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RADIATION EFFECTS
ON
POWER TRANSISTOR PERFORMANCE

CONTRACT NO. NAG3-793

FINAL REPORT

SUBMITTED TO

NASA-LEWIS RESEARCH CENTER
CLEVELAND, OHIO

by

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G3/33 0087616

INTRODUCTION

This report covers the research done under Grant No. NAG3-793 for the approximate three month period starting in April 1987, and ending in June 1987. The research grant was a continuation effort concentrating on evaluating radiation effects on commercially available high power semiconductor switches. The work was both theoretical and experimental. The theoretical work was centered on understanding radiation damage mechanisms and anticipated failures and/or degradation in performance. The experimental aspects of the grant were related to performing electrical tests on devices inside a nuclear reactor to simulate the neutron radiation environment anticipated in future reactor powered space missions.

The research work is a continuation of the research started at NASA-Lewis during the summer of 1986 and extended with a Case/NASA R&D Research Fellowship. The research utilized the facilities and equipment of NASA-Lewis, the Ohio State Nuclear Reactor Facility, and Wittenberg University.

RESEARCH DESCRIPTION

With regard to the work statement made in the original proposal, each item will be addressed and research effort discussed.

3.1 Irradiate D60T, D62T, and D75T transistors in the nuclear reactor with bias voltage and obtain high current I_C vs. V_{ec} curves to evaluate gain degradation at high power levels. Also perform pre- and post-irradiation high current switching tests to evaluate response.

Work on Item 3.1 was centered on room temperature irradiations of several groups of Westinghouse D60T devices and a solitron DST18329 device. Work with

D62T and D7ST devices was not done because communications with the manufacturer informed us of their similarity to the D60T devices. All three Westinghouse devices are produced in precisely the same manner and in fact, the same 6 mil silicon wafers are used to produce all three devices. The primary differences are the surface area of the emitter-base to control maximum current and the thickness of the collector which controls breakdown voltage. Also, the D62T and D7ST are fabricated in a flat pack (hockey puk) and the D60T devices are packaged in a standard stud mount (TO-83) design.

Two irradiations of two D60T455010 transistors were done. While being irradiated, they were monitored for gain change, leakage currents associated with BVCEO, BVEBO, and BVCBO as well as variations in V_{eb} as a function of collector current and base current. The first irradiation utilizing two D60T devices at a flux of $9.1\text{X}10^{8}$n/cm^{2}-sec for a period of six hours giving a fluence of $2\text{X}10^{13}$n/cm^{2}. The second irradiation was done for a period of six hours at $4.5\text{X}10^{8}$n/cm^{2}-sec for a fluence of $1\text{X}10^{13}$n/cm^{2}. In the latter run, two D60T devices and the SDT18329 device were irradiated. The purpose of the two irradiations was to detect any electrical characteristics that are flux dependent and to obtain preliminary information on the SDT device. The resulting degradation curves for the D60T devices indicate no neutron rate dependence at such low flux rates. Thus, at these rates, the damage is primarily due to fluence and not flux.

During the irradiations, the gamma ray dose never exceeded 30 kilorads for the first irradiation and 15 kilorads for the second irradiation. The resulting dose is considered quite low. Thus, the Ohio State Nuclear Reactor is an excellent source of "pure" neutron radiation.

The following figures summarize the results from the two reactor runs done on the D60T455010 and SDT18329 devices irradiated at the Ohio State University reactor under this grant.

Figures 1 through 5 plot the loss in current gain as a function of neutron fluence. In each case, the obvious result is a rapid decrease in gain immediately after the reactor is started. In each case, the dotted curve is the percent gain loss curve for the device for any collector current. Even though the gain (h_{FE}) is very current dependent, the percent loss in gain appears to be collector current independent. The graphs clearly point out the rapid decrease in gain which is not a desirable feature for the proposed application. Figures 3, 4, and 5 are gain loss curves for irradiations of $1X10^{13}n/cm^2$ at a flux of $4.5X10^8n/cm^2$-sec. Figures 1 and 2 are for irradiations of $2X10^{13}n/cm^2$ at a flux of $9.1X10^8n/cm^2$-sec. Both irradiations lasted six hours. Figure 6 is a plot of current gain as a function of fluence. Prior to irradiation, all four transistors were selected to have identical gains at 50 amperes. As can be seen from the plot, the gain loss of all four devices is a function of fluence, not flux. The SDT18329 had a similar percent gain loss curve (Fig. 5) to those of Figures 1-4. Unfortunately, the solitron device started with low current gain and quickly dropped in gain to values of less than unity.

Figures 7 through 10 are plots of device "on voltage" during conduction for cases before and after irradiation. As can be seen from the figures, the on-voltages before irradiation are very small and represent the device's internal resistance (mostly collector resistance). Also, the pre-irradiation information with its low on-voltage for rather low base currents and high collector currents suggests the ease of saturating the devices (forward biasing both junctions). However, after irradiation, the forward resistance increases (the movement of vertical traces to the right). Also, and more important, the curves drastically change slope which implies an inability to saturate the devices. In all four figures, a similar pattern is observed.

Figures 7 and 8 have more pronounced variations than Figures 9 and 10 because the former were irradiated to twice the level of the latter. The devastating result of the inability to saturate the devices with base currents up to twenty amperes is excessive heating during the "on" condition. Due to their inability to saturate, the power dissipated during conduction is excessive and the output voltage and current will be reduced. This result is very detrimental and for irradiations done at room temperature there appears to be no room-temperature annealing following irradiation.

Figures 11 and 12 display the breakdown voltage characteristics for the D60T and DST18329 devices. As can be seen from Figure 11, the VBCEO and BVCBO for the D60T455010 devices varied quite radically before irradiation (matched gains), but the irradiation appears to cause a convergence to a breakdown voltage of less than 200 volts. The breakdown voltages for the D60T devices (BVCEO and BVCBO) were recorded when their associated leakage currents reached 15 microamperes. For the case of the DST18329 device, the breakdown voltages (BVCBO and BVCEO) never reached 15 microamperes and the plots represent the actual curve tracer results. The BVEBO curves for the D60T455010 are not shown. The results were not significantly altered by the irradiation and a leakage current of 3 milliamperes at 8 volts was obtained before and after irradiation for all four devices tested.

3.2 Correlate gamma ray damage work done at Sandia with the neutron work done at the O.S.U. reactor with the above specified transistors.

The gamma ray work done on the D60T455010 devices indicated a high tolerance to gamma radiation. Gamma radiation levels 10 times the anticipated gamma dose only slightly altered the current gain and breakdown characteristics of the devices. These results are in strong contrast to the neutron effects. A neutron fluence of $2X10^{13}n/cm^2$ made drastic changes in the transistor's current gain and leakage currents. It is very obvious by looking at Figures 1-11 that the anticipated neutron dose - not the gamma dose from space reactors will be detrimental to D60T455010 and DST18329 devices.

3.3 Perform theoretical analyses of damage and electrical performance in terms of semiconductor physics.

The work done to fulfill 3.3 was that of carrying out an extensive literature search on neutron irradiation work on power semiconductors. The search yielded only a few related papers. It appears that very little work has been done on neutron damage to high power semiconductor switches. However, several books have recently been published on the subject and were beneficial in comprehending the damage modes and resulting behaviors. Current work in this area is continuing and will be presented in the 1987 NASA-Lewis Summer Faculty Fellowship Final Report.

3.4 Improve the experimental high current pulser in order to measure switching time changes which are less than one microsecond at currents of 100 to 200 amperes for in-situ testing.

The pulser circuit was altered to improve the rise-time of the output pulse by removing the .5Ω 10W series resistor in the D60T base drive circuit (see Figure 13). Also, the 2N4003 transistor was replaced with a MOSFET device (IRF130) with only slightly better results. The major problems in obtaining fast rise times for the base drive circuit can be circumvented by placing a 0.5Ω resistor to ground at the base lead of the D60T transistor. This greatly reduces the rise-time of the 2N4003 pulse designated I_b in Figure 13. However, the current pulse into the base of the D60T transistor (See Figure 14 - trace I_b) still suffers from a slight notch due to the device's input impedance. However, the output voltage and current pulses do not reflect the input current notch (Figure 14 - traces I_c and V_{ec}).

It has been found that the rise-time of the output current and voltage is reduced if the input voltage to the test device is increased to 250 VDC from 50 VDC and the load resistance is increased to 5Ω to maintain 50 amperes of current. The improvement in rise-time (approximately .5 μsec.) is contributed to the increase in load resistance which makes the transistor's resistance less significant to its function. Also, the transistor gives a flatter current and voltage pulse at 250V/50A. Figure 14 illustrates the output voltage, output current and input base current for a D60T455010 device operating at 250 VDC and having 5Ω of load resistance to limit the output current to 50 amps. Figures 15 through 18 are pulser photographs of four D60T455010 devices before and after irradiation. The striking differences between the pre- and post-irradiation traces are: a) the reduction in storage time; and b) the inability of the base current to turn the transistor "on".

For devices A and B, the storage time is shorter than for C and D. This is due to the difference in fluence. Devices A and B received $2X10^{13}n/cm^2$ and C and D received $1X10^{13}n/cm^2$. Likewise, it is more difficult to "turn-on" devices A and B than C and D. Also, the forward voltage drop for the former devices is more than the latter ones.

Figure 19 is the resulting pulser photograph of a SDT18329 exposed to $1X10^{13} n/cm^2$. As can be seen, the storage time is short and the resulting "on" voltage is excessive. For base currents of 15 amps, less than 10 amps of collector current was obtained. Also, no more than 8 volts of the applied 40 VDC was obtained at the load. The irradiation was very detrimental to the device's operation.

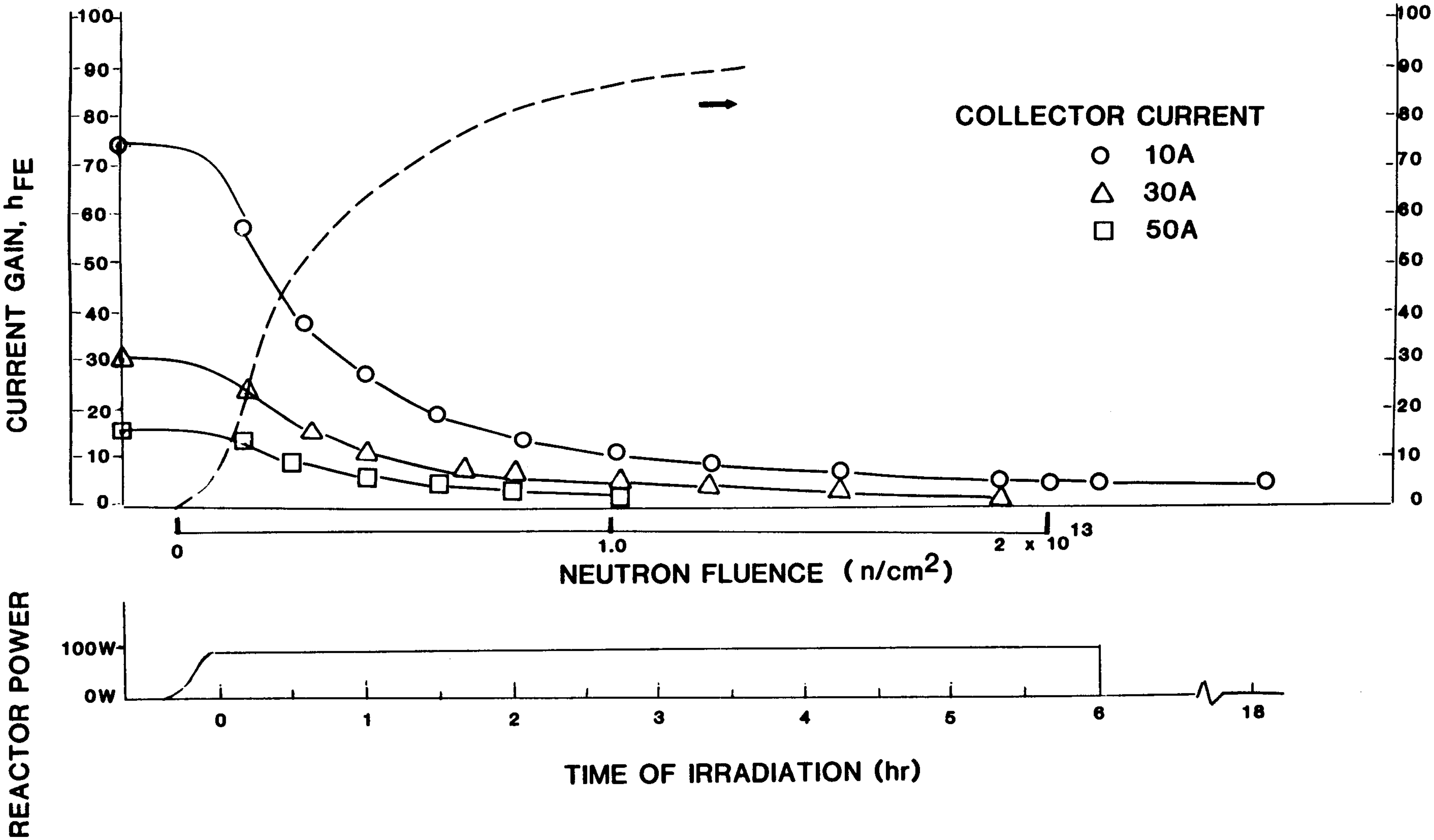


FIG. 1 DC CURRENT GAIN @ V_{ec} = 2.5V VS FLUENCE FOR DEVICE A. NPN TRANSISTOR; TYPE D60T455010; 450V/50A; NEUTRON EPITHERMAL FLUX = 9.1×10^{8} n/cm^2.s; GAMMA FLUENCE = 30 KILORADS.

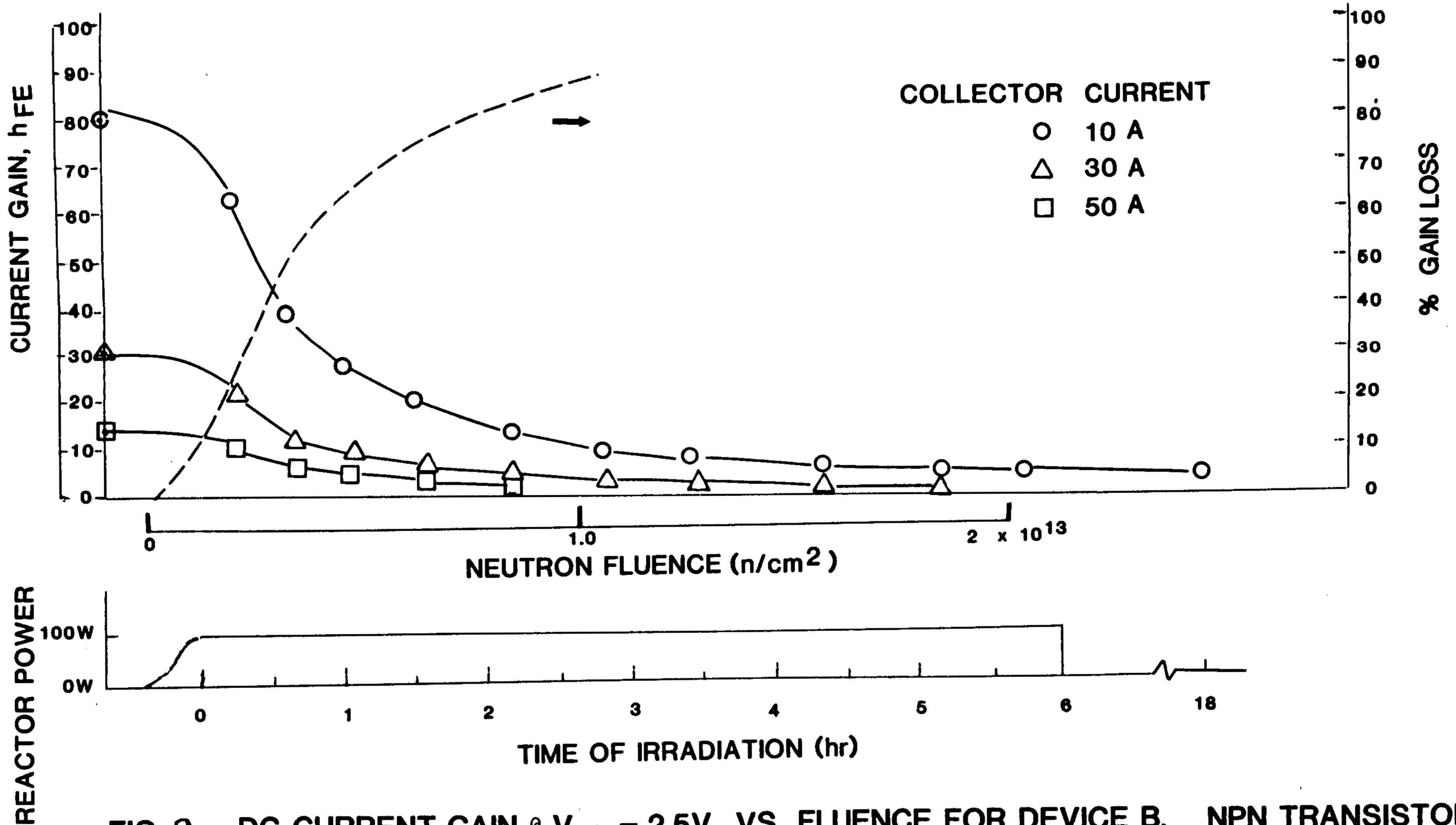


FIG. 2 DC CURRENT GAIN @ V_{ec} = 2.5V VS FLUENCE FOR DEVICE B. NPN TRANSISTOR; TYPE D60T455010; 450V/50A; NEUTRON EPITHERMAL FLUX = 9.1 x 10^8 $n/cm^2.s$; GAMMA FLUENCE = 30 KILORADS.

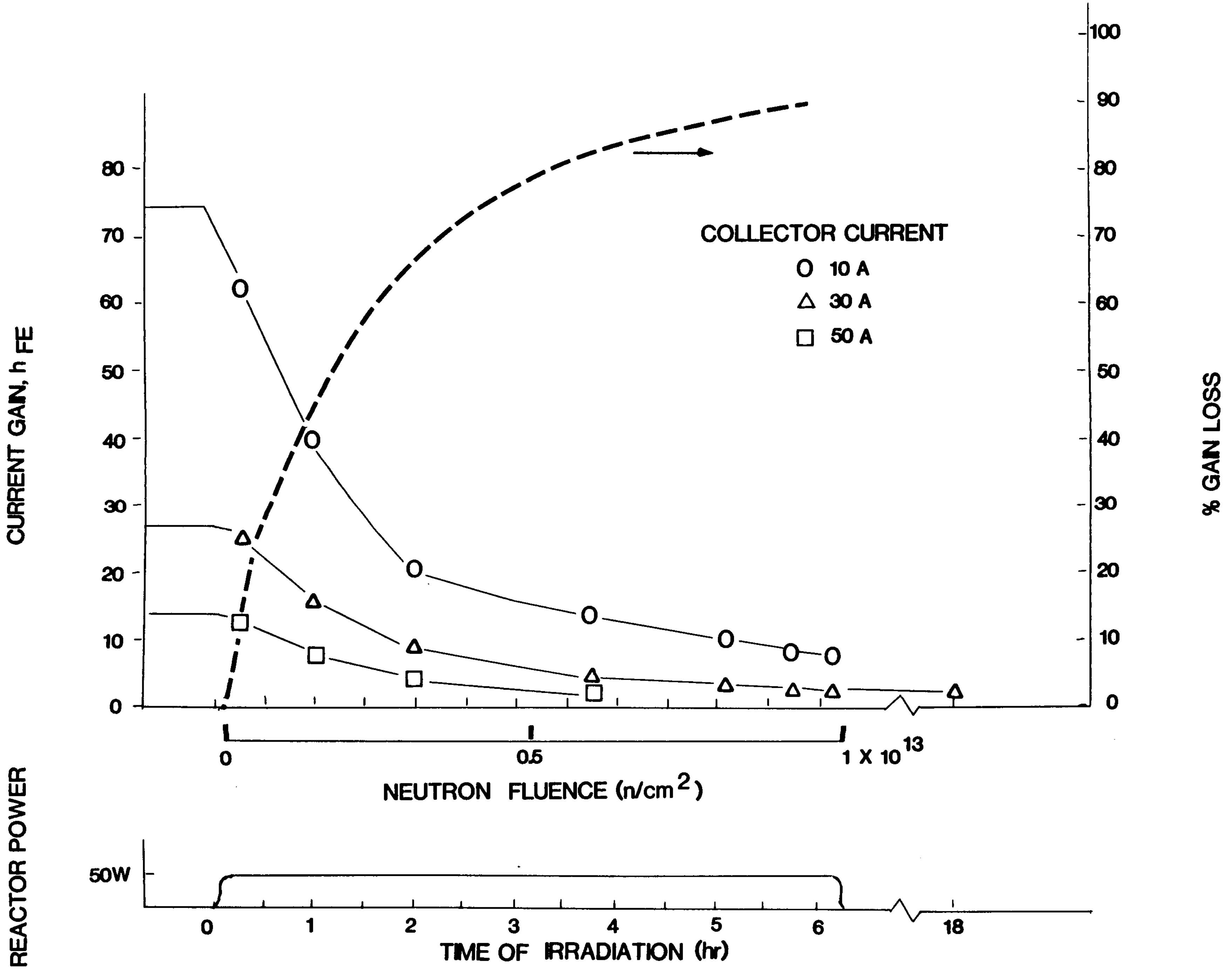


FIG. 3 DC CURRENT GAIN @ V_{CE} = 2.5 V VS FLUENCE FOR DEVICE C. NPN TRANSISTOR; TYPE D60T455010; 450V / 50A; NEUTRON EPITHERMAL FLUX = 4.5×10^8 n/cm^2.s; GAMMA FLUENCE = 15 KILORADS

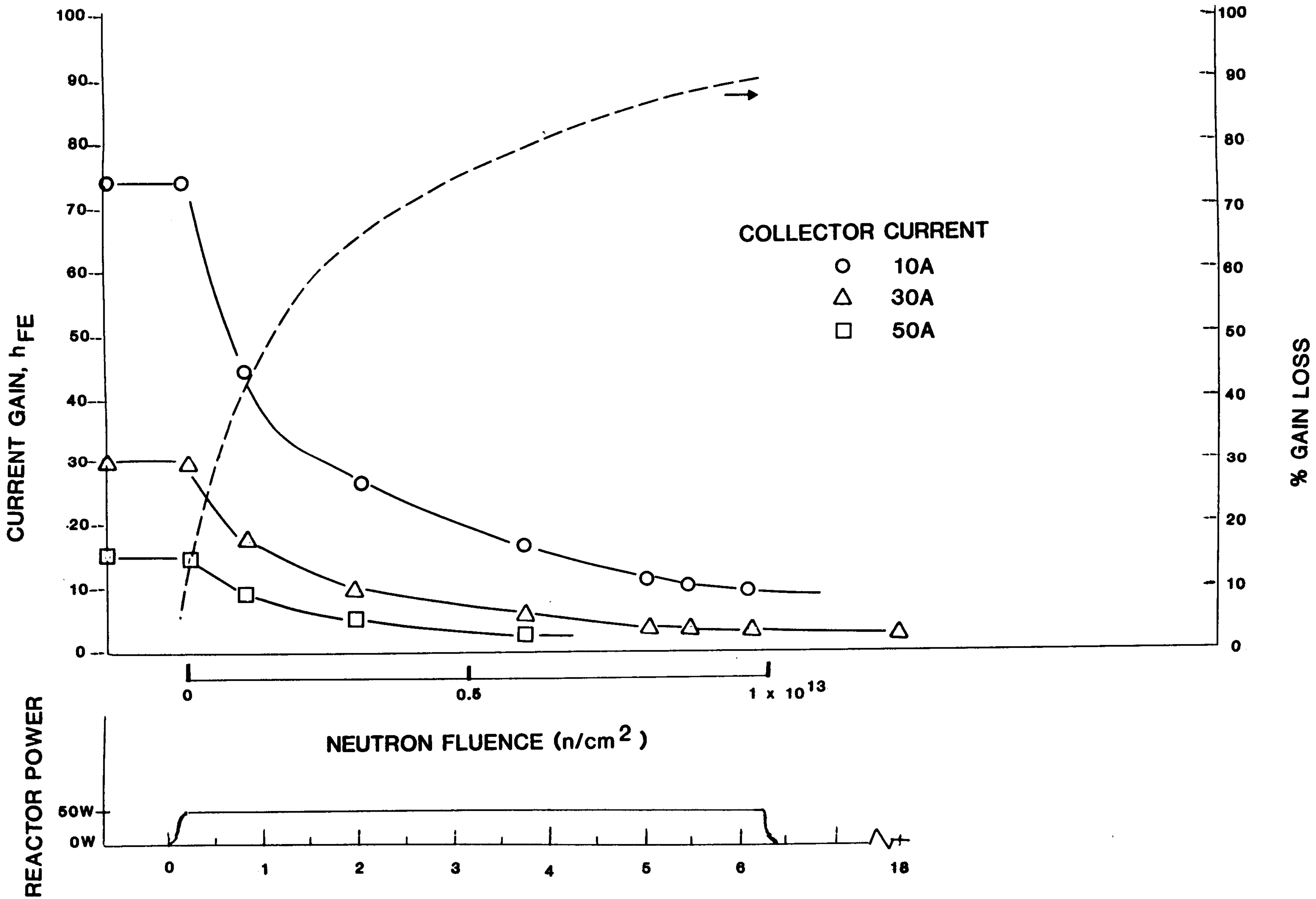


FIG. 4 DC CURRENT GAIN @ V_{ec} = 2.5V VS FLUENCE FOR DEVICE D. NPN TRANSISTOR; TYPE D60T455010; 450V/50A; NEUTRON EPITHERMAL FLUX = 4.5×10^8 n/cm^2.s; GAMMA FLUENCE = 15 KILORADS.

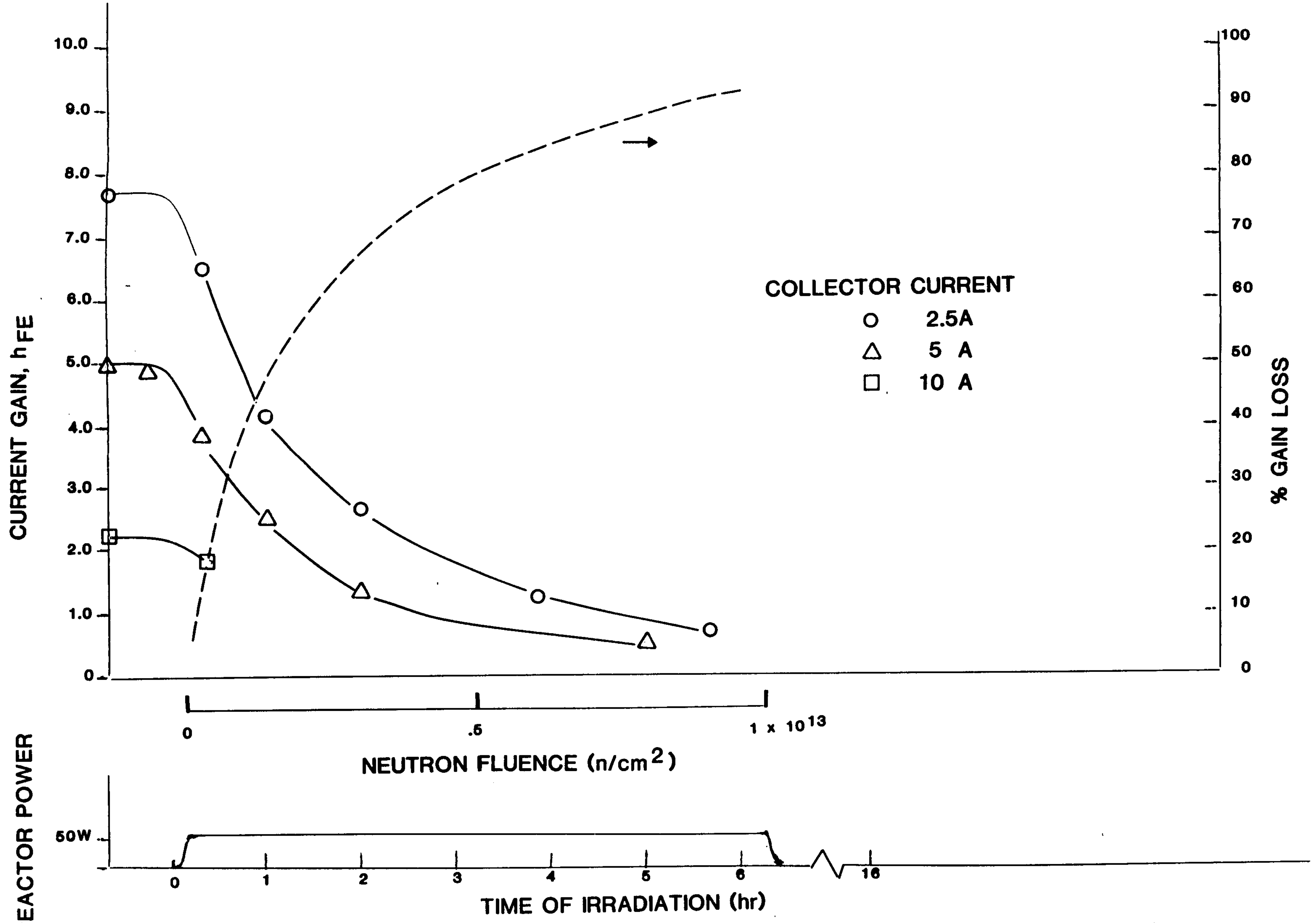


FIG. 5 DC CURRENT GAIN @ $V_{ce} = 2.5V$ VS FLUENCE FOR DEVICE NO. 7; NPN SOLITRON TRANSISTOR; TYPE SDT 18329; 700V/5A; NEUTRON EPITHERMAL FLUX = 4.5×10^8 $n/cm^2.s$; GAMMA FLUENCE = 15 KILORADS.

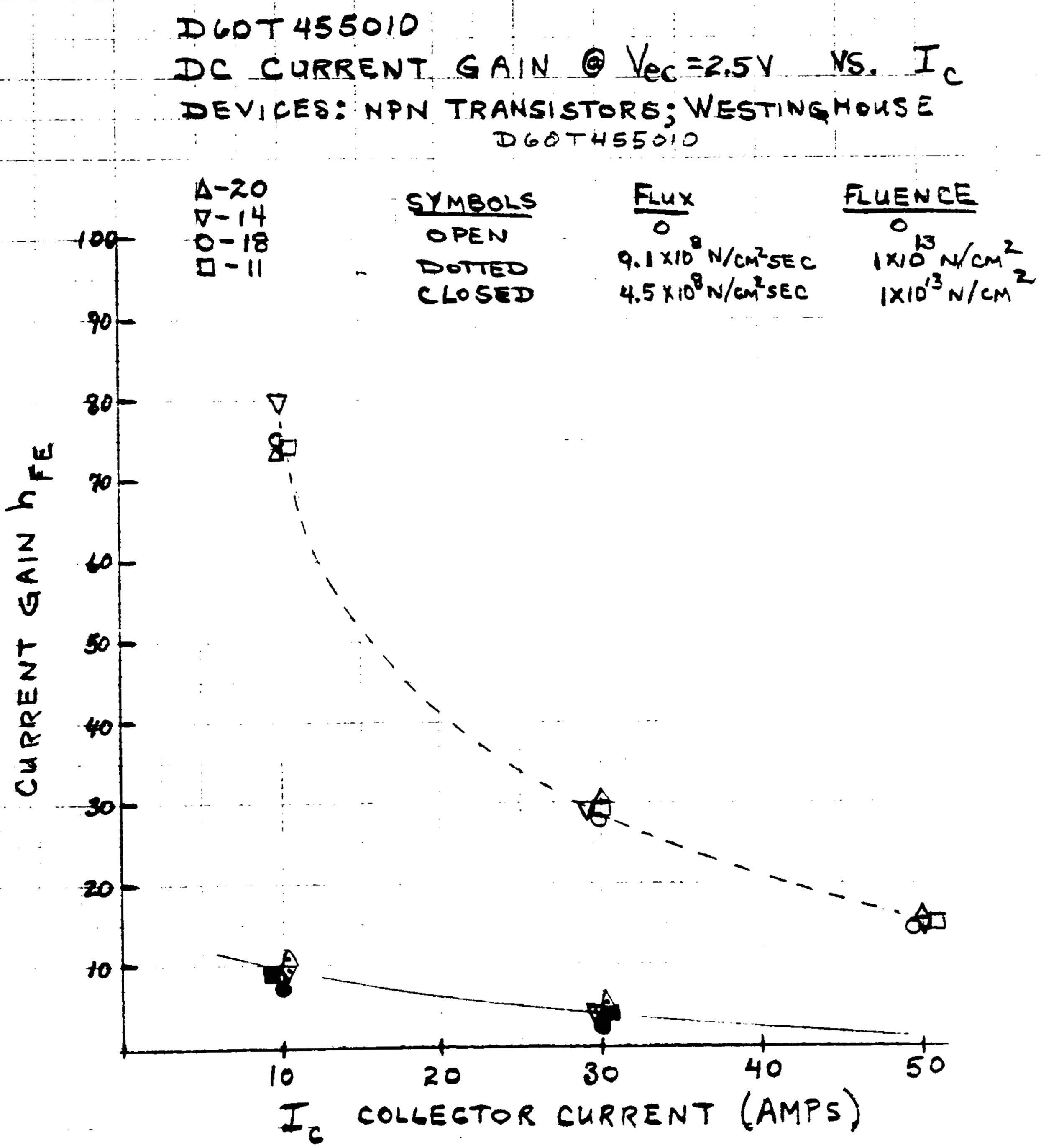

D60T 455010
DC CURRENT GAIN @ V_{ec}=2.5V VS. I_c
DEVICES: NPN TRANSISTORS; WESTINGHOUSE
D60T455010
Δ-20
∇-14
O-18
□-11
SYMBOLS
OPEN
DOTTED
CLOSED
FLUX
0
9.1×10^8 N/cm²sec
4.5×10^8 N/cm²sec
FLUENCE
0
1×10^{13} N/cm²
1×10^{13} N/cm²
CURRENT GAIN h_{FE}
100
90
80
70
60
50
40
30
20
10
10
20
30
40
50
I_c COLLECTOR CURRENT (AMPS)

FIG. 6

D60T455010 BASE CURRENT VS "ON VOLTAGE"
BEFORE & AFTER NEUTRON IRRADIATION.
FLUENCE = 2×10^{13} n/cm^2
DEVICE CODE – NO. 20

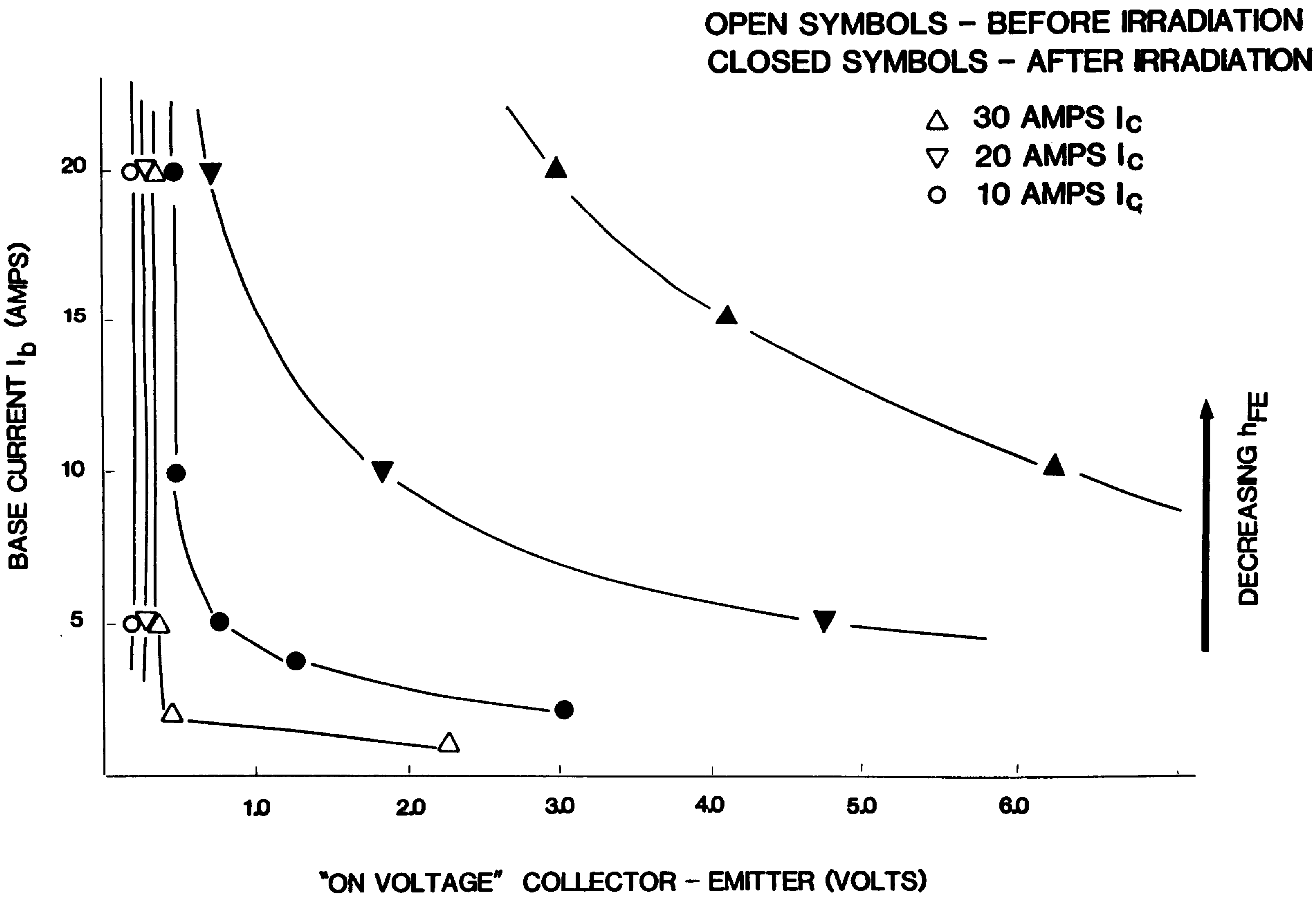


FIG. 7

D60T455010 BASE CURRENT VS "ON VOLTAGE"
BEFORE & AFTER NEUTRON IRRADIATION.
FLUENCE = 2×10^{13} n/cm^2
DEVICE CODE – NO. 14

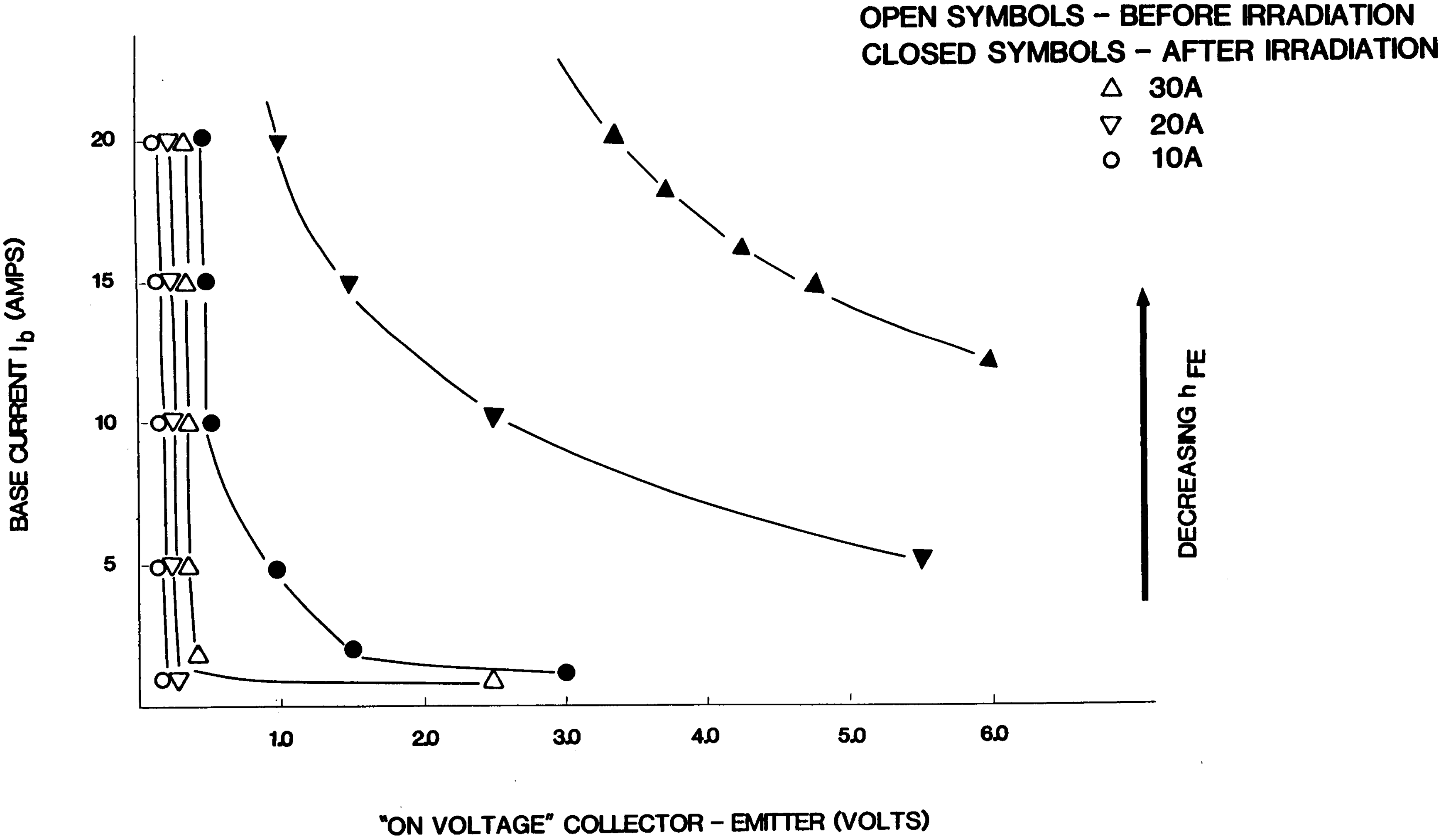
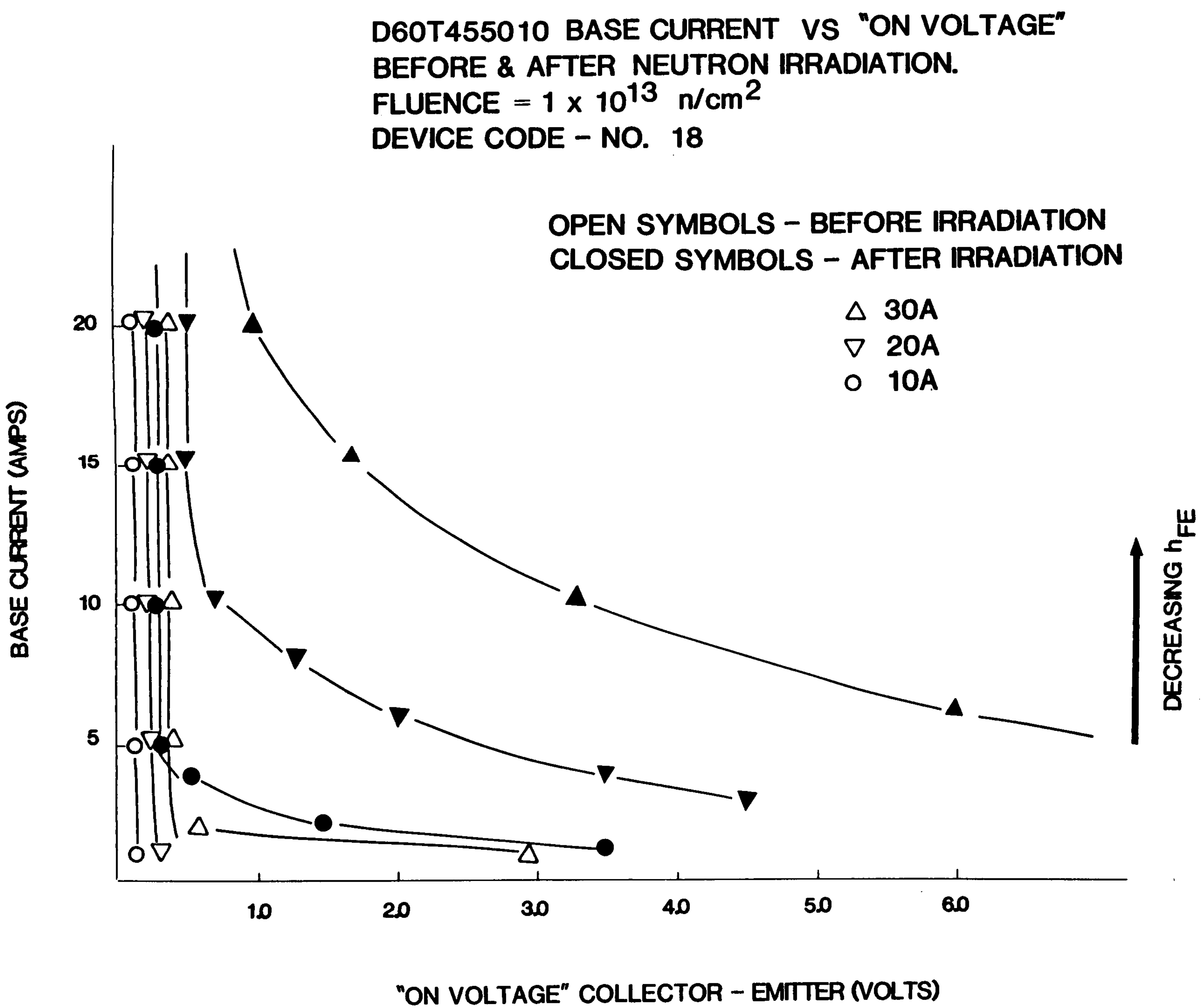


FIG. 8



D60T455010 BASE CURRENT VS "ON VOLTAGE"
BEFORE & AFTER NEUTRON IRRADIATION.
FLUENCE = 1 x 10^{13} n/cm^2
DEVICE CODE – NO. 18
OPEN SYMBOLS – BEFORE IRRADIATION
CLOSED SYMBOLS – AFTER IRRADIATION
△ 30A
▽ 20A
○ 10A
DECREASING h_{FE}
BASE CURRENT (AMPS)
20
15
10
5
1.0
2.0
3.0
4.0
5.0
6.0
"ON VOLTAGE" COLLECTOR – EMITTER (VOLTS)

FIG. 9

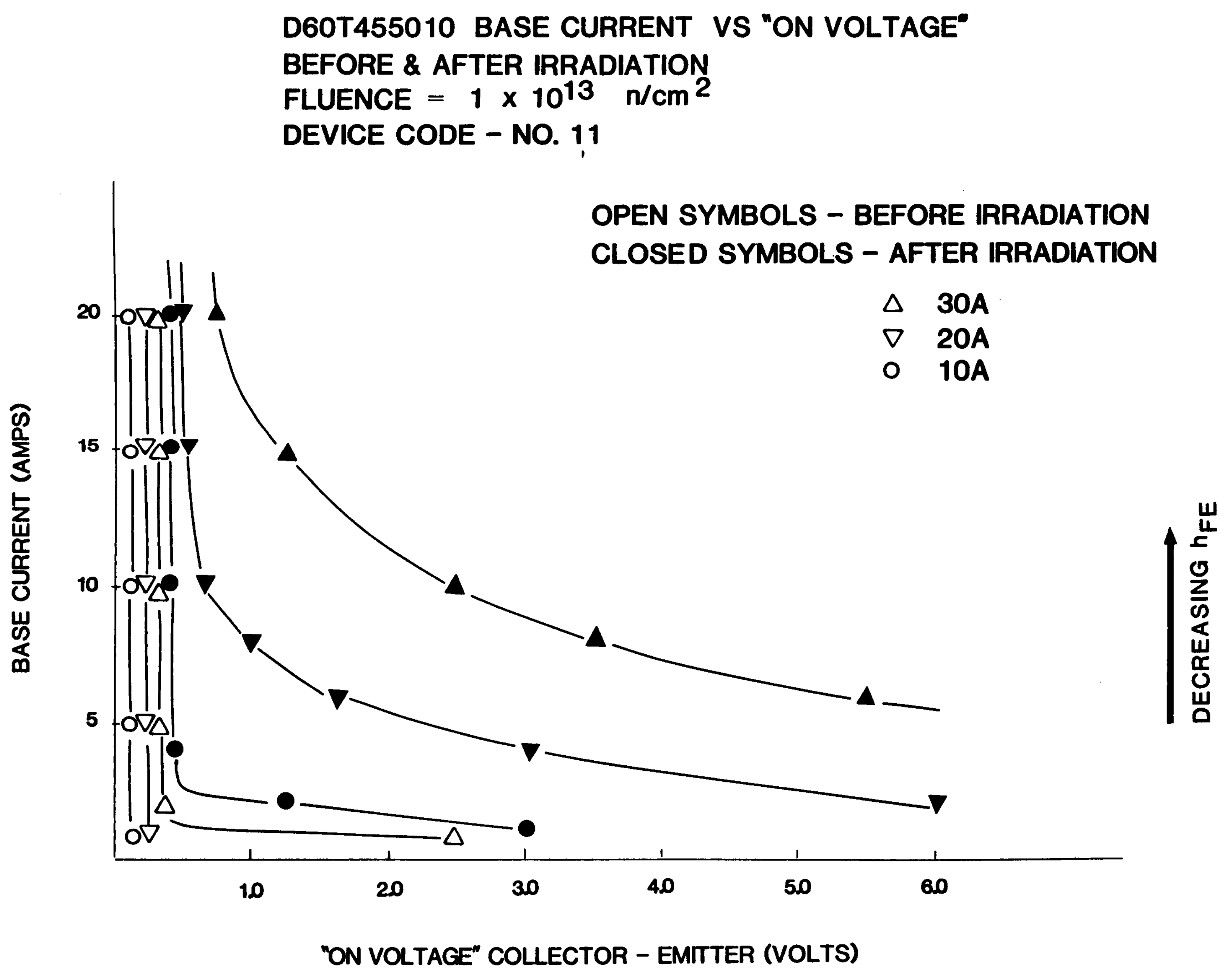

D60T455010 BASE CURRENT VS "ON VOLTAGE"
BEFORE & AFTER IRRADIATION
FLUENCE = 1 x 10^13 n/cm^2
DEVICE CODE - NO. 11
OPEN SYMBOLS - BEFORE IRRADIATION
CLOSED SYMBOLS - AFTER IRRADIATION
30A
20A
10A
BASE CURRENT (AMPS)
20
15
10
5
1.0
2.0
3.0
4.0
5.0
6.0
"ON VOLTAGE" COLLECTOR - EMITTER (VOLTS)
DECREASING h_FE

FIG. 10

D60T455010
BV(CEO) & BV(CBO) VS. FLUENCE
FOR A LEAKAGE CURRENT OF 15 μAMPS.

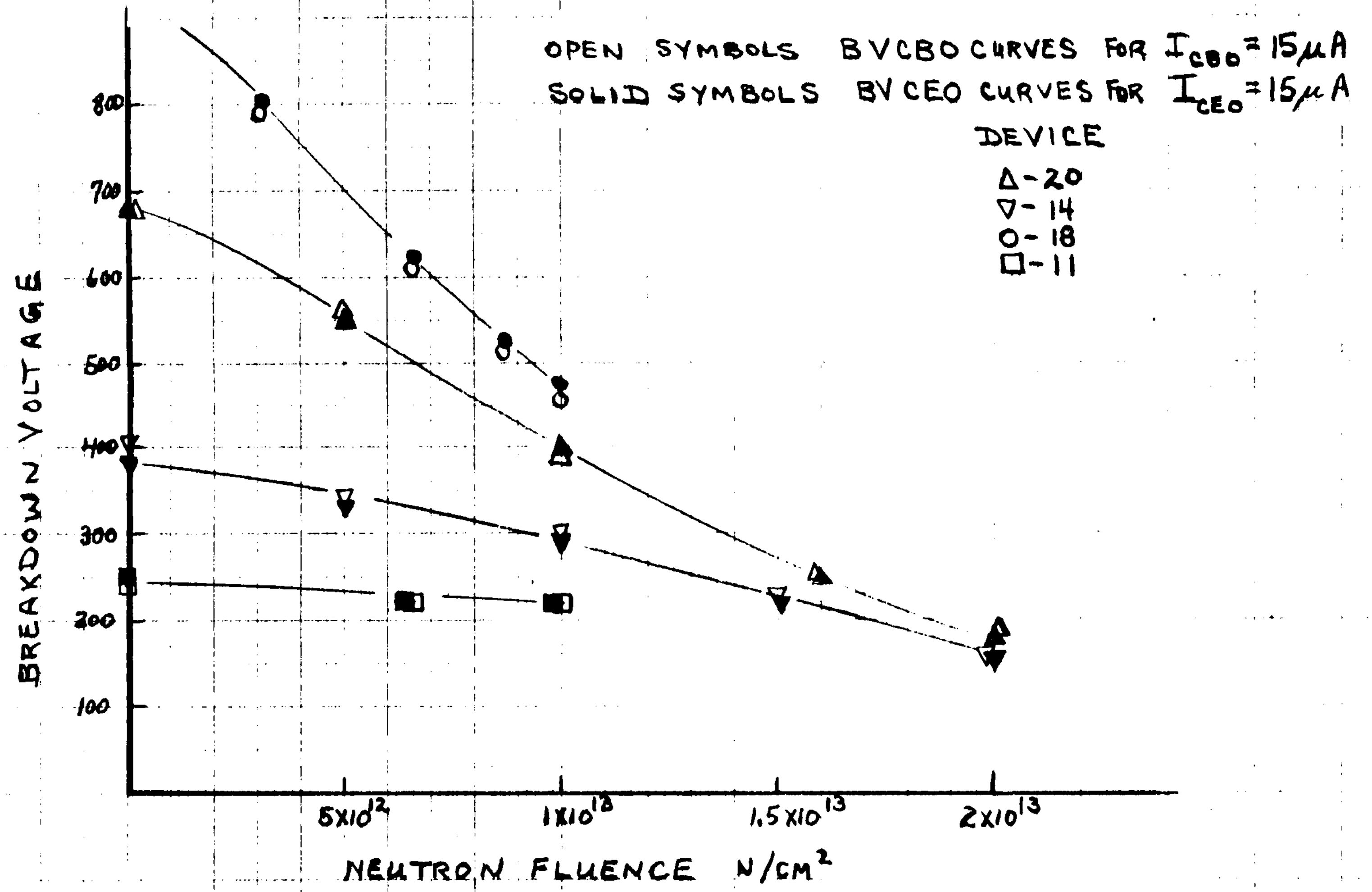
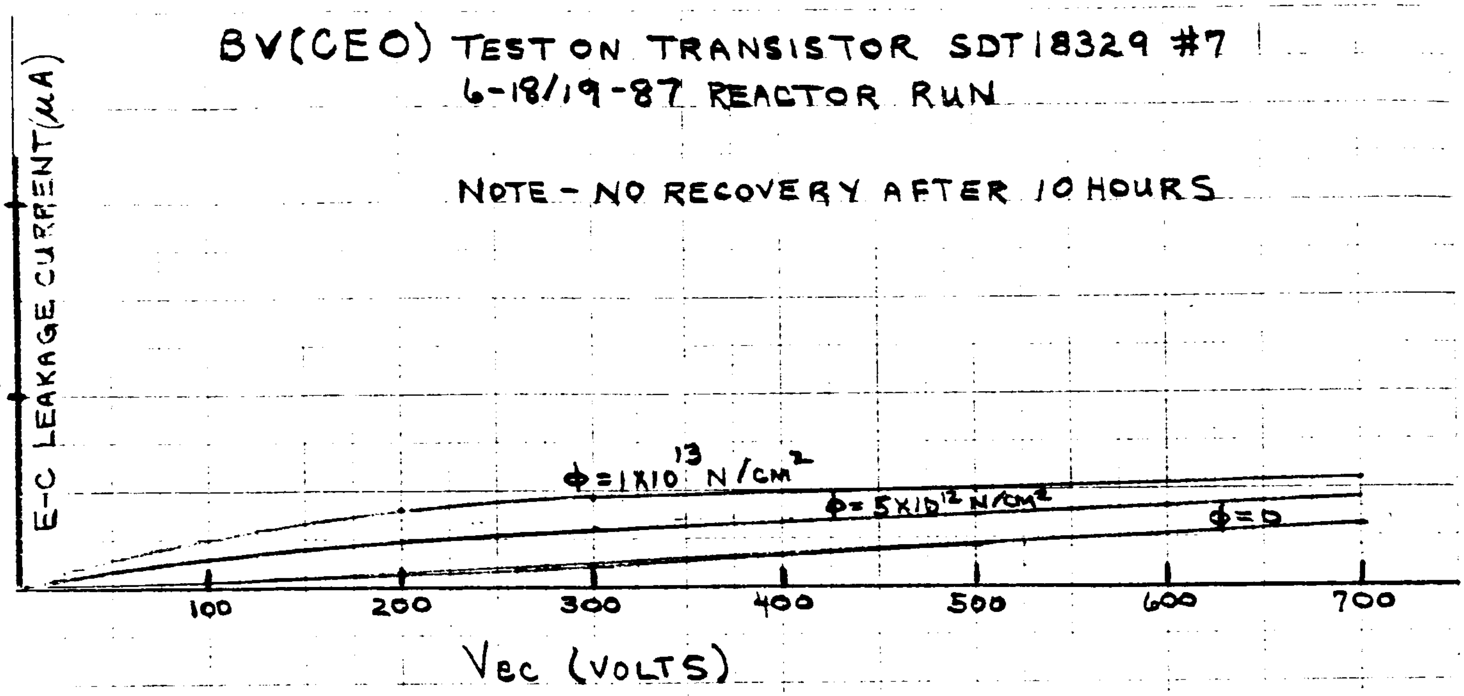
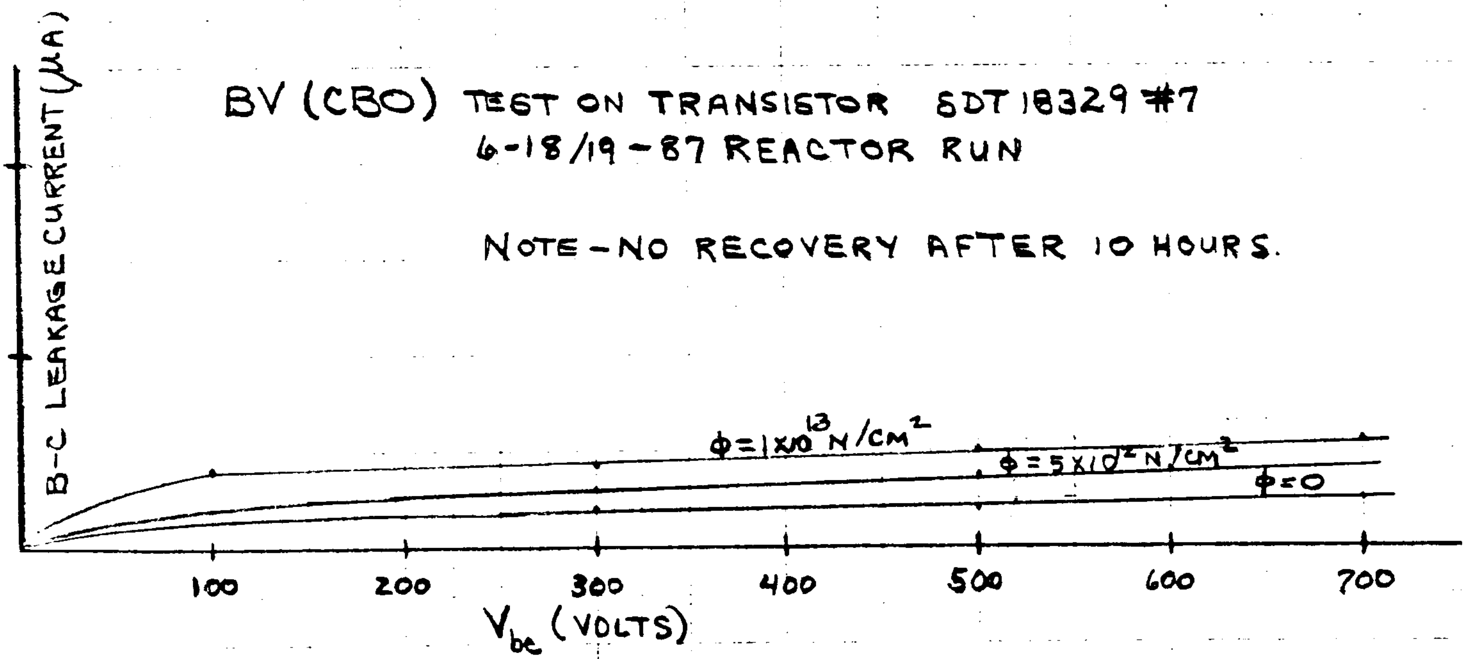


FIG. 11


BV(CEO) TEST ON TRANSISTOR SDT18329 #7
6-18/19-87 REACTOR RUN
NOTE - NO RECOVERY AFTER 10 HOURS
E-C LEAKAGE CURRENT (μA)
10
5
φ=1X10^13 N/CM^2
φ=5X10^12 N/CM^2
φ=0
100
200
300
400
500
600
700
Vec (VOLTS)


BV (CBO) TEST ON TRANSISTOR SDT 18329 #7
6-18/19-87 REACTOR RUN
NOTE - NO RECOVERY AFTER 10 HOURS.
B-C LEAKAGE CURRENT (μA)
10
5
φ=1X10^13 N/CM^2
φ=5X10^12 N/CM^2
φ=0
100
200
300
400
500
600
700
Vbe (VOLTS)

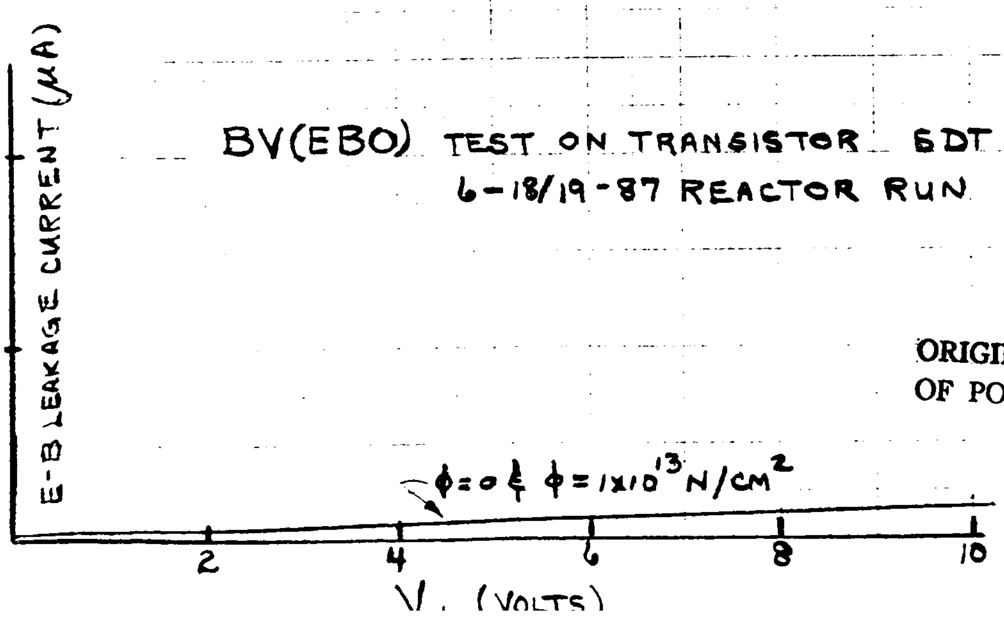

BV(EBO) TEST ON TRANSISTOR SDT 18329 #7
6-18/19-87 REACTOR RUN
E-B LEAKAGE CURRENT (μA)
10
5
φ=0 & φ=1X10^13 N/CM^2
2
4
6
8
10
(VOLTS)

FIG. 12

FIGURE 13

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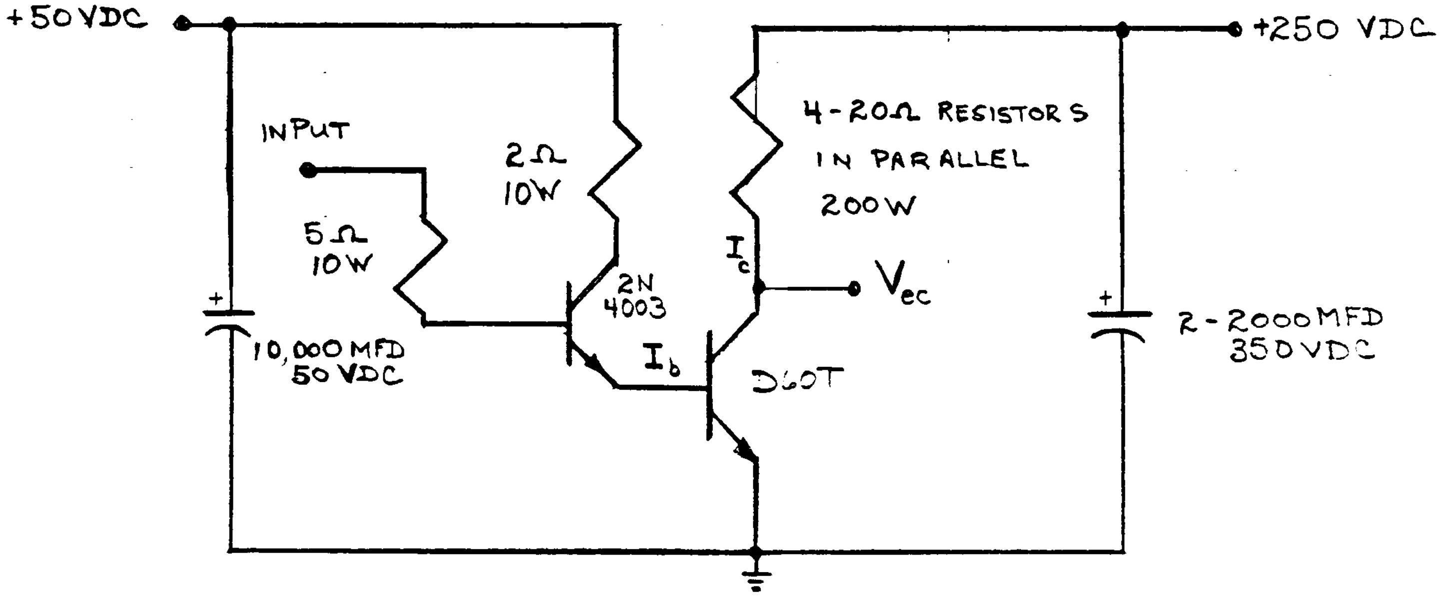
HI-POWER PULSER

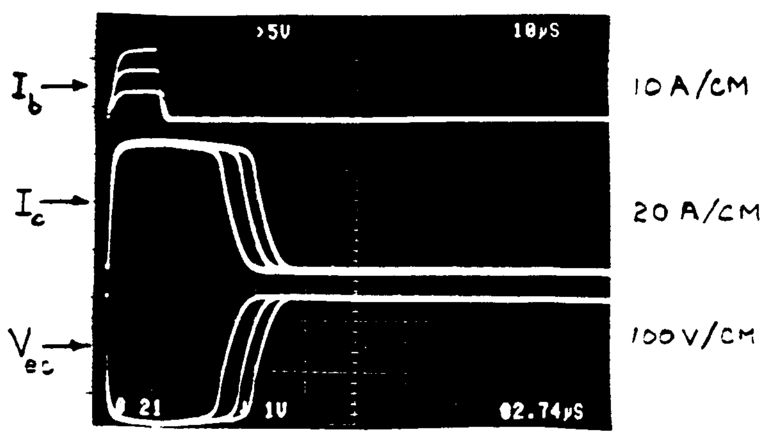
SCHEMATIC



INPUT - MONSANTO MODEL 300 A

FIGURE 14

PULSE OUTPUT FOR DEVICE
D60T 455010 CODE # 19
AUGUST 11, 1987



SWEEP - 10μSEC/CM

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Date 6-13-87
6-22-87

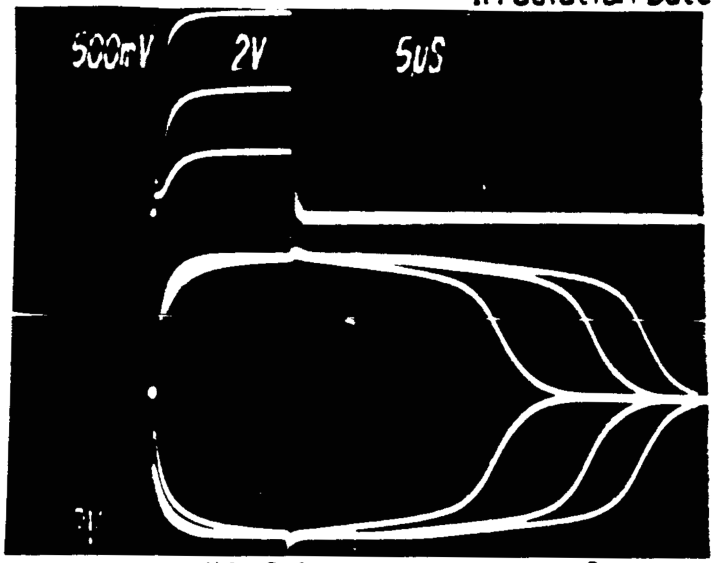
TRANSISTOR
D60T 455010

Code # 20/A

Cable Length 0 M

Fluence 2×10^{13} N/cm²

Irradiation Date 6/15-16/87



$I_b \uparrow$

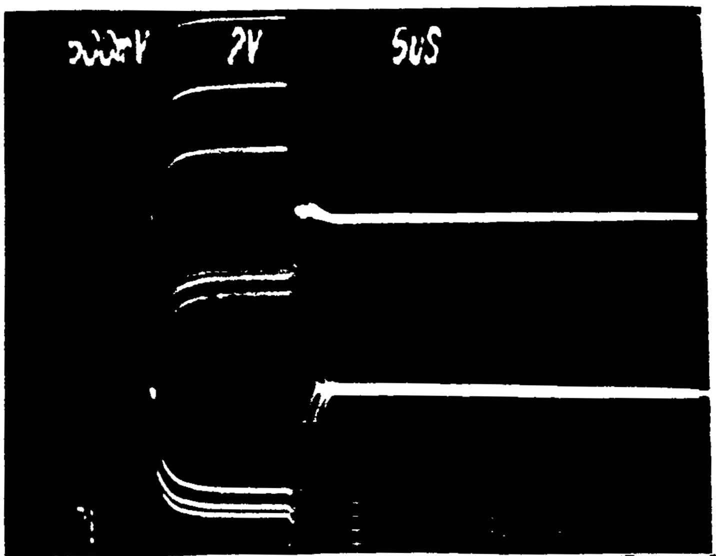
Vertical I_c 20 A/cm

$I_c \uparrow$ Base Drive I_b 5.0 A/step

V_{ec} 20 V/cm

$V_{ec} \downarrow$

Photo # 40 VDC Irrad. 0



$I_b \uparrow$

Vertical I_c 20 A/cm

$I_c \uparrow$ Base Drive I_b 5.0 A/step

V_{ec} 20 V/cm

$V_{ec} \downarrow$

Photo # 40 VDC Irrad. 2×10^{13} N/cm²

FIG. 15

Date 6-13-87
6-22-87

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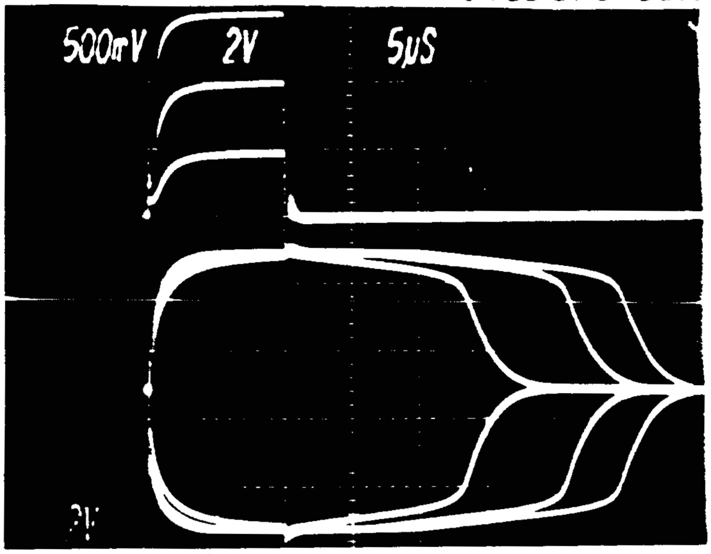
TRANSISTOR
D60T 455010

Code # 14/B

Cable Length 0 M

Fluence 2×10^{13} N/cm²

Irradiation Date 6/15-16/87



$I_b \uparrow$

$I_c \uparrow$

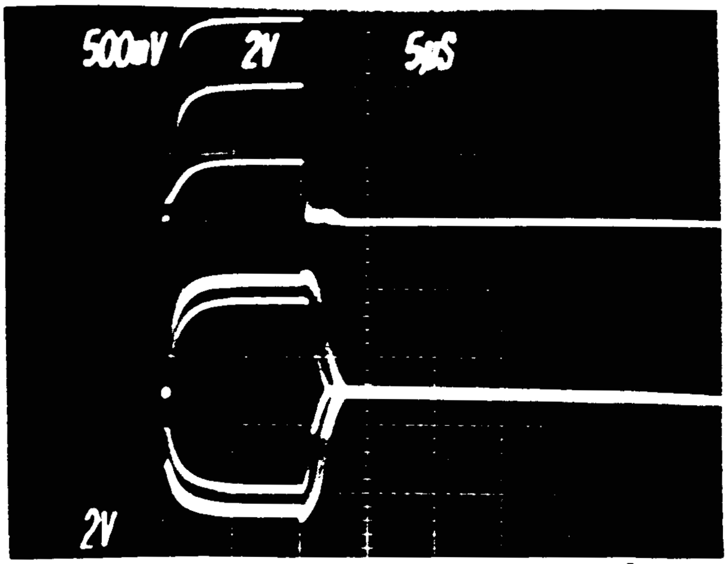
$V_{ec} \downarrow$

Vertical I_c 20 A/cm

Base Drive I_b 5.0 A/step

V_{ec} 20 V/cm

Photo # 40 VDC Irrad. 0



$I_b \uparrow$

$I_c \uparrow$

$V_{ec} \downarrow$

Vertical I_c 20 A/cm

Base Drive I_b 5.0 A/step

V_{ec} 20 V/cm

Photo # 40 VDC Irrad. 2×10^{13} N/cm²

FIG. 16

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Date 6-17-87
6-22-87

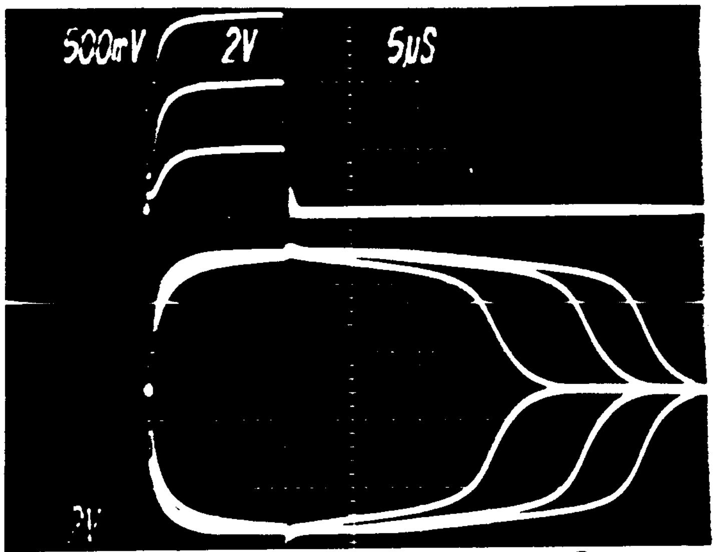
TRANSISTOR
D60T 455010

Code # 18/C

Cable Length 0 M

Fluence 1×10^{13} N/cm^2

Irradiation Date 6/18/87



$I_b \uparrow$

$I_c \uparrow$

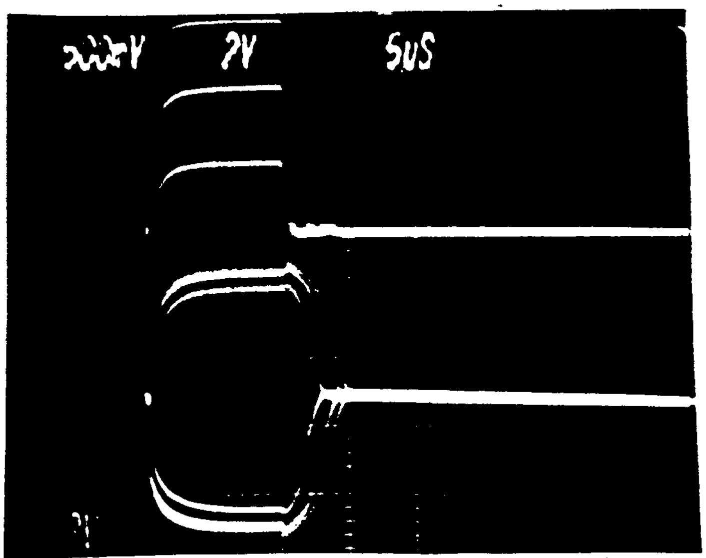
$V_{ec} \downarrow$

Vertical I_c 20 A/cm

Base Drive I_b 5.0 A/step

V_{ec} 20 V/cm

Photo # 40VDC Irrad. 0



$I_b \uparrow$

$I_c \uparrow$

$V_{ec} \downarrow$

Vertical I_c 20 A/cm

Base Drive I_b 5.0 A/step

V_{ec} 20 V/cm

Photo # 40VDC Irrad. 1×10^{13} N/cm^2

FIG. 17

Date 6-13-87
6-22-87

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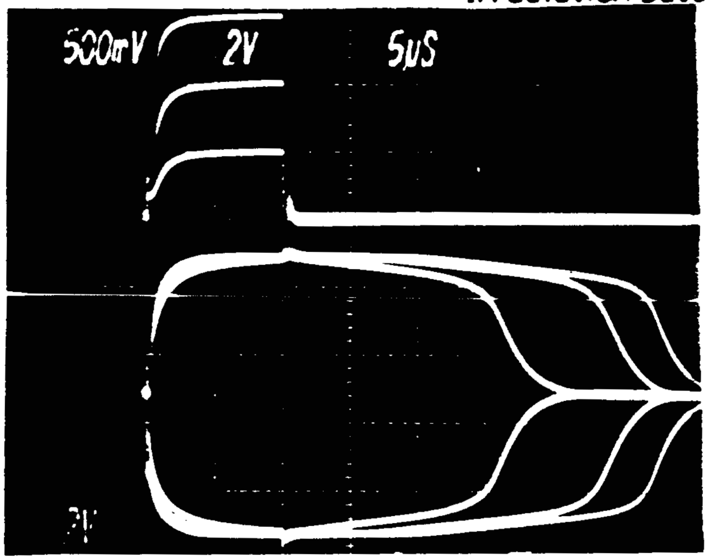
TRANSISTOR
D60T 455010

Code # 11/D

Cable Length 0 M

Fluence 1×10^{13} N/cm²

Irradiation Date 6/18/87



I_b ↑

Vertical I_c 20 A/cm

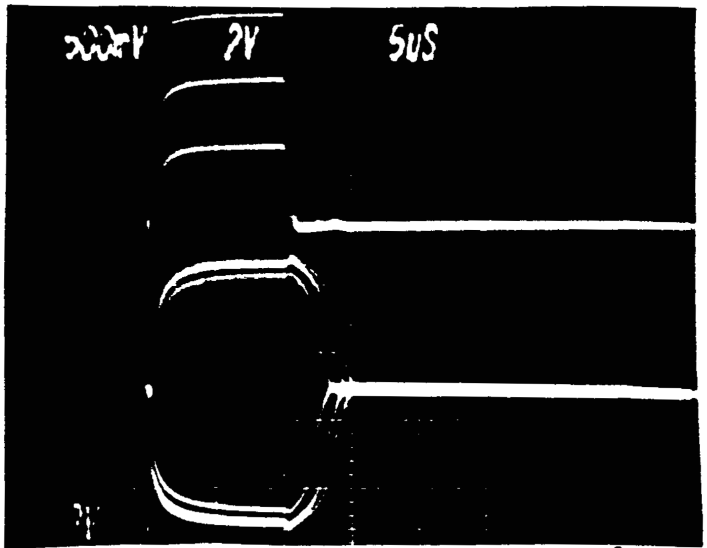
I_c ↑

Base Drive I_b 5.0 A/step

V_{ec} 20 V/cm

V_{ec} ↓

Photo # 40 VDC Irrad. 0



I_b ↑

Vertical I_c 20 A/cm

I_c ↑

Base Drive I_b 5.0 A/step

V_{ec} 20 V/cm

V_{ec} ↓

Photo # 40 VDC Irrad. 1×10^{13} N/cm²

FIG. 18

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Date 6-15-87
6-22-87

TRANSISTOR
SDT 18329

Code # 7

Cable Length 0 M

Fluence 1×10^{13} N/cm²

Irradiation Date 6/18/87

NOT AVAILABLE

I_b↑

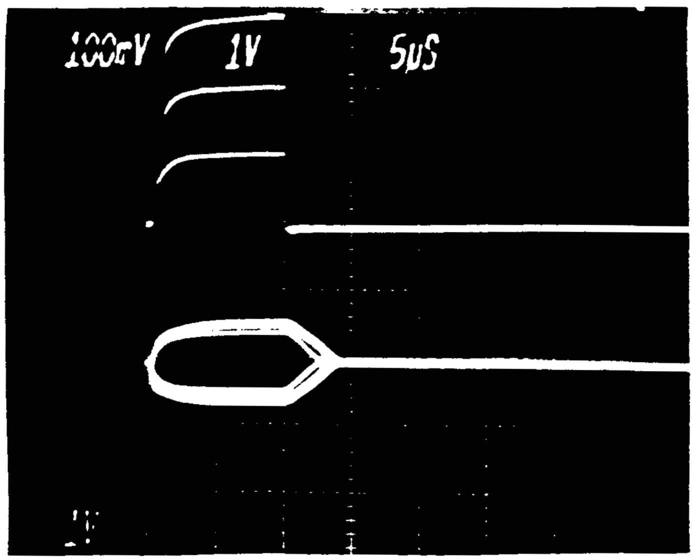
Vertical I_c 10 A/cm

I_c↑ Base Drive I_b 5.0 A/step

V_{ec} 10 V/cm

V_{ec}↓

Photo # 40VDC Irrad 0



I_b↑

Vertical I_c 10 A/cm

Base Drive I_b 5.0 A/step

I_c↑

V_{ec} 10 V/cm

V_{ec}↓

Photo # 40VDC Irrad. 1×10^{13}

FIG. 19