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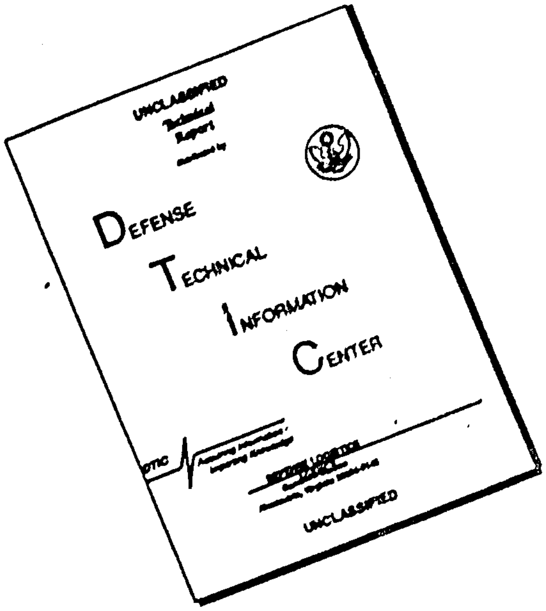

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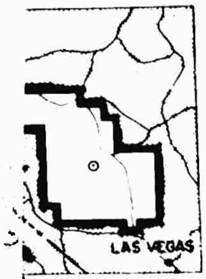


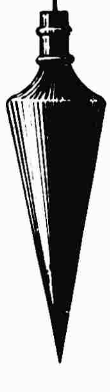
NEVADA TEST SITE
MAY-OCTOBER 1957

Project 6.2a

EFFECT of NUCLEAR RADIATION on SEMICONDUCTOR DEVICES (U)

Issuance date: October 7, 1960

HEADQUARTERS FIELD COMMAND
DEFENSE ATOMIC SUPPORT AGENCY
SANDIA BASE, ALBUQUERQUE, NEW MEXICO



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OPERATION PLUMBBOB—PROJECT 6.2a

EFFECT of NUCLEAR RADIATION on SEMICONDUCTOR DEVICES (U)

P.H. Haas, ~~Project Officer~~
J.M. Shaull
W.V. Behrens

Diamond Ordnance Fuze Laboratories
Washington 25, D.C.

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FOREWORD

This report presents the final results of one of the 46 projects comprising the military-effects program of Operation Plumbbob, which included 24 test detonations at the Nevada Test Site in 1957.

For overall Plumbbob military-effects information, the reader is referred to the "Summary Report of the Director, DOD Test Group (Programs 1–9)," ITR–1445, which includes: (1) a description of each detonation, including yield, zero-point location and environment, type of device, ambient atmospheric conditions, etc.; (2) a discussion of project results; (3) a summary of the objectives and results of each project; and (4) a listing of project reports for the military-effects program.

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ABSTRACT

A total of 350 transistors and semiconductor diodes, including germanium and silicon types, were exposed to nuclear detonations. Some of the transistors were operational during exposure as oscillators, amplifiers, and trigger circuits. Radiation levels varied from ~~10^{11} to 4 × 10^{11}~~ NVT ~~(n/cm^2)~~ integrated neutron flux, accompanied by gamma radiation between 0.1 and 100,000 r.

The transistors showed a decrease in common-emitter current gain ~~(beta)~~ and an increase in collector-diode reverse leakage current ~~(I_{co})~~. The higher-frequency transistors were less affected by neutron fluxes than were the audio units, and the surface-barrier types were virtually undamaged by the maximum fluxes obtained. Semiconductor diodes showed an increase in forward resistance and a decrease in back resistance, ~~with point-contact types showing much less change~~ than ~~the junction types.~~

Transistors and diodes in operating equipment suffered permanent damage comparable to those passively exposed. Degradation of performance of this equipment was almost entirely attributable to changes in the semiconductor parameters.

The results obtained are in reasonable agreement with data obtained from pile-type reactors, indicating that total integrated neutron flux is of primary significance, rather than rate of exposure.

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EFFECT of NUCLEAR RADIATION on SEMICONDUCTOR DEVICES

OBJECTIVES

The object of the work described herein was to ascertain the continued effects of neutron, gamma, and electromagnetic radiation upon commercially available transistors and diodes and upon electronic circuits employing these components. Particularly desired was specific information of value to the applications researcher as to the relative radiation susceptibility of the different types of semiconductor devices.

BACKGROUND

The use of nuclear weapons in modern warfare makes necessary the obtaining of information concerning the effects of nuclear radiation upon armaments and equipment. Since many of the armament control circuits either presently utilize semiconductor devices, or may advantageously do so, it is essential to obtain information on the performance of transistors and semiconductor diodes in the environment of a nuclear explosion.

Preliminary high-intensity, short-duration neutron-irradiation tests were made in 1956 (Reference 1) using the Los Alamos Scientific Laboratory's Godiva pulse reactor as a neutron source. The choice of semiconductor devices and the design of electronic circuitry exposed during Operation Plumbbob were made as indicated by the results of the Godiva test.

THEORY

Since the operation of semiconductor devices depends upon carrier movement through a well-ordered crystal lattice, it should be expected that particle bombardment of the crystal would disrupt its orderly arrangement and thereby cause device performance to deteriorate. In addition, the accompanying gamma rays were expected to cause ionization of matter (grease, potting compound, etc.) in contact with the crystal, resulting in surface effects detrimental to transistor action.

Decrease in the common-emitter forward current gain (beta) of transistors as a result of continuous low-level neutron radiation over a long period of time has been measured by others (References 2 and 3). Since the loss of beta has been attributed primarily to a decrease in minority carrier lifetime (References 3 and 4), it was expected that this would be of less proportional importance for high-frequency units, wherein the minority carriers diffuse through a thinner base region.

An increase in collector diode backward leakage current (I_{CO}) of irradiated transistors has also been measured by investigators using continuously operated reactors (References 2 and 3). This degradation has been attributed to a combination of surface effects at the collector-base junction, together with changes in bulk characteristics of the semiconductor that tend to destroy the barrier. The former effects, that of conductances shunting the collector-base barrier, have been considered to result (References 2 and 4) primarily from exposure to gamma radiation and are reported to vary considerably with the type of grease or filling compounds surrounding the crystal, whereas the changes in [illegible] characteristics were attributed principally to neutron irradiation.

PROCEDURE

The semiconductor devices and circuits to be exposed were placed between sponge rubber pads and contained in aluminum cans. The cans were packed in glass-wool insulation and placed inside heavy marine plywood boxes. The plywood boxes were buried at various distances from the ground-zero point of the nuclear detonation and at various depths in the ground in such a manner that exposure to neutron flux would vary from 10[illegible] to about 4×10^{11} total neutrons per square centimeter (NVT)[1], and gamma radiation from less than [illegible] r to 66,000 r. Gold foils were included in each box to act as indicators of the relative intensity of neutron irradiation.

Figure 1 is a photograph of the containers for the transistors and devices exposed.

Semiconductor devices in both the passive and active states were exposed; however, monitoring was limited to before installation and after recovery. Indicators were included on the trigger circuits to show if they [illegible] actuated.

Figure 1 Containers for semiconductor devices for special tests.

Since the results of preliminary tests (Reference [illegible]) indicated that [illegible] frequency transistors were damaged less by neutron irradiation than were [illegible] transistors, the majority of the transistors selected for test were of the former type.

Transistorized devices [illegible] operated [illegible] included: (1) sine-wave oscillators [illegible] stage, Class A amplifiers, (3) transistor trigger circuits, two types, and (4) [illegible]-rectifier, power supplies. Schematic circuit diagrams of the devices are shown in Figure 2.

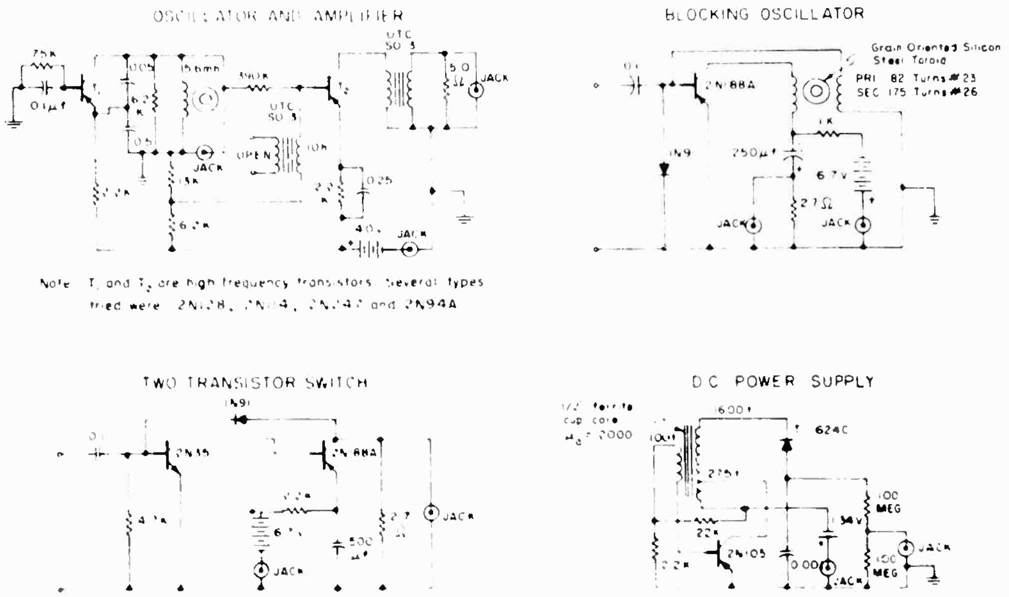
In order to eliminate possible malfunctioning due to pickup from interconnecting cables, each sine-wave oscillator and [illegible] combination was constructed on a common chassis, and the

---

[1] N [illegible] (sec)(sec) [illegible]

unit was powered by a single battery. Each self-powered oscillator-amplifier combination was contained in an aluminum can. Similarly, the trigger circuits and the transistorized power supplies were also each contained in individual aluminum cans and powered by self-contained batteries.

The checking of the transistors' forward current gain (beta) and collector diode back leakage current (I_{CO}) was done with a laboratory-type beta checker. An ac-vacuum-tube voltmeter was used to monitor the outputs of the oscillators and amplifiers. The trigger circuits were self-monitoring by the use of small squibs, which ignited at a predetermined current level. Monitoring of the outputs of the dc-to-dc high-voltage power supplies was accomplished by using a high-impedance electrostatic voltmeter.



Note T1 and T2 are high frequency transistors. Several types tried were 2N128, 2N?4, 2N?4? and 2N94A

Figure 2 Circuit diagrams of transistorized devices.

The measurements indicated above were taken and recorded before exposure to the radiation and were repeated again afterwards. In every case, after-exposure recovery of the equipment and its monitoring were accomplished before the self-contained batteries had run down enough to cause consequential error.

Data from several types of detectors, placed at various distances from ground zero as part of Project 2.3, provided a means for computing the total integrated neutron flux (NVT) levels. These values correlated well with relative values obtained from the gold-foil detectors placed inside the boxes.

A total of 293 transistors and 60 semiconductor diodes were irradiated in these tests; of these, 45 transistors were in the operating state during irradiation. Three samples each of representative types of commercially available transistors were exposed to the selected levels of nuclear radiation. A few of the less-available types were tested in smaller quantities.

Figure 3 shows the placement of the boxes containing the semiconductors and semiconductor devices relative to Shot Priscilla. The one box exposed to Shot Hood was buried 4 inches below the ground at 800 feet from ground zero.

RESULTS

The permanent performance capabilities of these particular transistorized devices were only slightly affected by exposure (under operating conditions) to atomic radiation up to 2.9 × 10^{12}

NVT and 3.3×10 r. As was experienced in the preliminary tests, component damage was manifest only in the semiconductor devices.

The oscillator and amplifier units, which utilized the same type of high-frequency transistors for both functions, showed negligible permanent effect from irradiation as intense as 10^{12} NVT and 150 r. A slightly higher exposure of 2.9×10^{12} NVT and 3.3×10^{3} r resulted in percentage reductions in the amplifiers' outputs, by type of transistor used, as follows: 2N128, 3.0 percent; 2N114, 7.5 percent; 2N247, 15 percent; and 2N94A, 18 percent. The outputs of the oscillators remained practically unchanged after exposure at the above levels.

Trigger circuits of two types, blocking oscillators, and two transistor switches were exposed in the operative state with indicator squibs connected in the circuits to disclose false triggering. Although inspection of the circuits after recovery showed that no permanent damage to performance resulted from irradiation as high as 1.6×10^{12} NVT and 900 r, the expended indicator squibs showed that all circuits exposed to fluxes greater than 1.9×10^{10} NVT (with negligible gamma radiation) had been caused to trigger by the nuclear radiation. Two of the blocking oscillator circuits, which were more sensitive than the two-transistor trigger circuits, triggered from exposures of 4.5×10^{9} and 6.2×10^{8} NVT, respectively.

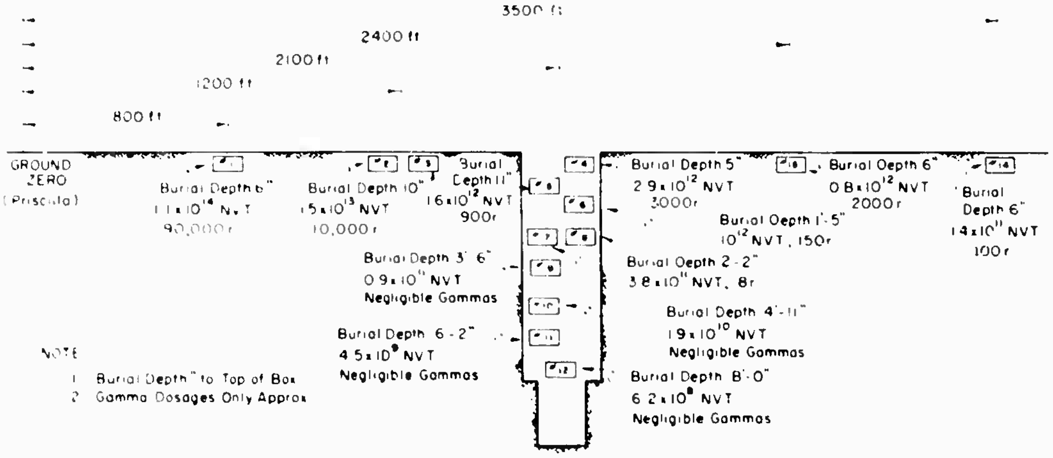


Figure 3 Placement of boxes and flux levels.

Subsequent checking showed that the batteries powering the two-transistor trigger circuits had run down considerably following the irradiation, whereas similar batteries powering the blocking oscillators remained at nearly original strength.

The results of irradiating the transistorized high-voltage power supplies were somewhat erratic. A unit exposed to 3.8×10^{11} NVT and 8 r suffered a 19 percent drop in output, whereas a similar one exposed to 1.6×10^{12} NVT and 900 r had its output decreased by only 2.4 percent (both four days after exposure).

The output of a unit irradiated at 0.9×10^{11} NVT and negligible gamma was not reduced. Laboratory testing of the supplies approximately 3 weeks after their irradiation showed that all the voltage outputs had reccovered to within 2 percent of their pre-exposure values.

A check of semiconductor devices exposed to a nuclear detonation when in the passive state showed that most high-frequency transistors suffered moderate damage from exposure to fluxes of 1.1×10^{11} NVT (highest flux accurately instrumented) and 8.8×10^{4} r. Exceptions to this were the surface-barrier transistors, the characteristics of which were only slightly altered by irradiation at this level. Of the several types of surface-barrier transistors tested, the 2N128 transistors exhibited the highest resistance to radiation damage. The average characteristics of three 2N128 transistors exposed to fluxes of 1.1×10^{11} NVT and 8.8×10^{4} r indicated a loss in beta of less than 3.2 percent and an increase in I_{co} of about 70 percent. (Highest I_{co} was still less than 2 μa.) The change of characteristics of the 2N247 drift transistors from irradiation at the 1.1×10^{14} NVT level was somewhat unusual, since the average beta of the transistor dropped only about 30 percent, whereas the average I_{co} increased to twelve times its pre-exposure level.

Results similar to those above were obtained when the same types of transistors were contained in a two-layer Boral (slow-neutron) shield container inside the regular aluminum housing, and this assembly was exposed to the same neutron and gamma-flux intensity.

Figures 4 and 5 show the decrease in forward current gain (beta) and the increase in reverse collector diode leakage current (I_{co}), respectively, of several of the types of transistors passively exposed. Data showing the effects of radiation on the beta and I_{co} of each of the transistors passively exposed appears in Table 1. Both the graphs and the table show normalized values, i.e., the average original value altered by the average percent change. Where several transistors were exposed at a given flux level, the individual deviations from the average change were generally less than 30 percent. The transistors exposed while in operating condition in equipment were affected to approximately the same degree by irradiation as were the same type of passively exposed transistors.

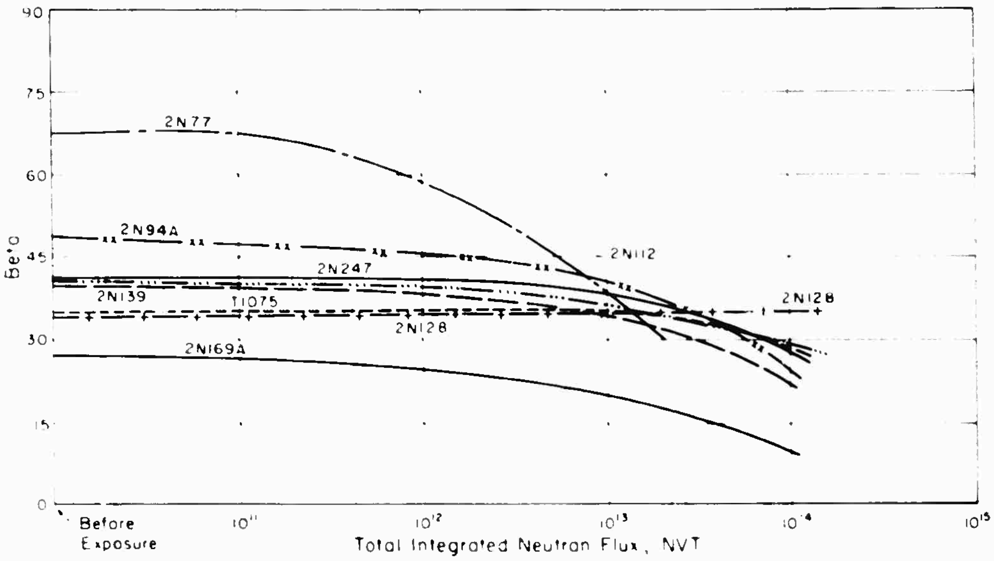


Figure 4 Decrease in beta with neutron bombardment.

Figures 6 and 7 show the increase in forward resistance and decrease in back resistance, respectively, of several types of semiconductor diodes included among the components passively exposed.

The changes in h parameters of the Type 2N139 transistors exposed to nuclear radiation when in the passive state are shown in Figure 8.

Table 2 lists the measured values of minority carrier lifetime and forward current gains for 2N77 transistors before and after exposure to several intensities of nuclear radiation.

DISCUSSION

It is believed that neutron bombardment was responsible for the permanent damage to the semiconductor devices exposed in these tests. Other investigators (References 2 and 3) have found that a gamma dosage of about 10^7 r was required to reach the threshold of permanent semiconductor damage. Since the maximum gamma dosage received by any component in these tests was less than 10^5 r, the possibility of permanent damages from gamma radiation is ruled out.

Although it was planned to irradiate the units of operating equipment at levels up to 2×10^{13} NVT, the maximum level to which operating units actually were exposed was 2.9×10^{12} NVT, a

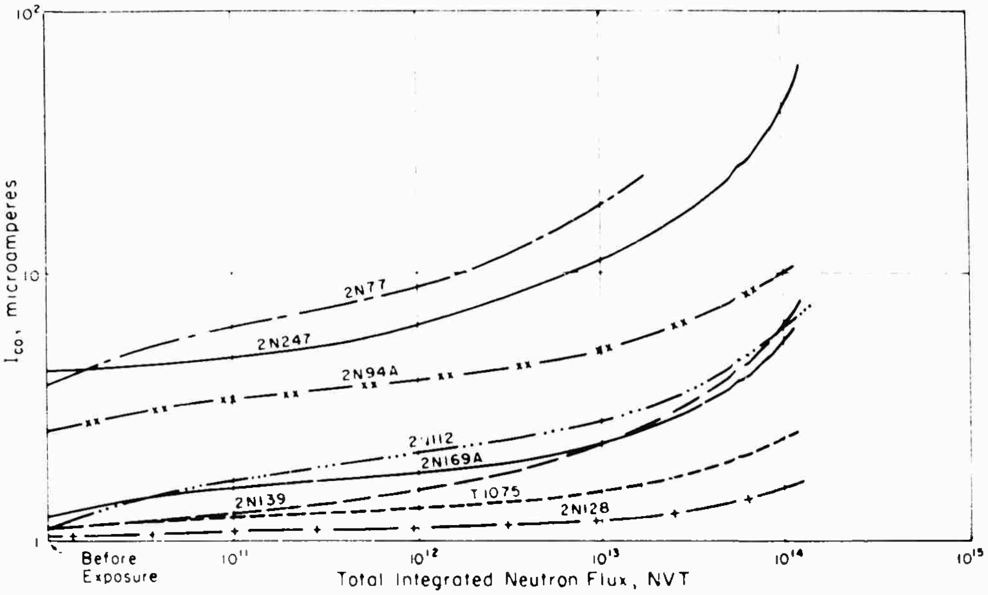


Figure 5 Increase of I_{co} with neutron bombardment.

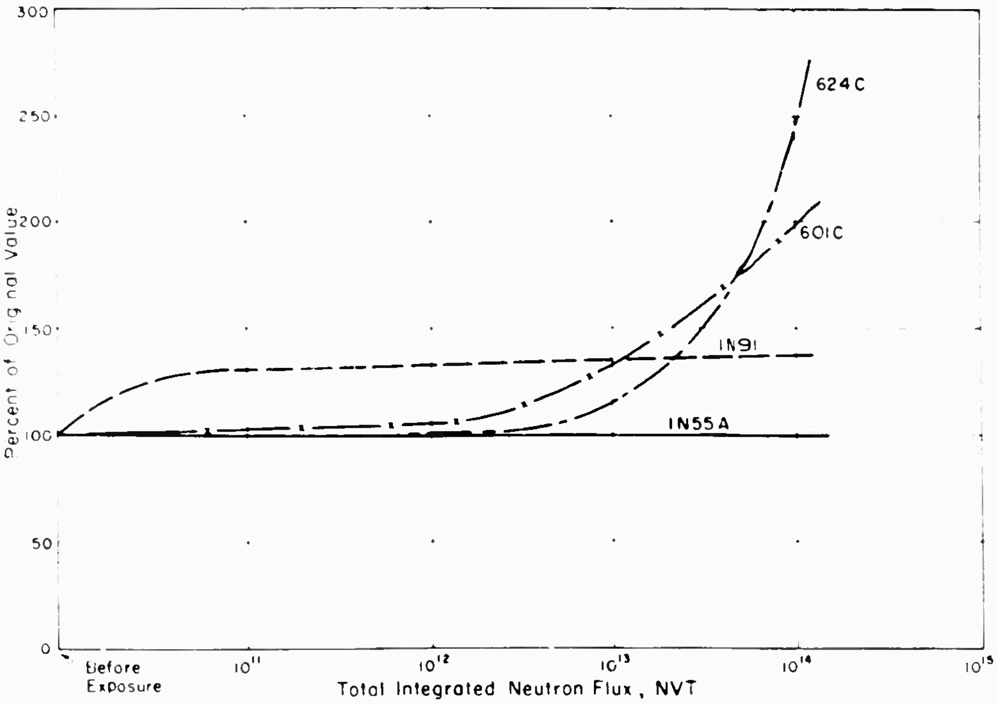


Figure 6 Change of forward resistance with neutron bombardment, semiconductor diodes.

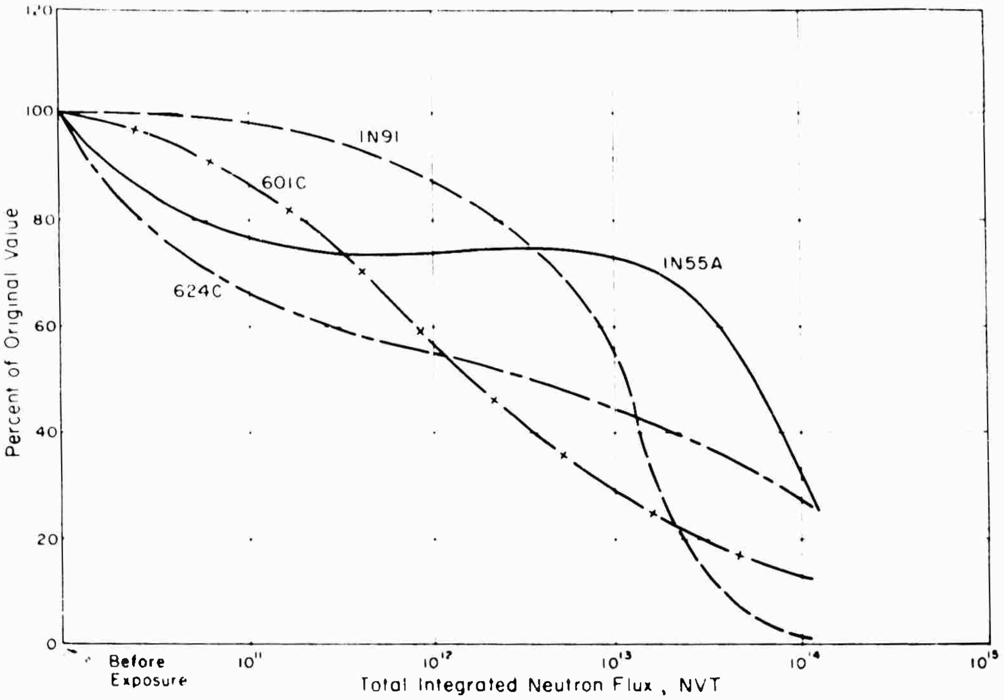


Figure 7 Change of back resistance with neutron bombardment, semiconductor diodes.

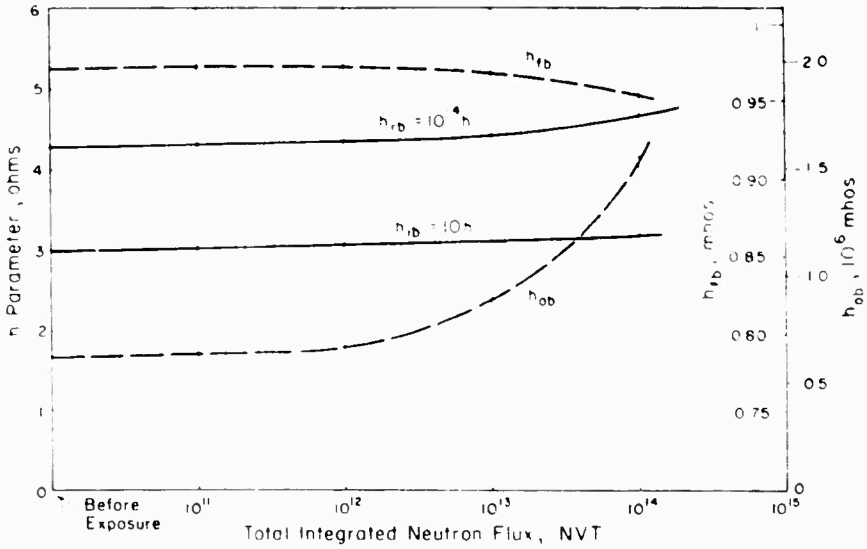


Figure 8 Changes in h parameters with neutron bombardment, total of twenty-four 2N139 transistors.

flux value less than expected at the selected exposure site and considerably below that to which the passive units were exposed.

It is to be expected that a neutron flux of 2.9×10^{12} NVT would only slightly affect the performance of transistorized devices using the high-frequency, thin-base, transistors. As occurred in the preliminary tests, the oscillator outputs were not affected, since the oscillators were designed with a relatively large amount of positive feedback and since the performance of the high-frequency transistors used as oscillators in this test deteriorated only slightly at exposures of 2.9×10^{12} NVT and below.

The reduction in output of the amplifiers, which occurred at the maximum exposure level (for active devices) of 2.9×10^{12} NVT, was almost directly proportional to the loss in forward current gain of the transistors. As was done in the preliminary tests, the amplifiers were purposely designed to reflect this deterioration. The maximum decrease in output of 18 percent (1.7 db), however, cannot be considered to constitute a device failure, for variances greater than this exist in commercially available transistors and are allowed for in conventional electronic design.

The false triggering of the blocking oscillator and two-transistor switch circuits is believed to be due to transient currents resulting from either the effects of neutron and gamma radiation on the semiconductor devices or the circuit intercepting the radiated electromagnetic field. The results indicate a triggering sensitivity to nuclear radiation of several orders of magnitude greater than that for permanent radiation damage to audio transistors.

The fact that the batteries powering the two-transistor switches ran down rapidly was attributed to the direct coupling employed from the collector of the NPN transistor to the base of the PNP transistor. The use of this type of coupling results in the I_{co} of the NPN transistor being amplified by both transistors to cause a large collector current to flow in the PNP units. Since the I_{co} of a transistor increases from irradiation, the disadvantage of using a direct coupled circuit is apparent.

The erratic behavior of the high-voltage power supplies may have been due to the combination of the spread of characteristics of the transistors and the fact that this particular design requires a transistor with high forward current gain and a high collector-base resistance at the instant of current cutoff.

Since only one supply was tested at each dosage level, anomalous behavior of the one sample (which would average out for many samples) could be responsible for the incongruous data. When laboratory tests were made, 3 weeks after the exposure, there had been sufficient annealing so that the direct-current output of the damaged unit was almost up to its original value.

The majority of transistors exposed to the nuclear radiation while in the passive state exhibited a decrease in beta and an increase in I_{co} to approximately the same degree as was experienced for similar transistors in the preliminary tests. Since those contained in a Boral container were damaged to almost the same degree as were similar units not so contained, it appears that the elimination of low-energy neutrons causes no appreciable change in radiation damage.

The effects of the changes in h parameters on the performance of conventional transistor amplifiers should be considered. The power gain (P.G.) of a typical grounded emitter-transistor-amplifier stage is approximated by:

$$\text{P.G.} \qquad (h_{fe})^2 \left(\frac{h_{oe}}{h_{oe} + R_L} \right) \frac{R_L}{h_{ie}} \tag{1}$$

Where: R_L the load resistance
h parameters per Institute of Radio Engineers' standards, corresponding to the hybrid parameters for a four-terminal network.

TABLE I AVERAGE VALUES OF BETA AND I_{co} AFTER IRRADIATION*

Transistor Type	Parameter	Before Exposure	Shot Priscilla								Shot Hood
			1.1 × 10^{14} (Borah)	1.1 × 10^{14}	1.5 × 10^{13}	1.6 × 10^{12}	3.8 × 10^{11}	0.9 × 10^{11}	0.8 × 10^{12}	1.4 × 10^{11}	Approx 1 × 10^{14}
2N77	β	67.0			[illegible]	55.7	64.4		58.7	67.0	4.0
Ge, audio, PNP	I_{co}	3.9 μa			× 5.5	× 3.6	× 1.7		2.7	× 1.7	× 42
2N188A	β	70.5	20.7		39.0			74.6	74.2	73.1	
Ge, audio, PNP	I_{co}	7.1 μa	× 7.8		× 2.6			× 1.4	× 1.8	× 1.4	
2N139	β	39.3	18.5	22.6, 23.8	32.1, 31.6	37.2	38.4	37.9	38.5	37.9	11.9
Ge, IF, PNP	I_{co}	1.1 μa	× 6.8	× 6.6	× 2.7	× 1.5	× 1.3	× 1.3	× 1.6	× 1.4	× 11.1
2N112	β	40.2	28.5	18.8	33.7	38.4	39.9	40.2			8.0
Ge, IF, PNP	I_{co}	[illegible]	× 6.0	× 6.4	× 2.6	× 2.0	× 1.7	× 1.6			× 13
2N114	β	73.1		47.8	63.0	76	71.6				
Ge, IF, PNP	I_{co}	[illegible]		× 4.3	× 2.2	× 1.4	× 1.3				
[illegible]	β	41.4	[illegible]	28.2	35.6	41.4	39.7				
[illegible] PNP	I_{co}	[illegible]	× 10.6	12.4	× 2.8	× 1.5	× 1				
[illegible]	β	[illegible]		4.4	[illegible]	[illegible]	33.2				35.6
[illegible] PNP	I_{co}	[illegible]		× 1.7	× 1.0	× 1.4	× 1.3				× 2.1
[illegible]	β	[illegible]	[illegible]	26.9	[illegible]				[illegible]	[illegible]	
[illegible] PNP	I_{co}	1.1 μa	× 1.9	[illegible]	× 1.5				× 1.4	× 1.6	
[illegible]	β	27.6		21.0	[illegible]				26.8	26.3	
[illegible] PNP	I_{co}	[illegible]		× 2.1	× 1.1				× 1.0	× 1.5	
[illegible]	β	127		91.7	94.5	[illegible]	113				[illegible]
[illegible] PNP	I_{co}	[illegible]		× 3.9	× 4.6	× 1.7	× 2.5				× 4.2
[illegible]	β	10.6			[illegible]						
[illegible] PNP	I_{co}	0.76 μa			× 1.03						
[illegible]	β	[illegible]		[illegible]	10.0						
[illegible] PNP	I_{co}	[illegible]		× 0.96	× 1.4						
[illegible]	β	[illegible]				[illegible]	171	206			
[illegible] PNP	I_{co}	1 μa				[illegible]	× 1.0	× 1.0			
[illegible]	β	[illegible]		10.2	18.7				[illegible]	27.2	
[illegible] NPN	I_{co}	[illegible]		× 7.6	[illegible]				× 3.4	× 1.9	
[illegible]	β	[illegible]		[illegible]	21.7				34.7	34.2	
[illegible] NPN	I_{co}	[illegible]		× 6.4	× 1.9				× 6.0	× 2.3	
2N169A	β	27.4	[illegible]	10.5	[illegible]				26.0	26.5	
[illegible] NPN	I_{co}	[illegible]	[illegible]	[illegible]	× 2.2				× 1.5	× 1.4	
[illegible]	β	48.4	[illegible]	[illegible]	37.1				48.5	45.0	
[illegible] NPN	I_{co}	[illegible]	[illegible]	× 4.9	× 1.9				× 2.3	× 1.8	
[illegible]	β	[illegible]		[illegible]	[illegible]				118	114	
[illegible] NPN	I_{co}	1.7 μa		4.0	[illegible]				× 3.1	× 2.5	
[illegible]	β	[illegible]				4.5	10.9				
[illegible] PNP	I_{co}	[illegible]				× 1.5	[illegible]				
[illegible]	β	[illegible]				46.4	54.0	54.8			
[illegible] NPN	I_{co}	Negl									
[illegible]	β	[illegible]				18.9	20.0				
[illegible] PNP	I_{co}	[illegible]				× 1.0	[illegible]				
[illegible]	β	95.0				87.2		95			
[illegible] NPN	I_{co}	[illegible]				× 1.0		× 1.0			
[illegible]	β	88				78.3	78.7				
[illegible] NPN	I_{co}	0.2 μa				× 0.87	× 1.0				

* [illegible] NVT

If one assumes that R_L is considerably smaller than h_{oe}, a condition met in most RC coupled transistor amplifiers and in many others, then the power gain equation reduces to:

$$P.G. = (h_{fe})^2 \frac{R_L}{h_{ie}} \qquad (2)$$

Equation 2 indicates that the power gain of an amplifier stage is a function of the transistor parameters h_{fe} and h_{ie}; however, the variance of the input impedance, h_{ie}, of a transistor from irradiation is relatively small in comparison to the change in h_{fe}, the forward current gain (beta). It follows that the power gain is approximately proportional to $(h_{fe})^2$. The extent of damage to an amplifier stage is thus seen to be a drop in power gain of about 6 db for each 50-percent decrease in beta of the transistor. Since 40 db of gain per transistor-amplifier stage is possible with high-gain transistors, a 6-db loss due to transistor damage might be tolerated in most cases. Variations of this relative magnitude could be reduced considerably by the application of negative feedback, and in addition, the negative feedback, if of the dc type, would increase the circuit stability. High circuit stability is particularly desirable for circuits exposed to nuclear radiation, because of the unavoidable increase in transistor I_{CO}.

TABLE 2 CHANGES IN MINORITY CARRIER LIFETIME AND BETA WITH NEUTRON BOMBARDMENT

Transistor Number	Time, μsec Before	Time, μsec After	Beta Before	Beta After	NVT Exposure
1	4.2	0.5 or less	61	4	10^{14}
2	5.7	*	79	5	10^{14}
3	5.2	*	67	3.2	10^{14}
4	4.6	2.7	71	36.5	1.5×10^{13}
5	4.4	3.5	46	22	1.5×10^{13}
6	5.0	2.5	57	25.5	1.5×10^{13}
7	4.4	3.1	57	47.5	$1.6 \quad 10^{12}$
8	8.3	3.5	78	66	1.6×10^{12}
9	4.9	5.5	93	76	1.6×10^{12}
10	3.5	4.8	60	54	3.8×10^{11}
11	8.5	5.6	76	75	3.8×10^{11}
12	8.3	2.1	57	56	3.8×10^{11}

* Value too low to measure.

The analysis above was made using the common-emitter transistor h parameters, since the majority of circuits now employ transistors using the common-emitter connection. Figure 8 shows radiation effects on the transistors' common base h parameters, the latter being used because they are the more commonly measured classical parameters. For either type of h parameter, the significant changes from irradiation are such as to cause similar performance degradations.

With the exception of a few anomalies, the measured minority carrier lifetimes listed in Table 2 are proportional to the loss of beta of the transistors. Of particular interest are Transistors 1, 2, and 3, which suffered an almost complete loss of beta and also showed extremely short minority carrier lifetimes.

CONCLUSIONS

Of the components normally used in electronic circuits, semiconductor devices are the most-susceptible to damage by nuclear radiation. In locations where physical survival of electronic equipment from the effects of a nuclear weapon is possible, fast-neutron bombardment alone is believed to be responsible for the permanent damage to semiconductor devices.

By designing circuits to be highly stable (using negative feedback and optimized biasing networks) and by using high-frequency transistors, the transistorized oscillators and amplifiers of low-power type should still be usable after exposure to neutron fluxes as high as 10^{14} NVT. During the nuclear detonation, however, malfunctioning of certain electronic equipment employing semiconductor devices can be expected from exposures as low as 10^{9} NVT, with negligible gamma radiation. It is yet to be determined whether either the neutron flux or the radiated electromagnetic field, or both, were responsible for malfunctioning during detonation.

Permanent damage to transistors from a nuclear detonation consists chiefly of a decrease in forward current gain, beta, and an increase in collector back leakage current, I_{CO}. Therefore, transistorized circuits subject to exposure to a nuclear detonation should be designed to be as self-compensating as possible for changes in these parameters. The designer should avoid circuits with outputs that are proportional to the forward current gain of the transistors.

High-frequency transistors were less susceptible to damage by fast-neutron irradiation than were the audio units. Surface-barrier units underwent an exposure of 1.1×10^{14} NVT from a detonation without suffering appreciable damage, whereas audio units were damaged severely by irradiation at this level. Of the surface-barrier transistors tested, Type 2N128 exhibited greatest resistance to radiation damage.

The irradiation of semiconductor diodes at levels up to 1.1×10^{14} NVT caused the back resistance of the diodes to decrease in all cases and, in most cases, caused the forward resistance to increase. The behavior of the germanium point-contact Type 1N55A was unusual, since its forward resistance remained fairly constant after irradiation.

The reasonable correlation in measured drop of minority carrier lifetime with loss of beta of irradiated transistors supports the theory that the decrease in beta is caused principally by the minority carrier lifetime decrease.

RECOMMENDATIONS

Tests should be made to ascertain and record semiconductor performance during exposure to a nuclear detonation and to ascertain specifically the degree of contribution to semiconductor malfunctioning of gamma, neutron, and electromagnetic field radiation during the explosion.

Functional transistor (and diode) circuitry should be constructed to be as radiation resistant as possible, and these circuits should be irradiated in operating condition to ascertain and record their performance both during and after exposure.

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4. D.B. Kret, "Analysis of Radiation Effects on Transistors"; Electronic Design, Vol. 5, No. 14, 15 July 1957; Unclassified.

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RITA M. METRO
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