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"BIOLOGICAL AND CLINICAL DOSIMETRY"
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TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	2
II. ABSORBED DOSE CALORIMETRY	4
A. Graphite Calorimeter	4
1. Calorimetric and Ionometric Methods Applied to High Energy Electrons.	5
2. Calibration of The Fricke Ferrous Sulphate Dosimeter	10
3. Calibration of Thermoluminescent Dosimeters for High Energy Electrons	11
4. Calibration of a Semiconductor Diode for High Energy Electrons.	13
B. Tissue Equivalent Absorbed dose Calorimeters	15
1. Calorimeter Design	15
2. Radiochemical Effects	18
3. Measurements in Neutron Radiotherapy Beams	20
4. Calorimetric Dosimetry in a 160 MeV Photon Beam	23
5. Measurements in P1-Meson and Heavy Charged Particle Beams	26
6. High Energy Photon and Electron Measurements	29
7. Thermal Defect Measurements	36
III. NEUTRON DOSIMETRY	40
A. Measurements at The Sloan-Kettering Cyclotron	40
1. Dose Rate Measurements and Depth Dose Distributions	42
2. Fast Neutron Flux	46
3. Thermal Neutron Flux	47
4. Target Design	47
5. Angular Distributions	52
6. Gamma Ray Measurements	59
7. Microdosimetry	61

IV.	DOSIMETRY OF ULTRA-HIGH INTENSITY RADIATION SOURCES	69
A.	30 Nanosecond Electron Generator	70
1.	Beam Monitoring System	72
2.	Intensity Calorimeter	73
3.	Current Monitor	75
4.	Energy and Charge Fluence	77
5.	TLD Studies	80
B.	3 Nanosecond Electron Generator	82
1.	Beam Monitoring System	83
2.	Scintillation Detector	85
3.	Thin Foil Calorimeter	88
V.	SOLID STATE DETECTOR AND GERMANIUM GAMMA CAMERA PROGRAM	93
1.	Germanium Gamma Camera	93
2.	Construction and Testing of Ultra Pure Germanium Diodes	100
3.	Construction of a new Orthogonal Strip Matrix	111
VI.	DOSIMETRY FOR BRACHYTHERAPY	113
1.	TLD Measurements	113
2.	Dosimetry for ^{252}Cf Medical Neutron Sources	117
VII.	FUTURE PLANS	121
VIII.	REFERENCES	122
IX.	Graduate Students	129
X.	PUBLICATIONS AND PRESENTATIONS	130
XI.	SIGNIFICANCE	135
XII.	RESEARCH SUPPORT	135

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I. INTRODUCTION

The dosimetric studies at this laboratory were initiated with the primary goal of developing systems for the determination of absorbed dose in biological research and clinical applications. The primary method under study is the local absorbed dose calorimeter, a concept initiated and developed by J.S. Laughlin. In addition, secondary dosimetric systems such as ionization chambers, chemical dosimeters and thermoluminescent dosimeters (TLD) are being developed and applied to provide an absolute basis for the evaluation and comparison of experiments, treatments and other procedures using radiation. In keeping with these objectives this project has accomplished significant advances in the following areas:

A. Local Absorbed Dose Calorimetry

- 1) A portable absorbed dose calorimeter, constructed of graphite was developed in 1964 and applied to study the response of various secondary dosimeters to high energy electrons and photons.
- 2) Calorimetric methods were successfully applied to ultra-high intensity pulsed radiation sources in 1968.
- 3) A portable tissue equivalent plastic calorimeter was completed in 1973 and has since been applied to measurements of absorbed dose in neutron fields produced at our own cyclotron as well as other high-LET radiotherapy trial centers throughout the United States including: Harvard University, Los Alamos Meson Physics Facility, Lawrence Berkeley Laboratory, Fermilab, Texas A. and M. University, Naval Research Laboratory and The University of Washington.
- 4) We are currently collaborating with several task groups of the American Association of Physicists in Medicine (AAPM) in order to provide data from calorimetric and ionometric measurements which will be used for dosimetry protocols in, Neutron Dosimetry (TG-18) charged Particle Dosimetry (TG-20) and High Energy Electron and Photon Dosimetry (TG-21).

B. NEUTRON DOSIMETRY

- 1) Tissue equivalent plastic parallel plate type ionization chambers were constructed and employed for measurements in Neutron fields at the SKI cyclotron in 1968.
- 2) Microdosimetric measurements in neutron fields were carried out from 1970 to 1973.
- 3) A miniature energy compensated Geiger-Mueller (G-M) dosimeter was developed in 1976 for measuring the photon dose fraction in fast neutron fields.
- 4) Intercomparisons of commercial TE ionization chambers were carried out at the U.S. neutron radiotherapy trial centers.

C. DOSIMETRY OF ULTRA-HIGH INTENSITY RADIATION SOURCES

- 1) A comprehensive beam monitoring and dosimetric system for the nanosecond pulsed electron sources (Febetrons) in our laboratory from 1968 to 1972.
- 2) The response of secondary dosimetric systems such as a scintillation detector and TLD were studied as a function of dose rate up to 10^{14} rad/sec.
- 3) A miniature ($\frac{1}{8}$ " diameter) absorbed dose calorimeter was devised for measurements using small area biological samples in 1976.

D. SOLID STATE DETECTOR AND GERMANIUM GAMMA CAMERA PROGRAM

- 1) Extensive measurements were made of the radiation response characteristics of silicon p-i-n and pn junction diodes in all dc modes of operation for various radiation fields from 1965 thru 1970.
- 2) An orthogonal electrode strip matrix array germanium gamma camera was developed in this Laboratory in 1970.
- 3) The germanium gamma camera was enlarged and plans for a clinical sized unit were underway in 1974.

E. DOSIMETRY FOR BRACHYTHERAPY

- 1) TLD was applied to measurements of iso-dose contours in phantoms around sources of ^{137}Cs , ^{125}I , ^{198}Au and ^{222}Rn
- 2) The neutron and photon dose distributions around implantable ^{252}Cf sources was studied from 1971 to 1974.
- 3) The first microdosimetric measurements using ^{125}I implantable sources were carried out in our laboratory in 1977.

II. ABSORBED DOSE CALORIMETRY

A) Graphite Calorimeter

A quantity of primary importance in the clinical and experimental applications of high energy radiation is the distribution of local absorbed dose produced in the irradiated medium. The most direct method of determining absorbed dose is by calorimetry, in which the temperature increase produced by the absorption of radiation in an isolated segment of a suitable medium is measured. Calibration is carried out by means of electrically heating the isolated segment, or core. Therefore, the method is a primary standard, independent of calibration in a radiation beam and is based upon electrical, thermal and mechanical standards alone. The absorbed dose calorimeter represents the physical realization of the quantity energy per unit mass.

The quasiadiabatic local absorbed dose graphite calorimeter developed at the Sloan-Kettering Institute (1) is portable and has been used to measure depth dose distributions. The response of ionometric, chemical, thermoluminescent and semiconductor dosimeters have been compared with this instrument with respect to response as a function of depth in the irradiated medium as well as for different energies of incident electrons. Measurements with Cobalt-60 gamma rays have also been performed.

Figure 1 illustrates the appearance of the Institute's graphite calorimeter and Figure 2 is a cross-section drawing of this instrument. This calorimeter was specifically designed to facilitate depth-dose measurements: graphite discs can be conveniently added inside the vacuum jacket above the absorbing element. The sensitive volume of the calorimeter consists of a graphite wafer, three centimeters in diameter and four millimeters in thickness. This wafer contains four microminiature thermistors and a chromel heating coil. The thermistors are used singly, but their multiplicity provides for continued operation should one unit fail. The wafer is suspended on nylon monofilaments within an adiabatic shield 6.5 cm in diameter by 1 cm in thickness. This adiabatic shield contains a chromel heater to permit calibration by simulating the energy absorption from the radiation field and is also suspended by nylon monofilaments. Surrounding the adiabatic shield is a control shield 11 cm in diameter and 2 cm in thickness. This shield contains 3 thermistors to sense its temperature, and a set of control heaters which are used to regulate the temperature. It is suspended within the main body of the graphite calorimeter which itself contains a set of thermistors and a control heater. The quantity of radiation entering the calorimeter is monitored by a transmission ionization chamber of multiple parallel plate design with two millimeter spacing.

The precision of measurement with this instrument is on the order of 1/2 to 1% for dose rates as low as 50 rads per minute.

1) Calorimetric And Ionometric Methods applied to High Energy Electrons

The earliest series of experiments undertaken was a comparison of the central axis depth dose distributions for 20 MeV electrons measured with a Baldwin Farmer ion chamber and determined by the calorimeter. Figure 3 shows the depth dose curves plotted directly in rads. The upper two plots are based on the ion chamber measurements of dose using a value of $W = 33.73$ eV, and allowing for a displacement of the measuring point by 0.75 of the chamber radius (2).

Fig. 1. Carbon Calorimeter in Place under Betatron

FIELD CALORIMETER

Fig. 2. Cross Section of Carbon Calorimeter

For the stopping power calculations used in this conversion, the electron spectra as a function of depth given by Harder (3) were employed. The upper curve neglects the polarization correction while the lower includes this correction based on the Sternheimer formulation (4). Measurements were made at sufficiently low dose rates to insure saturation. Chamber volume was assessed by a combination of direct and X-ray determinations of its dimensions. Unfortunately, because of the nature of the circuit of the Baldwin Farmer, the ionization current cannot be conveniently measured for both positive and negative collecting potentials. These problems, coupled with the uncertainty in the effective depth of measurement, made it desirable to elaborate this experiment by the use of the extrapolation chamber.

The chamber, of plane parallel geometry, was constructed so that graphite rings annular to the collecting volume could be inserted. These rings compensated for electron loss from the collecting volume and also served to determine the spacing of the chamber. They were incorporated because preliminary experiments had demonstrated an increase of 3 to 5% in the ionization current compared with "wallless" operation. A similar result has been discussed by Attix, et al (5) who compared extrapolation chambers with and without inserts of the wall material surrounding the collecting volume. Measurements with a dial indicator showed that spacing was reproduceable to better than 0.01 mm.

Saturation characteristics were determined for betatron electrons using the method described by Kemp (6). Measured at a spacing of 2.8 mm and utilizing the criteria that the current J extrapolated to $(J/V)^2 = 0$ lies within the standard deviation of the average measured current for positive and negative polarities, saturation occurred at an electric field intensity of 360 volts/mm. Polarization voltages were subsequently adjusted with spacing which varied from 0.25 to 4.0 mm to provide this field intensity.

Utilizing the extrapolation chamber and graphite calorimeter, values of esu/cc/monitor unit and rads/monitor unit, were determined at thirteen depths between 1.76 and 12.8 gm/cm² of carbon. By electro-disintegration thresholds, the incident electron energy was determined to be 20.35 ± 0.15 MeV. Assuming a constant value of 33.73 ev for the W of air, one can directly determine from these measurements the mean stopping power ratio between carbon and air for electron spectra traversing the cavity at each depth. This is of particular interest, since it directly displays the influence of the polarization effect (4); and, therefore, the relative influence of high and low energy electrons upon the ionization produced.

A graphical representation of the measured stopping power ratio compared with values computed by two methods is given in Figure 4. The primary and secondary electron spectra for a 20 MeV electron beam penetrating water, have been calculated as a function of depth by Kassarís (7). Kassarís recomputed these spectra for carbon, including the effect of higher order electrons; and from the resulting spectra calculated the mean stopping power ratio. Tables of the ratio of absorbed dose to cavity ionization for electron beams at various depths derived from the above computations are included in an appendix to this report.

Harder (8) has stated that the stopping power ratio for a cavity ionization chamber at a given depth may be adequately represented by that calculated for the mean electron energy at that given depth. The mean electron energy is given by the formula $E_m = E_o (1 - d/R_p)$

where E_o = incident energy

d = depth of interest

R_p = practical extrapolated range.

Agreement between either set of calculated values and the experimental results is better than 2.5% for all points except those in the tail of the electron dose curve where the bremsstrahlung (approximately 4% of the maximum dose) becomes a strong influence.

Fig. 3. Comparison of Calorimetric and Ionometric Depth Dose Distributions

Fig. 4. Variation of (Carbon/Air) Stopping Power Ratio with Depth

Indeed, the experimental value of the stopping power ratio at a depth of 12.8 gm/cm^2 ; 0.959 is comparable with the values given by Skaarsgard (9) and Bewley (10) for 20 MeV X-rays.

Since the uncertainty of the computed stopping powers is of the order of $\pm 1\%$, both methods of calculation are in satisfactory agreement with experimental results. It appears on the basis of the comparison with the values computed by Kessaris, that the contribution to cavity ionization by non-primary electrons whose energies are sufficiently low to avoid the polarization effect is small.

2) Calibration of the Fricke Ferrous Sulfate Dosimeter

The $G(\text{Fe}^{+++})$ value for the Fricke ferrous sulfate dosimeter was determined for Cobalt-60 gamma rays and for 20 MeV electrons at several depths. The dosimeter solution was irradiated in thin (1.0mm) wall polystyrene capsules of dimensions equal to the calorimeter absorber. The capsules were placed in a graphite phantom which located the central plane of the dosimeter at the same depth (gm/cm^2) as the central plane of the calorimeter absorber. Measured at a depth of 1.76 gm/cm^2 , the $G(\text{Fe}^{+++})$ values for Cobalt-60 gamma rays and 20 MeV electrons were found to be 15.60 ± 0.22 respectively. These compare favorably with the definitive work of Pettersson (11) utilizing a water calorimeter, who obtained values of 15.57 ± 0.14 for Cobalt-60 gamma rays and 15.51 ± 0.12 for 20 MeV electrons.

The $G(\text{Fe}^{+++})$ value was also determined at depths in carbon corresponding to the 100, 73, 45, and 18 percent dose levels for 20 MeV incident electrons and the results are shown in Figure 5. The slight elevation ($\sim 2\%$) of the $G(\text{Fe}^{+++})$ at the 9.07 and 10.7 (gm/cm^2) depths is not considered significant since it may reflect the experimental difficulties caused by the reduced dose rate and steep gradient in the radiation fields. In any case, the values of $G(\text{Fe}^{+++})$ determined for these two depths are within the range of published values (12), and within two standard deviations of the value at the dose maximum.

Experience indicates that the Fricke dosimeter can be used with a precision better than or equal to 1% and is suitable within the limitations imposed by the relatively large doses required to a wide variety of situations. While appreciable variations in the yield of this dosimeter for a given radiation have at times been reported, recent evaluations (11,12) indicate freedom from any strong energy dependence for high energy sources.

Because of the unambiguous nature of the information obtained with this method, it appears to be the most satisfactory high energy secondary dosimeter currently available, and its response unlike that of an ionization chamber, need not be corrected for the polarization effect (4).

3.) Calibration of Thermoluminescent Dosimeters for High Energy Electrons

Despite its convenience, wide dose range, near tissue equivalence, and the possibility of fabricating miniature dosimeters, the measurements of absorbed dose with lithium fluoride presents several problems. The tendency to supralinear response at increasing doses of radiation is well recognized. However, in many cases this is not significant because of the limited dose range required, frequently less than a decade. The energy dependence of this material, however, was until recently not well understood.

In 1965, in the course of experiments on the use of lithium-7 enriched phosphor as a transfer dosimeter for high energy electrons and Cobalt-60 gamma rays (13), we observed a reduction in response of the dosimeters to electrons compared with the response to gamma rays. These observations were verified by ourselves and others (14,15) and the subject of subsequent investigations (16,17) which showed that the magnitude of the effect appeared somewhat variable, depending on the batch of phosphor involved but independent of total dose up to 10,000 rads. These results were in contradiction to those of Whorton and Holoway (18) with unenriched phosphor which showed uniform response for high energy electrons and Cobalt-60 gamma rays below

Fig. 5. $G(Fe^{+++})$ for 20 MeV Electrons

Fig. 6. Response of LiF Thermoluminescent Dosimeters

200 rads and enhancement of the response to electrons at high doses.

Subsequently, using the calorimeter, we repeated our measurements on the lithium-7 enriched phosphor and the same type phosphor in a thin 0.3 mm teflon matrix. The results for Cobalt-60 gamma rays and 6, 8, 10, 12, 15, 18, and 20 MeV electrons are shown in Figure 6. The response/rad has been normalized at 20 MeV, and the Cobalt-60 value is plotted at an energy corresponding to the mean energy of the Compton electrons. There is a striking variance between the results: while the loose phosphor encapsulated in 1mm wall polyethylene capsules with 3 mm inner diameter shows increasing response with decreasing energy, the lithium-7 teflon dosimeters do not. Calcium fluoride teflon dosimeters were also compared to the graphite calorimeter for the same radiations used above. The results are shown in Figure 7. The response of these dosimeters appears to be relatively constant for high energy radiations, and their reproducibility as indicated by the standard deviations, was somewhat better than the lithium fluoride dosimeters, although the sensitivity is lower.

4) Calibration of a Semiconductor Diode for High Energy Electrons

The conversion of ionization measurements with high energy electrons to absorbed dose in a tissue equivalent medium involves several corrections. These include corrections for the large variation with energy in stopping power ratio arising from the density or polarization effect, chamber saturation, effect of the polarity of the collecting voltage, and the displacement of the effective measuring point from the geometrical center of the chamber. These uncertainties can be significantly reduced by the use of a miniature silicon diode.

Since the current yield of the diode is almost 2×10^4 as great as an ion chamber of equivalent dimensions, the device can be made very small; for example, a 1/2 mm cube. This dimension corresponds to the range of a 0.3 MeV electron in silicon and consequently, the perturbation of the electron spectra would not be serious for most depths and incident energies. The stopping power ratio between silicon and tissue equivalent materials undergoes a total

Fig. 7. Response of CaF Thermoluminescent Dosimeters

Fig. 8. Response of Si Diode

variation of about 6% between 0.3 and 20 MeV while the variation for air is 19% for the same energy range [19].

The response of a small commercial diode has been evaluated with graphite calorimeter. A micro semiconductor MC-150A diode was mounted in graphite sleeve to permit its insertion into the calorimeter phantom and the integrated short circuit current per rad in graphite measured for 6, 8, 10, 12, 15, 18, and 20 MeV incident electrons. A sensitivity of 1.37×10^{-10} coul./rad (carbon) was observed for 20 MeV electrons, and the response normalized to this value plotted as a function of mean electron energy at the diode is shown in Fig. 8. The response for this diode, in which the silicon wafer is approximately 1/2 mm thick by 1 mm in diameter, is extremely uniform and within experimental limits a constant value.

Measurements were also made with Cobalt-60 gamma rays. However, in this case a variation in sensitivity of up to 11% was observed depending on the rotational orientation of the diode relative to the direction of the beam. This was not observed for the electron irradiations and undoubtedly arose from the asymmetry of the silicon wafer or the presence of the leads attached to the faces of the diode. The results indicated that special efforts are required in design and mounting of a diode intended for general dosimetry measurements.

B) Tissue Equivalent Absorbed Dose Calorimeters

1) Calorimeter Design

The instrument was designed to measure absorbed dose in cyclotron produced fast neutron fields and, since the dose gradients in the particular fields employed are relatively steep, the sensitive element is disc shaped 2 cm in diameter and

0.2 cm thick. Measurements can be carried out at different depths in liquid media and the design does not require a collimated neutron beam.

A photograph of the calorimeter, with lids and internal cover plates removed, is shown in Fig. 4. The central absorbing element, or core, is insulated from its surroundings by a 0.05 cm vacuum gap and is supported by 0-80 nylon screws. The vacuum gaps between elements in this design represent a minor perturbation to the homogeneity of the calorimeter and, therefore, the dose measured in the core will be a close approximation to the energy deposited in a small mass at depth in a homogeneous tissue equivalent medium. Immediately surrounding the core is a jacket which is constrained to heat at nearly the same rate as the core so that the temperature differential between the two elements is small. This method, reduces heat loss from the core during calibration. The three elements which enclose the core and jacket are thermal buffers which serve to damp out ambient temperature fluctuations before they reach the core (22). Dynamic temperature regulation is provided by the massive control shield. A thermal regulator sends current through the plastic which is electrically conducting so that it can be used as a resistance heater, and a thermistor embedded in the shield serves as the sensing element for the regulator.

The electrical calibration relies on precise resistance heating of the central absorber and, since the resistance of the conducting T.E. plastic core is small (3.41 ohm) a high resistance in series was always avoided. The electrical calibration leads consist of a 20 cm length of 0.008 cm diameter copper wire epoxied to the core at one end and then soldered to a 20 cm length of 0.025 cm diameter copper wire. The smaller wire helps reduce thermal loss by conduction and the connection to a larger wire maintains a reasonably low resistance of 0.78 ohms per lead. These electrical leads are in thermal

Fig. 9

contact with both the core and the surrounding jacket so that heating in the wire between the elements can be shown to contribute equally to both bodies (23).

In order to avoid the use of imbedded heating elements in the core, the resistivity of the T.E. plastic is used to provide precise resistance heating during calibration. The two opposing faces of the disc shaped absorber are made conducting to serve as equipotential surfaces so that the thermal distribution during electrical calibration will be similar to the pattern generated during irradiation. The adiabatic jacket surrounding the core is heated in a similar manner. The components of the core are listed in Table I along with their relative percentages by weight. The amount of material perturbing the tissue equivalence of the core has been kept to a minimum, and the relative contribution of each element to the total kerma ratio relative to tissue is evaluated by the method described in I.C.R.U. Report 26 (24,25).

2. Radiochemical effects

Earlier work in this laboratory (26) described the endothermic radiochemical effect which occurs when a tissue equivalent plastic mixture is irradiated. Using ^{60}Co gamma-rays, it was determined that approximately 3% of the energy absorbed did not appear as heat, but rather produced radiochemical changes in the plastic. In addition, it has been reported by Bewley et al. (27) that initial measurements performed with his Shonka plastic calorimeter were about 10% greater than expected when compared to an ionization chamber. After irradiation with 100 krad of 7 MV x-rays the measurements were 2-5% lower than the value determined by the ionization chamber, which was assumed to have measured the absolute dose.

TABLE 1

Component	Weight	Percentage
Tissue equivalent plastic	.7365	98.29
Conducting paint	.0055	.73
Conducting epoxy	.0027	.36
Thermal epoxy for thermistor	.0022	.29
Thermistor head	.0020	.27
Electrical leads on core	.0004	.05
	<hr/> .7493 gm	<hr/> 99.99%

Removal of the dissolved oxygen from the T.E. plastic is essential to avoid the large initial exothermic effect, and pre-irradiation is one method of achieving this result. Irradiation radiochemically consumes oxygen, and Chapman et al. (28) have found that for several common plastics the concentration of dissolved oxygen under one atmosphere of air at room temperature ranges from 600 to 800 $\mu\text{M/liter}$, and the $G(-\text{O}_2)$ for consumption of oxygen by x-rays is about 6 to 7 $\mu\text{M/liter}$ per krad. This leads to an expected dose of about 100 krad to deplete dissolved oxygen. Chadwick (29) has also found that thermal processing at low pressure stabilized the optical density of irradiated polymethyl methacrylate by removing oxygen. The process of preparing the calorimeter core by heating in a vacuum also removes the dissolved oxygen, however, if air is admitted into the calorimeter for an extended period of time, oxygen will re-diffuse into the plastic. The rate at which this process will take place is low due to the apparently small diffusion coefficient for the T.E. plastic: This was demonstrated experimentally by allowing the calorimeter to be filled with room temperature air for 24 hours and then resuming experiments which demonstrated no measurable change in response.

3. Measurements in Neutron Radiotherapy Beams

The Sloan-Kettering portable TE calorimeter, has been employed for the measurement of absorbed dose in several neutron radiotherapy fields. The therapy facilities visited so far include: The University of Washington, Seattle; Fermi National Accelerator Laboratory, Chicago; Texas A and M University, College Station and the Naval Research Laboratory, Washington, D.C. Comparisons of spherical, cylindrical and thimble shaped TE ionization chambers have been carried out using either air, or a flow of TE gas in the chambers. The dosimeters were mounted within a 25 cm cubic polystyrene phantom, and measurements were carried out at several depths within A-150 plastic. The field

experiments carried out to date have been encouraging. The ionization chamber based dosimetry has been found to be in close agreement to the absorbed dose measured by the calorimeter. The largest differences in dosimetric methods have been generally less than 1-2%. Therefore, it appears that the values employed by the U.S. neutron radiotherapy trial centers for $\bar{p}$ and $\bar{W}_n$ are probably correct to within the limits of experimental uncertainty. In addition, the correction applied to dose obtained using the 1 cm³ spherical chambers in order to account for the material displaced by the collecting volume has been verified to be 0.97 as initially computed by Shapiro. This correction can also be made by placing the effective measuring point of the 1 cm³ chamber at approximately 0.7 R (where R is the internal radius).

In addition to the E.G.G. chambers used at each center, we evaluated a Far West Technology (FWT) version of the original E.G.G. design. It appears to be acceptable from the limited data we were able to accumulate.

The absolute accuracy of the calorimetric measurement of absorbed dose in A-150 plastic is estimated to be $\pm 2.5\%$. The largest contribution to this quantity is due to the conservative estimate of a $\pm 2\%$ uncertainty in the value of the thermal defect for A-150 plastic, which is taken to be 4% at present. Experiments are now underway to measure the thermal defect in a more complete manner, and this should help reduce the overall uncertainty to better than $\pm 1.5\%$.

All values are expressed in terms of A-150 rads/monitor unit, using the normal monitoring procedure at each institution.

TABLE II

<u>U. OF W.</u>			
<u>Instrument</u>	<u>Dose (rad/m.u.)</u>	<u>Instrument</u>	<u>FERMILAB Dose (rad/m.u.)</u>
U. of W. EGG IC-17	1.799	FERMILAB EGG IC-17	1.001
SKI EGG IC-17	1.778	SKI EGG IC-17	1.002
SKI CYLINDRICAL	1.792	SKI CYLINDRICAL	1.002
CALORIMETER	1.807	CALORIMETER	.997
		FWT	.993

<u>TAMVEC</u>		<u>NRL</u>	
<u>Instrument</u>	<u>Dose (rad/m.u.)</u>	<u>Instrument</u>	<u>Dose (rad/m.u.)</u>
TAMVEC EGG IC-17	1.787	NRL EGG IC-17 (Air)	0.9878
SKI EGG IC-17	1.813	SKI Cylindrical (TE)	0.9860
SKI CYLINDRICAL	1.812	SKI Cylindrical (Air)	0.9736
CALORIMETER	1.793	SKI EGG-IC-17	0.9822
FWT	1.797	CALORIMETER	0.9654

4. Calorimetric Dosimetry in a 160 MeV Proton Beam

The portable tissue equivalent calorimeter was also employed to measure dose in two radiation fields which are currently in use both for clinical radiotherapy and experimental radiobiology. A ^{60}Co irradiator at the Cox Cancer Management Center of Massachusetts General Hospital (MGH) and the 160 MeV proton beam generated at the Harvard Cyclotron Laboratory were calibrated calorimetrically and a number of secondary dosimeters were intercompared.

The clinical application of the Harvard cyclotron proton beam depends critically upon accurate dosimetry and, in order to provide an independent dosimetric calibration, it was agreed that the tissue equivalent calorimeter should be employed to measure absorbed dose both in the ^{60}Co and proton fields. Intercomparison would then be possible with other dosimetric methods such as: a diode probe and Faraday cup, a Baldwin-Farmer ionization chamber and a PTW ionization chamber.

The exposure rate of an AECL Theratron 780 was first determined using an MGH Baldwin-Farmer ionization chamber in a 10 x 10 cm field at a depth of 5 cm in a 20 cm cubic water tank at 80 cm SAD. The absorbed dose in tissue was then calculated with the appropriate tissue-to-air ratio, back-scatter factor, displacement and saturation corrections.

The calorimeter was then placed in a 30 cm cubic water tank with the absorber at a depth of 5 g/cm² at 80 cm SAD and a 10 x 10 cm field at the absorber. Positioning of both dosimeters was carried out carefully, but may have contributed a few tenths of a percent to systematic uncertainty. Thermal drift in the calorimeter runs was excessive during these measurements but in spite of experimental difficulties, the system performed satisfactorily. The value calculated for absorbed dose using the MGH Baldwin-Farmer ionization chamber was in good agreement with the calorimetric calibration as indicated in Table III.

TABLE III . SECONDARY DOSIMETRY NORMALIZED TO THE TE CALORIMETER

<u>Depth</u>	<u>Diode Calorimeter</u>	<u>PTW Chamber Calorimeter</u>
*		
2.5 cm	1.009	1.026
2.5	.992	1.011
7.5	.996	1.007
12	1.020	1.020
15	1.051	1.010

*Range modulator off.

After equilibration during the day following the ^{60}Co measurements, a series of exposures in the proton beam at the Harvard cyclotron was carried out. The characteristics of the proton beam have been described by Koehler et al. (30). A rotating Lucite range modulator, which operates on the principle of a ridge filter, serves to produce a depth dose distribution which is uniform to within a few percent over more than 10 cm along the central axis. The diameter of the field was approximately 25 cm and it is produced by a scattering foil upstream and a circular collimator adjacent to the range modulator (see fig. 10). Uniformity in the x-y plane was measured to be within +5% at the start of the experiment. In addition, a depth dose scan with a diode probe and a PTW ion chamber was performed. Calibration of both instruments was carried out on the preceeding day using a small field collimator without range modulation. The absorbed dose was calculated by measuring the particle fluence with a Faraday cup and multiplying by the energy loss per particle (31). This small field calibration was then used for dosimetry in the large field, and measurements were normalized to a dual transmission monitor ion chamber shown in Fig. 9.

Fig. 10

The doses measured by the calorimeter and computed from the Baldwin-Farmer ionization chamber measurements for a 2.69 min. exposure in the ^{60}Co field are indicated below:

Calorimeter	$395.51 \pm 2.4\%$ (rad)
Baldwin-Farmer Chamber	$397.5 \pm 1.4\%$ (rad)

The difference in these values is 0.5% and the uncertainties represent estimates of the r.m.s. combination of random and systematic uncertainties.

5. Measurements in Pi-Meson and Heavy Charged Particle Beams

At the peak of the negative pion beam at Los Alamos scientific laboratory, absorbed dose per monitor count was measured using:

1. The SKI TE Calorimeter
2. The SKI TE Parallel Plate Chamber
3. LASL 0.1 cc FWT Chamber
4. The NBS Graphite Calorimeter
5. The NBS Graphite Parallel Plate Chamber

At the peak of a positive pion beam absorbed dose per monitor count was again measured with the five devices listed above. In the plateau of a positive pion beam absorbed dose was also measured with the same five devices. In each, case, dose was expressed in terms of A-150 rads or Graphite rads (no kerma correction was applied).

Negative Pion Peak

TE Calorimeter = 1.19×10^{-3} rad/monitor count

TE Parallel Plate = 1.17×10^{-3} rad/monitor count

Positive Pion Peak

TE Calorimeter = 8.49×10^{-4} rad/monitor count

TE Parallel Plate = 8.81×10^{-4} rad/monitor count

Positive Pion Plateau

TE Calorimeter = 3.83×10^{-4} rad/monitor count

TE Parallel Plate = 3.86×10^{-4} rad/monitor count

Using the TE Parallel Plate ionization chamber measurements of charge and the absorbed dose determined by the calorimeter it is possible to compute the value of W at the negative pion peak for methane based TE gas.

$$\hat{W}_{pi} = 29.8 \pm 0.6 \text{ eV/ion pair}$$

At two positions (about 6 and 13 g/cm²) on a spread-out, constant RBE (about 15% roll off) Bragg peak using helium nuclei of approximately 900 MeV at the 184" Cyclotron, of the Lawrence Berkeley Laboratory, and carbon nuclei at 400 MeV/nucleon at the Bevalac, absorbed dose in A-150 plastic per monitor count was measured using:

1. SKI TE Calorimeter
2. SKI TE Parallel Plate Chamber (TE gas)
3. LBL 1 cc FWT Chamber (Air)
4. LBL 0.1 cc FWT Chamber (Air)

At each accelerator, we also measured and compared depth dose distributions using:

1. SKI TE Parallel Plate Chamber
2. LBL 1 cc FWT Chamber
3. LBL 0.1 cc FWT Chamber

Helium Ions at 184

28

(Proximal Peak)

TE Calorimeter = 0.999 rad/monitor count

TE Parallel Plate = 1.007 rad/monitor count

LBL 1 cc FWT Chamber = 1.0 rad/monitor count

(Distal Peak)

TE Calorimeter = 0.778 rad/monitor count

TE Parallel Plate = 0.787 rad/monitor count

LBL 1 cc FWT Chamber = 0.803 rad/monitor count

Carbon Ions at Bevalac

(Proximal Peak)

TE Calorimeter = 0.915 rad/monitor count

TE Parallel Plate = 0.928 rad/monitor count

LBL 1 cc FWT Chamber 1.0 rad/monitor count

(Distal Peak)

TE Calorimeter = 0.738 rad/monitor count

TE Parallel Plate = 0.705 rad/monitor count

LBL 1 cc FWT Chamber = 0.772 rad/monitor count

The dose per monitor unit determined by LBL chambers is the nominal value which may be changed due to calibration checks.

The dose to A-150 plastic calculated by the SKI TE Parallel Plate Chamber assumed a constant value for W at both positions in both beams of 29.2 eV/ion pair (i.e. the Cobalt-60 value).

6. High Energy Photon and Electron Measurements

It is generally agreed that a calibration of absorbed dose in a Co-60 field should be carried out at a depth of 5 cm in water or tissue-equivalent material (32). It represents a depth which is clinically meaningful since many tumors are treated at such a depth. In this intercomparison, the ionization chamber was irradiated at a depth of 5.5 cm in polystyrene using a 10x10 cm field, 80 cm from the face of the source of the teletherapy unit to the center of the active volume of the chamber. The average of positive and negative charge collected was computed, although they differed by less than a tenth of a percent. The collection potential was varied as a function of spacing to assure a collection efficiency of at least 99.9%. The standard deviation of the charge measurements was +0.1% or less.

The dose at a depth of 5.5 cm of polystyrene was also determined by measuring the exposure in air at 80 cm from the face of the source, using a Shonka-Wyckoff type air-equivalent ionization chamber which had been previously calibrated at NBS. The dose at depth was then computed from the exposure to free air by the use of A_{eq} , the factor for polystyrene, and tissue-air-ratios for polystyrene. The agreement between these two methods was 1.1%. The ratio of $\frac{D(B.G.)}{D(X)}$ was obtained by the use of the following equation:

$$\frac{D(B.G.)}{D(X)} = \frac{0.869 (Q/V)_0 \bar{s}_{air}^{poly} \cdot K(T,P)}{X_a \cdot A_{eq} \left[0.869 \left[\frac{\mu_{en}}{\rho} \right]_{air}^{poly} \right] TAR}$$

Where $D(B.G.)$ is the dose as determined from the extrapolation chamber (Bragg-Gray cavity), and $D(X)$ is the dose at the same depth as determined from the exposure to free air (NBS traceable). The ratio of $\frac{D(B.G.)}{D(X)}$ extrapolated to zero volume is 1.011.

The depth of the central plane of the calorimeter core was computed in terms of electron density for A-150 plastic and polystyrene. The ionization chamber was placed at a depth of 5.5 cm in polystyrene using a 5 cm thick block over the chamber. Another such block, for the calorimeter, was machined from the same polystyrene stock, whose density had been measured to be 1.047 g.cm^{-3} . The thickness of this block was determined by equating the number of electrons per cm^2 in both cases. Table IV shows the values employed for the electron densities, mass energy absorption coefficients (33) and densities of materials.

The calorimeter was placed in the same field as the extrapolation chamber, and a series of radiation measurements and electrical calibrations was carried out. The relative displacement due to irradiation (or electrical calibration) heating $\Delta R/R_0$ is computed with respect to the displacement of a known resistance change. In this case, a one ohm change in the bridge balancing resistance was employed. There is virtually no heat loss, therefore, the drift rates before and after irradiation are small and virtually identical. The displacement due to radiation heating is determined by graphical analysis and the known amount of resistance change necessary to null the bridge circuit.

The measurement of absorbed dose using an A-150 plastic calorimeter must take into account the percentage of energy absorbed which does not subsequently appear as heat. Endothermic radiochemical effects in tissue analog plastics were initially described theoretically and measured experimentally in our laboratory (26), but there has been relatively little recent research in this area. Our current experimental program includes direct measurements of the thermal defect for secondary charged particles. A value of $(4 \pm 2)\%$ has been employed for the thermal defect in these experiments.

PROPERTIES OF MATERIALS EMPLOYED

	Polystyrene	A-150 Plastic
ρ	1.047	1.125 g.cm ⁻³
ρ	3.238x10 ²²	3.307 electrons.g ⁻¹
$\frac{\mu_{en}}{\rho}$	0.0287	0.0293 cm ² .g ⁻¹

The values obtained for the absorbed dose in tissue by the three measurement methods are shown in Table V along with the estimated uncertainties. The largest source of uncertainty in the ionometric measurements is the effective collection area delineated by the separation between collector and guard electrodes. The largest sources of uncertainty in the calorimeter are the thermal defect, and the perturbation due to the presence of vacuum gaps. However, our current research on these problems should help to reduce further these uncertainties.

TABLE V

ABSORBED DOSE TO TISSUE AT A DEPTH OF 5.5 cm
IN POLYSTYRENE

D(X _a)	D(B.G.)	D(CAL)
101.1 ± 2%	102.2 ± 2%	100.0 ± 2.5%

The dose to water for high energy electrons and photons was calculated from the measurements made with a polystyrene pancake chamber in the polystyrene phantom according to the Spencer-Attix formulation of the Bragg-Gray relation as indicated by equations (2) and (3).

$$\text{Photons: } D_{\text{water}, \lambda} = \frac{Q}{V_0} \cdot \frac{W}{e} \cdot \left(\frac{\bar{L}}{\rho} \right)_{\text{air}, E(\lambda)}^{\text{poly}} \cdot \frac{\bar{\mu}_{\text{en}}^{\text{water}}}{\rho_{\text{poly}, \lambda}} \quad (2)$$

$$\text{Electrons: } D_{\text{water}} = \left(\frac{Q}{\rho V_0} \right) \cdot \frac{W}{e} \cdot \left(\frac{\bar{L}}{\rho} \right)_{\text{air}, E}^{\text{poly}} \quad (3)$$

Where $\frac{Q}{\rho V_0}$ is the cavity ionization expressed in coulombs kg^{-1} of air extrapolated to zero volume. In this ratio, ρV is the mass calibration constant expressed in kg as determined from a cobalt-60 calibration and equation (1).

$\frac{\bar{W}}{e}$ is the average energy expended per ionization in air. If is taken as $33.7 \text{ Joules coulomb}^{-1}$, the dose will be expressed in Grays (100 rads).

$\left(\frac{\bar{L}}{\rho} \right)_{\text{air}, E}^{\text{poly}}$ is the quotient of the restricted collision mass stopping powers of polystyrene to air, averaged over the secondary electron spectrum entering the cavity. The minimum cut-off energy $E = 15 \text{ keV}$ has been omitted in this notation.

$\left(\frac{\bar{L}}{\rho} \right)_{\text{air}, E}^{\text{tissue}}$ is the quotient of the restricted collision mass stopping powers of tissue to air, averaged over the electron spectrum at depth Z .

$\left(\frac{\bar{\mu}_{\text{en}}}{\rho} \right)_{\text{poly}}^{\text{tissue}}$ is the quotient of the mass energy absorption coefficients of tissue to polystyrene, evaluated over the photon spectrum.

Equations (2) and (3) assume that there are no perturbations of the electron or photon fluence due to the cavity or the chamber material, which is the case for the pancake chamber. The appropriate values of the parameters used in equations (2) and (3), as well as the electron density and stopping powers used for the calorimeter measurements, are summarized in Appendix I.

Table VI lists the results of the absorbed dose inter-comparison for the four radiation modalities investigated.

TABLE VI

	⁶⁰ Co	Photons 10 MV	Electrons 11 MeV	Electrons 20 MeV
Calorimeter*	1.000 + 2.5%	1.000 + 2.5%	1.000 + 2.5%	1.000 + 2.5%
Pancake Chamber**	1.009 + 2.5%	1.000 + 2.5%	1.010 + 2.5%	1.003 + 2.5%

*Measured in A-150 and computed to tissue

**Measured in polystyrene and computed to tissue

As can be seen, the agreement between the two methods is excellent. The precision of the ionometric measurements was within .2%, but the uncertainty of the measurement is difficult to estimate. NBS states the absolute uncertainty in the exposure calibration as +2.2%, although unofficially this figure has been reduced to less than 1%. The uncertainties in the ratios of the stopping powers and absorption coefficient is not too well known since these calculations depend on the electron and photon spectra at the point of measurement. The uncertainty of 2.5% assigned to the ionometric measurement represents a conservative estimate. As for the calorimeter, the greatest uncertainty encountered is the determination of the thermal defect. The endothermic radiochemical effects in tissue analog plastics were initially described theoretically and measured experimentally in our laboratory (26). A value of $4 \pm 2\%$ has been employed for the thermal defect in these experiments. Nevertheless, the uncertainty in the estimate of the experimental errors should not detract from the good agreement obtained in the determination of the absorbed dose to tissue by the two methods.

TABLE VII

Physical Constants for Pancake Chamber for Computation of Dose to Water at $d_{\max}$ (Equation 2)
from 4 - 20 MeV and ^{60}Co Gamma Rays

$(h\nu)_{\max}$	$h\nu$	$\frac{\mu_{\text{en}}}{\rho}(h\nu)_{\text{water}}$	$f = \text{Fraction of Energy Retained by Compton Electron}$	Average Energy of Electron Traversing Cavity $E = .4 * (f * h\nu)$	$(\frac{L}{\rho})_{\text{poly air, E}}$
^{60}Co	1.25	1.032	.470	.235	1.121
4	1.60	1.032	.500	.320	1.119
6	2.50	1.035	.550	.528	1.109
8	3.20	1.038	.580	.742	1.100
10	4.00	1.044	.603	.965	1.092
15	6.00	1.057	.641	1.54	1.073
20	8.00	1.071	.665	2.13	1.059

Hubble (1976) (13) NBS Circular 542 (14)

Berger & Seltzer (15)

NOTE: $D_{\text{tissue}} = D_{\text{water}} \left(\frac{\mu_{\text{en}}}{\rho} \right)_{\text{tissue water}}$

(1964)

TABLE VIIIPHYSICAL CONSTANTS FOR A - 150 CALORIMETER

	<u>^{60}Co</u>	<u>10 MV</u>
$\left(\frac{u}{e}\right)_{\text{muscle}}^{\text{A-150}}$	1.000	1.009

	<u>11 MeV</u>	<u>20 MeV</u>
$s_{\text{muscle}}^{\text{A-150}}$	1.005	1.004

7. THERMAL DEFECT MEASUREMENTS

The thermal defect for A-150 plastic is not well known for the secondary charged particles generated by the interactions of fast neutrons or other densely ionizing radiation in the plastic. The only direct measurement of the thermal defect using charged particles was performed by Fleming and Glass using only one particle type and energy 1.7 MeV protons (34).

Measurement of the thermal defect for a range of charged particle types and energies has been initiated by McDonald and Goodman (35). The calorimeter employed is the same instrument used by Fleming and Glass, but modifications have been made in design and many of the critical internal elements have been redesigned and replaced. In addition, samples of A-150 plastic have been obtained from other laboratories in the United States and Europe, chemical analyses of their composition have been performed so that any differences in thermal defect may be correlated to measureable physical quantities (36). If the thermal defect is significantly different in samples prepared at different laboratories it will mean that a separate determination of the thermal defect would be required if a calorimeter were constructed of material prepared in another laboratory. If no such variations are detected then the value obtained for the thermal defect will be applicable for any A-150 plastic calorimeter. These measurements are expected to reduce the uncertainty of $\pm 2\%$ presently assigned to the value of the thermal defect for cyclotron produced fast neutrons (35) to a few tenths of a percent.

This calorimeter system has been described previously and a brief summary of its operation will now be given. The charged particle beam from the accelerator is swept across the absorber face by electrostatic deflection plates, in the manner of a video raster, in order to produce a uniform irradiation pattern. The calorimeter is adiabatically controlled by a thermopile which detects the temperature difference between the absorber and the surrounding adiabatic jacket. The thermopile signal is amplified and used to control a thermal regulator which provides current for a heater surrounding the adiabatic jacket.

Since the absorber and adiabatic jacket are constrained to rise in temperature simultaneously, the measuring thermistor is placed in the jacket in order to minimize power dissipation in the absorber. Electrical calibration is achieved through the use of a resistance element between the TE plastic and aluminum faces.

The cross-sectional diagram in Fig. 11 shows the various elements of the calorimeter. The aluminum isothermal jacket is maintained at a set temperature by a thermal regulator, and its interior is at vacuum. Within this element is the adiabatic jacket, which is thermally and electrically insulated from the outer aluminum wall. The adiabatic jacket is maintained at a negative potential in order to suppress the emission of secondary electrons from the absorber and assure a reliable measurement of the beam current. The measuring thermistor and thermopile are mounted with a high thermal conductivity epoxy and are electrically guarded from the negative high potential to prevent leakage currents.

The absorber can be rotated so that either face will completely stop the charged particle beam. One face is aluminum 0.018 cm thick and 1.4 cm in diameter and the other is 0.025 cm thick TE plastic of the same diameter. The

Fig. 11

Fig. 12

CROSS SECTION OF DUAL ABSORBER

ratio of power measured using both sides of the absorber yields the thermal defect. Details of the absorber assembly are shown in Fig. 12.

III. NEUTRON DOSIMETRY

A. Measurements at the Sloan-Kettering Cyclotron

These measurements were performed with fast neutron beams produced by a 30-inch cyclotron at the Sloan-Kettering Institute. This cyclotron is capable of producing external beam currents in excess of 150 microamperes of 8.0 MeV deuterons, 15 MeV protons or alpha particles, and 23.2 MeV helium-3 ions. In our initial experiments during 1968 and 1969, we employed the following combinations of particles and target materials: helium-3 ions, deuterons and protons on beryllium; protons on deuterium (heavy water); and helium-3 ions on lithium (fluoride). Their maximum energies range from 12.3 MeV for the deuteron on beryllium reaction to 30.7 MeV for the helium-3 ions on beryllium, with median energies in the range of 3.5 and 6 MeV, respectively.

Our first objective was to determine the absorbed dose rates obtainable with the various reactions and also the depth dose characteristics for these neutron beams. The experimental apparatus included a collimator made of a polyethylene-lead-boron mixture 40 cm long with a 10 cm x 10 cm aperture, and a water tank with remotely positionable tissue equivalent ionization chamber. The ion chamber was designed to facilitate comparison with a tissue equivalent calorimeter, and is made of Shonka A-150 plastic. It has a plane parallel geometry with a collection volume 2 cm in diameter and 2 mm thick. The wall thickness is 2.5 mm and provides charged particle equilibrium, even when the chamber is not in "tissue equivalent" medium. The chamber and calibration jig are shown in Fig. 13.

Fig. 13. Tissue Equivalent Ion Chamber

Fig. 14. (Uncollimated) Neutron Depth Doses 50cmSSD

Calibration of the chamber filled with air, or a tissue equivalent gas of 64.4% methane, 33.5% carbon dioxide and 3.1% nitrogen, was performed by comparison with the absorbed dose from Cobalt-60 gamma rays as measured by Fricke dosimetry, with correction for the ratio of W values between electrons and protons, as well as proton stopping power ratios. Initial measurements were made in a water phantom, since the results of Greene and Thomas for 14 MeV neutrons little difference from TE liquid in terms of absorption and scattering. The measurements were corrected for proton stopping power averaged for proton energies from 0.25 MeV up to the median neutron energy assuming a proton spectral distribution inversely proportional to proton energy. This approximation was employed since the neutron spectra are skewed towards the lower energies. The chamber spacing of 2 mm is less than the range in air of protons with energies greater than 0.25 MeV, and should be sufficiently small to avoid perturbation of the secondary particle flux. The validity of these assumptions was subsequently checked for two of the reactions, and found reasonably accurate in the case of the helium-3 on beryllium reaction but somewhat less satisfactory for the deuteron on beryllium reaction. These corrections are discussed below.

1. Dose Rate Measurements and Depth Dose Distributions

Table IX shows the total tissue dose rates measured for the various reactions near the surface of the phantom for a variety of experimental geometries. For 50 cm SSD and no collimation, the dose rate in rad/min/ μ ampere range from 0.17 for the helium-3 ions on beryllium reaction to 0.67 for the proton reaction. For a typical target current of 50 microamperes, this corresponds to dose rates from 8.2 to 33 rads per minute. Results for the 10 cm x 10 cm field show an approximately 30 percent increase in available dose rate.

relative to the uncollimated beam. Measurements at 30 cm SSD are included to indicate the dose rate available for biological irradiations. While it is difficult to compare results obtained with different machines, collimator geometries and chambers, comparison with the results of Broerse (37) and Lucas (38) for the helium-3 beryllium reaction indicates that the dose rates observed from this reaction agreed within 5%.

TABLE IX
Total Tissue Dose Rate at 0.5 gm/cm² Depth in Water Phantom
Air Filled Tissue Equivalent Ion Chamber

Reaction	50 cm SSD 10 cmx10cm Field	50 cm SSD Field	30 cm SSD Field
⁹ Be(³ He,n)	0.21	0.17	0.46
⁹ Be(d,n)	0.60	0.48	1.20
⁹ Be(p,n)	0.82	0.67	-
² H(p,np)	-	0.34	-
⁷ Li(d,n)	-	0.22	-

To investigate the accuracy of the approximation used in calculating the dose rates shown in Table VII, measurements were made with the chamber filled with tissue equivalent gas for the helium-3 ions and deuteron on beryllium reaction using both collimated and uncollimated beams. In the case of the helium-3 reaction, agreement between the dose rate measure with air or tissue equivalent gas filling was 3% or better. For the deuteron reaction, a difference of 6% was noted.

Central axis depth dose distributions for all the indicated reactions measured at 50 cm SSD with infinite field size are shown in Fig. 14. The minimum depth of measurement was 0.5 gm/cm^2 and was taken as the 100% depth. The distributions are rather similar with the 50% depths ranging from 7.5 gm/cm^2 for the deuteron on lithium reaction to 8.8 gm/cm^2 for the helium-3 ion on beryllium reaction and with 25% depths ranging from 14 to 15.5 gm/cm^2 , respectively. Depth dose distributions for the three beryllium reactions with the beam collimated to a $10 \text{ cm} \times 10 \text{ cm}$ field are shown in Fig. 19 together with that for 230 KVP X-rays for the same field size and SSD with which they are nearly equivalent. The 50% depths vary from 6.2 to 7.1 gm/cm^2 and the 25% depths from 11.5 to 13.0 gm/cm^2 .

The beams used above were generated using heavy target assemblies originally intended for isotope production. The targets themselves were from 3 to 10 times the maximum bombarding particle range, and an additional 7 to 10 mm thickness of cooling water and aluminum or titanium structure existed behind the target. The extent of the energy loss and flux reduction due to this excess scattering material is uncertain. Investigation of the effect of a more nearly optimum target was made using the helium-3 ion on beryllium reaction. It was not the purpose of this experiment to examine the improvement in beam penetration made possible by using targets thinner than maximum particle range as reported by Goodman et al. (39), but to study the effect of reduced scattering in a target assembly capable of handling full beam power and producing maximum neutron yield. This unit consisted of a 3 mm thick beryllium disc cooled on its periphery by water and on its face by an air blast. For an infinite field and 50 cm SSD, a small but definite increase, 0.5 gm/cm^2 at 50% depth in beam penetration, was observed and 19% in dose rate obtained.

Fig. 15. Collimated Neutron Depth Doses 50CmSSD

Fig. 16. Beam Profiles at Different Depths

2. Fast Neutron Flux

Measurements of the fast neutron flux in the 3 to 15 MeV energy interval were made near the surface of the phantom using sulfur pellets for helium-3 ion and deuteron on beryllium reactions for both collimated and uncollimated beams. The results of these measurements together with the ratios of tissue dose and fast neutron flux for collimated relative to uncollimated beams are shown in Table X.

TABLE X

Comparison of Collimated and Uncollimated Neutron Beams

Reaction	Flux $n/cm^2/sec/u$ amp 3-15 MeV		Flux Ratio <u>10 cmx10cm Field</u>	Dose Ratio <u>10cmx10cm Field</u>
	Field 10cmx10cm Field			
⁹ Be(³ He,n)	2.1×10^5	2.5×10^5	1.2	1.3
⁹ Be(d,n)	5.2×10^5	6.1×10^5	1.2	1.3

Since the measured γ -ray contamination was approximately equal for both collimated and uncollimated beams, the greater increase in dose relative to flux for the collimated beams indicates degradation of neutron energy by scattering from the collimator as might also be inferred from the reduction of beam penetration.

3. Thermal Neutron Flux

Relative thermal neutron flux was determined as a function of phantom depth by irradiation of ^6LiF teflon thermoluminescent dosimeters in aluminum shields. This technique is convenient because the very large cross section of the $^6\text{LiF} (n,\alpha)$ reaction permits much shorter irradiations than are required for foil activation. Fast neutron and gamma ray sensitivity of the ^6LiF dosimeters do not represent a problem since, although the response of ^6LiF to Cobalt-60 gamma rays is nearly identical to that of ^7LiF , and the elastic scattering cross section for fast neutrons is similar, the thermoluminescent response for equal irradiations at a given depth was approximately one hundred times greater than for ^7LiF . Fig. 18 shows the thermal neutron distribution versus depth for the helium-3 ion on beryllium reaction with a 10 cmx10cm field. The maximum at 4 gm/cm² was found by comparison with gold foils irradiated at this depth to be 4.1×10^5 neutrons/cm²/sec/u amperes. The dose from this thermal flux is about 0.5% for the total tissue dose and is, therefore, negligible.

4. Target Design

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

Two beryllium target assemblies were fabricated and are shown in Figs. 19,20. The first accepts solid beryllium discs from 3 to 5 mm thick which

Fig. 17. Total Dose, Gamma Ray Dose and Neutron Flux

Fig. 18. Thermal Neutron Flux

Fig. 19. Water-Air cooled Beryllium Target

Fig. 20. Variable Thickness Beryllium Target

are cooled by water flow surrounding the irradiated area and by an air flow on the opposite side. In Fig. 19, the beryllium disc is removed to show the cooling channel. This target is capable of accepting full beam power, producing maximum neutron yield with minimum scattering and is therefore suitable for most experimental applications. The second target assembly shown in Fig. 20 is similar to the first and 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 (39); however, no data on helium-3 ions and protons or alpha particles have yet been published and therefore these experiments are warranted. The beryllium discs backed by a tantalum beamstop are clamped against a water cooled aluminum plate.

TABLE XI

TOTAL TISSUE DOSE RATE AT 0.5gm/cm² DEPTH IN WATER
 PHANTOM 10 cm DIAM. FIELD 100 cm SSD TISSUE
 EQUIVALENT GAS FILLED TISSUE EQUIVALENT ION CHAMBER

<u>Reaction</u>	<u>Rad/min/ μA</u>
⁹ Be(³ He,n)	0.058
⁹ Be(p,n)	0.215
⁹ Be(d,n)	0.184
⁹ Be(α ,n)	0.034
² H(p,np)	0.158
² H(d,n)	0.058

While these data may be subject to influence by improvements in collimator design or the use of filtration as described by Greene and Thomas (40) or by better targets, it is evident that small cyclotrons are capable of producing beams with 50% depth and dose rates adequate for certain clinical investigations, if beam currents on the order of 100 micro-amperes can be obtained.

5. Angular Distributions

Additional neutron field parameters were investigated using the $^9\text{Be}(d,n)$ and $^9\text{Be}(^3\text{He},n)$ interactions including the variation of the field intensity with angle, and the dose attenuation properties of various materials. The neutron energy spectra produced by the $(^3\text{He},n)$, and (d,n) reactions on beryllium have been discussed above. The relative angular distribution of the total dose for these reactions is shown in Fig. 21. These distributions were measured with the 0.05 cc T.E. ionization chamber described above which was moved in 7.5° steps about the target at a 30 cm radius. The contribution to the total dose due to the gamma radiation arising both from the prompt and activation gamma rays at the target is expected to be less than 10% and to exhibit an isotropic distribution. Similarly, any scattering from the room walls will be small and isotropic. Therefore, the angular distributions of the total dose reflect the behavior of the neutron component of the field plus a small isotropic component. The excellent agreement of $^9\text{Be}(d,n)$ distribution measured here with that of ref. (41) in which the neutron angular distribution was measured by time-of-flight techniques, indicates that the gamma ray and wall scatter components are negligible. The strong forward peaking of the $(^3\text{He},n)$ and (d,n) reactions suggests a large direct reaction component in the respective cross sections. Conversely, the relatively isotropic behavior at forward angles of the $^9\text{Be}(p,n)^9\text{B}$ reaction component in its cross section. Forward peaked neutron fields have obvious advantages when collimation problems are to be considered.

Dose attenuation curves for the $^9\text{Be}(^3\text{He},n)$ and $^9\text{Be}(d,n)$ fields were measured in the experimental arrangement shown schematically in Fig. 8. The 1.0 cc T.E. ionization chamber was positioned 45 cm in front of an 8 cm diameter, collimated field. Steel, lead and polyethylene-lead-boron (80% Pb, 1% by weight) bricks (cross sectional dimensions of 10 x 20 cm) were placed between the collimator face and the ionization chamber. The initial brick

RELATIVE ANGULAR DISTRIBUTION OF TOTAL DOSE

Figure 21. Relative angular distributions for three neutron producing reactions.

Figure 22. Dose attenuation curves for three materials in ${}^9\text{Be}({}^3\text{He}, n)$ fast neutron field. A schematic of the experimental arrangement is shown.

Figure 23. Dose attenuation for three materials in ${}^9\text{Be}(d,n)$ fast neutron field.

was placed 10 cm in front of the ionization chamber. Additional bricks were added as shown in the figure. The results for the two fields and the three materials are summarized in Figs. 22 and 23. All of the curves show a deviation from a purely exponential behavior at larger thickness which is due to scattering from the absorbing material and the room walls. These data show the superior attenuation properties of steel.

Fig. 24 summarizes the results of some composite material measurements. In this case, 25 cm of the polyethylene mixture (placed adjacent to the ionization chamber) was followed by up to 10 cm of steel or lead. These data show that the attenuation achieved by 30 cm of steel is equal to that achieved by 25 cm of the polyethylene mixture plus 5 cm of steel for the deuteron (or 10 cm for the ^3He) induced neutron field. Thus, an optimum collimator system for these fields does not have to include a large amount of heavy material such as steel or tungsten. A relatively small amount is adequate to degrade the average neutron energy to a region where light weight hydrogenous materials are effective.

The variation of the total dose with depth in water represents a fundamental parameter of interest for any given neutron field under study. Fig. 26 shows the depth dose behavior for the deuteron and ^3He on beryllium fields measured at SSD's of 100 cm and 85 cm respectively. The measurements were made with the 0.05 cc T.E. chamber in the water tank which was placed either 25 cm (for the $^9\text{Be}_d$ field) or 10 cm ($^9\text{Be}+^3\text{He}$ field) in front of the 5 cm diameter collimator. These collimator to surface distances (CSD) were necessary because of space considerations. The representations of the dose between the surface and 0.8 cm in Fig. 26 are approximate extrapolations. The half value depths are 6.5 cm

Figure 24. Dose attenuation curves for some composites of materials in ${}^9\text{Be}({}^3\text{He},n)$ and ${}^9\text{Be}(d,n)$ fast neutron fields.

Figure 26. Depth dose curves measured for the collimated fast neutron fields produced by the SKI cyclotron compared with that obtained in the $^9\text{Be}(d,n)$ reaction at the Hammersmith cyclotron. The latter includes only that part of the total dose arising from neutrons.

and 7.2 cm for the deuteron and ^3He induced fields respectively. The corresponding dose rates at the surface for these geometries are 7.5 (^3He) and 13 (d) rads/100 $\mu\text{a-min}$. For comparison the depth dose measured at the Hammersmith cyclotron for a $^9\text{Be}+\text{d}$ (E-16 MeV), 6x4 cm field is also shown in Fig. 26. With an SSD of 120 cm, the penetrability of the Hammersmith field is only slightly better than that of the $^9\text{Be}+^3\text{He}$ field at an SSD of 85 cm.

6. Gamma Ray Measurements

The components of the total dose arising from gamma rays and neutrons as a function of depth have been studied in detail. The results are summarized in Fig. 27. The solid lines labeled "Total Dose" and "Gamma Dose" were measured using the .05 cc T.E. and the .05 cc aluminum (argon filled) ionization chambers respectively. The gamma-ray dose is plotted as a percentage of the total dose at the surface. It is larger for the ^3He induced field and increases relative to the total dose as a function of depth for both the ^3He and deuteron induced fields.

The data points show the variation of the neutron planar fluence as determined using two sets of activation foils. The threshold for the $^{115}\text{In}(n,n')$ $^{115\text{m}}\text{In}$ reaction is at approximately 1 MeV. The reaction cross section rises rapidly and has a reasonable value (200 mb) up to at least 10 MeV. Therefore, the data from these foils, shown as open circles, approximate the behavior of the total neutron spectrum. The fact that the neutron fluence drops off faster with depth than does the total dose is due to the increasing gamma-ray contamination. The $^{27}\text{Al}(n,p)^{27}\text{Mg}$ cross section increases slowly from approximately 4 MeV and reaches a peak between 11 and 13 MeV. The relative neutron fluences measured with these foils (the solid data points) show the behavior of the higher energy portions of the neutron energy distributions. The divergence of the aluminum and indium activation data indicate an increase in the average

Figure 27. Total dose, gamma dose, and relative neutron planar fluence as functions of depth in water for an 8 cm collimated field.

neutron energy with increasing depth in water.

Similar data, obtained along a line 4 cm in front of the 8 cm diameter prototype collimator, are shown in Fig. 28. The total dose in air (the dashed line) was measured with the 0.05 cc T.E. chamber and is compared in the figure with the relative neutron fluences determined using the indium foils. The approximation, that these activation data represent the behavior of the total neutron fluences, is less valid here than it was in the discussion above. Large differences between the central axis and penumbra neutron energy distributions will directly influence the results. Nevertheless, the differences between the total dose curves and the activation data are, to first order, directly proportional to the gamma ray dose. The differences between the "in-air" and the 1.8 cm depth "in-water" total dose curves are due to scatter within the water phantom. A final collimator design will require that this latter difference be large relative to the total dose measured in air.

Examples of the isodose distributions obtained with this prototype collimator (a nominal 5 cm field) are shown for the deuteron and ^3He induced fields in Fig. 29. These were measured in the water tank described above at SSD's of 100 cm (CSD-25 cm) and 85 cm (CSD-10) respectively.

7. Microdosimetry

Simple total dose characterizations of high linear energy transfer (LET) radiation fields are inadequate to describe the observed radiobiological response of systems exposed to them. This response is found to have a strong dependence upon the LET of the radiation. In the case of a fast neutron field, the dose is deposited by charged secondary particles which have a large range of LET values.

In hydrogenous materials, neutrons in the energy range of interest here ($E_n < 10$ MeV) lose their energy primarily by scattering with protons. The recoil protons have a minimum LET depending upon the maximum energy available (< 10 keV/ μ),

Figure 28. Relative dose in water, in air, and relative neutron fluence as functions of position across the collimated 8 cm diameter neutron fields.

Figure 29. Iso-dose distributions for the ${}^9\text{Be}({}^3\text{He},n)$ and ${}^9\text{Be}(d,n)$ reactions.

and a maximum LET (~ 90 keV/ μ) at the Bragg peak. Similar behavior is exhibited by alpha particles, produced in (n, α) reactions, which have a maximum LET at the end of their track of approximately 220 keV/ μ . Heavier reaction products and recoiling nuclei are densely ionizing resulting in LET values of greater than 200 keV/ μ . Any variation of the neutron energy spectrum will alter this complex distribution of dose in LET and result in a change in the biological response.

To determine the degree of variation, dose distributions in LET have been measured at various positions within a water phantom for the collimated fields described above. Event spectra were measured with the T.E., 1.27 cm diameter, spherical proportional counter. Because the range of event sizes exceeds the dynamic range of the multichannel analyzer, it was necessary to obtain the data at three different gain settings. The data were reduced by a computer program which combined the spectra and smoothed the resultant spectrum using a cubic spline technique.

Fig. 30 shows the distribution of dose in LET, $D(L)$, times the LET, L , as a function of L , for the ^3He induced field at a depth of 2.2 cm. This plot shows the various features, namely, the dose arising from the heavy recoils, the alpha particles, the low energy protons and the increasingly energetic protons. Fig. 31 shows another way of presenting these data. $E(L)$ is the portion of dose which appears above a given value of LET.

Fig. 32 shows how the major part of these distributions vary as a function of position within the field. The solid and dashed curves were obtained on axis, at depths of approximately 2 and 12 cm. There is observed, in both reactions, an increase in the portion of the dose delivered at lower values of LET as the depth is increased. That is, the average energy of the recoil protons increases with depth. This is consistent with the hardening of the neutron energy distribution observed with the activation foils. The

Figure 30.

- (a) Distribution of dose in LET, $D(L)$ times the LET (L) vs LET for ${}^9\text{Be}({}^3\text{He},n)$ reaction.
 (b) $E(L)$, the portion of dose appearing above a given value of LET for the above reaction.

Figure 31. $E(L)$ distributions for two neutron producing reactions measured on axis at a depth of 2.2 cm in water.

Figure 32. LET distributions for two neutron producing reactions as a function of position in the neutron field.

Figure 33. Comparison of calculated and measured D_0 values for HeLa cells at three depths in water.

dotted curves were obtained 2 cm inside the penumbra of the collimator. The neutron energy has been markedly degraded resulting in the recoil proton dose appearing at higher values of LET.

In order to estimate the variation of the biological response which would be associated with the measured distributions of dose in LET, and the increasing gamma dose at depth, the R.B.E. versus LET mammalian cell data of Barendsen *et al.* (42) were used to calculate R.B.E. values at a 0.5% survival level. These were then compared with the HeLa S-3 cell survival curves measured at three depths, for both the Be+d and Be+³He fields. These measurements were made in collaboration with B. Djordjevic.

At a 0.5% level of survival the R.B.E. approaches the ratio of D_0 values obtained for the neutron and X-ray survival curves. Using an X-ray D_0 value of 119 ± 8 rads gives a range of predicted D_0 values shown in Fig. 33. These show that little variation of biological response is expected with depth. Experimental D_0 values, shown as data points, are consistent with this. They lie somewhat below the calculated values, but considering the accuracy of the calculation, the agreement is reasonable.

W. DOSIMETRY OF ULTRA-HIGH INTENSITY RADIATION SOURCES

The program of studies to investigate phenomena connected with ultra-high intensity pulsed radiation sources is of considerable interest in its relationship to both biological and chemical effects (43-47) and their dependence on the delivered dose rate. Research performed in the dosimetry of sources with dose rates greater than 10^9 rad/sec is essential to radiobiological and radiochemical investigations of a fundamental nature. Current experiments in radiobiology involve measurements of the radiation response of bacterial cells (43) and mammalian cells exposed to single and double pulses of electrons of very short time duration (a few nanoseconds). These experiments are aimed at understanding the response of cells irradiated at very high dose rates and at gaining information important to elucidation of the mechanism of the oxygen effect in cells.

The dosimetric program includes the development of fundamental methods of absorbed dose measurement, secondary dosimeter systems, beam monitoring methods, depth-dose distributions in very thin layers of tissue equivalent material, the characterization of beam parameters and the investigation of the dose rate response of various secondary dosimeters.

A. 30 Nanosecond Electron Generator

Two types of pulsed electron sources were employed. They are the Field Emission Corporation Model 701 and dual channel Model 706 system, consisting of two generators which can irradiate a single sample from opposite sides with a controlled time delay between pulses. Fig.34 shows a block diagram of this dual channel system.

The 701 system produces a singly-occurring pulse of electrons whose average energy is about 500 KeV. The pulse duration is 30 nanoseconds measured by the full width at half maximum, and the beam current is about 1000 amperes. Doses of a few megarads per pulse can be delivered near the tube face, yielding maximum dose excess of 10^{12} rads/second.

The Model 706 electron generator produces a 3 nanosecond pulse of 530 KeV electrons with a beam current of 4000 amperes. Here the dose is again a few megarads near the tube face, but the maximum dose rate is in excess of 10^{14} rads/second.

These pulsed electron generators using the phenomenon of field emission are characterized by: 1) very short irradiation times, 2) high beam currents, 3) ultra-high dose rates, and 4) low penetration into materials (typically 2mm in water) due to the relatively low energy. The following section will deal with the systems which have been developed since these generators were installed at this laboratory.

Fig. 34. Experimental Set Up of Dual Channel 706 System

Fig. 35. Apparatus for Monitoring 30 Nanosecond Electron Pulses and Calorimeter System

Early work involved the use of blue cellophane dosimetry and thermoluminescent dosimeter powders to establish the dose at various distances from the source. The necessity of these measurements is dictated by the nature of the pulsed electron sources, since dose is most conveniently varied by changing source to sample distance. The developments to which this preliminary work contributed will now be presented.

Fig. 35 shows a block diagram of the apparatus used in conjunction with the 30 nanosecond Model 701 electron generator. Starting from left to right, the Field Emission generator is shown with a beam current monitoring transformer in the form of an annular ring such that the electron pulse passes through the center of this annulus. The beam continues on moving from left to right, whereupon it is intercepted by an intensity measuring calorimeter. The recording systems for these two devices are shown at top and bottom right. Fig. 35a shows a photograph of the Field Emission generator which is the large cylindrical device in the center. The beam current monitoring transformer is held by the rectangular plate of aluminum in the center of the photograph. To the left of center, the calorimeter is supported on a cylindrical aluminum stand. The device in the lower foreground is an irradiation jig which can hold thermoluminescent dosimeters in a geometry which is identical to the calorimeter for intercomparison.

1. Beam Monitoring System

A current monitoring transformer in the shape of annular ring was chosen due to the relatively low energy of the electron beam which requires that a non-intercepting type monitor be used. It has been shown (48) that such a monitor could be used with high precision. This particular application of a current transformer for very high speed, non-repetitive current pulses is unique. As the

electron pulse passes through the aperture of the current transformer, a voltage pulse is produced which is passed through a delay line and then integrated with a matched filter. The peak height of the integrated pulse is then read out with a memory voltmeter. These electronics have their own battery operated power supply so that transients cannot be transmitted through the a.c. line. Further investigation has shown that the beam current monitor pulse can be integrated directly on a capacitor with the use of a recently developed high back-resistance diode which has a turn on time of about 100 picoseconds. The monitor output can then be compared to any measuring device that is at the irradiation position.

2. Intensity Calorimeter

The calorimeter consists of a 3 mm thick disc of aluminum with diameter of 35 mm. This disc is suspended on nylon monofilaments inside an aluminum vacuum jacket which has an entrance window of 0.5 mm Mylar. The aluminum wafer contains a single thermistor to measure temperature changes, and four small precision resistors to permit calibration by depositing a known amount of energy in the calorimeter electrically. A lead is also provided to either return the stopped electrons to ground, or to allow the charge to collect on a capacitor, whereby the number of electrons absorbed can be determined by measuring the voltage across this capacitor. Fig. 36 shows the interior of the calorimeter along with the suspended aluminum.

Since it is possible to measure simultaneously the following quantities: intercepted energy, collected charge and monitor output for each pulse, the monitor can be calibrated in terms of either energy or charge. It is also possible to determine how charge collected by the calorimeter is related to the energy deposited.

Fig. 35a. 30 Nanosecond Model 701 Electron Generator and Associated Apparatus

Fig. 36. Interior view of Calorimeter with Vacuum Jacket Removed

3. Current Monitor

The integrated current transformer output was compared with both the average beam intensity and charge collected on the calorimeter at various distances from the tube window. Fig. 37 shows data taken on different days comparing the calorimeter and monitor output. Fig. 38 shows a comparison to the charge collected. Data points are seen to lie within $\pm 1.5\%$ of a linear least square fit line. Fig. 38 shows the result of integrating the coil output directly on a capacitor with a high back-resistance diode. Some problems of long term drift associated with the method of recording the coil monitor output on the peak reading voltmeter have been overcome by using a diode-capacitor integrator. This result is demonstrated in the following Table.

Fig. 37. Linear Least Squares Fit Comparing Beam Intensity to Monitor Output

Fig. 38. Linear Least Squares Fit Comparing Collected Charge to Monitor Output

TABLE XII

COMPARISON OF CALORIMETER AND COIL READINGS TAKEN OVER A PERIOD OF ONE MONTH

Distance of Calorimeter wafer to Field Emission tube (in cm.)	Percent Difference in Calorimeter Reading inferred by coil (in %)
9.3	1.44
12.0	1.09
15.0	2.46
20.0	1.53
28.0	1.94

If the energy deposited per pulse and the collected charge per pulse are known, the average electron energy is determined. Average electron energies for various distances from the source are shown in Fig. 40. The average electron energy was calculated at each distance along with the r.m.s. fluctuation. The fall off beyond 10.3 cm reasonably follows the approximately 2 KeV/cm slope expected for 500 KeV electrons in air.

4. Energy and Charge Fluence

Using the intensity calorimeter, the manner in which intercepted energy or charge varies with distance from the source along the beam axis was determined. This information is required since the output of the electron source cannot be easily controlled; therefore, dose is controlled by varying the source to target distance. The variation of these quantities with distance is shown in Fig. 41. Intercepted energy varies as $r^{-2.41}$ while charge varies as $r^{-2.39}$. Due to energy losses in the intervening air, the slope is slightly greater for the variation of energy with distance than for charge.

Fig. 39. Linear Least Squares Fit Comparing Beam Intensity to Monitor Output with Improved Recording Method

Fig. 40. Mean Electron Energy as a Function of Source to Detector Distance

Fig. 41. Linear Least Squares Fit Comparing Collected Energy and Collected Charge with Source to Detector Distance

Fig. 42. Calorimetric and TLD Distance Functions

The response of ^7LiF and $\text{CaF}_2\text{:Mn}$ thermoluminescent dosimeters has been studied over the dose rate region corresponding to the variation in beam intensity used in radiobiological studies. Teflon matrix dosimeters 0.3 mm thick were placed on a disc in a dummy calorimeter to insure similar irradiation geometries. Nine dosimeters of each type were irradiated in groups of three at each distance and the corresponding distance functions computed by least squares analysis. Fig. 42 shows the normalized calorimetric and TLD distance functions. The field emission tube used here was not the same one previously discussed and, consequently, the calorimeter distance function is slightly different. The LiF and calorimetric distance functions are highly similar, while $\text{CaF}_2\text{:Mn}$ shows a somewhat greater slope. Calculations based on fractional energy absorption of the incident electrons by the dosimeters given an estimated dose rate variation of from 1.5×10^{11} to 3×10^{12} rads/sec. The area covered by the $\text{CaF}_2\text{:Mn}$ dosimeters was only 10% of the area of the calorimeter wafer while the area covered by the ^7LiF dosimeters was about 40% due to differences in their diameters. The spatial distribution of energy could influence the distance function obtained with $\text{CaF}_2\text{:Mn}$ dosimeters. To study the variation in field flatness, a number of irradiations with a total of twelve dosimeters affixed to the wafer in the dummy calorimeter were made at various distances. Typical results are shown in Fig. 43. The central area is shown to have about 15 to 25% higher dose than the periphery and consequently the normalization of the $\text{CaF}_2\text{:Mn}$ data based on average intensity was biased. Results obtained to date indicate a lack of dose rate dependence in these two dosimeter systems in the range investigated here.

For the purpose of investigating the dose delivered to thin cellular layers used in radiobiological studies, the depth dose distribution has been examined using microtomed $\text{CaF}_2\text{:Mn}$ teflon dosimeters. A depth dose distribution in polystyrene obtained with dosimeters from 15 to 30 microns thickness is

TYPICAL % DOSE DISTRIBUTIONS ON
CALORIMETER WATER AT VARIOUS
DISTANCES FROM SOURCE

Fig. 43. TLD Field Mappings

DEPTH DOSE IN POLYSTYRENE FIELD EMISSION ELECTRON SOURCE

Fig. 44. Depth Dose Distribution in Polystyrene

shown in Fig. 44. The experimental points were fitted to a fourth degree polynomial by least squares analysis. This fit indicates a surface dose of approximately 67% of that at the dose maximum. The extrapolated range of 173 mg/cm^2 compares favorably with the value of 178 mg/cm^2 calculated for monoenergetic 500 KeV electrons in polystyrene.

B 3 Nanosecond Electron Generator

The Field Emission Corporation Model 706 electron generator produces singly occurring pulses of electrons whose average energy is about 530 KeV. The pulse length is about 3 nanoseconds, measured by the full width at half maximum. Beam current is on the order 4000 amperes and doses of up to a megarad can be delivered, yielding a maximum dose rate in excess of 10^{14} rads/sec.

This machine depends upon the phenomenon of field emission of electrons from metal discharge points whose radius of curvature is about one micron. These discharge points are arranged in a ring which is in a glass envelope under high vacuum (about 10^{-8} torr). The individual firing of these emitters cannot be controlled and this fact contributes to the observed pulse to pulse variation in the machine's output.

The high beam current, short duration, and relatively low energy of the electron pulses produced by these generators create several problems. In our progress report (48) our experience with beam containment detailed the solution to the problem of the Bennett "Pinch Effect" (49) in which ionization of the air surrounding the beam tends to electrostatically re-focus the moving electrons in an unstable manner. The 30 nanosecond 701 system does not suffer from this problem due to its lower beam current. This instability of the output of the 3 nanosecond electron generator was removed by the use of adjustable length vacuum columns which have the added advantages of maintaining a good cylindrical geometry and allows the source to experiment distance to become stable and repeatable. This second consideration is a necessary

consequence of the machine design, since the delivered dose is most conveniently varied by changing the source to experiment distance.

The techniques which were developed during research performed with the Model 701, 30 nanosecond electron generator provided a basis for measurements made with the Model 706 generator which has a factor of 10 shorter pulse duration and four times the beam current.

1. Beam Monitoring System

Pulse to pulse variations have been monitored with a small beam current monitor acting as a current transformer (50). This device consists of a loop of wire whose plane is perpendicular to the field emission tube window. When a pulse of electrons passes over the loop, the magnetic field associated with the moving charge induces an e.m.f. in this loop which is proportional to the time derivative of the beam current pulse. The operation of the pick-up loop as a current transformer is achieved by damping its output with a resistor. The area under the pulse which results is found to be proportional to the area under the pulse produced by the Faraday cup. A block diagram of the experimental arrangement appears in Fig. 45.

The detection circuit (51) integrates the total area under the pulse. This process is electronically equivalent to a measurement of charge. The integration is performed by two transistors which act as high speed switches. The first transistor contains an R-C network in its collector circuit which charges during the duration of the nanosecond input pulse. After amplification this signal charges another R-C network in the collector stage of a transistor. The result is a microsecond pulse whose peak amplitude is proportional to the charge contained in the input pulse. Recording of this peak amplitude is achieved with a peak detector circuit (52) which stores the measured value in volts. This measurement is then displayed on a digital voltmeter.

Fig. 45. Block Diagram of 3 Nanosecond Electron Beam Monitoring System

Fig. 46. Nanosecond Pulse Integrator System

Two nanosecond integrators have been built and are housed in a single chassis as shown by the photograph in Fig. 46. One of the integrators is shown in the operating position and the other has been removed to show the interior construction. Power for these units is derived from a storage battery powered d.c. to a.c. inverter which eliminates fluctuation and transients which can occur when normal line current is used.

2. 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, are that a scintillator will yield a direct read-out with suitable electronics, follow fast pulses, cover a large dose range and be made in various thicknesses down to 0.005 inches.

A high speed scintillation detection system has been constructed which employs "Pilot-8", 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, which matches the fluorescence spectrum of the scintillator fairly well.

Fig. 47 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. 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 obtained with an optical transmission that is essentially flat in the region of emission from the Pilot-B.

It has been found (53) 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 (.0007") has been placed in contact with the scintillator and the holder so that the front surface is grounded. This foil is shown in Fig. 48, 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 (51). 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.

BLOCK DIAGRAM OF SCINTILLATION DETECTOR SYSTEM

Fig. 47. Experimental Set Up for Scintillation Detector

Fig. 48. Exploded View of Scintillation Detector

Using a 1/8" thick disc of Pilot-8 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 Fig. 47. This graph shows that the scintillation detector and the Faraday cup (Fig. 48) have essentially the same dependence of measured output versus distance from the electron source. Further experiments are under way 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.

3. Thin Foil Calorimeter

Calorimetric methods can be used to measure the dose due to absorption of high intensity pulse radiation incident on a material (54,55). 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 to 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 = $1.455 \text{ MeV cm}^2/\text{gm}$

Fig. 47. Linear Least Squares Fit Comparing Collected Charge with Monitor Output

Fig. 48. Linear Least Squares Fit Comparing Beam Intensity to Monitor Output

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

Convertin 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 quantity of heat

$H = .612 \times 10^{-2} \text{ cal}$ $S = \text{specific heat} = \frac{H}{m \Delta t} = .112 \text{ cal/gm}^\circ \text{C}$

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 in terms of absorbed dose to yield readings for doses of 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, we can obtain direct measurements of the absorbed dose in a thin layer of material over a wide range of dose.

Fig. 49 shows a photograph of the calorimeter. A block diagram of the experimental set-up is shown in Fig. 50. 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 at which biological samples would be placed. The beam current pick-up loop has now

Fig. 49. Thin Foil Calorimeter (Right) and 3 Nano-second Pulsed Electron Generator (Left)

Fig. 50. Experimental Set-Up for Thin Foil Calorimeter

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 radiation heating from the window of the field emission tube, a 0.007" by radiant heating from the window of the field emission tube, a 0.007" aluminum foil is therefore, placed before the calorimeter as a shield.

The material used for the calorimeter disc is 0.002" titanium to which a micro-miniature iron-constant thermocouple is 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 provides 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 (52) 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.

V. Solid State Detector and Germanium Gamma Camera Program

The solid state detector program is currently centered upon the development of a semiconductor gamma camera from an array of ultra pure germanium diodes and the evaluation of the utility of this device in both clinical and biological applications. Demonstration of the practical imaging capabilities of a small prototype germanium camera has been presented in previously reported biological tests on small mammalian organs (56,57). For convenience of reference these results are illustrated in Fig. (51). The lower half of the figure is a germanium camera image of a rat thyroid obtained after the animal's injection with ^{123}I (159 keV). The upper section of the figure is an anterior and posterior photograph of the thyroid taken following its excision. The individual thyroid lobes are resolved in the gamma camera image although their separation is less than 4 mm. Ultra pure germanium diodes have been chosen over lithium drifted diodes in this work because of their superior bulk and surface properties and because they do not require the lithium drift process and continuous cryogenic cooling. The camera development is based upon an orthogonal strip geometry is shown in Fig. (52) a with its mode of signal address schematically depicted in (b) of the same figure.

1. Germanium Gamma Camera

Initial electrical and biological test results were for a prototype gamma camera with a $(2 \times 2) \text{ cm}^2$ detector. This determined consisted of a 36 cell matrix of 5mm thickness which was shown to have a spatial resolution of less than 4 mm from both phantom and point source measurements. The successful operational testing of this prototype device provided a basis for construction of a larger matrix which will be discussed below. Fig. (53) was obtained with

Dot image of thyroid of rat injected with ^{123}I

Figure 51. A. Anterior and posterior photograph of excised rat thyroid
B. Germanium camera image of rat thyroid after animal was
injected with ^{123}I (159 KeV).

B

POSITION INDICATION FOR GAMMA RAY ABSORBED IN ORTHOGONAL STRIP MATRIX

Figure 52. A. Orthogonal Strip Geometry
B. Mode of Signal Address

Figure 53. A. Image of ^{99m}Tc (140 KeV) phantom containing 3 and 4 mm diameter hot spots, 9 mm separation
B. 5 mm hot spot has been introduced between the other two

the (2 x 2) cm² prototype matrix and is a photograph of a storage scope image of a ^{99m}Tc phantom which appeared in the last report. The image of the same phantom which appeared in the last report. The image of the same phantom obtained with an Anger scintillation camera through the same collimator is shown in Fig. (54). The separate radioactive regions in the phantom could not be resolved by the Anger camera under optimum operating conditions. A similar test was made with a ^{99m}Tc point source and showed the inability of this instrument to detect position separations of less than one centimeter at this isotope energy.

The importance of adequate groove resistance, as noted there, is in the effective elimination of "crosstalk: between electrode strips and in the reduction of charge loss at the electrode strip boundaries through the restriction of the electric field lines to the electrode strip regions. Further tests were conducted on the prototype matrix. The importance of adequate groove resistance levels is further demonstrated by the data appearing in Fig. (55) where measured noise levels (FWHM) for the p-side electrode strips have been plotted against reverse bias across the matrix. The upper half contains the noise levels (FWHM) for each p-side electrode strip as obtained with an r.m.s. volt meter. In the lower half, the same data were derived directly from measurements of a ⁵⁷Co(122 keV) source. The agreement between the two sets of data is quite good considering that the ⁵⁷Co measurements reflect other sources of line broadening over and above those it has in common with the rms measurements. It can be seen in this figure that for both sets of data, the resolution curves become relatively flat over a range of between 180-220 volts reverse bias. This is the voltage range at which the depletion region reaches the bottom of all p-side grooves for the prototype device. The noise contribution

Figure 54. Anger scintillation camera image of ^{99m}Tc phantom through the same collimator used with the germanium camera. The separate hot spots are not resolved.

Figure 55. Resolution of p side electrode strips versus reverse bias

due to diode capacitance, which varies with reverse bias, is insignificant in these resolution curves. This is evidenced in the lower half of the same figure by the early flattening of the plot of the measured resolution for a representative n-side strip. The relatively narrow voltage range in which these curves level out for all p-side electrode strips is a coarse but significant indication of a corresponding uniformity of crystal impurity concentration along the grooves. These data imply, at most, a variation of 22% in impurity concentration along the grooves. These data imply, at most, a variation of 22% in impurity concentration along the equally spaced grooves.

The question of matrix stability was further pursued with the first prototype matrix. The device was temperature cycled several times between liquid nitrogen and room temperature without opening the cryostat. The total exposure time to room temperature was two days. No degradation in spectral resolution was observed. Following a single opening of the cryostat to room ambient conditions, measurements with ^{57}Co were repeated. Initially, these showed that some broadening of the base of the 122 keV ^{57}Co peak on the low energy had resulted for two p-side electrodes while the resolution (FWHM) remained unchanged. These conditions became somewhat worse with time and eventually appeared at all p-side strips. The deterioration was the result of matrix surface contamination occurring during opening of the matrix to air.

2. Construction and Testing of Ultra-Pure Germanium Diodes

Diode 2038-4. The facilities for producing boron implanted p^+ contact was the last report period. This apparatus is modelled, in principal, after that used at General Electric where this type of p^+ contact was developed. The first ultra pure germanium wafer employed with these facilities was a p type (4 x 4) cm, 4.4 mm thick wafer with a specified impurity concentration of 2.1×10^{10} atoms/cc. This was supplied as a research specimen by the vendor

prior to delivery of two 5 cm diameter pieces on order for purchase.

Repeated efforts were made to produce an acceptable diode from this germanium sample using the new boron implant facilities and the conventional techniques for forming a lithium diffused n+ layer. However, the resolution of the ^{57}Co (122 keV) peak never improved below 6 keV even when the bias across the diode was well beyond the depletion voltage. Further, probing the diode surface with a ^{57}Co (122 keV) pencil beam showed that the diode had regions of charge trapping where the 122 keV and 136 keV peak were barely discernible in the pulse height spectrum. Further work with this germanium was suspended and work begun on a smaller diameter (3 cm) wafer of ultra pure germanium from crystal #415 to determine whether the poor diode quality achieved with the previous piece was due to the germanium or to an inferior p+ boron contact.

Diode 415-5.

The same procedures were followed in the construction of a diode from the new material and yielded a diode with resolution (FWHM) of under 4 keV for .5 microsecond filter time constants and a warm f.e.t. The overvoltage capability of the diode was almost twice as great as the depletion voltage before breakdown. These results, while not dramatic, demonstrated the effectiveness of the boron contact applied with the "in house" facilities and provided a basis for attempting to construct diodes from the then received larger diameter (5 cm) wafers of ultra pure germanium from crystal #2077. The two sections of this p-type crystal were of 5 and 10mm thickness before processing.

Diode 2077-5. It was decided to attempt construction of a diode from the thinner piece first. The quoted impurity concentration for this section was 1.6×10^{10} atoms/cc. This was cut into an approximate 12 cm² square. The same fabrication procedures were employed as with #415. A diode of acceptable quality was obtained. In the reprocessing which required repeated

etching of the wafer, the thickness was reduced to 4mm. Spectral measurements of ^{57}Co were made on this diode with a room temperature f.e.t. and yielded resolution of 3.5 keV. Considering the rather high capacitance (around 45pf) of the nearly 12 cm^2 diode this resolution figure contains a substantial electronic component which when eliminated yields a resolution of less than 3 keV. Measurements of diode capacitance versus reverse bias were made with the diode in its cryostat at liquid nitrogen temperatures. According to the vendor's quoted impurity concentration for the germanium, the voltage expected to produce full depletion of the diode was 144 volts. The capacitance measurements indicated that A in Fig. (56). This data implies an impurity concentration less than 1×10^{10} atoms/cc. Since this diode was considered a suitable candidate for eventual conversion into an orthogonal strip matrix, it was removed from its cryostat for the additional processing which has been found necessary to protect the electrodes. Further spectral measurements were made following this which showed that the overall resolution (FWHM) had improved to below 3 keV for ^{57}Co (122 keV) even with a warm f.e.t. Elimination of the room temperature electronic noise component reduced the resolution figure to around 2 keV. Capacitance measurements were repeated and are shown as curve B of Fig. (56). The flattening of the curve at under 100 volts again implies an impurity concentration of less than 1×10^{10} atoms/cc. The capacitance of 45pf measured at depletion of the diode was around 6% high than the calculated geometric capacity. This is not an unusual discrepancy.

As a check on the impurity concentration inferred from the capacitance measurements with the capacitance bridge, a collimated source of ^{241}Am (59 keV) was used to measure the variation in the thickness of undepleted germanium with bias voltage at different points on the diode surface. Particular attention was given to the use of short filter time constants in the amplifier in these measurements to minimize the effects of charge diffusion into the depletion

CAPACITANCE VERSUS SQUARE ROOT OF RECIPROCAL BIAS VOLTAGE
DIODE 2077-5

Figure 56. Diode 2077-5. Capacitance versus reverse bias measured with capacitance bridge.

region as observed by Baertsch (58). The capacitance variation with reverse bias calculated from these absorption measurements is shown in Fig. (57) along with the capacitance bridge measurements for ready comparison. It can be seen that the radiation attenuation measurements also support a value of less than 1×10^{10} atoms/cc for the impurity concentration of the ultra pure germanium. A plausible reason for the discrepancy between these data and the vendor's figure for impurity concentration is that the germanium in the diode under test came from the more central region of the original wafer since the latter was cut into a square. A high impurity concentration in the outer section of the germanium wafer could have contributed undue weight to the value of impurity concentration obtained for the total volume.

Diode 2077-9

The second section of crystal 2077 was nearly 10 mm thick upon receipt. The specified impurity concentration was $.8 \times 10^{10}$ atoms/cc. A diode was fabricated from this material using the same procedures employed with the first section from the same crystal. The diode electrodes were prepared in advance for eventual matrix formation since there was no longer reason to doubt the effectiveness of the boron implant procedures. As before, a square piece of germanium was cut from the original wafer after lapping both of its faces into within .0005 inch of plane parallelism. The finished diode, after etching, had dimensions of $12 \text{ cm}^2 \times 8.7 \text{ mm}$ in thickness. Spectral measurements of ^{57}Co (122 keV) were made and a resolution of 2.5 keV was obtained with the room temperature f.e.t. A typical spectrum obtained on the multichannel analyser is shown in Fig. (58). Capacitance measurements were made to determine the variation of depletion thickness with bias voltage. The measured capacitance of 19.41pf at 250 volts, which is essentially the

Figure 57. Diode 2077-5. Capacitance versus reverse bias determined by ^{241}Am (59 KeV) absorption measurements.

Figure 58. Typical spectral measurement of ^{57}Co (122 KeV) with diode 2077-9. Resolution of 122 KeV peak is 2.5 KeV (FWHM).

depletion voltage, is remarkably close to the value obtained for the calculated geometric capacitance of 19.43pf. The occurrence of full depletion of the diode at 250 volts or less implied an impurity concentration of $.6 \times 10^{10}$ atoms/cc as compared to the manufacturers specification of $.8 \times 10^{10}$ atoms/cc. Since the performance of this diode was better than the one produced from the thinner section of the crystal and since it offered a greater gamma ray absorption efficiency with its more than twice greater thickness, it was decided to form the first of the larger matrix arrays from this diode. To confirm the results of the capacitance measurements with the bridge and to obtain an appreciation of the degree of uniformity of the impurity concentration across the diode, radiation attenuation measurements were again made with a narrow beam probe constructed from a collimated source of ^{241}Am . The capacitance calculated from typical data obtained from these measurements and its variation with depletion voltage is shown in Fig. (59). Capacitance values obtained with a capacitance bridge are shown in the same figure. The agreement between the two data sets over the range of 20 to 200 volts is quite good, the extreme deviation between points being less than 8%. In an effort to detect small variations in the depletion voltage over the diode surface, a narrow beam probe was constructed from a collimated source of ^{125}I (28.4 keV). A germanium layer of around .075mm is sufficient to attenuate a beam of this energy by 50%. It was expected that the full depletion voltages obtained from these measurements for the diode would be somewhat less than the full value because of the diffusion of charge carriers from the undepleted region on the p-side into the depletion region. However, no slow charge component peak associated with this effect could be observed on the multichannel analyzer. The absorption measurements and the radiation absorption measurements obtained with the ^{241}Am source of Figure (59) where capacitance curves depart from linearity at 200 volts.

Figure 59. Diode 2077-9. Capacitance versus reverse bias from capacitance bridge and ^{241}Am (59KeV) absorption measurements.

To test the uniformity of the charge collection process in the diode before using it in the construction of a matrix, a 1 mm beam of ^{57}Co (122 keV) gamma rays was used to probe the diode response at sample points on the diode surface. As part of this work an intensity profile measurement of the narrow beam source was made to determine the effective beam diameter at the diode surface. The axis of the collimated source was mounted at a right angle to the shaft of a micrometer and moved across the edge of a lead absorber in increments of .005 inch. The distance between the source aperture and the plane of the lead absorber was 1 cm. The radiation passing the edge of the source was monitored with the diode which was located immediately beneath. The thickness of the lead was such that the transmission was effectively zero (less than 10^{-7}) when the source aperture was over the lead slab. The data so obtained are presented in Fig. (60). Each point represents the integration of the counts under the 122 keV photopeak at the particular source position. It can be seen that the intensity across the beam axis rises from 10% to 90% of its full intensity in about 1.2mm. Measurements were made of diode response to this source at twenty different points over the diode p-side surface. A resolution of 2.5-2.7 keV for the 122 keV photopeak was obtained at all positions with a warm f.e.t. while the charge collection efficiency varied less than 5% for the entire set of measurements.

The photoelectric absorption efficiency of the diode was measured relative to a one inch thick sodium iodide crystal for both ^{57}Co (122 keV, 136 keV) and $^{99\text{m}}\text{Tc}$ (140 keV). At these energies, this thickness of sodium iodide crystal provides 100% absorption efficiency. Such data provide a basis of comparison between the diode and the orthogonal strip matrix formed from the diode. For both isotopes, a collimated source was fixed in position and the detectors moved

Figure 60. Intensity profile of narrow beam probe of ^{57}Co gamma rays.

under them in turn. The ^{57}Co source used was the narrowly collimated one whose intensity profile appears in Fig. (60). The $^{99\text{m}}\text{Tc}$ source was a pertechnetate solution provided by the Institute's Central Isotope Laboratory and was collimated to a 1 1/2mm beam through over an inch of collimator path. In all measurements the same fixed source to detector distance was used for both the germanium diode and the sodium iodide crystal. For ^{57}Co , including both the 122 keV and 136 keV lines, the photoelectric absorption efficiency for the 122 keV line is .62 while it is .49 for the 136 keV component. The measured photoelectric absorption efficiency of the diode for $^{99\text{m}}\text{Tc}$ was .51. The calculated value is .47.

3. Construction of a New Orthogonal Strip Matrix

Upon completion of the above tests, diode 2077-9 was formed into a 10 x 10 electrode strip matrix 3.25 cm on a side. The resulting device is shown in Fig. (61) where the original (2 x 2)cm² ultra pure germanium matrix is shown next to it for comparison. In addition to almost a factor of 3 increase in area, the increase in absorber thickness (5mm compared to 8.7 mm) will result in a significant improvement in gamma ray sensitivity. Initial tests performed at the writing of this report indicate that all electrode strips of the matrix are operating despite two unplanned openings of the cryostat due to a mechanical problem with the cryogenic system. Spectral resolution for ^{57}Co (122 keV) of 4 keV (FWHM) has been measured.

Tests required to characterize the image quality and ultimate stability of camera properties along with biological applications of the device will be complete before the end of the current contract year.

Figure 61. Photograph of new ultra pure germanium orthogonal strip matrix along with original (2 x 2) cm prototype matrix.

VI DOSIMETRY FOR BRACHYTHERAPY

1. TLD Measurements

Extensive application was made of lithium fluoride microdosimeters to define the radiation fields present in the vicinity of discrete isotope sources utilized in interstitial therapy. The dosimeters, in the form of lithium-fluoride impregnated teflon rods, 1 mm in diameter, permitted the measurement of the dose from these sources at distances as close as 0.2 cm from the center of the source. Sources of various isotopes used for interstitial implantation were placed in a tissue equivalent phantom made of mix D. A double spiral of dosimeters located at radial source. The spiral placement of the dosimeters prevented them from shielding one another from the radiation source and permitted the simultaneous exposure of two dosimeters at each distance.

It had been intended originally to examine the radiation field about cesium-131 sources. This isotope decays by electron capture, emitting a characteristic X-ray approximately 30 KeV, and considerable advantages in therapy had been anticipated from its application. However, shortly after the initiation of the experiments, this isotope became available in suitable form for use in interstitial implant therapy. Consequently, emphasis was placed on the examination of the radiation fields produced by iodine-125 and Xenon-133, both low energy gamma emitters, and a comparison of their radiation fields with those produced by radon-222 radium, and gold-198. Appreciable differences in the scattering and absorption of the low energy emitters. The computer program employed at this Center for the determination of dose distributions in interstitial implant therapy, utilizes the inverse square law relationship from the source to a point in the field in order to

calculate the dose at that point. It was therefore desirable to see to what degree the actual radiation fields differed from the mathematical model, and the influence which this difference has upon the compute dose distributions.

* The dosimeters were removed at varying times from the initiation of the exposure to compensate for the variations in dose expected as a result of the distance of the dosimeter from the source and the decay of the isotope source. The use of varying times permitted all dosimeters to be dosed at exposure levels that were approximately equal. The advantage of this method is that it does not require correction for the non-linearity of the lithium fluoride phosphor. Typical standard deviations of $\pm 3\%$ were obtained for the dosimeters and within these limitations the measurements are considered satisfactory.

Consider a linear radiation source L cm long and of strength q millicuries of an isotope with a specific dose rate constant Γ . The average dose rate detected by a linear dosimeter w cm in length whose center lies in the equatorial plane of the source at a distance of d cm from the source is given by the expression:

$$R_{\Gamma} = \frac{2 \Gamma q}{Lw} \left[\frac{L+w}{2d} \tan^{-1} \frac{L+w}{2d} + \frac{w-L}{2d} \tan^{-1} \frac{L-L}{2d} - \frac{1}{2} \log \left(\frac{1 + \left(\frac{L+w}{2d} \right)^2}{1 + \left(\frac{L-L}{2d} \right)^2} \right) \right] \tau / \text{hr}$$

If we evaluate this expression for the constants pertinent to the experiment and with Γ and q set equal to 1, it may be used as a geometric normalization factor for the dosimeter readings. The results of the measurements for sources of the various isotopes normalized for the geometric factor are plotted versus distance in Fig. 12.

Several striking features may be observed in the resulting dose distributions. Of the isotopes measure, only Au-198 produces a dose distribution directly comparable to the idealized inverse square law. That is, the absorption build-up and scattering are almost compensatory, so that the dose corrected for geometric effects is almost constant.

For I-125 and Ra-226, the dose close to the source is reduced in comparison with the values at 1.0 cm: this undoubtedly arises from the presence of oblique filtration in the sources which would be pronounced because of the heavy filtration. For these isotopes, as well as for Xe-133 and Rn-222, a reduction in dose with distance due to the absorption of radiation is observed, although it is most evident for the low energy emitters I-125 and Xe-133.

The Rn-222 distribution shows a pronounced rise near to the source. This is the result of the relatively light filtration employed, which permits the less energetic gamma rays and high energy betas to increase the dose close to the source. Transmission measurements in the phantom material indicated a rapid decrease in the first 0.8 cm which substantiates the observed dose distribution.

The physical characteristics of the isotopes sources used in these experiments are given in Table XIII.

TABLE ~~XIII~~
ISOTOPE SOURCES FOR IMPLANTS

<u>Isotope</u>	<u>Half Life</u>	<u>Source Filtration</u>	<u>Gamma Radiations</u>	<u>Other Radiations</u>	<u>HVL-cm Broad Beam</u>	<u>(Mix D) HVL Lead</u>
Au ¹⁹⁸	2.70 days	0.2mm Pt	0.411 Mev	0.97 Mev	8.03	.13"
Ra ²²⁶	1620 yrs	0.5mm Pt	0.060-2.43 Mev(many)	$\alpha(2)$ and 0.65Mev β	12.65	.53"
Rn ²²	3.82 days	0.3mm Au	"	"	10.70	.53"
I ¹²⁵	57.4 days	.076mmAl +.076mmNi	28 Kev 35 Kev	None	2.07	< .001"
Xe ¹³³	5.27 days	.076mmAl	31 Kev	0.35 Mev β	2.55	.01"
Cs ¹³¹	9.7 days	-	29.4 Kev	None	2.9	< .001"

In order to investigate the effect of the dose distribution produced by a low energy gamma emitter (for example, iodine-125) upon an interstitial implant, a sample computation using the computer dosimetry system developed at this Institute was made. In this computation for a 27 see implant in a 3 x 3 x 3 array on 1.0 cm centers, an interpolated table of dose values was first generated by the computer at 0.1 cm increments from the experimental data. The dose at each point in a 23 x 23 matrix at 0.2 cm intervals in the 0.5 cm plane was then computed. A comparison of the result with the inverse square law distribution is shown in Fig. 13. While readily discernible variations occur within the boundaries of the implant volume, exterior to the implant there is little or no effect. Indeed, even within the volume of the implant, no variation greater than approximately 10% occurs. The variations observed are not of clinical significance and consequently with the choice of an appropriate dose constant, the computer program can be used to compute the dose distributions for low energy gamma emitters. This conclusion would, of course, be altered if bone were present in the field due to the increased photo-electric absorption for the low energy emitters, which could not be compensated for by including a simple dosimetry correction.

2. DOSIMETRY FOR ^{252}Cf MEDICAL NEUTRON SOURCES

The Memorial Sloan-Kettering Cancer Center has participated in the U.S. Atomic Energy Commission's program to evaluate ^{252}Cf neutron sources for radiation therapy. Dosimetry projects during the years have included the preparation of a survey report on ^{252}Cf neutron and gamma ray dosimetry, extensive ion chamber measurements of neutron and gamma ray dose distributions

in tissue-equivalent fluid, and a preliminary evaluation of an apparent problem with high beta ray dose rates from singly-encapsulated, stainless steel after loading cells.

The status of dosimetry for ^{252}Cf medical neutron sources has been thoroughly treated in a report (59) on an intercomparison study performed here for an advisory committee to the Division of Biology and Medicine. This report contains an analysis of data from four sets of measurements and five sets of calculations performed at various laboratories to assess neutron and gamma ray dose distributions for application to brachitherapy. Among effects investigated for the purpose of explaining discrepancies in the data were (1) source size and encapsulation, (2) phantom size and material, including air interface effects, (3) energy response and material of detector, and (4) neutron spectrum assumptions. The results of this study were presented in part at the Third International Conference on Medical Physics, July 30-August 4, 1972 in Goteborg, Sweden (60) and have been submitted for publication.

Both neutron and gamma ray absorbed dose distributions have been measured in the vicinity of ^{252}Cf applicator tube sources. These measurements employ paired miniature ionization chambers having tissue-equivalent wall and gas for total neutron-plus-gamma ray dose, and aluminum walls and argon gas for gamma ray dose only. In order to obtain high ion current, without sacrificing spatial resolution by increasing chamber volume, six ^{252}Cf sources are suspended simultaneously at equivalent geometrical positions in radial fashion about the chamber. A multiple-source manipulator apparatus designed specifically for this purpose permits positioning at 0.5 cm intervals up to 8.5 cm in both radial and axial directions. Data analysis is not yet complete, but the results show agreement to within about 10% with values recommended in the intercomparison report and with previous measurements here in nylon phantom (61).

The results of RBE and OER measurements last year using HeLa cells have been published (62). This paper includes a derivation of formulas for correcting measured RBE and OER values to those which would be expected for the ^{252}Cf neutron component only. The neutron OER formula is at variance with a previously published formula (63) derived in another laboratory, but the error in the latter case has been acknowledged.

In a collaborative study with E. Hahn (64) a series of rabbit testis irradiations with ^{252}Cf sources has been performed, using the exposure apparatus developed last year, in studies designed to measure the RBE of ^{252}Cf neutrons with respect to ^{60}Co and ^{226}Ra gamma rays. Reduced sperm production in the post-irradiation period serves to indicate the extent of radiation injury to the spermatogonial cell system. Semen samples are collected weekly and the concentration, motility and number of abnormalities are determined. Preliminary data indicate that 50 rad and 100 rad ^{252}Cf neutrons produce similar response curves. More data are required.

The singly encapsulated, stainless steel afterloading cells recently made available by the Atomic Energy Commission for ^{252}Cf brachytherapy have dimensions (6 mm length and 0.5 mm diameter) which made them quite compatible with the narrow lumens and sharp bends of after loading tubing in a typical removable implant. However, it is apparent that the very thin encapsulation also permits a large fraction of the emitted beta radiation to penetrate the wall. Before the new sources can be applied clinically, it is essential that the contribution of beta rays to the total dose be accurately determined.

Preliminary measurements have been made, using thermoluminescent dosimetry, of the combined beta and gamma ray dose rate at 0.5 cm from a source of this type, along the transverse axis. The 0.5 cm distance is important clinically since sources in actual implants will be spaced about 1 cm apart. The measurements were made in a polystyrene phantom, using ^7LiF powder (99.99% ^7Li) placed in a ring-shaped cavity in the plane perpendicular to the source axis and passing through its center. Without added filtration the combined $\beta + \gamma$ absorbed dose rate from a source of 0.5 μg nominal activity was found to be 19 ± 1 rad/h. Further measurements employed close-fitting cylindrical gold and platinum filters of various thickness. For a platinum filter of wall thickness 0.23 mm, the $\beta + \gamma$ dose rate was reduced to a 4.5 rad/h, roughly twice the dose rate expected (on the basis of measurement with much thicker filters) from gamma rays alone. The corresponding neutron dose rate, 4.7 rad/h, produces negligible interference with the ^7LiF measurement.

VII. FUTURE PLANS

Our plans include the development of cryogenic calorimetry applications. This technique of carrying out absorbed dose calorimetry at liquid nitrogen and possibly liquid helium temperatures offers the hope of increasing the sensitivity of fundamental measurements. Experiments could then be carried out in low intensity monoenergetic radiation fields so that comparisons of ionization chambers to calorimeters could be made as a function of energy. In this way, systematic studies of energy dependent parameters such as W could be continued and extended from our present work.

In addition, microdosimetric studies will continue in a number of radiation fields where measurements have not been carried out before. Beam quality changes will be assessed in conventional as well as densely ionizing radiation beams.

A number of ionization chamber parameters will be studied in conventional beams by using polystyrene chambers and a polystyrene calorimeter. Other materials and other designs for calorimeters will continue to be investigated.

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IX. GRADUATE STUDENTS

<u>Student</u>	<u>Degree Earned</u>	<u>Year Awarded</u>
P. Milvy	M.S.	1964
M. Sapozink	Ph.D.	1974

X PUBLICATIONS AND PRESENTATIONS

Publications

1. Detko, J., A Semiconductor Diode Matrix for Isotope Localization. Phys. Med. Biol. 14: 245, April, 1969.
2. Evans, R.G., Pinkerton, A., Djordjevic, B., Mamacos, J., and Laughlin, J.S. Changes in Biological Effectiveness of a Fast Neutron Beam with Depth in Tissue Equivalent Material. Submitted to Radiation Research.
3. Kim, J.H., Pinkerton, A., and Laughlin, J.S. Studies on the Biological Effectiveness of High Energy Electron Beams at Different Depths in Tissue Absorbing Material. Radiation Res. 33: 419, 1968.
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5. McDonald, J., Weiss, H., Pinkerton, A.P., and Epp, E. Electronic Monitoring of Nanosecond Pulses from a Field Emission Electron Source. Radiation Res., In Press.
6. McDonald, J. and Pinkerton, A., Long Term Peak Holding Detector for Microsecond Pulses. Electronics, Vol. 42, No. 23, p. 105, 1969.
7. Pinkerton, A., Comparison of Calorimetric and Other Methods for the Determination of Absorbed Dose. High Energy Radiation Therapy Dosimetry. Ann. N.Y. Acad. Sci., Vol. 161, 1969.

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21. McDonald, J.C. and Ma, I.C. Geiger-Mueller counter for mixed neutron-gamma beam dosimetry. *Nucl. Inst. and Meth.* 148:61-64, 1978.
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23. Holt, J.G., McDonald, J.C., Buffa, A., Perry, D., Ma, I. and Laughlin, J.S. Primary dosimetric standards at Memorial Sloan-Kettering Cancer Center. *Proc. International Symposium on National and International Standardization of Radiation Dosimetry*. IAEA - SM - 222/12, 1978.
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Presented Papers

1. Detko, J.F., Matrices of Lithium Drifted Diodes. Presented at the Radiation Research Society Meeting, May 22, 1969. (Invited Symposium Presentation).
2. 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.
3. Holt, J.G. and Pinkerton, A.P., The Dosimetry of Low Energy Gamma Ray Emitters. Presented at the Radiological Society of North America, Chicago, 1965.
4. McDonald, J., Weiss, H., Pinkerton, A.P., and Epp, E.R., A Nanosecond Electron Pulse Current Monitor. Presented at the 2nd International Conference on Medical Physics, Boston, 1969.
5. Pinkerton, A.P., Mamacos, J., and Laughlin, J.S., Dosimetry Studies of Cyclotron Produced Neutron Beams. Presented at the 2nd International Congress of Medical Physics, Boston, 1969.
6. Pinkerton, A.P., Alsop, B., Weiss, H., and Epp, E.R., Dosimetry Studies with a High Intensity Field Emission Electron Source. Presented at the AAPN Meeting, Chicago, 1967.
7. Pinkerton, A.P., Alsop, B., Weiss, H., and Epp, E.R., Dosimetry of a High Intensity Field Emission Electron Source. Presented at the Radiation Research Society Meeting in Houston, 1968.

8. McDonald, J.C., Pinkerton, A., Weiss, H. and Epp, E.R. Dosimetry for thin biological samples irradiated at ultra-high dose rates by electron pulses of nanosecond durations. Radiation Research Society Meeting, Boston, Mass. May, 1971.
9. McDonald, J.C., Canada, T.R., Freeman, R. and Laughlin, J.S. Physical properties of shonka A-150 tissue equivalent plastic for an absorbed dose neutron calorimeter. Fifth International Congress of Radiation Research in Seattle, Washington, July 14-20, 1974.
10. McDonald, J.C. Cyclotron produced fast neutron fields: physical and radiobiological properties. Invited Seminar at Franklin McLean Institute, University of Chicago. November, 1974.
11. McDonald, J.C., Laughlin, J.S. and Freeman, R.E. A portable tissue equivalent calorimeter. Radiation Research Society Meeting, Miami, Florida. May 11-15, 1975.
12. McDonald, J.C. and Laughlin, J.S. Fast neutron dosimetry with a tissue equivalent plastic calorimeter. Annual Meeting of The American Physical Society, New York. February 2-5, 1976.
13. McDonald, J.C. and Laughlin, J.S. Calorimetric dose measurements in fast neutron and cobalt-60 gamma-ray fields. Symposium on Measurements for the Safe Use of Radiation, National Bureau of Standards, Gaithersburg, Md. March 1-4, 1976.
14. Goodman, L.J. and McDonald, J.C. Investigations into the thermal defect of tissue-equivalent plastic. Neutron Dosimetry Workshop, Rijswijk, Netherlands. May, 1976.
15. McDonald, J.C., Kuo, T.Y.T., Freed, B.R. and Laughlin, J.S. Physical properties of a D-D neutron field. Radiation Research Society Meeting, San Francisco, California. June 27-July 2, 1976.
16. McDonald, J.C., Ma, I.C., Laughlin, J.S., Attix, F.H., August, L.S., Koehler, A., Verhey, L., and Goitein, M. Calorimetric dosimetry in fast neutron and proton fields. Radiation Research Meeting, San Juan, Puerto Rico. May, 1977.
17. McDonald, J.C., Ma, I.C., and Laughlin, J.S. Calorimetric and ionometric dosimetry for cyclotron produced fast neutrons. Third Symposium on Neutron Dosimetry in Biology and Medicine, Munich, Germany. May, 1977.
18. Holt, J.G., McDonald, J.C. and Laughlin, J.S. Primary dosimetric standards at Memorial Sloan-Kettering Cancer Center. International Symposium on National and International Standardization of Radiation Dosimetry. Atlanta, Georgia. December 5-9, 1977.

XI. SIGNIFICANCE

The value of this program is that it helps to establish reliable and accurate dosimetry for radiotherapy. It also contributes and helps to make more complete, the data set collected by radiobiology and ionization chamber measurements.

There have been problems over the years in establishing accurate dosimetry in neutron radiotherapy. The 8% error at Hammersmith was discovered and confirmed by David Bewley using his own TE calorimeter. More recently, there has been an adjustment in the dosimetry at Amsterdam of approximately 7%. We hope that our research will help solve such problems.

The further development of absorbed dose calorimetry is also of benefit to the National and International Standards Laboratories, since they are able to utilize, and have done so in the past, techniques and instrument designs originated at our laboratory.

XII. RESEARCH SUPPORT

(See following three pages).

COST CENTER 5501

PRINCIPAL INVESTIGATOR: J. LAUGHLIN

AWARDED

Source	Project Title	% Time & Effort	Annual Amount	Project Period
CA-18153-03	Cancer Studies With New Radioactive Scanning	20	\$107,206	12/1/75-2/28/79
T32-CA-09022-01	Radiation Oncology Research Training Program	10	41,282	9/30/78-8/9/82

Pending

CA-18153-04	Cancer Studies With New Radioactive Compounds	20	140,009	12/1/78-11/30/81
DOE-EE-77-S-02-4268-A002	Biomedical Research With Cyclotron Produced Radionuclides	30	1,002,272	1/1/79-12/31/79

STATEMENT OF SUP. DRT

COSI CENTER 5511

PRINCIPAL
INVESTIGATOR:

J. LAUGHLIN

AWARDED

Source

Project Title

% Time &
Effort

Annual Amount

Project Period

Pending

EY-76-02-3522

Biological And Clinical Dosimetry

15

\$37,064

1/1/79-12/31/79

STATEMENT OF FACTS

COST CENTER 5511

CO-PRINCIPAL
INVESTIGATOR:

J. C. McDONALD

AWARDED

AWARDED				
Source	Project Title	% Time & Effort	Annual Amount *	Project Period
CA-22038-02	Calorimetric Dosimetry For Neutron Radiotherapy	10	\$36,532	9/1/77-12/31/79
CA-22286-02	(Sub-Contract With American Association Of Physicists In Medicine) "AAPM Charged Particle Beam Dosimetry Task Group"	-	12,280	8/1/77-7/31/79
Pending				