ET Enterprises
electron tubes

UNDERSTANDING Photomultipliers

Understanding photomultipliers

1. Introduction

This introduction is intended to provide an understanding of photomultiplier (pmt) performance. If your purpose is to select a pmt please also refer to our photomultiplier brochure. Final selection should be confirmed in consultation with ET Enterprises or its international representatives who will advise on the latest developments.

2. Principles of operation

Photomultipliers are extremely sensitive light detectors providing a current output proportional to light intensity. They are used to measure any process which directly or indirectly emits light. Large area light detection, high gain and the ability to detect single photons give the photomultiplier distinct advantages over other light detectors.

The photomultiplier detects light at the photocathode (k) which emits electrons by the photoelectric effect. These photoelectrons are electrostatically accelerated and focused onto the first dynode (d_1) of an electron multiplier. On impact each electron liberates a number of secondary electrons which are in turn, electrostatically accelerated and focused onto the next dynode (d_2). The process is repeated at each subsequent dynode and the secondary electrons from the last dynode are collected at the anode (a). The ratio of secondary to primary electrons emitted at each dynode depends on the energy of the incident electrons and is controlled by the inter-electrode potentials. By using a variable high voltage supply and a voltage divider network, to provide the inter-electrode voltages, the amplitude of photomultiplier output can be varied over a wide dynamic range.

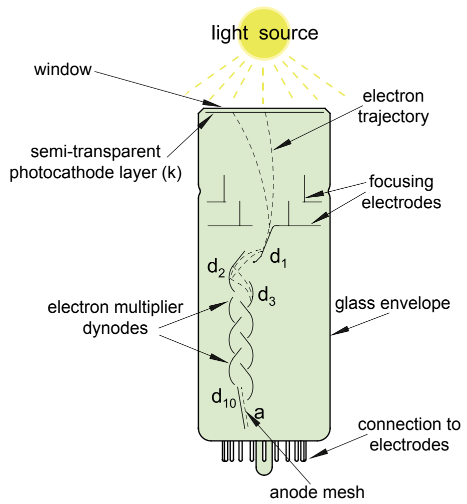

figure 1 *Illustrating the operation of a photomultiplier.*

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3. The photocathode

This section gives information on :

the light sensitive area of the photomultiplier

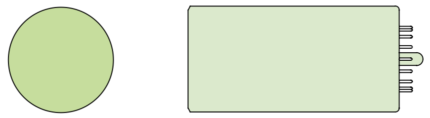
the effect of the window on light transmission

photocathode spectral response

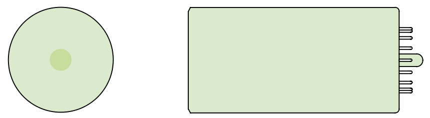
photocathode sensitivity units

3.1. Photocathode active area

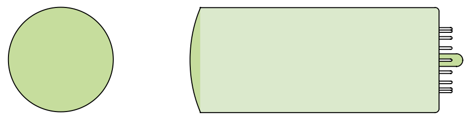
Photomultipliers are offered in a range of geometries and sizes to cover applications involving both remote and directly coupled light sources. In end window photomultipliers, the photocathode is deposited as a semitransparent layer directly on the inside of the window. In the majority of types the active area has a circular geometry **(figure 2a).** Some have a reduced active area, achieved by electrostatic focusing, which can be an advantage in the detection of very weak light sources **(figure 2b).** Special photocathode geometries, **(figures 2 c,d and e),** have been introduced for large volume, extended area and large solid angle applications.



a) circular
Range of diameters available to suit diffuse and directly coupled light sources.
Application: General purpose; scintillation.

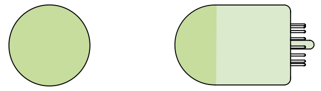


b) reduced
Electrostatically reduced diameter for minimum dark count..
Application: Photon counting; laser light detection.

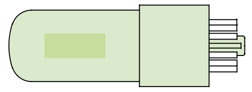


c) domed window
The inherent strength of this construction allows us to use a very thin, and consequently low radioactivity window. The window is often supplied shot blasted to enhance quantum efficiency.
Application: astronomy, high energy physics

d) 2π
Side wall sensitivity allows wide angle detection.
Application: Probes for scintillation counting



e) hemispherical
For diffuse light sources, e.g. arrays of photomultipliers.
Application: Fundamental scientific research.



f) side window
Matches exit slit, for example, of prism/grating monochromator. The photocathode, is a reflective type located within the glass envelope.
Application: Spectrophotometers and photometers.

figure 2
Various photomultiplier geometries are available and the light sensitive areas are shown in a darker colour; a) through e) are end window types. f) is a side window type where the photocathode is separate from the envelope.

Side window photomultipliers **(figure 2f)** have the photocathode deposited on a metallic substrate mounted within the envelope. These have a rectangular area 24x8 mm

3.2. Window material

The optical transmission of the window influences the spectrum of light reaching the photocathode. The window material is particularly important when measuring ultraviolet light. Certain applications, such as low level scintillation counting, also require window material free from naturally occurring radioactive contaminants. Photomultipliers are manufactured with the following window materials.

borosilicate glass This is suitable for incident light of wavelength greater than 300 nm and is the standard glass used. For critical applications, low background borosilicate glass is also available.

ultraviolet glass (W) this extends the sensitivity down to185 nm.

quartz (Q). made from fused silica, this material transmits down to 160 nm and has the added advantage of low radioactive background.

magnesium fluoride (MgF_2) transmits ultraviolet radiation down to 115 nm and is free from radioactive contaminants.

sapphire (S) Al_2O_3 is used in metal-ceramic photomultipliers for harsh environments. It has good ultraviolet transmission and low background.

The light transmission properties of these materials are shown in **figure 3.**

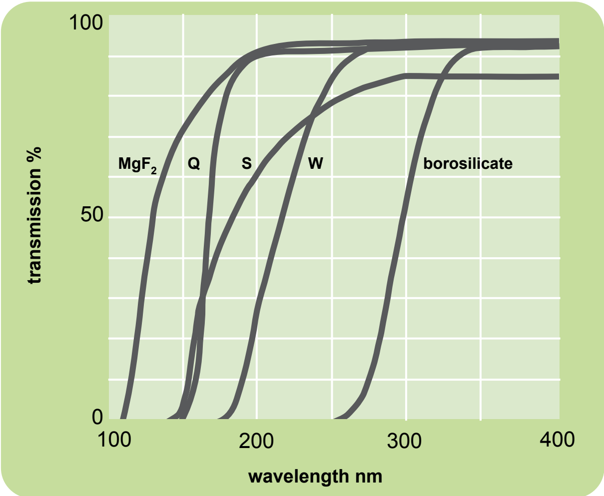


figure 3 Typical ultraviolet transmission curves for windows used in the manufacture of ET Enterprises photomultipliers. The window material used for metal ceramic photomultipliers is sapphire, S.

3.3. Photocathode types

Photocathodes can be manufactured from a variety of compounds and each type has a characteristic spectral response. The best choice is usually the one with the maximum response over the wavelength region of interest.

There are other considerations, such as operation at high light levels, and dark current, which are covered in detail elsewhere. **(See table 5.3(a) page 10** and **figure 23 page 15).**

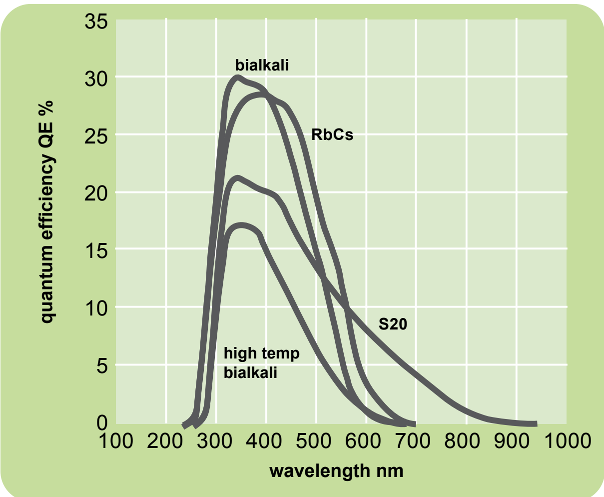


figure 4a Spectral response curves for various photocathodes deposited on borosilicate glass. The naming of photocathode types is historical. Measured values of QE against wavelength can be provided, at extra cost.

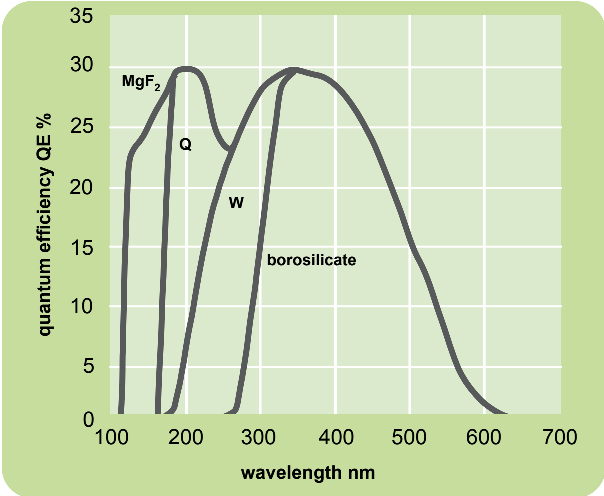


figure 4b Response to uv light can be increased by choosing the apppropriate window material. This is illustrated for the bialkali photocathode.

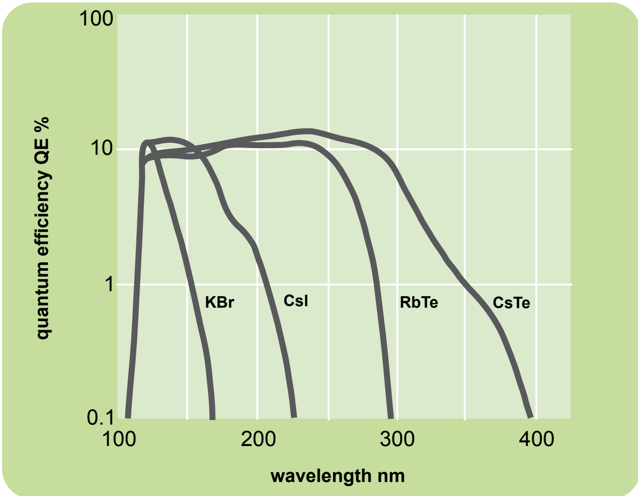


figure 4c Solar blind photocathodes deposited on MgF_2 are sensitive to uv light only.

Photocathode materials and designations used in ET Enterprises photomultipliers are:

solar blind (KBr, CsI, RbTe, CsTe) these photocathodes are sensitive to vacuum-ultraviolet and ultraviolet light only – hence the terminology. The long wavelength response for KBr and CsI cuts off at 200 nm while RbTe and CsTe extend to 350 nm.

high temperature bialkali (NaKSb) recommended for operation at high temperature because of its very low dark current. This photocathode also finds application in low level light detection.

S11 (SbCs) one of the earliest photocathodes with a spectral response covering the ultraviolet and visible range.

bialkali (SbKCs) this photocathode has mostly superseded the S11, offering better blue response and lower dark current.

rubidium bialkali (RbCsSb) offers high blue and enhanced green response but with twice the dark current of the bialkali.

S20, trialkali or multialkali (NaKSbCs) the multialkali photocathode response extends from uv to the near infra-red. It has high light level capability but may require cooling to reduce dark current.

3.4. Photocathode sensitivity

Photocathode sensitivity describes the conversion efficiency for photons into photoelectrons; the relationship between photocathode sensitivity and wavelength is called the spectral response. The terms quantum efficiency, radiant sensitivity, luminous sensitivity are used to specify photocathode response. The optimum way of quantifying a photocathode depends on the application. The terms used and their inter-relationships are discussed below.

quantum efficiency: $\eta(\lambda)$ or QE%

$\eta(\lambda)$, the quantum efficiency at wavelength λ is the average photoelectric yield per incident photon and is normally expressed as a percentage. It is the most fundamental unit concerning the performance of the photomultiplier. Important practical considerations such as resolution, signal/noise ratio and detectivity are all related to quantum efficiency.

radiant sensitivity (responsivity): $E(\lambda)$

Radiant sensitivity is defined as the photocathode current emitted per watt of incident radiation at wavelength λ and is expressed in mA/W. It is related to quantum efficiency in the following way

$$E(\lambda) = \frac{\lambda\eta(\lambda)}{1.24} \quad mA/W \qquad ...(1)$$

provided that λ is expressed in nanometres.

For example, a QE of 25% at 400 nm is equivalent to a radiant sensitivity of 80.7 mA/W.

luminous sensitivity: S

S is the most relevant specification for light sources which have a spectral response corresponding to that of the human eye. The human eye is sensitive to electromagnetic radiation between 400 and 760 nm and its relative luminous efficiency $V(\lambda)$ has been agreed internationally.

A tungsten filament lamp operated at a colour temperature of 2856 K, is used as the light source. This approximates to a black body radiator at the same temperature and has a known radiant power spectrum $I(\lambda)d\lambda$ W/m. The relationship between the photocathode luminous sensitivity S, $\eta(\lambda)$, $I(\lambda)$ and $V(\lambda)$ is as follows :

$$S = \frac{10^3 \int_0^\infty I(\lambda)\lambda\eta(\lambda)\,d\lambda}{1.24 x 680 \int_0^\infty I(\lambda)\,V(\lambda)\,d\lambda} \quad \mu A/lm \qquad ...(2)$$

For a particular photocathode, S is calculated from measured values of $\eta(\lambda)$ and tabulated values of $I(\lambda)$ and $V(\lambda)$ by integration.

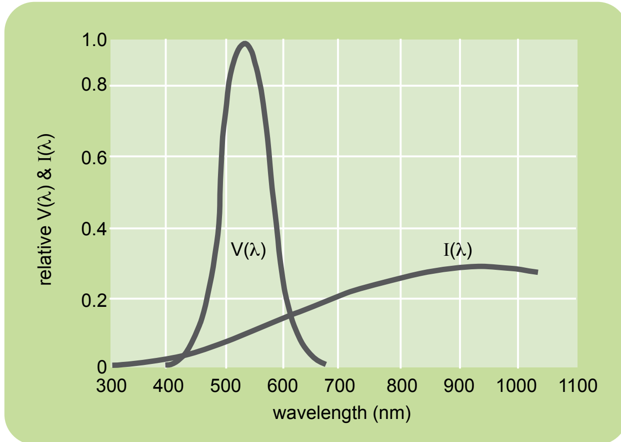


figure 5 Relative luminous efficiency of human eye $V(\lambda)$ and radiant power of a tungsten filament lamp operated at 2856 K.

The luminous sensitivity specification has been adopted by all photomultiplier manufacturers. Values of S range from 20 μA/lm to over 400 μA/lm, depending on the photocathode type. For this test the lamp output is adjusted to 1 millilumen and approximately 80% of the photocathode area is illuminated.

filter measurements (CB, CR, IR)

It is clear from (2) that S is derived by integrating terms which are wavelength dependent, with a high contribution coming from long wavelengths. Luminous sensitivity figures cannot, therefore, be used to compare photocathode types with appreciably different spectral responses. In other words, because it refers to white light, S is not always a good selection parameter. By using specific colour filters placed between the standard light source and the photomultiplier the usefulness of S measurement has been extended. For practical purposes photocathodes are thus individually characterised by noting the response to filtered light from a white light source. The filters used are standard throughout the industry with transmission characteristics selected to match the entire range of photomultiplier applications. The filters characterised in **figure 6** reflect the fact that photomultiplier applications tend to divide into: blue light; red light and infra-red light. Filter measurement results are recorded on the test ticket supplied with each tube, as illustrated in **figure 13, page 9.**

Grading and selection with these filter measurements has become standard practice. The filters of **figure 6** are specified as follows:

3. The photocathode

corning blue (CB)

A Corning CS-5-58 filter, of half stock thickness, is used for this measurement. CB values range from about 5 to 16 and are a useful relative measure of sensitivity for sources emitting in the blue region of the spectrum. This filter is most relevant to photomultipliers with bialkali photocathodes.

corning red (CR)

A Corning CS-2-62 filter provides the CR value and is appropriate for selecting photomultipliers intended for sources emitting in the red and near IR regions of the spectrum.

infrared (IR)

A Wratten 87 filter is used to select S20 photocathodes for applications requiring response in the IR region of the spectrum.

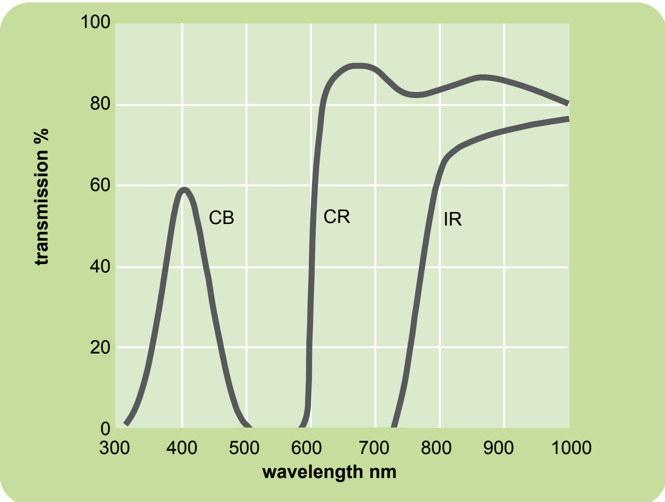


figure 6 *Filter transmissions.*

cathode QE% measurement

ET Enterprises has spectral response equipment which provides tabulated values of quantum efficiency and radiant sensitivity traceable to standards calibrated at the National Physical Laboratory, England. Spectral response is measured with 360 V between k and d_1 and with all other electrodes connected to d_1. Approximately 80% of the photocathode area is illuminated for this test.

This calibration is available to customers as an option. Values can be provided at any wavelength which is a multiple of 10 nm within the range 110 nm to 1100 nm.

The calibration also provides values of S, CB, CR and IR.

effective diameter and uniformity

The effective cathode diameter is governed by the inner diameter of the glass envelope and the electron optical design (refer to data sheets for nominal values). The photomultiplier output is examined using a flying spot scanner to check uniformity as illustrated in **figure 7.** Ideally, the output from the photomultiplier should be independent of the point of illumination on the photocathode but in practice there is variation over the active surface. This arises from:

spatial variation in the sensitivity of the photocathode, particularly in the side window types

variation in the angle of incidence and point of impact of photoelectrons on the first dynode, resulting in variation of secondary electron emission

Some photomultipliers include a focus electrode to allow individual trimming of overall uniformity. The optimum $V(f\text{-}d_1)$ and $V(k\text{-}d_1)$ settings are included on the test ticket. In critical applications, diffusing the incident light over the photocathode may be beneficial. ET Enterprises can provide photomultipliers with a shot blasted entrance window to special order.

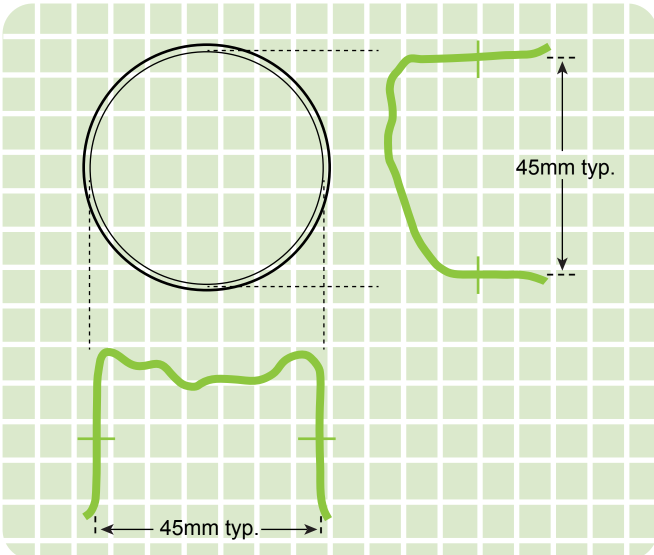


figure 7 *Typical flying spot uniformity scans for a 52mm photocathode. The spot size is 2mm.*

4. The electron multiplier

The electron multiplier is a very low noise, high gain, wide band amplifier with the capability of providing an output compatible with the input sensitivity of commercial instrumentation. The attributes of the range of structures and active surfaces that are used in ET Enterprises photomultipliers are discussed in 4.2.

4.1. The input region

Photoelectrons must be accelerated and focused onto an active area of the first dynode. The design of the $k\text{-}d_1$ region has been optimised to maximise the collection of photoelectrons from the entire photocathode area, as illustrated in **figure 8.** Some photomultiplier types have a separate focus electrode in the $k\text{-}d_1$ region which can be used:

to maximise the photomultiplier output from non-uniform light sources.

to gate the photomultiplier on or off [1)]

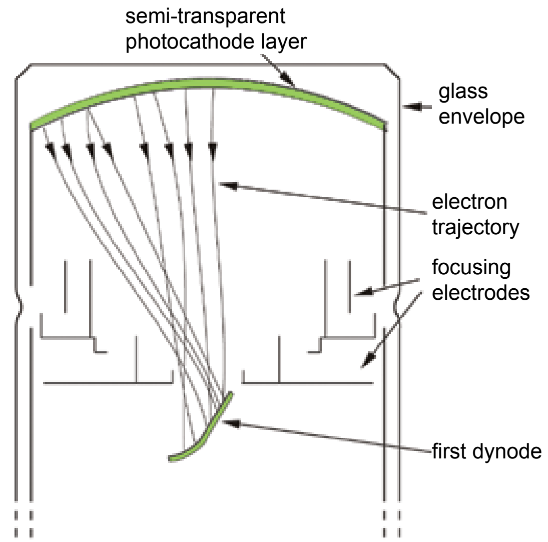


figure 8 *Photoelectron trajectories between photocathode and first dynode.*

4.2. Types of multiplier structure

A number of multiplier structures is available. Generally the various structures represent a compromise between physical size and electrical performance, particularly with reference to gain, timing, linearity, and immunity from external magnetic fields. **Table 4.2** summarises these attributes and indicates the relative merits of individual structures.

type	size most compact	gain max	timing fastest	linearity best	magnetic immunity best	ap(t) lowest
LF	●●●	●●●●	●●●	●●●●	●●	●●●
CF	●●●●	●	●●●●	●●●	●●●●	●
BG	●●	●●	●	●	●	●●●
VB	●	●●●	●●	●●	●●●	●●●●

table 4.2 *Ranking of the attributes of the multiplier structures where ap(t) is the afterpulse rate*

4.3. Secondary emission surfaces

Two secondary emitting surfaces are available – oxidised beryllium copper (BeCu) and caesiated antimony (SbCs).

In some cases there is a choice of dynode material available. The choice is governed by the nature of the application. The principal properties are summarised in **table 4.3.**

dynode material	gain max	linearity best	stability highest	rate effect lowest
SbCs	●●●●	●●	●●●●	●●●●
BeCu	●	●●●●	●●	●

table 4.3 *Performance differentiators of secondary emission surfaces*

4.4. Gain

Gain in a photomultiplier is derived by current amplification. Each dynode amplifies the incident electron current and the overall gain is given by the product of the individual dynode contributions. With many stages of gain, a small photoelectric signal is amplified to a measurable level. Denoting the gain of the first dynode as δ_1, and so on, the final current at the anode, for a photomultiplier with n dynodes is

$$I_a = \delta_1 \delta_2 \ldots \delta_{n-1} \delta_n I_k \qquad \ldots(3)$$

or

$$I_a = G\, I_k \qquad \ldots(4)$$

where I_k and I_a are the photocathode and anode currents, respectively. G is the photomultiplier gain. The gain of each dynode is related to the energy of the incident electrons; and hence to the inter-dynode voltage. The gain of the first dynode is shown in **figure 9** for both BeCu and SbCs surfaces. The gain of each dynode in the photomultiplier follows a similar curve

In general, a single high voltage power supply is used, with a resistive voltage divider network, to provide suitable inter-electrode voltages. The more dynode stages in the photomultiplier, the higher is the gain at a specific overall applied voltage and the higher the maximum gain attainable. This is illustrated in **figure 10. It should be noted that gain figures and curves are obtained with a particular voltage distribution specified by the manufacturer. The gain curve isdifferent if the voltage distribution is different from that specified.**

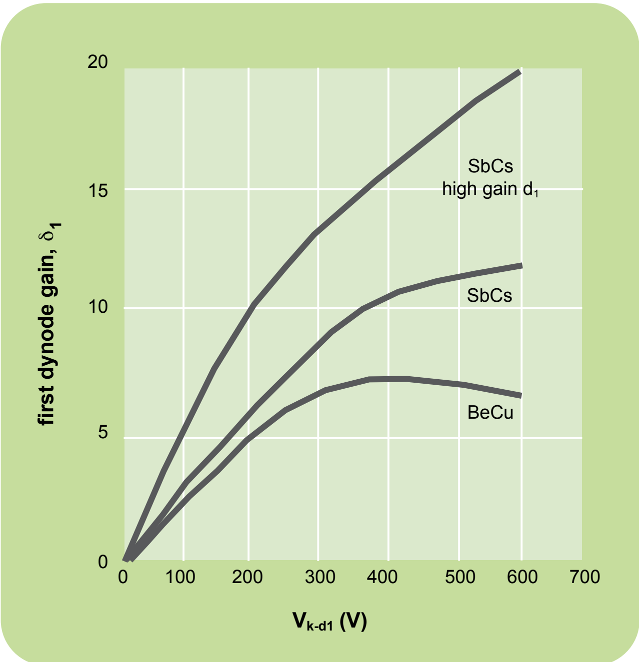


figure 9 *Variation of first dynode gain, δ_1, with k-d $_1$voltage.*

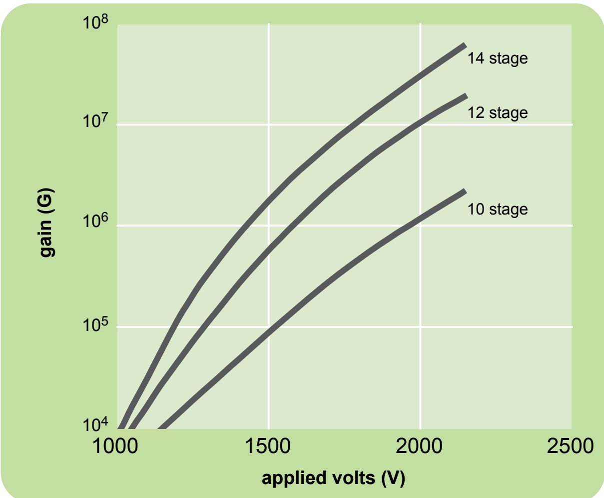


figure 10. *Variation of photomultiplier gain G with applied voltage, illustrating effect of number of dynode stages.*

4.5. Anode sensitivity A/lm

The voltage required to attain the specified anode sensitivity is recorded on the test ticket. Specified in this way the output is referred to the cathode sensitivity, S, quoted in µA/lm. The gain can be derived from this and S by using the following relationship:

$$G = \frac{\text{Anode Sensitivity (A/lm)}}{\text{Cathode Sensitivity (µA/lm)}} \times 10^6 \quad \text{...(5}$$

ET Enterprises specifies the voltages required on each photomultiplier to achieve two fixed anode sensitivities (the nominal and the maximum) with inter-dynode voltage distributions as specified in our **photomultiplier data sheets.** It is sometimes useful to construct a gain-voltage curve using these two points on log-log paper.

4.6. Anode equivalent circuit

The equivalent circuit for a photomultiplier is an **ideal current source** in parallel with an output resistance R_0 ($>10^{12}\Omega$) and capacitance C_0(<10 pF). The measured output depends on the load resistance R_L and capacitance C_L in combination with R_0 and C_0.

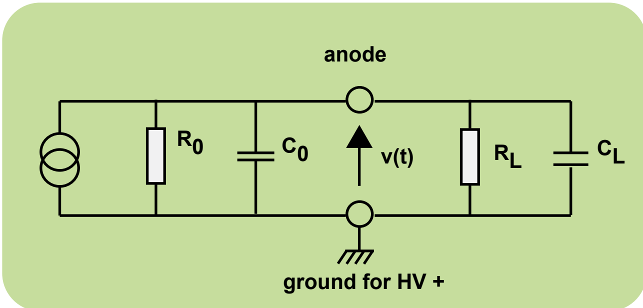


figure 11 *The equivalent circuit for a photomultiplier.*

The equivalent circuit applies to both dc and pulsed applications. In the case of pulsed light sources, the nature of the output signal depends upon the time profile of the input. Many applications involve light sources with an exponential profile. The following analysis is useful to determine the amplitude and the timing profile for such input stimuli.

4. The electron multiplier

The time constant of the circuit is: $\tau = RC$, where:

$$R = \frac{R_0 R_L}{R_0 + R_L} \quad \text{...(6)}$$

and

$$C = C_0 + C_L$$

Consider the output voltage response to a light source which decays with a single exponential time constant, τ_s,

then: $$i(t) = \frac{N\,e\,G\,\exp(-t/\tau_s)}{\tau_s} \quad \text{...(7)}$$

and: $$v(t) = \frac{N\,e\,G\,R\,[\exp(-t/\tau_s) - \exp(-t/\tau)]}{\tau - \tau_s} \quad \text{...(8)}$$

where:

N is the number of photoelectrons in the light pulse,
e is the electronic charge,
G is the photomultiplier gain.

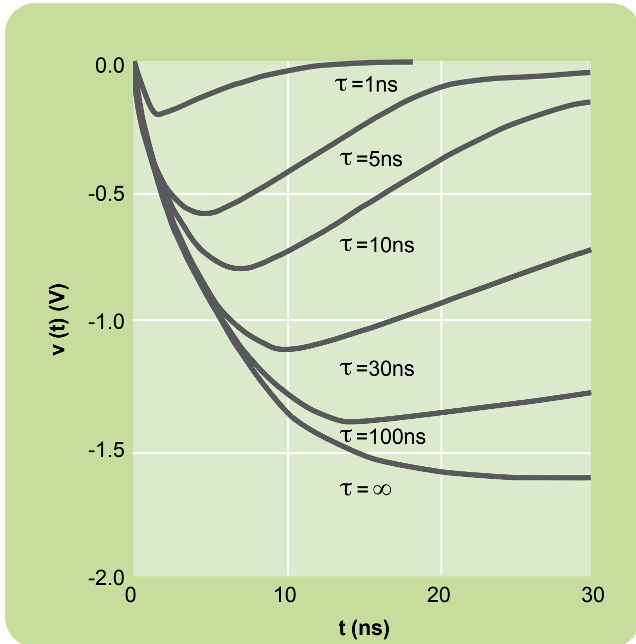


figure 12 *The output v(t) for various time constants, assuming N = 100, G = 1 x 10^6, τ_s = 5 ns, C = 10 pF*

By inspection of (8), the output voltage is a faithful representation of the input current when $\tau << \tau_s$ and this is referred to as **current mode operation.** **Voltage mode operation** applies with $\tau >> \tau_s$, in which case the pulse height in volts is proportional to the total input charge. For high or variable pulse rates there is a danger of overlap, in voltage mode operation. It is usual practice to use a value of $1/\tau$ less than one quarter of the event rate to avoid pulse pile up effects. In pulsed light applications, the choice of τ depends principally on the characteristic decay time of the light source and the anticipated event rate. For example, in Na(Tl) applications, where τ_s = 230 ns, choosing τ = 1 µs ensures good integration of the signal while permitting event rates of up to about 50 kHz, before the onset of serious pile-up effects.

In the extreme case $\tau \rightarrow \infty$,C integrates the charge and the output rises with a time constant τ_s and remains there:

$$v_0(t) = \frac{N\,e\,G}{C}\,[\exp(-t/\tau_s) - 1] \quad \text{...(9)}$$

There are applications where the output is not pulsed but it varies unpredictably with time. In film scanning for example, a transition from light to dark gives a step change in output, measured in microseconds. Here the consideration is one of choosing the output time constant to match the fastest anticipated transition, while simultaneously providing some smoothing of unwanted statistical fluctuations. For example, if the fastest transition t_r has a time constant of 1 µs, and, if $(C_0 + C_L)R_L$ is chosen to be < 3×10^{-7}, the output circuit will reproduce the transition quite faithfully. For R_L = 10kΩ, for example, $(C_0 + C_L)$ needs to be ≤ 30pF. With this time constant, transitions faster than 100 ns will not be followed.

Photomultipliers are high gain, wide bandwidth optical detectors and as with all sensors, limitations apply to the quality of performance with regard to:

maximum gain (sensitivity)
time or frequency response
linearity of response
dark current
stability and hysteresis
noise-in-signal

5.1. Maximum voltage and sensitivity

The photomultiplier must not be operated beyond the maximum specified overall sensitivity.
Beyond this limit, feedback effects may become significant, resulting in unstable performance and high dark current with the possibility of breakdown under extreme conditions. Permanent damage will occur if the photomultiplier suffers breakdown. The sensitivity limit is determined by the maximum allowable gain of the multiplier, which depends on the type of multiplier structure. The maximum allowable inter-electrode voltages are determined by the spacing of the electrodes in the photomultiplier. Excessive voltage causes electrical breakdown, and this must be borne in mind in voltage divider network design (Section 8). Similarly, the maximum allowable overall voltage is limited to less than the sum of the stated maximum inter-dynode voltages. Maximum allowable inter-electrode voltages are given for each tube type in the photomultiplier data sheets.

A test ticket, an example of which is shown in **figure13,** is supplied with every photomultiplier. This includes two overall voltage figures. The **nominal sensitivity,** and the overall volts required to attain this, is the recommended operating condition. The **maximum overall sensitivity,** and the overall voltage at which this is achieved, refers to the maximum gain beyond which the pmt should not be operated. These voltages are measured using the standard voltage divider distributions quoted in our data sheets. If a voltage distribution other than that used by ET Enterprises is chosen, the overall voltage required to achieve the maximum overall sensitivity will be different.

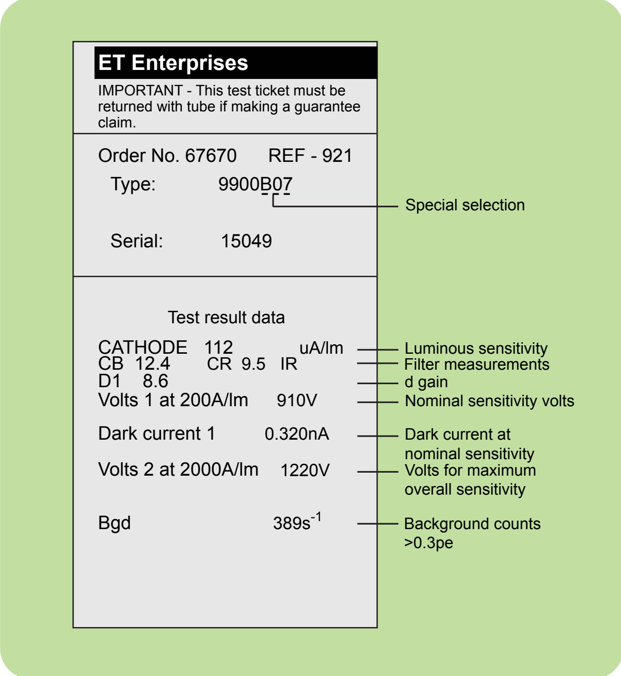


figure 13 Sample photomultiplier test ticket. Parameters are measured using standard voltage dividers.

5.2. Time response

The response of a photomultiplier to a delta pulse of light is governed by the electron trajectories within the tube. Photoelectrons created by the light pulse follow individual paths to the first dynode, depending on their point of origin on the photocathode and on their emission velocities. It follows that they land on the first dynode at different points and at different times. Secondary electrons travel individual paths between dynodes, causing further time dispersion.
A photomultiplier output pulse is characterised by:

rise time t_r

full width at half maximum t(fwhm)

transit time t_t

These parameters are defined in **figure 14.**

Bandwidth is not a parameter usually quoted for photomultipliers, although it can be derived from the approximate formula:

$$\Delta f\,(3dB) = \frac{1}{3t_r} \quad H_z \qquad ...(10)$$

The variation in transit time from one light pulse to the next is a critical parameter when using photomultipliers to detect the time occurrence of events. The standard deviation, σ, derived from a large sample of such events is known as the transit time jitter (sometimes the fwhm of the distribution, equal to ~2.35 σ, is quoted as the transit time jitter).

5. Limits on performance

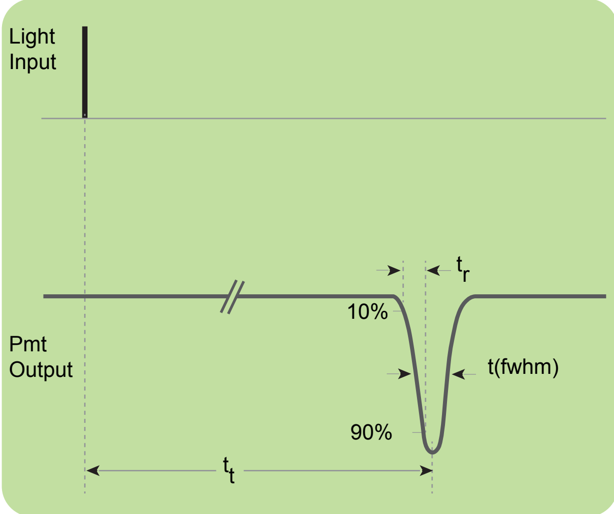


figure 14 Illustrating photomultiplier time response (rise time, full width at half maximum, transit time).

Photomultipliers with plano-concave windows and linear focused or circular focused multipliers give the best time performance. Other factors affecting timing include:

i) the number of dynodes. Fewer stages give better timing.
ii) the overall voltage. Higher field strengths improve timing. The best timing is attained with high k-d_1 voltage, with operation at the maximum recommended gain. The time response varies approximately as $1/V^{1/2}$.
iii) the photocathode diameter. Smaller diameters have better timing. The best timing is achieved when illuminating the central area only.

structure	transit time (ns)	rise time (ns)	transit time jitter (σ) (ns)
VB	40-110	8-15	2.2-5.7
BG	50-80	12-18	4.2-6.4
CF,SW	20-35	1.5-2.5	0.5-1.0
LF	20-55	1.8-2.7	0.5-1.2

table 5.2 Timing performance of ET Enterprises photomultipliers. Transit time jitter figures refer to single photon excitation.

5.3. Linearity and maximum currents

a) direct current limits
High, mean, anode currents cause fatigue effects and reduced photomultiplier lifetime; the maximum mean anode current should be less than 100 μA and more stable performance is achieved by operating below 10 μA. With correct voltage divider design all multiplier structures are linear, within one percent, up to anode currents of 100 μA. Limits on maximum photocurrent also apply, governed by the resistivity of the photo-sensitive layer. Exceeding these limits results in non-linear performance. Side window photomultipliers, with a metal substrate supporting the photosensitve layer, can sustain much higher currents than end window types. Photocurrent limits are given in **table 5.3(a).**

cathode type	I_k (nA/cm^2)
biakali	2.5
high temperature bialkali	2.5
S1	5
S11, RbCs	15
S20	250
Side Window	5000

table 5.3 (a) Maximum cathode currents at 20°C.

b) pulsed anode current limits
Pulsed anode currents greater than 100 μA can be drawn with the proviso that the mean anode current, averaged over one second, is below 100 μA. The photomultiplier output current will be linear with respect to light input until the onset of space charge effects. The current at which non-linearity first appears depends on the type of multiplier structure and on the operating conditions. Linearity can be improved with a voltage divider distribution which has higher inter dynode voltages on the later stages. Linearity also depends on the dynode secondary emitting surfaces as detailed in **table 5.3(b).** Recommended divider distributions are given in Section 8.

Linearity measurements are made using two LEDs and a double pulse generator. Two pulses are applied with the second delayed with respect to the first (individual outputs). Then the two pulses are applied in coincidence (summed output). Non-linearity becomes evident when the summed output pulse differs from the expected sum of the individual pulses.

dynode structure	peak anode current (mA) at $V_{d\text{-}d}$ = 100 V dynode surface CsSb	BeCu	at $V_{d\text{-}d}$ = 300 V dynode surface CsSb	BeCu
LF	30	50	100	150
CF	10	20	30	50
VB	2	4	5	20
BG	0.1	0.2	0.5	1

table 5.3 (b) peak anode current for which there is 5% departure from linear operation. $V_{d\text{-}d}$ is the inter dynode voltage

5.4. Noise, dark current and dark count

For the purpose of analysis it is convenient to categorise photomultiplier applications as

continuously variable (sometimes referred to as dc)
or
pulsed.

A film scanner is a good example of dc: the intensity of the light reaching the photomultiplier is continuously variable over a wide dynamic range and is subject to sudden transitions in level.

The required bandwidth of the associated output circuit and electronics may be 3 MHz in order to follow these fast transitions. The output produced by a NaI(Tl) crystal has a characteristic time of 230 ns, and between events, the photomultiplier output is ideally zero. This is an example of pulsed operation.

The purpose of this section is to examine how statistical fluctuations and photomultiplier dark current contribute to non-ideal performance in the two modes of operation above. An understanding of this will ultimately lead the user to the achievement of best performance through both selection of a tube with the right parameters and operating the chosen device optimally.

Consider a light source which remains constant in intensity, over a period of seconds. If the anode output is observed on an oscilloscope, it will be noticed that the trace will always have some fluctuation superimposed upon it. There are two sources causing the fluctuation illustrated in **figure 15:**

dark current contributions

statistical noise-in-signal effects

The nature of, and the contributions from, dark current are discussed in section 5.5 while statistical effects are considered in the next section, noise.

In the pulsed mode of operation, the consideration is: how faithfully the photomultiplier preserves the pulse height information. In other words, what variation from one pulse to the next can be expected from a light source giving nominally the same output in each light pulse. **Figure 16** is a snap-shot of the output from a photomultiplier illuminated from a steady pulsed light source, in this instance an LED. The statistical contribution to the pulse-to-pulse variation can be predicted approximately from (11) and more correctly, from (14).

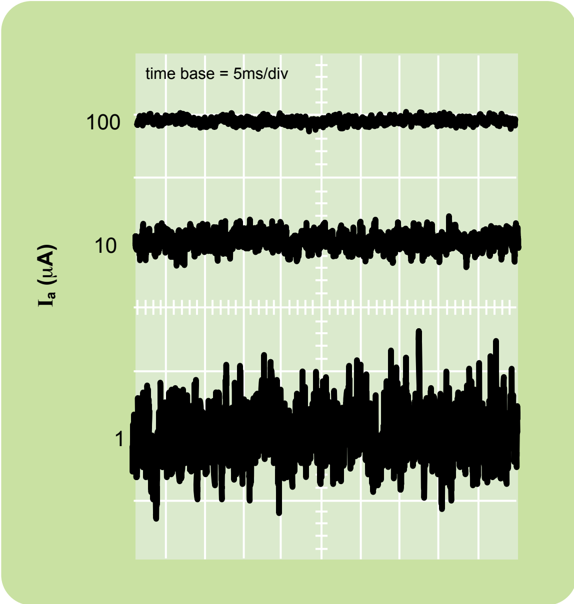


*figure 15 dc detection: illustrating the output signal for three different levels of illumination; measured at g = 10^6. The rms noise contribution can be predicted by using the chart in **figure 18.***

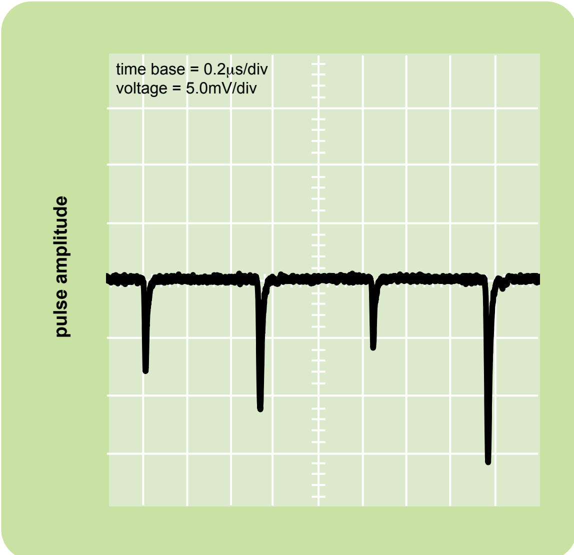


figure 16 Pulsed Operation. The output from a photomultiplier viewing a pulsed light source set to give 100 photoelectrons, average, per pulse. The fluctuations in size from one pulse to the next are an inescapable manifestation of noise.

A fluctuation in area under each pulse and a fuzziness of the trace is apparent. As before, the two sources of fluctuation contribute. A multichannel analyser can be used to measure the area of each pulse assigning it to a specific memory location. The result of analysing a a sequence of pulses shown in **figure 16** is displayed as a spectrum in **figure 17.**

5. Limits on performance

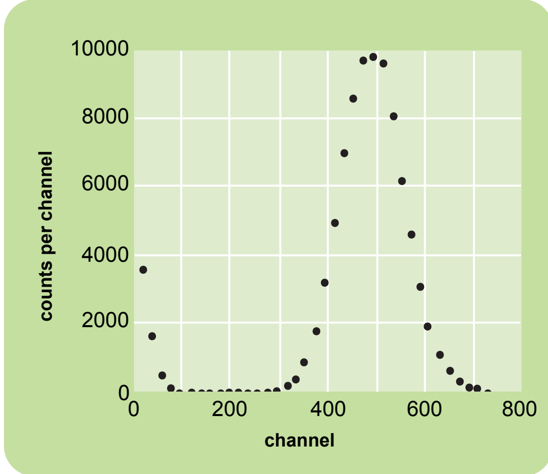


figure 17 A pulse height distribution measured with a multichannel analyzer (MCA). When the photomultiplier measures a pulsed light source of constant intensity, there is variation in pulse height from one pulse to the next.

noise
In common with the measurement of all physical processes, repeated measurement does not always give exactly the same value. In the photomultiplier the variation in output signal is related to the statistical fluctuation in the number of photoelectrons created (photoelectron noise). There is an additional contribution from the statistical variation in the number of secondary electrons created per incident electron on each dynode (multiplication noise). These effects yield expressions for signal-to-noise ratio, (S/N), which can be applied to any detection system using photomultipliers.

photocathode noise
Consider a steady light flux incident on the photocathode producing M photoelectrons per second. The photoelectric effect is a quantum mechanical one and is subject to statistical fluctuations described by Poisson statistics. If the photomultiplier output is measured over a period of time T, there will be an average of MT photoelectrons produced. Based on Poisson statistics, the standard deviation associated with MT is $(MT)^{1/2}$. The signal-to-noise ratio is

$$S/N = \frac{MT}{(MT)^{\frac{1}{2}}} = (MT)^{\frac{1}{2}} \qquad ...(11)$$

If we assume that the gain of the multiplier is ideal, that is, not itself noisy, then at best the output signal will have the fluctuation of (11) imposed on it. Equation (11) explains the origin of noise-in-signal; in this form it is useful for predicting quantitative performance in pulsed applications. For continuously variable applications, the effect must be treated in a different way by taking account of the bandwidth of the measuring electronics rather than the sampling time T.

The shot noise formula relates T to the inverse of the bandwidth through the Fourier transform and predicts the noise on a cathode current of I_k as:

$$(\overline{i_k^2})^{\frac{1}{2}} = (2\, e\, I_k \Delta f)^{\frac{1}{2}} \qquad ...(12)$$

Where for any parallel combination of load resistances R and capacitance C, Δf=1/4RC. Again, assuming ideal gain G, the S/N ratio is

$$S/N = \frac{I_k}{(\overline{i_k^2})^{\frac{1}{2}}} = \frac{I_k}{(2\, e\, I_k \Delta f)^{\frac{1}{2}}} \qquad ...(13)$$

Equation (13) is illustrated in **figure 18.**

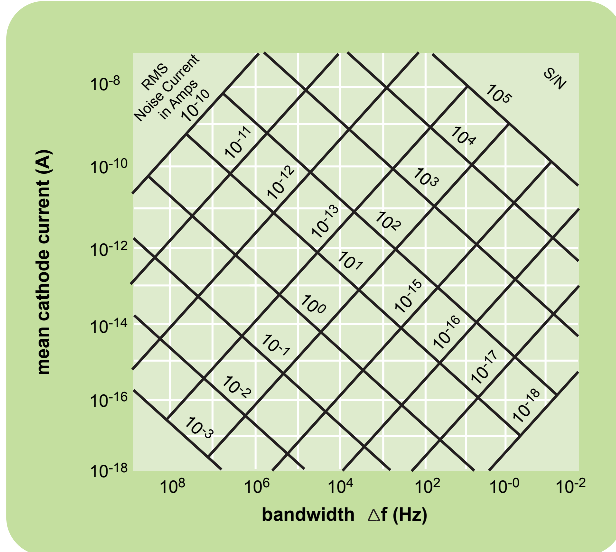


figure 18 Graphical representation of the shot noise formula. (If the multiplier noise is taken into account, the signal to noise ratio read off above should be multiplied by 1/a, as discussed in the multiplication noise section

Referring to a film scanning example, with Δf=3 MHz, if the requirement is S/N ≥ 100, then I_k needs to be >10^{-8} A. To put this in perspective, for a gain of 10^4, the associated anode current will be 100 μA.

multiplication noise
The signal-to-noise ratio is always less than predicted by equation (13) because the electron multiplier is non ideal. For every dynode there is a statistical spread in secondary emission coefficient around the mean value.

The statistical effect is of greatest importance at the first dynode, d_1, than at any subsequent dynode. This is because the number of secondary electrons, N, is relatively small at d_1 and hence subject to high fluctuation, $1/N^{1/2}$. As the cascade develops in the multiplier, it soon becomes statistically well defined since N increases rapidly at each subsequent dynode. For completeness, equation (13) must include an additional noise factor to allow for this multiplication noise.

Note (11) is unaffected (this in fact is one of the major attributes of photon counting) The equations become:

$$S/N = (MT)^{\frac{1}{2}} \qquad ...(14)$$

while (12) becomes

$$S/N = \frac{I_k}{(2\, e\, I_k \Delta f)^{\frac{1}{2}}} \; \frac{1}{a} \qquad ...(15)$$

where, for a multiplier which obeys Poisson statistics

$$a = \left[\frac{\delta}{\delta - 1} \right]^{\frac{1}{2}} \qquad ...(16)$$

This is a theoretical expression assuming Poisson statistics apply at each dynode of mean gain δ. However, in practice, the secondary emission process is poorly described by the simple statistical model assumed in (16). The measured output pulse height distribution for a photomultiplier excited by single photons (and hence single electrons at d_1) does not conform to the predictions of (16). The resolution is broader and there is an excess of small pulses in the distribution; see section 5.7. Examples of actual single electron distributions are shown in **figure 19.**

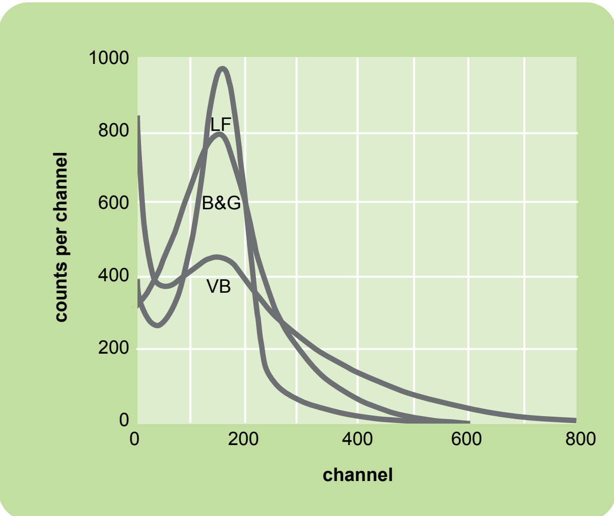


figure 19 Single photoelectron pulse height spectra for various photomultiplier structures taken with a charge sensitive multi-channel analyzer (equal area curves). Channel number can also be expressed as gain or charge.

Noise factors can be deduced directly from any measured single electron distribution by numerical calculation of the variance, var(g), of the multiplier gain g. Var(g) is related to the standard deviation σ, by var(g)= σ^2. Thus:

$$a' = \left[1 + \frac{var(g)}{\bar{g}^2} \right]^{\frac{1}{2}} = \left[\frac{\overline{g^2}}{\bar{g}^2} \right]^{\frac{1}{2}} \qquad ...(17)$$

tube type	$\sigma(g)/\bar{g}$	$\overline{g^2}/\bar{g}^2$	a'	δ_1	$(\delta_1/(\delta_1-1))^{\frac{1}{2}}$
6097	0.76	1.58	1.26	10	1.05
9814	0.52	1.27	1.13	16	1.03
9924	0.57	1.32	1.15	10	1.05

table 5.4 Calculated noise factors by applying (17) to the curves of figure 19. The entries for δ_1, in the penultimate column, are typical d_1 gain values for tubes of these types. The figures for a in the last column are calculated from (16).

The interpretation and practical use of these noise factors is straightforward. Referring to the 9814 photomultiplier, illustrated in **Table 5.4,** the S/N predicted by (11) and (13), which allows only for photocathode statistics, is further degraded by 1/1.13 or 0.89 by the action of the multiplier. A more detailed account of statistics and noise is given in the ET Enterprises Technical Reprint Series.

The statistical considerations given in the above paragraphs account for the noise on the traces shown in **figure 15** and explain why a pulsed light source giving a constant mean number of photons per pulse leads to an output distribution with finite width. However, to explain why the measured rms noise is always greater than predicted by (14) or (15), we need to examine the contribution from dark current, and dark counts.

5.5. Dark current and dark count

Output from a photomultiplier is obtained even in the absence of light input; this is referred to as **dark current** in dc applications and **dark count** in pulsed applications (also referred to as **background**).

If the dark current is observed on a chart recorder, a trace similar to **figure 20** will be obtained. There is variation around a mean value with large spikes superimposed at random times. Part of the fluctuation can be explained by contributions from shot noise, but to account fully, it is necessary to examine the sources which contribute to dark current. The dark current comprises a dc component (leakage current) plus a contribution derived from pulsed sources.

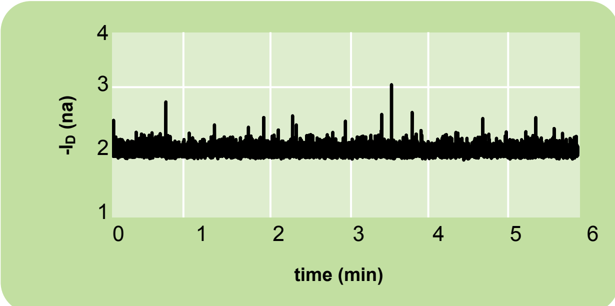


figure 20 Dark current from a 9829B pmt with a thin quartz window (at 2 x 10^7 gain).

5. Limits on performance

5.6. Dark count spectrum

The dark count spectrum depicted in **figure 21** shows a peak corresponding to the emmision of single electrons from the cathode. Pulse height has been scaled in photoelectrons equivalent, using the peak as reference.

The contribution i_q to dark current, from pulses in the spectrum of **figure 21** is given by integration of the curve where

$$i_q = \int_0^{\infty} n(q)\, q\, dq \qquad ...(18)$$

where n(q) is the number of pulses/sec with charge q. If I' represents the contribution from leakage currents flowing into the anode, due to applied biassing voltages on the dynodes, then:

$$I_D = I' + i_q \qquad ...(19)$$

where I_D is the measured dark current. For a detailed explanation of how I' is measured, the reader is referred to a technical publication on Photomultiplier Background [3]). Equation (19) provides an accurate description of dark current in photomultipliers and correctly predicts the relationship between dark current and gain.

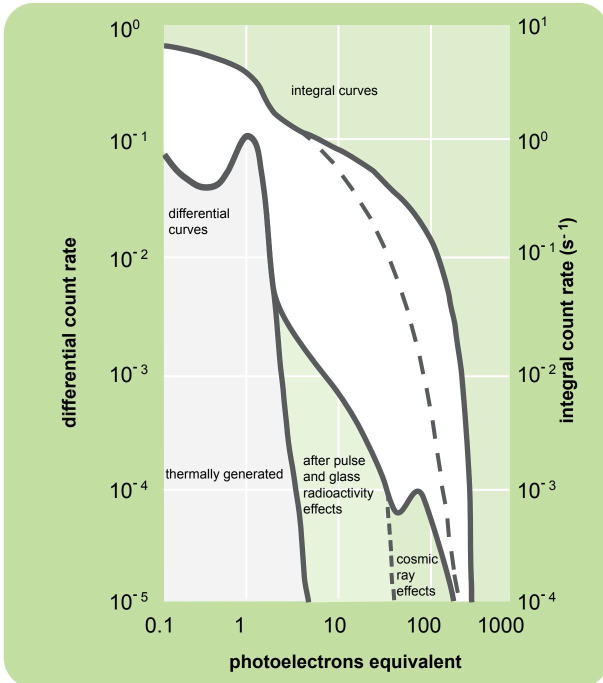


figure 21 Illustrating dark counts at 20°C in a 9813B as a function of pulse height. The differential curve normally obtained with a pulse height analyzer has also been integrated to provide count rate as a function of threshold. Data have been obtained at sea level (solid lines) and 30 metres underground (broken lines) to illustrate the contribution from cosmic radiation. Note the absence of the cosmic ray peak at about 100 photoelectrons equivalent, when underground.

Figure 22 illustrates a number of points of practical significance. The dark current is dominated by the leakage component at low gain. I' varies linearly with applied voltage while i_q varies linearly with gain.

This holds true until the onset of feedback at high gain where i_q starts to increase more steeply. For dc measurements, this suggests that for each tube there is a window of optimum performance for signal/background. In the photomultiplier characterised by **figure 22,** this is at a gain of 2x10^7. To find the optimum operating point it is sufficient to plot the ratio of signal (derived from a steady light source) to dark current, as a function of applied volts.

At low gain I_D is dominated by leakage. For optimum performance in low light level applications, operate the photomultiplier at high gain, but below the point a which dark current increases more rapidly than gain.

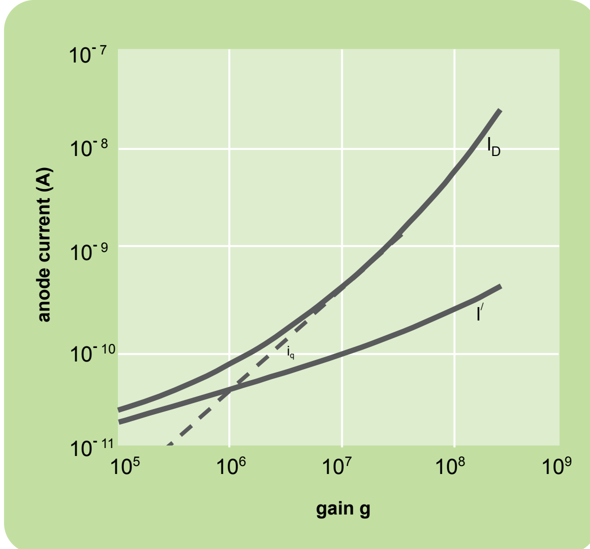


figure 22 Dark current I_D comprises a leakage component I' and a contribution i_q from dark counts. Note how the measurements predict the correct magnitude of I_D and its dependence on gain, g.

To summarise, the output from a photomultiplier when viewing a steady light source shows fluctuations which can be explained by:

contributions from statistical effects, referred to as noise-in-signal

contributions from fluctuations in the dark counts

The dark current or dark count varies considerably even amongst photomultipliers of the same type. ET Enterprises can provide photomultipliers selected for low dark current or dark count, to special order.

It should be noted that in dc measurements it is possible to back off the dark current but there is no way in which the fluctuations in dark current can be nullified. The fluctuations inherent in the signals shown in **figures 16 and 17** are due to statistical fluctuation in the number of photoelectrons in each pulse the fluctuation in gain for each pulse, and a contribution from the dark count spectrum. It is important to understand the sources of background which contribute to **figure 21.** Such knowledge helps explain why measured pulse height distributions deviate from ideal.

5.7. Sources of background

For the purpose of discussion it is convenient to divide the background pulse height distribution of **figure 21** into four regions: A, B, C and D.

Region A: Small pulses <0.5 photoelectrons equivalent. Small amplitude pulses occur in the signal and in the background. A proportion of these counts can be explained in terms of the statistical nature of photomultiplier gain. Contributions from thermionic electrons originating at the dynodes and secondaries generated from ion impact on the dynodes also contribute.

Region B: 0.5<B<2 photoelectrons equivalent. Contributions to this region are primarily caused by thermionic emission. However, on cooling the photocathode, a component attributed to natural radioactivity and other sources within the multiplier, remains.

Region C: 2<C<15 photoelectrons equivalent. Counts in region C are made up of afterpulses and from natural radioactivity in the window.

There is a finite probability that a signal or background pulse will be followed by a satellite or afterpulse. These are caused by ionisation of residual gases within the photomultiplier by the energetic electrons from the initial pulse. If the ion reaches the photocathode it is likely to cause a multielectron pulse; if intercepted by a dynode then a contribution to region A or B may result. Afterpulses are particularly undesirable in correlation studies or applications where temporal information is involved. The 9863B and 9130B ranges of photomultipliers provide performance with very low afterpulse rates.

Traces of naturally occurring ^{40}K, ^{238}U and ^{232}Th are present in all window material, although ET Enterprises selects special glasses to minimise these contributions. The decay of these isotopes produces light by Cerenkov radiation and electrons by direct interaction with the photocathode. More detailed information on low background considerations is given in section 5.9.

Region D: D>15 photoelectrons equivalent. These very large pulses are a direct consequence of the passage of cosmic rays (mainly muons and electrons) through the photomultiplier window. At sea-level this rate is about 15 per minute for a 51 mm diameter photomultiplier. Relativistic particles produce Cerenkov light emission in the windows. Since emission is biassed towards the uv, the quartz window variants give the largest pulse height. In each event, between 15 and 200 photoelectrons are produced depending on the window material, thickness and photocathode. In a typical event, the initial big pulse is followed by a series of single photoelectrons – up to 50 within a period of 100 μs.

5.8. Effect of cooling

At room temperature, the contribution from thermally generated electrons from the cathode dominates. The emmision rate depends on the temperature, the photocathode type and the area. In addition to thermal electrons, pulses occur in this region from the sources previously discussed, such as cosmic radiation, natural radioactivity and afterpulses. However, these are unaffected by temperature. **Figure 23** shows the effect of temperature on dark counts and the advantage of cooling in low level detection is obvious. For all cathodes shown, there is little advantage in cooling below -25°C.

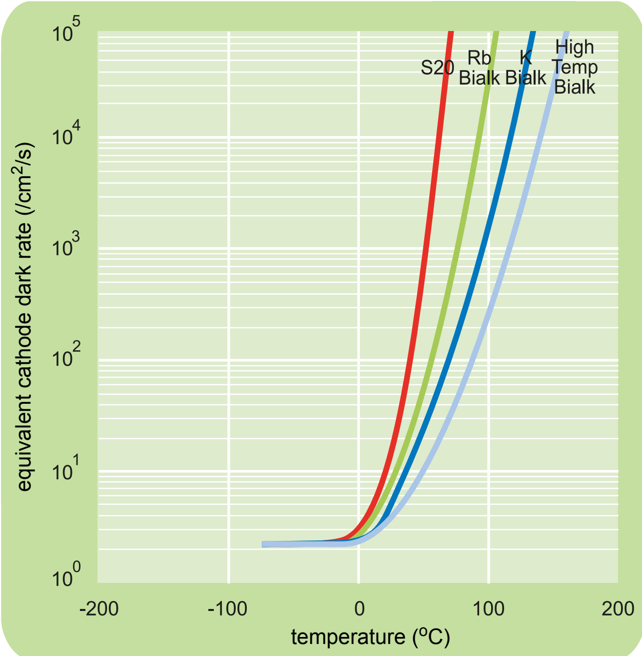


figure 23 *The dark counts from a photomultiplier as a function of temperature (above a threshold of 0.2 photoelectrons).*

5.9. Low background glass

ET Enterprises manufactures photomultipliers with low and ultra low levels of naturally occurring radioisotopes. Their use is recommended in low background scintillation counting, with both organic and inorganic scintillators. In these applications the interaction of the isotope decay products with the scintillator itself results in large amplitude signals.

Absolute levels of radionuclides, quoted in (ppm) or (ppb), are given in **table 5.9.** These figures refer to levels of activity in the window only. Although other parts of the photomultiplier contribute, the window is the major source. Total decays per minute given in the penultimate column, refer to the total number of γ rays of all energies from 5-2500keV. Note that there is a spectrum of accompanying betas as well.

To give some perspective to the magnitude of this source of background, the counts in a 75 x 75 mm NaI(Tl) crystal are presented for a selection of glasses offered. The last column in **table 5.9** gives an indication of the contribution to the count rate of a 75 x 75 mm Na (Tl) crystal in contact with the stated window material. The actual count rate in any particular arrangement depends quite critically on where the lower energy threshold is set, so these figures should be regarded as order of magnitude only.

material	k ppm	Th ppb	U ppb	total decays /minute	contribution counts /minute
standard borosilicate	< 60,000	< 1000	< 1000	< 400	< 100
low background	300	250	100	25	5
ultra-low background	60	20	10	5	1
quartz	< 5	< 5	< 5	< 0.3	< 0.1

table 5.9 *Background levels in photomultiplier windows. Decays per minute refer to a 50mm diameter window of weight 30g.*

5.10. Photomultiplier stability

The overall sensitivity of the photomultiplier is known to vary:

with operating time while maintaining constant illumination, applied voltage and ambient conditions.

on switching the output current, after removing and re-applying either the light input or overall voltage.

with change in ambient temperature and external electromagnetic fields. These environmental effects are discussed in section 6.

stability
The action of drawing anode current alters the secondary emission coefficient of the dynodes, in particular the later stages where current densities are highest. The slow variation of anode current with operating time is usually termed 'drift' and its magnitude depends on the dynode surface **(figure 24)** and on the mean anode current **(figure 25).**

The change in multiplier gain is not necessarily permanent; if the photomultiplier is switched off it will slowly recover its initial performance. Where stability is of prime importance, the recommendation is to maintain the anode current below 1 μA.

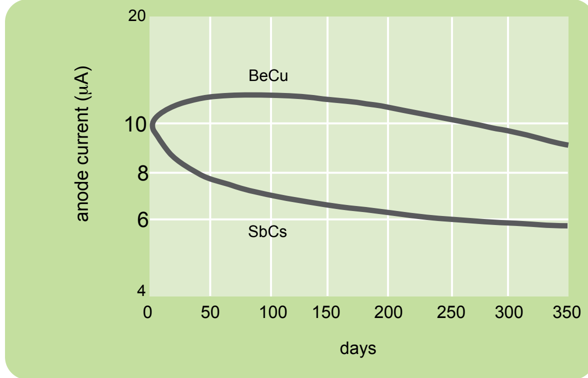


figure 24 *Sample stability curves for photomultipliers illustrating the different performance with BeCu and SbCs dynodes. The stability of individual tubes varies within the same type.*

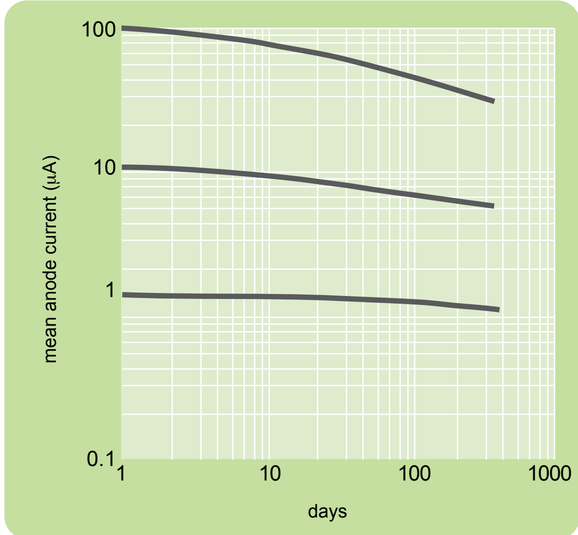


figure 25 *Illustrating long term stability (1 year) for SbCs dynodes as a function of mean anode current, under conditions of constant applied voltage and illumination.*

hysteresis
When a light source of constant intensity is interrupted and then re-applied, the photomultiplier may not immediately recover its previous anode current level. The effect shown in **figure 26** is attributed to charging effects within the photomultiplier which temporarily alter the photomultiplier gain.

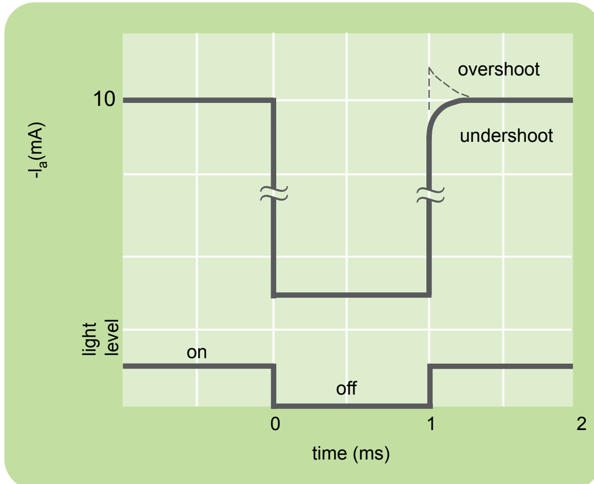


figure 26 (a) *Sample curves illustrating hysteresis effects after switching light input ON/OFF/ON. Photomultiplier type 9106B operated at 10^4 gain. The overshoot is of the order of 0.5%.*

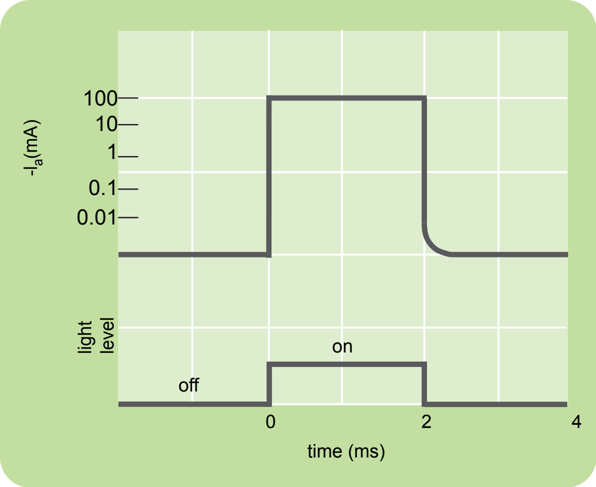


figure 26 (b) Sample curve illustrating memory effects after switching light input OFF/ON/OFF. Photmulitplier type 9781B operated at 10^5 gain

A similar effect may occur when the overall voltage is removed and then re-applied. The effect is more pronounced if the illumination is maintained during the off period. The magnitude of these hysteresis effects and the recovery time are determined by the mean current, the gain, the dynode surface and the multiplier structure. Linear focused variants, such as the 9102B, and side window types, have excellent recovery characteristics.

Rate Effect

In pulsed applications there is a hysteresis effect which produces a change in pulse height with count rate. It is not directly the count rate which causes the effect but the related changing anode current. Such an effect can be caused by poor voltage divider design but for the present we refer to an intrinsic dynode gain variation only. In Na (Tl) applications, a standard test is to change the position of a ^{137}Cs source on the axis of the scintillator producing at first pulses at a rate of 1000 s^{-1}, then pulses at 10,000 s^{-1} and observing the mean pulse height in each case. For the test to have any meaning, the gain must be specified. In high energy physics applications, count rates may increase to many MHz for short time durations.

The cause of rate effect is not fully understood but what is well established is that ET Enterprises SbCs dynodes offer far superior performance to BeCu dynodes. In photomultipliers with BeCu dynodes there will be gain changes at the 1% level for anode currents in excess of 1μA. With SbCs dynodes the level of performance is a factor of ten better under similar conditions. Where rate effect is critical, selection for this parameter is recommended

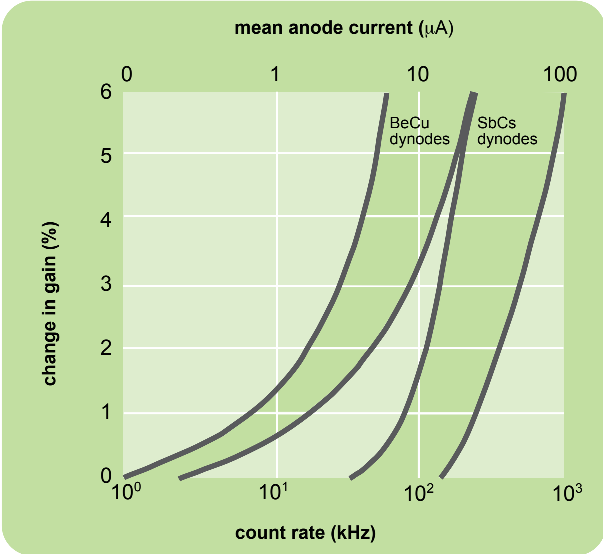


figure 27 The change in gain with increasing count rate is known as the rate effect. The gain change is related directly to the mean anode current, which in turn is a function of count rate. The rate effect is independent of gain. The hatched regions indicate the spread in this parameter from tube to tube of the same type.

5.11. Pulse height resolution

Pulse height resolution is an important, practical measure of the ability of a photomultiplier to reveal structure in spectral measurements. The source of the spectrum of pulse heights may be a Na (Tl) crystal excited by a mixture of isotopes, or some other light emitting process where peaks in the distribution have some physical significance. In both cases, the resolution, R, is by definition

$$R = \frac{fwhm}{peak\ position} \ x \ \ 100\ \% \qquad \text{...(20)}$$

where fwhm is the full width at half maximum height.

For a Normal distribution, the relationship between standard deviation, σ, and Resolution is:.

$$Resolution = 2.35\sigma \qquad \text{...(21)}$$

where σ is expressed as %

Equation 21 can be used with confidence for most practical distributions. A spectrum measured with a 9266B coupled to a 44 x 44 mm NaI(Tl) crystal is shown in **figure 28(a).** The peak in the distribution corresponds to the capture of the entire energy of the ^{137}Cs monoenergetic gamma-ray and is known as the photopeak

Applying the definition of (20) to this distribution gives a resolution of 6.9%. The complete capture of a ^{137}Cs gamma-ray in a NaI(Tl)/photomultiplier combination corresponds to about 5000 photoelectrons from the photocathode (a useful figure to remember is ~8 photoelectrons/keV for a 2" x 2" crystal). From the statistical arguments culminating in (14), taking the mean number of photoelectrons as ~5000, the expected resolution should be about half that measured. The explanation for this discrepancy lies in the intrinsic resolution associated with Na (Tl) crystals[2].

Figure 28(b) illustrates an application at the low energy end of the X-ray scale. The 5.9 keV X-ray from 55Fe corresponds to only ~80 photoelectrons and in this case the width of the distribution is reasonably well described by (14). A low energy tail is always present in 55Fe spectra. This stems from contributions originating in regions C and D in the background spectra.

The photomultiplier used to obtain the spectrum in **figure 28(b)** included a low background window and was selected for low counts. With an unselected tube, the noise can encroach to 1-2 keV and affect the resolution.

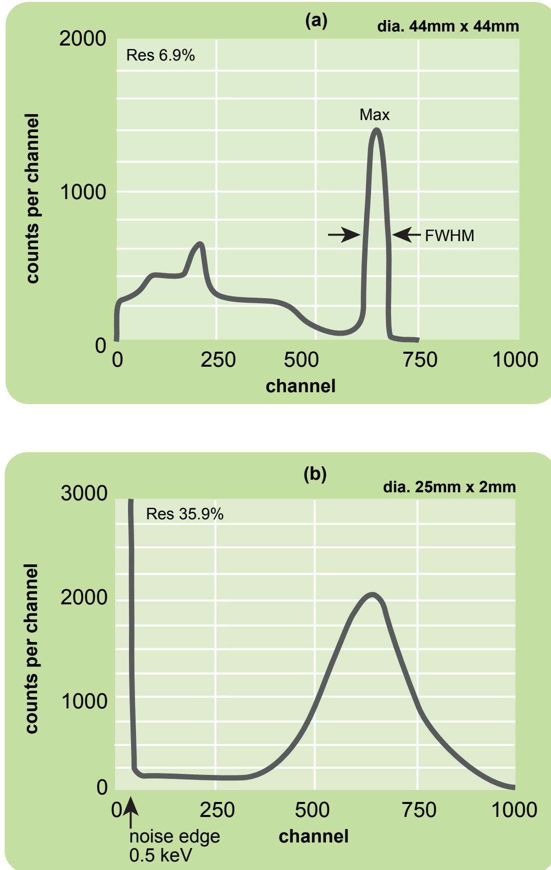


figure 28 Typical spectra from NaI(T1) scintillator, optically coupled to a 9266B photomultiplier responding to radioactive decay from (a) 137Cs, and (b) 55Fe.

table 5.11 - Typical pulse height resolution for photomultipliers optically coupled to standard, factory, NaI(Tl) crystals.The yield in photoelectrons/keV is given in the second row.

isotope	^{55}Fe	^{129}I	^{57}Co	^{137}Cs	^{60}Co
energy (keV)	6	30	122	662	1332
pe/keV	12	8	8	8	6
crystal mm (dxh)	20x3	25x25	44x44	50x50	75x75
resolution (%)	32-40	25-35	8.5-10	6.8-7.4	10-15*

*It is standard practice to quote ^{60}Co performance in terms of the peak-to-valley ratio referred to 1.332 MeV, rather than in terms of resolution.

Photomultiplier operation is sensitive to environmental conditions. Precautions can be taken to limit the environmental effects but often more can be gained by the correct choice of the pmt for the particular application.

6.1. Temperature

dark current and dark counts

Photomultiplier dark current and dark count are critically dependent on temperature. This is illustrated in **figure 23** where for most cathode types there is a doubling in dark current every 5°C rise above room temperature. Dark current varies considerably even for photomultipliers of the same type. ET Enterprises can provide photomultipliers selected for low dark current or dark count rate. Detailed specifications for dark current and dark count rate are given for each tube type in the **photomultiplier brochure.**

overall sensitivity

The overall sensitivity varies with temperature because of the combined effects of cathode sensitivity and multiplier gain changes.

The electron multiplier gain change is approximately -0.2 %/°C for both BeCu and SbCs dynodes.

The change in photocathode sensitivity with temperature depends on the photocathode type and the wavelength of incident light and is illustrated in **figure 29.** Note how the variation is greatest at the long wavelength limits of sensitivity. The loss in red sensitivity should be noted whenever cooling is employed to reduce dark counts. The temperature coefficient of the photomultiplier is the combination of the change in photocathode sensitivity and electron multiplier gain, e.g. -0.3 %/°C for the 9954B at 400 nm.

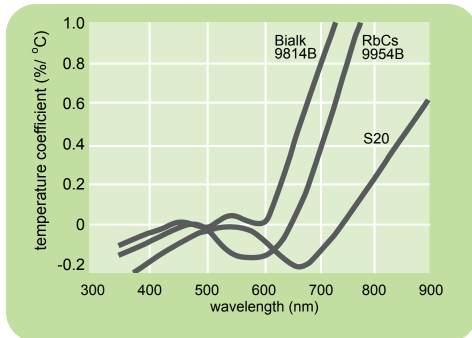


figure 29 Temperature coefficient of photocathode sensitivity.

operating temperature

The resistivity of the photocathode layer increases with decreasing temperature. Therefore, below room temperature the maximum current that can be drawn from the photocathode, if non-linear operation is to be avoided, is less than the value quoted in **table 5.3(a).** Maximum currents must be scaled by a factor of 2 per 5°C temperature drop below 20°C.

6.2. Magnetic fields

An external magnetic field causes photoelectrons and secondary electrons to deviate from their normal trajectories. The effect is critically dependent on electron optical design and multiplier structure, the focused structures being most susceptible. Both photoelectron collection efficiency, and electron multiplier gain, g, are affected, giving a combined effect on the overall gain G, as illustrated in **figure 30.**

The use of a mu-metal shield is recommended to minimise the effect and in the best designs extends from the rear of the photomultiplier to a distance half of the diameter beyond the photocathode.

ET Enterprises offers integral mu-metal shields for end window photomultipliers up to 52 mm in diameter. **Figure 31** shows the construction of an integral shield; the mu-metal is wrapped around the graphite coated envelope and electrically protected by an insulating sleeve. The relative output of the photomultiplier is shown in **figure 32** as a function of external magnetic field with an integral shield. Further details on this technique and the benefits it offers are contained in the ET Enterprises reprint RP 084[4] .

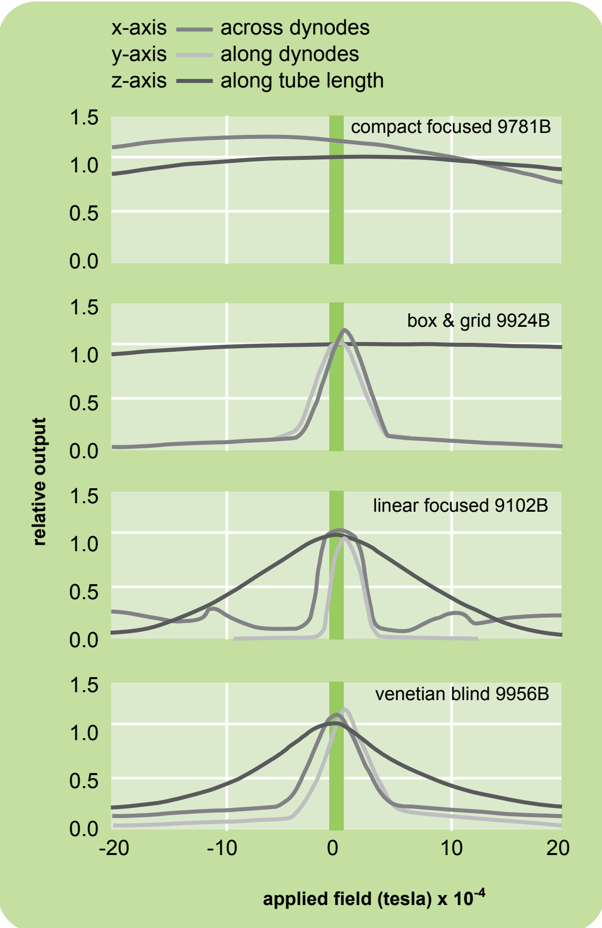


figure 30 *Relative output as a function of external magnetic field. (for photomultipliers operated at nominal gain).*
Note: Earth's Field is shown in darker colour.

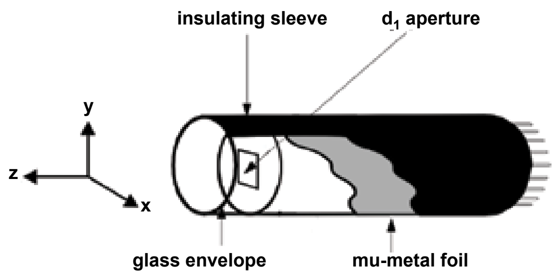


figure 31 *Cut away section illustrating the construction of the integral mu-metal shield. The co-ordinate axes adopted for the photomultiplier are also shown.*

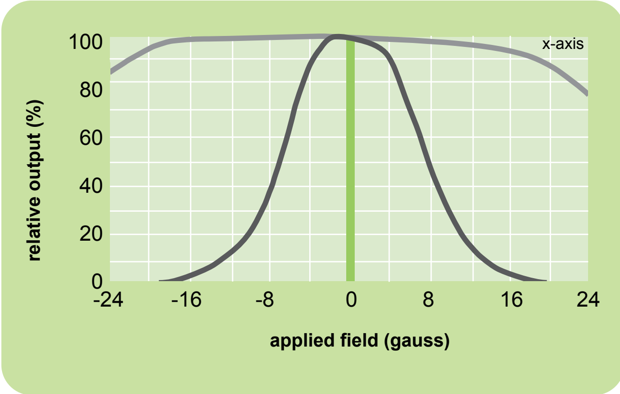


figure 32 *Demonstrating how a wrapped mu-metal shield reduces the sensitivity of a 9106B photomultiplier to external magnetic fields. Solid line: unshielded; grey line: wrapped shield; darker region: earth's field. Field aligned across the first dynode, x axis.*

6.3. Electric fields

Photomultiplier stability and lifetime are strongly influenced by electric fields. It is important to distinguish between external and internal electric fields. Internal electrical fields are generated in the glass envelope and immediate surroundings of the photomultiplier by the application of high voltage. These fields are often responsible for erratic and unstable photomultiplier behaviour. However their effect can be minimised by application of appropriate shielding techniques.

Gain stability and dark counts are strongly affected by field gradients in the vicinity of the photocathode. This is illustrated in **figure 33** where dark counts are recorded as a function of envelope potential. In this investigation, a cylindrical screen covering the envelope, but leaving the window free, was varied in potential using a separate power supply. The effect on performance is dramatic and represents typical behaviour when photomultipliers are operated under these conditions.

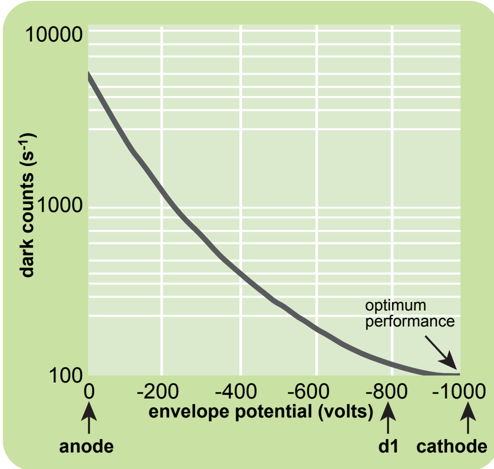


figure 33 *Effect of envelope potential on the dark counts of a 9924B photomultiplier. Best performance is obtained when the envelope is maintained at cathode potential.*

The use of positive high voltage dictates that the cathode is at ground potential. If associated housings, shielding and material in contact with the window (for example a NaI(Tl) crystal) are all maintained at ground potential then there will be no field gradients and stable performance is assured. Positive high voltage is always the preferred mode of photomultiplier operation but note this requires the anode to be ac coupled.

Certain photomultiplier applications demand the use of negative high voltage (where the anode is directly coupled to external circuitry). Optimum and stable performance can be obtained provided precautions are taken to eliminate electric field gradients in the vicinity of the window. **Figure 34** illustrates the precautions to be taken when a NaI(Tl) crystal is coupled to a photomultiplier. It is not acceptable practice to ground the can of the crystal. Instead it must be maintained at cathode potential, and in addition, insulated from the surroundings.

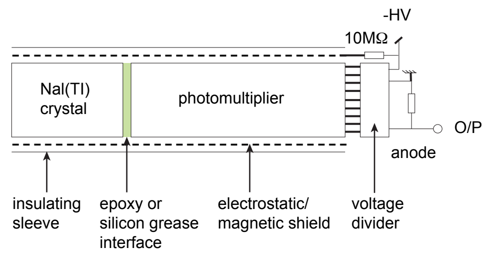


figure 34 *Stable performance with negative high voltage is achieved by eliminating potential gradients in the vicinity of the photocathode. The electrostatic shielding and the can of the crystal are both maintained at cathode potential by this arrangement.*

Important

Any conductor in contact with the window or envelope of the photomultiplier must be connected to cathode potential. When the photomultiplier is operated at cathode negative with respect to ground, a 10 MΩ safety resistor between -HV and the shield is advised. Only very good insulators, e.g. PTFE, should be brought into direct contact with the photomultiplier window. All too often, unstable output, high dark current and reduced photomultiplier lifetime can be traced to a ground contact on the photomultiplier window (or envelope) when the photomultiplier is operated with cathode negative with respect to ground. For similar reasons the casing of NaI(Tl) crystals must be maintained at cathode potential.

RFI shielded ambient and cooled housings, available from ET Enterprises, have been designed for use with positive or negative high voltage by observing the precautions outlined above.

ET Enterprises can also provide a conductive coating on the envelope of the photomultiplier, with the coating connected directly to the cathode pin. An insulating sleeve covers the conductive coating for safety reasons, adding approximately 0.8 mm to the published photomultiplier diameter. This option is especially recommended in low light level applications.

6.4. Effect of ionising radiation

As discussed in Section 5.7 ionising radiation causes electron emission in the photomultiplier. At high energies it causes 'browning' of the glass window and envelope affecting transmission of light to the photocathode. The amount of discolouration depends on the exposure and on the type of glass; a quartz (fused silica) window is least affected.

6.5. Shock and vibration

Photomultipliers will withstand the demands of portable instrumentation and everyday handling. There are, however, levels of shock and vibration which will cause mechanical failure or impair electrical performance.

Excessive shock can give rise to mechanical failure should any support or electrical connection fracture. Excessive vibration gives rise to mechanical failure of the envelope or of the internal structure. In addition loose material may be produced which can accumulate and cause internal short circuits.

Shock and vibration can manifest itself at the anode as microphony – caused by changes in electrode capacitance from movement of electrodes. In addition, where ac coupling is used, the coupling capacitor itself may be microphonic. The use of charge sensitive amplifiers minimises these effects. Mu-metal shields are recommended to eliminate the effects of changing magnetic fields. When operated at negative high voltage, external insulators or potting materials in contact with the envelope may breakdown electrically or produce light. The method of mounting a photomultiplier is critical: encapsulation can be designed to damp external shock and vibration.

6. Environmental effects

Flexible potting materials applied over the full length of the photomultiplier are generally recommended for radial support. Axial load is recommended to prevent movement of the window with respect to the housing.

Ruggedized glass and quartz photomultipliers can be specially manufactured to meet severe operating conditions experienced for example in military, oil well logging and space launch applications. ET Enterprises will design, qualify, manufacture and test devices to specific project requirements. After qualification it is normal practice to test all project devices at an acceptance level, which is normally half of the random vibration qualification level.

ET Enterprises has extensive environmental test facilities including sinusoidal and random vibration, shock, thermal and vacuum test. Representative shock and vibration tests for ruggedized tubes are shown in **table 6.5** while **figure 35** illustrates power spectral density curves for random vibration. The frequency range, acceleration values and test duration are agreed with each customer.

table 6.5 *Shock and vibration limits for ruggedized glass and metal ceramic photomultipiers. These limits apply for all orientations, with the photomultiplier non operational. The frequency profile shown in* ***figure 35*** *applies to random vibration.*

parameter	test	glass/quartz types	metal ceramic types
shock (1/2 sine)	$\hat{g}$ duration shocks/axis	30 11 ms 3	250 2 ms 30
sinusoidal vibration	frequency amplitude (p-p) frequency $\hat{g}$ sweep rate	10-32 Hz 10 mm 30-2000 Hz 20 2 octave/min	10-40 Hz 10 mm 40-2000 Hz 30 2 octaves/min
random vibration	maximum composite duration/axis	0.6 g^2/Hz 20g rms 2 mins	2 g^2/Hz 36g rms 10 mins

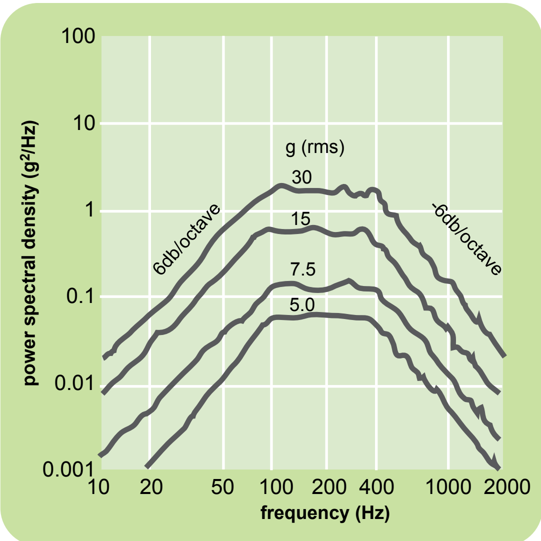


figure 35 *Standard, random vibration power spectral density profiles used by ET Enterprises. The square root of the area under each curve is related to g(rms).*

6.6. Exposure to daylight

The photomultiplier is an extremely sensitive light detector and should not be operated under daylight or room lighting levels. Even when non-operational, exposure to daylight or normal lighting levels causes photocathode excitation, especially under uv illumination. Although this does not damage the tube, it causes an increased dark current (count) level. Initially this may be several orders of magnitude higher than the final dark current value. The effect is particularly pronounced in photomultipliers with quartz windows. Although the photomultiplier can be used immediately after exposure without any effect on overall sensitivity, the dark current will not settle to its ultimate value for many hours. **Figure 36** illustrates the dark current decay of a 9829QB. For these reasons it is recommended that tubes are not exposed to daylight or fluorescent room lights but are loaded into instruments under subdued lighting conditions.

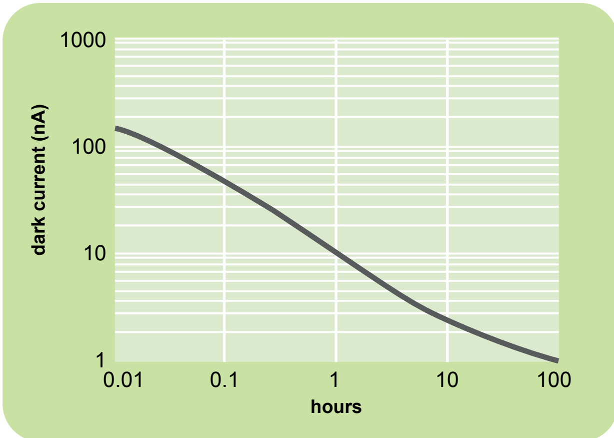


figure 36 *Dark current decay of 9829Q after exposure to daylight for 1 hour (non-operating).*

6.7. Helium

Helium is able to permeate glass, especially quartz (fused silica). While chemically inert, the increase in gas pressure within the photomultiplier results in an increase in afterpulse rate. If the pressure exceeds 10^{-3} torr, electrical breakdown becomes likely and the photomultiplier is inoperable.
For this reason storage or operation in helium-enriched environments must be avoided.

7. Choice of photomultiplier

At first sight this appears to be a formidable task because the number of variants offered by ET Enterprises. However, the choice is rapidly reduced to within a few, or just one device, when external factors and performance characteristics of particular photomultipliers are considered. External factors such as the area over which the light extends and physical restraints on overall dimensions usually play an important role in selection.

Performance measurements requirements such as:

spectral response

gain

dark current

linearity

speed of response

invariably reduce the choice to within a few types.

7.1. End window or side window

The overall performance offered by the two types usually favours the selection of the end window form. In end window tubes there is a wide choice of active areas, photocathode types and window geometry. Gathering the maximum light flux on to the photocathode from remote, diffuse and directly coupled light sources is best with an end window. The side window types are recommended when space is limited or when light levels are very high.

7.2. Spectral response

The most suitable photocathode type is the one that has the maximum quantum efficiency over the wavelength range emitted by the light source. At low light levels the signal-to-background ratio may be more important. At high light levels consideration should be given to the maximum cathode current allowed. This is discussed in detail in Section 5.3. The choice of window is important when the light source to be measured emits in the uv. Transmission curves given in Section 3.2 should be consulted. In the detection of ionising radiation using a scintillator, there is a contribution to background count rate from the naturally occurring isotopes in the photomultiplier window. When this is critical, it is advisable to discuss your particular requirements with ET Enterprises.

7.3. Electron multiplier structure

The choice is often restricted by the diameter of the photomultiplier; the widest variety of multipliers is available in 52 mm diameter tubes.

The linear focused structure is recommended in pulsed light applications for fastest time response, for best linearity and for highest available multiplier gain.

The circular focused structure is the most compact design with good magnetic immunity, good timing, good linearity but is limited in the number of stages available.

The venetian blind structure is an excellent general purpose type with a wide choice in the number of stages.

The box and grid structure is most commonly used in 30 mm diameter photomultipliers and is suited to a variety of applications from high light levels down to the photon counting region.

7.4. The number of dynodes

It is important to choose a photomultiplier with the correct number of stages. When too many stages are chosen to provide the required gain, the electrical performance is degraded. This is a consequence of low inter-electrode voltages, causing poor linearity and timing. If too few stages are chosen, there may be insufficient gain available within the constraints of the maximum allowed operating voltage. Operation beyond the maximum overall sensitivity will result in excessive dark current, breakdown and short lifetime.

For low light intensities, down to photon counting levels, 10 to 14 stages will be required. For intermediate light levels, 8 - 12 stages are usually sufficient. High light levels require between 6 and 10 stages of gain. An aid to selecting the right number of stages is presented in **table 7.4.**

light level	high	medium	low
photocurrent	$I_k > 1$ nA	1 nA $> I_k > 10$ pA	$I_k < 10$ pA
pmt gain	$g < 10^4$	$10^4 < g < 10^6$	$10^6 < g < 10^8$
number of SbCs stages	< n < 8	8 < n < 10	10 < n < 12
number of BeCu stages	n < 10	10 < n < 12	12 < n < 14

table 7.4 *Relationship between light level and number of dynodes.*

7.5. SbCs or BeCu dynode surface

At any applied voltage SbCs dynodes have higher gain than BeCu ones but this is not always an advantage. Since the time response depends on applied voltage, BeCu is recommended for time-critical pulsed light applications. In addition, it has better pulsed current linearity.

SbCs requires lower operating voltages. It also has better hysteresis and rate effect performance due to its low surface resistivity, enabling it to settle quickly between changing light levels. Consequently it is the best choice in optically chopped light applications such as colour film scanning. Further details are given in sections **4.3 and 5.**

7.6. Electrical performance

As explained in section 5, various limitations apply in photomultiplier performance which may further influence the choice of photocathode, multiplier structure and number of dynodes. Reference should be made to this section before making the final choice.

Having chosen the most suitable photomultiplier, it is recommended that a prototype of the optical detection system is built. It is important to confirm the mean cathode current, the mean and peak anode current and the range of operating voltages. 'Order of magnitude calculations' are sufficient for this purpose. It is often found that the light levels are either much higher or much lower than expected and re-selection of the most suitable photomultiplier may be necessary.

Manufacturers are continually upgrading equipment performance, which may place additional demands on the photomultiplier. Engineers making changes which affect the operating voltages or the currents flowing in the photomultiplier should always re-confirm that the photomultiplier remains within its performance limits. When re-design takes place, it is advisable to contact ET Enterprises to keep up to date with the latest products.

A series of voltages is applied to the photomultiplier to: accelerate and focus photoelectrons on to d_1; accelerate and focus the secondary electrons between successive dynodes and to collect the secondaries from the last dynode at the anode. It is common practice to derive the voltages from a single supply using a resistive divider network.

Voltage divider design is critical to achieving optimum performance from a photomultiplier. An outline of design considerations is given in this section but for a detailed account, the reader is referred to 'Voltage Divider Design' RP069[6]. All photomultipliers will operate with the linear divider, shown in **figure 37,** although not necessarily with ideal performance. For example, if linearity and timing are of prime importance, it will be necessary to modify the basic configuration of **figure 37.** Voltage dividers actually used by ET Enterprises for testing purposes are listed in the **photomultiplier data sheets.**

Voltage divider networks are available to suit most photomultiplier tube types and applications. Ask for publication 'Voltage Divider Networks' RP085[7].

8.1. DC applications

Direct current applications require negative high voltage applied at the cathode, leaving the anode at ground potential for ease of interfacing. The choice of R in **figure 37** is governed by the maximum anode current I_a(max) the application demands, subject to I_a(max) always <100 µA. R should be chosen to satisfy the relationship $I_a(max)<0.01I_{HV}$, where I_{HV} is the divider current. This will ensure that gain linearity is preserved up to anode currents of I_a(max). Once I_a(max) exceeds one tenth I_{HV}, serious deviation from linearity will become apparent.

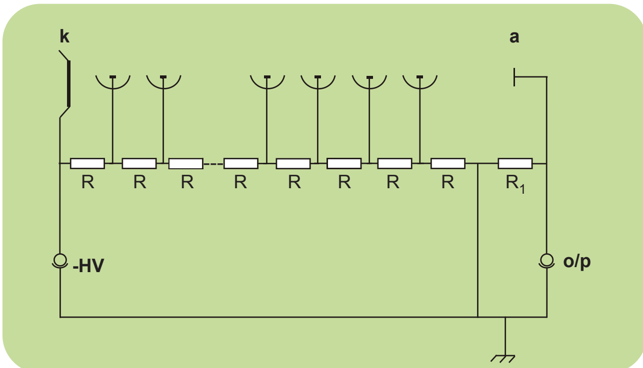


figure 37 A linear voltage divider for dc applications. R may be in the range 10 KΩ -10 MΩ. R_1=10 MΩ is a safety resistor, which prevents the anode floating to dn potential when the external load is removed. R_1 is often omitted because it can cause preamplifier offsets.

8.2. Pulsed applications

Some photomultipliers are capable of handling peak currents of the order of 200 mA. To achieve this level of performance requires a divider that differs from that in **figure 37** in two important respects:

i) the potentials applied to the last few stages must be increased to overcome space charge effects;

ii) capacitors are added to supply the charge pulse. With NaI(Tl) applications it is common to use positive high voltage with the cathode at ground potential. The coupling capacitor, C, shown in **figure 38,** isolates the dc potential at the anode from the measuring electronics. In high energy physics applications it is usual to couple the anode directly to external electronics to avoid base line shift.

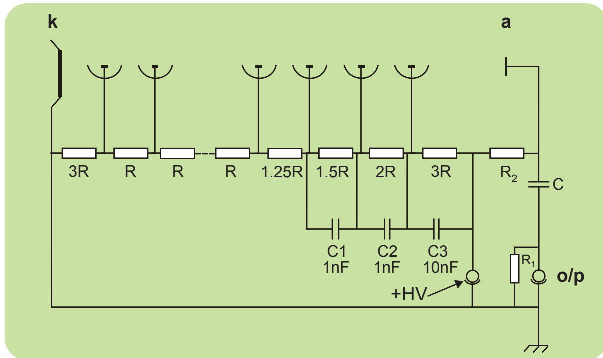


figure 38 A tapered divider suitable for pulse applications. In this example, positive high voltage is used. R_2 is the load resistor, 10KΩ -1MΩ. R1=10MΩ safety resistor.

As with the linear voltage divider of **figure 37,** R is chosen to satisfy

$$I_{HV} > 100\,\bar{I}_a \qquad ...(22)$$

Where $\bar{I}_a$ is the mean anode current

The degree of taper on the last few stages of the divider depends on the tube type and on the level of performance required.

The size of decoupling capacitors can be calculated from the basic relationship for a capacitor: Q = CV. It is sufficient to demand that the inter dynode voltage remains constant to ~0.1%, that is $\Delta V/V \leq 0.001$, while peak charge ΔQ is drawn. If C is chosen to satisfy

$$C > \frac{\Delta Q / V}{\Delta V / V} \qquad ...(23)$$

the divider will cope with short bursts of pulses of variable magnitude. It is important to appreciate that decoupling capacitors only cover short bursts of pulses. A sustained high count rate leads to a high mean anode current I_a and there is the possibility that the relationship (22) will be violated.

A resistive divider poses a power dissipation problem, if properly designed in accordance with (22), for high count rates. Practical dividers, ideal for high count rates, either incorporate zener diodes or transistors in the final stages. These provide the required level of performance without having to draw excessive divider current.

8.3. Active dividers

Active dividers (figure 39) consist of a series of FETs interposed between the dynodes and a high impedance resistive divider. The FETs hold the dynodes at fixed potentials. This type of divider ensures constant gain up to a mean anode current of 100uA, the maximum permitted in most pmt types. Power consumption is typically 100 mW and they are particularly suited to portable instrumentation.

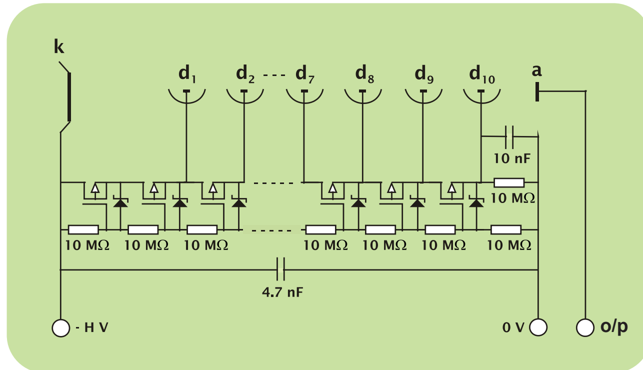


figure 39 Active, uniform divider providing high performance and low power consumption over a wide dynamic range of operation.

9. Photon counting

There are three modes of photomultiplier operation,

analogue (current mode detection)

pulse counting and encoding

photon counting

Information on both the intensity and the time signature of a light source can be obtained by using the photon counting method.

Certain high gain photomultipliers give you the ability to detect single photons. When used in this mode, referred to as **photon counting**, the fundamental and unique characteristic of a photomultiplier is utilised - the ability to detect single photons over a large photocathode area Photon counting is that mode of operation where each detected photon is separately time resolved at the anode of the photomultiplier. This is illustrated in **figure 40** where the intensity of the incident light is sufficiently low that there is no overlapping in the sequence of detected photons. Because the multiplier gain process is statistical in nature, events which all start as single electrons at the cathode produce a range of output pulse heights. The narrower the spread in pulse heights, the better suited is the photomultiplier to photon counting.

A photon counting photomultiplier is one with a well defined **single electron peak**, shown in **figure 41.** This is a pulse height distribution, measured at fixed gain, using a source of single photons and a multichannel analyser. A characteristic of a **single electron response**, SER, spectrum is that increasing or decreasing the light intensity changes the area under the curve, but not the position of the peak.

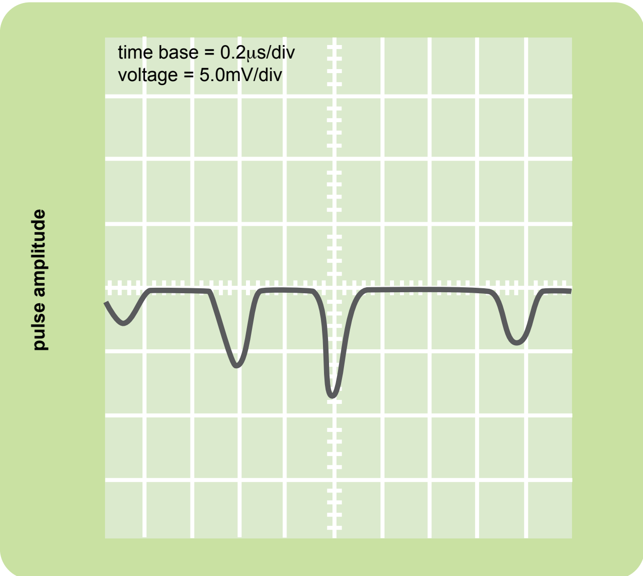


figure 40 *Photomultiplier output produced by a source of single photons.*

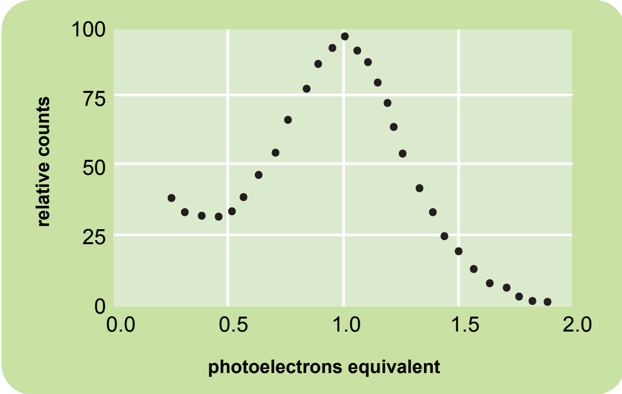


figure 41 *The pulse height distribution of the output of* ***figure 40,*** *known as the single electron response (SER)*

In practice, photon counting is done using a circuit with a single fixed threshold as opposed to a multichannel analyser. An amplifier-discriminator combines a fast amplifier and a fixed threshold discriminator with an overall sensitivity of the order of one millivolt. Deciding upon the optimum operating point of a photon detection system depends on the nature of the application and to some degree on personal judgement. It is standard practice to record signal and background curves as shown in **figure 42.** Noting that the output pulses from the photomultiplier have a range of size, characterised by the SER, the shape of the signal curve is explained as follows. Few counts are recorded at low applied HV because the gain of the photomultiplier is insufficient to produce a significant number of pulses that exceed the threshold (region ①). As the HV, and hence gain, is increased to 1.2kV, about half the output pulses exceed the threshold and all pulses to the right of the peak in the SER contribute to the measured count rate (region ②). As the gain is further increased most of the distribution in the SER is counted and a plateau is reached (region ③). Further increase in HV results in a slight increase in counts until the onset of photomultiplier breakdown (region ④). Note that the plateau characteristic is in effect an integration of the SER moving from right to left across **figure 41.** Also note that gain follows a power law with respect to HV and and the gain span across the plateau characteristic is typically two decades in magnitude. All photomultipliers produce unwanted afterpulses. Curve (d) shows that the afterpulse rate is a strong function of HV.

Good experimental technique suggest that operating at a point on the plateau that maximises signal/background is sound practice. This ratio, shown in **figure 42,** indicates a wide window of acceptable performance. Taking account of the benefits of operating on the flattest part of the signal curve (providing stable performance against gain changes) and the steeply increasing afterpulse rate, leads to the suggested operating point indicated.

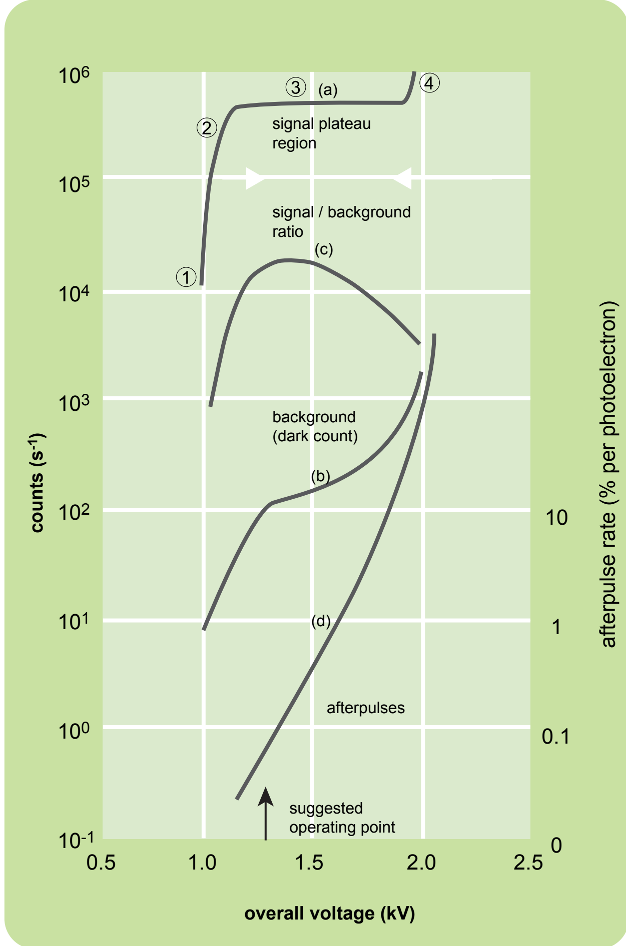


figure 42 *Finding the optimum operating voltage for photon counting. The steeply rising afterpulse curve suggests a preferred operating point to the left of the Signal/Background plateau region.*

current mode detection

Every discriminator circuit has an intrinsic dead time. This refers to the period the circuit requires to deal with each signal. Should a second pulse appear during this period then it is lost to the count rate. In theory it is possible to allow for the affects of overlapping pulses by correcting the measured rate, n. If T is the dead time for an ideal, non-paralisable, amplifier-discriminator then the true rate N is

$$N = n / (1 - nT) \qquad ...(24)$$

Discriminators are not ideal and the correction becomes unreliable if the dead time exceeds 50%. For a dead time of 100 ns, for example, the correction will exceed 10% at count rates in excess of 1 MHz. At such high count rates, the statistical advantages associated with photon counting become less important and it may be desirable to resort to **current mode detection.**

10. Further information

References available on request

1) Gating of Photomultipiers (RP 061)

2) Monte Carlo Simulation of Photomultiplier Resoulution (RP 080)

3) An Investigation of Photomultiplier Background (RP 075)

4) Integral mu-metal* Shields (RP084)

5) Metal Ceramic Photomultipliers (RP079)

6) Voltage Divider Design (RP069)

7) Voltage Divider Networks (RP085)

We have a worldwide network of representatives. Please contact us for details of your local representatives.

*mu-metal is a registered trademark of Magnetic Shield Corporation.

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