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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-576

Radiation Effects on Three Low-Power Microcircuits

K. A. Yamakawa

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CALIFORNIA INSTITUTE OF TECHNOLOGY
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PREFACE

The work described in this report was performed by the Astrionics Division under the auspices of the Electronics Component Screening and Qualification Development Project of the Jet Propulsion Laboratory.

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ABSTRACT

This report gives the results of irradiation of several low power circuit elements by Co^{60} gamma radiation, low and high energy electrons (i. e. 1.5 MeV and 28-85 MeV) and neutrons. The bipolar circuits used were the SE480Q NAND gate and a micropower frequency divider used in electronic wrist watches, designated ICB-9002. The MOS device used was a dual p-Channel MOSFET designated 2N4067.

I. INTRODUCTION

Radiation tolerant electronic components of low power consumption are one of the major requirements for outer planet and other space missions of long duration. We have made a preliminary investigation of the radiation tolerance of several representative device types and present the results in this report.

II. RADIATION SOURCES

The radiation sources used were the following:

(1) 500 curie Co^{60} source at JPL

(2) 4000 curie Co^{60} source at JPL

(3) 1.5 MeV Van der Graaf electron source at Goddard Space Flight Center

(4) Triga neutron source at Northrup Corp., Hawthorne, Calif.

(5) 28 to 85 MeV LINAC electron source at Naval Post Graduate School, Monterey, California

III. DESCRIPTION OF CIRCUITS

A. Micropower Frequency Divider (ICB-9002, Intersil)

This is a bipolar digital microcircuit of extremely low power consumption. It divides the frequency by a factor of 2^{14} and has input and output stages. Its supply voltage is approximately one volt and the total supply current during operation is approximately five microamperes or a total power consumption of five microwatts.

B. Dual p-Channel MOSFET (2N4067-Teledyne)

These devices are dual p-channel MOS field effect transistors designed primarily for low-power chopper or switching applications. Two types were used, glass passivated and unpassivated devices. This was done to investigate surface effects including those produced by low temperature glass passivation methods.

C. Monolithic TTL Element (SE 480Q, Signetics)

These circuits are bipolar quadruple twc-input NAND gates. They are low power TTL elements with power consumption of approximately 3. 5 milliwatts per gate. The results are compared with those for the SN54L00 and the RSN54L00 TTL elements, both bipolar quadruple two-input NAND gates, the latter being circuit hardened for radiation pulses. Both of these have a power consumption per gate of approximately one milliwatt.

IV. DISCUSSIONS OF RESULTS AND CONCLUSIONS (Ref. 1)

A. Micropower Circuits

The micropower digital circuit ICB-9002 frequency divider was very resistant to ionizing radiation considering its very low current densities and power consumption (Ref. 2). The pulse heights do not degrade to fluences of 10^5 rads (silicon) and they are still operable after a fluence of 10^6 rads (silicon) (Fig. 1). The power consumption per gate is estimated at about 100 nanowatts with corresponding low currents and high impedances, conditions under which the lifetime of minority carriers and thus the gain of the transistor are vulnerable to radiation.

B. TTL Elements

The bipolar digital circuit SE480Q TTL NAND gate with a power consumption per gate of 3.5 milliwatts is more resistant to ionizing radiation than the SN54L00 and RSN54L00 TTL NAND gates with power consumption per gate of approximately 1 milliwatt. The RSN54L00 is more resistant to radiation than the SN54L00. The circuits differ in their diffusion depths and base widths (Table 1). Bipolar circuits are vulnerable to radiation through surface ionization effects as well as to displacement damage in the base. The relative importance of surface effects becomes greater as device geometries become smaller and closer to the surface (Ref. 3). Thus the fact that the base width of the RSN54L00 is narrower than that of the SN54L00 (Table 1) may be why it is more radiation resistant whereas low current densities and the relatively greater importance of surface effects made the 54L's more vulnerable than the SE480Q (Fig. 10).

C. SN4067 MOSFET

All shifts in threshold voltage were in the negative direction consistent with a net positive space charge build-up in the oxide. Also, gates unbiased during irradiation showed greater shift in threshold voltage than those biased negatively, consistent with a movement of the space charge with voltage (Ref. 4).

No passivation effects were observed (Figs. 3 and 4). This is believed to be due to shielding of the active region by overlapping gate electrodes. It is believed that shielding will be less and fringe fields will become important as device geometries become smaller thus making requirements on passivation materials more stringent (Ref. 5). There was also no evidence of saturation in the threshold voltage shift to the highest fluence levels used, i.e. 10^7 rads (silicon) Co^{60} gamma and 10^{15} electrons/cm^2 at 85 MeV (Ref. 4).

D. Displacement and Ionization Effects

Damage due to neutrons was very small for the MOSFET SN4067 (i.e. a shift of 0.3 volts in output saturation voltage for a neutron fluence of $1.86 \times 10^{13}/cm^2$) almost accounted for by the background gamma radiation of the neutron source, 4.7×10^3 rads (silicon) (Fig. 7, a and b). A shift of this magnitude in threshold voltage was produced by a Co^{60} gamma radiation fluence of less than 10^4 rads (silicon) (Fig. 3). The SE480Q NAND gate, however, was more vulnerable to neutron irradiation. The same neutron fluence as before produced a shift in the output saturation voltage (VO_o) of seven percent (Fig. 14) a change requiring 10^7 rads (silicon) of Co^{60} radiation to produce (Fig. 10). Since neutrons produce primarily displacement damage while Co^{60} gamma radiation produces primarily ionization damage, the MOSFET circuit is primarily vulnerable to ionization effects while the bipolar digital SE480Q circuit is more vulnerable to displacement effects.

E. High and Low Energy Electrons

A comparison of the high energy (85 MeV) and low energy (1.5 MeV) electron irradiations of the SN4067 MOSFET circuits and the SE480Q TTL element shows the following. The MOSFET circuit shows less damage as seen by a shift in the threshold voltage for the high energy electrons than for the low energy electrons (Fig. 6). However, the TTL element shows greater damage as seen by a shift in the output saturation voltage (VO_o) for high energy electrons than for low energy electrons (Fig. 13). From the discussion in paragraph D these results show that high energy electrons (i.e. ~ 85 MeV) do produce appreciable displacement damage as well as ionization damage compared to low energy electrons (i. e. ~ 1. 5 MeV) which produce primarily ionization damage. Published results of radiation effects on microcircuits caused by high energy radiation are few. More work in this area is necessary before confidence can be placed in extrapolations and equivalences based on low energy results.

V. RADIATION TEST RESULTS

A. Micropower Frequency Divider - (ICB 9002, Intersil)

This integrated circuit is a micropower frequency divider made for use in electronic wrist watches. It operates with a supply voltage of approximately one volt and draws a total dc current of approximately five microamperes making a total power consumption of five microwatts. The circuit divides the frequency by a factor of 2^{14} and has input and output stages. It is driven by a square wave pulse input of one half volt and a frequency of 2^{14} Hz or approximately 16.5 kHz. The output is approximately 0.8 volts with a frequency of one Hz.

It is a digital bipolar integrated circuit where the currents and current densities in the individual gate circuits are extremely low (i.e. currents of less than 100 nanoamps) with correspondingly high impedances. The frequency of operation is low being less than about 20 kHz.

1. Gamma Irradiation With Co^{60}

Eight circuits were exposed to Co^{60} gamma rays for radiation fluences of 10^4, 10^5, 10^6 and 10^7 rads (silicon). The devices were open circuited during irradiation. An effort was made to choose those parameters that show early indication of degradation by radiation.

The following parameters were measured after each fluence level: the output pulse height, the rise time of the output pulse and the supply voltage threshold for operation as functions of the radiation fluence. The input was obtained from a square wave generator operating at 16.5 kHz with the negative portions of the wave clipped resulting in positive square wave pulses of 0.5 volts magnitude with a duty cycle of 50 per cent.*

The supply voltage used for the pulse height and rise time measurements was 0.9 volts. This is approximately twice the threshold voltage for circuit operation.

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*Radiation measurements by D. Reed, JPL.

2. Results

Figure 1 gives the results obtained for the threshold supply voltage for operation, the output pulse height, and the reciprocal rise time as a function of the radiation fluence. All of the circuits except one survived to a radiation fluence of 10^6 rads (silicon) although the pulse heights and the rise times suffered considerable degradation. All of the circuits were inoperative after a radiation fluence of 10^7 rads (silicon). The rise time of the output pulse showed the earliest indication of degradation due to radiation. The threshold supply voltage showed the least change with radiation. When the low currents and current densities involved are considered, these circuits are remarkably resistant to radiation degradation. This is in accordance with the observation that bipolar digital elements are resistant to degradation by radiation as discussed in a later section where results are given for the TTL element, SE480Q.

B. Dual p -Channel MOSFET - (2N4067-Teledyne)

These devices are dual p-channel MOS field effect transistors designed primarily for low-power chopper or switching applications. They have one source with two drains. There were two types used, unpassivated and glass passivated devices. These were obtained as engineering samples. These circuits were exposed to Co^{60} gamma, high (25-85 MeV) and low (1.5 MeV) energy electrons, and to neutrons. The parameter measured was the shift in threshold voltage. Bias conditions during irradiation were also considered by irradiating the devices with the leads shorted and with a negative bias on the gates.

1. Gamma Irradiation

Six passivated and six unpassivated dual channel MOSFETS (2N4067) were used, for a total of twenty four devices. These were divided into three groups of four devices each for the passivated and unpassivated devices in the following way: controls, those with gates biased to minus 20 volts, and those with their leads shorted during irradiation.

A Co^{60} gamma source of 500 curies at JPL was used to irradiate the circuits to 10^4 and 10^5 rads (silicon) at a radiation fluence rate of 10^4 rads/hour. The JPL ring Co^{60} gamma source of 4000 curies which produces a radiation fluence rate of 6.5 x 10^5 rads/hour at the center of the ring was used to irradiate to fluences of 10^6 and 10^7 rads (silicon).*

2. Results

A block diagram of the circuit used to measure the shift in the threshold voltage is given in Fig. 2. The threshold voltage was measured as that value of negative bias between gate and source to produce 10 microamperes of current between source and drain with V_{DS} (drain to source voltage) equal to -15 volts. Figs. 3 and 4 give the results obtained for the passivated and unpassivated circuits. The results are given in terms of the shift in threshold voltage. The threshold voltages of the control devices were measured at the time of measurement of the irradiated samples as a check on the measurement set up. All shifts were in the negative direction and were about two volts at 10^5 rads (silicon). This corresponds to a shift in the threshold voltage of fifty percent from the initial value which is about minus 4 volts. The negative shift in threshold voltage is consistent with a positive charge build-up near the silicon-silicon dioxide interface. Also, the shift in threshold voltage is greater for the case with the leads shorted than for the case where the gate is biased negative with respect to the source. This is consistent with a migration of the positive space charge away from the silicon-silicon dioxide interface towards the gate electrode. There is no evidence of saturation of the threshold voltage shift up to 10^7 rads (silicon), the maximum radiation fluence level attained. The results for the passivated and unpassivated devices are similar except for a small difference in behavior of the biased and shorted conditions of irradation.

3. 1.5 MeV Electron Irradiation

Six unpassivated p-type channel dual gate MOSFETS (2N4067), totaling twelve devices, were exposed to 1.5 MeV electrons using the Van der Graaf generator at the Goddard Space Flight Center.** The twelve devices were divided into three groups of four each as follows: those with gates biased to

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*Data from R. Campbell and D. Lawson, JPL.
**Irradiated at Goddard Space Flight Center, P. Newman.

minus twenty volts, those with leads shorted, and controls. The maximum radiation fluence to which the devices were exposed was 10^{14} electrons/cm^2. The caps of the T05 packages in which the devices were packaged were not removed.

4. Results

The shift in threshold voltage as a function of electron fluence was measured and is presented in Fig. 5. The measurements for the case where the gate was biased to minus twenty volts and where the leads were shorted are given together with the measurements taken on the control devices. The results are similar to those obtained for the unpassivated devices exposed to gamma radiation and discussed in the previous section.

Figure 6 gives a comparison between results obtained with 1.5 MeV electrons and 85 MeV electrons. The low energy electron results are those obtained with a minus 20 volt bias applied to the gate during irradiation. In the case of the high energy electron irradiation the devices were connected to measure the threshold voltage during irradiation and thus a bias of from minus four to approximately minus ten volts was applied to the gate during irradiation. Also, the sampling was small, especially for the high energy irradiation where the results are based on measurements of only two devices. Faraday cup dosimetry was used in both cases; however, the irradiations were performed at two different facilities (i. e. Goddard Space Flight Center and the Naval Post Graduate School). Although these conditions are not ideal the data indicates that there is less shift in the threshold voltage for the high energy irradiation (i.e. 85 MeV) than for the low energy electrons (i.e. 1.5 MeV).

5. Neutron Irradiation

Six passivated and six unpassivated dual channel MOSFETS making a total of twenty four devices were divided into three groups of four devices each. One group was used as control and the other two groups were irradiated with the gates biased to minus twenty volts and with the gates shorted. The irradiation was performed using the Northrup Triga Reactor. The total fluence was 1.86×10^{13} n/cm^2 greater than 10 KeV. The fluence was determined using sulfur foil dosimetry which is sensitive to neutrons of energy greater than 3 MeV and this fluence was converted to neutrons greater than 10 KeV. There was a background of gamma radiation with a total fluence of 4.7×10^3 rads (silicon). This fluence was obtained using a CaF_2:Mn dosimeter shielded to give a flattened response.*

6. Results

The shift in threshold voltage was measured before and after irradiation. The change in threshold voltage is shown in Fig. 7A and B for the unpassivated and passivated devices with gates biased to minus twenty volts, for those with leaks shorted and for the control devices. The initial values of the threshold voltages were approximately minus 4 volts. All shifts were in the negative direction. The shifts in threshold voltages are very small compared to those obtained with gamma radiation and electrons discussed in the previous sections and can almost be accounted for by the gamma background (i.e., compare Fig. 3 on Co^{60} radiation).

C. Monolithic TTL Element (SE480Q, Signetics)

These monolithic TTL elements are bipolar devices. They are quadruple two-input NAND gates. These circuits are low power TTL elements with a power consumption of approximately 3.5 mw/gate. They are exposed to Co^{60} gamma radiation, high (25-85 MeV) and low (1.5 MeV) electrons, and to neutrons. The parameter measured was the output saturation voltage (VO_0). This parameter is the most sensitive to degradation by radiation. Figure 8 gives the circuit used to measure the output saturation voltage (VO_0). The results are compared with those for the SN54L00 and the RSN54L00 for the case of gamma irradiation to a fluence of 10^5 rads (silicon). Fan out conditions and bias conditions during irradiation were also considered.

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*Data on source supplied by W. E. Price, Div. 37, JPL.

1. Gamma Irradiation

The integrated circuits were divided into four groups of ten circuits each. The shift in the output saturation voltage (VO_o) was measured at various radiation fluence levels up to 10^7 rads (silicon). One group was used as control to check the measurement instrumentation. The other three groups were irradiated at three fluence rates, 10^3, 10^4, and 6×10^5 rads/hour to see if rate effects can be observed in this range of fluence rates. The JPL radiation facilities described in a previous section were used. The results obtained are compared with those obtained for the SN54L00 and RSN54L00 integrated circuits which are also quadruple two-input NAND gates, but have smaller power consumption per gate. The comparison is made at a gamma ray fluence level of 10^5 rads (silicon).

2. Results

Figure 9 gives the results obtained for the change in output saturation voltage using radiation fluence rates of 10^3, 10^4, and 6×10^5 rads/hour. Radiation fluence rate effects were not observed. Figure 10 gives the results for the radiation fluence rate of 6×10^5 rads/hour for the SE480Q together with the results obtained at a radiation fluence level of 10^5 rads for groups of ten SN54L00 and RSN54L00 quadruple two-input NAND gates (Texas Instruments). These results were obtained from radiation tests of electronic parts for the Thermo-electric Outer Planets Spacecraft (TOPS)*. Table 1 gives some of the electronic and design characteristics of the three device types. The primary difference in their electronic characteristics is in the power consumption per gate being approximately 3.5 mw for the SE480Q's and about 1 mw for the 54L's. Their design characteristics differ in the diffusion depths and base thicknesses (Table 1). The RSN54L00 is hardened for radiation pulses and thus uses dielectric isolation and photo current compensation. All of these circuits are very resistant to degradation due to radiation where the maximum specification value of the output saturation voltage (VO_o) is 0.300 volts and the average value of the unirradiated output saturation voltage is approximately 0.18 volts, thus allowing for a large rise in output saturation voltage.

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*Data supplied by K. Martin, JPL.

3. Electron Irradiation

Eight circuits consisting of four devices each for a total of thirty-two devices were used for the test. Of these, two circuits were controls. The six circuits remaining were operated during irradiation with the following conditions:

DEVICE #	INPUT	OUTPUT
1	10 μs Square wave	7 Fan out
2	10 μs Square wave	1 Fan out
3	High	7 Fan out
4	Low	7 Fan out

The shift in the saturation output voltage was measured before and after various levels of fluence to a total fluence of 3.16×10^{15} electrons/cm^2. Electrons of 1.5 MeV from a Van der Graaf generator were used and the fluence rate was 10^{11} e/cm^2 -sec to a fluence of 3.16×10^{13} e/cm^2 and then at 10^{12} e/cm^2 -sec to a fluence of 3.16×10^{15} e/cm^2. The fluence was measured by integrating the current in a Faraday cup placed at the center of the devices irradiated. The electron beam was scanned electro-magnetically so that all the samples were uniformly irradiated.

4. Results

Fig. 11 gives the percent change in output saturation voltage (VO_o) as a function of electron irradiation fluence for devices where the output was kept high during irradiation and for devices where the output was kept low during irradiation. Figure 12 gives the corresponding results for simulated fan outs of one and seven. In both cases there is not a significant difference in behavior with electron irradiation. Figure 13 gives the average results for all devices irradiated at 1.5 MeV. The results obtained for 28 and 85 MeV electrons are superimposed on this figure.* The irradiation damage as observed by a shift in the output saturation voltage is in approximate agreement for low and high energy electrons at the lower fluence values, but the shift in output

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*Data obtained at Naval Post Graduate School, Monterey, Calif., Contract NPS-61DY71121B, J. Dyer.

saturation voltage is much greater for high energy electrons at the higher fluences than for low energy electrons (i. e. 28 and 85 MeV electrons compared with 1. 5 MeV electrons). Although these measurements were made at separate facilities using different Faraday cup dosimetry (i. e. high energy and low energy cups) and the sampling is small, the data shows that the degradation in output saturation voltage is greater for high energy electrons (i.e. 28-85 MeV) than for low energy electrons (i. e. 1. 5 MeV).

5. Neutron Irradiation

Ten SE480Q quad TTL logic elements making a total of forty devices were used for the neutron irradiation test. Thirty two of these devices were irradiated and eight of them were used as controls to check the measurement system and were not exposed to radiation. The devices were unpowered during irradiation. The irradiation was carried out using the Northrop Triga Reactor. The total fluence was 1.86×10^{13} n/cm^2 greater than 10 KeV. The fluence was determined by sulfur foil dosimetry. There was a background of gamma radiation with a total fluence of 4.7×10^3 rads (silicon). This fluence was obtained using a CaF_2: Mn dosimeter.

6. Results

The shift in the output saturation voltage, VO_o was measured before and after irradiation. The results are given in Fig. 14 for the control measurements and for the irradiated samples. By comparing these results with those obtained by irradiation with Co^{60} in Fig. 10 the gamma radiation background produced negligible effect and the major effect is due to neutrons. The shift in output saturation voltage is small and the circuits will withstand considerable increase in neutron fluence levels before going beyond the limits set by the specifications (i. e. approximately 70%).

Table 1. Additional design and electrical characteristics of TTL devices tested.

Device	SE480Q	SN54L00	RSN54L00
Vin (1)	1.9 V min	1.9 V min	2 V min
Vin (0)	0.9 V max	0.8 V max	0.8 V max
V (out) (1)	2.3 V min	2.4 V min	2.4 V min
V (out) (0)	0.3 V max	0.3 V max	0.4 V max
I in (0)	-.55 mA	-.18 ma max	—
I in (1)	10 µA	10 µA	40 µA
Power/gate	3.5 mW	1 mW	1 mW
*t_{pd0}	30 - 75 ns	30 - 60 ns	—
Base diffusion depth	2.9 microns	3 - 4.5 microns	2-2.5 microns
Base thickness	0.9 microns	0.6 - 0.9 microns	0.3 - 0.6 microns
Isolation	Junction	Junction	Dielectric
Photo current comp	None	None	Yes
Size	1/4 x 5/16 x 0.050 in.	1/4 x 1/8 x 0.050 in.	1/4 x 1/4 x 0.050 in.
Resistors	Diffused	Diffused	Thin film nichrome

*Propagation delay time to logical 0 level

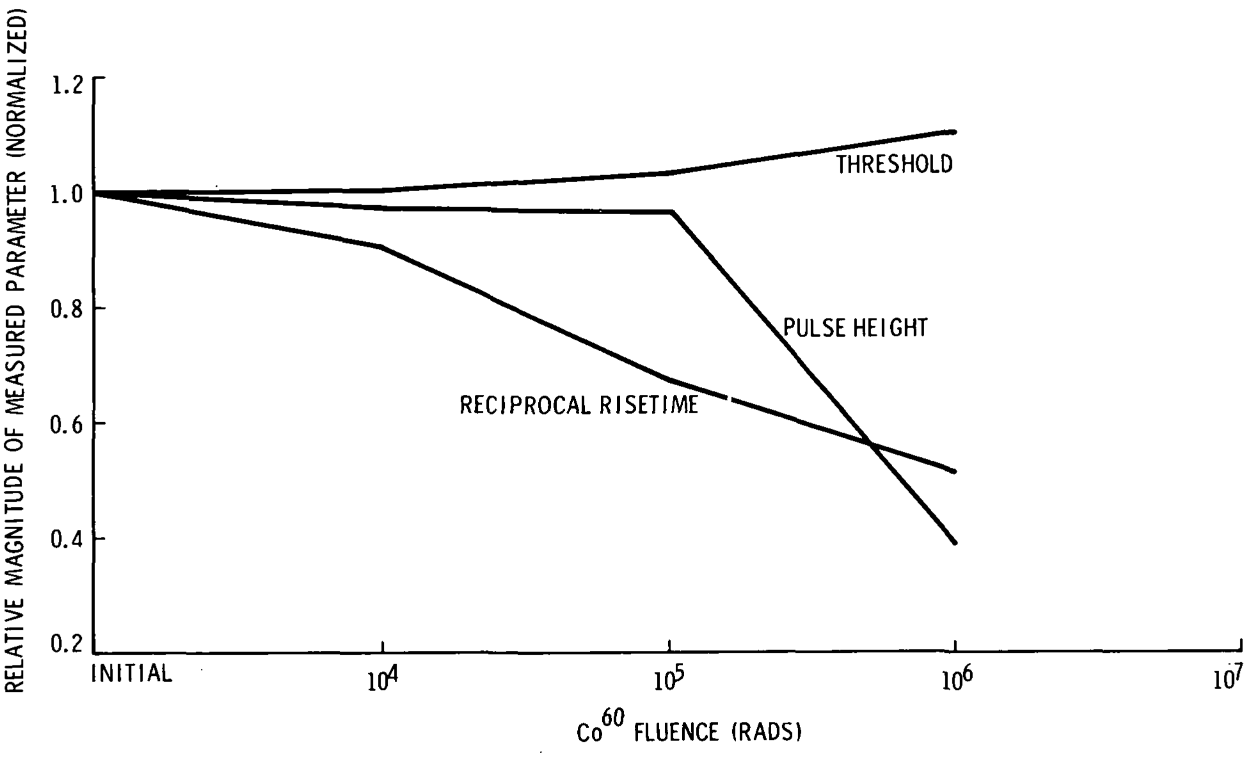
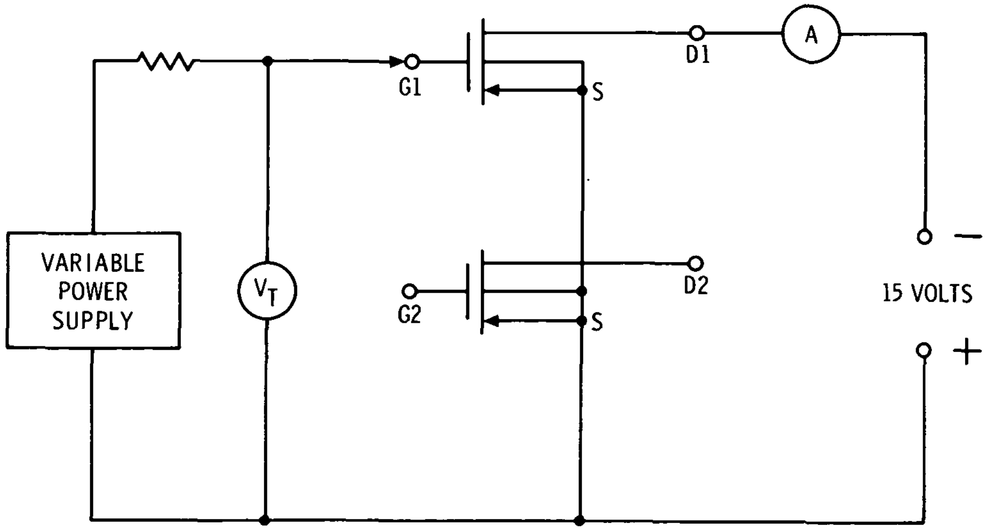


Fig. 1. The effect of Co^{60} gamma irradiation on micropower circuit, ICB-9002. Threshold, pulse height, and reciprocal rise time vs radiation fluence.



Note: A gate voltage is applied to produce 10 microamperes between source and drain defining V_T.

Fig. 2. Circuit used to measure threshold voltage V_T.

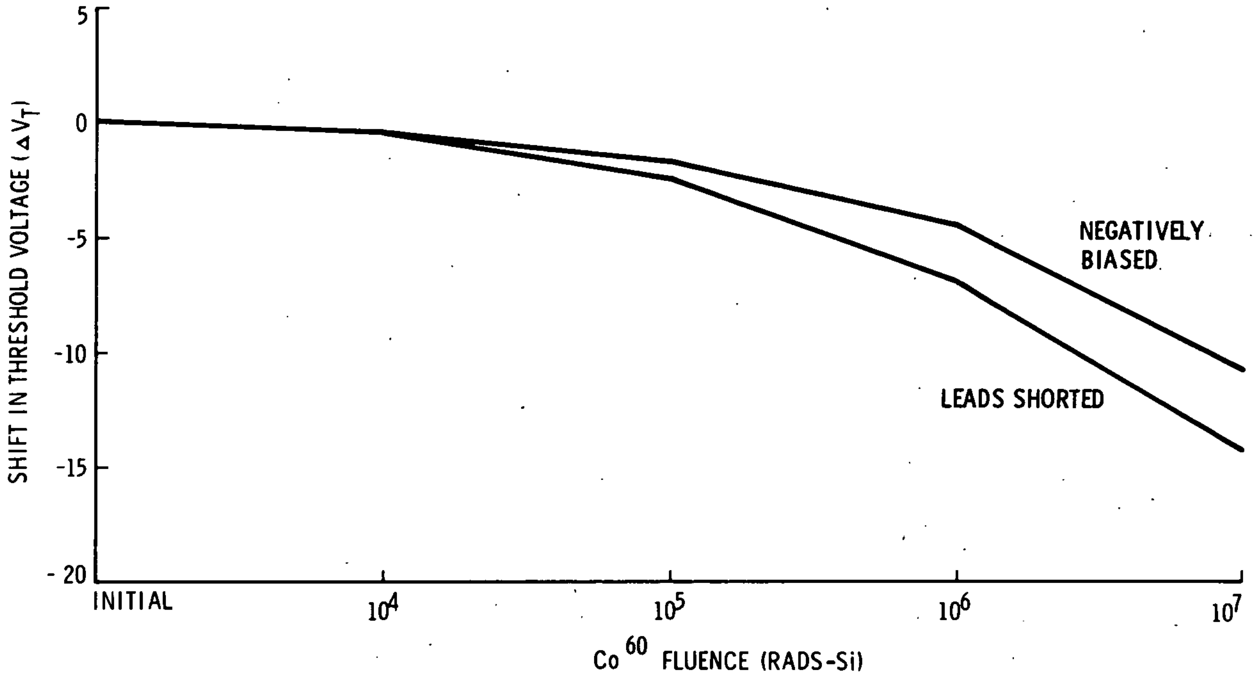


Fig. 3. The effect of Co^{60} gamma irradiation on passivated dual p-Channel MOSFETs.

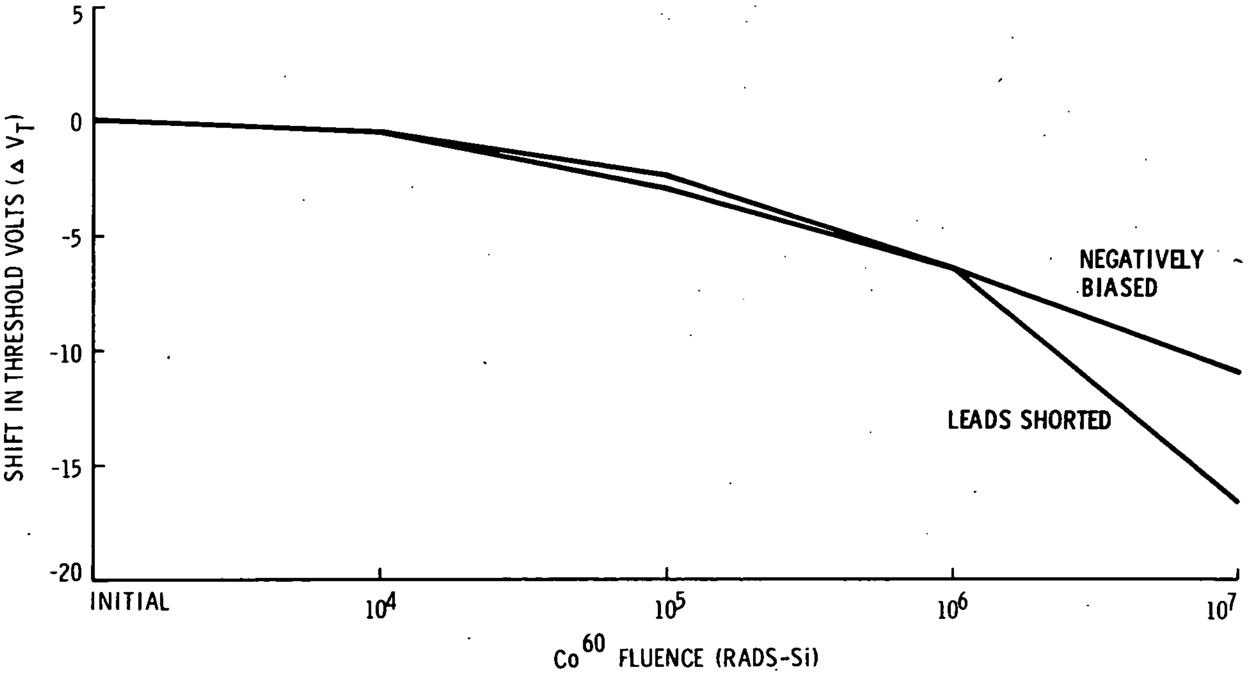


Fig. 4. The effect of Co^{60} gamma irradiation on unpassivated dual p-Channel MOSFETs.

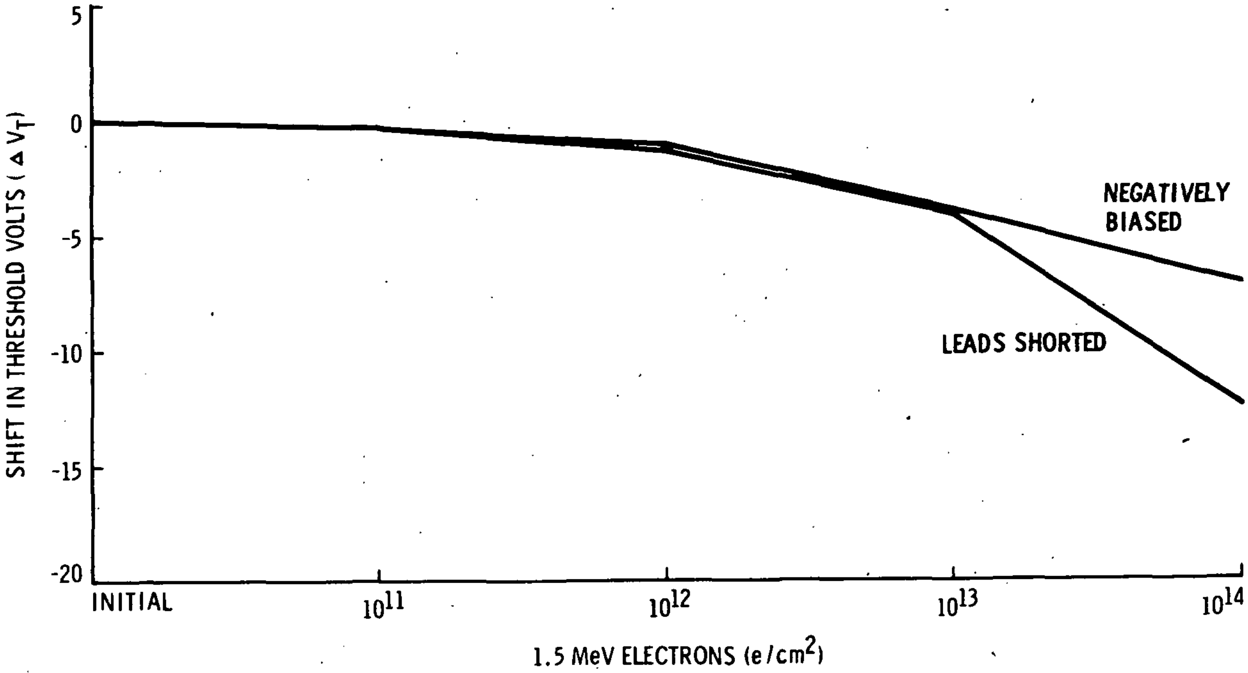


Fig. 5. The effect of 1.5 MeV electron irradiation on unpassivated dual p-Channel MOSFETs.

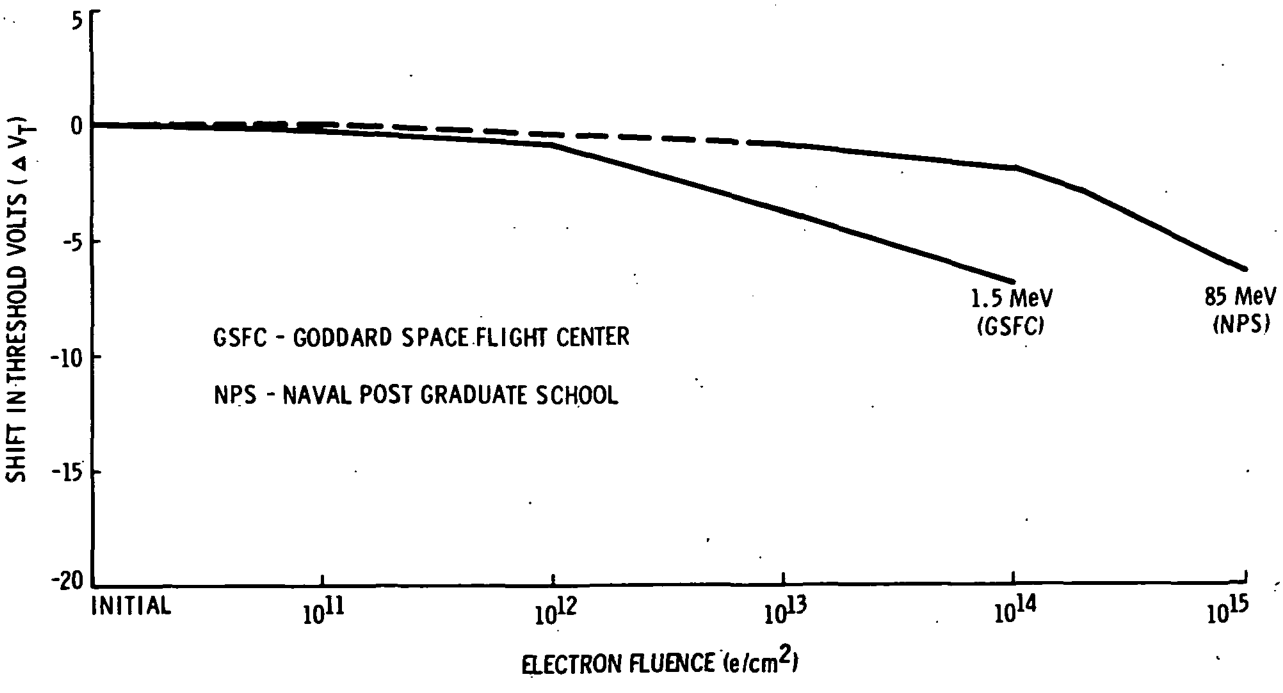
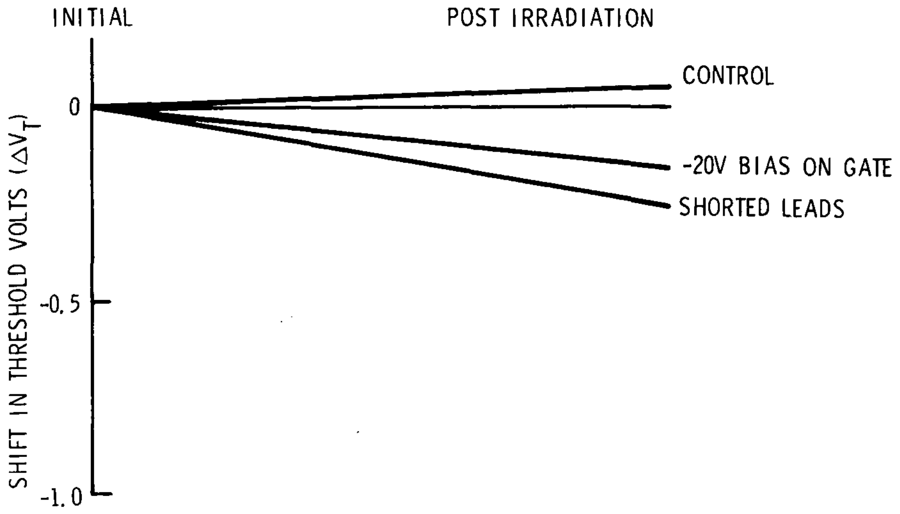
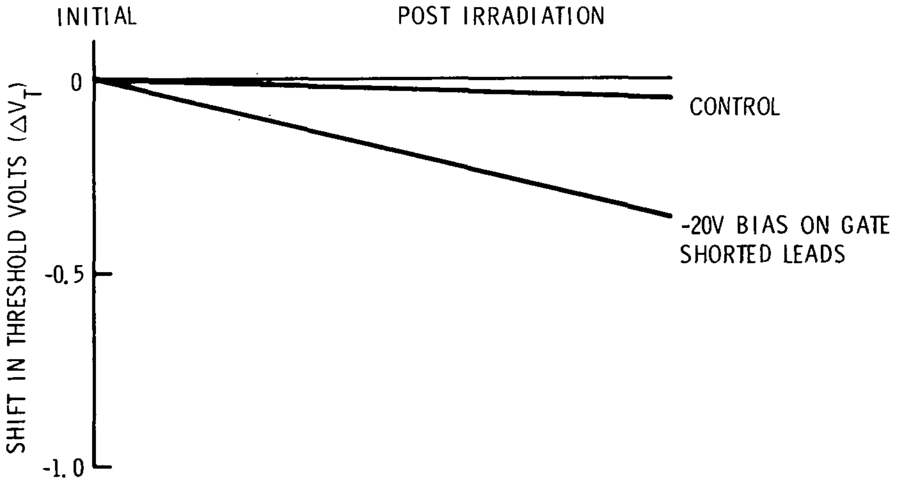


Fig. 6. A comparison of the threshold shift for low (1. 5 MeV) and high (85 MeV) electrons in p-Channel MOSFETS.



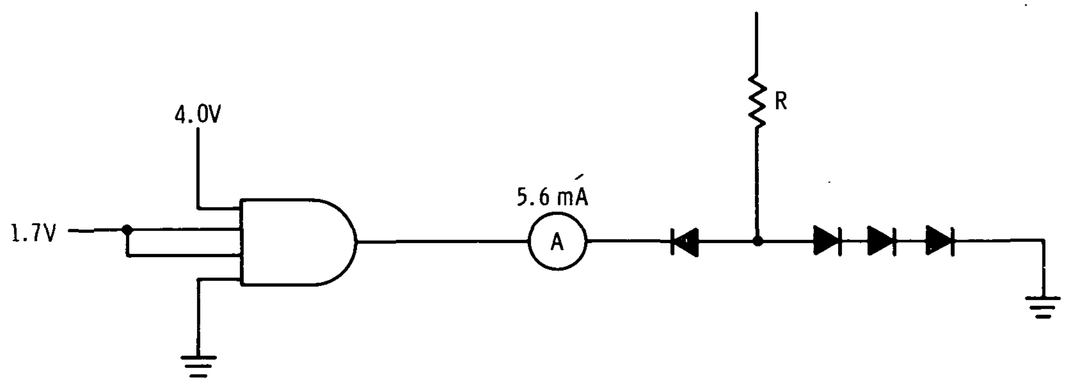
A UNPASSIVATED DEVICES



B PASSIVATED DEVICES

Note: Total neutron fluence, 1.86×10^{13} n/cm^2 gamma background fluence, 4.7×10^3 rads (silicon)

Fig. 7. The effect of neutron irradiation on p-Channel MOSFET devices (2N4067).



Note: Fan out simulated by R = 4000Ω for one and 680Ω for seven. VO_o measured with R = 680 Ω.

Fig. 8. Circuit used during irradiation and measurement of the output saturation voltage (VO_o).

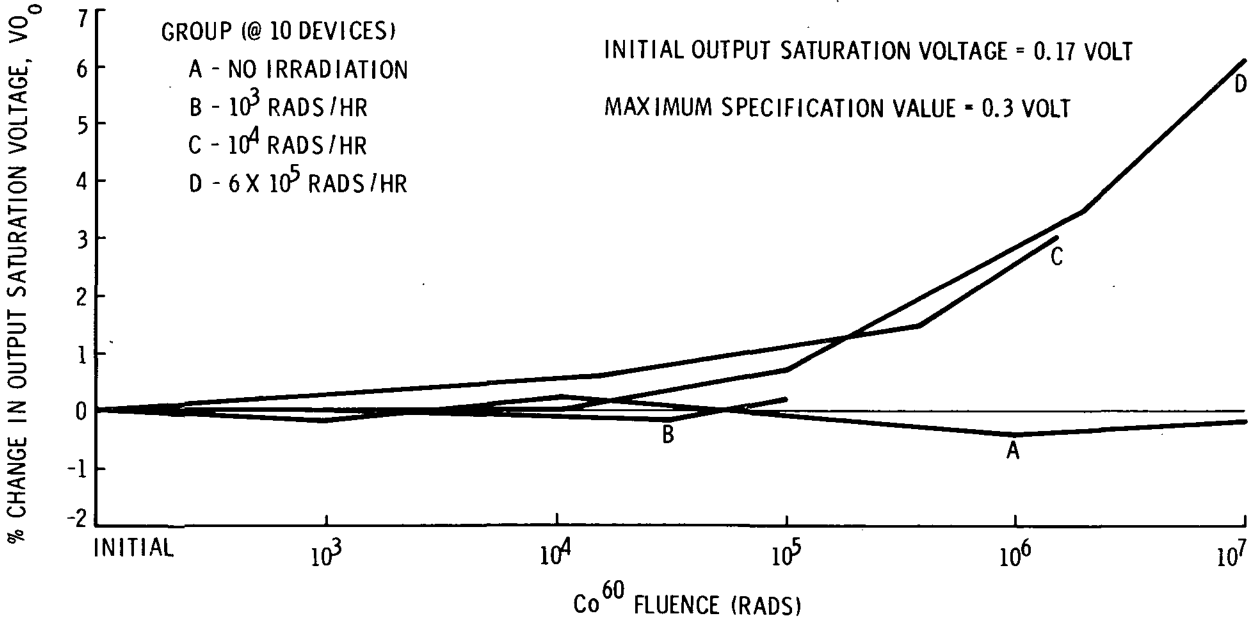


Fig. 9. The effect of Co^{60} gamma irradiation on TTL element SE 480Q at different fluence rates.

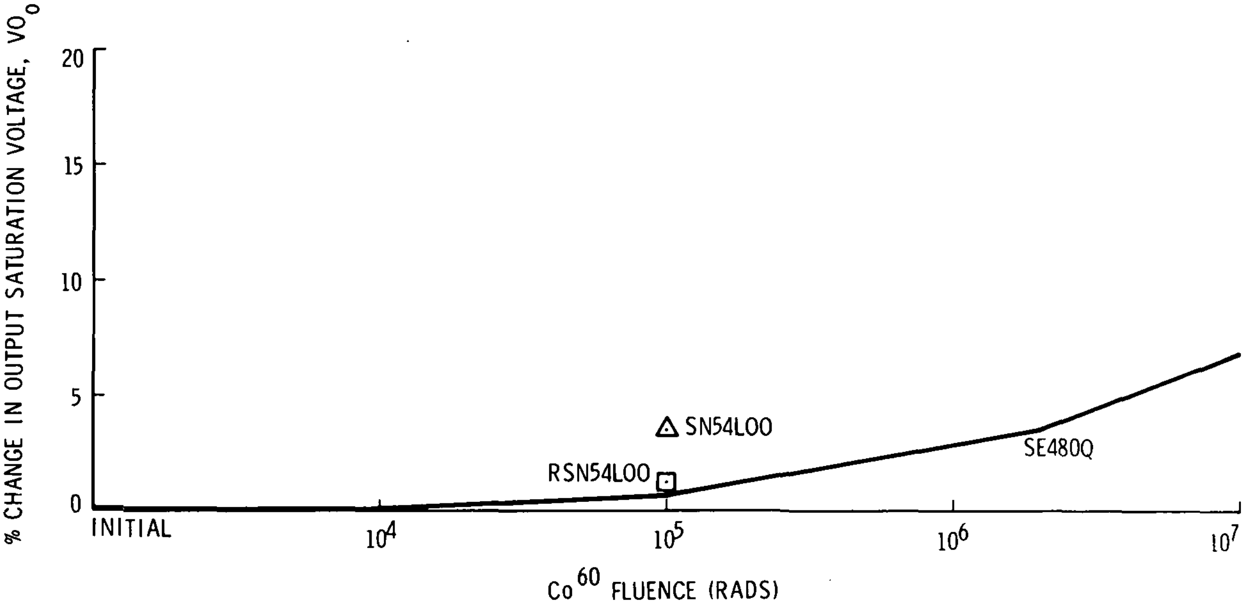


Fig. 10. A comparison of the effect of Co^{60} gamma irradiation on TTL elements SE 480Q, SN54L00 and RSN54L00.

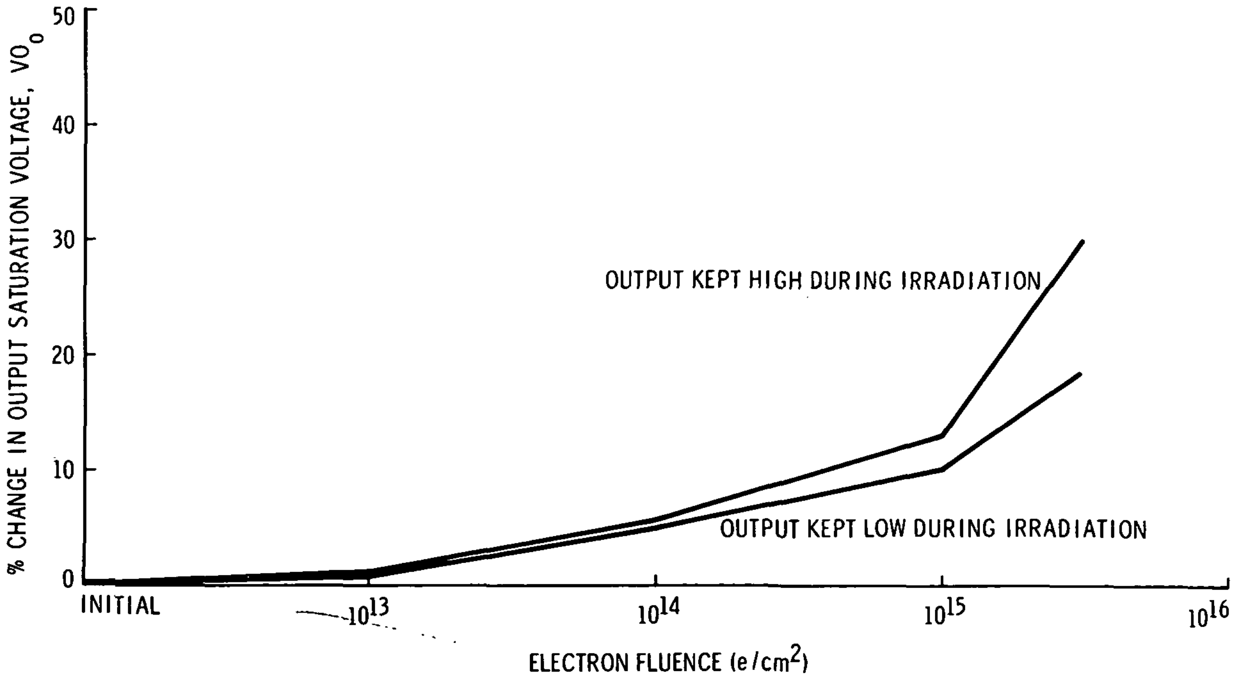


Fig. 11. The effect of 1.5 MeV electron irradiation on TTL element SE 480Q for different conditions of output.

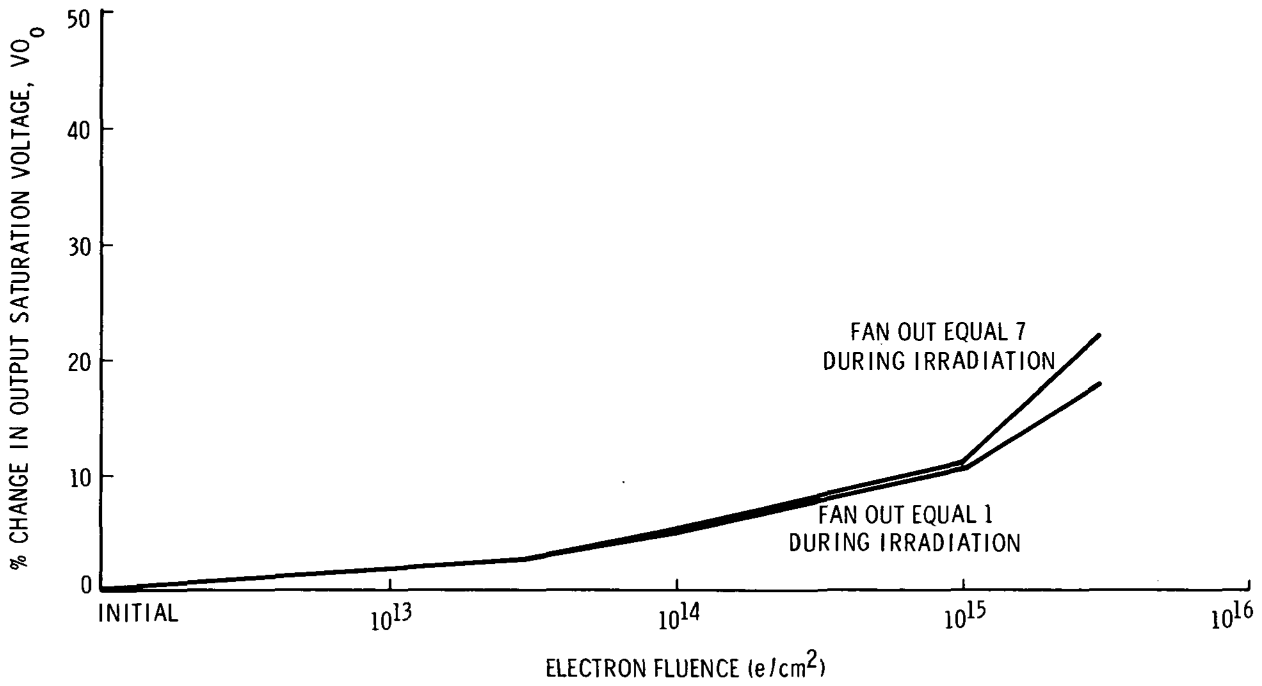


Fig. 12. The effect of 1.5 MeV electron irradiation on TTL element SE 480Q for different conditions of fan out.

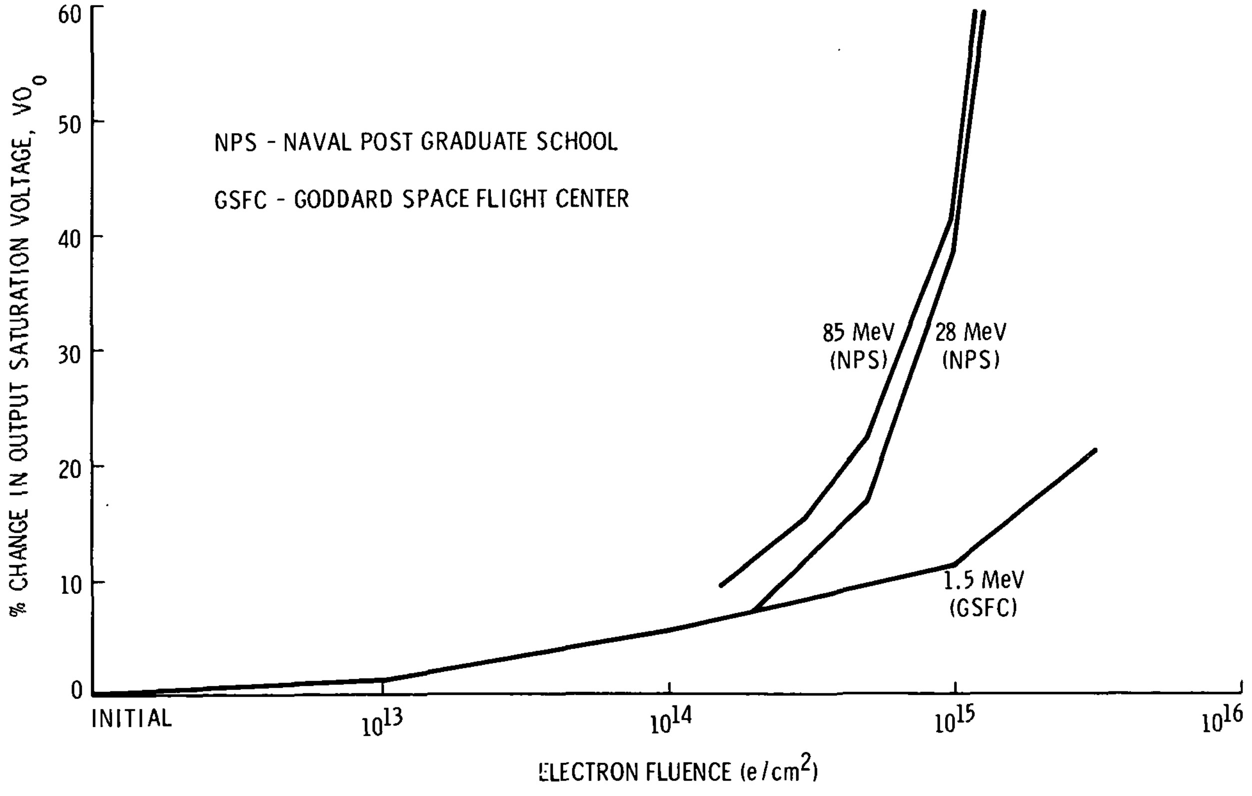
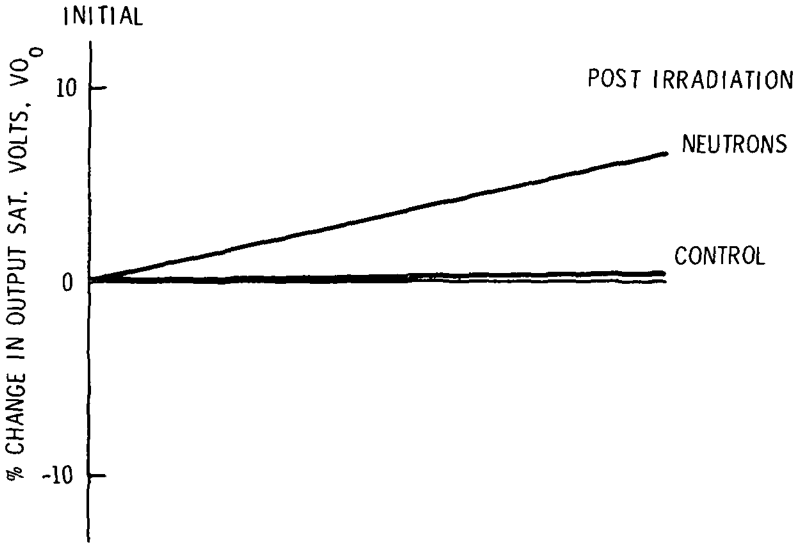


Fig. 13. A comparison of low (1. 5 MeV) and high (85 MeV) electron irradiation of TTL element SE480Q.



Note: Total neutron fluence, 1.86×10^{13} n/cm^2, gamma background fluence, 4.7×10^3 rads (silicon).

Fig. 14. The effect of neutron irradiation on TTL element SE 480Q.

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This report gives the results of irradiation of several low power circuit elements by Co^{60} gamma radiation, low and high energy electrons (i.e. 1.5 MeV and 28-85 MeV) and neutrons. The bipolar circuits used were the SE480 Q NAND gate and a micropower frequency divider used in electronic wrist watches, designated ICB-9002. The MOS device used was a dual p-Channel MOSFET, designated 2N4067.

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