_{FWD}	330 percent	> 300 percent
I_R	220 percent	—

Table 11.4 Forward Voltage Drop at 4A (Ref. 11.72)

Unit	Irradiation Conditions		Before (volts)	After (volts)
	Bias $R_{GK} = 1\ k\Omega$	Total Dose (e/cm^2)		
632	$V_A = 20$ V, off	1.0×10^{13}	1.5	1.58
635	$V_A = -20$V, off	4.95×10^{13}	1.56	1.58
633	$V_A = 20$ V, off	1.0×10^{14}	1.66	1.66
639	$V_A = 20$ V, on	1.0×10^{14}	1.71	1.70
636	$V_A = -20$ V, off	5.1×10^{14}	1.45	1.5
640	$V_A = 20$ V, on	5.1×10^{14}	1.52	1.55
634	$V_A = 20$ V, off	1.05×10^{15}	1.66	1.82
638	$V_A = -20$ V, off	1.05×10^{15}	1.76	1.86
644	$V_A = 20$ V, on	1.05×10^{15}	1.82	1.88
100	$V_A = 50$ V, off	2.0×10^{15}	1.7	2.05
101			1.8	2.85
102			1.5	2.2
103	$V_A = -50$ V, off	2.0×10^{15}	1.46	1.85
104			1.42	1.9
105			1.72	2.35

Table 11.5 Leakage Currents After Irradiation (Ref. 11.72)

Unit	Irradiation Conditions		Forward Blocking Current $V_{FX} = 50$ volts, $R_{OK} = 1\ k\Omega$		Forward Blocking Current $V_{FX} = 50$ volts, $R_{OK} = 1000$ ohms		Gate Reverse Leakage Current $V_{GR} = 6$ volts $I_{AK} = 0$	
	Bias $R_{GK} = 1\ k\Omega$	Total Dose (e/cm^2)	Before	After	Before	After	Before	After
632	$V_A = 20$ V, off	1.0×10^{13}	1.6 pA	1.3 µA	1.0 pA	7.5 nA	8.0 nA	10 nA
633		1.0×10^{14}	0.8 pA	87 nA	0.6 pA	78 nA	140 nA	178 nA
634		1.05×10^{15}						
635	$V_A = -20$ V, off	4.95×10^{13}	1.3 pA	1.55 µA	0.85 pA	127 nA	3.1 µA	3.1 µA
636		5.1×10^{14}	1.5 pA	240 nA	1.1 pA	5.8 nA	2.2 µA	2.2 µA
638		1.05×10^{15}	1.5 pA	450 nA	1.2 pA	26 nA	20 µA	20 µA
639	$V_A = +20$ V	1.0×10^{14}	1.3 pA	670 µA	1.0 pA	7.6 nA	1.5 nA	3.3 nA
640	$I_{AK_{on}} = 1.95$ mA,	5.1×10^{14}	1.5 pA	13.4 nA	0.95 pA	70 nA	20 µA	26 µA
644		1.05×10^{15}	1.4 pA	660 nA	0.9 pA	2.55 pA	5.30 pA	23.5 nA

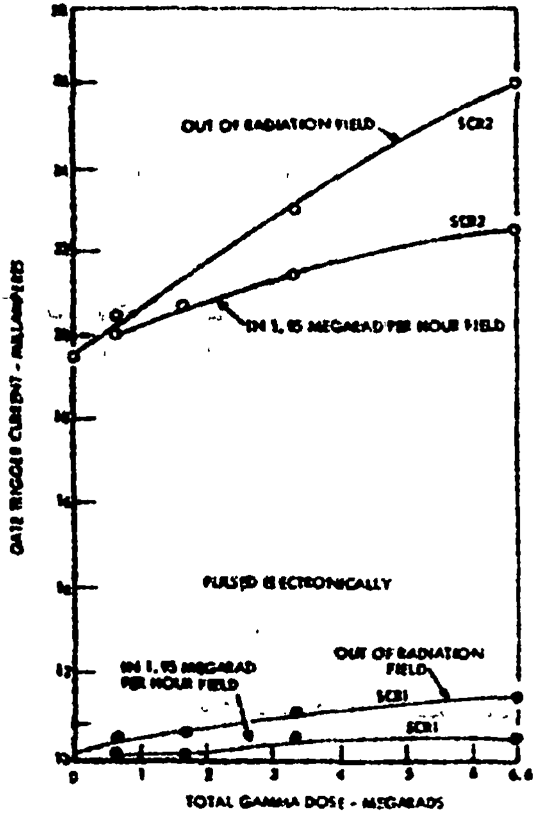


Figure 11.13 Gate Trigger Current - Milliamperes

(Ref. 11.78)

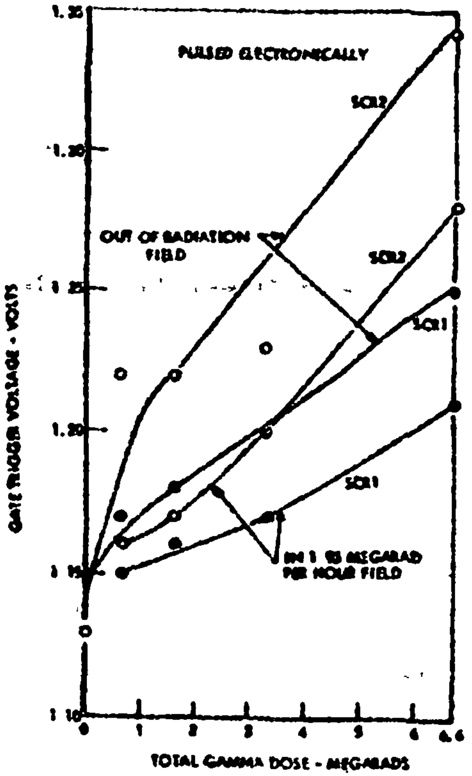


Figure 11.14 Gate Trigger Voltage - Volts

(Ref. 11.78)

- - - - 1.38 MEGARADS PER HOUR
——— 1.95 MEGARADS PER HOUR

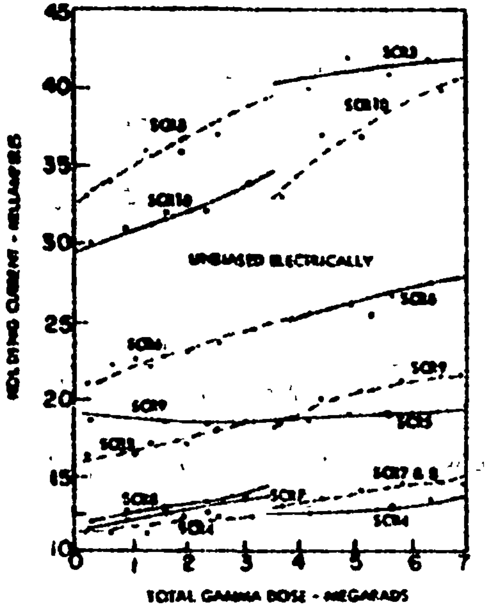


Figure 11.15
Holding Current - Milliamperes
(Ref. 11.78)

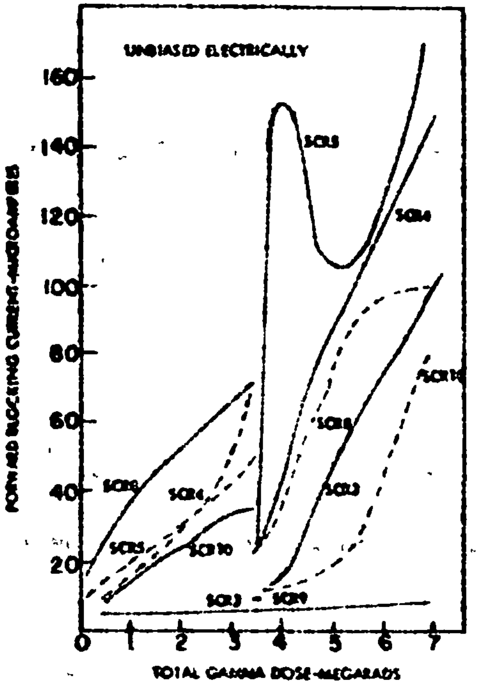


Figure 11.16
Forward Blocking Current -
Microamperes (Ref. 11.78)

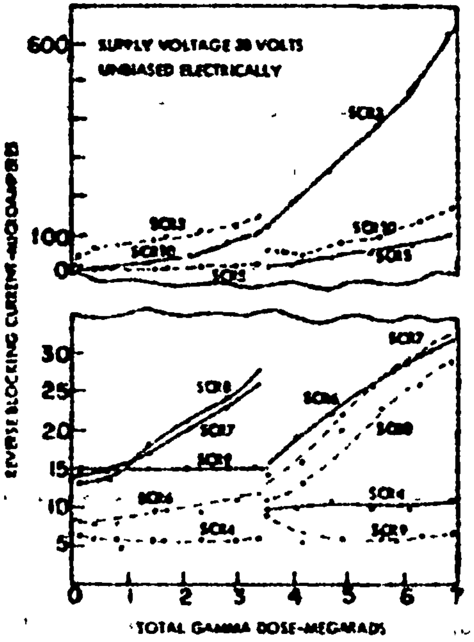


Figure 11.17
Reverse Blocking Current -
Microamperes(Ref. 11.78)

Table 11.6 2N2323 S.C.R. (Ref. 11.76)

Unit No.	V_{GT} (Volts)	Pre-Irradiation REV. Blocking I I_{RO} (amps)	Pre-Irradiation FWD Blocking I I_{FO} (amps)	I_{RGO} (amps)	Fired in Field
1	.5	2.2×10^{-9}	5.6×10^{-9}	4.4×10^{-6}	---
2	.60	8.2×10^{-9}	2.3×10^{-8}	6.6×10^{-10}	---
3	.545	4.4×10^{-9}	5.0×10^{-9}	1.5×10^{-9}	---
4	.55	1.6×10^{-9}	7.0×10^{-9}	3.2×10^{-10}	---
5	.6	2.0×10^{-9}	2.2×10^{-8}	4.0×10^{-10}	---
		10^4 rad			
1	.5	2.5×10^{-9}	6.4×10^{-8}	5.8×10^{-6}	yes
2	.55	1.1×10^{-8}	1.0×10^{-8}	1.0×10^{-9}	no
3	.55	5.9×10^{-9}	9.2×10^{-6}	2.2×10^{-9}	yes
4	.55	2.1×10^{-9}	1.1×10^{-7}	1.3×10^{-9}	yes
5	.56	2.5×10^{-9}	9.5×10^{-8}	6.0×10^{-10}	no
		4×10^5 rad			
1	.5	3.4×10^{-9}	2.2×10^{-4}	6.2×10^{-6}	no
2	.56	7.7×10^{-9}	1.8×10^{-4}	3.0×10^{-9}	no
3	.55	7.5×10^{-9}	2.0×10^{-4}	2.3×10^{-9}	yes
4	.58	2.5×10^{-9}	3.0×10^{-4}	1.3×10^{-9}	yes
5	.56	3.8×10^{-9}	1.0×10^{-5}	2.2×10^{-9}	yes

11.4 Radiation Hardening

It has been pointed out that narrow base PNPN or P^+ NIPN$^+$ devices may be more radiation resistant than previously reported for conventional devices. Further, by decreasing the base region lifetime, applying a negative gate bias during irradiation, decreasing the impedance between cathode and gate, or by decreasing anode bias one may achieve some improvement in circuit hardening. However, it is concluded that silicon controlled rectifiers should not be used in a radiation environment where gamma radiation approaches 10^3 rad(Si) or the neutron fluences is greater than 5×10^{13} n/cm^2.

11.5 Recommended Testing

It is recommended that SCR devices not be used in significant radiation environments, however, if any PNPN devices are to be considered for circuit application, it is recommended that each type to be used be tested. SCR's are sensitive to all components of the TOPS environment and the combined effects from proton damage has not been investigated. It should also be noted that the devices should be tested while under electrical bias.

11.6 Screening

There have been no screening techniques suggested in the literature.

11.7 References

11.71 Wilson, D. K., Lee, H. S., "Permanent Radiation Damage Effects in Narrow-Base PNPN Devices", IEEE Trans. on Nuclear Science, Vol. NS-14, Oct. 1967, p. 15-32.

11.72 Stanley, A., - "Effect of Electron Irradiation on Electron Devices", AD 489-617, Nov. 1965.

11.73 Leith, F. A., and Blair, - "Study of the Effects of Fast Neutrons on Silicon Controlled Rectifiers", IEEE Trans. on Nuclear Science, Vol. NS-12 (Dec. 1965).

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11.75 C. W. Gwyn, - "An Analysis of Ionizing Radiation Effects in Four-Layer Semiconductor Devices", IEEE Trans. on Nuclear Science, NS-16, Dec. 1969.

11.76 P. R. Measel, "Total Gamma Dose Effects on Several Types of Semiconductor Devices", The Boeing Co. Memorandum 2-7911-00-882, Aug. 1968.

11.77 "Components Irradiation Test No. 1, Transistors and SCR's", NASA-CR-56575, ER-6785, N65-16805.

11.78 Smith, Gail. D. - "Performance of SCR in Radiation Environment", IEEE Annual Conf. on Nuclear and Space Radiation Effects, Palto Alto, Calif., July 18-21, 1966; IEEE on Nuc. Sci., Vol. NS-13, Dec. 1966.

12.0 MICROCIRCUITS

12.10 Permanent Parameter Degradations

Integrated circuits differ from discrete component circuits (for junction isolated devices) due to the presence of parasitic components such as substrate transistors and diodes and increased capacitance to ground. While these differences can have a dramatic effect on the transient response of the circuit to high dose rate ionizing radiation environments, they appear to have no significant effect on the permanent degradation of the circuit parameters due to low level steady state environments.

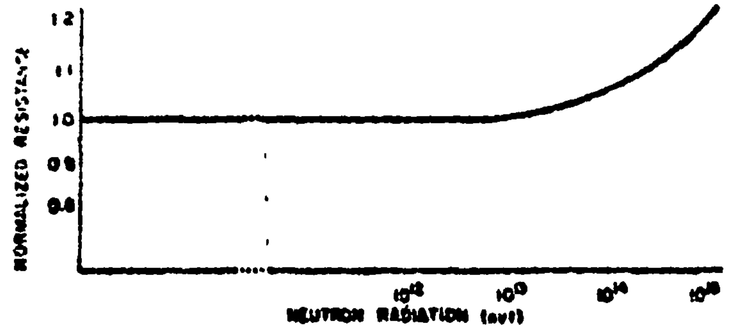
The parameters most adversely affected by permanent degradation are circuit gain, changes in bias currents, output voltage swing capability, and changes in voltage offsets for linear circuits. In logic circuits the transistor gain degradation results in a degraded fan out capability and changes in propogation delay times, while the increased leakage currents can modify the fan in capability for some type of circuits (i.e., ECL). The environment levels at which these circuit parameters become significantly affected are a strong function of the environment (i.e., particle and energy spectrum) and the circuit design (i.e., linear, logic, degree of feedback, transistor gains, etc.).

12.11 Neutron Effects

The primary damage mechanism of neutrons in microcircuits is atomic displacement damage. For low-level steady state radiation the effects on circuit components are no different than the effects on discrete components already discussed. Therefore, the designer is referred to the preceding sections on discrete components for active elements. The discussion here will be limited to effects on semiconductor resistors and capacitors.

Integrated resistors formed by diffusing a strip of p-material into an n-type epitaxial layer show increases in resistance with increasing neutron fluence. The percentage of change for a given fluence is dependent on the initial impurity concentration. Low value resistors (higher impurity levels) are less affected by neutron irradiations. Figure 12.1 shows a typical degradation curve for silicon resistors. Normally, the change for ~ 10^{15} n/cm^2 is less than the initial tolerance on the resistors (± 20 percent). Further in the case of bias networks where resistance ratios are of interest, the ratios tend to stay approximately constant if the resistors involved have comparable initial impurity levels.

Integrated capacitors may be formed by back biasing a diode. For back biased diodes, since both n and p-type materials tend towards the electrical properties of intrinsic material, the capacitance decreases. As in the case of resistors, the decrease in capacitance is usually less than the original device tolerance at about 10^{15} n/cm^2.



1 Integrated resistors increase in value under radiation, because the p-type material tends to change its behavior toward that of the intrinsic semiconductor. The percentage increase depends on the amount of radiation received and the original impurity concentration.

Figure 12.1 Typical Semiconductor Resistor Degradation (Ref. 12.71)

12.20 Proton Effects

As stated earlier in discrete component sections, proton effects should produce displacement damage similar to neutron damage with additional ionization dose due to the positive charge of the proton.

The protons are more efficient for producing displacements than neutrons. The equivalences for producing displacements that have been established (12.72) are: 1 (100 MeV) Proton ≃ 8 Neutrons (fission) and 1 (8-17 MeV) Proton ≃ 33 Neutrons (fission). The ionization dose associated with the protons would produce surface effects similar to those for transistors (i.e., increased junction leakage currents and decreased transistor gains).

12.13 Gamma Effects

The effects of gamma radiation on microcircuit elements are essentially the same as those on discrete components described in previous sections. Some workers have suggested that microcircuits are less susceptible to surface effects (12.73) than discrete components although it is not clear that this is generally true.

12.20 Temporary Parameter Degradation

For high level burst type environments short term annealing occurs. Short term annealing data is very limited for integrated circuits. There is some data for the neutron environment which indicates annealing factors as high as two exist for times shorter than a millisecond. The data indicate the similarity between circuit and transistor annealing factors. However, for low intensity, steady-state environments there is no evidence of annealing or drift other than the permanent degradation discussed earlier except that some parameters of linear circuits vary as a function of fluence. This effect is discussed in Section 12.30.

12.30 Parameter Degradation Factors

Due to the many variations in circuits found in I. C.'s, it is not very practical to try to list parameter degradation factors for each circuit type. Rather, general thresholds for broad circuit categories are presented in Table 12.2 and typical examples of data are shown in figures 12.2 through 12.15 and Tables 12.1 through 12.6. A general summary of thresholds of damage for broad categories of circuits is presented in Table 12.1.

12.40 Radiation Hardening

Major manufacturers are currently designing "Radiation Hardened" integrated circuits. In general, the hardening is for a transient environment which includes permanent damage due to neutrons and total dose. The techniques are mostly oriented around using high gain high frequency transistors in low gain applications.

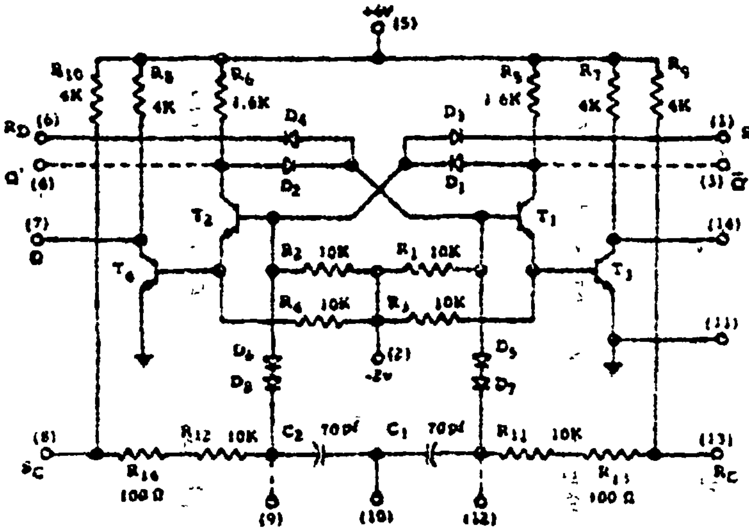


Figure 12.2 Signetics SE124 Monolithic Binary Element. (Ref. 12.73)

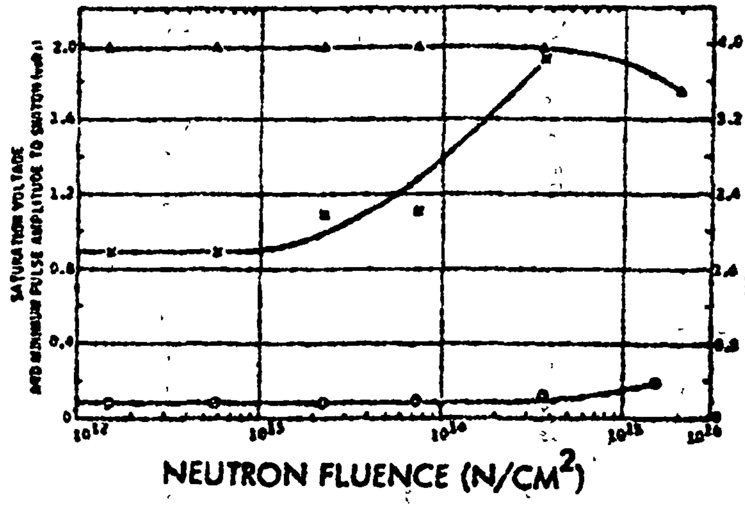


Figure 12.3 Neutron Degradation of SE124K-1 "off" Voltage, Saturation Voltage, and Minimum Pulse Amplitude to Switch Q Output. (Ref. 12.73)

currents and decreased transistor gains).

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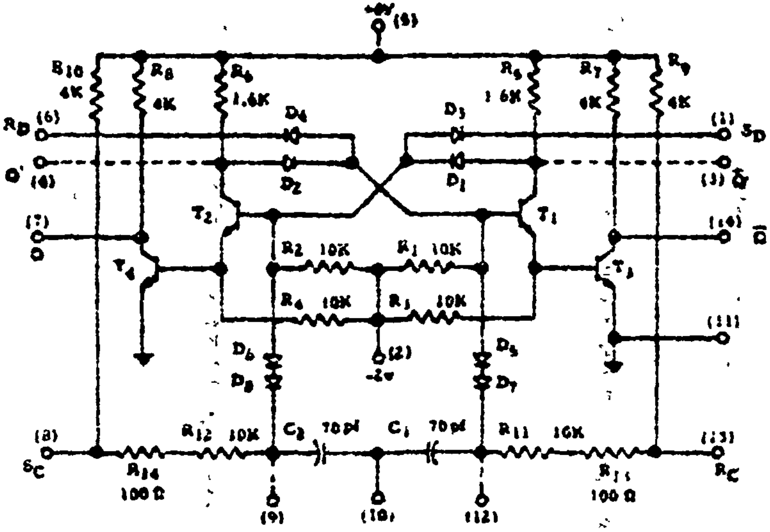


Figure 12.2 Signetics SE124 Monolithic Binary Element. (Ref. 12.73)

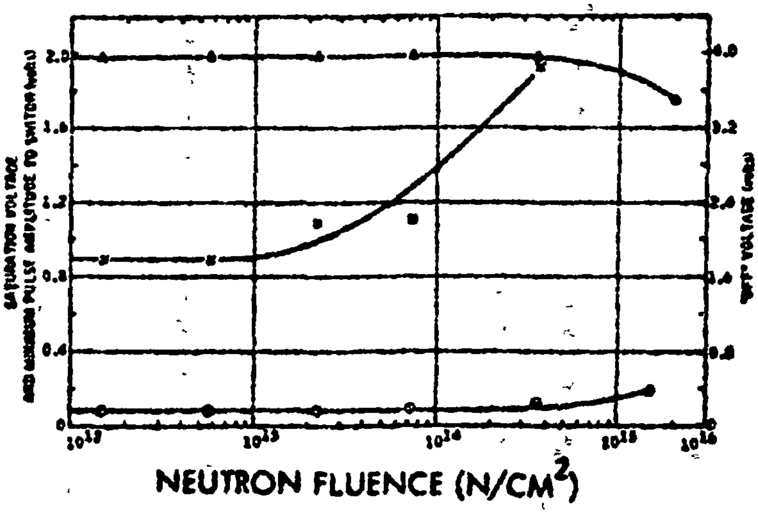
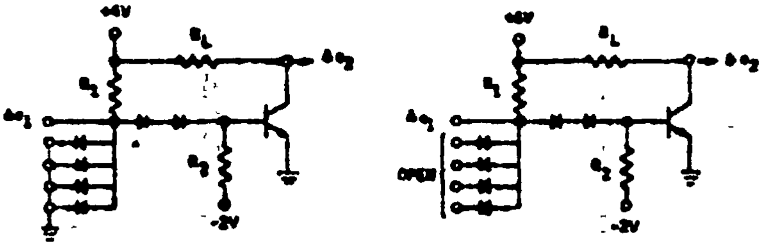
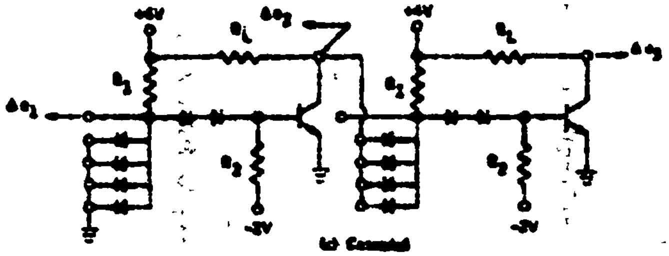


Figure 12.3 Neutron Degradation of SE124K-1 "off" Voltage, Saturation Voltage, and Minimum Pulse Amplitude to Switch Q Output. (Ref. 12.73)



(a) Inputs Grounded

(b) Inputs Open



(c) Cascaded

Figure 12.4 MC201 Test Circuit Configuration. (Ref. 12.73)

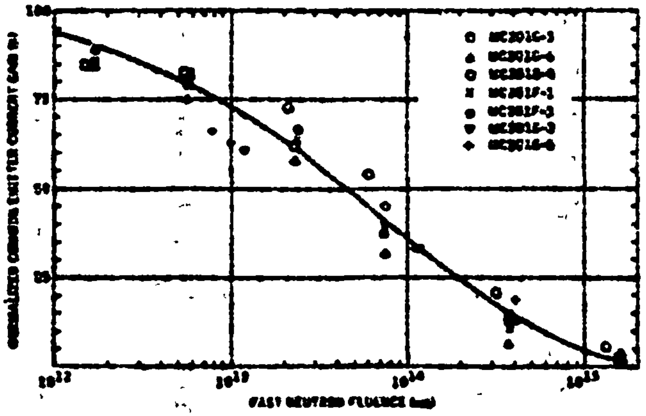


Figure 12.5 MC201 Transistor Current Gain Degradation. (Ref. 12.73)

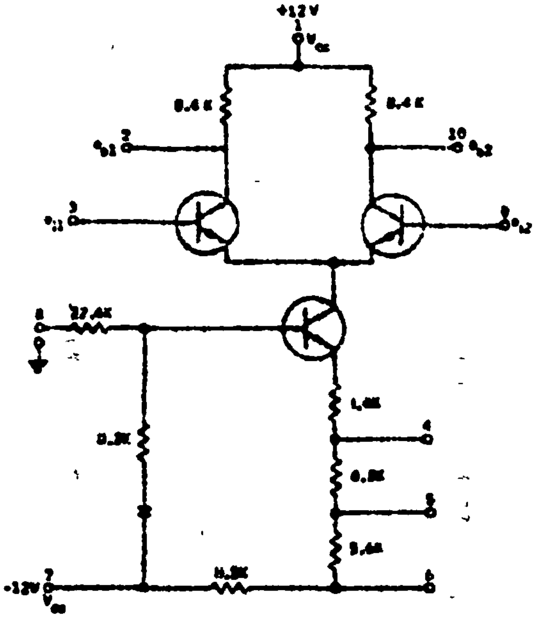


Figure 12.6 MC1525 Monolithic Differential Amplifier (Ref. 12.73)

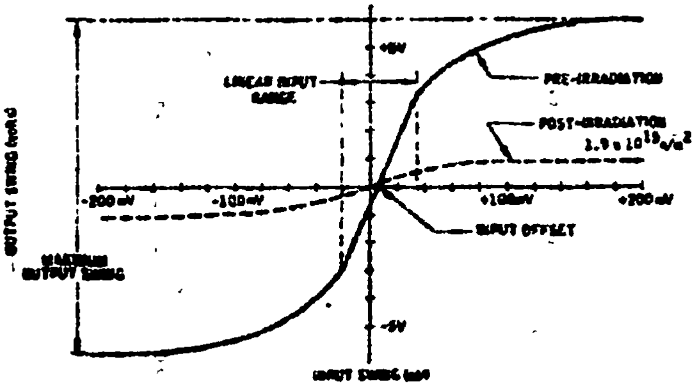


Figure 12.7 MC1525 Typical Transfer Characteristics (Ref. 12.73)

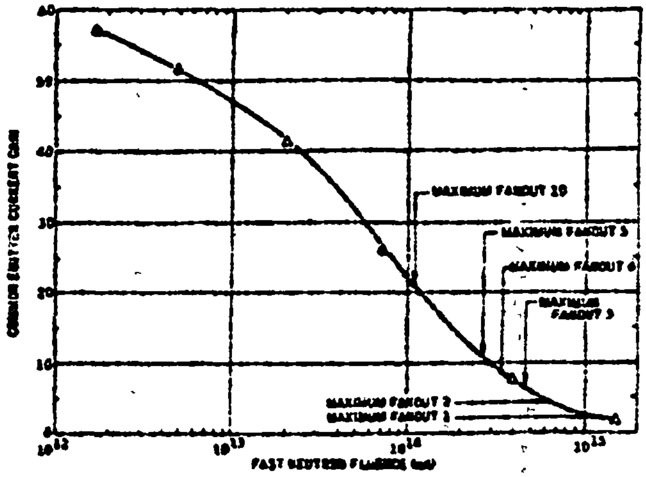


Figure 12.8 MC201 Monolithic DTL Gate Circuit Vulnerability (Ref. 12.73).

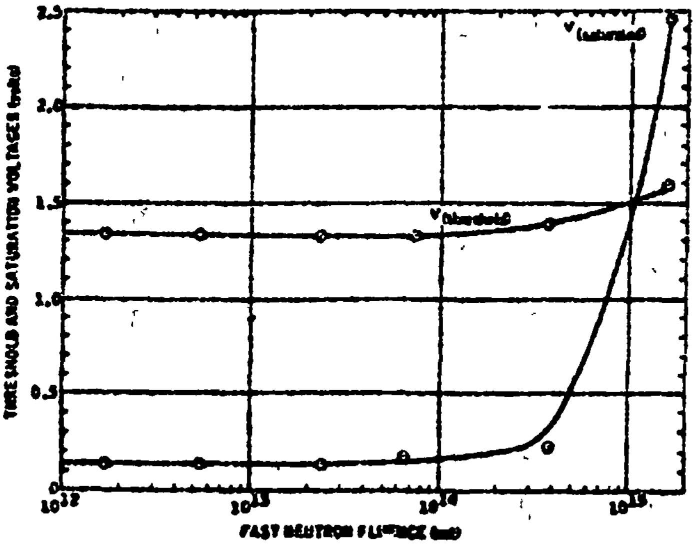


Figure 12.9 Neutron Degradation of MC201-3 Threshold and Saturation Voltages. (Ref. 12.73)

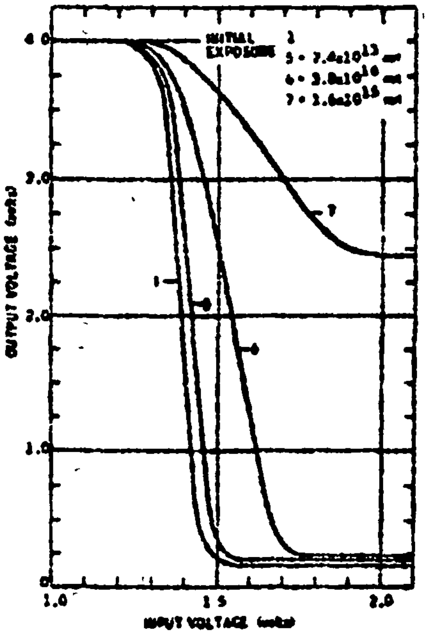


Figure 12.10 Neutron Degradation of MC201F-3 Transfer Function. (Ref. 12.73)

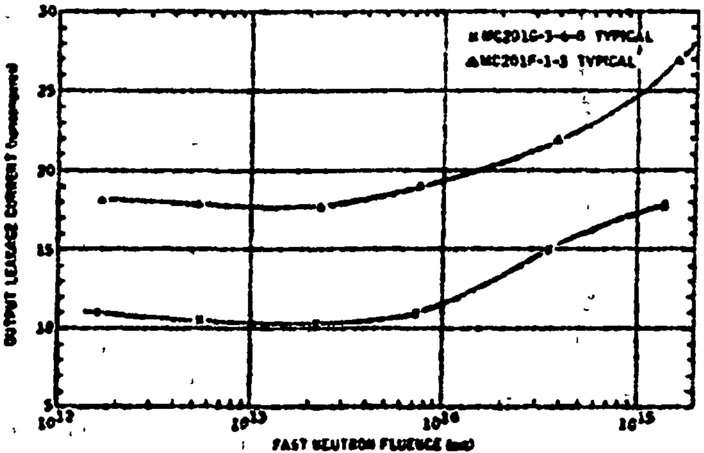


Figure 12.11 Neutron Degradation of MC201 Output Leakage Current. (Ref. 12.73)

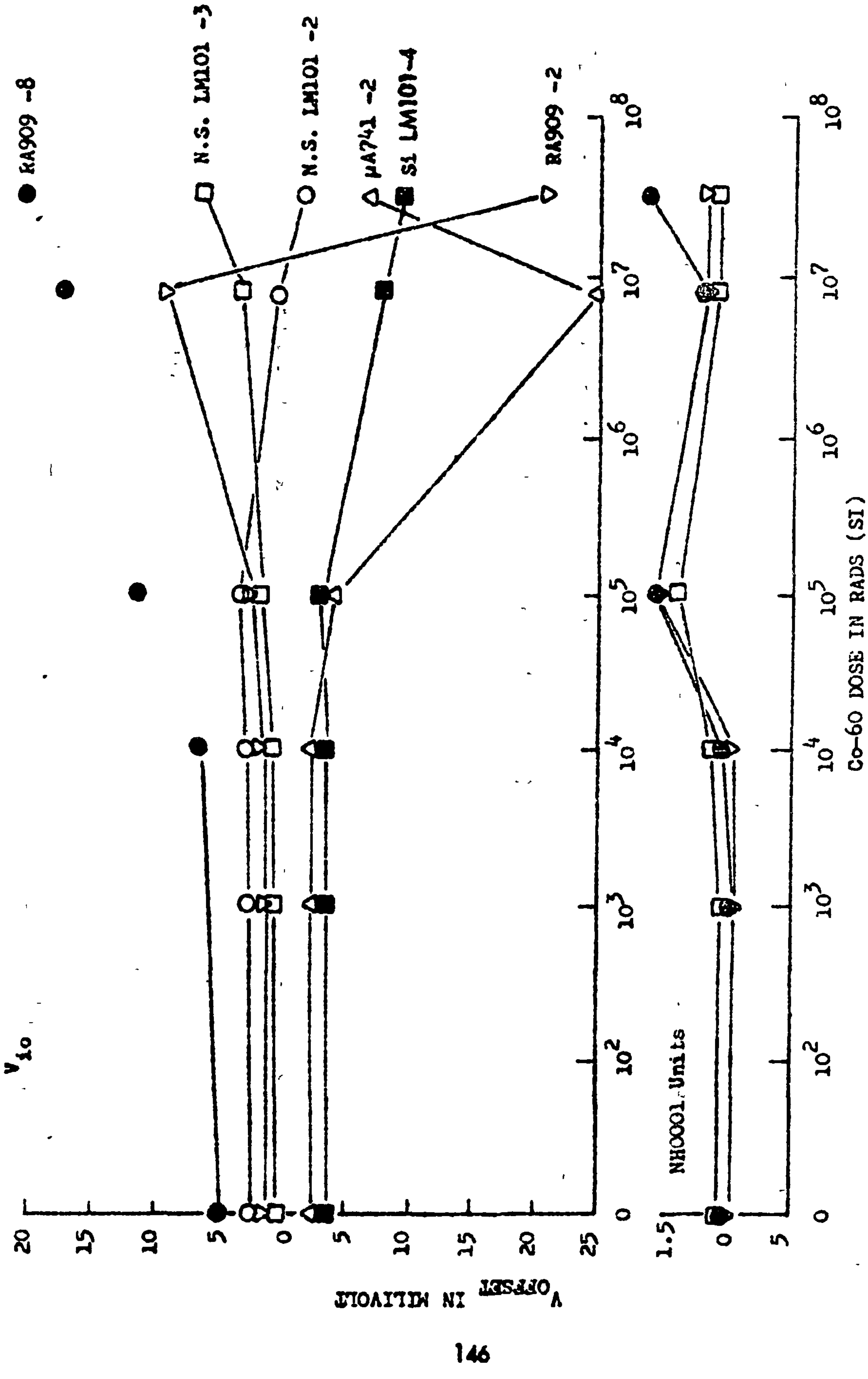


Figure 12.12 Illustrative V_{OFFSET} Variations Versus Co-60 Dose. (Ref. 12.76)

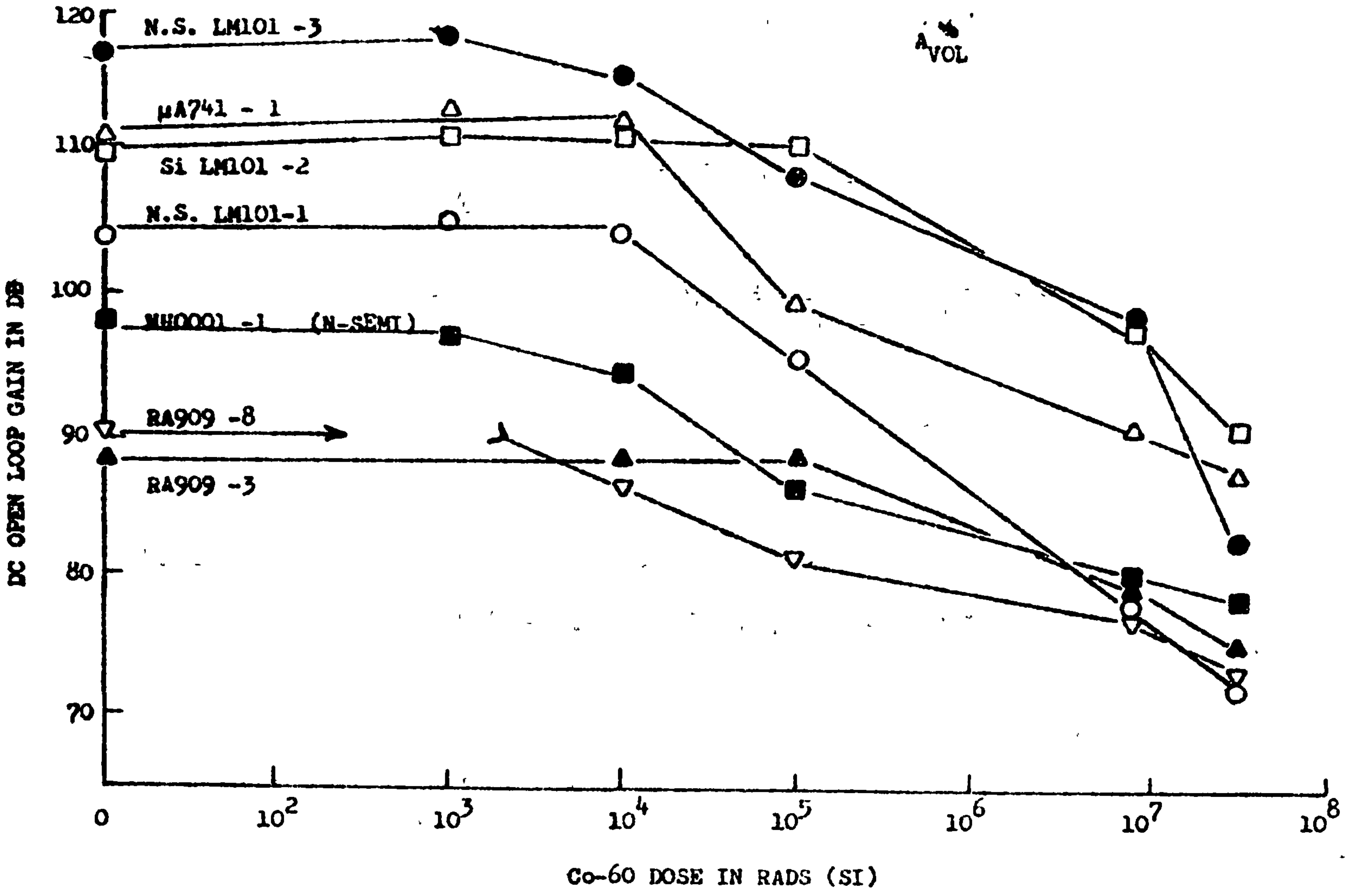


FIGURE 12.13 Illustrative Gain Degradation Versus Co-60 Dose. (Ref. 12.76)

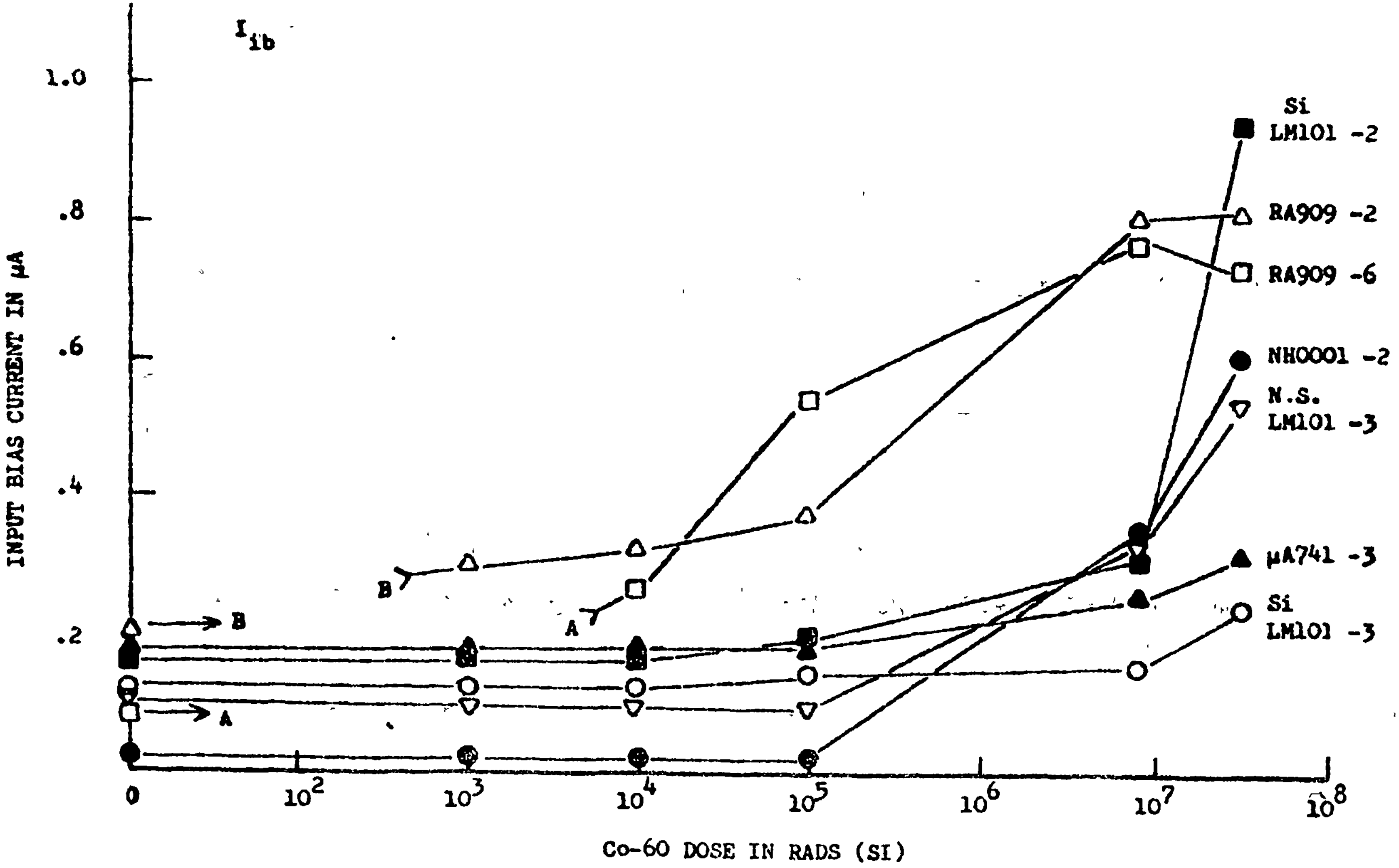


Figure 12.14 Illustrative Input Bias Current Variations Versus Co-60 Dose. (Ref. 12.76)

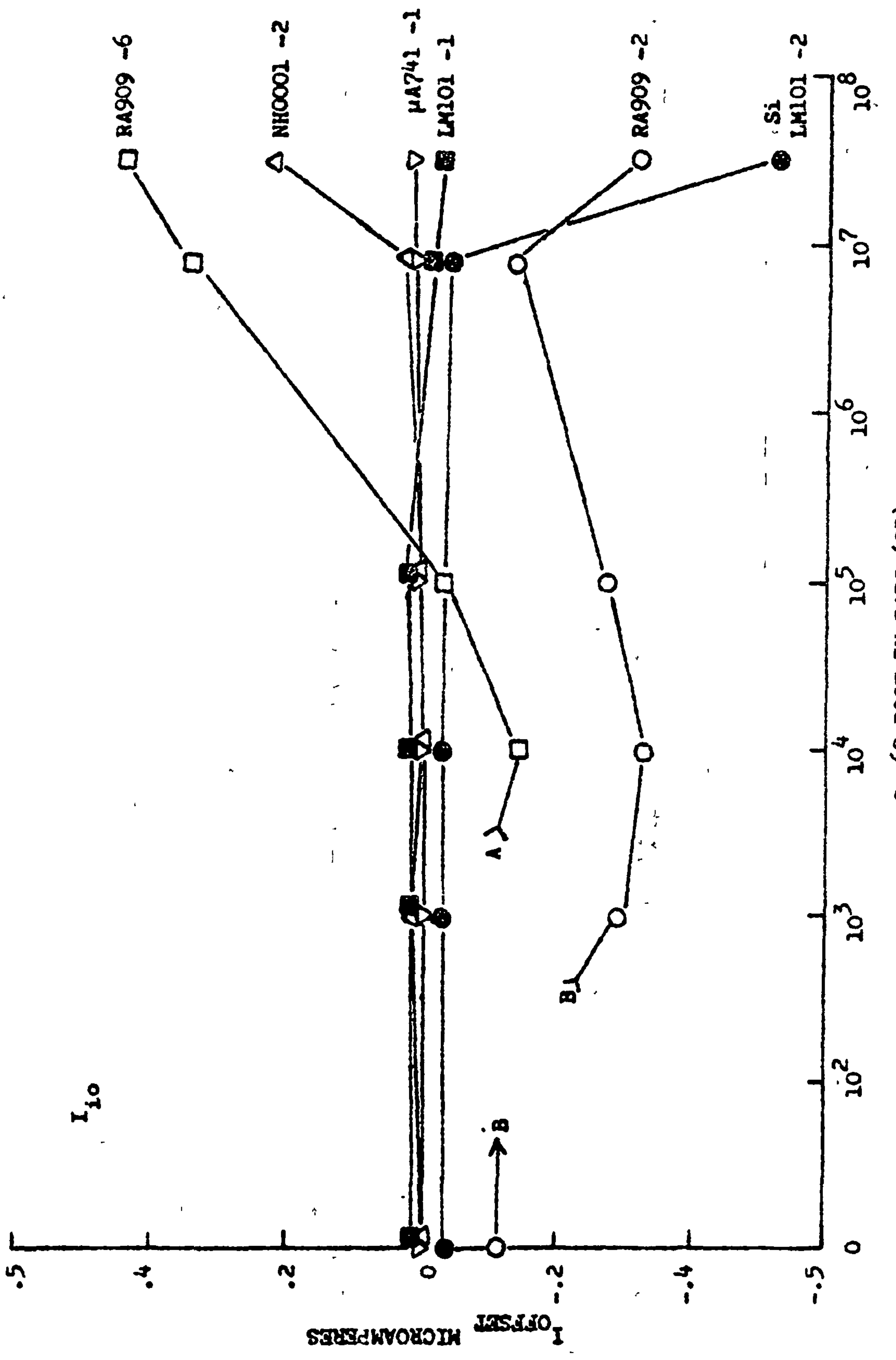


Figure 12.15 Illustrative I_{OFFSET} Variations Versus Co-60 Dose. (Ref. 12.76)

Table 12.1 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 at Boeing has indicated that Digital MOS circuitry can survive $> 10^6$ rad(Si) and other workers (12.74) have indicated that properly designed MOS logic can survive $> 10^7$ rads(Si).

** Estimated.

Levels of hardness due to permanent degradation are somewhat better than for normal I.C.'s. System designers should rely on data to determine the level of hardness for a given circuit type. System hardening can be achieved by using circuits in low fan out or low gain configurations.

12.50 Recommended Testing

It is recommended that test data be obtained for each integrated circuit in the environment in question.

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	ϕ
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.	ϕ
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.
ϕ = All units failed test.
-- = Data not taken or not conclusive.

12.60 Screening

Pre-irradiation and thermal annealing of circuits while still in the wafer stage has been found to be successful. Such a screening technique requires irradiation to specification levels, however, because data is not readily extrapolated to high levels with any degree of accuracy. The temperature required to anneal the circuits (400° - 500°C) are experienced in the normal packaging process. The effects of irradiation on normal reliability for this screening procedure have not been determined. The screening procedure is currently being carried out at Motorola for neutron environments and may well be in effect elsewhere. It is thought that surface damage due to ionization would be amenable to such a screen as well as bulk damage.

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13.0 PHOTOCELLS

The photocells were light sensitive semiconductor devices with peak response in or near the visible spectrum (.4 to .75 microns). Data collected in the search were primarily on CdS, Si, and GaAs materials and/or devices. The data reported are on permanent damage effects mostly in the bulk material.

Only a brief summary from a few of the many extensive solar cell reports are cited here. For photovoltaic devices used as solar cells the main parameters of interest are the short circuit current, the efficiency, and the open circuit voltage.

In general, the parameters of interest on photocells include the effects on both electrical properties and optical properties. Electrical properties of interest include carrier concentration, resistivity, and energy (activation) levels introduced into the semiconductor. These electrical properties, and the optical properties of interest (attenuation, transmission versus wavelength) together with noise are useful in giving the usual detector parameters of interest(impedance, resistance, noise, spectral responsivity, noise equivalent power, detectivity, time constant, and quantum efficiency).

13.10 Permanent Parameter Degradation

13.11 Neutron Effects

For n-type cadmium sulfide material thermal neutron irradiations at 30° C introduced acceptors (13.71) thought to be due to preferential displacement of S atoms over Cd atoms. Table 13.1 shows radiation damage introduction rates (centers introduced per incident particle) (13.71). Figure 13.1 shows the effect of thermal neutrons on carrier concentration.

Fast neutrons (13.72) give rise to a continuous optical absorption spectrum for wavelengths beyond the fundamental absorption edge, with the absorption increasing as the inverse square of the wavelength. Figure 13.2 shows the percent transmission versus photon energy (wavelength in microns is given by 1.24/photon energy in eV). Some annealing (after 3 months at room temperature) is evident.

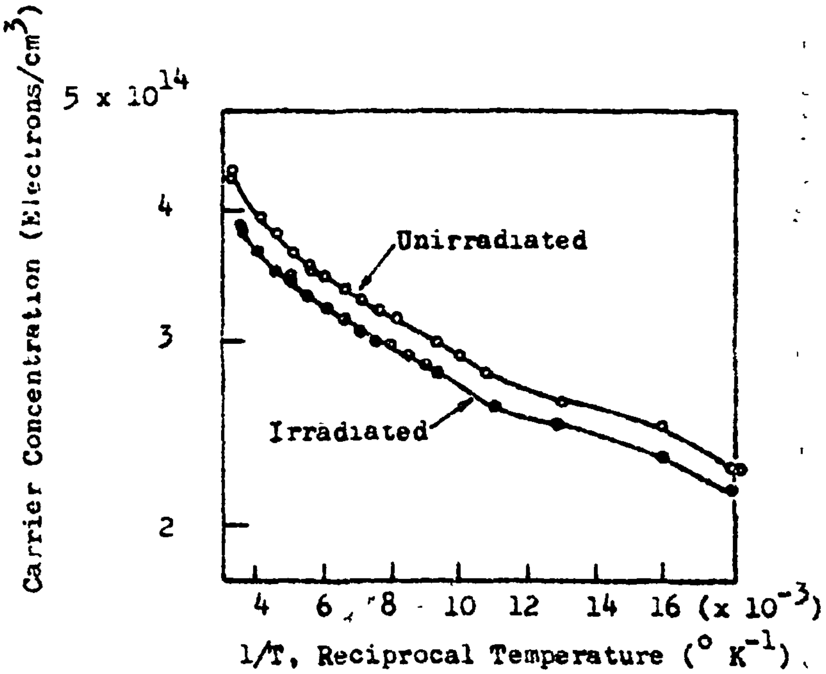

Figure 13.1 Cadmium Sulfide Irradiated with 2.8 x 10^{12} Thermal Neutrons/cm^2 (Ref. 13.71)

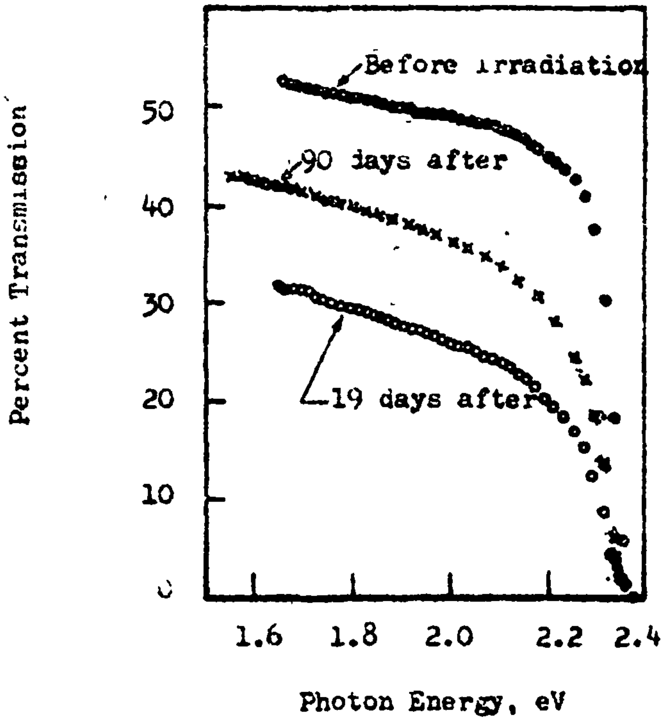

Figure 13.2 Effect of Fast-Neutron Irradiation on Optical Transmission of Cd S ($\Phi = 1.3 \times 10^{17}$ n/cm^2) (Ref. 13.71)

This continuous absorption is attributed to a similar mechanism to that to be discussed in the case of GaAs (below), and is exhibited as a continuous radiation-induced attenuation, beyond the fundamental edge at 2.4 eV photon energy, with no evidence that discrete levels are introduced into the semiconductor. These would be evidenced by peaks in the absorption spectrum.

For silicon, two units of the Texas Instruments LS 600 npn silicon planar phototransistor were irradiated with fission neutrons at the White Sands Fast Burst Reactor. (13.73) Figure 13.3 shows the damage produced by fast neutrons in terms of decrease in the transfer ratio, T, defined as $\Delta I_{out}/\Delta I_{in}$.

Table 13.1 Radiation Damage Rates Determined From CdS Data. (13.71)

	Type of radiation and total dose		
	^{60}Co $\sim 6.0 \times 10^{8}$ rads	^{137}Cs $\sim 1.4 \times 10^{9}$ rads	Thermal neutrons 5.4×10^{16} n/cm^2
Hydrogenic donor (0.049 eV)			
Damage rate[a]	$15.0(\pm 3.0) \times 10^{-4}$	$0.2(\pm 0.1) \times 10^{-4}$	$20.0(\pm 200.0) \times 10^{-4}$
Center density[b]	3.2×10^{16}	0.79×10^{16}	12.3×10^{16}
Acceptors			
Damage rate	$3.0(\pm 4.0) \times 10^{-4}$	$0.5(\pm 0.1) \times 10^{-4}$	$480.0(\pm 10.0) \times 10^{-4}$
Center density	0.023×10^{16}	0.22×10^{16}	0.52×10^{16}
0.11 eV level			
Damage rate	$4.0(\pm 2.0) \times 10^{-4}$	$0.5(\pm 0.1) \times 10^{-4}$	$-140.0(\pm 240.0) \times 10^{-4}$
Center density	1.02×10^{16}	0.23×10^{16}	2.2×10^{16}

[a] Damage rate is observed radiation-damage rate in units of centers introduced per cc per incident particle.

[b] Density of the center before irradiation.

For GaAs, specimens of either n on p type, after sufficiently heavy neutron irradiation, (~ 10^{17} n/cm^2, or to where carrier concentration is reduced below 10^{14}/cm^3) are characterized by the following properties: (a) a very low carrier density (semi-insulating), (b) anomalously low Hall mobility, (c) anomalously steep temperature dependence of Hall mobility, (d) photoconductivity with a very long recovery time (hours or days), (e) instability and sensitivity to ambient temperature (13.72). All of these observations point to the presence of slow surface states which may considerably modify the bulk properties.

Carrier removal rate is 4 to 8 electrons/cm of path for an n-type sample with 10^{17} carriers/cm^3 initially. Annealing of conductivity change begins at 220°C with a second stage at 550° C and a final anneal between 600 and 700°C.

Optical attenuation beyond the fundamental absorption edge in GaAs is surprisingly large after fast neutron irradiation (Fig. 13.4). The attenuation coefficient increases as λ^{-2} and is proportional to the integrated flux when free carrier absorption can be neglected. No structure was observed in unannealed samples at room temperature or 60°K. This fact is not well understood but may be related to the damage characteristic of fast neutrons or other heavy particles,(i.e., inhomogeneous damage such as clusters or dislocation loops, etc.) since a GaAs sample heavily irradiated with electrons did not show these effects.

Even heavily neutron irradiated specimens (carrier concentration below $10^{14}/cm^3$) remained the same conductivity type. Three levels, E_c-0.1, E_c-0.5, and E_v +0.6 eV were introduced.

13.12 Proton Effects

Two thin film polycrystalline CdS p-on-n photocells were studied using 1.6 MeV protons to a total fluence of 10^{15} protons/cm^2. The short circuit current of cell 1 was reduced 33 percent while that of cell 2 was down 66 percent. (13.74)

Typical data for n-on-p silicon photovoltaic cells show (13.74) that at 10^{11} 1.6 MeV-protons/cm^2 the short-circuit current has dropped 33 percent. Other data (13.75) on silicon phototransistors irradiated by 30, 60, 100, and 140 MeV protons to 1 x 10^{10} protons/cm^{-2}, showed no significant changes in the important phototransistor parameters, which is consistent with the above data.

13.13 Gamma Effects

Low energy gamma irradiations (^{137}Cs, 0.662 MeV) of n-type CdS introduce acceptors by preferential displacement of sulfur atoms, while higher energy gamma irradiations ^{60}Co, 1.17 and 1.33 MeV) introduce donors by preferential displacement of cadmium. (13.71)

Figure 13.5 shows the effect of ^{60}Co gamma ray irradiations at ambient on carrier concentration. The effects of ^{137}Cs gammas are shown in Figure 13.6. Some irradiations at liquid nitrogen were made to determine whether results would

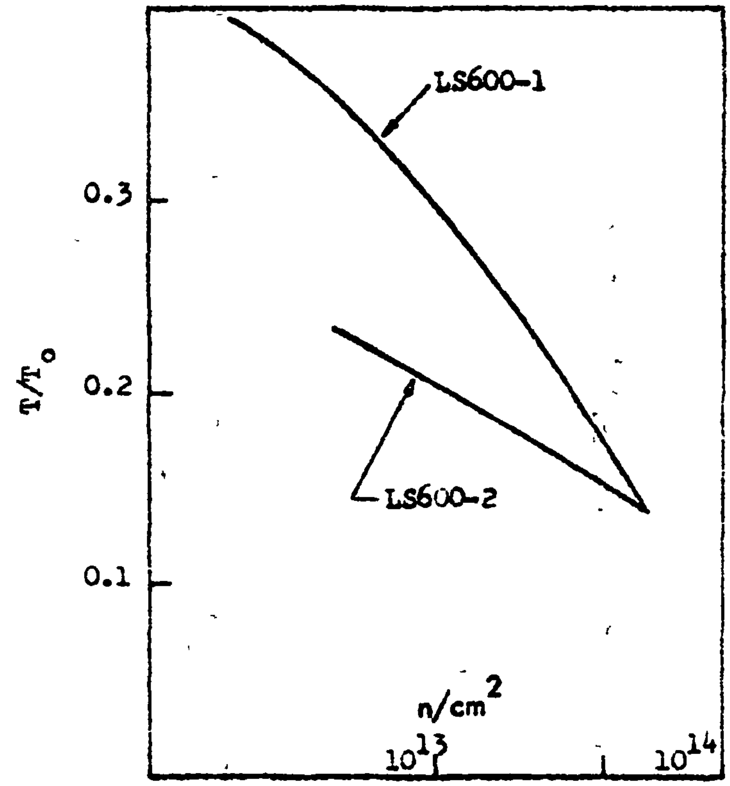

Figure 13.3 Normalized Current Transfer Ratio T/T_o vs. Neutron Fluence for LS600. (Ref. 13.73)

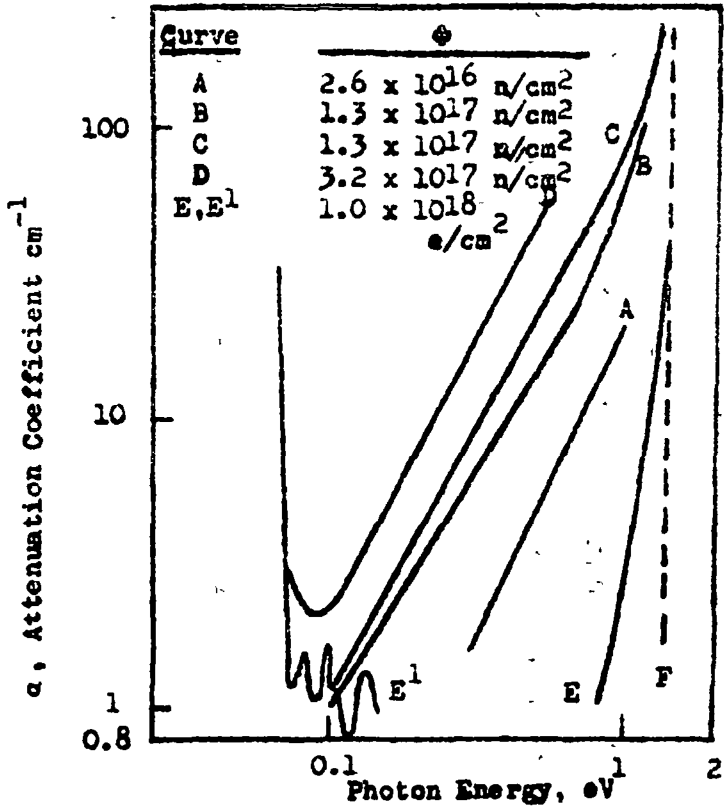

Figure 13.4 Optical Attenuation in n-type GaAs after Neutron and Electron Irradiation. (Ref. 13.72)

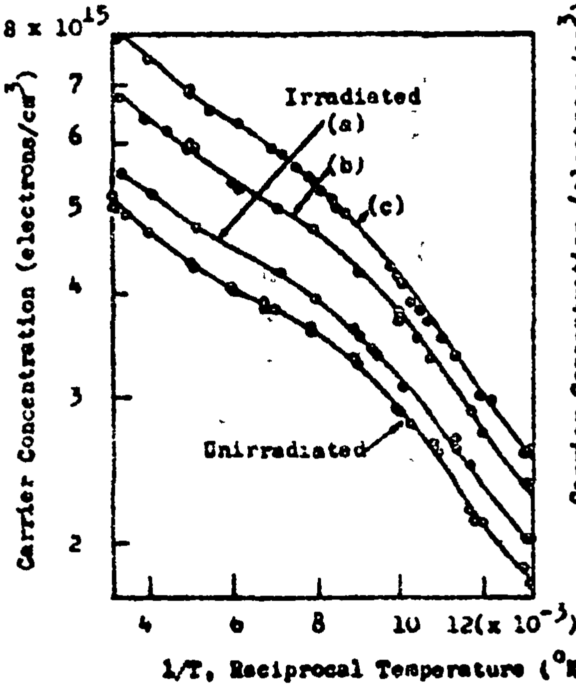

Figure 13.5 - Cadmium Sulfide Irradiated with Co-60 Gamma Radiation Curve -
(a) 1.1 x 10^8 R
(b) 6.0 x 10^8 R
(c) 1.2 x 10^9 R
(Ref. 13.71)

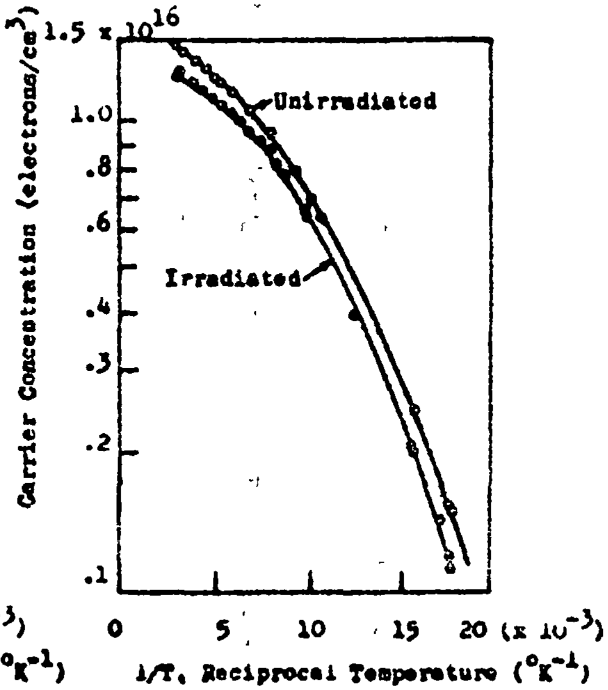

Figure 13.6 Cadmium Sulfide Irradiated with 6.6 x 10^8 R, CS-137 gamma radiation. (Ref. 13.71)

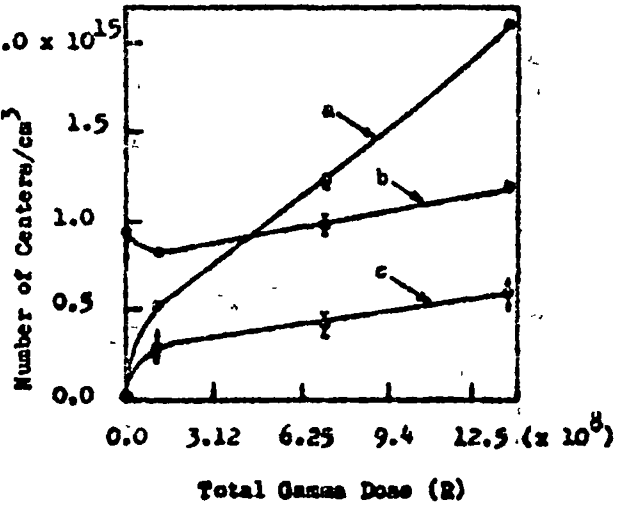

Figure 13.7 Number of Centers Introduced in Cadmium Sulfide Versus Total Gamma Dose (Co - 60) Curve
(a) hydrogenic donor
(b) total acceptor concentration
(c) 0.11 - eV level
(Ref. 13.71)

be significantly different. No differences were noted.

Damage introduction rates are shown in Table 13. 1. The rate of center introduction versus total dose is shown in Figure 13. 7 and is seen to decrease with total dose.

Data for 10 Hoffman Electronics Corp. Type 120 C silicon solar cells tested by Lockheed Missiles and Space Center (13. 76) were obtained with a ^{60}Co source. Permanent damage (in short circuit current) was noted at 8. 8 x 10^4 rad (C), and for some cells at doses as low as 8. 8 x 10^3 rad (C). On the average, the reduction in this parameter was 25 percent at 8. 8 x 10^5 and 50 percent at 8. 8 x 10^6 rad (C). The open circuit voltage was permanently affected at 8. 8 x 10^4 rad (C). On the average, it dropped 10 percent at 4. 4 x 10^6 rad (C).

13. 14 Electron Effects

The proton-irradiated cells of 2 above were also irradiated with 0. 8 MeV electrons to determine efficiency degradation. It was found that the efficiency of cell 1, initially less than 1 percent, was degraded 11 percent by 9. 7 x 10^{15} electrons/cm^2, and cell 2, initially 3. 4 percent was degraded 39 percent by 8. 8 x 10^{16} electrons/cm^2.

In another study (13. 77) CdS was irradiated by electrons to determine the mechanisms involved in producing fluorescence. It was found that the threshold for displacement of a sulfur atom in CdS from a lattice point is 8. 7 eV, but requires electrons (perpendicular to the C axis of the material) of at least 115 keV. This is also the threshold for production of the well known green edge emission centers responsible for photoluminescence (fluorescence excited by ultraviolet) at liquid nitrogen with peaks at 5140, 5225 and 5310A, and for production of the red fluorescence band centered at 7200A. In crystals which show (green) edge emission before bombardment this is removed by electrons in the energy range available for use in the reference (2. 5-200 keV). The red fluorescence was, however, not removed by this electron irradiation but increased in intensity with bombardment above the threshold.

Green edge-emission has been produced in CdS whiskers (single crystals) by 130 KeV electrons from 40 μA-hr/cm^2 to 160 μA-hr/cm^2, at which total electron fluence it disappeared. At 120 keV and 240 μA-hr/cm^2 red fluorescence was produced; the intensity of this increased with bombardment.

The model proposed to account for the various effects observed assumes that an interstitial sulfur atom is the responsible center for edge emission and a sulfur vacancy is the center for the red fluorescence. The threshold for the production of vacancy-interstitial pairs of sulfur atoms in CdS by electron irradiation is 115 ± 5 keV corresponding to a maximum energy transfer of 8.7 eV. The sulfur interstitial exists as a negatively charged ion at room temperature in these crystals. It is proposed that another electron could be bound to the sulfur interstitial at liquid nitrogen and that the recombination of a free hole with the second electron trapped at this center would result in edge emission.

A very extensive study was made of permanent damage effects of electrons on silicon n-on-p photovoltaic cells using electron energies in the 0.5 to 7 MeV range. (13.78) The main effect appeared to be a decrease in the base diffusion length brought about by a decrease in the p-type base lifetime. A reduction in short circuit current of 25 percent was arbitrarily used as a criterion to establish a critical electron fluence, Φ_K. The change in reciprocal lifetime with fluence and of short circuit current with fluence were obtained for various electron energies (Fig. 13.8). From this the dependence of damage constant ($K' = \Delta \frac{1}{\tau} / \Delta \Phi$) and Φ_K on electron energy was obtained and fitted to two different models (Figure 13.9). The model that has the much better fit to the data (solid curve) attribures the electron damage to bound pairs of primary defects rather than to individual defects. This model allows predictions of damage to be made.

The data of Figure 13.8 (b) indicate that the short circuit degradation "threshold" is between 10^{10} and 10^{11} for all three energies considered (1, 2, and 4.9 MeV) with the damage increasing with electron energy. The original base resistivity of 1 ohm-cm corresponds to an acceptor concentration of 2 x 10^{16} atoms per cm^3. The initial lifetime of ~ 2 μsec was reduced by a fluence of 10^{14} electrons/cm^2 to the following values from Figure 13.8 : ~ 2 μsec (4.9 MeV), ~ .33 μsec (2 MeV), and 1 μsec (1 MeV). The threshold for electron damage in

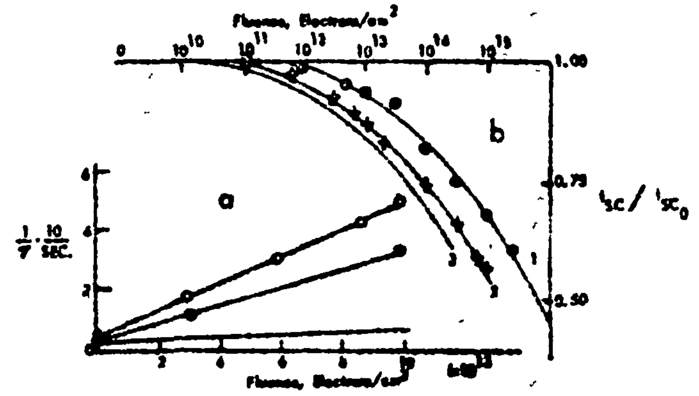

Figure 13.8 Reciprocal lifetime $1/\tau_n$ (a) and current I_{sc} (b) in silicon photocells as functions of electron fluence. Electron energy 1) 1 MeV; 2) 2 MeV; 3) 4.9 MeV. (Ref. 13.78)

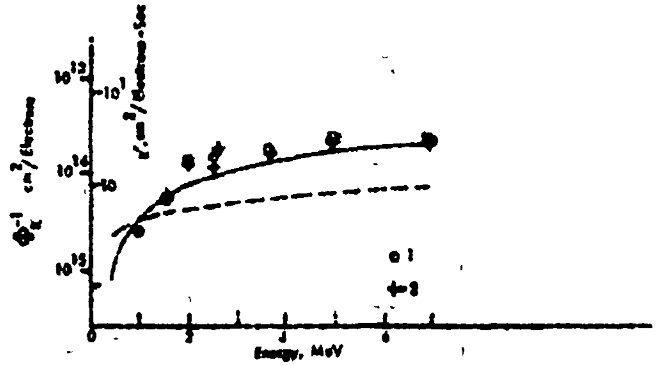

Figure 13.9 Damage coefficient (1) and reciprocal of the critical fluence (2) as functions of the bombarding electron energy E. Continuous curve shows bound defect pairs model. Dashed curve shows individual defect model. (Ref. 13.78)

p-type silicon was found to be 220 keV.

Electron irradiation effects on optical transmission have also been studied (13.79). While the reported findings were somewhat qualitative, they are worth noting. The absorption in silicon induced by 1.5 MeV electron irradiation (bands at 7.75 and 11.98 microns) is only 6 percent as severe for liquid-nitrogen-ambient irradiation followed by warming to room temperature as for room temperature ambient irradiation. The proposed interpretation is that defect motion is required for formation of the defect center responsible for the absorption.

For 4.5 MeV electron irradiations at liquid nitrogen and warming to room temperature (induced absorption bands at 11.98, 11.56 and 1.8 microns) the absorptions were over 50 percent as severe as the room temperature irradiation induced absorptions. The assumed implication was that a defect motion requiring an activation energy was not as important for irradiations with high energy electrons.

An important finding (from practical considerations)was that the irradiation induced absorption (at 1.8 microns) is anisotropic. This could be significant where the photocell mounting introduces strain in the semiconductor - a fairly likely situation.

For GaAs Figure 13.4 presents the optical attenuation data for electrons. 1 MeV electron irradiation induced conductivity is annealed out by 220°C.

13.20 Temporary Parameter Degradation

No data.

13.30 Parameter Degradation Factors

Since the data discussed in the literature deals primarily with radiation effects on material parameters, no device degradation factors are listed. It is noted, however, that the thresholds for material damage appear to be about $\sim 10^{12}$ n/cm^2, $> 10^{10}$ p/cm^2, $\sim 10^8$ rads gamma, $\sim 10^{13}$ e/cm^2.

13.40 Radiation Hardening

No data.

13.50 Recommended Testing

It is recommended that any photocells to be used in the environment be tested in neutron, proton, and electron environments to characterize the device behavior.

13.60 Screening

No techniques for screening for radiation sensitive photocells were found in the literature.

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14.0 Piezoelectric Crystals

14.10 Permanent Parameter Degradation

There are many types of crystals that exhibit piezoelectric response. Of these, quartz is the most widely used. Due to the precision required of crystals used as frequency standards, it is important to know their response under radiation.

Most of the earlier tests on crystals involved complete working devices and it is difficult to separate the radiation response of the crystals from that of the package and mountings. Due to this fact, no general theory of damage was developed. The early tests evaluated specific crystals and very little more. Thatcher (14.71) has adequately summarized the studies of steady state radiation effects on crystals before 1964. His summation is presented here with the only changes being conversion of radiation units to maintain consistency in the present report. Following his summary is a recap of more recent work as located in this program.

"Most studies of radiation effects deal directly with the complete working device which consists of the quartz control element and the crystal holder as opposed to crystal sections or configurations. As such, the crystal loses its identity as to its type of material and sometimes class of crystal section and becomes identified with type numbers and manufacturers' names. In view of the loss of crystal identity, the exact nature of the damage mechanism has become extremely difficult to identify and, in most cases, left unexplained. The most commonly used electrical parameters for determining radiation effects are: (1) series resonant frequency, (2) parallel resonant frequency, (3) equivalent parallel impedance, (4) equivalent series impedance, and (5) electrostatic shunt capacitance. A comprehensive study of radiation effects on crystals by manufacture and type number was made by Pfaff and Shelton (Ref. 14.72). In their report, it was concluded that the radiation effects depended on the type of crystal cut, the manufacturer's processes, and the type of radiation. The nuclear environment to which the crystal units were exposed was approximately: thermal neutron flux, 2.5×10^{12} n/cm^2-sec, epicadmium neutron flux, 3×10^9 n cm^{-2} sec^{-1}; and gamma exposure rate, 5.6×10^3 rads/sec. The total neutron fluence for various crystal units varied from 2×10^{13} n/cm^2 to 9×10^{13} n/cm^2. Frequencies of the 14 types of crystals varied from 60 kHz to 70 MHz, and crystal units from five manufacturers were used in this study. An analysis and study of the data obtained during this experiment indicated that, in general, the low-frequency crystal units, i.e., those under 1 megacycle, showed the least radiation effects. A majority of the higher frequency crystals exhibited decreases in series and parallel resonance frequencies up to more than 4000 parts per million. Examination of measurements under transient radiation fields indicated that the changes were gradual. No apparent rate effect, such as abrupt changes in frequency, were observed with changes in reactor power level. For the lower frequency crystal units, some indications of rate effect were observed and frequency changes were both negative and positive. In some instances, nuclear damage was observed on the various crystal holders. In particular, the glass bases were found to be affected. No one manufacturer's crystal units displayed superior resistance to radiation for all the units tested. There was some indication that some of the manufacturers consistently produced a radiation-resistant crystal unit within a narrow frequency category; however, other frequency units that they manufactured failed. In determining when a crystal unit was considered to have failed, the criterion used depended on whether the crystal unit could or could not be resonated. In the interest of pointing out the sensitivity to nuclear radiation, a summary was made of the 154 crystal units without regard to manufacturer or frequency category. Of the 154 units tested and exposed to nuclear radiation, 54 percent were classified as failures. When 41 crystal units were irradiated in a gamma ray environment, only one crystal unit was observed to fail. In attempting to correlate changes and failure occurrence with material differences and manufacturing procedures, it appears that certain types of crystal cuts are more sensitive to nuclear radiation than others. For example, it was stated that AT cut quartz plates are more susceptible to radiation damage than any of the other types of cuts studied. It was hypothesized that this may be a factor of orientation of the dimensions of the plate with respect to the crystallographic planes. Thus, it appears that radiation effects on completed crystal units are of major concern, and designers of electronic equipment utilizing crystal units have many factors to explore when selecting crystal devices for possible use in nuclear environments.

In a test by Belser, Hicklin, and Young (Ref. 14.73), the effects of gamma radiation on quartz crystals and their coverings were studied. Four kinds of quartz (natural, swept natural, cultured, and swept cultured) were used with three types of plating (aluminum, silver, and gold). The Q-values of the resonators exposed to 3.0 x 10^7 rads from a GS-137 source were found to change with the species of quartz. The Q of natural and cultured quartz resonators was degraded by about 25 percent, whereas that of the swept natural and swept cultural quartz was changed little.

Crystals other than quartz are also being studied to determine the effect of nuclear radiation. Lead zirconium titanate and barium titanate have been exposed to 1 x 10^{18} n/cm^2 (Ref. 14.74). The barium crystals showed about -22 percent change in voltage and an average change in resonant frequency of + 7.5 percent. This average was raised because one unit (of five) showed + 16.4 percent change while another showed 12.5 percent change. The lead zirconium crystals showed an average change of + 4.0 percent for frequency response and an average negative change of 19 percent for voltage. Separate gamma exposures were performed on these types of crystals, and the barium crystals showed an average -2.0 percent change in capacitance for an exposure of 1.5 x 10^8 rads. The lead zirconium crystals showed an average negative change of 14 percent in capacitance for an exposure of 1.2 x 10^7 rads.

In another study (Ref. 14.75), a lead metaniolate crystal was tested in a General Electric Type LM-278 transducer to an exposure of about 3 x 10^8 rads and at temperatures up to 800°F. Under these conditions the device operated favorably.

The relation between nonelectrical parameters, such as crystal lattice shifts as indicated by X-ray diffraction and those parameters mentioned earlier, is not clear. In the interest of establishing threshold information, a comparison of effects was studied so that data and results from many of the experiments conducted in which effects were discussed in terms of physical characteristics could be used. For example, one report states that barium titanate was exposed to fast-neutron irradiation up to a neutron fluence of 10^{18} n/cm^2 and no changes were observed in the crystal lattice parameters, (Ref. 14.76). However, with increased exposure up to 1.4 x 10^{20} n/cm^2, a transformation of the tetragonal barium titanate into a non-ferroelectric cubic phase similar to properties possessed by Rochelle salt was indicated by X-ray diffraction. Earlier reports have been issued concerning radiation effects on piezoelectric crystals in which resonant frequencies remained relatively stable at fast fluences of 3.6 x 10^6 n/cm^2, the frequency changes being less than 1000 parts per million. Some exceptions (Ref. 14.77) have been reported where presence of discoloration, because of radiation exposure, coincided with large resonant frequency changes for BT crystal cuts. The relationship between color change and resonant frequency change is more obvious in the various synthetic quartz types. Studies conducted with AT crystal cuts have indicated that the natural quartz is less sensitive to radiation than the synthetic quartz.

The improvement of electron-component resistance to radiation damage through use of shielding against damage from thermal-neutron bombardment has been recommended for various future studies. Some work along these lines is currently in progress for crystal units at the Admiral Corporation (Ref. 14.78) which has as its objective the determination of frequency shift at high temperature for units exposed to a radiation environment. The units being studied in this program consist of Types CR-24/U and CR-51U crystals. A portion of the crystal units were wrapped in a cadmium foil to determine whether any improvement could be detected in the irradiated state. Some units were active in circuits, whereas others were passive. Frequency characteristics at 180°C were used to determine wherher the radiation environment caused measureable changes in the various crystal units. The crystal units were exposed to a total radiation flux of between 0.40 and 1.4 x 10^{18} n/cm^2 at an energy level greater than 0.5 Mev. An examination of the pre-and postirradiation curves of high-temperature frequency characteristics for the shielded Type CR-51/U crystal showed a 10.003 percent transalation, and the crystal would not oscillate at 180°C. The unshielded crystal unit, Type CR-51/U, exhibited the same percent of frequency translation; however, failure to function at the high temperature was not indicated. The reverse was noted for the Type CR-24/U crystal units. For these crystals, the unshielded units exhibited increases in frequency and finally went out of tolerance. The shielded Type CR-24/U unit displayed a decrease in frequency; however, it remained within the specified tolerance for the unit.

Some low-frequency crystals, Type CR-18/U, were studied in much a similar manner as those above. Both shielded and unshielded (Ref. 14.78) units displayed increases in frequency; however, frequency jumps or discontinuities were observed for the unshielded crystals. Discontinuities of this type were not noticed in any previous crystal studies. It was postulated that this occurrence was caused by structural changes in the crystal blank, resulting in coupling to spurious modes. The ultimate effects of cadmium shielding could not be defined at this time since the mechanisms involved are not completely understood, and further conjecture on this phenomenon was left to future observation."

More recent studies, (References 14.79, 14.710, 14.711) have shown that crystals of Z-growth swept-synthetic quartz are the most resistant to steady-state radiation effects. AT-cut 5.27 MHz crystals were found to withstand > 10^5 rads with only about 8 pp 10^8 max shift in frequency. The spread between crystals of the same type cut from different bars of material was found to be approximately 12 pp 10^8 at 10^5 rads gamma. For a mixed neutron and gamma environment such crystals exhibited shifts of 11 pp 10^8 at 3.0×10^{13} n/cm^2 and 1.4×10^6 rads.

The area of proton effects on crystals has not been explored. This could be a serious discrepancy since protons cause both heavy ionization and displacement along their paths.

14.20 Temporary Parameter Degradation

14.30 Parameter Degradation Factors

Due to the complexity of responses observed for cystals of different cuts and manufacturing techniques, it is not practical to list degradation factors. However, the relative sensitivities of several types of crystals are shown in Table 14.1. It is recommended that any crystal type being considered for use, be fully characterized in the radiation environment of interest and that strict quality control be maintained to see that manufacturing techniques not be altered.

14.40 Radiation Hardening

No specific hardening techniques were noted in the literature except that certain crystal cuts (as described in Section 14.10) seem more resistant than others. It has also been noted that Z-growth swept synthetic quartz seems to be more resistant than other types.

14.50 Recommended Testing

It is recommended that crystals to be used be tested in neutron and proton radiation environments to fluences of the order of 10^{14} n/cm^2 and 10^{12} P/cm^2.

14.60 Radiation Screening

No screening techniques for radiation resistant quartz crystals were noted in the literature.

Table 14.1 Relative Sensitivity of Various Crystal Types

Crystal Type	Radiation Level for Moderate Damage
Natural quartz	3×10^7 rads (Co-60)
Cultured quartz	3×10^7 rads (Co-60)
Swept natural	$> 3 \times 10^7$ rads (Co-60)
Swept cultured	$> 3 \times 10^7$ rads (Co-60)
Lead Zirconium titanate	1.5×10^8 rads (Co-60)
Barium titanate	$> 1.5 \times 10^8$ rads (Co-60)
Lead metaniolate	$> 3 \times 10^8$ rads (Co-60)
Quartz	$10^{13} - 10^{14}$ n/cm^2
Swept quartz	3×10^{13} n/cm^2
Lead Zirconium titanate	10^{18} n/cm^2
Barium titanate	10^{18} n/cm^2
Lead metaniolate	———

14.70 References

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14.72 Pfaff, E. R., and Shelton, R. D., "Effects of Nuclear Radiation on Electronic Components", Admiral Corporation, WADC TR-57-361, Part. 2, AF 33 (616)-3091, ASTIA, AD 155790 (Aug., 1958).

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14.74 Kesselman, R., "Preliminary Report on Nuclear Radiation Effects on Piezo-Electrics", Picatinny Arsenal, PA-TR-3045, Jan., 1963.

14.75 "NARF Final Progress Report", General Dynamics/Fort Worth, Nuclear Aerospace Research Facility NARF-62-18P, FZK-9-184, Final Prog. Rpt., AF33(657)-7201, Sept., 1962.

14.76 Wieder, H. H., "Performance of Solid State Materials and Devices Subject to a Nuclear Radiation Flux", U. S. Naval Ordnance Laboratory, Corona, Calif., NAVORD-4621, ASTIA, AD 143467, Aug., 1957.

14.77 Bechmann, R., "Effects of Irradiation on Quartz and Quartz Crystal Units - Recorded Experiments - A Bibliography", U. S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey, Tech. Memo M-1892, May, 1958.

14.78 Graham, F. E., Fueyo, A., and Donovan, A. F., "Nuclear Study of Crystal Controlled Oscillations", Admiral Corporation, Nuclear Radiation Laboratory, Chicago, Illinois, Interim Report BSR-120, AF 33(600)-35026, June, 1959.

14.79 Flanagan, T. M., Wrobel, T. F., "Radiation Effects in Swept-Synthetic Quartz", Gulf General Atomic, IEEE Annual Conf. on Nuclear and Space Radiation Effects, Penn. State U., July, 1969.

14.710 Price, W. E., et al; "Electronic Components and Materials", in Goetzel, C. G., Rittenhouse, J. B., Singletory, J. B., "In Space Materials Handbook Ed.", Lockheed Missiles and Space Co., 3-06-64-1, X65-14878, ASTIC 004082, Jan., 1964.

14.711 Lockheed-Georgia Co., "Components Irradiarion Test No. 2", NASA-CR-69074, ER-7346, ND-4005, X66-12393, April 3, 1964.

15.0 CAPACITORS

Hanks and Hammond (Ref. 15.71) published a rather thorough survey of the effects of a combined environment of neutron and gamma radiation on capacitors in 1966. Since no more recent data has been located in this search, and since the expected fluences for the TOPS mission are below levels expected to produce significant degradation in capacitors, only a brief summary of effects are treated in this report.

Figure 15.1 shows ballpark ranges for neutron damage in the capacitor types included in the TOPS parts list. It appears that the neutron exposure expected for the TOPS mission should not cause significant effects in capacitors except for metallized mylar units under elevated temperatures. However, for completeness, a summary of effects in each part type is included.

15.A GLASS AND PORCELAIN CAPACITORS

15.1A Permanent Effects

Glass and porcelain type capacitors can be considered as the most radiation-resistant capacitors of all the conventional types. They have shown permanent changes ranging from -2.5 to + 3.5 percent under neutron irradiation. Changes in dissipation factor are generally temporary although some permanent changes have been reported in porcelain devices.

Proton damage in capacitors is not so well characterized as neutron damage. At present, one can only estimate proton damage in capacitors since very little data exists.

15.2A Temporary Parameter Drifts

Glass and porcelain capacitors show temporary changes in capacitance ranging from -2.5 to 4.0 percent and increases in dissipation factors. These changes recover after removing the devices from the radiation field. It is felt that the temporary changes are ionization effects and as such in the low intensity ionization fields of the TOPS mission should not be a significant factor.

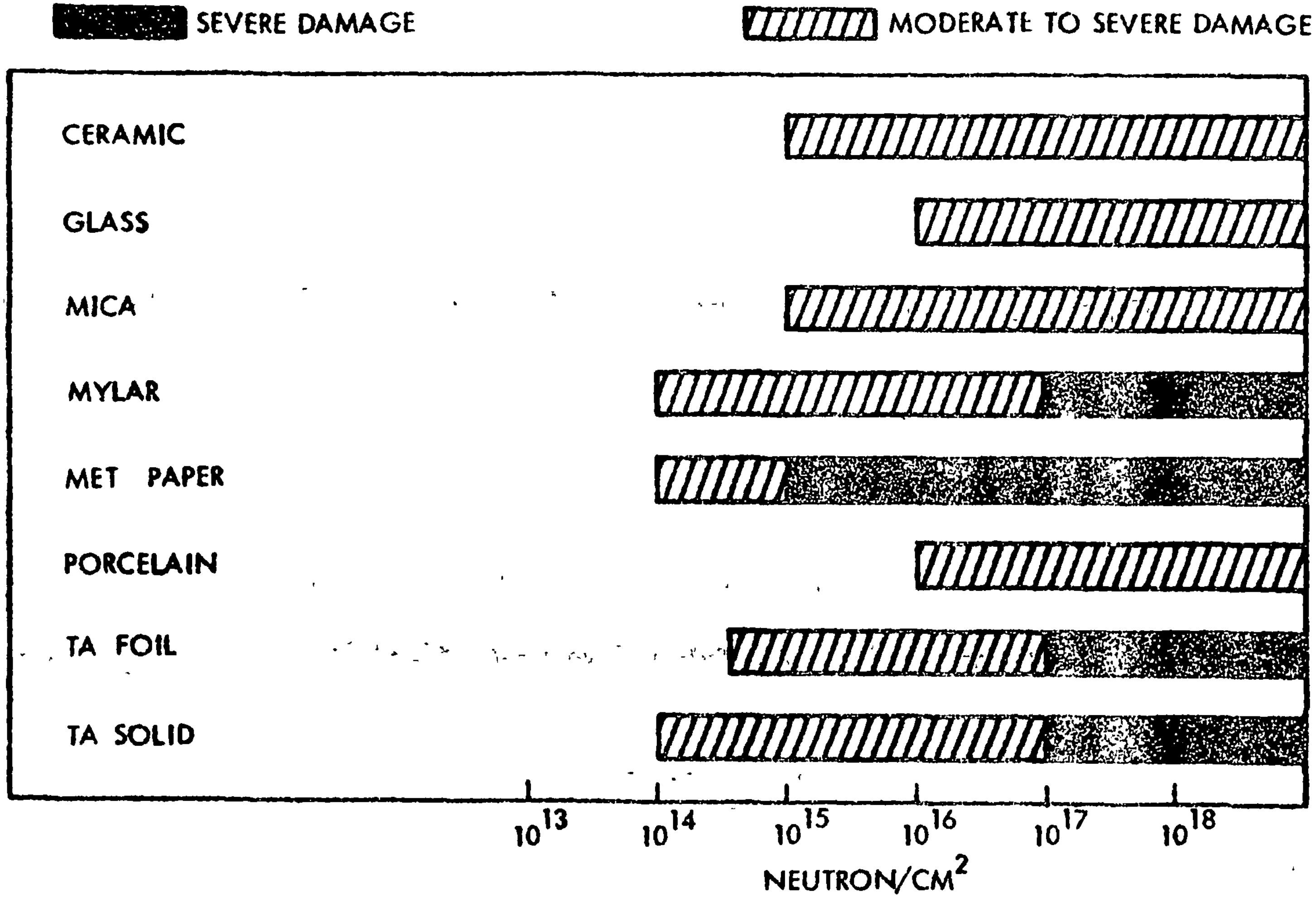

Figure 15.1 Approximate Damage Threshold Ranges for Various Capacitor Types

15.3A Parameter Degradation Factors

From the literature, the parameter degradation factors listed in Table 15.1 are estimated. These factors are felt to be conservative and usually the parameter shifts would be smaller. No estimates for temporary changes due to protons are given due to the unknown absorbed dose due to the charged particles. Further, no permanent changes are listed for the dissipation factor since the results that have been reported are erratic.

Table 15.1 Parameter Degradation Factors

Parameter	Radiation Type	Fluence	Derating Factor	
			Permanent	Temporary
Capacitance	Fission Neutrons + Gammas	1.9×10^{16} n/cm^2 3.8×10^{10} rads(C)	± 4.0 Percent	± 3.5 Percent
Dissipation Factor	Fission Neutrons + Gammas	1.9×10^{16} n/cm^2 3.8×10^{10} rads(C)	---	< 0.10
Capacitance	8 - 15 MeV Protons	5.7×10^{14} p/cm^2	± 4.0 Percent	---
Dissipation Factor	8 - 15 MeV Protons	5.7×10^{14} p/cm^2	---	---

15.4A Radiation Hardening

No specific hardening techniques were found in the literature of glass and porcelain capacitors.

15.5A Radiation Testing

No radiation testing is recommended for glass and porcelain capacitors for the TOPS mission.

15.6A Radiation Screening

No screening techniques were reported.

15B MICA CAPACITORS

15.1B Permanent Parameter Degradation

Steady-state nuclear radiation (fission neutron and gamma) has been observed to cause permanent changes in the capacitance values and dissipation factors of mica capacitors. This damage is thought to be due to changes in the physical structure of the devices.

Proton irradiation should cause similar effects to those stated above for fission neutrons and gammas.

15.2B Temporary Parameter Drifts

The insulation resistance of mica capacitors decreases during irradiation and recovers upon termination of the radiation. These changes are probably due to ionization and should not be a problem for the low intensity TOPS environment.

15.3B Parameter Degradation Factors

Capacitance measurements on mica capacitors may show permanent changes of 6 percent when exposed to 10^{16} n/cm^2 (fast) and 10^8 rads(C) gamma. Dissipation factors may increase by as much as 6 percent at neutron fluences of 10^{16} n/cm^2, and 10^8 rads(C) gamma. The insulation resistance may decrease to the order of 10^8 to 10^9 ohms during radiation as opposed to 10^{10} to 10^{11} ohms before irradiation. These resistance changes recover upon termination of the radiation. Further, since they are probably ionization induced, they should be a function of the ionization dose rate or intensity.

15.4B Radiation Hardening

No specific hardening techniques were located.

15.5B Radiation Testing

No radiation testing is recommended for mica capacitors for the TOPS mission.

15.6B Radiation Screening

No screening techniques were located.

15C CERAMIC CAPACITORS

15.1C Permanent Parameter Degradation

Ceramic capacitors generally show decreases in capacitance and increases in dissipation factors due to neutron and gamma irradiation. From the literature, it is not clear just how much of the observed effects are due to temperature and aging.

Proton radiation should produce similar effects to those of combined neutron and gamma environments.

15.2C Temporary Effects

The capacitance, dissipation factor, and insulation resistance of ceramic capacitors are all susceptible to temporary changes. These changes are thought to be due to ionization.

15.3C Parameter Degradation Factors

The capacitance of general purpose ceramic capacitors has been observed to change as much as 20 percent, but a more typical change is 10 to 15 percent. Such changes occur, however, at much higher fluences than those expected for the TOPS mission.

Limited information on the dissipation factor of ceramic capacitors indicates that it may increase by as much as a factor of five.

The insulation resistance decreases as much as two orders of magnitude during irradiation, but recovers after irradiation. For the low intensity TOPS environment this should not be a problem.

15.4C Radiation Hardening

No hardening techniques were reported.

15.5C Radiation Testing

No radiation testing of ceramic capacitors is recommended for the TOPS mission.

15.6C Radiation Screening

No screening techniques were noted in the literature.

15.D MYLAR CAPACITORS

15.1D Permanent Parameter Degradation

Generally, mylar capacitors show damage at neutron fluences one order of magnitude lower than the types having inorganic insulation such as glass + ceramic. The devices show damage due to several possible mechanisms. For example, in oil impregnated devices (high voltage) the hydrocarbons tend to breakdown and release gases which distort the capacitor element and in some cases to rupture the encapsulant.

It has also been observed that the application of voltage and high temperature during irradiation enhances the damage.

No data were located for proton effects, but the damage mechanisms probably are similar to those for a reactor environment, i.e., combined neutrons and ionizing gamma radiation.

15.2D Temporary Parameter Drift

The insulation resistance of mylar capacitors show decreases during irradiation due to ionization effects. The decreases recover when the radiation is terminated.

15.3D Parameter Degradation Factors

Maximum changes that have been recorded in dry mylar dielectric capacitors are decreases of 10 percent at 10^{16} n/cm^2 ($E > 0.1$ MeV) plus 1.3×10^7 rads(C) and an increase of 3.4 percent at 3.6×10^{15} n/cm^2 $E > 0.1$ MeV and 4.0×10^6 rads(C). The leakage current at these fluences showed average increases during irradiation of from 20 percent to 100 percent.

For metallized mylar units, catastrophic failures due to shorting were reported at fluences of the order of 1×10^{13} n/cm^2 plus 1×10^7 rads(C) when the devices were irradiated in a combined environment of 100°C, vacuum and under electrical load. The failure rate was shown to be enhanced by both the electrical loading and the elevated temperature. Table 15.2 shows the failure rates for these devices. Figure 15.2 shows the reliability index for mylar units.

15.4D Radiation Hardening

No specific hardening techniques have been located in the literature.

15.5D Radiation Testing

If metallyzed mylar dielectric devices are to be used at elevated temperatures, it might be advisable (in the light of the tests on metallized units) to perform radiation tests on a large sample of the device to be used to fluences of the order of 10^{14} n/cm^2 at the ambient and electrical conditions to which the devices will be subjected during the mission.

15.6D Radiation Screening

No specific screening techniques were located in the literature.

15.E METALLIZED PAPER CAPACITORS

15.1E Permanent Parameter Degradation

Paper dielectric capacitors show permanent degradation in capacitance at neutron fluences approximately three orders of magnitude lower than do glass and ceramic devices.

Perhaps the most significant mechanism is the distortion of the capacitive elements due to dimensional changes and due to the evolution of gas in the case oil or hydrocarbon impregnated devices. Also, changes in the dielectric constant of the dielectric may be a contributing factor.

No data were found for proton effects, but the proton damage mechanisms should be similar to those for neutron plus gamma environments.

15.2E Temporary Parameter Degradation

Ionization causes a decrease in insulation resistance which recovers upon termination of the radiation.

Table 15.2 Failure Rate For 683G10592W2 Capacitor at 50, 60, and 90 Percent Confidence Levels. (Ref. 15.73)

Test Group*	Failure Rate at Indicated Confidence Level, percent/1000 hr.			
	50 Percent	60 Percent	90 Percent	Percent Recorded as Failed
I	1.23	1.43	2.44	10
II	0.30	0.39	0.98	0
III	36.70	38.85	48.38	95
IV	18.76	20.02	25.53	75
V	0.30	0.39	0.98	0
VI	0.30	0.39	0.98	0
VII	0.30	0.39	0.98	0
All test groups	2.83	2.95	3.48	25.7

* Group Test Conditions

(1) A temperature of 100 C and normal atmospheric pressure (Test Group I).

(2) A temperature of 100 C and a vacuum of approximately 10^{-5} mm Hg (Test Group II).

(3) A temperature of 100 C, a vacuum the same as (2), and exposed to radiation for a period of 10,000 hours. The neutron fluence and total gamma exposure were approximately 10^{13} n cm^{-2} ($E > 0.1$ MeV) and 10^{9} ergs g^{-1} (C) (Test Group III).

(4) A temperature of 100 C, under vacuum, and the same total radiation exposure as in (3) but at a flux that would provide this exposure in 100 hours. The capacitors were then left on operational load for the balance of the 10,000-hour period with no further irradiation (Test Group IV).

(5) A temperature of 50 C, under vacuum, and exposed to radiation under the same conditions as in (3) (Test Group V).

The additional test groups (VI and VII) of 20 capacitors were subjected to the same conditions as (1) and (3) above, but without the application of a d-c voltage.

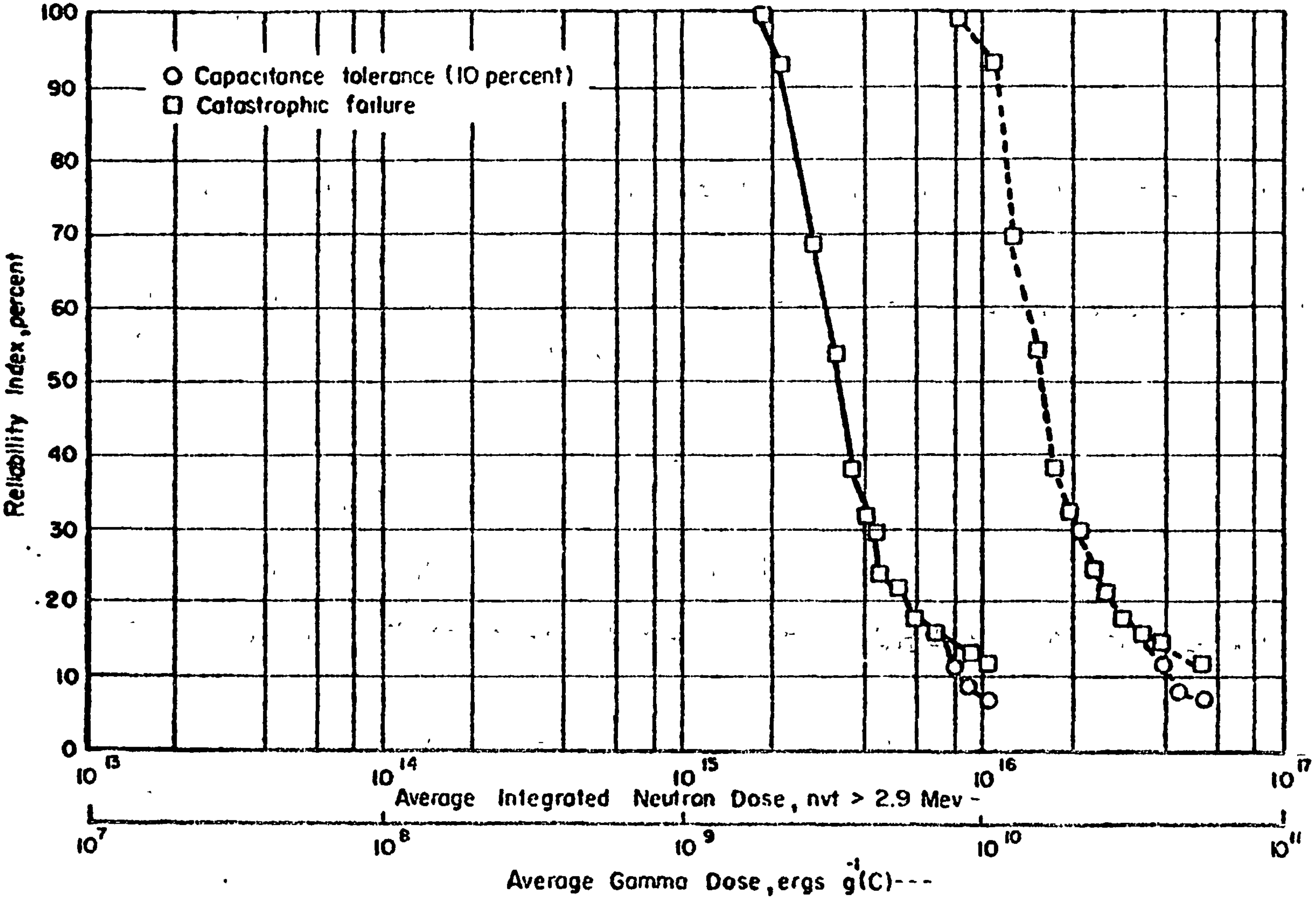

Figure 15.2 Reliability Index for Mylar Capacitors for a 95 Percent Confidence Level, Based on a Sample Size of 98 Units (Capacitance and Catastrophic Failure) (Ref. 15.72)

15.3E Parameter Degradation Factors

The reported changes for metallized paper capacitors range between 8 percent increases and decreases greater than 20 percent. Generally, the dissipation factor shows increases of less than 1 percent with radiation. These typical changes have been observed in experiments in which the radiation levels ranged to 4×10^{17} n/cm^2 (fast) + 3.0×10^8 rads(C).

One study of metallized paper capacitors provided some insight into the reliability of the devices. Table 15.3 and Figure 15.3 shows the failure rates and reliability index for capacitors irradiated under various conditions of electrical loading, temperature, and atmospheric pressures. The results of this study indicate that for radiation levels of 10^{13} n/cm^2 and 10^7 rads(C), the radiation is an insignificant factor compared to the effects of temperature and vacuum.

15.4E Radiation Hardening

No specific techniques for hardening paper capacitors were located; however, it was observed that units impregnatec with oils are more sensitive than the non-impregnated units due to gas evolution as the hydrocarbons break down.

15.5E Radiation Testing

From the test reported in the literature, it appears that no radiation testing of metallized paper capacitors is necessary for TOPS environment.

15.6E Radiation Screening

No screening techniques were reported.

Table 15.3 Failure Rate for 118P10592S2 Capacitor at 50, 60, and 90 Percent Confidence Levels. (Ref. 15.73)

Test Group*	Failure Rate at Indicated Confidence Level, percent/1000 hr.			
	50 Percent	60 Percent	90 Percent	Percent Recorded as Failed
I	0.30	0.39	0.98	0
II	0.30	0.39	0.98	0
III	0.30	0.39	0.98	0
IV	0.29	0.39	0.97	0
V	0.30	0.39	0.98	0
All test groups	0.06	0.08	0.20	0

* Group Test Conditions

(1) A temperature of 100 C and normal atmospheric pressure (Test Group I).

(2) A temperature of 100 C and a vacuum of approximately 10^{-5} mm Hg (Test Group II).

(3) A temperature of 100 C, a vacuum the same as (2), and exposed to radiation for a period of 10,000 hours. The neutron fluence and total gamma exposure were approximately 10^{13} n cm^{-2} ($E > 0.1$ MeV) and 10^{9} ergs g^{-1} (C) (Test Group III).

(4) A temperature of 100 C, under vacuum, and the same total radiation exposure as in (3) but at a flux that would provide this exposure in 100 hours. The capacitors were then left on operational load for the balance of the 10,000-hour period with no further irradiation (Test Group IV).

(5) A temperature of 50 C, under vacuum, and exposed to radiation under the same conditions as in (3) (Test Group V).

The additional test groups (VI and VII) of 20 capacitors were subjected to the same conditions as (1) and (3) above, but without the application of a d-c voltage.

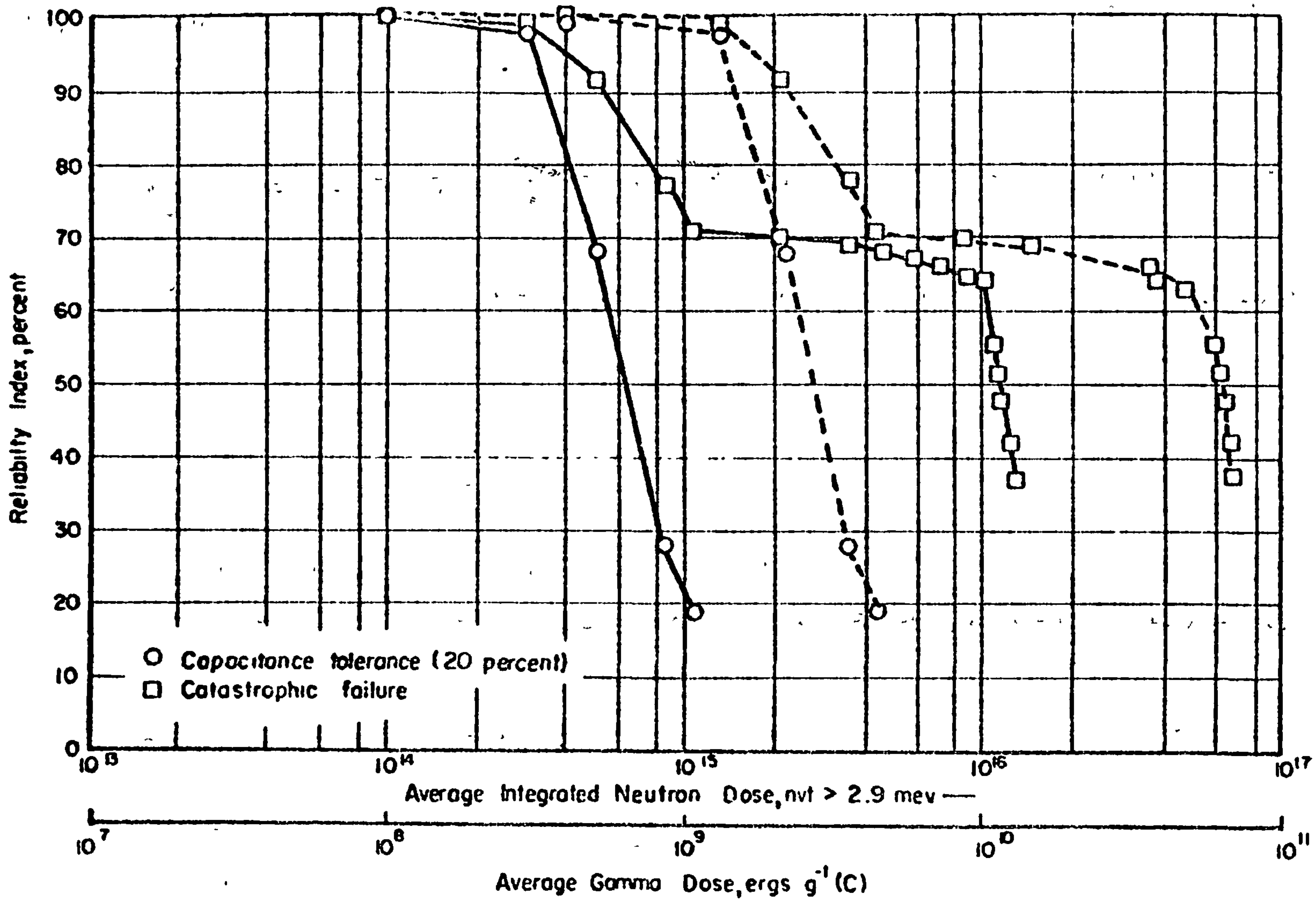

Figure 15.3 Reliabiliy Index for Paper Capacitors for a 96 Percent Confidence Level, Based on a Sample Size of 100 Units (Capacitance and Catastrophic Failure) (Ref. 15.72)

15.5F TANTALUM CAPACITORS

15.1F Permanent Parameter Degradation

The capacitance and dissipation factor of tantalum capacitors experience permanent changes under irradiation. In addition, they sometimes show structural damage due to dimensional changes particularly in units employing teflon seals.

15.2F Temporary Parameter Changes

The capacitance, dissipation factor, and the leakage current in tantalum capacitors all show temporary changes due to irradiation. The temporary effects usually are attributed to ionization and recover upon termination of the radiation.

15.3F Parameter Degradation Factors

The capacitance of tantalum capacitors has been observed to vary between maximum of -25 percent and +20 percent while more typical changes are ± 10 percent. The changes have been observed in some cases to recover and in some cases not to recover or even to increase upon radiation being terminated.

The dissipation factor has been observed to increase to values ranging from < 0.05 to 0.10.

The above changes occurred in experiments in which neutron fluences ranged from 0.3×10^{12} n/cm^2 (fast) to 6×10^{17} n/cm^2 (fast) plus gamma doses ranging from 8.7×10^5 rads(C) to 4.4×10^8 rads(C).

The leakage current of tantalum capacitors have increased as much as two orders of magnitude due to ionization; however, for the low intensity TOPS environment, this should not be a problem.

The reliability of tantalum capacitors has been checked in several tests. Figure 15.4 shows the reliability index and Tables 15.4 and 15.5 shows failure rates observed.

15.4F Radiation Hardening

No specific hardening techniques were observed in the literature; however,

Table 15.4 Failure Rate For 5K106AA6 Capacitor at 50, 60, and 90 Percent Confidence Levels. (Ref. 15.73)

Test Group*	Failure Rate at Indicated Confidence Level, percent/1000 hr.			
	50 Percent	60 Percent	90 Percent	Percent Recorded as Failed
I	0.30	0.39	0.98	0
II	0.30	0.39	0.98	0
III	0.39	0.39	0.98	0
IV	0.29	0.39	0.97	0
V	0.30	0.39	0.98	0
VI	0.30	0.39	0.98	0
All test groups	0.05	0.06	0.16	0

* Group Test Conditions

(1) A temperarure of 100 C and normal atmospheric pressure (Test Group I).

(2) A temperature of 100 C and a vacuum of approximately 10^{-5} mm Hg (Test Group II).

(3) A temperature of 100 C, a vacuum the same as (2), and exposed to radiation for a period of 10,000 hours. The neutron fluence and total gamma exposure were approximately 10^{13} n cm^{-2} ($E > 0.1$ MeV) and 10^{9} ergs g^{-1} (C) (Test Group III).

(4) A temperature of 100 C, under vacuum, and the same total radiation exposure as in (3) but at a flux that would provide this exposure in 100 hours. The capacitors were then left on operational load for the balance of the 10,000-hour period with no further irradiation (Test Group IV).

(5) A temperature of 50 C, under vacuum, and exposed to radiation under the same conditions as in (3) (Test Group V).

The additional test groups (VI and VII) of 20 capacitors were subjected to the same conditions as (1) and (3) above, but without the application of a d-c voltage.

Table 15.5 Failure Rate for HP56C50D1 Capacitor at 50, 60, and 90 Percent Confidence Levels. (Ref. 15.73)

Test Group *	Failure Rate at Indicated Confidence Level, percent/1000 hr.			
	50 Percent	60 Percent	90 Percent	Percent Recorded as Failed
I	11.82	12.56	15.80	85
II	7.31	7.81	10.05	30
III	0.30	0.39	0.98	0
IV	0.75	0.89	1.74	5
V	0.75	0.90	1.72	5
All test groups	3.25	3.39	4.02	25

* Group Test Conditions

(1) A temperature of 100 C and normal atmospheric pressure (Test Group I).

(2) A temperature of 100 C and a vacuum of approximately 10^{-5} mm Hg (Test Group II).

(3) A temperature of 100 C, a vacuum the same as (2), and exposed to radiation for a period of 10,000 hours. The neutron fluence and total gamma exposure were approximately 10^{13} n cm^{-2} (E > 0.1 MeV) and 10^{9} ergs g^{-1} (C) (Test Group III).

(4) A temperature of 100 C, under vacuum, and the same total radiation exposure as in (3) but at a flux that would provide this exposure in 100 hours. The capacitors were then left on operational load for the balance of the 10,000-hour period with no further irradiation (Test Group IV).

(5) A temperature of 50 C, under vacuum, and exposed to radiation under the same conditions as in (3) (Test Group V).

The additional test groups (VI and VII) of 20 capacitors were subjected to the same conditions as (1) and (3) above, but without the application of a d-c voltage.

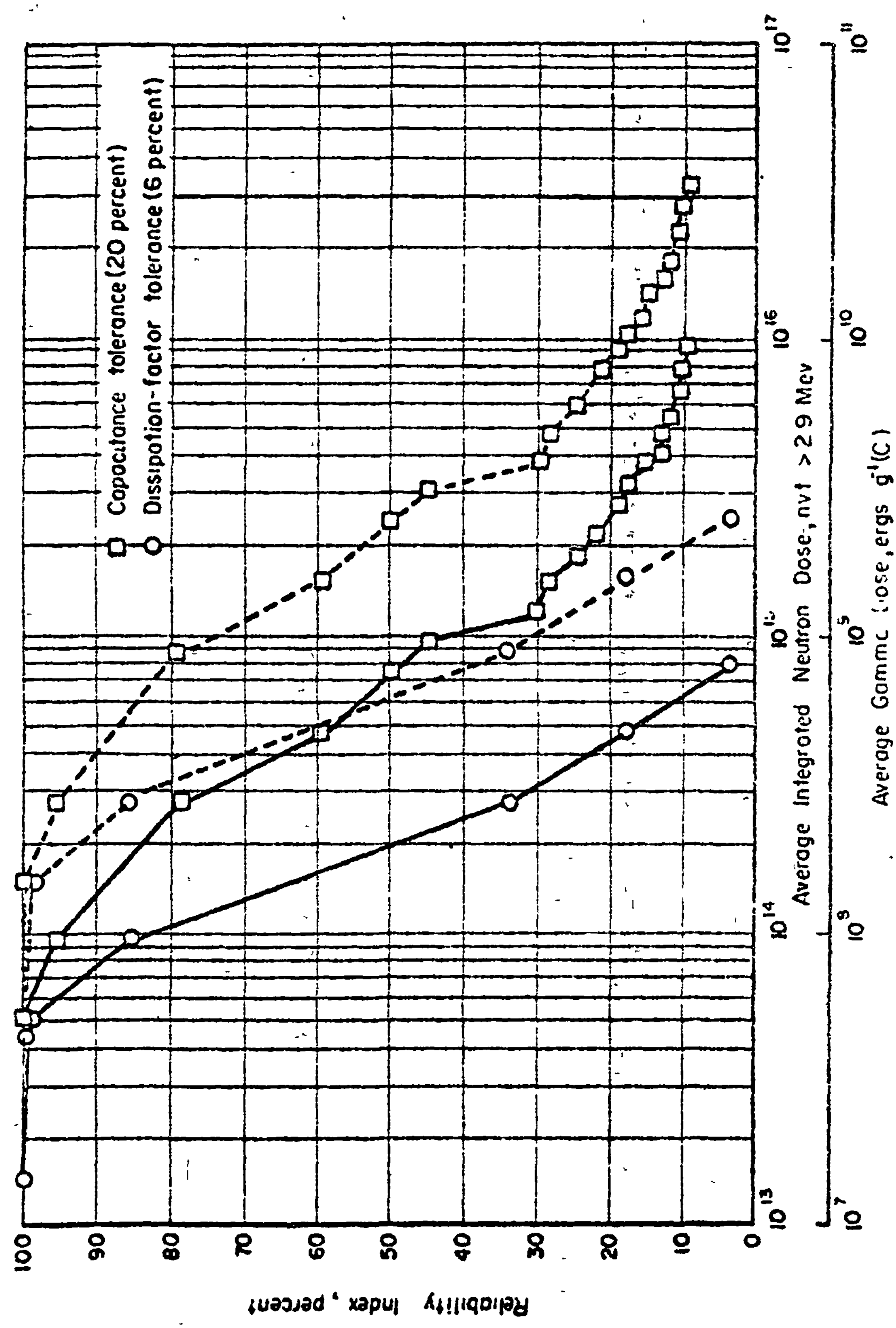

Figure 15.4 Reliability Index for Tantalum Capacitors for a 95 Percent Confidence Level, Based on a Sample Size of 98 Units (Capacitance and Dissipation Factor) (Ref. 15.72)

it was observed that units having teflon seals are more susceptible to mechanical damage due to radiation.

15.5F Radiation Testing

No specific radiation testing of tantalum capacitors is recommended for the TOPS mission.

15.6F Radiation Screening

No radiation screening techniques were located in the literature.

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16.0 RESISTORS

Due to their relative hardness, resistors have received little attention in recent years. The data that exist have been summarized by other workers quite thoroughly (16.71). Since permanent effects in resistors are dependent on materials and mechanical construction details, no prediction models have been formulated; therefore, this report will discuss the effects of radiation that are particularly pertinent to the TOPS environment. Very little proton data were found for resistors; therefore, damage threshold estimates are made for protons.

16.1 Permanent Parameter Degradation

Carbon Composition Resistors

Carbon composition resistors are the most radiation sensitive of the four common types discussed in this report. They have been observed to be sensitive to fast neutrons and, to a lesser degree, to gamma rays. Very little data were found for proton effects on resistors, but an estimate can be made based on the assumption that protons produce displacement damage. This estimate ignores the ionizing effects of protons which, based on gamma radiation (principally ionization) results, is probably not too serious. This is substantiated by the fact that carbon composition resistors have been exposed to 2×10^{13} (22 MeV) p/cm^2 without significant permanent damage. (16.72)

The resistance of carbon composition resistors usually decreases under neutron and gamma radiation. It has been postulated that the decrease is probably a result of carbonization of the epoxide-resin binder, which increases the conductivity of the resistor. In general, for carbon composition resistors, the higher the resistance value, the larger the percentage resistance change due to radiation. In addition, rate effects have been observed for high resistance values. The rate effect is not very significant for a low level environment such as TOPS.

Carbon Film Resistors

Generally, deposited-carbon-film resistors show better results than carbon composition resistors. However, there are several techniques used in manufacturing deposited-carbon-film resistors and these techniques have some influence on radiation degradation of the devices. Out of the different manufacturing techniques, there are essentially two basic types; the coated film resistor and the moisture-resistant resistor. Coated film resistors usually have an acrylic coating to protect the film. The moisture-resistant units are either hermetically sealed in an impervious ceramic sleeve via silver-alloy solder or are molded using an epoxide-resin encapsulation. The conductive element is a pyrolytically deposited carbon film on substrates such as steatite, alumina, or alkali-free glass.

It should be further pointed out that carbon film resistors without encapsulation are no better than carbon composition resistors. Exposures of 2×10^{13} (22 MeV) p/cm^2 produce no permanent effects in carbon film resistors. (16.72)

Metal Film Resistors

In construction metal-film type resistors are similar to carbon-film resistors except that the resistive element is composed of a metal alloy or metal oxide. The body enclosure is usually an acrylic or Vitreous material. Sometimes the devices are enclosed in an epoxide resin.

The radiation resistance appears to be quite good, especially for units having low nominal values of resistance. Low resistance devices come close to wire-wound resistors in hardness. Unfortunately, all types of metal-film resistors do not show good radiation resistance and in some cases catastrophic failures have been observed. As with the case of carbon-film resistors, the epoxide-resin encapsulated devices are preferable. For resistive elements, elemental tin has been observed to be less radiation sensitive than oxides and alloys. The above discussion is based on neutron and gamma data. No data was found for proton effects.

Wire-wound Resistors

Wire-wound resistors are the least radiation sensitive type of resistor. Although there is some variation in the response of units from different manufacturers, it is not felt the wire-wound resistors should present any problem in TOPS environment.

16.2 Temporary Parameter Degradation

There is no evidence of drift other than the permanent degradation discussed earlier for carbon composition, carbon film, and metal film resistors at the dose rates expected on the TOPS mission.

Wirewound resistors sometimes show a small change (0.1 percent) in resistance immediately upon insertion in a radiation environment, but they eventually settle back to their original values.

16.3 Parameter Degradation Factors

From the data presented in the preceding section, semiquantitative estimates can be made of the amount of degradation of carbon composition resistors in a nuclear environment. For the TOPS mission, the threshold fluence for damage appears to be above the neutron fluence expected; however, for protons, the fluence expected could produce as much as 4 percent change. The average changes that have been observed are presented in Figure 16.1.

Due to the many construction types available in metal film resistors, it is not possible to make accurate degradation predictions. However, from the data available, the average parameter changes have been estimated and are presented in Figure 16.2 and 16.3. For the TOPS environment , it appears that carbon film resistors would change no more than 1 percenr.

Figure 16.4 shows estimated changes for metal film resistors in a nuclear environment. An equivalent proton environment has been estimated. It should be noted that there is no experimental data for proton effects.

From the Figure, it can be further noted that at fluences of neutrons and protons well above those expected for the TOPS mission the change in resistance is less than one-half percent. Early studies indicate that for high-value resistors (> 1 megohm) the change was greater and diallyl phthalate plastic units are hardest.

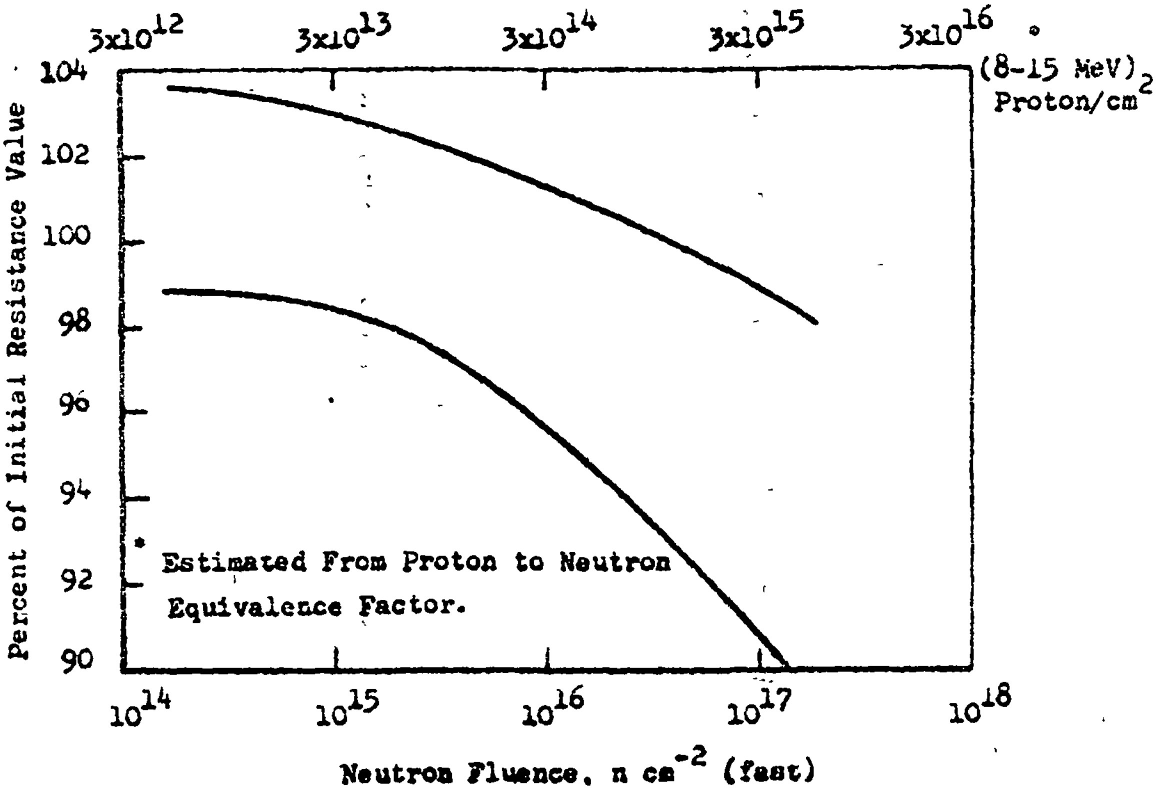

Figure 16.1 Nuclear-Radiation Effects on Carbon Composition Resistors (Ref. 16.71)

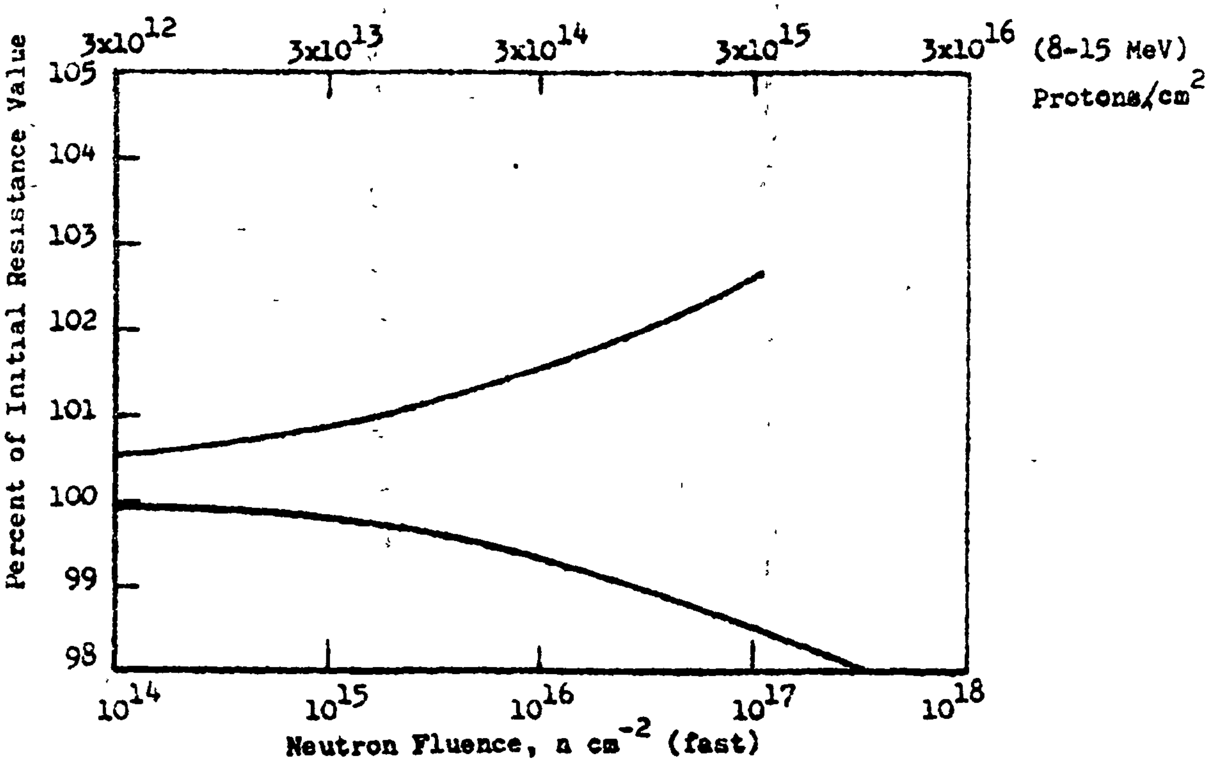

Figure 16.2 Nuclear-Radiation Effects on Carbon-Film Resistors (Ref. 16.71)

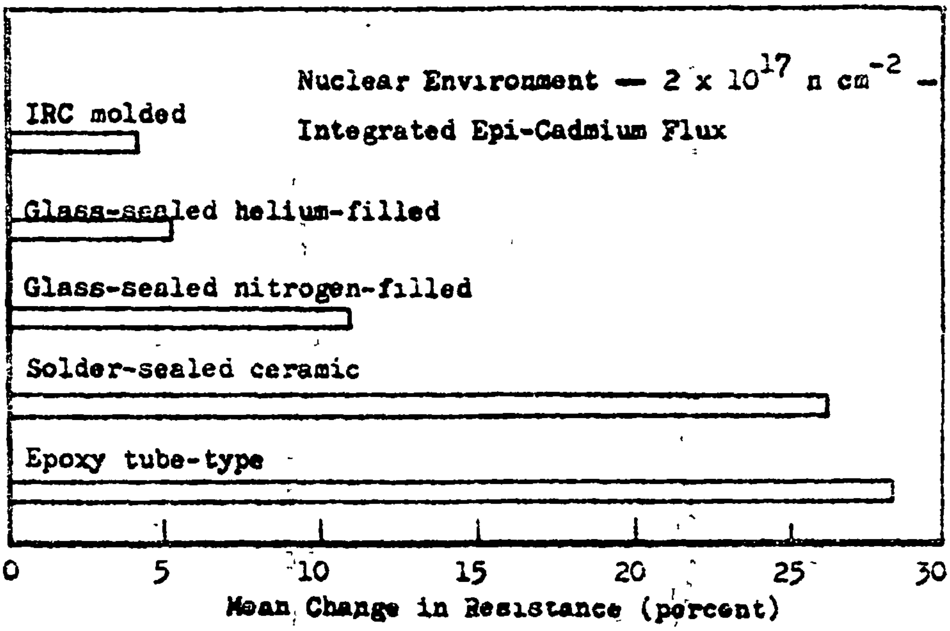

Figure 16.3 Effects of Radiation on Resistance of 1-Megohm Carbon-Film Resistors (Ref. 16.71)

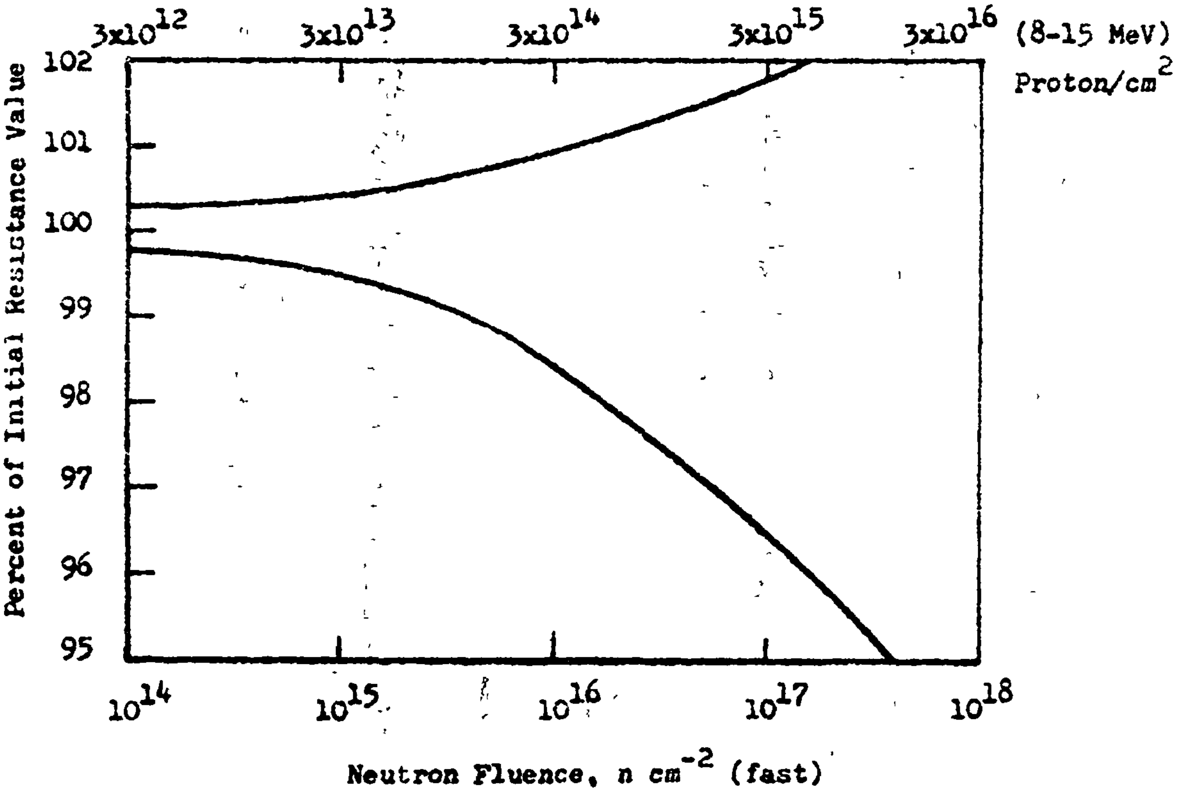

Figure 16.4 Nuclear-Radiation Effects on Metal-Film Resistors (Ref. 16.71)

Wirewound resistors should be adequate for the TOPS mission with a degradation factor (or tolerance) of ± 0.1 percent applied. Figure 16.5 shows the average observed changes.

16.4 Radiation Hardening

No hardening procedures have been proposed for carbon composition resistors.

Aside from the comments in the permanent parameter section regarding construction type selection, there are no specific hardening techniques suggested in the literature for carbon film resistors.

Further, no hardening techniques have been found in the literature for metal film or wirewound resistors.

16.5 Radiation Testing

No specific testing of resistors is recommended for the TOPS program.

16.6 Radiation Screening

No screening techniques for identifying radiation sensitive resistors were found in the literature.

16.7 References

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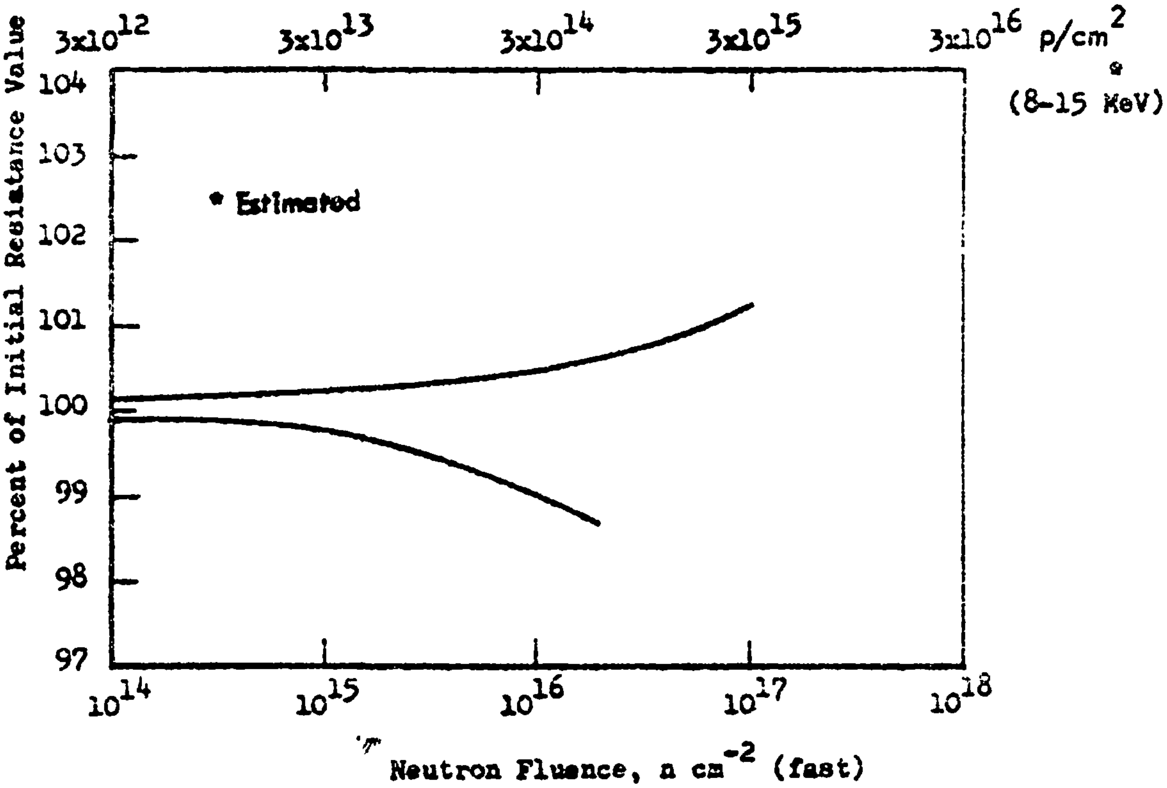

Figure 16.5 Nuclear-Radiation Effects on Wire-Wound Resistors (Ref. 16.71)

17.0 Relays, Switches, and Fuses

No recent work has been located on relays, switches, and fuses. The work that has been done has been reviewed by other workers (17. 21) and reveals that for missions such as TOPS there probably is no real radiation problem with these devices.

Most of the reported effects arise from insulation breakdown or degradation. Figure 17. 1 shows the approximate tolerances of popular insulation materials.

Thatcher (17. 21) has reviewed the literature on relays and switches and his report is included here with only the radiation units converted for consistency.

Hardening of switches and relays is accomplished by choosing hard materials for construction; however, for a mission such as TOPS it appears that (with the possible exception of teflon) the thresholds for damage of most insulation materials is well above the expected mission radiation levels.

"Nuclear radiation effects relays and switches primarily by damage to the organic insulating and construction materials. Data examined for some relays (17. 22) indicate that they operate satisfactorily in a nuclear-radiation field up to integrated neutron fluxes of 6.5×10^{14} n/cm^2, with energies greater than 2. 9 MeV or 5.7×10^{15} n/cm^2 (epicadmium) or integrated gamma-ray exposures of 10^9 rads (17. 23). Some micro-switches suffer damage to the plastic cases and actuators (17. 24) at gamma-ray exposures as low as 4 to 6×10^6 rads or integrated neutron fluxes at 10^{15} n/cm^2 (> 0. 7 MeV). Typical behavior of relays and switches in the nuclear environment is shown in Table 17. 1."

"Other experiments (17. 25) have indicated that ionizing radiation does not affect the potential of the air gap, but does affect the potential required to quench any arc struck. Solutions to this problem would be to operate the relay in an evacuated container, or to operate the relay in a container filled with an arc-quenching gas, such as sulfur hexa-fluoride."

The major factor in the radiation resistance of relays and switches is insulating materials. Teflon is an especially undersirable material for such applications. The only screening technique suggested is on the basis of materials used. Designers

Table 17.1 Radiation Effects on Relays and Switches

	Radiation Exposure			
Relay or Switch Type	n/cm^2	Rads	Effects	Reference
Sensitive-type, 1800-ohm, 65 mw, coil relay	5.7×10^{15} (epicadmium)	1×10^7	Four samples were tested and showed negligible degradation. No indication of any insulation failure. One sample showed an increase in contact resistance from 0.015 to 0.5 ohm. Postirradiation examination showed this unit to have slightly blackened contact points, but no evidence of pitting or burning. Drop-out resistance showed no change from pre- to postirradiation and less than 5 per cent change in-pile. Pull-in voltage and current changed ± 2 per cent in-pile and ± 6 percent pre- to postirradiation.	(17.26)
SRJ-2000G(hermetically sealed)	4.5×10^{12} above 2.9 Mev	5.3×10^8	Some showed decreases in contact resistance as much as 35 per cent from pre- to postirradiation measurements. This was not thought to be a radiation effect but rather a mechanical removal, during operation, of an oxide layer built up during storage. Changes in coil resistance and operating times were noted as large as 10-15 per cent. However, these changes were determined to be primarily temperature effects with the radiation contribution less than 2 per cent. Release times showed initial decrease of 5-10 per cent, then steady operation in-pile with random permanent effects. Pull-in current showed no trend.	(17.27)
SR-2000G (dust cover)	7.6×10^{12} above 2.9 Mev	1×10^9		
SP-11D (uncovered)	4.5×10^{12} above 2.9 Mev	5.2×10^8		
275-C (hermetically sealed)	4.8×10^{12} above 2.9 Mev	5.4×10^8		
MH-18D (hermetically sealed)	4.4×10^{12} above 2.9 Mev	4.9×10^8		
A-29634 (uncovered)	3.4×10^{12} above 2.9 Mev	4.4×10^8		

Table 17.1 (Continued)

Relay or Switch Type	Radiation Exposure n/cm^2	Radiation Exposure Rads	Effects	Reference
SMSDS (hermetically sealed)	4.9×10^{12} above 2.9 Mev	5.5×10^{8}		
22RJC-200G (hermetically sealed)	6.1×10^{12} above 2.9 Mev	7.9×10^{8}		
76-3 (uncovered)	6.1×10^{12} above 2.9 Mev	7.6×10^{8}		
Microswitch	1×10^{15} above 0.7 Mev	5×10^{6}	25 per cent change in plastic case and actuator.	(17.28)
Westinghouse, Type UN312587-002 relays	2×10^{16} (epicadmium)	5×10^{7}	Twelve tested. All units exceeded specification limits.	(17.29, 17.30)
Price, Type 300RG22 relays	2×10^{16}	5×10^{7}	Twelve tested. All units exceeded specification limits.	(17.29, 17.30)
Ledex rotary switches	6.2×10^{15} above 0.5 Mev	--	Four switches tested. All switches were erratic.	(17.31, 17.32)
Centralab high-voltage switch-special	1.3×10^{15}	--	At this exposure the ratchet mechanism jammed, and the consequent overheating destroyed the coil.	(17.33)
Ledex ceramic wafer switch-standard low voltage	6.2×10^{15}	--	Solenoid action become intermittent. However, switch rotation could be continued by manually pulsing the voltage. Solenoid coil resistance, coil insulation resistance, and switch contact resistance varied slightly.	(17.33)
Standard ceramic wafer switches-Ledex	1.1×10^{16}	--	Insulation resistance remained fairly constant at 6×10^{7} ohms when reactor was at a power level of 1 Mw.	(17.33)
Centralab high-voltage switch	5×10^{16}	--	Some contacts failed after an exposure of about 0.5×10^{15} n cm^{-2}.	(17.33)
Potter-Brumfield relay	6.1×10^{15} $E > .5$ Mev	--	Performed fair; pitting of contacts caused resistance to increase to about 1 ohm.	(17.34)

Table 17.1 (Continued)

	Radiation exposure			
Relay or Switch Type	n/cm^2	Rads	Effects	Reference
Potter-Brumfield relay	1.2×10^{17} E > .5 Mev	--	Performed good, no increase in contact resistance; about 1-volt change in pull-in and drop-out voltage.	(17.34)
Iron Fireman	1.2×10^{16} E > .5 Mev	--	Performed excellent regarding pull-in and drop-out current stability.	(17.34)
MH Type X-27516 microswitch	$\sim 3.8 \times 10^{16}$	--	Operated satisfactorily throughout test.	(17.35)
MH V3-245 1SX1 11SM3	1.2×10^{10}	--	An over-all and thorough inspection of the irradiated switches indicated the V3 series and SM series units were only affected by case embrittlement, and the electrical functioning of the switches was not altered. Other switches showed a variety of weaknesses such as seal failures and boot embrittlement.	(17.36)
GLA 30302 Bendix L-15514-65	1.41×10^{15} (E > 2.9 Mev)	3.9×10^8	Leakage currents remained constant during test. After exposure the GLA switch showed drop in leakage current and the other switch showed a large increase.	(17.37)
Microswitch 1HT1, high temperature	None	9.3×10^8	Operated satisfactorily.	(17.38)
GE, FB100Y1, ZL176, magnet wire GE, FB100Y2, TFE, Teflon magnet drive GE, FB100Y3, ML, enamel magnet wire Potter-Brumfield, LMSC 1600639-1, PBSC11DA, DPDT	6×10^{15}	8.8×10^6	Coil resistance showed no more than 2 per cent change between pre- and post-test measurements for all twelve relays. Insulation resistance decreased with increasing temperature and flux. Post-test measurements showed full recovery. The General Electric units appear to meet specifications. The Potter-Brumfield (PB) relays exceeded the specifications at 2 amp (but not at 100 ma). It was specified that the maximum contact resistance allowable was 50 milliohms.	(17.39)

Table 17.1 (Continued)

Relay or Switch Type	Radiation exposure		Effects	Reference
	n/cm^2	Rads		
Kinetics Corp. M362-1, Ser 0045, SPDT	5.8×10^{15}	8.8×10^{6}	Operated satisfactorily throughout the test.	(17.39)
Leach Corp. 400 cps, 9410, LMSC 1060603-1, Serial 123	8×10^{13}	8.8×10^{4}	Operated satisfactorily to at least this exposure.	(17.39)
Autronics Corp. 400 cps, Type III, 1300, LMSC 1461396.	6.8×10^{14}	--	Operation became questionable at 4×10^{12} n cm^{-2} when the drop-out voltage increased from 65 to 93 volts. The unit failed to transfer at the measurement taken at 3×10^{13} n-cm^{-2}.	(17.39)
Transco Products, Inc. SPDT, RF switch, 13730-30	8×10^{15}	1.3×10^{7}	Insertion loss showed negligible changes during and after test.	(17.39)
Microswitch 1SM1	--	1.1×10^{8}	The case material was becoming brittle.	(17.40)
Microswitch 1SE1-3	--	1.1×10^{8}	There was an increase in operating and release force and pretravel at 1.3×10^{7} rads (C). By end of test this was further magnified due to seal boot hardening.	(17.40)
Microswitch V3-1	--	1.1×10^{8}	The cover material was becoming brittle.	
Microswitch V3-1301	--	1.05×10^{8}	The case material was suspected of becoming brittle.	(17 40)
Microswitch BZ-2R	--	1.1×10^{8}	Case material became brittle.	(17.40)
Microswitch BA-2R	--	1.1×10^{8}	Case material became brittle.	(17.40)
Microswitch 1EN1-6.	--	1.3×10^{8}	Possibly some deterioration of the Teflon seal ring.	(17.40)
Microswitch 2EP2-8	--	1.1×10^{8}	At 1.1×10^{8} rads there was a slight decrease in operating and release force and differential travel. At end of test the seal became brittle and broken on first operation.	(17.40)
Microswitch 1LS1	--	1.05×10^{8}	No effect on switch, but rubber seals had hardened.	(17 40)
Microswitch 1HS1	--	1.1×10^{8}	No effect.	(17.40)

should select devices on the basis of the most resistant materials (see Figure 17. 1). A general idea of the effects to be expected can be obtained from Table 17. 1.

17. 20 References

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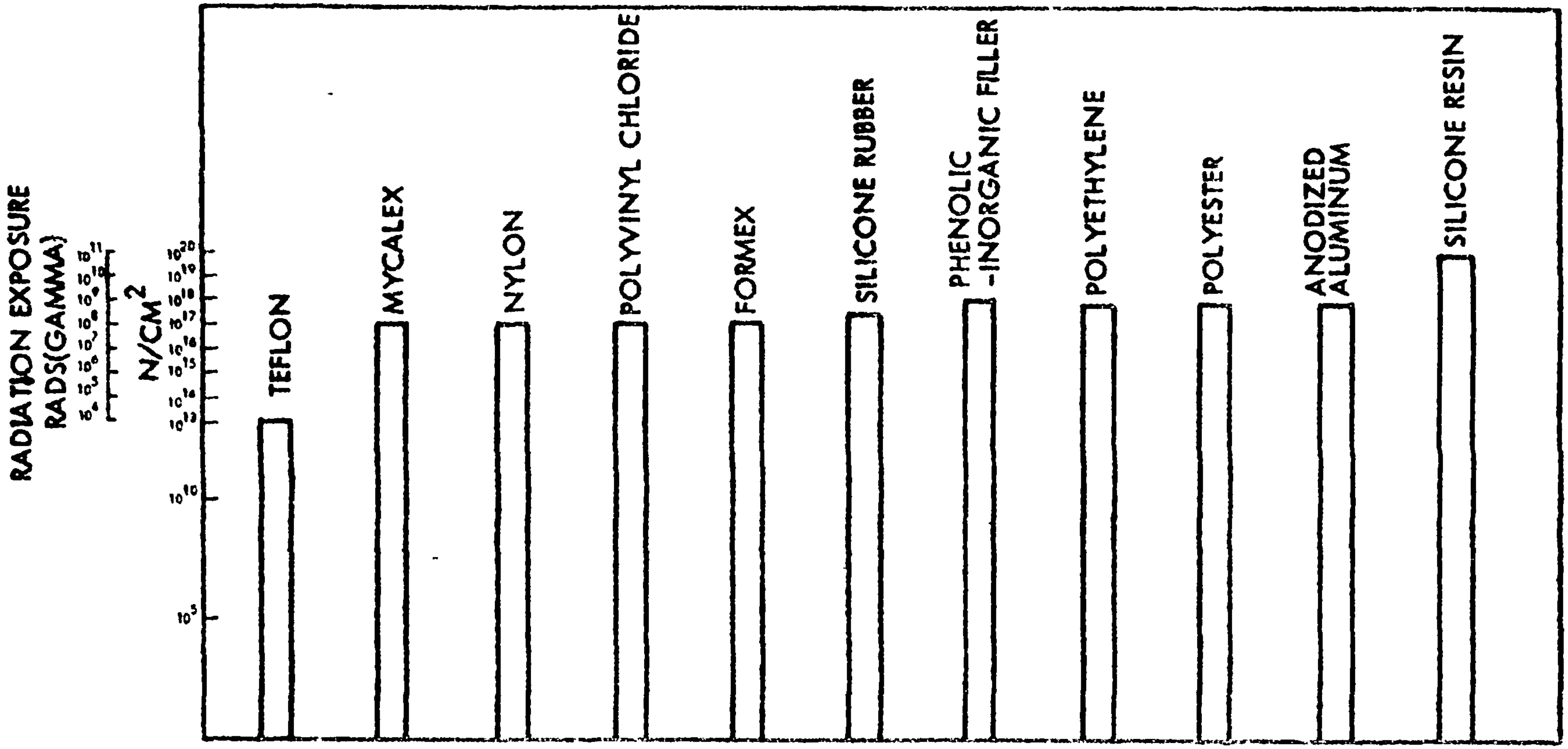

Figure 17.1 Maximum Radiation Exposure for Various Electrical Insulating Materials

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18.0 GLOSSARY OF TERMS

1. ATOM - Smallest particle of an element which is capable of entering into a chemical reaction.

2. BETA PARTICLE - A negatively or positively charged electron with an energy range of approximately 1 mev.

3. CARRIER REMOVAL - A radiation effect in semiconductors whereby a defect is introduced into the material which may act as a donor or acceptor. In the event that the defects act as donors in a material doped with acceptors, then the net external effect is the removal of a carrier from the semiconductor.

4. CHARGED PARTICLE - Any nuclear particle (electron, proton, etc.) having an electrical charge associated with it.

5. COLLISION - Encounter between two subatomic particles (including photons) which changes the existing momentum and energy conditions. The products of the collision need not be the same as the initial systems.

6. COMBINED ENVIRONMENT - A radiation field or environment consisting of two or more types of radiation.

7. COMPTON EFFECT - The interaction of a photon with an electron where some of the energy of the photon goes to the recoil electron and the rest remains with the photon (non degraded in energy) which may make still more collisions.

8. COSMIC RAY - High-energy particles or electromagnetic radiation originating in interstellar space.

9. CROSS SECTION - The probability that a certain reaction between a nucleus and an incident particle or photon will occur. It is expressed as the effective area that the nucleus presents for the reaction. Usually expressed in barns.

10. CUMULATIVE DOSE (Radiation) - The total dose resulting from repeated exposures to radiation of the same region, or the whole body.

11. DAMAGE THRESHOLD - The fluence or dose at which detectable degradation of a component parameter or parameters occurs.

12. DISPLACEMENT DAMAGE - Degradation induced in a material by the displacement of atoms from their initial locations by collisions with bombarding nuclear radiation.

13. DISPLACEMENT SPIKE - When a fast moving atom collides with another atom, displacing it from its normal position, the end of the trail of the displaced atom is believed to be in a region containing 1 to 10 K atoms in which local melting and turbulent flow have occurred in an extremely short period of time. Effect is important where heavy metals and semiconductors are subjected to displacement forces.

GLOSSARY OF TERMS (Continued)

14. DOSE - According to current usage, the radiation delivered to a specified area or volume or to the whole body. Units for dose are roentgens for X or Gamma ray, reps or equivalent roentgens for beta rays. No statement of dose is complete without specifying location. It is usually specified as the amount of energy absorbed by tissue at the site of interest per unit mass.

15. DOSE RATE - Radiation dose delivered per unit time.

16. EPITHERMAL NEUTRON - Neutron having energy between 0.1 and 100 eV.

17. ELECTRON - A charged particle with unit mass and unit charge which is a constituent of every neutral atom. Has a rest mass of 9. 107 x 10^{28} grams. These particles are less massive than protons or alpha particles, therefore have greater penetration powers.

18. ELECTRON VOLT - The kinetic energy of an electron based on its mass and the velocity attained through an acceleration produced by a potential difference of one volt (abbreviated ev, 1 ev = 1.6 x 10^{-12} ergs of energy).

19. ENERGY LEVELS - Groups of energy bands or levels in which the electron and nucleus of a solid material exist.

20. ENERGY SPECTRUM - Number of particles per unit energy over range of energy represented in a nuclear radiation field.

21. ENVIRONMENTAL COMPONENT - Any specific type of radiation contributing to a radiation environment consisting of mixed radiation types.

22. EV - Electron volt

23. EXCITATION - Process by which an atom or molecule gains energy to raise its ground state to an excited state without particles being ejected. Process often produces secondary radiation.

24. FAST NEUTRON - A neutron with an energy level of 10 kev or more.

25. FISSION - The splitting of a nucleus into at least two fragments accompanied by emission of a number of neutrons and the release of energy.

26. FLUENCE - Number of particles incident on a one square centimeter surface or area, i.e., particles/cm^2.

27. GAMMA RAY - A quantum of short wavelength electromagnetic radiation emitted by a nucleus in its transition from a lower energy state. The range of wavelengths is from about 10^{-8} to 10^{-11} cm. Gamma rays have zero rest mass and zero charge but energies in the range of approximately 1 mev. The intensity of 1 mev of gamma is halved in 4 inches of water.

GLOSSARY OF TERMS (Continued)

28. HARDNESS - Radiation Resistance

29. INTERFACE STATES - Allowable energy levels at the interface or junction of silicon material and silicon dioxides passivation layer.

30. INTEGRATED FLUX - Cumulative number of particles per square centimeter over an interval of time.

31. INTERSTITIAL ATOMS - Atoms which are displaced from their equilibrium positions in a nearby vacancy.

32. IONIZATION DAMAGE - Damage caused by interaction of incident radiation with orbital electrons.

33. IONIZATION EFFECT - An effect resulting from material being ionized by incident radiation, ionization damage.

34. IONIZING RADIATION - Radiation that interacts primarily with orbital electrons of material it is incident upon.

35. MEV - One million electron volts

36. NEUTRON - An atomic particle with zero charge and a mass approximately that of a hydrogen atom. Neutrons are highly penetrating and when passing through matter are attenuated exponentially while colliding with nuclei. (Do not collide with electrons). In a free state, neutrons decay into a proton and an electron.

37. NUCLEAR RADIATION - Neutrons, alpha, beta, and gamma rays from primary or secondary power plants, nuclear weapons, natural space radiation. Only neutrons and gamma rays penetrate shielding. Neutron energies range to 20 mev (about 35 percent at 0.8 mev). Gamma ray energies range from about 300 kev to at least 8.0 mev (average about 1.5 mev)

38. NUCLEUS - The positively charged core of an atom which accounts for practically all of the atom's mass.

39. NVT - Total number of neutrons passing through a unit area during period of time under consideration.

40. PARTICLE RADIATION - Radiation consisting of energetic particles such as electrons, protons, neutrons, and alpha particles.

41. PERMANENT DAMAGE - Occurs when displacement and/or rearrangement of atoms or groups of atoms takes place in a material. Degree of permanent damage depends on total or integrated dose received, type of radiation, and temperature.

42. PROTON - An elementary nuclear particle with a positive electric charge equal numerically to the charge of an electron but whose mass is equal to approximately 1847 times the mass of an electron.

GLOSSARY OF TERMS (Continued)

43. R - Abbreviation for roentgen

44. RAD - A unit of absorbed dose. One rad is equal to 100 ergs of absorbed energy per gram of absorbing material. This unit cannot be used to describe a radiation field.

45. ROENTGEN - Quantity of X or gamma rays which will produce as a result of ionization electostatic unit of electricity (either sign) in 1 cc of dry air at 0°C and standard atmospheric pressure. One roentgen = absorption of 83.8 ergs of energy per gram of air.

46. SCATTERED ELECTRON - Electron that has been freed from its atomic orbit due to collisions with bombarding radiation.

47. SLOW NEUTRON - See thermal neutron.

48. SOLAR FLARES - Chromospheric eruptions occurring in the vicinity of sunspot groups. These eruptions are observable in certain lines in the visible and far ultraviolet ranges. Consist of intense streams of X rays, ultraviolet rays, protons and electrons ejected from the sun at irregular intervals by electromagnetic storms associated with sun spots. Most of these streams are absorbed by the earth's atmosphere.

49. SOLAR WINDS - Streams of protons that have been ejected by the sun and are traveling through space.

50. STOPPING POWER - Total energy lost by incident particle per unit distance.

51. TEMPORARY DEGRADATION - Radiation induced damage or degradation which recovers at room temperatures upon termination of the radiation, usually in times of a few hours or less.

52. THERMAL NEUTRON - A neutron which is in thermal equilibrium with its surroundings. Energy level is less than 1 ev. Thermal neutrons cause capture gamma radiation (excitation energy emitted on capture).

53. THRESHOLD DOSE - The minimum dose fluence that will produce a detectable degree of any given effect.

54. TRANSIENT EFFECTS - A phenomena which occurs when radiation causes electronic excitation without atomic displacement in a material. Usually results from ionizing radiation and is a function of the dose rate.

55. TRANSMUTATION - The process in which one species of atom is transformed into another by a nuclear radiation.

56. THRESHOLD OF DAMAGE - Dosage level at which any additional radiation will change the basic characteristics of the material under irradiation.

GLOSSARY OF TERMS (Continued)

57 VACANCIES - Vacant lattice sites created by collision of energy particles with atoms in a solid lattice.

58. X RAY - A form of penetrating electromagnetic radiation (zero charge, zero mass) having wave lengths shorter than those of visible light (approximately 10^{-8} cm). Usually produced by bombarding a metallic target with a particle in a high vacuum. In nuclear reaction, it is customary to refer to photons originating in the nucleus as gamma rays and those in the extra nuclear part of the atom as X rays. Often called roentgen rays.

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