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A pulse reader for ionization chambers has been developed, tested, and calibrated. An insulated gate field effect transistor (IGFET) was used to detect the pulses and Victoreen Model 362 Pocket Chambers were used as ionization chambers. The energy dependence of the Victoreen Model 362 Pocket Chamber was determined to be zero to -14% for photon energies ranging from 152 keV to 33 keV. The pulse reader was found to be stable at room temperature over a period of two months. Exposures of 30 mR $\pm$ 1.0 mR and exposures as low as 1.0 mR $\pm$ 0.5 mR were measured.

# Pulse Reader for Ionization Chambers

by

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# PULSE READER FOR IONIZATION CHAMBERS

## I. INTRODUCTION

### Objective

It was the objective of this study to develop, test, and calibrate a pulse reader for ionization chambers. The pulse reader was to be constructed using an insulated gate field effect transistor. The pulse reader was to have the capability of accurately measuring radiation exposures from approximately 0.1 mR to 100 mR.[1]

### Definition of Pulse Reader

A pulse reader measures radiation exposure by measuring the voltage pulse required to recharge an ionization chamber after the chamber has been exposed to radiation.

In the conventional application of an ionization chamber (Hine and Brownell, 1956), the chamber is charged to an initial voltage, $V_i$. When the chamber is exposed to radiation, some of the charge is dissipated and a smaller final voltage, $V_f$, remains. The exposure is determined by measuring the difference between the

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[1] A milliroentgen (mR) is 1/1000th of a roentgen, which is a unit of x or gamma radiation exposure.

initial and final voltages, $(V_i - V_f)$.

In the pulse reader system the chamber is charged to an initial voltage, $V_i$, as above. When the chamber is exposed to radiation some of the charge is dissipated. The exposure is determined by measuring the height of the voltage pulse that then is required to recharge the chamber to voltage $V_i$.

## Advantages of Pulse Reader

The conventional ionization chamber measuring system has certain disadvantages when small exposures are to be measured. The exposure is determined by measuring the difference between two large voltages. If the exposure is small, this difference will be small and measuring small voltage differences with a high degree of accuracy is difficult. For example, the Victoreen Model 130 chamber (used in conjunction with the Victoreen Condenser R-Meter Model 570) is initially charged to 525 volts. With the Victoreen Model 130 chamber, which measures from zero to 250 mR (Victoreen, n. d. b.), a ten mR exposure will dissipate approximately ten volts. The ten mR exposure must be determined by measuring the difference between 525 volts and 515 volts. If the error in voltage measurement is as low as two percent of full scale of the electrometer voltage, or about ten volts, the error is as large as the voltage difference that is to be measured.

In the pulse reader system, instead of measuring the difference between two voltages, a voltage pulse is measured directly and greater accuracy is attained. It is not necessary to measure the final voltage on the chamber, or even the initial charging voltage. It is only necessary to measure the height of the voltage pulse which is proportional to the exposure received by the chamber.

## Previous Pulse Readers

Pulse readers for ionization chambers have been built previously by Roesch, McCall, and Rising (1958) and by Braby (1968).

Roesch, McCall, and Rising employed a driven anode electrometer circuit for the detection of pulses and a pulse stretching amplifier to measure and read out the pulses. Exposures of one mR ± 20% and ten mR ± 10% were measured.

Braby employed pulse electronics to measure 1.5 rad ± 15% with a minimum sensitivity of 0.05 rad.[2] The equipment used consisted of a voltage follower preamplifier to detect the pulses and a pulse height voltmeter to measure and read out the pulses.

The principal difference between the pulse reader developed in this study and previous pulse readers is that in this study an

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[2]The rad is a unit of absorbed radiation dose.

insulated gate field effect transistor is used to detect the pulses. The pulse reader in this study is also simpler in design, less expensive, battery operated, small, and completely portable.

## Applications of Pulse Reader

In general, a pulse reader extends the sensitivity and increases the accuracy of conventional ionization chambers. Consequently, the pulse reader could have application wherever ionization chambers are used. More specifically, a pulse reader facilitates the measurement of low exposures in small air volumes (Braby, 1967). In the usual application of ionization chambers, the use of small chambers implies a loss of sensitivity. This is due to the fact that the response of a chamber, or the voltage dissipated per mR, depends on the collecting volume of the chamber. If greater sensitivity is desired, larger chambers must be used. Since the pulse reader extends the sensitivity of ionization chamber systems, small air volumes can be used to measure smaller exposures.

One important application of the pulse reader would be in the area of personnel monitoring. Present systems of personnel monitoring include film badges, solid state dosimeters, and conventional ionization chamber systems.

Film badges are only about 10% accurate (U. S. National Bureau of Standards, 1960), and they are quite energy dependent

(Clarke, 1963). Film badge dosimetry is also dependent on the radiation angle of incidence and on the film development process (Hine and Brownell, 1956). Furthermore, the fact that film badges require comparatively elaborate processing is a distinct disadvantage. Typically, films are developed weeks or even months after the exposures have occurred, and as Sievert (1959) has pointed out, it often is desirable to know what exposures have been received immediately after their occurrence.

Solid state dosimeter systems have been expensive when compared to other systems of personnel monitoring. In addition, none of the solid state systems developed at the present time are entirely satisfactory with respect to precision, accuracy, energy dependence, or calibration procedures (Attix and Roesch, 1966).

In the case of conventional ionization chamber systems, adequately small chambers are too insensitive to accurately measure personnel exposures below ten mR.

The pulse reader system offers several distinct advantages for personnel monitoring. Low exposures can be measured quite accurately and conveniently. The type of ionization chamber that can be used with the pulse reader is quite small, durable, easily worn by personnel, and costs only a few dollars each. The total cost of the pulse reader would be relatively low also. The read-out and charging processes are simultaneous, which would facilitate automation. Recording the exposure on a computer card, and recharging the chamber could be accomplished in a single operation.

## II. BASIC THEORY OF PULSE READER

There are essentially four components required for a pulse reader:

1. An ionization chamber
2. An ionization chamber charging circuit
3. A component to develop the pulse
4. A component to detect and measure the pulse

The schematic in Figure 1 shows the essentials of a pulse reader. Capacitor $C_1$ represents the ionization chamber which is charged to voltage $V_i$ by the insertion of the chamber into the socket. The socket is represented by another capacitor, $C_2$. The pulse is developed by resistor R. The pulse is detected and measured by another circuit as shown in the diagram.

In the steady state condition the socket $C_2$ is charged to voltage $V_i$ and no current flows through resistor R. When an ionization chamber charged to voltage $V_f$ is inserted into the socket, there is an immediate transfer of charge from socket to chamber. The resultant charge, Q, on the two capacitors in parallel is given by the equation:

$$Q = V_f C_1 + V_i C_2 \tag{1}$$

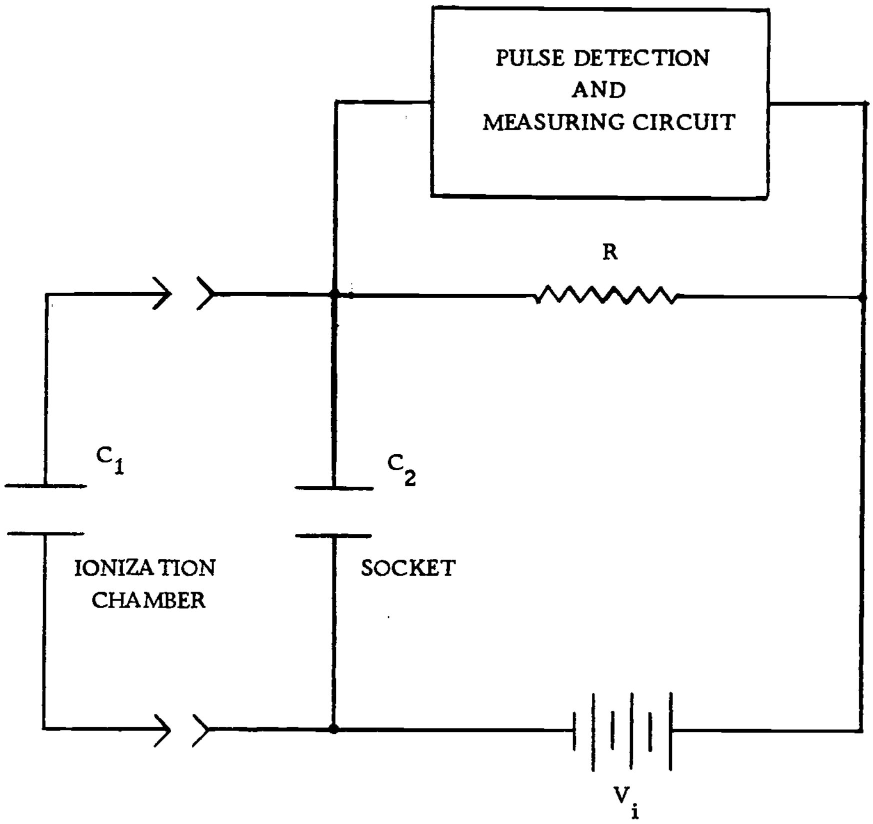



Figure 1. Essentials of a pulse reader for ionization chambers.

The voltage pulse, $V_p$, developed across R upon the insertion of the chamber into the socket is:

$$V_p = V_i - \frac{V_f C_1 + V_i C_2}{C_1 + C_2} \tag{2}$$

If $V_d$ is the voltage dissipated from the chamber by exposure to radiation, then:

$$V_f = V_i - V_d$$

Substituting the above expression for $V_f$ in equation (2) gives:

$$V_p = \frac{V_d C_1}{C_1 + C_2} \tag{3}$$

From equation (3), the height of the voltage pulse $V_p$, which is to be detected and measured, depends only on the voltage that is dissipated from the chamber due to radiation exposure and on the capacitances of the chamber and of the socket.

In addition to the capacitances of the chamber and socket there is stray capacitance associated with the wiring and the other components of the circuit. This stray capacitance is in parallel with the socket $C_2$ and can be assumed to be included in the value of $C_2$ since capacitances in parallel are additive.

If $C_2$ (socket and stray capacitance) is very large, then according to equation (3) the pulse developed across R would be very small. On the other hand, if $C_2$ was zero the pulse would be at the maximum value of $V_d$. Obviously, it is desirable to have $C_2$ as small as possible.

The capacitance of the Victoreen Model 362 Pocket Chamber used throughout this study is approximately five picofarads and the value of $C_2$ is also about five picofarads (Roesch, McCall, and Rising, 1958). Assuming equivalent values for $C_1$ and $C_2$, equation (3) reduces to:

$$V_p = \frac{V_d}{2} \qquad (4)$$

From equation (4), the height of the voltage pulse developed when the chamber is inserted into the socket is one-half the voltage dissipated from the chamber by exposure to radiation.

The value of $V_d$ depends on the chamber that is used and the radiation exposure received by the chamber. With the Model 362 Pocket Chamber, a ten mR exposure dissipates 3.09 volts. The value of 3.09 volts was calculated from the definition of the roentgen and from the air volume and capacitance of the chamber in the following manner:

A roentgen is defined as the unit of exposure that produces $2.59 \times 10^{-4}$ coulombs of charge of either sign in one kilogram of air (International Commission on Radiation Units and Measurements, 1968). The mass of air in the Model 362 Pocket Chamber at standard temperature and pressure (STP) can be calculated from the density of air at STP ($1.29 \times 10^{-6}$ kg/cm$^3$) and from the volume of the chamber. The volume of the chamber was calculated from dimensions of the chamber which were determined from a radiograph. The volume was found to be approximately five cubic centimeters. The air mass in the Model 362 Pocket Chamber is then:

$$1.29 \times 10^{-6}\,kg/cm^3 \times 5.0\,cm^3 = 6.46 \times 10^{-6}\,kg$$

The amount of charge dissipated by a ten mR exposure is given by:

$$Q = 2.58 \times 10^{-6}\,C/kg \times 6.46 \times 10^{-6}\,kg = 16.70 \times 10^{-12}\,C$$

The voltage dissipated is given by:

$$V_d = \frac{Q}{c_1} = \frac{16.70 \times 10^{-12}\,C}{5.0 \times 10^{-2}\,F}$$

$$V_d = 3.34 \text{ volts at STP}$$

This is the voltage dissipated at $0^{o}C$ and 760 mm Hg atmospheric pressure. At some other temperature and pressure a correction factor must be applied (Johns, 1964):

$$\text{Correction factor} = 273/T \times P/760$$

where:

T = actual temperature in degrees absolute
P = actual pressure in millimeters of mercury

At a room temperature of $22^{o}C$ and at a pressure of 760 mm Hg:

Correction factor = 273/295 x 760/760 = 0.925

$V_d$ = 3.34 x 0.925 = 3.09 volts at room temperature and 760 mm Hg

Since 3.09 volts are dissipated from the chamber by a ten mR exposure, the voltage pulse expected when the chamber is inserted into the socket would be:

$$V_p = \frac{3.09}{2} = 1.55 \text{ volts}$$

Pulses of 1.55 volts are easily measured, but a problem not yet considered is the duration of the pulses. When the chamber is inserted into the socket the charges on the capacitors $C_1$ and $C_2$ (Figure 1) stabilize immediately since the resistance in the circuit is negligible. Current begins to flow through the resistor R until both socket and ionization chamber are recharged to voltage $V_i$. The instantaneous voltage drop, v, across resistor R is given by:

$$v = V_p e^{-t/R(C_1+C_2)} \qquad (5)$$

where:

$V_p$ = maximum and initial size of the pulse (1.55 volts for a ten mR exposure)

t = time (sec) after the insertion of chamber

The RC time constant, T, (Malmstadt and Enke, 1963) is given by:

$$T = R(C_1 + C_2) \qquad (6)$$

Since $(C_1 + C_2)$ is on the order of $10^{-11}$ farads, the resistance R must be quite large in order to have a pulse with sufficient duration to be measured. From equation (6), if R = $10^{11}$ ohms, then T = one second. This means that in one second the voltage pulse has decreased to 63% of its initial value, or v = 0. 37 x $V_p$. Figure 2 illustrates the theoretical pulse that is developed across a resistor R of $10^{11}$ ohms when a chamber previously exposed to ten mR is inserted into the socket.

The necessity of using a very large resistor for R poses a major problem. The input impedance of the pulse detection and measuring circuit must be comparable to and perferably much greater than the value of R. This means that high impedance electrometer tubes must be used, such as the driven anode elctrometer employed by Roesch, McCall, and Rising. Or alternatively, if a smaller value of R is used, sophisticated electronics capable of measuring pulses of very short duration must be employed, such as the pulse electronics used by Braby. Another alternative is to use one of the recently developed insulated gate field effect transistors which have input impedances on the order of $10^{13}$ ohms (Lancaster, 1966). Such a transistor was used in this study for the pulse detection circuit.

To summarize the basic theory of the pulse reader: an ionization chamber is inserted into the socket and becomes charged

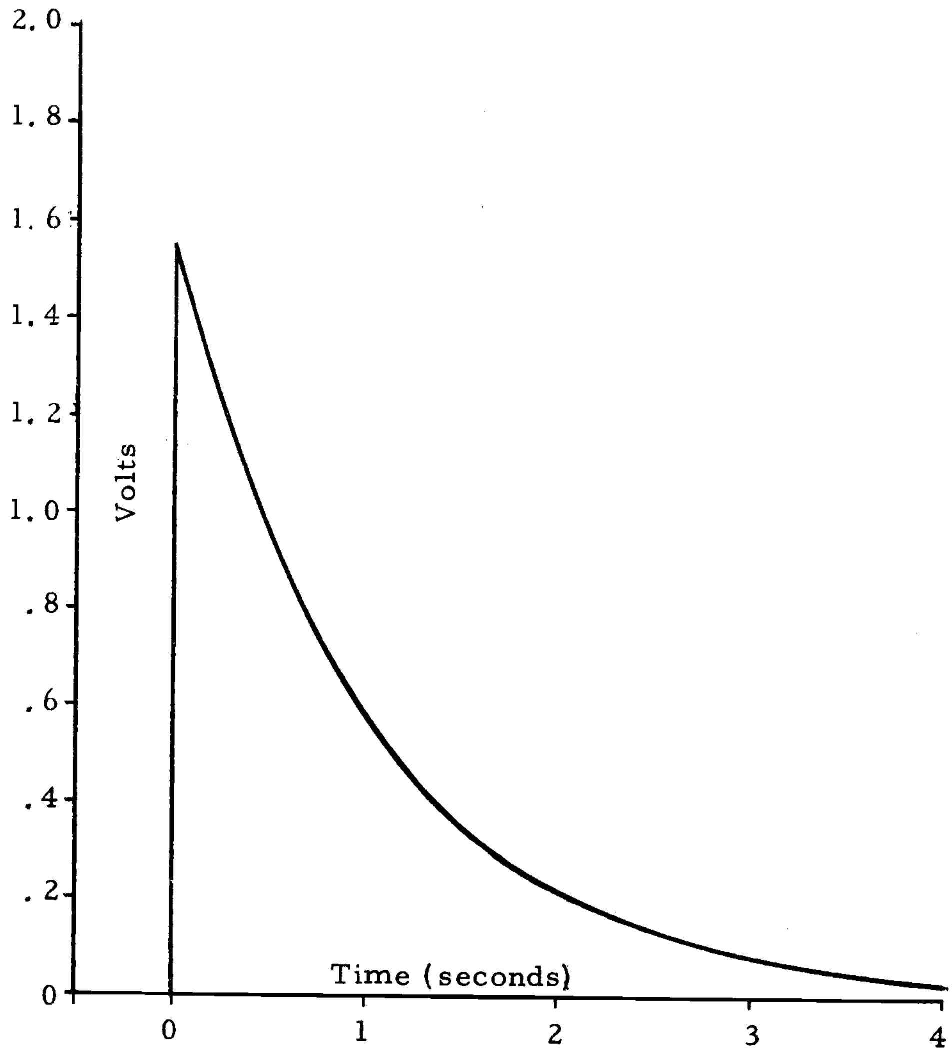



Figure 2. Theoretical pulse developed across a resistor R of $10^{11}$ ohms when a chamber exposed to ten mR is inserted into the socket.

The initial voltage across R is 1.55 volts and in one second the voltage drops to 0.58 volts. The size and duration of the pulse was calculated assuming a value of 10 picofarads for the total chamber, socket, and stray capacitance, and a value of five cubic centimeters for the chamber collecting volume.

to some fixed voltage, $V_i$. When the chamber is removed and exposed to radiation some of the voltage, $V_d$, is dissipated and a voltage, $V_f$, remains on the chamber. When the exposed chamber is inserted into the socket a voltage pulse, $V_p$, is developed. The height of the voltage pulse is proportional to the exposure received by the chamber. The value of the voltage pulse is given by:

$$V_p = \frac{(V_i - V_f)}{2} = \frac{V_d}{2}$$

After a time which is determined by the RC time constant of the charging circuit, the chamber will be recharged to voltage $V_i$ and the chamber is ready for use again.

# III. CONSTRUCTION OF PULSE READER

## Design of Pulse Reader

The completed pulse reader is illustrated in Figure 3. The components are housed in an 11 x 7-1/4 x 6-1/2 inch metal cabinet and the instrument weighs ten pounds. The pulse reader was designed and wired for rigidity and for minimum stray capacitance. All components are securely fastened and wires are as short as possible. Figure 4 is a complete schematic of the pulse reader. The transistor $T_1$ is mounted in a transistor socket and this socket is mounted directly on the center post of the ionization chamber socket. The outer cylinder of the chamber socket is in direct contact with the cabinet which is represented as ground on the schematic. All resistors are fixed on vector board, which is securely attached to the back of the milliammeter.

## Description of Components

Ionization Chamber. A Victoreen Model 362 Pocket Chamber (Victoreen, n. d. c.) was used throughout this study. For maximum utility the chamber should be small and have a flat radiation response over a wide range of photon energies, that is, the chamber should have little energy dependence (Hine and Brownell, 1956). The Model 362 Pocket Chamber is 5-1/2 inches long by 1/2 inch in diameter

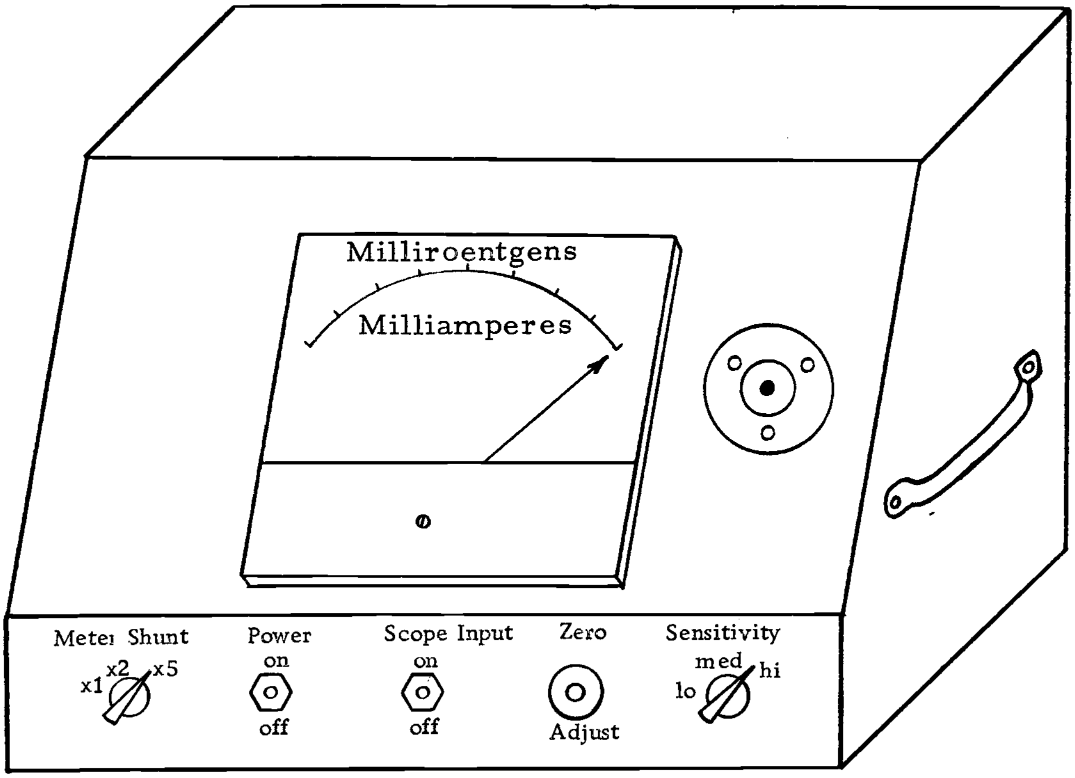



Figure 3. Pulse reader for ionization chambers.

Scale: 1 cm = 3 cm

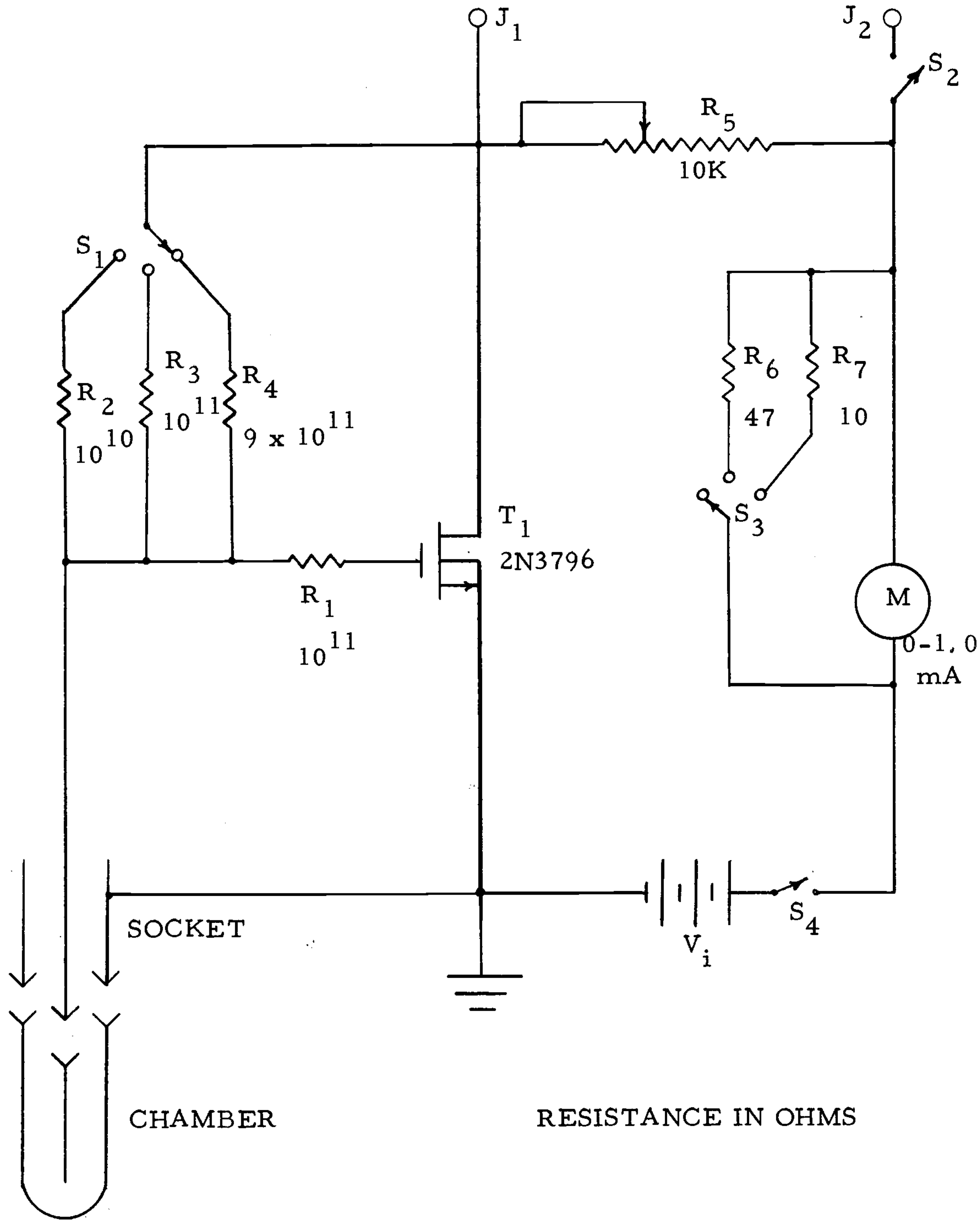



Figure 4. Pulse reader schematic.

and has an energy dependence of about ±15% for photon energies from 1.2 MeV to 30 keV (Victoreen, n.d.c.). In view of these specifications, the Model 362 Pocket Chamber was considered suitable.

Electronically, the Victoreen Model 362 Pocket Chamber is an air dielectric capacitor. It consists of a cylindrical electrode and a wire electrode co-axially positioned in the cylinder. A cross section of the chamber is shown in Figure 5.

Socket. The construction of the socket which receives the ionization chamber is extremely important since spurious voltages are produced when the chamber is inserted into the socket. These spurious voltages must be minimized since they will be detected and measured along with the voltage pulse due to the radiation exposure to the chamber. Since these spurious voltages are not constant or reproducible, it is not possible to compensate for the error by using a simple subtraction factor.

Spurious voltages are due to several factors: contact potential, insulator strain, and a changing electrical field (Braby, 1965).

Contact potential is the potential difference that is developed when two different metals are placed in contact. These potentials can be as high as one volt (West and Thomson, 1964), and this would add a significant error to the pulse measurement. Consequently, the metal parts of the socket must be a type that result in low contact

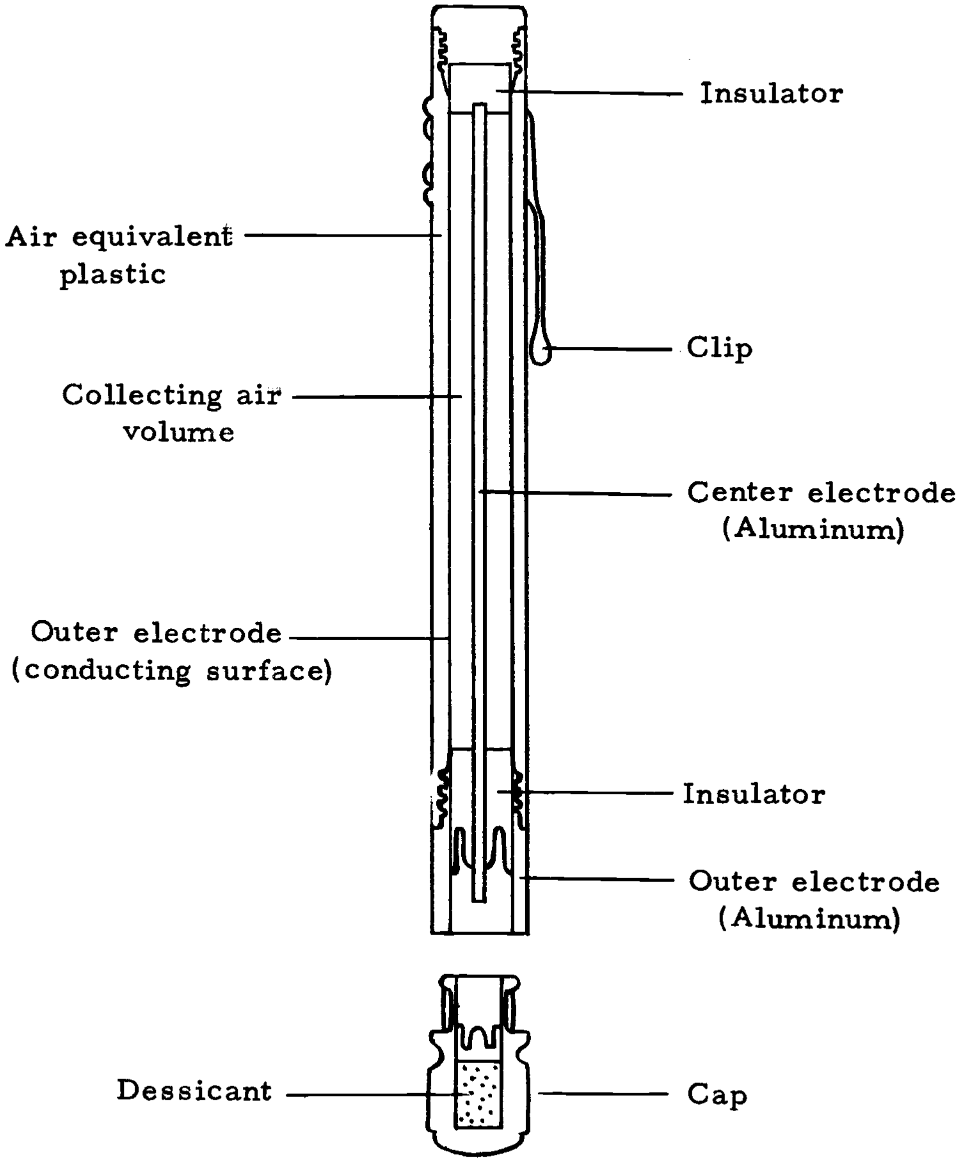



Figure 5. Cross section of Victoreen Model 362 Pocket Chamber.

Scale: 1 cm = 1 cm

potential when the chamber is inserted.

When insulators are strained, voltages are created due to the polarization of the material. This effect is called the piezoelectric effect (West and Thomson, 1964). Although these voltages are usually quite small, on the order of millivolts, they are a source of error and should be minimized. Consequently, the socket must receive the chamber in such a way that no appreciable strain is placed on either the chamber insulator or the socket insulator.

The electric field in the socket must be the same whether the chamber is in or out of the socket. If not, the change in the electric field caused by the insertion of the chamber will produce voltages. To avoid a change in field, the socket must be rigid and have essentially no moving parts.

Several sockets were tested and the one found to be the most suitable with regard to spurious voltages was a socket that was built at Battelle Northwest Laboratory. Figure 6 shows a cross section of this socket which was used in the pulse reader. The socket is a stainless steel cylinder with a polystyrene insulator. Three phosphor bronze springs contact the outer electrode of the ionization chamber and a brass center post contacts the center electrode of the chamber. In the final construction of the pulse reader, this socket produced spurious voltages equivalent to less than 0.5 mR.

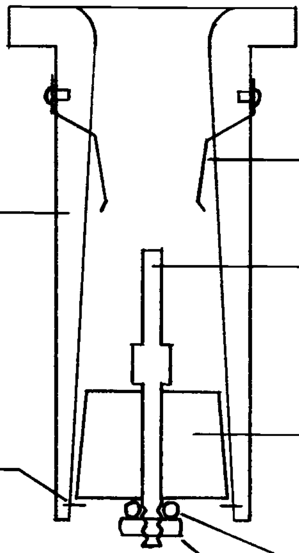



Figure 6. Cross section of ionization chamber socket.

Scale: 1 cm = 1 cm

Voltage Supply $V_i$. Two 22.5 volt Burgess 5156 zinc-carbon dry batteries were used. These batteries supply charging voltage for the insulated gate field effect transistor $T_1$. The batteries are multi-terminal, which allows a selection of voltages up to 45 volts. Each battery has terminals which provide 3, 6, 12, 13-1/2, 16-1/2, 18, 19-1/2 and 22-1/2 volts.

The initial chamber voltage must be low enough so that the insulated gate field effect transistor is not damaged, yet high enough for good collection efficiency (Hine and Brownell, 1956). If the voltage on the chamber is too low, ion pairs produced by radiation will recombine, and the dissipated voltage will be somewhat lower than expected. With the Victoreen Model 362 Pocket Chamber, an initial charge of 45 volts is sufficient for over 99% collection efficiency at an exposure rate as high as nine R per second. If the chamber is discharged to a level as low as ten volts, exposure rates as high as 500 mR per second still would result in a collection efficiency of 99%. These values of collection efficiency and exposure rate were calculated from the expression given by Attix and Roesch (1966).

$$f = \frac{1}{1 + \frac{q}{6}\left[\frac{m(a-b)^2}{V_i} \cdot \frac{a/b + 1}{a/b - 1} \cdot \frac{\ln a/b}{2}\right]^2} \qquad (7)$$

where:

$f$ = collection efficiency
$q$ = exposure rate
$m$ = 35.4
$V_i$ = chamber voltage (volts)
$a$ = radius of outer electrode of chamber (cm)
$b$ = radius of inner electrode of chamber (cm)

The chamber radii a and b were measured from a radiograph of the Model 362 Pocket Chamber and found to be 0.4 cm and 0.1 cm respectively.

The actual value of $V_i$ is not as important as the requirement that the voltage remain constant. If the value of $V_i$ changes between the time the chamber is charged and the time the chamber is read, erroneous results will be obtained. Also, the response of the transistor $T_1$ which facilitates the measurement of pulses is dependent on the value of $V_i$. If $V_i$ changes, the calibration of the pulse rader will also change.

Ideally, mercury batteries would be used for voltage supply $V_i$ since mercury batteries remain at a constant voltage throughout their lifetime (Malmstadt and Enke, 1963). Zinc-carbon batteries were used in this study however, since they are comparatively inexpensive and since their voltage could be expected to remain relatively constant due to the small current load that would be demanded. The zinc-carbon batteries proved to be satisfactory for the duration of this study.

Biasing Resistors $R_2$, $R_3$, and $R_4$. These are Victoreen Hi-Meg Precision Deposited Carbon Resistors (Victoreen, 1968). These resistors, which are selected by switch $S_1$, develop the pulse that is to be measured. The resistors are essentially biasing resistors for the insulated gate field effect transistor.

It is necessary to use resistors on the order of $10^{10}$ to $10^{11}$ ohms so that the pulses have sufficient duration to be measured. The most important requirement of these resistors is that their values remain constant. If their values change, the response of the transistor $T_1$ changes and this changes the calibration of the pulse reader. Victoreen Hi-Meg resistors are noted for their stability and accuracy and therefore, were chosen for use in the pulse reader.

When $R_2$ ($10^{10}$ ohms) is biasing the transistor, the pulses have an RC time constant of 0.1 second. This is too fast to allow the pulses to be read easily with the milliammeter, however, the response of the meter is the most linear when $R_2$ is used. Also, reading and recharging the ionization chambers can be accomplished rapidly. Measuring the pulses can be facilitated by using an oscilloscope connected across $R_5$.

When $R_3$ ($10^{11}$ ohms) is used, the RC time constant of the pulses is one second. These pulses are long enough to be read with the milliammeter and not too much time is required for the recharging process. For these reasons, $R_3$ was chosen as the biasing resistor for the calibration of the pulse reader. The milliroentgen scale of the milliammeter is only applicable when $R_3$ is biasing the transistor.

When $R_4$ ($9 \times 10^{11}$ ohms) is used, the RC time constant of the pulse is nine seconds. The meter response is slow and it is easy to read the pulses with the milliammeter. However, the recharging process takes the most time.

The sensitivity of the pulse reader is increased by increasing the value of the biasing resistor. However, the value of the biasing resistor must be small compared to the value of the input impedance of the insulated gate field effect transistor, which is about $10^{13}$ ohms. If the value of the biasing resistor is too large, the transistor will be cut off. With the use of $R_1$, which is described below, the maximum value of the biasing resistor is $9 \times 10^{11}$ ohms.

Resistor $R_1$. This is also a Victoreen Hi-Meg resistor. The resistor adds to the input impedance of the transistor so that the $9 \times 10^{11}$ ohm resistor, $R_4$, can be used to increase the sensitivity and to increase the duration of the pulses. Without $R_1$ and with $R_4$ biasing the transistor, only a very small current can be drawn by the transistor (less than 0.1 milliampere), and the transistor is essentially cut off. However, with $R_1$ and with $R_2$ or $R_3$ biasing the transistor, the sensitivity of the pulse reader is decreased by about

20%. That is, if either $R_2$ or $R_3$ is used as the biasing resistor and if $R_1$ is removed from the circuit, the sensitivity of the instrument is 20% higher than if $R_1$ is left in the circuit.

Potentiometer $R_5$. This is a 10K ohm precision potentiometer that serves as the load for transistor $T_1$ and serves as a zero adjust. In the normal operation of the pulse reader, $R_5$ is adjusted such that the transistor draws one milliampere, which corresponds to zero on the milliroentgen scale of the meter M.

Meter M. This is a Simpson zero to one d-c milliammeter. The meter monitors the transistor current and measures the inverted current pulse which results from the insertion of the chamber into the socket. The meter is essential as a current monitor since the response of the transistor $T_1$ is dependent on the current drawn. The meter also serves as a read-out system and has been calibrated to read in mR when biasing resistor $R_3$ is used, when the operating current of transistor $T_1$ is one milliampere, and when the supply voltage is 45 volts.

The meter has certain disadvantages as a read-out system. The meter response can never be precisely linear since the voltage pulse that is being measured is varying with time. The voltage pulse reaches a maximum and begins to decrease before the meter registers the maximum pulse height. Therefore, the observed meter deflection will always be less than the theoretical meter deflection. With larger voltage pulses the meter deflection will be greater and the deviation from a linear response will be greater.

Other disadvantages of using the meter as a read-out system are that the read-out display is temporary and that a reading can not be stored or repeated. If a mistake is made in reading the meter, the chamber can not be re-inserted and read again.

In spite of these disadvantages, the meter served as an adequate read-out system for the purposes of this study.

Shunt Resistors $R_6$ and $R_7$. These resistors are shunts for the meter M. They extend the range of the zero to one milliammeter. When $R_6$ is selected by switch $S_3$, the current indicated by the meter should be multiplied by two, and when $R_7$ is selected, the multiplication factor is five. When $S_3$ is in the x 1 position, no shunt is in the circuit and the actual value of the transistor current is indicated by the meter.

The transistor response depends on the operating current of the transistor; the use of $R_6$ and $R_7$ allows the selection of different operating currents. Various tests made during the course of this study indicate that optimum operating current for this pulse reader design is one mA. Using larger currents slows the meter response, but the load on the batteries is greater and overall sensitivity is decreased so that less meter response is obtained for a given exposure.

Transistor $T_1$. This is an insulated gate field effect transistor, Motorola 2N3796. The insulated gate field effect transistor (IGEFT) is a fairly recent development (Lancaster, 1966). The most prominent feature of this transistor is its high input impedance of from $10^{13}$ ohms to $10^{15}$ ohms, and this feature makes this transistor suitable for use in the pulse reader. Figure 7 shows the basic construction of the insulated gate field effect transistor.

The Motorola 2N3796 is a p-channel transistor which consists primarily of p-type and n-type silicon. A p-type material is a semiconductor that is deficient in electrons, and an n-type material is a semiconductor that has an excess of electrons (Wiesner, 1964). The actual size of the transistor is approximately the size of a pin head, but when the transistor is placed in a Type TO-18 can, the entire component is the size of a large pea. The small size allows the transistor socket to be mounted directly on the center post of the ionization chamber socket, which reduces the stray capacitance.

As shown in Figure 7 (a) the transistor consists of a p-type substrate into which two identical n-type regions have been diffused. The source and drain terminals are formed by making contact to the two n-type regions. Between the two n-type regions a one picofarad capacitor is formed by the p-type substrate, a silicon dioxide insulator, and a metallic gate terminal.

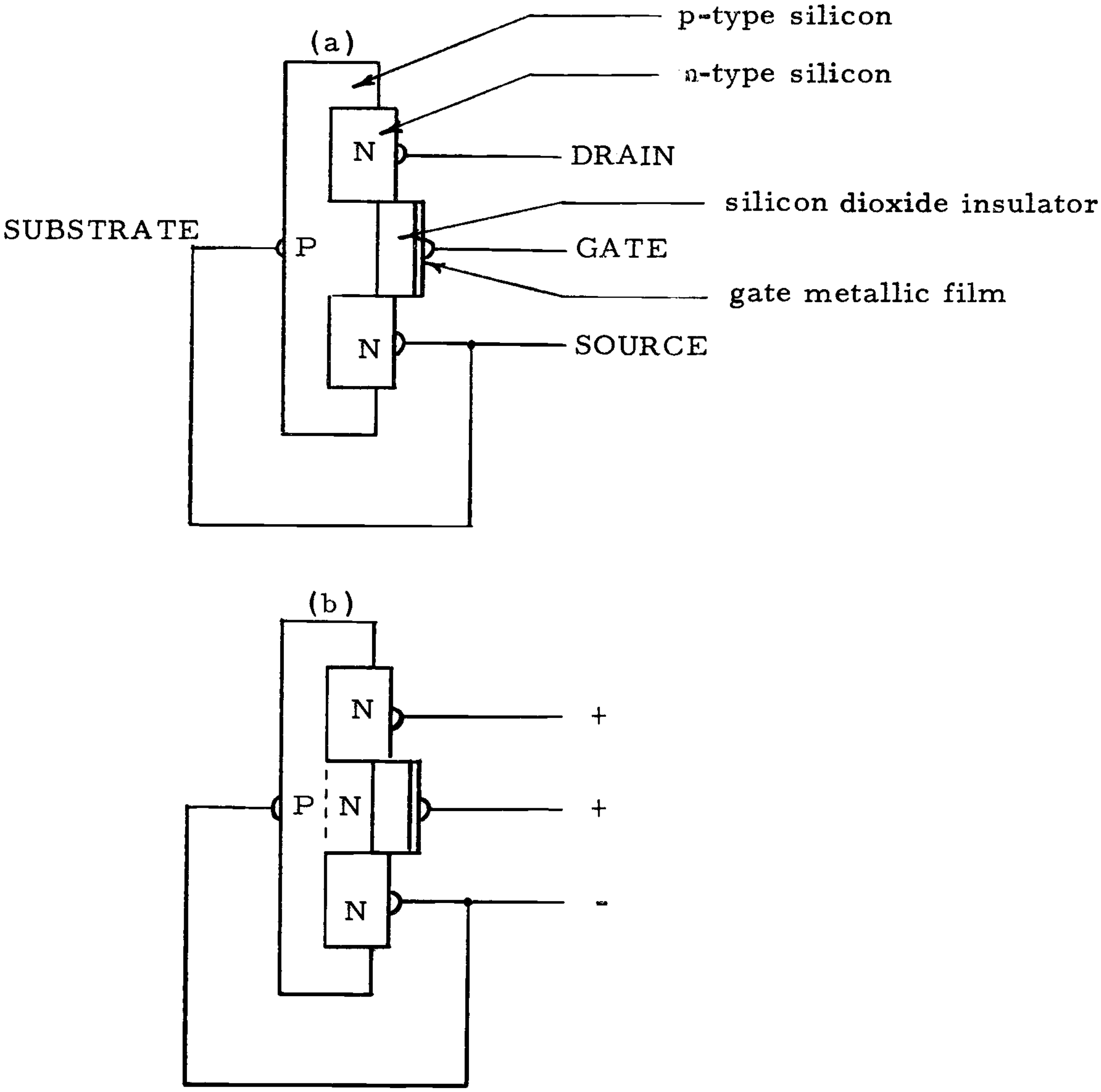



Figure 7. Insulated gate field effect transistor.

In (a) no voltage is on the gate and the transistor is off. In (b) the gate is biased positively and the transistor is on.

The source and substrate are connected to a negative potential and the drain is connected to a positive potential. With no positive gate voltage, no current will flow between drain and source since the n-p-n configuration will not conduct. With a positive voltage on the gate which implies a positive charge on the gate terminal end of the gate capacitor, a negative charge builds up on the substrate end of the gate capacitor. The negative charge causes the p-type region between drain and source to become more like n-type material. The transistor then becomes an n-n-n configuration as shown in Figure 7(b), and the transistor conducts. The extent to which the transistor conducts is directly proportional to the amount of positive voltage on the gate.

In the normal operation of the pulse reader, the source is at ground potential and the drain is at approximately +45 volts (disregarding any voltage drop across $R_5$, meter M, and other components). The gate is also at +45 volts, and so is the ionization chamber socket. The positive bias on the gate causes the transistor to conduct and the milliammeter indicates the current being drawn. When an exposed ionization chamber is inserted into the socket, a negative pulse is developed by the biasing resistor and this pulse is felt on the gate of the IGFET. This causes the transistor to conduct less, and the minimum current drawn is proportional to the voltage pulse on the gate, which is proportional to the radiation exposure received by the ionization chamber.

As in the case with most transistors, the IGFET is temperature sensitive (Motorola, 1967). Also, there may be long term changes in the transistor that affect its performance. Temperature and other effects were not measurable in this study. The pulse reader was operated at room temperatures, and during the limited time of this study, the transistor was stable.

<u>Terminals $J_1$ and $J_2$</u>. These terminals are jacks to which an oscilloscope can be connected. The oscilloscope was used to study and measure the pulses detected by the transistor and developed across $R_5$. The height of the pulse observed is proportional to the radiation exposure received by the chamber, and the oscilloscope can be used as a read-out system instead of meter M.

<u>Switches $S_1$, $S_2$, $S_3$, and $S_4$</u>. Switch $S_1$ selects the biasing resistor for the transistor $T_1$. The switch is labled "Sensitivity". The "lo", "med", and "hi" positions select $R_2$, $R_3$, and $R_4$ respectively.

Switch $S_2$ facilitates changing from one read-out system to another. With $S_2$ closed, terminals $J_1$ and $J_2$ are connected across $R_5$. The switch is labled "Scope Input".

Switch $S_3$ selects the shunt resistor for the milliammeter. The switch is labled "Meter Shunt". The xl postion selects no shunt resistor, the x2 position selects resistor $R_6$, and the x5 position selects resistor $R_7$.

Switch $S_4$ is the on-off switch for the pulse reader. The switch prevents battery drain when the pulse reader is not in use. The switch is labled "Power".

# IV. OPERATION OF THE PULSE READER

## Operating Instructions

The instrument is operated by first turning the switch designated "Power" to the "on" position. If the meter is to be used to read an exposure, no meter shunt should be used and the biasing resistor should be $R_3$. Therefore, the switch designated "Meter Shunt" should be in the xl position and the switch designated "Sensitivity" should be in the "med" position. Also, the voltage supply should be 45 volts. The zero to one d-c milliammeter should be zeroed (adjusted to zero on the mR scale of the meter or 1.0 mA on the milliampere scale of the meter) with the control designated "Zero Adjust." A chamber can then be inserted and after a few seconds the meter will again read zero mR. The chamber is now charged and can be removed and exposed to radiation. To read the exposure, insert the chamber into the socket and read the maximum meter deflection in milliroentgens.

The operation of the pulse reader is similar to the above when other shunt resistors, other biasing resistors, or different supply voltages are used. However, the milliroentgen scale of the meter is no longer calibrated.

When the meter shunt switch is placed in the x2 or x5 position, the current indicated on the mA scale of the meter should be multiplied by a factor of two and five respectively. When the sensitivity switch is in the "lo" position, $R_2$ is selected as the biasing resistor. When the sensitivity switch is in the "hi" position, $R_4$ is the biasing resistor. Various voltages can be selected by choosing the proper battery terminals of the voltage supply.

## Circuit Dynamics

The following description of circuit operation applies when the resitor $R_3$ is used and when no meter shunt is used. The operation of the circuit is similar when either $R_2$ or $R_4$ is used for transistor biasing and when either $R_6$ or $R_7$ is used for a meter shunt.

When the power switch is turned to the on position, current begins to flow through $R_3$ and the ionization chamber socket begins to charge. As the ionization chamber socket charges, a positive potential develops on the gate of the transistor $T_1$. This causes the transistor to conduct. After sufficient time, the ionization chamber socket is fully charged. This charge will actually be somewhat less than the battery voltage $V_i$, due to the IR drop across $R_5$. The final voltage on the socket will also be the potential on the gate of the IGFET. The potentiometer $R_5$ is used to adjust the final transistor current to one milliampere. When an exposed chamber is inserted into the socket, the charge on the chamber and the charge on the socket immediately equalize. The reduced positive charge of the socket and chamber is felt almost immediately on the gate of the IGFET. (The gate capacitor discharges through $R_1$ with a time constant of 0.1 second.) The reduced positive gate potential causes the transistor to conduct less current, which is indicated by the response of meter M. Current begins to flow through $R_3$ and the combined capacitors of chamber and socket begin to charge. Eventually, the chamber and socket are fully charged and the transistor is again drawing one milliampere of current.

# V. TESTING OF PULSE READER

## Pulse Reader Response to Charged Ionization Chambers

A method of testing the theory and operation of the pulse reader was devised without having to expose chambers to radiation. A socket nearly identical to the socket used in the pulse reader was charged to various voltages using a variable voltage source. A chamber inserted into this socket becomes charged to whatever voltage is selected and this simulates radiation exposure to the chamber. The chamber is then read with the pulse reader and the height of the pulses corresponding to various chamber voltages can be determined.

Figure 8 is a plot of current pulse versus chamber voltage when biasing resistors $R_2$, $R_3$, and $R_4$ are used. Operating current for the transistor is one milliampere and supply voltage is 45 volts. The sensitivity of the pulse reader is indicated by the slope of the curve; the steeper the slope the greater is the sensitivity. The graph indicates that the pulse reader is most sensitive when $R_4$ is used and least sensitive when $R_2$ is used. The graph also indicates that the actual initial chamber voltage (and drain voltage for the transistor) is 39 volts instead of 45 volts. This is due to the voltage drop across $R_5$.

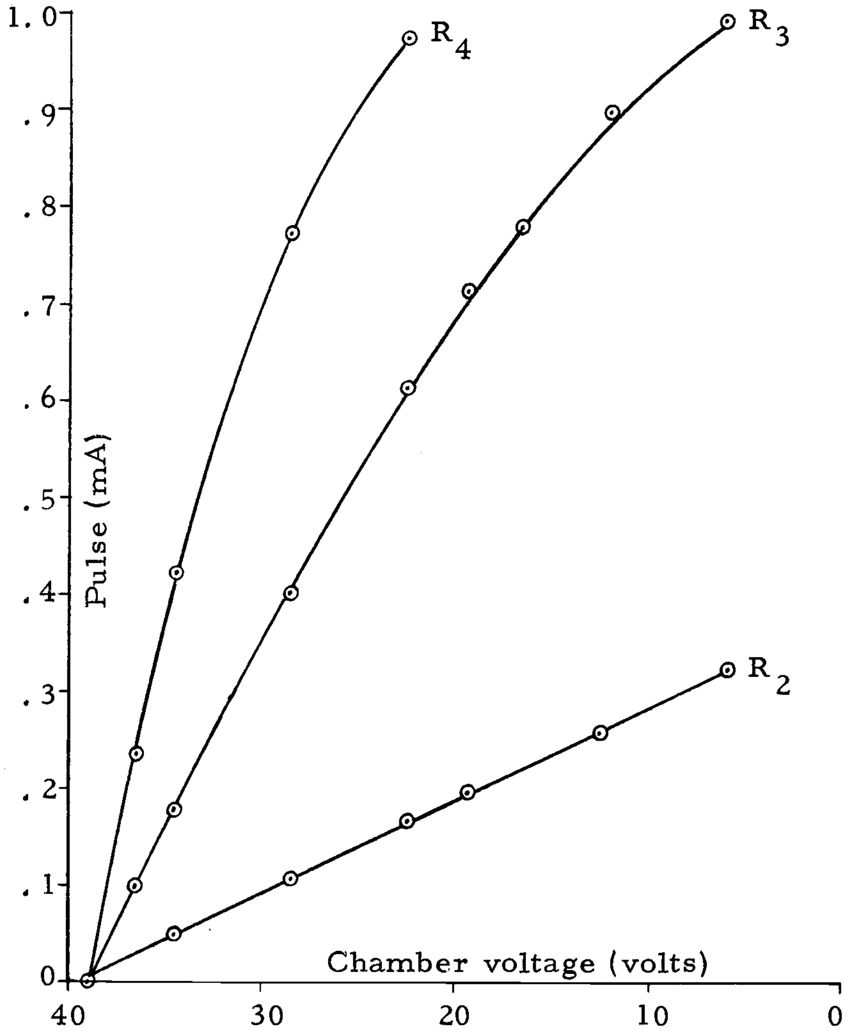



Figure 8. Pulse reader response to charged ionization chambers using biasing resistors $R_2$, $R_3$, and $R_4$.

Transistor current: 1.0 mA
Supply voltage: 45 volts

Date: February 26, 1969

In section II it was calculated that a ten mR exposure would dissipate 3.09 volts from the Model 362 Pocket Chamber. If the initial chamber voltage is 39 volts, then the final chamber voltage after a ten mR exposure would be:

$$V_f = 39.00 - 3.09 = 35.91 \text{ volts}$$

According to Figure 8, a chamber charged to 35.91 volts produces a pulse of 0.13 mA when $R_3$ is used, and if all the preceeding theory and calculations are correct, this 0.13 mA pulse should correspond to a ten mR exposure. It can be seen from Figure 20, which is the pulse reader calibration curve, that a pulse of 0.13 mA is actually equivalent to an 8.0 mR exposure. This shows good agreement between theory and observation.

The fact that the response is not linear when either $R_3$ or $R_4$ is used as the biasing resistor does not imply that the transistor is non-linear in its response. Rather, the deviation from linearity is due to the variation of the voltage pulses with time.

To illustrate how a different type of read-out system can be employed to measure the pulses, an oscilloscope was used to view the pulses developed across $R_5$ when chambers charged to various voltages were inserted into the socket. A plot of pulse height as measured from the oscilloscope versus chamber voltage is given in Figure 9. Biasing resistor $R_2$ was used, operating current was one

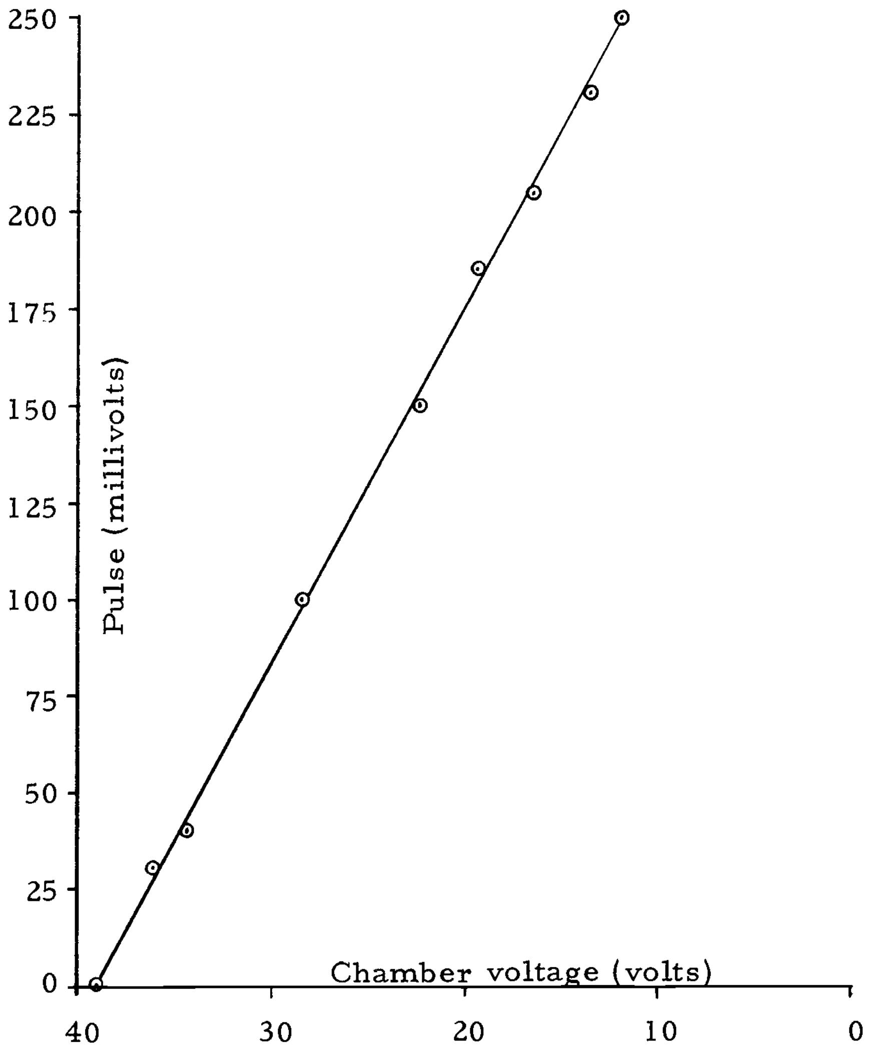



Figure 9. Pulse reader response to charged ionization chambers, pulse height measured with oscilloscope.

Biasing resistor: $R_2$

Transistor current: 1.0 mA

Voltage supply: 45 volts

Date: April 14, 1969

mA, and the supply voltage was 45 volts.

The response observed with the oscilloscope is linear. Since a chamber charged to 35.91 volts is approximately equivalent to a chamber exposed to ten mR, it can be seen from Figure 9 that a ten mR exposure produces about a 30 millivolt pulse across $R_5$. A one mR exposure would then produce a pulse of 3.0 millivolts. Since pulses much smaller than one millivolt are easily amplified by conventional amplifiers (Malmstadt and Enke, 1963), it appears that it would be theoretically possible to measure exposures much smaller than one mR with the pulse reader if a suitable amplifier and an adequate read-out system were used.

## Pulse Reader Response to Radium

A two milligram Victoreen Radium Standard, Model 540B (Serial no. 261) was used to study the pulse reader response to radium radiation. The data shown in Figures 10, 11, and 12 were obtained by exposing five chambers simultaneously and averaging the readings obtained from the chambers. Each chamber was placed three centimeters from the surface of the lead cylinder which serves as the source container. A stop watch was used to measure the exposure time. The exposure rate was measured with the calibrated pulse reader and found to be 1.67 mR per minute.

This exposure rate agrees with measurements made with a survey meter.

Figure 10 shows the pulse reader response to radiation when biasing resistor $R_3$ or $R_4$ is used. Figure 11 shows how the response varies when different operating currents are used, and Figure 12 shows how the response of the pulse reader varies when different supply voltages are used.

The radium response graphs show that the sensitivity of the pulse reader can be adjusted by changing the biasing resistor, the operating current, or the supply voltage.

## Pulse Reader Response to X-Rays

The purpose of this test was to check the enery dependence of the pulse reader. X-rays with effective energies of 33, 70, 100, 122, 139, and 152 keV were used to expose a single chamber. Effective energies were estimated from half-value layer determinations (Trout, Kelley, and Lucas, 1960). Exposures were measured with a Victoreen Model 555 Radicon II Integrating Ratemeter, using either chamber 1MA or 1OLA. Chamber 1MA was used to measure the 70, 100, 122, 139, and 152 keV x-rays, and chamber 1OLA was used to measure the 33 keV x-rays. Exposure rates were always less than two mR per second. Exposures were corrected for temperature, pressure, and for energy dependence of the 1OLA or the 1MA chamber.

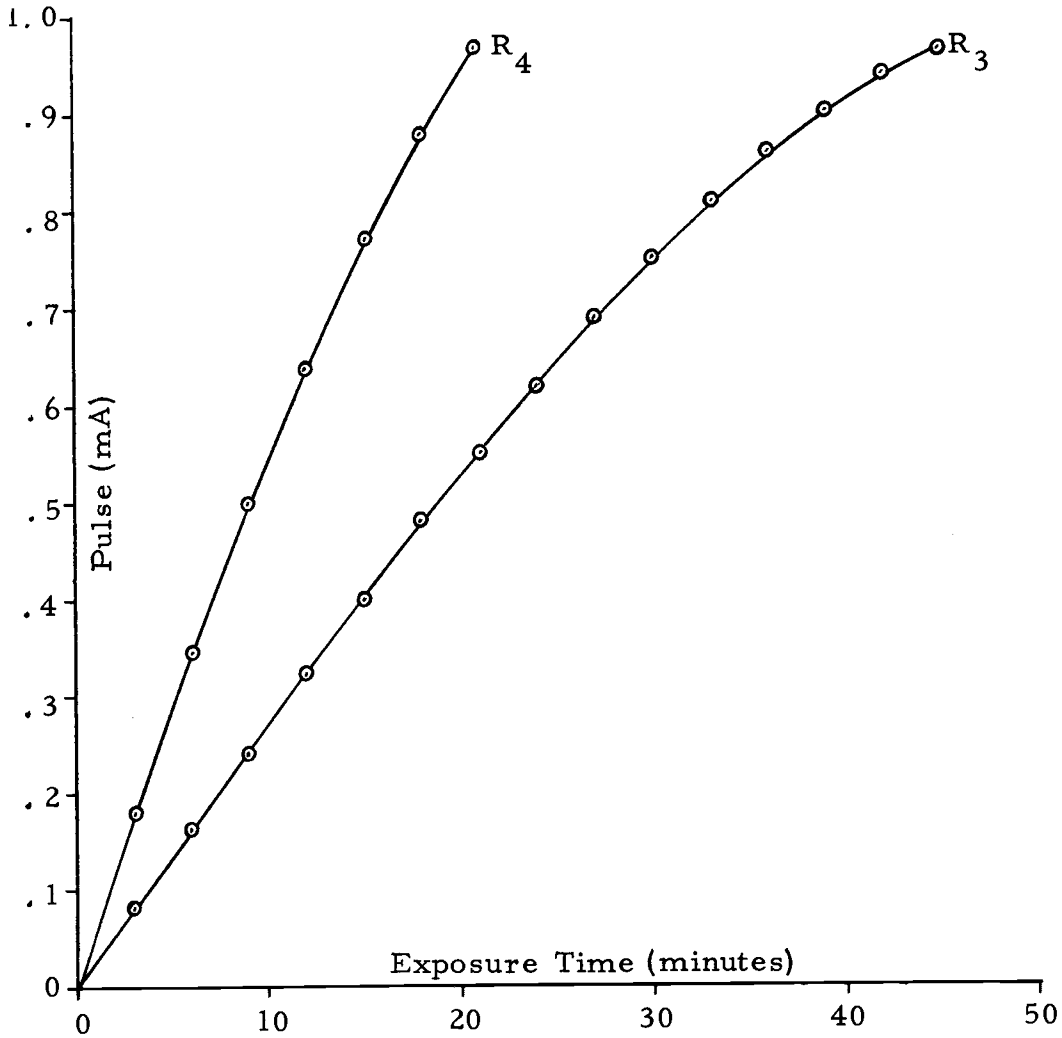



Figure 10. Pulse reader response to radium using biasing resistors $R_3$ and $R_4$.

Transistor current: 1.0 mA
Supply voltage: 45 volts

Victoreen Radium Standard
Model 540B, Serial no. 261
Source container to chamber
distance: 3 cm

Date: March 4, 1969
Temperature: 22°C
Pressure: 766 mm Hg

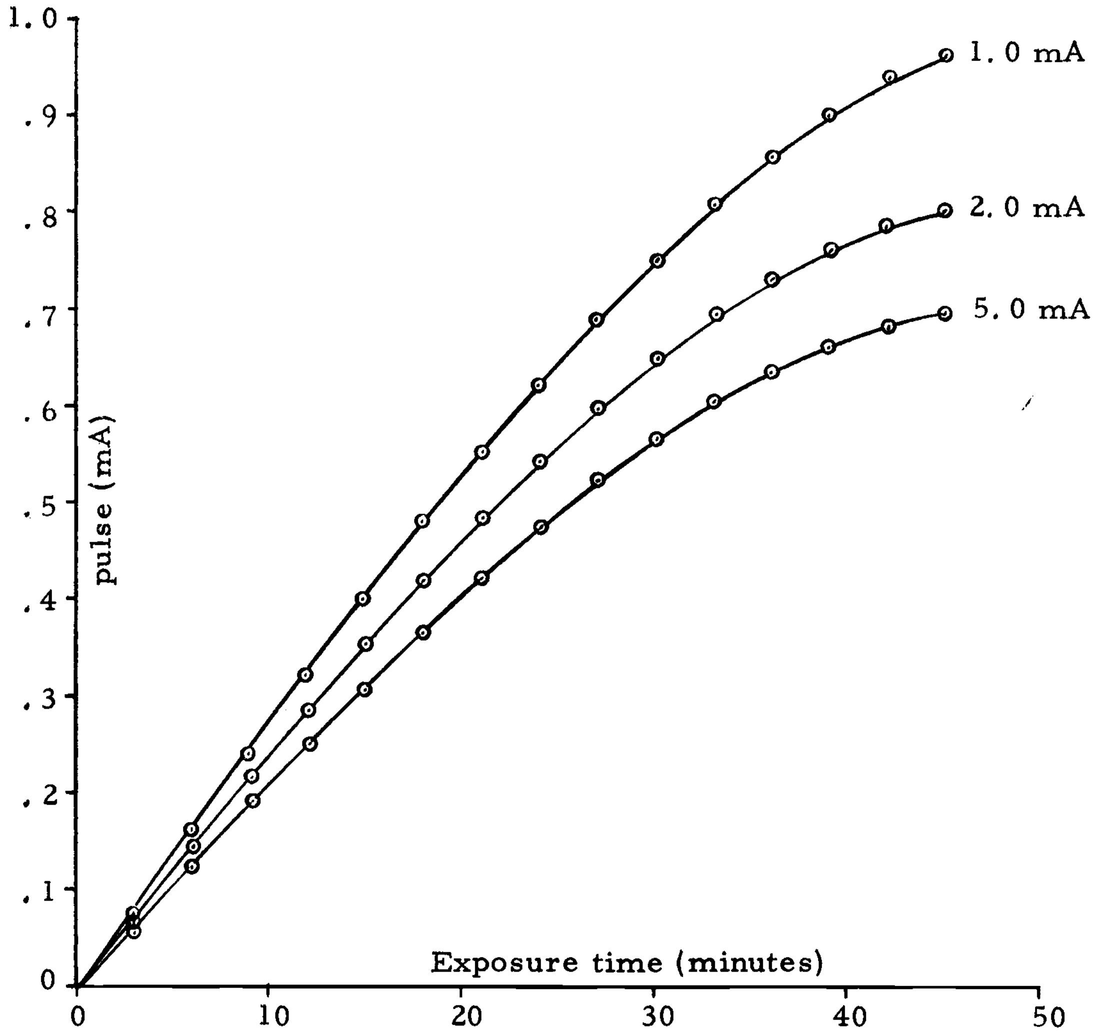



Figure 11. Pulse reader response to radium using transistor operating currents of 1.0, 2.0, and 5.0 mA.

Supply voltage: 45 volts
Biasing resistor: $R_3$

Victoreen Radium Standard Model 540B, Serial no. 261
Source container to chamber distance: 3 cm

Date: January 24, 1969
Temperature: 23 °C
Pressure: 756 mm Hg

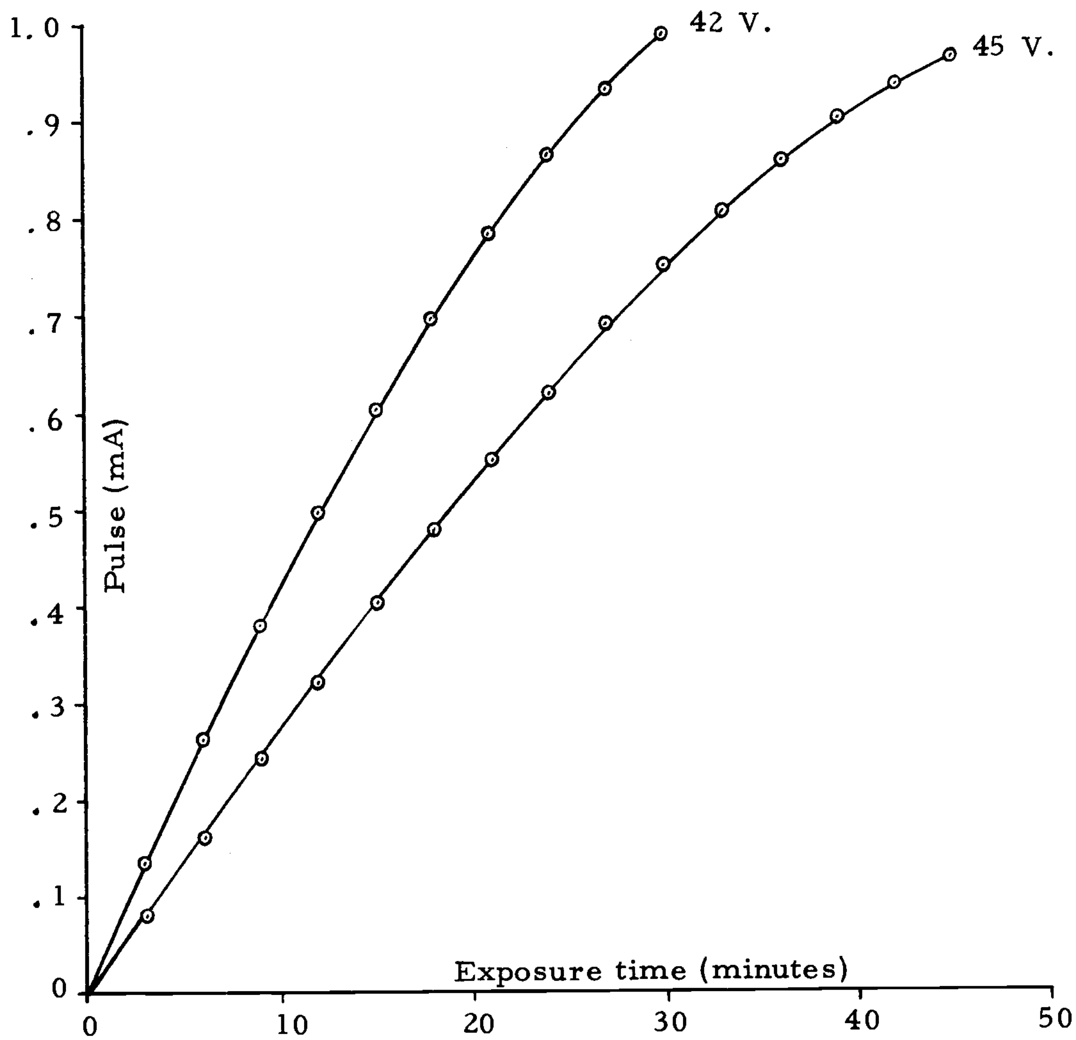



Figure 12. Pulse reader response to radium using supply voltages of 42 and 45 volts.

Biasing resistor: $R_3$

Transistor current: 1.0 mA

Victoreen Radium Standard
Model 540B, Serial no. 261
Source container to chamber distance: 3 cm

Date: June 27, 1969
Temperature: $23^{\circ}C$
Pressure: 760 mmHg

A General Electric Maximar 100 was used to produce the 33 keV x-rays. Data were collected under the following operating conditions:

Tube voltage: 100 kVp
Tube current: 0.5 mA
Total filtration: 3.00 mm Al
Cone: 10 cm diameter and 30 cm from source to end of cone
Source to filter distance: 7.0 cm
Source to chamber distance: 400 cm

Figure 13 is a plot of the pulse reader response to 33 keV x-rays. Biasing resitor $R_4$ was used, the operating current for the transistor was 1.0 mA, and the pulse reader voltage supply was 45 volts.

A General Electric Maxitron 300 was used to produce the 70 to 152 keV x-rays. Data were collected under the following operating conditions:

Tube voltage: 100, 150, 200, 250 and 300 kVp for 70, 100, 122, 139, and 152 keV respectively.
Tube current: 2.0 mA
Total filtration: 4.00 mm Cu
Field size at chamber: 10 x 10 cm
Source to chamber distance: 290 cm

Figure 14, 15, 16, 17, and 18 are plots of the pulse reader response to the 70 to 152 keV x-rays. The biasing resistor $R_4$ was used, transistor current was one mA, and the pulse reader supply voltage was 45 volts.

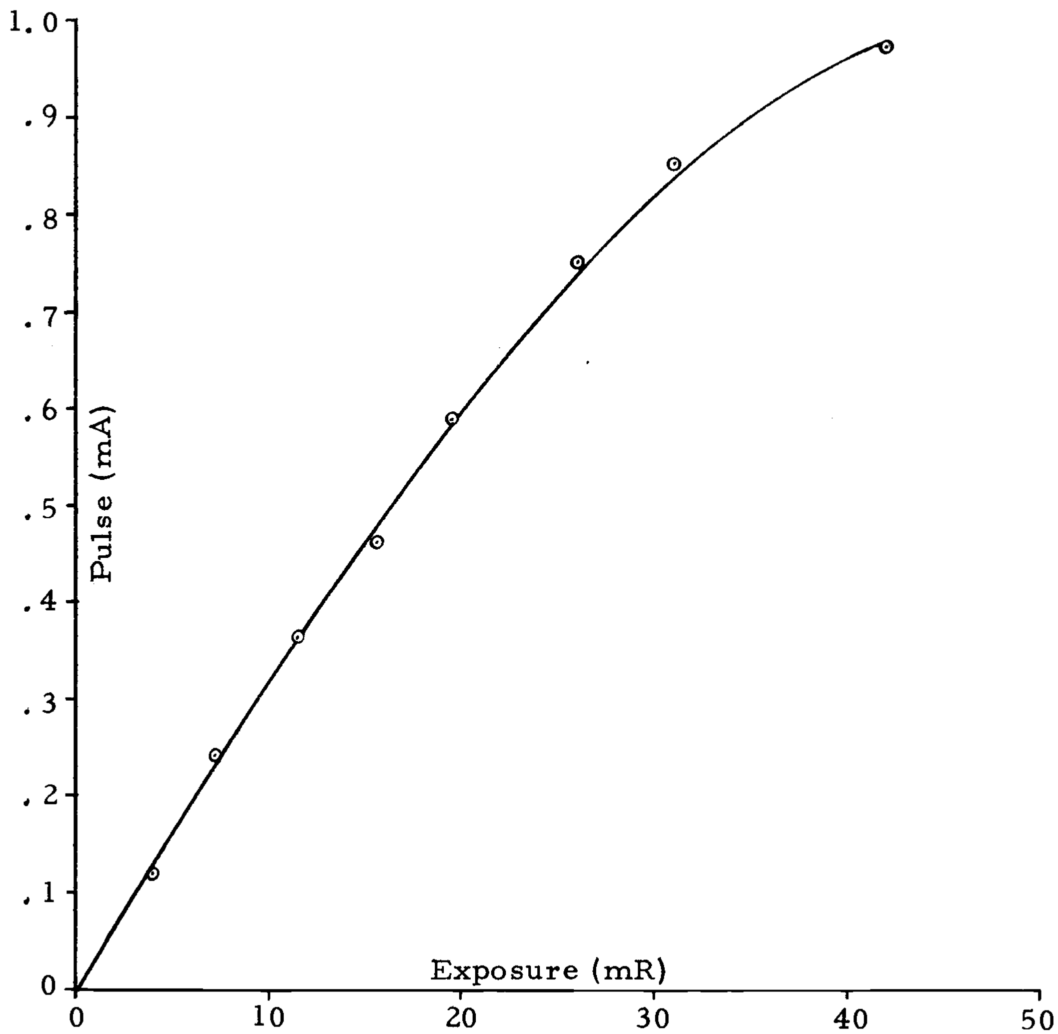



Figure 13. Pulse reader response to x-rays: 33 keV

Biasing resistor: $R_4$
Transistor current: 1.0 mA
Supply voltage: 45 volts

Date: May 9, 1969
Temperature: $23^{o}C$
Pressure: 763 mm Hg

Tube voltage: 100 kVp
Tube current: 0.5 mA
Total filtration: 3.0 mm Al
Cone: 10 cm diameter, 30 cm from source to end of cone
Source to filter distance: 7 cm
Source to chamber distance: 400 cm

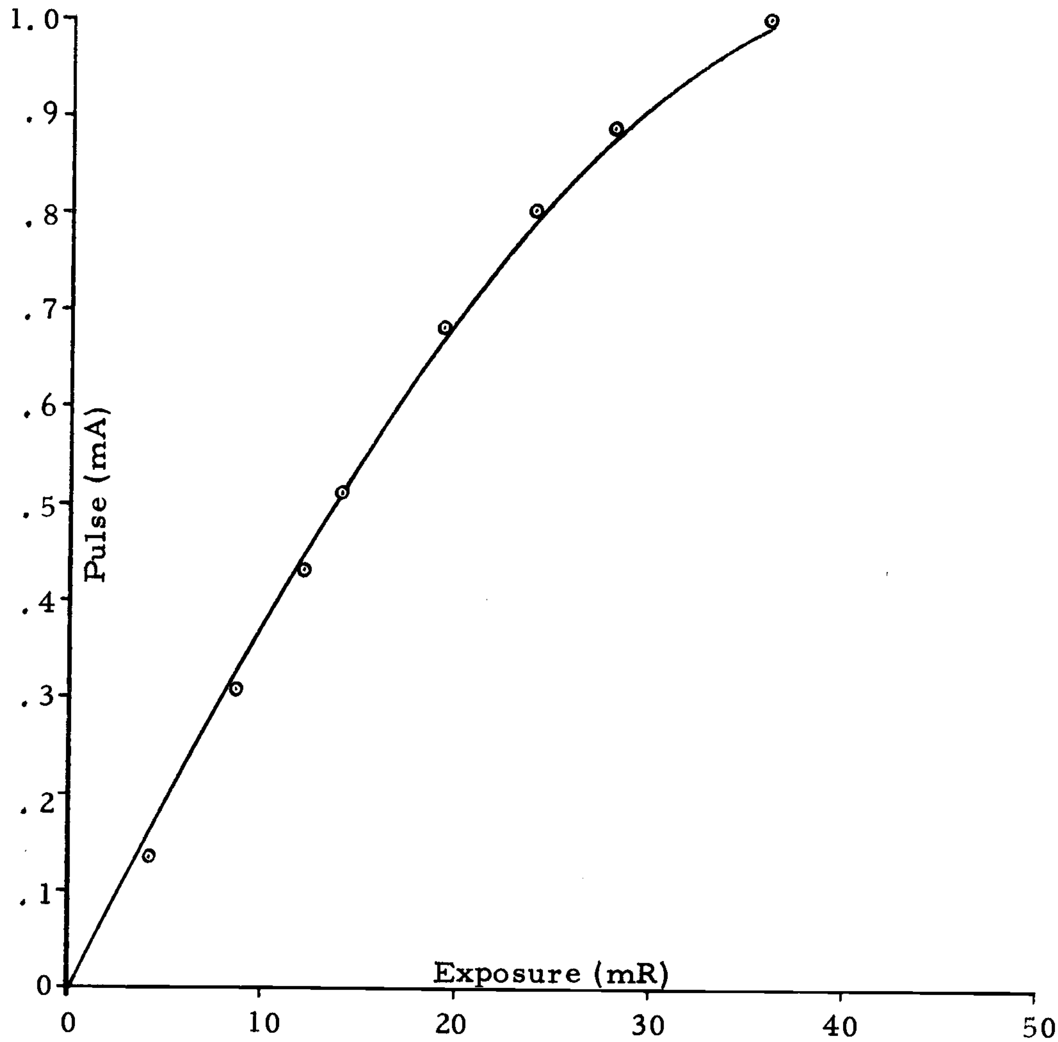



Figure 14. Pulse reader response to x-rays; 70 keV

Biasing resistor: $R_4$

Transistor current: 1.0 mA
Supply voltage: 45 volts

Date: May 9, 1969
Temperature: 23$^{o}$C
Pressure: 763 mm Hg

Tube voltage: 100 kVp
Tube current: 2.0 mA
Total filtration: 4.0 mm Cu
Field size at chamber:
10 x 10 in cm
Source to chamber distance:
290 cm

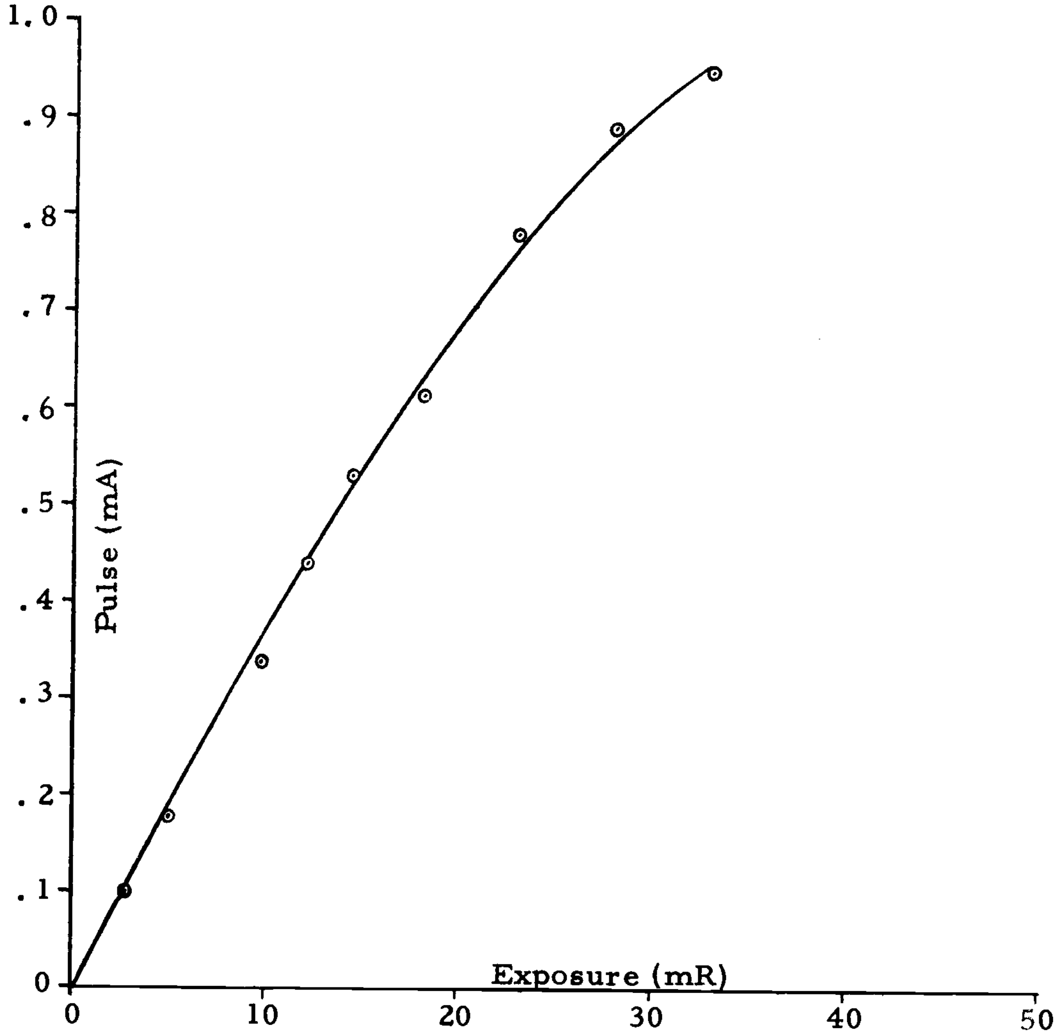



Figure 15. Pulse reader response to x-rays; 100 keV

Biasing resistor: $R_4$

Transistor current: 1.0 mA
Supply voltage: 45 volts

Date: May 9, 1969
Temperature: 23°C
Pressure: 763 mm Hg

Tube voltage: 150 kVp
Tube current: 2.0 mA
Total filtration: 4.00 mm Cu
Field size at chamber:
10 x 10 in cm
Source to chamber distance:
290 cm

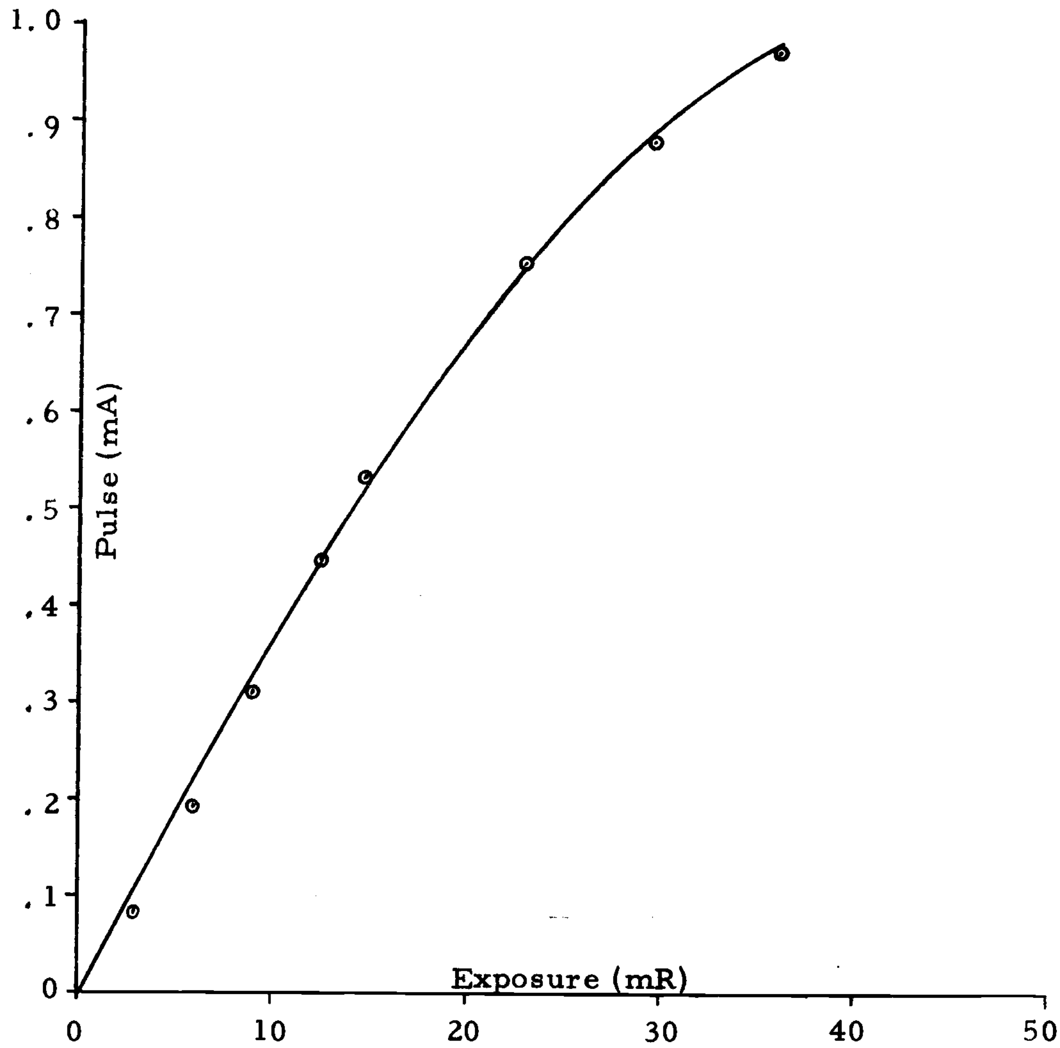



Figure 16. Pulse reader response to x-rays; 122 keV

Biasing resistor: $R_4$
Transistor current: 1.0 mA
Supply voltage: 45 volts

Date: May 9, 1969
Temperature: 23°C
Pressure: 763 mm Hg

Tube voltage: 200 kVp
Tube current: 2.0 mA
Total filtration: 4.00 mm Cu
Field size at chamber:
10 x 10 in cm
Source to chamber distance:
290 cm

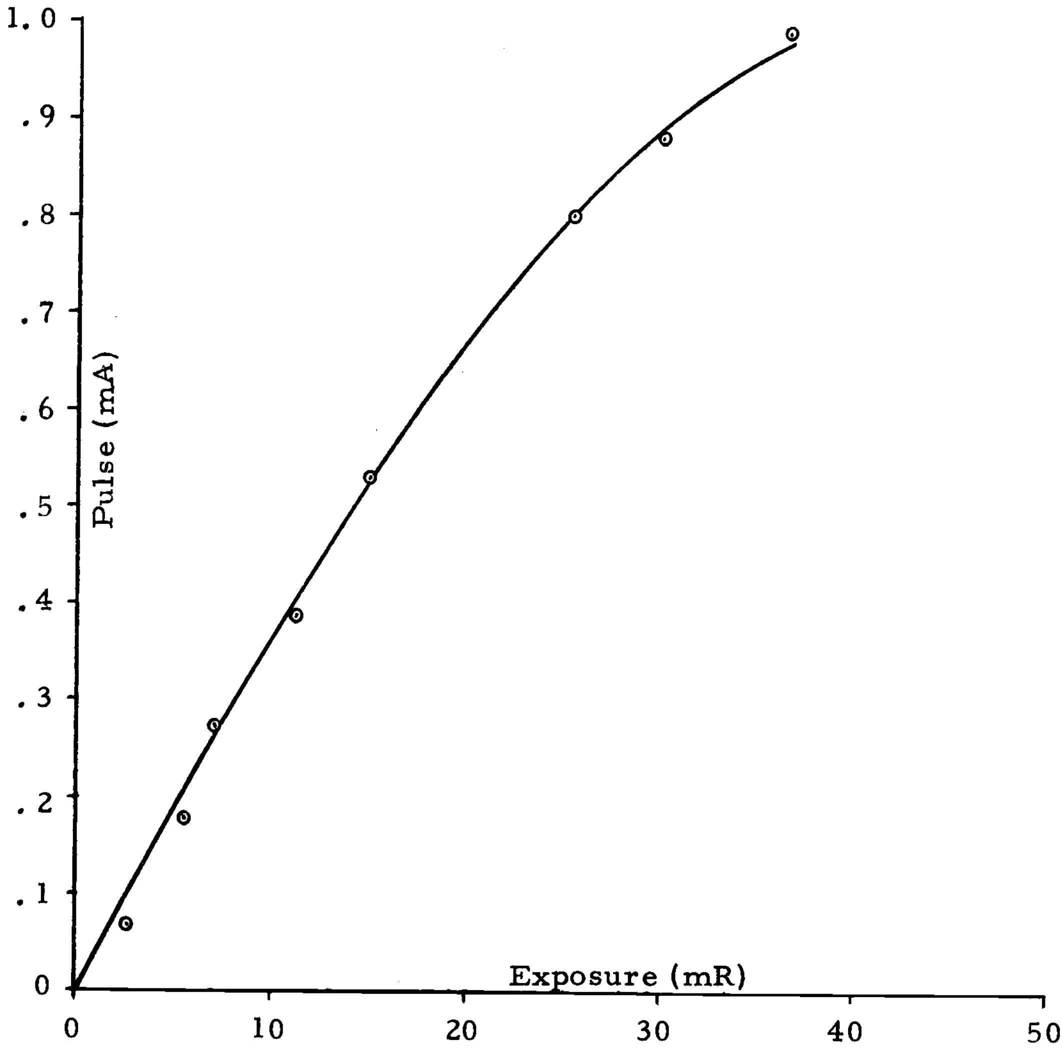



Figure 17. Pulse reader response to x-rays; 139 keV

Biasing resistor: $R_4$

Transistor current: 1.0 mA
Supply voltage: 45 volts

Date: May 9, 1969
Temperature: 23°C
Pressure: 763 mm Hg

Tube voltage: 250 kVp
Tube current: 2.0 mA
Total filtration: 4.00 mm Cu
Field size at chamber:
10 x 10 in cm
Source to chamber distance:
290 cm

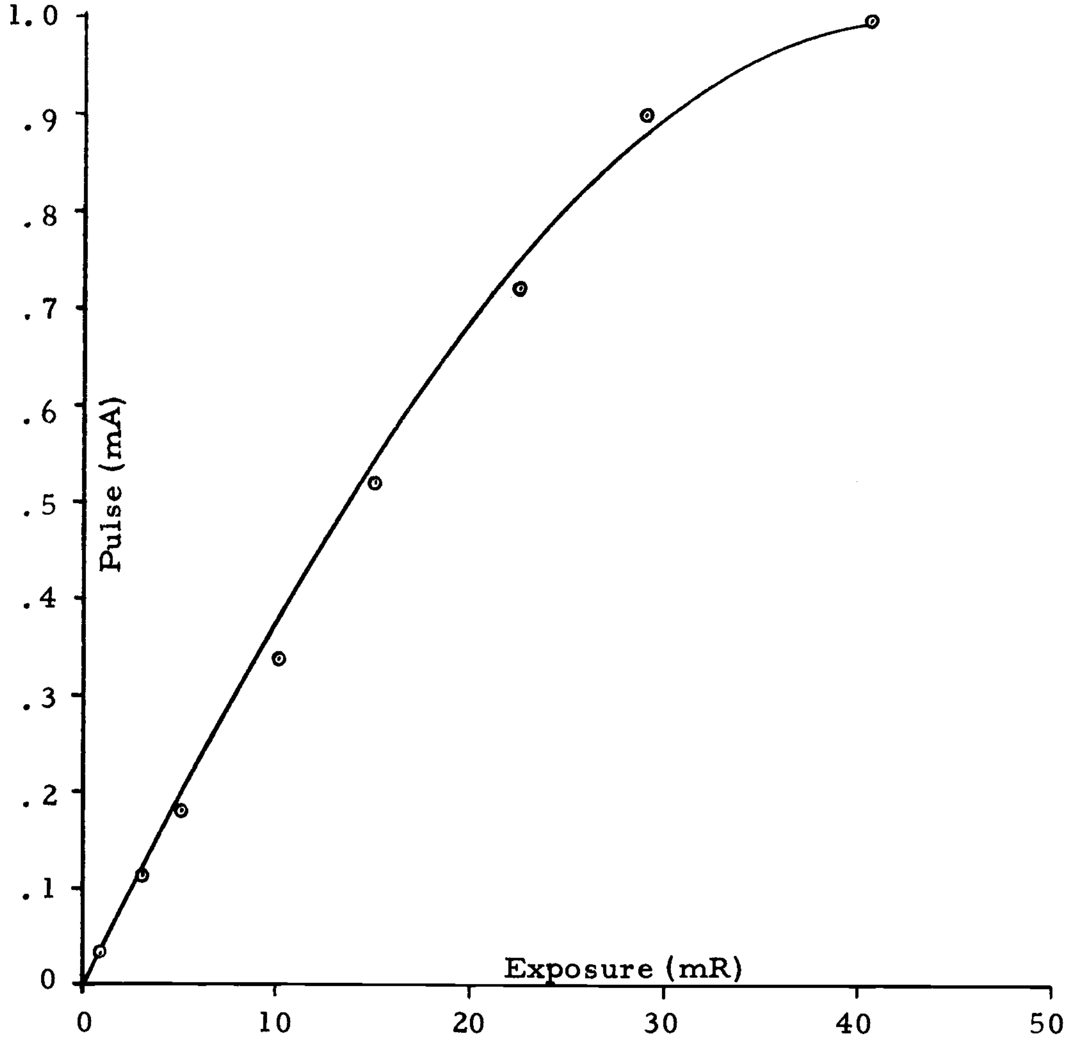



Figure 18. Pulse reader response to x-rays; 152 keV

Biasing resistor: $R_4$
Transistor current: 1.0 mA
Supply voltage: 45 volts

Date: May 9, 1969
Temperature: 23° C
Pressure: 763 mm Hg

Tube voltage: 300 kVp
Tube current: 2.0 mA
Total filtration: 4.00 mmCu
Field size at chamber:
10 x 10 in cm
Source to chamber distance:
290 cm

Figure 19 is a plot of the relative pulse reader response versus effective x-ray energy. The response at 15 mR with 152 keV x-rays was set equal to unity and the relative responses at 15 mR for the other x-ray energies were determined from the graphs in Figures 14 through 18. It can be seen from Figure 19 that the energy dependence of the pulse reader is approximately 14% for x-ray energies between 33 keV and 152 keV. This energy dependence is within the Victoreen specifications for the Model 362 Pocket Chamber. The specifications give the energy dependence as ± 15% for energies between 30 keV and 1.2 MeV.

## Pulse Reader Stability

Temperature Dependence. The temperature dependence of the pulse reader was investigated after the instrument had been calibrated to read in mR with 152 keV x-rays. The purpose of the investigation was to determine if the pulse reader calibration would change with a change in temperature. A Victoreen Radium Standard, Model 540B (Serial no. 261) was used since this source produces a constant radiation field. A single chamber (Victoreen Model 362 Pocket Chamber, Serial no. 24450) was exposed to the radium source for 18 minutes. The chamber was placed three centimeters from the source container. All exposures were corrected to a temperature of 22$^{o}$C and a pressure of 760 mm mercury.

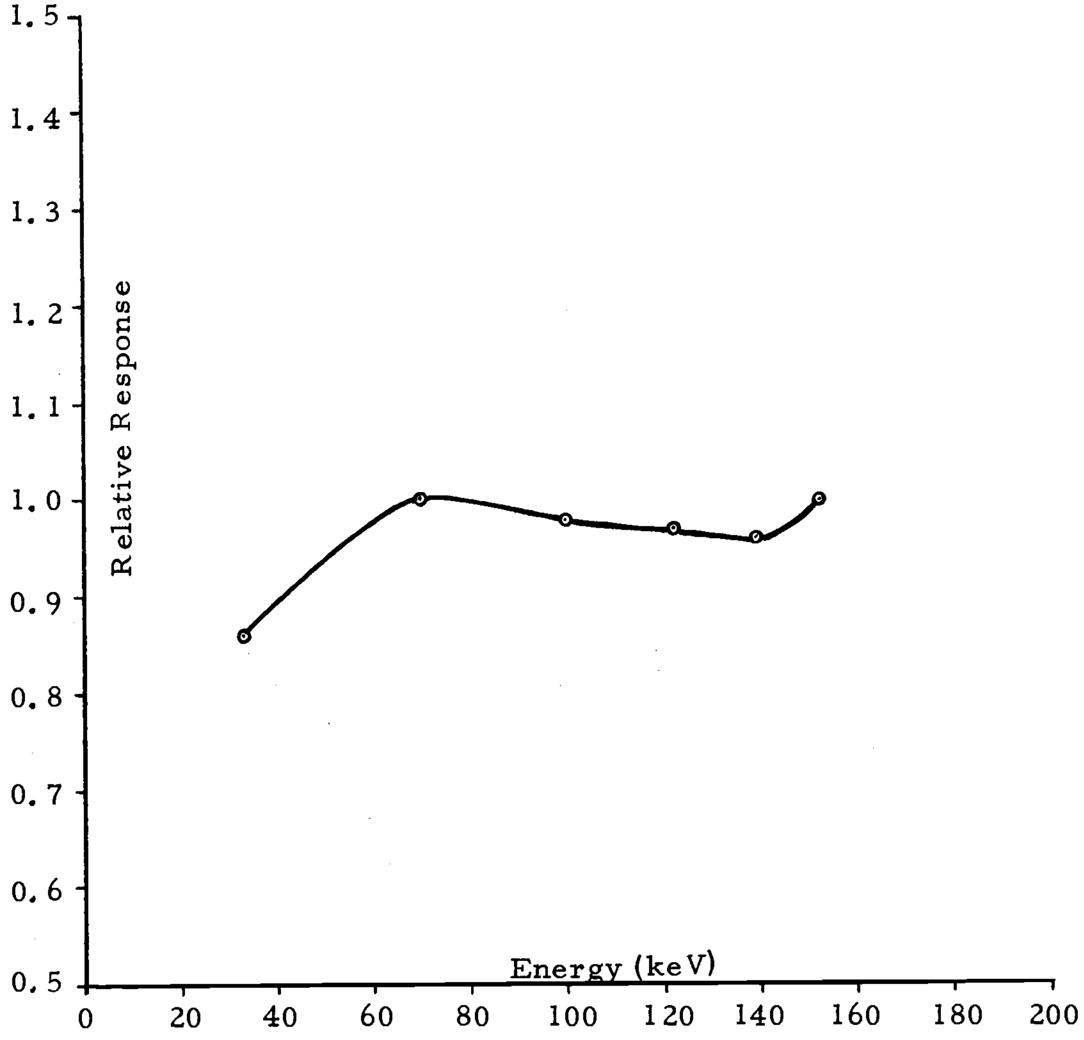



Figure 19. Pulse reader energy dependence.

The data in Table I were collected over a period of twelve hours. For each exposure, the charging, exposing, and reading of chambers were performed at the same temperature.

The average of the exposures in Table I is 29.9 mR and the standard deviation is 0.57 mR. The data indicate that the pulse reader temperature dependence when chambers are charged, exposed, and read at the same temperature is not significant when compared to the precision of the pulse reader which was measured to be ± 1.0 mR for exposures of 30 mR.

TABLE I. CHARGING, EXPOSING, AND READING AT THE SAME TEMPERATURE

| Temperature (°C) | Exposure (mR) |
|---|---|
| 21.0 | 29.6 |
| 22.0 | 30.0 |
| 23.0 | 30.0 |
| 23.5 | 29.0 |
| 24.0 | 31.0 |
| 26.0 | 29.6 |
| 27.0 | 29.9 |
| 28.0 | 30.1 |

The pulse reader response when chambers are charged, exposed, and read at different temperatures was also investigated. The data in Table II were collected over a period of four hours. The different temperatures were obtained by using a Revco freezer or by using two different rooms that were at different temperatures.

The average of the exposures in Table II is 29.6 mR and the standard deviation is 0.93 mR. The data indicate that the pulse reader response does not vary significantly when charging, exposing, and reading the chamber are performed at different temperatures ranging from 20°C to 29°C.

It should be noted that the zero of the meter changes slightly when the temperature of the pulse reader changes. If the meter is zeroed at 25°C and the temperature is then raised to 28°C, the meter will read 5.0 mR. Care must be taken to keep the meter zeroed when reading exposures and when charging chambers.

TABLE II. CHARGING, EXPOSING, AND READING AT DIFFERENT TEMPERATURES

| Charging Temperature (°C) | Exposing Temperature (°C) | Reading Temperature (°C) | Exposure (mR) |
|---|---|---|---|
| 27.5 | 27.5 | 24.0 | 28.9 |
| 24.0 | 28.0 | 21.0 | 30.4 |
| 28.0 | 28.0 | 25.0 | 29.2 |
| 25.0 | 28.0 | 28.0 | 30.4 |
| 28.0 | 28.0 | 20.0 | 28.3 |
| 29.0 | 29.0 | 20.0 | 30.5 |

There is little doubt that temperature effects on the pulse reader do exist. The values of the Victoreen Hi-Meg resistors change slightly with temperature and there are temperature effects on the insulated gate field effect transistor. Significant temperature effects were not measurable in this study since the temperature range investigated was small and the temperature effects were of the same magnitude as the precision of the pulse reader.

Time Dependence. The purpose of this test was to investigate any changes in the pulse reader calibration over a period of time. Five chambers were exposed simultaneously to the Victoreen Radium Source, Model 540B for 18 minutes. The exposures were determined by averaging the five chamber readings. The chambers were placed three centimeters from the surface of the source container. All exposures were corrected to a temperature of 22°C and a pressure of 760 mm of mercury.

The data in Table III were collected over a period of two months. The data indicate that the pulse reader is stable for the period of time investigated.

TABLE III. PULSE READER RESPONSE OVER A TWO MONTH PERIOD

| Date | Temperature (°C) | Pressure (mm Hg) | Corrected Exposure (mR) |
|---|---|---|---|
| June 6, 1969 | 22.0 | 756.0 | 30.0 |
| June 16, 1969 | 23.0 | 758.7 | 29.8 |
| June 27, 1969 | 23.0 | 760.1 | 31.0 |
| June 30, 1969 | 23.0 | 759.9 | 30.1 |
| July 7, 1969 | 21.0 | 758.5 | 30.0 |
| July 9, 1969 | 23.0 | 760.0 | 31.0 |
| July 22, 1969 | 26.0 | 761.0 | 29.6 |
| July 23, 1969 | 28.0 | 758.7 | 30.7 |
| July 24, 1969 | 30.0 | 759.1 | 30.7 |
| July 28, 1969 | 24.0 | 761.8 | 29.1 |
| July 31, 1969 | 24.0 | 763.4 | 28.9 |
| August 1, 1969 | 25.0 | 763.5 | 29.2 |
| August 4, 1969 | 23.5 | 762.5 | 29.0 |

## Pulse Reader Precision

The precision of the pulse reader with a single chamber and with 20 different chambers was established after the pulse reader had been calibrated using 152 keV x-rays. The Victoreen Radium Standard, Model 540B was used as the radiation source. Exposures were corrected to a temperature of 22°C and a pressure of 760 mm of mercury.

The data in Table IV for a single chamber (serial no. 24450) were collected by making repetitive 18 minute exposures. The average of the 20 readings is 30.80 mR and the standard deviation is 0.927 mR. For a single chamber the precision of the pulse reader is approximately ± one mR for exposures of 30 mR.

The data in Table V for twenty different chambers were also collected by making 18 minute exposures. The chambers were exposed one at a time and during the exposures each chamber was placed in the same position with respect to the radium source.

The average of the 20 readings in Table V is 31.00 mR and the standard deviation is 3.08 mR. The precision of the pulse reader with different chambers is about ± three mR for exposures of 30 mR.

Exposures as low as one mR can be measured with the pulse reader with an error of about ± 0.5 mR. The precision and

TABLE IV. PRECISION OF PULSE READER WITH SINGLE CHAMBER

| Trial | Exposure (mR) |
|---|---|
| 1 | 31.0 |
| 2 | 29.0 |
| 3 | 29.8 |
| 4 | 30.0 |
| 5 | 28.0 |
| 6 | 30.0 |
| 7 | 30.0 |
| 8 | 30.5 |
| 9 | 31.0 |
| 10 | 31.0 |
| 11 | 31.0 |
| 12 | 30.0 |
| 13 | 30.5 |
| 14 | 30.5 |
| 15 | 30.5 |
| 16 | 31.0 |
| 17 | 31.0 |
| 18 | 31.0 |
| 19 | 29.5 |
| 20 | 30.0 |

TABLE V. PRECISION OF PULSE READER WITH TWENTY CHAMBERS

| Chamber # | Exposure (mR) |
|---|---|
| 24450 | 30.0 |
| 24250 | 30.0 |
| 24531 | 33.0 |
| 24989 | 31.5 |
| 24696 | 33.0 |
| 23047 | 28.5 |
| 22521 | 33.0 |
| 22904 | 30.0 |
| 22940 | 28.5 |
| 21528 | 33.0 |
| 31916 | 33.0 |
| 31921 | 30.0 |
| 25064 | 30.0 |
| 25127 | 31.0 |
| 25159 | 31.0 |
| 25188 | 28.5 |
| 25318 | 33.0 |
| 25340 | 33.0 |
| 24296 | 31.5 |
| 24314 | 28.5 |

sensitivity of the instrument is limited by the fact that spurious voltages are produced when the chamber is inserted into the socket. These spurious voltages produce readings that are always less than 0.5 mR.

# VI. CALIBRATION

## Method of Calibration

The pulse reader was calibrated with 152 keV x-rays. The biasing resistor used during the calibration was $R_3$, the transistor operating current was one mA, and the supply voltage was 45 volts. The calibration curve is shown in Figure 20.

A General Electric Maxitron 300 was used to produce the x-rays. Data were collected with a single chamber (Serial # 24450) under the following operating conditions:

Tube voltage = 300 kVp
Tube current = 2.0 mA
Total filtration = 4.00 mm Cu
Field size at chamber = 10 x 10 cm
Source to chamber distance = 290 cm
Temperature = 22°C
Pressure = 756.0 mm Hg

The exposures were measured using a Victoreen Model 555 Radicon II Integrating Ratemeter, with chamber Model 1MA, serial no. 115. The exposure rate was approximately two mR per second. The exposures were corrected for temperature, pressure, and for energy dependence of the 1MA chamber.

From the data in Figure 20, the milliammeter scale was calibrated to read in milliroentgens. The scale reading is from zero to 60 mR. The meter scale was made linear, but as the calibration curve shows, the meter response deviates slightly

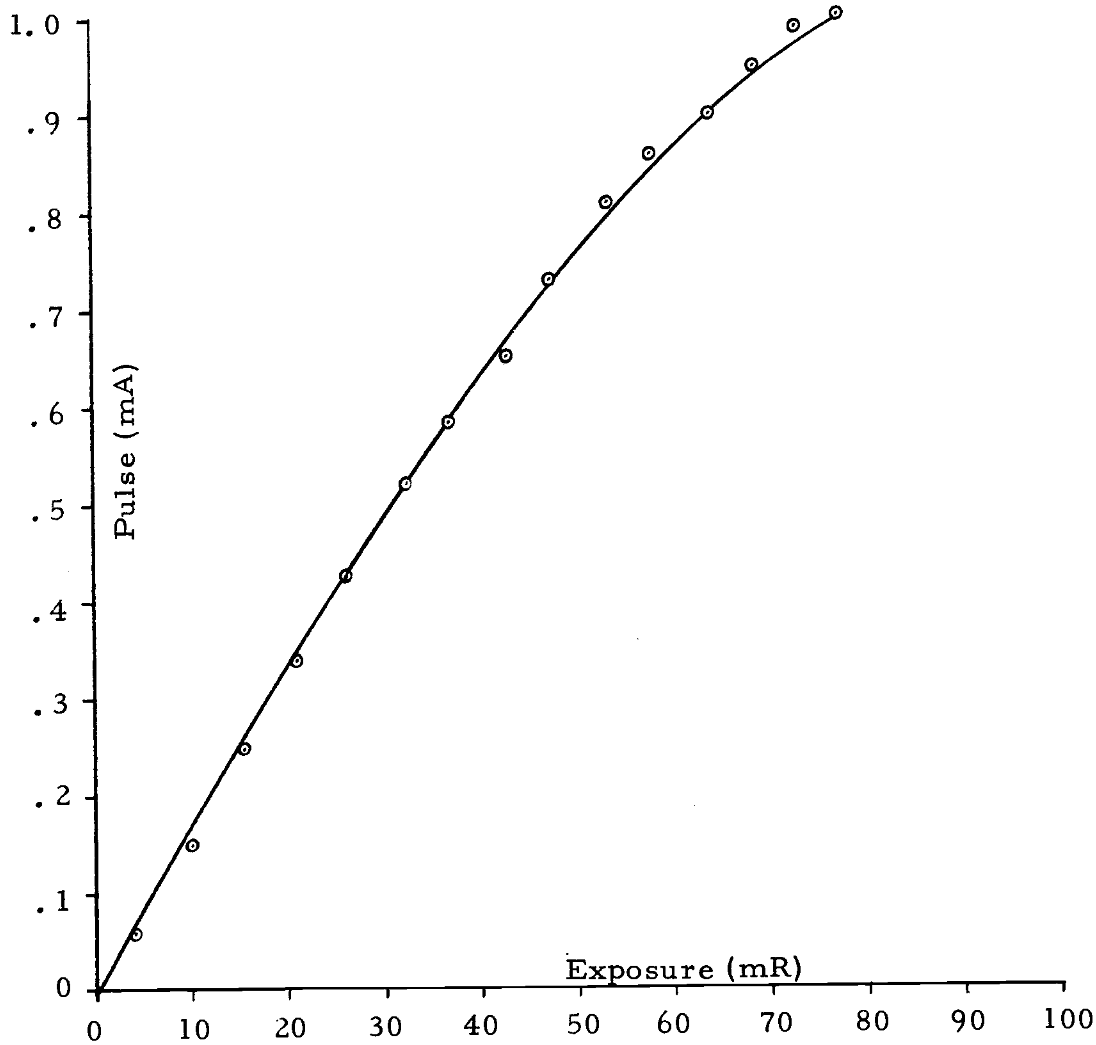



Figure 20. Pulse reader calibration curve; 152 keV x-rays.

Biasing resistor: $R_3$

Transistor current: 1.0 mA
Supply voltage: 45 volts

Victoreen Model 362 Pocket Chamber, Serial no. 24450

Date: June 6, 1969
Temperature: 22°C
Pressure: 756 mm Hg

Tube voltage: 300 kVp
Tube current: 2.0 mA
Total filtration: 4.00 mm Cu
Field size at chamber: 10 x 10 cm
Source to chamber distance: 290 cm

from linearity. The meter scale errors for various indicated exposures are given in Table VI.

TABLE VI. METER SCALE ERRORS FOR INDICATED EXPOSURES

| Indicated Exposure (mR) | Meter Error |
|---|---|
| 60 | 13% low |
| 50 | 5% low |
| 40 | 2% low |
| 30 or less | 0% |

## Accuracy of Calibration

The error of the Victoreen Model 555 chamber 1MA is given by Victoreen as ± 5%. Since the precision of the pulse reader with a single chamber is ± one mR or about 3% for a mid-scale reading of 30 mR, the mid-scale error of the pulse reader can be as low as 8% under the following conditions:

1. A correction is made for meter scale errors, These errors are given in Table VI.

2. A correction is made for energy dependence. This correction factor can be estimated from the data in Figure 19.

3. A correction is made for the temperature and pressure effects on the ionization chamber. The correction factor is given by:

$$\text{Correction factor} = T/295 \times 760/P$$

where T is the temperature in degrees absolute and P is the pressure in mm of mercury during the time the chamber is exposed. The pulse reader was calibrated at 22°C (or 295°A) and at 760 mm Hg pressure.

If the above conditions are not met the error of the pulse reader is greater than 8%, and the errors could be as high as 15% or 20%. Furthermore, since the pulse reader was calibrated with a single chamber, the use of different chambers could also introduce an additional error as high as 10%.

A Radium Chemical Corporation radium needle (serial no. 28972) was used to check the calibration of the pulse reader. The radium needle had 0.97 mg of radium encapsulated in 1/2 mm of platinum, and had been calibrated by the National Bureau of Standards. A single chamber (serial no. 24450) was placed 20 cm from the needle and exposed for 30 minutes. The actual exposure was calculated from the specific activity and radiation level of radium (National Bureau of Standards, 1960) in the following manner:

Exposure rate = 0.825 R/hr for one Ci at one meter

$0.97 \text{ mg} \times 10^{-3} \text{ g/mg} \times 0.98 \text{ Ci/g} = 0.925 \text{ mCi}$

Exposure rate = 0.825 x 0.95 = 0.784 mR/hr at one meter

$$\text{Exposure rate} = \frac{0.784 \times 25}{60} = 0.327 \text{ mR/min at 20 cm}$$

Exposure = 0.327 x 30 = 9.81 mR for 30 min at 20 cm

The exposure indicated by the pulse reader and corrected for temperature and pressure was 9.22 mR. This is only a 6% discrepancy from the true exposure, and some of this error can be attributed to energy dependence of the Model 362 chamber.

# VII. DISCUSSION

## Evaluation

The pulse reader constructed in this study can measure exposures from zero to 60 mR with a precision of ± one mR for mid-scale readings. Exposures down to one mR can be measured with a precision of ± 0.5 mR.

These specifications are good considering the fact that the essential components are a pocket chamber, a transistor, a resistor, a battery, and a milliammeter. The total cost of all the components of the pulse reader is less than one-hundred dollars. The pulse reader was constructed as an experimental instrument rather than a laboratory instrument, and the insulated gate field effect transistor presumably has never been used before in a pulse reader.

In order to appreciate the results of this study, the size of the current pulses being detected and measured by the pulse reader must be considered. When a chamber previously exposed to ten mR is inserted into the socket, the voltage drop across the biasing resistor is 1.55 volts, but the current pulse through the resistor is extremely small. For example, if $R_3$ is used as the biasing resistor, the maximum size of the current pulse is $1.55 \times 10^{-11}$ amperes. The current pulse at the output of the transistor is

$0.16 \times 10^{-3}$ amperes. In effect then, the pulse reader has multiplied a current pulse by a factor of $9.7 \times 10^{6}$ or nearly ten million times. This is a respectable multiplication factor for even the most sophisticated amplifiers.

There are several disadvantages and shortcomings of the pulse reader constructed in this study. The read-out system is inadequate and the precision and sensitivity of the instrument is limited.

The response of the milliammeter which was used as the read-out system is not linear. This results in meter scale errors if the scale is linear, or necessitates the use of a non-linear meter scale which would be difficult to construct and read. Futhermore, the response of the meter is brief and temporary. If a reading is read incorrectly, it cannot be repeated.

It was the objective of this study to construct a pulse reader capable of accurately measuring exposures as low as 0.1 mR. However, the sensitivity and the precision of the pulse reader are limited due to the spurious pulses produced when the chamber is inserted into the socket. These pulses vary from zero to 0.5 mR. Consequently, exposures below one mR cannot be measured accurately with the present design of the pulse reader.

The pulse reader described in this study is not suitable as a laboratory instrument or as a personnel monitoring system due to the above shortcomings. However, there are many improvements that could be made to increase the precision, sensitivity, and utility of the instrument. The following suggestions are for improvements that would make the pulse reader a more useful and a more valuable instrument.

## Recommended Improvements

Read-out system. A more sophisticated read-out system could be used. Preferably, the system would amplify the voltage pulses or current pulses at the output of the IGFET and store them until they are discarded. Some of the systems that could be applicable include: (1) A pulse stretching amplifier such as the amplifier found in most oscilloscopes. (2) A preamplifier and peak reading voltmeter such as the one used by Braby (1967). (3) An analog to digital converter that would convert the height of the pulses to numbers (Smith, 1967). (4) A circuit that would integrate the pulses. The area under the pulse is proportional to the radiation exposure just as is the height of the pulses, however, the area is not a linear function of the exposure. Integrating the pulses would have an advantage in that it would be possible to integrate out the spurious voltage pulses to some extent (Roesch, McCall, and Rising, 1958).

Eliminating Spurious Voltages. Perhaps the most important improvement to be made on the pulse reader is the elimination of the spurious pulses that are produced when the chamber is inserted into the socket. One recommendation is to use a socket and ionization chamber that have the same type of metal parts, since this would reduce contact potential. Another suggestion is to employ dry reed switches. The chamber and socket could be completely insulated from all the components until a dry reed switch is thrown, which would connect the chamber and socket to the pulse reader circuit. A problem that may be encountered would be leakage from the socket when it is not connected to the charging voltage supply.

Temperature Effects. If a more sensitive pulse reader were to be constructed, it is probable that temperature effects on the transistor would have to be eliminated. These effects could be eliminated by the use of matched pairs of IGFET's (Lancaster, 1966). These transistors are made from the same chip of silicon and are housed in the same can. They are identical in every respect. It would be possible to devise a circuit such that a change in one of the transistors due to temperature or other effects, would be compensated for by an identical change in the other transistor.

Matched pairs of transistors are available for about thirty dollars from Fairchild Semiconductor, Motorola Semiconductor, Texas Instruments, Inc., and a few other manufacturers.

Voltage Supply. If a more sensitive pulse reader is to be built, mercury batteries should be used to insure voltage stability. It is essential that the initial charging voltage remains constant, and this requirement becomes more critical as lower exposures are measured.

Changes in Design. The basic design of the pulse reader developed in this study is probably not the optimum design, although many other circuits were tried and these either did not work at all or resulted in a loss of sensitivity. Additional Hi-Meg resistors can be placed between the gate and drain or between the socket and source. This increases the duration of the pulses but results in a loss of sensitivity. The resistor $R_1$ can be removed from the circuit to increase the sensitivity but the value of the biasing resistor is then limited to $10^{11}$ ohms. The socket must be grounded and the entire device must be shielded for stability. Stray capacitance must be minimized by using short leads and rigid construction.

Despite the above restrictions on the design of the pulse reader, there are some changes that could improve the performance of the instrument. It might be feasible to place a switch between the biasing resistor and the drain of the transistor. Normally, the switch would be closed, but when an ionization chamber was inserted into the socket, the switch would open. With the switch open, the chamber and the socket would not begin to re-charge and the RC time constant of the pulse would be determined by the gate impedance of the transistor ($10^{13}$ ohms) and the capacitances of chamber and socket ($10^{-11}$ farads). This would give a time constant of 100 seconds. There would be no need for a Hi-Meg biasing resistor, since the gate impedance of the transistor would develop the pulse.

Different biasing resistors, different operating currents, and different supply voltages could be used to find the optimum response for a different type of read-out system. Larger ionization chambers could be used to increase the sensitivity of the pulse reader, and the use of higher quality chambers would reduce the variation among individual chambers.

# VIII. CONCLUSION

The pulse reader developed, tested, and calibrated in this study used an insulated gate field effect transistor for the detection and measurement of pulses. Victoreen Hi-Meg resistors were used to develop the pulses and the Victoreen Model 362 Pocket Chamber was used as the ionization chamber. The response of the pulse reader to charged ionization chambers agreed well with the theoretical predictions. The response of the instrument was found to vary with the supply voltage, the resistance of the biasing resistor, and the operating current of the transistor. The energy dependence of the device was found to be 14% for photon energies from 33 keV to 152 ke V. The pulse reader was found to be stable over a period of two months. The precision of the pulse reader with a single ionization chamber was determined to be ± one mR for exposures of 30 mR. The variation among chambers was determined to be ± 10%. The instrument was calibrated with 152 keV x-rays to read from zero to 60 mR. The accuracy of the calibration was estimated as ± 8%.

The major consequence of this study is the demonstration of the fact that the recently developed insulated gate field effect transistor can be used successfully in a pulse reader. The study indicates that with certain improvements, a more useful pulse reader could be developed that would extend the sensitivity and increase the accuracy of conventional ionization chambers.

# BIBLIOGRAPHY


Arnson, M. H. and Charles F. Kezer, 1957. One-hundred electronic circuits. Vol. 1. Pittsburg, Pittsburg Instrument Publishing Company, 150 p.

Attix, Frank H. and William C. Roesch (eds.). 1966. Radiation dosimetry. Vol. 2. 2d ed. New York, Academic Press. 462 p.

Braby, L. A. 1965. Pulse reader for ion chambers. In: Hanford Radiological Sciences Research and Development annual report for 1964. Hanford, Washington. n. p. (BNWL-36)

________________ 1967. Ion chamber with integral switches for pulse reading. In: Hanford Radiological Sciences Research and Development annual report for 1966. n. p. (BNWL-36)

________________ 1968. Pulse read ion chamber system. Health physics 15:351-356.

Clark, George L. (ed.). 1963. The encyclopedia of x-rays and gamma rays. New York, Reinhold Publishing Corporation. 1149 p.

Hine, G. J. and G. L. Brownell (eds.). 1956. Radiation dosimetry. New York, Academic Press. 932 p.

International Commision on Radiation Units and Measurements. 1968. Radiation quantities and units. Washington, D. C., ICRU Publications. 8 p.

Johns, H. E. 1964. The physics of radiology. 2d ed. Springfield, Ill., Charles C. Thomas. 767 p.

Lancaster, Donald E. 1966. The insulated gate transistor. Electronics World 76:34-36.

Malmstadt, H. E. and C. O. Enke. 1963. Electronics for scientists. New York, W. A. Benjamin. 619 p.

Motorola Semiconductors. 1965. Silicon n-channel MOS field effect transistor. Phoenix, Arizona. 4 p.

Radio Corporation of America. 1967. RCA transistor manual. Harrison, New Jersey. 544 p.

Roesch, W. C., R. C. McCall and F. L. Rising. 1958. A pulse reading method for condenser ion chambers. Health Physics 1:340-344.

Sievert, Rolf M. 1947. Two automatic methods for measuring condenser chambers. Acta Radiologica 28:784.

__________ 1959. A method for the automatic recording of ionizing radiation. Acta Radiologica, sup. 188, p. 224-234.

Smith, Ralph J. 1967. Circuits, Devices and Systems. New York, Wiley and Sons. 776 p.

Trout, E. D., J. P. Kelley and A. C. Lucas, 1960. Determination of half-value layer. American Journal of Roentgenology 84:729-740.

U. S. National Bureau of Standards. 1960. Protection against radiation from sealed gamma sources. Washington, D. C. 70 p. (Handbook 73)

__________ 1962. Radiation quantities and units. Washington, D. C. 8 p. (Handbook 84) (International Commision on Radiological Units and Measurements (ICRU). Report 10a).

__________ 1963. Radiobiological dosimetry. Washington, D. C. 26 p. (Handbook 85).

__________ 1964. Physical aspects of irradiation. Washington, D. C. 106 p. (Handbook 85).

U. S. Public Health Service, 1960. Radiological Health handbook. Washington, D. C. 568 p.

Victoreen Instrument Company. 1967. Instruction manual. Model 555, Radicon II, Integrating ratemeter. Cleveland, Ohio. 90 p.

__________ n. d. a. Instruction manual. Model 570 Condenser r-meter. Cleveland, Ohio. 12 p.

__________ n. d. b. Radiation standardization of measurement. Cleveland, Ohio. 12 p.

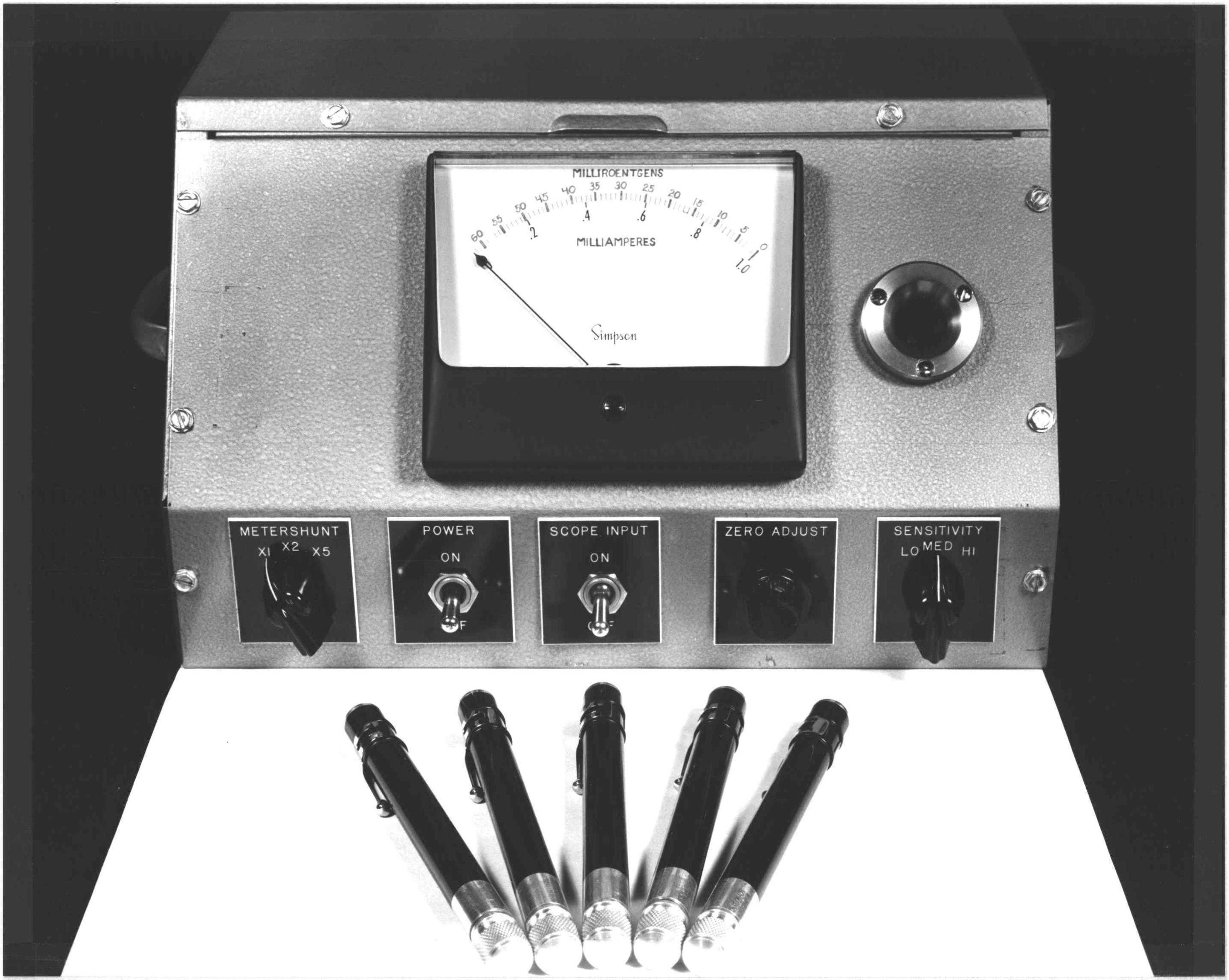
__________ n. d. c. Operating instructions. Model 362. Indirect reading dosimeter. Cleveland, Ohio. 2 p.

Victoreen Instrument Division. 1968. Victoreen carbon film resistors. Cleveland, Ohio. 5 p.

West, Charles A. and Robb M. Thomson. 1964. Physics of solids. New York, McGraw-Hill Book Company. 436 p.

Wiesner, Patrick E. 1964. Practical transistor theory. New York, Howard W. Sams and Company. 128 p.

# APPENDIX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