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The establishment of a radiation effects program at the NPGS linear accelerator facility.

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THE ESTABLISHMENT OF A RADIATION EFFECTS PROGRAM AT THE NPGS LINEAR ACCELERATOR FACILITY

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ABSTRACT

The establishment of a program to study the effects of radiation on solid state electronic devices is discussed. The design and testing of experimental equipment used in connection with this project, and the techniques developed for the exposure of devices to the electron beam of the NPGS LINAC, form the main topics of this paper. Also included are the results of a beam profile analysis done using calorimetric techniques, and some results concerning the behavior of transistors exposed to the LINAC electron beam.

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I. INTRODUCTION

The studies reported in this paper were undertaken as initial steps in the establishment of a facility to investigate the effects induced in electronic circuitry when exposed to radiation. Although such studies have been underway for several years in industry and at government installations, at the inception of this project no similar work had been attempted at the Naval Postgraduate School. The recent completion of the Electron Linear Accelerator facility (LINAC)[1] enabled us for the first time to start a significant research program in this area. There was, however, no experimental equipment designed for such a job, nor had any techniques been developed to accomplish it here. In an effort to ascertain what sort of equipment we should have, and upon what effects we should try to focus our attention, a survey of current efforts in this field was made by consulting with some representative industrial research groups as well as selected government agencies. Our efforts in this area revealed a lack of exchange of information between the research agencies consulted and a minimum of liason between the systems developers and the research teams. Little well correlated information was found in this field and it was decided, therefore, to start the project from basic principles, developing our own experimental techniques and equipment as the results of each experiment indicated. The major efforts thus far have been to develop equipment for the exposures of samples; to devise a satisfactory method for beam dosimetry; and to study the gross radiation effects in transistors.

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[1] Barnett and Cunneen, Thesis, Naval Postgraduate School, May 1966.

This paper is developed according to the chronology of the events. The basic objectives of the study are established followed by a description of the experimental equipment and then an explanation of the techniques used. The final section is devoted to a discussion of the results and effects which we have observed thus far.

II. ESTABLISHMENT OF RESEARCH GUIDELINES

It was decided that prior to any attempt to conduct experiments in radiation effects we should establish some basic guiding principles based on the information we had gathered during our inquiry into the current efforts in the field. After a careful examination of the information we had obtained, the following points were considered to be pertinent to this project. These points are listed without qualification and are justified in the subsequent paragraphs.

1. The existing data should be assumed to be incomplete and possibly in error.
2. The exposure apparatus should provide for the mounting of many samples simultaneously.
3. Remote control of the experimental equipment would be necessary.
4. It would be necessary to obtain output data from the samples while they were being exposed.
5. It would be necessary to have equipment which would be sensitive to very short lived transient effects.
6. Equipment capable of providing accurate dosimetry would be required.
7. Equipment capable of monitoring a single pulse of the LINAC as well as continuous operation would be needed.

Our survey of the literature indicated that there was not complete agreement on the magnitude of radiation effects in solid state circuitry. In fact, there was not even complete agreement on the types of effects which could be observed. We did find some work had been done with specific components and some facts had been established about them, but no satisfactory model had been developed to predict the behavior of untested elements or devices. It was more or less generally accepted that radiation of "sufficient" intensity would cause the breakdown of solid state devices, but the mechanism which caused the failure and the criteria for what is meant by sufficient were not well defined.

The need for many exposures is obvious in order that statistical predictions can be made. A circular holder was used by one facility which allowed a maximum number of samples with a minimum space requirement. Most research facilities used a "ladder" on which to mount components. A ladder is a device which positions components by linear motion. Because of space limitations at NPGS, the wheel mounting arrangement seems to be the best. However, as is explained later, a ladder is currently being used as an interim expedient.

The gathering of data from a number of specimens during a run would become a time consuming process if each sample had to be placed in the beam manually. In addition to the time required to make the trip from the LINAC control area to the end station, a "cool-off" period must be allowed so that the target area radiation intensity may drop to a safe level. The time involved in such a procedure can cause serious experimental problems. (If the electron beam is turned off for more than a few minutes its intensity when turned on again is subject to severe fluctuations). Thus, remote control of experimental equipment is not just a convenience but a necessity for a satisfactory experimental procedure.

As is discussed in later sections, the instantaneous dose rate delivered by the NPGS LINAC is considerably higher than the average rate. The energy deposition rates in either case are not sufficient to cause structural damage, so it is not anticipated that any startling gross effects will be noted. Since we do not anticipate this sort of effect, it is assumed that if there are any effects of a severe nature they are necessarily a short lived response to the pulse input of the LINAC. If this type of response is to be studied then it is necessary to obtain output from the samples while they are being exposed and to have equipment which will be sensitive to effects whose lifetime is of the order of one microsecond.

One of the primary aims of the project is to gain knowledge of the response of solid state circuitry to radiation as a function of absorbed dose and dose rate. If this is to be accomplished, it will be necessary to have accurate measurements of the dose to which samples are exposed. The dosimetry equipment presently installed for the LINAC gives an average of the total beam over its cross section. It is apparent that any calculations of dose received by a sample have to assume some type of intensity distribution over the beam area. Most of the single component devices to be exposed are much smaller than the beam cross section so the position of the sample in the beam may be of great importance as far as the dose received is concerned. If an assumption about the beam intensity distribution is to be avoided it will be necessary to have a monitoring device which is sensitive to intensity over a "small" area. As is discussed above we will want to study component response to single pulses of the electron beam. If this is to be done and the pitfalls already discussed are to be avoided, the beam monitoring equipment must give accurate readouts for a single pulse as well as for continued pulsing.

III. DESIGN OF EXPERIMENTAL EQUIPMENT

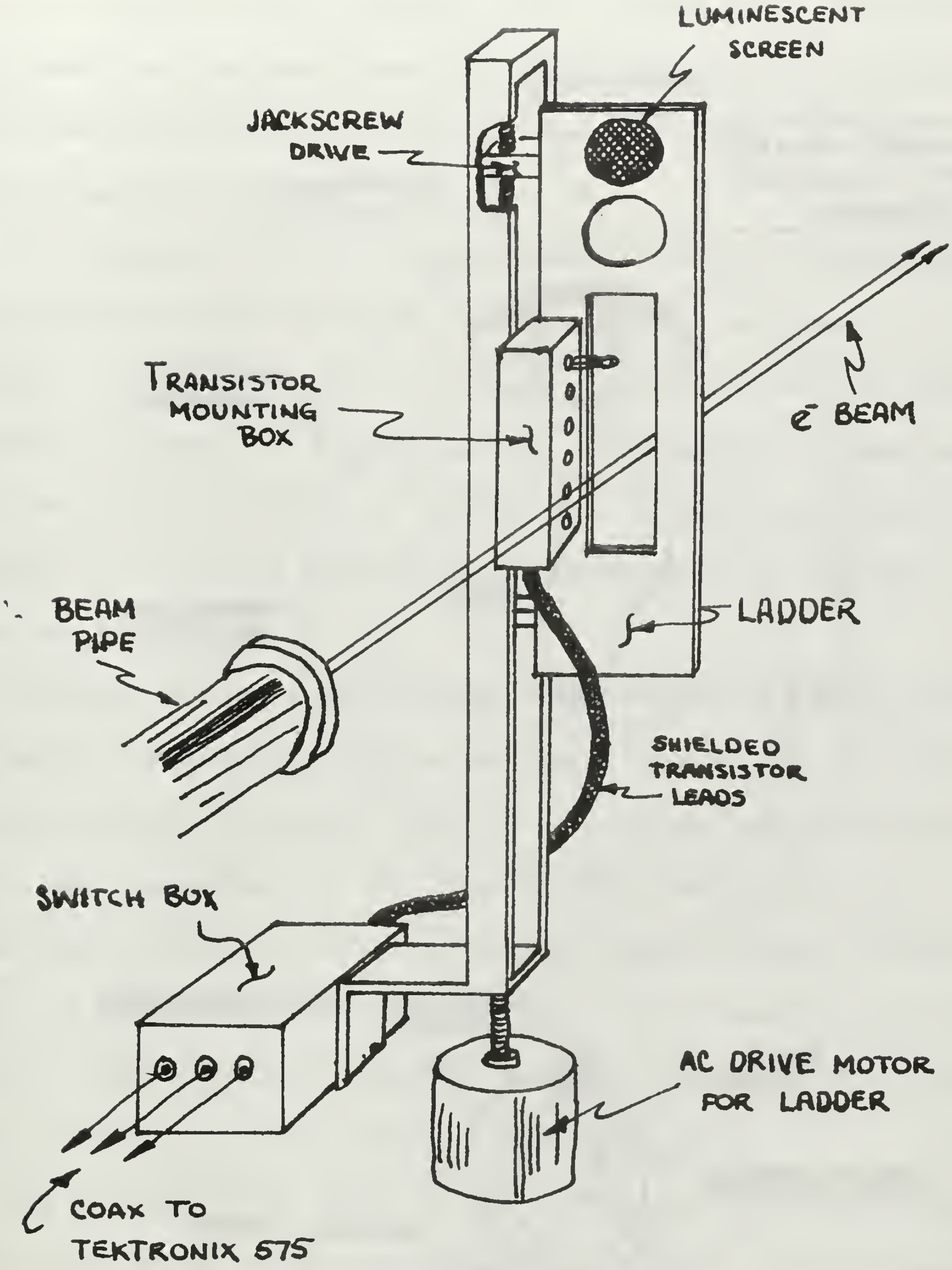
A. Transistor Exposure Device.

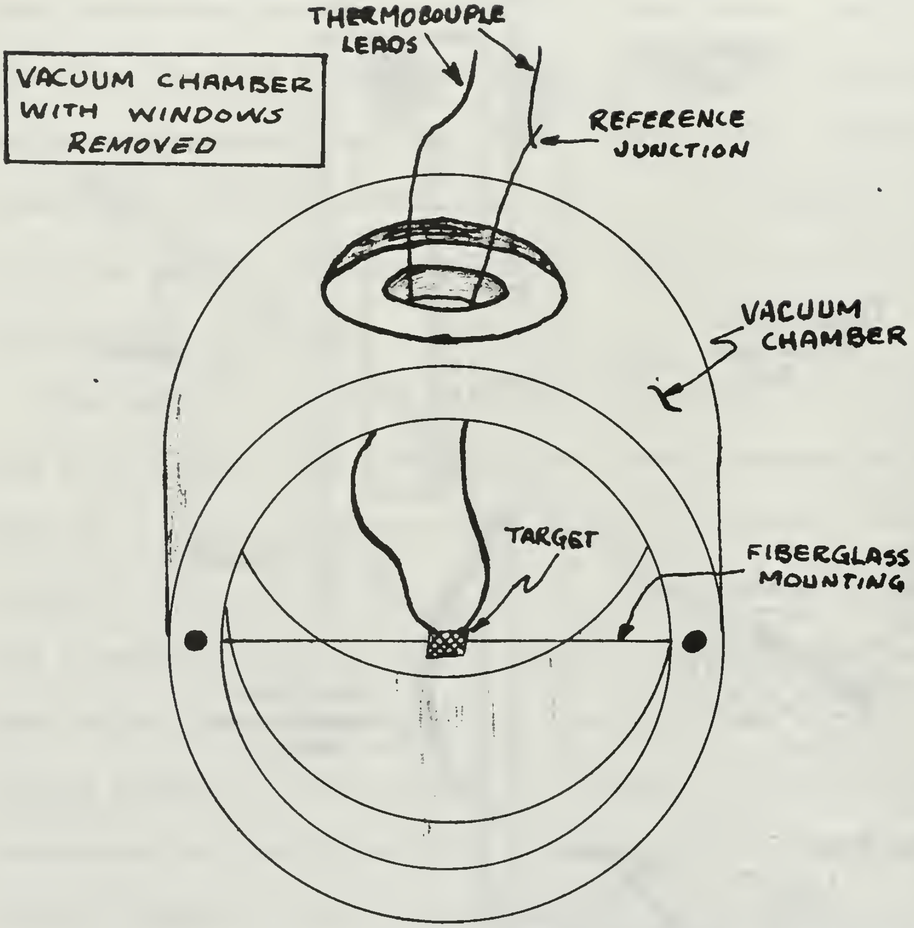
Money and time requirements dictated some sort of device for sample exposure which could be constructed locally. Since our first experiments were to be done with transistors, a mobile device containing mounting sockets which could accept most commercially available transistors was indicated. Remote control features had already been accepted as a design feature. The immediate availability of a drive assembly dictated a device which would position samples by linear motion in the beam (see figure 1).

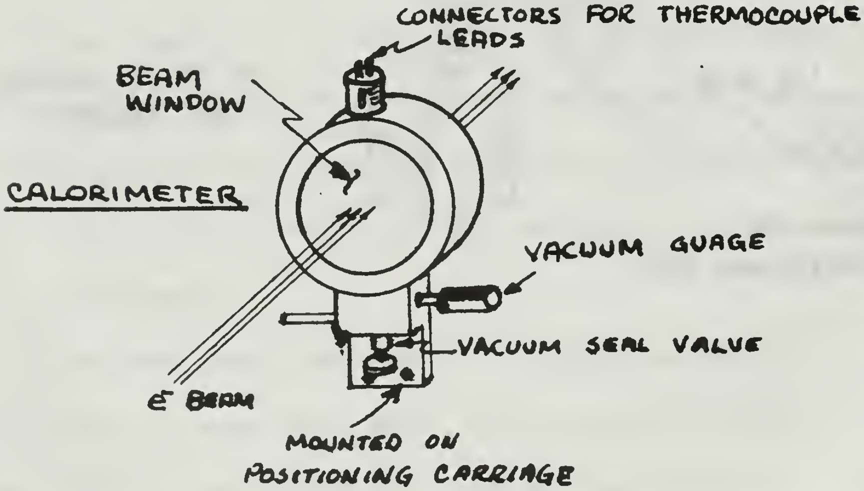
The ladder is designed to allow the mounting of six transistors plus a luminescent screen which allows visual focusing of the LINAC beam via a closed circuit TV setup already installed. The ladder is mounted on the rack and pinion and the rack is driven by a slosyn motor. Each transistor requires three leads for a complete monitoring of its input/output characteristics; thus three RG/52 cables are run to the control station for this purpose (a distance of about 80 feet). The transistors are individually connected to these cables through a solenoid operated rotary switch. By this means electrical connection to any of the samples can be made remotely from the control station. A display is also installed to indicate which socket is being monitored. All the data collection leads are shielded to minimize R. F. interference. For a wiring diagram of the connection box see the appendicies.

B. Calorimeter

The calorimeter consists of a target suspended in a vacuum chamber that is mounted on a motor driven rack and pinion arrangement to allow vertical and horizontal movement (see figure 2). The vacuum


LUMINESCENT SCREEN
JACKSCREW DRIVE
TRANSISTOR MOUNTING BOX
e⁻ BEAM
BEAM PIPE
LADDER
SHIELDED TRANSISTOR LEADS
SWITCH BOX
AC DRIVE MOTOR FOR LADDER
COAX TO TEKTRONIX 575


VACUUM CHAMBER WITH WINDOWS REMOVED
THERMOCOUPLE LEADS
REFERENCE JUNCTION
VACUUM CHAMBER
TARGET
FIBERGLASS MOUNTING


CONNECTORS FOR THERMOCOUPLE LEADS
BEAM WINDOW
CALORIMETER
VACUUM GUAGE
VACUUM SEAL VALVE
ē BEAM
MOUNTED ON POSITIONING CARRIAGE

chamber is designed with a port valve so that once the vacuum has been established the chamber may be moved independent of any external pumping system. The chamber is massive with respect to the target, thus it may be treated as an ideal heat sink. The target is suspended in the chamber on fiberglass thread to insulate the target from the case. Thin aluminum foils at either end of the chamber serve as beam entrance and exit windows.

The temperature of the target is measured with a Cromel-Alumel thermocouple with the reference junction outside the chamber, but in contact with it. In this way the readout directly gives the target to chamber temperature difference. The thermocouples are constructed from two mil wire to minimize heat transfer from the target and to maximize their ability to follow rapid temperature fluctuations. The junctions are welded.

Temperature responses from tenths of a degree to hundreds of degrees are anticipated depending on target construction and beam characteristics. This means that the thermocouple output will range from a few hundredths of a millivolt to about twenty millivolts. The thermocouple output is fed to the control station through shielded cables to avoid stray noise interference, and is connected to a strip recorder which provides a record of target temperature. This information is used for the data reduction described later.

The calorimeter is driven by two d.c. motors which allow the target to be moved to any desired point in the beam, or to be removed entirely from the beam. It is equipped with limit switches so the assembly cannot be driven into the stops causing the motors to burn up. In addition, a visual display on the control panel indicates when a limit switch has been activated. These switches may be used as a positioning reference when doing beam profile studies. For a circuit diagram of the control section of this device see the appendicies.

C. LINAC

The electron linear accelerator at the NPGS is used as the radiation source. This machine delivers a high energy electron beam which can be used directly or can be used to generate a gamma beam from a suitable radiator. The beam is pulsed, each pulse being two microseconds long, with 120 pulses per second. Each pulse contains about 10^{11} electrons, yielding an average current of one to two microamperes. The intensity distribution over the beam cross section has been measured, and is discussed later in this paper. The electron energy used in our experiments is 80 to 90 Mev, although the machine is designed to permit operation at 120 Mev. At the present time there is no means for single pulsing, although such an arrangement is planned. There are facilities for beam steering, both horizontal and vertical, as well as beam focusing and shaping, which is monitored visually by observing the beam "spot" on a luminescent screen via closed circuit TV. Installed beam monitoring equipment also includes two Secondary Emission Monitors and a Faraday cup.

IV. EXPERIMENTAL PROCEDURES

A. Transistor Exposures.

The initial phase of this experiment included exposures of transistors to the beam for various times to determine any gross effects which might occur, and to test the functioning of our equipment. In the first experiment the electron beam was focused on a luminescent screen mounted on the ladder and the beam position was marked on the TV screen in the control station. The beam was then turned off and the first sample raised into the position marked on the viewing screen. The transistor leads were connected to a Tektronic 575 Transistor Curve Tracer for a visual presentation of its pre-radiation characteristics. Photographs of the gain characteristics were taken and the beam was turned on; during the irradiation changes that occurred were noted. After a prescribed time the beam was turned off, the gain characteristics at this point were photographed, the next sample was put into position for radiation, and this cycle repeated. Upon completion of the exposure of all samples in the run, the gain characteristics were again observed and photographed. Pictures were taken again at various intervals thereafter to observe the recovery characteristics of the samples; this was continued for periods up to six days. Both NPN and PNP transistors were exposed and each type given various radiation doses to obtain some idea of the sample behavior as a function of the dose received. A study was also made of temperature characteristics of the samples by heating the transistors to specified temperatures and photographing the characteristics so that it was possible to eliminate erronious interpretations of behavior which may have been due to thermal effects.

During one experiment, in order to check the visual positioning procedure used, the transistors themselves were coated with a luminescent material.

The transistors were connected in a grounded emitter configuration, and during the initial run a great deal of R.F. noise interferfered with the 575 display. A number of grounding schemes were tried and it was found that by grounding the cable shields for transistor input/output and the metal box housing the remote switching apparatus to the accelerator beam pipe, nearly all of the R.F. noise in the signals was eliminated.

B. Integrated Circuit Exposures.

An adapter which would attach to the ladder previously described was designed to hold an integrated circuit. The circuit was a Fairchild DTLU 969 which is designed to shift its output voltage in a step at a predetermined input voltage. A periodic ramp function was supplied to this circuit and the output observed. This was done to see if the radiation would in any way alter the response characteristics of this device. The input and output were simultaneously displayed on a Tecktronic 556 with a common trigger arrangement so that the input voltage switching level could be determined. A grounding scheme similar to that used for the transistors was used to suppress R.F. interference. Detailed studies on these devices are just beginning at the present time, and will not be included in this paper.

C. Calorimeter Measurement of the Electron Beam.

In the initial phase of the work on the calorimeter, a number of rather massive thermocouples were exposed to the beam to determine if any spurrious effects would result in the thermocouple output due to its exposure to the beam. These studies indicated that no significant unwanted effects were induced by the electrons and that the temperature increases were about as anticipated. In the next phase a number of different types of targets were exposed to the beam in order to verify the theoretical calculations and to get an experimental feel for the best target to use for a given beam intensity. No interference was present in the output signal of the thermocouple, thus special grounding or shielding is unnecessary.

A number of techniques were tested to measure an accurate intensity profile of the electron beam. In the initial experiments, the target was placed in the beam and allowed to come to thermal equilibrium. The thermal properties of the target were derived by an analysis of its cooling characteristics in the absence of the LINAC input. In later experiments, an effort was made to observe the intensity of varying positions in the beam by looking at the equilibrium temperature at these points. The results of this method were quite difficult to analyze accurately and the method itself was time consuming. Tests were then done by moving the target through the beam at constant speed, observing the temperature response rate. The analysis of this response was done by the methods derived in Section V. This technique proved to be quite adequate for our needs and was adopted as the standard procedure for future beam analysis. The final phase of this study was to do an analysis of the spatial structure of the beam, the details of which are shown in the section on experimental results. This examination was done by passing the target through the beam horizontally at various vertical positions, then vertically at various horizontal positions, all at fixed speed.

V. EXPERIMENTAL RESULTS

A. Dosimetry.

1. Theory.

The calorimeter is designed to measure the beam intensity by determining the energy deposited in the calorimeter target by the beam.

This is accomplished by allowing the temperature of the target placed in the beam to rise above the temperature of a surrounding heat sink, (the vacuum chamber walls). Equilibrium is established when the rate of energy deposit in the target by the beam is equal to the power radiated from the target.

If the temperature of the calorimeter wall is T_o and the energy loss in the target material by the incident electrons is dE/dx (energy loss in Mev cm^2/gm), then the total input to the target is

$$N \left\{ \frac{dE}{\rho dx} \right\} \rho V + \epsilon \sigma A T_o^4$$

where N = number of electrons per square cm per second incident on the target, ρ target density, V = volume of the target, ϵ is the emissivity of the target, σ is the Stephan-Boltzmann constant, and A = surface area of the target.

Energy is dissipated by the target to the walls according to AT^4, where T is the target temperature. Thus the net energy flux Φ into the target is

$$\Phi = N \left\{ \frac{dE}{\rho dx} \right\} \rho V + \epsilon \sigma A \left(T_o^4 - T^4 \right). \qquad (1)$$

The equilibrium temperature is reached when $\Phi = 0$;

$$N\left\{\frac{dE}{\rho dx}\right\}\rho V + \epsilon\sigma A\left(T_o^4 - T_{eq}^4\right) = 0,$$

or

$$T_{eq}^4 = N\left\{\frac{dE}{\rho dx}\right\}\frac{\rho V}{\epsilon\sigma A} + T_o^4 \quad . \tag{2}$$

Provided that the temperature of the walls T_o is fixed, the equilibrium temperature T_{eq} is strictly a function of N, giving

$$N = \left\{T_{eq}^4 - T_o^4\right\}\frac{\epsilon\sigma A}{\rho V\alpha} \quad , \quad \text{where } \alpha = \left\{\frac{dE}{\rho dx}\right\}. \tag{3}$$

This formulation requires that the equilibrium temperature be reached in order to find N, and that $\epsilon\sigma A/\rho V$ be measured.

This method makes accurate analysis of the beam profile tedious, because the cooling rate of the target is dependent on the target temperature; thus it is useful to try to find some other approach for the analysis of the beam. On the assumption that the only mechanism by which the target can dissipate energy is thermal radiation, the time response behavior is given by

$$\frac{dT}{dt} = \frac{\Phi}{C_p \rho V} , \tag{4}$$

where Cp is the specific heat of the target material. Thus,

$$\frac{dT}{dt} = \frac{N\alpha\rho V + \epsilon\sigma A\left(T_o^4 - T^4\right)}{C_p\rho V} \quad . \tag{4.1}$$

This can be simplified somewhat by noting that

$\epsilon\sigma A T_{eq}^4 = N\alpha\rho V + \epsilon\sigma A T_o^4$ which gives $\dfrac{dT}{dt} = \dfrac{\epsilon\sigma A}{C_p\rho V}\left(T_{eq}^4 - T^4\right),$

or

$$\int_{T_o}^{T}\frac{dT}{T_{eq}^4 - T^4} = \int_0^t \frac{\epsilon\sigma A}{C_p\rho V}\,dt .$$

The exact solution to this is

$$t = \frac{\rho V C_p}{\epsilon \sigma A}\left(\frac{1}{T_{eQ}^3}\right)\left\{2\tan^{-1}\frac{T}{T_{eQ}} + \ln\frac{T+T_{eQ}}{T-T_{eQ}} - \left[2\tan^{-1}\frac{T_o}{T_{eQ}} + \ln\frac{T_o+T_{eQ}}{T_o-T_{eQ}}\right]\right\}. \tag{5}$$

As can be seen, (5) is quite cumbersome and it would be desirable to have the temperature as a function of time. There are certain approximations which simplify this equation considerably. If $T \simeq T_o$, that is, if radiation loss can be neglected, then Φ depends only on the beam energy deposition term

$$\frac{dT}{dt} \cong \frac{N\alpha\rho V}{C_p \rho V} = \frac{\alpha}{C_p} N ,$$

or

$$\int_{T_o}^{T} dT = \int_0^t \frac{\alpha}{C_p} N\, dt ,$$

therefore,

$$T = T_o + \frac{\alpha}{C_p} N t .$$

Initially the temperature increase of the calorimeter is linear and N can be directly determined from the slope of the time versus temperature graph of the calorimeter readings without knowledge of ϵ, which is difficult to measure. If m_h is the slope of this plot then

$$N = \frac{C_p}{\alpha} m_h \tag{6}$$

The physical constants of any given target in the calorimeter may be determined by its cooling characteristics. These constants may be calculated by two independent methods for comparison.

The cooling of the calorimeter is determined by the Stephan-Boltzmann radiation law,

$$\Phi = \epsilon \sigma A \left(T_o^4 - T^4\right).$$

Then from (4),

$$\frac{dT}{dt} = \frac{\epsilon\sigma A}{C_p\rho V}\left(T_0^4 - T^4\right). \tag{7}$$

If $T \simeq T_{max}$,

$$\frac{dT}{dt} \cong \frac{\epsilon\sigma A}{C_p\rho V}\left(T_0^4 - T_{max}^4\right),$$

or

$$T = T_{max} - \frac{\epsilon\sigma A}{C_p\rho V}\left(T_{max}^4 - T_0^4\right)t .$$

Thus the constants can be determined by the initial slope of the cooling curve; that is

$$m_c = \frac{\epsilon\sigma A}{C_p\rho V}\left(T_{max}^4 - T_0^4\right).$$

Since σ, T_o and T_{max} are known,

$$\frac{\epsilon A}{\rho V C_p} = \frac{m_c}{\sigma\left(T_{max}^4 - T_0^4\right)} . \tag{8}$$

This value can be checked by analyzing the cooling curve when T is near T_o. In this case we have

$$T = T_0(1+\Delta) \text{ , where } \Delta = \frac{T-T_0}{T_0} << 1 ,$$

or

$$T^4 = T_0^4(1+\Delta)^4 \simeq T_0^4(1+4\Delta)$$

Then

$$T_0^4 - T^4 \cong T_0^4\left(1-4\Delta-1\right) = -4T_0^4\,\frac{(T-T_0)}{T_0} = -4T_0^3\,(T-T_0).$$

Now from (7) we get

$$\frac{dT}{dt} = -\frac{\epsilon\sigma A}{C_p\rho V}\left(T-T_0\right)4T_0^3,$$

or

$$\int_{T_i}^{T}\frac{dT}{T-T_0} = -\int_0^t\frac{\epsilon\sigma A}{C_p\rho V}\left(4T_0^3\right)dt,$$

where T_i is the initial temperature of the plot

$$\ln(T-T_0)\Big|_{T_i}^{T} = -\frac{4T_0^3\epsilon\sigma A}{C_p\rho V}t,$$

giving

$$\ln(T-T_0) = \ln(T_i-T_0) - \frac{4T_0^3\epsilon\sigma A}{C_p\rho V}t \qquad (9)$$

The elope of a semilog plot of $\ln(T - T_o)$ versus time also yields the quantity $\epsilon A/\rho VCp$. As can be readily seen, equation (5) reduced to this result when T_{eq} is replaced by T_o and $T \simeq T_o$.

2. Dynamic Response Characteristics.

The next problem is to find a method by which the response of the target due to thermal radiation may be subtracted out of the temperature-time response curves, so that the energy deposit by the beam can be measured. This is necessary when obtaining beam profiles since the target is moved across the beam, thereby experiencing a continually changing beam intensity. The change in beam intensity which will be responsible for particular temperature change can be closely approximated by methods already derived using certain modifications.

As has already been shown if T is near T_o, N - the number of electrons incident per sec per cm^2 - is given by the slope of the time-temperature curve; thus by finding the change of the slope of this curve the change in the beam intensity can be directly found.

The method outlined is obviously accurate only if the contribution to the net energy input to the target is solely a function of the beam intensity, and this is accomplished when

$N\alpha\rho V \gg \epsilon\sigma A\left(T_0^4 - T^4\right)$. This analysis may still be used at higher temperatures which preclude this approximation by the addition of a correction term. From (4.1) we have

$$\frac{dT}{dt} = \frac{N(t)\alpha\rho V + \epsilon\sigma A(T_0^4 - T^4)}{C_p \rho V},$$

or

$$N(t) = \frac{C_p}{\alpha}\frac{dT}{dt} + \frac{\epsilon\sigma A}{\alpha\rho V}(T^4 - T_0^4),$$

Thus by the addition of the correction term $\frac{\epsilon\sigma A}{\alpha\rho V}(T^4 - T_0^4)$ the slope method may be used at any point on the temperature-time plot. The only restriction to this is that if the calorimeter is being operated near the equilibrium temperature this method is insensitive to sharp drops in the beam intensity. The maximum rate of temperature decrease is limited by the thermal radiative term. Therefore, if this rate is reached there is no longer any beam intensity information contained in the temperature response behavior.

To make the calorimeter most sensitive, the target should be selected to give equilibrium temperatures at least 100° above the environment temperature for the anticipated beam. This will allow a large operating range in which the high temperature problems can be avoided; also, the beam intensity response will be more sharply defined. The use of a target with a very small emissivity ($<.05$) will accomplish this end, but has the disadvantage that long cooling times will be encountered.

3. Target Choice Considerations.

The beam intensity is found from

$$\frac{C_p}{\alpha} m_h + \frac{\epsilon\sigma A}{\alpha\rho V}(T^4 - T_0^4)$$

Small changes in the slope are most easily detected if the slope of the time-temperature plot is near one. If the slope is to be kept near one, then the value of C_p/α should be of the same order of magnitude as the anticipated beam intensity. Undoubtedly in most cases there will be a number of possible materials which will satisfy this requirement. A further guideline in making the target choice might be to attempt to minimize the correction term so the slopes may be used directly; this is accomplished by variation of the parameters $\epsilon A/\rho V$. By minimizing this term the time to undergo a given temperature drop is maximized which should be considered when selecting the target configuration.

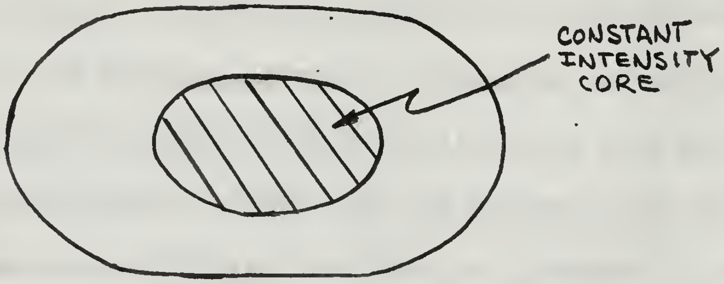
4. Expected Results for Single Pulse Operations.

When the linear accelerator is capable of single pulse operation it will be necessary to monitor these pulses and have an accurate knowledge of the dose delivered by each pulse. The calorimeter may be placed downstream in the beam from the sample, thus not interfering with the sample exposure. The sample will absorb a negligible amount of the beam. A single pulse will yield a small jump increase in the temperature of the calorimeter target and the maximum of this increase will be the equilibrium temperature of equation (2). The temperature increases due to a single pulse are anticipated to be quite small, $\sim$0.1 degree Centigrade or less, thus the decay back to the environment temperature will be very slow, obeying the exponential decay of equation (9). Since the scales to do this work will necessarily have to be magnified to detect such small changes and the input will have to be considered a delta function, the inherent lags in the recorder will dominate the characteristics of the temperature response curves. The recorder response is non-linear above a certain rise time and an analysis of this response would be inaccurate or impossible. Therefore, the slope methods described for steady state operation will be inadequate, leaving an analysis of the equilibrium temperatures reached the only alternative of practical value. This method should be quite accurate so long as the temperature of the thermocouple target is kept near T_o.

5. NPGS LINAC Beam Analysis.

Profile studies were done on the accelerator beam with the calorimeter, using the techniques outlined in the preceding sections. These data are shown as Figures 4 and 5. It should be realized that the characteristics of the beam are not static, since a certain amount of beam shaping can be done with the LINAC controls. The beam shape is also deformed somewhat in that it must travel through about two feet of air prior to impinging on the calorimeter.

The beam was found to be symmetric about the longitudinal beam center. The shape of the beam is approximately elliptical although the data indicates that is "bulges" out more than an ellipse, that is, its bounds are contained between a rectangle and the inscribed ellipse. (See Figures 3, 4, 5)



LINAC BEAM CROSS SECTION

Figure 5

At the center of the beam there is a constant intensity core whose shape is the same as the overall beam cross section.

The semiaxes of the core are about one third the corresponding dimensions of the total beam. The intensity fall off from the core is approximately linear and falls to 50% of its maximum value within 2 mm of the core edge. The beam is oriented with its longest axis in the horizontal plane and is 1.45 cm ± 0.05 cm in length.

B. Transistors.

Since it is desired to obtain the behavior of these components as a function of the radiation level, it is necessary to have a measure of the dose received by the transistors. The dose received for these experiments is measured in rads (100 ergs deposited per gram of material) and the calculation of the dose is based on the following approximations. The flux of electrons during any given run is known from the calorimeter and S.E.M. read-outs. Since the center of the beam is of uniform intensity it can be assumed that there is a uniform energy deposit over the entire device. The electrons which pass through the material loose energy by bremsstrahlung and by ionization. However, only the loss by ionization is effective in depositing energy since virtually all of the photons with energy more than one to two Mev escape the material without interaction. (The mean free path for photons of two Mev or more is greater than 15 cm). Therefore, if α is the energy loss for electrons by ionization then the absorbed dose rate in rads/sec is given by

$$D = N\alpha\,(1.6 \times 10^{-8}) \text{ rad/sec}$$

The quantity α is well known for most materials and graphs of versus electron energy for various materials are given in the appendices. The experiments were run at beam intensities of

figure 4

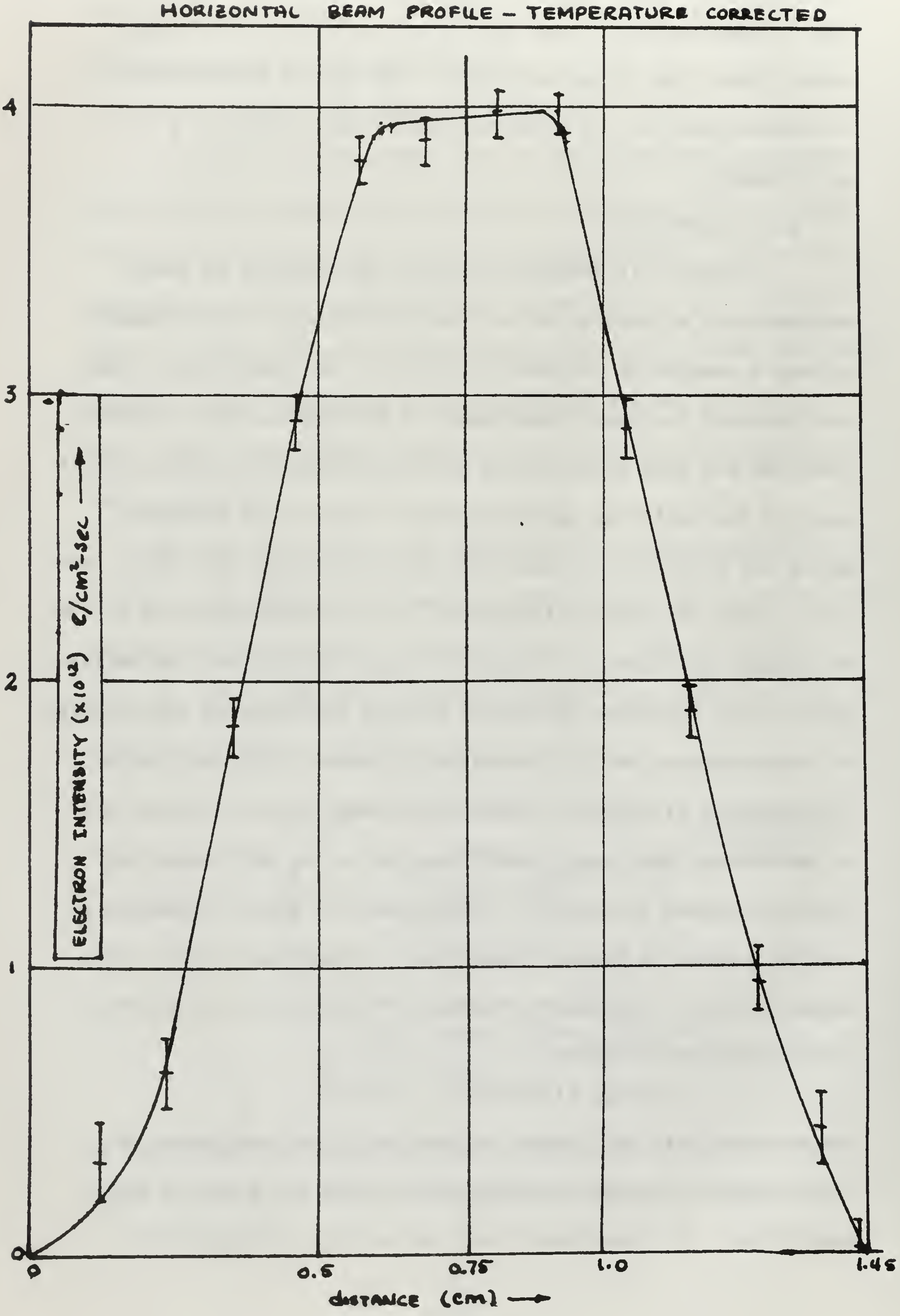
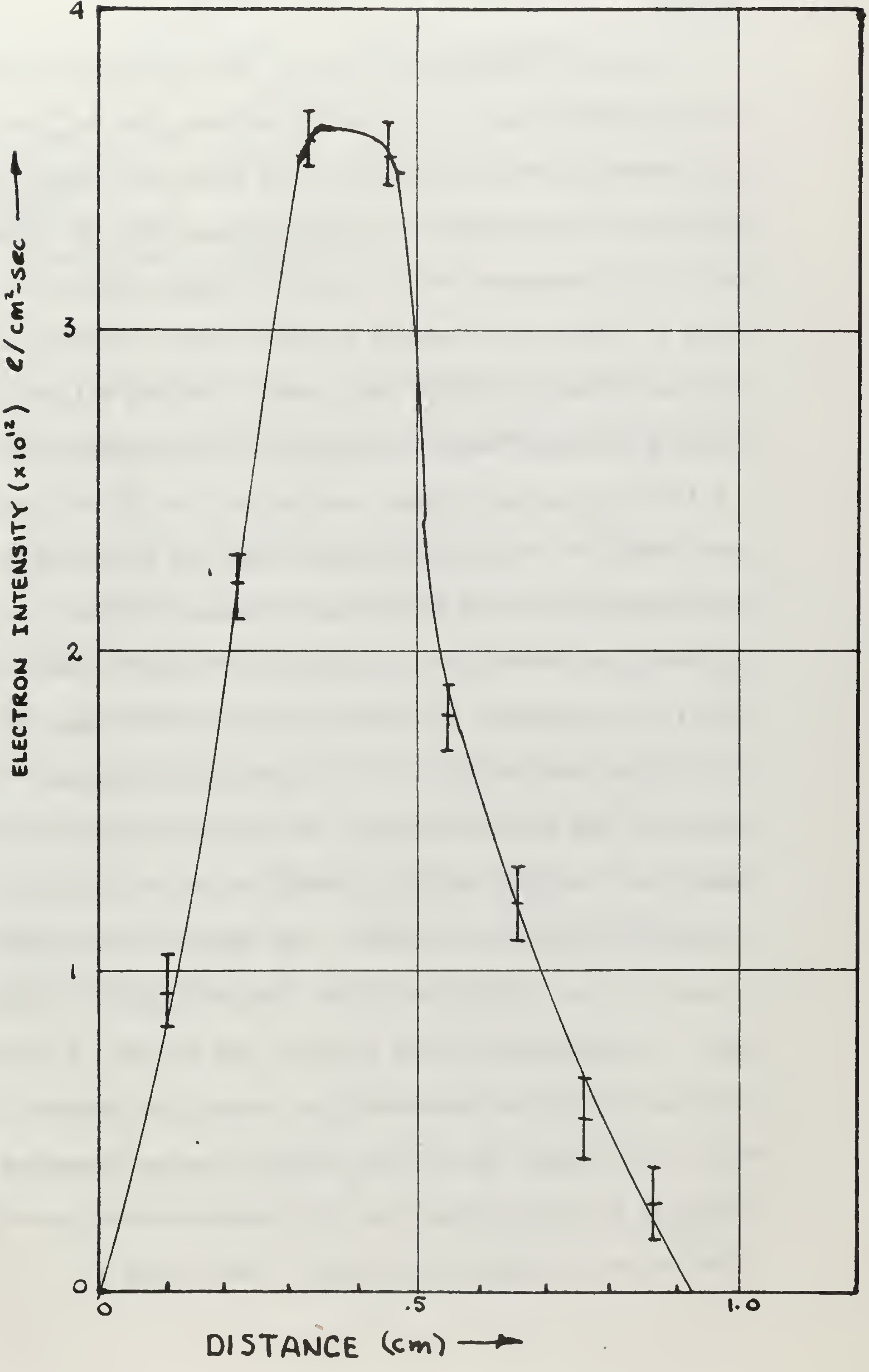

HORIZONTAL BEAM PROFILE – TEMPERATURE CORRECTED
ELECTRON INTENSITY (x10¹²) e/cm²-sec ⟶
4
3
2
1
0
0
0.5
0.75
1.0
1.45
distance (cm) ⟶

figure 5

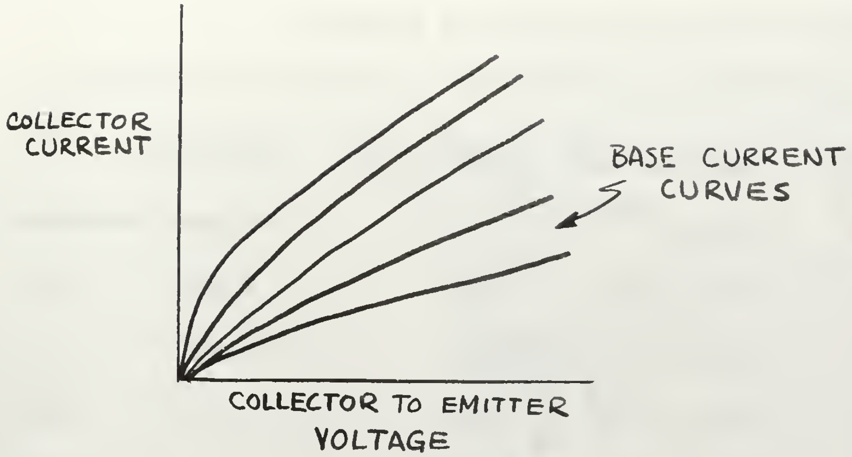
VERTICAL BEAM PROFILE - TEMPERATURE CORRECTED



about 5 x 10^{12} e/sec cm^2 which gives a dose rate of 10^5 rad/sec. Since the LINAC is pulsed and a pulse is 2 μsec long, the instantaneous dose rate is much higher, of the order of 10^9 rad/sec.

It was decided for the initial investigations to observe how the small signal a.c. forward current gain, h_{fe}, and the d.c. forward current gain, h_{FE}, were affected. Three types of transistors were exposed: 2N 3904 Silicon NPN, 2N 736 Silicon NPN, and 2N 535B Germanium PNP. There were not a sufficient number of types of transistors exposed to come to many specific conclusions, but the following effects were noted: The NPN Silicon transistors showed a definite loss of current gain for exposures in excess of 4 x 10^5 rads and for a dose received of 5 x 10^6 rad the gain was down about 40%. It was also noted that the devices did not recover during the observation time after exposure, in fact for most samples h_{FE} continued to decrease, although very slowly (down 2-3% in 50 hours). The behavior of these transistors for doses of less than 4 x 10^5 rads was very erratic, some showing increases, other decreases, and some unchanged. This behavior, based on the temperature response analysis, would at least in part be attributable to heating effects of the beam. The samples which showed increase in gain did not retain any of the increase after a 40 hour recovery time. A strange effect was noted in the 2N 736: a complete loss of all transistor-like characteristics during its exposure in the beam. While in the beam, the current response became dependent on the collector to base voltage, and the characteristics were those of a base current dependent resistor. (See Figure 6).

FIGURE 6



This behavior disappeared almost immediately upon removal from the beam and decayed back to the normal transistor response curves.

The Germanium PNP transistor appeared to be much more resistant to the above effects. While in the beam the gain characteristics increased in most cases, although the characteristics after the recovery period were down slightly, 10%. At this time, it is believed the increases noted were present due to a thermal response domination of the radiation effects. It seems apparent there were radiation effects because of the loss of gain observed after recovery, although they were much less marked than those noted in the silicon devices.

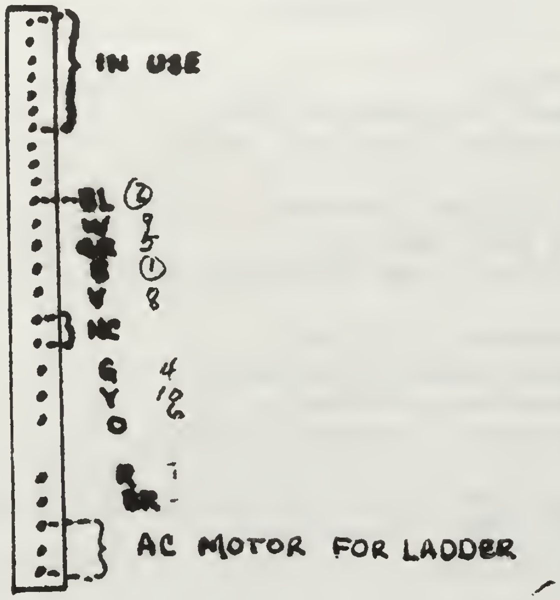
APPENDIX A

Physical Constants for Selected Materials

Material	Density	Specific Heat	Melting Pt.	Emissivity	
	gm/cm^2	erg/gm - ^{o}K	^{o}C	Polished	Oxidized
Al	2.7	1.04×10^7	660	0.08	0.1
Cu	8.9	4.19×10^6	1083	0.02	0.6
Fe	7.7	6.27×10^6	1535		0.74
Pb	10.6	1.55×10^5	327		0.63
Ni	8.6-8.9	5.31×10^6	1455	0.12	0.37
Pt	21.3	1.42×10^5	1773	0.05-0.09 (Temp. dependent)	
Ag	10.4	2.58×10^5	960	0.02-0.03	
Au	19.3	1.30×10^5	1062	0.02-0.03	

APPENDIX B

DOSIMETER TERMINAL BOARD WIRING ARRANGEMENT



COLOR CODE

B	Blue
BL	Black
BR	Brown
G	Green
GR	Gray
O	Orange
R	Red
V	Violet
W	White
Y	Yellow
NC	Not Connected

LHL	Left Hand Limit
RHL	Right Hand Limit
LL	Lower Limit
UL	Upper Limit

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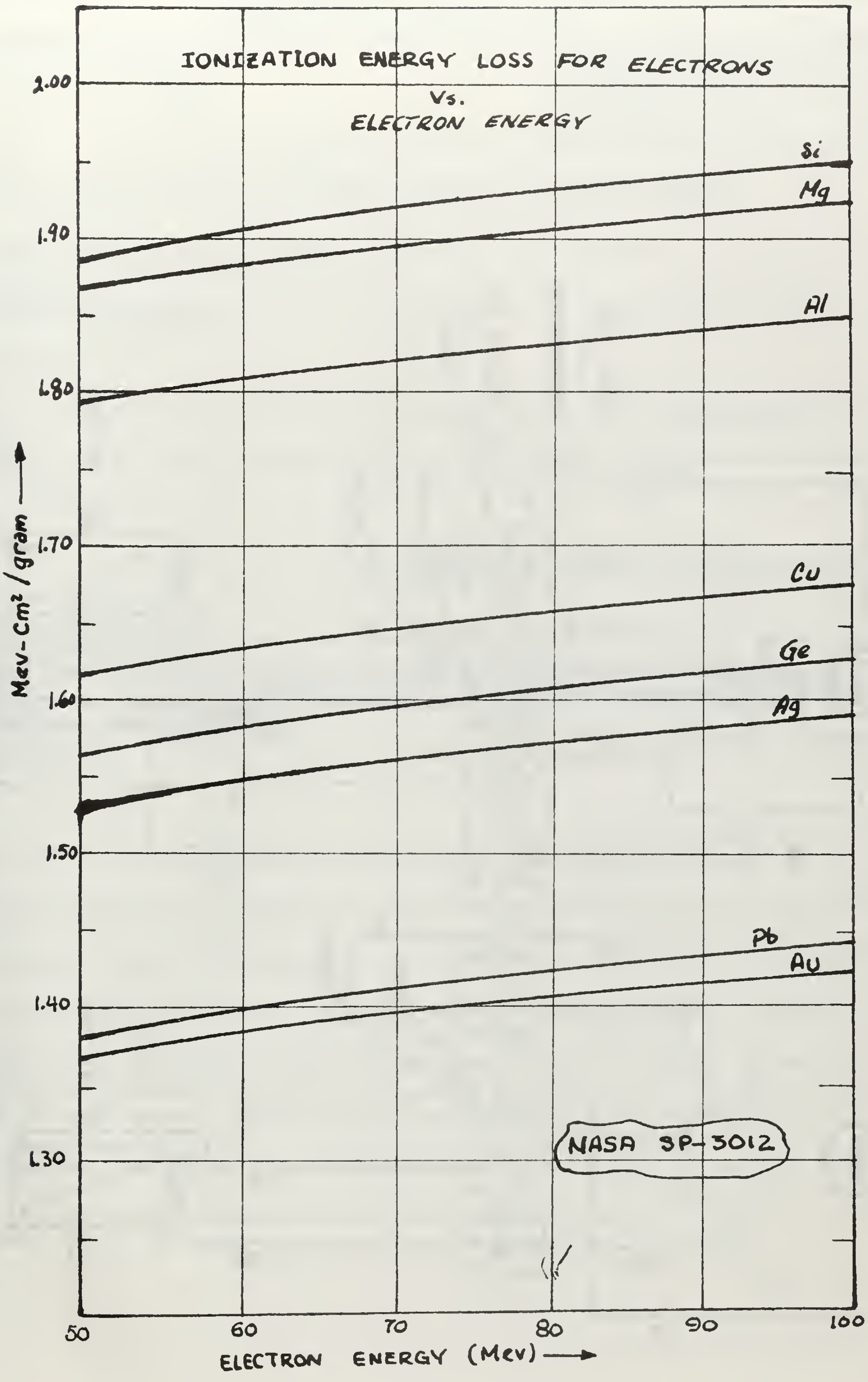
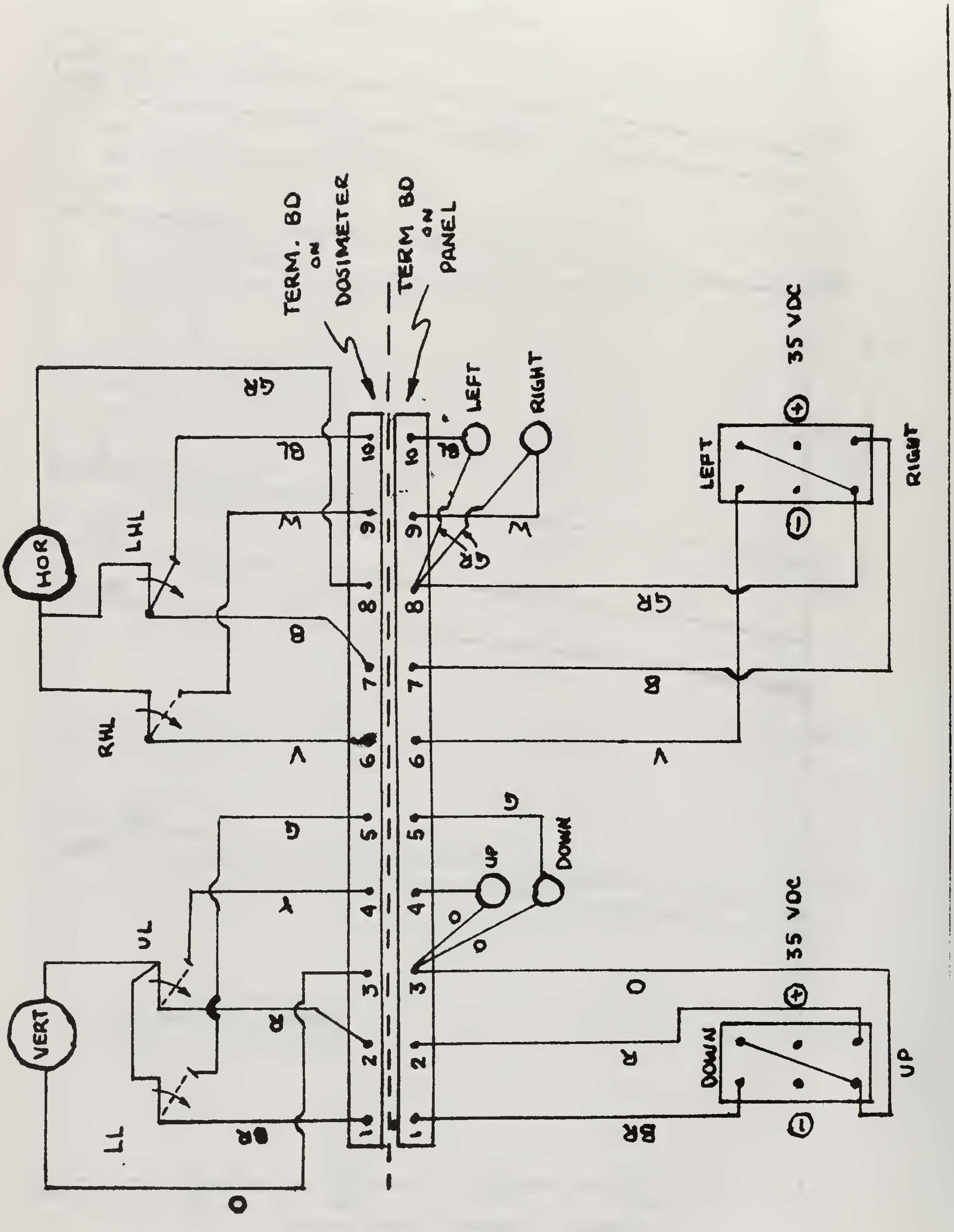
APPENDIX C


IONIZATION ENERGY LOSS FOR ELECTRONS
Vs.
ELECTRON ENERGY
Si
Mg
Al
Cu
Ge
Ag
Pb
Au
NASA SP-3012
2.00
1.90
1.80
1.70
1.60
1.50
1.40
1.30
Mev-Cm² /gram →
50
60
70
80
90
100
ELECTRON ENERGY (Mev) →


TERM. BD ON DOSIMETER
TERM BD ON PANEL
HOR
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13. ABSTRACT

The establishment of a program to study the effects of radiation on solid state electronic devices is discussed. The design and testing of experimental equipment used in connection with this project, and the techniques developed for the exposure of devices to the electron beam of the NPGS LINAC, form the main topics of this paper. Also included are the results of a beam profile analysis done using calorimetric techniques, and some results concerning the behavior of transistors exposed to the LINAC electron beam.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Solid State Radiation Damage Dosimetry By Calorimetry LINAC Intensity Profile Radiation Effects in Transistors						

[redacted]