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First Quarterly Report

STUDY TO INVESTIGATE THE EFFECTS OF IONIZING RADIATION ON TRANSISTOR SURFACES

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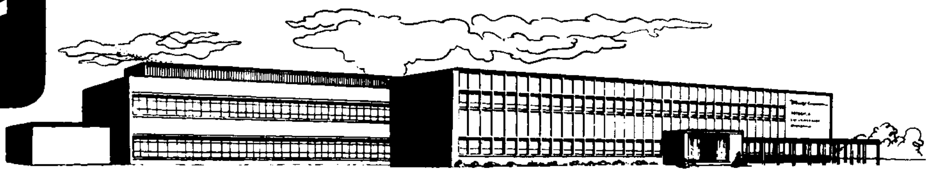

RESEARCH LABORATORIES DIVISION

SOUTHFIELD, MICHIGAN

Contract NAS8-20135
Bendix Project 2400

Report No. 3157

FIRST QUARTERLY REPORT

FOR THE PERIOD JULY 1 THROUGH SEPTEMBER 30, 1965

(Includes Monthly Progress Report No. 3 for September)

STUDY TO INVESTIGATE THE EFFECTS OF IONIZING RADIATION ON TRANSISTOR SURFACES

Submitted to:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812, Attn: PR-EC

October 26, 1965

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ABSTRACT

Steady state ionizing radiation such as exists in the Van Allen belts around the earth or in the vicinity of reactors used for nuclear propulsion or nuclear space power, can cause degradation of transistor parameters. The major effects are a decrease in current gain and an increase in leakage current due to changes in surface characteristics. The purpose of this contract is to investigate the effects of ionizing radiation on transistor surfaces, using 150 kV X-rays, to determine the physical mechanisms involved and to formulate screening techniques which will enable categorizing devices as to their surface stability in ionizing radiation.

This report discusses work accomplished during the first three months of the program. During this period X-ray facilities were prepared for testing, fixtures were constructed and instrumentation was assembled in preparation for radiation testing of Fairchild 2N1613 transistors. Facilities, fixtures, and instrumentation were checked out with a cursory test intended to evaluate capabilities and limitations of the test system. Transistors were procured also and initial measurements were performed in preparation for the first test which is scheduled to begin early in the second quarter.

Author

INTRODUCTION

This report has two major sections. The first is the third monthly report, consisting of a summary of work accomplished during September 1965 and a forecast of work to be performed in October 1965. The second section is the First Quarterly Report, containing a detailed discussion of work accomplished during the first three months (July-September) of this investigation.

1.0 THIRD MONTHLY PROGRESS REPORT

Progress in September consisted of preparing the X-ray machine test fixtures, interconnecting cables, and I_{cbo}, $1/h_{FE}$ and temperature measurement instrumentation for the first X-ray test to be conducted in October. The plan for this test was formulated also.

1.1 Preparation of Test Facilities and Instrumentation

The first X-ray test requires simultaneous irradiation of 12 Fairchild type 2N1613 transistors at the maximum rate attainable (3.8×10^5 r/h) with the Bendix X-ray facility. A test fixture was prepared for mounting up to 12 devices in sockets at the face of the X-ray tube. Special shielded three-conductor cables were attached to each transistor socket, replacing the existing coaxial cables, to achieve a higher current capacity and more efficient suppression of RF and 60 c/s noise pickup during measurement of transistor parameters while the devices are in the X-ray shield.

An electrical biasing panel was constructed which applies bias conditions to devices during irradiation. This panel can be programmed to apply a different combination of junction bias conditions to each of the 12 devices mounted in the X-ray fixture. Provisions were also made on this panel for remote measurement of $1/h_{FE}$ or I_{cbo} on devices mounted in the X-ray machine.

Temperature inside the X-ray shield is not necessarily the same as room temperature. A thermocouple was mounted on the transistor mounting fixture inside the shield and an adapter package was constructed which allows the temperature difference between the X-ray machine ambient and room ambient to be read out digitally using the low level $1/h_{FE}$ readout equipment.

With the test system completely assembled, a cursory X-ray test was performed to: (a) check out measurement instrumentation, (b) check out the bias panel, and (c) determine measurement system limitations caused by noise pickup due to the long cables and leakage currents caused by the ionizing radiation environment. When very high frequency transistors were measured with the pulsed h_{FE} tester (Birtcher) or the low level $1/h_{FE}$ systems, a high frequency oscillatory condition occurred. The test systems were modified to correct this failure by adding small RF chokes in series with the emitter and collector leads.

With the X-ray machine turned off and devices installed in the test fixture, leakage currents were measured through the remote cables. These currents were in excess of junction leakage current measurements, which indicated considerable stray leakage due to cables and fixtures. These stray leakage effects were reduced to a tolerable level by dipping the entire fixture in melted paraffin. Tests were then performed with the X-ray machine on. Typical leakage of the cables and mounting fixture with no transistor installed, was 0.2 nA (collector lead to base lead with 5 V applied). It increased to 42 nA when a Fairchild 2N1613 transistor was installed in the mounting fixture. This leakage component was accompanied by a 1.5 nA, 60 c/s ripple component due to ripple on the high voltage supply for the X-ray machine. To preclude such high leakage currents, low level $1/h_{FE}$ data points for all X-ray tests will be taken with the X-ray high voltage supply shut off.

1.2 Work Plans for October

The first X-ray test investigating the effects of junction bias conditions during irradiation on the degradation of h_{FE} and I_{cbo} will be performed during this period. It will involve 12 devices separated into six groups of two devices, each group with a different set of bias conditions. The test will consist of several steps, each step being an exposure of approximately 5×10^6 r at one set of bias conditions. Several $1/h_{FE}$ and I_{cbo} data points will taken during each test step. Table 1 defines the bias conditions to be used during the first two test steps.

Table 1. Bias Conditions for First X-ray Test

Transistor Group	Bias Conditions	
	Test Step 1	Test Step 2
A	$V_{cb} = 6$ V, $I_e = 0$	$V_{cb} = 6$ V, $I_e = 10$mA
B	Passive	$I_c = -10$mA (fwd.), $I_e = 0$
C	$I_c = -10$mA (fwd.), $I_e = 0$	$V_{cb} = 6$ V, $I_e = 10$mA
D	$V_{be} = -3$ V, $I_c = 0$	$V_{be} = 3$ V, $I_c = -10$mA
E	$I_b = 10$mA, $I_c = 0$	$I_b = 1$mA, $I_c = 0$
F	$V_{cb} = 6$ V, $I_e = 10$mA	$V_{cb} = 6$ V, $I_e = 1$mA

After completion of the second test step, all 12 devices will be subjected to a two-day recovery cycle consisting of one day of irradiation at 3.8×10^5 r/h with a 100 mA forward bias applied to the base emitter junction, followed by a second day with the same junction bias but no X-ray irradiation. This cycle recovers the h_{FE} of X-ray irradiated devices to its original value before irradiation. Following this recovery cycle, test steps 3 and 4, which are a repetition of steps 1 and 2, will be performed.

The further insight into degradation as a function of dose (or time), junction bias, and measurement conditions provided by this test will enable a separation of the degradation into several components or mechanisms. The effects of the recovery cycle will also be studied to determine if this cycle alters the behavior in ionizing radiation of devices with biased junctions.

Also during October, design will be initiated of an evacuated fixture to be used for evaluating Fairchild 2N1613 transistors in a combined hard-vacuum and X-ray environment. Additional X-ray tests may be performed to complement the first X-ray test.

2.0 FIRST QUARTERLY REPORT

Work accomplished during the first quarter consisted of: (a) a meeting with NASA contract monitors to discuss program plans, (b) preparation of X-ray facilities, fixtures, and test instrumentation, (c) performance of a cursory X-ray test to evaluate the instrumentation system's ability to measure transistor parameters through long cables with the transistors installed in the X-ray machine, and (d) taking initial data (h_{FE}, I_{cbo}, I_{ebo}, BV_{cbo}, BV_{ebo}, and V_{be} vs I) on 12 type 2N1613 transistors in preparation for the first X-ray test.

2.1 Results of the Meeting With NASA Personnel

Surface instabilities in transistors exposed to ionizing radiation are often severe enough to completely mask or at least distort the bulk radiation damage to semiconductors. This problem was experienced with a number of devices tested for NASA-MSFC by Lockheed-Georgia under Contract NAS8-5332. For this reason, an agreement was reached at the meeting to consider as one of the primary goals of this contract: the establishment of screening techniques for identifying stable and unstable surfaces by nondestructive testing. These tests should be simple and applicable to all device types.

Two types of high power transistors (2N2772 and STC 1739) on the list of devices scheduled for testing in Phase II require h_{FE} measurements beyond the range originally intended for this study ($0.1\ \mu A \leq I_c \leq 100\ mA$). Bendix agreed to modify its instrumentation to extend the measuring current range. This was done by procuring a Birtcher model 70 pulsed h_{FE} tester capable of measuring h_{FE} for collector currents from 1 mA to 30 A. Bendix pointed out at the meeting that the relatively thick housing of these devices would require new X-ray dosimetry measurements. Dosimeters and mechanical sample housings for these power devices were procured in preparation for this dosimetry test.

2.2 Preparation of X-ray Facilities and Instrumentation

Essentially the same facilities and instrumentation will be used throughout Phases I and II of this study. This section gives a detailed description of these facilities and equipment.

2.2.1 X-ray Machine

The X-ray facility used for this study has as its source of radiation a Siefert Isovolt 150 kilovolt, constant potential X-ray generator capable of continuous operation. The control console, high voltage transformer, and X-ray tube shield are shown in the photograph of Fig. 1. The transformer section contains a step-up transformer and filter network to smooth the full wave rectified 150 kv to a ±3 percent ripple.

The target end of the X-ray tube is 1.5 inches in diameter and 25 inches long. The tungsten target is embedded in a block of copper near the end of the tube, to and from which a divided annulus

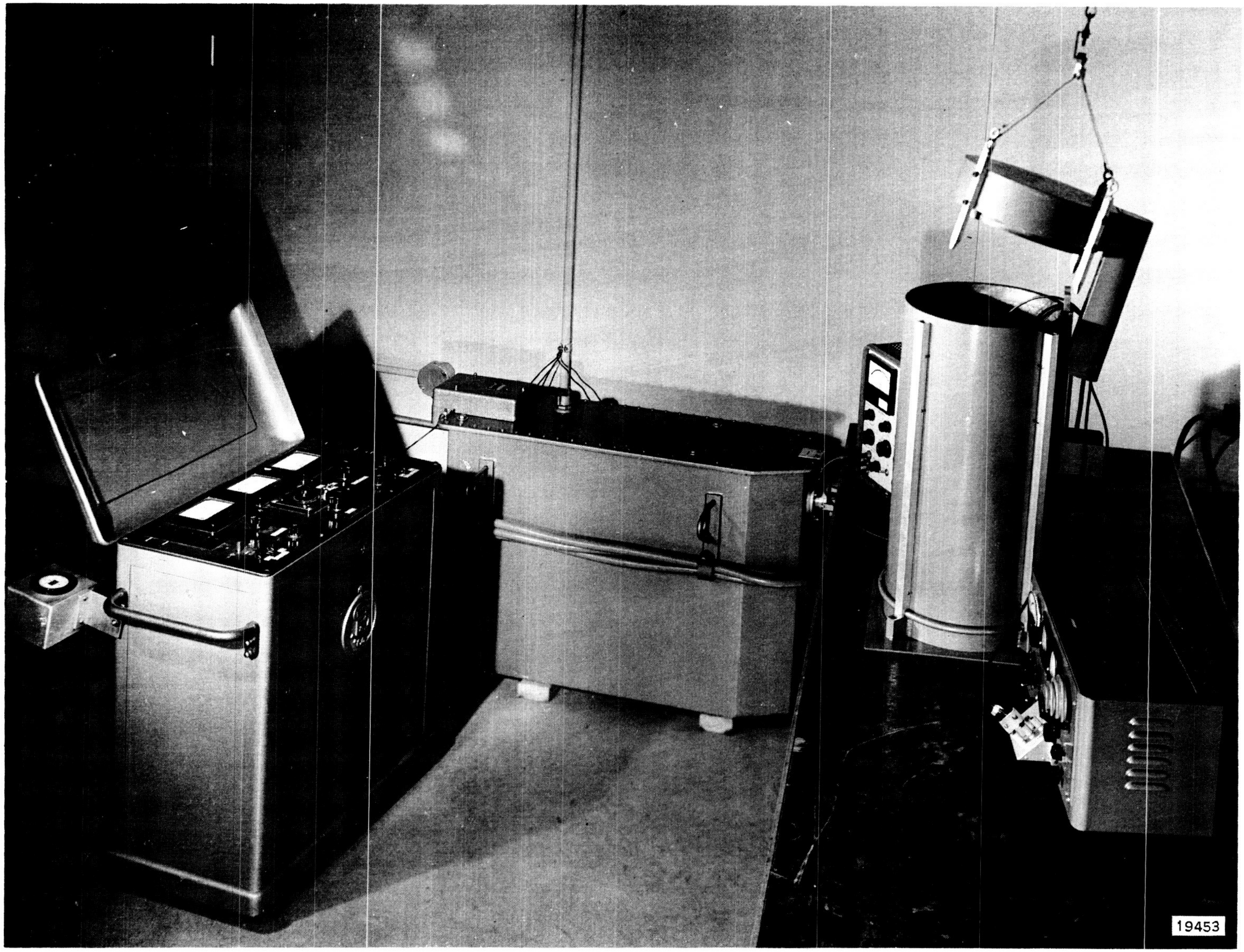

Figure 1 - X-Ray Facility

conducts coolant water. The X-ray beam from the tube, as depicted in Fig. 2, is a radial cone of about 0.5 inch apex at the tube surface and 29^{o} wide. The closest the beam can approach the target is 0.75 inch or the surface of the tube. Fig. 3 is a photograph of the X-ray tube mounted in its shield with the shield cover removed. The transistors are mounted in a fixture and located radially around the tube as close to it as possible in the maximum intensity of the beam.

In the X-ray tube the electrons from the electron gun are accelerated through the 150,000 volt potential until they attain energies close to 150 kev in a narrow band. As these electrons are decelerated in the tungsten target, they are converted into photons of a white noise energy spectrum asymptotic to 150 kev. The maximum energy possible for a photon to possess is 150 kev, while the most probable energy is two-thirds of the maximum or 100 kev. The average energy of the spectrum is about one-half the maximum; however, the photons of less than 15 kev are so strongly attentuated by the cooling water and structural plastic annulus that the average photon energy of the field irradiating the transistors is significantly higher than 75 kev. In this energy range the photoelectric interaction is the predominant effect between the X-ray beam photon and the irradiated semiconductor material.

Dosimetry measurements were made in January of 1965 using thermoluminescent dosimeters* composed of a LiF phosphor. Five measurements were made with dosimeters housed in 0.013 inch thick Kovar containers (similar to TO-5 cans) to determine dose rates at various locations inside the X-ray shield. Results indicated that the rate can be expressed as:

$$\Phi = 3.77 \times \left(\frac{0.76}{R}\right)^2 \times 10^5 \text{ r/h}$$

where R is the distance from the X-ray tube center line (0.76 inch $\leq R \leq$ 4.9 inch). The rms error for the five readings was 12.5 percent. The R^2 dependence in the expression above will produce rates as low as 9×10^3 r/h at the shield wall and as high as 3.77×10^5 r/h at the tube surface.

2.2.2 Low Current $1/h_{FE}$ Tester

As was discussed in Section 2 of Bendix Proposal 2642 submitted to NASA, the reciprocal of current gain or $1/h_{FE}$ is a very useful parameter for analyzing degradation of the base-emitter junction characteristics caused by ionizing radiation. Fig. 4 is a simplified block diagram of a custom-built measurement system designed specifically to

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*Controls for Radiation

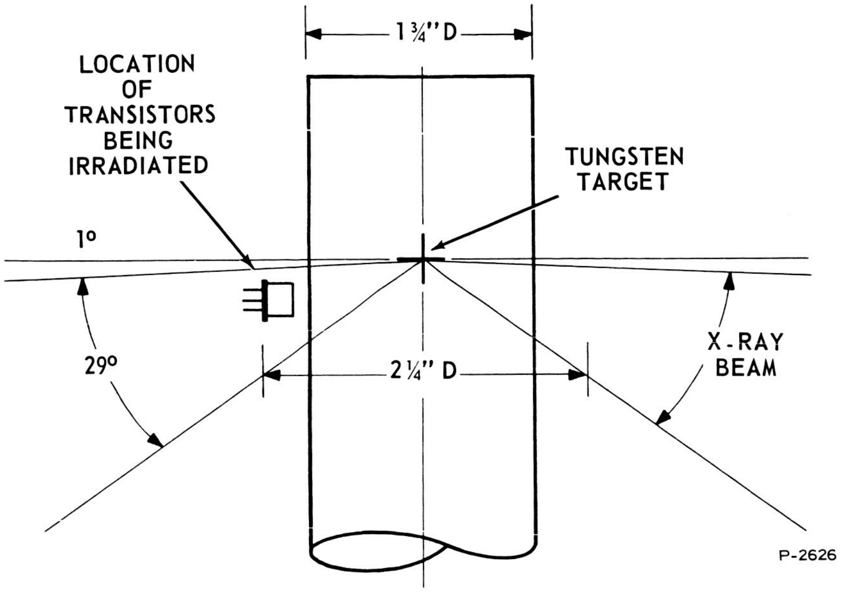

Figure 2 - X-Ray Beam Geometry

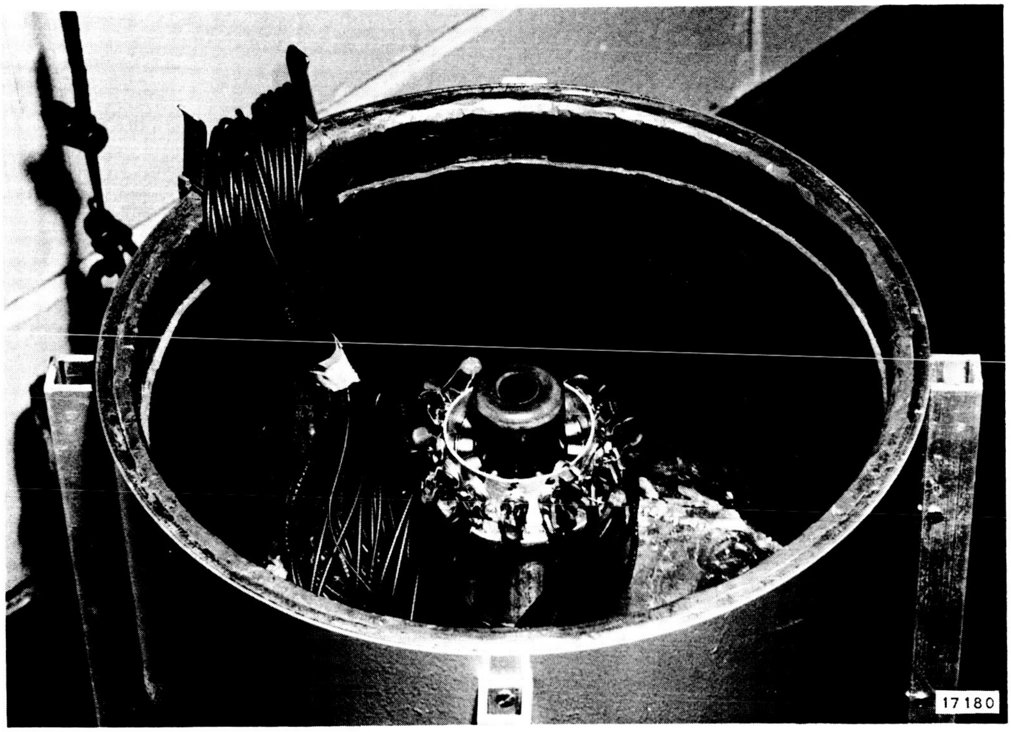

Figure 3 - X-Ray Tube Mounted in its Shield with Transistors in Place Around the Tube in Preparation for Irradiation

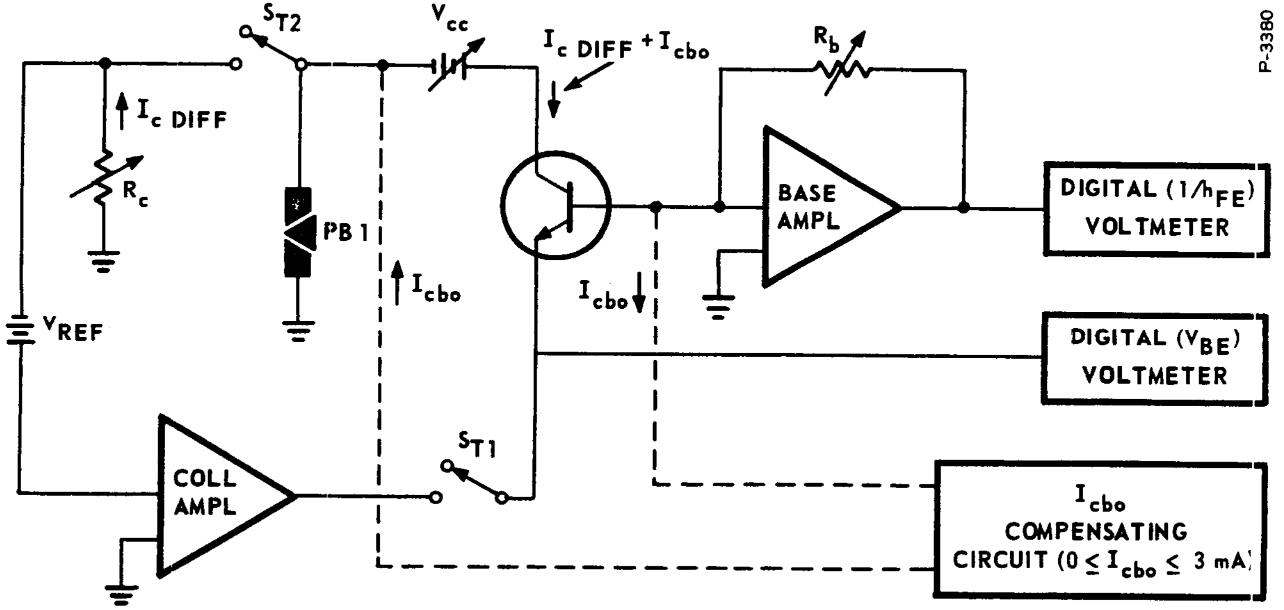

Figure 4 - Block Diagram of the Low Current $1/h_{FE}$ Tester

measure $1/h_{FE}$ as a function of collector current from 0.1 µA to 100 mA. The circuit consists of a control loop which forces the collector current to a predetermined value and a base current sensor which measures $1/h_{FE}$ or I_b/I_c.

The base current sensor consists of an extremely high gain low noise operational amplifier (base amplifier) with an adjustable current feedback resistor (R_b). This circuit has a very low input impedance, which causes the base of the transistor to be at ground potential. It is capable of measuring currents as low as 50 pA and as high as 100 mA.

The collector current control loop in Fig. 4 is in a de-energized position. When the loop is activated by closing switches S_{T1} and S_{T2}, collector current is sensed by measuring the voltage across R_c. This voltage is compared with a reference voltage (V_{REF}) and the error voltage is amplified (collector amplifier) and used to control the emitter voltage. The collector current can be adjusted by R_c from 0.1 µA to 100 mA.

Large values of collector leakage current (I_{cbo}) can seriously distort the $1/h_{FE}$ vs I_c relationships at low measurements since the actual current measured in the base lead is the device base region current minus I_{cbo}. The effect of I_{cbo} is partially compensated for in this measurement system by inducing a current equal in magnitude and opposite to I_{cbo} into the base lead. This is accomplished by depressing PB1 and adjusting the I_{cbo} compensating circuit to produce a null at the output of the base current sensor. I_{cbo} values from several picoamps to several milliamps can be compensated for in this fashion. It should be noted also that an equal compensating current is fed into the collector side of the collector base junction. This compensates for the effect of I_{cbo} on collector current by allowing the collector current control loop to control on collector diffusion current alone and thus maintain a constant emitter injection level. An additional feature of this circuit is that when the compensating current is set to zero and PB1 is depressed, a digital reading of I_{cbo} appears on the base current sensor output meter.

The accuracy of this system varies somewhat with collector current range. It may be as great as ±5 percent on the 0.1 µA range and less than ±0.2 percent for the 10 µA range and above. I_{cbo} readings are accurate to ±30 pA or ±0.2 percent, whichever is greater.

2.2.3 High Current Pulsed h_{FE} Tester

The high current h_{FE} tester is a commercially built (Birtcher No. 70) pulsed unit with a 2 percent duty cycle and a pulse width of about 200 µs. This unit has a current range from 1 mA to 30 A, and its accuracy is 2 percent of full scale where full scale h_{FE} is either 1000 or 100. Modifications are being made on this instrument to provide a full scale of 30 also, to enable more accurate h_{FE} measurement at relatively low gain.

2.2.4 X-ray Facility Measurement and Test System

To enable remote measurement of transistor parameters while the devices are installed in the X-ray machine, and also to provide for the electrical biases required during irradiation, three-conductor electrostatically shielded cables were installed on each transistor socket of the mounting fixture. In addition, a biasing panel was constructed which allows up to 27 different bias conditions to be placed on a transistor in the mounting fixture. Fig. 5 is a diagram of the X-ray facility test setup including remote cabling, the test panel and measurement instrumentation assembled for this program. When measurements of the parameters of a device in the mounting fixture are desired, the appropriate cable plug is transferred from a bias condition socket to one of the measuring instruments.

2.2.5 Pre- and Post-Irradiation Measurement Instrumentation

Prior to irradiation and after a test step has been completed, transistor parameters are measured in a bench test setup (no remote measurements). These measurements include both collector-base and emitter-base junction leakage current and reverse breakdown measurements made with a Hewlett-Packard Model 425 A ammeter and a Tektronix Model 575 curve-tracer. In addition, h_{FE} and V_{be} vs I_c and I_b are measured while the transistor is mounted in a special temperature controller fixture which maintains the transistor case temperature at 35°C. The h_{FE} measurements for this test use the equipment described in Sections 2.2.2 and 2.2.3.

A special low noise mounting fixture is used in the V_{be} vs I_c measurements. Fig. 6 is a schematic of this fixture. A_1 and A_2 in this figure are Hewlett-Packard type 425 A ammeters which measure base and collector currents respectively. The measurement point is adjusted by means of R_e and V_e; and V_{be}, I_c and I_b are recorded at several points in a collector current range from 10^{-11} A to 10^{-3} A. This test set is capable of measuring gain characteristics of transistors at very low currents because it eliminates the influence of I_{cbo} on gain

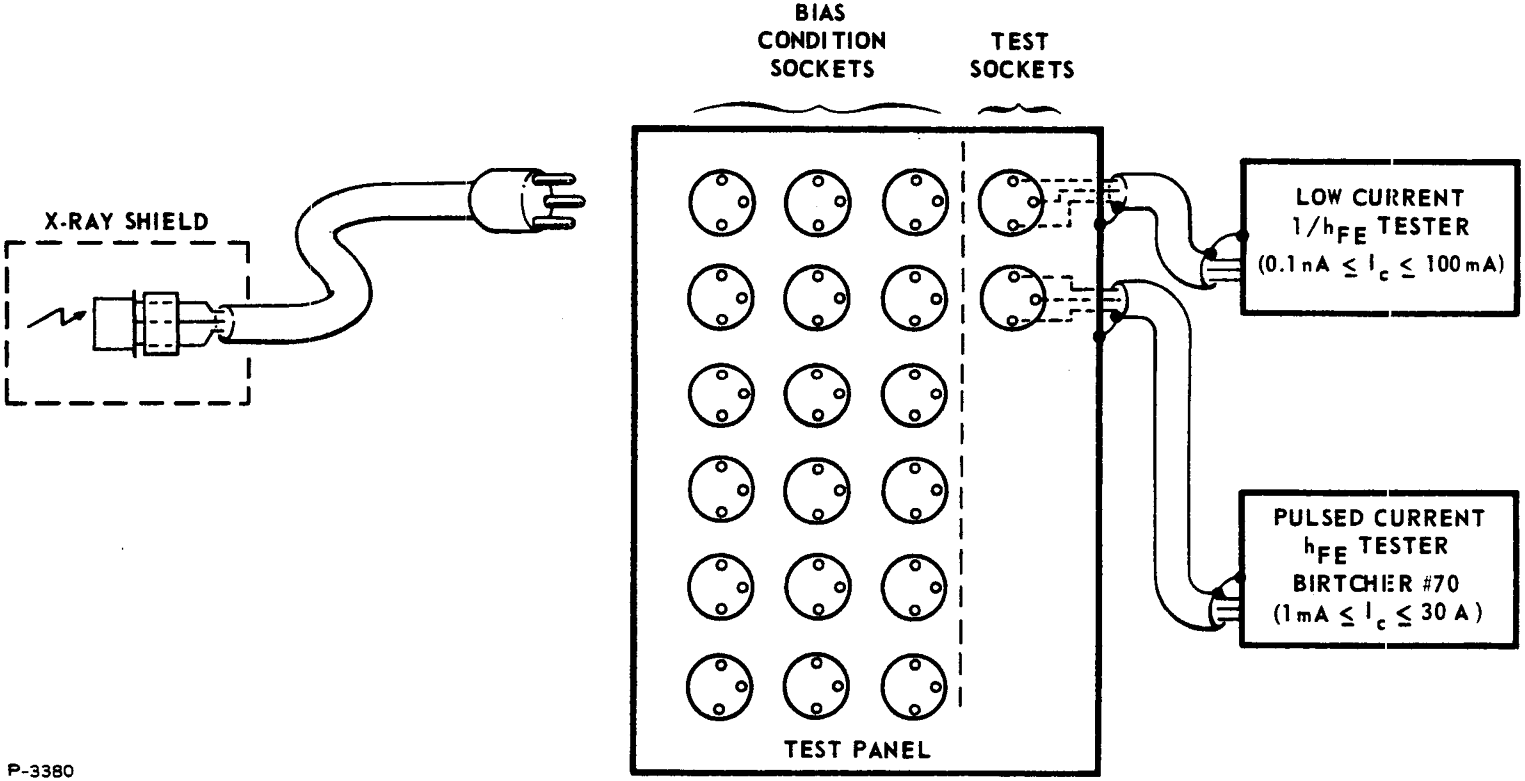

Figure 5 - Diagram of X-Ray Facility Remote Test Instrumentation

measurements. It does this by holding both the collector and base leads very close to ground potential, reducing the collector-to-base voltage to a negligible value. With a zero voltage between collector and base, no leakage current exists.

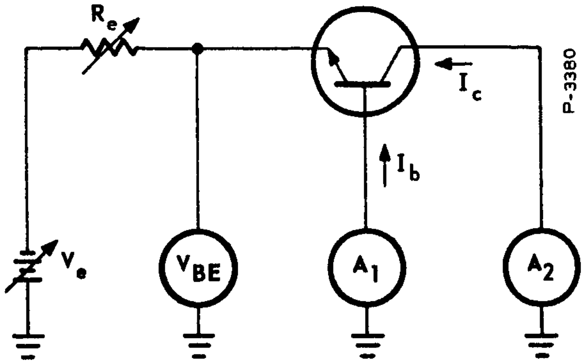

Figure 6 - Test Schematic for the Transistor V-I Tester

2.3 Evaluation of Instrumentation System Capabilities

2.3.1 Measurement Parameters

Phase I of this program is a detailed study of the effects of ionizing radiation on the Fairchild type 2N1613 transistor parameters, leading to an ultimate understanding of the physical mechanisms which cause electrical parameter changes. The electrical parameters I_{cbo} and h_{FE} were selected for the study of damage mechanisms because they can be used to identify mechanisms occurring on the device surface and at the junctions.

I_{cbo} is a simple measurement used to detect changes at the surface near the collector base junction. The current gain measurement (h_{FE}) used to detect base current components induced by ionization, is not so simple. X-ray irradiation usually produces two or more base current components simultaneously. To separate these accurately, h_{FE} must be measured precisely and over a wide collector current range.

The accuracy of h_{FE} measurements at low collector currents is affected by noise, collector-base junction leakage current, and external cable leakage currents. At high currents also measurement accuracy is affected by changes in transistor die temperature caused by heat dissipation. The test described in Section 2.3.2 was performed to evaluate sources of h_{FE} measurement error, reduce instrumentation errors where possible, and establish an acceptable measurement procedure for all Phase I tests.

2.3.2 Instrumentation Test

A cursory X-ray test was performed to determine the leakage current and noise levels inherent with the remote measurement system. Table 2 is a summary of results of this leakage test.

Table 2 - Remote Leakage (I_{cbo}) Measurements

History	X-ray Machine OFF	X-ray Machine ON *
Initial (empty socket)	0.12 nA	0.74 nA
After Paraffin Dip	0.03 nA	0.27 nA
Transistor Installed	0.12 nA	42 nA
X-ray Exposure $\simeq 10^5$ r	0.60 nA	42 nA

*Ionizing rate was approximately 3.8×10^5 r/h

The transistor mounting fixture (containing no transistors) was installed in the X-ray machine, and the low level $1/h_{FE}$ tester was connected to measure I_{cbo}. With the X-ray machine ON I_{cbo} measurements indicated a cable and fixture leakage current of about 1 nA due to air ionization. Coating the entire mounting fixture and cable ends with a thin film of paraffin reduced this leakage current to less than 0.3 nA with the X-ray machine ON and 0.03 nA with the X-rays OFF. A transistor was then mounted in the X-ray fixture and I_{cbo} measurements were repeated. With the X-ray machine OFF the I_{cbo} reading was approximately the same as I_{cbo} for the transistor measured without the cables and fixture. When the X-ray machine was turned ON the I_{cbo} increased instantaneously to 42 nA and remained at this level throughout the test, which amounted to an exposure in excess of 10^5 r. This large current, apparently due to carrier pair generation within the device, was accompanied by a 60 c/s ripple component ($\sim$1.5 nA peak-to-peak). The ripple component is apparently due to the ripple content in the X-ray machine high voltage power supply since when the high voltage supply was turned OFF both the large dc leakage and the ripple vanished leaving a dc leakage component of 0.6 nA. Based on (a) the effect of the large I_{cbo} component on $1/h_{FE}$ measurement, (b) the presence of a significant 60 c/s

I_{cbo} ripple component, and (c) the dominance of the carrier generation current component of I_{cbo}, all of which exist when the X-ray source is ON, a standard remote $1/h_{FE}$ and I_{cbo} measurement procedure was established for future X-ray tests. This procedure requires shutdown of the X-ray machine prior to measurement. However, prior tests of 2N1613s indicate that partial recovery may occur after X-ray shutdown. The amount of this recovery is minor at room temperature.

In the test described above $1/h_{FE}$ ($0.1\ \mu A \leq I_c \leq 300$ mA) for the transistor was measured before and after the X-ray exposure of 5×10^5 r. The effect of applying measurement conditions to a damaged transistor was investigated by applying a bias of $I_c = 100$ mA, $V_{cb} = 5$ V for 60 sec, then measuring $1/h_{FE}$ again over the entire current range. This electrical stress removed 20 percent to 64 percent of the X-ray induced damage, with larger recovery occurring at low measurement currents. This test sequence emphasizes the need to minimize the stress applied to transistors during measurement. Based on these results, two types of h_{FE} data will be taken during X-ray test, an "abbreviated" set and a "complete" set. The complete set will consist of h_{FE} measurements at collector currents of 0.1, 0.3, 1, 3, 10, 30, 100, and 300 μA, and 1, 10, 30, 100 and 300 mA with transistors removed from the mounting fixture and mounted in the temperature controller (T = 35°C). These tests will be performed before and after each major test step and possibly at an intermediate point. The abbreviated h_{FE} data will be taken at room temperature through remote cables and will consist of measurements at I_c's of 1, 10, and 100 μA and 1, 10, 30, 100 and 300 mA. These data are to be taken at intermediate points during each major test step to determine response of accumulated damage vs time or dose.