CHARACTERISTICS OF AN NO_2 FILLED GEIGER-MUELLER TUBE

by

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Table of Contents

CHARACTERISTICS OF AN NO_2 FILLED GEIGER-MUELLER TUBE

INTRODUCTION

History

It has been known for a number of years that gas discharge tubes could be used to detect the passage of nuclear particles. Geiger and Mueller were the first to develop such tubes with a large sensitive volume, and since then, counters of the same type have been called Geiger-Mueller tubes.

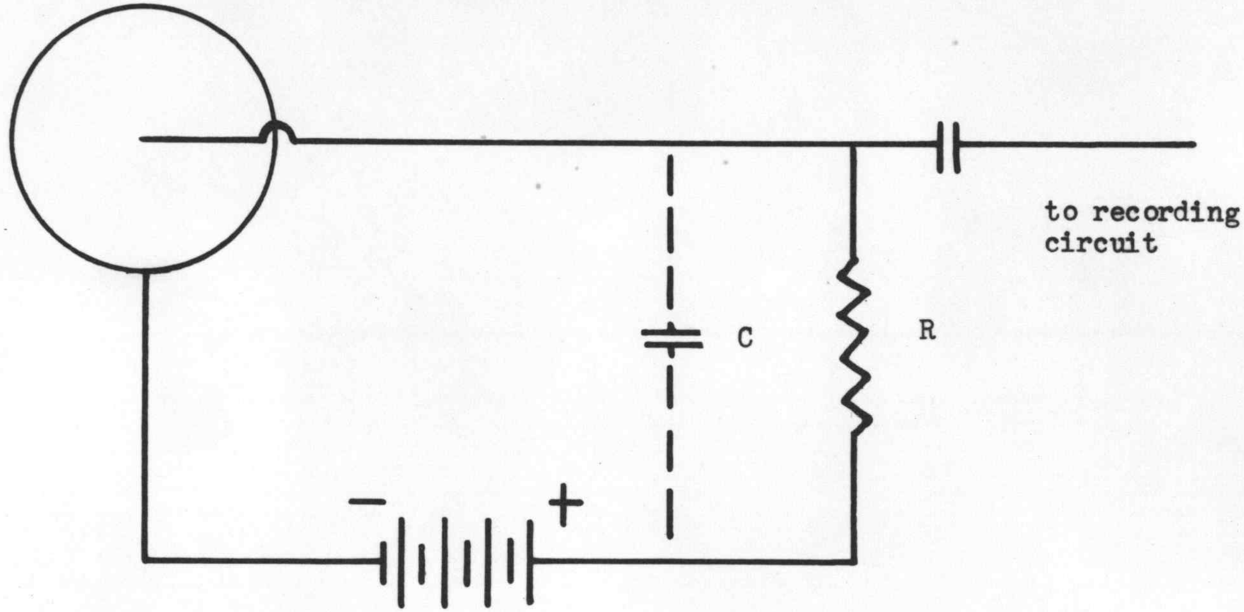
Ionization Chambers

First let us consider the general action of a counter. It is assumed to be of the ordinary type, that is, a cylindrical cathode with an axial wire anode. This tube is placed in a circuit similar to the one shown in Figure 1. The capacitance which is shown includes all of the distributed capacitance present. With this circuit, it can be seen that any current through the tube will cause a variation in the potential difference across the resistance.

Let us assume that some ionizing event occurs in the tube. An ionizing event is an event that produces a free electron in the gas. With no potential difference across the tube, occasional very small voltage pulses will be noticed across the resistor as a result of the random arrival of individual ions on the wire. A small voltage is then applied to the tube. This will establish a field in which positive ions will drift to the cylinder, and negative ions

Figure 1

Basic Geiger Counter Circuit



and electrons toward the center wire. This is then an ionization chamber, with the size of the detected pulse dependent directly on the number of ions initially produced in the tube. For low potentials on the tube, the electrons do not gain enough energy to create additional ions by collision when moving across the tube. If the field is fairly high, and the pressure of the enclosed gas is low, few of the electrons will be involved in recombinations. From these facts it can be seen that the number of electrons arriving at the center wire will be approximately equal to the number originally produced in the initial ionizing event. Since the total number of ion pairs produced in an ionization chamber is proportional to the energy loss of the particle within the chamber, the time integral of the current pulse or the total charge collected on one of the electrodes is a measure of the energy loss.

Proportional Counters

As the potential difference across the tube is increased, the field near the wire soon becomes high enough so that secondary electrons can be formed. If the primary electron is to ionize the gas to form a secondary electron, it must have an amount of energy equal to the product of the ionization potential of the gas and the electronic charge. The electron must gain this energy between collisions, as, on the average, it loses most of its energy of forward motion each time it has a collision. This ionization process requires a high field. Then the original electron and the new one produced will each be able to produce more electrons by ionization. Soon there is an avalanche of electrons approaching the center electrode. The lowest potential at which this cumulative ionization will begin is defined as the threshold potential for proportional counter action.

In the process of formation of the avalanche radiation is emitted, usually as a result of electron impact. These emitted quanta can sometimes cause the release of electrons at the cathode or in the gas, by a photoelectric process. This then contributes to an increase in the ionization, and the discharge may spread over the whole tube. Whether this contribution is large or not depends upon the probability that a photon produced by an electron will produce a photoelectron. If this probability is P, and a single electron produces n electrons by collision, the multiplication factor N will be: $N = \frac{n}{1-Pn}$. As long as Pn is much less than one, the counter will act as a proportional counter (9, p.73).

The cumulative ionization can be seen to be an amplification of the original pulse. This amplification increases as the voltage across the tube increases, because secondary ionization may be produced in a larger region around the wire. As the amplification increases, the pulse size produced by an initial event is increased. The size of the pulse, however, is still directly proportional to the amount of initial ionization produced. The gas amplification varies from one in the ionization chamber region to 10^7 at the upper end of the proportional counter region. As the voltage is increased still further, the amplification factor begins to depend upon the pulse size. This is due to the modification of the field by the electrons that have been collected. This region is called the region of limited proportionality.

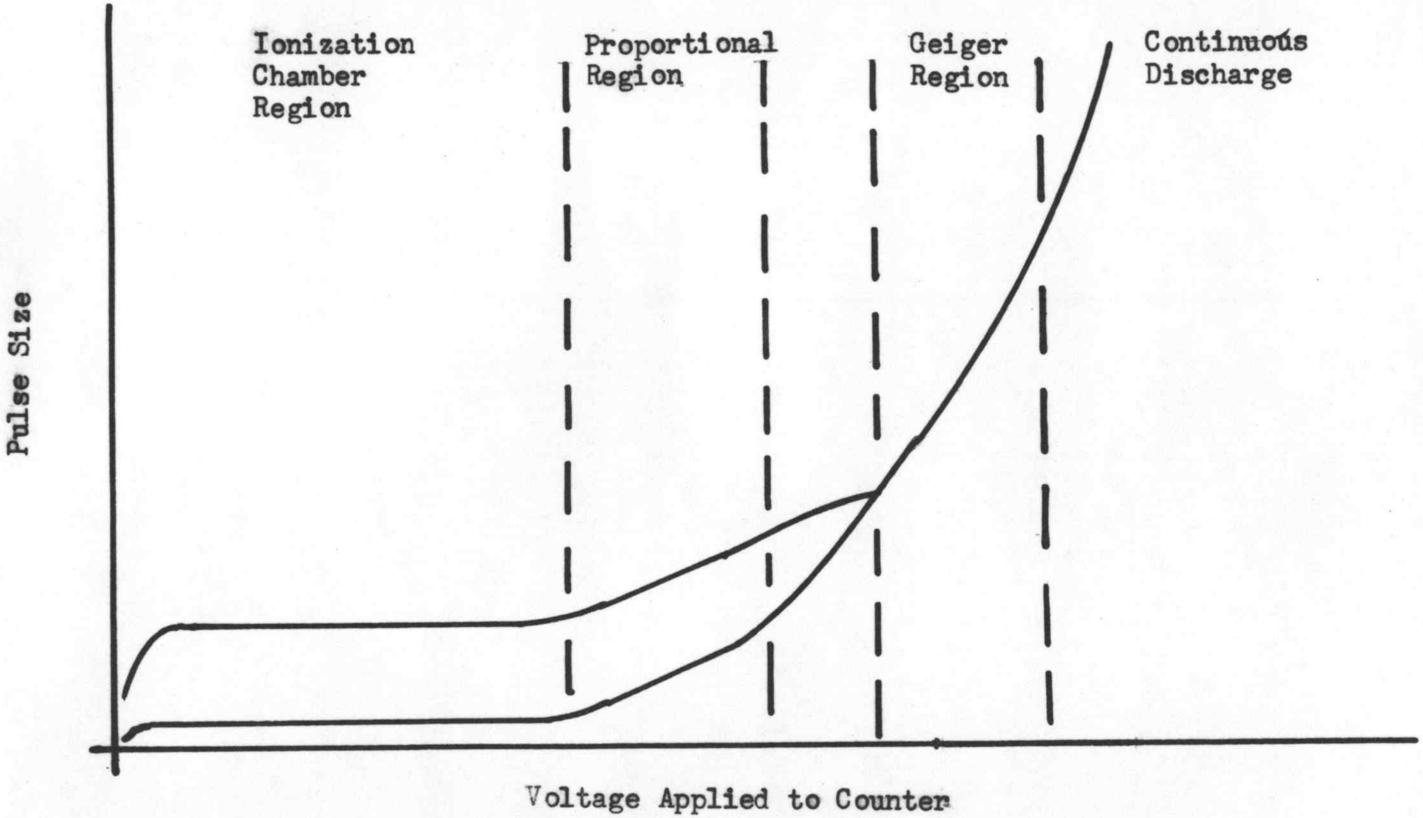
Geiger Region

The total charge arriving at the wire depends upon the number of initial ions formed, times the gas amplification. In the ionization and proportional regions, the number of ions depends only on the initial event, and the gas amplification depends only on the applied voltage. As the potential is increased to bring about the region of limited proportionality, the gas amplification begins to depend upon the amount of initial ionization. When the potential exceeds that of the proportional region, the amplification becomes inversely proportional to the number of initial ions, so all pulses, if viewed on an oscilloscope screen, would appear to have the same height. This region is called the Geiger region.

The above comments can be illustrated by considering two different amounts of initial ionization. A curve of pulse size as a function of potential across the counter would have the shape shown in Figure 2. The different regions can be seen clearly.

Figure 2

Pulse Size as a Function of Voltage



THEORY OF GEIGER COUNTER ACTION

Formation of Ions

First let us consider the cause of the discharge action in the tube. The discharge starts with a free electron in the sensitive volume of the tube. This electron may be released by any of several processes. If the cause of the discharge is a charged particle, it will produce ionization by collision as it passes through the gas. The number of ion pairs formed depends upon the loss of energy which the particle undergoes in the sensitive gaseous volume. The average amount of energy spent in producing the ion pair is almost independent of the velocity or charge of the primary particle. From this it can be seen that the number of ion pairs produced is proportional to the energy loss of the particle. Most of the electrons knocked out by the primary particle have comparatively little energy and will not travel far, although an occasional high energy electron is produced. On the other hand, most of the primary ionization electrons will still have sufficient energy to produce additional ionization, and may account for a large part of the total or specific ionization.

If the initial particle is uncharged, for example a neutron, it may produce ionization by producing either ionizing disintegrations, or recoils. A slow neutron, with very small kinetic energy, may enter a nucleus and cause a disintegration resulting in fragments which are capable of producing a considerable amount of ionization. If the neutron has sufficient energy, it may produce ionization by a recoil process.

Quanta passing through the gas may produce ionization by several different processes. High energy quanta may produce electron-positron pairs. The probability of such pair production is very small unless the quantum has a very large amount of energy, and would contribute little to the over-all effects in an instrument. High energy quanta may also produce ionization by means of the Compton effect. The probability of a Compton encounter occurring in an ionizing volume is proportional to the volume of the chamber and to the pressure of the gas in the chamber. This effect is important only for high energies.

If the photon has an equivalent energy equal to or greater than the ionization potential of the gas, it may directly ionize the gas by a photoelectric process. Quanta incident upon the metallic surface of the electrode in a counter can also produce electrons by the photoelectric effect. This may happen if the energy of the incident photon is equal to or greater than the photoelectric work function of the surface in question. The photoelectric efficiency of most surfaces is usually low, but may be greatly affected by the past history of the surface (gas layers, etc.).

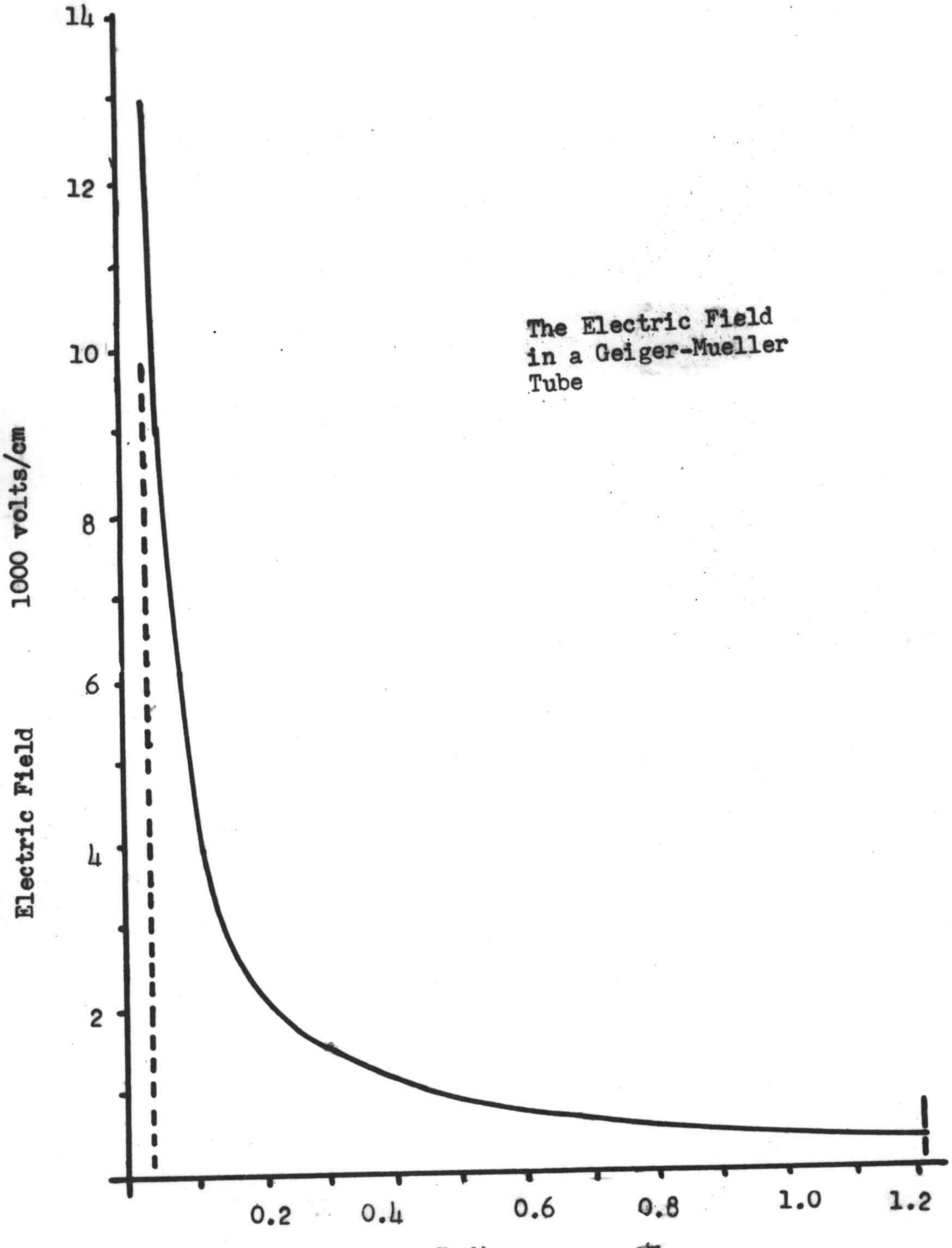
<u>Production of Pulse</u>

A Geiger-Mueller counter usually operates with a high potential between the center wire and a cylindrical cathode surrounding it. The field E inside the tube at a radius r is given by: $E = \frac{V}{r \ln\frac{r_2}{r_1}}$ where V is the potential across the tube, and r_1 is the radius of the wire, r_2 the inner radius of the cathode ($r_1 < r < r_2$). This equation shows that there is a very large field in the vicinity of the wire (4, p.792). The field is demonstrated in Figure 3, which is drawn for the case of 1500 volts between a cylinder of 1.21 cm radius and a wire with radius 0.031 cm.

Assume that some ionizing event occurs in the sensitive volume of the tube. The ion formed has a very low mobility compared with an electron. It will therefore move slowly toward the outer cylinder. The electron has a much greater mobility, and will start toward the center wire. As it moves in the field, it will gain energy. On its way toward the wire, it will be involved in many collisions, losing most of its energy each time. As it moves toward the wire into a stronger field, the electron gains more energy between collisions. When the electron gets within a distance of about a millimeter of the center wire, the field is great enough so that the electron can acquire sufficient energy between collisions to ionize the gas. When it does this, we have the start of an avalanche, as the electrons formed by ionization will also acquire enough energy to ionize. This type of avalanche is called a Townsend avalanche. It is characterized by a quantity α, the mean number of ion pairs formed by an electron per centimeter of its path measured along the field, called the first Townsend coefficient. Then the mean number of electrons present at x_2 is greater than that at x_1 by a factor:

$A = \exp(\int_{x_1}^{x_2} \alpha \, dx)$. A is called the gas amplification from x_1 to x_2.

Figure 3


14
12
10
8
6
4
2
Electric Field 1000 volts/cm
The Electric Field
in a Geiger-Mueller
Tube
0.2
0.4
0.6
0.8
1.0
1.2
Radius cm

With the production of so many electrons, light quanta will also be produced in large numbers. The probability of photoelectrons being formed in the first avalanche approaches unity. Photoelectrons will also be produced at the cathode, and the discharge will spread through the whole volume of the counter.

If the counter has a length L and a capacitance C, the positive charge per unit length on the center wire is initially $q = CV/L$, and the electric field at a distance r from the wire axis is $E = 2q/r$. This then gives the curve previously shown. When the discharge occurs, the electrons are quickly collected on the center wire, so that the total positive charge on the wire is reduced from q to a value q'. Because of this reduction of the charge on the wire, the field around the wire is lowered. Meanwhile the slow positive ions have just begun to move across the tube, and so they form a positive ion sheath around the wire. The field is lowered in the region from the wire to the positive ion sheath, increases through the sheath, and has its normal value from the outer edge of the sheath to the cylinder. The positive ion sheath surrounds the center wire, and so has no effect on the field between the wire and the sheath (12, p.253). The field is reduced, by the collection of electrons on the wire, below the critical value necessary for avalanche production. The counter is now effectively quenched, and any other electrons present in the tube will not produce cumulative ionization.

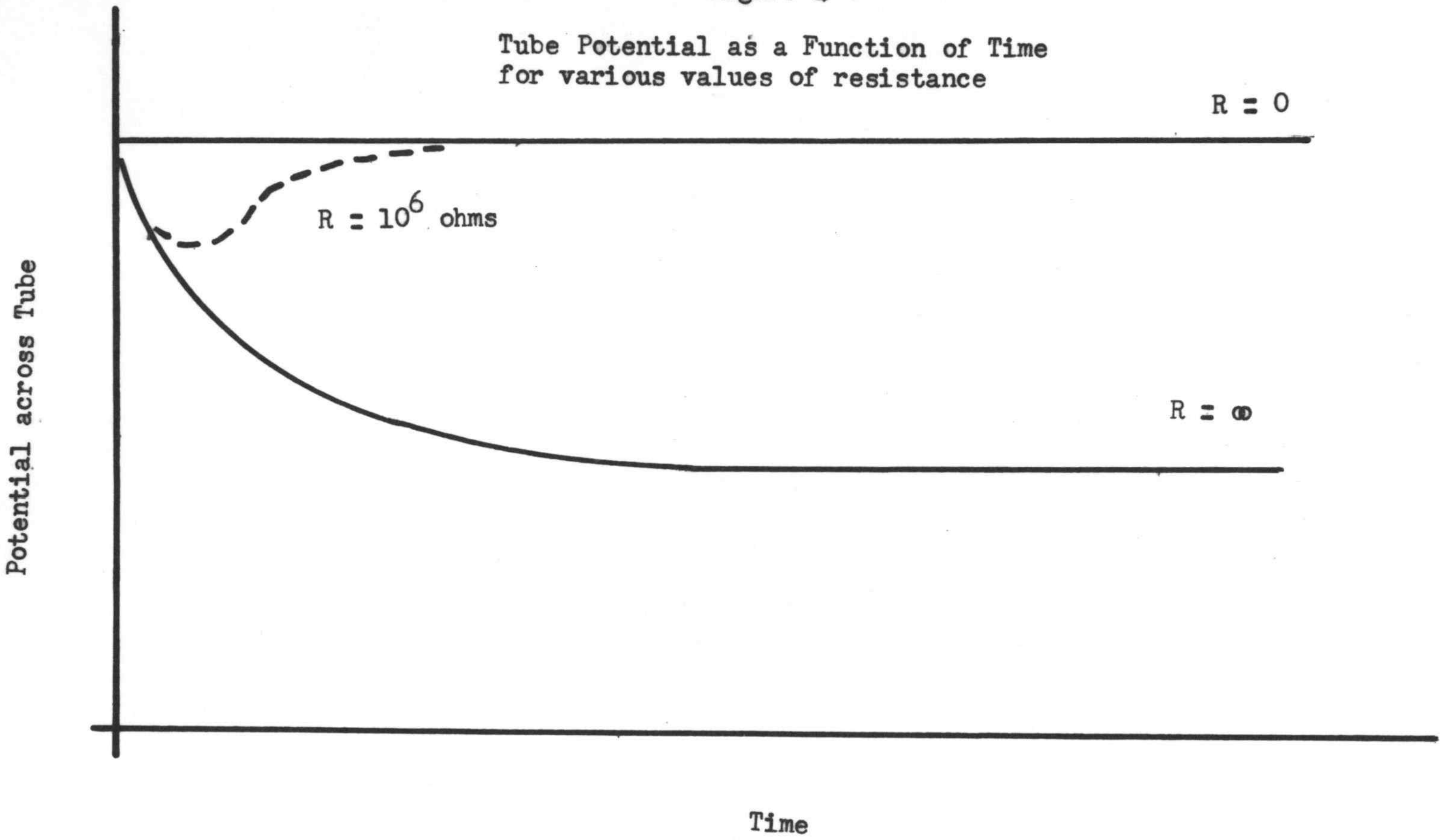
While the electrons are being collected, the positive ion sheath starts to move across the tube. As it does, the potential across the tube begins to drop. If the resistance R in Figure 1 is infinite, there will be no leakage of charge back on to the center wire. The potential across the tube drops, and a pulse can be detected with an external recording circuit. The reduced field $E = 2q'/r$ now extends throughout the whole cylinder, and no more ionizing events can be detected.

If there is no resistance in the circuit, the potential across the tube will remain constant. Therefore, as the positive ion sheath moves out, electrons will flow from the wire. Thus the field gradually recovers as the sheath moves outward. With zero external resistance, we have a rapid recovery but no pulse: with infinite resistance, we have a pulse but no recovery. In practice neither of these cases is used; instead, a series resistance of about 10^6 ohms is used. This then allows the tube to recover, and also permits a pulse to be detected, although the pulse is smaller than the pulse for an infinite resistance.

Figure 4 shows the tube potential for the various values of resistance. For the 10^6 ohm resistance, the potential initially drops fast, because the electrons cannot leak from the wire fast enough to make up for the drop of potential due to the motion of the ion sheath. At a later time the two rates become equal, and the wire potential reaches its minimum value. Later, the rate of rise of potential caused by electrons leaking off is faster than the rate of fall due to the motion of the ion sheath, and the wire potential rises back to its initial value.

Figure 4

Tube Potential as a Function of Time
for various values of resistance

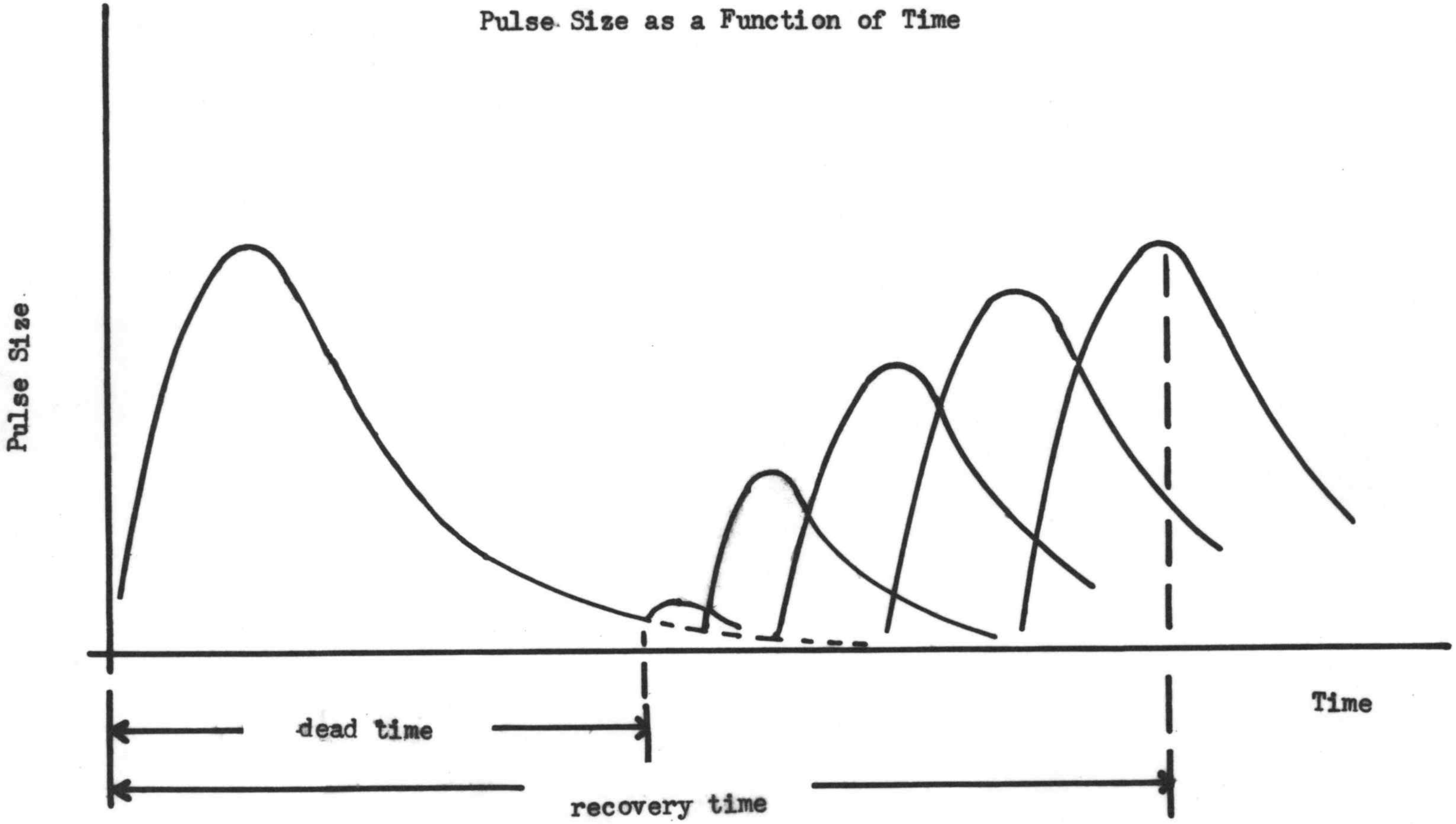


There is a time when the potential has dropped below the value necessary for the production of avalanches. During this time, no new primary ionizing events can be detected. As the potential rises, it finally reaches the necessary potential to produce avalanches again. The intermediate time is called the dead time of the counter. As the positive ion sheath moves out the size of the pulse caused by any new ionizing event will increase. When the sheath reaches the cathode, the field is fully recovered, and a full discharge can be produced. The time between the start of the counted pulse and the time of full recovery is called the recovery time of the counter (10, p.930). Figure 5 shows the size of the pulses, and the various regions, for primary ionizing events occurring after an initial pulse (12, p.40).

Quenching

When the positive ions arrive at the cathode, they cause secondary emission of electrons. These electrons can then start for the center wire and initiate another discharge. It can be seen that unless something out of the ordinary happens, the tube will go into what is effectively a continuous discharge. If the counter is to be useful, i.e., if it is to be in a condition so that the next ionizing event will be detected, this discharge must be stopped, and the wire must return to the original potential. This quenching may be implemented in several ways. The original method of quenching was to have the resistance of the circuit very large. This meant that charge leaked back onto the central wire very slowly. In this way the potential of the wire is held below the threshold potential until all

Figure 5


Pulse Size as a Function of Time
Pulse Size
Time
dead time
recovery time

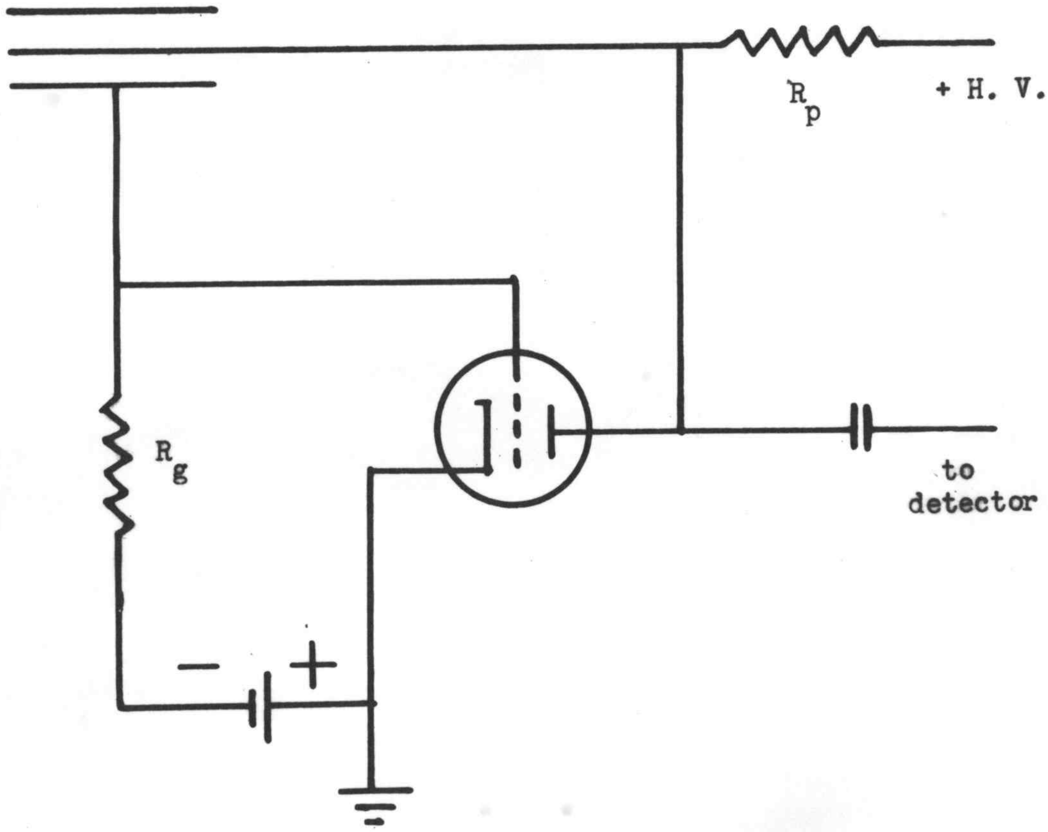
of the electrons and ions in the tube have been collected. The trouble with using a large resistance is that it means that the circuit has a large RC time, and therefore a long dead time.

The discharge may also be stopped by the use of an electronic circuit to hold the voltage down while the charged particles are being collected. An example is the Neher-Harper circuit shown in Figure 6 (8, pp.940-943). In this circuit, the grid is held negative so that the tube is normally non-conducting. When the counter records a pulse, the current through the counter tube causes the grid bias to swing positive, which enables the quenching tube to conduct. The current passing through the plate resistor R_p produces a potential drop which is effectively subtracted from the high voltage. Therefore the voltage on the counter tube is reduced until the grid returns to its former value (11, p.100). The time for this is determined by the RC time of the grid circuit. There are several other circuits also commonly used, but the scheme of operation is similar.

By the use of the proper gases in the tube, the counter can be made selfquenching and the use of external circuits avoided. In the non-selfquenching counter, the discharge is semi-continuous because of the photo-ionization of the gas, and the secondary emission caused when positive ions hit the cathode. A polyatomic gas, when added to the counter, will usually absorb the photons that are emitted by the excited atoms during the discharge. This absorption will produce photoelectrons in the gas, and consequently very few at the cathode. These photoelectrons are produced near the

Figure 6

Neher-Harper Quenching Circuit



center wire, so that the discharge spreads in a narrow sheath along the central wire (13, p.536). When most of the electrons are collected, the discharge ceases. As the positive ions move away from the central electrode, the counter gas ions collide with the molecules of the quenching gas. In this collision, an electron is transferred from the quenching molecule to the ion of the counter gas. This releases a photon which is absorbed in the quenching gas. The ions arriving at the cathode are almost entirely those of the quenching gas, which do not produce any electrons at the cathode by secondary emission (6, p.278).

This process then decomposes the quenching gas, so that the counter has a finite life. About 10^{10} ions are decomposed in each discharge, and there are approximately 10^{20} molecules initially present, so the tube is practically useless after about 10^{9} counts. This is a shorter life time than that of the non-selfquenching counter (14, p.240).

Tube Characteristics

The general characteristics of a counter can now be discussed. One of these is starting potential. This is the potential across the tube which first enables pulses to be detected. This voltage depends upon the amplifiers and so is not as important as the threshold potential, for a Geiger tube. The threshold potential is defined as the lowest potential at which the pulses are all of the same size. This potential depends upon the nature of the gas and upon the gas pressure. At the common pressures, the curve of threshold potential as a function of pressure is approximately linear for any one gas. In non-selfquenching counters, noble gases result in lower threshold potentials than do the common diatomic gases. The threshold potential is in general higher for selfquenching counters than it is for non-selfquenching counters. This is due to the fact that selfquenching counters contain more complex molecules which in turn have more energy levels. Therefore the electrons have more opportunities to lose energy upon collision. Hence the electron will have to be in a higher field before it gains enough energy to produce ionization.

The important characteristic curve is that of counting rate versus voltage, with constant radiation flux. This curve is characterized by a rapid rise from the starting potential to the Geiger threshold potential. Beyond this point, the curve levels off to form a plateau. At the upper end of the plateau, the counting rate again starts rising with potential. The flat plateau indicates that all of the pulses have a certain size, and that the counting action is truly Geiger. The flatness of the plateau is defined as the percentage increase in counting rate as the voltage is raised. The non-selfquenching counter generally has a very flat plateau, unless a gas is present that forms negative ions, or has metastable states. In selfquenching tubes, the plateau slope depends upon the quenching gas. Apparently this is also due to the formation of negative ions. The amount of quenching gas controls the length of the plateau. At either high or low concentrations, there is no plateau.

As the voltage across the tube is raised, the counting rate again begins to rise. This signifies the end of the plateau. This termination is caused mainly by spurious pulses resulting from metastable decay. Positive ion bombardment also contributes to this termination (15, p.303).

Another important characteristic of a counter is its efficiency. This involves two factors: first, the probability that any given ionizing event will produce an electron in the counter, and second, the probability that an electron in the counter will start an avalanche. The first factor is related to the specific ionization of the particle being detected. The specific ionization, s, is the number of ion pairs, per centimeter of path, per atmosphere pressure, left in the gas when the particle passes through it. The probability that no electrons will be produced when a particle passes through the counter is e^{-slp}, where l is the length of path and p is the pressure of the gas in atmospheres. The efficiency of the counter, which is the probability that one electron will be produced, is therefore equal to $1 - e^{-slp}$. If we are to have a counter with a high efficiency, we must use a gas with high specific ionization, and must have a high pressure, above 0.1 atmosphere. Counters with low pressures are not very efficient.

Effects of Different Gases

Next, we must consider the effects of various kinds of gases in the counter. First let us consider monatomic gases. Helium is sometimes used in counters, but has a low specific ionization and so has to be used at fairly high pressures. However, a helium filled tube has a low starting potential, so it is sometimes practical to use this gas at the pressures necessary. Neon and argon are quite often used. They have high specific ionization, and do not require high starting potentials. Extremely pure argon can not be used because of the formation of metastable states.

Of the diatomic gases, nitrogen and hydrogen are quite often used. Each of these requires a comparatively high starting potential. In addition hydrogen has the disadvantage of a low specific ionization. Oxygen is not advisable, as it forms negative ions.

Negative ions in the gas lead to poor performance in a counter. The mobility of negative ions is approximately the same as that of positive ions. Therefore negative ions will travel to the center wire much slower than the electrons. It is thus possible for the negative ions to approach the wire after the wire has recovered to nearly its normal value. In the high field near the wire, the ion may release its electron, which may then start another Townsend avalanche. If the ion does not release its electron, it may itself produce ionization by collision, and thus trigger another Townsend avalanche. Since at this time the counter has partially recovered from the first count, it may register a new count. It can be seen, therefore, that the production of negative ions in the counter may give rise to spurious counts, usually in the form of two counts very close together.

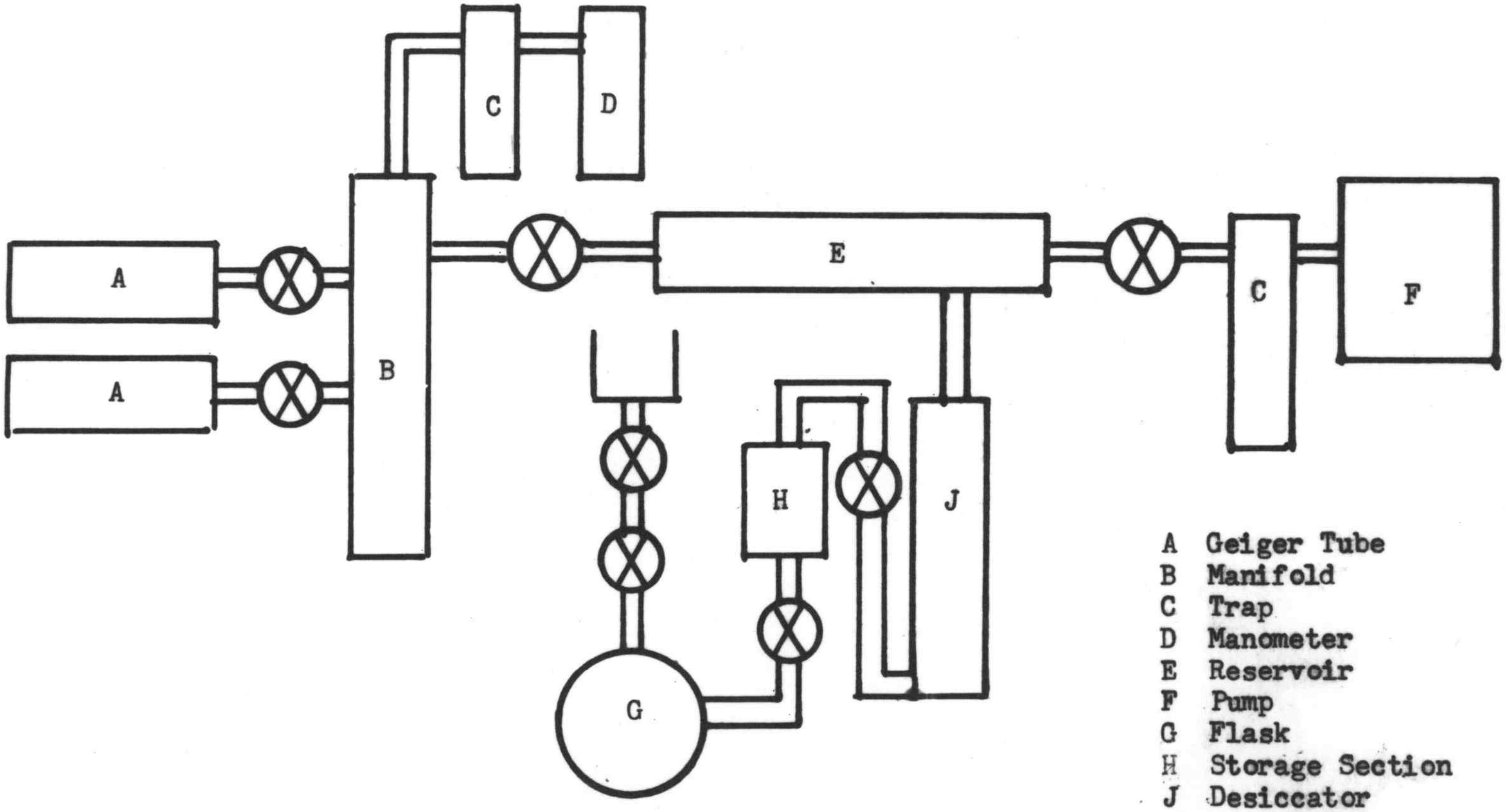
The probability of negative ion formation may be found if the electron attachment coefficient of the gas is known. This coefficient is defined as the average number of collisions an electron must make before it forms a negative ion. If this number is smaller than the number of collisions the electron makes crossing the tube, there is a good probability that negative ions will be formed.

Mixtures of gases have been used in counter tubes also. Air has been used; however, it permits the formation of negative ions and is not so desirable. In addition, water vapor has to be eliminated as it forms negative ions, and it also may affect the surface of the cathode.

Recently counters have been developed containing a small amount of halogen as a quenching gas. These seem to be the most promising of the new counters.

Figure 7

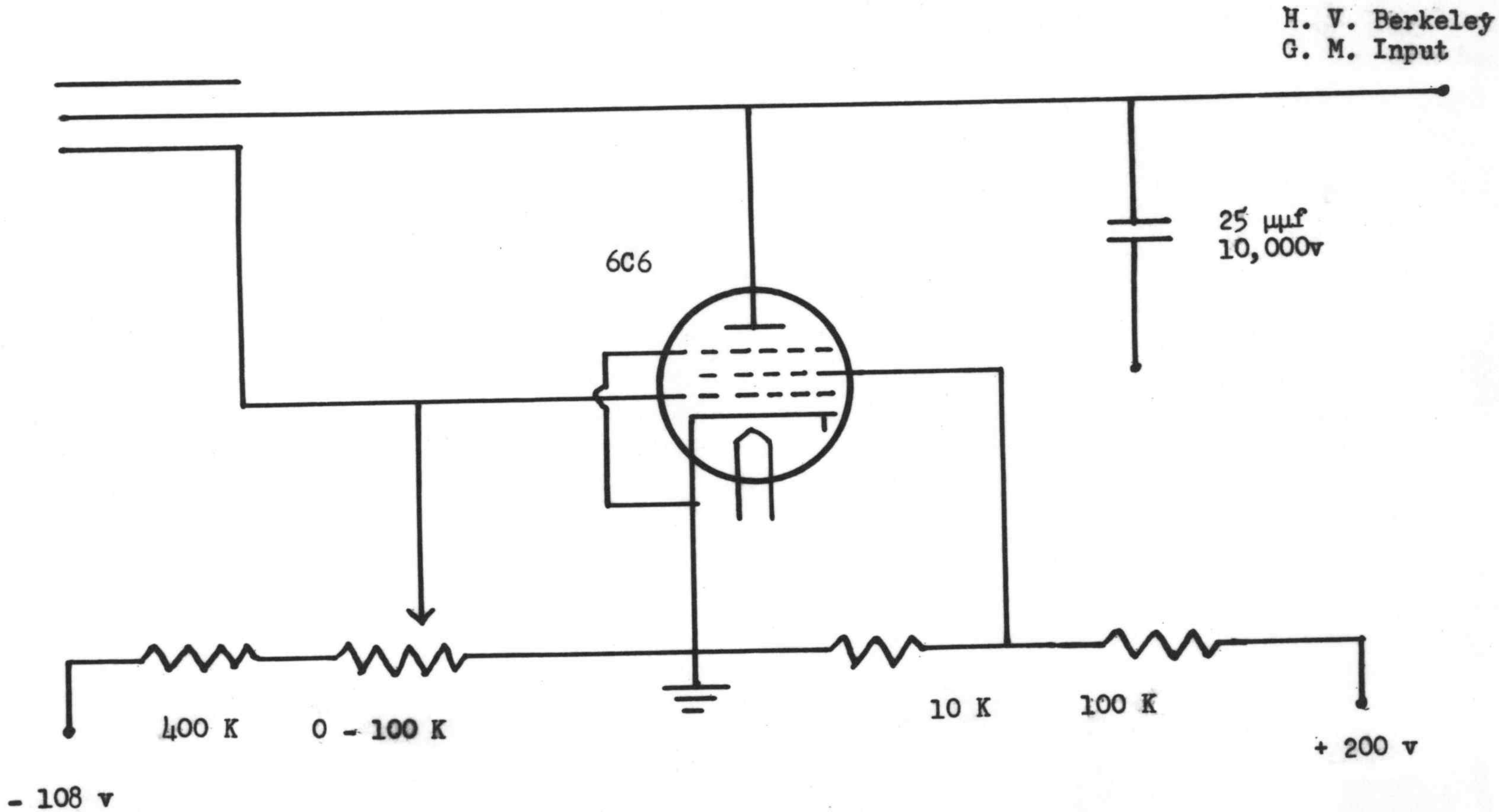
Diagram of NO_2 Generating System



A Geiger Tube
B Manifold
C Trap
D Manometer
E Reservoir
F Pump
G Flask
H Storage Section
J Desiccator

Figure 8

Quenching Circuit



EXPERIMENTAL RESULTS

History

In 1947, Stuart Forbes, an Oregon State College graduate student, built a coincidence counter. During the course of his work he discovered that a Geiger counter filling of nitrogen dioxide seemed to have favorable characteristics (3, p.41). Several tubes were constructed and used in the Physics Department for a number of years. When the following experiment was started just one of these tubes was operating, and it had started to deteriorate.

Forbes had not gone to a great deal of trouble to purify the ordinary nitrogen dioxide, which is readily available in any laboratory. When these facts were considered, it appeared that this gas might be useable in laboratories that did not have either the expensive gases usually used in Geiger counter tubes, or the elaborate purification apparatus necessary to obtain pure gas. For these reasons, it was decided to make a more thorough investigation of Geiger tubes filled with nitrogen dioxide.

The first step was to check Forbes' results with his tube and amplifier. A plateau was obtained, although not quite as long as the plateaus initially reported by Forbes. When his amplifier was adjusted to deliver the long pulses necessary to operate the mechanical counter, the measured resolving time was 0.08 seconds (1, pp.72-76). This resolving time is too long for most applications.

The efficiency of Forbes' tube would appear to be low. We can calculate the efficiency if we use an empirical formula to find the specific ionization s by high speed cosmic ray (4, p.109):

$S = 1.1\ n_e + 3$, where n_e is the number of electrons per molecule. The nitrogen dioxide molecule has 23 electrons, therefore $n_e = 23$. This gives a value for s of 28 ions per centimeter per atmosphere. The Geiger tube had a brass cylinder 2.43 cm inside diameter and 13.5 cm long. The center wire was 25 mil tungsten. The wire was not accessible from one of the ends, so it could not have been flashed after construction. The tube was initially filled with nitrogen dioxide at a pressure of 2 cm of Hg. Assuming that the path of the particle is 2.4 cm, and using a pressure of 2 cm, we obtain 1.76 for the average number of electrons left in the counter by a cosmic ray particle. The efficiency is then: $E = 1 - e^{-1.76}$. This gives an efficiency of 83%, which is very low for a Geiger counter.

Apparatus

A gas generator system was constructed so that tubes could be filled easily. The gas generator was a flask with an inlet for nitric acid. Some copper was placed in the flask, and the flask attached to the rest of the system. The flask was connected to the system through a storage section to the desiccator. The storage section could be sealed off from the generator so that the flow of gas through the desiccator could be regulated. CaCl was used as a desiccant. The desiccator lead directly to the main reservoir. This reservoir was connected to the vacuum pump and to the gas manifold by means of stopcocks. The Geiger tubes were then connected to the manifold to be filled and tested. Gas pressure in this part of the system could be read by means of a mercury manometer. Figure 7 shows the arrangement of the parts of the system.

The voltage supply and the scaler were in a Berkeley scaling unit. Stable voltages in the range from 300 volts to 2500 volts were obtainable this way. A preset count was also available, so that the scaler would automatically turn off after a predetermined number of counts. The preset count also turned off a clock, which enabled the counting rate to be accurately determined. Power connections for the quenching circuit were also available from the power supply. The quenching circuit was of the Neher-Harper type already described, with the circuit parameters shown in Figure 8.

The Geiger tubes were constructed with Pyrex glass. Pyrex to Nonex to tungsten seals were used for the leads entering the tube. The cylinder was a piece of copper tubing which was thoroughly washed with nitric acid after the tube was constructed. The tube was washed with water to remove the nitric acid, and then dried. Two of the tubes had the center wire connected so that it could be heated to remove dust from the surface of the wire.

Experimental Procedure

Tests were made on two tubes with an 11 mm inside diameter copper cylinder, and a 20 mil tungsten wire. The initial runs were made without a quenching circuit, and as expected, no plateau was obtained. An example of this data is shown in Figure 9. One of these tubes was tested with Forbes' power supply and

Figure 9

Counting Rate as Function of Voltage

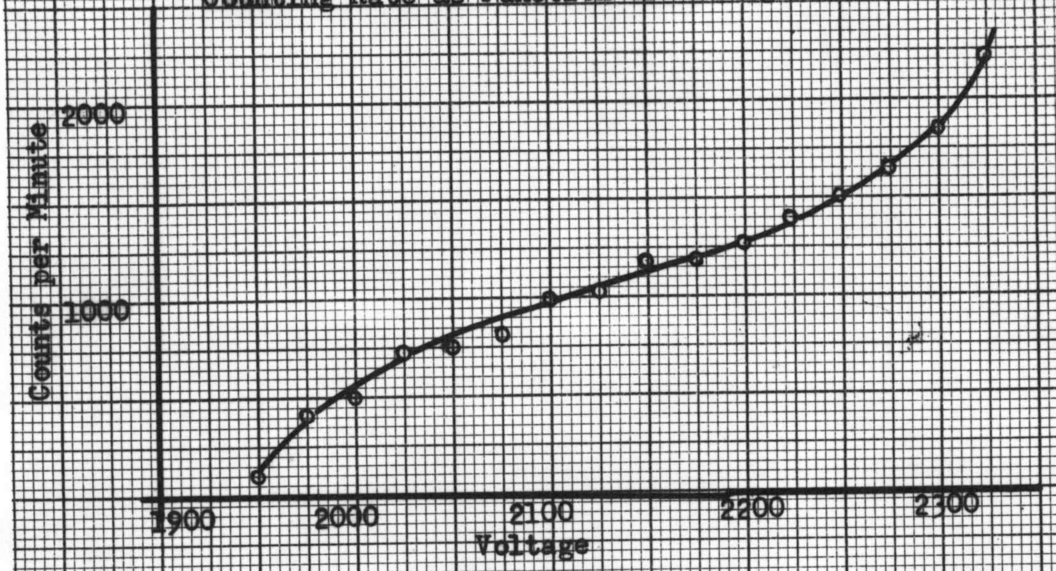
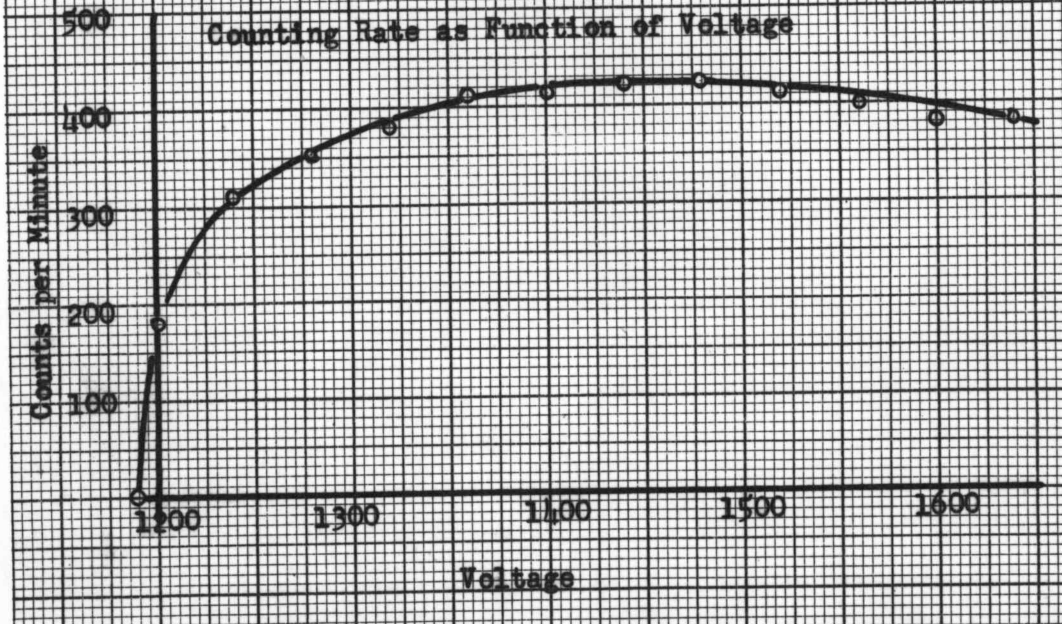


Figure 10

Counting Rate as Function of Voltage



quenching circuit, and a plateau was obtained. One of the curves is shown in Figure 10. The voltage was not stabilized above 1600 volts, and the upper end of the plateau could not be reached with this power supply. The falling off of the curve at higher voltages indicated that the action was not pure Geiger action. This tube was sealed off and used in the modern physics laboratory. It deteriorated during the first week of use. The starting voltage decreased, and the plateau disappeared.

The other tube and Forbes' tube were then tested with the Berkeley power supply and the quenching circuit. The voltage pulses could be viewed after the first stage of amplification in the scaling unit. These pulses were viewed on a Tektronix Type 514-D oscilloscope. It became apparent that the Geiger tubes were not working properly because the pulses were quite often multiple. These spurious pulses were counted by the scaler, so that consistent data could not be obtained. The time lag between the initial pulse and the spurious pulse was very short, so that the latter would not be counted in circuits with a long resolving time.

A capacitor coupling was added to the quenching circuit so that the pulses could be viewed directly. The length of the majority of pulses was approximately 150 microseconds, which was reasonable. The pulses that were viewed this way did not have a constant pulse height, and they sometimes showed irregularities. This was convincing evidence that the tubes with the large wires were not working properly. A large number of data runs were taken with and without the quenching circuit. None of these runs showed any possibility of obtaining satisfactory counter action.

Two tubes with smaller wires were then constructed. One tube had a 5 mil wire and the other a 3 mil wire. Wires of these sizes are very commonly used in Geiger tubes. The smaller wire produces a higher field near the surface of the wire. This means that these tubes can operate at a higher pressure, and therefore a higher efficiency. An increase in the number of spurious pulses was observed when experiments were made with these tubes. The operating pressure for these tubes was 4 cm of Hg, which would lead to relatively poor efficiency. The tubes also did not show any possibility of satisfactory action.

Conclusion

The results of these experiments show that Geiger tubes filled with nitrogen dioxide do not have satisfactory characteristics. The tubes require a low gas pressure, so that they are very inefficient. In addition, the tubes have too many spurious pulses to be satisfactory in a circuit with a high resolving time. Because of these faults, no effort was made to obtain a tube with a long lifetime. The experimental results might have been slightly more satisfactory if an effort had been made to obtain a high vacuum system that could be thoroughly outgassed. When the experiments were started, it was not felt that this would be necessary.

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