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EFFECTS OF NUCLEAR RADIATION ON A HIGH-RELIABILITY SILICON POWER DIODE I-CHANGE IN I-V DESIGN CHARACTERISTICS

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ABSTRACT

Tests were conducted on 100 diodes in the NASA Plum Brook Reactor facility, which was designed to simulate a SNAP-8 nuclear environment. The diodes were irradiated in different operational and temperature modes for approximately 480 hr, with a resultant diode exposure to a total fast-neutron fluence (energies of 0.1 MeV and above) of 5×10^{13} neutrons/cm^2 and to a total gamma dose of 3×10^{7} rads (C). Results showed that this diode could be reliably used in a nuclear electric generating system such as SNAP-8 provided that the total radiation levels were within those of the tests. No catastrophic failures occurred. The electrical characteristic that would limit the useful lifetime of the device with increased radiation is the forward voltage drop at high current levels.

STAR Category 09

EFFECTS OF NUCLEAR RADIATION ON A HIGH-RELIABILITY SILICON POWER DIODE

I-CHANGE IN I-V DESIGN CHARACTERISTICS

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SUMMARY

The results of nuclear tests conducted on 100 high-reliability silicon power diodes are presented. The tests were conducted in the HB-6 facility of the NASA Plum Brook Reactor. The facility was designed so that the mixed neutron-gamma field would simulate a SNAP-8 environment. The diodes were irradiated in different operational and temperature modes for a total time of approximately 480 hours, with a resultant exposure of the diodes to a total fast-neutron fluence (neutron energies of 0.1 MeV and above) of approximately 5×10^{13} neutrons per square centimeter and a total gamma dose of 3×10^{7} rads (C).

Data from these tests indicate that this particular type of diode could be used reliably in a nuclear electric power generating system provided that the levels of total radiation were within the levels of the tests. No catastrophic failures occurred, although radiation caused degradation to some of the electrical characteristics. The increase in the forward voltage drop with radiation at high forward currents is the electrical characteristic that would limit the useful lifetime of the diode in a system. The diodes that were irradiated at elevated temperatures (nominal 125° C) showed no significant difference in degradation rates when compared with the diodes irradiated at a nominal 60° C. The rate of change, however, did depend on the operational modes: the reverse-biased diodes showed greater changes in electrical characteristics than those diodes operated in forward bias or ac operational modes. The reverse currents increased in most cases, but the increases were not great enough to impair the operation of the diode as a power rectifier. The avalanche breakdown voltage remained essentially constant in the majority of cases; however, the sharpness of the breakdown knee was reduced in all cases.

INTRODUCTION

A nuclear electric power generating system has an added requirement of reliability associated with it which is not found in a nonnuclear system. This additional requirement is the nuclear radiation tolerance of the electrical components. This requirement could possibly become the controlling factor in determining the actual reliability of a system. The possible future use of space nuclear electric power generating systems such as SNAP-8 prompted an investigation of the nuclear radiation effects on specific electrical components. Considerable work has been done in the field of nuclear radiation effects on semiconductors, as summarized by Messenger et al. (ref. 1). Semiconductors were recognized as the most sensitive electrical components to nuclear radiation. Therefore, the factor most likely to control electrical component reliability, and possibily system lifetime, would be radiation damage to semiconductor components.

A testing program was developed to investigate specifically the nuclear radiation effects on semiconductors. This report describes the nuclear testing of high-reliability silicon power diodes. The test was the first of a series of nuclear radiation tests to be performed on several types of silicon power devices that are applicable to SNAP-8 or similar nuclear space power systems. The purpose of the tests was primarily to provide information that could be used for design and reliability estimates for SNAP-8, and, in addition, to furnish data that could be used to correlate changes in the electrical parameters of the device to basic radiation damage theory.

To provide sufficient data for design and reliability information and, yet, to stay within the physical limitations imposed by the HB-6 facility required that a total of 100 diodes be irradiated in two separate tests of 50 diodes each. The two tests were similar with the exception that the diodes were irradiated at different temperatures. Each group of 50 was divided into three groups according to operating modes. Current-voltage measurements were taken on the diodes prior to irradiation, peridoically during irradiation, and after the test assembly was removed from the facility. Other measurements, such as change in reverse current with temperature, variation in capacitance with voltage, and the effects of neutron bombardment on the photocurrents generated by accompanying gamma rays, were taken on a selected basis to support later analysis of radiation damage not included in this report. The data from the tests were computer processed and plotted where applicable to show the change resulting from radiation in the electrical characteristics of these diodes.

TEST AND EQUIPMENT DESCRIPTION

Diode Selection and Description

The selection of the particular diodes that were irradiated was based on two requirements: the first was that the construction and performance of each diode, prior to irradiation, be known as completely as possible and that it be of the highest quality and reliability. The requirement of reliability is, of course, mandatory for any component contemplated for use in a space power system such as SNAP-8. The diode performance history also provides a basis for isolating those changes due to nuclear radiation from those that are due to normal operation. The second requirement was that the temperature-voltage-current capabilities of the diodes be compatible with the requirements of SNAP-8 or similar space power systems.

The diode designated S1N1189 was considered capable of meeting both these requirements. The prefix "S" in the part number indicates that the diode passed the NASA Marshall Space Flight Center screening and performance specifications (ref. 2). The 1N1189 is the standard JEDEC code designation. The S1N1189 is a 35-ampere, silicon, diffused-junction, power-rectifier diode with a rated peak inverse voltage of 500 volts. Each diode was serialized and its performance record kept during the 100-percent acceptance testing. Included in the acceptance testing were 96 hours of 175° C temperature bake, 10 temperature cycles from -65° to 175° C, 240 hours of operational power burn in at 35 amperes dc average forward current with 350 volts ac applied, shock and acceleration tests, radiographic examinations, and so forth. For detailed screening specifications and quality assurance provisions see reference 2.

Test Sequence and Procedure

The irradiation testing of the diodes actually consisted of two separate tests in each of which 50 diodes were irradiated consecutively in the reactor under similar conditions, the important difference being the temperature at which the two sets of diodes were irradiated. Each test set of 50 diodes was divided into groups according to the operating modes given in table I.

TABLE I. - DIODE TEST GROUPING

BY OPERATING MODES

Group	Diodes	Conditions
I	1 to 10	Forward current, 10 A dc
II	11 to 20	Reverse biased, 100 volts dc
III	21 to 50	Operated as ac rectifiers; average forward current, 10 A; peak reverse applied, 150 volts

The diodes were operated in these modes during their irradiation except when measurements were taken. Each set of 50 diodes was irradiated for two reactor cycles, the nominal cycle being 10 days at rated power, depending on the reactor power scheduling. The average temperatures at which the diodes were irradiated (given in table II) were

TABLE II. - DIODE TEST TEMPERATURES

Group	Test			
	I		II	
	Average initial temperature, °C	Average final temperature, °C	Average initial temperature, °C	Average final temperature, °C
I	48.5	60	106	125
II	38	43	103	102
III	50.5	66	99	124

different for the three operating groups because one coolant line served all the diodes on each test plate, and each diode was its own heat source. For example, the reverse-biased group generated less heat than the forward-biased group and therefore operated at lower temperatures. Table II also includes the change in average operating temperatures as each test progressed. As used in this report, designated nominal temperatures represent the average final temperature. The first set of diodes (test I, 60° C nominal) received a fast-neutron fluence of $4.6\pm1.5\times10^{13}$ neutrons per square centimeter (neutron energies of 0.1 MeV and above), and the second set of diodes (test II, 125° C nominal) received $4.9\pm1.6\times10^{13}$ neutrons per square centimeter (ref. 3).

The methods for determining the fast-neutron flux and gamma dosage and the conditions for which a calculated flux can be obtained are described in appendix A. The gamma dosage for each group of diodes was 3.2×10^{7} rads (C) (ref. 4).

Test Assembly, Measurement, and Instrumentation

Each set of 50 diodes was mounted on a round aluminum plate 38.1 centimeters in diameter and 0.64 centimeter thick. The plate was cooled by water flowing in 0.80-centimeter tubing welded to the plate. The desired temperatures of the diodes were obtained by allowing the diodes to be their own heat source and then controlling the rate of heat removal by the water coolant. Each diode mounting stud temperature was monitored by a Chromel-Alumel thermocouple epoxy-bonded to the diode. The mounting and wire routing of the test-sample assembly are shown in figures 1 and 2. Coaxial cable

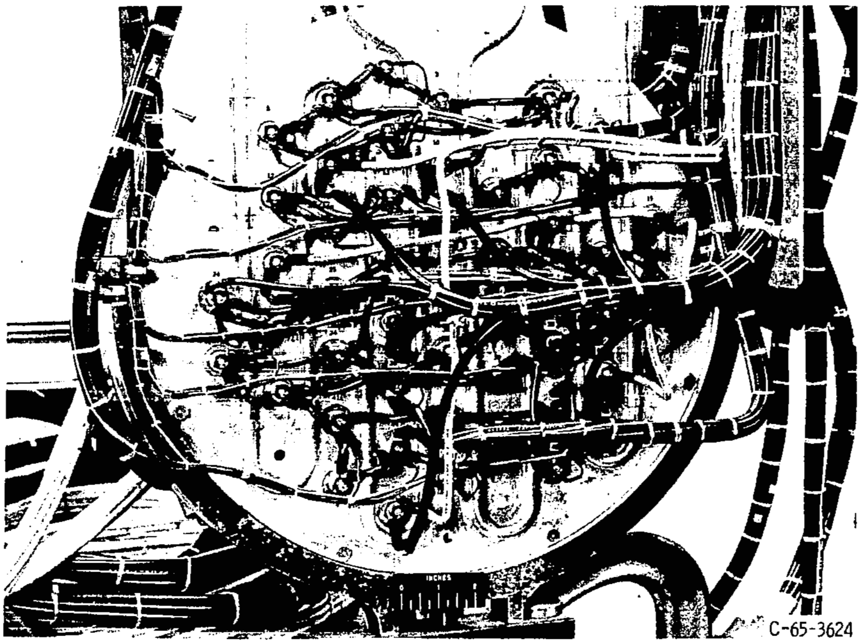


Figure 1. - Stud view of diode test-plate assembly.

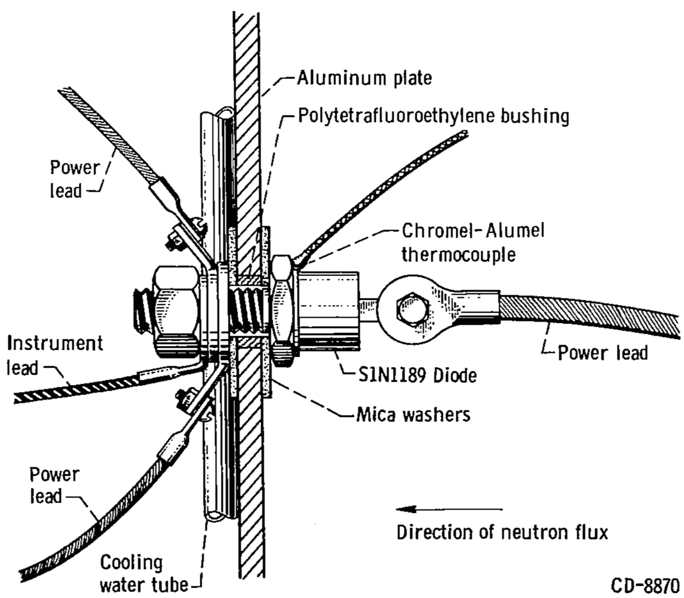


Figure 2. - Typical diode installation on test plate.

was routed to nine selected diodes for low-current measurements. These nine diodes were selected equally from each operating mode (see table I); that is, from group I, diodes 8 to 10; group II, diodes 18 to 20; and group III, diodes 30, 40, and 50. Figure 1 shows one of two assemblies that was irradiated in the HB-6 beam hole facility.

This facility is a 38.1-centimeter-diameter fast-neutron beam port. The fast-neutron beam exits into the dry quadrant B of the reactor (fig. 3). A water-cooled

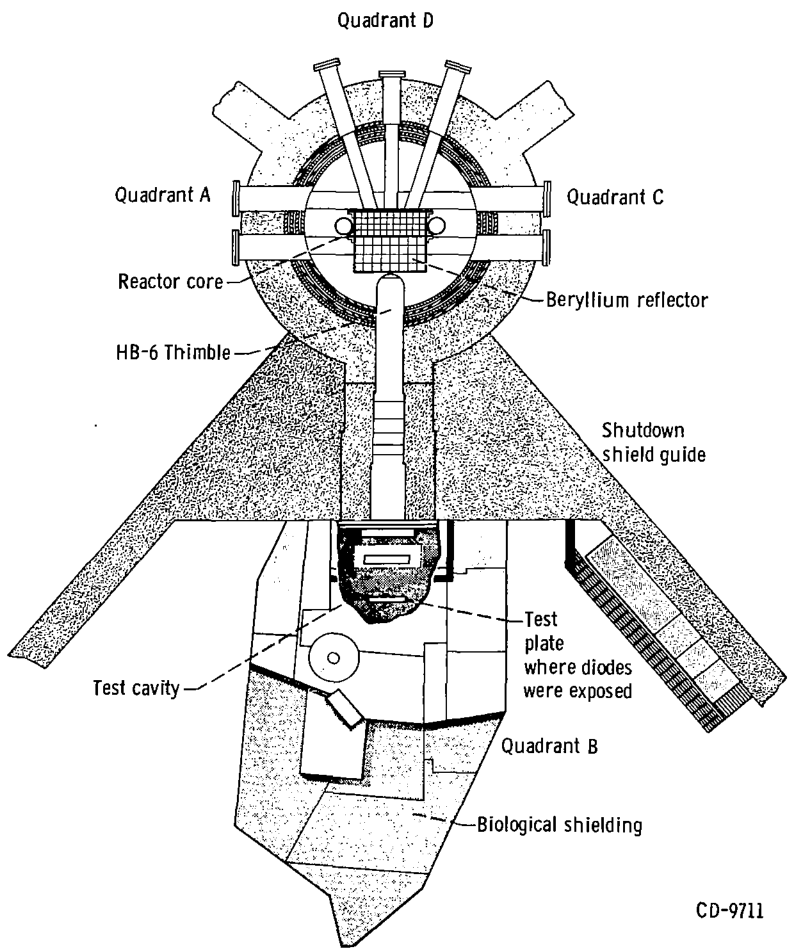


Figure 3. - Plan view of quadrants and location of HB-6 facility in Plum Brook Reactor.

aluminum thimble (fig. 4) is located on the beryllium reflector side of the reactor core. The shielding blocks are borated paraffin encapsulated in sheet aluminum and steel. The maximum gamma exposure rate anywhere outside the shielding is 10 milliroentgens per hour, and in most areas is much less than this amount. Detailed shielding calculations for the HB-6 and a description of the facility are given in references 5 and 6. The lead

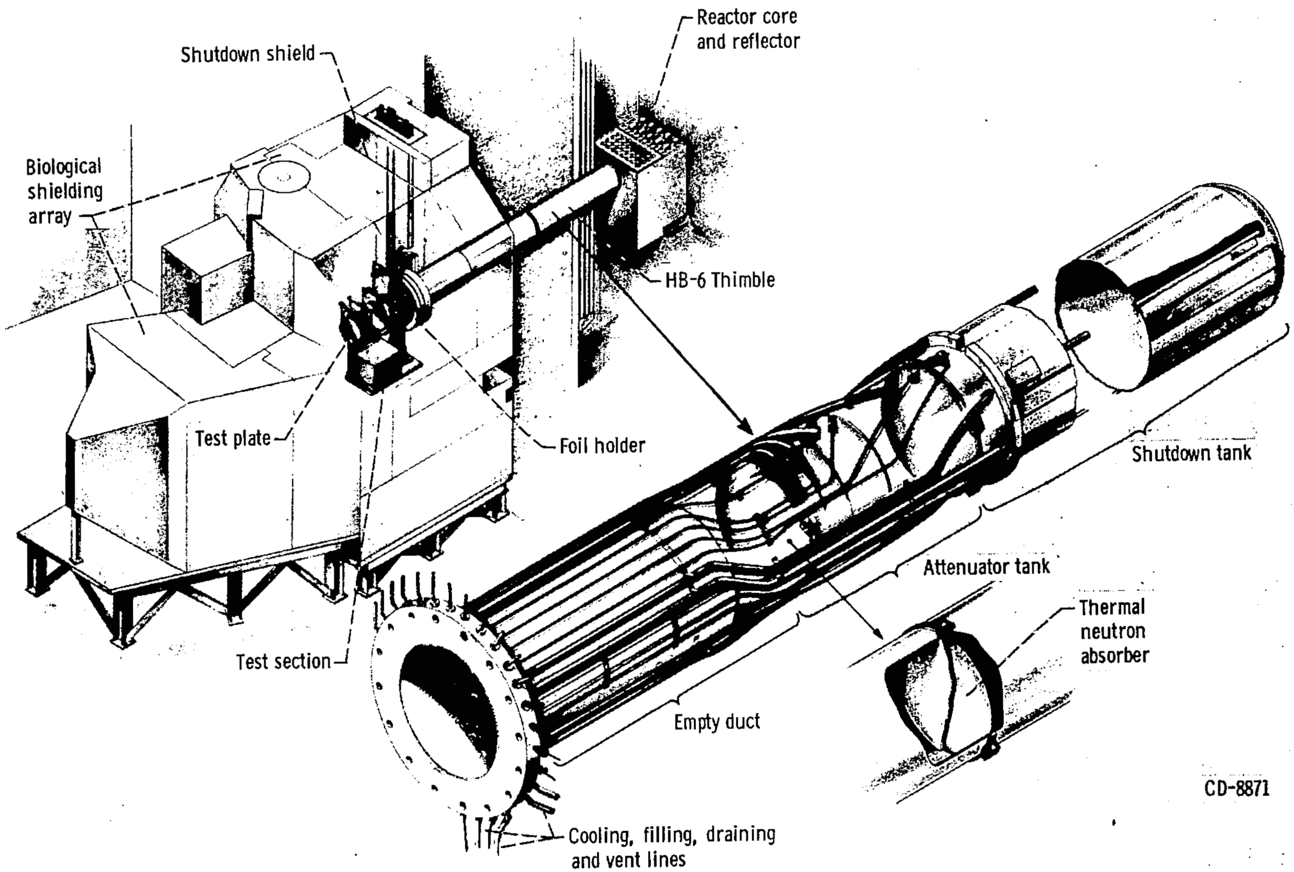


Figure 4. - HB-6 Thimble tank assembly.

wires from the test sample were routed through the shielding blocks to the electrical test equipment mounted in the quadrant and to the measuring instruments located in the control room.

The measurements taken were selected on the basis that the diode, as a device, would be as completely defined as possible. Most measurements were taken on all diodes prior to, during, and after irradiation; however, in some cases, measurements were taken only before and after irradiation. In still other cases, only a selected group of diodes were measured because of the limited time available during irradiation to make measurements or because of the limitations imposed by the circuitry. The circuits used for measurements during irradiation are shown in figure 14 of reference 5. In addition to the 100 diodes irradiated in the two tests, other individual diodes were irradiated separately to obtain measurements in support of a later analysis not included in this report.

The circuit used for furnishing the necessary currents and voltages as required for the ac operation of the diodes is shown schematically in appendix B. The circuit was unique because it utilized silicon-controlled rectifiers for switching the unusually large load currents of the 30 power diodes acting as rectifiers (300 A dc full cycle average). This switching allowed a reduction in input power requirements from approximately 30 to 0.6 kilowatt.

DISCUSSION OF EXPERIMENTAL RESULTS

Any detailed discussion, graphical presentation, or analysis of the electrical characteristics of a semiconductor diode necessitates treating separately individual sections of the current-voltage characteristics, which are dependent on the polarity and magnitude of an externally applied voltage (ref. 7). The current-voltage relation, the curve of the diode electrical characteristics, can be generally divided into a minimum of five sections: forward bias, low-level currents and voltages; forward bias, high injection (current) levels; reverse bias, low-level currents and voltages; reverse bias, high voltages; and reverse bias, avalanche breakdown region. Also, the data from these various sections of the current-voltage curve can be conveniently categorized according to their intended use. The low-level regions, whether or not they are forward or reverse biased, lend themselves almost exclusively to theoretical analysis. The high injection (current) level of the forward-bias region, the reverse current at high reverse bias or the avalanche breakdown region, are especially useful in electrical circuit design, although these data can also be used for analysis. This last category is relevant to this report and is important in the areas of device performance, application, and reliability. This information concerns the changes in the electrical characteristics at rated operating conditions, that is, changes in the forward voltage drop at 5 amperes forward current when operation is in a given nuclear radiation environment, or changes to be expected in the reverse leakage currents at 500 volts reverse bias with nuclear radiation. Such information indicates to the electrical designer which electrical characteristic will change with radiation and to what extent it will limit the operational performance of a particular semiconductor diode.

Forward Voltage Drop at High Current Levels

Neutron damage to the particular diodes tested at high current levels results in two distinct effects: one is the magnitude of the change in forward voltage drop for particular individual diodes, and the other is an increase in the spread in forward voltage drops for a given current among the individual diodes. These effects are illustrated in figures 5 to 8. Figures 5 and 6 include two envelopes of forward voltage drops for given currents. The area between the curves represented by the circular symbols includes the forward voltage drops of 100 percent of the diodes. The shaded area represented by the diamond symbols (after irradiation) includes the forward voltage drops of 80 percent of the diodes, or the 10- to 90-percent points, which means that the five highest and the five lowest values of forward voltages were excluded in the 10- to 90-percent plots. Also shown in these figures are the mean values of forward voltage drops for all diodes in each test. The maximum change in forward voltage by an individual diode was a factor of approximately $2\frac{1}{2}$ for test I and approximately 3 for test II. The spread, or variation in values, increased by a factor of 10 with radiation; that is, a spread of approximately 3 percent before irradiation increased to 30 percent after irradiation. If the intended use of these diodes were for straightforward single- or full-wave rectification, the main problem would be heat dissipation and efficiency. However, if these diodes were to be used in a bridge circuit or in parallel combinations, the imbalance caused by the differences in forward voltage drop with radiation would have to be considered in the design.

It would be desirable if the magnitude of change that could be expected as a result of radiation could be predicted from an examination of the characteristic curves of the pre-irradiated diodes. Inspection of the individual diode curves, however, indicates that such a prediction is not possible. Figures 7 and 8 include those diodes that represented the greatest change in forward voltage drop for a given current with radiation in test I (60° C nominal) and test II (125° C nominal), respectively. Figure 7 shows diode 767, which, prior to irradiation, had the largest forward voltage drop in test I (60° nominal). After irradiation, this particular diode also had changed more in forward voltage drop than any other diode in test I. On the other hand, figure 8 includes diode 827 which, prior to irradiation, had a forward voltage drop slightly above the average of all forward voltage drops in test II (125° C nominal); yet, after irradiation it had the largest forward voltage drop of either test I or test II. Other examples could be cited to illustrate the

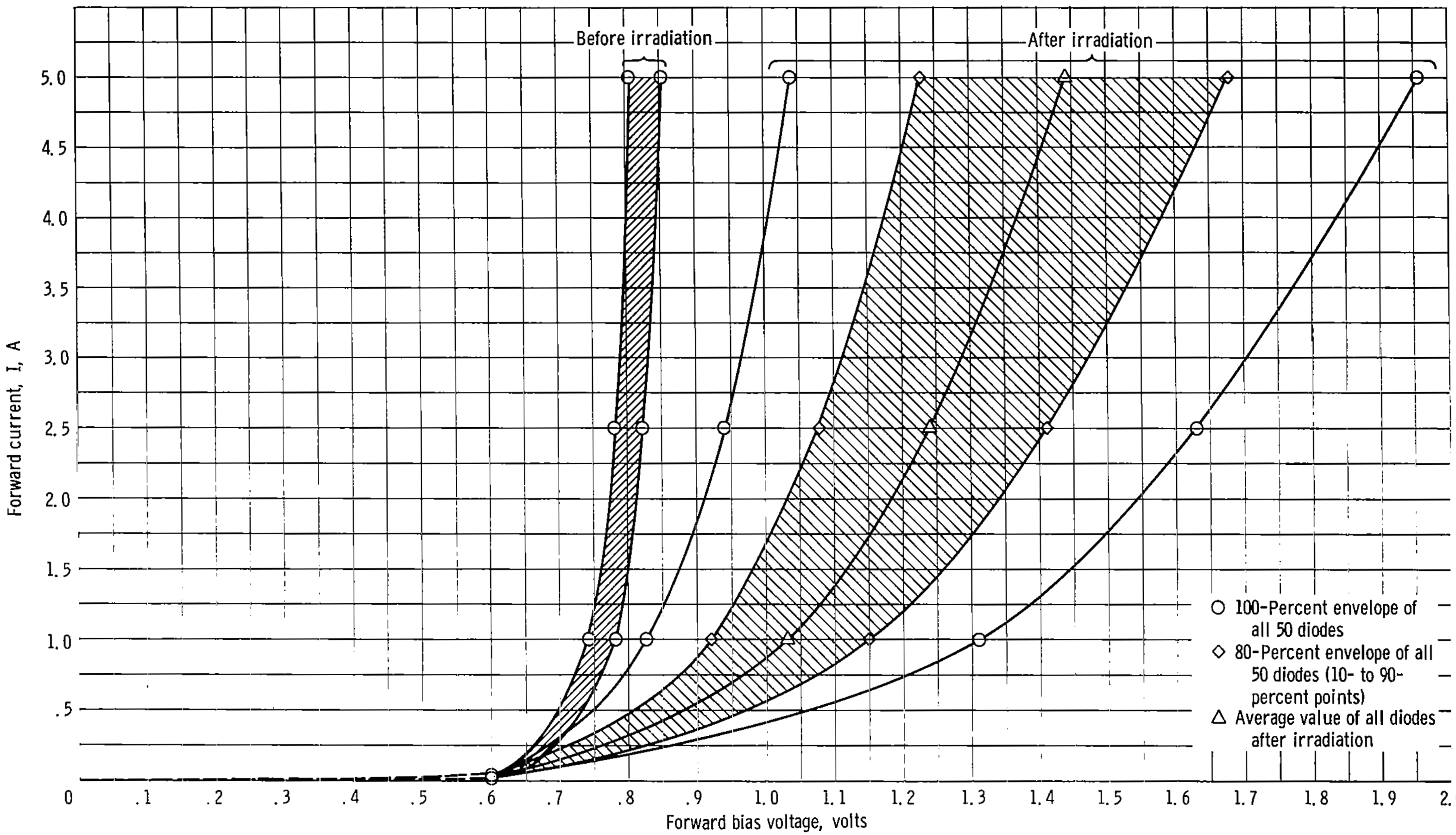


Figure 5. - Forward currents as function of voltage of all diodes before and after irradiation for test I. Temperature, 60° C nominal; neutron fluence, 4.6×10^{13} neutrons per square centimeter.

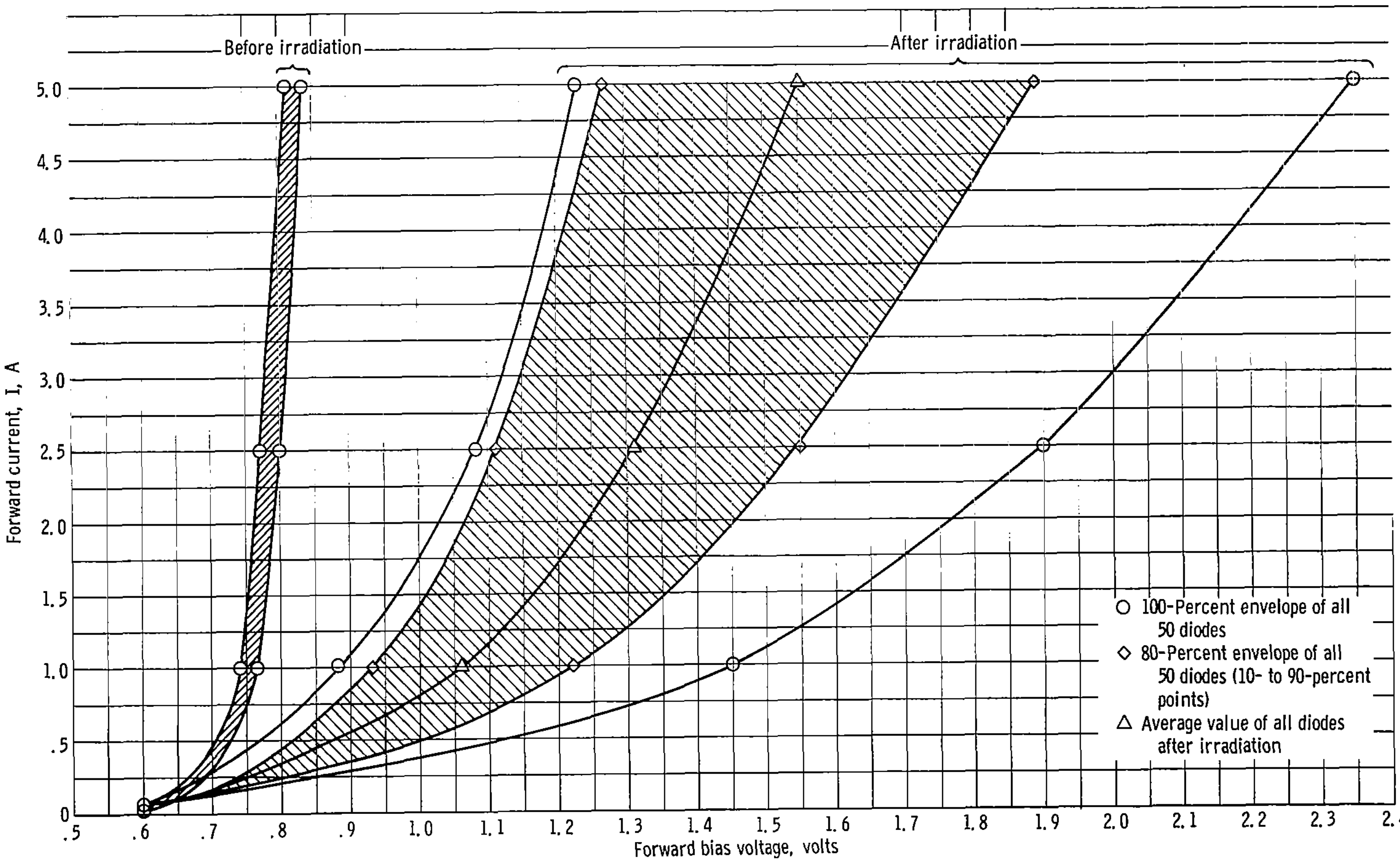
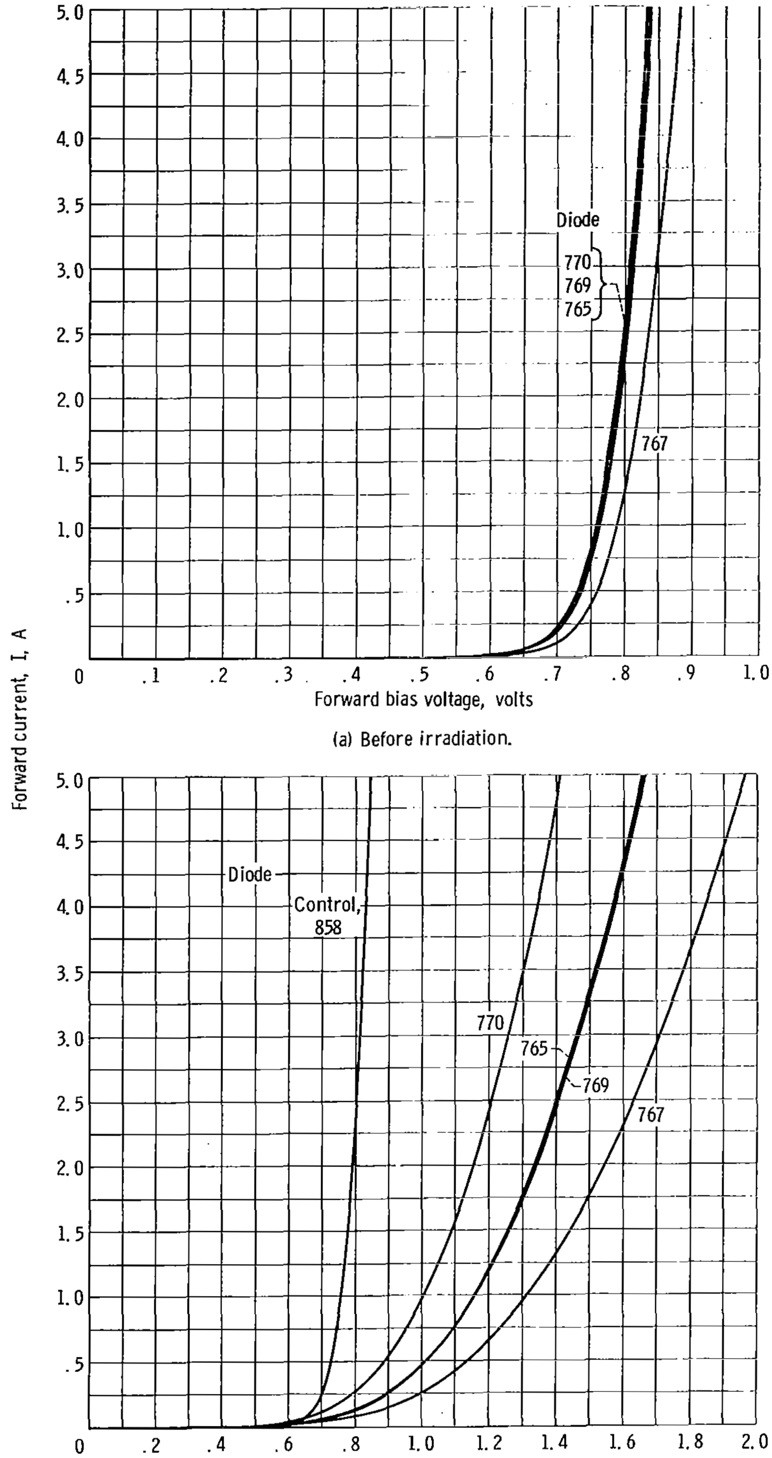


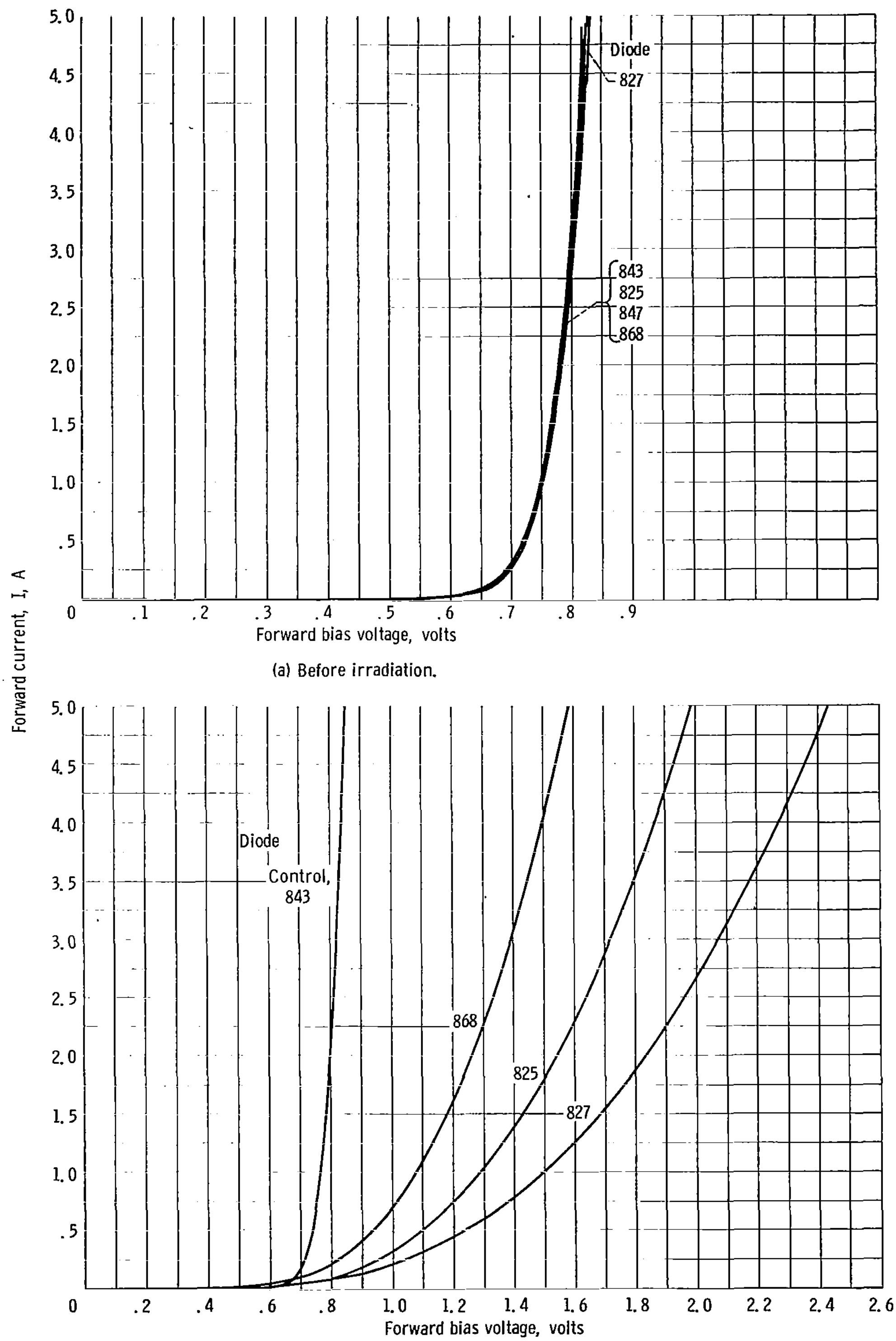
Figure 6. - Forward currents as function of voltage of all diodes before and after irradiation for test II. Temperature, 125° C nominal; neutron fluence, 4.9×10^{13} neutrons per square centimeter.



(a) Before irradiation.

(b) After exposure to neutron fluence of 4.6×10^{13} neutrons per square centimeter. Test I (60° C nominal).

Figure 7. - Linear X, Y-plot of forward current as function of applied voltage for test I.



(b) After exposure to neutron fluence of 4.9×10^{13} neutrons per square centimeter. Test II (125° C nominal).

Figure 8. - Linear X, Y-plot of forward current as function of applied voltage for test II.

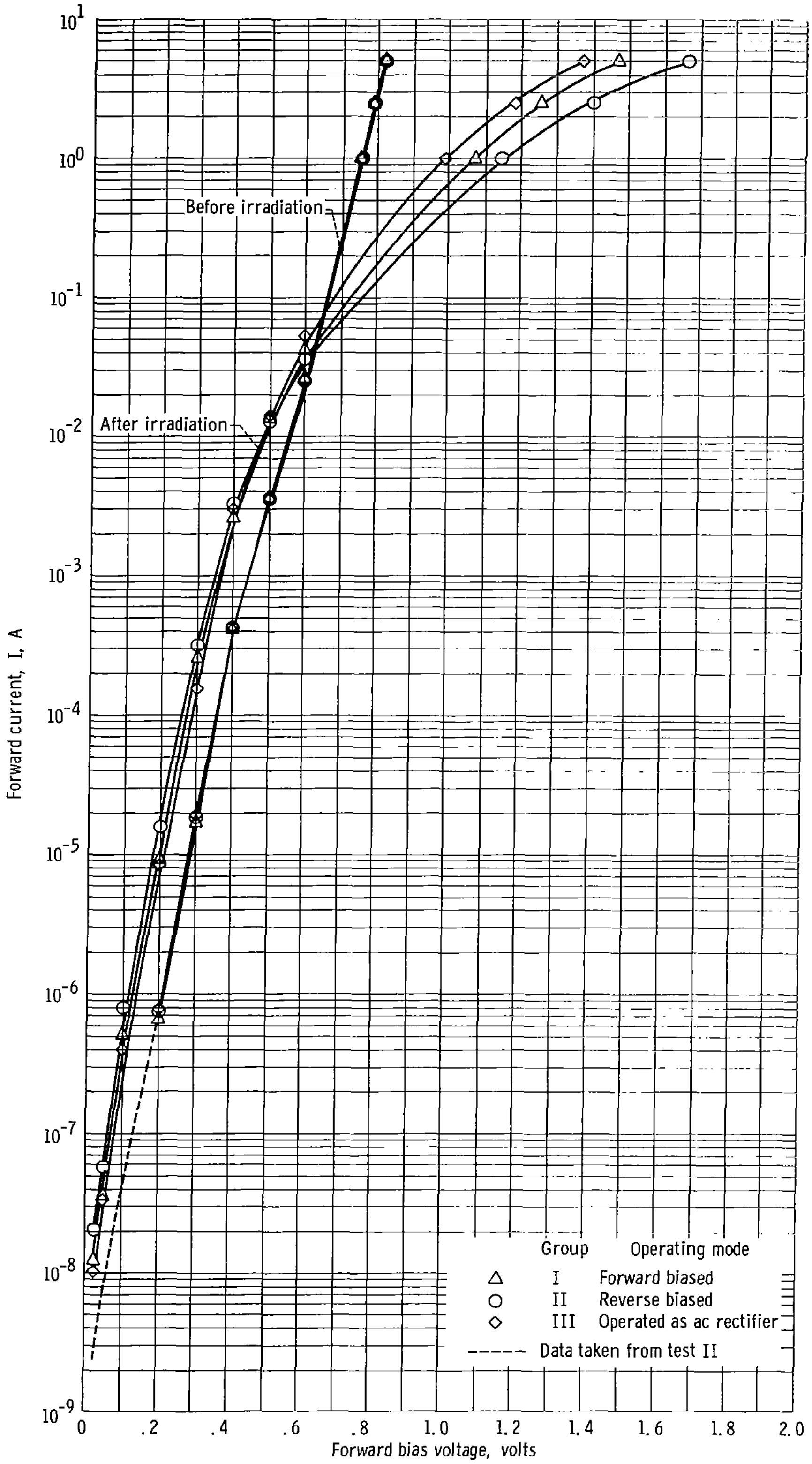


Figure 9. - Average values of forward current as function of voltage according to operating modes for test I (60° C nominal). Neutron fluence, 4.6×10^{13} neutrons per square centimeter.

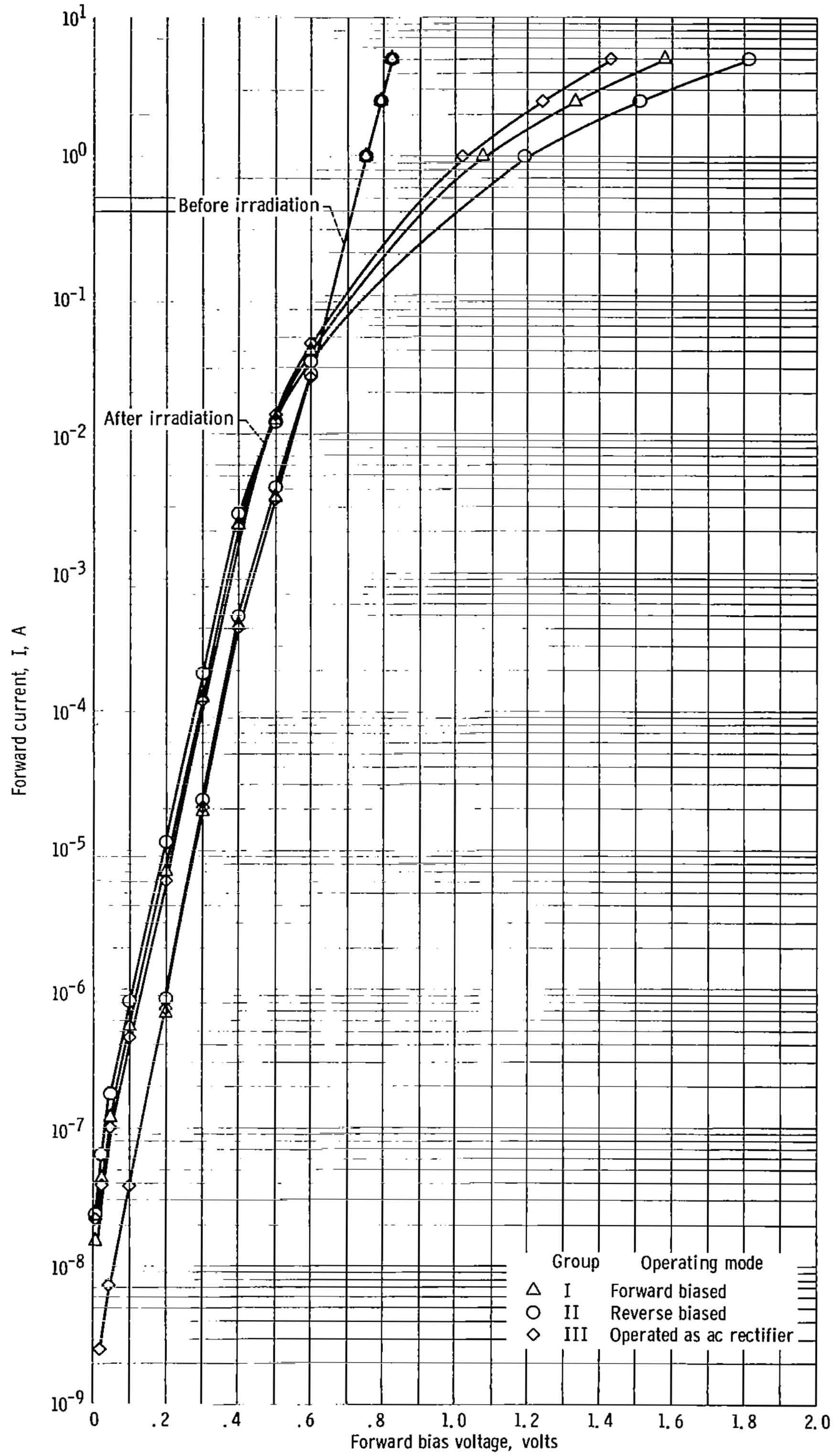


Figure 10. - Average values of forward current voltage according to operating modes for test II (125° C nominal). Neutron fluence, 4.9×10^{13} neutrons per square centimeter.

type of inconsistency that makes it impossible to use the current-voltage curves of preirradiated diodes to predict a change in the forward voltage drop with radiation.

The effects on the forward-current-voltage characteristics of operating the diodes in different modes are shown in figures 9 and 10. In these figures, the curves represent the average values of forward voltage drops for different operating modes in test I (60° C nominal) and test II (125° C nominal), respectively. With respect to operating modes, the spread in values of the average forward voltage drops before irradiation is negligible, as seen from the curves; however, the postirradiated values of the average forward voltage drops show a significant spread in the groups. Those diodes that were operated as ac rectifiers during their irradiation showed the least change in forward voltage drop, whereas those diodes that were operated with a reverse-bias dc voltage displayed the largest average increase in forward voltage. The intermediate group was the dc forward-biased group. Both tests I and II showed the same radiation effects on the forward-current-voltage characteristics with respect to the relative amount of change evidenced in different operating modes.

Figure 11 is a linear plot of the average values of the forward voltage drops for groups by operating modes in both tests. These curves provide a comparison of the effects of different operating temperatures on the diodes during their irradiation. On the basis of the curves in figure 11, an increase appears to occur in the amount of damage to the diode when it is operated at higher temperatures (test II). This observation is interesting in that at the higher temperatures some annealing of the damage was expected and, therefore, less permanent damage to the diode would have resulted. The differences in the average forward voltage drops between the two tests are not so significant as to restrict the use of the diode. The difference represents an increase of 10 percent in voltage as a result of operating the diode at higher temperatures during radiation. This increase, however, is compensated by the fact that test II also received a 6-percent greater neutron fluence than did test I. The groups that were dc reverse biased again showed the largest difference in average forward voltage drop. The groups that were ac operated showed the least difference in voltage drops between tests I and II. Examination of the curves in figures 9 to 11 also provides information concerning the current-voltage relation in the forward voltage region before and after irradiation. Figures 9 and 10 show that before irradiation the current has an exponential dependence on the voltage, because the curve is essentially straight. However, the curve is not straight after irradiation, which obviously indicates that the current is not an exponential function. Also evident from figures 9 to 11 is that the current is not a linear function of the voltage. Current-voltage curves of the average forward voltage drops (after irradiation) for given currents by operating modes were plotted on log-log grid (fig. 12) The resulting straight lines indicate a power dependency $I \propto (V_A - V_B)^n$, where V_A is the applied voltage and V_B is the built-in voltage. The values of n were approximately 2, which suggests that

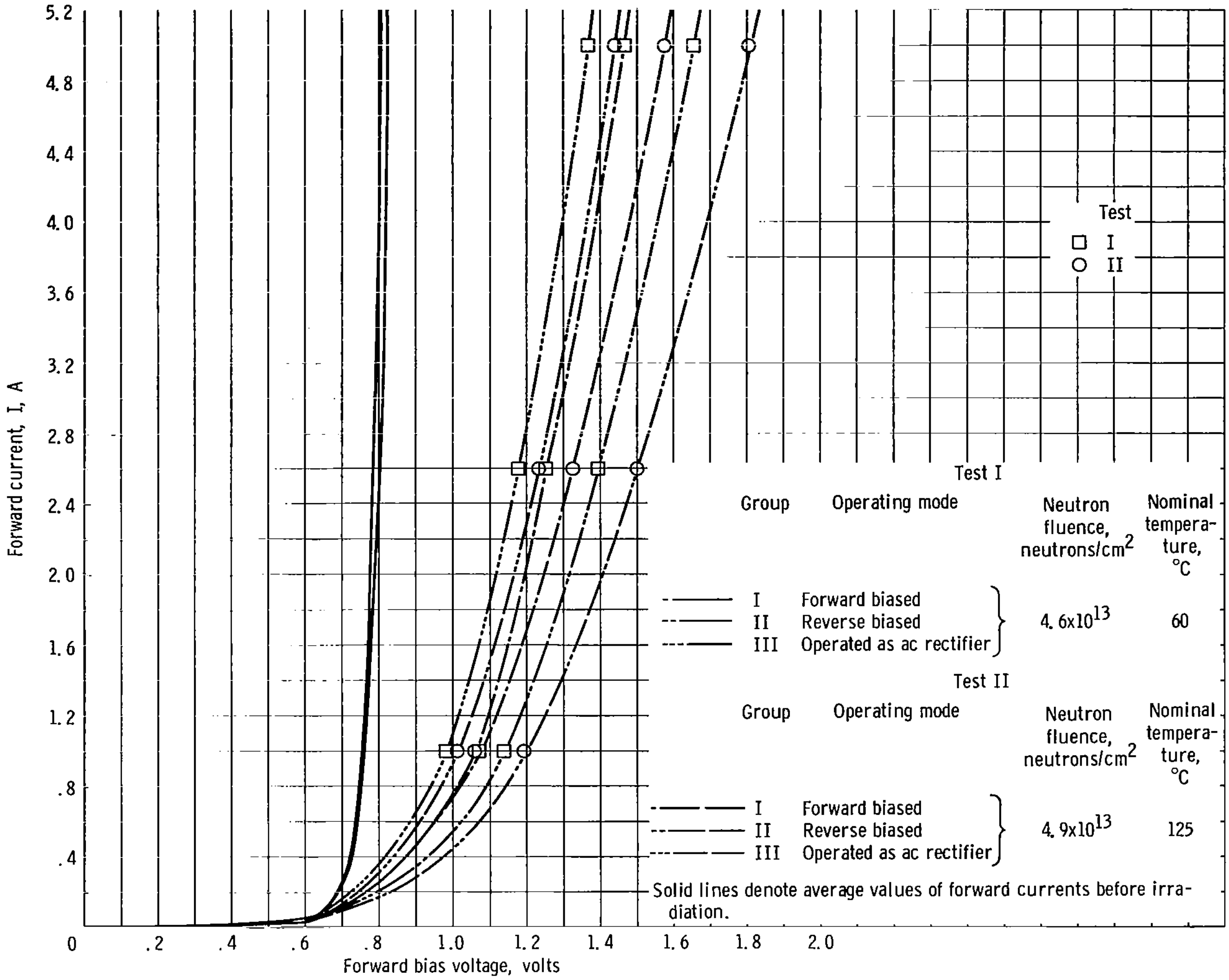
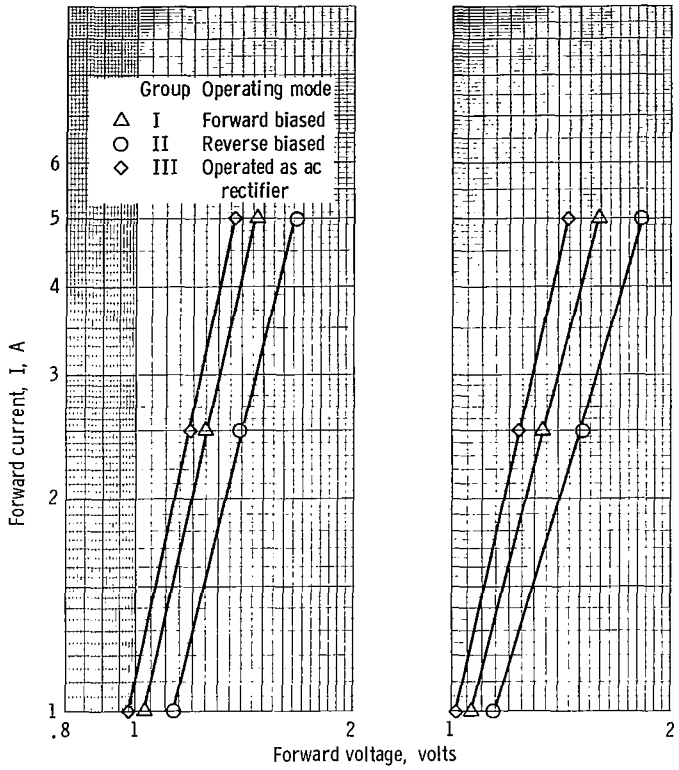


Figure 11. - Average values of current as function of voltage according to operating modes for tests I and II.

after radiation, the diodes are space-charge limited (refs. 8 and 9). The slopes of the curves for these different operating modes are slightly different, as pointed out previously.

The rate of increase in the forward voltage drop for a given current with increasing neutron fluence is shown in figure 13. The curves are approximately linear but have different slopes. As was observed in the preceding figures, the 5-ampere curve exhibits a greater rate of change than that of the 1- or $2\frac{1}{2}$- ampere curves. The curve representing the 0.66-milliampere points actually has a negative slope and indicates a decrease in the forward voltage drop of the diode with irradiation in this bias region. This decrease can also be seen in figures 9 and 10. Another observation made from figure 13 is the absence of any change in the forward voltage drop for a given current as a result of reactor scram or shutdown. This absence is also evident in figures 14 and 15, which



(a) Test I (60° C nominal) with neutron fluence of 4.6×10^{13} neutrons per square centimeter.

(b) Test II (125° C nominal) with neutron fluence of 4.9×10^{13} neutrons per square centimeter.

Figure 12. - Current as function of voltage for forward biases after irradiation. Data points are average values based on operating modes.

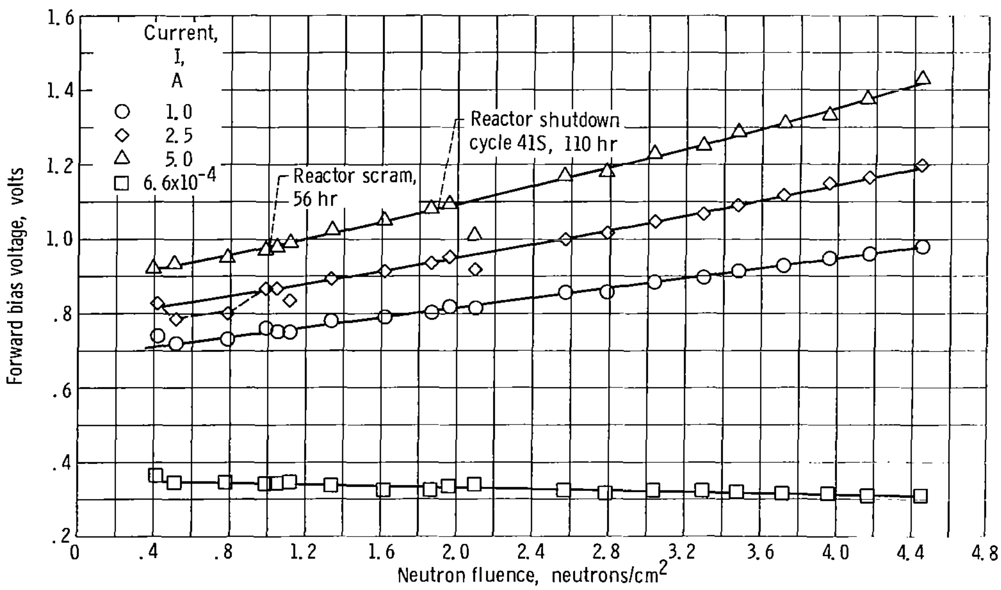


Figure 13. - Change in forward voltage drop with neutron flux for diode 754 in test I (60° C nominal).

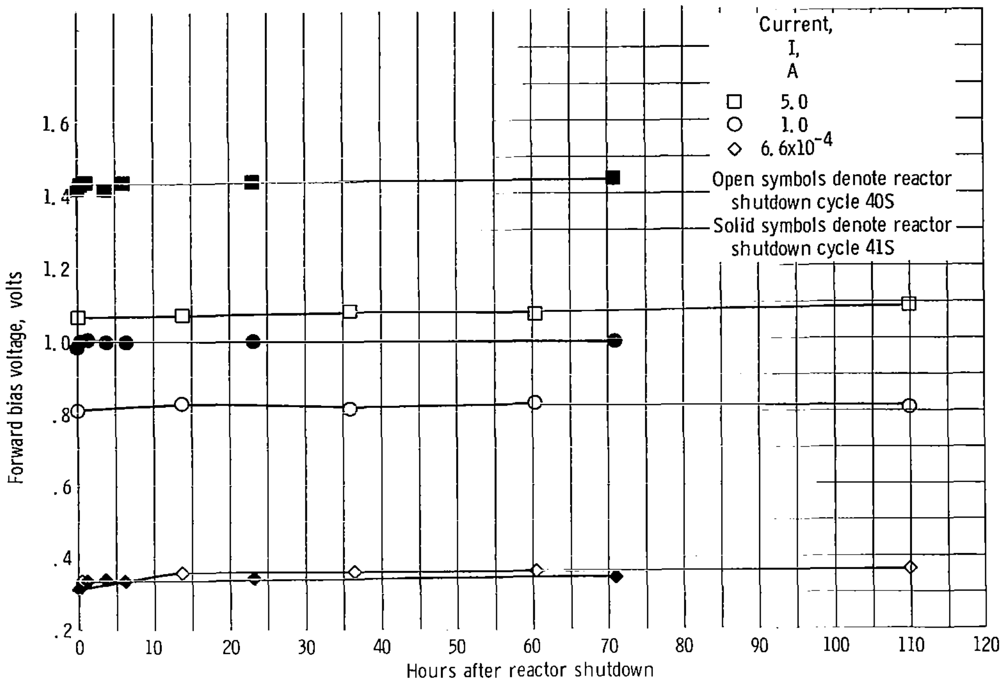


Figure 14. - Annealing curves showing stability of forward voltage drop at given currents with time after irradiation for diode 802.

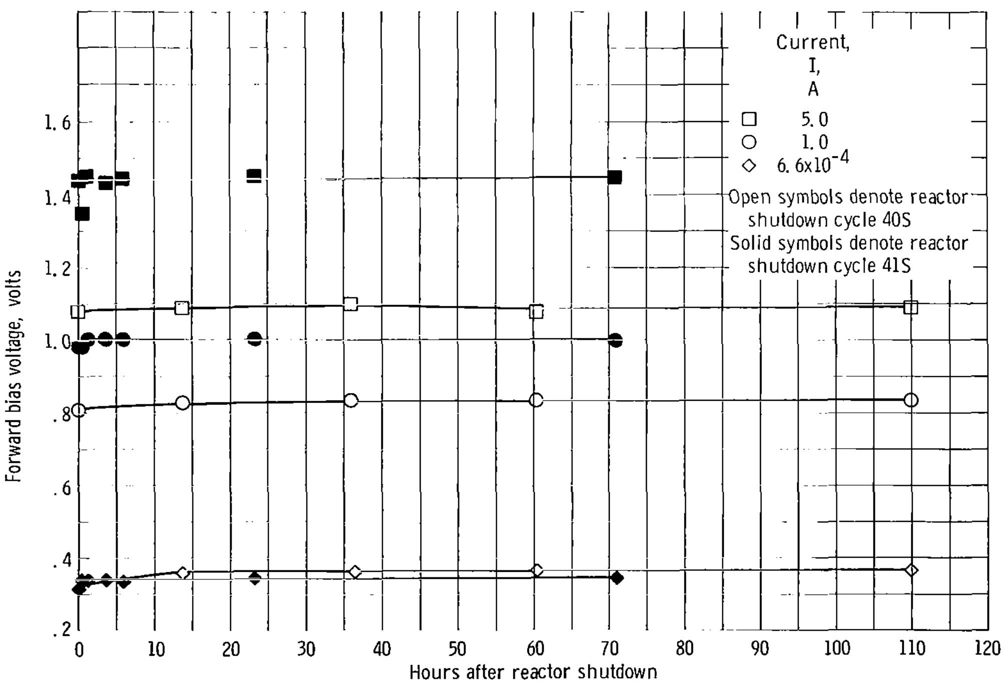


Figure 15. - Annealing curves showing stability of forward voltage drop at given currents with time after irradiation for diode 756.

show data taken after shutdown between reactor cycles. Little, if any, apparent recovery of the forward voltage drops occurs for up to 110 hours after shutdown; that is, no annealing occurs.

Reverse Bias Characteristics

The reverse currents at high reverse bias voltages showed larger percentage changes with radiation than did the forward voltage drops. The percentage change, however, when the operation of the device is considered, is not as important as the actual magnitude of the reverse currents after irradiations, as illustrated by the curves of figures 16 to 19. These curves show the reverse current as a function of the reverse voltage, represented by a 100-percent envelope of all the diodes in the test (denoted by triangular symbols) and by an 80-percent envelope of all the diodes (denoted by circular symbols). For the 50 diodes investigated in each test, the 80-percent envelope excludes the five with the highest reverse current and the five with the lowest reverse current for given volt-

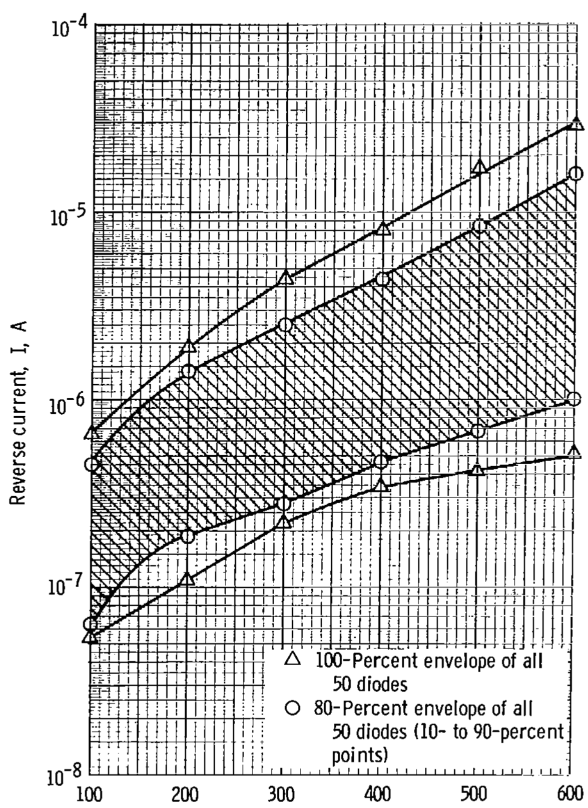


Figure 16. - Reverse current as function of reverse bias voltage for all diodes in test I (60° C nominal) before irradiation.

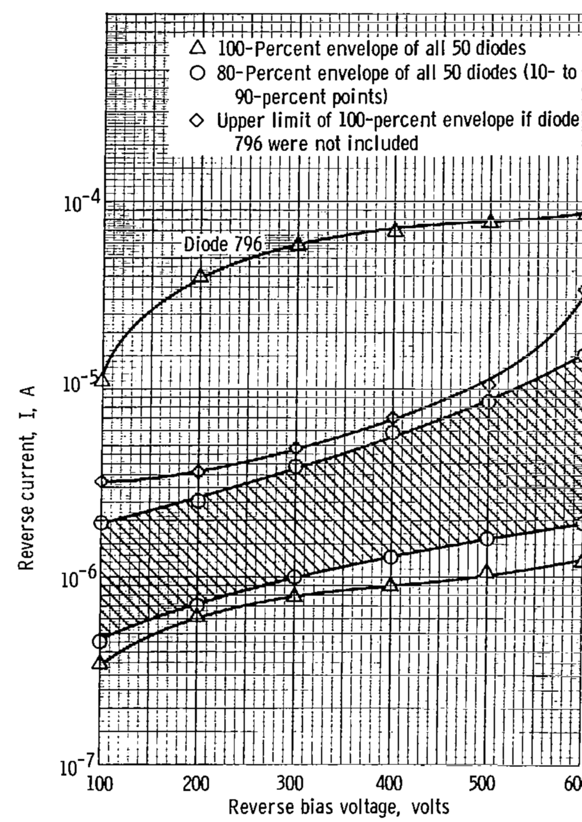


Figure 17. - Reverse current as function of reverse bias voltage for all diodes in test I (60° C nominal) after irradiation with neutron fluence of 4.6×10^{13} neutrons per square centimeter.

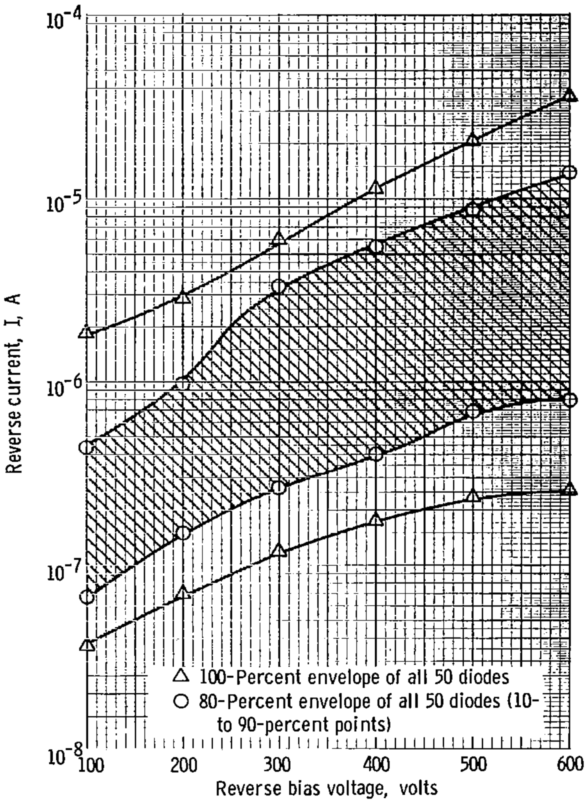


Figure 18. - Reverse current as function of reverse bias voltage for all diodes in test II (125° C nominal) before irradiation.

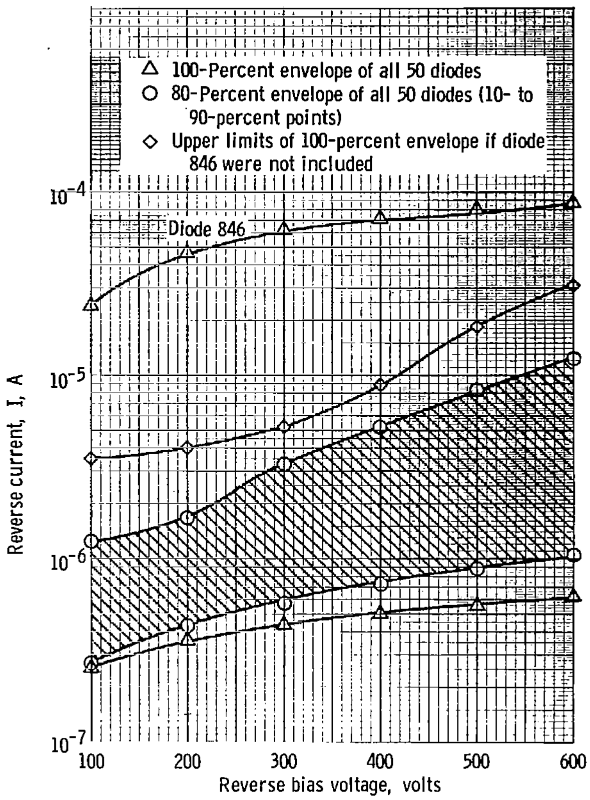


Figure 19. - Reverse current as function of reverse bias voltage for all diodes in test II (125° C nominal) after irradiation with neutron fluence of 4.9×10^{13} neutrons per square centimeter.

ages. A considerable spread in reverse currents for given applied voltages occurred in both tests before and after irradiation. In figures 17 and 19, envelopes of reverse currents after irradiation show that in each test one diode increased considerably more than the other 49. Therefore, in figures 17 and 19, another curve is indicated by diamond symbols representing the upper limit of the 100-percent envelope if the diode that changed the greatest were not included. It is interesting to note that the slopes of the envelopes and the spread in values decreased with radiation. The effects of radiation tend to smooth the curves of reverse currents as a function of reverse voltage. The curves showing 100-percent envelopes, however, do not indicate the manner in which the individual diodes changed. In figure 20, the change in reverse characteristics for a single diode at room temperature with successive reactor cycles of radiation illustrates a general straightening of the reverse-current curve after radiation. In general, the reverse current increases with radiation; however, at higher reverse voltages, such as 800 volts dc, the reverse currents in some instances decrease. This decrease in reverse currents is illustrated in figures 21 and 22 for four diodes measured at room temperature. Diode 829 has an unusual reverse-current-characteristic curve before

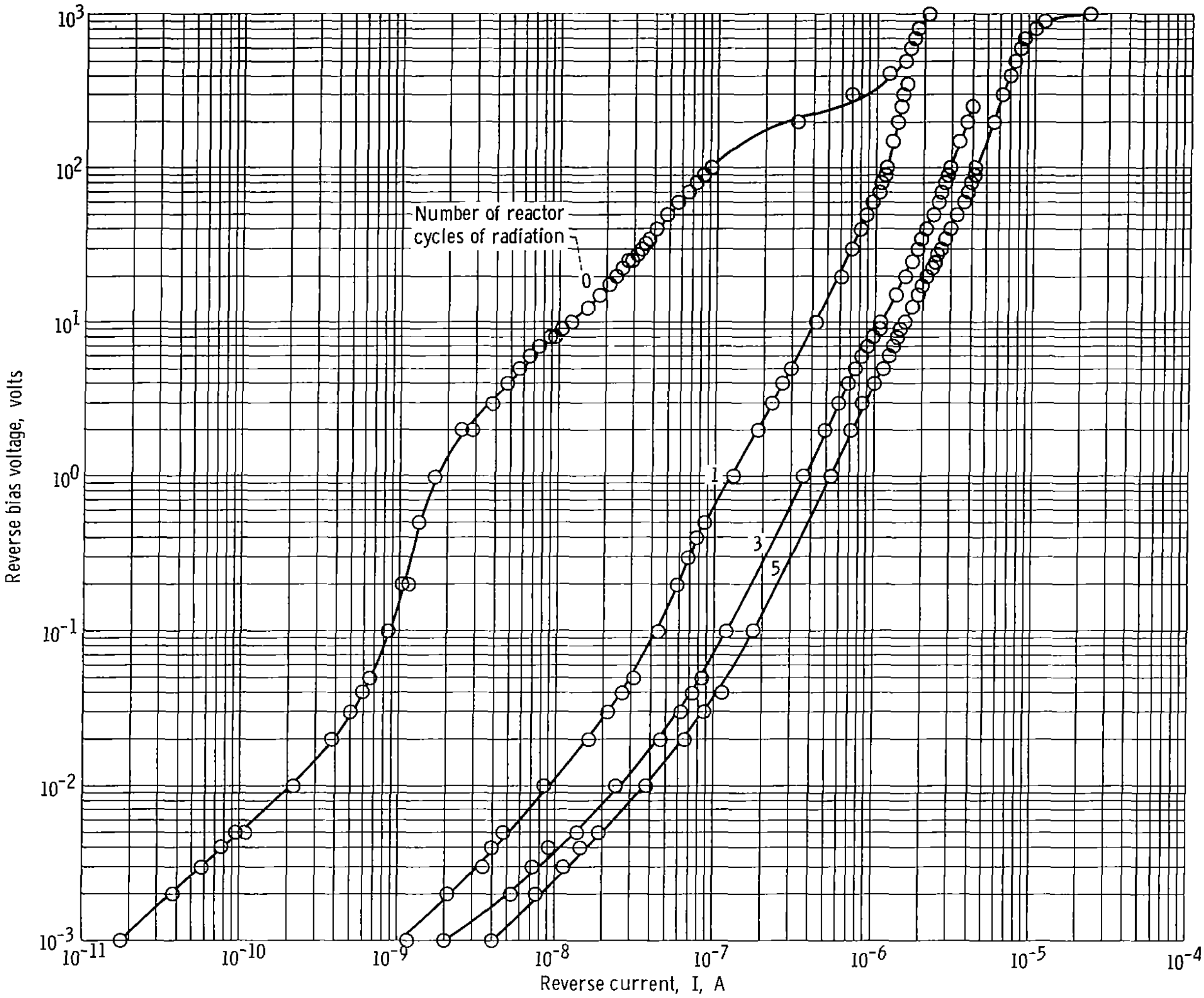


Figure 20. - Room-temperature reverse current-voltage characteristics for diode 805 after successive reactor cycles of radiation. (Neutron fluence for one reactor cycle is approximately 2.5×10^{13} neutrons/cm^2.)

radiation: as the voltage increases, the slope increases initially and then tends to decrease before avalanche breakdown occurs. After irradiation, this characteristic changes to a more constant increasing slope with a lower magnitude of reverse current, as shown in figures 21 and 22. These unusual reverse-current characteristics occur for several diodes in each test of 50, and generally for these diodes, the current is reduced by radiation. Although, as pointed out, individual diodes may show a decrease in reverse currents, the 100-percent envelopes still increased (see figs. 17 and 19). Of importance is the fact that, although a general increase in reverse currents with radiation occurred, none of the reverse currents of the diodes increase to the extent that their use as power rectifiers was limited.

The effects of radiation on the avalanche breakdown voltages for the diodes just discussed are evident in figures 23 and 24. Diodes 827, 828, and 830 indicated no observ-

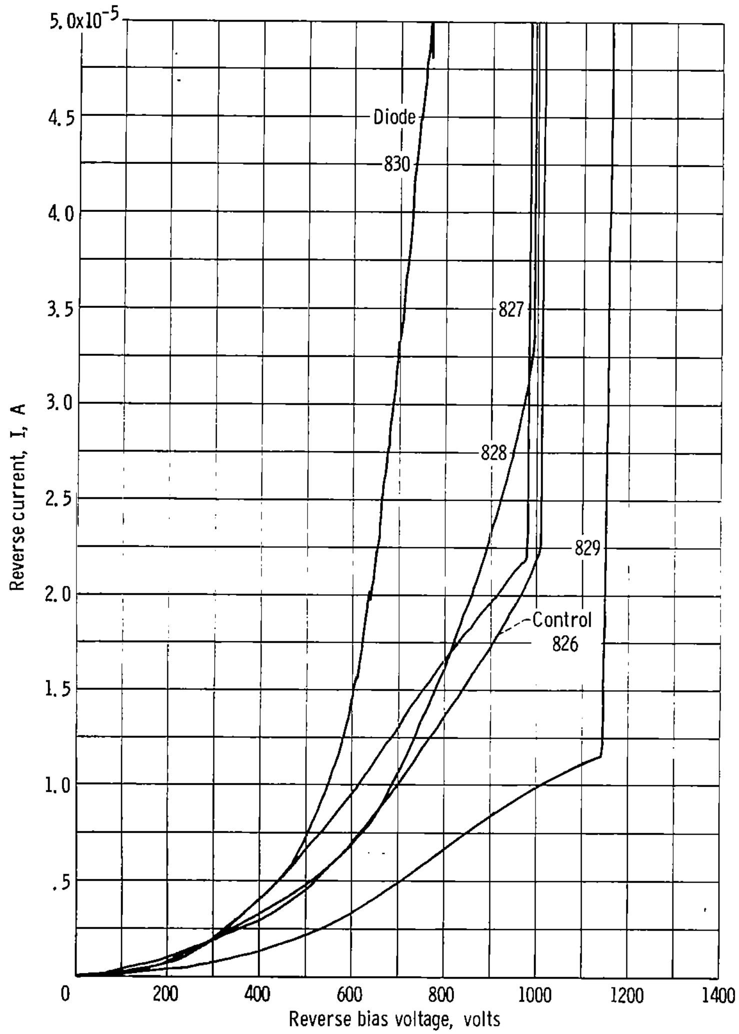


Figure 21. - X, Y-Plot of reverse current as function of applied voltage (with avalanche region included) for test II before irradiation.

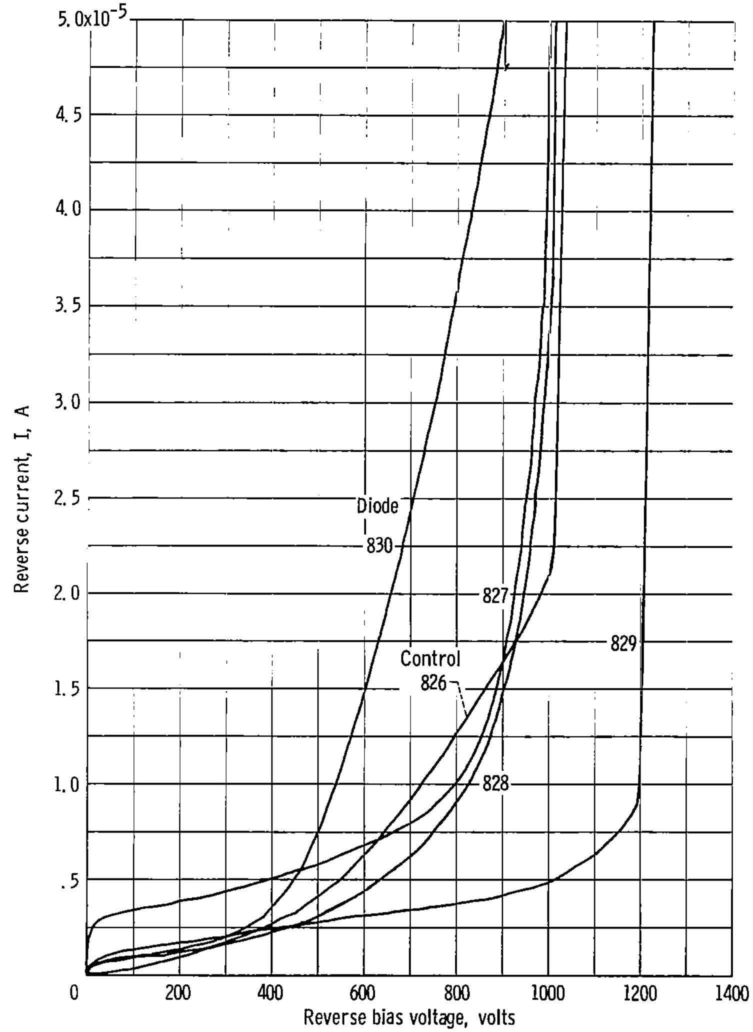


Figure 22. - X, Y-Plot of reverse current as function of applied voltage (with avalanche region included) for test II after irradiation with neutron fluence of 4.9×10^{13} neutrons per square centimeter.

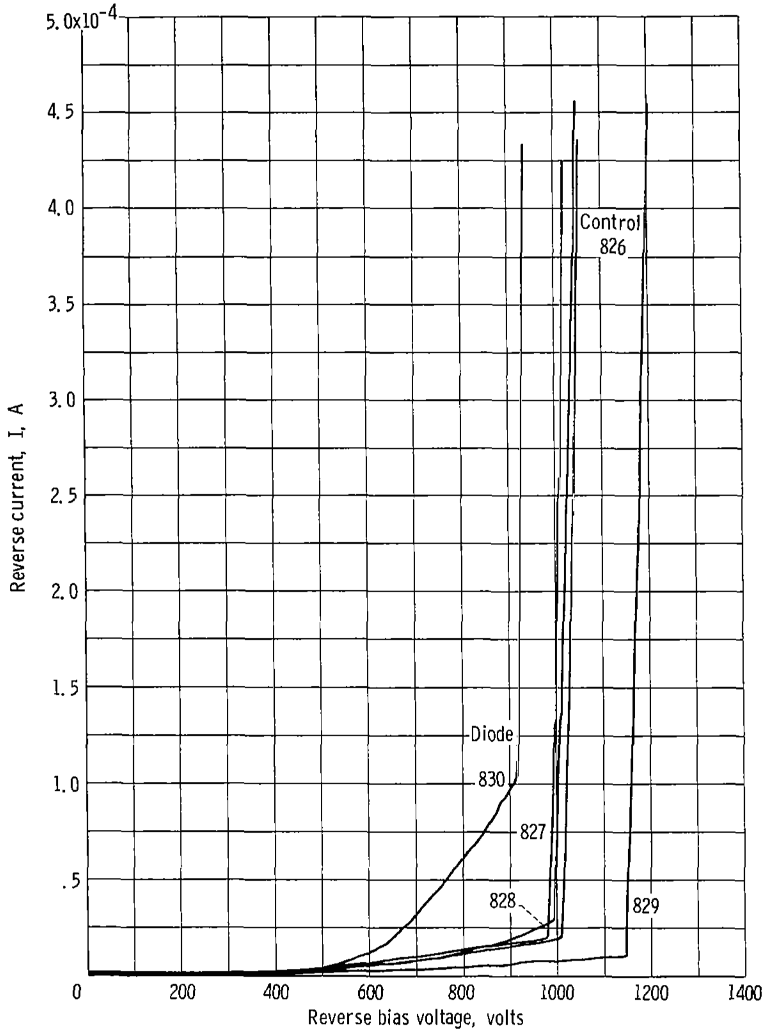


Figure 23. - X, Y-Plot of reverse current as function of applied voltage (with avalanche region included) for test II before irradiation.

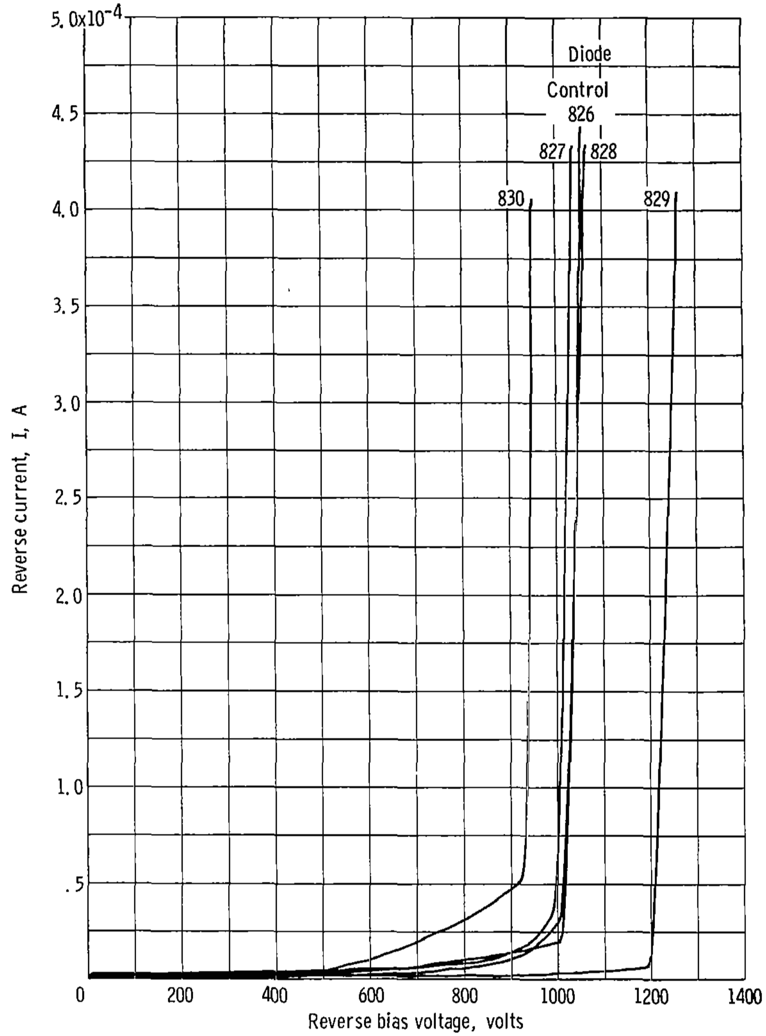


Figure 24. - X, Y-Plot of reverse current as function of applied voltage (with avalanche region included) for test II after irradiation with $4.9x10^{13}$ neutrons per square centimeter.

able changes in their avalanche voltages, whereas diode 829 showed an approximate 50-volt increase. Most of the diodes tested showed little or no change in avalanche voltage with radiation; however, exceptions occurred, as shown in figures 23 and 24. Also of interest was the fact that, even though the avalanche voltage increased for diode 829, the reverse current was reduced with radiation all the way to the new avalanche voltage. In all cases, a rounding of the avalanche knee appeared, as shown for the diodes in figures 21 and 22. Since these diodes have a specified peak inverse voltage of 500 volts dc, the effects of radiation on the avalanche obviously do not impair the application of the device.

The rate of increase in the reverse current with increasing fast-neutron fluence (energies of 0.1 MeV and above) is illustrated in figures 25 to 27. Figure 25 reveals the change in reverse currents for several diodes as a function of an increasing neutron fluence which was uninterrupted by reactor scrams, or shutdowns. These increases in reverse currents appear approximately linear with the neutron flux, but the increases are at different rates. Figures 26 and 27 also show increases in reverse currents for four diodes as a function of increasing neutron fluence, but the flux is interrupted by

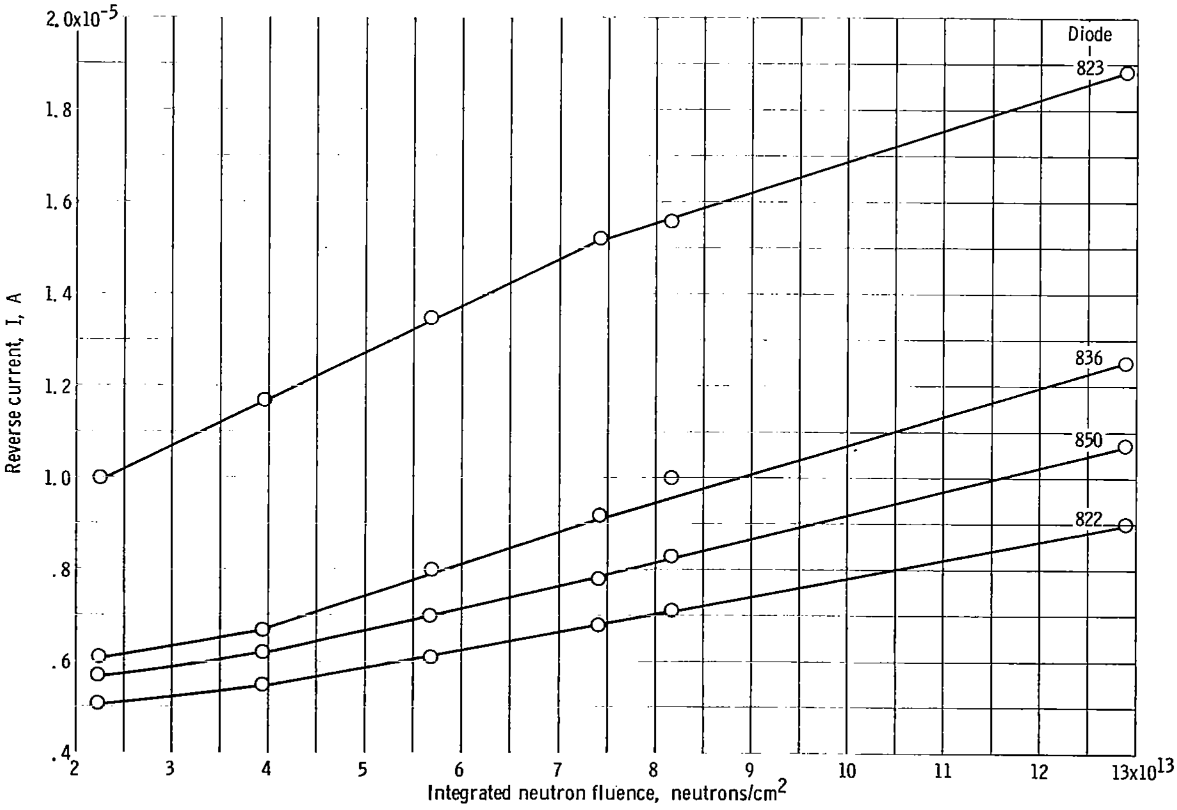


Figure 25. - Reverse current as function of neutron fluence at 100 volts reverse bias.

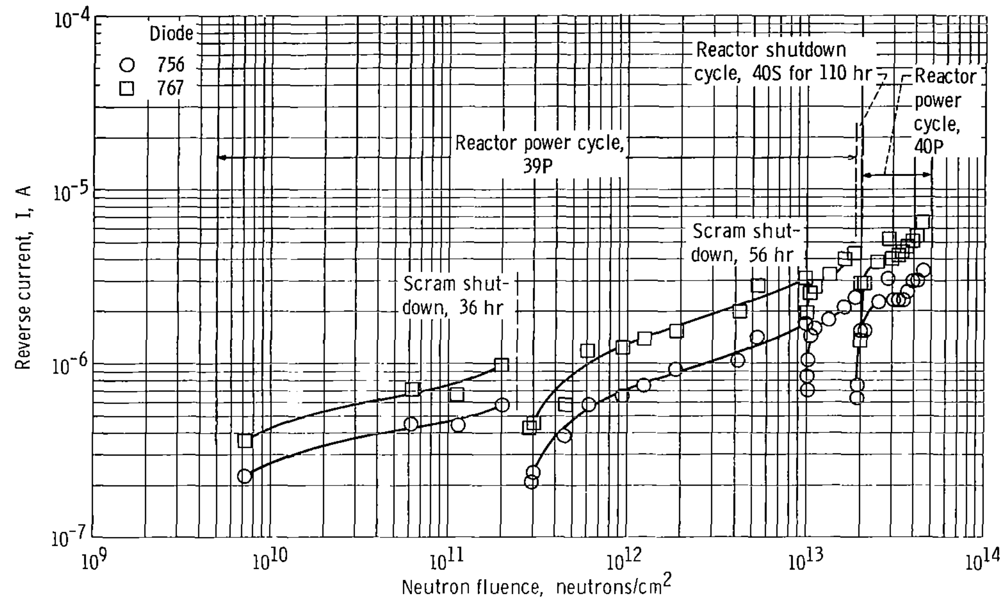


Figure 26. - Increase in reverse current at 100 volts reverse bias with neutron fluence for diodes 756 and 767.

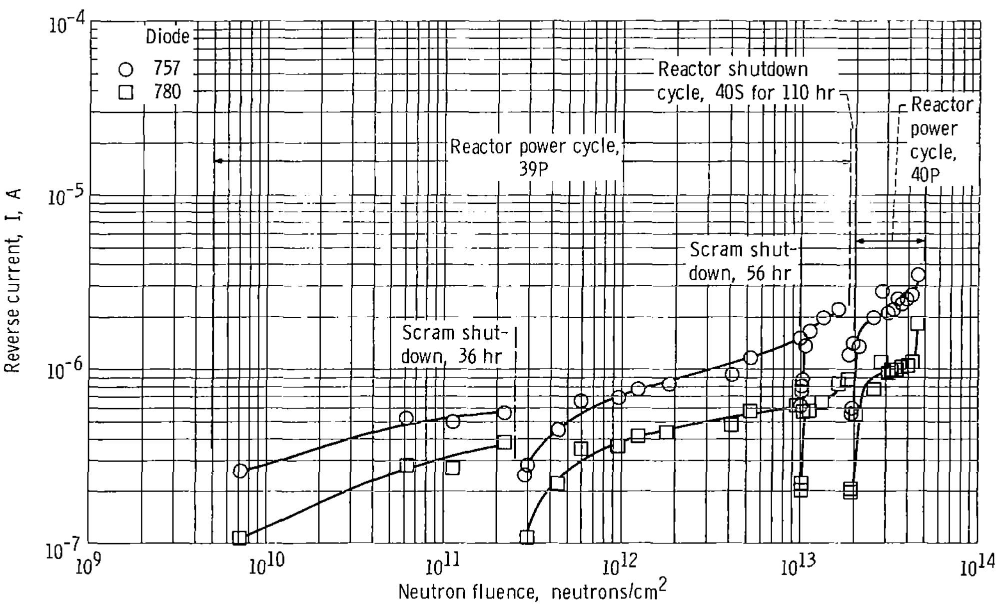


Figure 27. - Curves showing increase in reverse current at 100 volts reverse bias with neutron fluence for diodes 757 and 780.

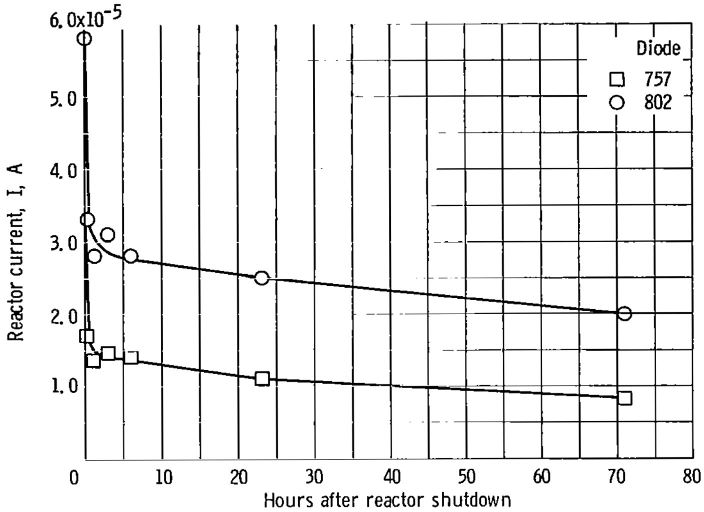


Figure 28. - Annealing curves showing change in reverse current with time after irradiation. Reverse bias voltage, 100 volts dc; reactor shutdown cycle 41S.

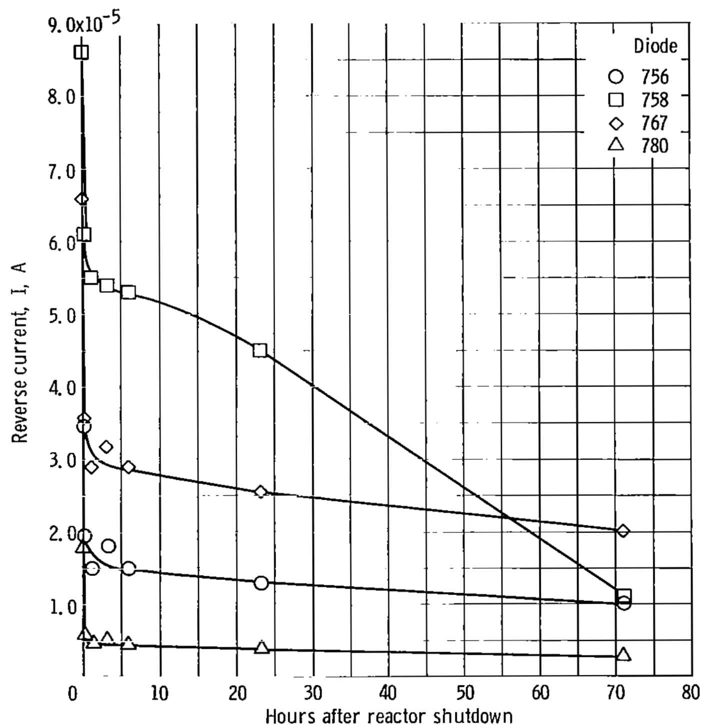


Figure 29. - Annealing curves showing change in reverse current with time after irradiation. Reverse bias voltage, 100 volts dc; reactor shutdown cycle 41S.

reactor scrams and shutdowns. These curves also show an annealing effect after a reactor scram or shutdown, in that after reactor startup, a period of time and radiation are necessary for the reverse currents to recover to their prereactor shutdown values. Even with this annealing effect, however, a steady overall increase in reverse currents with neutron flux occurred. The annealing effects on reverse currents are shown in figures 28 and 29. The initial sharp decline in the reverse current after reactor shutdown results from the drop in the test facility temperature, but the gradual decline with time is caused by some type of annealing. The amount of recovery in reverse currents at room temperature does not appear significant.

SUMMARY OF RESULTS

One hundred high-reliability silicon power diodes were irradiated in two separate tests, each of 50 diodes, at different temperature and operating modes. The diodes were exposed to an approximate fast-neutron fluence (0.1 MeV and above) of 5×10^{13} neutrons per square centimeter and to a gamma dose of 3×10^{7} rads (C). The following results were obtained:

1. The change in the electrical characteristics of the diodes with radiation was not great enough to limit their use in a nuclear electric generating system at the fluence level of the tests.

2. No catastrophic failures occurred in the 480 hours of irradiation.

3. The increase in the forward voltage drop with radiation at high injection levels was the most likely electrical characteristic that would limit the use of the diode with the increased radiation of a nuclear system.

4. The mode of operation of a diode during its irradiation affected the amount of degradation it underwent. A reverse-biased mode of operation caused more degradation in the electrical characteristics than did the forward-bias or ac rectifier modes of operation.

5. The degradation of diode electrical characteristics appeared relatively independent of the temperature at which they were irradiated (60° and 125° C nominal).

6. The increase in reverse currents as a result of radiation showed some type of room-temperature anneal, whereas the increase in forward voltage drop indicated little, if any, annealing.

7. Reverse currents in general increased with radiation, but none increased to the extent that the use of the diode as a power rectifier was limited.

8. The values of avalanche breakdown voltage in general were not affected by irradiation; however, specific cases were observed which illustrated both increases and decreases in the avalanche voltages.

9. Diodes having similar electrical characteristics before irradiation did not necessarily show the same degradation during irradiation and therefore had dissimilar characteristics after irradiation.

10. Any conclusions based on data from a small sampling of one or two diodes, measured as two-terminal devices, would be subject to question because of the considerable spread in the electrical characteristics between individual diodes before and after irradiation.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 2, 1968,
120-27-04-35-22.

APPENDIX A

DETERMINATION OF NEUTRON FLUX AND GAMMA EXPOSURE RATES IN HB-6 FACILITY

The values for fast-neutron fluxes used in this report were obtained from reference 3, which contains the methods of measurements, calculations, and data analysis for the fast-neutron fluxes in the neutron beam port of the HB-6 facility in the Plum Brook Reactor. The fast-neutron and thermal neutron fluxes were measured with the use of conventional gold foils and sulfur pellets. The value of 2.76×10^7 fast neutrons per square centimeter per second, (energies of 0.1 MeV and above) as used in the analysis, is valid provided that a number of variables is considered. These variables can be expressed in terms of correction factors to a standardized flux φ_0, so that a calculated flux can be obtained for any given set of conditions. The various factors affecting the flux are as follows:

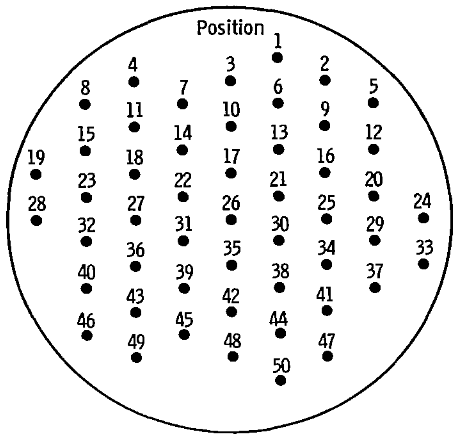
M_1	vertical position factor
M_2	*shim rod position*
M_3	horizontal position factor
M_4	attenuator tank configuration
M_5	reactor power
M_6	attenuation by other experiments

The fast-neutron flux at a given time and set of reactor conditions can be evaluated by the relation

$$\varphi = \varphi_0 M_1 M_2 M_3 M_4 M_5 M_6$$

The value of the flux φ used in this report was obtained from the standard flux; that is, the flux when each correction factor, M_1 to M_6, is equal to 1. This condition occurs when the position of the sample is vertically and horizontally centered in the beam port (M_1 and M_3), the shim rod is at a position (M_2) of 23 inches (58.4 cm), no water is in the attenuation tanks (M_4), the reactor power is at 60 megawatts, and no other experiments are present in the reactor (M_5 and M_6). The value of the sulfur flux (>2.48 MeV), under the conditions of standard flux and on the basis of a fission spectrum, was determined to be 8.2×10^6 neutrons per square centimeter per second. The estimated absolute error in flux was ±30 percent. However, a flux value for neutron energies greater than

0.1 MeV was desired; therefore, the value 8.2×10^6 neutrons per square centimeter per second was multiplied by a factor of 3.37 (from ref. 3) to obtain 2.76×10^7 neutrons per square centimeter per second, the value used in this report. This value was considered average, but, as pointed out, the actual neutron flux varies with time and position. The positions of the diodes on the test plate are shown in figure 30.



Test I				Test II			
Position	Diode	Position	Diode	Position	Diode	Position	Diode
1	749	26	775	1	808	26	844
2	751	27	776	2	809	27	845
3	750	28	777	3	815	28	846
4	752	29	778	4	816	29	849
5	753	30	780	5	817	30	850
6	754	31	781	6	818	31	852
7	755	32	782	7	820	32	853
8	756	33	783	8	822	33	855
9	757	34	784	9	823	34	859
10	758	35	785	10	824	35	860
11	759	36	786	11	825	36	861
12	760	37	787	12	827	37	862
13	761	38	788	13	828	38	863
14	762	39	790	14	829	39	864
15	763	40	804	15	830	40	866
16	764	41	793	16	831	41	867
17	765	42	794	17	832	42	868
18	766	43	795	18	833	43	869
19	767	44	796	19	835	44	870
20	769	45	797	20	836	45	872
21	770	46	798	21	837	46	874
22	771	47	799	22	838	47	876
23	772	48	800	23	839	48	877
24	773	49	801	24	840	49	878
25	774	50	802	25	841	50	879

Figure 30. - Location of diodes on test-sample plate.

The gamma-ray dose rate in the HB-6 facility was measured (ref. 9) with lithium fluoride thermoluminescent dosimeters and ionization chambers. The dose rate was dependent on position and time factors similar to those that affected the fast-neutron fluxes, except that the degree of sensitivity to the particular factors was less. In the determination of the exposure rate, the gamma dose rate was treated as a perturbed standard gamma dose rate analogous to the correction-factor equation used to evaluate the fast-neutron flux. The resulting value for the gamma exposure rate was 7.6×10^4 roentgens per hour. The absolute error was estimated to be ±14 percent with a ±12 percent reproducibility.

APPENDIX B

DESCRIPTION OF CIRCUIT FOR TESTING DIODES IN AC RECTIFICATION OPERATING MODE

In the silicon-power-diode radiation program, 30 of the 50 diodes were operated during irradiation in a 400-cps, half-wave rectification circuit arrangement. The required forward current was 10 amperes full cycle average, and the reverse voltage was 115 volts ac on alternate half cycles. This test method would normally require the application of 115 volts ac across a dropping resistor in series with the diodes under test, as shown in figure 31. However, a simple calculation demonstrates that this commonly

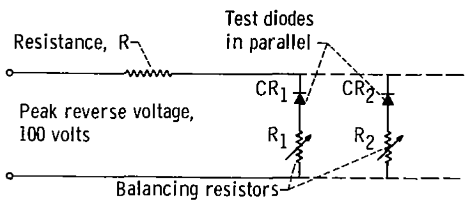


Figure 31. - Conventional test circuit for operation of diodes as ac rectifiers.

used testing method has a disadvantage. The desired peak reverse voltage across the diode is obtained on the half cycle where the test diode is reverse biased. The circuit condition here presents no problem because the reverse current is small, and the diode acts essentially like an open circuit. The power dissipation is negligible. However, when the diode is forward biased on the alternate half cycle with an average forward current of 10 amperes flowing in the circuit, the diode looks essentially like a short circuit (0.8-volt drop). In this case, 114.2 volts at 10 amperes must be dropped across the resistance R. Thus, the value of R for one test diode would have to be

$$\frac{114.2\ \text{volts}}{10.0\ \text{A}} = 11.42\ \Omega$$

and power that must be dissipated in R for one diode is

$$114.2\ \text{volts} \times 10\ \text{A} = 1142\ \text{W}$$

Thus, the power dissipated in R for 30 diodes is

$$\frac{1142\ \text{W}}{\text{diode}} \times 30\ \text{diodes} = 34\ 260\ \text{W} = 34.26\ \text{kW}$$

These circuit requirements of a large voltage, small current on one half cycle, and a small voltage, large current on the alternate half cycle suggest that some type of switching would be practical. The basic circuit illustrated in figure 32 meets these circuit requirements.

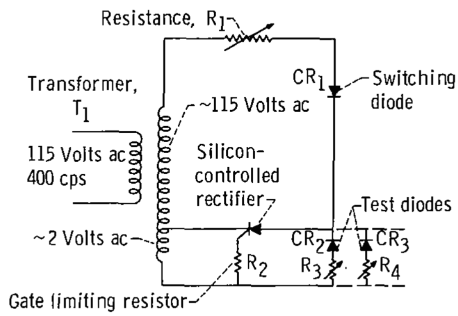


Figure 32. - Test circuit for testing diodes operating as ac rectifiers to reduce input power requirements.

In this circuit, the secondary of transformer T_1 is tapped at approximately 2.0 volts ac, and the total secondary voltage is 115 volts ac, or a 1:1 ratio. The silicon-controlled rectifiers and the diode CR_1 act as switches on alternate half cycles. The test diodes in parallel are CR_2, . . ., CR_n. The operation of the circuit is illustrated in figures 33 and 34.

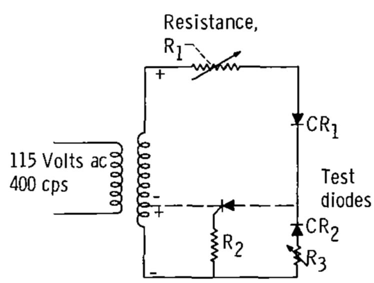


Figure 33. - Circuit condition when test diodes are reverse biased.

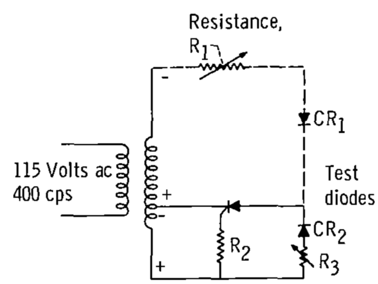


Figure 34. - Circuit condition when test diodes are forward biased.

In figure 33, with the polarity of the secondary of T_1 as shown, the silicon-controlled rectifier (SCR) is turned off and CR_1 is forward biased, which then places 115 volts ac across R_1, CR_1, and CR_2 in series. Since the current flowing in the circuit is the reverse leakage current of the test diode CR_2, R_1 is adjusted until the desired reverse voltage is dropped across the diode. On the alternate half cycle, the SCR is turned on and the diode CR_1 is reverse biased (turned off), as shown in figure 34. The 2.0-volt tap now furnishes 2 volts to the SCR, R_3, and the test diodes in series. R_3 is adjusted until 10 amperes flow in the diode CR_2. Since R_3 is negligible as compared with R_1, the drop across R_3 in the reversed bias condition will be negligible.

The advantages of this circuit are apparent in the power requirement for a test diode, which is

$$2.0 \text{ volts} \times 10 \text{ A} = \frac{20 \text{ W}}{\text{Diode}}$$

and the requirement for 30 test diodes, which is

$$30 \text{ Diodes} \times \frac{20 \text{ W}}{\text{Diode}} = 0.6 \text{ kW}$$

Therefore, the current requirement from the 115-volt ac source is

$$\frac{2 \text{ volts}}{115 \text{ volts}} = \frac{x \text{ A}}{300 \text{ A}}$$

where $x = 5.2$ amperes.

REFERENCES

1. Messenger, George C.; Pretzer, Donavon D.; Chang, William W.; Kimble, Stewart G.; and Steele, Edward J.: Device Performance Characteristics As Related to Radiation Damage in Semiconductor Materials. Rep. No. ARD-66-42-R (AFCRL-66-462, DDC No. AD-643703), Northrop Corp., June 1966.
2. George C. Marshall Space Flight Center: Screening Specifications for Semiconductor Device S1N1189, April 1963.
3. Bozek, John M.; and Godlewski, Michael P.: Experimental Determination of neutron Fluxes in Plum Brook Reactor HB-6 Facility with Use of Sulfur Pellets and Gold Foils. NASA TM X-1497, 1968.
4. Bozek, John M.: Experimental Determination of Gama Exposure Rate in Plum Brook HB-6 Facility. NASA TM X-1490, 1968.
5. Smith, John R.; Kroeger, Erich W.; Asadourian, Armen S.; and Spagnuolo, Adolph C.: Fast-Neutron Beam Irradiation Facility in the NASA Plum Brook Test Reactor. NASA TM X-1374, 1967.
6. Bloomfield, Harvey S.: Shielding Requirements for the NASA Plum Brook HB-6 Beamhole Radiation Effects Facility. NASA TM X-1461, 1967.
7. Sah, Chih-Tang; Noyce, Robert N.; and Shockley, William: Carrier Generation and Recombination in P-N Junctions and P-N Junction Characteristics. Proc. IRE, vol. 45, no. 9, Sept. 1957, pp. 1228-1243.
8. Howard, N. R.; and Johnson, G. W.: $P^{+}IN^{+}$ Silicon Diodes at High Forward Current Densities. Solid State Electronics, vol. 8, no. 3, Mar. 1965, pp. 275-284.
9. Jonscher, A. K.: Measurement of Voltage-Current Characteristics of Junction Diodes at High Forward Bias. J. Electr. Control, vol. 5, no. 3, Sept. 1958, pp. 226-244.

NASA-Langley, 1968 —— 9 E-4215