DEVELOPMENT OF A WIDE-RANGE AIR-EQUIVALENT INDICATING DOSIMETER

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PREFACE

In the field of radiation chemistry there exists a need for a rapid, accurate, and reproducible technique to measure the intensity of a gamma-ray field from 1 r/hr to 10^4 r/hr. Since the radiation itself is a controlled variable, the precise measurement of the intensity is of paramount importance. This paper deals with the dosimetry of gamma radiation emitted from spent reactor fuel rods. The fuel rods used in this study were removed from a Materials Testing Reactor operated by the Phillips Petroleum Company at Idaho Falls, Idaho.

The instrument used to satisfy the above requirements consists basically of a scintillation crystal, a multiplier phototube, and a D-C amplifier. By integrating the scintillations produced by gamma rays, a measurement of the radiation intensity is effected. The instrument described in this study has good resolution due to the incorporation of an expanded scale and range switching.

It is a pleasure to acknowledge the guidance and encouragement given by Dr. H. L. Jones; the cooperation of the personnel at the Atomic Radiation Laboratory, Continental Oil Company in the testing of the detector; the permission of my supervisors to publish this paper; and certainly to Mrs. Betty L. Erickson for final preparation of the figures.

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CHAPTER I

INTRODUCTION

In the study of radiation chemistry, the radiation field generally assumes the role of a controlled variable. Therefore, it is necessary to have a method of determining the radiation dosage permitted to impinge on an experiment. In the theoretical case of radiation being emitted from a point source, the radiation at any given point can be defined by the "distance squared" law. In the theoretical case a complete field could be defined by measuring the intensity at one point and determining the geometry of the field. In the practical case of radiation from spent fuel rods, the intensity pattern is not uniform at any given distance from the source. This is due to the fact that the source is not a point source at all, but is actually a radiation volume of approximately 27 cubic feet (the volume required for four fuel rods). This is shown in Figure 1. The curve for the point source is a theoretical curve. It is calculated with reference to a point where the intensity is the same for the point source and the distributed source. In order to accurately map the intensity, it is necessary to investigate a large number of locations. The mapping is mandatory

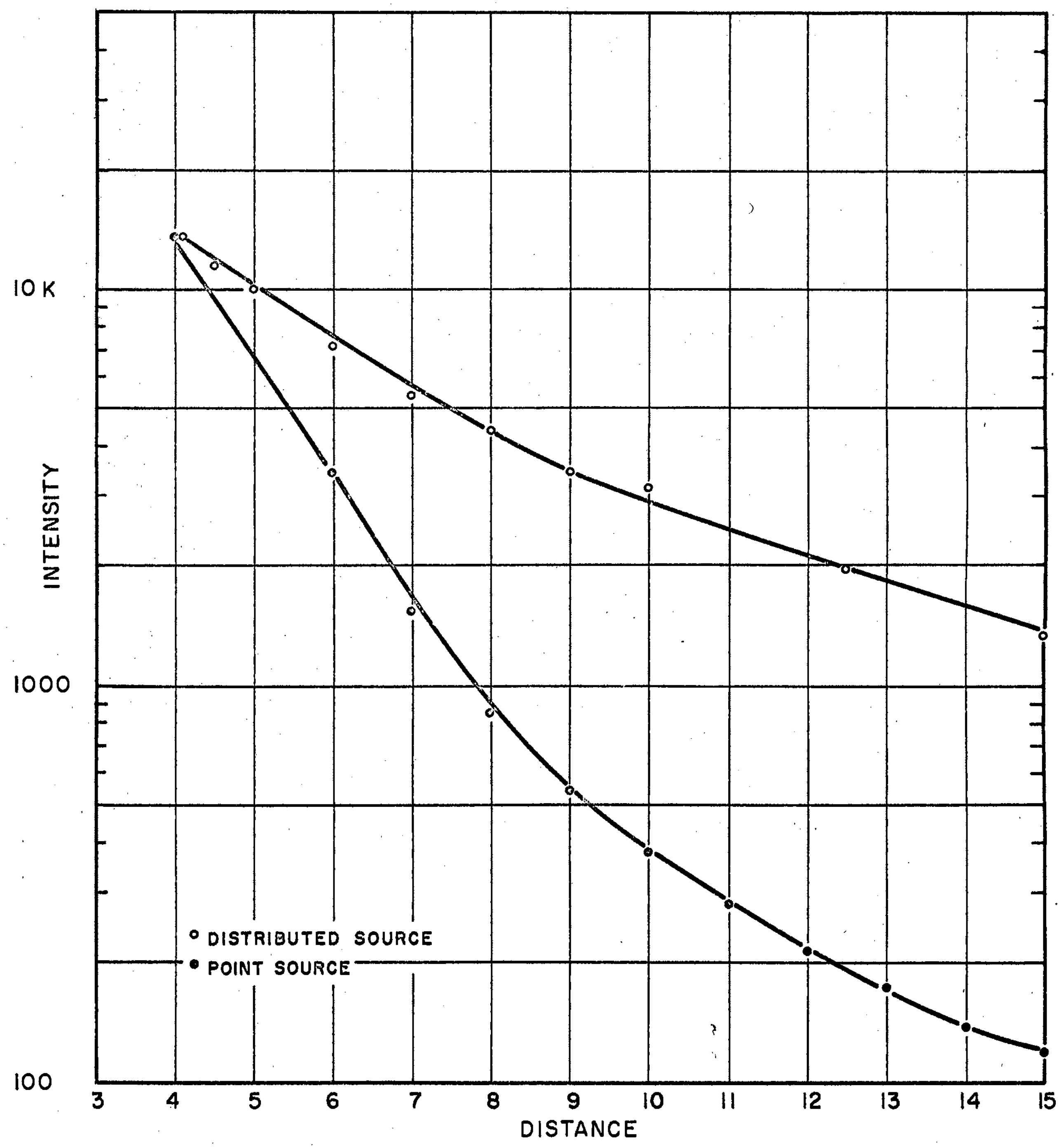

FIGURE 1. COMPARISON OF POINT SOURCE AND DISTRIBUTED SOURCE

if a large specimen is to be irradiated since this is the only method that can determine the radiation intensity at all locations on the specimen.

Ease of operation of the measuring instrument is also an important criteria to consider. A considerable amount of valuable time and manpower can be expended in making dosage measurements when some of the existing methods are used. Therefore, rapid operation and expedient results are important features to be considered in the design of a dosimeter.

The problem of dosimetry is currently resolved by two general techniques. The first technique depends on the use of a gas, liquid, or solid. On absorption of ionizing radiation, it undergoes a definite change in physical or chemical properties. This change is related in a known way to the amount of radiation absorbed. Such dosimeters are known as integrating dosimeters since the cumulative property change is measured at the end of the irradiation period. The cumulative change is then used as a measure of the total absorbed dose. Some of the more common types of chemical integrating dosimeters are: (1) ferrous-ferric, (2) ceric-cerous, and (3) methylene blue (1). One of the physical dosimeters commonly used is called "adiabatic calorimeter" (2). The actual method used in the chemical dosimeters is very similar for all three types listed. Considering the ceric-cerous as typical, it is known that the number of ceric ions reduced to cerous ions is a linear function of absorbed dosage (3). After irradiation, the ceric ion concentration is determined either by titration or by photometric techniques. As the ceric ions concentration was known before irradiation, the amount of ceric ions that were reduced to cerous ions can be found. The value of the yield is then used to calculate the dosage absorbed. A typical yield value for the ceric-cerous dosimeter, as published by Hochanadel and Ghormley (4), is 2.46 micromoles per liter per 1,000 reps.

As the name "adiabatic calorimeter" implies, this technique takes advantage of the rise in temperature of a substance when irradiated. This is a very slow and tedious method since controlled temperatures must be maintained to satisfy the adiabatic conditions. It does have the advatage of high accuracy and finds use in the calibration of the various chemical dosimeters (3).

The second technique currently employed for dosimetry measurements uses sensing elements placed directly in the radiation field for continuous measurement of parameters that will characterize the field. Any gamma-ray field can be defined by specifying the three following parameters: (1) geometry of the emitting source, (2) the intensity-time variation of the field, and (3) the energy spectrum of the emitted gamma-rays. Therefore an installation with fixed source geometry can have dosimeter techniques applied that measure the relative intensity and the energy spectrum of the emitted gamma rays. Of the types found in practice, the instrument is generally designed to measure the intensity independently of the energy spectrum. The relative intensity can then be related by separate measurements to the dose rate in the materials being irradiated. The total dosage absorbed in the material can then be calculated.

Experimental information is available in the literature which illustrates the feasibility of using an organic scintillator for air-equivalence dosimetry measurements (5). The basic unit of radiation measurement is not yet firmly established, but one unit which finds wide acceptance is the roentgen. This unit is defined by a certain quantity of ion pairs formed in air. Therefore, dosimetry based on air-equivalence would furnish useful information in quarters where the roentgen unit is accepted. The most efficient method of handling the individual scintillations from a crystal is to optically couple the light energy to the cathode of a multiplier phototube. In this study this method was utilized.

A multiplier phototube exhibits a straight line characteristic when anode current is plotted against incident light flux if the ratio of anode current to total voltage-divider current is 0.1 or less. Also the anode current vs. potential between dynode 9 and anode curve is very similar to the plate current vs. plate voltage curve for an ordinary pentode vacuum tube. Therefore, by placing a load line on the linear portion of the characteristic curve, the variations of anode current would be linear with respect to the incident light flux. The light flux emitted from the scintillator will be directly proportional to the impinging ionizing radiation. Therefore, the anode current could be measured by a VTVM, and the VTVM could be calibrated directly in roentgens/hour.

The advantages of this type of dosimeter will be found in the ease of operation, the production of a permanent record when a strip-chart recorder is used, the rapid read-out characteristic in an electronic instrument, and the ease of calibration. Also the probe can be made to a convenient size and shape. The sensitivity per unit volume is higher than an ionization chamber, and the probe may be used in a solution, solid or other inaccessible spots.

CHAPTER II

CONSIDERATION OF X AND GAMMA-RAY RADIATION AND IONIZATION DOSIMETRY

General Considerations

The subject of radiation dosimetry has its origin in the last years of the nineteenth century when gamma rays and X-rays, then newly discovered, found practical usage in the medical profession. Both the successful and unsuccessful early uses of the newly found electromagnetic radiation underlined the necessity for some quantitative measurement of the emanating energy waves.

Gamma rays and X-rays are forms of electromagnetic radiation, differing only in their origins. Gamma rays are produced in nuclear reactions, whereas X-rays are caused by the excitation or removal of orbital electrons or by the deceleration of electrons. The technique used by the great majority of the early workers to measure the intensity of the electromagnetic radiation was that of photographic and fluorescence methods (4). Also, a few chemical and physical methods were used. For example, as early as 1897 a measurement was reported showing the quantity of heat produced in a metal beam when X-ray absorption in the beam was complete. The problems encountered with the techniques mentioned above have paved the way for the ionization methods now commonly used in many laboratories.

It is interesting to note that a period of approximately thirty years passed before an internationally recognized unit of electromagnetic radiation was accepted. In 1928 the roentgen was introduced as an acceptable method of defining a gamma and X-ray radiation field.

The rapid advance of nuclear technology has now posed the problem of measuring the dosage absorbed from sources other than the X-ray units and radium sources found in the medical field. It is becoming increasingly necessary to determine the physical energy deposition in a variety of media when irradiated by any one of a wide energy range of quanta, or by any type of ionizing particle. Currently there are appearing sophisticated versions of the earlier chemical and physical methods used for dosimetry purposes. But even these methods leave something to be desired for general routine use in the laboratory. To give an indication of the extent and nature of the current problem of radiation dosimetry, attention is called to Table I (4). Electromagnetic radiation, having energies above a few Kev, ionize matter by virtue of the secondary electrons released when they are absorbed. Corpuscular radiations, those emanating from individual molecular structures, can ionize matter by either of two methods. Directly, because they are charged, or indirectly through charged particles set in motion by collision processes.

TABLE I

SOME TYPES OF IONIZING RADIATION

	Radiation	Energy Range Mev	Ionizing Particle In Tissue	Average Range of Ionizing Particle In Low Atomic Number Material	
				gm/cm^2	cm of air at NTP
1.	Beta Rays	0.015 - 5	Electron	10^{-4} - 1.0	0.1 - 800
2.	Electron Beams	2 - 20	Electron	1 - 10	800 - 8000
3.	Gamma Rays	0.05 - 2.9	Electron	5×10^{-4} - 0.6	0.4 - 450
4.	X-Rays	0.01 - 0.4	Electron	10^{-4} - 5×10^{-3}	0.1 - 4
5.	X-Rays	1 - 10	Electron	5×10^{-2} - 1.2	30 - 230
6.	X-Rays	10 - 30	Electron	1.2 - 3.5	1500 - 2700
7.	Fast Neutrons	0.1 - 10	Proton	10^{-4} - 6×10^{-2}	0.1 - 45
8.	Slow Neutrons	0.1 ev	0.6 Mev Protons (+2.2 Mev gamma ray)	10^{-3} (Protons) 0.5 (Electrons)	0.8 (Protons) 400 (Electrons)
9.	Proton Beams	5 - 400	Proton	3×10^{-2} - 10^2	23 - 8×10^4
10.	Alpha Rays	5 - 10	Alpha Particle	3×10^{-3} - 10^{-2}	2 - 8

The ionizing particles have complex energy spectra, and hence only the order of the mean range is given in Table I. In biological materials which have nearly unit density, the range can vary from about one micron to a few centimeters, or even to as much as one meter in the extreme case of very-high-energy protons. Likewise the particle range in air or other gases is an important criterion in the practical realization of ionization dosimetry. Particularly in the case of gamma and X-ray radiation, the air-ionization methods are applicable where the same type of particle empinges on both the chamber and the tissue.

It is important to note that a complete specification of the physical quality of a radiation field must include a spectrum distribution of energies present. Although for many purposes, an exact determination of the radiation quality is not necessary. In such a case, a useful function denoted as the <u>half-value layer</u> can be defined and used. This function is defined as the amount of some standard material which transmits fifty per cent of the incident radiation. The effective energy of the beam derived simply from the half-value layer does not necessarily coincide with the mean energy more correctly deduced from the photon energy spectrum. To illustrate this Figure 2 is presented (4). The effective energies derived from the half-value layers are 34 Kev and 71 Kev for radiations which have mean energies of 52 Kev and 90 Kev, respectively. The deductions from the single absorption measurement of the half-value layer underestimate

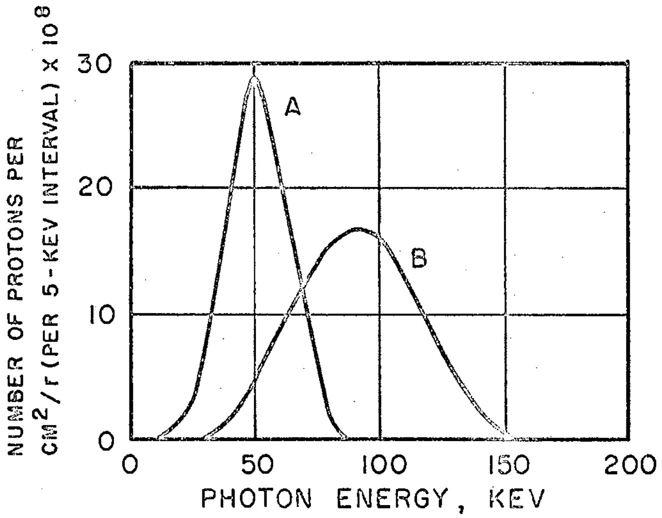

FIGURE 2. PHOTON SPECTRA DEDUCED FROM ABSORPTION DATA

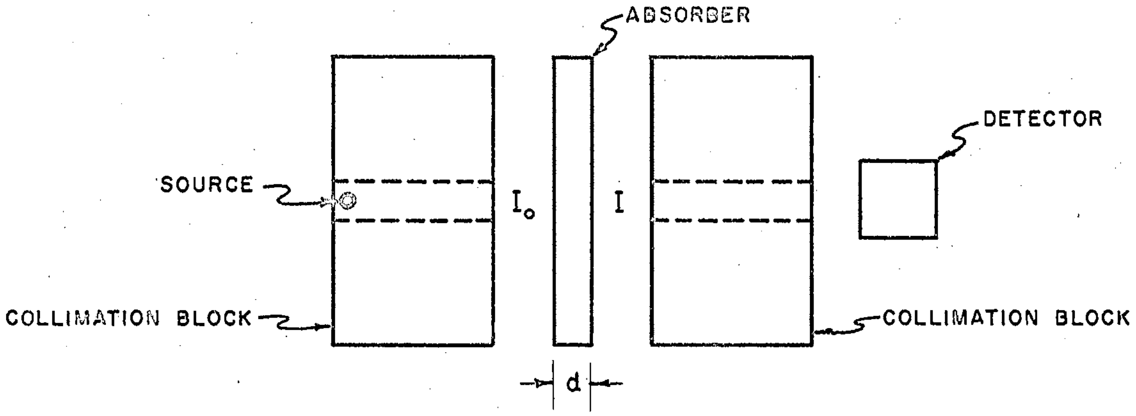

FIGURE 3. EXPERIMENTAL ARRANGEMENT FOR THE MEASUREMENT OF THE TOTAL LINEAR ABSORPTION COEFFICIENT FOR GAMMA RAYS

the mean energy of the radiation.

The <u>intensity</u> of electromagnetic radiation at any point is defined in its precise sense as the radiation energy in ergs flowing per second through 1 sq. cm of area perpendicular to the direction of propagation. This corresponds to a unit of energy flux. Therefore, the radiation of a given point is completely specified if the photon energy spectrum and the energy flux are known. An equivalent specification is the statement of the number and energy of photons flowing per second through 1 sq. cm perpendicular to the incident direction. The relationship of the energy flux to the rate of energy absorption in any particular physical or chemical system depends primarily on the photon energy and the density of the absorber (6, 7). The detection and measurement of any electromagnetic radiation necessarily involves energy absorption in a practical measuring system. Intensity measurements and dose or dose-rate measurements will be seen to present very similar problems.

It is rather axiomatic, but nevertheless it is to be emphasized, that radiation can bring about a physical change in a system only when energy is absorbed from the radiation field. A chemical or biological effect, however, may also depend on the spatial distribution of the energy released along the track of the ionizing particle. Therefore, the relative effect will depend on the type and quality of the radiation, and equal energy absorptions of different radiations may not produce equal chemical or biological effects.

The concept of "dose" in terms of a defined reaction of some standard chemical or biological indicator does not avoid the difficulty that doses of different radiations, which are equal in the defining system, may produce unequal reactions in other systems. To define "dose" in physical terms, and to use another factor to allow for the "relative effectiveness" of different quality radiation seems preferable (4).

The primary physical action of ionizing radiation is then based on energy absorption. Therefore, the fundamental concept of physical dose is the energy absorbed in ergs per gram of the irradiated material.

As mentioned above, the principle method of dosimetry has been based on ionization of standard gases, usually air. Although air ionization affords only an indirect measure of energy absorption in other media, it has found wide acceptance and has even lead to a term, "air-equivalence," which denotes the dose that an ideal air-ionization system would detect. There are two outstanding reasons for the air-ionization acceptance. One is the relative ease by which the method can be accomplished. The other is the closeness of data obtainable with air and body tissue. This closeness has also lead to a term, "tissue-equivalent," which is a measure of the dose that would be absorbed in tissue.

Units of Absorbed Dose

The original definition of a unit of X-ray dose was established at the Stockholm Congress of Radiology (1928). The definition is as follows:

> The roentgen is the quantity of X-radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produces in 1 cubic cm of atmospheric air at 0°C and 76 cm of mercury pressure such a degree of conductivity that 1 esu of charge is measured at saturation current.

At the Chicago Congress of Radiology (1937) the original definition was modified, and it is still valid, to the following:

> The roentgen (r) shall be the quantity of X- or gamma-radiation such that the associated corpuscular emission per 0.001293 gm of air produces, in air, ions carrying 1 esu of quantity of electricity of either sign.

Both forms of wording have left room for discussion as to the precise quantity which the roentgen is intended to define. What is perhaps most significant is that an amount of ionization is defined which, in fact, implies an energy absorption per unit mass of air which is almost invariant with photon energy.

It is not to be expected that the roentgen could apply without qualifications to the whole range of quantum and corpuscular radiations now available. The validity of the roentgen becomes questionable when the secondary corpuscular emission is not in equilibrium with the primary quantum radiation. For example, the roentgen is inadequate as a statement of the dose at an air-tissue interface, such as the skin, where a finite depth must be reached before secondary electronic equilibrium is attained. The difference between the true energy absorption in the surface tissue and that implied by the roentgen dose is unimportant for X-rays generated at potentials up to a few hundred Kilovolts, but becomes one of considerable magnitude in the case of high-energy radiations. In order to avoid such difficulties and to bring corpuscular radiation dose under one and the same definition, a number of units have been proposed. All are expressed essentially in terms of energy absorption without necessarily specifying the type of radiation producing it.

In order to express the total energy absorbed throughout a volume of irradiated tissue in terms of a unit related to the roentgen, a gram-roentgen has been defined. It is equal to the X or gamma ray energy absorbed when 1 gm of air is exposed to 1 r. The gram-roentgen has a value of approximately 84 ergs and is almost independent of the radiation quality. The energy absorption in 1 gm of aqueous tissue is greater than this when 1 r is received since the mass absorption coefficients of tissue and air are not identical.

The roentgen is unsuitable for expressing dose in the case of corpuscular radiations. Another unit called the roentgen-equivalent-physical (rep) has been defined to alleviate this situation. It is "that dose of ionizing radiation which produces an energy absorption of 84 ergs per cubic cm in tissue." The original choice of values has been changed in later years to 93 ergs per cubic cm since this figure represents more accurately the energy absorption per cubic centimeter of aqueous tissue which has received a dose of 1 r of hard X-rays or gamma rays. The rep specifies a fixed energy absorption per cubic centimeter of tissue, irrespective of tissue composition or type of ionizing radiation.

A unit has been proposed which would correspond to the energy value of the roentgen for gamma rays. It is the energy unit. By definition it is that dose delivered to tissue by ionizing radiation such that the energy absorbed per gram of tissue is equal to the energy absorbed per gram of water exposed to 1 r of gamma radiation.

One important unit commonly used in the field of radioactive isotopes is the curie. The expression of the activity of a particular sample in term of disintegration rate is insufficient, since for calculations of the dose the desired quantity is the total energy emitted in the form of α, β, or γ -radiation and the fractions of this energy that are absorbed. The disintegration rate together with the average β and γ -ray energy becomes the simplest way of expressing the necessary information. Therefore, in terms of disintegration rate, the curie is defined as the amount of nuclide which disintegrates at the rate of 3.700×10^{10} disintegrations per second.

For gamma ray energies in the 1- to 2-Mev range, the roentgen, the rep (93), and the energy unit all imply the same energy absorption of approximately 93 ergs per gram of soft tissue. At other quantum energies the rep and the energy unit no longer correspond to the energy absorption per roentgen in soft tissue. They are applicable, however, to any type of quantum or corpuscular radiation, and they imply a fixed energy absorption per gram of tissue. The *roentgen-equivalent-man* (rem) was defined originally as the dose which, delivered to man exposed to any ionizing radiation, is biologically equivalent to the dose of 1 r of X- or gamma ray. The rem is thus intended to take into account the relative biological effectiveness of different types of radiation.

The final terms to be considered are *absorbed dose* and *rads*. Absorbed dose is defined as the amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. It is expressed in rads. The rad is then defined as the unit of absorbed dose and is numerically 100 ergs/gm. It is to be noted that the term is "absorbed dose" and not "dose."

In consideration of the above units the rad refers to absorbed dose and the word "dose" appears only in conjunction with the definition of the roentgen, which is retained on practical grounds for use up to photon energies of 3 Mev. A dose of 1 r implies an absorbed dose of about 93 ergs/gm of soft tissue, or 0.93 rad in the range of photon energies from 0.3 to 3 Mev; but the precise value of the energy absorption depends on tissue composition and, in the lower photon energy range, on the radiation quality. The rep$_{93}$ and the energy unit, however, are both equivalent to 0.93 rad independently of radiation type and tissue composition.

A calculation of the gram-roentgen will show that its value will be nearly constant for all photon energies. The charge released by the absorption of one roentgen per 0.001293 gm of air is one esu. The number of ion pairs produced by the energy absorption is 1/Q, where Q is the electronic charge in electrostatic units. If W is the energy lost by a secondary electron per ion pair formed in air, the energy represented by this number of ion pairs is W/Q. The value of W is shown to be independent of the energy of the secondary electron except at very low energies (5). The quantity W/Q represents, therefore, a nearly constant energy absorption per roentgen for all photon energies. The value of W in air is approximately 32.5 ev, or 32.5 x Q/300 ergs. Therefore, the value of W/Q is 32.5/300 ergs. Converting this to ergs per gram of air, we have $E_a = 32.5/300 \times 0.001293 = 83.8$ ergs where E_a is the energy absorbed per roentgen in one gram of air. The value calculated for E_a is seen to be the numerical value of the gram-roentgen.

Properties of Gamma and X-Rays

The emission of gamma rays is a mechanism by which the energy of excitation of a nucleous can be removed. Such excited states may accompany the decay of radioisotopes, or they may result from induced nuclear transmutations. The gamma rays accompanying a particular type of nuclear reaction are composed of photons with either a single or a group of discrete energies. Typical energies of gamma rays range from a few Kev to several Mev. The excitation or removal of orbital electrons, which precedes the production of X-rays, may be accomplished in a variety of ways. The energy released upon the return of the orbital electrons to the ground state appears as X-ray photons. The energy of the photons is characteristic of the excited element.

The interaction of X and gamma rays with matter is primarily through three mechanisms; namely, the photoelectric effect, Compton scattering, and pair production (8). Since neither X nor gamma rays possess an electric charge, the detection process must depend on interaction with matter. The detector itself must be capable of producing interaction with the impinging electromagnetic waves. Familiarity with the mechanisms named above would enhance the ability to understand the various detectors used in dosage measurements. In the photoelectric effect, a photon of energy $\underline{hv}$ interacts with the atom as a whole. Its energy is transferred to an electron. Approximately 80% of the time the affected electron is in the innermost, or K, shell. The electron is ejected with a kinetic energy given by

$$E_{KE} = \underline{hv} - E_b \qquad (1)$$

where E_b is the binding energy of the orbital electron. When the electron shell is refilled, one or more characteristic X-rays with total energy E_b are emitted.

In Compton scattering, the primary photon may interact with any one of the orbital electrons. The electrons are considered essentially as free electrons under the condition that the primary-photon energy is large compared with the electron binding energy. The interaction may be analyzed as an elastic collision between primary photon and the electron. The energy is shared between the recoil electron and the secondary photon. This secondary photon travels in a direction generally differing from that of the primary photon, and it is referred to as the scattered photon. At low energies where the photon energy is nearly equal to or less than the binding energy, the primary photon may be reradiated or scattered with almost the entire energy. In this latter process, known as coherent scattering, the entire atom absorbs the recoil momentum; since its mass is large, it receives negligible energy from the photon.

In pair production the primary photon disappears, and its energy goes into the rest-mass energy and the kinetic energy of the positron-electron pair which is produced.

The absorption of X- and gamma rays may be studied through the measurement of their transmission through absorbers (8). If one uses an arrangement similar to Figure 3 to measure the intensity of the beam which reaches the detector, the relationship indicated is obtained.

$$I/I_o = e^{-ud} \qquad (2)$$

where I/I_o is the fraction of the photons remaining in the beam after passage through an absorber of thickness <u>d</u>. In the processes which remove photons from the beam, each absorbed photon is eliminated individually in a single event.

Since the number of photons eliminated from the beam in traversing a distance <u>dx</u> through the absorber is proportional to <u>dx</u> and to the number of incident photons, the exponential function results. The quantity u is known as the total linear absorption coefficient. The coefficient measured by the arrangement in Figure 3 includes both the true absorption of photons and the scattering from the collimated beam. This coefficient is referred to as the "narrow beam" coefficient. Its value is greater than that which would be measured by an arrangement in which scattered photons could not reach the detector. The total coefficient u can be expressed as

$$u = T + S + K \qquad (3)$$

where T, S and K represent the partial absorption coefficients due to the photoelectric effect, Compton effect, and pair production, respectively.

The most widely used unit for specifying the interaction of X and gamma radiation with matter is the roentgen. As mentioned above, the roentgen is defined as a unit based on the affect of X and gamma radiations on the air through which they pass. The measurements of the energy dissipated by ionizing radiation in a material rests on the Bragg-Gray principle. It states that the amount of ionization produced in a gas cavity serves as a measure of the energy dissipated in the surrounding material (8). This procedure relies on the assumption that the gas cavity is traversed by the same flow of corpuscular radiation as exists in the material under consideration. It is important to remember that the roentgen unit applies only to X and gamma radiations in air. Any extension of this definition to allow application to other radiations or media must be carefully scrutinized. When considering interaction with matter, the principal quantity of interest is dE/dm, the energy absorption per unit mass. Since the mechanism for transfer of energy from radiation to matter involves the ionizing processes caused by the primary radiation, ionization-cavities have played a central role in the measurement of ionization.

Determination of Dose in Roentgens

The determination of dose in roentgen units requires the measurement of an ionization current under saturation conditions. The electric field between the electrodes of the ionization chamber must be sufficient to collect all the ions without recombination, but not so strong that the moving ions produce further ionization by collision processes. In air at atmospheric pressure, ionization by collision is unlikely at field strengths less than 3000 volts/cm. For dose rates normally used in clinical and experimental work with X and gamma rays, saturation conditions are achieved with collecting field strengths well below this level. When saturation conditions do not hold, recombination may occur in two ways: (1) by "initial" or "columnar" recombination between ions along the tract of the ionizing particle; (2) by "general" or "volume" recombination between ions from neighboring tracks. Columnar recombination depends on the density of ionization along the particle track and is not itself influenced by dose rate (4). Volume recombination, however, is dose-rate dependent, since the dose rate controls the number of tracks per unit volume. Of course, the relative importance of the two phenomena in relation to the efficiency of ion collection varies with the nature of the radiation, the dose rate, and the gas pressure in the ionization chamber. For atmospheric air ionized by X or gamma rays, recombination is almost entirely due to volume recombination processes.

An examination of the definition of the roentgen shows that the ionization which is produced by all the secondary electrons ejected from a known mass of air is considered. These electrons produce some ionization outside the region in which they receive their energy. In order to apply the definition to obtain the dosage in roentgens, it is necessary either that this ionization be collected wherever it is produced or that it be compensated for by an equal amount of ionization which enters the region in question.

For absolute measurements based on the roentgen unit, the free-air standard chamber may be used. Such a chamber is shown in Figure 4. This chamber provides compensation for the corpuscular emission which leaves the sensitive volume of the chamber before producing all its ionization. This compensation is made possible by establishing artificial boundaries on the chamber by means of guard rings. Thus the "wall" of the chamber is composed of air, and any

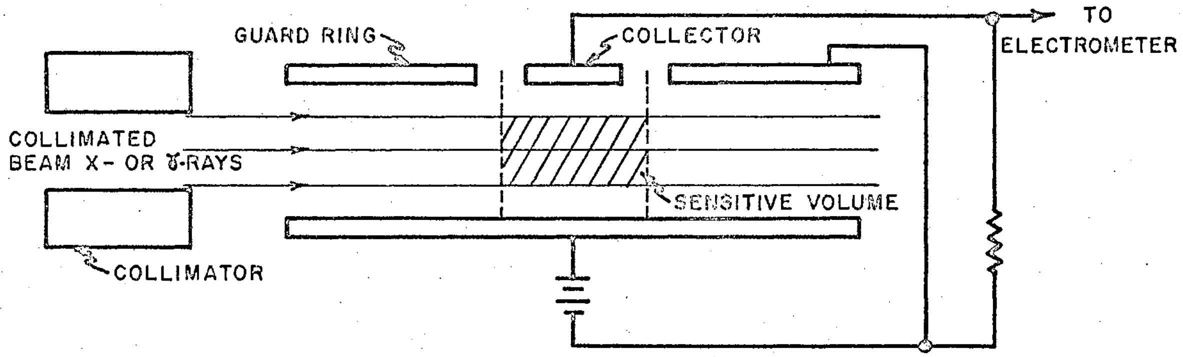

FIGURE 4. STANDARD AIR-WALL IONIZATION CHAMBER

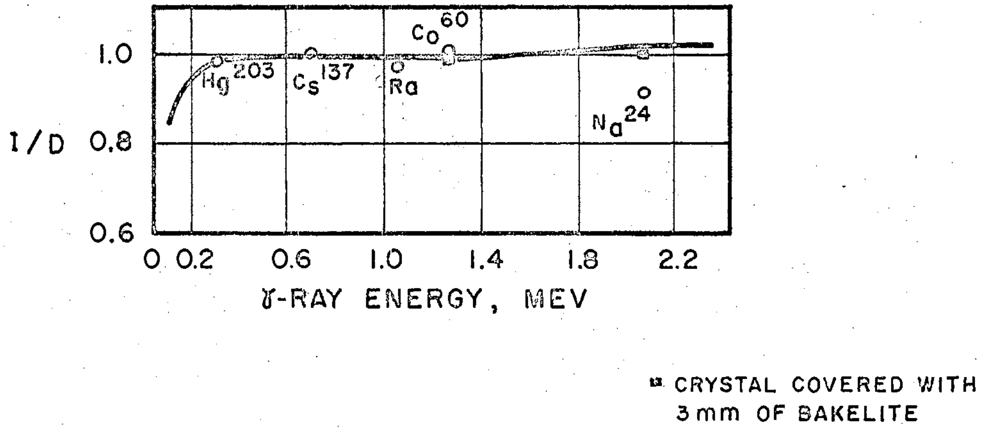

FIGURE 5. ENERGY ABSORPTION RATIO VS. GAMMA RAY ENERGY FOR A COLLIMATED BEAM

loss of corpuscular emission from the active volume of the chamber is compensated by gain from the air "walls" of the chamber as long as the secondary electrons from the small central volume are completely absorbed within the air of the chamber.

As the energy of the X- or gamma-ray photon increases, so does the size of the standard ionization chamber. This condition arises since the air "wall" surrounding the sensitive volume of the chamber must have a thickness greater than the range of the secondary electrons. By the Bragg-Gray principle, this difficulty could be circumvented through the use of an ideal solid wall of material with the same chemical composition as the air. Such a wall is referred to as an air-equivalent wall. Small air-equivalent chambers are known as thimble chambers. An air-equivalent wall can be approximated by using a material with a mean atomic number near that of air. Bakelite, lucite, and other plastics are suitable materials for this purpose. The surface of the plastic is ordinarily coated with colloidal carbon to give it the conductive properties necessary for electrodes of ionization chambers. For other wall materials, both the magnitude of the ionization in the air volume and its energy dependence will differ from those with an air-wall chamber (6, 7).

It has been shown that some organic crystals exhibit "air-equivalence" qualities when irradiated with gamma rays whose energy is between 0.2 and 3.0 Mev. (5). This facet of organic scintillators is to be used in this study. The scintillator can be optically coupled to a multiplier phototube to form a radiation detector. A scintillation detector has the desirable characteristics of high intrinsic sensitivity and enormous range. Also the physical size required of an ionization chamber to measure low values of radiation is sometimes a problem. With a scintillator, the physical construction of the detector can generally be varied to satisfy the necessary spatial configuration.

The primary purpose of this instrument is to serve as a dosimetry tool for measurements of the gamma ray field emanating from spent Materials Testing Reactor fuel rods. After a "cooling off" period of from one to three weeks these rods decay with the principal radiation being a 0.7 Mev gamma ray (9). From Figure 5 it is seen that the instrument can be used equally well to measure dose rate from Hg^{203}, Cs^{137}, Ra and Co^{60}.

To obtain a crystal which responds in a manner equivalent to air, the absorption of the primary radiation in a given thickness of the crystal must be proportional to the absorption of the primary radiation in an equivalent thickness of air. Therefore, the term "air-equivalence" is taken to mean proportionality between the energies absorbed in a given thickness of crystal and the energies absorbed in an equivalent thickness of air. In general, the absolute values of the energies absorbed will be quite different. To determine the air-equivalent energy range for scintillation materials, calculations of the ratio of the energy absorbed per second in the scintillation material, I, to the energy absorbed per second in air, D, have been made (5). For ideal air equivalence, I/D must be independent of the incident gamma ray energy. Reference to Figure 6 points out that for gamma energy between 0.2 and 3.0 Mev a thin crystal of anthracene maintains true air-equivalence. It is also noted that as the crystal thickness increases the energy band of true air-equivalence becomes more narrow. For dosage measurements to an accuracy of approximately 5%, it appears that an anthracene crystal of a few centimeters thickness may be regarded as air-equivalent over a small energy range. While Figure 6 is plotted for anthracene, it has been shown that the curve holds equally well for a variety of other compounds composed of carbon and hydrogen. Because all these compounds have their majority weight in the form of carbon, they sometimes are grouped into a general classification, and labeled C_6H_5. Some of these compounds are napthalene, stilbene, diphenyl acetylene, terphenyl, and polyvinyltoluene (5, 10).

The average secondary-electron energy in anthracene is approximately 1.0 Mev. for the gamma-rays from Na^{24} (5, 11). The maximum range in an organic scintillator for electrons of this energy is 3 mm. Therefore, the secondary electrons initiated in the last 3 mm of a crystal have a finite chance of leaving the crystal before all their energy is absorbed.

To compensate for this loss of secondary electrons, a

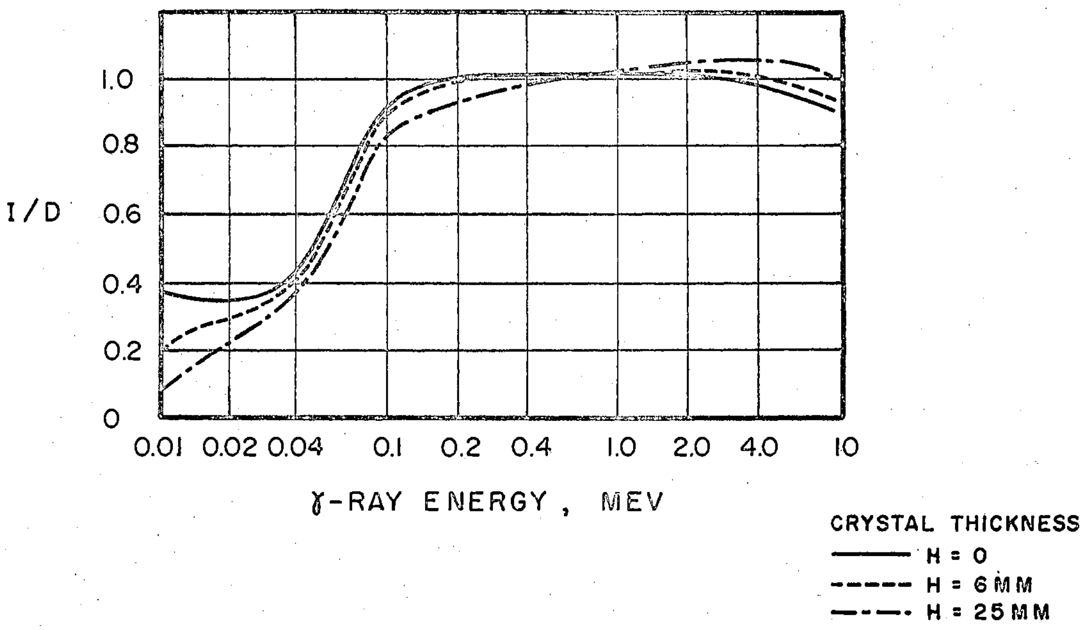

FIGURE 6. CALCULATED ANTHRACENE-TO-AIR RATIO OF ENERGY ABSORPTION VERSUS GAMMA RAY ENERGY

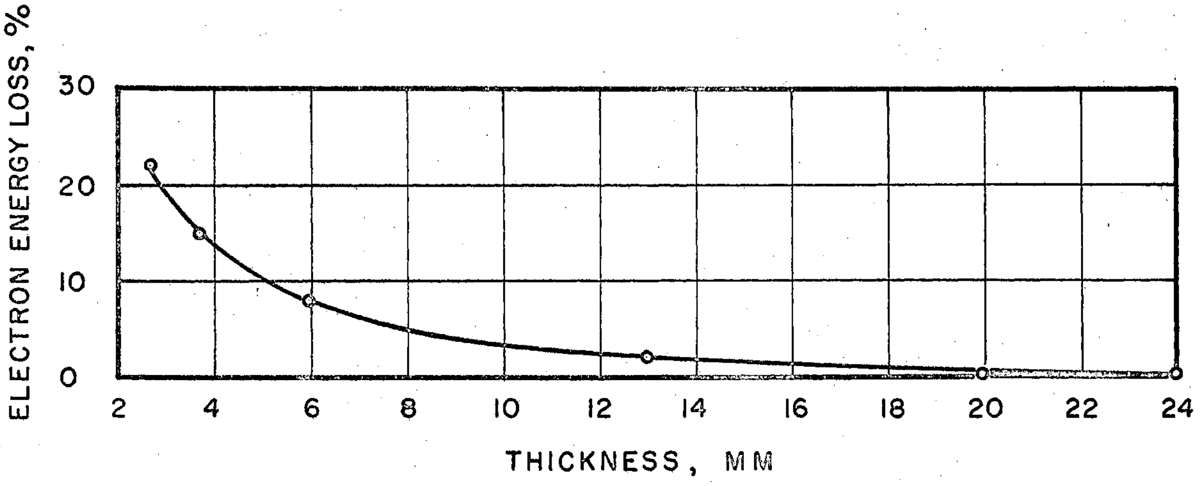

FIGURE 7. LOSS OF SECONDARY ELECTRON ENERGY VERSUS THICKNESS OF SCINTILLATOR

piece of Bakelite 3 mm thick may be placed on top of the crystal. The experimental results for this arrangement are shown in Figure 5. The Na^{24} data are now seen to be in good agreement with the theoretical prediction of true air-equivalence. Those secondary electrons produced in the Bakelite that enter the front face of the crystal compensate for the secondary electrons leaving the crystal back side. For the Na^{24} gamma rays an increase in dosage intensity was observed as the thickness of the Bakelite was increased from 0 to 3 mm. For thicknesses greater than 3 mm, the intensity slowly decreased due to absorption of gamma-rays and associated secondary electrons in the Bakelite.

The maximum range of the secondary electrons in an organic scintillator is approximately 1.5 mm for the Co^{60} gamma-rays. Since Figure 5 was originally plotted with the crystal covered with a thin cardboard light shield and aluminum foil, the addition of Bakelite did not appreciably increase the observed intensity.

The loss of secondary electrons by leakage depends on the crystal thickness as well as on the energy of the incident gamma-rays. Figure 7 shows the percentage loss of secondary electrons as a function of crystal size for the Na^{24} gamma-rays. It shows, as expected, that if the volume from which electrons can leak out becomes small in comparison with the total volume of the scintillator, the percentage loss becomes negligible. This curve was obtained using plastic scintillators of various thickness and 2.6 cm diameter. The data for Na^{24} were compared with those from lower energy gamma-ray sources for which the electron leakage is negligible even for small crystals. Therefore, when measuring gamma-ray sources with energies above 1.0 Mev, a thin scintillator must be covered by a suitable amount of air-equivalent material to maintain secondary-electron equilibrium.

Figure 5 shows the ratio I/D for gamma ray beams from a collimated source. The measurements of I/D have been repeated with uncollimated sources, and the results are shown in Figure 8 (5).

Since the crystal is not truly air-equivalent (Figure 6), the change in average gamma ray energy (primary plus scattered radiation) will affect the I/D values in two ways. A reduction in average gamma ray energy will lower I/D for low-energy gamma rays (Hg^{203}, I^{131}) and will reduce leakage loss for high-energy radiation (Na^{24}). The Cs^{137}, Ra, and Co^{60} results remained unchanged since they lie on the plateau of the air-equivalent energy region, and leakage loss is negligible for these sources and the crystal specified.

From the tube characteristics of the RCA 931-A MPT it is readily seen that a linear relationship exists between anode current and total divider current if the ratio of divider current to anode current is greater than 10 (Figures 9 and 10). Also the anode-to-dynode 9 voltage vs. anode current curves display linear anode current change to linear changes in the incident light flux on the cathode. This

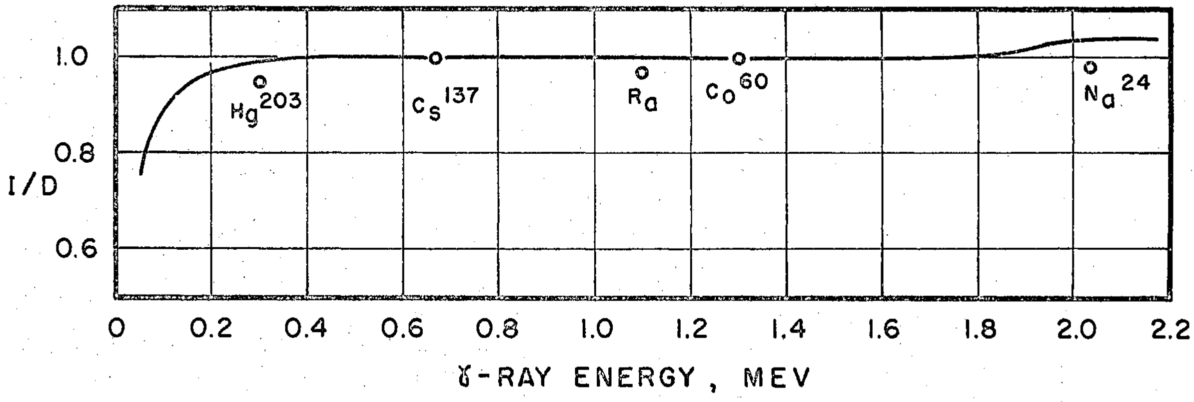

FIGURE 8. SCINTILLATOR-TO-AIR ENERGY ABSORPTION RATIO VERSUS GAMMA RAY ENERGY FOR AN UNCOLLIMATED BEAM

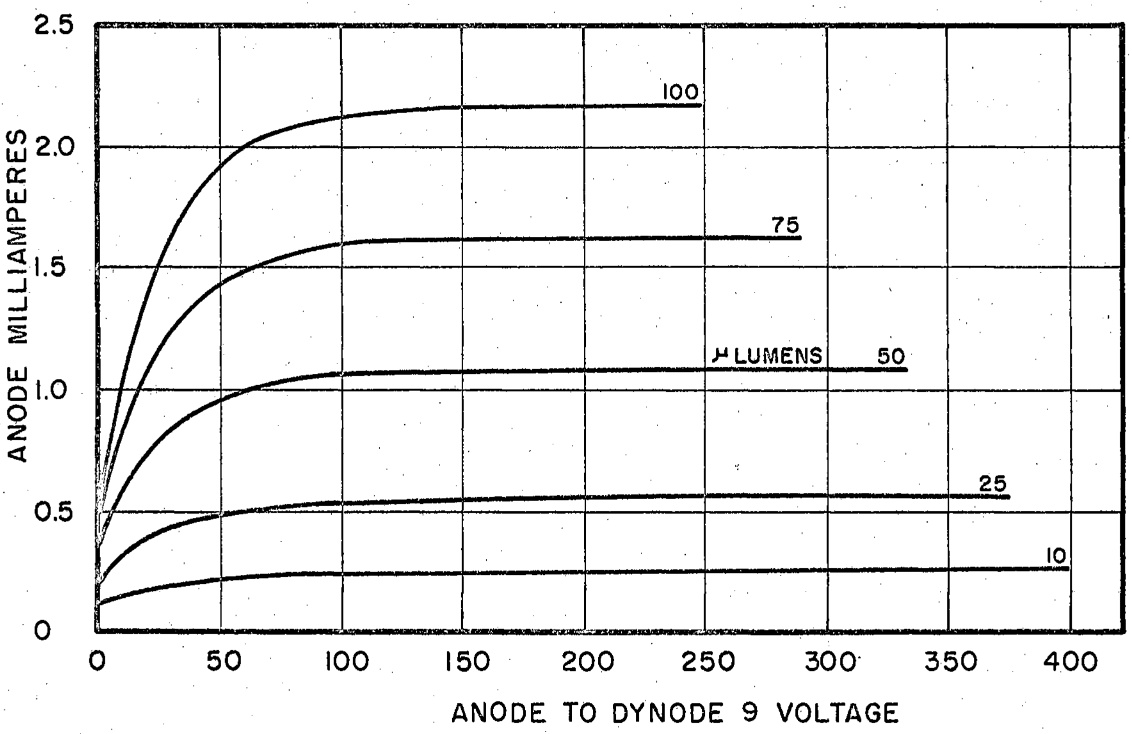

FIGURE 9. AVERAGE ANODE CHARACTERISTICS OF TYPE 931-A

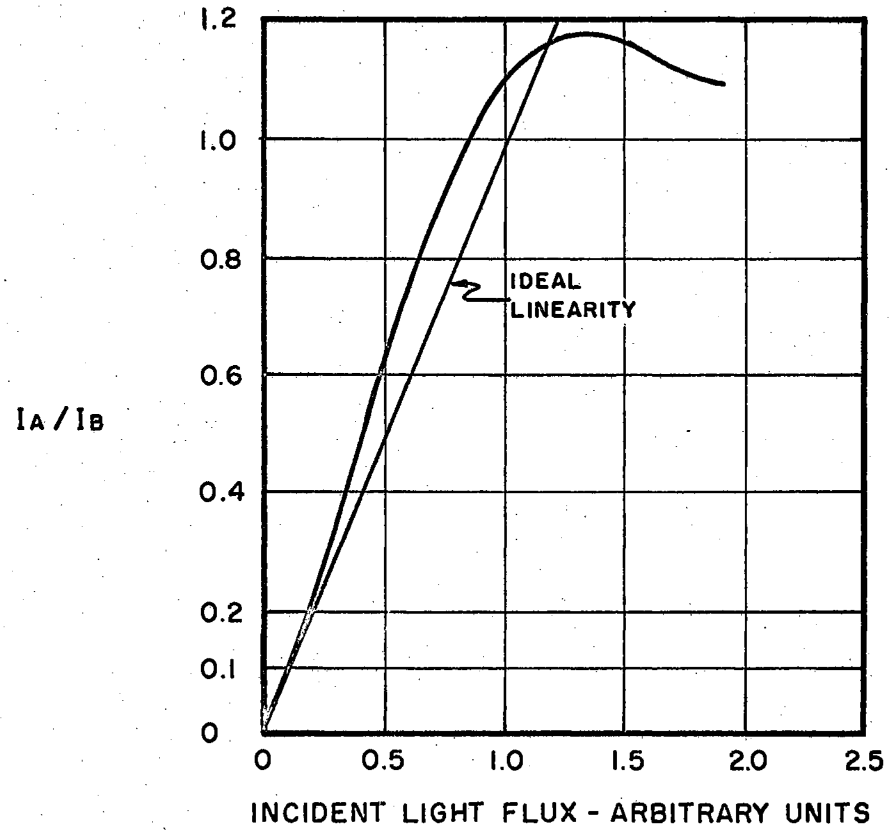

FIGURE 10. INCIDENT LIGHT FLUX VERSUS RATIO OF ANODE CURRENT TO TOTAL DYNODE DIVIDER CURRENT

suggests that by proper selection of circuit parameters an instrument can be designed that will have a linear response to incident gamma rays on an organic scintillator. The design of such an instrument is described in Chapter IV.

CHAPTER III

SOME REPRESENTATIVE METHODS OF DOSIMETRY

Objectives in Dosimetry Measurement

In the study of gamma radiation effects on matter, it is mandatory to establish the intensity of the impinging electromagnetic energy. The establishment of this quantity must be made periodically due to its decrease through radioactive decay. The half-life of the gamma emitting source will determine the frequency of intensity measurement. It is seen that ease of performing the measurement is of considerable importance when the frequency is high. Also of paramount importance is the need for accurate and reproducible measurements.

In general laboratory work it would be difficult, if not impossible, to examine individually a system of dosimetry to exactly duplicate the interaction of the gamma radiation with the specific matter under consideration. Although this would be an ideal system, an infinite number of systems would have to be devised. The approach used in practice is to examine a particular location which is related emperically to the irradiated location in question. By the relationship which exists, both the intensity and the resulting interaction with matter at the desired location can be determined. It is to be emphasized that the relationship, being emperical in nature, must be carefully used so as not to violate the initial conditions of the equality.

Dosimetry Techniques Described

To illustrate a few of the systems now being used in X and gamma radiation dosimetry, a brief description of the salient features of the following methods is given:

1. Ceric Sulfate Dosimetry - The reaction which takes place is a reduction of ceric to cerous ions (1). The amount of reduction is related to total dose absorbed.
2. Ferrous Sulfate Dosimetry - An aqueous solution of ferrous ions will be oxidized to ferric ions when subjected to ionizing radiation (1). The amount of oxidation is related to total dose absorbed.
3. Glass Dosimetry - Most glass undergoes changes which can easily be measured as a result of irradiation (12). Optical-absorption and luminescence changes are most applicable to dosimetry.
4. Photographic Film Dosimetry - Photographic film is the oldest radiation detector for determining total radiation dose (13). Photographic high-level dosimetry (10^4-10^8r) has

been made possible by the photographic print-out effect; i.e., the photolytic reduction of silver without development.

5. Electrostatic Dosimetry - The potential difference between a silvered quartz rod and an outer chamber is made equal to the voltage between the center electrode and outer shell of a thimble ionization chamber (8). After the ion chamber has been irradiated, the change from the resultant voltage on the thimble to the voltage originally set is measured by the quartz rod deflection. The measurement is a function of the total dose absorbed in the thimble.
6. Electrodynamic Dosimetry - A steady D-C current is collected when a cylindrical chamber with a coaxial center electrode has a D-C potential impressed on it in the presence of a radiation field (2, 8).

Ceric Sulfate Dosimetry

When an aqueous solution of ceric sulfate is irradiated by gamma radiation, a reaction occurs which results in reduction of ceric ions (Ce^{4+}) to cerous ions (Ce^{3+}). The yield has been shown to be independent of photon energy from about 100-KV X-rays to 2-Mev X-rays (1). Dose rates appear to have no effect on the yield from approximately 1/2 r/sec to 500 r/sec. The quantity of ceric sulfate, and therefore ceric ion concentration, to be used per unit volume is determined by the total dose to be measured. The cerous ion concentration is determined by the difference between initial and final ceric concentration. Therefore, it is obvious that it will be advantageous to begin the determination with as low a ceric ion concentration as possible since the difference between two large numbers is being taken.

Ceric ions have a light absorption maximum at 320 millimicrometers in H_2SO_4 solution. The absorption band is narrow and requires experimental location on each individual spectrophotometer. Quartz cells and a hydrogen lamp are usually used with a slit width of 0.5 mm. The cerous yield is obtained by noting the difference between pre-irradiation and post-irradiation readings on the solution. For total dose measurements less than 5×10^5 rads, the accuracy of this system is approximately ± 20%. Between 5×10^5 and 2×10^8 rads the system is accurate to ± 5% of indicated dose.

Ferrous Sulfate Dosimetry

Ferrous ions contained in an aqueous solution will be oxidized to ferric ions when subjected to ionizing radiation. The oxidation yield has been shown to be independent of original ferrous ion concentration from 10^{-2} to 4×10^{-5}M. Also the yield has been shown to be independent of quantum energy for 100-KV X-rays to 2-Mev gamma rays. Dose rates from 1/50 r/sec to approximately 200 r/sec seem to have no affect on the amount of yield. Ferrous ions (Fe^{2+}) are readily available in the form of ferrous ammonium sulfate, which can be recrystallized. The exact concentration of ferrous ions need not be known since only the ferric concentration will be determined.

Ferric ions have a light absorption maximum at approximately 304 mμmeters. It is found that the absorption peak is quite broad and therefore is not extremely sensitive to wavelength changes in the spectrophotometer. It is possible, indeed this method is used, to determine the amount of iron oxidized by using the non-irradiated sample as a reference and compare the optical density of the irradiated sample to the reference. The iron oxidation is dependent upon oxygen concentration and therefore the yield is different for aerated and deaerated solutions. The reaction in aerated solutions, which are more convenient to use, consumes oxygen up to total doses of approximately 50,000 rep. At this point all the original oxygen in the solution will have been consumed (1). It is not to be recommended that this dosimeter be used to measure total doses greater than 50,000 rep.

Glass Dosimetry

Optical-absorption and luminescence changes in glass are most applicable to dosimetry. The advantages of glass as a dosimeter material include ruggedness, shelf-life stability, stability of radiation-induced changes, reproducibility, low cost, and capability of being manufactured in practically unlimited size and shape. The dose range covered by existing systems is from 1 rad to 5×10^6 rads.

Calibration against a standard is necessary for direct dose readings. The absorption change in silver-activated phosphate glass is very useful in the dose range from 10^3 to 3×10^5 rads. In this range a linear relation is found between dose and change in absorption. A boro-silicate glass has been developed that shows linearity of response up to 10^6 rads with high sensitivity and good stability. As a result of the work done for the Quartermaster Food and Container Institute, the Quartermaster Corps is giving serious consideration to the use of glass as a secondary standard for its food-irradiation program (12).

Photographic Film Dosimetry

Because of its sensitivity, ordinary photographic film has been confined mainly to the measurement of small doses, usually less than 1 r. Photographic high-level dosimetry has been made possible by the photographic print-out effect; i.e., the photolytic reduction of silver without development (13). The advantages of print-out dosimetry are simplicity, non-directional response, no need for processing, instantaneous indication of the integral dose received and low cost. Photographic print-out emulsions do not require wet processing; i.e., developing and fixing, as do standard photographic negative and positive emulsions.

A print-out emulsion contains excess silver ions, which deposit on the sites where silver ions were reduced to silver by light absorption. In a normal photographic emulsion, there are no excess silver ions. Silver is reduced and deposited by the catalytic reaction of the developer from the silver-halide crystal at the latent-image specks that are formed by light absorption. This reaction with the developer represents an enormous amplification factor (greater than 10^9), thus explaining the greater sensitivity of normal emulsions as compared with print-out emulsions.

The sensitivity of any photographic emulsion is constant for energies higher than 0.6 Mev. Below 0.6 Mev, the response of any photographic emulsion increases with decreasing radiation energy, and therefore a separate calibration for each energy is needed.

Ordinary commercial X-ray film can also be used for high-level dosimetry. Photolytic print-out silver is formed on these films by gamma ray exposures in the range of 10^4 to 10^8 r. No rate dependence for Co^{60} exposure over the dose rates of 2×10^2 to 5×10^5 r/hr is observed. One specific factor to consider in the print-out process is temperature of the film. To enhance accuracy the film temperature must be held constant to within ± 10°C of calibration temperature.

Electrostatic Dosimetry

An electrostatic dosimeter generally consists of a cylindrical condenser-type ionization chamber. With a potential Vo connected to the electrodes of the chamber, the resultant charge Q will be given by

$$Q = C\ Vo \qquad (4)$$

where C is the capacity of the chamber. If the applied voltage is suddenly removed, the charge Q will be left on the chamber.

If a mechanism for charge transportation exists between the two electrodes, a change in charge Δq will occur which results in a change of voltage Δv. A high quality ion chamber will allow appreciable charge transfer only under the influence of ionizing radiation. In some particular cases a certain amount of charge will be transferred by insulation leakage in the chamber. This usually is negligible.

It is clear from the above considerations that to measure the change in voltage caused by impinging radiation the measuring system must remove negligible charge to effect an accurate measurement. If the ion chamber is to be physically removed from the voltmeter, the capacitance of the voltmeter must be negligible compared to the capacitance of the chamber. The gold-leaf electroscope will satisfy all the conditions outlined above. In fact, one of the original instruments used to measure the ionizing properties of nuclear radiation was an electroscope. A quartz-fiber electroscope has been developed that has many advantages over the original gold-leaf electroscope. It is more compact, less dependent on position, and more portable. As a result of its lower electrical capacity and delicate fiber, it is more sensitive. The sensitive element consists of a fine metallized quartz fiber, the metal film usually being either gold or silver.

A typical electrostatic dosimeter is described by Victoreen (8). It consists of an ion chamber and a charger-reader. The chamber is charged by inserting it in the charger-reader unit and pressing the button which connects an internal power supply across the chamber. The charge-reader uses a metallized quartz rod for charge read-out. Following the charging process, the chamber is removed from the charger-reader and exposed to the radiation field under consideration. After exposure, the chamber is reinserted into the electrometer , the latter having been first fully charged. The charge which remains on the chamber is measured by the electrometer, the deflection of the string being proportional to the ionization within the chamber. The scale of the electrometer can be calibrated in roentgens thus permitting direct determination of absorbed dose.

Electrodynamic Dosimetry

By measuring the instantaneous ion current formed in an ionization chamber with a constant voltage applied, electrodynamic dosimetry can be performed. Certain other conditions must be met to calibrate this type of dosimeter in roentgen units. One very fundamental and extremely important condition is the consideration of the ionization caused by all of the secondary electrons formed in a given mass of material. It is readily seen that this consideration can easily be violated at an interface of two dissimilar materials.

Due to the motion of the secondary electrons they can produce some ionization outside the region in which they receive their energy. For example, consider a secondary electron formed on the inside wall of an aluminum ion chamber. It is possible that the electron will travel into the wall of the chamber thus giving up its energy to the wall and contributing no ionization to the interior of the chamber where it received its original energy. In order to apply the definition of the roentgen, it is necessary either that all ionization be collected whenever it is produced or that it be compensated for by an equal amount of ionization which enters the region in question.

For absolute measurements based on the roentgen unit, the free-air standard chamber (air-wall ionization chamber) may be used. This chamber provides compensation for the corpuscular emission which leaves the sensitive volume of the chamber before producing all its ionization. This compensation is made possible by establishing artificial boundaries of the chamber by means of guard rings. Thus, the "walls" of the chamber are composed of air, and any loss of corpuscular emission from the active volume of the chamber is compensated by gain from the air "walls" of the chamber as long as the secondary electrons from the small central volume are completely absorbed within the air of the chamber.

As the energy of X- or gamma-ray photons increases, so does the size of the standard ionization chamber. This condition arises since the air "wall" surrounding the sensitive volume of the chamber must have a thickness greater than the range of the secondary electrons. By the Bragg-Gray principle, this difficulty could be circumvented through the use of an actual wall of solid material with the same chemical composition as air. Such a wall is referred to as an "air-equivalent" wall. An air-equivalent wall is approximated by using a material with a mean atomic number near that of air. Bakelite, lucite, and other plastics are suitable materials for this purpose. The surface of the plastic must be coated with a conducting material to serve as electrodes. It is important to recognize that for other wall materials both the magnitude of the ionization in the wall and its energy dependence will differ from those with an air-wall or an air-equivalent wall chamber. When atmospheric air at STP is considered to contain approximately 79% nitrogen, it is seen that the atomic number of air-equivalent walls should be close to 7. Other suitable materials are given by Marinelli with their correction factor relative to air-wall (6, 7).

CHAPTER IV

A WIDE-RANGE AIR-EQUIVALENT INDICATING GAMMA RAY DOSIMETER

Any instrument used in the field of measurement is characterized by its resolving power; i.e., its ability to separate characters which are closely related. In the case of electronic instruments the characters are usually represented by numbers on a panel meter, images on an oscilloscope, or separation on a recorder chart. One method of improving resolution commonly in use is "scale expansion." By expanding the scale in the region of interest at a particular time, it is not difficult to obtain three figure accuracy. The expanded portion of the scale should be as linear as practical to insure equal resolving power over the scale.

In the case at hand, the measurement of radiation dosage is necessary to give information about the energy transfer in a chemical reaction. Therefore, the actual operation should be as simple and straightforward as possible. To this end, there should be a minimum number of controls to operate and the data should be directly available with no intermediate steps or correction factors to apply. Also when range switching is implied, an indication should be given. A dosimeter that is capable of constant surveillance of a field can be calibrated in dose rate and greatly aid in the mapping of a large field. It is possible to map a field in approximately the same time it takes to determine the dose rate of one location with a thimble ion chamber or a chemical dosimeter. The advantages of this rapid mapping technique are obvious.

Typical D-C Amplifier Characteristics

A D-C amplifier, referred to also as a direct-coupled or direct-current amplifier, plays a very important role in industrial electronics. Such amplifiers find extensive use in analog computers, D-C voltmeters, oscilloscope deflection amplifiers, geophysical amplifiers, biological instruments and numerous other applications. The method of interstage coupling in this amplifier is such that extremely low frequencies can be amplified with a large gain. The coupling is characterized by a direct-current conduction path from the plate of one tube to the grid of the following tube.

An elementary form of a D-C amplifier is shown in Figure 11. There are several disadvantages to this form of amplifier. First, it requires a voltage E_c that is in series with the signal, and also neither terminal of the battery is grounded. Secondly, neither end of the output impedance is at ground potential. The most serious disadvantage of this amplifier is the changes of output level for a constant input signal, sometimes called "zero drift."

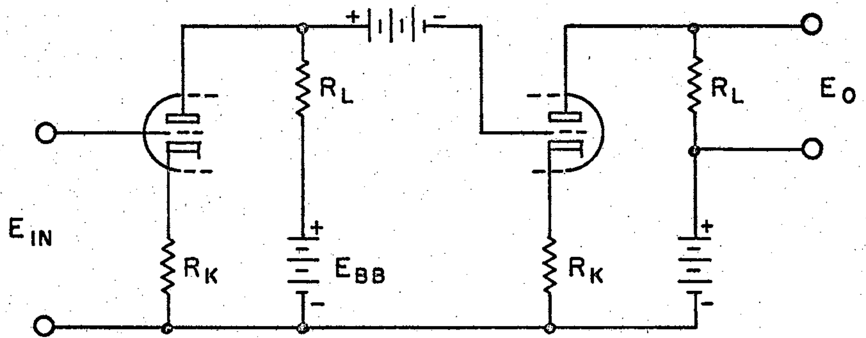

FIGURE 11. ELEMENTARY D.C. AMPLIFIER

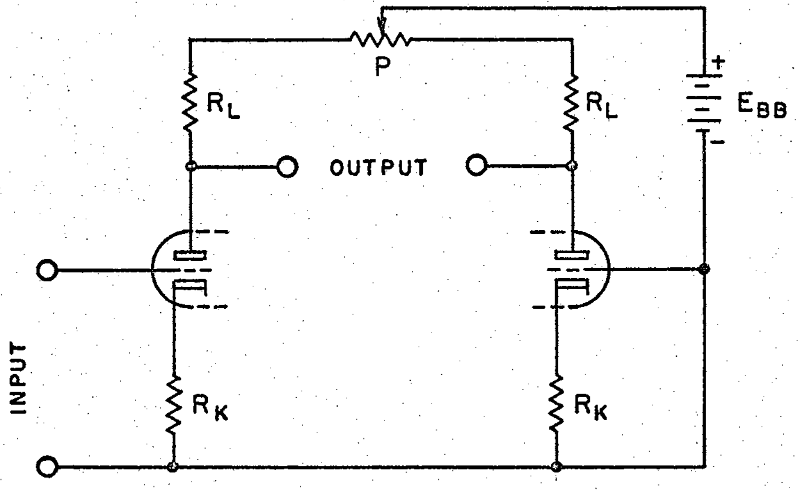

FIGURE 12. BALANCED CIRCUIT

This drift is due in part from the fact that the characteristics of the various tubes in the amplifier change with age. Also the plate and heater voltages may have a tendency to change with time. These changes may be regarded as a type of noise or modulation of extremely low frequency. The changes in the forward end of the amplifier are particularly serious since their change will be amplified by the succeeding stages. This drift must be cancelled by some method for satisfactory operation of the circuit. Several techniques are available including manual and automatic potentiometer adjustment of a "zero" control, balanced circuits, highly regulated and filtered power supplies, and modulation or carrier methods (8, 14).

A balanced circuit is shown in Figure 12. This circuit is adjusted by varying the potentiometer P to give zero output voltage between the plates when the input is shorted to ground. The positioning of P is normally adjusted manually, but circuits have been published that utilize a servo system to position P periodically. The amplifier output signal is used as a null-balance error signal. This circuit incorporates two tubes that are matched with respect to changes in plate voltage and heater voltage. Therefore, any change in either potential will effect both tubes equally and the net effect on the amplifier will be zero. Tubes used in a balanced circuit must be matched as closely as possible to insure that the affect of fluctuations in heater and plate potential be reduced to a minimum. One example of a tube that is manufactured for use in these circuits is the Western Electric 5755. It is especially designed to have low thermal noise, low drift due to the tube aging, and its response to changes in heater and plate voltages is closely controlled in the manufacturing process.

In the measurement of D-C currents less than 10^{-8} amperes by electronic means, specially constructed tubes are necessary (15). This is because of the grid current that will normally flow in a standard vacuum tube. The grid current is due mainly to gas molecules in the bulb being ionized by the emitted electrons of the cathode. A number of electrometer-tube circuits have been developed to circumvent this problem. It is to be emphasized that this type circuit is for measurement of D-C currents. Of course, most current measurements, by electronic means, are made by forcing the unknown current through a known resistor and measuring the resultant voltage drop. It is readily seen that in small current measurements this technique will be unsatisfactory if normal grid current of a standard receiving type tube is allowed to flow in the circuit. Therefore, the necessity of the electrometer circuits. A simplified electrometer input circuit is shown in Figure 13. As with the balanced triodes, the electrometers are frequently found in a balanced configuration. One circuit that has been used with good results is a balanced bridge circuit (8).

Carrier D-C amplifiers have important advantages over a conventional balanced amplifier (14). The D-C input signal

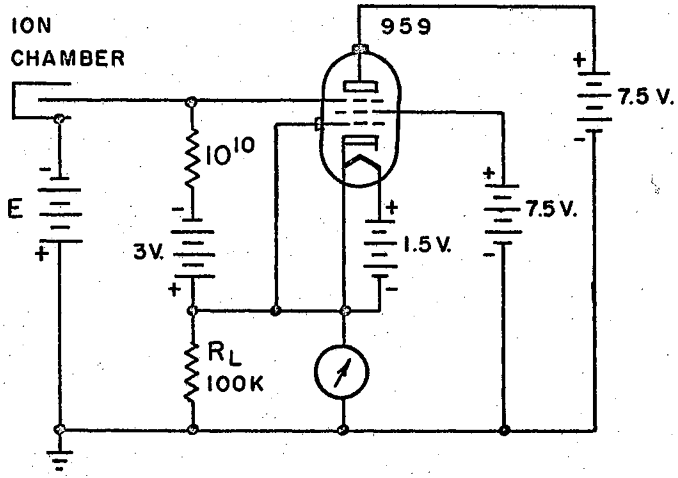

FIGURE 13. ELECTROMETER INPUT CIRCUIT

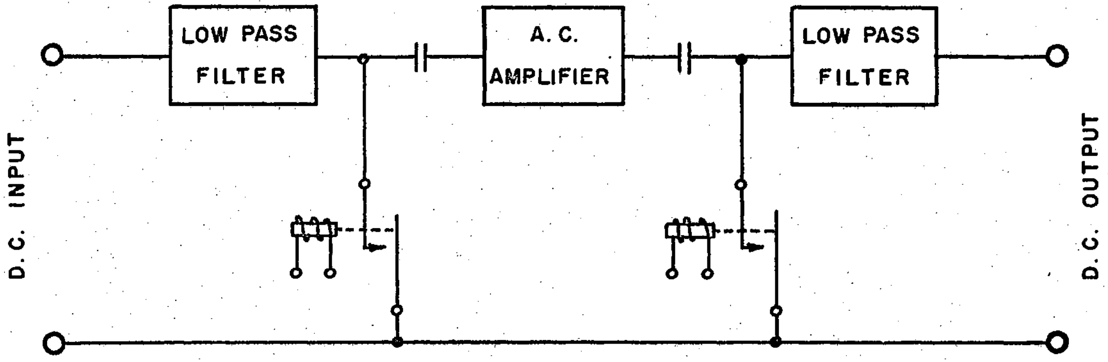

FIGURE 14. DIAGRAM OF A CARRIER TYPE D.C. AMPLIFIER

is filtered in a low-pass filter and then converted into an A-C signal. The A-C signal is of constant frequency while the amplitude is proportional to the D-C voltage input. The A-C signal is amplified by an A-C coupled amplifier. The A-C output is converted back to a D-C signal by the reverse process used in the original conversion. The D-C signal is passed through another low-pass filter to obtain the resultant D-C output. This operation is shown in Figure 14. The input band-width is usually limited to some frequency less than one-half the carrier frequency. Also, the band-width of the output low-pass filter must be made less than the frequency of the carrier, otherwise the carrier will appear in the output.

The major advantage of a carrier amplifier is the ease of amplification of the input signal; i.e., the use of an A-C amplifier, and the reduction of zero drift. One disadvantage that is felt in practice is the cost and fragile nature of the mechanical carrier generator, commonly called a chopper. One important consideration when a high-gain A-C amplifier is used is whether to use make-before-break or break-before-make contacts. If the input circuit will allow the use of make-before-break, this configuration should be used since switching transients will be introduced otherwise and can cause oscillations. When break-before-make choppers are used, it is usually necessary to use separate input and output choppers for isolation due to the capacitance between the contacts in an individual chopper.

The D-C voltage measurement in this study is made with a chopper type amplifier with internal negative feedback. This selection was made due to the consideration of minimum panel controls and the random operational periods of the instrument. In random operation all D-C amplifiers except the chopper type exhibit a substantial short-term drift for approximately one hour. This dictated the use of a chopper amplifier since the instrument would be turned on and off as many as three or four times in an eight-hour period.

Amplifier and Detector Performance

The D-C amplifier used in this study utilizes a break-before-make type chopper. The carrier frequency is 60 cps. Due to the high driving impedance (approximately one megohm), the make-before-break type chopper could not be used. In the latter type the dwell time of the movable arm on both contacts is about 5% of the driving frequency. This would short circuit the driving impedance to such an extent that it would load the source and give an erroneous output voltage. It was found that the chopper and associated input network caused a 3.55% reduction of the detector output signal. This corresponds to a D-C input impedance of 27.5 megohms. To smooth any transient surge currents from the MPT a 0.5 mfd capacitor was shunted across the input; i.e., MPT plate load resistance.

From Figure 15 the output voltage for each range, or decade of intensity, can be obtained. The range switching is

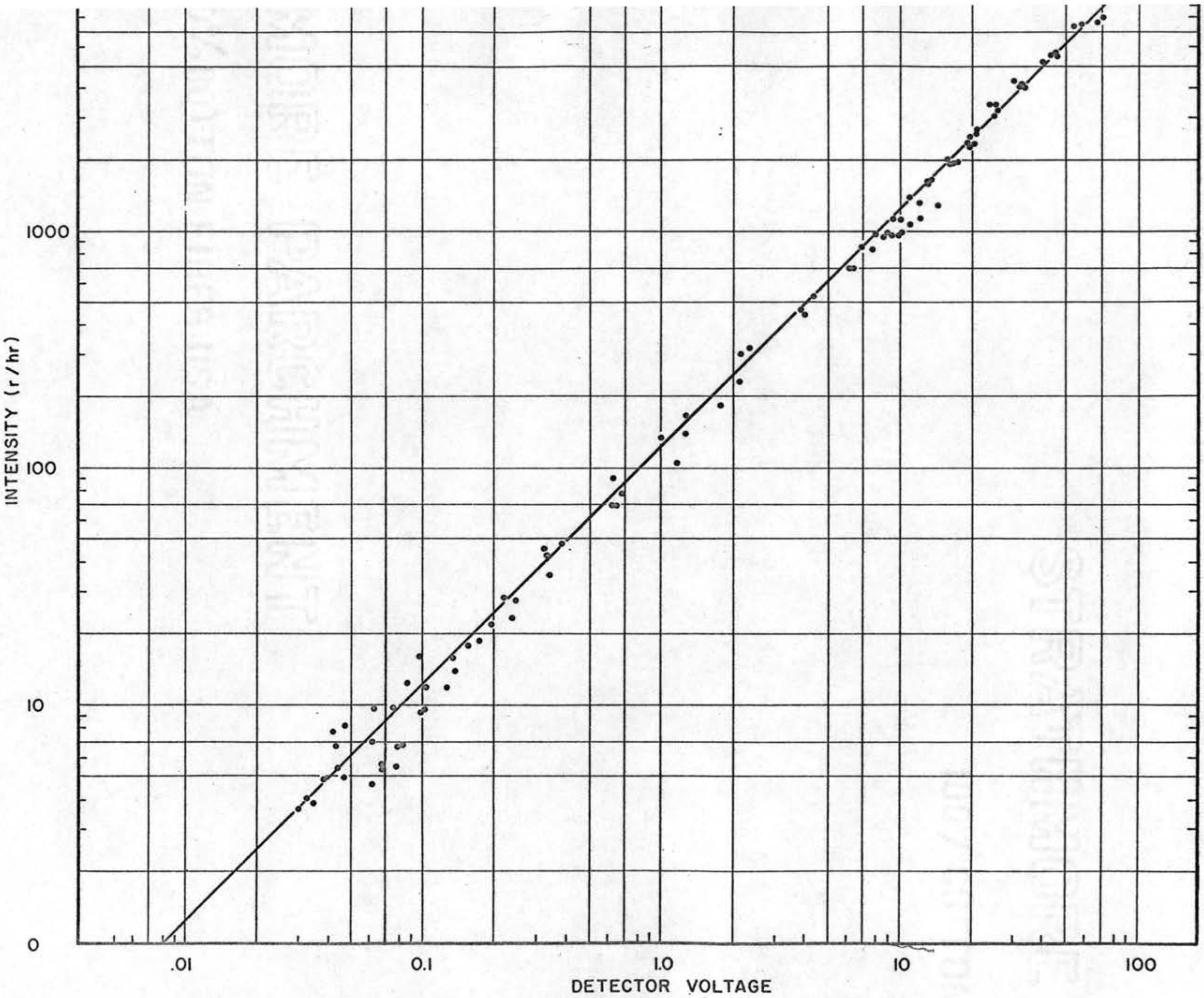

FIGURE 15. COMPOSITE CURVE OF DETECTOR VOLTAGE VS. INTENSITY

accomplished with S_1. The various range input resistors can be calculated with the aid of Figure 15. At an intensity of 1 r/hr there is an input potential of 8 millivolts. As will be seen from the output circuit discussion, this is to indicate 10% of f.s.d. of the panel meter. Also from Figure 15, an output potential of 80 millivolts corresponds to an intensity of 10 r/hr. Therefore, the f.s.d. of the meter is equivalent to an input voltage of 80 millivolts. Also, it is noticed that the voltage output is a linear function of the incident radiation. The meter can then be calibrated to read directly in r/hr.

A two-tube low gain voltage amplifier with a cathode follower output is used for the amplifier network of the instrument. Figure 16 shows the schematic diagram. The input into V_1 is through a high-pass R-C filter which has an 8.3% sag. To aid in linearity of the output signal, two tubes are used so that the grid voltage swing will be kept to a small value. A feedback loop consisting of R_f, C_f, R_k and C_k is incorporated to give a more desirable frequency response. The open loop gain at the fundamental frequency (60 cps) is 204. The closed loop gain also at the fundamental frequency is 130. V_1 and V_2 are conventional R-C coupled self-biased voltage amplifiers. A relatively large value of coupling capacitor is used to aid in the coupling of the low frequency components of the chopper square wave input.

With the compensating network R_f and C_f removed, the

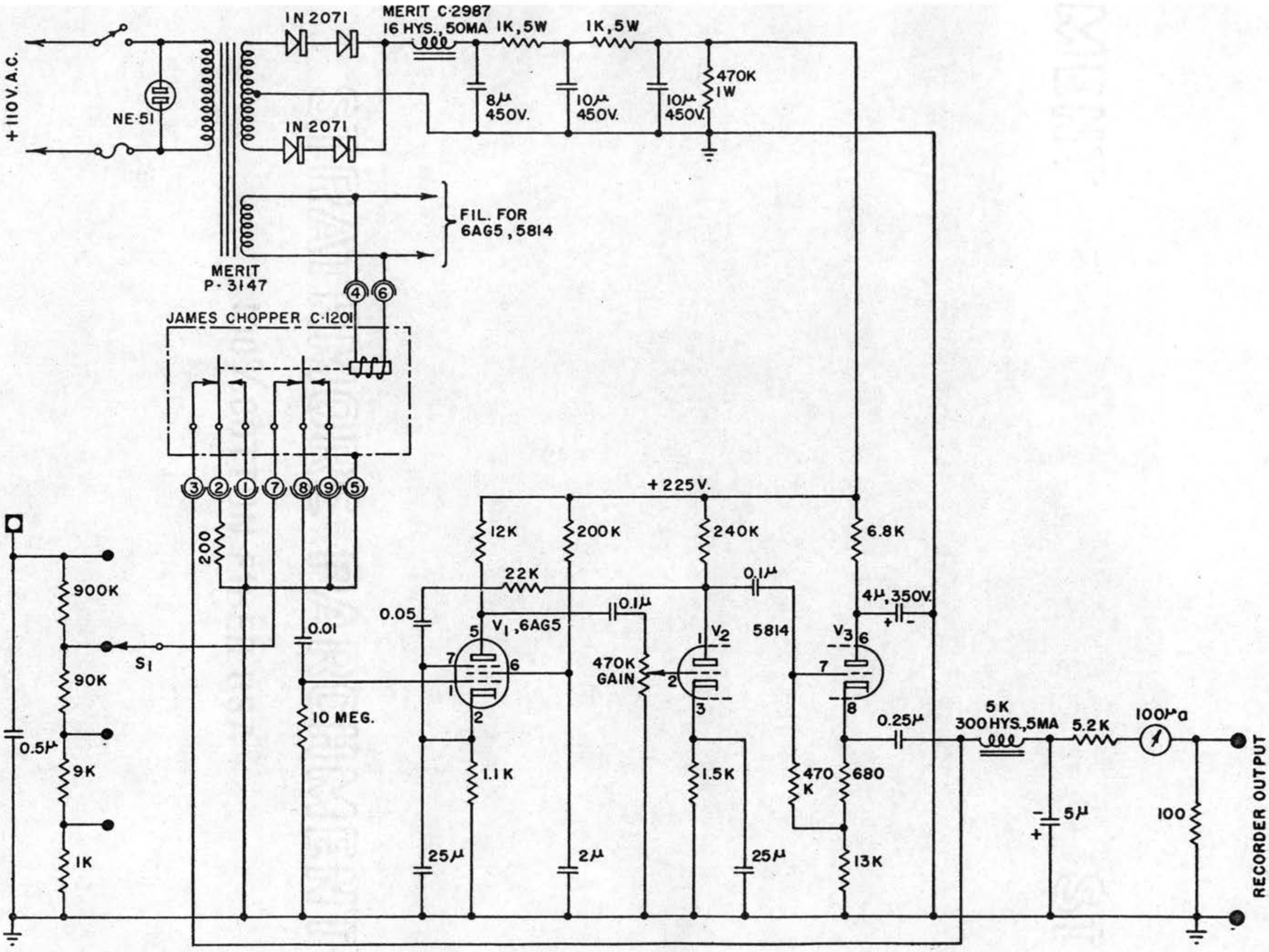

FIGURE 16, AMPLIFIER SCHEMATIC

amplifier frequency response is as shown in A, Figure 17. The response curve is as expected for an R-C amplifier of this type. The compensation network $C_fR_fC_k$ and R_k are qualitatively explained as follows. Consider curve C. It is seen that the response at 10 cps is relatively independent of the compensation network. This is due to the inefficient signal bypass of C_k. The reactance of C_k at this low frequency is such that negative feedback due to C_k of sufficient magnitude is introduced so that the feedback of the C_fR_f network can be neglected. This assumption has been verified both by calculation and observing the waveform at the cathode of V_1. As the frequency is increased, it is noticed that the gain goes through a maximum and then decreases continually as the frequency is increased.

There are two important considerations that cause this behavior. Actually both effects are due to the feedback, or compensation network. At low frequencies the capacitor C_f is a high reactance, and therefore most of the available feedback signal voltage at P_2 will be dropped across C_f. Although, there will be enough voltage passed to cause a negative feedback effect across the cathode impedance of V_1. Since the reactance of C_k is much smaller than R_k at the frequencies in question, consider the cathode impedance to consist of only C_k. It has been found both theoretically and experimentally that the feedback voltage of the cathode of V_1 goes through a maximum in the region of 150 cps. This maximum is not obvious from curve C, but the effect of the negative

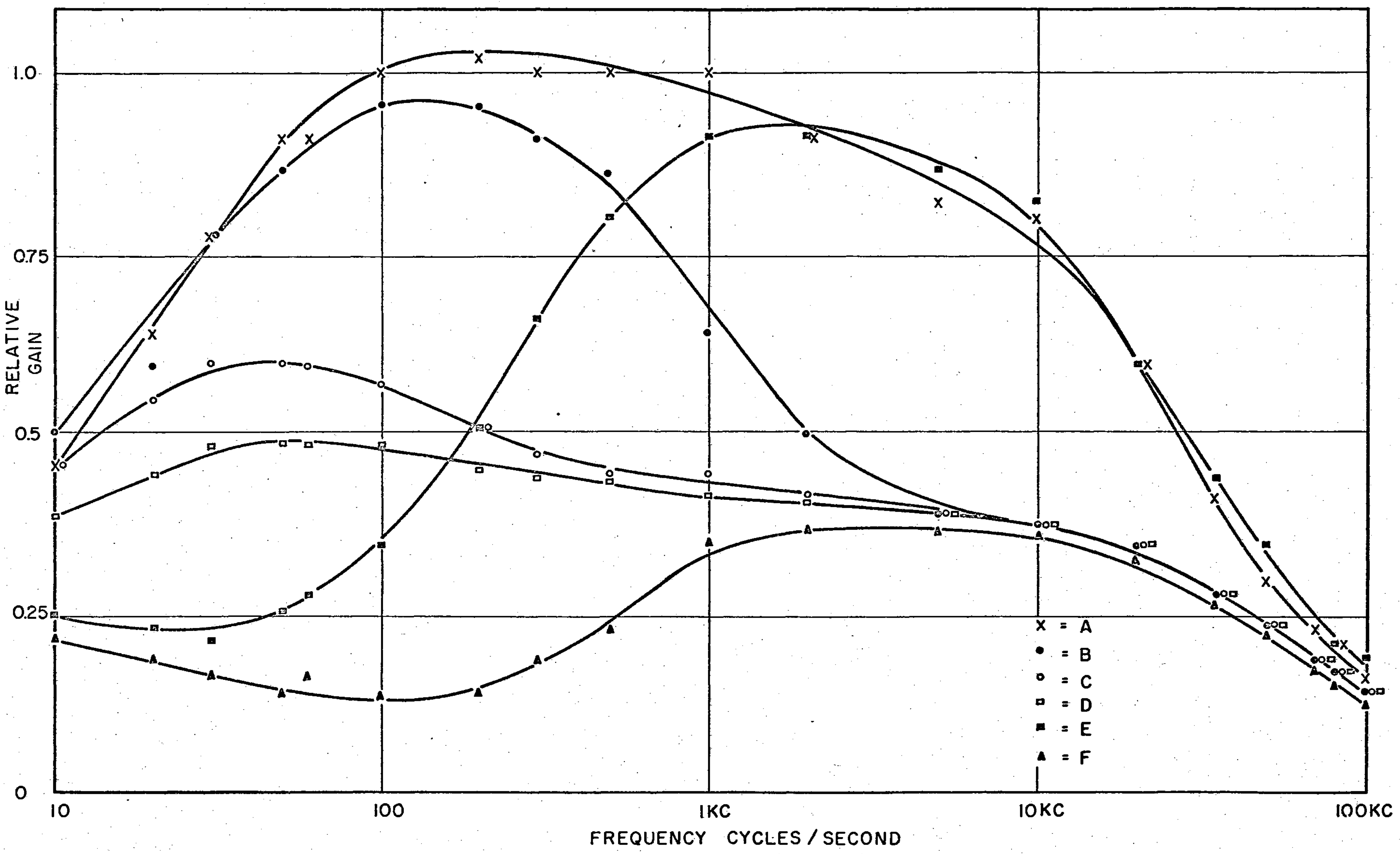

FIGURE 17. AMPLIFIER RESPONSE CURVES

feedback is readily seen. For the series loop R_fC_f the "break" frequency is calculated to be 145 cps. The "break" frequency for a C_f of 0.08 and 0.36 μfd are found to be 90 and 200 cps, respectively. This effect is seen from curve D and C. The compensation network, therefore, has the advantages of negative feedback only in the range of frequencies from about 30 cps to 500 cps. This is important, however, since the fundamental frequency to be passed is 60 cps. The importance of this is obvious when the meter circuit is examined.

The compensation network is now considered at high frequencies. If the high frequency equivalent circuit of V2 is drawn, it is seen that the plate impedance of V_2 is a function of frequency. As the frequency is increased, the plate load of V_2 is decreased, causing a variable gain amplifier. Therefore, the amplifier gain is seen to decrease with an increase in frequency. Two immediate advantages are obtained with this type response curve. The first is the efficiency of the demodulator. This is discussed later. The second is the reduction of the possibility of oscillations in the amplifier chain as a result of using a break-before-make chopper. The chopper movable arm has a 10% no-connection cycle for each cycle of the driving voltage. This open circuits the input grid of the amplifier and is very conducive to triggering oscillations. The oscillations that occur are generally in the high frequency range, 10 KC to 500 KC. With the variable gain of this amplifier, it is unusually difficult to sustain an oscillatory condition.

Curve E and curve F are the open and closed loop response curves for a C_k equal to 2 mfd.

The meter, or output, circuit consists of a mechanical clamping circuit, an L-C low-pass filter, and a 100μ amp panel meter with its current limiting resistor. The output circuit is driven by a cathode follower. The cathode resistor is tapped, and the grid return resistor is tied onto the tap to allow a symmetrical output signal. The cathode follower provides both power gain and impedance match in its role as the output tube. The output chopper contacts are mechanically ganged to the input chopper contacts. This gives synchronous output since both sets of contacts are driven by the same coil. The low-pass filter is used to filter out any carrier or carrier harmonic which may be present after rectification. Also, the filter smooths the D-C and prevents surge currents from damaging the meter. A 100 ohm resistor is placed in series with the output meter to drive a 0-10 millivolt null-balance recorder.

As noted above, there is considerable ambiguity in the defining of the amount of energy transfer from a radiation field to matter. When a particular type of matter is considered, such as hydrocarbons, various parametric equations can be derived relating the standard units such as roentgen to the energy absorbed in the given matter (9). It has been shown that an organic scintillator can be used as an air-equivalent absorber if certain conditions are met (5). Since the roentgen unit is defined as being proportional to energy absorbed in air, an organic scintillator should be observed to have scintillation properties that can be directly correlated to roentgen units.

Organic scintillators are readily available in both the liquid and the solid state. The liquid scintillator has the advantage of rapid replacement if it becomes damaged in some manner. Its principal disadvantage is the necessity of having a suitable container mounted on the multiplier phototube (MPT). The solid scintillator has the advantage of being easy to machine to various forms, and it is relatively inexpensive. Due to the experimental techniques necessary to determine the proper amount of scintillator to satisfy the design criterion, a solid scintillator in the rod form was used in this study. This enabled a rapid evaluation of various amounts of scintillator. The rod is 1 inch in diameter, and slices of the rod were cut off and polished to a smooth finish. Wafers of 1/4, 1/8, and 1/16 inch were used in this study.

The particular scintillator used was furnished by Nuclear Enterprises Ltd. It is their NE102 plastic phosphor. The major component in the scintillator is polyvinyltoluene. The material is very similar to common polystyrene. The supplier states that the phosphor has been subjected to very large amounts of radiation in a nuclear reactor at Harwell, England, and no damage is to be expected at levels of 10^4 r/hr. An RCA 931-A multiplier phototube was chosen to be used with the scintillator. The photocathode of the 931-A is rectangular in shape with sides 15/16 x 5/16 inch. Therefore, when a suitable 1 inch lucite light-piper was mounted on the 931-A envelope, there was complete coverage of the photocathode insuring good light-collection efficiency.

The scintillation wafers were joined to the light-piper with Dow Corning 200 fluid with a viscosity index of 100,000 at 25°C. Likewise, the light-piper was joined to the MPT envelope with the fluid. To minimize the loss of secondary electrons from the scintillator, an aluminum cup was fabricated that would both prevent secondary electron loss, and serve as a holder for the wafer. The cup has a 1 inch inside diameter so that the waver and the light pipe could be slid into its cavity. The walls and bottom of the cup were 1/16 inch thick. Also the inside walls were polished to a smooth, glossy finish to aid in scintillation reflection.

The RCA 931-A has an S-4 response curve; i.e., the photocathode is most sensitive to energy of wavelength equal to 4000 Angstroms. This is particularly well suited to the NE102 phosphor which has its maximum emissive peak at 4500 Angstroms. The 931-A is down 10% in sensitivity on both sides of 4000 A, so it is seen that good energy coupling is achieved with this combination. The maximum anode current of the MPT is 1 milliamp. Therefore, for satisfactory lifetime and operating stability the average D-C current should be derated by a factor of ten. This is one of the design factors to be met when selecting the proper size phosphor wafer. Probably the outstanding characteristic of a MPT is its current gain. The 931-A with a supply potential of 835 volts has a nominal current gain of 200,000. From Figure 9 it is seen that the output section has voltage-current characteristic curves similar to a pentode; i.e., constant current over a wide range of operating potential. These characteristic curves also point out the linear relationhip between anode current and incident light flux. Also the tube exhibits a linear relationship between anode current and total divider current when the anode current is less than 0.1 of divider current.

By averaging the anode current and taking its D-C value, a correlation of D-C anode current to incident radiation was made. Remembering the constant-current output characteristics of the MPT and that the maximum anode current is limited to 100 microamperes, an anode load resistor was chosen such that at maximum anode current the anode-to-dynode 9 voltage would be 80 volts. This value of voltage is still in the linear range of the characteristics. Writing the anode-dynode 9 loop equation and solving for Rc

$$V_{9-A} + I_a (R_c + R_1) = I_B R_1 \qquad (5)$$

where $I_B = 1\text{ma}$
$R_1 = 200\ \text{K}$
$V_{9-A} = 80\ \text{V}$
$I_a = 100\mu\text{a}$

$$Rc = \frac{200\text{V} - 80\text{V} - (100\mu\text{a})(0.2\text{M})}{100\mu\text{a}}$$

$$Rc = \frac{100\text{V}}{100\mu\text{a}} = 1\ \text{Megohm}$$

With the plate load resistor determined for conditions of maximum anode current, the experimental determination of the proper scintillation wafer was made. It is seen from Figure 9 that a light flux of approximately four microlumens is needed to give 100μa anode current. It was found by cut-and-try procedure that both the 1/4 and 1/8 inch thick wafers were too large; i.e., at the maximum intensity of 10^4 r/hr that they would force the MPT to deliver greater than 100μa plate current. The 1/16 inch wafer, however, was quite satisfactory and from Figure 15 it is seen that the maximum anode current is 80μa. This allows a 20% safety factor in maximum current output thereby giving an added degree of stability to the detector. The slope of the output voltage vs. incident radiation for the 1/16 inch wafer is seen from the graph to be very close to unity. The slope of the curve for the 1/8 inch wafer was found to be 0.847, which shows that excessive anode current will violate the normal linear relationship of anode current to incident light. The detector schematic diagram is shown in Figure 18.

Results

The results of this study were very satisfactory. The detector-amplifier combination performed very well, and the operation of the instrument is very simple. The detector output circuit used in the final model was designed after the first scheme to measure the differential anode current in the

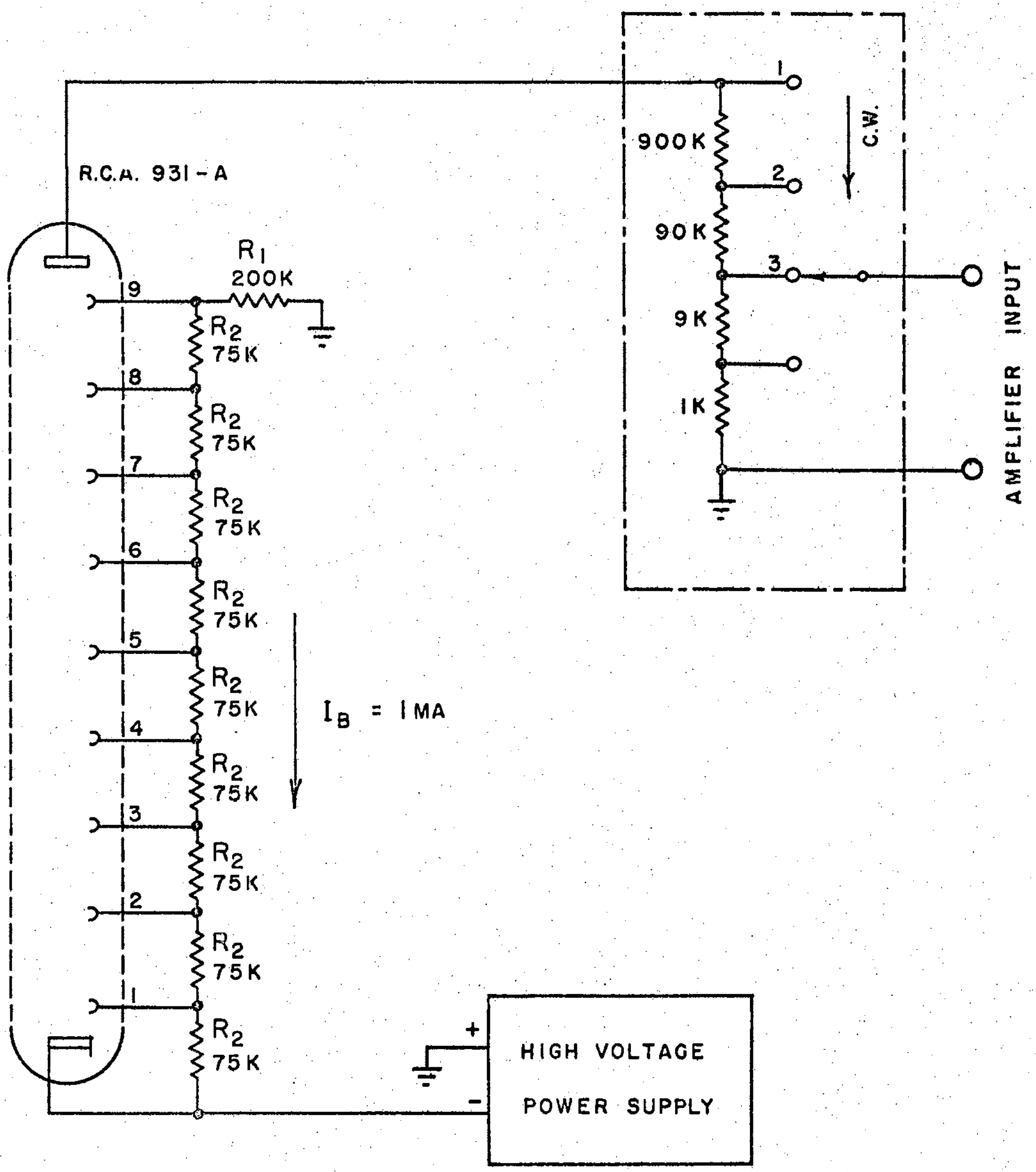

FIGURE 18. DETECTOR SCHEMATIC DIAGRAM

MPT proved unsatisfactory. The first method consisted of measuring the anode-to-ground potential of the MPT at a reference intensity. Next a "bucking-out" potential equal to the anode-to-ground potential is inserted in series, but with opposite polarity, with the amplifier input terminals. This would result in zero input voltage at the reference intensity and the potential would then change with a change in anode current, assuming the "bucking-out" voltage remained constant. There were inherent inaccuracies in this technique since a small difference was being detected between two large potentials. This scheme gave way to the one now being used, and this method works very well. The detector is coupled to the amplifier and high-voltage power supply through approximately 50 feet of coaxial cable. No detrimental effects were observed by using such a long signal path. The MPT high-voltage is supplied from a V-R tube regulated power supply.

The amplifier has performed very well in this study. The maximum deviation from linearity is 1% at maximum signal input. The short-term equivalent input drift was found to be less than ± 80 μv/hr. Long-term equivalent input drift is no more than ± 40 μv/hr. There is no noticeable effect from amplifier noise. The time constant of the instrument is approximately 0.03 msec. Two amplifiers were built and both exhibited essentially the same characteristics.

The presentation of the intensity can be observed on a panel meter and recorded on a 0-10 mv recorder. The readout is basically the same as a center-zero meter. The main difference is the shifting of the balance point to the normal 10% point on a conventional 0-100μa meter. The right side, or positive side, of the scale has been expanded; and the negative side, or left side, has been defined as an invalid reading. At zero, or background radiation, the meter will always read to the left of the 10% reference point on all ranges, assuming background is less than 1 r/hr. This indicates that the radiation field is less than 1 r/hr. Any reading to the left of the reference calls for a range switch to the next more sensitive scale. Therefore, on range 1 if the meter reads to the left of the reference point, this indicates a field of less than 1 r/hr. It is beyond the capacity of this instrument to detect and display an intensity less than 1 r/hr. It must be emphasized that in an unknown field the instrument must be initially set on the least sensitive range; i.e., range 4, to prevent overloading of the amplifier and possible damage to the meter. Then progressive switching to more sensitive ranges can be made to determine the intensity of the field.

The calibration of the detector was performed emperically. A Landsverk thimble ionization chamber and charger-reader system was used to determine the intensity along a straight line directed away from the center of the source. The ion chamber was placed on a ring stand at a level of 33½ inches off of the floor to reduce the possible effects of localized shileding. After the intensity was determined at 15 points along this line, an intensity vs. distance curve was plotted. An aluminum ionization chamber 2 inches in diameter, 6 inches long, and with $\frac{1}{4}$ inch thick walls was then moved along the known intensity path; and the resultant ion current was measured. This ion current vs. distance graph was plotted. A plot of ion current vs. intensity could then be made. This graph provided a quick check of the approximate intensity of any random point. Due to the small changes in current for relatively large changes of intensity, the ion chamber had poor resolving capabilities, although the ease and speed of approximate determinations is very desirable.

The accuracy of the calibration of the ion chamber is rather poor at the lower levels of intensity. The detector output voltage was measured with a VTVM of approximately 200 megohms input impedance. This insured no loading across the 1 megohm output resistor. The exact position of the fuel elements, ion chamber, and detector was exceedingly difficult to determine. The fuel elements were on a platform suspended in a water bath by four steel cables. To position these in a vertical plane there are four angle brackets, one at each corner of the platform, which run from the lower to the upper limit of the vertical travel. The cables are wound on a spool to raise the platform to the desired height. It was found in the low level range that a thirty degree change in the spool rotation caused a fifty per cent change in intensity. Therefore, the calibration of the low range is good only to a first approximation. This is illustrated in Figure 15.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

In the study of radiation chemistry it is important that the amount of energy transferred from the radiation field to the irradiated matter be known. There are currently a variety of energy transfer units in use, all defined as an amount of energy absorbed from a radiation source. The oldest, and perhaps best known is the roentgen. It can be crudely defined as the amount of gamma or X-rays necessary to produce 1 electrostatic unit of charge at standard temperature and pressure. It has been shown that an organic scintillation phosphor will absorb energy from a gamma ray field in a manner directly proportional to the amount that would be absorbed in air (5). When a scintillator absorbs gamma ray energy, this energy is emitted from the phosphor in the form of light photons. Therefore, light photons can be produced in a manner directly proportional to the quantity of energy that would be absorbed in air. From the definition of the roentgen, the number of light photons emitted per unit time can be correlated to a value of intensity of the radiation field; i.e., roentgens/hr. It is emphasized that the intensity given in r/hr. is not a measure of energy absorbed in any matter other than air. To correlate the energy absorbed in other matter, the chemical and physical properties of the matter relative to air must be considered. Nevertheless, the intensity of the field given in r/hr is of considerable value.

Using the principles outlined above, an instrument was designed, fabricated, and tested to measure the intensity of spent reactor fuel elements. These fuel rods emit gamma rays with a wide range of energy values. The principal gamma ray emitted has an energy value of 0.7 Mev. The scintillator response is independent of the impinging photons energy from 0.2 to 3.0 Mev. The light photons from the scintillation crystal are optically coupled to a multiplier phototube. The anode current of this tube is averaged, and the voltage drop across its plate load resistor is fed into a D-C amplifier. The anode current varies linearly with incident light flux if excessive current is not delivered from the tube. The instrument was designed to cover the range of intensity from 1 r/hr to 10^4 r/hr. There are four ranges, one range for each decade of intensity. The intensity of the impinging radiation on the detector is displayed on a panel meter. A 0-10 mv recorder output is also provided. The instrument has proved to be very sensitive and reliable. The ease of operation and interpretation of the data are also attractive features of the instrument.

It is recommended that the following items be considered in the use of this instrument:

1. To enhance the ease of operation, a high-voltage power supply should be built into

the same cabinet with the amplifier. The power supply should have good regulation to insure that no high-voltage changes occur during the measurement of a field.

2. A MPT with its cathode on the end; e.g., an RCA 5819, would greatly help in coupling the light photons from the scintillator to the MPT cathode. Also, if the scintillator is removed, it would be easier to relocate it on its original position. If a small MPT were used, the detector package could be greatly reduced in size, which would be a definite advantage in some cases.
3. To determine the effective lifetime of the scintillator and MPT, it would be desirable to run long-term studies on the damage caused by large exposures in a radiation field. Preliminary investigation indicates that this damage is slight, but qualitative information is not available at present.
4. The calibration used in this study left something to be desired. A Landsverk thimble ion chamber was used as a primary standard. This is a tedious and laborious process, and the absolute accuracy is poor. Chemical dosimetry is considered accurate to ± 5%, but it is also very difficult to obtain the many check

points needed to calibrate such a wide-range instrument. In the calibration of future models, an investigation into different calibration techniques would be desirable.

5. On two of the tests with the detector in a field of approximately 8×10^3 r/hr, a decrease from the initial reading of approximately 8% was noticed. This decrease has not been studied in detail. It is thought that the MPT might be exhibiting some cathode fatigue as this was noted only in the latter stages of testing. If this is the case, it is possible that before the next operation the cathode had restored its electron emitting properties. The manufacturer states that slight cathode fatigue can be overcome if the tube is left out of service for a period of time.

6. Due to the off-set reference point in the meter circuit, the range switching could be made automatic with a minimum amount of modification. This would aid in the operation when the instrument is to be used to survey intensities that vary over wide ranges.

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