The Photomultiplier and its Operation

1 Introduction

This introduction is intended to provide an understanding of photomultiplier performance and guide designers to the correct choice for their applications. Final selection should be confirmed in consultation with THORN EMI 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.

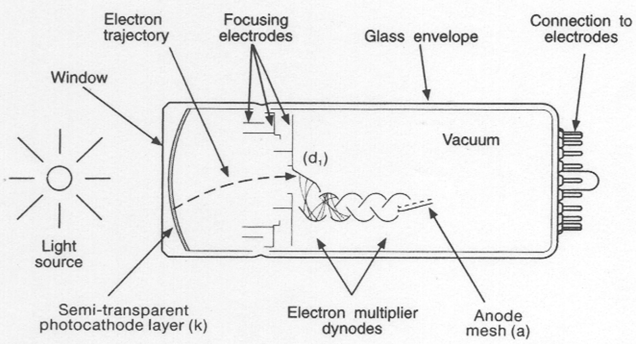


Figure 1
Illustrating the operation of a photomultiplier.

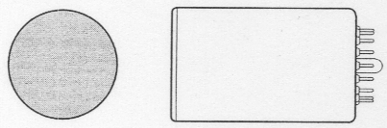
3 The Photocathode

This section gives information on:

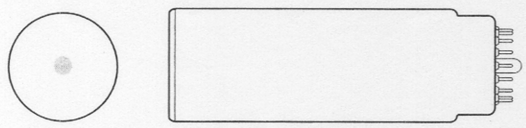
- the light sensitive area of the photomultiplier
- the effect of the window on light transmision
- photocathode spectral response
- photocathode sensitivity units

3.1 Photocathode Active Area

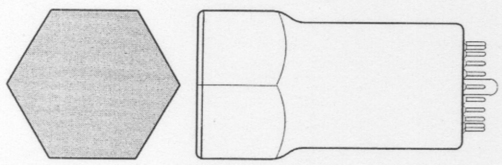
Photomultipliers are offered in a range of geometries and sizes to cover applications involving both remote and directly coupled light sources. In end window photomultipliers, the photocathode is deposited as a semitransparent layer directly on the inside of the window. In the majority of types the active 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.



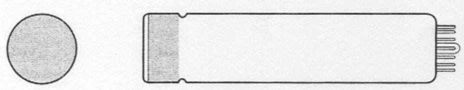
a) Circular
Range of diameters available to suit diffuse and directly coupled light sources.
Application: General purpose; scintillation.



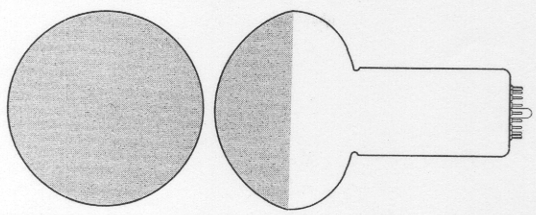
b) Reduced
Electrostatically reduced diameter for minimum dark count.
Application: Photon counting and laser light detection.



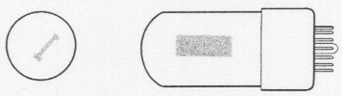
c) Hexagonal
Close packing allows maximum coverage of large areas.
Application: Gamma Camera.



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



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 Application: Spectrophotometers and photometers.

Figure 2

Various photomultiplier geometries are available and the light sensitive areas are shown coloured; 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 UV 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. For critical applications, low background borosilicate glass is also available.

UV glass This is used predominantly for side window photomultipliers. The UV cut-off is approximately 185 nm.

Quartz 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 Al_2O_3 is used in metal-ceramic photomultipliers for harsh environments. It has good UV transmission and low background.

The transmission properties of these materials are shown in Figure 3.

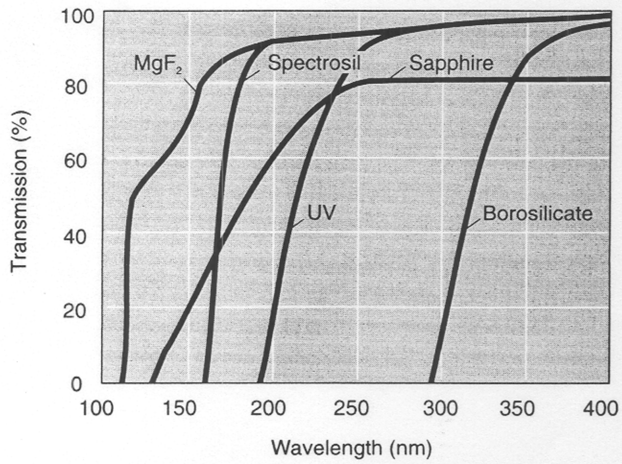


Figure 3

Typical UV transmission curves for windows used in the manufacture of THORN EMI photomultipliers.

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 thermionic emission which are covered in detail elsewhere. (See Table 5.3(a) and Figure 23).

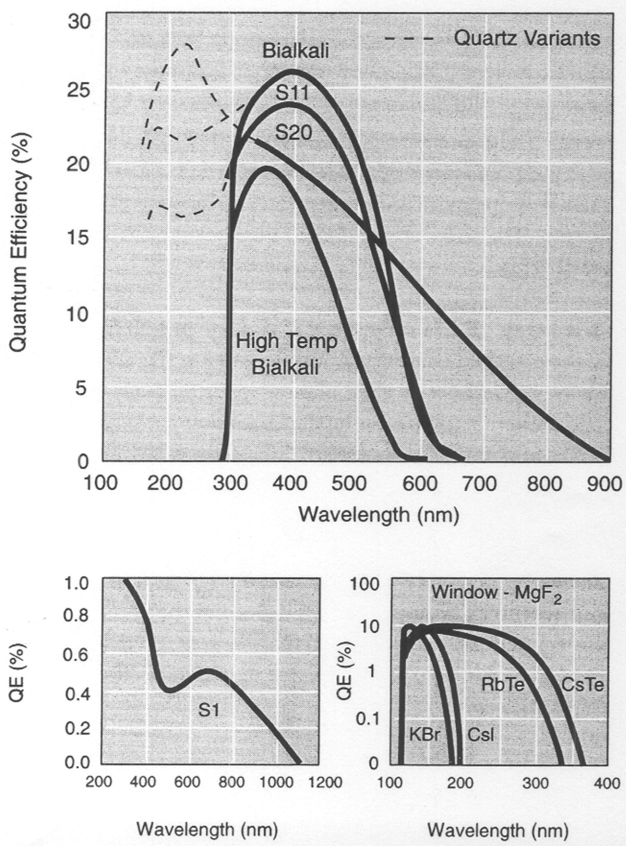


Figure 4

Typical spectral response curves for 52 mm diameter photomultipliers.

Photocathode materials and designations used in THORN EMI photomultipliers are :

i) **Solar Blind** (KBr, CsI, RbTe, CsTe)
These photocathodes are sensitive to VUV and UV 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.

ii) **High Temperature Bialkali** (Na-K-Sb)
Recommended for operation at high temperature because of its very low thermionic emission. This photocathode also finds application in low level light detection.

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

iv) **Bialkali** (Sb-K-Cs, Sb-Rb-Cs)
This photocathode has mostly superseded the S11, offering better blue response and lower thermionic emission.

v) **S20 Trialkali** (Na-K-Sb-Cs)
The multialkali photocathode response extends from the UV to near infra-red. It has high light level capability but may require cooling to reduce dark current.

vi) **S1** (Ag-O-Cs)
The S1 sensitivity extends to 1100 nm. Its infra-red response exceeds that of the GaAs types, and it is invariably cooled.

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-relationship 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 and detectivity are all related to quantum efficiency.

Radiant Sensitivity $E(\lambda)$ or QE%

Radiant sensitivity or responsivity 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:

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

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.

One of the standard calorimetry illuminants, 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 :

$$S = \frac{10^3\int_0^\infty I(\lambda)\lambda\eta(\lambda)\,d\lambda}{1.24\times680\int_0^\infty I(\lambda)\,V(\lambda)\,d\lambda} \quad \mu A/lm \qquad \ldots(2)$$

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

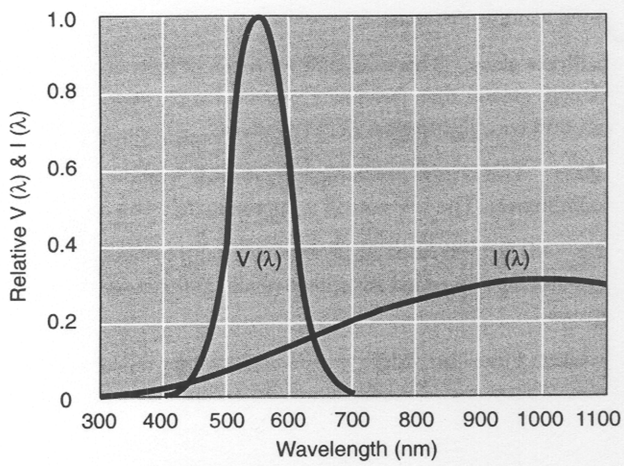


Figure 5
Relative luminous efficiency of human eye $V(\lambda)$ and radiant power of a tungsten filament lamp operated at 2856 K.

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. In the THORN EMI 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 fron long wavelengths. Luminous sensitivity figures cannot therefore be used to compare photocathode types with appreciably differen

Photon Counting Modules

Photon Counting

Certain high gain photomultipliers have 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 utilized — 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 41 where the intensity of the incident light is sufficiently feeble 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.

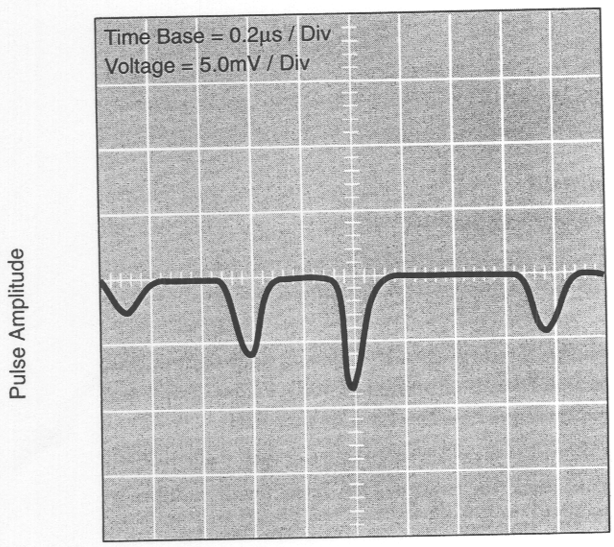


Figure 41
Photomultiplier output produced by a source of single photons.

A photon counting photomultiplier is one with a well defined **single electron peak**, shown in Figure 42. This is a pulse height distribution, measured at fixed gain, using a source of single photons and a multi channel analyser. A characteristic of a **single electron response**, SER, spectrum is that increasing or decreasing light intensity affects the area under the curve, but not the position of the peak.

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. When properly set-up, the output from an amplifier-discriminator will be representative of the area under the SER of Figure 42. 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

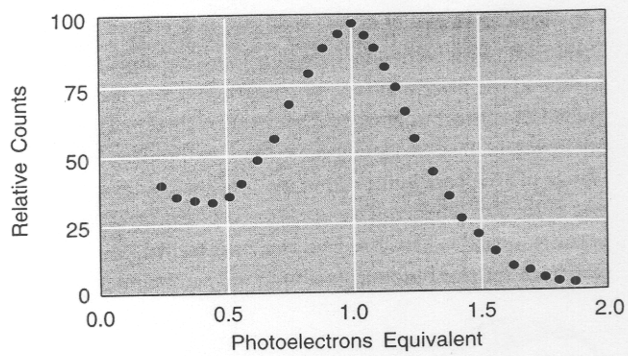


Figure 42
The pulse height distribution of the output of Figure 41 known as the single electron response (SER)

shown in Figure 43(a) and (b). 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. As the HV and hence gain is increased to 1.2 kV, about half the output pulses exceed the threshold and the count rate derives from all pulses to the right of the peak in the SER. As the gain is further increased most of the distribution in the SER is counted and a plateau is reached. Further increase in HV results in a slight increase in counts until the onset of photomultiplier breakdown. Note that the plateau characteristic is in effect an integration of the SER moving from right to left across Figure 42. Also note that gain follows a power law with respect to HV and the gain span across the plateau characteristic is typically two orders of magnitude. All photomultipliers produce unwanted **afterpulses**. Curve (d) measured with a correlator 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 43(c), 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, the suggested operating point is as indicated.

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 effects 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

$$N = n / (1 - nT)$$

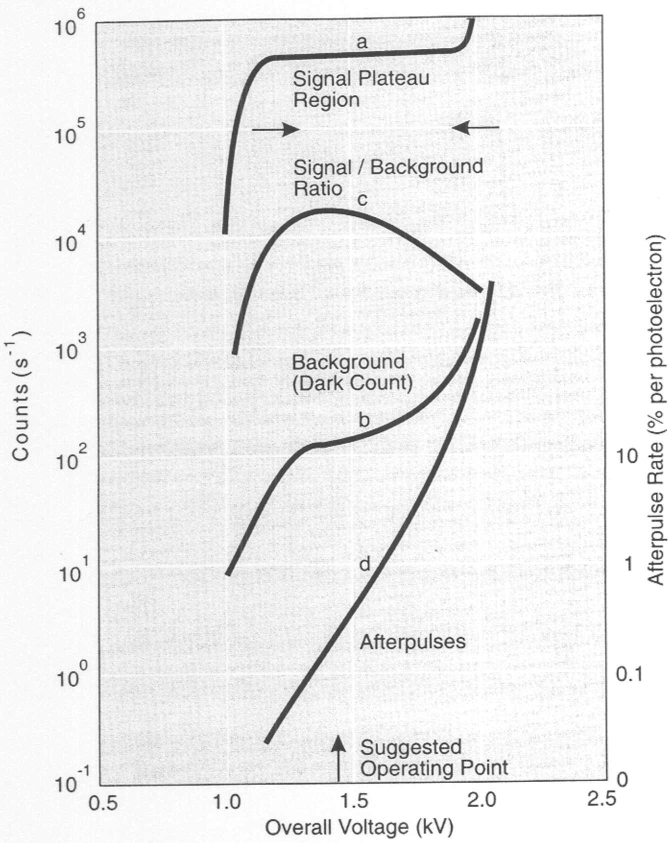


Figure 43

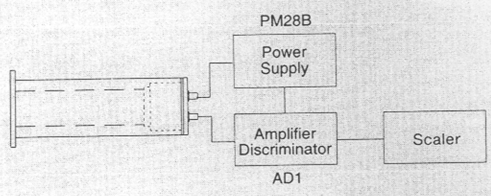
Finding the optimum operating voltage for photon counting. The steeply rising afterpulse curve suggests a preferred operating point to the left of the Signal/Background plateau region.

Discriminators are not ideal and the correction becomes unreliable if the dead time exceeds 10-20%. 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 unimportant and it is desirable to resort to **current mode detection**.

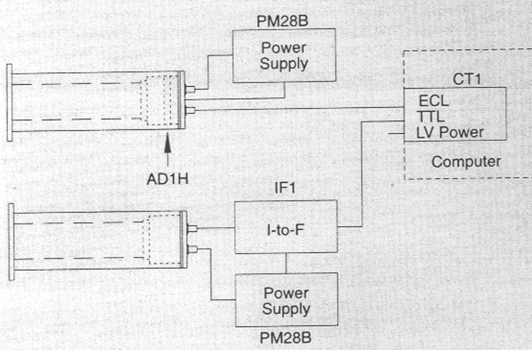
The circuit modules described in this catalogue provide the means for setting up photon counting systems. They include: amplifier-discriminators offered as stand alone units or incorporated into housings; current-to-frequency converters for extending the range of photon counting.
A combined amplifier-discriminator and current-to-frequency converter, the ADIF1, allows simultaneous counting and current mode measurement.

System Configurations

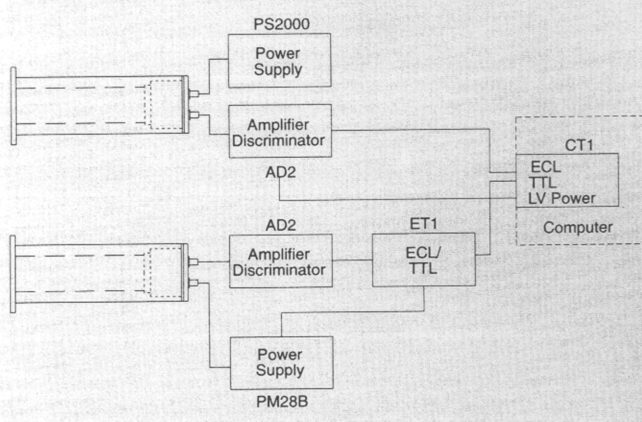
The THORN EMI range of voltage dividers, electronic modules, power supplies and housings provide the building blocks for making successful light level measurements. The CT1 timer counter board interfaces to an IBM compatible PC allowing the user to realise a photon detection system under computer control. Examples of typical configurations are given in a) to d).



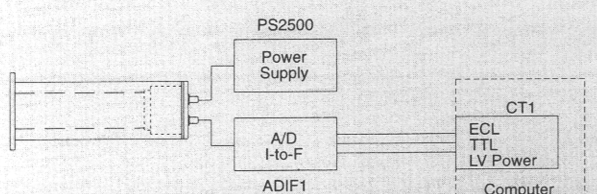
a) basic photon counting system.



b) photon counting with simultaneous monitoring of a dc reference signal. The system is controlled by a PC and a CTI board. Note the use of a PM28B to supply low voltage power to the AD1H, located within the housing.



c) two channels of photon counting under computer control.



d) photon counting with wide dynamic range. An ADIF1 simultaneously monitors anode count rate and current.