Geiger Müller tubes

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With increasing awareness of the environment and of protection levels, the detection and measurement of nuclear radiation becomes increasingly important. The Geiger Müller tube, with its high detection sensitivity, robust construction and simple circuitry, continues to be one of the most widely used radiation detectors in all areas of application.

Centronic Ltd has been manufacturing Geiger Müller tubes for over 50 years: indeed, we were the first to do so on a commercial scale. Since the mid-1940s our continuous programme of research and development has ensured that our range of tubes has remained one of the most comprehensive available.

Our unsurpassed experience in Geiger Müller tube design is complemented by an impressive production capability based at our centre in the UK, which is registered as complying with the requirements of ISO 9001. Rigorous production control and 100% testing ensures that the quality of our tubes is second-to-none. And although our capacity is large, we can still rapidly adapt our production to meet special customer requirements.

When designing radiation detection equipment, specifying a Centronic type ensures rapid acceptance in the market place. This publication indicates typical applications for Geiger Müller tubes, describes the characteristics of the tubes and shows how to operate them in typical application circuits. It also defines the most commonly used terms in the published data, and gives our current range of Geiger Müller tubes.

TUBE APPLICATIONS

Geiger Müller tubes provide an easily-used means of both detecting and measuring the following types of radiation:

- alpha particles
- beta particles
- X-rays
- gamma rays

Typical applications of Geiger Müller tubes include the following, which occur in and around nuclear power stations:

- checking satisfactory performance of shielding
- ensuring safety of working staff
- warning of any release of contamination
- recording exposure levels
- monitoring environment near nuclear installations
- detecting hazards for emergency service staff

The environment near nuclear power sources is generally monitored by a number of peripheral instrument stations, each with two Geiger Müller tubes. If release of activity occurs, it is immediately detected and a signal is fed to a computer-controlled monitoring system. The computers trigger alarm warnings and provide an indication of the location of probable 'downwind' areas where precautions should be taken. They also indicate the most probable 'upwind' location of the leakage source. For this type of application, our ZP1301 or ZP1313 for monitoring high level radiation, or our ZP1221/01 for monitoring low level radiation are ideal.

For detectors used at nuclear installations by the various emergency services, a suitable choice is our ZP1301. Additional applications not specifically associated with nuclear power stations include:

- external monitoring of fluid levels in processing tanks in the chemical and petroleum industries
- external monitoring of levels in coal hoppers, smelting furnaces, and liquified gas containers
- thickness measurement by absorption in paint layers, thin metal sheets, and abrasive layers on 'sand papers'
- finding cracks or voids in metal or stone
- tracking the radioactive isotope 'labels' frequently used as tracers in chemistry, agriculture, civil engineering, petroleum engineering, and medicine
- detecting tracers used for indicating a change of oil in a time-share oil pipe line, or for tracking underground movement of water
- oil well logging
- measuring output from nuclear sources in various types of educational experimentation

In educational establishments, the robust ZP1481, for example, with its plug-in base and window guard, is ideal for beta and gamma radiation experiments.

CONSTRUCTION

A Geiger Müller tube, like other gas-filled detectors, has an anode and a cathode in an envelope that contains a gas at low pressure (for most tubes, in the range 50 to 100 torr). There may also be a special 'window' of radiation transparent material either at one end of the tube or in its side. Some tubes also have an integral radiation-shield as part of the outer walls where this is required for modifying the performance characteristic (see 'Energy Compensation').

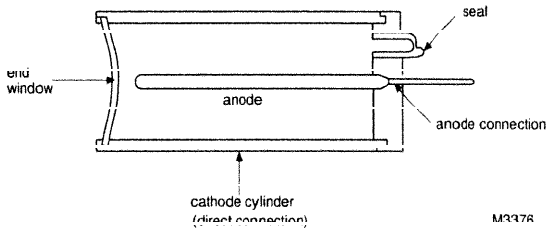

Figure 1 General arrangement of the main parts of a typical Geiger Müller tube

Figure 1 shows the general arrangement for a typical unshielded tube with an end window. In most tubes the anode is a wire about 1mm thick supported through the axis of, but insulated from, a gas-tight cathode tube. This simple arrangement gives a high electric field when the necessary voltage is applied, and it also helps to propagate the required avalanche of ion multiplication through the tube.

Device types

The design of a Geiger Müller tube is usually optimised for a specific application, and there are therefore considerable differences in shape, size, gas formulation, gas pressure, and radiation 'window'. The type of construction varies broadly with the radiation to be detected:

- *Alpha particles and low energy beta particles*
  The tube is sealed at one end by a thin mica window through which the radiation enters (similar to that shown schematically in Figure 1).

- *High energy beta radiation only*
  Tube design is similar to that for alpha particles and low energy beta radiation, but the window is thicker. Other possible designs consist of a windowless tube with either a thin metal wall or a metal-coated glass wall.

- *Low energy X-rays*
  Tubes are similar to those for alpha radiation except that they are longer. The extra length improves radiation absorption. These tubes also have thicker mica windows. A heavy gas such as argon or krypton is normally used, and the gas pressure is generally higher than that of most other types of tube (generally between 600 and 650 torr).

- *Gamma radiation*
  Tubes for the detection of gamma radiation have thick walls and no windows. Most of the counts in such tubes are produced by high energy electrons that are generated in the walls of the counter tube by photo-emission. These electrons interact with the gas and trigger the discharge. For maximum sensitivity, the tube is presented transversely to the source of radiation. Some tubes are constructed so that they are suitable for either X-rays or gamma rays with photon energies in excess of about 40 keV (the exact value varying with the tube type).

BEHAVIOUR OF GAS-FILLED DETECTORS

Geiger Müller tubes are members of the gas-filled radiation detector family which also includes ionisation chambers and proportional counters. The simplest gas-filled radiation detectors consist merely of two electrodes in a low pressure gas chamber; the walls of the chamber are constructed to permit penetration by the radiation of interest.

Figure 2 shows a simplified detector circuit with a tube similar to that shown in Figure 1. Voltage is applied between the cathode (the wall of the tubular gas container) and the anode (the central wire, insulated from the tube wall). Current in the external circuit is governed by the conductivity of the gas inside the tube and consequently by its ionisation.

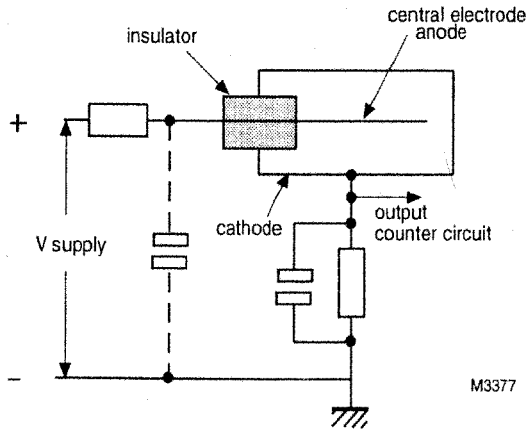

Figure 2 Simplified gas-filled detector and circuit

Ionisation absent. If none of the gas molecules are ionised, the gas behaves as an insulator and no current flows in the external circuit.

Ionisation present. If some of the gas molecules are ionised by a particle or radiation quantum having recently entered the detector, some current could flow. The immediately subsequent events, however, depend on the electric field applied between the electrodes:

1. If the field is weak, newly-produced ions and electrons simply recombine.

2. If the electric field high is enough, the positive ions and the electrons become fully separated, being attracted towards the electrodes. Those ions that reach the cathode will be neutralised by electrons from the cathode. This transfer of electrons, and the arrival of electrons at the anode, causes a current pulse in the external circuit. Provided that sufficient ions and electrons arrive more or less simultaneously, the current pulse can be detected by sensing the associated voltage across the resistor in the external circuit.

Figure 3 shows the characteristic curves for gas-filled detectors with both alpha and beta particle radiation. The form of these curves is determined to some extent by:

- the design of the detector
- the gas used
- the gas pressure

In general, however, increasing voltage reveals five regions (see Figure 3):

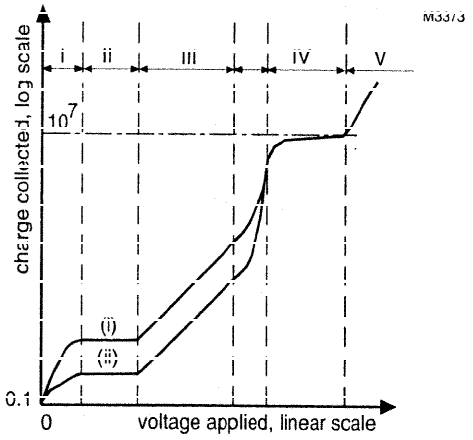

Figure 3 Variation of charge collected (i) due to alpha particles and (ii) due to beta particles both shown as a function of the applied voltage

Region I

The low electric field in Region I has negligible effect. Most ions recombine and current is small. Detectors are not usually operated in this region.

Region II: Ionisation Chamber Region

Separated ions and electrons are forced to drift towards the electrode in Region II, and because recombination is delayed or prevented, many reach the electrodes. Current in this region depends almost exclusively upon the number of ions generated by the radiation, and is almost independent of the exact value of the applied voltage. Ionisation chambers operate in this region.

Region III: Proportional Region

In Region III, electrons are accelerated to high velocities and produce secondary ions by collision, leading to a multiplication of charge. Particles moving through the counter can produce a large current and voltage pulse in suitable circuitry, with the amplitude proportional to the energy of the ionising particles. Proportional counters operate in this region.

ion multiplication gains of up to 10^6 are attainable in this method of operation. (The upper end of Region III is generally known as 'the region of limited proportionality' where output becomes more dependent on applied voltage than on initial ionisation).

Region IV: Geiger Region

ion multiplication escalates in Region IV and, in the ensuing 'avalanche', virtually all primary and secondary electrons are accelerated sufficiently to create more secondary and tertiary ions. Though the detector can no longer distinguish between the different kinds of radiation or between different energies in this region, detection sensitivity is excellent. Geiger Müller tubes operate in this region which is also often called the 'Geiger Müller plateau '.

Region V

Further escalation of avalanche in Region V produces total ionisation of the gas between the electrodes. A self-sustaining discharge, which will continue as long as voltage is applied, can be instigated by a single pulse. This type of discharge can be harmful to the detector and lengthy operation in this region should be avoided.

OPERATION

Despite variations in construction, all Geiger Müller tubes are designed to operate under the conditions of Region IV (Figure 3). The following description of the discharge is deliberately simplified (quenching gas is described later):

Initiation of the discharge

When a particle or energy quantum enters the detection gas (usually neon, argon, or helium, and sometimes krypton), some initial gas ionisation may occur, creating electrons and positive ions. If the correct operating voltage is applied to the tube, electrons in the gas near the anode and positive ions in the gas near the cathode are collected almost instantaneously. The remainder of the electrons and ions, together with products of ion multiplication, follow in rapid succession. The resulting current pulse produces a fast-rising voltage pulse across the series resistor chain in the external circuit, and the pulse can be detected by a 'scaler' or counter.

Collapse of the discharge

The main energy for the discharge is derived from the self capacitance of the tube and from stray capacitances. When these are significantly discharged, tube current collapses and gas de-ionisation follows. While this de-ionisation continues, the recharging of the capacitances gives an almost exponential tail to the pulse in the external circuit, the rate of fall depending on the RC values.

Recovery from the discharge

When the primary discharge is complete. residual positive ions drift towards the cathode and combine with electrons from the cathode surface. Residual positive ions near the anode weaken the field strength temporarily, and this reduces tube sensitivity for a short period after each discharge. Recovery from this lower sensitivity is described later (see 'Dead Time and Recovery').

QUENCHING GAS

Together with the normal gas selected for the discharge, a small amount of additional 'quenching gas' is also included.

Purpose of quenching gas

If the tube were allowed to operate simply as outlined above, then after the main discharge, the impact of some of the residual high energy positive ions on the cathode would cause the emission of some secondary electrons. These newly-released electrons would be accelerated towards the anode and the subsequent high energy collisions with gas atoms would trigger a spurious repetition of the discharge.

This process would be repeated several or many times, and so a string of spurious discharges would follow the single initial ionisation. Such repeated triggering or oscillation is avoided by the addition of a 'quenching gas'.

Action of quenching gas

The quenching gas has an ionisation potential less than that of the main detection gas. De-ionisation of the main gas is hastened because the slow-moving residual ions of the main gas combine with electrons taken from the quenching gas. The newly-formed positive ions of the quenching gas drift towards the cathode, and on impact they are merely neutralised, there being insufficient total energy to cause emission of secondary electrons.

Types of quenching gas

Quenching gases in modern tubes generally contain traces of halogens, usually chlorine or bromine. These atoms can recirculate after being ionised and neutralised, there being no permanent change in their nature. As a result, long life and stable characteristics are typical of Geiger Müller tubes with halogen-quenching. (Older tube designs had quenching gases consisting of organic vapours; the quenching action thus broke down the quenching gas molecules irreversibly, gradually modifying the characteristics of the tube and limiting its life. All our tubes are halogen-quenched except B12C, M6C and ZP1610).

CHARACTERISTICS

Figure 4 shows a simplified version of part of the characteristic curve of a Geiger Müller tube. This characteristic is obtained by plotting the count rate in pulses per second as a function of supply voltage in a constant radiation field. Note that the constant radiation field strength used for obtaining this curve is fixed so that a rate of 100 to 300 counts per second is obtained at the operating voltage (the centre of the Geiger Müller plateau). The main features of this characteristic are given below.

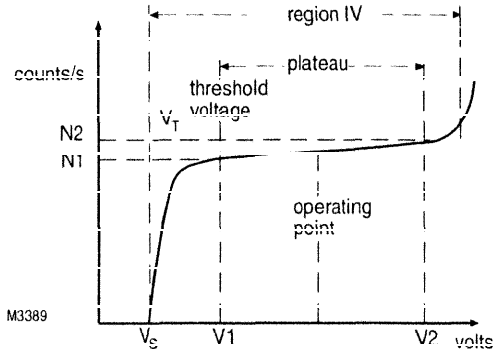

Figure 4 Characteristic curve of Geiger Müller tube showing the count rate as a function of the applied anode voltage

Low applied voltage

At very low voltages, the count rate is insignificant. Tubes cannot generally be operated usefully in this region.

Starting voltage

The starting voltage V_S is defined as 'the lowest voltage applied to a counter tube at which pulses can be detected by a system with certain defined characteristics'. The value of V_S varies with design of tube but is generally between 350 V and 500 V.

Threshold voltage

Above the starting voltage V_S the count rate increases rapidly. The voltage is increased by between 50 V and 100 V to reach the threshold voltage V_T. Above V_T all fully distinguishable ionising events produce the same size normal output pulses, the charge collected by the anode per ionisation event being substantially independent of the number of ions originally created. The threshold voltage V_T depends on the conditions defined for the circuit.

Plateau

The threshold voltage V_T also marks the beginning of the Geiger Müller plateau for the conditions under which the circuit is operating. The plateau extends for about 100 V. The large voltage range of the plateau, and its very low gradient, permit accurate measurements of radiation intensity without the need for stabilised power supplies. (The slight gradient is not a problem and is explained below).

Plateau length = (V2 - V1) volts

$$\text{Plateau slope} = \frac{N2-N1}{0.5(N2+N1)} \times \frac{100}{V2-V1} \ \%/V$$

Plateau slope

The small positive slope that always occurs on the plateau is caused in the following way:

1. Increasing voltage lengthens the active volume of the tube slightly (the spatial region where ions are in an adequate electric field to ensure that they have a chance of initiating an avalanche discharge). The number of counts thus increases for a given radiation intensity.

2. Since even a quenched discharge leaves some residual charges or molecules in an excited state, there remains a possibility of a second discharge being induced. The probability of this occurring is low but rises with increasing voltage. The small number of such spurious counts will add slightly to the initial count rate and thus contribute to the slope of the plateau.

Instability beyond plateau

At the upper end of the plateau there is a sharp rise in the count rate. The relationship between the count rate and the radiation intensity is no longer linear. The tube circuit becomes unstable and oscillations may occur.

Output signal connection

In theory, the output signal from a Geiger Müller tube can be taken from an RC network connected either in the anode circuit or in the cathode circuit of the tube (see Figure 2). These two different approaches are outlined below:

1. *Cathode connection - preferred*
   In practice, cathode connection should always be used if possible (as indicated in Figure 2 and shown in more detail in the application circuits later). This is mainly because it is less likely to affect the characteristics of the tube. The extra capacitance of the output circuitry added to the cathode is considerably less significant than when added to the relatively small anode. Cathode pick-up also obviates the need for the high voltage capacitor that is generally required by circuits with anode HT supply. (This capacitor is required because the HT normally has to be blocked at the point where the output signal is coupled to the scaler circuit).

2. *Anode connection - non-preferred*
   Anode connection should be used only if it is, for some reason, unavoidable. This situation may occur, for example, in some types of remote probes where the cathode needs to be grounded. The circuit capacitance added to the small anode capacitance may produce undesirable effects that are difficult to eradicate.

Operation in the plateau

As indicated previously, the amplitude of the output signal that can be derived from a Geiger Müller tube is always a function of the supply voltage of the circuit, the starting voltage V_S of the particular tube, and the specific component values in the RC network. However, for given circuit components, operation with the supply voltage set nominally in the centre of the plateau gives a counting rate substantially independent of the applied voltage over the range of the plateau when the tube is operated in a uniform radiation field.

This is the circuit arrangement generally used for Geiger Müller tubes in normal applications. The output pulses are fed into a threshold detector which is usually set to detect any pulse with an amplitude of, say, 10% or more of the maximum obtainable pulse height. Full details of the method of processing the output pulses are described later under 'Application Circuits'.

DEAD TIME AND RECOVERY

The maximum counting performance of a tube is determined by two interrelated characteristic times. These are known as 'dead time' and 'recovery time', and both relate to the period immediately following a full-size discharge. The meanings of terms are defined below in relation to Figure 5.

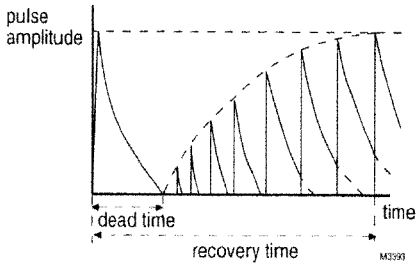

Figure 5 Possible heights of a second pulse as a function of time subsequent to a single initial full-size pulse.

Dead time

The dead time, which has a major influence on the total recovery time, is the very brief period following a discharge, during which the Geiger Müller tube is incapable of responding to any subsequent ionising event. This short period lasts while the effective circuit capacitance is recharged. Normally, most of the residual positive ions are collected by the electric field during this period, but the field is nevertheless too low to allow another discharge, even if further ionising events occur.

Dead time and applied voltage

Dead time varies with applied voltage. Figures in the selection guide are typical for the working mid-point of the plateau with a stated series resistance, and with the counting threshold set to 10% of maximum pulse amplitude.

Dead time and count rate

The dead time after each ionisation discharge will limit the maximum count rate because events that occur in the dead period cannot produce a count.

The relationship between dead time τ, the true count rate N_1, and the measured count rate N, is:

$$N_1 = N/(1 - N\tau)$$

This expression is valid only when $N\tau << 1$.

At high dose rates the probability of an ionising event occurring within the dead time is high and so a significant number of counts are lost. Tube dead time therefore has a more marked effect on detector circuit performance at higher dose rates. This effect is usually seen as a non-linearity in the tube characteristic relating dose rate to count rate. A typical example of this slight but inherent non-linearity in the characteristic of the tube itself is shown in Figure 6. (Certain kinds of inadequate circuit design can also cause an additional apparent exaggeration of this non-linearity which is then called 'foldback'. Circuits should be correctly designed to minimise the foldback effect).

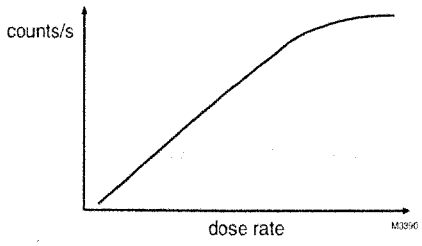

Figure 6 Count rate versus dose rate for a typical Geiger Müller tube

Ionising events repeated at close to the maximum count rate will produce output pulses of limited amplitude (see 'Recovery Time'). Because of this, as the count rate increases, the detector takes less time on average to recover from each event, and so the effective dead time falls. The difference between the true and observed count rate therefore increases. For large detectors the change in effective dead time is slight, but for small detectors the change is significant.

Clearly, for optimum counting performance, circuit designers should always use counting equipment or a scalar circuit with a resolution time significantly shorter than the minimum attainable dead time of the tube.

Reducing dead time

Dead time can be reduced somewhat by decreasing the value of the series anode resistor. This expedient can be used with either the non-preferred anode signal connection method or the preferred cathode connection. In either case, however, the reduction in value of the resistor might adversely affect the quenching and so the method should be used with caution.

Dead time can also safely be minimised by ensuring that the anode resistor is connected directly to the anode clip on the tube, thus reducing the circuit capacitance that is added directly to the anode. This also enhances the physical durability of the tube under conditions of vibration or physical shock. The method of attaching the anode resistor is described briefly under 'Tube Durability-series resistor'.

The advantage of having a short connection lead between anode and external circuit can be seen, for example, with the tube type ZP1300. This has an exceptionally short dead time of 5µs at high count rates when it is connected directly to the circuit without an anode lead, but the insertion of only 20mm of anode lead can double the effective dead time.

Recovery time

Figure 5 shows the dead time and this can be seen to be the initial part of the full recovery time. After the dead time, but before the field is completely restored, only a limited discharge can be supported. If additional time elapses before a subsequent discharge occurs, the voltage across the detector tube rises. The next ionising event can then produce a more substantial discharge and a larger output pulse. The amplitude of such subsequent pulses will eventually rise to the normal maximum after a full recovery period.

The recovery time is defined as 'the minimum time between two successive normal pulses', as shown in Figure 5. Recovery time is approximately twice the dead time.

BACKGROUND

The background is the count rate in the absence of all other radiation that the detector is intended to measure. The most important sources of background radiation are:

- gamma radiation from the environment and from cosmic radiation
- mesons from cosmic radiation
- beta particles from impurities in the materials from which the detector is made

From published experimental data, the gamma contribution accounts for 60-70% of the background, and cosmic mesons account for 20-35%. For some applications the background count can be reduced by shielding the tube with lead or steel, thus excluding most of the gamma radiation.

TEMPERATURE RANGE

Halogen-quenched tubes can generally be operated in the temperature range -40°C to +70°C, though tubes of older design can be operated over only part of this range. Our high temperature tubes operate up to 175-200°C, depending on the tube type. Published data should always be consulted.

OPTIMUM PERFORMANCE

To ensure optimum performance it is advisable to avoid having more than one parameter at its limit value, particularly when one of these is the temperature limit. For example, operation at -40°C with an anode resistor of minimum value and also with maximum anode voltage should be avoided.

TUBE DURABILITY

Under working conditions, halogen-quenched tubes are very resilient and will recover from most forms of operational over-stressing because they have the following features:

- tube characteristics are not impaired by a large but temporary over-voltage
- tubes are unaffected by a temporary reversal of polarity of the supply voltage
- exposure of tubes to excessive radiation has no deleterious effects

Though this operational ruggedness and reliability of Geiger Müller tubes has been thoroughly proven over several decades, equipment designers should nevertheless bear in mind the following points:

- tube characteristics can be permanently damaged by circuit operating conditions that produce an excessive charge per pulse
- excessive shock or vibration may cause gas leakage, thus permanently affecting the characteristics
- operation in an ambient temperature or pressure beyond the specified limits (or in a helium-laden atmosphere) can lead to changes in gas content and so to changes in characteristics

Any difficulties associated with the above points can be avoided by observing these recommendations:

- ensure that the permanent operating voltage is kept within the limits specified in published data
- keep the tube reasonably protected from aggressive physical and chemical conditions
- minimise any circuit capacitance connected to the tube electrodes, particularly the anode

Caution over this last point leads to the circuit design recommendations given in the next section.

Series resistor

The output pulse should be taken from a resistor connected to the cathode or from a resistive potential divider in the anode circuit. However, to minimise the total capacitance at each electrode (to achieve acceptable discharge currents and therefore maximum tube life, as explained above), any series resistor should be placed physically close to the relevant electrode of the tube. This recommendation applies particularly to the anode resistor, where even a few centimetres of unnecessary wiring will degrade performance, possibly shortening the plateau length and increasing the non-linearity of the dose rate/count rate characteristic (Figure 6).

Anode output connection and anode resistor

If a potential divider is used in the anode circuit, the output should be taken from the resistor electrically most remote from the anode itself.

The resistor that is electrically adjacent to the anode in the circuit should be connected physically as close as possible to the anode clip itself, so that the stray capacitance of the anode circuit is kept to a minimum. (Performance figures in published data are obtained with such a configuration).

Shock protection arrangements

When an instrument has to withstand severe shock (as might occur when a personal dosimeter is dropped), ensure that any anode resistor that may be used is connected to the anode clip via a short flexible wire which includes a small half-loop to permit flexing in the direction of the wire itself. This will minimise mechanical forces applied to the anode pin.

The tube itself should be mounted using silicone rubber or foam rubber. Care should be taken to avoid any possible damage to the wall of the tube, particularly to the walls of thin wall tubes for beta detection.

Life and reliability

When our Geiger Müller tubes are used within the limits stated in published data they will give a total count life of at least 5×10^{10} counts.

Shelf life

The shelf life of Geiger Müller tubes, when out of commission or when installed in equipment that is itself out of commission, is extremely long. This is because normally there is virtually nothing (other than the unlikely transmigration of helium) that can cause deterioration of the tube. However, it is nevertheless good practice to check the tube characteristics periodically.

RESPONSE TO RADIATION

Though Geiger Müller tubes can be constructed so that they are sensitive to alpha and beta particles and to X-rays and gamma rays, more than one mechanism is responsible for the ionisation. For alpha and beta particles, ionisation is induced by the particles colliding with gas atoms. For both X-rays and gamma radiation, if they are of very low energy, the mechanism is mainly photo-ionisation of the gas atoms. For any significantly higher level of radiation of these types, ionisation of the gas is initiated by electrons ejected by photo-emission at the inner surface of the cathode cylinder.

Detection efficiency varies with the type of incident radiation. Efficiency for tubes with thin end windows approaches 100% for high energy beta particles. However, efficiency is lower with low energy beta particles and with alpha particles because of absorption in the window material. Detection efficiency with photon radiation is as low as a few per cent in the energy range 30 keV to 1.25 MeV, leaving most of the radiation passing through the tube without causing ionisation.

Alpha particles

Since alpha particles have large mass, and because they travel relatively slowly through matter, there is a high probability of their interacting with atoms along their route. They therefore have great ionising power, lose energy rapidly, and have poor penetration. The energy of the majority of alpha particles is between 4 MeV and 6 MeV. The range of such alpha particles in air is about 25mm to 50mm, as can be seen from Figure 7. The implication of this is that alpha particles will be efficiently detected only if the counter window is not more than about 10mm from the source.

To maximise tube penetration of alpha particles, we make the 'thickness' of the mica window as low as 1.5 to 2.0 mg cm^{-2}. Hence the window should be protected from mechanical forces and particles should be able to reach the window reasonably unimpeded.

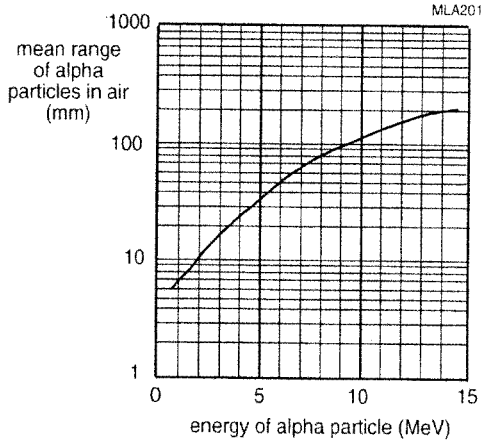

Figure 7 Mean range of alpha particle in air as a function of energy

Beta particles

In every day use, the term 'beta radiation' refers to electrons emerging from nuclear decay with energies ranging from zero to a value E_{max} that characterises each nuclide. Most values of E_{max} lie in the range 150 keV to 2.5 MeV and the average energy is approximately $E_{max}/3$.

Beta particles retain their energy longer than alpha particles and can be detected by tubes with a mica end window. High energy beta particles can be detected by tubes with thin metal or metallised glass walls. Figure 8 shows the relationship between the E_{max} of several types of beta emitter, the thickness of the wall or end window for several types of tube, and the absorption of the tube. The window or wall thickness for each of our tube types is also indicated.

Low energy X-rays

Low energy X-radiation, such as that produced by crystallography equipment, can be detected efficiently using 'high pressure' counting tubes like the ZP1600. The tube is mounted end-on to the radiation which enters through the end window and can travel the length of the tube. For energies lower than 25 keV there is a significant chance, in a tube that contains a gas with a high coefficient of absorption, that the radiation and the gas will interact and a count pulse will be generated. To absorb the characteristic X-radiation from copper or iron targets in X-ray generating equipment, the tubes are normally filled with argon at a pressure higher than that of gases in other tubes. However, other gases of high atomic number such as xenon and krypton can also be used for detecting both X-rays and low energy gamma rays.

Gamma rays and higher energy X-rays

X-rays and gamma rays of energy greater than 25 keV are highly penetrating. They can, however, be detected by a Geiger Müller tube, as previously stated, when the radiation ejects electrons from the inner metal surface of the cathode.

The counting efficiency for gamma rays depends on the probability of a gamma ray interacting with the cathode wall and producing an electron, and also on the probability that the electron will ionise the detection gas before arriving at the end of its track. The probability of interaction at the cathode generally increases with the atomic number of the wall material. The efficiency of the tube is therefore higher if the cathode is made of materials with high atomic numbers.

Chromium iron (28% Cr) is the most commonly used material and it has the advantage of being non-reactive with the halogen-quenching gas. It can be processed to give a high work function which inhibits the production of secondary electrons. In older tube designs, bismuth (Z=83) and lead (Z=82) were used for higher detection efficiency, but tubes with platinum-lined cathodes (Z=80) are currently used for enhancing counting efficiencies.

For the conventional chromium iron tubes, the detection efficiency is approximately 1% over a wide range of energies for gamma radiation and X-rays, that is, only 1% of the incident photons trigger a count. In radiation dosimetry, however, the dose per photon per unit area depends on the energy of the radiation. The dose rate response of the tube depends strongly on radiation energy and a typical example, with the characteristic peak at about 60 keV, is shown in Figure 9. The response of a 'naked' tube can be adjusted to meet the required characteristic by adding energy filters (see 'Energy Compensation').

The majority of interactions that produce pulses take place in the cathode wall. For low energy radiation (less than, say, 20 keV) the walls of normal chromium iron tubes considerably attenuate the incident radiation and reduce the response of the detector.

Neutrons

Geiger Müller tubes are seldom used for counting neutrons because the capture cross-section of the normal detection gases is too low to give an acceptable counting efficiency. It is possible, however, by wrapping cadmium foil on to the exterior of a Geiger Müller tube, to convert the neutron flux to radiation that is detectable by the tube.

ENERGY COMPENSATION

The variation of tube sensitivity with radiation energy, especially at lower energies, can be partially reduced with a filter placed around the tube. Some tubes are constructed with such a filter already included as part of the tubular structure.

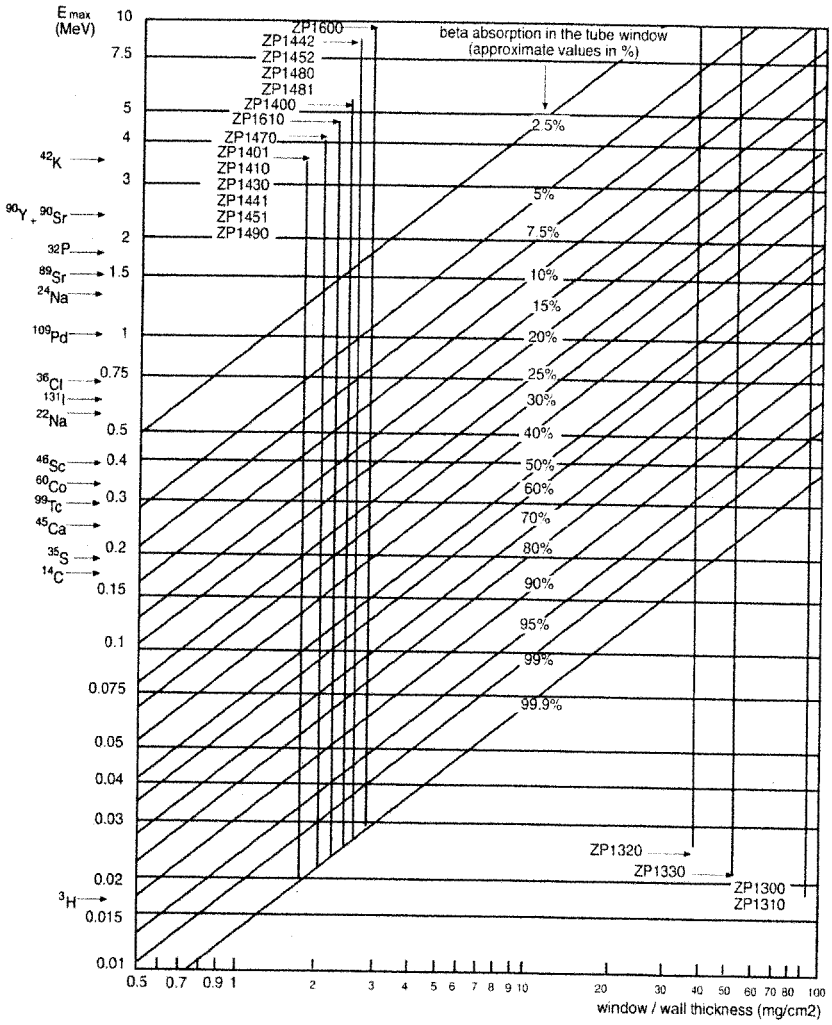

Figure 8 Relationship between maximum beta energy, thickness of wall or end window and tube absorption for typical tubes

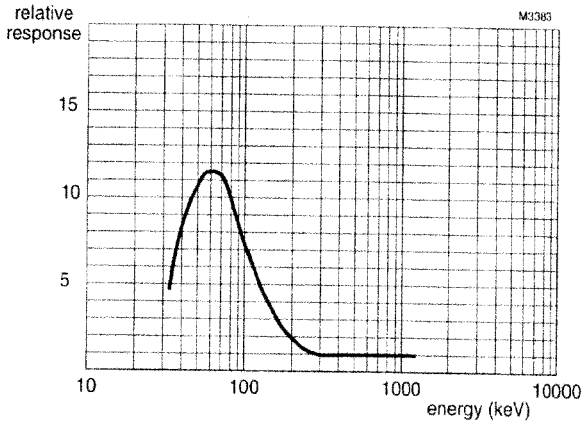

Figure 9 Energy response of unfiltered ZP1310 Geiger Müller tube relative to ^{137}Cs

Physics of compensation

Energy correction is possible because the absorption coefficient of any material increases gradually and smoothly over a wide range of decreasing energies. Such changes take place very gradually at the higher energies, but usually more quickly at lower energies. The exceptions to this smooth variation are the rapid change at low energy 'absorption edges'. The energy levels at which these edges occur vary with the material, generally increasing with atomic number Z.

Compensation materials

Some high-Z materials that would be desirable for filtering, such as tantalum, tungsten, platinum, gold and lead are either expensive or difficult to work. Of this group, lead is the most commonly used, though its absorption edge at 88 keV makes it undesirable for use below this energy level. Tin (Z=50), with an absorption edge at 29 keV, is frequently used. It provides some advantages in designs where energy compensation over a wide energy range is required. Sometimes a tin/lead alloy is used.

Compensation matching

Ideally, the sensitivity/energy relationship of the tube should be exactly matched by the absorption/energy relationship of the compensation filter material, but in practice, a compromise is necessary. In some instances it may be necessary for the filter to be made from components of different materials or from a mixture of materials. The thickness t of the chosen material can be determined from the relationship:

$$\frac{I}{I_o} = -e^{-\mu t}$$

where $\frac{I}{I_o}$ is the ratio of transmitted to incident radiation, and μ is the attenuation coefficient.

It is possible to get a relatively flat exposure or dose equivalent response above 150keV with a simple compensation filter, consisting of a continuous sheath of material. To improve the lower energy sensitivity and to obtain good performance down to (normally) 50 keV, a gap is left in the filter. The width of this gap is chosen so that the maximum response of the naked tube (usually between 60 keV to 80 keV) is reduced to unity compared with the response at the upper parts of the energy spectrum. For example, a typical tube may over-respond by a factor of 10 at 60 keV, but if the filter leaves 10% of the sensitive area of the tube exposed then the final response at that energy will be close to unity.

The final design is a compromise between filter gap dimensions, filter material, and filter thickness. These can be chosen to produce the required characteristics. For example, a good dosimeter response for X-ray and gamma radiation energy greater than about 50 keV can be produced with an appropriately designed filter.

Polar response

The above measures will provide effective energy compensation for incident radiation normal to the axis of the tube, but there is also usually an additional requirement for uniform polar response over a specified energy range. The design of a filter that provides a uniform response over a wide range of angles will depend on the construction and size of the Geiger Müller tube.

The requirement introduces additional but manageable complications into the basic design process. The resulting compensated tubes have a cylindrical filter with a circular gap arranged around the middle of the tube. A typical polar response curve is shown in Figure 10 where the example shown is the ZP1321. Figure 11 shows the energy/response curve for the same tube.

APPLICATION CIRCUITS

A practical Geiger Müller tube circuit is described in the published data for tubes and is similar to the circuit already shown in Figure 2. The circuit is analysed below.

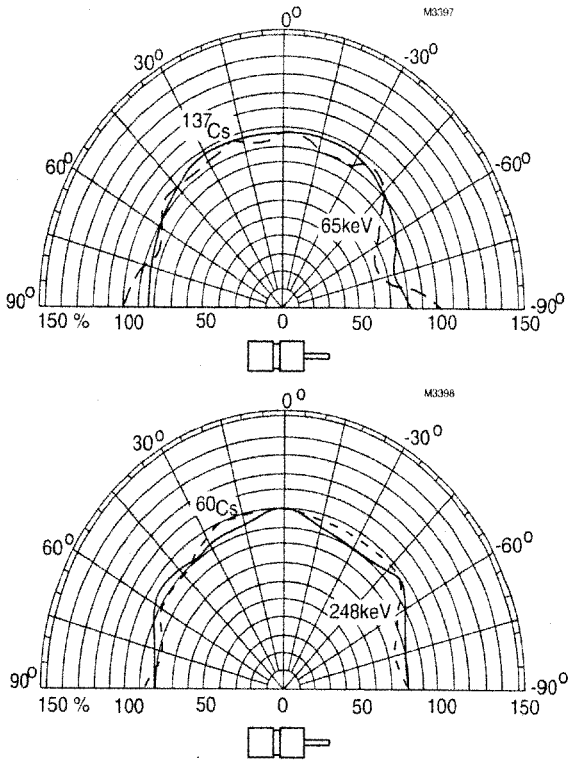

Figure 10 Typical polar response of a Geiger Müller tube (ZP1321) over 180°. A mirror image curve would give the same response over the opposite 180°.

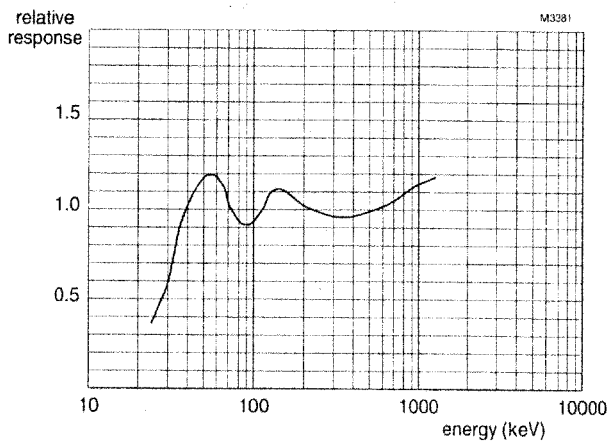

Figure 11 Energy response of compensated ZP1321 Geiger Müller tube relative to ^{137}Cs

Quenching

Quenching can be assisted, as mentioned previously, by the design of the external circuit. The two forms of circuit-assisted quenching are as follows:

- Passive circuit-assisted quenching
- Active circuit-assisted quenching

Passive circuit assistance is relatively easy. The active form requires additional circuitry but is considerably more versatile. We describe these two approaches below.

Passive quenching circuits

A simple passive quenching circuit consists of a high value resistor, R1 in Figure 12 in the main discharge circuit. This resistor increases the time constant of the recharge current path and thus allows a longer period with reduced voltage. (The published data for each tube gives a minimum value for R1, the anode resistor, but it is better to use a higher value whenever the application allows this). The resultant extension in the period during which there is a lower voltage assists de-ionisation because the time constant of the circuit then becomes much greater than the probable collection period of positive ions. The increased time constant may not, however, be acceptable in some applications.

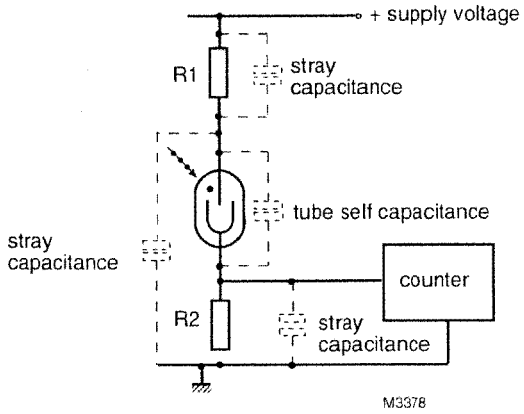

Figure 12 Typical operating circuit. Anode connection resistor R1 gives correct operation of the tube. Cathode resistor R2 gives output pulses. Tube performance is affected by every component in this circuit, especially the stray capacitances.

Active quenching circuits

The second approach to quenching uses fast positive-acting, voltage-reducing circuits applied to the simple discharge circuit. These relatively elaborate circuits reduce the voltage substantially for a preselected brief period after each discharge. As well as merely assisting the quenching, this arrangement offers the two further advantages of higher count rates and also some control over the characteristics.

Figure 13 shows a block diagram of such a system in which the voltage applied to the Geiger Müller tube is reduced whenever a pulse is detected. The pulse first passes through a buffer threshold detector X2 which will detect only pulses of a predetermined height. The shaper X3 then shapes the output of X2 to a constant amplitude and duration before the pulse is fed to the counter and display circuit X4.

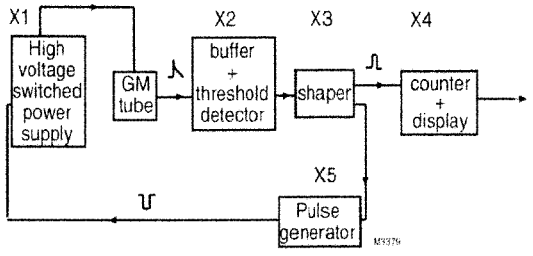

Figure 13 Quenching circuit using switchable power supply

A second output is taken from the shaper X3 and this triggers the pulse generator X5. This produces a pulse of suitable duration which, by switching X1, reduces the voltage applied to the Geiger Müller tube to a value well below the starting voltage of the tube. The full operating voltage is then automatically restored after the pulse is complete. Some high voltage supplies are switched to zero volts by short-circuiting the output (via a limiting resistor) with a fast-acting, solid-state switch. This is often referred to as a 'crowbar' method. It is not energy-efficient, however, and for portable dosimeters, such circuitry will reduce battery life.

EQUIVALENT CIRCUIT

Figure 14 shows all the components in a standard application circuit for a Geiger Müller tube. The equivalent capacitances C1 to C4 represent primarily the inherent stray capacitances of components and wiring, but in the case of C4 an actual capacitor might be added for compensation purposes, as explained later (see 'Energy Compensation').

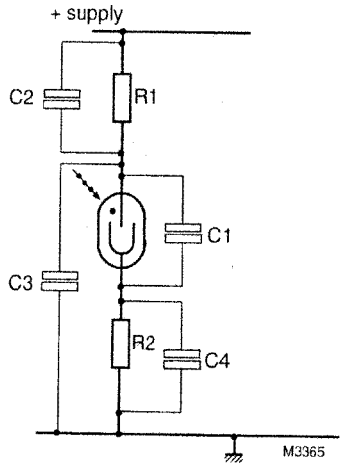

Figure 14 Equivalent Geiger Müller application circuit

Anode resistor R1

Resistor R1 is an essential component for correct operation of the Geiger Müller tube. The minimum value of R1 for any particular tube type is always specified in the data sheet but, as mentioned above, it is better to use a higher value if the application allows it.

This anode resistor reduces anode voltage after a discharge has been initiated, the voltage dropping to below the starting voltage V_s while sufficient discharge ionisation is present. This severe reduction in anode voltage allows the tube and circuit to recover from the discharge.

Recovery time is determined partly by R1 (because recovery is complete only after the current through R1 has recharged all of the relevant capacitances) as well as by the time taken for the gas ions to recombine.

Average tube current flowing during quickly repeated multiple discharges is also limited by R1, and the recommended value of R1 given in the data is selected to give a current that will lead to long tube life.

The anode resistor also has an effect on the plateau length, a lower value of R1 giving a shorter plateau length.

Cathode resistor R2

When a discharge occurs, the current through the tube develops a positive going voltage across the cathode resistor R2. This is the preferred way of taking the output signal from the circuit (though the non-preferred alterative of taking a signal from the anode circuit is briefly described below under the heading 'Anode signal connection'). In most applications, the ratio of R2:R1 is normally set at 1:45 and the manufacturing test methods also adhere to this relationship.

A lower value can be used for the cathode resistor and this offers the advantage of a lower source resistance but at the cost of reduced output pulse amplitude. This reduction might be unimportant, however, because of the substantial amplitude of the unreduced pulse.

When the gas in the tube ionises, the voltage across the tube falls somewhat below the starting voltage V_S. The extent to which the voltage falls below V_S depends on several factors but the difference between the two voltages is small enough to be ignored to a first approximation. If we therefore assume that the anode voltage falls approximately to V_S, then the output pulse amplitude V_{pulse} is given by:

$$V_{pulse} = \frac{(V_{supply} - V_s)}{45}$$

Example: For the ZP1300, which has V_S= 400V, operating at 550V anode voltage, the output pulse can be expected to be (550 - 400)/45 or approximately 3.3V. In practice, it is a little higher than this. R2 also assists in limiting the current that flows out of C3 when the tube is discharged. This effect will, however, be somewhat negated by C4, particularly if C4 >> C3, a condition frequently met in practice.

Anode signal connection

The function of R2 discussed above is primarily to generate the output signal voltage from the discharge current but, as mentioned previously, a resistor with this function could be placed in the anode circuit. This approach gives a negative going output signal.

Signals must never be taken directly from the anode itself because of the highly undesirable resultant increase in the value of C3 in Figure 14 (the effects of C3 are discussed below).

The circuit in Figure 15 shows a suitable way of deriving a signal from the anode circuit. The 'measuring' resistor R3 (performing the same function as that of the cathode resistor R2 in Figure 14) also usually has the value 1/45 of the main anode resistor R1. This method of deriving signals is not preferred because:

1. A high voltage will be present at the junction of the two resistors, and this normally necessitates a suitable high voltage blocking capacitor.

2. At the moment of switch-on, there will be a high voltage transient fed to the measuring circuit via capacitor C_b. Protection of the input part of the measuring circuit may be necessary.

3. Any noise on the power supply rail will be fed to the measuring circuit via R3. The measuring circuit will see a noise voltage determined by the ratio of the impedance of the input to the measuring circuit and the impedance of R3 and associated components.

Hence, a cathode circuit resistor for signal generation is always preferred.

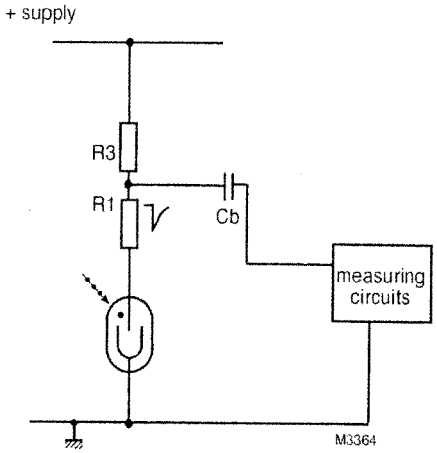

Figure 15 Anode signal detection (non-preferred)

Tube self-capacitance C1

The self-capacitance C1 of the tube (Figure 14) cannot be reduced in any way. Its value (typically about 1 pF) is given for each tube type in the relevant data sheet.

Stray anode capacitance C2

The stray anode capacitance C2 in Figure 14 consists of the self-capacitance of the anode resistor, and the stray capacitance between the anode and the supply connections. Careful layout of wiring, and the use of a resistor with a low self-capacitance, will keep this value to a minimum. (In particular resistors with end caps should be avoided, as should the use of more than one resistor).

The discharge pulse is affected by the two stray capacitances C2 and C3 as though they were in parallel. Clearly, when the tube discharges, the capacitance C2 must be charged before the voltage on the anode can fall. A significant value of C2 will therefore cause a sharp current spike on the leading edge of the output pulse. As a result of this, tube life may be reduced. Furthermore, the operational dead time will be lengthened because, as the tube de-ionises, capacitance C2 has to discharge through R1 before the working anode voltage can be re-established.

Anode-ground capacitance C3

For maximum performance, it is essential to keep to a minimum any stray capacitance between the anode and the ground circuit. As mentioned previously, the anode resistor R1 in Figure 14 must be positioned as close as possible to the anode, and all other wirings must be kept away from the anode. Even short lengths of wire from the anode resistor to the tube will reduce the performance of the tube perceptibly, particularly at high counting rates.

Since, prior to the discharge of the tube, capacitance C3 will be charged to the supply voltage through R1, C3 has to be discharged through the tube before the anode voltage can fall. This modifies the tube response and its behaviour when counting.

Unfortunately, C3 cannot be entirely eliminated and its existence causes:

- increased dead time
- reduced tube life
- spurious counts
- shortened plateau length
- increased plateau slope

The reasons for these deleterious effects are as follows:

Dead time. The dead time is increased because the anode voltage cannot be re-established immediately after the ionisation of the tube is finished. This is due to the increased delay in the rise of anode voltage caused by the recharging of C3.

Tube life. The life of the tube might be reduced because the anode-cathode current in the tube has to supply additional current to flow out of C3.

Spurious counting and plateau changes. Spurious counts, and the changes in the length and slope of the plateau, are all changes in the operational mode of the tube by which it approaches an unstable region of operation (see Figure 16).

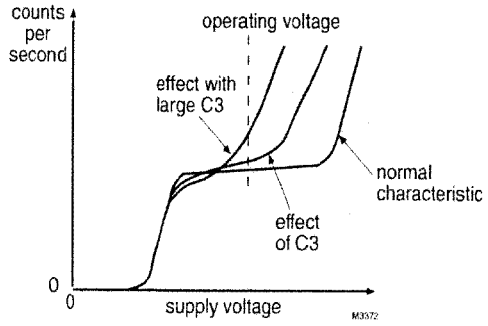

Figure 16 Effect of increased anode capacitance

R2 and capacitor C4

When the output signal is taken from the cathode resistor R2 in the preferred way, usually via screened cable, the signal connection to the counter (whether it is via a series capacitor or not) will inevitably make some additional capacitance appear across this resistor. (The deliberate addition of a further parallel capacitor for compensation purposes is described in the next section).

As the capacitance C4 will bypass the higher frequency components of the output pulse that would otherwise have developed a voltage across R2, the effect is to slow down the leading edge of the pulse and also to lengthen the tail slightly. Provided the value of C4 is not excessive (say, <100pF), it has little effect on the operation of the tube as a counter.

Compensation

If the tube is considered as a generator, and if its shunt capacitance and source resistance are ignored, the application circuit can be redrawn as shown in Figure 17(a). We can then consider R1 and R2 together as forming a potential divider connected across the generator, and C_T to C4 must equal the division ratio of R1 and R2. We can then write the following equation:

$$\frac{R2}{(R1 + R2)} = \frac{C_T}{C_T + C4}$$

So,

$R1.C_T = R2.C4$

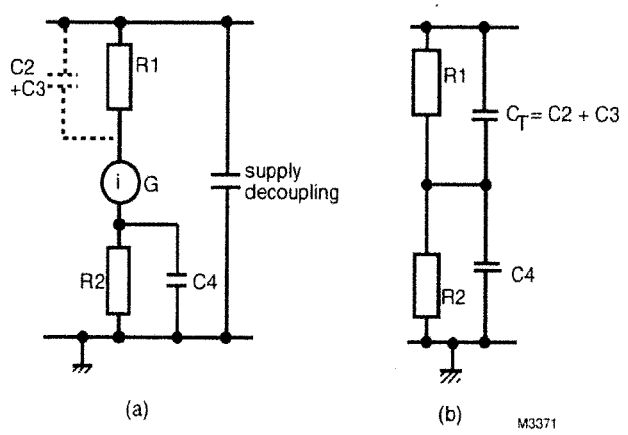

Figure 17 (a) Tube regarded as generator
(b) Equivalent RC network

The stray capacitances C2 and C3 shows in Figure 14 have been lumped together. This is permissible because, for the pulse generated by the tube, the supply rail and ground are at the same AC potential.

Some practical values that are typical for the ZP1300 tube, R1 = 2.2 MΩ, R2 = 47kΩ, and (C2+C3) = 2pF. With these values, a value of 90pF for capacitor C4 will give appropriate compensation.

Shape of output pulse

Although the output pulse from the Geiger Müller tube can be examined with a general purpose oscilloscope, such examination will give only an approximate indication of the pulse shape. This is because, with such an oscilloscope it is not possible to look at individual pulses. Any multiple pulses will be displayed only fleetingly and these can therefore be seen only with the most careful observation.

A digital storage oscilloscope is a more suitable measuring instrument because individual pulses can be 'captured' and can then be examined at leisure. This procedure will also enable multiple pulses to be seen with ease.

Although only the cathode signal is considered here, it should be noted that any attempt to probe the anode will simultaneously modify the waveform there. With certain tubes, it might also even cause multiple pulses.

Figure 18 shows the two extremes of pulse shape, first with good layout and then with additional circuit capacitance present.

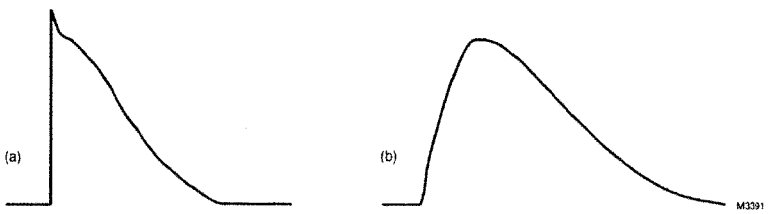

Figure 18 Extreme shapes of output pulse from tube
(a) with good circuit layout
(b) with stray circuit capacitance

Figure 19 shows a single output pulse taken at the cathode of a ZP1320 tube and Figure 20 shows a single pulse from the cathode of a ZP1200. Figure 21 shows an example of two cathode pulses from a ZP1200, the second pulse occurring after the dead time. It is worth noting that, in all the cases shown, the fast rise-time (of around 1 µs) is achieved with minimum overshoot, this being consistent with a good circuit layout with minimal stray capacitance.

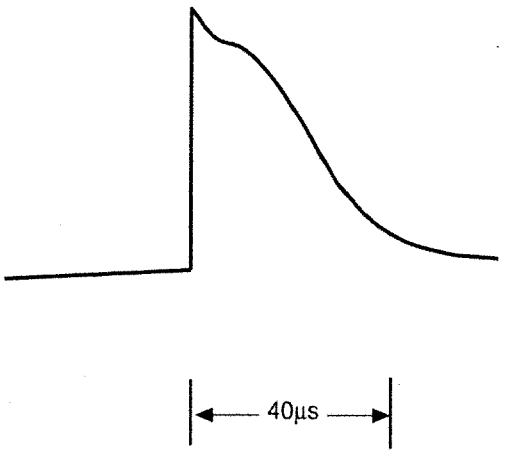

Figure 19 Single cathode pulse with ZP1320

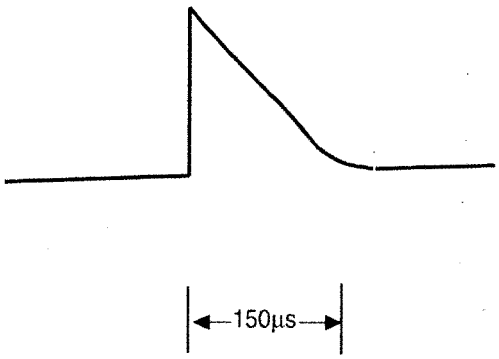

Figure 20 Single cathode pulse with ZP1200

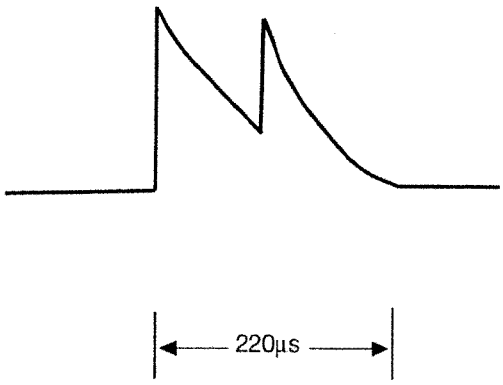

Figure 21 Double cathode pulse with ZP1200

Cathode pulse display connections

If cathode connections are to be built permanently into a piece of equipment that also contains the measuring circuitry, there is usually no difficulty in keeping cathode capacitances to an acceptably low level.

If, however, remote sensing is employed, with the tube considerably displaced from the vicinity of the measuring circuit, then there will often be significant loading of the cathode by the cable capacitance. Figure 22 shows such a remote connection.

Since R_K in Figure 22 will be relatively large, generally between 47 and 220kΩ, the cable capacitance will degrade the rise time of the pulse. High capacitive loading (some hundred of picofarads) will extend the tail of the pulse noticeably. It is therefore prudent to use low capacitance cable.

If a value of R_K lower than the value given in published data is used, then the effect of the capacitance will be reduced but the pulse amplitude will also be smaller.

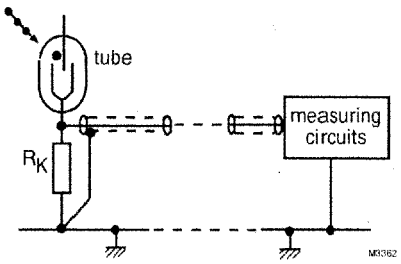

Figure 22 Remote cathode connection

Buffer amplifier at cathode

An effective way of overcoming difficulties that could be caused by cable capacitance is to 'buffer' the pulse with a suitable amplifier as shown in Figure 23. The amplifier, which should be located physically close to the cathode resistor of the tube circuit, can provide a low output source resistance for driving the cable without significantly loading the tube output pulse. However, this approach does require power supply rails for the amplifier.

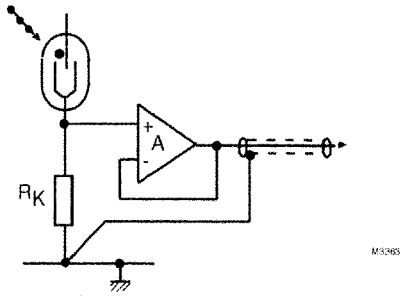

Figure 23 Simple cathode buffer amplifier

Input circuit

The measuring circuit should not significantly load the tube circuit in any way and so the use of a buffer amplifier as the input stage to the main measuring circuit is good practice. However, the buffer must clearly be able to handle the maximum pulse amplitude that can be expected from the cathode resistor of the tube without exhibiting any saturation effects. A unity-gain operational amplifier, as shown in Figure 24, offers a suitable approach.

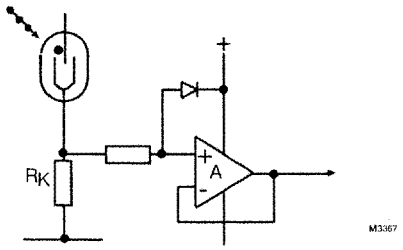

Figure 24 Unity-gain operational amplifier buffer

Threshold levels

Statistical pulse height analysis shows that there will generally be a range of pulse heights present at the output of the tube. A spread of 4:1 is common, with pulse heights at the low end being down to 1V or less (the actual voltage depending on the circuit details). Furthermore, the centre of the spread and the width of the spread will change with dose rate. At high dose rates the spread will be narrow and the average pulse height will be significantly reduced.

It is possible to design an economical detection circuit by combining with the buffer circuit a mechanism such as a Schmitt trigger circuit to predetermine a 'threshold trigger level'. (Certain disadvantages of this type of circuit become evident later). The predetermined threshold levels can be important, as is explained below.

At low to medium count rates, and with pulses that are generally well separated, the threshold setting requirement is straightforward. The detection level must be above any noise level but below the peak level of the smallest expected pulses, and as mentioned previously, a threshold detection level equal to 10% of the maximum pulse height is customarily recommended. (The maximum pulse height for comparison occurs at low count rates when all of the output pulses are 'normal' or full-size). The 10% level is low enough to ensure that even at high count rates, when the mean pulse size diminishes, the majority of the pulses will still be counted and it is also high enough to exclude most noise pulses.

However, in practice, the pulses are not necessarily well separated, even at low to medium count rates. Figure 25 shows an example of such a set of closely spaced and overlapping pulses. After the tube has been discharged for the first pulse, the second pulse occurs outside the dead time of the first pulse but before the tail of the first pulse has fallen away to zero. Similarly, the third pulse occurs within the 'tail period' of the second pulse, but after its dead time.

It is clear that the three detection threshold levels (a), (b) and (c) in Figure 26 would give different counts. Level (c) would count a single pulse, whereas level (b) would count two pulses, and level (a) would count three. So, in effect, level (c) detects small pulses but cannot distinguish the separate parts of a set of overlapping pulses and therefore counts each set of such pulses as one. Level (a) counts large pulses and can distinguish individual pulses among overlapping pulses and will count each one individually, but it will miss all small pulses.

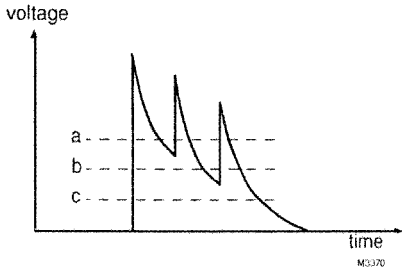

Figure 25 Three threshold levels with multiple pulse

Figure 26 shows an additional effect that may occur at higher count rates where the output pulse amplitude is reduced due to significant 'pile-up' of pulses combined with high noise content. The reduction in pulse size is caused by the average anode voltage being lower since there is inadequate time for full recovery. The effect is an apparent DC level being present at the cathode. If the DC threshold detection level is then set as shown in Figure 26, then although the tube itself continues to respond, none of the pulses will be detected by the measuring circuits except the first pulse. This difficulty (which is one example of 'foldback' mentioned in relation to Figure 6) therefore places stringent requirements on the electronic measuring circuit. The optimum approach is generally to use differentiation of the pulses, together with subsequent integration and pulse shaping, with the result that all pulses are detected and, simultaneously, the signal-to-noise ratio is also improved.

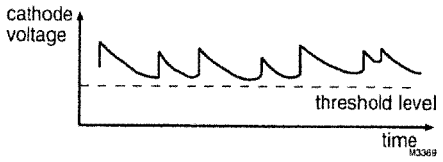

Figure 26 Repetitive multiple pulses above threshold level

It is essential that measuring circuits do not become overloaded which would cause them to give lower count readings when very high dose rates are encountered. One option is to design a 'current trip' to prevent such readings from occurring.

Closely spaced pulses and differentiation

Differentiation of the pulse-train waveform might be essential in some applications. For example, there may be a requirement for accuracy in counting for measurement purposes, and thus to count the separate pulses shown in Figure 26 since each of the pulses is real and is outside the dead time of the tube. Alternatively, a requirement to count under higher dose rate conditions may raise the need to count all pulses of the type shown in Figure 27. In such cases, a fixed low threshold can be combined with differentiation of the pulses within the counting circuitry. The DC threshold should thus be set to detect any small pulses, and the differentiator should be set to respond to all fast rising edges so that it will separately record all events above the DC threshold level. The time constant of the differentiator should be between 1 and 2 µs and because of this, it is essential to retain a fast leading edge in the tube pulse (see figures 27 and 28).

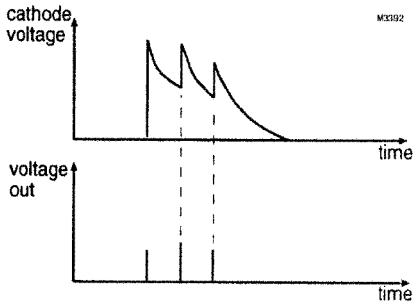

Figure 27 Differentiated outputs for Figure 25

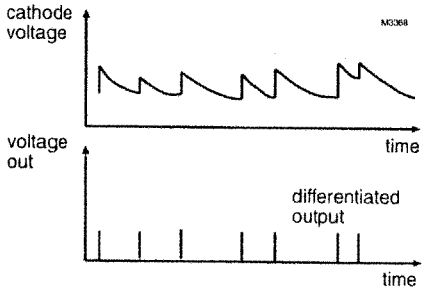

Figure 28 Differentiated outputs for Figure 26

Figure 29 shows a basic block diagram of a combined DC threshold and differentiator pulse detector. The output of the tube is first buffered and is then split into two paths relating to threshold detection and differentiation. The output from the next stage along each of these paths triggers one of two identical pulse generators. These are coupled to the logic gate 'G', from which the output is fed to the main counting circuit. So, by combining the stream of pulses from the differentiator and from the threshold detector, all pulses are available in the circuit and will be counted but noise pulses will be excluded.

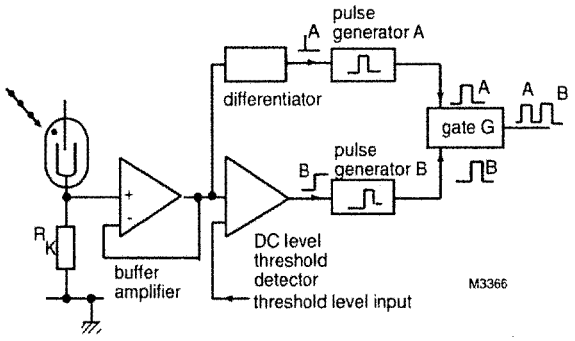

Figure 29 Arrangements for combined detection of DC threshold and differentiated pulse