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BIOLOGICAL AND CLINICAL DOSIMETRY

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I. SUMMARY

Investigations of the characteristics of neutron beams from the SKI cyclotron are being continued, and a tissue equivalent calorimeter to permit direct determination of absorbed dose from the neutron beams is under construction. Biological studies indicating a decrease in RBE with depth for neutrons from the $^9\text{Be}(^3\text{He},n)$ reaction have been correlated with measurements of the dose fraction as a function of LET.

The nanosecond integrator system described in our previous progress report (1) served as a prototype for the final system which is now essentially complete. It has been thoroughly tested and used to measure the output pulse produced by the beam current monitor (2). A Scintillation detector system has been constructed to measure the output of ultra-high intensity pulsed electron sources. A thin foil calorimeter has been constructed, and is being used to measure the dose delivered to a thin layer of material in fundamental units (rads).

The techniques for fabrication of germanium diodes were successfully established. A plane, cylindrical, germanium diode, lithium drifted 3mm deep, was selected for use in an orthogonal strip array. Resolution of ^{60}Co (1.17, 1.33 MeV) and ^{57}Co (122 KeV) gamma-rays was 3 KeV (FWHM) and 1.4 KeV (FWHM) respectively. A novel dual chamber vacuum cryostat was designed and constructed. This unit is needed to house and test a germanium diode matrix at cryogenic temperatures. An experimental system was designed and constructed for operating and evaluating germanium diode matrix arrays fabricated at the Institute.

II. NEUTRON DOSIMETRY AND ABSORBED DOSE MICROCALORIMETRY

During the current report period, our research on neutron dosimetry has been divided among three areas:

- 1) Continuing evaluation of small isochronous cyclotrons, represented by the unit at Sloan-Kettering, as sources of fast neutrons for radiobiological and clinical research.
- 2) Design and construction of a tissue equivalent absorbed dose microcalorimeter to serve as a primary standard for the calibration and study of the response of other dosimetry systems to neutron irradiation.
- 3) Undertaking dosimetric measurements and experimental design necessary to research on the biological response of mammalian cell cultures to fast neutrons.

A. Dosimetry of Fast Neutron Beams from a Small Cyclotron

In the first quarter of the current contract period, the preliminary data on dose rate, dose and flux distributions of neutron beams produced by a variety of reactions described in our previous report (1) were completed. These data have been presented in a paper (2), a reprint of which is appended to this report and therefore will be only briefly summarized here. These initial measurements were made, using target assemblies originally intended for isotope production and with a 50 cm SSD. In order to obtain data more suitable to an evaluation of the potential clinical application of small cyclotrons, additional measurements with improved targets and collimation are in progress.

Fig. I shows the central axis depth dose distributions for the helium-3 ion, proton, deuteron and alpha particle, on beryllium and proton and deuteron on heavy water reactions. These measurements were made in water at 100 cm SSD, using a tapered collimator designed to produce a 10 cm diameter field at the phantom surface. The collimator, 60 cm in length, was made of a polyethylene-lead, boron mixture.* The tissue equivalent ion chamber used and its calibration have been described in (1) and (2). For these measurements it was filled with tissue equivalent gas composed of 64.4% methane, 33.5% carbon dioxide and 3.1% nitrogen. The 50% depth doses lie between 7.5 cm and 10.5 cm. The unusually deep penetration of the ${}^9\text{Be}(\alpha, n){}^{12}\text{C}$ beam is perhaps due to the relatively large number of γ rays produced from the excited ${}^{12}\text{C}$ nucleus. The total tissue dose rates measured for these reactions are shown in Table I.

TABLE I
TISSUE DOSE RATE AT 0.5 gm/cm DEPTH
IN WATER PHANTOM 10 cm. DIAMETER
FIELD 100 cm SSD
TISSUE EQUIVALENT GAS FILLED TISSUE
EQUIVALENT ION CHAMBER

<u>Reaction</u>	<u>Rad/min/μampere</u>
${}^9\text{Be}({}^3\text{He}, n)$	0.058
${}^9\text{Be}(p, n)$	0.215
${}^9\text{Be}(d, n)$	0.184
${}^9\text{Be}(\alpha, n)$	0.034
${}^2\text{H}(p, np)$	0.158
${}^2\text{H}(d, n)$	0.058

*Obtained from Reactor Experiments, Inc., San Carlos, California

The target assemblies used for these measurements are described in the following section. While these data may be subject to influence by improvements in collimator design or the use of filtration as described by Greene and Thomas (3,4) or by better targets, it is evident that small cyclotrons are capable of producing beams with 50% depths and dose rates adequate for certain clinical investigations if target currents on the order of 100 microamperes are employed.

Our continuing work in this area is intended to evaluate further the neutron producing reactions which seem most suitable for potential clinical application, under conditions more closely approximating such application. The following problems are therefore being examined: optimization of target design, effect of collimator material design upon beam quality, LET distribution as a function of depth, and neutron spectral distribution measurement by proton recoil spectrometry.

1) Choice of Reactions and Target Design.

The production of neutron beams with the highest possible mean energy from a small cyclotron such as that at Sloan-Kettering Institute requires the use of high pressure gas targets to permit efficient use of either the $^3\text{H}(\text{d},\text{n})^4\text{He}$ or $^3\text{H}(\text{p},\text{n})^3\text{He}$ reactions (5). However, in view of the rather complex target technology involved, it was determined to restrict initial measurements to reactions with solid and liquid targets. Based on our initial experience reported in our previous progress report (1) and in (2), our attention has focused on the neutron beams produced by helium-3 ions, protons, deuterons, and alpha particles incident on beryllium and protons and

deuterons on heavy water.

Two Beryllium target assemblies were fabricated and are shown in Figs. II and III. The first accepts solid beryllium discs from 3-5 mm thick which are cooled by water flow surrounding the irradiated area and by an air flow on the distal side. In Fig II, the beryllium disc is removed to show the cooling channel. This target is capable of accepting full beam power, with production of the maximum neutron yield and is suitable for most experimental applications. The second target assembly, shown in Fig. III, is similar in appearance to the first but is intended for study of the effects of using targets with thickness less than the maximum range of bombarding particles on beam characteristics. Such studies using deuterons on beryllium have been reported by Goodman et al (6); however, no data on helium-3 ions, protons, or alpha particles have yet been published, and these developments and experiments were therefore necessary. The beryllium discs backed by a tantalum beam-stop are clamped against a water cooled aluminum plate. Measurements with this second assembly will be carried out when installation of the beam profile monitor on the cyclotron is complete. This is required to assure that the beam of charged particles is accurately focused on the small 2.5 cm diameter, target discs. In initial trials, the use of a double tantalum collimator to achieve this end was attempted, but since more than five times the current reaching the target disc was incident on the collimator, a large and variable component of low energy neutrons were generated which obscured the results. A schematic representation of the heavy water target is

shown in Fig IV. In this target, a flowing layer of heavy water 3 mm thick is irradiated by protons passing through a 0.025 mm Ta foil. The water layer is backed by 2 mm of aluminum. The heavy water flows from a reservoir equipped with a pressure gauge and catalyst chamber for recombination of the radiolytically released hydrogen and oxygen through a heat exchange or to a pump. The water leaving the pump passes through a flow meter to the target chamber and returns to the reservoir. The apparatus is designed to handle 100 microamps of 15 MeV protons with a 10°C increase in water temperature flowing through the target. In actual operation with lower beam currents, no detectable rise in water temperature was observed.

2) Collimator Material and Design

The collimator used in the current investigations is composed of a series of 10 cm x 10 cm x 5 cm polyethylene-lead-boron blocks with a 3° tapered hole machined in them which are inserted into an aperture in a solid 60 cm thick barrier of the same material. To investigate the influence of collimator material on penetration and other beam parameters, similar sets of blocks of steel, polyethylene and proprietary materials such as Chemtree 26 M are being prepared. These will be used either singly or in combination, and their effect on beam quality ascertained.

3) Neutron Spectra Distributions

Unfortunately, a relatively small volume of data is available on neutron spectra produced by thick targets since most neutron spectra measurements are made for the purpose of studying nuclear energy levels and not for dosimetric purposes. Spectral information is of considerable importance for dosimetry and biological research

and must therefore be obtained. In general, neutron spectra are measured either by foil activation or by one of a variety of other methods such as proton recoil spectroscopy. While for fission spectra whose nature is well known, foil activation may be readily employed to obtain the flux in given energy intervals; for other spectra the process of unfolding is difficult and often lacking in accuracy. An initial review of the problem indicated that the SPECTRA program developed at Sandia Laboratories (7) was probably the most applicable. However, investigation of the computational cost, since the use of an off premises computer was required, coupled with the large variety of foils which must be employed for optimum results, and the considerable amount of experimental time required for each spectra have made another approach preferable.

Parnell (8) has described a simple proton recoil spectrometer utilizing semiconductor detectors intended for the measurement of cyclotron neutron spectra. Fig. V shows the plan of this spectrometer and associated electronics. Neutrons from a collimated beam strike a thin polyethylene radiator. The recoil protons pass through a thin ($\approx 10\mu$) silicon detector which is operated in coincidence with a thick 2 mm silicon detector. The sum of the outputs is proportional to the total energy of the proton which is in turn proportional to the original neutron energy. The coincidence requirement permits excellent discrimination against background radiation and the location of the detectors off axis minimizes radiation damage effects. Since experience at the MRC cyclotron at Hammersmith has indicated that satisfactory spectra for neutron energies from 1 MeV up to the

maximum produced by a given reaction may be obtained in about two hours of measuring time, the suitability of such apparatus to our program is evident. The mechanical details of this system are currently being designed, and it is intended to commence fabrication when machine shop time becomes available.

B. Design and Construction of Tissue Equivalent Absorbed Dose Calorimeter

A major objective of our current research is to construct a tissue equivalent absorbed dose microcalorimeter. This will function as a primary standard for the evaluation of the response of various dosimetry systems to fast neutrons. Such a program would be analogous to our work with fast electrons and gamma rays as reported in various publications. The quasiadiabatic microcalorimeter is similar to those previously constructed at our laboratory (9,10,11,12). The device incorporating both active and passive thermal shields is constructed from Shonka A-150 tissue equivalent conducting plastic* and may be located at various depths in a tank of tissue equivalent liquid. This tank serves as a primary thermal shield and contains a temperature regulating circulator. A tissue equivalent plastic phantom, in which ion chambers or other dosimeters can be placed, can be substituted for the calorimeter.

Figs. VI and VII show two views of the structure of the calorimeter. Since the maximum dose rates routinely available from our cyclotron are from $1/4$ to $1/10$ those obtained from the betatron, a total of three buffer shields are placed between the thermal control

*Obtained from Dr. Francis Shonka, St. Procopius College, Lisle, Ill.

and adiabatic shields, in order to improve thermal isolation. The advantages of this approach have been described by Laughlin and Genna (13). Provision is also made for the measurement of the temperature of the adiabatic shield during calibration and irradiation.

An alternate set of elements to permit operation in the temperature loss compensated mode as described by Domen (14,15) has been designed. The various elements are supported by sharpened hollow nylon screws which fit into recesses as shown in the detailed drawing of Fig. VII. This permits good thermal insulation coupled with a stable mechanical structure which can be easily dismantled for repair. The relative dimensions of the cover plates and bodies of both adiabatic and control shields have been chosen to assure uniform rates of electrical heating. This more nearly simulates the effect of radiation heating during calibration and prevents thermal gradients in the control shield thereby improving its action.

The calorimeter wafer is 2 cm in diameter and 2 mm thick, corresponding to the collecting volume of the tissue equivalent ion chamber described in our previous report (1). The thickness of material from the front surface of the calorimeter to the center is 1.2 cm, which will place the minimum depth of measurement at approximately 1.5 cm. Fig VIII shows the calorimeter partially assembled.

One significant problem associated with calorimetric dose measurements in polymeric materials is the tendency to endothermic chemical reactions induced by the radiation. Fleming and Glass (16) have made a careful study of this effect in Shonka A-150 irradiated with protons. Since these represent the major source of energy

deposition for neutron irradiations, their values for endothermic losses will be assumed initially. Replication and expansion of these measurements using protons and other particles available from our cyclotron will be considered for latter stages of this project.

C. LET Measurements and Biological Dosimetry

1) LET Distributions

In order to further specify the nature of the radiation field and to study the physical phenomena underlying radiobiological experiments, a miniature Rossi type proportional counter* suitable for in-phantom measurements has been employed. The theory of these devices which permits determination of the distribution of dose as a function of LET has been discussed by Rossi (17), and many facets of its operation have been described by Lucas (18). This counter may be employed to obtain several types of information substantive to the understanding of the biological effect of a given radiation field.

(1) By multiplying by an appropriate constant the summation of the product of the number of events possessing a given LET times the given LET, the absorbed dose for a selected range of LETs may be obtained.

(2) By dividing the number of events per unit LET by the total number of events, the probability $P(Y)$ of an event occurring in a given LET interval is obtained

*Obtained from EG & G, Inc, Goleta, California

(3) Dividing the product of number of events of a given LET times the LET by the summation of these products yields the fractional dose distribution $D(Y)$ versus LET.

(4) Evaluation of the following equation (18) yields the distribution of dose with LET $D(L)$:

$$D(L) = \frac{6.32 \times 10^{-8} \cdot h^2 \left[Q(h) - Q(h + \Delta h) + \frac{Q(h + \Delta h) \Delta h}{h + \Delta h} \right] \frac{1}{\Delta h^2}}{1.89 \times 10^{-7} \left[c \sum h \cdot Q(h) \right]}$$

where: h is the channel number for the pulse height analyzer

c is the calibration factor in KeV/micron/channel

$Q(h)$ is the number of counts in the h th channel

$Q(h + \Delta h)$ is the number of counts in the $(h + \Delta h)$ th channel

Δh is the increment in channel numbers chosen for the analysis.

Satisfactory evaluation of $D(L)$ is extremely dependent upon the statistical smoothing of the raw data. A comparison of various techniques is currently in progress, since a polynomial least squares method initially used has not proven satisfactory. For this reason, the following discussion will be confined to the first three categories.

Considerable experimental difficulty was encountered due to gain shifts caused by radiation induced leakage effects in one of the counter's insulators which required replacement. Additional difficulty arose due to the presence of high amplitude noise pulses generated by the cyclotron magnet power supply which we have been unable to far to entirely eliminate. This latter

difficulty limited our measurements to the region above 2.8 KeV/micron. The elimination of this noise is the subject of continuing effort, since measurements by Lucas (19) have indicated that an appreciable fraction (although a biologically less important portion) of the total dose for fast neutrons lies in the region from 0.5 to 3.0 KeV/micron.

Figure IX shows the variation of $P(Y)$ with LET as measured for the various depths at which cell survival was determined. The following observations may be made based on these curves; the probability of an event occurring is less than 1% of its maximum value for LET greater than 60 KeV/micron and less than 0.1% of its maximum for LET greater than 80 KeV/micron. Figure X shows the dose fraction $D(Y)$ for a given LET as computed from the data represented in Figure IX.

2) Correlation with Biological Results

Doctors Djordjevic and Evans of this Institute have recently completed a lengthy series of experiments on the change of biological effectiveness with depth in a phantom of a neutron beam generated by the ${}^9\text{Be}({}^3\text{He},n)$ reaction. The results of these determinations for which dosimetric evaluation was provided have been reported (20) and will be published (21). It was found that a monotonic decrease occurred in the biological effectiveness of the neutron beam with depth. The RBE of this beam for the test system consisting of monolayers of HeLa cells referred to cobalt-60 rays, varies from 3.2 at 2.4 cm to 2.7 at 8.0 cm, to 2.2 at 16 cm.

In Figure IX, it may be noted that for equal probability, events occur at lower LET for the 8 cm and 16 cm depths than for the 2.4 cm depth in the region below 60 KeV/micron. The dose fraction $D(Y)$ for a given LET shows a similar displacement to lower LET with increasing depth. If one assumes that the RBE for the HeLa cells varies with LET in the same fashion as that reported by Barendsen et al (22), then the measured events above 60 KeV/micron contribute less than 12% of the biologically effective dose. Consequently, the apparent shift to lower LET with increasing depth can be expected to effect the biological effectiveness. While these observations tend to affirm qualitatively the trend observed in the biological data, stronger support for the results is obtained by comparing the change of dose in the LET range from 2.8 to 180 KeV/micron with the change in RBE as a function of depth. Table II shows the change in dose in this LET range with depth relative to 2.4 cm and the change in RBE for 37% survival.

TABLE II
VARIATION OF ABSORBED DOSE (2.8-180 KeV/MICRON
AND RBE WITH DEPTH

Depth	<u>Absorbed Dose Ratio</u>	<u>R.B.E. Ratio</u>
	2.8-180 KeV/micron	
2.4cm	1.0	1.0
8.0cm	0.9	0.85
16.0cm	0.75	0.70

Measurements of the gamma ray contamination of the neutron beam at the various depths indicate that its variation is not sufficiently large to account for the observed effect. It therefore seems probable that the change in biological effectiveness is due to a change in neutron spectra with depth. Further investigations are planned when the experimental difficulties described in the part (1) of this section are resolved.

Another aspect of the current biological research is to study the variation of OER with depth. To facilitate the comparison of biological results with dosimetric measurements, an irradiation jig was designed and constructed from tissue equivalent plastic. This jig is shown in Figure XI and permits the cells to be irradiated under conditions of controlled atmosphere and in such fashion as to permit direct utilization of dose measurements made with the tissue equivalent ion chamber described in our earlier report (1).

III. DOSIMETRY OF ULTRA-HIGH INTENSITY ELECTRON SOURCES

A. Introduction

The dosimetric studies at this laboratory in the high dose rate region include the development of beam monitoring methods, the determination of absorbed dose in very thin layers of tissue-equivalent and other materials, the characterization of electron beam parameters and the investigation of the dose rate response of various secondary dosimeters. Techniques have been developed which are suitable for a wide range of pulsed sources. This report will discuss developments relating to a pulsed electron generator which uses the field emission phenomenon. This electron generator produces singly occurring pulses of electrons whose average energy on emergence is about 530 KeV. The pulse duration is 3 nanoseconds as measured by the full width at half maximum. Beam current is of the order of 4000 amperes and doses of up to a megarad per pulse can be delivered, yielding a dose rate in excess of 10^{14} rads/sec.

Current radiobiological experiments involve measurements of the radiation response of thin layers of bacterial cells and mammalian cells exposed to single and double pulses of electrons. Therefore, the determination of the absorbed dose in a thin layer of material is of great interest. It is also of considerable importance to determine the depth-dose distribution of the pulsed electron beam. This measurement can be performed by using thin detectors such as thermoluminescent dosimeter discs, thin scintillating materials, or a thin foil calorimeter.

Thin thermoluminescent dosimeters provide a means whereby the dose delivered to a thin layer of material can be directly determined. However, this method of measurement has inherent difficulties related to accuracy, precision and convenience. Two methods of determining the dose delivered to a thin layer of material will be discussed along with their application to the radiobiological experiments. These two methods employ a scintillation detector and a thin foil calorimeter.

One problem related to the use of the electron generator is the r.m.s. variation of $\pm 4.5\%$ which is observed when a series of pulses are measured with either a Faraday cup or an intensity calorimeter. It follows that pulse to pulse variations of $\pm 10\%$ or greater are possible. In view of the relatively low energy of the electrons (530 KeV), it is desirable to have a monitor which will not intercept the beam. A nanosecond pulsed beam current monitor, developed in this laboratory, was described in our last year's progress report (23). A paper describing this work is in press (24). This monitor utilizes a pick-up loop operating as a current transformer, and, since it is non-intercepting, it can be used without disturbing the measurement taken with either the Faraday cup or calorimeter. A dual version of this system, has been finalized and part of the system, the nanosecond pulse integrator, has been applied to measure the area under a scintillation pulse.

B. Dual Channel Nanosecond Pulse Integrator System

The electronic pulse monitoring scheme described in our previous progress report (23) served as a prototype for the final system which is now essentially complete. The initial application

of the electronic integration system was to measure the area under the pulse produced by the beam current pick-up loop operated as a current transformer. The area under the pulse was then compared to the output of the Faraday cup and the intensity calorimeter to establish the validity of the pick-up loop as a beam monitor.

Figure XII shows the integrator electronics package. Each module contains a nanosecond pulse integrator and a peak detector circuit. These units are capable of measuring the area under a nanosecond pulse, and storing a voltage proportional to this measurement which is displayed digitally on the front panel. The entire system has its own a.c. power supply driven by a storage battery operated inverter. This allows the input to the integrator to have a floating ground eliminating transients.

The following section will show how this same system can be used to measure accurately the output pulse produced by a scintillation detector. Since the system has two channels, it is therefore possible to use one channel to measure the output of the beam current pick-up loop while the other channel measures the output of a scintillation detector. In this way, it is possible to measure simultaneously the output of one of the pulsed electron generators with a scintillation detector and monitor this same output.

C. Scintillation Detector

Plastic scintillating materials can be used as a secondary method of measuring partially or totally absorbed radiation energy. The advantages of this approach, when used in conjunction with a calorimeter which yields a measure of absorbed energy in fundamental units, will now be described. The scintillation detector can:

- (1) Cover a large dose range
- (2) yield a direct readout with suitable electronics
- (3) follow fast pulses
- (4) be variable in thickness from 0.125 to 0.0005 inches
- (5) provide enough sensitivity to measure doses below 100 rads which are needed in some experiments such as in mammalian cell irradiations. Such small levels are not conveniently measured with either a Faraday cup or a totally absorbing calorimeter.

The type of measurements that can be performed with thin plastic scintillators are: (1) the measurement of absorbed dose in a thin layer (2) depth dose curves (3) integral depth dose curves with an infinitely thick detector behind the absorber (4) low dose measurements at large distances from the pulsed electron source.

A high speed scintillation detection system is being constructed which employs "Pilot-B", a commercially available high speed plastic scintillator. Its fluorescence spectrum peaks in the visible blue (400 nm.) and its pulse response decay time is about 2 ns. Preliminary indications are that its region of linear response will likely not be exceeded by the maximum dose rate provided by the pulsed electron generators.

The detection device is an ITT model FW-114 high current bi-planar phototube. This tube is operated at a potential of -2.1 KV, at which its rise time is less than 0.5 ns. The spectral response of the phototube is S-4, such that the 3-db down points on the sensitivity curve range from about 310 nm to 550 nm. Thus, the sensitivity of the tube matches the fluorescence spectrum of the scintillator fairly well.

Figure XIII shows a diagram of the experimental set up for the scintillation detector. The Pilot-B scintillator is cut into a disc shape and mounted in a holder which will be the standard geometry for dosimetry using this system. This holder allows a detector to be maintained in a cylindrical geometry at a constant position relative to the beam or the experiment. It also allows the beam to be completely contained, and, after striking the detector, all electrons have a good return path to ground which helps to reduce electronic noise. The holder is so designed to permit convenient changing of scintillator discs. It also provides a means for inserting build-up material of known stopping power before and/or after the scintillator, a necessary arrangement for various types of depth dose measurements. Since the light output from the Pilot-B is quite large, it is necessary to attenuate this light by using neutral density filters. Such filters have been purchased with an optical transmission that is essentially flat in the region of emission from the Pilot-B. When thin sheets of this scintillator are used to determine locally

absorbed dose, there is a provision for mounting a transparent absorber which will prevent the electron beam from hitting the phototube but will allow the passage of light.

It has been found (24) that pulsed electron beams incident on solid dielectrics such as the Pilot-B scintillator can result in beam perturbation due to surface charge build-up. Therefore, a disc of aluminum foil which is thin enough to allow the passage of the beam (0.0007") has been placed in contact with the scintillator and the holder so that the front surface is grounded. This foil is shown in Figure XIV where it appears at the lower right. Immediately behind it is a disc of Pilot-B which is 1/8" thick.

The light output of the scintillator causes current to flow in the phototube for the duration of the light pulse. This signal is a.c. coupled through a capacitor which serves to block the 2100 volts d.c. produced by the power supply. The recording of the area under this pulse is achieved through the use of the nanosecond pulse integrator. In this case, the signal passes through a 1:1 pulse transformer which inverts the positive pulse and produces a negative-going signal which can be handled by the integrator.

Using a 1/8" thick disc of Pilot-B scintillator and appropriate attenuators, several readings were taken at four distances from the electron generator tube using the aluminum vacuum columns. A Faraday cup which is housed in an identical

aluminum holder such that the entrance aperture is at the same position as the scintillator front face was used to take readings at the same distances. The result of this experiment is shown in Figure XV. This graph shows that the scintillation detector and the Faraday cup (Figure XVI) have essentially the same dependence of measured output versus distance from the electron source. Further experiments are underway to verify these preliminary findings and establish a basis for the use of this scintillation detector as a secondary means of determining the dose delivered to a thin layer of material.

D. Thin Foil Calorimetry

Calorimetric methods can be used to measure the absorbed dose due to absorption of high intensity pulsed radiation incident on a material. They provide a direct measurement of absorbed dose in terms of fundamental units since essentially all the energy dissipated in an absorber appears as heat. A measurement of the temperature rise, using a thermocouple provides a means of computing the absorbed dose in ergs/cm^2 . If the absorber is made sufficiently thin, then the absorbed dose delivered to a layer which is comparable in thickness to the biological samples used in this laboratory can be computed. The following calculation of temperature rise will be used to illustrate how a thin foil of titanium can be used in a calorimeter for the dose range generated by the pulsed electron sources:

Collision stopping power for 500 KeV electrons = $1.455 \text{ MeV cm}^2/\text{gm}$
Density of titanium = 4.5 gm/cm^3 ; thickness = 0.00508 cm

Energy loss per electron = 0.0333 MeV

Number of electrons at 2" from source = 5×10^{12}

Total energy loss = $(3.33 \times 10^4 \frac{\text{eV}}{\text{electron}}) 5 \times 10^{12} = 1.67 \times 10^{17} \text{ eV}$

Converting ergs by $1.602 \times 10^{-12} \text{ ergs/eV}$ gives $2.67 \times 10^5 \text{ ergs}$;

$1 \text{ cal} = 4.185 \times 10^7 \text{ ergs}$. For this case, the quality of heat

$$H = .612 \times 10^{-2} \text{ cal}$$

$$S = \text{specific heat} = \frac{H}{m \Delta t} = .112 \text{ cal/gm}^\circ\text{C}. \text{ Therefore, } \Delta t = 0.935^\circ\text{C}$$

This temperature rise is measurable with an iron-constantan thermocouple which has a relatively high thermoelectric voltage of 52.7 microvolts per degree centigrade. The use of high gain amplifier makes it possible to measure temperatures on the order of 0.01°C . On the basis of the measured variation of intensity with distance for the pulsed electron generators, it should be possible to utilize the thin foil calorimeter down to doses of a few kilorads. At this point, it is proposed that the scintillation detector which has been calibrated with the calorimeter be used to determine absorbed doses down to less than 100 rads. Since these two devices have exactly the same geometry, such an extension of the useful range of the two systems, when combined by calibrating one in terms of the other, should be possible. In this way, one can obtain direct measurements of the absorbed dose in a thin layer of material over a wide range of dose.

Figure XVII shows a photograph of the calorimeter. A block diagram of the experimental set-up is shown in Figure XVIII. The aluminum holder assembly is essentially identical to those used for the scintillation detector and the Faraday cup. It places the calorimeter disc at the same position as the Pilot-B scintillator, the Faraday cup aperture, or the position at which biological samples would be placed. The beam current pick-up loop has now been placed at the base of the sample holder so that it can serve as a monitor of the changes in electron output very near the irradiation position. When very short columns are used, it is possible for the calorimeter to be influenced by radiant heating from the window of the field emission tube. To prevent this effect, a disc of 0.0007" aluminum is placed before the calorimeter disc.

The material used for the calorimeter disc is 0.002" titanium to which a micro-miniature iron-constantan thermocouple is attached by thermally conductive silver epoxy. Prevention of charge build-up on the disc or thermocouple was achieved through the use of a fine grounding wire which was affixed between the thermocouple sheath and the casing. The design of this thermocouple is such that although intimate thermal contact is established with the titanium disc, the junction is electrically insulated by a thin jacket of ceramic material. Radial support of the thermocouple and attached disc is accomplished by a styrofoam ring and a small piece of plastic tubing acting as a standoff. This makes for a long path of thermal conduction which tends to minimize

conductive losses of heat.

The thermocouple is connected to an electronic reference junction which allows readings to be made with respect to 0°C . The thermoelectric voltage produced is then measured with a Kiethley model 150 micro-voltmeter whose output drives a recorder which is placed in the control room. The recorder trace shows a fast rise to a rounded peak followed by an exponential decay as the disc cools. To find the peak temperature rise at $t=0$, it is necessary to extrapolate the cooling curve. For our initial experiments, this was done graphically. When more data is taken, it should be possible to analyze these cooling curves and establish a relationship between the observed peak height and the extrapolated height at $t=0$. This will allow the peak height to be measured electrically with the peak detecting circuit (23) described in our previous progress report. In this way, a direct read-out of thermoelectric voltage can be displayed on a panel meter. This voltage can then be used to compute the absorbed dose in rads.

Preliminary experiments have been performed and the results are shown in Figure XIX. This graph shows a comparison of the distance function for the thin foil calorimeter and a thin scintillator. These experiments indicate a slope which differs from the data taken with a Faraday cup or the thick scintillation detector, which appears in Figure XV. Although this data is preliminary, it bears further investigation, since such differences

between thin and thick absorbers may be due to anomalies in the character of the electron beam. Further experiments are presently being conducted to verify this effect and to help explain its cause.

IV. SOLID STATE DETECTOR PROGRAM

A. Semiconductor Gamma Camera

During the period covered by this report, experimental efforts at Sloan-Kettering Institute have continued towards the application of germanium lithium drifted diodes to two dimensional arrays for in vivo radioisotope imaging. The ultimate goal of this work is the construction of a prototype semiconductor gamma camera with spatial resolution of within (3×3) mm.

The matrix configuration upon which the experimental program for germanium is based is one which was developed successfully on a single substrate in a silicon diode and from which resolution of within (3×3) mm was obtained for a 2 mm beam of P 32 beta particles. This work was reported previously (25,26). The orthogonal strip matrix configuration is shown in Figure XX for convenience of reference.

1. Germanium Diode Fabrication Procedures

The fabrication procedures and electronics employed at the Sloan-Kettering Institute for lithium drifting germanium are modeled after those employed at Brookhaven National Laboratories and were provided by the instrumentation group (28). The electronics of the drift assembly were discussed in a previous report (1). Germanium from only two germanium ingots* has been used to date. Additional material will be included in future work. Material from three new ingots has been obtained recently. Four different wafers of germanium were processed during this period. Repetition

*Hoboken, NPC Metals and Chem. Co., Los Angeles, California

of the fabrication procedures was sometimes warranted for an individual wafer, for example, in rediffusion of the lithium n region.

It is necessary that the thickness of the lithium n region be sufficiently controlled from diode to diode to avoid significant differences in gamma-ray attenuation in the dead layers among diodes of an array. This is most readily accomplished by performing the lithium diffusion in vacuum. Although facilities for vacuum diffusion are being constructed at this Institute, all lithium diffusions to date have been performed of necessity in a quartz tube furnace in a pure argon atmosphere. For the initial germanium diffusion, an estimate was made of the depth of the lithium diffusion during warm-up of a large piece of germanium in the tube furnace. Allowance was made for a substantial warm-up period to minimize thermal shock. The temperature rise of the tube furnace was measured and curve fitted for a number of different sized wafer loads. Typical plots are shown in Figure XXI.

Heating curves for all wafer sizes were found to be satisfactorily represented by an exponential relation between time and temperature, the temperature being measured by a digital platinum resistance thermometer. Two constants in the expression on the graph distinguish different wafers. Warm-up time of twenty to twenty-five minutes is usual.

These empirical functions were used in conjunction with the appropriate error function solution of the diffusion equation to determine the total lithium diffusion that occurs in the wafer during the warm-up to final temperature in this particular tube furnace. The details of the calculation are readily drawn from

the fact that when the diffusion coefficient of lithium in germanium is time dependent (as in the case during warm-up in the tube furnace), the complementary error function solution instead of

$$K = \operatorname{erfc} \left(\frac{x_j}{(Dt_0)^{1/2}} \right)$$

becomes

$$K = \operatorname{erfc} \left(\frac{x_j}{\left(\int_0^{t_0} D(t) dt \right)^{1/2}} \right)$$

where K is a constant for a particular resistivity material, x_j is the junction depth, t_0 the total diffusion time, and D the diffusion coefficient.

Calculated results for the largest wafer used are shown in Figure XXII for resistivity of around 17 ohm-cm. The required integrals were readily obtained via an available program of the International Telephone and Telegraph R.T.S. Fortunately, the calculated values for the set-up used here are optimistic due to a temperature gradient from the thermometer (below the wafer) to the wafer. Actual measured junction penetration due to warm-up was found to be less than .3 mm for the largest wafer tested (44 mm diameter by 1 cm thickness.) Since most wafers used in the future will be around this size, significant differences between n layer thicknesses are not expected to be a serious problem during further use of the tube furnace. Diffusion depths of .6 mm were used for the diodes discussed below.

Diodes produced are ultimately intended for use in a two dimensional orthogonal strip array. Although lithium drifted as circular

wafers, it is necessary that each eventually be cut into a square before it can be used as a unit in such an array. For this purpose, it is desirable that the wafer's starting dimensions be precisely adjusted for flatness, parallelism of the plane faces, squareness of the periphery with respect to the faces, and thickness. It was found that all of these requirements can be conveniently met by using a lathe and a lapping jig constructed for the purpose. Accurate adjustment of wafer thickness as well as face parallelism can be achieved using conventional glass plate lapping with alumina and the jig shown in Figure XXIII. Using quartz type sticky wax^{*}, the wafer is mounted on the face of a sliding brass piston whose axis is accurately parallel to an aluminum housing whose lower edge is square with its own axis. This edge provides reference to the lapping plate surface. Rotation of the aluminum housing during lapping adequately distributes wear of the reference edge. Using this jig, parallelism of wafer faces of well within 0.0005" is easily achieved. Squareness of circular wafer periphery with respect to the faces allows square diodes to be cut accurately and rapidly from circular units. Wafer edge lapping to true roundness and squareness with its faces were found to be most reliably achieved using a lathe and #150 grit alumina. The flattened and face paralleled wafer is clamped between the machined surface of two rods, one in the lathe chuck, the other in a "live" center. Two layers of filter paper are used as a cushion. A teflon tool bit was cut to press the alumina slurry against the wafer. The use of #150 grit alumina produces radial lapping rates of around .001"/minute. A smooth

^{*}Tizon Corporation, New Jersey

surface results if the slurry is not too dry. The lapping rate falls off sharply with finer grades of alumina.

2. Germanium Diode Characteristics

Of the three wafers drifted from ingot 97B09, only two yielded functioning diodes. Of these two, the earlier one degenerated beyond use after the lithium drift depth exceeded 3 mm. In all three units, copper staining revealed non-uniform lithium drift depth (around 10% maximum) although the units drifted relatively fast - 3 mm in less than two days.

a. Diode Ge 51B. Originally, it was hoped that the germanium from the larger diameter (44 mm) ingot, Ge 51B, would yield an acceptable diode which might then be formed into an orthogonal strip matrix. However, weeks of repeated processing and testing of this wafer before and after lithium drift including progressive lapping of edge material between tests proved futile. Reverse leakage current at cryogenic temperatures remained unacceptably high - tens of nanoamps at a few hundred volts. Ultimately, it was concluded that the quality of this germanium slice was inferior and that no acceptable diode could be obtained from it for this purpose. Therefore, this piece was laid aside and work started on the material from the other ingot. The procedures employed in the handling of Ge 51B were essentially the same as will be described below in connection with the other germanium ingot.

The ingot from which the rest of our germanium was sliced was thirty-five millimeters in diameter. Over three centimeters were

purchased instead of the usual one centimeter, on the basis of favorable information provided by the vendor over and above his usual test information.

b. Diode 97B09-1. Spectral measurements of several isotopes were made with this diode after a drift of 1.5 mm. Representative data are shown in Figure XXIV. Although only a 512 channel multi-channel analyzer was available, a back bias amplifier was used to spread the peaks. Resolution of better than 3 KeV full width at half maximum was obtained for Co 60 (1.17, 1.33 MeV).

After further lithium drifting (beyond 3 mm), this diode's reverse leakage current at liquid nitrogen temperature rose to around one microamp at less than 500 volts bias. Further efforts at restoration were unsuccessful.

c. Diode 97B09-2. This unit was drifted to a depth of slightly over 3 mm. Copper staining of the edges before and after cutting it into a square indicated a lithium drift depth variation of around 10% (3.1 - 3.4 mm). Although, as a result, a comparable variation in diode sensitivity can be expected for Co 57 (85% 122 KeV), it was still thought worthwhile to try to convert this surviving unit into an orthogonal strip matrix. This will eventually serve a double purpose. It will uncover latent problems, if any, in the procedures used for matrix formation and will provide a necessary check on the diagnostic value of a 1 mm diameter gamma ray beam of Co 57 in evaluating the diode and matrix structure.

The circular wafer's diameter after lithium drifting was 1.3095 $\pm$.005". The thickness was one centimeter. From this, a square of

.895 inches was eventually cut after the completion of response measurements.

(1) Electrical Properties. Extensive spectral measurements were made with the diode to characterize its response for comparison during the different stages of matrix fabrication. Curves of leakage current versus reverse bias were also recorded. No infra red shield was used over the diode in the cryostat during any of the measurements discussed below. Although this contributes to the reverse leakage current, this step was necessary to allow required access to the diode surface during some of the later measurements.

Figure XXV is a plot of reverse leakage current versus bias for both circular and square shapes. The departure from flatness in the I-V characteristic after the diode was cut square was compensated for by a higher breakdown voltage.

(2) Spectral measurements. Spectral measurements were made of Co 60 (1.172, 1.333) MeV, Co 57 (85% 122 KeV) and Am 241 (59.5 KeV) for a range of bias voltage and pulse shaping time constants. All measurements were made with a room temperature field effect transistor in the preamplifier.

A 1408 C preamplifier, 1417 main amplifier by Carberra and a 408 biased amplifier and 411 pulse stretcher by Ortec were used for all measurements. A 512 channel Northern Scientific multichannel analyzer was used throughout.

Typical data for resolution and pulse height linearity of the square diode at 800 volts bias are shown in Figures XXVI and XXVII

for energy levels in the vicinity of 100 KeV and 1 MeV. Identical measurements made while the diode was circular yielded similar data. Major interest for this work lies around the lower energy range due to the clinical importance of Tc 99m (140 KeV). These plots were obtained from computer readout of punched paper tape generated by the multichannel analyzer. The resolution of around 3 KeV for Co 60 and 1.5 KeV for Co 57, although not up to the highest spectrometric standards, should be more than adequate for the construction of a germanium orthogonal strip matrix. The low energy side skewing of the lower energy peaks is partly due to scattering in the material between the radiation source and the diode's collecting region.

The effects of different bias voltages on charge collection in the diode were measured. For both Co 60 and Co 57, a significant increase in skewing of the peaks on the low energy side and some loss of pulse height occurs at around 300 volts. The effect of a change in pulse shaping to bipolar and shorter time constants was also measured. This was done in anticipation of a need to operate a matrix at around 0.5 microseconds to assure an adequate count rate capacity. In Figure XXVII, it can be seen that the resolution at 800 volts bias using 0.5 nanoseconds bipolar pulse shaping deteriorates to around 3.5 KeV at Co 57 energies. This is still thought to provide adequate diode resolution for formation into a matrix since it is expected that the resolution associated with the individual strips of the matrix will be better than that obtained for the whole diode.

3. Dual Chamber Cryostat

The vacuum cryostats used at the Sloan-Kettering Institute for germanium diodes of conventional planar geometry are fashioned after the one designed by Chasman (27) of Brookhaven National Laboratories. Fabrication drawings were kindly provided for units used here by the instrumentation group of Brookhaven (28).

These cryostats consist of a diode chamber containing a brass plate against which the diode is clamped. The brass plate is connected to a cylindrical copper cold finger, part of which extends into the evacuated diode chamber while the other end, outside of the chamber, is submerged in liquid nitrogen. An absorption agent such as charcoal is contained in the lower region of the diode chamber by a thin stainless steel sheath which surrounds that part of the cold finger's length which extends into the evacuated region. Activation of the absorption agent after placing a germanium diode in the cryostat calls for applying heat to the absorption agent from outside the cryostat through the stainless steel wall. Usually, a hot air gun or propane torch is used. When this process has been completed properly, the cryostat vacuum will be maintained for long periods (months) as long as the absorption agent is held at cryogenic temperatures.

In considering this cryostat design for use with a germanium diode orthogonal strip array, a serious disadvantage became apparent. This is that during "outgassing," the absorption agent is in the same chamber with the diode. Diode contamination is apparently no problem where the charcoal, after bake-out, can be stored in sealed glass ampules until just prior to loading it in the cryostat with the

insertion of a diode. For the orthogonal strip geometry, however, with its large surface area and possibly delicate surface properties, this seemed a risk worth avoiding if practical - all the more so since repeated opening of the cryostat holding the matrix was foreseen. The requirement of outgassing the absorption agent each time the cryostat is opened to air was another undesirable feature from this latter point of view. It therefore seemed reasonable to try to find a construction which allowed isolation of the absorption agent (charcoal) from the diode chamber.

Of a number of possible designs, the one that appeared to be the most promising involved the construction of a cryostat with two concentric chambers. In this unit, the charcoal is contained in a permanently sealed outer annular chamber surrounding the cold finger and communicates with the diode chamber through an external, high vacuum valve * and a short segment of 1/4 inch copper tubing. Another valve connects the charcoal chamber directly to a vacuum pump when needed, also through 1/4 inch tubing. A third valve is analogous to the single one usually found in the conventional cryostat in the wall of the diode chamber to evacuate the entire cryostat. A schematic of the dual chamber cryostat is shown in Figure XXIX.

A prototype unit was built and tested at SKI. All joints were argon arc welded. Helium leak tests were made on the cryostat during successive stages of construction through the use of aluminum O-ring flanges made for this purpose.

*Hoke, Inc., New Jersey

Ion gauge pressure measurements were made to compare the terminal pressure reached under charcoal pumping in the conventional cryostat to that of the dual chamber unit. A loss of pumping speed is to be expected as a result of the impedance of the interconnect valve and tubing in the latter unit. Despite this, the pressure readings in the two cryostats were within a factor of around two, the dual chamber unit reading around 0.9×10^{-4} Torr. Where needed, this could be improved by using 3/8 inch tubing and a wide bore valve in the interconnect circuit. As it is, the vacuum quality is certainly suitable for the intended application.

Liquid nitrogen consumption was measured to be one liter per day for the unloaded cryostat (no diode).

In summary, the main advantages of this type of cryostat include a number of features. First is a permanent charcoal charge isolated from the diode chamber which can be outgassed without the need of exposing the matrix (or diode) to the outgassing products. The diode chamber may be opened repeatedly to air and pumped down again with the interconnect valve closed without depleting the charcoal's pumping capacity each time. Where needed, this cryostat can be transported separately with an activated charcoal charge, or can be fabricated and stored in this condition for long periods while awaiting use. With the interconnect valve closed, outgassing of the charcoal can be accomplished using the usual procedures with a diode in the chamber. This need might arise as a result of a leak into the diode chamber while the interconnect valve is open, or after long use of the charcoal charge warrants that it be outgassed without removal

of the diode. The diode may be maintained at cryogenic temperatures during this operation by keeping the cold finger immersed in liquid nitrogen. Beyond serving the purpose for which it was designed, it is expected that this cryostat will be also found generally useful in connection with conventional diode structures.

4. Experimental Apparatus for Testing a Germanium Matrix in Vacuum

The operation and testing of a germanium orthogonal strip matrix in a vacuum cryostat presents special access problems. Reliable, noise free contacts must be made to each row and column of the array. Electrical lead wires must be brought out of the cryostat to the electronics monitoring the signals from the matrix. The evaluation of a single matrix block requires a means of measuring the response over different parts of the matrix surface. Moreover, it is desirable to be able to obtain the data for each cell (detection region) of the matrix. This requires a narrow beam probe whose position over the array can be located to the required precision.

The apparatus for meeting these requirements has been constructed. A photograph of part of the set-up is shown in Figure XXX. A 2" diameter by .110" thick platform was constructed to support the matrix on the cold finger in the cryostat. Because of the required electrical isolation of the matrix electrode strips, an electrical conductor cannot be used beneath the matrix. However, it is also necessary that enough thermal conductivity exist in the material beneath the matrix that it will be maintained at cryogenic temperature.

Hard anodized aluminum appears to be suited to the purpose. The contact platform was machined of pure (1100) aluminum and then hard anodized*. Although the anodized layer is less than .003 inches, after the disc was anodized, the electrical resistance along the surface and through the anodized layer was measured to be in excess of 100 meg-ohms, at cryogenic temperatures and below 20 volts. No measurements were made at higher voltages. This was unnecessary since the contact platform will be on the low voltage side of the diode. A slot was machined into the aluminum disc before it was anodized. Into this slot was fitted a teflon bar containing ten spring electrode strip contacts whose position is controlled from below by attached stainless steel 2-56 screws threaded into the teflon. The teflon bar can be seen in the black anodized disc in the figure.

Another type of disc was necessary for the upper contacts. It consists of a transparent disc of lucite 1 cm thick and 2 inches in diameter. A similar row of contact springs was fitted into it. On the face of this disc was scribed a checkerboard pattern, each square of which is as large as the cell size chosen for the first orthogonal strip matrix - 2.8 mm. Straight bore holes were drilled into each square of the checkerboard pattern to within .5 mm of the opposite face of the disc. Guide pins in the anodized platform beneath the matrix have been used to reference the upper lucite contact disc to the platform. Alignment marks on the anodized platform allow the matrix to be oriented with respect to upper and lower contacts.

*Service Hard Chromium Corporation, New Jersey

When aligned properly, each matrix cell will be beneath a hole drilled in the checkerboard pattern. The diameter of these holes accommodates the tip of a Co 57 source holder constructed in a probe. This assembly can also be seen in the same figure without the aluminum vacuum chamber which houses it. The lucite disc can be seen with the tip of the Co 57 source holder occupying one of its matrix cell-locating holes. The feed-through assembly and lucite cover holding it are also shown in operating position.

Using Mallory metal (90% tungsten) for the holder shown in the previous figure, a collimated Co 57 source with a 1 mm diameter beam was constructed to probe the surface of germanium diode matrices. Spectral measurements of the source indicate relatively little low energy contamination of the emerging beam (see Figure XXXI). The schematic of the source holder is shown in Figure XXXII.

Formation and testing of the germanium diode described above (97B09-2 sq.) into an orthogonal strip matrix is imminent at this writing.

- V. APPENDIX: Dosimetry of Fast Neutron Beams from a Small Medical Cyclotron by A. Pinkerton, J. Mamacos and J. S. Laughlin, Radiology 96: 131, 1970.

*Removal
Accepted as Reprint*

(Reprints from publisher will be available for binding in copies for submission to the AEC.)

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1. Evans, R.G., Pinkerton, A.P., Djordjevic, B., Mamacos, J., and Laughlin, J.S. Biological Effectiveness and Oxygen Dependence of Fast Neutron Beams at Different Depths of Tissue Equivalent Material. Presented at the Radiation Research Society Meeting, March 1970.
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FIGURE I

Fig. II: Water-Air Cooled Beryllium Target

Fig. III: Variable Thickness Beryllium Target

CIRCULATING HEAVY WATER CYCLOTRON TARGET

FIGURE IV

PROTON RECOIL SPECTROMETER

FIGURE V

TISSUE EQUIVALENT CALORIMETER WITH COVER PLATES REMOVED

FIGURE VI

SCALE
INCHES
0.0 0.1 0.5 1.0

TISSUE EQUIVALENT CALORIMETER WITH COVER PLATES INSTALLED (cross section)

Fig. VIII: Partial Assembly of Tissue Equivalent Calorimeter

$P(Y)$ $\frac{\text{Events/KeV/micron}}{\sum \text{Events}}$

FIGURE IX

$D(Y) \frac{\text{Ergs/gm/KeV/micron}}{\Sigma \text{ Ergs/gm}}$

FIGURE X

Dose Fraction vs. LET for a 2 micron diameter sphere of tissue equivalent material at several depths.

Fig XI: OER Irradiation Jig

Fig. XII: Dual Channel Nanosecond Pulse Integrator System

BLOCK DIAGRAM OF SCINTILLATION DETECTOR SYSTEM

FIGURE XIII

Fig. XIV: Exploded View of Scintillation Detector
and Photodiode

FIGURE XV

FARADAY CUP and SCINTILLATION DETECTOR Response vs. Distance

Fig. XVI: Faraday Cup Assembly

Fig. XVII: Thin Foil Calorimeter Assembly with
Mounting Flange. Vacuum Column
Attached to Electron Generator at Left

BLOCK DIAGRAM OF THIN FOIL CALORIMETER SYSTEM

FIGURE XVIII

FIGURE XIX

THIN FOIL CALORIMETER
and
THIN SCINTILLATION DETECTOR
Response vs. Distance

Fig. XX: Schematic of Orthogonal Strip Matrix

FIGURE XXI

FIGURE XXII

Computed depth of junction penetration in Germanium
Wafer during warm-up to final temperature
in tube furnace

JIG USED TO LAP WAFER FACES INTO PARALLELISM

FIGURE XXIII

FIGURE XXIV

FIGURE XXV

FIGURE XXVI

FIGURE XXVII

FIGURE XXVIII

FIGURE XXIX
DUAL CHAMBER CRYOSTAT

Fig. XXX. Apparatus for Testing Germanium Orthogonal Strip Matrix in Vacuum Cryostat

FIGURE XXXI

FIGURE XXXII
CO 57 SOURCE HOLDER