# Photomultiplier Tubes

## Construction and Operating Characteristics
## Connections to External Circuits

HAMAMATSU

# PHOTOMULTIPLIER TUBES

## Construction and Operating Characteristics

### INTRODUCTION

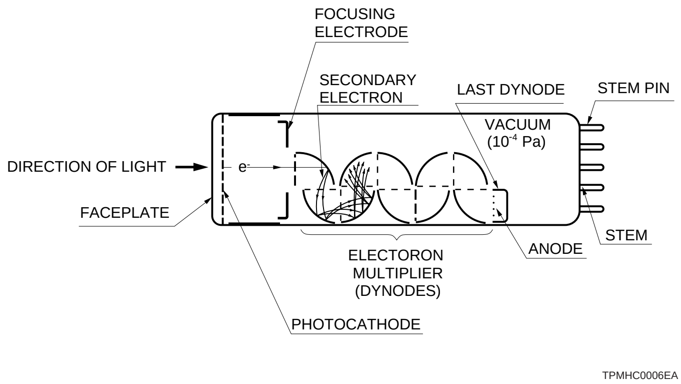
Among the photosensitive devices in use today, the photomultiplier tube (or PMT) is a versatile device that provides extremely high sensitivity and ultra-fast response. A typical photomultiplier tube consists of a photoemissive cathode (photocathode) followed by focusing electrodes, an electron multiplier and an electron collector (anode) in a vacuum tube, as shown in Figure 1.

When light enters the photocathode, the photocathode emits photoelectrons into the vacuum. These photoelectrons are then directed by the focusing electrode voltages towards the electron multiplier where electrons are multiplied by the process of secondary emission. The multiplied electrons are collected by the anode as an output signal.

Because of secondary-emission multiplication, photomultiplier tubes provide extremely high sensitivity and exceptionally low noise among the photosensitive devices currently used to detect radiant energy in the ultraviolet, visible, and near infrared regions. The photomultiplier tube also features fast time response, low noise and a choice of large photosensitive areas.

This section describes the prime features of photomultiplier tube construction and basic operating characteristics.

**Figures 1: Cross-Section of Head-On Type PMT**




### CONSTRUCTION

The photomultiplier tube generally has a photocathode in either a side-on or a head-on configuration. The side-on type receives incident light through the side of the glass bulb, while in the head-on type, it is received through the end of the glass bulb. In general, the side-on type photomultiplier tube is relatively low priced and widely used for spectrophotometers and general photometric systems. Most of the side-on types employ an opaque photocathode (reflection-mode photocathode) and a circular-cage structure electron multiplier which has good sensitivity and high amplification at a relatively low supply voltage.

The head-on type (or the end-on type) has a semitransparent photocathode (transmission-mode photocathode) deposited upon the inner surface of the entrance window. The head-on type provides better spatial uniformity (see page 7) than the side-on type having a reflection-mode photocathode. Other features of head-on types include a choice of photosensitive areas from tens of square millimeters to hundreds of square centimeters.

Variants of the head-on type having a large-diameter hemispherical window have been developed for high energy physics experiments where good angular light acceptability is important.

**Figure 2: External Appearance**

**a) Side-On Type** **b) Head-On Type**

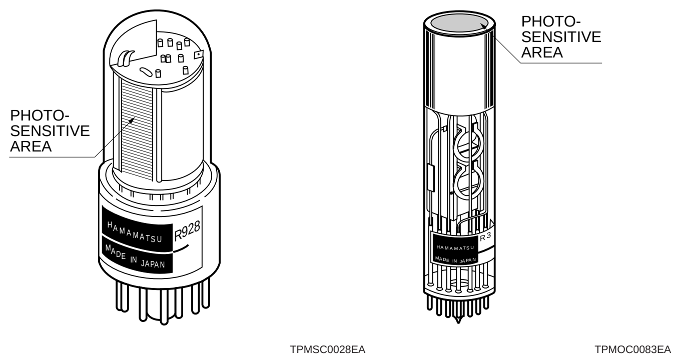
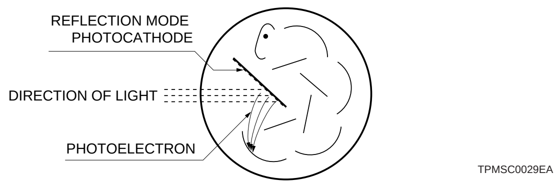
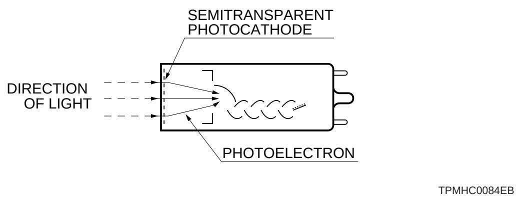



**Figure 3: Types of Photocathode**

**a) Reflection Mode**




**b) Transmission Mode**



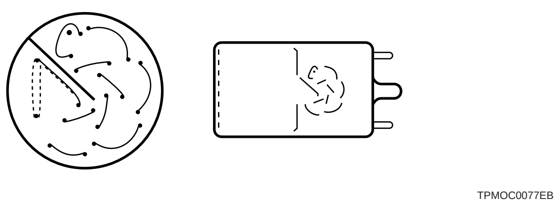

### ELECTRON MULTIPLIER

The superior sensitivity (high current amplification and high S/N ratio) of photomultiplier tubes is due to the use of a low-noise electron multiplier which amplifies electrons by a cascade secondary electron emission process. The electron multiplier consists of from 8, up to 19 stages of electrodes called dynodes.

There are several principal types in use today.

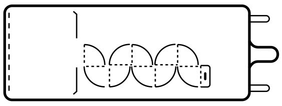
#### 1) Circular-cage type

The circular-cage is generally used for the side-on type of photomultiplier tube. The prime features of the circular-cage are compactness and fast time response.



### 2) Box-and-grid type

This type consists of a train of quarter cylindrical dynodes and is widely used in head-on type photomultiplier tubes because of its relatively simple dynode design and improved uniformity, although time response may be too slow in some applications.



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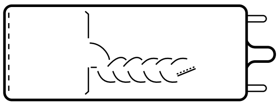
### 3) Linear-focused type

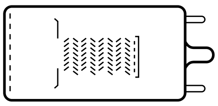
The linear-focused type features extremely fast response time and is widely used in head-on type photomultiplier tubes where time resolution and pulse linearity are important.



TPMOC0079EA

### 4) Venetian blind type

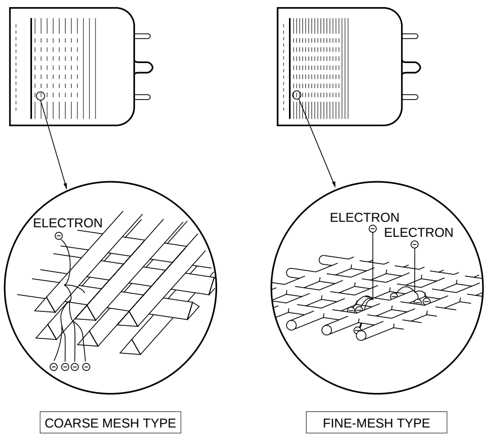
The venetian blind type has a large dynode area and is primarily used for tubes with large photocathode areas. It offers better uniformity and a larger pulse output current. This structure is usually used when time response is not a prime consideration.



TPMOC0080EA

### 5) Mesh type

The mesh type has a structure of fine mesh electrodes stacked in close proximity. This type provides high immunity to magnetic fields, as well as good uniformity and high pulse linearity. In addition, it has position-sensitive capability when used with cross-wire anodes or multiple anodes.

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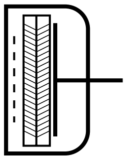
### 6) Microchannel plate (MCP)

The MCP is a thin disk consisting of millions of micro glass tubes (channels) fused in parallel with each other. Each channel acts as an independent electron multiplier. The MCP offers much faster time response than the other discrete dynodes. It also features good immunity from magnetic fields and two-dimensional detection ability when multiple anodes are used.



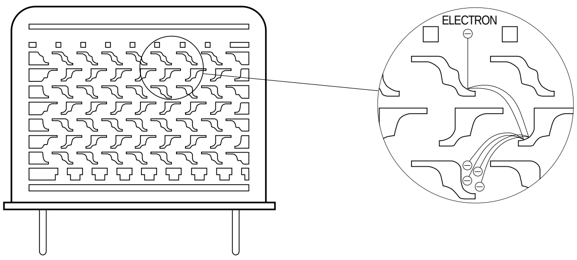
TPMOC0082EA

### 7) Metal channel type

The Metal channel dynode has a compact dynode costruction manufactured by our unique fine machining technique.

It achieves high speed response due to its narrower space between each stage of dynodes than the other type of conventional dynode construction.

It is also adequate for position sensitive measurement.




TPMOC0084EA

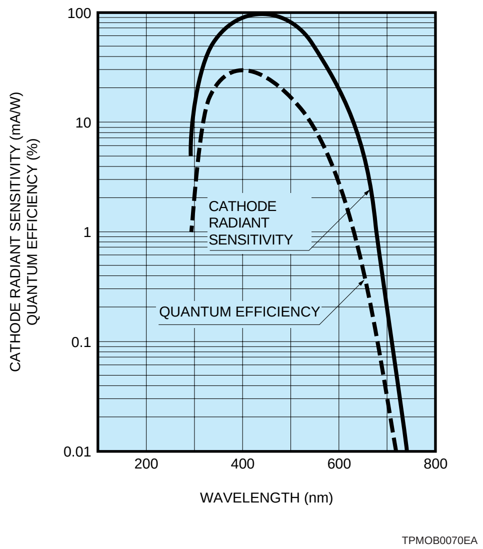
In addition, hybrid dynodes combining two of the above dynodes are available. These hybrid dynodes are designed to provide the merits of each dynode.

## SPECTRAL RESPONSE

The photocathode of a photomultiplier tube converts energy of incident light into photoelectrons. The conversion efficiency (photocathode sensitivity) varies with the wavelength of the incident light. This relationship between photocathode sensitivity and wavelength is called the spectral response characteristic. Figure 4 shows the typical spectral response of a bialkali photomultiplier tube. The spectral response characteristics are determined on the long wavelength side by the photocathode material and on the short wavelength side by the window material. Typical spectral response characteristics for various types of photomultiplier tubes are shown on pages 88 and 89. In this catalog, the longwavelength cut-off of spectral response characteristics is defined as the wavelength at which the cathode radiant sensitivity becomes 1% of the maximum sensitivity for bialkali and Ag-O-Cs photocathodes, and 0.1% of the maximum sensitivity for multialkali photocathodes.

Spectral response characteristics are typical curves for representative tube types. Actual data may be different from type to type.

**Figure 4: Typical Spectral Response of Head-On, Bialkali Photocathode**




## PHOTOCATHODE MATERIALS

The photocathode is a photoemissive surface usually consisting of alkali metals with very low work functions. The photocathode materials most commonly used in photomultiplier tubes are as follows:

### 1) Ag-O-Cs

The transmission-mode photocathode using this material is designated S-1 and sensitive from the visible to infrared range (300 to 1200nm). Since Ag-O-Cs has comparatively high thermionic dark emission (refer to "ANODE DARK CURRENT" on page 8), tubes of this photocathode are mainly used for detection in the near infrared region with the photocathode cooled.

### 2) GaAs(Cs)

GaAs activated in cesium is also used as a photocathode. The spectral response of this photocathode usually covers a wider spectral response range than multialkali, from ultraviolet to 930nm, which is comparatively flat over 300 to 850nm.

### 3) InGaAs(Cs)

This photocathode has greater extended sensitivity in the infrared range than GaAs. Moreover, in the range between 900 and 1000nm, InGaAs has much higher S/N ratio than Ag-O-Cs.

### 4) Sb-Cs

This is a widely used photocathode and has a spectral response in the ultraviolet to visible range. This is not suited for transmission-mode photocathodes and mainly used for reflection-mode photocathodes.

### 5) Bialkali (Sb-Rb-Cs, Sb-K-Cs)

These have a spectral response range similar to the Sb-Cs photocathode, but have higher sensitivity and lower noise than Sb-Cs. The transmission mode bialkali photocathodes also have a favorable blue sensitivity for scintillator flashes from NaI (Tl) scintillators, thus are frequently used for radiation measurement using scintillation counting.

### 6) High temperature bialkali or low noise bialkali (Na-K-Sb)

This is particularly useful at higher operating temperatures since it can withstand up to 175°C. A major application is in the oil well logging industry. At room temperatures, this photocathode operates with very low dark current, making it ideal for use in photon counting applications.

### 7) Multialkali (Na-K-Sb-Cs)

The multialkali photocathode has a high, wide spectral response from the ultraviolet to near infrared region. It is widely used for broad-band spectrophotometers. The long wavelength response can be extended out to 930nm by special photocathode processing.

### 8) Cs-Te, Cs-I

These materials are sensitive to vacuum UV and UV rays but not to visible light and are therefore called solar blind. Cs-Te is quite insensitive to wavelengths longer than 320nm, and Cs-I to those longer than 200nm.

## WINDOW MATERIALS

The window materials commonly used in photomultiplier tubes are as follows:

### 1) Borosilicate glass

This is frequently used glass material. It transmits radiation from the near infrared to approximately 300nm. It is not suitable for detection in the ultraviolet region. For some applications, the combination of a bialkali photocathode and a low-noise borosilicate glass (so called K-free glass) is used. The K-free glass contains very low potassium ($K_2O$) which can cause background counts by $^{40}$K. In particular, tubes designed for scintillation counting often employ K-free glass not only for the faceplate but also for the side bulb to minimize noise pulses.

### 2) UV-transmitting glass (UV glass)

This glass transmits ultraviolet radiation well, as the name implies, and is widely used as a borosilicate glass. For spectroscopy applications, UV glass is commonly used. The UV cut-off is approximately 185nm.

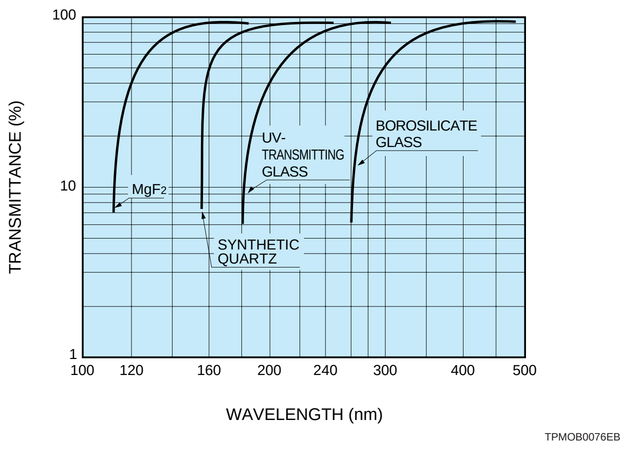
### 3) Synthetic silica

The synthetic silica transmits ultraviolet radiation down to 160nm and offers lower absorption in the ultraviolet range compared to fused silica. Since thermal expansion coefficient of the synthetic silica is different from Kovar which is used for the tube leads, it is not suitable for the stem material of the tube (see Figure 1 on page 1). Borosilicate glass is used for the stem, then a graded seal using glasses with gradually different thermal expansion coefficients are connected to the synthetic silica window. Because of this structure, the graded seal is vulnerable to mechanical shock so that sufficient care should be taken in handling the tube.

### 4) $MgF_2$ (magnesium fluoride)

The crystals of alkali halide are superior in transmitting ultraviolet radiation, but have the disadvantage of deliquescence. Among these, $MgF_2$ is known as a practical window material because it offers low deliquescence and transmits ultraviolet radiation down to 115nm.

**Figure 5: Typical Transmittance of Various Window Materials**




As stated above, spectral response range is determined by the photocathode and window materials. It is important to select an appropriate combination which will suit your applications.

## RADIANT SENSITIVITY AND QUANTUM EFFICIENCY

As Figure 4 shows, spectral response is usually expressed in terms of radiant sensitivity or quantum efficiency as a function of wavelength. Radiant sensitivity (S) is the photoelectric current from the photocathode, divided by the incident radiant power at a given wavelength, expressed in A/W (amperes per watt). Quantum efficiency (QE) is the number of photoelectrons emitted from the photocathode divided by the number of incident photons. It is customary to present quantum efficiency in a percentage. Quantum efficiency and radiant sensitivity have the following relationship at a given wavelength.

$$QE = \frac{S \times 12400}{\lambda} \times 100\%$$

Where S is the radiant sensitivity in A/W at the given wavelength, and $\lambda$ is the wavelength in nm (nanometers).

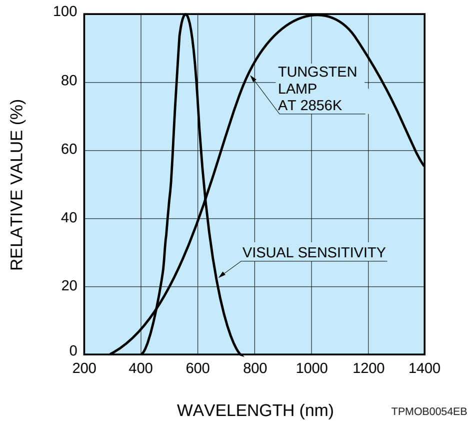
## LUMINOUS SENSITIVITY

Since the measurement of the spectral response characteristic of a photomultiplier tube requires a sophisticated system and much time, it is not practical to provide customers with spectral response characteristics for each tube ordered. Instead cathode or anode luminous sensitivity is commonly used.

The cathode luminous sensitivity is the photoelectric current from the photocathode per incident light flux ($10^{-5}$ to $10^{-2}$ lumens) from a tungsten filament lamp operated at a distribution temperature of 2856K. The anode luminous sensitivity is the anode output current (amplified by the secondary emission process) per incident light flux ($10^{-10}$ to $10^{-5}$ lumens) on the photocathode. Although the same tungsten lamp is used, the light flux and the applied voltage are adjusted to an appropriate level. These parameters are particularly useful when comparing tubes having the same or similar spectral response range. Hamamatsu final test sheets accompanying the tubes usually indicate these parameters except for tubes with Cs-I or Cs-Te photocathodes, which are not sensitive to tungsten lamp light. (Radiant sensitivity at a specific wavelength is listed for those tubes instead.)

Both the cathode and anode luminous sensitivities are expressed in units of A/lm (amperes per lumen). Note that the lumen is a unit used for luminous flux in the visible region and therefore these values may be meaningless for tubes which are sensitive beyond the visible region. (For those tubes, the blue sensitivity or red/white ratio is often used.)

**Figure 6: Typical Human Eye Response and Spectral Energy Distribution of 2856K Tungsten Lamp**



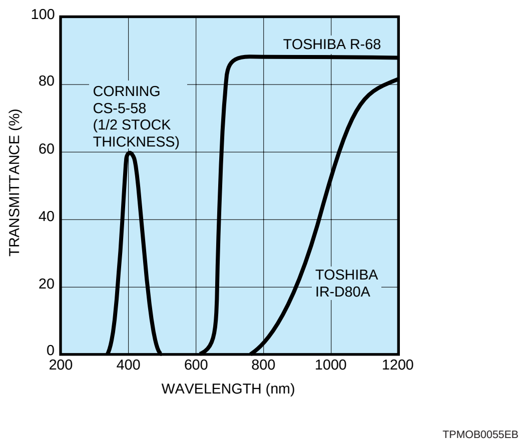

## BLUE SENSITIVITY AND RED/WHITE RATIO

For simple comparison of spectral response of photomultiplier tubes, cathode blue sensitivity and red/white ratio are often used.

The cathode blue sensitivity is the photoelectric current from the photocathode produced by a light flux of a tungsten lamp at 2856K passing through a blue filter (Corning CS No. 5-58 polished to half stock thickness). Since the light flux, once transmitted through the blue filter cannot be expressed in lumens, blue sensitivity is conveniently expressed in A/lm-b (amperes per lumen-blue). The blue sensitivity is an important parameter in scintillation counting using an NaI (Tl) scintillator since the NaI (Tl) scintillator produces emissions in the blue region of the spectrum, and may be the decisive factor in energy resolution.

The red/white ratio is used for photomultiplier tubes with a spectral response extending to the near infrared region. This parameter is defined as the quotient of the cathode sensitivity measured with a light flux of a tungsten lamp at 2856K passing through a red filter (Toshiba IR-D80A for the S-1 photocathode or R-68 for others) divided by the cathode luminous sensitivity with the filter removed.

**Figure 7: Transmittance of Various Filters**




## CURRENT AMPLIFICATION (GAIN)

Photoelectrons emitted from a photocathode are accelerated by an electric field so as to strike the first dynode and produce secondary electron emissions. These secondary electrons then impinge upon the next dynode to produce additional secondary electron emissions. Repeating this process over successive dynode stages, a high current amplification is achieved. A very small photoelectric current from the photocathode can be observed as a large output current from the anode of the photomultiplier tube.

Current amplification is simply the ratio of the anode output current to the photoelectric current from the photocathode. Ideally, the current amplification of a photomultiplier tube having n dynode stage and an average secondary emission ratio $\delta$ per stage is $\delta^n$. While the secondary electron emission ratio $\delta$ is given by

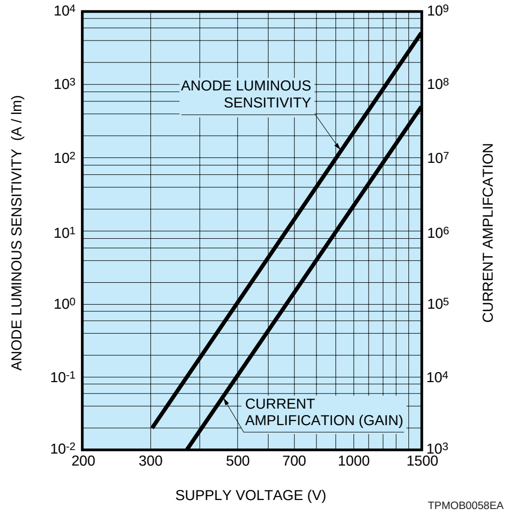
$$\delta = A \cdot E^{\alpha}$$

where A is constant, E is an interstage voltage, and $\alpha$ is a coefficient determined by the dynode material and geometric structure. It usually has a value of 0.7 to 0.8.
When a voltage V is applied between the cathode and the anode of a photomultiplier tube having n dynode stages, current amplification, $\mu$, becomes

$$\mu = \delta^n = (A \cdot E^{\alpha})^n = \left\{A \cdot \left(\frac{V}{n+1}\right)^{\alpha}\right\}^n$$
$$= \frac{A^n}{(n+1)^{\alpha n}} \cdot V^{\alpha n} = K \cdot V^{\alpha n}$$

Since photomultiplier tubes generally have 9 to 12 dynode stages, the anode output varies directly with the 6th to 10th power of the change in applied voltage. The output signal of the photomultiplier tube is extremely susceptible to fluctuations in the power supply voltage, thus the power supply must be very stable and provide minimum ripple, drift and temperature coefficient. Various types of regulated high-voltage power supplies designed with this consideration are available from Hamamatsu .

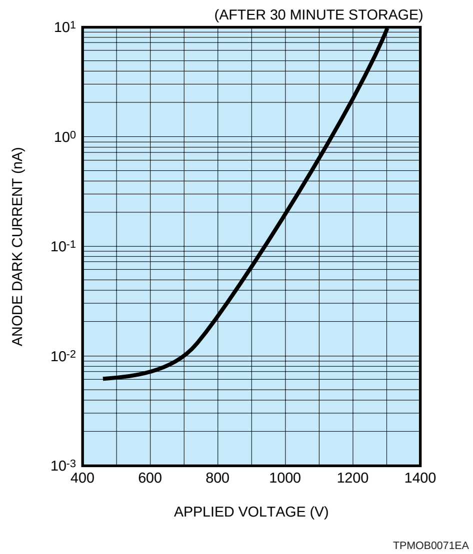
**Figure 8: Typical Current Amplification vs. Supply Voltage**




## ANODE DARK CURRENT

A small amount of current flows in a photomultiplier tube even when the tube is operated in a completely dark state. This output current, called the anode dark current, and the resulting noise are critical factors in determining the detectivity of a photomultiplier tube. As Figure 9 shows, dark current is greatly dependent on the supply voltage.

**Figure 9: Typical Dark Current vs. Supply Voltage**



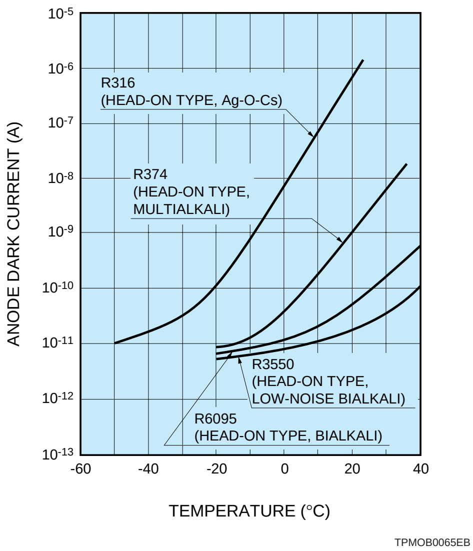

Major sources of dark current may be categorized as follows:

### 1) Thermionic emission of electrons

Since the materials of the photocathode and dynodes have very low work functions, they emit thermionic electrons even at room temperature. Most of dark currents originate from the thermionic emissions, especially those from the photocathode as they are multiplied by the dynodes. Cooling the photocathode is most effective in reducing thermionic emission and, this is particularly useful in applications where low dark counts are essential such as in photon counting.

Figure 10 shows the relationship between dark current and temperature for various photocathodes. Photocathodes which have high sensitivity in the red to infrared region, especially S-1, show higher dark current at room temperature. Hamamatsu provides thermoelectric coolers (C659 and C4877) designed for various sizes of photomultiplier tubes.

**Figure 10: Temperature Characteristics of Dark Current**




### 2) Ionization of residual gases (ion feedback)

Residual gases inside a photomultiplier tube can be ionized by collision with electrons. When these ions strike the photocathode or earlier stages of dynodes, secondary electrons may be emitted, thus resulting in relatively large output noise pulses. These noise pulses are usually observed as afterpulses following the primary signal pulses and may be a problem in detecting light pulses. Present photomultiplier tubes are designed to minimize afterpulses.

### 3) Glass scintillation

When electrons deviating from their normal trajectories strike the glass envelope, scintillations may occur and dark pulses may result. To minimize this type of dark pulse, photomultiplier tubes may be operated with the anode at high voltage and the cathode at ground potential. But this is inconvenient to handle the tube. To obtain the same effect without difficulty, Hamamatsu provides "HA coating" in which the glass bulb is coated with a conductive paint connected to the cathode. (See "GROUND POLARITY AND HA COATING" on page 10.)

### 4) Leakage current (ohmic leakage)

Leakage current resulting from the glass stem base and socket may be another source of dark current. This is predominant when the photomultiplier tube is operated at a low voltage or low temperature. The flatter slopes in Figures 9 and 10 are mainly due to leakage current.

Contamination from dirt and moisture on the surface of the tube may increase the leakage current, and therefore should be avoided.

### 5) Field emission

When a photomultiplier tube is operated at a voltage near the maximum rated value, electrons may be emitted from electrodes by the strong electric field and may cause noise pulses. It is therefore recommended that the tube be operated at a voltage 20 to 30% lower than the maximum rating.

The anode dark current decreases with time after the tube is placed in a dark state. In this catalog, anode dark currents are measured after 30-minute storage in a dark state.

## ENI (EQUIVALENT NOISE INPUT)

ENI is an indication of the photon-limited signal-to-noise ratio. It refers to the amount of light usually in watts or lumens necessary to produce a signal-to-noise ratio of unity in the output of a photomultiplier tube. ENI is expressed in units of lumens or watts. For example the value of ENI (in watts) is given by

$$\text{ENI} = \frac{\sqrt{2q \cdot \text{Idb} \cdot \mu \cdot \Delta f}}{S} \quad \text{(watts or lumens)}$$

where

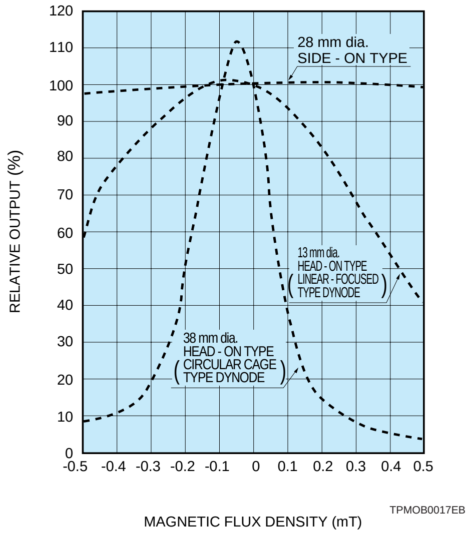
$q$ = electronic charge ($1.60 \times 10^{-19}$ coul.)
Idb = anode dark current in amperes after 30-minute storage in darkness
$\mu$ = current amplification
$\Delta f$ = bandwidth of the system in hertz (usually 1 hertz)
S = anode radiant sensitivity in amperes per watt at the wavelength of interest or anode luminous sensitivity in amperes per lumen

For the tubes listed in this catalog, the value of ENI may be calculated by the above equation. Usually it has a value between $10^{-15}$ and $10^{-16}$ watts or lumens.

## MAGNETIC FIELD EFFECTS

Most photomultiplier tubes are affected by the presence of magnetic fields. Magnetic fields may deflect electrons from their normal trajectories and cause a loss of gain. The extent of the loss of gain depends on the type of photomultiplier tube and its orientation in the magnetic field. Figure 11 shows typical effects of magnetic fields on some types of photomultiplier tubes. In general, tubes having a long path from the photocathode to the first dynode are very vulnerable to magnetic fields. Therefore head-on types, especially large diameter tubes, tend to be more adversely influenced by magnetic fields.

**Figure 11: Typical Effects by Magnetic Fields Perpendicular to Tube Axis**

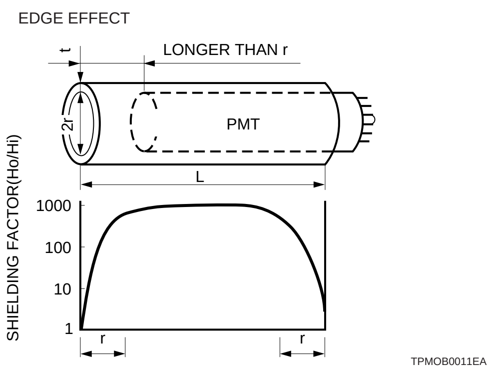



When a tube has to be operated in magnetic fields, it may be necessary to shield the tube with a magnetic shield case. Hamamatsu provides a variety of magnetic shield cases. To express the effect of a magnetic shield case, the magnetic shielding factor is used. This is the ratio of the strength of the magnetic field outside the shield case, $H_{out}$, to that inside the shield case, $H_{in}$. It is determined by the permeability $\mu$, the thickness t (mm) and inner diameter D (mm) of the shield case, as follows:

$$\frac{H_{out}}{H_{in}} = \frac{3\mu t}{4D}$$

It should be noted that the magnetic shielding effect decreases towards the edge of the shield case as shown in Figure 12. It is recommended that the tube be covered by a shield case longer than the tube length by at least half the tube diameter.

**Figure 12: Edge Effect of Magnetic Shield Case**




Hamamatsu provides photomultiplier tubes using fine mesh dynodes. These tube types exhibit much higher immunity to external magnetic fields than the photomultiplier tubes using other dynodes. In addition, when the light level to be measured is rather high, triode or tetrode type photomultiplier tubes can be used in hishly magnetic fields.

## SPATIAL UNIFORMITY

Spatial uniformity is the variation of sensitivity with position of incident light on a photocathode.

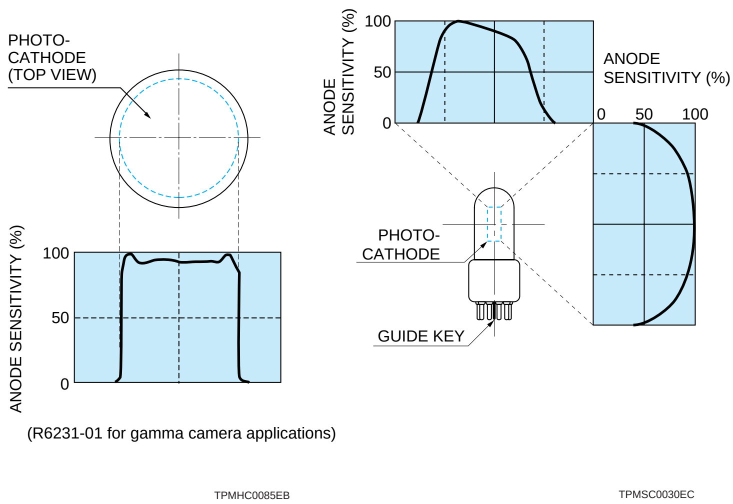
Although the focusing electrodes of a photomultiplier tube are designed so that electrons emitted from the photocathode or dynodes are collected efficiently by the first or following dynodes, some electrons may deviate from their desired trajectories in the focusing and multiplication processes, resulting in a loss of collection efficiency. This loss of collection efficiency varies with the position on the photocathode from which the photoelectrons are emitted and influences the spatial uniformity of a photomultiplier tube. The spatial uniformity is also determined by the photocathode surface uniformity itself.

In general, head-on type photomultiplier tubes provide better spatial uniformity than side-on types because of the photocathode to first dynode geometry. Tubes especially designed for gamma camera applications have excellent spatial uniformity, because uniformity is the decisive factor in the overall performance of a gamma camera.

**Figure 13: Examples of Spatial Uniformity**

**(a) Head-On Type** **(R6231-01 for gamma camera applications)**

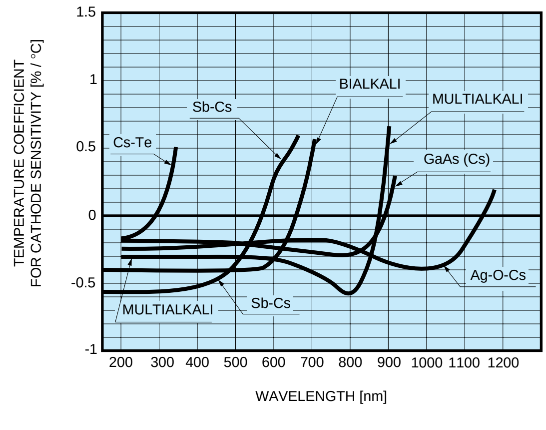
**(b) Side-On Type** **Reflection-mode photocathode**



## TEMPERATURE CHARACTERISTICS

By decreasing the temperature of a photomultiplier tube, dark current originating from thermionic emission can be reduced. Sensitivity of the photomultiplier tube also varies with the temperature. In the ultraviolet to visible region, the temperature coefficient of sensitivity usually has a negative value, while near the long wavelength cut-off it has a positive value. Figure 14 shows temperature coefficients vs. wavelength of typical photomultiplier tubes. Since the temperature coefficient change is large near the long wavelength cutoff, temperature control may be required in some applications.

**Figure 14: Typical Temperature Coefficients of Anode Sensitivity**

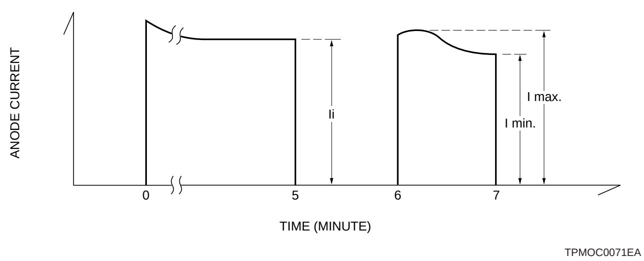



## HYSTERESIS

A photomultiplier tube may exhibit an unstable output for several seconds to several tens of seconds after voltage and light are applied, i.e., output may slightly overshoot or undershoot before reaching a stable level (Figure 15). This instability is called hysteresis and may be a problem in spectrophotometry and other applications.

Hysteresis is mainly caused by electrons being deviated from their planned trajectories and electrostatically charging the dynode support ceramics and glass bulb. When the applied voltage is changed as the light input changes, marked hysteresis can occur. As a countermeasure, many Hamamatsu side-on photomultiplier tubes employ "anti-hysteresis design" which virtually eliminate hysteresis.

**Figure 15: Hysteresis Measurement**

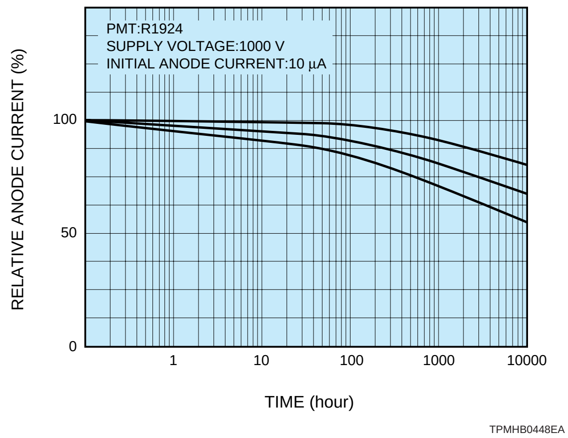



## DRIFT AND LIFE CHARACTERISTIC

While operating a photomultiplier tube continuously over a long period, anode output current of the photomultiplier tube may vary slightly with time, although operating conditions have not changed. This change is reffered to as drift or in the case where the operating time is $10^3$ to $10^4$ hrs it is called life characteristics. Figure 16 shows typical life characteristics.

Drift is primarily caused by damage to the last dynode by heavy electron bombardment. Therefore the use of lower anode current is desirable. When stability is of prime importance, the use of average anode current of 1µA or less is recommended.

**Figure 16: Examples of Life**




## TIME RESPONSE

In the measurement of pulsed light, the anode output signal should reproduce a waveform faithful to the incident pulse waveform. This reproducibility is greatly affected by the electron transit time, anode pulse rise time, and electron transit time spread (TTS).

As illustrated in Figure 17, the electron transit time is the time interval between the arrival of a delta function light pulse (pulse width less than 50ns) at the photocathode and the instant when the anode output pulse reaches its peak amplitude. The anode pulse rise time is defined as the time required to rise from 10% to 90% of the peak amplitude when the whole photocathode is illuminated by a delta function light pulse (pulse width less than 50 ps). The electron transit time has a fluctuation between individual light pulses. This fluctuation is called transit time spread (TTS) and defined as the FWHM of the frequency distribution of electron transit times (Figure 18) at single photoelectron event. The TTS is an important factor in time-resolved measurement.

The time response characteristics depend on the dynode structure and applied voltage. In general, tubes of the linear-focused or circular-cage structure exhibit better time response than tubes of the box-and-grid or venetian blind structure. MCP-PMTs, which employ an MCP in place of conventional dynodes, offer better time response than tubes using other dynodes. For example, the TTS can be significantly improved compared to normal photomultiplier tubes because a nearly parallel electric field is applied between the photocathode, MCP and the anode. Figure 19 shows typical time response characteristics vs. applied voltage for types R2059 (51mm dia. head-on, 12-stage, linear-focused type) .

**Figure 17: Anode Pulse Rise Time and Electron Transit Time**

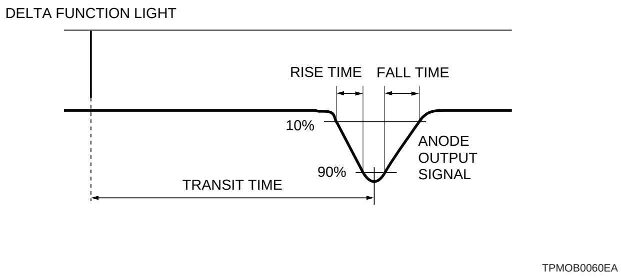



**Figure 18: Electron Transit Time Spread (TTS)**

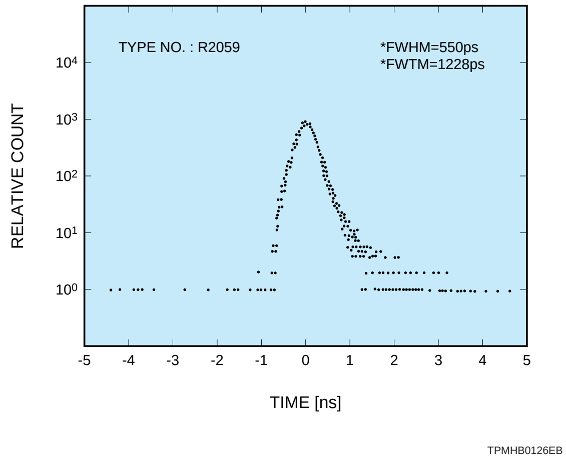
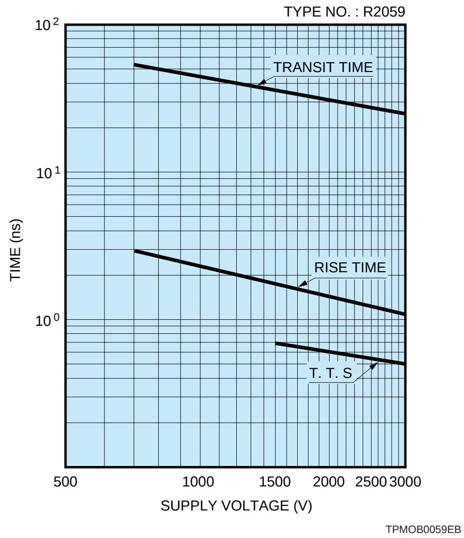



**Figure 19: Time Response Characteristics vs. Supply Voltage**

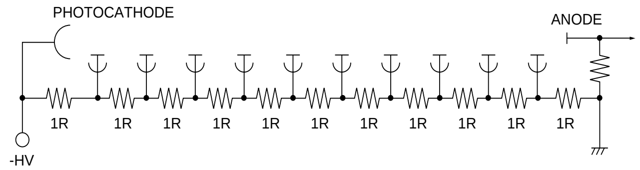



## VOLTAGE-DIVIDER CONSIDERATION

Interstage voltages for the dynodes of a photomultiplier tube are usually supplied by a voltage-divider circuits consisting of series-connected resistors. Schematic diagrams of typical voltage-divider circuits are illustrated in Figure 20. Circuit (a) is a basic arrangement (DC output) and (b) is for pulse operations. Figure 21 shows the relationship between the incident light level and the average anode output current of a photomultiplier tube using the voltage-divider circuit (a). Deviation from the ideal linearity occurs at a certain incident level (region B). This is caused by an increase in dynode voltage due to the redistribution of the voltage loss between the last few stages, resulting in an apparent increase in sensitivity. As the input light level is increased, the anode output current begins to saturate near the value of the current flowing through the voltage divider (region C). Therefore, it is recommended that the voltage-divider current be maintained at least at 20 times the average anode output current required from the photomultiplier tube.

**Figure 20: Schematic Diagrams of Voltage-Divider Circuits**

**(a) Basic arrangement for DC operation**




**(b) For pulse operation**

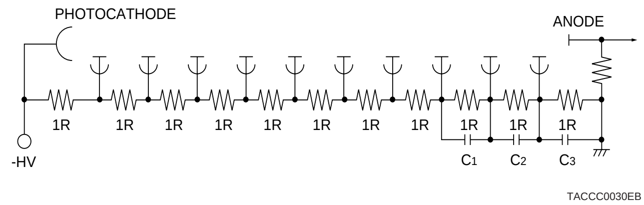
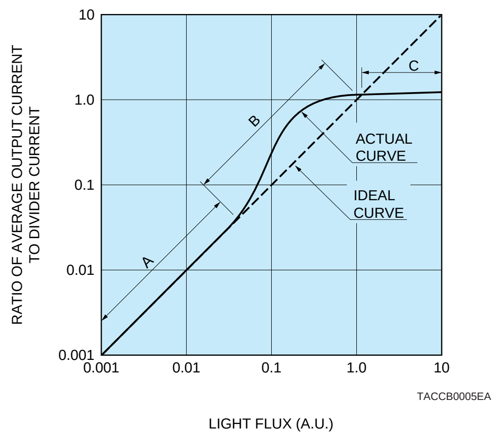



**Figure 21: Output Characteristics of a PMT Using Voltage-Divider Circuit (a)**



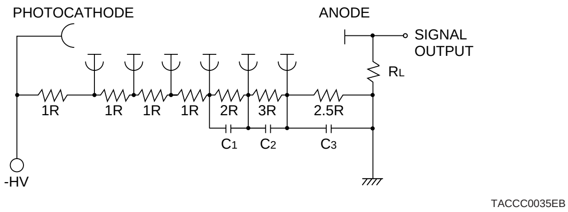
Generally high output current is required in pulsed light applications. In order to maintain dynode potentials at a constant value during pulse durations and obtain high peak currents, large capacitors are used as shown in Figure 20 (b). The capacitor values depend on the output charge. If linearity of better than 1% is needed, the capacitor value should be at least 100 times the output charge per pulse, as follows:

$$C > 100 \frac{I \cdot t}{V} \text{ (farads)}$$

where I is the peak output current in amperes, it is the pulse width in seconds, and V is the voltage across the capacitor in volts.
In high energy physics applications where a high pulse output is required, as the incident light is increased while the interstage voltage is kept fixed, output saturation will occur at a certain level. This is caused by an increase in the electron density between the electrodes, causing space charge effects which disturb the electron current. As a corrective action to overcome space charge effects, the voltage applied to the last few stages, where the electron density becomes high, should be set at a higher value than the standard voltage distribution so that the voltage gradient between those electrodes is enhanced. For this purpose, a so-called tapered bleeder circuit (Figure 22) is often employed. Use of this tapered bleeder circuit improves pulse linearity 5 to 10 times better than that obtained with normal bleeder circuits (equally divided circuits).

Hamamatsu provides a variety of socket assemblies incorporating voltage-divider circuits. They are compact, rugged, lightweight and ensure the maximum performance for a photomultiplier tube by simple wiring.

**Figure 22: Tapered Bleeder Circuit**




## GROUND POLARITY AND HA COATING

The general technique used for voltage-divider circuits is to ground the anode with a high negative voltage applied to the cathode, as shown in Figure 20. This scheme facilitates the connection of such circuits as ammeters or current-to-voltage conversion operational amplifiers to the photomultiplier tube. However, when a grounded anode configuration is used, bringing a grounded metallic holder or magnetic shield case near the bulb of the tube can cause electrons to strike the inner bulb wall, resulting in the generation of noise. Also, for head-on type photomultiplier tubes, if the faceplate or bulb near the photocathode is grounded, the slight conductivity of the glass material causes a current to flow between the photocathode (which has a high negative potential) and ground. This may cause significant deterioration of the photocathode. For this reason, when designing the housing for a photomultiplier tube and when using an electrostatic or magnetic shield case, extreme care is required.

In addition, when using foam rubber or similar material to mount the tube in its housing, it is essential that material having sufficiently good insulation properties be used. This problem can be solved by applying a black conductive layer around the bulb and connecting to the cathode potential (called HA Coating), as shown in Figure 23.

As mentioned above, the HA coating can be effectively used to eliminate the effects of external potential on the side of the bulb. However, if a grounded object is located on the photocathode faceplate, there are no effective countermeasures. Glass scintillation, if it occurrs in the faceplate, has a larger influence on the noise. It also causes deterioration of the photocathode sensitivity and, once deteriorated, the sensitivity will never recover to the original level. To solve these problems, it is recommended that the photomultiplier tube be operated in the cathode ground scheme, as shown in Figure 24, with the anode at a positive high voltage. For example, in scintillation counting, since the grounded scintillator is directly coupled to the photomultiplier tube, it is recommended that the cathode be grounded, with a high positive voltage applied to the anode. Using this scheme, a coupling capacitor Cc is used to separate the high positive voltage applied to the anode from the signal, making it impossible to obtain a DC signal output.

**Figure 23: HA Coating**

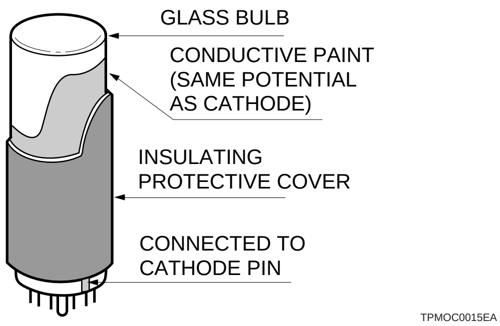
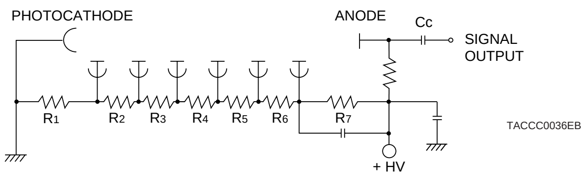


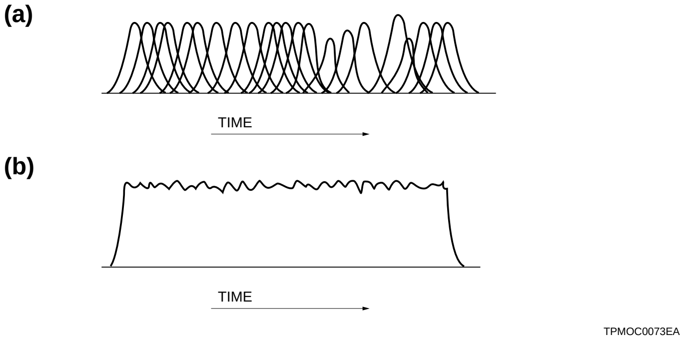

**Figure 24: Cathode Ground Scheme**



## SINGLE PHOTON COUNTING

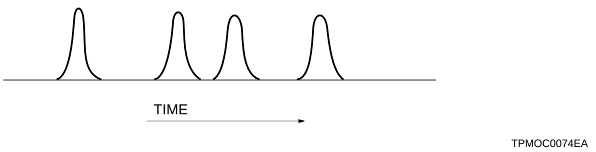
Photon counting is one effective way to use a photomultiplier tube for measuring very low light levels. It is widely used in astronomical photometry and chemiluminescence or bioluminescence measurement. In the usual application, a number of photons enter the photomultiplier tube and create an output pulse train like (a) in Figure 25. The actual output obtained by the measurement circuit is a DC current with a fluctuation as shown at (b).

**Figure 25: Overlapping Output Pulses**



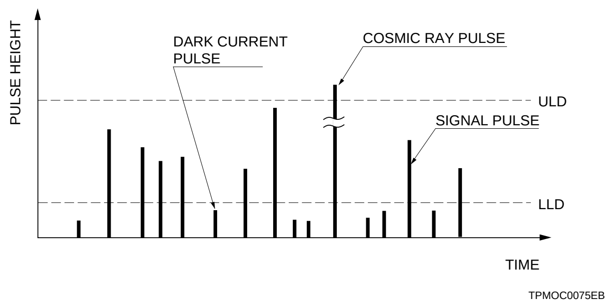

When the light intensity becomes so low that the incident photons are separated as shown in Figure 26. This condition is called a single photon (or photoelectron) event. The number of output pulses is in direct proportion to the amount of incident light and this pulse counting method has advantages in S/N ratio and stability over the DC method averaging all the pulses. This pulse counting technique is known as the photon counting method.

**Figure 26: Discrete Output Pulses (Single Photon Event)**




Since the photomultiplier tube output contains a variety of noise pulses in addition to the signal pulses representing photoelectrons as shown in Figure 27, simply counting the pulses without some form of noise elimination will not result in an accurate measurement. The most effective approach to noise elimination is to investigate the height of the output pulses.

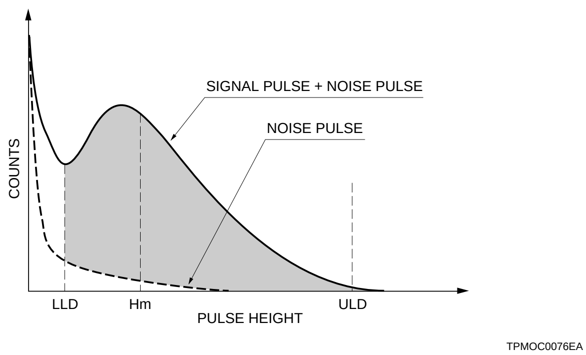
**Figure 27: Output Pulse and Discrimination Level**




A typical pulse height distribution (PHD) for the output of photomultiplier tubes is shown in Figure 28. In this PHD, the lower level discrimination (LLD) is set at the valley trough and the upper level discrimination (ULD) at the foot where the output pulses are very few. Most pulses smaller than the LLD are noise and pulses larger than the ULD result from cosmic rays, etc. Therefore, by counting pulses between the LLD and ULD, accurate light measurements becomes possible. In the PHD, Hm is the mean height of the pulses. It is recommended that the LLD be set at 1/3 of Hm and the ULD at triple Hm. In most cases, however, the ULD setting can be omitted.

Considering the above, a clear definition of the peak and valley in the PHD is a very significant characteristic for photomultiplier tubes for use in photon counting.

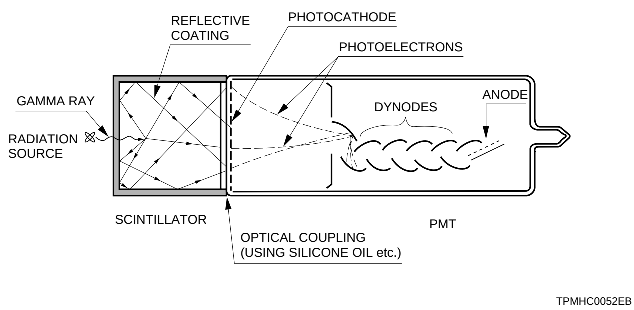
**Figure 28: Typical Pulse Height Distribution**




## SCINTILLATION COUNTING

Scintillation counting is one of the most sensitive and effective methods for detecting radiation. It uses a photomultiplier tube coupled to a transparent crystal called scintillator which produces light by incidence of radiation.

**Figure 29: Diagram of Scintillation Detector**




In radiation measurements, there are two parameters that should be measured. One is the energy of individual particles and the other is the amount of particles. Radiation measurements should determine these two parameters.

When radiation enters the scintillator, it produce light flashes in response to each particle. The amount of flash is proportional to the energy of the incident racliation. The photomultiplier tube detects individual light flashes and provides the output pulses which contain information on both the energy and amount of pulses, as shown in Figure 30. By analyzing these output pulses using a multichannel analyzer (MCA), a pulse height distribution (PHD) or energy spectrum is obtained, and the amount of incident particles at various energy levels can be measured accurately. Figure 31 shows typical PHDs or energy spectra when gamma rays ($^{55}$Fe, $^{137}$Cs, $^{60}$Co) are detected by the combination of an NaI(Tl) scintillator and a photomultiplier tube. For the PHD, it is very important to have distinct peaks at each energy level. This is evaluated as pulse height resolution (energy resolution) and is the most significant characteristic in radiation particle measurements. Figure 32 shows the definition of energy resolution taken with a $^{137}$Cs source.

**Figure 30: Incident Particles and PMT Output**

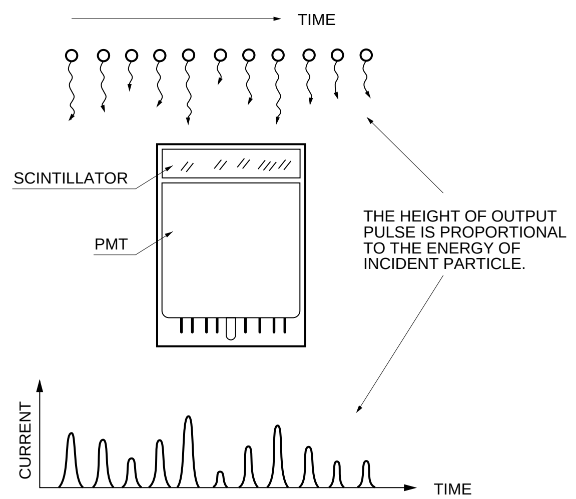
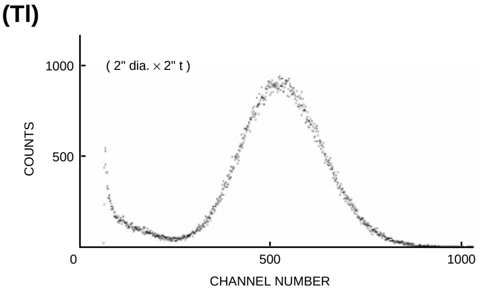
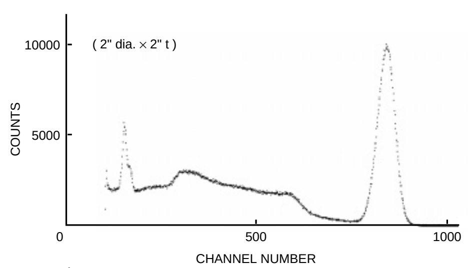



**Figure 31: Typical Pulse Height Distributions (Energy Spectra)**

**a) $^{55}$Fe+NaI (Tl)**




**b) $^{137}$Cs+NaI (Tl)**




**c) $^{60}$Co+NaI (Tl)**

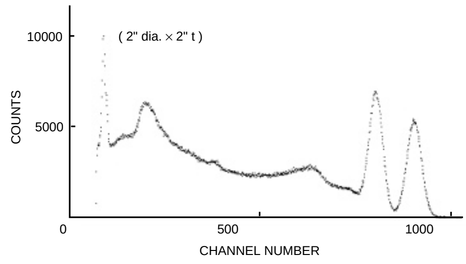



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**Figure 32: Definition of Energy Resolution**

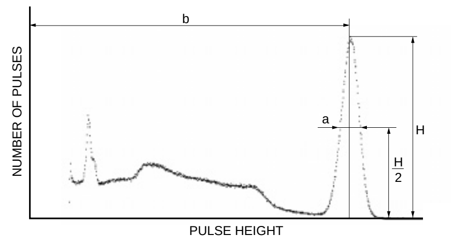


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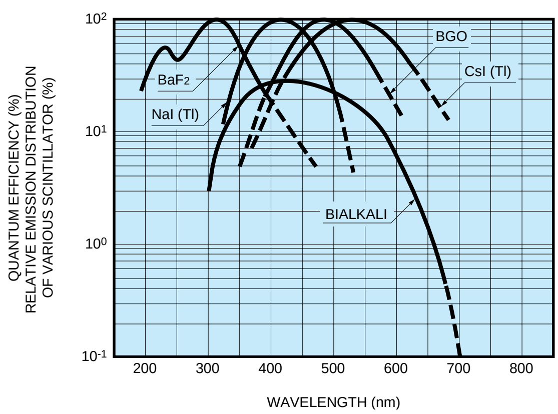
**Figure 33: Spectral Response of PMT and Spectral Emission of Scintillators**

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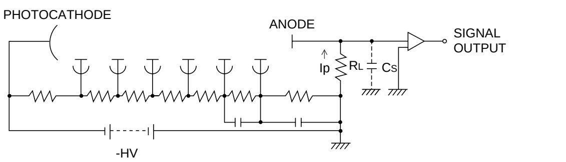
Pulse height resolution is mainly determined by the quantum efficiency of the photomultiplier tube in response to the scintillator emission. It is necessary to choose a tube whose spectral response matches with the scintillator emission. In the case of thallium-activated sodium iodide, or NaI(Tl), which is the most popular scintillator, head-on type photomultiplier tube with a bialkali photocathode is widely used.

# Connections to External Circuits

## LOAD RESISTANCE

Since the output of a photomultiplier tube is a current signal and the type of external circuit to which photomultiplier tubes are usually connected has voltage inputs, a load resistance is used to perform a current-voltage transformation. This section describes considerations to be made when selecting this load resistance. Since for low output current levels, the photomultiplier tube may be assumed to act as virtually an ideal constant-current source, the load resistance can be made arbitrarily large, thus converting a low-level current output to a high-level voltage output. In practice, however, using very large values of load resistance creates the problems of deterioration of frequency response and output linearity described below.

**Figure 34: PMT Output Circuit**

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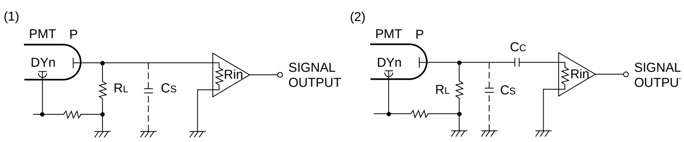
If, in the circuit of Figure 34, we let the load resistance be $R_L$ and the total of the capacitance of the photomultiplier tube anode to all other electrodes, including such stray capacitance as wiring capacitances be $C_s$, the cutoff frequency $f_c$ is expressed by the following relationship.

$$f_c = \frac{1}{2\pi C_s \cdot R_L}$$

From this relationship, it can be seen that, even if the photomultiplier tube and amplifier have very fast response, response will be limited to the cutoff frequency $f_c$ of the output circuit. If the load resistance is made large, at high current levels the voltage drop across $R_L$ becomes large, affecting a potential difference between the last dynode stage and the anode. As a result, a loss of output linearity (output current linearity with respect to incident light level) may occur.

**Figure 35: Amplifier Internal Resistance**

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In Figure 35, let us consider the effect of the internal resistance of the amplifier. If the load resistance is $R_L$ and the input impedance of the amplifier is $R_{in}$, the combined parallel output resistance of the photomultiplier tube, $R_o$, is given by the following equation.

$$R_o = \frac{R_L \cdot R_{in}}{R_L + R_{in}}$$

This value of $R_o$, which is less than the value of $R_L$, is then the effective load resistance of the photomultiplier tube. If, for example, $R_L$=$R_{in}$, the effective load resistance is 1/2 that of $R_L$ alone. From this we see that the upper limit of the load resistance is actually the input resistance of the amplifier and that making the load resistance much greater than this value does not have significant effect. While the above description assumed the load and input impedances to be purely resistive, in practice, stray capacitances, input capacitance and stray inductances influence phase relationships. Therefore, as frequency is increased, these circuit elements must be considered as compound impedances rather than pure resistances.

From the above, three guides can be derived for use in selection of the load resistance:

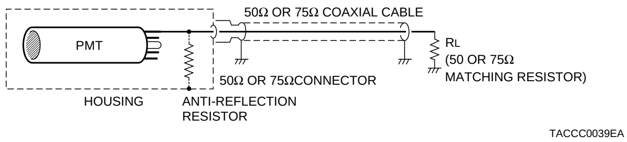
1) In cases in which frequency response is important, the load resistance should be made as small as possible.
2) In cases in which output linearity is important, the load resistance should be chosen such that the output voltage is below several volts.
3) The load resistance should be less than the approximate input impedance of the external amplifier.

## HIGH-SPEED OUTPUT CIRCUIT

For the detection of high-speed and pulsed light signals, a coaxial cable is used to make the connection between the photomultiplier tube and the electronic circuit, as shown in Figure 36. Since commonly used cables have characteristic impedances of 50 Ω or 75 Ω, this cable must be terminated in a pure resistance equivalent to the characteristic impedance to provide impedance matching and ensure distortion-free transmission for the signal waveform. If a matched transmission line is used, the impedance of the cable as seen by the photomultiplier tube output will be the characteristic impedance of the cable, regardless of the cable length, and no distortion will occur in signal waveforms.
If proper matching at the signal receiving end is not achieved, the impedance seen at the photomultiplier tube output will be a function of both frequency and cable length, resulting in significant waveform distortion. Such mismatched conditions can be caused by the connectors used as well, so that the connector to be used should be chosen with regard given to the frequency range to be used, to provide a match to the coaxial cable.

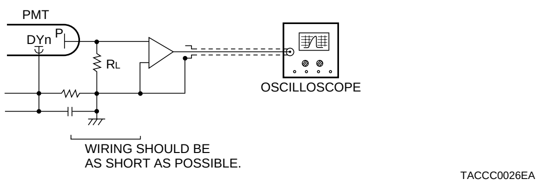
When a mismatch at the signal receiving end occurs, all of the pulse energy from the photomultiplier tube is not dissipated at the receiving end, but is partially reflected back to the photomultiplier tube via the cable. While this reflected energy will be fully dissipated at the photomultiplier tube when an impedance match has been achieved at the tube, if this is not the case, because the photomultiplier tube itself acts as an open circuit, the energy will be reflected and, thus returned to the signal-receiving end. Since part of the pulse makes a round trip in the coaxial cable and is again input to the receiving end, this reflected signal is delayed with respect to the main pulse and results in waveform distortion (so called ringing phenomenon). To prevent this phenomenon, in addition to providing impedance matching at the receiving end, it is necessary to provide a resistance matched to the cable impedance at the photomultiplier tube end as well. If this is done, it is possible to virtually eliminate the ringing caused by an impedance mismatch, although the output pulse height of the photomultiplier tube is reduced to one-half of the normal level by use of this impedance matching resistor.

**Figure 36: Typical Connections Used to Prevent Ringing**




Next, let us consider waveform observation of high-speed pulses using an oscilloscope (Figure 37). This type of operation requires a low load resistance. Since, however, there is a limit to the oscilloscope sensitivity, an amplifier may be required.
For cables to which a matching resistor has been connected, there is an advantage that the cable length does not affect the characteristics of the cable. However, since the matching resistance is very low compared to the usual load resistance, the output voltage becomes too small. While this situation can be remedied with an amplifier of high gain, the inherent noise of such an amplifier can itself be detrimental to measurement performance. In such cases, the photomultiplier tube can be brought as close as possible to the amplifier and a load resistance as large as possible should be used (consistent with preservation of frequency response), to achieve the desired input voltage.

**Figure 37: With Ringing Suppression Measures**




It is relatively simple to implement a high-speed amplifier using a wide-band video amplifier or operational amplifier. However, in exchange of design convenience, use of these ICs tends to create problems related to performance (such as noise). It is therefore necessary to know their performance limit and take corrective action.

As the pulse repetition frequency increases, baseline shift creates one reason for concern. This occurs because the DC signal component has been eliminated from the signal circuit by coupling with a capacitor which does not pass DC components. If this occurs, the reference zero level observed at the last dynode stage is not the actual zero level. Instead, the apparent zero level is the time-average of the positive and negative fluctuations of the signal waveform. This will vary as a function of the pulse density, and is known as baseline shift. Since the height of the pulses above this baseline level is influenced by the repetition frequency, this phenomenon is of concern when observing waveforms or discriminating pulse levels.

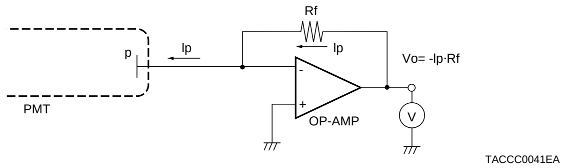
## OPERATIONAL AMPLIFIERS

In cases in which a high-sensitivity ammeter is not available, the use of an operational amplifier will enable measurements to be made using an inexpensive voltmeter. This technique relies on converting the output current of the photomultiplier tube to a voltage signal. The basic circuit is as shown in Figure 38, for which the output voltage, $V_o$, is given by the following relationship.

$$V_o = -R_f \cdot I_p$$

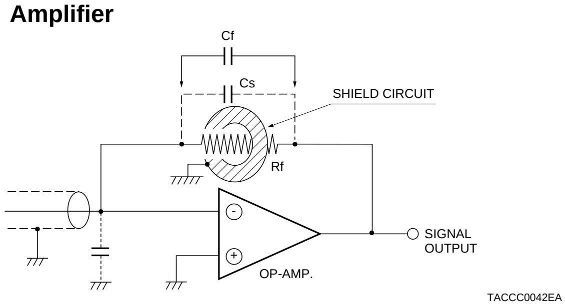
This relationship is derived for the following reason. If the input impedance of the operational amplifier is extremely large, and the output current of the photomultiplier tube is allowed to flow into the input terminal of the amplifier, most of the current will flow through $R_f$ and subsequently to the operational amplifier output circuit. Therefore, the output voltage $V_o$ is given by the expression $-R_f \times I_p$. When using such an operational amplifier, it is of course, not possible to increase the output voltage without limit, the actual maximum output being approximately equal to the operational amplifier power supply voltage. At the other end of the scale, for extremely small currents, limitations are placed by the operational amplifier offset current ($I_{os}$), the quality of $R_f$, and other factors such as the insulation materials used.

**Figure 38: Current-Voltage Transformation Using an Operational Amplifier**




If the operational amplifier has an offset current ($I_{os}$), the above-described output voltage becomes $V_o=-R_f(I_p+I_{os})$, the offset current component being superimposed on the output. Furthermore, the magnitude of temperature drift may create a problem. In general, a metallic film resistor which has a low temperature coefficient is used for the resistance $R_f$, and for high resistance values, a vacuum-sealed type is used. Carbon resistors, with their highly temperature-dependent resistance characteristics, are not suitable for this application. When measuring such extremely low level currents as 100 pA and below, in addition to the considerations described above, the materials used in the circuit implementation require care as well. For example, materials such as bakelite are not suitable, and more suitable materials are Teflon, polystyrol or steatite. In addition, low-noise cables should be used, since general-purpose coaxial cables exhibit noise due to mechanical changes. In the measurement of these low level currents, use of an FET input operational amplifier is recommended.

**Figure 39: Frequency Compensation of an Operational Amplifier**




In Figure 39, if a capacitance $C_f$ (including any stray capacitance) exists in parallel to the resistance $R_f$, the circuit exhibits a time constant of ($R_f \times C_f$), so that response speed is limited to this time constant. This is a particular problem if $R_f$ is large. Stray capacitance can be reduced by passing $R_f$ through a hole in a shield plate. When using coaxial signal input cables, since the cable capacitance $C_c$ and $R_f$ are in the feedback loop, oscillations may occur and noise may be amplified. While the method of avoiding this is to connect $C_f$ in parallel to $R_f$, to reduce gain at high frequencies, as described above, this creates a time constant of $R_f \times C_f$ which limits the response speed.

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