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test parameters and general operating rules for photomultipliers

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introduction

This paper is divided into three sections. Section 1 deals with the important parameters specifying the operating characteristics of photomultiplier tubes, and covers in a general way the test methods used to evaluate these parameters. Section 2 considers the extrinsic (environmental) and instrinsic (tube) limitations on the operation of a photomultiplier, and gives guidance to ensure that the tube is operating in its optimum mode. Section 3 concludes with a few general comments.

1 parameters of test

1.1 photocathode characterisation

Essentially there are two types of measurement:

- those based on integrated luminous sensitivity, using a tungsten filament lamp,
- those based on individual wavelength calibration, using a monochromator.

1.1.1 luminous (or cathode sensitivity)

This is the most commonly used photocathode parameter, often criticised because of the physical interpretation but used by most manufacturers because of its simplicity in grading devices. The photomultiplier tube is operated as a diode, with between 100 and 500 volts applied from cathode to collector electrodes. The specified effective area of the photoathode is ulluminated by a tungsen filament lamp (operated at 2856K) at a flux of a millilumen or less. The measured photocurrent is normally expressed in terms of microamps per lumen (μA/lumen), having stubtracted any leakage current. Typical values depend upon the photocathode type, and vary from 20 to over 300 μA/lumen.

Particular care has to be taken when interpreting this measurement for bialkali photocathodes, where the red tail of the spectral response charactirstic weights the overall sensitivity measurment, and in addition resistivity effects of the photocathode layer can reduce the sensitivity reading due to saturation. In this case, the most common application area being scintillation detection, the sensitivity in the blue region of th espectrum is of interest, and a filter, interposed between the lamp and tube, has the dual effect of reducing the current drawn and eliminating the red sensitivity factor.

filter measurements

(a) Corning blue (CB). A Corning CS-5-58 filter (ground to half stock thikness), is specified for this test, and the photocurrent, measured in a similar way as the luminous sensitivity, is recorded as microamps/"blue" lumen. In practice, absolute values of filter measurement may vary by up to 40% from manufacturer to manufacturer, and this figure is useful as a relative measure only.

An approximate ratio may be established for quantum efficiency at 420 nm to CB ready (for example, 2.5). In some cases the luminous sensivitiy is not measured individually for each photomultiplier, but a conversion ratio is specified for the typcialy interpolationof luminous sensitivity from a CB filter measurement (for example, CB/0.15).

(b) Corning red (CR). A useful indication of 'red' sensitivity is given by a similar filter measurement, using a Corning CS-2-62 filter, and this is normally applied to trialkali cathode tubes.

(c) Infra red (IR). A useful indication of near infra red sensitivity (particularly for high grade trialkali and S1 photocathodes) is given by using a Wratten infra red filter, type 87.

(d) For side window type photomultiplirs in certain applications the relative spectral sensitivity is important, and a ratio of red to blue sensitivity using the appropriate filters is specified. In this case the photomultiplier is operated as a photomultiplier, under typical gain conditions.

For details of the filter characteristics, see Ref. [1].

1.1.2 spectral sensitivity

This is expressed interms of quantum efficiency per incident photon or absolute radiant sensitivity (in milliamps per watt), at a specified wavelength (**figure 1**). It is measured under the diode conditions specified earlier, but using a monochromatic source of radiation. Absolute calibration may be achieved by comparison with measurements taken on a standard phtoocathode, previously calibrated by the national standards laboratory. The accuracy of this measurement is obviously much higher than for a luminous sensitivity test, and manufacturers will carry out a single wavelength measurement or complete spectral response calibration on request. In general it is possible to achieve better than ±5% accuracy (of measured value) over the range 350 to 650 nm, whith less accuracy towards the UV and IR regions. However quite substantial differences in absolute calibration have been recorded between national standards laboratories in a recent survey, and therefore even radiant sensitivity figures are subject to some calibration uncertainty.

The quantum efficiency *(QE)* can be calculated from the absolute radiant sensitivity, S (in mAW^{-1}) at any wavelength λ (in nm) by the simple relationship:

$$QE = \frac{1.2395S}{\lambda}$$

1.2 device gain

1.2.1 The most common specification is the anode sensitivity in terms of amperes per lumen (AL^{-1}), at a specified overall voltage, or the voltage required to achieve a rated amperes per lumen overall sensitivity, operated with a specified voltage distribution to the dynodes. The light source may be fixed to give an overall cathode illumination, or it may be focused to produce a small spot of diameter about one millimetre, at a flux of 10^{-6} lumen or less. In the latter test, the spot is scanned across the photocathode and the corresponding output current converted to a voltage and displayed on a monitor screen (**figure 2**). This scanning method allows an extra flexibility to check for local variations in overall sensitivity, and a contour map of the complete spatial uniformity can be displayed.

The gain may be specified for the typical operating conditions, for the maximum gain condition with regard to sability, or it may be shown as a characteristic, see reference [1] for example. Anode sensitivity values depend on both cathode type and the dynode system; for a 10 stage venetian blind tube with a bialkali photocathode, for example, 50 A/lumen is a typical figure.

The anode spectral sensitivity is measured in a similar way but for monochromatic illumination at a specified wavelength.

1.2.2 current amplification

The effective overall gain of a photomultiplier is the multiplication factor which relates the signal output current at the anode to the signal cathode current. This is not usually measured directly because of the problems of measuring the very small cathode current accurately, but is calculated by dividing the anode sensitivity at a given voltage by the cathode luminous sensitivity. This approximate calibration is valid for most uses of the tube but direct readings must be taken by one of the standard techniques

Figure 2. Output display for 2" photomultiplier using flying spot raster scan.

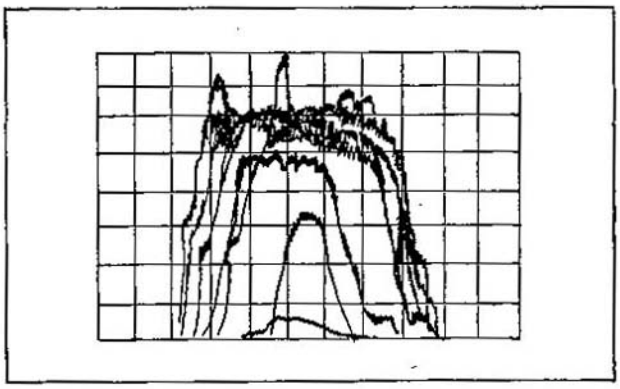


Figure 1. Typical spectral response characteristics shown together with quantum efficiency lines.

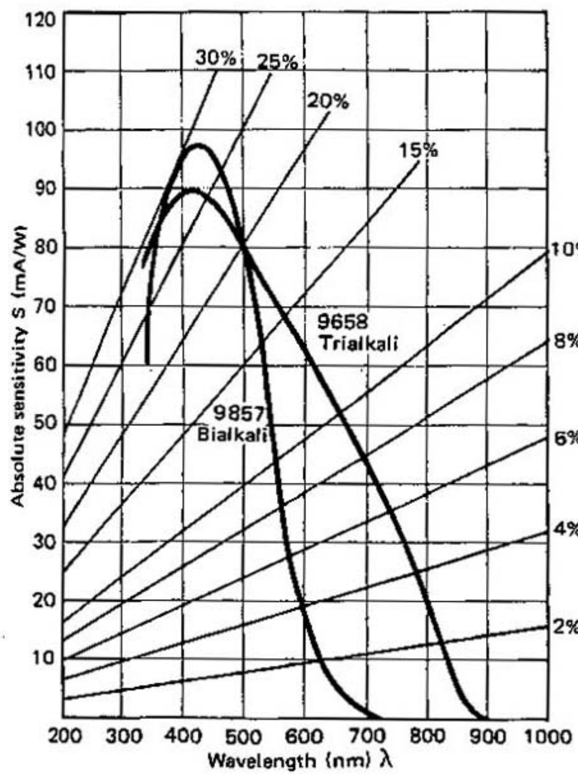
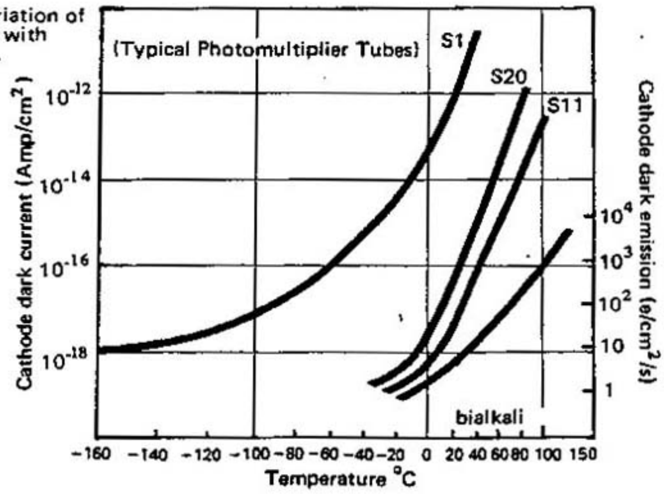


Figure 3. Variation of dark current with temperature.



available if an accurate calibration is required. It should also be noted that the absolute multiplier gain (appropriate in a single photoelectron operation for example) is greater than this value by a factor dependent upon the collection efficiency between the cathode and the first dynode of the tube.

1.3 dark current

1.3.1 The dark current usually limits the lower level of light detection of a photomultiplier, and it is therefore, an important parameter. It is measured in conjunction with the overall gain and is specified at a particular value of anode sensitivity. Due to the rapid variation of dark current with temperature (Richardson's law), the photomultiplier tube must be held at a fixed temperature, normally 20 ± 3 ºC (**figure 3**). Tubes are maintained under dark or semi-dark conditions for a minimum of twelve hours prior to test, to reduce dark current contributions from the window or the photocathode due to "energy storage" phenomena. It is important to minimise the exposure of tubes (particularly those with bialkali cathodes) to UV light before operation, because this may enhance the dark current by two or three orders of magnitude, decaying over a period of up to 24 hours.

1.3.2 Under conditions of pulsed operation, particularly low light level, the background pulse ampitude distribution and rate are more meaningful than the integrated dark current value. Conventional pulse height analyser (multichannel analyser) techniques may be used to determine the distribution, and integration over the amplitude range of interest will give the total count rate during the storage period. (**figure 4**). Alternatively, a simple discriminator and rate meter or counter will record the count rate for pulses above the discriminator threshold (such as in photon counting applications – see section 1.5.2). The temperature and the discriminator level in terms of single electron equivalent pulse height should be specified. Typically a bialkali photomultplier for photon counting will produce about 30 dark counts s^{-1} at 20 ºC.

1.3.3 When dark current or signal electrons impact with residual gas species in the tube positively charged ions may be created. If these ions are in a favourable field and position to travel back to the photocathod, then a spurious pulse or afterpulse is generated, in a time interval varying from 0.2 to 10 μs after the primary pulse event depending upon the tube operating conditions and the ion species [3]. This effect is reduced by careful electron optical design and good tube processing practice. Photomultiplier tubes may be screened for this parameter by a pulse counting test, using a coincident time window technique, or by a photon correlation analysis. Specification of performance should identify the tube operating condition (voltage divider, tube gain), the primary pulse amplitude, the amplitude level of the afterpulse counting discriminator, and the time window. Typical fast photomultipliers, incorporating residual gas gettering elements, generate only 2% afterpulse counts of amplitude greater than 1 photoelectron, for a 100 photoelectron stimulus, referred to the equivalent charge at the photocathode.

1.4 time response characteristics

The time response characteristics of the photomultiplier tube are important in pulse applications, particularly involving accurate time measurement or high count rates. In setting up to evaluate these characteristics it should be remembered that the measured time response is for the total system (light source, detector and electronics), and that allowance should be made for the effects of other components of the system. These may be minimised by using a fast rise time sampling scope (with 50 Ω input) and a light source approximating to a delta function. GaP light emitting diodes, used in conjunction with an avalanche transistor, or a spark light source, or a laser source are commonly used. The nominal photocathode diameter is illuminated, and the characteristic recorded under a specified electrode voltage distribution and at a stated gain – the rated gain (typical operation), maximum gain or maximum rated overall voltage. Because the measruements are sensitive to overall voltage the condition of measurement must be clearly stated. The time characteristics will also be a function of the level of light at the cathode ($k - d_1$ transit effects) and a weak function of the wavelength of illumination (due to initial energy effects of the photoelectrons).

There are five commonly specified (and commonly confused) measurements (**figure 5**).

a) Rise time: the time taken for the output pulse to rise from 10% to 90% of its peak value.

b) Full width at half maximum height (FWHM), or the response pulse duration, or the transit time spread: the full width of the output pulse measured at half maximum amplitude. The frequency response of a photomultiplier is related to the rise time and FWHM. Assuming the output pulse is represented by a normal distribution, the 2 dB passband is given by 0.3/FWHM. In practice, the frequency response is less than this due to the long tail of the output pulse (non-ideal statistics). For venetian blind type photomultpliers the useful bandwidth is of the order of 5 – 10 MHz, and for linear focused types, 50 – 100 MHz.

c) Overall electron transit time: the time interval between the arrival of the flash of light at the photocathode and the instant when the pulse output is at maximum. The transit time is normally of less interest in itself, as a "fixed" delay, than the variation in the transit time from pulse to pulse.

d) Transit time jitter, or dispersion, or fluctuation. This represents the variation in transit time between individual pulses, and may be defined for single electron pulses or multi-electron pulses. The tube is iluminated as previously described, and the output pulses are fed to a timing discriminator and time to pulse height converter. A distribution of transit time values is stored in a multichannel analyser (MCA), and the jitter is specified (conventionally for single photoelectron pulses) as the time duration between the half amplitude points of the distribution, or as the standard deviation of that distribution (see **table 1).** The time spread of the light source and trigger pulse must be taken into account or made negligible.

e) Transit time difference across the photocathode: the difference in transit time for illumination of a small area at the centre of the photocathode as compared to a small area at the edge. In effect, this isolates the geometic aberration of th einput system of the tube from the total (including statistical) variatins defined by the transit time jitter.

1.5 pulse height and resolution characteristics

1.5.1 This test measures the ability of the tube to discriminate between light excitations of very similar intensity and characterises the pulse height resolution of the photomultiplier tube/crystal combination. Resolution is an important general parameter of tube performance, apart from its direct applicability to selection for scintillation counting. The test equipment consists of a radiation source, scintillator crystal, the photomultiplier tube under test (which is optically coupled to the crystal with silicone grease or oil) and a MCA. The crystal size is important and must be specified. The tube is operated with a specified electrode voltage distribution, with the source positioned on the axis of the system to produce typically about 1000 counts s^{-1}. Analysis of the stored pulse height distribution gives the resolution figure, defined as the width of the photopeak at half maximum count rate (**figure 6**). This type of measurement is ideal for small computer control.

The conversion efficiency of the crystal, the statistical variations inherent in the conversion of photons to photoelectrons, and similar variations in second-

Figure 5. Output pulse from fast photomultiplier 9818, illustrating parameter definitions.

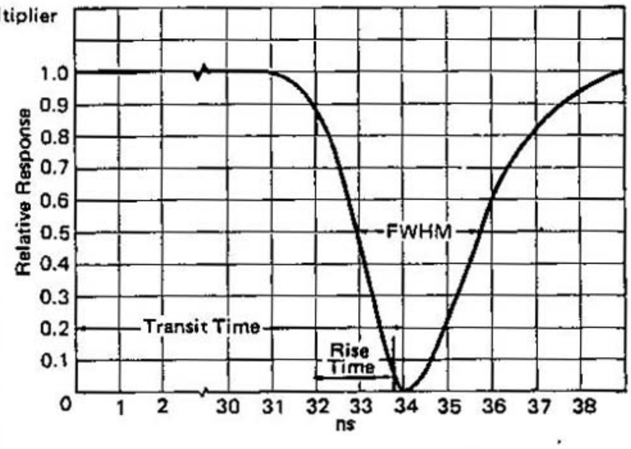
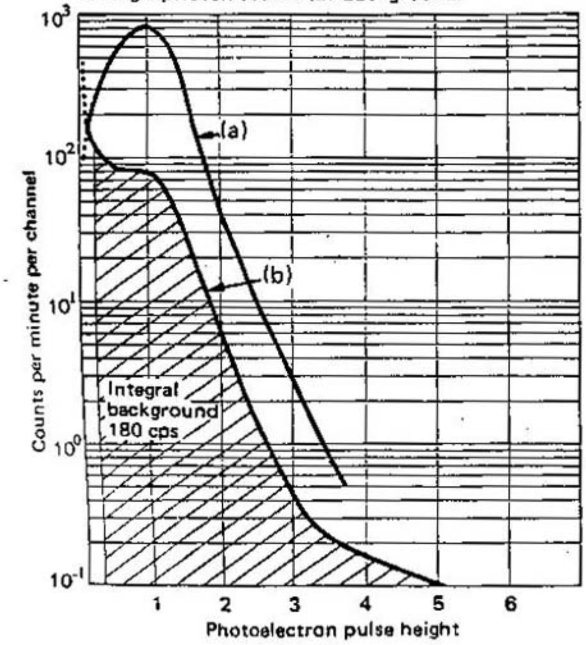


Figure 4. Pulse height distributions for photon counting photomultiplier, type 9813. (a) response to single photon source (b) background.



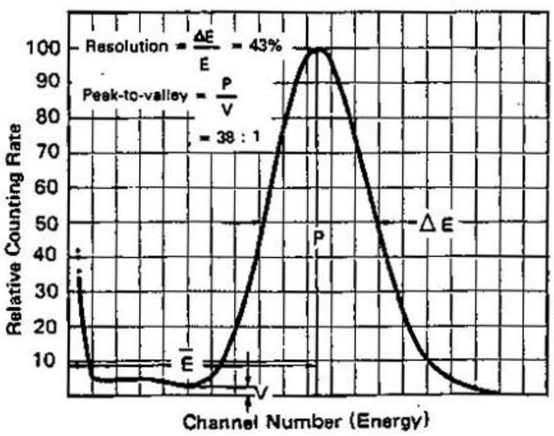


Figure 6. ^{55}Fe spectrum obtained with a thin NaI (Tℓ) crystal detector (D295 photomultiplier).

ary emission, limit the energy resolution of the photomultiplier tube/crystal combination. Absolute values depend upon the quality of the crystal, and therefore, tubes are guaranteed only to factory crystal specifications and measurements are a relative, grading procedure. Normally, a sodium-iodide crystal is used; its dimensions are important, and for best resolution the crystal diameter should be slightly smaller than the effective chathode area.

Commonly used sources and typical values of resolution are listed in **table 2**.

In low energy scintillation counting the background as well as the resolution is important, and a measure of the extent to which tube background interferes with low energy events is obtained from the peak-to-valley count ratio (**figure 6**).

1.5.2 An alternative method of measurement uses simpler electronic techniques to produce a plateau characteristic. This is essentially a single channel analyser with a fixed discriminator level, and the rate of change of counts is recorded around the pulse height of interest by variation of the tube overall voltage. The rate of increase of counts beyond the "knee" (which corresponds to the lowest pulse amplitude in the spectrum peak) is termed the plateau, and should be a minimum. Note also that this system is faster than a MCA system (long storage times) and therefore, capable of handling a higher count rate. The crystal, isotope, amplifier gain and discriminator level should all be specified, and a figure of merit of plateau slope (% change in count rate per overall voltage change) is derived.

This method is particularly useful for determining background and single photoelectron distributions, directly relevant to photon counting applications. Many tubes will produce a plateau for a low light level flux, but the slope and length of the plateau depends upon the multiplier design and the first dynode statistics. Not all tubes show a plateau on background distribution, which is a function of photocathode thermionic emission rate and other secondary effects.

The optimum point of operation is at the lowest overall voltage consistent with the required single photoelectron detection efficiency, [4], (**figure 7**).

1.6 stability

Few manufacturers will give a general specification for stability because of its dependence upon operating considitions (in particular the mean anode current) and the operating history of the tube. Most recommend a maximum mean current at the anode of 1 to 10 μA (dependent upon the tube type) for best stability. The greatest proportion of any output instability occurs within the first 30 minutes of operation, and for many modern photomultipliers the output change under these conditions will be only a few per cent.

There are three particular tests in general use. In scintillation counting it is important that the long term drift in pulse height (at a constant count rate) and the short term drift in amplitude with change of count rate are both minimal.

a) Mean pulse amplitude deviation at constant count rate. The photomultiplier tube is operated under specified conditions with a NaI(Tl)/^{137}Cs source combination, positioned to produce 1000 s^{-1} count rate in the integrated peak. The system is allowed to stabilise for ½ to 1 hour, and then the pulse height is recorded at 1 hour intervals for 16 to 24 hours. The mean gain deviation (MGD) is given by

$$MGD = \frac{\sum_{i=1}^{n} \left| \overline{p} - p_i \right|}{n} x \frac{100}{\overline{p}} \%$$

Where $\overline{p}$ is the mean pulse height
p_i is the i^{th} sample of pulse height
n is the number of sampling points.

Typically, photomultiplier tubes should have 1% stability under these conditions. Note the mean anode current for a tube with a quantum efficiency of 25% peak and operated at 10^5 gain is of the order of 0.1 μA for this test.

b) Pulse amplitude shift with count rate. The photomultiplier tube is operated under similar conditions but at 10,000 counts s^{-1}, for ½ to 1 hour for stabilisation. The count rate is then quickly changed to 1000 s^{-1} and the new pulse ampitude recorded at 10 minute intervals. The mean gain deviation is calculated using a similar formula to (a) above, and again should be better than 1% typically.

c) The shift under changing count rate is caused by dynode instability at different mean current levels, and partially bya temporary instability introduced for some time after a change in operating conditions. This is particularly noticeable after a change in inter-dynode voltage, and is termed hysteresis. It is often caused by electrons striking insulators in the dynode support structure, and charging effects associated with this cause deflection of the electron paths. This can be a problem, for instance in applications of photometry, if the overall voltage is changed as the input light level changes.

Standard tests have been devised to measure hysteresis. In one such test an output current of 1.0 μA is set with a low overall voltage on the photomultiplier tube under test. The light is removed and the voltage increased to a higher vaue for a short period of time. The low voltage is then re-applied to the tube simultaneously with opening the light shutter and the transient undershoot or overshoot recorded on an oscilloscope as the output settles towards its previously established value.

The effect has been reduced or eliminated in modern photomultiplier tubes by modified design to prevent insulator charging occurring.

1.7 linearity

When large peak pulse currents are to be drawn from the photomultplier, it is necessary to know the range of peak output current over which the device behaves in an essentially linear fashion. This depends upon the type of dynode structure in the tube and the voltage applied between dynodes, and the limit of linearity is set by space charge effects, occurring generally between the last few dynodes (assuming the electrode voltage distribution chain has been designed correctly to provide the necessary charge).

It is important to remember that it is the inter-stage voltage which largely determines the saturation characteristic for a particular type of photomultiplier tube, and for the same divider distribution, operation with a low gain sample tube (requiring higher overall voltage) will in general give a better result than for a high gain sample, operating at a lower overall voltage.

Linearity is normally measured using a non-linear voltage distribution to the dynoes, giving increased voltages in the last few stages. A number of techniques are available to measure the saturation characteristics, including the use of calibrated filters, or switched sets of LED pulsed light source,s or a single LED source pulsed with a “piggy-back” type control voltage giving a fixed amplitude ratio. It is usual to measure characteristics with a pulse of width 0.1 to 1.0 μS, at a rate of 1000 counts s^{-1}. Note that the bandwidth of the measurement system amy affect the characteristic; peak (or voltage output) saturation will occur earlier, due to a widening of the pulse shape, than will true loss of charge gain.

The definition of maximum peak linear current is generally taken to be the point at which the deviation from linearity is 10%, but it is sometimes specified as 5% or 2%. The space charge limited or saturated value is the maximum peak output pulse that can be obtained from the photomultiplier tube.

Typical values (for 10% deviation from linearity) are:

Box and grid structure	2 mA
Venetian blind structure	10 mA
Circular focused structure	40 mA
Linear focused structure	100 to 300 mA

(see also **figure 8**).

2 operating practice & precautions

2.1 environmental limitations

2.1.1 temperature

Maximum and minimum temperatures of operation are recommended for all types of photomultiplier.

a) Maximum. Most of the common types of photomultiplier tube contain caesium as an important activation element, and at temperatures of 70 to 80ºC it is likely that this will begin to redistribute itself inside the tube, resulting in a permanent change in performance. In addition, the dark current and residual gas pressure are critical functions of temperature, and at higher temperatures may reach a level such that the tube becomes unstable and breaks down.

For high temperature operation, at up to 175 ºC, tubes are processed without caesium. These tubes have bialkali (Na-K-Sb) photocathodes and usually beryllium copper dynodes, and give an inherent low dark current, see **figure 9**. Tubes are available of higher temperature operation possibly up to 200ºC, but there must be a trade-off between peak quantum efficiency and maximum operating temperature.

b) Minimum. A low temperature limitation is imposed by the photocathode resistivity, which increases with reduction in temperature. The increase in resistivity causes an increase in the voltage dropped across the photocathode layer, dependent upon the photocathode current drawn, and a consequent distortion of the k – d_1 collection field. The bialkali types are particularly susceptible to this effect, having the highest resistivity, and a low temperture limit has been set at -5ºC. However, they may be used at much lower temperatures dependent upon operation with a low level of photocathode current, 0.1 nA maximum at -20ºC for a 50 mm diameter photomultiplier tube.

table 1 standard deviation of time jitter, for single photoelectron events, typical fast linear focused photomultiplier (9813)

illumination conditions	k-d_1 voltage	d_1-d_2/d_2-d_3 bias	value of jitter (ps)
whole cathode	300	R/1.4R	550
whole cathode	430	1.4R/1.6R	475
central 10 mm dia. area	430	1.4R/1.6R	440

table 2 typical values of resolution for a combination of 50 mm photomultiplier and 44 x 44 mm dia. NaI(TI) crystal.

source	energy	resolution
^{55}Fe	5.9 keV X-ray	44%
^{57}Co	122 kev γ	9.8%
^{137}Cs	0.662 MeV γ	7.0%
^{60}Co	1.17, 1.33 MeV γ	Peak to Valley ratio 12:1

It is very important when cooling the photomultiplier tube to avoid thermal shock to the envelope partiularly with quartz window tubes whose envelopes incorporate a stressed graded seal. A standard (Teflon) socket should not be used below -40 ºC, because this may introduce pin strain due to the differential temperature coefficients. Individual pin contacts should be used instead. Tubes overcapped with DAP bases are subject to a lower temperature limit of -30 ºC. In practice, with the exception of S1 photocathodes, there is little advantage in cooling any photomultiplier tube below -20 ºC if the objective is to reduce dark current.

Precautions must be taken to avoid condensation, either on the window of the housing or tube, resulting in loss of transmission, or on the pin connections, which can result in breakdown or noisy operation.

c) It should be noted that there will be a change of response with temperature[6]. In general the photocathode will decrease in red sensitivity (due to surface effects) and increase in blue sensitivity, as the temperature is reduced. The threshold of an S30 photocathode may fall by 40 nm in cooling from +20 to -20 ºC. Except at the threshold these effects are usually minimal compared to a change in secondary emision coefficient, causing a change in gain (typically – ½%/ºC for antimony caesium coated dynodes over the range 20 to 40 ºC).

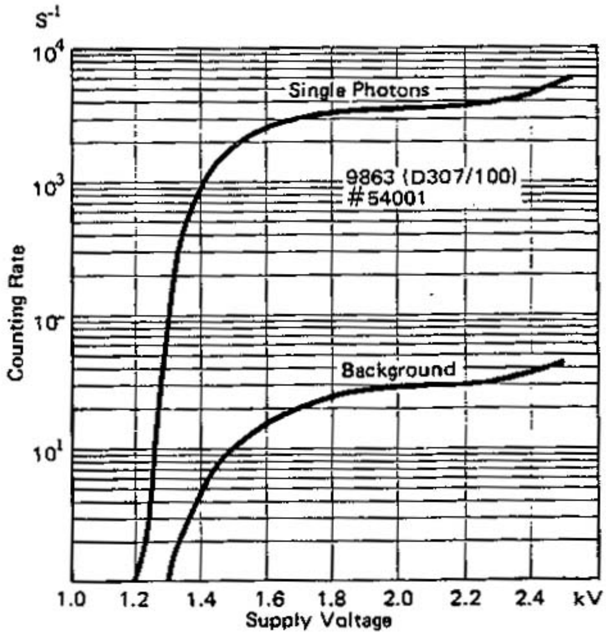


figure 7 integral pulse height distributions for a typical 9863 photon counting photomultiplier.Note that a good plateau is exhibited by both curves.

2.1.2 **magnetic fields**

All photomultipliers are sensitive to magnetic fields, which cause deflection of the electrons from normal trajectories defined by the electrostatic field. The effect is particularly noticeable in the k – d_1 region, where there are long electron path lengths. Obviously the magnitude of the effect depends upon the type of tube and its structure, the orientation of the field and its strength and the tube operating voltage (**figure 10**). Large diameter tubes, particularly fast focused photomultpliers, are very susceptible and a field of the order of the earth's magnetic field can defocus the tube such that the output is reduced by 50% in a particular orientation.

These effects are reduced by the use of high-mu material, either wrapped foil or preformed shields (electrically connected to cathode potential). The shielding required may be estimated from the relationship.

$$\frac{H_{out}}{H_{in}} = \frac{\mu}{2} x \frac{t}{d}$$

where H_{out} = ambient field
H_{in} = maximum field permissible inside the shield
μ = shield material permeability typically 10^4
t = thickness of material
d = diameter of the shield cylinder

Internal parts of the tube are generally made from non-magnetic material such as ferry (54% Cu, 46% Ni) or stainless steel, but some photomultiplier tubes do contain nickel or telcoseal (51% Fe, 49% Ni) and therefore, may retain some magnetic effect, having been exposed to a magnetic field. This may be removed by the standard technique of degaussing in a reducing alternating field. Tubes supplied for rugged applications do not contain any magnetic material (apart from the pinch pins at the base of the tube).

Defocusing by using a magnetic field, either from a coil or a permanent magnet, is a technique used to reduce the effective area of a photocathode for certain applications.

2.1.3 **electrostatic fields**

It is important that material in contact with the tube envelope should not disturb its potential stabilisation, and a mu-metal shield around the photomultiplier tube, acting as a magnetic and electrostatic shield, should be connected to cathode potential. A high potential across the envelope of the tube at the cathode may generate a small leakage current, and this will not only increase the dark current of the photomultplier by glass fluorescence effects (particularly noticeable under cooled conditions) but may also cause permanent damage to the photocathode layer itself. Direct interference with electrostatic fields between dynodes will produce only a small change in gain.

It is generally advisable to operate with the cathode at ground potential when the photomultiplier is coupled to a scintillation crystal or the cathode is in contact with the ground plane. The output pulses are taken through a high quality coupling capacitor, rated at least twice the operating voltage of the photomultiplier tube.

For DC signals or fast pusles into a 50 Ω system, the anode is operated at ground potential, and the reverse polarity used. In this mode the electrostatic shield (which is sometimes the envelope of the tube itself, coated with a graphite layer) will be at a high voltage, and adequate safeguards are obviously required.

2.1.4 **vibration and shock**

Most modern photomultipliers are inherently rugged in their construction and able to withstand fairly severe vibration conditions. For example, standard types (venetian blind and fast focused) have survived a vibration test over the frequency range 32 – 2000 Hz at a sweep rate of 1 octave/minute to an acceleration of 20 g (in all three axes). It has been found unwise to vibrate the tubes which are to be used in an operating system to the full specification, because of possible fatigue effects, and therefore, manufacturers specify a reduced vibration schedule for routine selection.

For particularly sever environments certain modifications to the stuctural supports and the cathode contacts are advisable. Photomultipliers are also available using a system of stacked dynodes with ceramic to metal brazed junctions, for use in applications where the tube must actually operate successfully during the period of severe vibration or shock.

2.1.5 **general environment**

Radioactive sources. It is obvious that if the tube is operated in proximity to intense radioactive sources, then there will be a contribution to the background from Cerenkov photons and fluorescence, and adequate shielding must be provided.

Atmosphere. Helium premeates throught glass(7), and the operation or storage of a photomultiplier tube in an environment of moderate helium partial pressure must be avoided. The internal pressure will rise, the tube will become noisy in operation and eventually breakdown will occur. Slow permeation of helium from the atmosphere makes a contribution to the after-pulsing.

Pressure. Tubes may be operated in vacuum conditions, providing the rate of change of pressure is not excessively fast or non-uniform along the length of the tube. The glass envelope should stand in excess of atmospheric pressure (up to 3 atmospheres), but this may vary from tube to tube, and in particular quartz window tubes are more susceptible to breakage.

Care should be taken when clamping tubes to avoid excess pressure on the envelope, particularly at graded seal points.

2.2 **tube limitations**

2.2.1 **voltage**

Maximum voltage ratings are specified because of voltage breakdown effects.

(a) cathode to first dynode ($k - d_1$).

The recommended voltage gives a general operating condition with regard to efficient photoelectron collection (avoiding photocathode saturation) and utilising the available first dynode gain. It is sometimes desirable to optimise this voltage in a particular application, up to the maximum specified $k - d_1$

voltage. If this voltage is exceeded, excess noise may be produced by field emission effects or high leakage currents, and these are particularly trouble-some due to the full gain applied to these front end effects. The use of a zener diode ensures that the $k - d_1$ voltage does not fall below a mimum valude under conditions of changing overall voltage, but a suitably selected resistor is perfectly adequate when the operating conditions are uniquely defined.

(b) interdynode ($d_n - d_{n-1}$)

Photomultipliers are processed with alkali vapours which deposit on all internal surfaces, and a maxi-mum voltage is specified to avoid the possibility of breakdown across a support member or output pins. It may be advantageous to operate some stages close to the maximum value where optimum linearity or time response is required.

(c) last dynode to anode ($d_n - a$)

This may be given a lower limit than (b) due to the small phsical separation between the last dynode and andode in most photomultiplier tube designs.

(d) Overall voltage (k – a)

This is the maximum safe voltage with respect to insulation breakdown.

2.2.2 **anode sensitivity**

A maximum anode sensitivity (or overall gain) is specified to avoid operating the photomultiplier tube in a region where feedback or regenerative effects may become troublesome. This critical value of gain depends upon the feedback mechanisms in the particular design of tube, e.g. light feedback from cathode luminescence or ion glow effects in the last stages, and the non-linear region can be determined by careful observation of the dark cur-rent in this non-linear region can be determined by careful observation of the dark current with increase of gain. Complete breakdown of the tube may occur for high values of anode current in this non-linear region of operation. It is important to note that this voltage rating (which depends upon the individual tube gain) overrides the maximum overall voltage specification (if this is a higher value), and the value of the voltage corresponding to the maximum anode sensitivity should be care-fully checked by reference to the supplied rated data and typical catalogue characteristics.

2.3 **saturation effects**

(a) photocathode

The magnitude of the maximum peak current that may be drawn from the photocathode depends upon the resistivity of the layer, (see also section

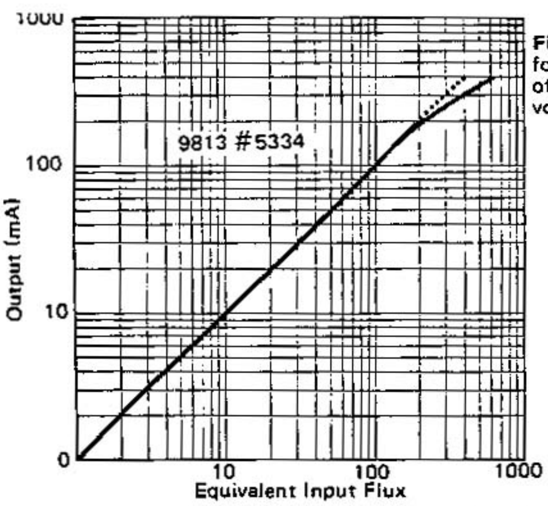


Figure 8. The anode current characteristic for a fast linear focussed 9813 as a function of the luminous flux. The recommended voltage divider network was used(1).

Figure 9. (a) Variation of dark current with temperature for a hot bialkali tube type D300.

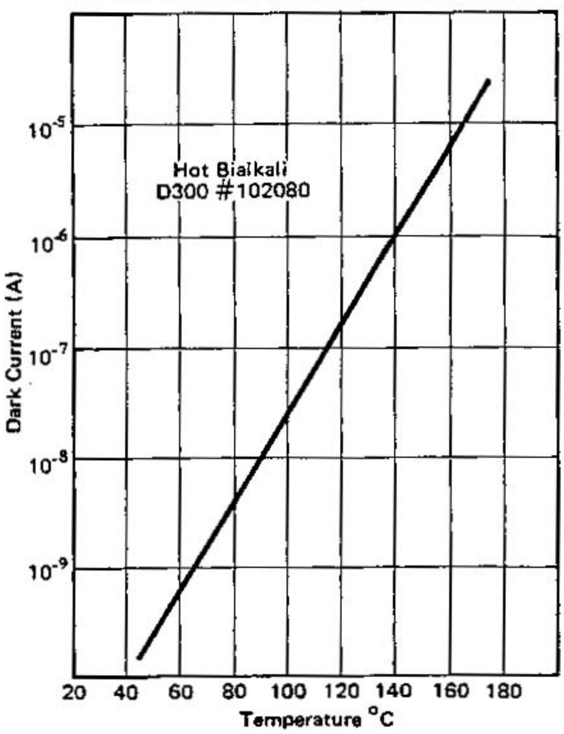
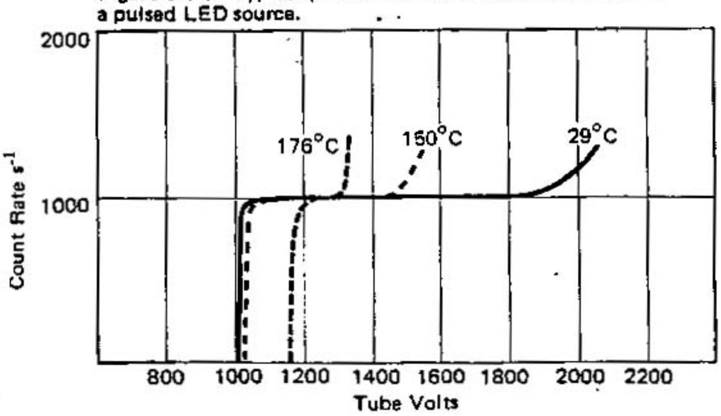


Figure 9 (b). Typical plateau characteristics, obtained with a pulsed LED source.



2.2.1). Opaque photocathodes can be operated at high peak cathode currents, such as 100 $\mu A\ cm^{-2}$. Semitransparent photocathodes vary in their resistivity, the bialkali being the most resistive and the trialkali the least. As a guide, the absolute maximum values recommended for a 50 mm diameter photomultiplier, with a conventional k – d_1 geometry, illuminating the whole cathode and operating at room temperature, are:

Bialkali	0.05 μA
S11	0.3 μA
Trialkali	5 μA

For a small area of illumination or a with a cooled system, the recommended maximum peak cathode currents must be reduced accordingly.

(b) anode

Anode saturation has been discussed previously (see section 1.7), and is minimised by selecting the appropriate tube design and operating with increased inter-stage voltages on the last few dynodes.

It should also be remembered that the anode load is effectively in series with the last dynode to anode voltage, and the output signal developed across it opposes this voltage. If the anode current or anode load resistance becomes too high then the output may become non-linear with input signal.

There is a limitation on the average anode current due to dissipation or heating effects in the last dynodes, and this dissipation should be limited to a fraction of a watt, or typically 0.2 μA mean current. In fact, instability due to dynode fatigue will generally become a problem at much smaller currents, and the maximum safe mean anode current is in the region of 10 μA.

3 general comments

After exposure to room-light (with no voltage applied) the photocathode will retain an amount of “excess energy” in metastable states, and the dark current of the tube will be in excess of its lowest value for a period varying from ½ to 24 hours, depending upon the conditions of exposure and the particular photomultipier tube. The slow component of dark current reduction can sometimes be accelerated by an ageing proces, operating the tube in the dark near its maximum gain rating for a period of hours or days (providing the dark current is not excessively high at the initial stage). Permanent damage may result from the tube being exposed to a bright light while in operating, but modern devices are surprisingly rugged and withstand short accidental exposure with only a temporary increase in noise level or small loss of gain. Intense illumination of the photocathode, particularly focused on to a small area, can cause a permanent loss of sensitivity due to either photo-chemical effects in the layer or ion bombardment of the surface.

A settling period of about one hour should be allowed under normal operating conditions if amplitude levels or integrated signals are to be recorded accurately.

Photomultiplier tubes should function for many thousands of hours, and particularly long life is commonplace in scintillation counting experiements where incident light levels and output current demands are fairly low. Factors shortening the life of the tube include high current operation, excessive voltage operation, high light leves and increased temperature.

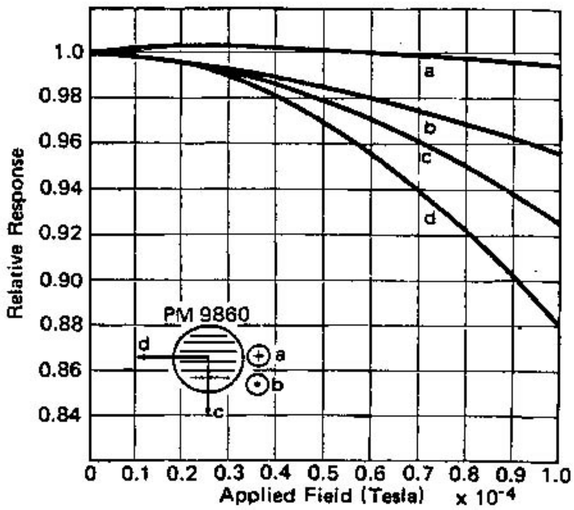


figure 10 variation of anode current under the influence of an applied magnetic field.
a) along the axis directed towards the anode b) along the axis directed away from the andoe c) at right angles to the axis of the photomultiplier and directed along the slats d) at right angles to the axis directed across the slats.

references

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recommend sources of further information

IEC 306 Measuremetn of photosensitive devices Parts I & IV.
IEC 462 Standard test procedures for photo multipliers for scintillation counting.

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