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CHAPTER 1

INTRODUCTION

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1. 1 Overview of This Manual

The following provides a brief description of each chapter in this technical manual.

Chapter 1 Introduction

Before starting to describe the main subjects, this chapter explains basic photometric units used to measure or express properties of light such as wavelength and intensity. This chapter also describes the history of the development of photocathodes and photomultiplier tubes, as well as providing a brief guide to photomultiplier tubes which will be helpful for first-time users.

Chapter 2 Basic Principles of Photomultiplier Tubes

This chapter describes the basic operating principles and mechanisms of photomultiplier tubes, including photoelectron emission, electron trajectories, and electron multiplication by use of secondary electron multipliers (dynodes).

Chapter 3 Characteristics of Photomultiplier Tubes

Chapter 3 explains the types of photocathodes and dynodes, and their basic characteristics. This chapter also provides the definitions of various characteristics of photomultiplier tubes, their measurement procedures, and specific examples of typical photomultiplier tube characteristics.

In addition, this chapter describes photon counting and scintillation counting - light measurement techniques that have become more popular in recent years. Also listed are definitions of their characteristics, measurement procedures, and typical characteristics of major photomultiplier tubes.

Chapter 4 MCP-PMTs (Microchannel Plate - Photomultiplier Tubes)

This chapter explains MCP-PMTs – photomultiplier tubes incorporating microchannel plates (MCPs) for their electron multipliers. The basic structure, operation, performance and examples of major characteristics are discussed.

Chapter 5 Electron Multiplier Tubes

Chapter 5 describes electron multiplier tubes (sometimes called EMT), showing the basic structure, typical characteristics and handling precautions.

Chapter 6 Position-Sensitive Photomultiplier Tubes

This chapter introduces recently developed position-sensitive photomultiplier tubes using grid type dynodes, mesh dynodes or fine-mesh dynodes combined with multianodes, and explains their structure, characteristics and applications.

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Chapter 7 How to Use and Operate Photomultiplier Tubes

To use photomultiplier tubes correctly, an optimum design is essential for the operating circuits (voltage-divider circuit and high-voltage power supply) and the associated circuit to which they are connected. In addition, magnetic or noise shielding may be necessary in some cases.

This chapter explains how to design an optimum electric circuit, including precautions for actual operation with photomultiplier tubes.

Chapter 8 Environmental Durability and Reliability

In this chapter, photomultiplier tube performance and usage are discussed in terms of environmental durability and operating reliability. In particular, this chapter describes ambient temperature, humidity, magnetic field effects, mechanical strength, influence of electromagnetic fields and the countermeasures against these factors. Also explained are operating life, definitions concerning reliability and examples of typical photomultiplier tube characteristics.

Chapter 9 Application

Chapter 9 introduces major applications of photomultiplier tubes, and explains how photomultiplier tubes are used in a variety of fields and applications. Moreover, this chapter shows how to evaluate characteristics of photomultiplier tubes which are required for each application along with their definitions and examples of data actually measured.

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1. 2 Photometric units

Before starting to describe photomultiplier tubes and their characteristics, this section briefly discusses photometric units commonly used to measure the quantity of light. This section also explains the wavelength regions of light (spectral range) and the units to denote them, as well as the unit systems used to express light intensity. Since information included here is just an overview of major photometric units, please refer to specialty books for more details.

1. 2. 1 Spectral regions and units

Electromagnetic waves cover a very wide range from gamma rays up to millimeter waves. So-called "light" is a very narrow range of these electromagnetic waves.

Table 1-1 shows designated spectral regions when light is classified by wavelength, along with the conversion diagram for light units. In general, what we usually refer to as light covers a range from 10^2 to 10^6 nanometers (nm) in wavelength. The spectral region between 350 and 700nm shown in the table is usually known as the visible region. The region with wavelengths shorter than the visible region is divided into near UV (shorter than 350nm), vacuum UV (shorter than 200nm) where air is absorbed, and extreme UV (shorter than 100nm). Even shorter wavelengths span into the region called soft X-rays (shorter than 10nm) and X-rays. In contrast, longer wavelengths beyond the visible region extend from near IR (750nm or up) to the infrared (several micrometers or up) and far IR (several tens of micrometers) regions.

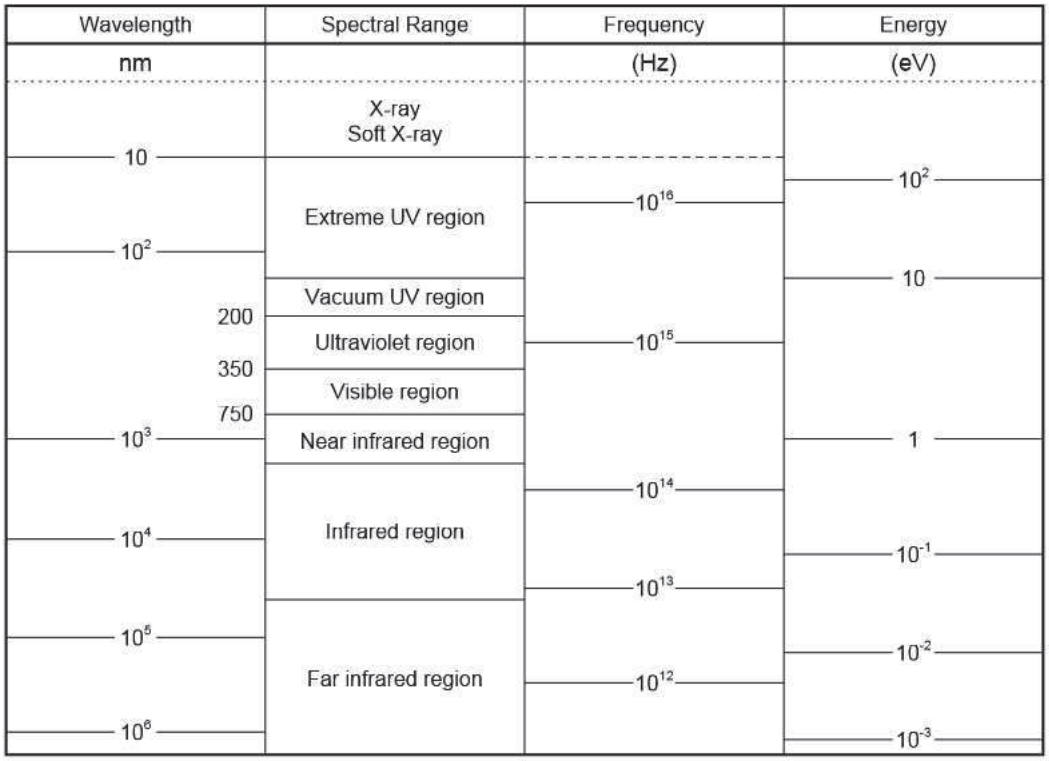


Table 1-1: Spectral regions and unit conversions

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Light energy E (eV) is given by the following equation (Eq. 1-1).

$$E = h\upsilon = h \cdot \frac{c}{\lambda} = ch\bar{\upsilon} \quad \text{(Eq. 1-1)}$$

h: Planck's constant $6.6265\ 10^{-34}$(J·S)
υ: Frequency of light (Hz)
$\bar{\upsilon}$: Wave number (cm^{-1})
c: Velocity of light $3\text{5}\ 10^{8}$m/s

Here, velocity of light has relation to frequency ν and wavelength λ as follow:

$$c = \upsilon\lambda$$

When E is expressed in eV (electron volts) and λ in nm, the relation between eV and λ is given as follows:

$$E\ (eV) = \frac{1240}{\lambda} \quad \text{(Eq. 1-2)}$$

From Eq. 1-2, it can be seen that light energy increases in proportion to the reciprocal of wavelength. This equation is helpful when discussing the relation between light energy (eV) and wavelength (nm), so remembering it is suggested.

1. 2. 2 Units of light intensity

This section explains the units used to represent light intensity and their definitions.

The radiant quantity of light or radiant flux is a pure physical quantity expressed in units of watts (W). In contrast, the photometric quantity of light or luminous flux is represented in lumens which correlate to the visual sensation of light.

The "watt (W)" is the basic unit of radiated light when it is measured as analog quantity, and the photon is the minimum unit of radiated light. The energy of one photon is given by the equation below.

$$P = h\upsilon = hc/\lambda \quad \text{(Eq. 1-3)}$$

From the relation W=J/sec., the following calculation can be made by substituting specific values for the above equation.

$$1\ \text{watt} = 5.05\ \lambda\ (\mu m) \times 10^{18}\ \text{photons/sec.}$$

This equation gives the number of photons (per second) from the radiant flux (W) measured, and will be helpful if you remember it.

Table 1-2 shows comparisons of radiant units with photometric units are listed. (Each unit is detailed in subsequent sections.)

Quantity	Unit Name	Symbol
Radiant flux [Luminous flux]	watts [lumens]	W [lm]
Radiant energy [Quantity of light]	joules [lumen· sec.]	J [lm·s]
Irradiance [Illuminance]	watts per square meter [lux]	W/m^2 [lx]
Radiant emittance [Luminous emittance]	watts per square meter [lumens per square meter]	W/m^2 [lm/m^2]
Radiant intensity [Luminous intensity]	watts per steradian [candelas]	W/sr [cd]
Radiance [Luminance]	watts per steradia·square meter [candelas per square meter]	$W/sr \cdot m^2$ [cd/m^2]

Table 1-2: Comparisons of radiant units with photometric units (shown in brackets [ ])

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1. Radiant flux [luminous flux]

Radiant flux is a unit to express radiant quantity, while luminous flux shown in brackets [ ] in Table 1-2 and the subhead just above is a unit to represent luminous quantity. (Units are shown this way in the rest of this chapter.) Radiant flux (Φe) is the flow of radiant energy (Qe) past a given point in a unit time period, and is defined as follows:

$$\Phi e = dQe/dt \text{ (joules per sec. ; watts)} \quad \text{(Eq. 1-4)}$$

On the other hand, luminous flux (Φ) is measured in lumens and defined as follows:

$$\Phi = km \int \Phi e(\lambda)\, v(\lambda)\, d\lambda \quad \text{(Eq. 1-5)}$$

where Φe(λ) : Spectral radiant density of a radiant flux, or spectral radiant flux
km : Maximum sensitivity of the human eye (638 lumens/watt)
v(λ) : Typical sensitivity of the human eye

The maximum sensitivity of the eye (km) is a conversion coefficient used to link the radiant quantity and luminous quantity. Here, v(λ) indicates the typical spectral response of the human eye, internationally established as spectral luminous efficiency. A typical plot of spectral luminous efficiency versus wavelength (also called the luminosity curve) and relative spectral luminous efficiency at each wavelength are shown in Figure 1-1 and Table 1-3, respectively.

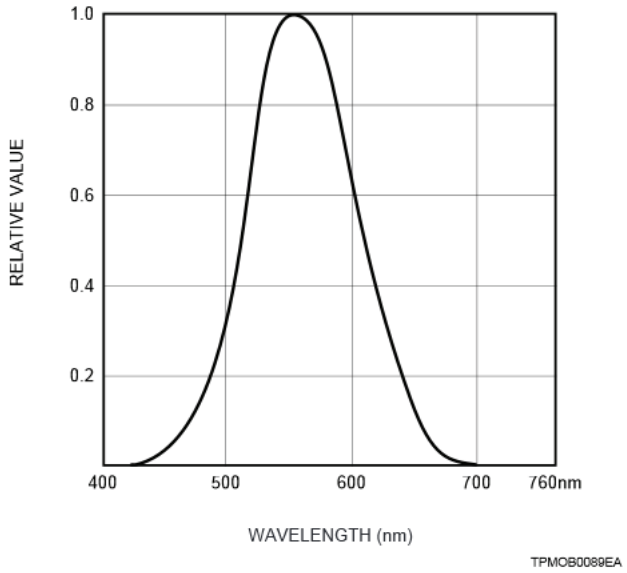


Figure 1-1: Spectral luminous efficiency distribution

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Wavelength (nm)	Luminous Efficiency	Wavelength (nm)	Luminous Efficiency
400	0.0004	600	0.631
10	0.0012	10	0.503
20	0.0040	20	0.381
30	0.0116	30	0.265
40	0.023	40	0.175
450	0.038	650	0.107
60	0.060	60	0.061
70	0.091	70	0.032
80	0.139	80	0.017
90	0.208	90	0.0082
500	0.323	700	0.0041
10	0.503	10	0.0021
20	0.710	20	0.00105
30	0.862	30	0.00052
40	0.954	40	0.00025
550	0.995	750	0.00012
555	1.0	60	0.00006
60	0.995		
70	0.952		
80	0.870		
90	0.757		

Table 1-3: Relative spectral luminous efficiency at each wavelength

2. Radiant energy (Quantity of light)

Radiant energy (Qe) is the integral of radiant flux over a duration of time. Similarly, the quantity of light (Q) is defined as the integral of luminous flux over a duration of time. Each term is respectively given by Eq. 1-6 and Eq. 1-7.

$$Qe = \int \Phi e dt \ (\text{watt·sec.}) \quad \text{(Eq. 1-6)}$$

$$Q = \int \Phi dt \ (\text{lumen·sec.}) \quad \text{(Eq. 1-7)}$$

3. Irradiance (Illuminance)

Irradiance (Ee) is the radiant flux incident per unit area of a surface, and is also called radiant flux density. (See Figure 1-2.) Likewise, illuminance (E) is the luminous flux incident per unit area of a surface. Each term is respectively given by Eq. 1-8 and Eq. 1-9.

$$\text{Irradiance } Ee = d\Phi e/ds \ (\text{watts per square meter; } W/m^2) \quad \text{(Eq. 1-8)}$$

$$\text{Illuminance } E = d\Phi/ds \ (\text{lumen per square meter; } lm/m^2 \text{ or lux}) \quad \text{(Eq. 1-9)}$$

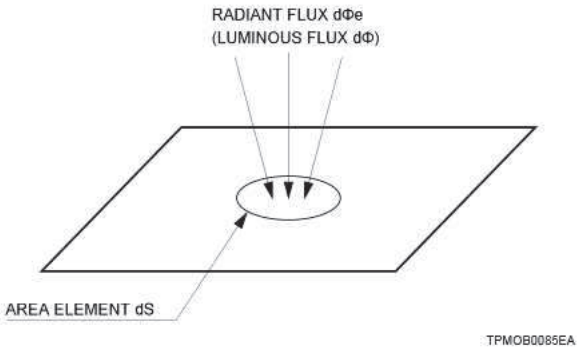


Figure 1-2: Irradiance (Illuminance)

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4. Radiant emittance (Luminous emittance)

Radiant emittance (Me) is the radiant flux emitted per unit area of a surface. (See Figure 1-3.) Likewise, Luminous emittance (M) is the luminous flux emitted per unit area of a surface. Each term is respectively expressed by Eq. 1-10 and Eq. 1-11.

Radiant emittance Me = dΦe/ds (watt per square meter; W/m^2) ..... (Eq. 1-10)

Luminous emittance M = dΦ/ds (lumen per square meter; lm/m^2) ..... (Eq. 1-11)

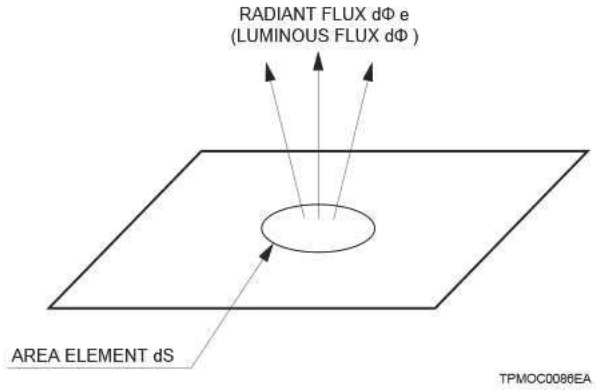


Figure 1-3: Radiant emittance (Luminous emittance)

5. Radiant intensity (Luminous intensity)

Radiant intensity (Ie) is the radiant flux emerging from a point source, divided by the unit solid angle. (See Figure 1-4.) Likewise, luminous intensity (I) is the luminous flux emerging from a point source, divided by the unit solid angle. These terms are respectively expressed by Eq. 1-12 and Eq. 1-13.

Radiant intensity Ie = dΦe/dw (watts per steradian; W/sr) ..... (Eq. 1-12)

Where

Φe :radiant flux (watts)
w :solid angle (steradians)

Luminous intensity I = dΦ/dw(candelas: cd) ..... (Eq. 1-13)

Where

Φ : luminous flux (lumens)
w : solid angle (steradians)

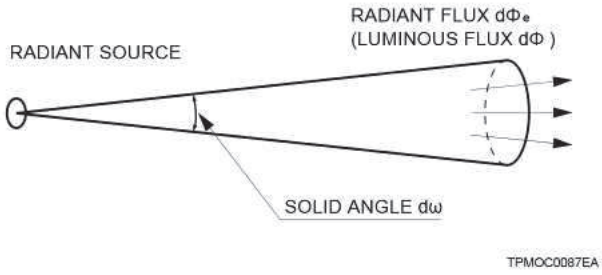


Figure 1-4: Radiant intensity (Luminous intensity)

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6. Radiance (Luminance)

Radiance (Le) is the radiant intensity emitted in a certain direction from a radiant source, divided by unit area of an orthographically projected surface. (See Figure 1-5.) Likewise, luminance (L) is the luminous flux emitted from a light source, divided by the unit area of an orthographically projected surface. Each term is respectively given by Eq. 1-14 and Eq. 1-15.

$$\text{Radiance } Le = dle/ds \times \cos\theta \ (\text{watts per steradian} \cdot m^2) \quad \text{(Eq. 1-14)}$$

Where

le: radiant intensity
s : area
θ : angle between viewing direction and small area surface

$$\text{Luminance } L = dl/ds \times \cos\theta \ (\text{candelas}/m^2) \quad \text{(Eq. 1-15)}$$

Where

l: luminous intensity (candelas)

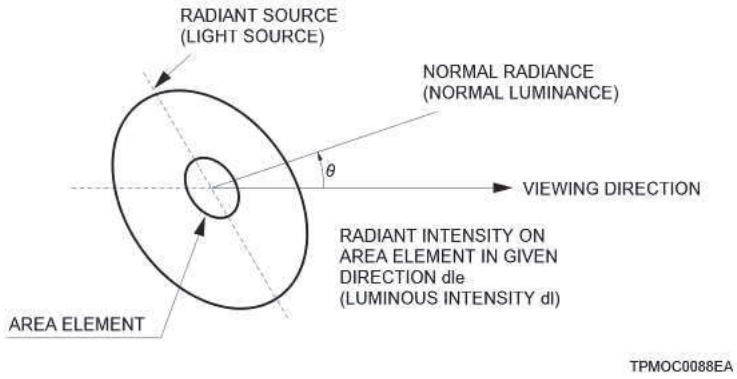


Figure 1-5: Radiant intensity (Luminous intensity)

In the above sections, we discussed basic photometric units which are internationally specified as SI units for quantitative measurements of light. However in some cases, units other than SI units are used.

Tables 1-4 and 1-5 show conversion tables for SI units and non-SI units, with respect to luminance and illuminance. Refer to these conversion tables as necessary.

	Unit Name	Symbol	Conversion Fomula
SI Unit	nit stilb apostilb lambert	nt sb asb L	$1nt = 1cd/m^2$ $1sb = 1cd/cm^2 = 10^4\ cd/m^2$ $1asb = 1/\pi\ cd/m^2$ $1L = 1/\pi\ cd/cm^2 = 10^4/\pi\ cd/m^2$
Non SI Unit	foot lambert	fL	$1fL = 1/\pi\ cd/ft^2 = 3.426\ cd/m^2$

Table 1-4: Luminance units

	Unit Name	Symbol	Conversion Fomula
SI Unit	photo	ph	$1ph = 1\ lm/cm^2 = 10^4\ lx$
Non SI Unit	food candle	fc	$1fc = 1\ lm/ft^2 = 10.764\ lx$

Table 1-5: Illuminance units

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1. 3 History

1. 3. 1 History of photocathodes[1)]

The photoelectric effect was discovered in 1887 by Herts[4)] through experiments exposing a negative electrode to ultraviolet radiation. In the next year 1888, the photoelectric effect was conclusively confirmed by Hallwacks.[5)] In 1889, Elster and Geiter[6)] reported the photoelectric effect which was induced by visible light striking an alkali metal (sodium-potassium). Since then, a variety of experiments and discussions on photoemission have been made by many scientists. As a result, the concept proposed by Einstein (in the quantum theory in 1905),[7)] "Photoemission is a process in which photons are converted into free electrons.", has been proven and accepted.

During this historic period of achievement, Elster and Geiter produced a photoelectric tube in 1913. Then, a compound photocathode made of Ag-O-Cs (silver oxygen cesium, so-called S-1) was discovered in 1929 by Koller[8)] and Campbell.[9)] This photocathode showed photoelectric sensitivity about two orders of magnitude higher than previously used photocathode materials, achieving high sensitivity in the visible to near infrared region. In 1930, they succeeded in producing a phototube using this S-1 photocathode. In the same year, a Japanese scientist, Asao reported a method for enhancing the sensitivity of silver in the S-1 photocathode. Since then, various photocathodes have been developed one after another, including bialkali photocathodes for the visible region, multialkali photocathodes with high sensitivity extending to the infrared region and alkali halide photocathodes intended for ultraviolet detection.[10)-13)]

In addition, photocathodes using III-V compound semiconductors such as GaAs[14)-19)] and InGaAs[20) 21)] have been developed and put into practical use. These semiconductor photocathodes have an NEA (negative electron affinity) structure and offer high sensitivity from the ultraviolet through near infrared region. Currently, a wide variety of photomultiplier tubes utilizing the above photocathodes are available. They are selected and used according to the application required.

1. 3. 2 History of photomultiplier tubes

Photomultiplier tubes have been making rapid progress since the development of photocathodes and secondary emission multipliers (dynodes).

The first report on a secondary emissive surface was made by Austin et al.[22)] in 1902. Since that time, research into secondary emissive surfaces (secondary electron emission) has been carried out to achieve higher electron multiplication. In 1935, Iams et al.[23)] succeeded in producing a triode photomultiplier tube with a photocathode combined with a single-stage dynode (secondary emissive surface), which was used for movie sound pickup. In the next year 1936, Zworykin et al.[24)] developed a photomultiplier tube having multiple dynode stages. This tube enabled electrons to travel in the tube by using an electric field and a magnetic field. Then, in 1939, Zworykin and Rajchman[25)] developed an electrostatic-focusing type photomultiplier tube (this is the basic structure of photomultiplier tubes currently used). In this photomultiplier tube, an Ag-O-Cs photocathode was first used and later an Sb-Cs photocathode was employed.

An improved photomultiplier tube structure was developed and announced by Morton in 1949[26)] and in 1956.[27)] Since then the dynode structure has been intensively studied, leading to the development of a variety of dynode structures including circular-cage, linear-focused and box-and-grid types. In addition, photomultiplier tubes using magnetic-focusing type multipliers,[28)] transmission-mode secondary-emissive surfaces[29)-31)] and channel type multipliers[32)] have been developed.

At Hamamatsu Photonics, the manufacture of various phototubes such as types with an Sb-Cs photocathode was established in 1953 (then Hamamatsu TV Co., Ltd. – The company name was changed in 1983.). In 1959, Hamamatsu Photonics marketed side-on photomultiplier tubes (type No. 931A, 1P21 and R106 having

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an Sb-Cs photocathode) which have been widely used in spectroscopy. Hamamatsu Photonics also developed and marketed side-on photomultiplier tubes (type No. R132 and R136) having an Ag-Bi-O-Cs photocathode in 1962. This photocathode had higher sensitivity in the red region of spectrum than that of the Sb-Cs photocathode, making them best suited for spectroscopy in those days. In addition, Hamamatsu Photonics put head-on photomultiplier tubes (type No. 6199 with an Sb-Cs photocathode) on the market in 1965.

In 1967, Hamamatsu Photonics introduced a 1/2-inch diameter side-on photomultiplier tube (type No. R300 with an Sb-Cs photocathode) which was the smallest tube at that time. In 1969, Hamamatsu Photonics developed and marketed photomultiplier tubes having a multialkali (Na-K-Cs-Sb) photocathode, type No. R446 (side-on) and R375 (head-on). Then, in 1974 a new side-on photomultiplier tube (type No. R928) was developed by Hamamatsu Photonics, which achieved much higher sensitivity in the red to near infrared region. This was an epoch-making event in terms of enhancing photomultiplier tube sensitivity. Since that time, Hamamatsu Photonics has continued to develop and produce a wide variety of state-of-the-art photomultiplier tubes. The current product line ranges in size from the world's smallest 3/8-inch tubes (R1635, etc.) to the world's largest 20-inch hemispherical tubes (R1449 and R3600). Hamamatsu Photonics also offers ultra-fast photomultiplier tubes using a microchannel plate for the dynodes (type No. R3809 with a time resolution as fast as 30 picoseconds) and mesh-dynode type photomultiplier tubes (R2490, etc.) that maintain an adequate gain of 10^5 even in high magnetic fields of up to one Tesla. More recently, Hamamatsu Photonics has developed subminiature metal can type photomultiplier tubes (R7400 series) using metal channel dynodes and various types of position-sensitive photomultiplier tubes capable of position detection. Hamamatsu Photonics is constantly engaged in research and development for manufacturing a wide variety of photomultiplier tubes to meet a wide range of application needs.

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1. 4 Using Photomultiplier Tubes

This section provides the first-time photomultiplier tube users with general information on how to choose the ideal photomultiplier tube (sometimes abbreviated as PMT), how to operate them properly and how to process the output signals. This section should be referred to as a quick guide. For more details, refer to the following chapters.

1. 4. 1 How to make the proper selection



Figure 1-6: Atomic absorption application

Figure 1-6 shows an application example in which a photomultiplier tube is used in absorption spectroscopy. The following parameters should be taken into account when making a selection.

Incident light conditions	Selection reference	
	<Photomultiplier tubes>	<Circuit Conditions>
Light wavelength	Window material Photocathode spectral response	
Light intensity	Number of dynodes Dynode type Voltage applied to dynodes	Signal processing method (analog or digital method)
Light beam size	Effective diameter (size) Viewing configuration (side-on or head-on)	
Speed of optical phenomenon	Time response	Bandwidth of associated circuit

It is important to know beforehand the conditions of the incident light to be measured. Then, choose a photomultiplier tube that is best suited to detect the incident light and also select the optimum circuit conditions that match the application. Referring to the table above, select the optimum photomultiplier tubes, operating conditions and circuit configurations according to the incident light wavelength, intensity, beam size and the speed of optical phenomenon. More specific information on these parameters and conditions are detailed in Chapter 2 and later chapters.

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1. 4. 2 Basic operating method

As shown in Figure 1-7, operating a photomultiplier tube requires a stable source of high voltage (normally one to two kilovolts), voltage-divider circuit (or bleeder circuit) that distributes an optimum voltage to each dynode, and sometimes a shield case that protects the tube from magnetic or electric fields. The following equipment is available from Hamamatsu Photonics for setting up photomultiplier tube operation.

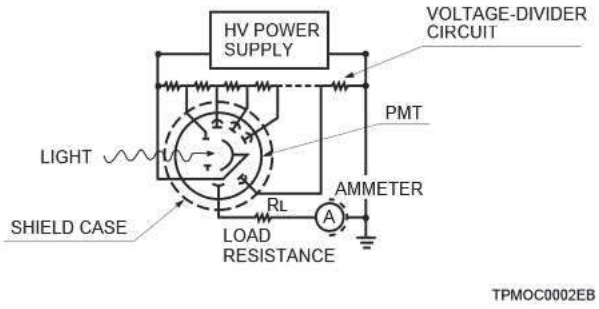


Figure 1-7: Basic operating method

High-voltage power supply

A negative or positive high-voltage power supply of one to two kilovolts is usually required to operate a photomultiplier tube. There are two types of power supplies available: modular power supplies like that shown in Figure 1-8 and bench-top power supplies like that shown in Figure 1-9.



Figure 1-8: Modular high-voltage power supply



Figure 1-9: Bench-top high-voltage power supply

Since the gain of a photomultiplier tube is extremely high, it is very sensitive to variations in the high-voltage power supply. When the output stability of a photomultiplier tube should be maintained within one percent, the power supply stability must be held within 0.1 percent.

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Voltage-divider circuit

It is necessary to distribute voltage to each dynode independently. For this purpose, a divider circuit is usually used to divide the high voltage and provide a proper voltage gradient between each dynode. To allow easy operation of photomultiplier tubes, Hamamatsu provides socket assemblies that incorporate a photomultiplier tube socket and a matched divider circuit as shown in Figure 1-10 (D type socket assemblies *1).

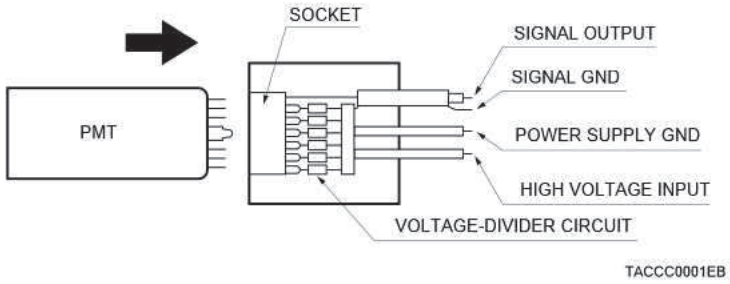


Figure 1-10: D type socket assembly

In addition, Hamamatsu offers socket assemblies that further include an amplifier (DA type socket assemblies *2) or a power supply (DP type socket assemblies *3), as shown in Figures 1-11 and 1-12 respectively.

*1 D type socket assemblies Built-in voltage divider
*2 DA type socket assemblies Built-in voltage divider and amplifier
*3 DP type socket assemblies Built-in voltage divider and power supply

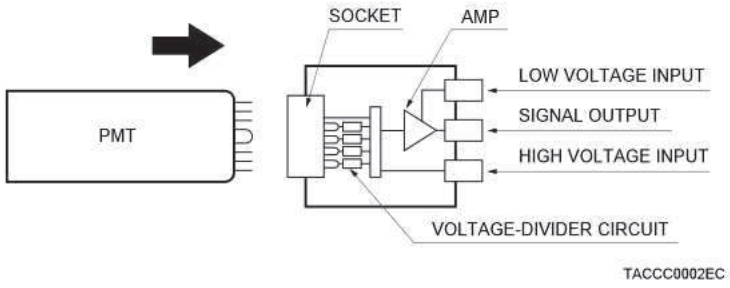


Figure 1-11: DA type socket assembly

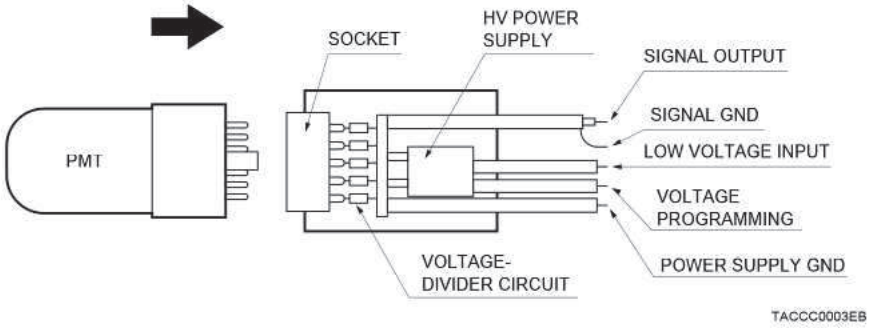


Figure 1-12: DP type socket assembly

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Shield

Photomultiplier tube characteristics may vary with external electromagnetic fields, ambient temperature, humidity, or mechanical stress applied to the tube. For this reason, it is necessary to use a magnetic or electric shield that protects the tube from such adverse environmental factors. Moreover, a cooled housing is sometimes used to maintain the tube at a constant temperature or at a low temperature, thus assuring more reliable operation.

Integral power supply module

There are easy-to-use modules which incorporate a photomultiplier tube into a compact case, along with all necessary components such as a high-voltage power supply and operating circuit. (Figure 1-13)

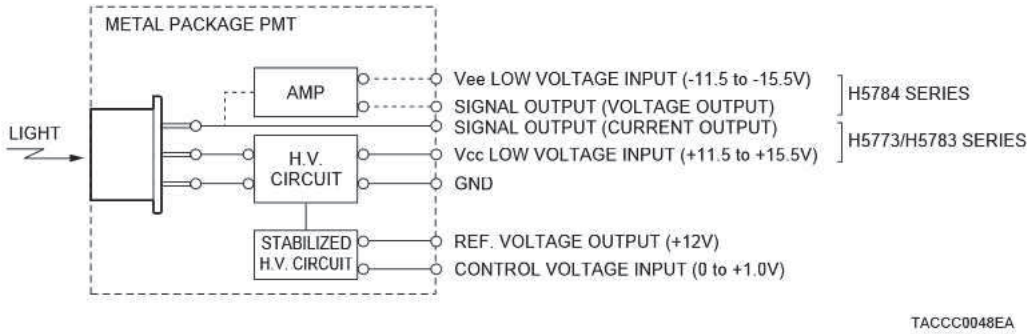


Figure 1-13: Structure of an integral power supply module

The description in this chapter is just an overview of operating a photomultiplier tube. For more detailed information, refer to Chapters 7 and 8.

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1. 4. 3 Operating methods (associated circuits)

The output from a photomultiplier tube can be processed electrically as a constant current source. It is best, however, to connect it to an optimum circuit depending on the incident light and frequency characteristics required. Figure 1-14 shows typical light measurement circuits which are commonly used. The DC method and AC method (analog method) are mainly used in rather high light levels to moderate light levels. At very low light levels, the photon counting method is most effective. In this method, light is measured by counting individual photons which are the smallest unit of light.

The DC method shown in Figure 1-14 (a) detects DC components in the photomultiplier tube output by means of an amplifier and a lowpass filter. This method is suited for detection of relatively high light levels and has been widely used. The AC method shown in (b) extracts only AC components from the photomultiplier tube output via a capacitor and converts them into DC components by use of a diode. This method is generally used in lower light regions where the AC components are predominate in the output signal over the DC components. In the photon counting method shown in (c), the output pulses from the photomultiplier tube are amplified and only the pulses with an amplitude higher than the preset discrimination pulse height are counted as photon signals. This method allows observation of discrete output pulses from the photomultiplier tube, and is the most effective technique in detecting very low light levels.

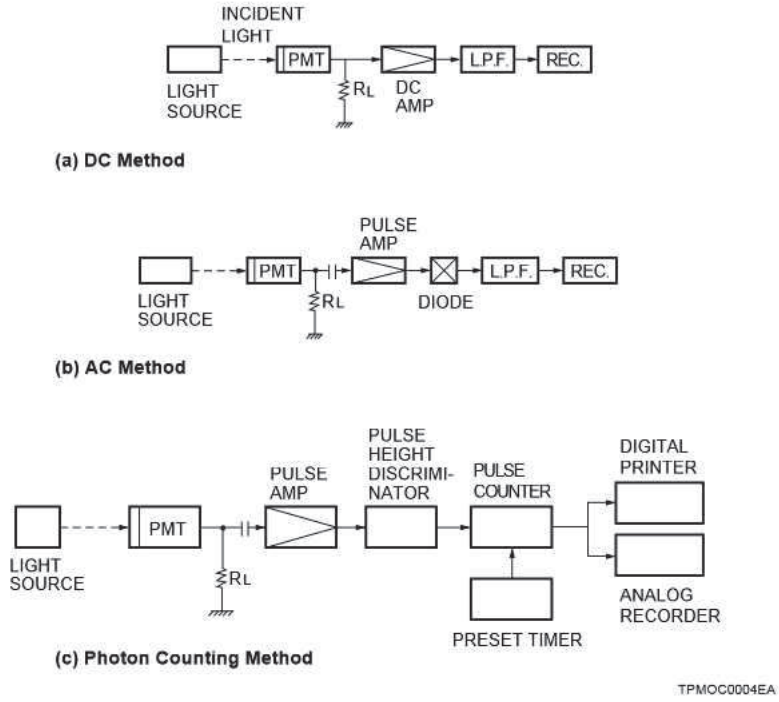


Figure 1-14: Light measurement methods using PMT

These light measurement methods using a photomultiplier tube and the associated circuit must be optimized according to the intensity of incident light and the speed of the event to be detected. In particular, when the incident light is very low and the resultant signal is small, consideration must be given to minimize the influence of noise in the succeeding circuits. As stated, the AC method and photon counting method are more effective than the DC method in detecting low level light. When the incident light to be detected changes in a very short period, it is also important that the associated circuit be designed for a wider frequency bandwidth as well as using a fast response photomultiplier tube. Additionally, impedance matching at high frequencies must also be taken into account. Refer to Chapters 3 and 7 for more details on these precautions.

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CHAPTER 2
BASIC PRINCIPLE OF PHOTOMULTIPLIER TUBES [1)-5)]

A photomultiplier tube is a vacuum tube consisting of an input window, a photocathode and an electron multiplier sealed into an evacuated glass tube. Figure 2-1 shows the schematic construction of a photomultiplier tube.

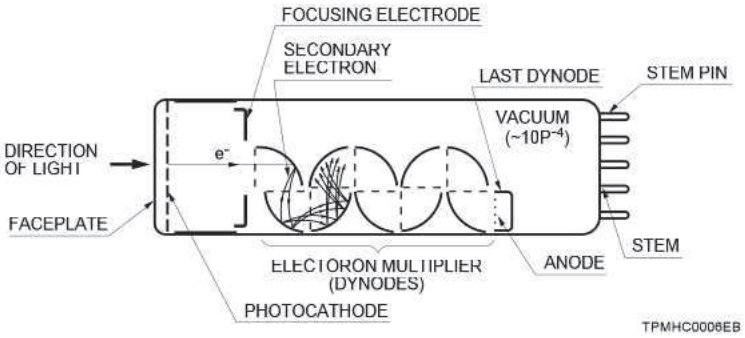


Figure 2-1: Construction of a PMT

Light which enters a photomultiplier tube is detected and produces an output signal through the following processes.

(1) Light passes through the input window.

(2) Excites the electrons in the photocathode so that photoelectrons are emitted into the vacuum (external photoelectric effect).

(3) Photoelectrons are accelerated and focused by the focusing electrode onto the first dynode where they are multiplied by means of secondary electron emission. This secondary emission is repeated at each of the successive dynodes.

(4) The multiplied secondary electrons emitted from the last dynode are finally collected by the anode.

This chapter describes the principles of photoelectron emission, electron trajectory, and the design and function of electron multipliers. The electron multipliers used for photomultiplier tubes are classified into two types: normal discrete dynodes consisting of multiple stages and continuous dynodes such as microchannel plates. Since both types of dynodes differ considerably in operating principle, photomultiplier tubes using microchannel plates (MCP-PMTs) are separately described in Chapter 4. Furthermore, electron multipliers intended for use in particle and radiation measurement are discussed in Chapter 5.

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2. 1 Photoelectron Emission[6) 7)]

Photoelectric conversion is broadly classified into external photoelectric effects by which photoelectrons are emitted into the vacuum from a material and internal photoelectric effects by which photoelectrons are excited into the conduction band of a material. The photocathode has the former effect and the latter are represented by the photoconductive or photovoltaic effect.

Since a photocathode is a semiconductor, it can be described using band models as shown in Figure 2-2, (1) alkali photocathode and (2) III-V compound semiconductor photocathode.

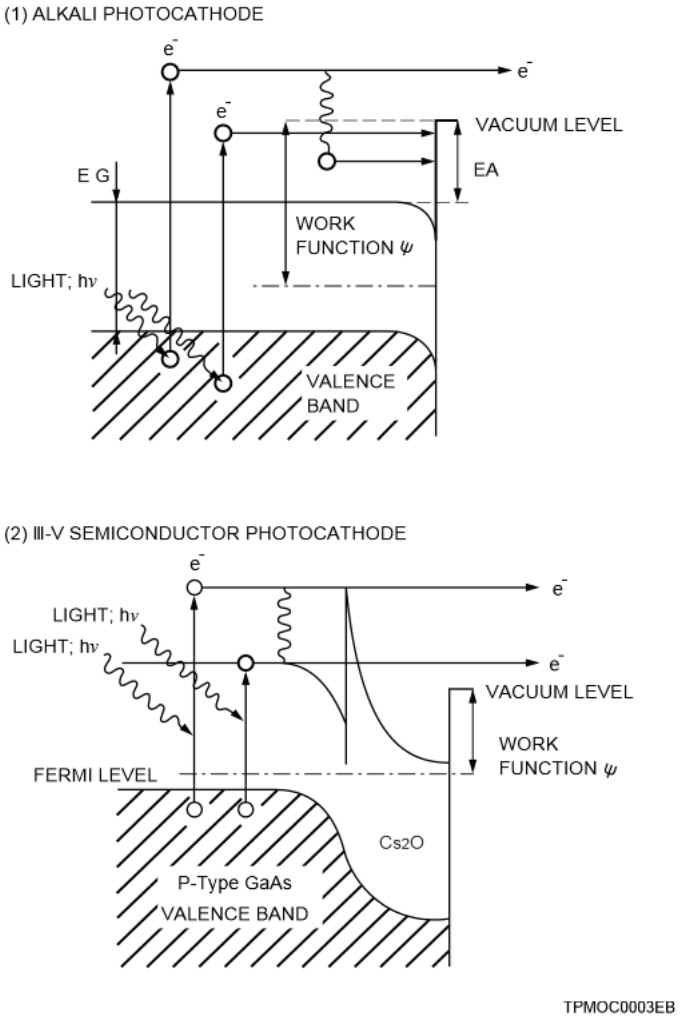


Figure 2-2: Photocathode band models

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In a semiconductor band model, there exist a forbidden-band gap or energy gap (EG) that cannot be occupied by electrons, electron affinity (EA) which is an interval between the conduction band and the vacuum level barrier (vacuum level), and work function (ψ) which is an energy difference between the Fermi level and the vacuum level. When photons strike a photocathode, electrons in the valence band absorb photon energy ($h\nu$) and become excited, diffusing toward the photocathode surface. If the diffused electrons have enough energy to overcome the vacuum level barrier, they are emitted into the vacuum as photoelectrons. This can be expressed in a probability process, and the quantum efficiency $\eta(\nu)$, i.e., the ratio of output electrons to incident photons is given by

$$\eta(v) = (1-R)\frac{Pv}{k} \cdot \left(\frac{1}{1+1/kL}\right) \cdot Ps$$

where

R : reflection coefficient
k : full absorption coefficient of photons
Pv : probability that light absorption may excite electrons to a level greater than the vacuum level
L : mean escape length of excited electrons
Ps : probability that electrons reaching the photocathode surface may be released into the vacuum
v : frequency of light

In the above equation, if we have chosen an appropriate material which determines parameters R, k and Pν, the factors that dominate the quantum efficiency will be L (mean escape length of excited electrons) and Ps (probability that electrons may be emitted into the vacuum). L becomes longer by use of a better crystal and Ps greatly depends on electron affinity (EA).

Figure 2-2 (2) shows the band model of a photocathode using III-V compound semiconductors.[8)-10)] If a surface layer of electropositive material such as Cs_2O is applied to this photocathode, a depletion layer is formed, causing the band structure to be bent downward. This bending can make the electron affinity negative. This state is called NEA (negative electron affinity). The NEA effect increases the probability (Ps) that the electrons reaching the photocathode surface may be emitted into the vacuum. In particular, it enhances the quantum efficiency at long wavelengths with lower excitation energy. In addition, it lengthens the mean escape distance (L) of excited electrons due to the depletion layer.

Photocathodes can be classified by photoelectron emission process into a reflection mode and a transmission mode. The reflection mode photocathode is usually formed on a metal plate, and photoelectrons are emitted in the opposite direction of the incident light. The transmission mode photocathode is usually deposited as a thin film on a glass plate which is optically transparent. Photoelectrons are emitted in the same direction as that of the incident light. (Refer to Figures 2-3, 2-4 and 2-5.) The reflection mode photocathode is mainly used for the side-on photomultiplier tubes which receive light through the side of the glass bulb, while the transmission mode photocathode is used for the head-on photomultiplier tubes which detect the input light through the end of a cylindrical bulb.

The wavelength of maximum response and long-wavelength cutoff are determined by the combination of alkali metals used for the photocathode and its fabrication process. As an international designation, photocathode sensitivity[11)] as a function of wavelength is registered as an "S" number by the JEDEC (Joint Electron Devices Engineering Council). This "S" number indicates the combination of a photocathode and window material and at present, numbers from S-1 through S-25 have been registered. However, other than S-1, S-11, S-20 and S-25 these numbers are scarcely used. Refer to Chapter 3 for the spectral response characteristics of various photocathodes and window materials.

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2. 2 Electron Trajectory

In order to collect photoelectrons and secondary electrons efficiently on a dynode and also to minimize the electron transit time spread, electrode design must be optimized through an analysis of the electron trajectory.[12)-16)]

Electron movement in a photomultiplier tube is influenced by the electric field which is dominated by the electrode configuration, arrangement, and also the voltage applied to the electrode. Conventional analysis of the electron trajectory has been performed by simulation models of an actual electrode, using methods such as rubber films and an electrolytic bath. Recently, however, numerical analysis using high-speed, large-capacity computers have come into use. This method divides the area to be analyzed into a grid-like pattern to give boundary conditions, and obtains an approximation by repeating computations until the error converges. By solving the equation for motion based on the potential distribution obtained using this method, the electron trajectory can be predicted.

When designing a photomultiplier tube, the electron trajectory from the photocathode to the first dynode must be carefully designed in consideration of the photocathode shape (planar or spherical window), the shape and arrangement of the focusing electrode and the supply voltage, so that the photoelectrons emitted from the photocathode are efficiently focused onto the first dynode. The collection efficiency of the first dynode is the ratio of the number of electrons landing on the effective area of the first dynode to the number of emitted photoelectrons. This is usually better than 60 to 90 percent. In some applications where the electron transit time needs to be minimized, the electrode should be designed not only for optimum configuration but also for higher electric fields than usual.

The dynode section is usually constructed from several to more than ten stages of secondary-emissive electrodes (dynodes) having a curved surface. To enhance the collection efficiency of each dynode and minimize the electron transit time spread, the optimum configuration and arrangement should be determined from an analysis of the electron trajectory. It is also necessary to design the arrangement of the dynodes in order to prevent ion or light feedback from the latter stages.

In addition, various characteristics of a photomultiplier tube can also be calculated by computer simulation. For example, the collection efficiency, uniformity, and electron transit time can be calculated using a Monte Carlo simulation by setting the initial conditions of photoelectrons and secondary electrons. This allows collective evaluation of photomultiplier tubes. Figures 2-3, 2-4 and 2-5 are cross sections of photomultiplier tubes having a circular-cage, box-and-grid, and linear-focused dynode structures, respectively, showing their typical electron trajectories.

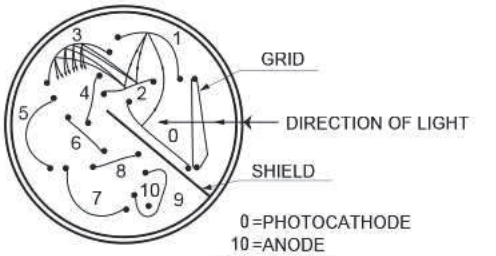


Figure 2-3: Circular-cage type

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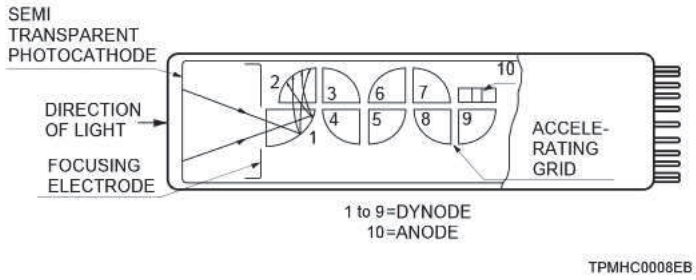


Figure 2-4: Box-and-grid type

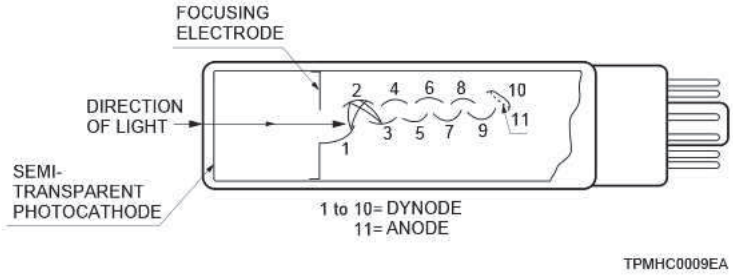


Figure 2-5: Linear-focused type

2. 3 Electron Multiplier (Dynode Section)

As stated above, the potential distribution and electrode structure of a photomultiplier tube is designed to provide optimum performance. Photoelectrons emitted from the photocathode are multiplied by the first dynode through the last dynode (up to 19th dynode), with current amplification ranging from 10 to as much as 108 times, and are finally sent to the anode.

Major secondary emissive materials[17)-21)] used for dynodes are alkali antimonide, beryllium oxide (BeO), magnesium oxide (MgO), gallium phosphide (GaP) and gallium arsenide phosphied (GaAsP). These materials are coated onto a substrate electrode made of nickel, stainless steel, or copper-beryllium alloy. Figure 2-6 shows a model of the secondary emission multiplication of a dynode.

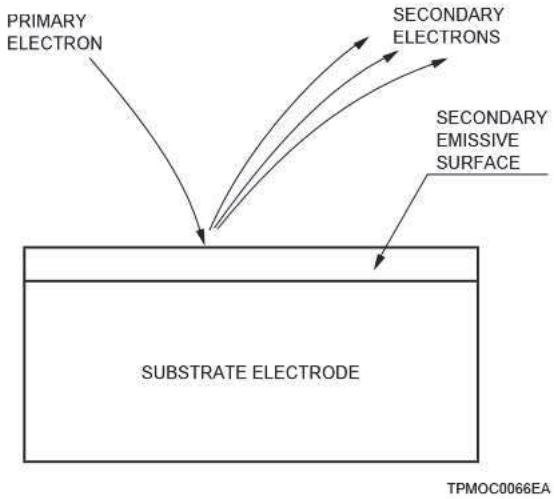


Figure 2-6: Secondary emission of dynode

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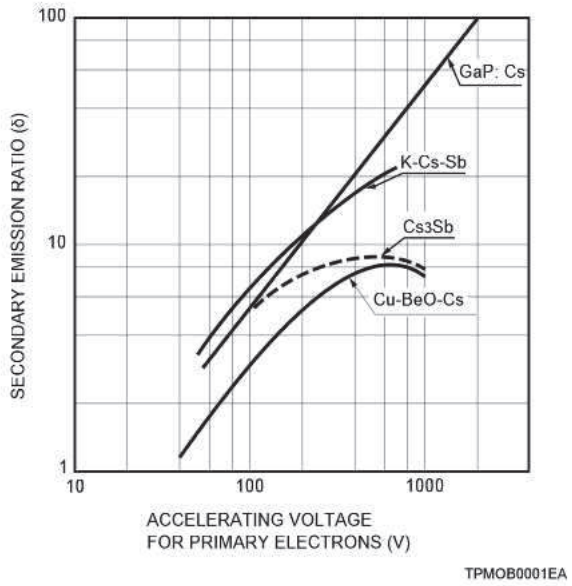


Figure 2-7: Secondary emission ratio

When a primary electron with initial energy Ep strikes the surface of a dynode, δ secondary electrons are emitted. This δ, the number of secondary electrons per primary electron, is called the secondary emission ratio. Figure 2-7 shows the secondary emission ratio δ for various dynode materials as a function of the accelerating voltage for the primary electrons.

Ideally, the current amplification or gain of a photomultiplier tube having the number of dynode stages n and the average secondary emission ratio δ per stage will be δ^n. Refer to Section 3.2.2 in Chapter 3 for more details on the gain.

Because a variety of dynode structures are available and their gain, time response, uniformity, and collection efficiency differ depending on the number of dynode stages and other factors, it is necessary to select the optimum dynode type according to your application. These characteristics are described in Chapter 3, Section 3.2.1.

2. 4 Anode

The anode of a photomultiplier tube is an electrode that collects secondary electrons multiplied in the cascade process through multi-stage dynodes and outputs the electron current to an external circuit.

Anodes are carefully designed to have a structure optimized for the electron trajectories discussed previously. Generally, an anode is fabricated in the form of a rod wire, metal plate or mesh electrode. One of the most important factors in designing an anode is that an adequate potential difference can be established between the last dynode and the anode in order to prevent space charge effects and obtain a large output current.

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CHAPTER 3
CHARACTERISTICS OF PHOTOMULTIPLIER TUBES

This chapter details various characteristics of photomultiplier tubes, including basic characteristics and their measurement methods. For example, Section 3.1 shows spectral response characteristics of typical photocathodes and also gives the definition of photocathode sensitivity and its measurement procedure. Section 3.2 explains dynode types, structures and typical characteristics. Section 3.3 describes various characteristics of photomultiplier tubes such as time response properties, operating stability, sensitivity, uniformity, signal-to-noise ratio as well as their definitions, measurement procedures and specific product examples. It also provides precautions and suggestions for actual use. Section 3.4 introduces the photon counting method, an effective technique for low-level light detection, including its principles, operating procedure, and various characteristics. In addition, 3.5 explains the principle of scintillation counting which is widely used in radiation measurements, along with the operating procedure and typical characteristics of photomultiplier tubes selected for this application.

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3. 1 Basic Characteristics of Photocathodes

This section introduces photocathode and window materials which have been put into practical use up through the present and also explains the terms used to evaluate photocathodes such as quantum efficiency, radiant sensitivity, and luminous sensitivity.

3. 1. 1 Photocathode materials

Most photocathodes[1)-11)] are made of a compound semiconductor mostly consisting of alkali metals with a low work function. There are about ten kinds of photocathodes which are currently in practical use. Each photocathode is available with a transmission (semitransparent) type or a reflection (opaque) type, with different device characteristics. In the early 1940's, the JEDEC (Joint Electron Devices Engineering Council) introduced the "S number" to designate photocathode spectral response which is classified by the combination of the photocathode and window materials. Presently, since many photocathode and window materials are available, the "S number" is not frequently used except for S-1, S-20, etc. The photocathode spectral response is instead expressed in terms of photocathode materials. The photocathode materials commonly used in photomultiplier tubes are as follows.

(1) Cs-I

Cs-I is insensitive to solar radiation and therefore often called "solar blind". Its sensitivity falls sharply at wavelengths longer than 200 nanometers and it is exclusively used for vacuum ultraviolet detection. As window materials, MgF_2 crystals or synthetic silica are used because of high ultraviolet transmittance. Although Cs-I itself has high sensitivity to wavelengths shorter than 115 nanometers, the MgF_2 crystal used for the input window does not transmit wavelengths shorter than 115 nanometers. This means that the spectral response of a photomultiplier tube using the combination of Cs-I and MgF_2 covers a range from 115 to 200 nanometers. To measure light with wavelengths shorter than 115 nanometers using Cs-I, an electron multiplier having a first dynode on which Cs-I is deposited is often used with the input window removed.

(2) Cs-Te

Cs-Te is insensitive to wavelengths longer than 300 nanometers and is also called "solar blind" just as with Cs-I. A special Cs-Te photocathode processed to have strongly suppressed sensitivity in the visible part of the spectrum has been fabricated. With Cs-Te, the transmission type and reflection type show the same spectral response range, but the reflection type exhibits twice the sensitivity of the transmission type. Synthetic silica or MgF_2 is usually used for the input window.

(3) Sb-Cs

This photocathode has sensitivity in the ultraviolet to visible range, and is widely used in many applications. Because the resistance of the Sb-Cs photocathode is lower than that of the bialkali photocathode described later on, it is suited for applications where light intensity to be measured is relatively high so that a large current can flow in the cathode, and is also used where changes in the photocathode resistance due to cooling affects measurements. Sb-Cs is chiefly used for the reflection type photocathode.

(4) Bialkali (Sb-Rb-Cs, Sb-K-Cs)

Since two kinds of alkali metals are employed, these photocathodes are called "bialkali". The transmission type of these photocathodes has a spectral response range similar to the Sb-Cs photocathode, but has higher sensitivity and lower dark current. It also provides sensitivity that matches the emission of a NaI(Tl) scintillator, thus being widely used for scintillation counting in radiation measurements. On the other hand, the reflection-type bialkali photocathodes are intended for different applications and therefore are fabricated by a different process using the same materials. As a result, they offer enhanced sensitivity on the long wavelength side, providing a spectral response from the ultraviolet region to around 700 nanometers.

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(5) High temperature, low noise bialkali (Sb-Na-K)

As with the above bialkali photocathodes, two kinds of alkali metals are used. The spectral response range of this photocathode is almost identical with that of the above bialkali photocathodes, but the sensitivity is somewhat lower. This photocathode can withstand operating temperatures up to 175°C while normal photocathodes are guaranteed to no higher than 50°C. For this reason, it is ideally suited for use in oil well logging where photomultiplier tubes are often subjected to high temperatures. In addition, when used at room temperatures, this photocathode exhibits very low dark current, thus making it very useful in low-level light detection, for instance in photon counting applications where low noise is a prerequisite.

(6) Multialkali (Sb-Na-K-Cs)

Since three or more kinds of alkali metals are employed, this photocathode is sometimes called a "trialkali". It has high sensitivity, wide spectral response from the ultraviolet through near infrared region around 850 nanometers, and is widely used in broad-band spectrophotometers. Furthermore, Hamamatsu also provides a multialkali photocathode with long wavelength response extending out to 900 nanometers, which is especially useful in the detection of chemiluminescence in NOx, etc.

(7) Ag-O-Cs

The transmission type photocathode using this material is sensitive from the visible through near infrared region, from 300 to 1200 nanometers, while the reflection type shows a slightly narrower region, spectral range from 300 to 1100 nanometers. Compared to other photocathodes, this photocathode shows lower sensitivity in the visible region, but has sensitivity at longer wavelengths in the near infrared region. Thus, both the transmission type and reflection type Ag-O-Cs photocathodes are chiefly used for near infrared detection.

(8) GaAs (Cs)

A GaAs crystal activated with cesium is also used as a photocathode. The spectral response of this photocathode covers a wide range from the ultraviolet through 930 nanometers with a plateau curve from 300 to 850 nanometers, showing a sudden cutoff at the near infrared limit. It should be noted that if exposed to incident light with high intensity, this photocathode tends to suffer sensitivity degradation when compared with other photocathodes.

(9) InGaAs (Cs)

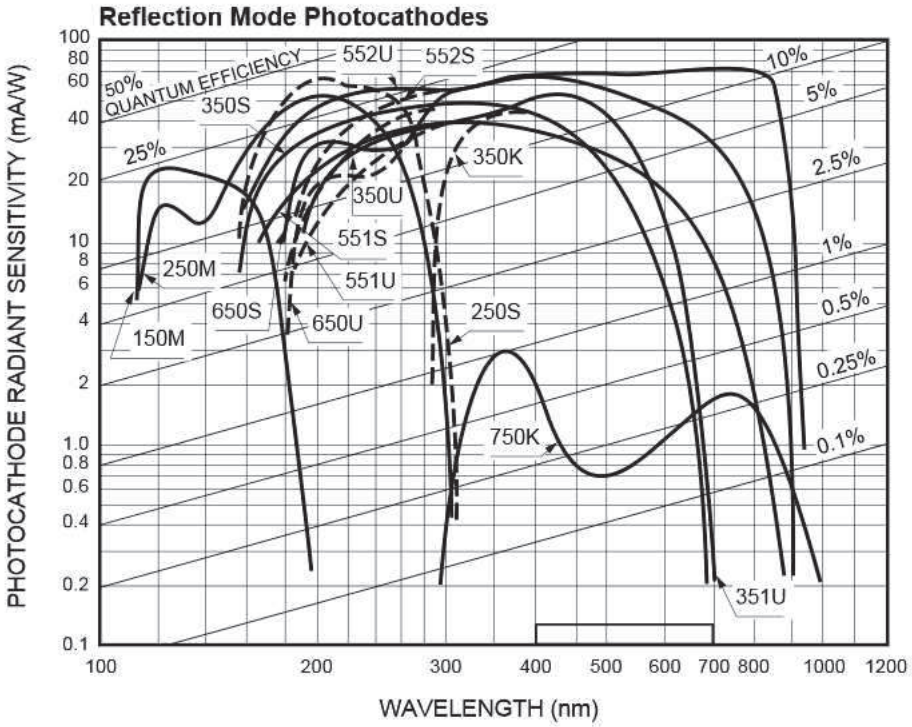
This photocathode provides a spectral response extending further into the infrared region than the GaAs photocathode. Additionally, it offers a superior signal-to-noise ratio in the neighborhood of 900 to 1000 nanometers in comparison with the Ag-O-Cs photocathode.

(10) InP/InGaAsP(Cs), InP/InGaAs(Cs)

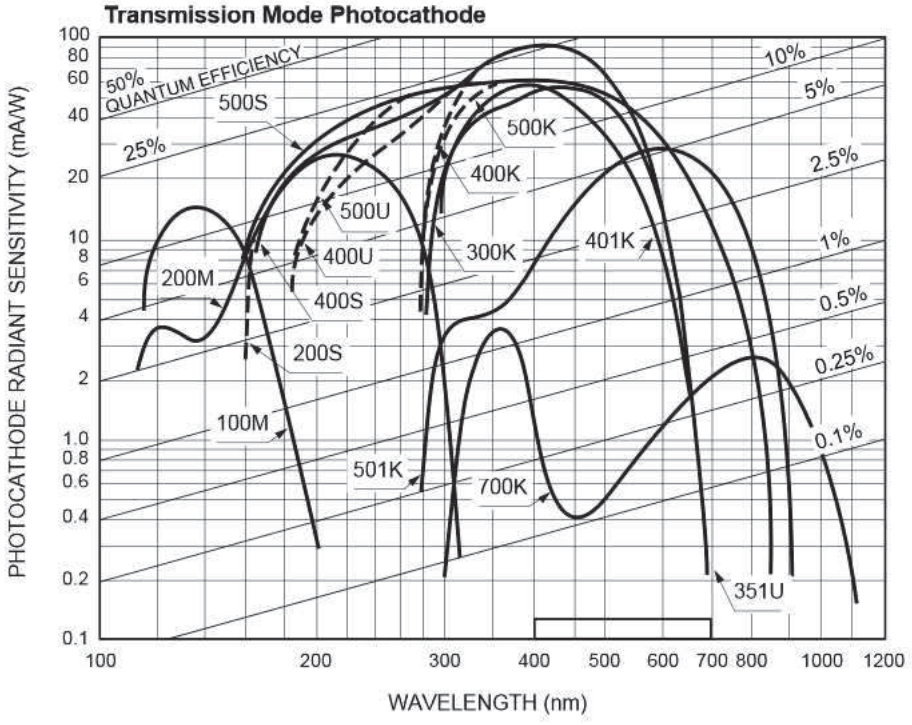
These are field-assisted photocathodes utilizing a PN junction by growing InP/InGaAsP or InP/InGaAs on a p+InP substrate, and utilized in practical use by means of our unique semiconductor micro-process technology.[16) 17)] These photocathodes are sensitive to long wavelengths extending to 1.4μm or even 1.7μm which have up till now been impossible to detect with a photomultiplier tube. Since these photocathodes produce large amounts of dark current when used at room temperatures, they must be cooled to about -80°C during operation.

Typical spectral response characteristics of major photocathodes are illustrated in Figure 3-1[1)] and Table 3-1.[1)] The JEDEC "S numbers" being frequently used are also listed in Table 3-1. The definition of photocathode radiant sensitivity expressed in the ordinate of Figure 3-1 is explained in Section 3.1.3, "Spectral response characteristics". Note that Figure 3-1 and Table 3-1 show typical characteristics and actual data may differ from tube to tube.

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Figure 3-1: Typical photocathode spectral response characteristics

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Transmission mode photocathodes

	Curve Code (S number)	Photocathode Material	Window Material	Spectral Response		
				Spectral Range (mm)	Peak Wavelength	
					Radiant Sensicivity (nm)	Quantum Efficiency (nm)
*	100M	Cs-I	MgF_2	115 to 200	140	130
*	200S	Cs-Te	Sythetic silica	160 to 320	210	200
*	200M	Cs-Te	MgF_2	115 to 320	210	200
–	201S	Cs-Te	Sythetic silica	160 to 320	240	220
–	201A	Cs-Te	Sapphire	150 to 320	250	220
*	300K (S-11)	Sb-Cs	Bolosilicate	300 to 650	440	410
*	400K	Bialkali	Bolosilicate	300 to 650	420	390
*	400U	Bialkali	UV	185 to 650	420	390
*	400S	Bialkali	Sythetic silica	160 to 650	420	390
*	401K	High temperature bialkali	Bolosilicate	300 to 650	375	360
–	402K	Bialkali	Bolosilicate	300 to 650	375	360
*	500K (S-20)	Multialkali	Bolosilicate	300 to 850	420	360
*	500U	Multialkali	UV	185 to 850	420	290
*	500S	Multialkali	Sythetic silica	160 to 850	420	280
*	501K (S-25)	Multialkali	Bolosilicate	300 to 900	650	600
*	700K (S-1)	Ag-O-Cs	Bolosilicate	300 to 1200	800	780

* : Spectral response curves are shown in Figure 3-1.
– : Spectral response curves are not shown in Figure 3-1.

Table 3-1: Quick reference for typical spectral response characteristics (1)

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Reflection mode photocathodes

	Curve Code (S number)	Photocathode Material	Window Material	Spectral Response		
				Spectral Range (nm)	Peak Wavelength	
					Radiant Sensicivity (nm)	Quantum Efficiency (nm)
*	150M	Cs-I	MgF_2	115 to 195	120	120
*	250S	Cs-Te	Sythetic silica	160 to 320	200	200
*	250M	Cs-Te	MgF_2	115 to 320	200	190
*	350K (S-4)	Sb-Cs	Bolosilicate	300 to 650	400	350
*	350K (S-5)	Sb-Cs	UV	185 to 650	340	270
*	350S (S-19)	Sb-Cs	Sythetic silica	160 to 650	340	210
–	351U (Extented S-5)	Sb-Cs	UV	185 to 700	450	235
–	451U	Bialkali	UV	185 to 730	340	320
–	452U	Bialkali	UV	185 to 750	350	315
–	453K	Bialkali	Bolosilicate	300 to 650	400	360
–	453U	Bialkali	UV	185 to 650	400	330
–	454K	Bialkali	Bolosilicate	300 to 680	450	430
–	455U	Bialkali	UV	185 to 680	420	400
–	456U	Low dark current bialkali	UV	185 to 680	375	320
–	457U	Bialkali	Bolosilicate	300 to 680	450	450
–	550U	Multialkali	UV	185 to 850	530	250
–	550S	Multialkali	Sythetic silica	160 to 850	530	250
*	551U	Multialkali	UV	185 to 870	330	280
*	551S	Multialkali	Sythetic silica	160 to 870	330	280
*	552U	Multialkali	UV	185 to 900	400	260
*	552S	Multialkali	Sythetic silica	160 to 900	400	215
–	554U	Multialkali	UV	185 to 900	450	370
–	555U	Multialkali	UV	185 to 850	400	320
–	556U	Multialkali	UV	185 to 930	420	320
–	557U	Multialkali	UV	185 to 900	420	400
–	558K	Multialkali	Bolosilicate	300 to 800	530	510
*	650U	GaAs(Cs)	UV	185 to 930	300 to 800	300
*	650S	GaAs(Cs)	Sythetic silica	160 to 930	300 to 800	280
–	651U	GaAs(Cs)	UV	185 to 910	350	270
*	750K	Ag-O-Cs	Bolosilicate	300 to 1100	730	730
–	850U	InGaAs(Cs)	UV	185 to 1010	400	330
*	—	InP/nGaAsP(Cs)	Bolosilicate	300 to 1400	—	—
*	—	InP/InGaAsP(Cs)	Bolosilicate	300 to 1700	—	—

* : Spectral response curves are shown in Figure 3-1.
– : Spectral response curves are not shown in Figure 3-1.

Table 3-1: Quick reference for typical spectral response characteristics (2)

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3. 1. 2 Window materials

As stated in the preceding section, most photocathodes have high sensitivity down to the ultraviolet region. However, because ultraviolet radiation tends to be absorbed by the window material, the short wavelength limit is determined by the ultraviolet transmittance of the window material.[18)-22)] The window materials commonly used in photomultiplier tubes are as follows:

(1) MgF_2 crystal

The crystals of alkali halide are superior in transmitting ultraviolet radiation, but have the disadvantage of deliquescence. A magnesium fluoride (MgF_2) crystal is used as a practical window material because it offers very low deliquescence and allows transmission of vacuum ultraviolet radiation down to 115 nanometers.

(2) Sapphire

Sapphire is made of Al_2O_3 crystal and shows an intermediate transmittance between the UV-transmitting glass and synthetic silica in the ultraviolet region. Sapphire glass has a short wavelength cutoff in the neighborhood of 150 nanometers, which is slightly shorter than that of synthetic silica.

(3) Synthetic silica

Synthetic silica transmits ultraviolet radiation down to 160 nanometers and in comparison to fused silica, offers lower absorption in the ultraviolet region. Since silica has a thermal expansion coefficient greatly different from that of a Kovar alloy used for the stem pins (leads) of photomultiplier tubes, it is not suited for use as the bulb stem. Because of this, a borosilicate glass is used for the bulb stem and then a graded seal using glasses with gradually different thermal expansion coefficient are connected to the synthetic silica bulb, as shown in Figure 3-2. Because of this structure, the graded seal is very fragile so that sufficient care should be taken when handling the tube. In addition, helium gas may permeate through the silica bulb and cause the noise to increase. Avoid operating or storing such tubes in environments where helium is present.

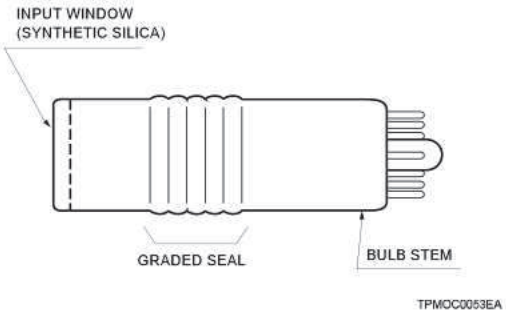


Figure 3-2: Grated seal

(4) UV glass (UV-transmitting glass)

As the name implies, this transmits ultraviolet radiation well. The short wavelength cutoff of the UV glass extends to 185 nanometers.

(5) Borosilicate glass

This is the most commonly used window material. Because the borosilicate glass has a thermal expansion coefficient very close to that of the Kovar alloy which is used for the leads of photomultiplier tubes, it is often called "Kovar glass". The borosilicate glass does not transmit ultraviolet radiation shorter than 300 nanometers. It is not suited for ultraviolet detection shorter than this range. Moreover, some types of head-on photomultiplier tubes using a bialkali photocathode employ a special borosilicate glass (so-called "K-free glass") containing a very small amount of potassium (K^{40}) which may cause unwanted noise counts. The K-free glass is mainly used for photomultiplier tubes designed for scintillation counting where low background counts are desirable. For more details on background noise caused by K^{40}, refer to Section 3.3.6, "Dark current".

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Spectral transmittance characteristics of various window materials are shown in Figure 3-3.

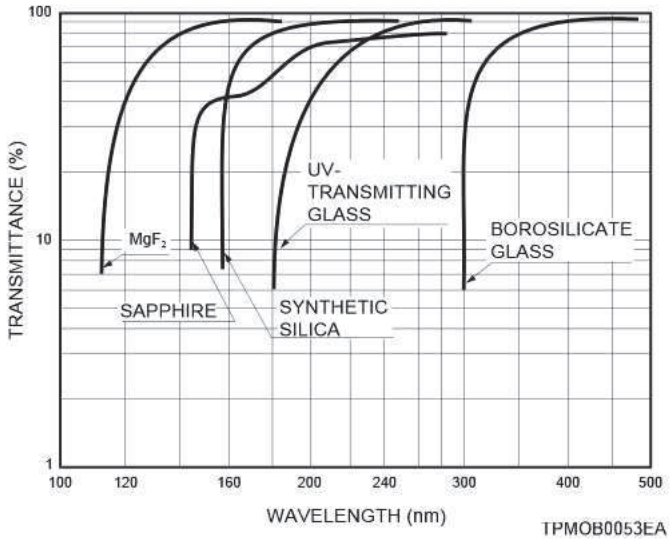


Figure 3-3: Spectral transmittance of window materials

3. 1. 3 Spectral response characteristics

The photocathode of a photomultiplier converts the energy of incident photons into photoelectrons. The conversion efficiency (photocathode sensitivity) varies with the incident light wavelength. This relationship between the photocathode and the incident light wavelength is referred to as the spectral response characteristics. In general, the spectral response characteristics are expressed in terms of radiant sensitivity and quantum efficiency.

(1) Radiant sensitivity

Radiant sensitivity is the photoelectric current from the photocathode divided by the incident radiant flux at a given wavelength, expressed in units of amperes per watts (A/W). Furthermore, relative spectral response characteristics in which the maximum radiant sensitivity is normalized to 100% are also conveniently used.

(2) Quantum efficiency

Quantum efficiency is the number of photoelectrons emitted from the photocathode divided by the number of incident photons. Quantum efficiency is symbolized by η and generally expressed in percent. Incident photons give energy to electrons in the valence band of a photocathode but not all electrons given energy are emitted as photoelectrons. This photoemission takes place under a certain probability process. Photons at shorter wavelengths carry higher energy compared to those at longer wavelengths and contribute to an increase in the photoemission probability. As a result, the maximum quantum efficiency occurs at a wavelength slightly shorter than that of the radiant sensitivity.

(3) Measurement and calculation of spectral response characteristics

To measure radiant sensitivity and quantum efficiency, a standard phototube or semiconductor detector which is precisely calibrated is used as a secondary standard. At first, the incident radiant flux L_p at the wavelength of interest is measured with the standard phototube or semiconductor detector. Next, the pho-

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tomultiplier tube to be measured is set in place and the photocurrent Ik is measured. Then the radiant sensitivity Sk of the photomultiplier tube can be calculated from the following equation:

$$Sk = \frac{I_K}{L_P} (A/W) \quad \text{(Eq. 3-1)}$$

The quantum efficiency η can be obtained from Sk using the following equation:

$$\eta(\%) = \frac{h \cdot c}{\lambda \cdot e} \cdot SK = \frac{1240}{\lambda} \cdot SK \cdot 100\% \quad \text{(Eq. 3-2)}$$

h : $6.6262765\ 10^{-34} J \cdot s$
c : $2.9979245\ 10^{8} m \cdot s^{-1}$
e : $1.6021895\ 10^{-19} C$

where h is Planck's constant, λ is the wavelength of incident light (nanometers), c is the velocity of light in vacuum and e is the electron charge. The quantum efficiency η is expressed in percent.

(4) Spectral response range (short wavelength limit, long wavelength limit)

The wavelength at which the spectral response drops on the short wavelength side is called the short wavelength limit or cutoff while the wavelength at which the spectral response drops on the long wavelength side is called the long wavelength limit or cutoff. The short wavelength limit is determined by the window material, while the long wavelength limit depends on the photocathode material. The range between the short wavelength limit and the long wavelength limit is called the spectral response range.

In this handbook, the short wavelength limit is defined as the wavelength at which the incident light is abruptly absorbed by the window material. The long wavelength limit is defined as the wavelength at which the photocathode sensitivity falls to 1 percent of the maximum sensitivity for bialkali and Ag-O-Cs photocathodes, and 0.1 percent of the maximum sensitivity for multialkali photocathodes. However, these wavelength limits will depend on the actual operating conditions such as the amount of incident light, photocathode sensitivity, dark current and signal-to-noise ratio of the measurement system.

3. 1. 4 Luminous sensitivity

The spectral response measurement of a photomultiplier tube requires an expensive, sophisticated system and much time is required, it is therefore more practical to evaluate the sensitivity of common photomultiplier tubes in terms of luminous sensitivity. The illuminance on a surface one meter away from a point light source of one candela (cd) is one lux. One lumen equals the luminous flux of one lux passing an area of one square meter. Luminous sensitivity is the output current obtained from the cathode or anode divided by the incident luminous flux (lumen) from a tungsten lamp at a distribution temperature of 2856K. In some cases, a visual-compensation filter is interposed between the photomultiplier tube and the light source, but in most cases it is omitted. Figure 3-4 shows the visual sensitivity and relative spectral distribution of a 2856K tungsten lamp.

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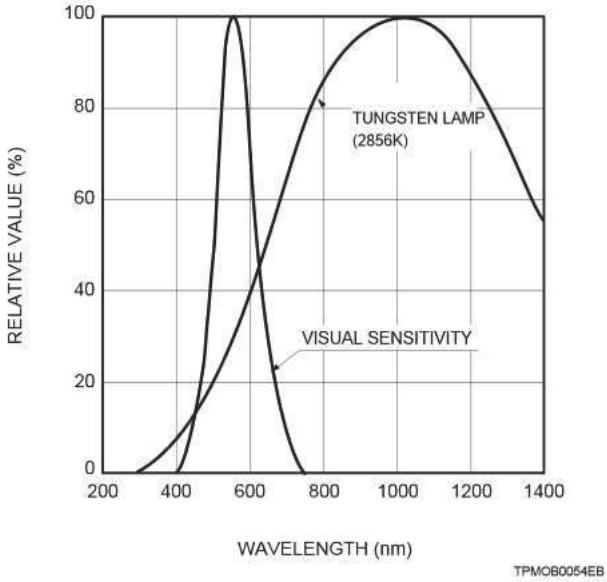


Figure 3-4: Response of eye and spectral distribution of 2856 K tungsten lamp

Luminous sensitivity is a convenient parameter when comparing the sensitivity of photomultiplier tubes categorized in the same types. However, it should be noted that "lumen" is the unit of luminous flux with respect to the standard visual sensitivity and there is no physical significance for photomultiplier tubes which have a spectral response range beyond the visible region (350 to 750 nanometers). To evaluate photomultiplier tubes using Cs-Te or Cs-I photocathodes which are insensitive to the spectral distribution of a tungsten lamp, radiant sensitivity at a specific wavelength is measured.

Luminous sensitivity is divided into two parameters: cathode luminous sensitivity which shows the photocathode property and anode luminous sensitivity which indicates the performance of the whole photomultiplier tube.

(1) Cathode luminous sensitivity

Cathode luminous sensitivity[23) 25)] is defined as the photoelectron current from the photocathode (cathode current) per luminous flux from a tungsten lamp operated at a distribution temperature of 2856K. In this measurement, each dynode is shorted to the same potential as shown in Figure 3-5, so that the photomultiplier tube is operated as a bipolar tube.

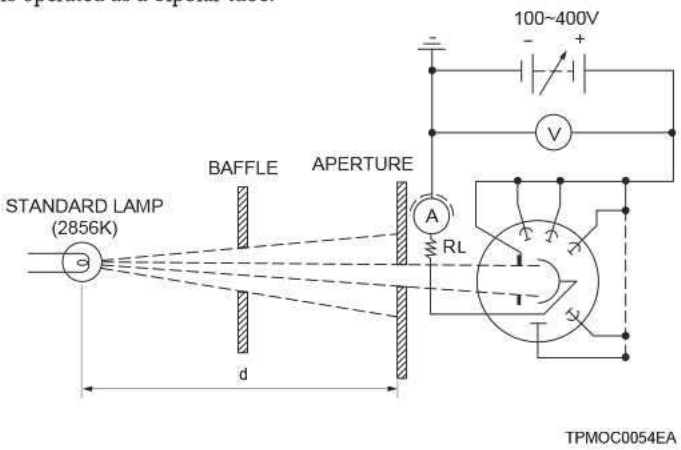


Figure 3-5: Cathode luminous sensitivity measuring diagram

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The incident luminous flux used for measurement is in the range of 10^{-3} to 10^{-2} lumens. If the luminous flux is too large, measurement errors may occur due to the surface resistance of the photocathode. Consequently, the optimum luminous flux must be selected according to the photocathode size and material.

A picoammeter is usually used to measure the photocurrent which is as small as several nanoamperes to several microamperes. Sufficient countermeasures against leakage current and possible noise source must be taken. In addition, be careful to avoid contamination on the socket or bulb stem and to keep the ambient humidity at a low level so that an adequate electrical safeguard is provided.

The photomultiplier tube must be operated at a supply voltage which establishes a complete saturation in the supply voltage vs. cathode current characteristics. A voltage of 90 to 400 volts is usually applied for this purpose. Cathode saturation characteristics are discussed in Section 3.3.2, "Linearity". The ammeter is connected to the cathode via a serial load resistance (R_L) of 100 kilohms to one megohm for circuitry protection.

(2) Anode luminous sensitivity

Anode luminous sensitivity[23) 25)] is defined as the anode output current per luminous flux incident on the photocathode. In this measurement, a proper voltage distribution is given to each electrode as illustrated in Figure 3-6. Although the same tungsten lamp that was used to measure the cathode luminous sensitivity is used again, the light flux is reduced to 10^{-10} to 10^{-5} lumens using a neutral density filter. The ammeter is connected to the anode via the series resistance. The voltage-divider resistors used in this measurement must have minimum tolerance and good temperature characteristics.

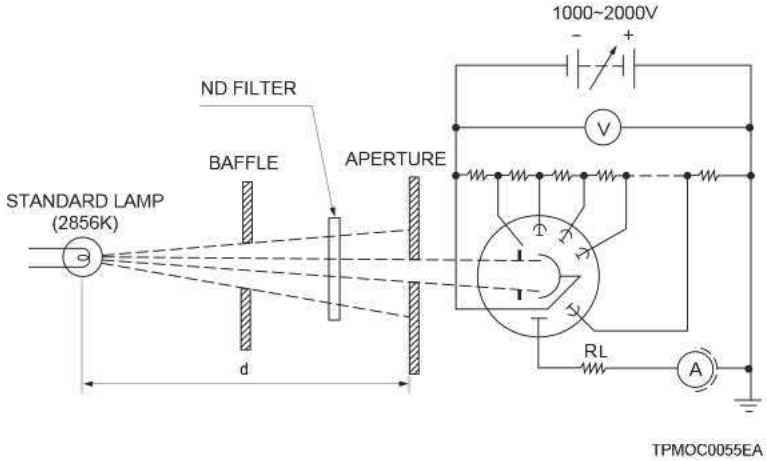


Figure 3-6: Anode luminous sensitivity measuring diagram

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(3) Blue sensitivity and red-to-white ratio

Blue sensitivity and red-to-white ratio are often used for simple comparison of the spectral response of photomultiplier tubes.

Blue sensitivity is the cathode current obtained when a blue filter is placed in front of the photomultiplier tube under the same conditions for the luminous sensitivity measurement. The blue filter used is a Corning Cs No.5-58 polished to half stock thickness. Since the light flux entering the photomultiplier tube has been transmitted through the blue filter once, it cannot be directly represented in lumens. Therefore at Hamamatsu Photonics, it is conveniently expressed in units of A/lm-b (amperes per lumen-blue). The spectral transmittance of this blue filter matches well the emission spectrum of a NaI(Tl) scintillator (peak wavelength 420 nanometers) which is widely used for scintillation counting. Photomultiplier tube sensitivity to the scintillation flash has a good correlation with the anode sensitivity using this blue filter, Furthermore, the blue sensitivity is an important factor to determine energy resolution in scintillation measurement. Refer to Section 3.5 for more details, "Scintillation counting".

The red-to-white ratio is used to evaluate 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 red or near infrared filter interposed under the same conditions for cathode luminous sensitivity divided by the cathode luminous sensitivity without a filter. The filter used is a Toshiba IR-D80A for Ag-O-Cs photocathodes or a Toshiba R-68 for other photocathodes. If other types of filters are used, the red-to-white ratio will vary. Figure 3-7 shows the spectral transmittance of these filters.

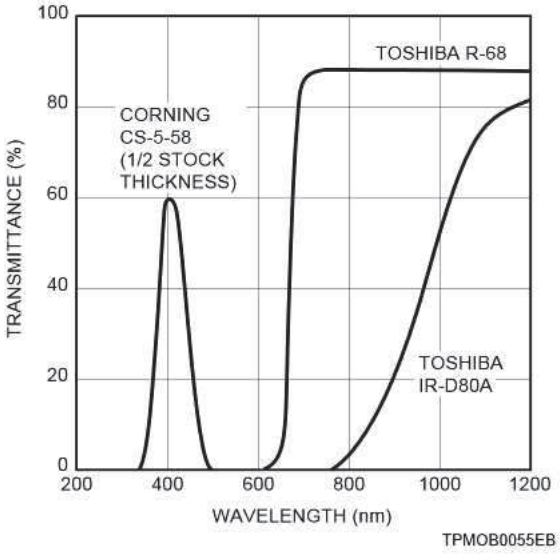


Figure 3-7 Typical spectral transmittance of optical filters.

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3. 1. 5 Luminous sensitivity and spectral response

There is a correlation between luminous sensitivity and spectral response to some extent at a specific wavelength. Figure 3-8 describes the correlation between luminous sensitivity, blue sensitivity (CS-5-58) and red-to-white ratio (R-68, IR-D80A) as a function of wavelength.

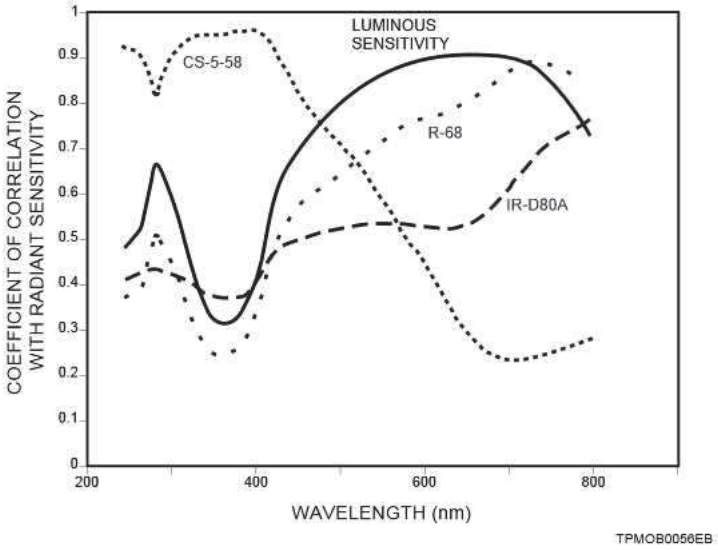


Figure 3-8: Correlation between luminous sensitivities and radiant sensitivity

It can be seen from the figure that the radiant sensitivity of a photomultiplier tube has a good correlation with the blue sensitivity at wavelengths shorter than 450 nanometers, with the luminous sensitivity at 700 to 800 nanometers, with the red-to-white ratio using the Toshiba R-68 filter at 700 to 800 nanometers, and with the red-to-white ratio using the Toshiba IR-D80A filter at 800 nanometers or longer. From these correlation values, it is possible to select a photomultiplier tube with optimum sensitivity at a certain wavelength by simply measuring the sensitivity using a filter which has the best correlation value at that wavelength rather than making troublesome measurements of the spectral response.

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3. 2 Basic Characteristics of Dynodes

This section introduces typical dynode types currently in use and describes their basic characteristics: collection efficiency and gain (current amplification).

3. 2. 1 Dynode types and features

There are a variety of dynode types available and each type exhibits different gain, time response, uniformity and secondary-electron collection efficiency depending upon the structure and the number of stages. It is essential to select the optimum type in accordance with your application. Figure 3-9 illustrates the cross sectional views of typical dynodes and their features are briefly discussed in the following sections. MCP-PMT's incorporating a microchannel plate for the dynode and photomultiplier tubes using a fine-mesh dynode are detailed in Chapter 4 and Chapter 6, respectively.

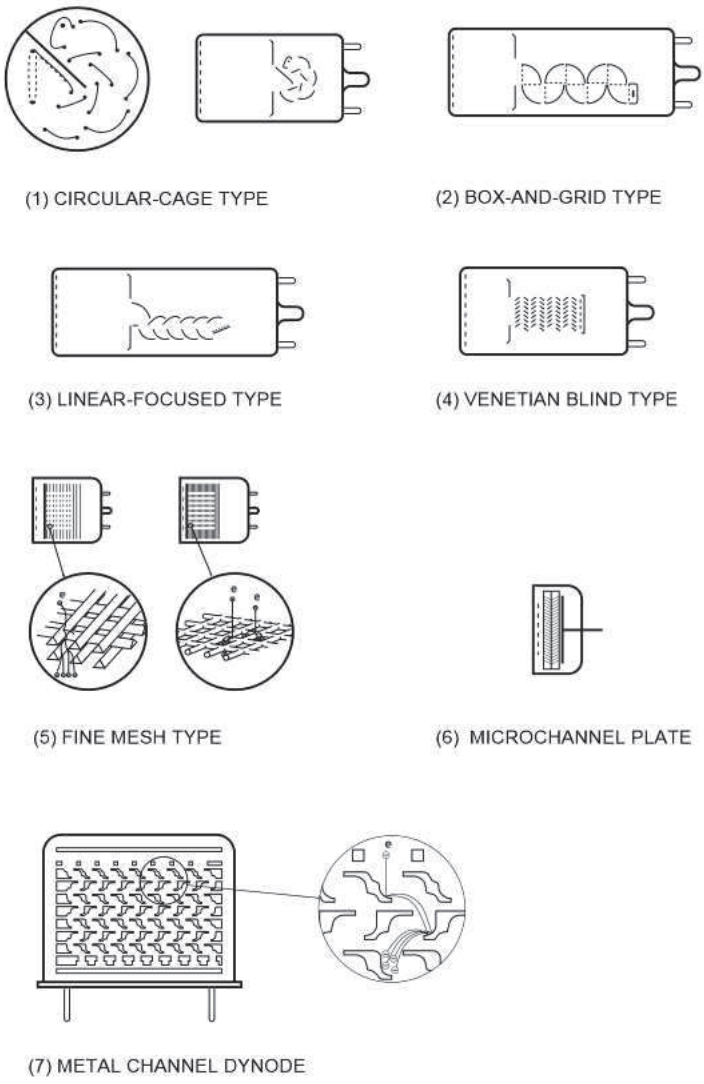


Figure 3-9: Types of electron multipliers

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(1) Circular-cage type

The circular-cage type has an advantage of compactness and is used in all side-on photomultiplier tubes and in some head-on photomultiplier tubes. The circular-cage type also features fast time response.

(2) Box-and-grid type

This type, widely used in head-on photomultiplier tubes, is superior in photoelectron collection efficiency. Accordingly, photomultiplier tubes using this dynode offer high detection efficiency and good uniformity.

(3) Linear-focused type

As with the box-and-grid type, the linear-focused type is widely used in head-on photomultiplier tubes. Its prime features include fast time response, good time resolution and excellent pulse linearity.

(4) Venetian blind type

The venetian blind type allows a simple design for photoelectron collection and is ideally suited for use in head-on photomultiplier tubes with a large photocathode diameter.

(5) Mesh type

This type of dynode uses mesh electrodes stacked in close proximity to each other. There are two types: coarse mesh type and fine mesh type. Both are excellent in output linearity and have good immunity to magnetic fields. When used with a cross wire anode or multianode, it is possible to detect the position of incident light. Fine mesh types are developed primarily for photomultiplier tubes which are used in high magnetic fields. (For further details, refer to Chapter 6.)

(6) MCP (Microchannel plate)

A microchannel plate (MCP) with 1mm thickness is used as a dynode. This dynode exhibits dramatically improved time resolution as compared to other discrete dynodes. It also assures stable gain even in highly magnetic fields and provides position-sensitive capability when combined with a special anode. (For more details, refer to Chapter 6.)

(7) Metal channel dynode

Our long experience with micromachining technology and computer simulation of electron trajectories allowed fabricating extremely thin electrodes and assembling them in a precisely stacked configuration. Since each dynode is in close proximity to each other, the overall length is very short ensuring excellent time characteristics and stable gain even in magnetic fields. (A detailed description is given in Chapter 6.)

The electrical characteristics of a photomultiplier tube depend not only on the dynode type but also on the photocathode size and focusing system. As a general guide, Table 3-2 summarizes typical performance characteristics of head-on photomultiplier tubes (up to 5-inch diameter) classified by the dynode type. Magnetic characteristics listed are measured in a magnetic field in the direction of the most sensitive tube axis.

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Dynode Type	Rise Time (ns)	Pulse Linearity at 2% (mA)	Magnetic Immunity (mT)	Uniform-ity	Collection Efficiency	Features
Circular-cage	0.9 to 3.0	1 to 10	0.1	Poor	Good	Comapct, high speed
Box-and-grid	6 to 20			Good	Very good	High collection efficiency
Linear-focused	0.7 to 3	10 to 250		Poor	Good	High speed, high linearity
Venetian blind	6 to 18	10 to 40		Good	Poor	Suited for large diameter
Fine mesh	1.5 to 5.5	300 to 1000	*700 to 1200 or more	Good	Poor	High magnetic immunity, high linearity
MCP	0.1 to 0.3	700	15 to *1200 or more	Good	Poor	high speed
Metal channel	0.65 to 1.5	30	1 to 20**	Good	Good	Comapct, high speed

* In magnetic field parallel to tube axis
**Metal package PMT

Table 3-2: Typical characteristics of head-on photomultiplier tubes classified by dynode type

3. 2. 2 Collection efficiency and current amplification (gain)

(1) Collection efficiency

The electron multiplier of a photomultiplier tube is designed with consideration to the electron trajectories so that electrons are efficiently multiplied at each dynode. However, some electrons may deviate from their favorable trajectories, not contributing to multiplication.

In general, the probability that photoelectrons may land on the effective area of the first dynode is termed the collection efficiency (α). This effective area is the area of the first dynode where photoelectrons can be multiplied effectively at the successive dynode stages without deviating from their favorable trajectories. Although there exist secondary electrons which do not contribute to multiplication at the second dynode or latter dynodes, they will tend to have less of an affect on the total collection efficiency as the number of secondary electrons emitted increases greatly. Thus the photoelectron collection efficiency at the first dynode is important. Figure 3-10 shows collection efficiency as a function of cathode-to-first dynode voltage. If the cathode-to-first dynode voltage is inappropriate, the photoelectrons will not enter the effective area of the first dynode, thereby degrading collection efficiency.

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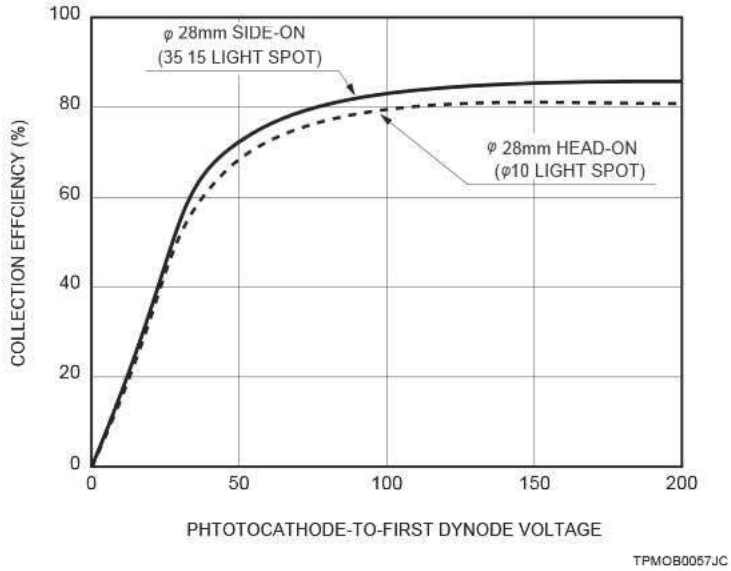


Figure 3-10: Collection efficiency vs. photocathode-to-first dynode voltage

From Figure 3-10, it can be seen that the cathode-to-first dynode voltage should be higher than 70 volts. The collection efficiency influences energy resolution, detection efficiency and signal-to-noise ratio in scintillation counting. The detection efficiency is the ratio of the detected signal to the input signal of a photomultiplier tube. In photon counting this is expressed as the product of the photocathode quantum efficiency and the collection efficiency.

(2) Gain

Secondary emission ratio δ is a function of the interstage voltage of dynodes E, and is given by the following equation:

$$\delta = a \cdot E^k \quad \text{(Eq. 3-3)}$$

Where a is a constant and k is determined by the structure and material of an electrode and has a value from 0.7 to 0.8.

The photoelectron current Ik emitted from the photocathode strikes the first dynode where secondary electrons Idl are released. At this point, the secondary emission ratio δ_1 at the first dynode is given by

$$\delta_1 = \frac{I_{dl}}{I_K} \quad \text{(Eq. 3-4)}$$

These electrons are multiplied in a cascade process from the first dynode → second dynode → .... the n-th dynode. The secondary emission ratio δn of n-th stage is given by

$$\delta_n = \frac{I_{dn}}{I_{d(n-1)}} \quad \text{(Eq. 3-5)}$$

The anode current Ip is given by the following equation:

$$Ip = Ik \cdot \alpha \cdot \delta_1 \cdot \delta_2 \cdots \delta_n \quad \text{(Eq. 3-6)}$$

Then

$$\frac{Ip}{Ik} = \alpha \cdot \delta_1 \cdot \delta_2 \cdots \delta_n \quad \text{(Eq. 3-7)}$$

where α is the collection efficiency. (See Section 3.4.2.)

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The product of α, δ_1, δ_2 .....δ n is called the gain μ , and is given by the following equation:

$$\mu = \alpha \cdot \delta_1 \cdot \delta_2 \cdots \delta_n \quad \text{(Eq. 3-8)}$$

Accordingly, in the case of a photomultiplier tube with α=1 and the number of dynode stages = n, which is operated using an equally-divided divider, the gain μ changes in relation to the supply voltage V, as follows:

$$\mu = (a \cdot E^k)^n = a^n \left(\frac{V}{n+1}\right)^{kn} = A \cdot V^{kn} \quad \text{(Eq. 3-9)}$$

where A should be equal to $a^n/(n+1)^{kn}$. From this equation, it is clear that the gain μ is proportional to the kn exponential power of the supply voltage. Figure 3-11 shows typical gain vs. supply voltage. Since Figure 3-11 is expressed in logarithmic scale for both the abscissa and ordinate, the slope of the straight line becomes kn and the current multiplication increases with the increasing supply voltage. This means that the gain of a photomultiplier tube is susceptible to variations in the high-voltage power supply used to operate the photomultiplier tube, such as drift, ripple, temperature stability, input regulation, and load regulation.

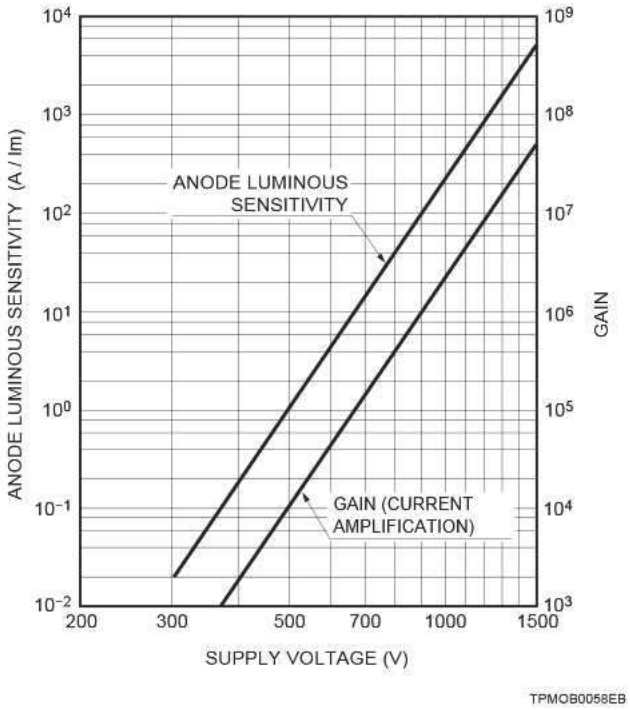


Figure 3-11: Gain vs. supply voltage

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3. 3 Characteristics of Photomultiplier Tubes

This section describes important characteristics for photomultiplier tube operation and their evaluation methods, and photomultiplier tube usage.

3. 3. 1 Time characteristics

The photomultiplier tube is a photodetector that has an exceptionally fast time response.[1) 23)-27)] The time response is primarily determined by the transit time required for the photoelectrons emitted from the photocathode to reach the anode while being multiplied and also the transit time difference between each photoelectron. Accordingly, fast response photomultiplier tubes are designed to have a spherical inner window and carefully engineered electrodes so that the transit time difference in the tube can be minimized.

Table 3-3 lists the timing characteristics of 2-inch diameter head-on photomultiplier tubes categorized by their dynode structure. As can be seen from the table, the linear-focused type exhibits the best time characteristics, while the box-and-grid and venetian blind types provide rather poor properties. Therefore, fast response photomultiplier tubes usually employ linear-focused dynodes.

Unit : ns

Dynode Type	Rise Time	Fall Time	Pulse Width (FWHM)	Electron Transit Time	T.T.S.
Linear-focused	0.7 to 3	1 to 10	1.3 to 5	16 to 50	0.37 to 1.1
Circular-cage	3.4	10	7	31	3.6
Box-and-grid	to 7	25	13 to 20	57 to 70	to 10
Venetian blind	to 7	25	25	60	to 10
Fine mesh	2.5 to 2.7	40	5	15	to 0.9
Metal channel	0.65 to 1.5	1 to 3	1.5 to 3	4.7 to 8.8	0.26 to 0.28

Table 3-3: Typical time characteristics (2-inch dia. photomultiplier tubes)

The time response is mainly determined by the electrode structure, but also depends on the supply voltage. Increasing the electric field intensity or supply voltage improves the electron transit speed and thus shortens the transit time. In general, the time response improves in inverse proportion to the square root of the supply voltage. Figure 3-12 shows typical time characteristics vs. supply voltage.

For the detection of high-speed phenomenon, wiring from the photomultiplier tube to external circuits such as a voltage-divider circuit and an anode signal processing circuit must be as short as possible to minimize stray capacitance and inductance. These circuit systems are discussed later in Chapter 7. In addition, some fast response photomultiplier tubes have a coaxial anode to suppress output waveform distortion.

The following explains definitions of time characteristics and their measurement methods.

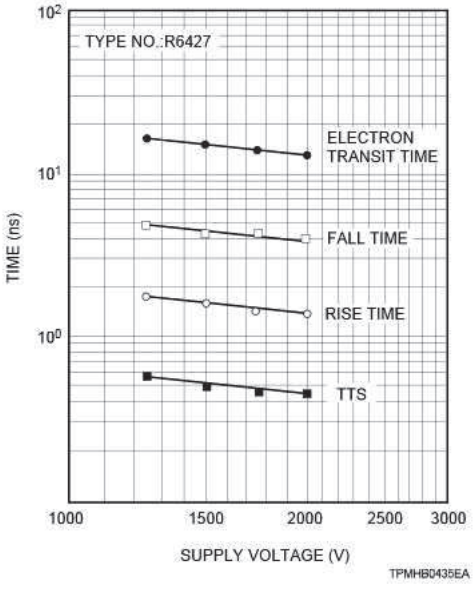


Figure 3-12: Time characteristics vs. supply voltage

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(1) Rise time, fall time and electron transit time

Figure 3-13 shows a schematic diagram for time response measurements and Figure 3-14 illustrates the definitions of the rise time, fall time and electron transit time of a photomultiplier tube output.

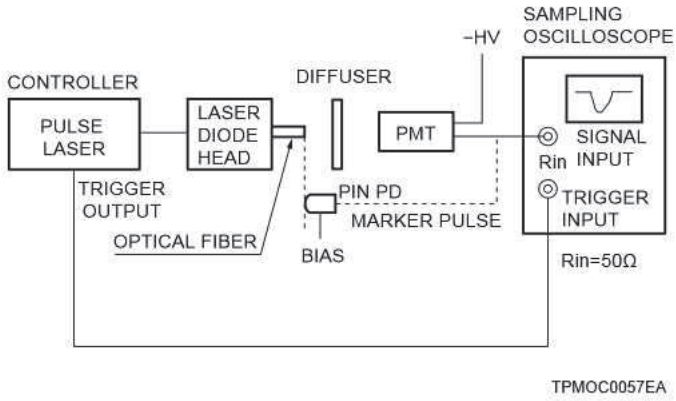


Figure 3-13: Measurement block diagram for rise/fall times and electron transit time

A pulsed laser diode is used as the light source. Its pulse width is 55 picoseconds (800 nanometers) which is sufficiently short compared to that attainable from a photomultiplier tube. Thus it can be regarded as a delta-function light source. A sampling oscilloscope is used to sample the photomultiplier tube output many times so that a complete output waveform is created. When measuring a photomultiplier tube with a bialkali photocathode, an SHG (second harmonic generator) is used to produce a light pulse with a wavelength of 400 nanometers which is twice the fundamental frequency of the light from the laser diode. At this point, the pulse width will be 30 picoseconds. The output pulse waveform obtained from the photomultiplier tube is composed of waveforms which are produced by electrons emitted from every position of the photocathode. Therefore, the rise and fall times are mainly determined by the electron transit time difference and also by the electric field distribution and intensity (supply voltage) between the electrodes.

As indicated in Figure 3-14, the rise time is defined as the time for the output pulse to increase from 10 to 90 percent of the peak pulse height. Conversely, the fall time is defined as the time required to decrease from 90 to 10 percent of the peak output pulse height. In time response measurements where the rise and fall times are critical, the output pulse tends to suffer waveform distortion, causing an erroneous signal. To prevent this problem, proper impedance matching must be provided including the use of a voltage-divider circuit with damping resistors. (See Chapter 7.)

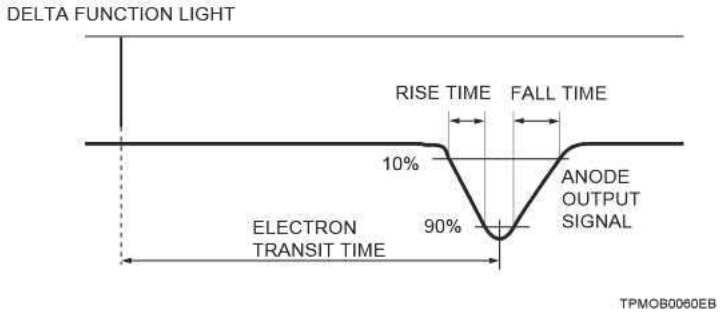


Figure 3-14: Definitions of rise/fall times and electron transit time

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Figure 3-15 shows an actual output waveform obtained from a photomultiplier tube. In general, the fall time is two or three times longer than the rise time. This means that when measuring repetitive pulses, care must be taken so that each output pulse does not overlap. The FWHM (full width at half maximum) of the output pulse will usually be about 2.5 times the rise time.

The transit time is the time interval between the arrival of a light pulse at the photocathode and the appearance of the output pulse. To measure the transit time, a PIN photodiode is placed as reference (zero second) at the same position as the photomultiplier tube photocathode. The time interval between the instant the PIN photodiode detects a light pulse and the instant the output pulse of the photomultiplier tube reaches its peak amplitude is measured. This transit time is a useful parameter in determining the delay time of a measurement system in such applications as fluorescence lifetime measurement using repetitive light pulses.

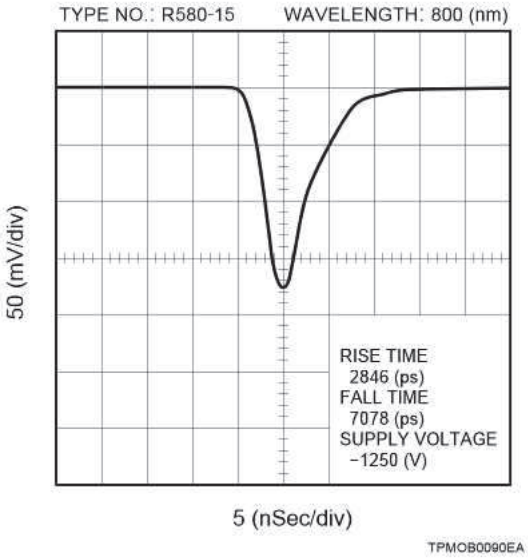


Figure 3-15: Example of output waveform

(2) TTS (transit time spread)

When a photocathode is fully illuminated, the transit time of each photoelectron pulse has a fluctuation. This fluctuation is called TTS (transit time spread). A block diagram for TTS measurement is shown in Figure 3-16 and typical measured data is shown in Figure 3-17.

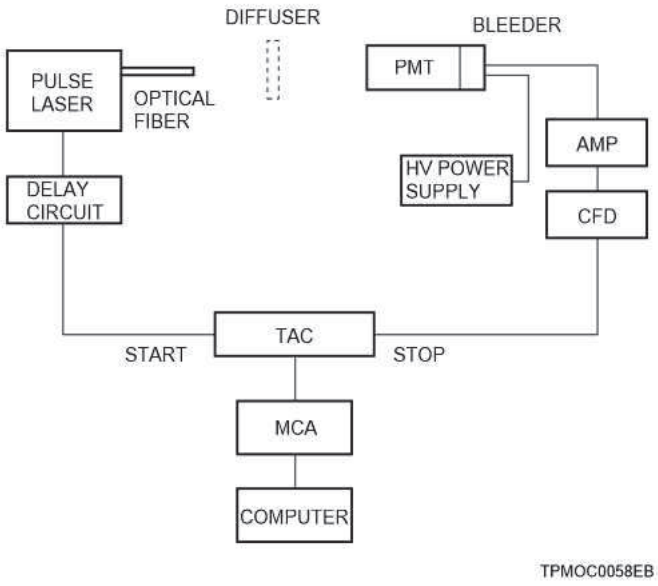


Figure 3-16: Block diagram for TTS measurement

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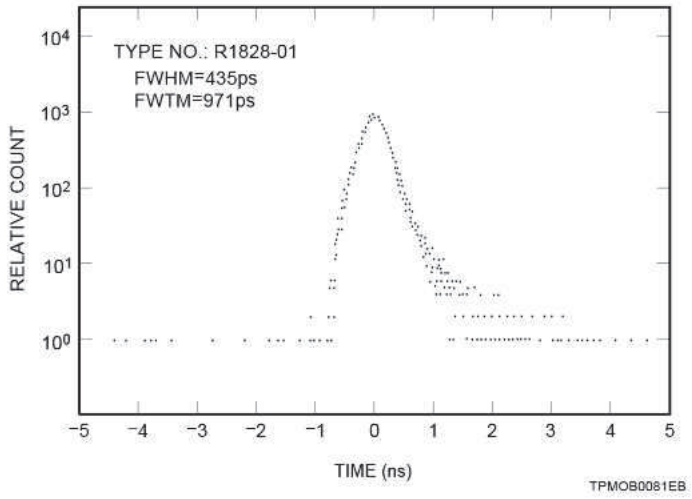


Figure 3-17: TTS data example

In this measurement, a trigger signal from the pulsed laser is passed through the delay circuit and then fed as the start to the TAC (time-to-amplitude converter) which converts the time difference into pulse height. Meanwhile, the output from the photomultiplier tube is fed as the stop signal to the TAC via the CFD (constant fraction discriminator) which reduces the time jitter resulting from fluctuation of the pulse height. The TAC generates a pulse height proportional to the time interval between the "start" and "stop" signals. This pulse is fed to the MCA (multichannel analyzer) for pulse height analysis. Since the time interval between the "start" and "stop" signals corresponds to the electron transit time, a histogram displayed on the MCA, by integrating individual pulse height values many times in the memory, indicates the statistical spread of the electron transit time.

At Hamamatsu Photonics, the TTS is usually expressed in the FWHM of this histogram, but it may also be expressed in standard deviation. When the histogram shows a Gaussian distribution, the FWHM is equal to a value which is 2.35 times the standard deviation. The TTS improves as the number of photoelectrons per pulse increases, in inverse proportion to the square root of the number of photoelectrons. This relation is shown in Figure 3-18.

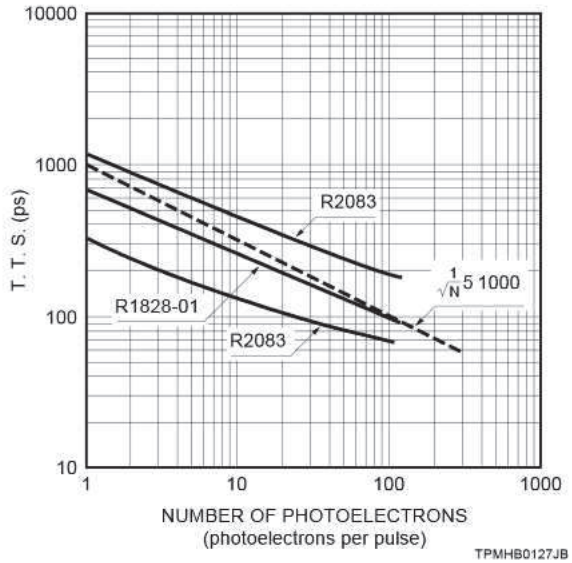


Figure 3-18: TTS vs. number of photoelectrons

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(3) CTTD (cathode transit time difference)

The CTTD (cathode transit time difference) is the difference in transit time when the incident light position on the photocathode is shifted. In most time response measurements the entire photocathode is illuminated. However, as illustrated in Figure 3-19, the CTTD measurement employs an aperture plate to shift the position of a light spot entering the photocathode, and the transit time difference between each incident position is measured.

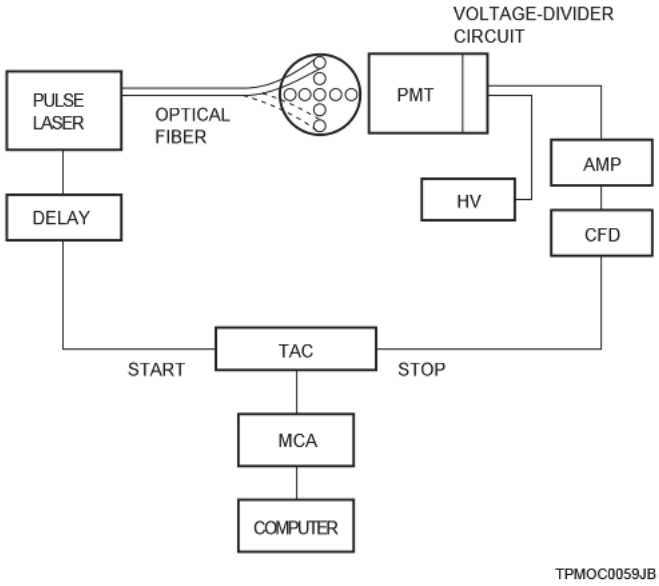


Figure 3-19: Block diagram for CTTD measurement

Basically, the same measurement system as for TTS measurement is employed, and the TTS histogram for each of the different incident light positions is obtained. Then the change in the peak pulse height of each histogram, which corresponds to the CTTD, is measured. The CTTD data of each position is represented as the transit time difference with respect to the transit time measured when the light spot enters the center of the photocathode.

In actual applications, the CTTD data is not usually needed but rather primarily used for evaluation in the photomultiplier tube manufacturing process. However, the CTTD is an important factor that affects the rise time, fall time and TTS described previously and also CRT (coincident resolving time) discussed in the next section.

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(4) CRT (coincident resolving time)

As with the TTS, this is a measure of fluctuations in the transit time. The CRT measurement system resembles that used for positron CT (See Section 9.3.) or TOF (time of flight) measurement (See Section 9.7.). Therefore, the CRT is a very practical parameter for evaluating the performance of photomultiplier tubes used in the above fields or similar applications. Figure 3-20 shows a block diagram of the CRT measurement.

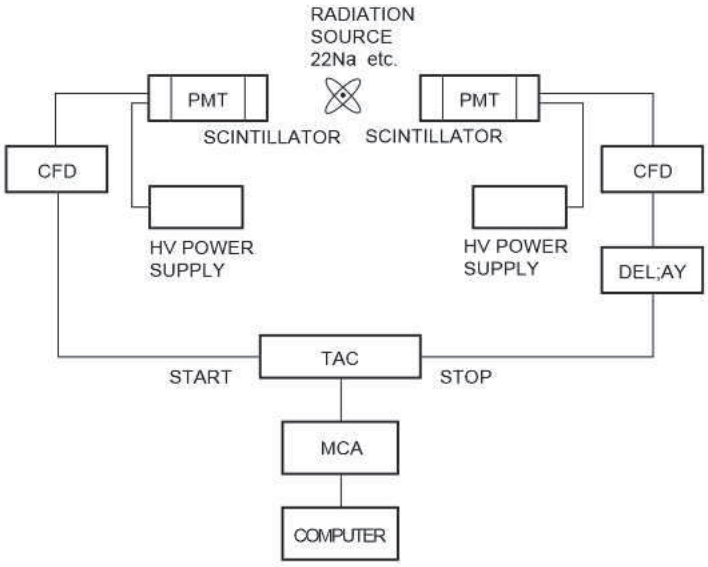


Figure 3-20: Block diagram for CRT measurement

As a radiation source ^{22}Na, ^{68}Ge-Ga or ^{60}Co is commonly used, while for the scintillator a BGO, BaF_2, CsF or plastic scintillator is used. A proper combination of radiation source and scintillator should be selected according to the application. The radiation source is placed in the middle of a pair of photomultiplier tubes and emits gamma-rays in opposing directions at the same time. A coincident flash occurs from each of the two scintillators coupled to the photomultiplier tube. The signal detected by one photomultiplier tube is fed as the start signal to the TAC, while the signal from the other photomultiplier tube is fed as the stop signal to the TAC via the delay circuit used to obtain proper trigger timing. Then, as in the case of the TTS measurement, the output pulse from the TAC is analyzed by the MCA and this operation is repeated many times so that a CRT spectrum is created. This spectrum statistically displays the time fluctuation of the signals that enter the TAC. This fluctuation mainly results from the TTS of the two photomultiplier tubes. As can be seen from Figures 3-12 and 3-18, the TTS is inversely proportional to the square root of the number of photoelectrons per pulse and also to the square root of the supply voltage. In general, therefore, the higher the radiation energy and the supply voltage, the better the CRT will be. If the TTS of each photomultiplier tube is τ_1 and τ_2, the CRT is given by

$$C.R.T. = (\tau_1^2+\tau_2^2)^{1/2} \quad \cdots\cdots \text{(Eq. 3-10)}$$

The CRT characteristic is an important parameter for TOF measurements because it affects the position resolution.

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3. 3. 2 Linearity

The photomultiplier tube provides good linearity[1) 24) 27) 28)] in anode output current over a wide range of incident light levels including the photon counting region. In other words, it offers a wide dynamic range. However, if the incident light amount is too large, the output begins to deviate from the ideal linearity. This is primarily caused by anode linearity characteristics, but it may also be affected by cathode linearity characteristics when a photomultiplier tube with a transmission mode photocathode is operated at a low supply voltage and large current. Both cathode and anode linearity characteristics are dependent only on the current value if the supply voltage is constant, while being independent of the incident light wavelength.

(1) Cathode linearity

Photocathode Materials	Spectral Response [Peak Wavelength] (nm)	Upper Limit of Linearity (Average Current)
Ag-O-Cs	300 to1200 [800]	1μA
Sb-Cs	up to 650 [440]	1μA
Sb-Rb-Cs/Sb-K-Cs	up to 650 [420]	0.1μA/0.01μA
Sb-Na-K	up to 650 [375]	10μA
Sb-Na-K-Cs	up to 850 [420], up to 900 [600] extended red	10μA
Ga-As	up to 930 [300~700]	(*) 0.1μA
Cs-Te	up to 320 [210]	0.1μA
Cs-I	up to 200 [140]	

(*) Linearity considerably degrades if this current is exceeded.

Table 3-4: Photocathode materials and cathode linearity limits

The photocathode is a semiconductor and its electrical resistance depends on the photocathode materials. As listed in Table 3-4, therefore, the cathode linearity also differs depending on the photocathode materials. It should be noted that Table 3-4 shows characteristics only for transmission mode photocathodes. In the case of reflection mode photocathodes which are formed on a metal plate and thus have a sufficiently low resistivity, the linearity will not be a significant problem. To reduce the effect of photocathode resistivity on the linearity without degrading the collection efficiency, it is generally recommended to apply a voltage of more than 100 volts between the photocathode and the first dynode. (Refer to Section 3.2.2.) For semiconductors, the photocathode surface resistivity increases as the temperature decreases. Thus, consideration must be given to the temperature characteristics of the photocathode resistivity when cooling the photomultiplier tube.

(2) Anode linearity

The anode linearity is limited by two factors: the voltage-divider circuit and space charge effects due to a large current flowing in the dynodes.

As shown below, the linearity in DC mode operation is mainly limited by the voltage-divider circuit, while the pulse mode operation is limited by space charge effects.

Linearity
- Pulse mode : Limited by the space charge effects.
- DC mode : Limited by a change in the voltage-divider voltage due to the magnitude of signal current.

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The linearity limit caused by the voltage-divider circuit is described in Chapter 7. The pulse linearity is chiefly dependent on the peak anode current. When an intense light pulse enters a photomultiplier tube, a large current flows in the latter dynode stages, increasing the space charge density, as a result current saturation occurs. The extent of these effects depends on the dynode structure, as indicated in Table 3-2. The space charge effects also depend on the electric field distribution and intensity between each dynode. The mesh type dynodes offer superior linearity because they have a structure resistant to the space charge effects. Each dynode is arranged in close proximity providing a higher electric field strength and the dynode area is large so that the signal density per unit area is lower. In general, any dynode type provides better linearity when the supply voltage is increased, or in other words, when the electric field strength between each dynode is enhanced.

Figure 3-21 shows the relationship between the linearity and the anode peak current with the supply voltage as a parameter for a Hamamatsu photomultiplier tube R2059. The linearity can be improved by use of a special voltage-divider (called "a tapered voltage-divider") designed to increase the interstage voltages at the latter dynode stages. Because such a tapered voltage-divider must have an optimum electric field distribution and intensity that match each dynode, determining the proper voltage distribution ratio is not simple but a rather complicated operation.

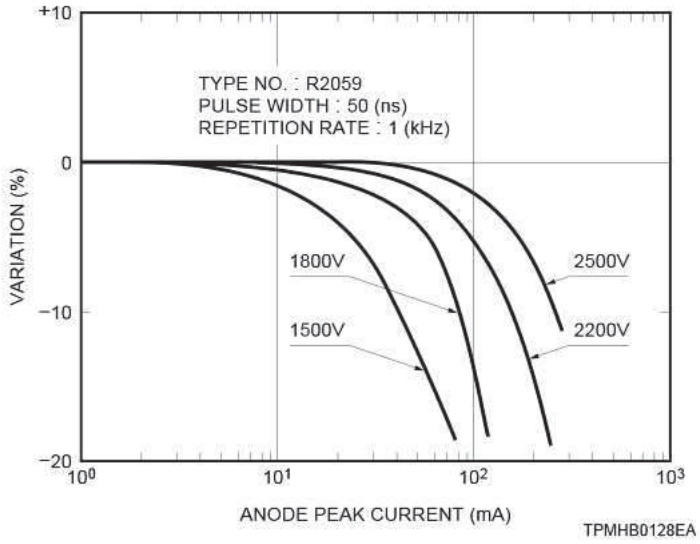


Figure 3-21: Voltage dependence of linearity

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(3) Linearity measurement

The linearity measurement methods include the DC mode and the pulse mode. Each mode is described below.

(a) DC mode

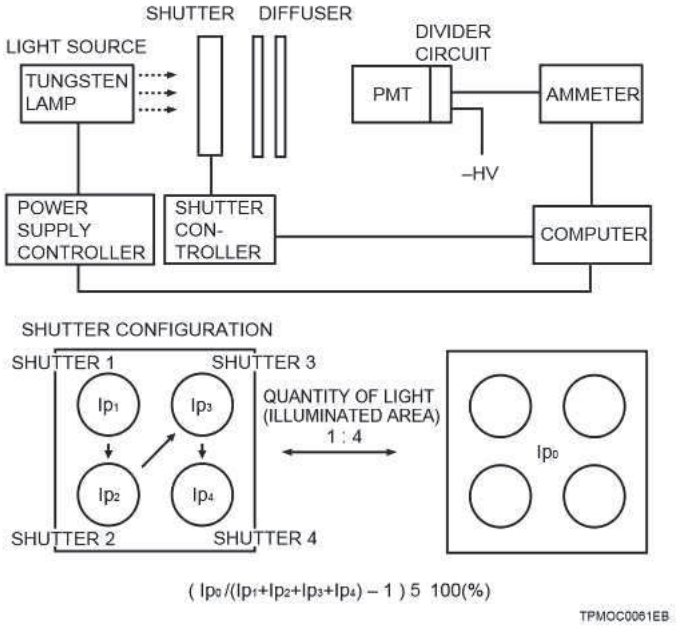


Figure 3-22: Block diagram for DC mode linearity measurement

This section introduces the DC linearity measurement method used by Hamamatsu Photonics. As Figure 3-22 shows, an aperture plate with four apertures equipped with shutters is installed between the light source and the photomultiplier tube. Each aperture is opened in the order of 1, 2, 3 and 4, finally all four apertures are opened, and the photomultiplier tube outputs are measured (as Ip_1, Ip_2, Ip_3, Ip_4 and Ip_0, respectively). Then the ratio of Ip_0 to (Ip_1+Ip_2+Ip_3+Ip_4) is calculated as follows:

$$(Ip_0/(Ip_1+Ip_2+Ip_3+Ip_4)-1)5\ 100(\%) \quad \cdots\cdots \text{(Eq. 3-11)}$$

This value represents a deviation from linearity and if the output is within the linearity range, Ip0 becomes

$$Ip_0 = Ip_1+Ip_2+Ip_3+Ip_4 \quad \cdots\cdots \text{(Eq. 3-12)}$$

Repeating this measurement by changing the intensity of the light source (i.e. changing the photomultiplier tube output current) gives a plot as shown in Figure 3-23. This indicates an output deviation from linearity. This linearity measurement greatly depends on the magnitude of the current flowing through the voltage-divider circuit and its structure.

As a simple method, linearity can also be measured using neutral density filters which are calibrated in advance for changes in the incident light level.

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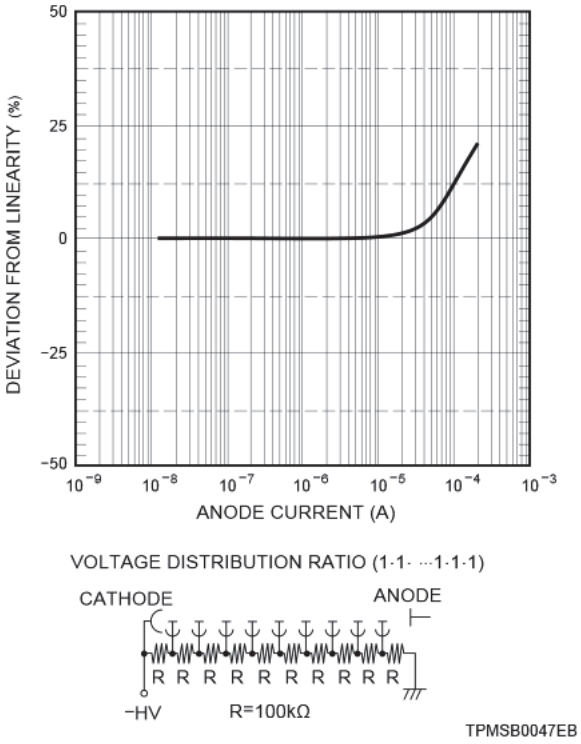


Figure 3-23: DC linearity (side-on type)

(b) Pulse mode

A simplified block diagram for the pulse mode linearity measurement is shown in Figure 3-24. In this measurement, an LED operated in a double-pulsed mode is used to provide higher and lower pulse amplitudes alternately. The higher and lower pulse amplitudes are fixed at a ratio of approximately 4:1. If the photomultiplier tube outputs in response to the higher and lower pulsed light at sufficiently low light levels, the peak currents are Ip_{02} and Ip_{02} respectively, then the ratio of Ip_{02}/Ip_{01} is proportional to the pulse amplitude; thus

$$Ip_{02}/Ip_{01} = 4 \quad \cdots\cdots \text{(Eq. 3-13)}$$

When the LED light sources are brought close to the photomultiplier tube (See Figure 3-24.) and the subsequent output current increases, the photomultiplier tube output begins to deviate from linearity. If the output for the lower pulsed light (A_1) is Ip1 and the output for the higher pulsed light (A_2) is Ip_2, saturation will usually occur first to the output current Ip_2. Thus the ratio between the two output pulses has the following relation:

$$Ip_2/Ip_1 < Ip_{02}/Ip_{01} \quad \cdots\cdots \text{(Eq. 3-14)}$$

By measuring the ratio between the two outputs of the photomultiplier tube, produced by the two different intensities of pulsed light, Ip_2/Ip_1, it is possible to measure the linearity as follows:

$$\frac{(Ip_2/Ip_1)-(Ip_{02}/Ip_{01})}{(Ip_{02}/Ip_{01})} 5\ 100\ (\%) \quad \cdots\cdots \text{(Eq. 3-15)}$$

This indicates the extent of deviation from linearity at the anode output Ip_2. If the anode output is in the linearity range. The following relation is established:

$$(Ip_2/Ip_1) = (Ip_{02}/Ip_{01}) \quad \cdots\cdots \text{(Eq. 3-16)}$$

Under these conditions, Eq. 3-15 becomes zero.

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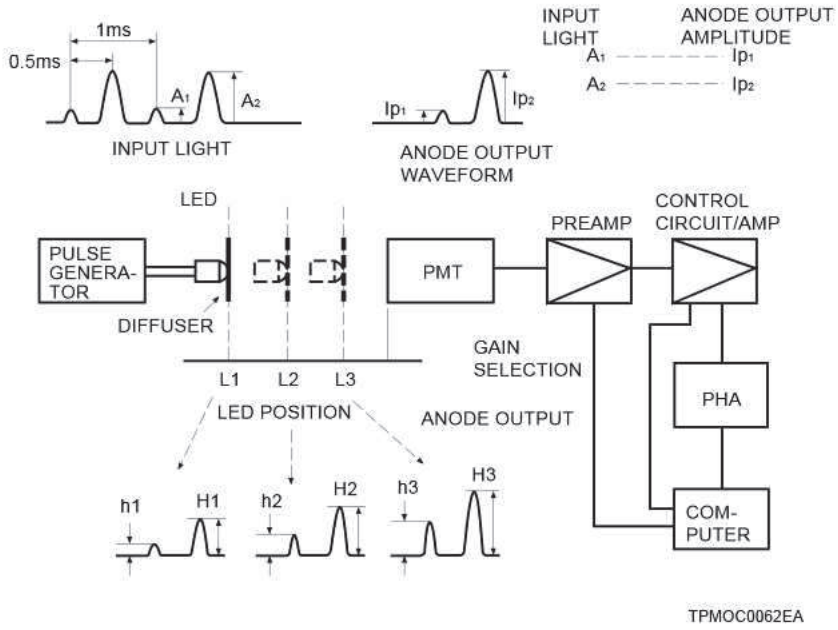


Figure 3-24: Block diagram for pulse mode linearity measurement

By repeating this measurement while varying the distance between the LED light source and the photomultiplier tube so as to change the output current of the photomultiplier tube, linearity curves like those shown in Figure 3-25 can be obtained. There are several other methods for measuring linearity, the above methods are just examples.

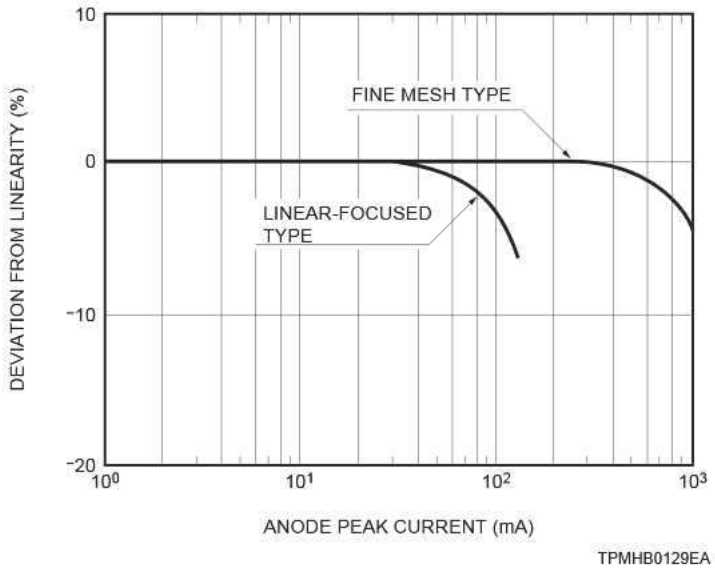


Figure 3-25: Pulse linearity

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3. 3. 3 Uniformity

Uniformity is the variation of the output sensitivity with respect to the photocathode position. Anode output uniformity is thought to be the product of the photocathode uniformity and the electron multiplier (dynode section) uniformity.

Figure 3-26 shows anode uniformity data measured at wavelengths of 400 nanometers and 800 nanometers. This data is obtained with a light spot of 1mm diameter scanned over the photocathode surface.

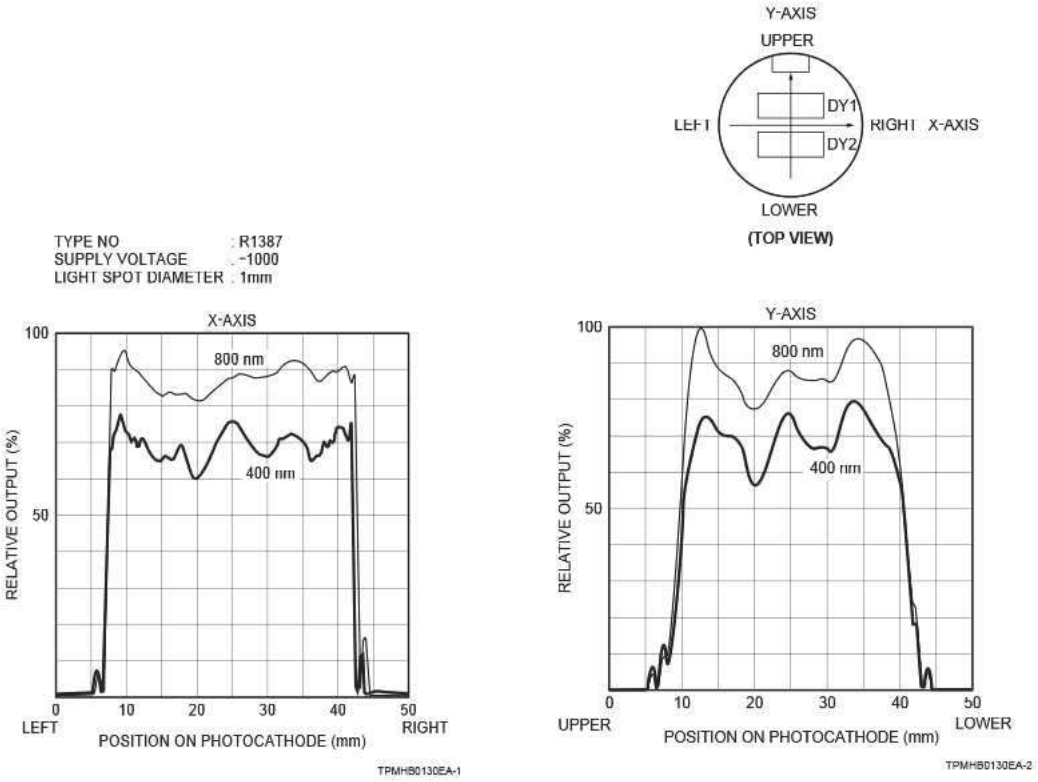


Figure 3-26: Difference of uniformity with wavelength

In general, both photocathode uniformity and anode uniformity deteriorate as the incident light shifts to a longer wavelength, and especially as it approaches the long-wavelength limit. This is because the cathode sensitivity near the long-wavelength limit greatly depends on the surface conditions of the photocathode and thus fluctuations increase. Moreover, if the supply voltage is too low, the electron collection efficiency between dynodes may degrade and adversely affect uniformity. It is therefore necessary to apply more than 100 volts between the photocathode and the first dynode, and more than 50 volts between each dynode.

Head-on photomultiplier tubes provide better uniformity in comparison with side-on types. In such applications as gamma cameras (See Section 9.2.) used for medical diagnosis where good position detecting ability is demanded, uniformity is an important parameter in determining equipment performance. Therefore, the photomultiplier tubes used in this field are specially designed and selected for better uniformity. Figure 3-27 shows typical uniformity data for a side-on tube. The same measurement procedure as for head-on tubes is used. Uniformity is also affected by the dynode structure. As can be seen from Table 3-2, the box-and-grid type, venetian blind type and mesh type offer better uniformity.

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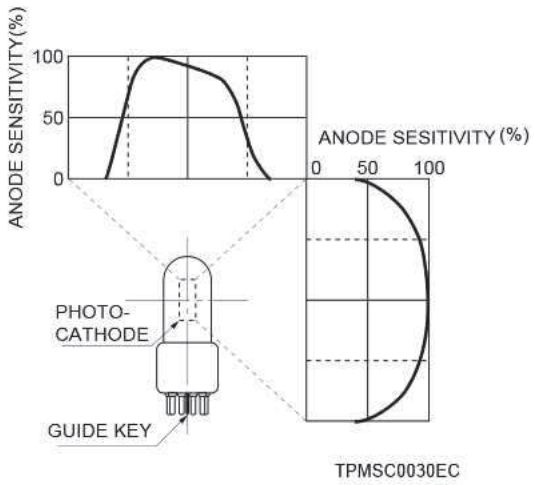


Figure 3-27: Uniformity of a side-on photomultiplier tube

Considering actual photomultiplier tube usage, uniformity is evaluated by two methods: one measured with respect to the position of incidence (spatial uniformity) and one with respect to the angle of incidence (angular response). The following sections explain their measurement procedures and typical characteristics.

(1) Spatial uniformity

To measure spatial uniformity, a light spot is scanned in two-dimensions over the photocathode of a photomultiplier tube and the variation in output current is graphically displayed. Figure 3-28 shows a schematic diagram for the spatial uniformity measurement.

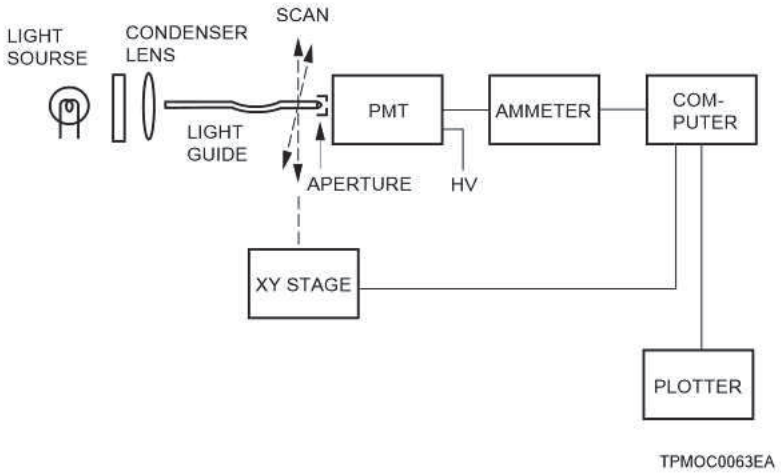


Figure 3-28: Schematic diagram for spatial uniformity measurement

For convenience, the photocathode is scanned along the X-axis and Y-axis. The direction of the X-axis or Y-axis is determined with respect to the orientation of the first dynode as shown in Figure 3-29.

The degree of loss of electrons in the dynode section significantly depends on the position of the first dynode on which the photoelectrons strike. Refer to Figure 3-26 for specific uniformity data.

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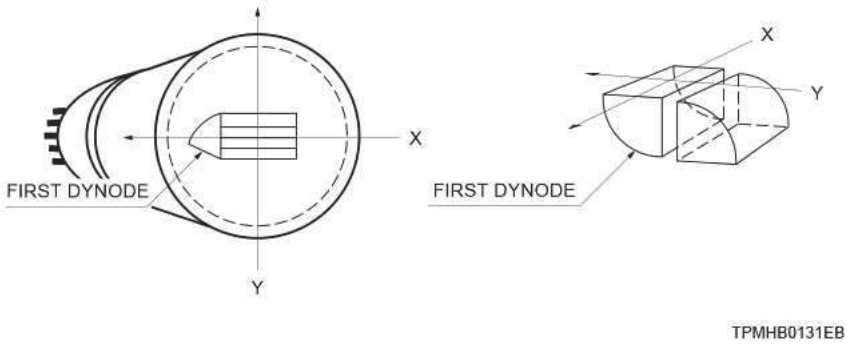


Figure 3-29: Spatial uniformity measurement for head-on types

While the photocathode is scanned by the light spot, the emitted photoelectrons travel along the X-axis or Y-axis of the first dynode as shown in Figure 3-30.

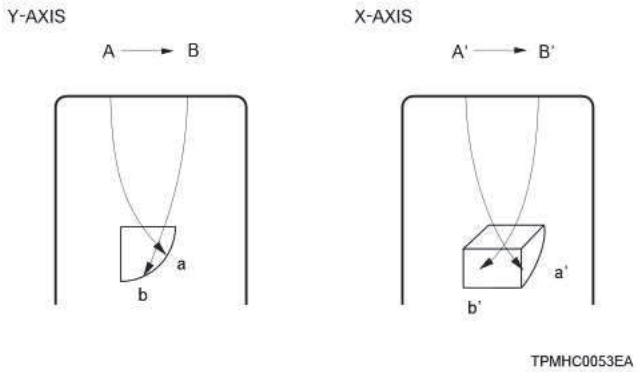


Figure 3-30: Position of photoemission and the related position on the first dynode

This method for measuring spatial uniformity is most widely used because the collective characteristics can be evaluated in a short time. In some cases, spatial uniformity is measured by dividing the photocathode into a grid pattern, so that sensitivity distribution is displayed in two or three dimensions.

The spatial uniformity in anode output ranges from 20 to 40 percent for head-on tubes, and may exceed those values for side-on tubes. To minimize the influence of the uniformity, placing a diffuser in front of the input window of a photomultiplier tube or using a photomultiplier tube with a frosted glass window will prove effective.

(2) Angular response

Photomultiplier tube sensitivity somewhat depends on the angle of incident light on the photocathode. This dependence on the angle of incidence is called the angular response.[28)-30)] To measure the angular response, the entire photocathode is illuminated with collimated light, and the output current is measured while rotating the photomultiplier tube. A schematic diagram for the angular response measurement is shown in Figure 3-31 and specific data is plotted in Figure 3-32. As the tube is rotated, the projected area of the photocathode is reduced. This means that the output current of a tube, even outputs having no dependence on the angle of incidence, are plotted as a cosine curve. Commonly, the photocathode sensitivity improves at larger angles of incidence and thus the output current is plotted along a curve showing higher sensitivity than the cosine (cos θ) curve. This is because the incident light transmits across a longer distance at large angles of incidence. In addition, this increase in sensitivity usually becomes larger at longer wavelengths.

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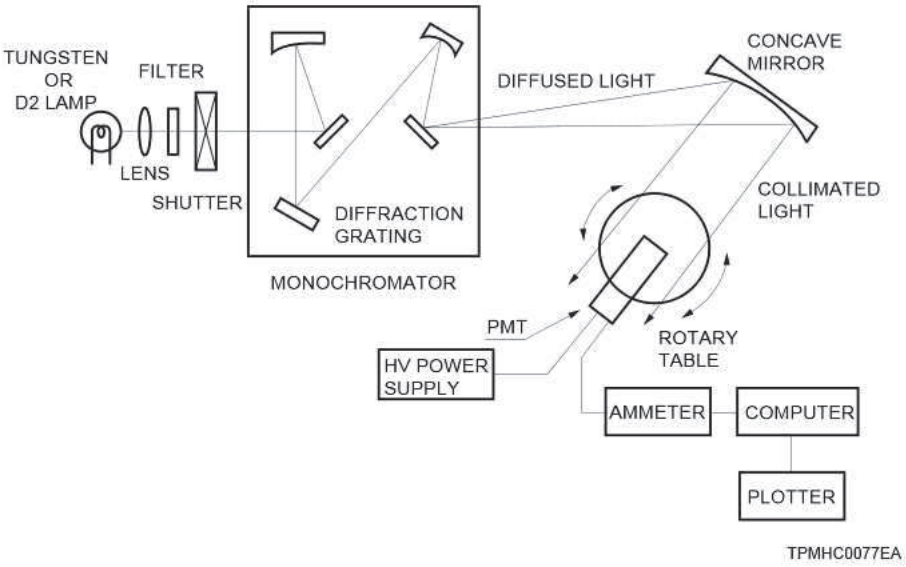


Figure 3-31: Schematic diagram for angular response measurement

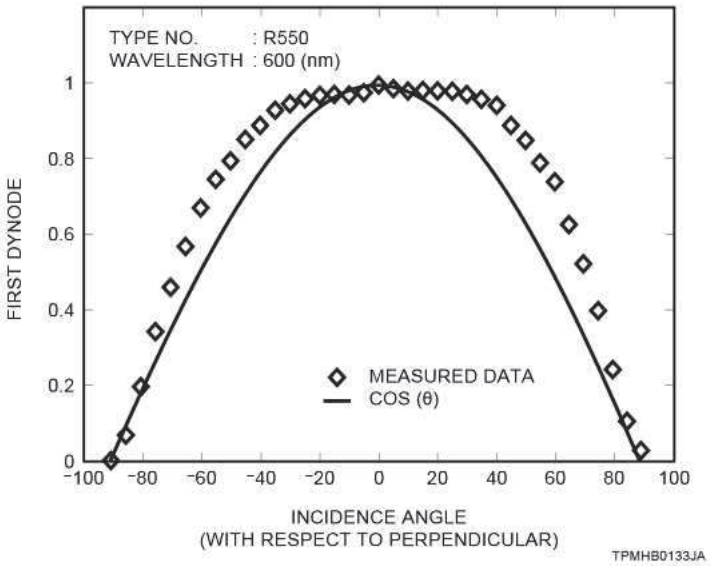


Figure 3-32: Typical angular response

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3. 3. 4 Stability

The output variation of a photomultiplier tube with operating time is commonly termed as "drift" or "life" characteristics. On the other hand, the performance deterioration resulting from the stress imposed by the supply voltage, current, and ambient temperature is called "fatigue".

(1) Drift (time stability) and life characteristics

Variations (instability) over short time periods are mainly referred to as drift[1) 31)], while variations (instability) over spans of time longer than 10^3 to 10^4 hours are referred to as the life characteristics. Since the cathode sensitivity of a photomultiplier tube exhibits good stability even after long periods of operating time, the drift and life characteristics primarily depend on variations in the secondary emission ratio. In other words, these characteristics indicate the extent of gain variation with operating time.

Drift per unit time generally improves with longer operating time and this tendency continues even if the tube is left unused for a short time after operation. It is therefore instrumental to perform aging or warm-up of the tube to stabilize the drift.

At Hamamatsu Photonics, drift is usually measured in the DC mode by illuminating a photomultiplier tube with a continuous light and recording the output current with the operating time. Figure 3-33 shows specific drift data for typical Hamamatsu photomultiplier tubes. In most cases, the drift of a photomultiplier tube tends to vary largely during initial operation and stabilizes as operating time elapses. In pulsed or intermittent operation (cyclic on/off operation), the drift shows a variation pattern similar to those obtained with continuous light if the average output current is of the same level as the output current in the DC mode.

In addition, there are other methods for evaluating the drift and life characteristics, which are chiefly used for photomultiplier tubes designed for scintillation counting. For more details refer to Section 3.5, "Scintillation counting".

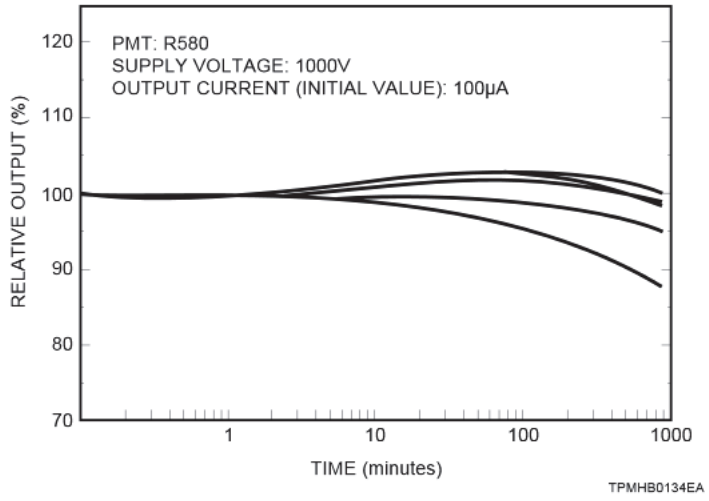


Figure 3-33: Examples of drift data

(2) Aging and warm-up

In applications where output stability within several percent is required, it is necessary to carry out aging or warm-up.

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(a) Aging

Aging is a technique in which a photomultiplier tube is continuously operated for a period ranging from several hours to several tens of hours, with the anode output current not exceeding the maximum rating. Through this aging, drift can be effectively stabilized. In addition, if the tube is warmed up just before actual use, the drift will be further stabilized.

(b) Warm-up

For stable operation of a photomultiplier tube, it is essential to warm up the tube for about 30 to 60 minutes. The warm-up period should be longer at the initial phase of photomultiplier tube operation, particularly in intermittent operation then, after a long period of operation warm up can be shortened. At a higher anode current the warm-up period can be shortened and at a lower anode current it should be longer. As one common method, the photomultiplier tube is operated at a voltage near the actual operating voltage and warmed up for about one hour with an anode current of several microamperes. However, in low current operation (average anode current: within one hundred up to several hundred nanoamperes), just applying a voltage to the photomultiplier tube prior to use for a period of one to two hours in the dark state serves as a warm-up to some extent.

3. 3. 5 Hysteresis

When the incident light or the supply voltage is changed in a step function, a photomultiplier tube may not produce an output comparable with the same step function. This phenomenon is known as "hysteresis".[1) 32)] Hysteresis is observed as two behaviors: "overshoot" in which the output current first increases greatly and then settles and "undershoot" in which the output current first decreases and then returns to a steady level. Hysteresis is further classified into "light hysteresis" and "voltage hysteresis" depending on the measurement conditions. Some photomultiplier tubes have been designed to suppress hysteresis by coating the insulator surface of the electrode supports with a conductive material so as to minimize the electrostatic charge on the electrode supports without impairing their insulating properties.

(1) Light hysteresis

When a photomultiplier tube is operated at a constant voltage, it may exhibit a temporary variation in the anode output after the incident light is changed in a step function. This variation is called light hysteresis. Figure 3-34 shows the Hamamatsu test method for light hysteresis and typical hysteresis waveforms.

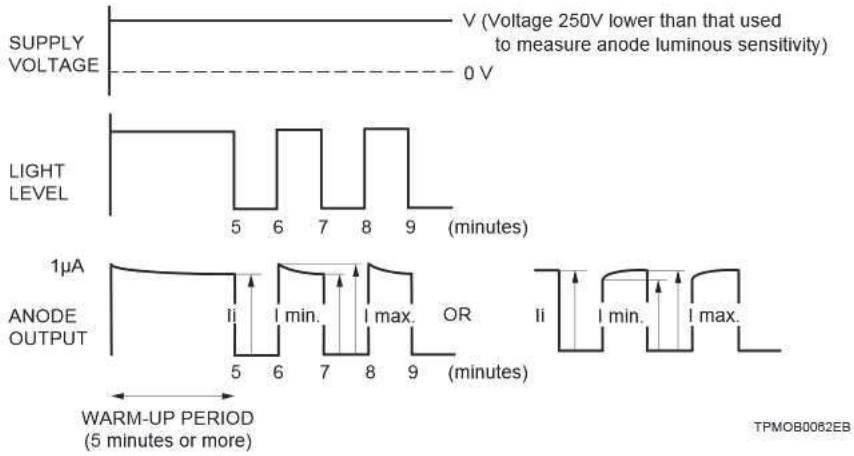


Figure 3-34: Light hysteresis

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As shown in Figure 3-34, a photomultiplier tube is operated at a voltage V, which is 250 volts lower than the voltage used to measure the anode luminous sensitivity. The tube is warmed up for five minutes or more at a light level producing an anode current of approximately one microampere. Then the incident light is shut off for one minute and then input again for one minute. This procedure is repeated twice to confirm the reproducibility. By measuring the variations of the anode outputs, the extent of light hysteresis can be expressed in percent, as follows:

$$\text{Light hysteresis } H_L = ((I_{MAX}-I_{MIN})/Ii)5\ 100(\%) \quad \cdots\cdots\cdots\cdots \text{(Eq. 3-17)}$$

where I_{MAX} is the maximum output value, I_{MIN} is the minimum output value and Ii is the initial output value.

Table 3-5 shows typical hysteresis data for major Hamamatsu photomultiplier tubes. Since most photomultiplier tubes have been designed to minimize hysteresis, they usually only display a slight hysteresis within ±2 percent. It should be noted that light hysteresis behaves in different patterns or values, depending on the magnitude of the output current.

(2) Voltage hysteresis

When the incident light level cycles in a step function, the photomultiplier tube is sometimes operated with a feedback circuit that changes the supply voltage in a complimentary step function so that the photomultiplier tube output is kept constant. In this case, the photomultiplier tube output may overshoot or undershoot immediately after the supply voltage is changed. This phenomenon is called voltage hysteresis and should be suppressed to the minimum possible value. Generally, this voltage hysteresis is larger than light hysteresis and even tubes with small light hysteresis may possibly exhibit large voltage hysteresis. Refer to Table 3-5 below for typical hysteresis data.

PMT	Light Hysteresis HL (%)	Voltage Hysteresis Hv (%)	Tube Diameter (mm)
R6350	0.3	0.5	13mm side-on
R212	0.2	1.0	28mm side-on
R928	0.1	1.0	28mm side-on
R647	0.9	2.5	13mm head-on
R6249	0.4	2.0	28mm head-on
R1306	0.07	0.06	52mm head-on

Table 3-5: Typical hysteresis data for major Hamamatsu photomultiplier tubes

Figure 3-35 shows a procedure for measuring voltage hysteresis, commonly used by Hamamatsu Photonics. A photomultiplier tube is operated at a voltage V, which is 700 volts lower than the voltage used to measure the anode luminous sensitivity. The tube is warmed up for five minutes or more at a light level producing an anode current of approximately 0.1 microampere.

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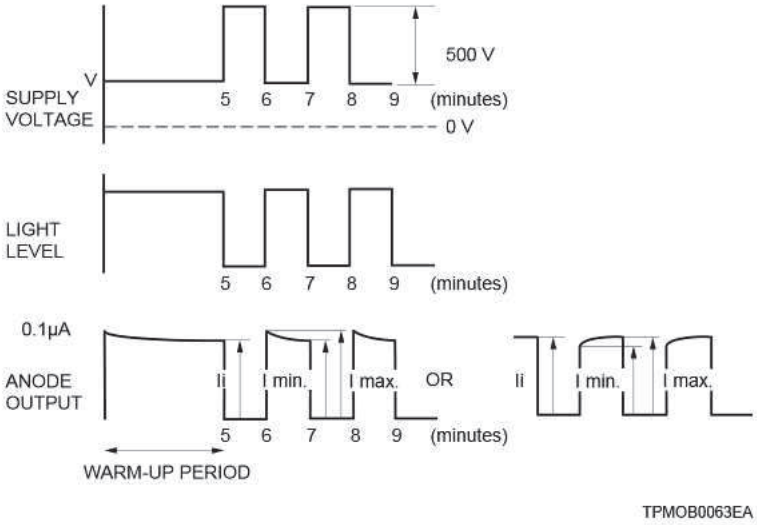


Figure 3-35: Voltage hysteresis

Then the incident light is shut off for one minute while the supply voltage is increased in 500 volt step. Then the light level and supply voltage are returned to the original conditions. This procedure is repeated to confirm the reproducibility. By measuring the variations in the anode outputs, the extent of voltage hysteresis is expressed in percent, as follows:

$$\text{Voltage hysteresis } H_V = ((I_{MAX}\text{-}I_{MIN})/Ii)5\ 100(\%) \quad \cdots\cdots\cdots\cdots\cdots\cdots \text{(Eq. 3-18)}$$

where I_{MAX} is the maximum output value, I_{MIN} is the minimum output value and Ii is the initial output value.

In general, the higher the change in the supply voltage, the larger the voltage hysteresis will be. Other characteristics are the same as those for light hysteresis.

(3) Reducing the hysteresis

When a signal light is blocked for a long period of time, applying a dummy light to the photomultiplier tube to minimize the change in the anode output current is effective in reducing the possible light hysteresis. Voltage hysteresis may be improved by use of HA coating. (Refer to Section 8.8.2.)

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3. 3. 6 Dark current

A small amount of current flows in a photomultiplier tube even when operated in a completely dark state. This output current is called the dark current[1) 23) 25) 33)] and ideally it should be kept as small as possible because photomultiplier tubes are used for handling minute amounts of light and current.

(1) Causes of dark current

Dark current may be categorized by cause as follows:

(a) Thermionic emission current from the photocathode and dynodes

(b) Leakage current (ohmic leakage) between the anode and other electrodes inside the tube and/or between the anode pin and other pins on the bulb stem

(c) Photocurrent produced by scintillation from glass envelope or electrode supports

(d) Field emission current

(e) Ionization current from residual gases (ion feedback)

(f) Noise current caused by cosmic rays, radiation from radioisotopes contained in the glass envelopes and environmental gamma rays

Dark current increases with an increasing supply voltage, but the rate of increase is not constant. Figure 3-36 shows a typical dark current vs. supply voltage characteristic.

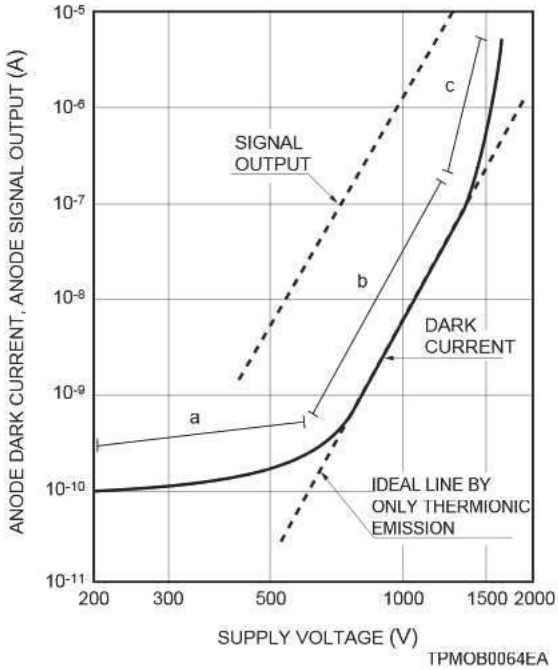


Figure 3-36: Typical dark current vs. supply voltage characteristic

This characteristic is related to three regions of the supply voltage: a low voltage region (**a** in Figure 3-36), a medium voltage region (**b** in Figure 3-36), and a high voltage region (**c** in Figure 3-36). Each region is largely controlled by the leakage current, thermionic emission, glass scintillation, field emission and glass or electrode support scintillation, respectively. In general, region b provides the best signal-to-noise ratio, so operating the photomultiplier tube in this region would prove ideal.

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Ion feedback[34] and noise[34) 35) 36] originating from cosmic rays and radioisotopes will sometimes be a problem in pulse operation.

Furthermore, when a photocathode is exposed to room illumination, the dark current will return to the original level by storing the tube in a dark state for one to two hours. However, if exposed to sunlight or extremely intense light (10000 lux or higher), the tube may be damaged to some extent and not recoverable. This should therefore be avoided. It is recommended that the photomultiplier tube be stored in a dark state before use.

The dark current data furnished with Hamamatsu photomultiplier tubes is measured after the tube has been stored in a dark state for 30 minutes. This "30-minute storage in a dark state" condition allows most photomultiplier tubes to approach the average dark current level attained after being stored for a long period in a dark state. This is also selected in consideration of work efficiency in measuring the dark current. If the tube is stored for a greater length of time in a dark state, the dark current will decrease further. The following sections explain each of the six causes of dark current listed above.

a) Thermionic emission

Since the photocathode and dynode surfaces are composed of materials with a very low work function, they emit thermionic electrons even at room temperatures. This effect has been studied by W. Richardson, and is stated by the following equation.[3) 37)]

$$i_s = AT^{5/4}e^{(-e\psi/KT)} \quad \text{(Eq. 3-19)}$$

where,

ψ : work function
e : electron charge
K : Boltzmann constant
T : absolute temperature
A : constant

It can be seen from this equation that the thermionic emission is a function of the photocathode work function and absolute temperature. Thus the magnitude of the work function and the photocathode material govern the amount of thermionic emission. When the photocathode work function is low, the spectral response extends to the right with lower energy or longer wavelengths, but with an increase in the thermionic emission. In general, the Ag-O-Cs photocathode with a spectral response in the longest wavelength range (See Figure 3-1.) exhibits the highest dark current. In contrast, the photocathodes for the ultraviolet range (Cs-Te, Cs-I) with the shortest wavelength limit provide the lowest dark current.

Eq. 3-19 also implies that the dark current decreases with decreasing temperature. Therefore, as shown in Figure 3-37, cooling a photomultiplier tube is an effective technique for reducing the dark current. The dark current resulting from the thermionic emission can be considerably reduced by cooling.

However, when the dark current reduces down to a level where the leakage current predominates, this effect becomes limited. Although thermionic emission occurs both from the photocathode and dynodes, the thermionic emission from the photocathode has a much larger effect on the dark current. This is because the photocathode is larger in size than each dynode and also because the dynodes, especially at the latter stages, contribute less to the output current. Consequently, the dark current caused by the thermionic emission vs. the supply voltage characteristic will be nearly identical with the slope of gain vs. supply voltage.

Figure 3-38 describes temperature characteristics for dark pulses measured in the photon counting method. In this case as well, the number of dark pulses decrease by cooling the photocathode.

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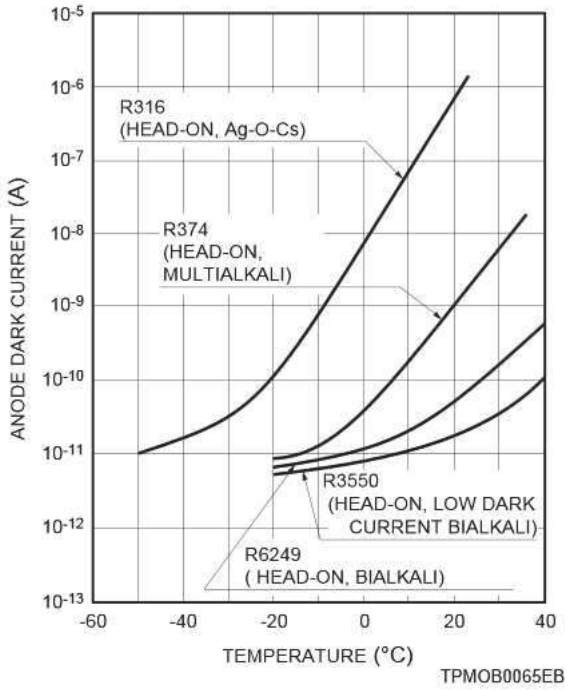


Figure 3-37: Temperature characteristics of anode dark current

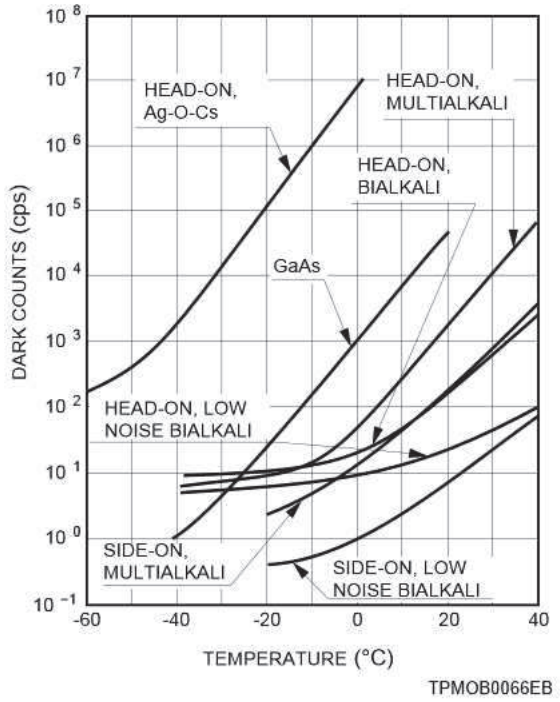


Figure 3-38: Temperature characteristics for dark current pulse

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b) Leakage current (ohmic leakage)

Photomultiplier tubes are operated at high voltages from 500 up to 3000 volts, but they handle very low currents from several nanoamperes to less than 100 microamperes. Therefore, the quality of the insulating materials used in the tubes is very important. For instance, if the insulation resistance is around 10^{12} ohms, the leakage current may reach the nanoampere level. The relationship between the leakage current from the insulating materials and the supply voltage is determined by Ohm's law, i.e., current value (I) = supply voltage (V)/insulation resistance (R), regardless of the gain of the photomultiplier tube as seen in Figure 3-36. On the other hand, the dark current resulting from thermionic emission varies exponentially with the supply voltage. Thus, as mentioned in the previous section, the leakage current has relatively more effect on the dark current as the supply voltage is lowered.

A leakage current may be generated between the anode and the last dynode inside a tube. It may also be caused by imperfect insulation of the glass stem and base, and between the socket anode pin and other pins. Since contamination from dirt and moisture on the surface of the glass stem, base, or socket increases the leakage current, care should be taken to keep these parts clean and at low humidity. If contaminated, they can be cleaned with alcohol in most cases. This is effective in reducing the leakage current.

c) Scintillation from the glass envelope or electrode support materials

Some electrons emitted from the photocathode or dynodes may deviate from their normal trajectories and do not contribute to the output signal. If these stray electrons impinge on the glass envelope, scintillations may occur slightly and result in dark pulses. In general, a photomultiplier tube is operated with a negative high voltage applied to the photocathode and is housed in a metal case at ground potential. This arrangement tends to cause stray electrons to impinge on the glass envelope. However, this problem can be minimized by a technique called "HA coating". Refer to Section 8.8.2 for further details on HA coating.

d) Field emission

If a photomultiplier tube is operated at an excessive voltage, electrons may be emitted from the electrodes by the strong electric field. Subsequently the dark current increases abruptly. This phenomenon occurs in region c in Figure 3-36 and shortens the life of the photomultiplier tube considerably. Therefore, the maximum supply voltage is specified for each tube type and must be observed. As long as a photomultiplier tube is operated within this maximum rating there will be no problem. But for safety, it is recommended that the tube be operated at a voltage 20 to 30 percent lower than the maximum rating.

e) Ionization current of residual gases (ion feedback)

The interior of a photomultiplier tube is kept at a vacuum as high as 10^{-6} to 10^{-5} pascals (about 10^{-7} Torrs). Even so, there exist residual gases that cannot be ignored. The molecules of these residual gases may be ionized by collisions with electrons. The positive ions that strike the front stage dynodes or the photocathode produce many secondary electrons, resulting in a large noise pulse. During high current operation, this noise pulse is usually identified as an output pulse appearing slightly after the main photocurrent. This noise pulse is therefore called an afterpulse[38) 39) 40)] and may cause a measurement error in pulsed operation.

f) Noise current caused by cosmic rays, radiation from radioisotopes contained in the glass envelopes and environmental gamma rays

Many types of cosmic rays are always falling on the earth. Among them, muons (μ) can be a major source of photomultiplier tube noise. When muons pass through the glass envelope, Cherenkov radiation may occur, releasing a large number of photons. In addition, most glasses contain potassium

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oxide (K_2O) which also contains a minute amount of the radioactive element ^{40}K. ^{40}K may emit beta rays and result in noise. Furthermore, environmental gamma rays emitted from radioisotopes contained in buildings may be another noise source. However, because these dark noises occur much less frequently, they are negligible except for such cases as liquid scintillation counting where the number of signal counts is exceptionally small.

(2) Expression of dark current

Dark current is a critical factor that governs the lower detection limit in low light level measurements. There are various methods or terms used to express the dark current. The following introduces some of them.

a) DC expression

In general, Hamamatsu photomultiplier tubes are supplied with the dark current data measured at a constant voltage. The dark current may be measured at a voltage that produces a certain anode sensitivity. In this case, the dark current is expressed in terms of equivalent dark current or EADCI (equivalent anode dark current input). The equivalent dark current is simply the dark current measured at the voltage producing a specific anode luminous sensitivity, and is a convenient parameter when the tube is operated with the anode sensitivity maintained at a constant value. The EADCI is the value of the incident light flux required to produce an anode current equal to the dark current and is represented in units of lumens or watts as follows:

EADCI (lm) = Dark current (A) / Anode luminous sensitivity (A/lm) ····· (Eq. 3-20)

When representing the EADCI in watts (W), a specified wavelength is selected and the dark current is divided by the anode radiant sensitivity (A/W) at that wavelength. Figure 3-39 illustrates an example of EADCI data along with the anode dark current and anode luminous sensitivity. A better signal-to-noise ratio can be obtained when the tube is operated in the supply voltage region with a small EADCI. It is obvious from this figure that the supply voltage region in the vicinity of 1000 volts displays a small, flat EADCI curve, yet offers an adequate anode sensitivity of three orders of magnitude.

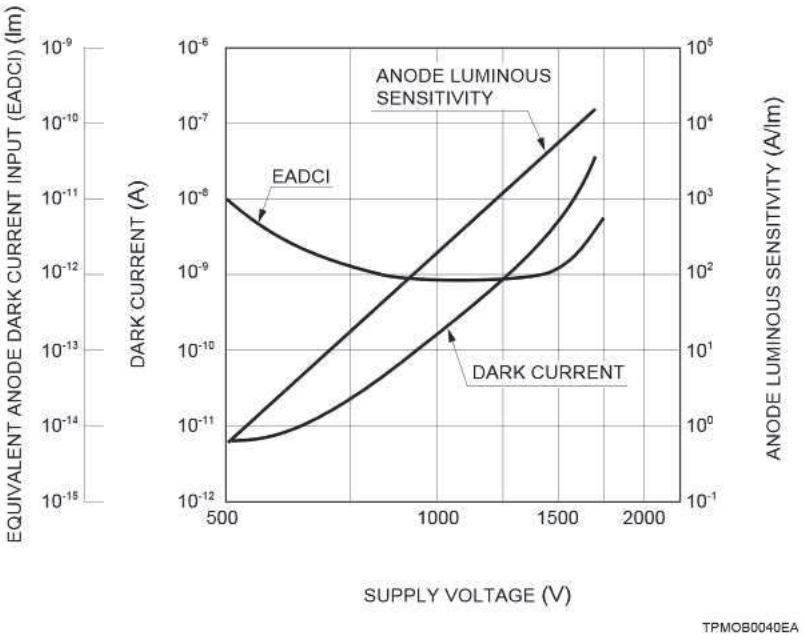


Figure 3-39: Example of EADCI

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b) AC expression

In low-level-light measurements, the DC components of dark current can be subtracted. The lower limit of light detection is determined rather by the fluctuating components or noise. In this case, the noise is commonly expressed in terms of ENI (equivalent noise input). The ENI is the value of incident light flux required to produce an output current equal to the noise current, i.e., the incident light level that provides a signal-to-noise ratio of unity. When the ENI is expressed in units of watts (W) at the peak wavelength or at a specific wavelength, it is also referred to as the NEP (noise equivalent power).

Because the noise is proportional to the square root of the circuit bandwidth, the ENI[23] is defined as follows:

$$ENI = (2e \cdot Id \cdot \mu \cdot B)^{1/2}/S \ (W) \quad \text{(Eq. 3-21)}$$

where

e: electron charge ($1.65\ 10^{-19}$coulombs)
Id: anode dark current (A)
μ: current amplification
B: circuit bandwidth (Hz)
S: anode radiant sensitivity (A/W)

Commonly, Δf=1Hz is used and the ENI value ranges from 10^{-15} to 10^{-16} (W) at the peak wavelength.

The ENI is a parameter to be considered when the frequency band width B of the circuit is low (up to several thousand hertz). However, it is not so important in a high frequency band because the noise originating from the signal light becomes predominant. (See 3.4, "Photon counting".)

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3. 3. 7 Signal-to-noise ratio of photomultiplier tubes

When observing the output waveform of a photomultiplier tube, two types of noise components can be seen: one is present even without light input, and the other is generated by the input of signal light. Normally, these noise components are governed by the dark current caused by the photocathode thermionic emission, and the shot noise resulting from the signal current, respectively. Both of these noise sources are discussed here.

The signal-to-noise ratio referred to in the following description is expressed in r.m.s. (root mean square). When signal and noise waveforms like those shown in Figure 3-40 are observed, they can be analyzed as follows:

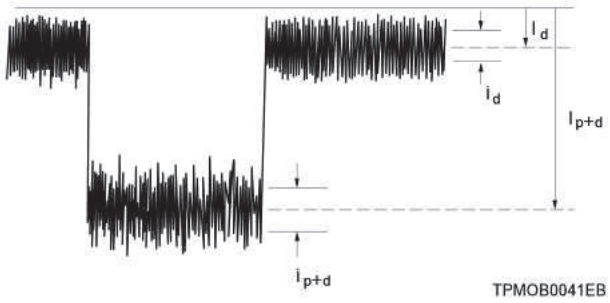


Figure 3-40: Example of signal-to-noise ratio

Mean value of noise component	: I_d
AC component of noise	: i_d (r.m.s.)
Mean value of signal (noise component included)	: I_{p+d}
AC component of signal (noise component included)	: i_{p+d} (r.m.s.)

Using these factors, the signal-to-noise ratio[25) 41) 42)] is given by

$$\text{SN ratio} = I_p/i_{p+d} \quad \cdots\cdots \text{(Eq. 3-22)}$$

where I_p is the mean value of the signal component only, which is obtained by subtracting I_d from I_{p+d}.

If the dark current Id is low enough to be ignored ($I_p >> I_d$), the signal-to-noise ratio will be

$$\text{SN ratio} \approx I_p/i_p \quad \cdots\cdots \text{(Eq. 3-23)}$$

where I_p is the mean value of the signal component and i_p is the AC component (r.m.s.) of the signal. i_p consists of a component associated with the statistical fluctuation of photons and the photoemission process and a component created in the multiplication process. The noise component produced in the multiplication process is commonly expressed in terms of the NF (noise figure). The NF is defined as follows:

$$NF = (S/N)^2_{in}/(S/N)^2_{out} \quad \cdots\cdots \text{(Eq. 3-24)}$$

where $(S/N)_{in}$ is the signal-to-noise ratio on the photomultiplier tube input side and $(S/N)_{out}$ is the signal-to-noise ratio on the photomultiplier tube output side. With a photomultiplier tube having n dynode stages, the NF from the cascade multiplication process is given by the following equation:

$$NF = (1/\alpha)\cdot(1+1/\delta_1+1/\delta_1\delta_2+\cdots+1/\delta_1\delta_2\cdots\delta_n) \quad \cdots\cdots \text{(Eq. 3-25)}$$

where α is the collection efficiency (Refer to 3.2.2.), δ_1, δ_2 ... δ_n are the secondary emission ratios at each stage.

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With α=1 and δ_1, δ_2, δ, ...δ_n=δ, Eq. 3-25 is simplified as follows:

$$NF \approx \delta/(\delta-1) \quad \text{(Eq. 3-26)}$$

Thus by adding the NF to the AC component i_p, ip is expressed by the following equation:

$$i_p = \mu \cdot (2 \cdot e \cdot I_k \cdot B \cdot NF)^{1/2} \quad \text{(Eq. 3-27)}$$

where μ is the gain, e is the electron charge, I_k is the cathode current and B is the bandwidth of the measurement system. From this equation and Eq. 3-25, ip becomes

$$i_p = \mu \cdot \{2 \cdot e \cdot I_k \cdot B \cdot (1/\alpha) \cdot (1+1/\delta_1+1/\delta_1\delta_2+\cdots+1/\delta_1\delta_2\cdots\delta_n)\}^{1/2} \quad \text{(Eq. 3-28)}$$

On the other hand, the average anode current I_p is expressed in the following equation:

$$I_p = I_k \cdot \alpha \cdot \mu \quad \text{(Eq. 3-29)}$$

From Eqs. 3-28 and 3-29, the signal-to-noise ratio becomes

$$\text{SN ratio} = I_p/i_p = \left(\frac{I_K \alpha}{2eB} \cdot \frac{1}{1+1/\delta_1+1/\delta_1\delta_2+\cdots+1/\delta_1\delta_2\cdots\delta_n}\right)^{1/2}$$

This equation can be simplified using Eq. 3-26, as follows:

$$\text{SN ratio} \approx \left(\frac{I_K}{2eB} \cdot \frac{1}{\delta/(\delta-1)}\right)^{1/2} \quad \text{(Eq. 3-30)}$$

From this relationship, it is clear that the signal-to-noise ratio is proportional to the square root of the cathode current I_k and is inversely proportional to the square root of the bandwidth B.

To obtain a better signal-to-noise ratio, the shot noise should be minimized and the following points observed:

(1) Use a photomultiplier tube that has as high a quantum efficiency as possible in the wavelength range to be measured.

(2) Design the optical system for better light collection efficiency so that the incident light is guided to the photomultiplier tube with minimum loss.

(3) Use a photomultiplier tube that has an optimum configuration for light collection.

(4) Narrow the bandwidth as much as possible, as long as no problems occurs in the measuring system.

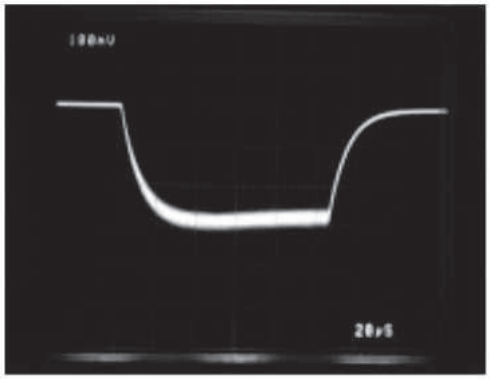
By substituting δ = 6 into Eq. 3-30, which is the typical secondary emission ratio of a normal photomultiplier tube, the value δ /(δ-1) will be 1.2, a value very close to 1. Consequently, if the noise in the multiplication process is disregarded, the signal-to-noise ratio can be rearranged as follows:

$$\text{SN ratio} = (I_k/2eB)^{1/2} \approx 1.755\ 10^3 \sqrt{\frac{I_k(\mu A)}{B(MHz)}} \quad \text{(Eq. 3-31)}$$

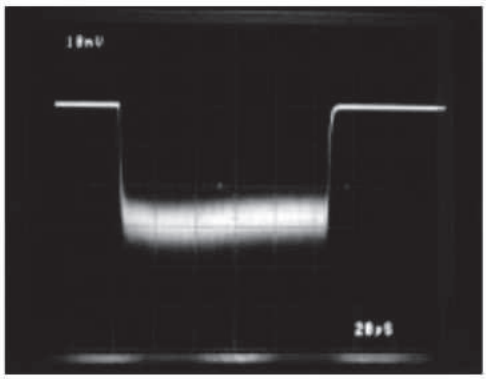
Figure 3-41 shows the output voltage waveforms obtained while the light level and load resistance are changed under certain conditions. These prove that the relation in Eq. 3-30 is correct.

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(a) R_l=20kΩ



(b) R_l=2kΩ (Bandwidth is 10 times wider than (a))



(c) Light level is 10 times higher than (b)

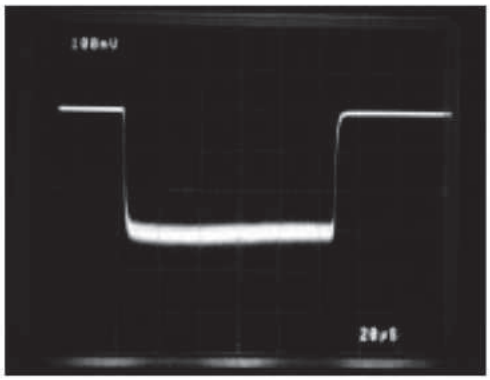


Figure 3-41: Change in the signal-to-noise ratio for R329 when the light level and load resistance are changed

In the above relationship however, the dark current is not involved. Taking into account the contribution of the dark current and the noise current of the amplifier circuit, the intrinsic signal-to-noise ratio will be as follows:

$$\text{SN ratio} = \frac{I_k}{(2eB\cdot\delta/(\delta-1)\cdot(I_k+2I_d)+N^2_A)^{1/2}} \quad \text{(Eq. 3-32)}$$

In cases in which the noise of the amplifier circuit is negligible (N_A=0), the signal-to-noise ratio becomes

$$\text{SN ratio} = \frac{I_k}{(2eB\cdot\delta/(\delta-1)\cdot(I_k+2I_d))^{1/2}} \quad \text{(Eq. 3-33)}$$

where $I_k=\eta\cdot e\cdot P\cdot\lambda\ldots/hc$, and each symbol stands for the following:

I_k: cathode current (A)	e: electron charge (C)
λ: wavelength (m)	h: Planck's constant (J·s)
c: velocity of light (m/s)	η: quantum efficiency
P: power (W)	B: bandwidth (Hz)
δ: secondary emission ratio	N_A: noise of amplifier circuit (A)
I_d: dark current (A)	

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3. 3. 8 Afterpulsing

When a photomultiplier tube is operated in a pulse detection mode as in scintillation counting or in laser pulse detection, extraneous pulses with small amplitudes may be observed. Since these pulses appear after the signal output pulse, they are called afterpulses. Afterpulses often disturb accurate measurement of low level signals following a large amplitude pulse, degrades energy resolution in scintillation counting (See "3.5".), or causes errors in pulse counting applications.

Types of afterpulses

There are two types of afterpulses: one is output with a very short delay (several nanoseconds to several tens of nanoseconds) after the signal pulse and the other appears with a longer delay ranging up to several microseconds, each being generated by different causes. In general, the latter pulses appearing with a long delay are commonly referred to as afterpulses.

Most afterpulses with a short delay are caused by elastic scattering electrons on the first dynode. The probability that these electrons may be produced can be reduced to about one-tenth in some types of photomultiplier tubes, by providing a special electrode near the first dynode. Usually, the time delay of this type of afterpulse is small and hidden by the time constant of the subsequent signal processing circuit, so that it does not create significant problems in most cases. However, this should be eliminated when measuring very short fluorescence lifetime in time-correlated photon counting.

In contrast, afterpulses with a longer delay are caused by the positive ions which are generated by the ionization of residual gases in the photomultiplier tube. These positive ions return to the photocathode (ion feedback) and produce many photoelectrons which result in afterpulses. The amplitude of this type of afterpulse depends on the type of ions and the position where they are generated. The time delay with respect to the signal output pulse varies ranging from several hundred nanoseconds to over a few microseconds, and depends on the supply voltage for the photomultiplier tube. Helium gas is known to produce afterpulses because it easily penetrates through a silica bulb, so use caution on the operating environments. Afterpulses can be reduced temporarily by aging (See 3.3.4, "Stability".), but this is not a permanent measure.

In actual measurements, the frequency of afterpulses and the amount of charge may sometimes be a problem. The amount of output charge tends to increase when the photomultiplier tube is operated at a higher supply voltage to obtain a high gain even though the number of generated ions is the same. In pulse counting applications such as photon counting, the frequency of afterpulses with an amplitude higher than a certain threshold level will only be a problem.

As explained, afterpulses appear just after the signal pulse. Another extraneous pulse may be observed just before the signal pulse output. But, this pulse is very close to the signal pulse and has a low amplitude, causing no problems.

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3. 3. 9 Polarized-light dependence

Photomultiplier tube sensitivity may be affected by polarized light.[43) 44)] It is therefore necessary to take this characteristic into account when polarized light is to be measured. Also it should be noted that light may be polarized at such optical devices as a monochromator. When polarized light enters the photocathode of a photomultiplier tube, the photocathode reflectance varies with the angle of incidence. This effect is also greatly dependent on the polarization component as shown in Figure 3-42. In this figure, Rp is the polarization component parallel to the photocathode surface (P component) and Rs is the polarization component perpendicular to the photocathode surface (S component). It is clear that the photocathode reflectance varies with the angle of incidence. Because this figure shows the calculated examples with the assumption that the absorption coefficient at the photocathode is zero, the actual data will be slightly more complicated.

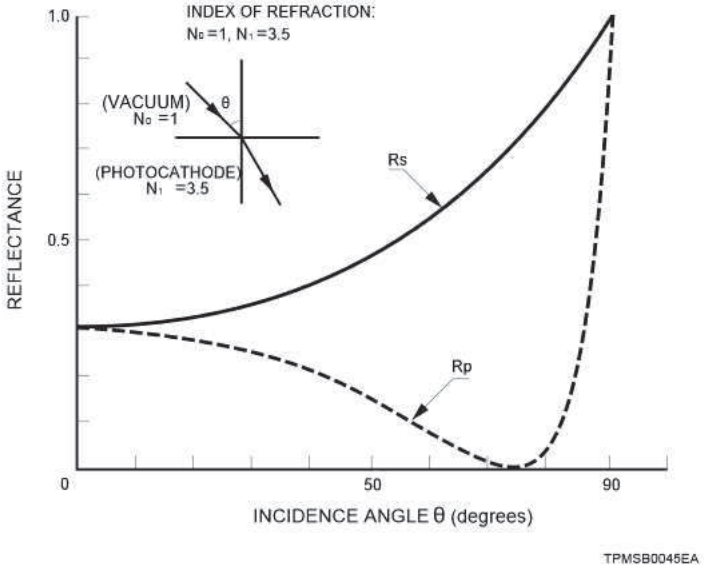


Figure 3-42: Angle dependence of reflectance

If the polarization plane of the incident light has an angle θ with respect to the perpendicular of the photocathode surface, the photocurrent I θ is given by the following expression:

$$I\theta = I_S \cos^2\theta + I_P \sin^2\theta = \frac{I}{2}(I_P+I_S)\left(1-\frac{I_P-I_S}{I_P+I_S}\cdot\cos^2\theta\right) \quad \text{(Eq. 3-34)}$$

where

I_S: Photocurrent produced by polarized component perpendicular to the photocathode
I_P: Photocurrent produced by polarized component parallel to the photocathode

while

$$I_O = \frac{I_P+I_S}{2},\ P = \frac{I_P-I_S}{I_P+I_S} \quad \text{(Eq. 3-35)}$$

then substituting Eq. 3-35 into Eq. 3-34 gives the following relationship

$$\theta = I_O(1-P\cdot\cos^2\theta) \quad \text{(Eq. 3-36)}$$

P is called the polarization factor and indicates the polarized-light dependence of a photomultiplier tube, and is measured using the optical system like that shown in Figure 3-43.

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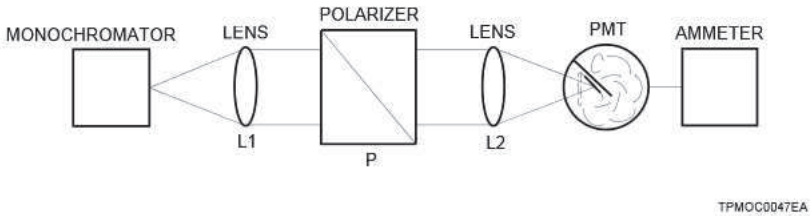


Figure 3-43: Optical system used for measuring polarized-light dependence

In the above measurement, monochromatic light from the monochromator is collimated by L_1 (collimator lens) and is linearly polarized by the polarizer (P). The polarized light is then focused onto the photomultiplier tube through L_2 (condenser lens). The dependence on the polarized light is measured by recording the photomultiplier tube output in accordance with the rotating angle of the polarizer.

In this case, it is necessary to remove the polarization component of the light source. This is done by interposing a diffuser plate such as frosted glass or by compensating for the photomultiplier tube output values measured when the tube is at 0 degree and is then rotated to 90 degrees with respect to the light axis.

Figure 3-44 illustrates the polarized-light dependence of a side-on photomultiplier tube with a reflection type photocathode. In principle, this dependence exists when the light enters slantways with respect to the photocathode surface. In actual operation, the polarization factor P is almost zero when the light enters perpendicular to the photocathode surface.

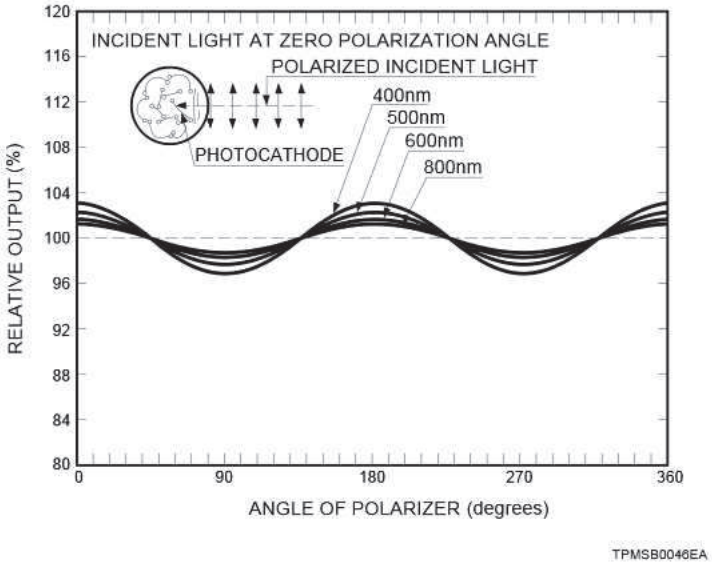


Figure 3-44: Typical polarization-light dependence of a side-on photomultiplier tube

In the case of reflection-type photocathode photomultiplier tubes, because the photocathode is arranged at a certain angle with respect to the input window, the sensitivity is affected by polarized light. Figure 3-45 indicates the relative output of a reflection-type photocathode photomultiplier tube as a function of the angle of incident light. It can be seen that the polarization factor P becomes smaller as the direction of the incident light nears the perpendicular of the photocathode surface.

The reflection-type photocathode photomultiplier tubes usually exhibit a polarization factor of about 10 percent or less, but tubes specially designed to minimize the polarization-light dependence offer three percent or less. A single crystal photocathode such as gallium arsenide (GaAs) has high reflectance and show a polarization factor of around 20 percent, which is higher than that of alkali antimonide photocathodes.

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The polarization that provides the maximum sensitivity is the component perpendicular to the tube axis (P component). In contrast, the polarization that gives the minimum sensitivity is the component parallel to the tube axis (S component), independent of the type of tube and wavelength of incident light. As can be seen from Figure 3-42, this is probably due to a change in the photocathode transmittance. The S component increases in reflectance as the angle of incidence becomes larger, whereas the P component decreases. Moreover, as the wavelength shifts to the longer side, the reflectance generally decreases and the polarization factor P becomes smaller accordingly, as shown in Figure 3-44.

In applications where the polarized-light dependence of a photomultiplier tube cannot be ignored, it will prove effective to place a diffuser such as frosted glass or tracing paper in front of the input window of the photomultiplier tube or to use a photomultiplier tube with a frosted window.

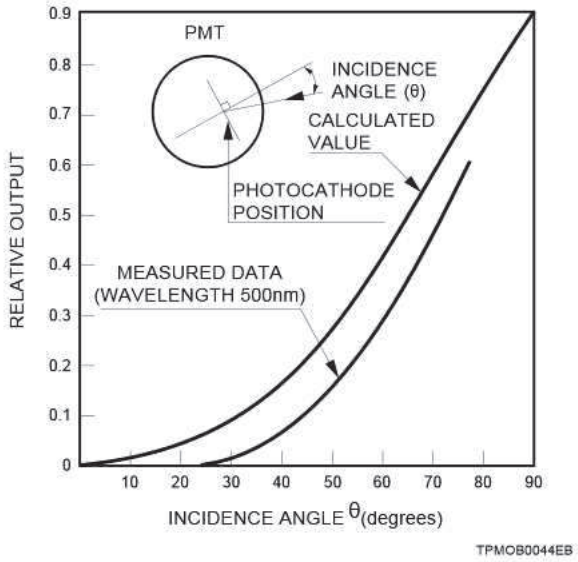


Figure 3-45: Relative output vs. incident angle of polarized light

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3. 4 Photon Counting[25) 41) 45)-52)]

Photon counting is an effective technique used to detect very-low-level-light such as Raman spectroscopy, fluorescence analysis, and chemical or biological luminescence analysis where the absolute magnitude of the light is extremely low. This section describes the principles of photon counting, its operating methods, detection capabilities, and advantages as well as typical characteristics of photomultiplier tubes designed for photon counting.

3. 4. 1 Analog and digital (photon counting) modes

The methods of processing the output signal of a photomultiplier tube can be divided broadly into analog and digital modes, depending on the incident light intensity and the bandwidth of the output processing circuit.

As Figure 3-46 shows, when light strikes the photocathode of a photomultiplier tube, photoelectrons are emitted. These photoelectrons are multiplied by the cascade process of secondary emission through the dynodes (normally 10^6 to 10^7 times) and finally reach the anode connecting with an output processing circuit.

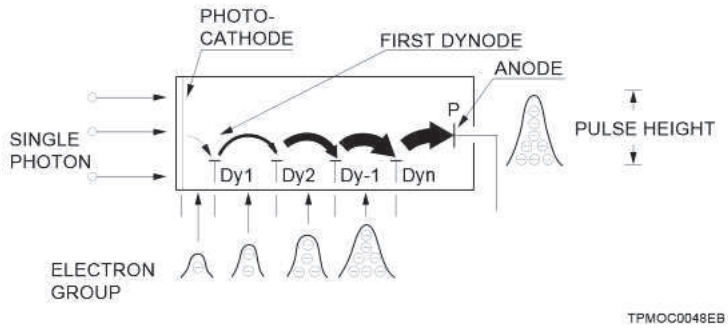


Figure 3-46: Photomultiplier tube operation in the photon counting mode

When observing the output signal of a photomultiplier tube with an oscilloscope while varying the incident light level, output pulses like those shown in Figure 3-47 are seen. At higher light levels, the output pulse intervals are narrow so that they overlap each other, producing an analog waveform (similar to (a) and (b) of Figure 3-47). If the light level becomes very low, the ratio of AC component (fluctuation) in the signal increases, and finally the output signal will be discrete pulses (like (c) of Figure 3-47). By discriminating these discrete pulses at a proper binary level, the number of the signal pulses can be counted in a digital mode. This is commonly known as photon counting.

In analog mode measurements, the output signal is the mean value of the signals including the AC components shown in Figure 3-47 (a). In contrast, the photon counting method can detect each pulse shown in Figure 3-47 (c), thus the number of counted pulses equals the signal. This photon counting mode uses a pulse height discriminator that separates the signal pulses from the noise pulses, enabling high-precision measurement with a higher signal-to-noise ratio in comparison with the analog mode. Therefore photon counting is exceptionally effective in detecting low level light.

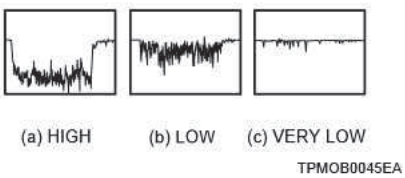


Figure 3-47: photomultiplier tube output waveforms observed at different light levels

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3. 4. 2 Principle of photon counting

When light incident on a photomultiplier tube becomes very low and reaches a state in which no more than two photoelectrons are emitted within the time resolution (pulse width) of the photomultiplier tube, this light level is called the single photoelectron region and photon counting is performed in this region. Quantum efficiency, an important parameter for photon counting, signifies the probability of photoelectron emission when a single photon strikes the photocathode.

In this single photoelectron region, the number of emitted electrons per photon is one or zero and the quantum efficiency can be viewed as the ratio of the number of photoelectrons emitted from the photocathode to the number of incident photons per unit time. The probability that the photoelectrons emitted from the photocathode (primary electrons) will impinge on the first dynode and contribute to gain is referred to as collection efficiency. Some photoelectrons may not contribute to gain because they deviate from the normal trajectories and are not collected by the first dynode. Additionally, in the photon counting mode, the ratio of the number of counted pulses (output pulses) to the number of incident photons is called detection efficiency or photomultiplier tube counting efficiency and is expressed by the following relation:

Detection efficiency (counting efficiency) = (Nd/Np) = $\eta 5\ \alpha$ ····· (Eq. 3-37)
in the photon counting region

where Nd is the counted value, Np is the number of incident photons, η is the quantum efficiency of the photocathode and α is the collection efficiency of the dynodes. The detection efficiency greatly depends on the threshold level used for binary processing.

The number of secondary electrons released from the first dynode is not constant. It is around several secondary electrons per primary electron, with a broad probability seen as a Poisson distribution. Therefore the average number of electrons per primary electron δ corresponds to the secondary-electron multiplication factor of the dynode. Similarly, this process is repeated through the second and subsequent dynodes until the final electron bunch reaches the anode. In this way the output multiplied in accordance with the number of photoelectrons from the photocathode appears at the anode. If the photomultiplier tube has n stage dynodes, the photoelectrons emitted from the photocathode are multiplied in cascade up to δ^n times and derived as an adequate electron bunch from the anode. In this process, each output pulse obtained at the anode exhibits a certain distribution in pulse height because of fluctuations in the secondary multiplication factor at each dynode (statistical fluctuation due to cascade multiplication), non-uniformity of multiplication depending on the dynode position and electrons deviating from their favorable trajectories. Figure 3-48 illustrates a histogram of photomultiplier tube output pulses. The abscissa indicates the pulse height and the anode output pulses are integrated with time. This graph is known as the pulse height distribution.

Figure 3-48 also shows the relation between the pulse height distribution and the actual output pulses obtained with a photomultiplier tube. The pulse height distribu-

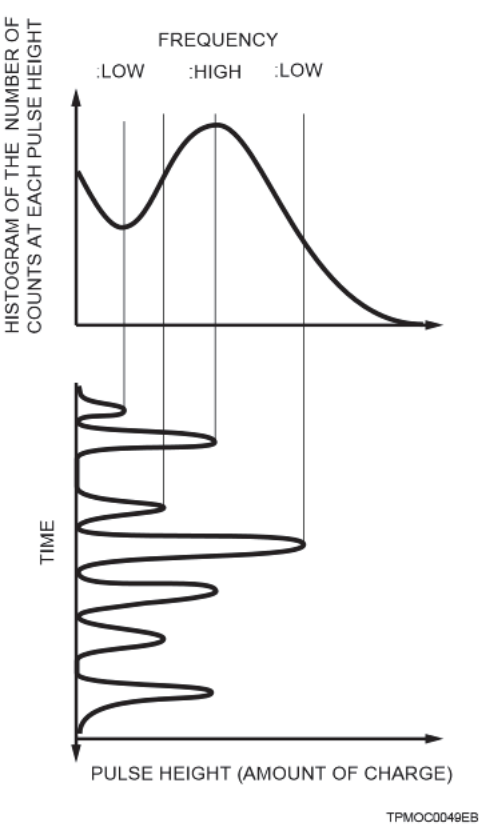


Figure 3-48 : Photomultiplier tube output and its pulse height distribution

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tion is usually taken with a multichannel analyzer (MCA) frequently used in scintillation counting applications.

Figure 3-49 (a) shows examples of the pulse height distribution obtained with a photomultiplier tube. The output pulses are present even if no light falls on the photomultiplier tube. (These are called dark current pulses or noise pulses.) The broken line indicates the distribution of the dark current pulses, with a tendency to build up somewhat in the lower pulse height region (left side). These dark pulses mainly originate from the thermal electron emission at the photocathode and also at the dynodes. The thermal electrons from the dynodes are multiplied less than those from the photocathode and are therefore distributed in the lower pulse height region.

Figure 3-49 (b) indicates the distribution of the total number of counted pulses S(L) with amplitudes greater than a threshold level L shown in (a). (a) and (b) have differential and integral relations to each other. Item (b) is a typical integral curve taken with a photon counting system using a photomultiplier tube.

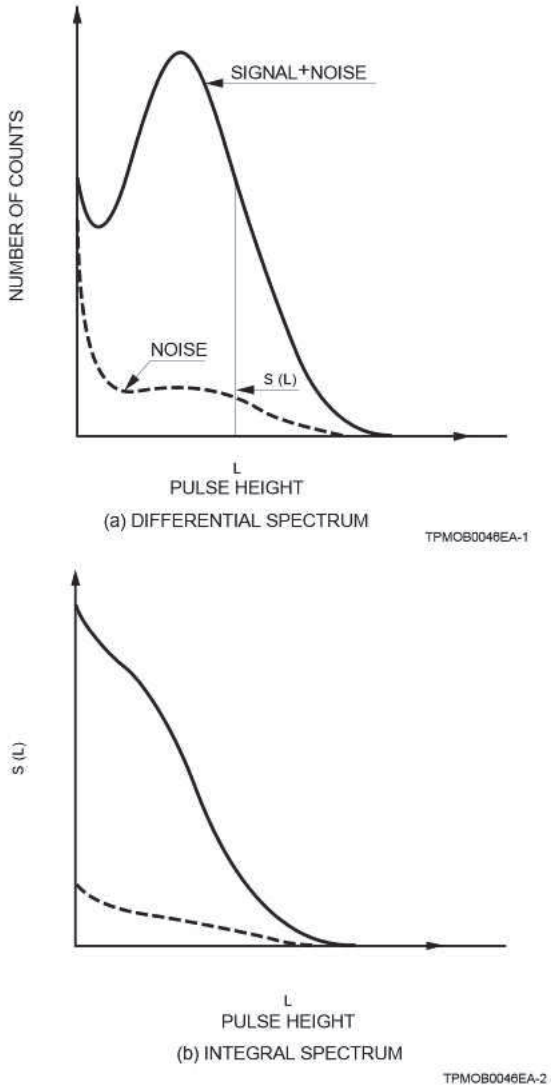


Figure 3-49: Differential and integral representations of pulse height distribution

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3. 4. 3 Operating method and characteristics for photon counting

This section discusses specific circuit configurations used to perform photon counting and the basic characteristics involved in photon counting.

(1) Circuit configuration

Figure 3-50 shows a typical circuit configuration for photon counting and a pulse waveform obtained at each circuit.

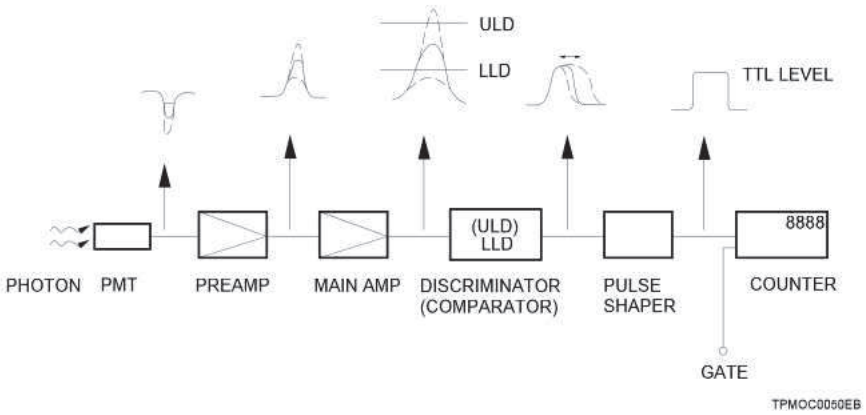


Figure 3-50: Circuit configuration for photon counting

In the above system, current output pulses from a photomultiplier tube are converted to a voltage by a wide-band preamplifier and amplified. These voltage pulse are fed to a discriminator and then to a pulse shaper. Finally the number of pulses is counted by a counter. The discriminator usually employs a comparator IC that compares the input voltage pulses with the preset reference voltage (threshold level) and eliminates those pulses with amplitudes lower than this value. In general, the LLD (lower level discrimination) level is set at the lower pulse height side. The ULD (upper level discrimination) level may also be often set at the higher pulse height side to eliminate noise pulses with higher amplitudes. The counter is usually equipped with a gate circuit, allowing measurement at different timings and intervals.

(2) Basic characteristics in photon counting

a) Pulse height distribution and plateau characteristics

If a multichannel pulse height analyzer is available, a proper threshold level can be set in the pulse height distribution. Because the dark current pulses are usually distributed in the lower pulse height region, setting the LLD level in the vicinity of the valley (L_1) of the distribution can effectively eliminate such noise pulses without sacrificing the detection efficiency. In actual operation, however, using a pulse height analyzer is not so popular. Other methods using plateau characteristics are more commonly employed instead. By counting the total number of pulses with amplitudes higher than the preset threshold level while varying the supply voltage for the photomultiplier tube, plots similar to those shown in Figure 3-52 can be obtained. These plots are called the plateau characteristics. The pulse height obtained at the supply voltage giving the maximum rising gradient in the signal plateau characteristic corresponds to the L_1 level in Figure 3-51. From this relation, the pulse height for the LLD level can be predicted.

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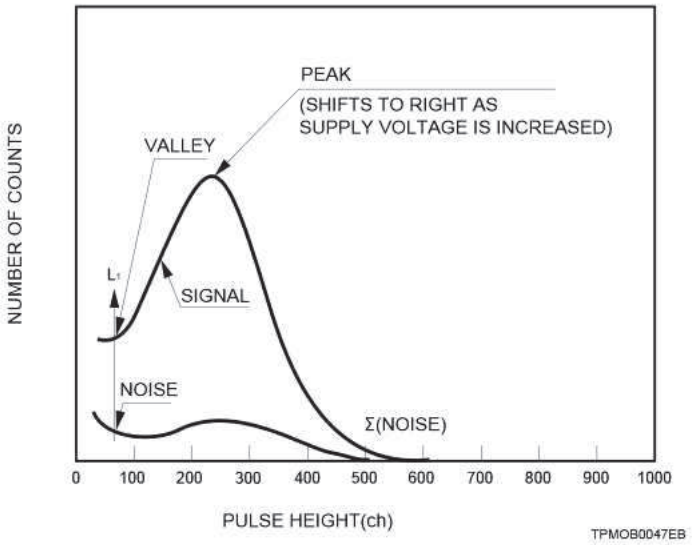


Figure 3-51: Typical example of pulse height distribution

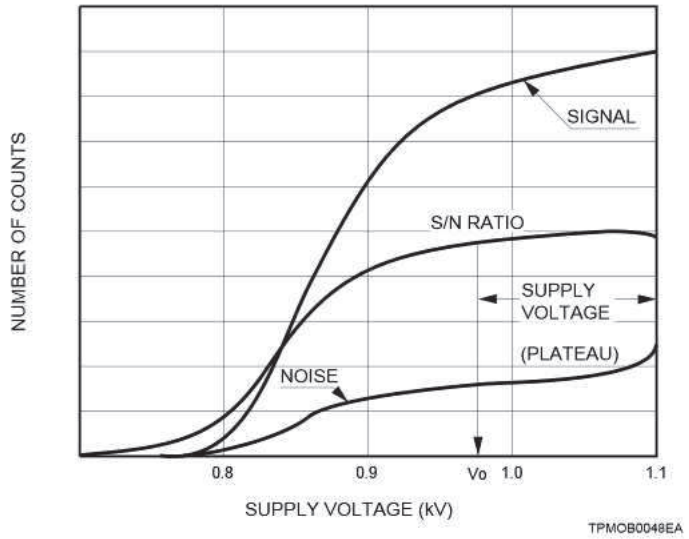


Figure 3-52: Plateau characteristics

b) Setting the photomultiplier tube supply voltage

The signal-to-noise ratio is an important factor from the viewpoint of accurate measurements. Here the signal-to-noise ratio is defined as the ratio of the mean value of the signal count rate to the fluctuation of the counted signal and noise pulses (expressed in standard deviation or root mean square). The signal-to-noise ratio curve shown in Figure 3-52 is plotted by varying the supply voltage, the same procedure which is used to obtain the plateau characteristics. This figure implies that the photomultiplier tube should be operated in the range between the voltage (Vo) at which the plateau region begins and the maximum supply voltage.

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c) Count rate linearity

The photon counting mode offers excellent linearity over a wide range. The lower limit of the count rate linearity is determined by the number of dark current pulses, and the upper limit by the maximum count rate. The maximum count rate further depends on pulse-pair resolution, which is the minimum time interval at which each pulse can be separated. The reciprocal of this pulse pair resolution would be the maximum count rate. However, since most events in the photon counting region usually occur at random, the counted pulses may possibly overlap. Considering this probability of overlapping, the actual maximum count rate will be about one-tenth of the calculated above. The loss of count rateÉÃ from pulse overlapping is given by

$$\xi = \frac{n\tau}{1+n\tau} \quad \text{(Eq. 3-38)}$$

where

n: ture count rate(cps)
τ: pulse pair resolution(s)

Figure 3-53 shows the typical linearity taken using a system with a pulse pair resolution of 8 nanoseconds.

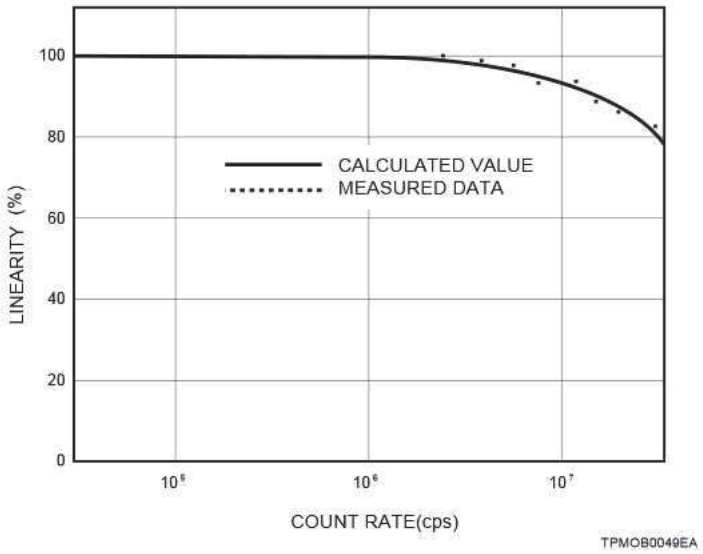


Figure 3-53: Linearity of count rate

d) Setting the threshold level

In photon counting, it is most important to determine where to set the threshold level. In general, the optimum threshold level may be determined according to the suggestions listed below. But setting threshold is not simple and therefore careful selection must be made in accordance with individual needs.

(1) To optimize the signal-to-noise ratio and stabilize the count rate with respect to gain variations of the photomultiplier tube, the threshold level should be set near the valley or the plateau region of the pulse height distribution.
(2) Setting the threshold level at the lowest possible level gives the best detection efficiency. Practically, however, setting it near the valley or the plateau region is recommended.
(3) To optimize the elimination rate between the signal and noise, the threshold level should be set at the middle of the peak and valley in the pulse height distribution.

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e) Advantages of photon counting

Photon counting has many advantages in comparison with the analog mode. Among them, stability and signal-to-noise ratio are discussed in this section.

(I) Stability

One of the significant advantages photon counting offers is operating stability. The photon counting mode is resistant to variations in supply voltage and photomultiplier tube gain. If the supply voltage is set within the plateau region, a change in the voltage has less effect on the output counts. In the analog mode, however, it affects the output current considerably. Immunity to variations in the supply voltage means that the photon counting mode also assures high stability against gain fluctuation of the photomultiplier tube. Normally the photon counting mode offers several times higher immunity to such variations than the analog mode. (Refer to Figure 3-54.)

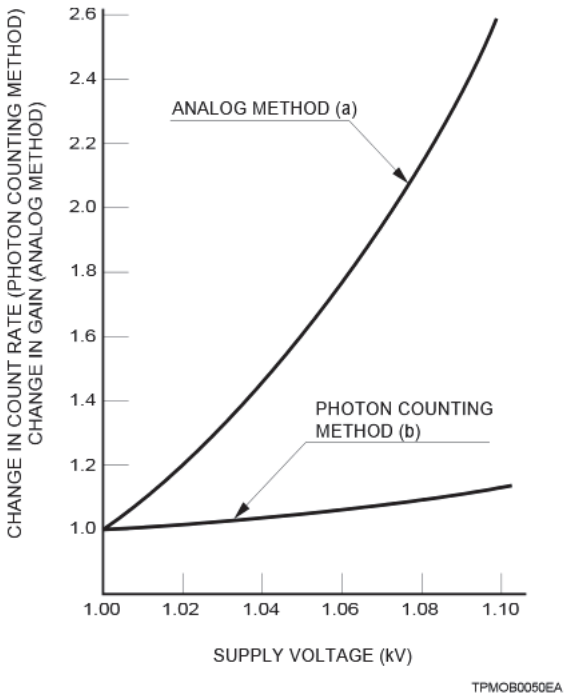


Figure 3-54: Stability versus changes in supply voltage

(II) Signal-to-noise ratio

When signal light strikes the photocathode of a photomultiplier tube, photoelectrons are emitted and directed to the dynode section where secondary electrons are produced. The number of photoelectrons produced per unit time and also the number of secondary electrons produced are determined by statistical probability of events which is represented by a Poisson distribution. Thus they are accompanied by statistical fluctuations (AC current components) expressed as a binomial distribution, having an effect on the signal-to-noise ratio. The signal-to-noise ratio is also described in Section 3.3.7. The AC component noise which is superimposed on the signal can be categorized by origin as follows

(1) Shot noise resulting from signal light
(2) Shot noise resulting from background light
(3) Shot Noise resulting from dark current

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In the analog mode, the signal-to-noise ratio[41) 42) 45) 46) - 50) 51)] of the photomultiplier tube output including these shot noises becomes

$$\text{SN ratio(current)} = \frac{Iph}{\sqrt{2eNFB\{Iph+2(Ib+Id)\}}} \quad \cdots\cdots \text{(Eq. 3-39)}$$

where

Iph: signal current produced by incident light (A)
e: electron charge (c)
F: noise figure of the photomultiplier tube (A)
Ib: cathode current resulting from background light (A)
Id: cathode current resulting from dark current (A)
B: Bandwidth of measurement system (Hz)

Here the true signal current Iph is obtained by subtracting Ib+Id from the total current. The noise originating from the latter-stage amplifier is considered to be negligible because the typical gain μ of a photomultiplier tube is sufficiently large.

The signal-to-noise ratio in the photon counting mode is given by the following equation.

$$\text{SN ratio} = \frac{Ns\sqrt{T}}{\sqrt{Ns+2(Nb+Nd)}} \quad \cdots\cdots \text{(Eq. 3-40)}$$

where

Ns: number of counts/sec resulting from incident light per second
Nb: number of counts/sec resulting from background light per second
Nd: number of counts/sec resulting from dark current per second
T: measurement time(sec)

Here the number of counts/sec of true signals Ns is obtained by subtracting Nb+Nd from the total number of counts.

From the common equivalent relation between the time and frequency, if B=1 (Hz) and T=0.5 (sec), then the signal-to-noise ratio will be as follows:

in the analog mode

$$\text{SN ratio(current)} = \frac{Iph}{\sqrt{2eNF\{Iph+2(Ib+Id)\}}} \quad \cdots\cdots \text{(Eq. 3-41)}$$

in the photon counting mode

$$\text{SN ratio} = \frac{Ns}{\sqrt{2\{Ns+2(Nb+Nd)\}}} \quad \cdots\cdots \text{(Eq. 3-42)}$$

Through the above analysis, it is understood that the photon counting mode provides a better signal-to-noise ratio by a factor of the noise figure NF. Since the dark current includes thermal electrons emitted from the dynodes in addition to those from the photocathode, its pulse height distribution will be an exponential spectrum shifted toward the lower pulse height side. Therefore, the dark current component can be effectively eliminated by use of a pulse height discriminator while maintaining the signal component, assuring further improvement in the signal-to-noise ratio. In addition, because only AC pulses are counted, the photon counting mode is not influenced by the DC leakage current. Amplifier noises can totally be eliminated by a discriminator.

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3. 4. 4 Characteristics of photomultiplier tubes for photon counting

Table 3-6 lists typical characteristics[52] of Hamamatsu photomultiplier tubes currently available for photon counting.

Wavelength Range	Diameter/ Configuration inch (mm)	Type No.	Spectral Response (nm)	Sensitive Area (mm)	Photocathode Quantum Efficiency		Dark Count			Rise Time (ns)	Remarks
					QE (%)	Wavelength (nm)	Typ (cps)	Max. (cps)	Temperature (°C)		
VUV to UV	28 (1-1/8), side-on	R7154P	160~320	85 24	35	200	5	20	25	2.2	MgF_2: R1220P
UV to Visible	28 (1-1/8), head-on	R7207-01	160~650	55 8	22	390	10	30	25	1.7	Low dark count
	13 (1/2), side-on	R6350P	185~680	45 13	20	270	10	30	25	1.4	
	13 (1/2), side-on	R6353P	185~680	45 13	23	330	10	30	25	1.4	
	28 (1-1/8), side-on	R1527P	185~680	85 24	19	300	10	50	25	2.2	Low dark count
	28 (1-1/8), side-on	R2693P	185~650	185 16	20	300	15	50	25	1.2	Semi-transparent photocathode
	28 (1-1/8), side-on	R4220P	185~710	85 24	23	320	10	50	25	2.2	High sensitivity Low dark count
	15 (3/5), head-on	R7400P-06	160~650	8 dia.	20	360	80	400	25	0.78	Metal package type
	15 (3/5), head-on	R7400P-03	185~650	8 dia.	20	360	80	400	25	0.78	Metal package type
Visible	10 (3/8), head-on	R1635P	300~650	8 dia.	26	390	100	400	25	0.8	
	13 (1/2), head-on	R647P	300~650	10 dia.	26	390	80	400	25	2.5	
	13 (1/2), head-on	R2557	300~650	10 dia.	20	375	10	30	25	2.2	Low dark count
	19 (3/4), head-on	R5610	300~650	15 dia.	20	375	15	45	25	1.5	Low dark count
	25 (1), head-on	R1924P	300~650	21 dia.	26	390	100	300	25	2.0	
	25 (1), head-on	R3550	300~650	21 dia.	20	375	20	60	25	2.0	Low dark count
	28 (1-1/8), head-on	R6249P	300~650	25 dia.	25	390	120	300	25	4.0	
	28 (1-1/8), head-on	R7205-01	300~650	25 dia.	22	390	10	30	25	1.7	Low dark count
	51 (2), head-on	R329P	300~650	46 dia.	26	390	200	600	25	2.6	
	15 (3/5), head-on	R7400P	300~650	8 dia.	20	360	80	400	25	0.78	Metal package type
Visible to Near IR	28 (1-1/8), head-on	R3206-01	300~850	10 dia.	20 (0.3)	340 800	300	1000	25	1.7	Low dark count
	28 (1-1/8), head-on	R2228P	300~900	25 dia.	8 (1.5)	600 800	150	500	-20	15.0	
	51 (2), head-on	R2256P	300~900	46 dia.	10 (2)	600 800	600	2000	25	2.6	
	51 (2), head-on	R3310-02	300~1010	105 10	13 (0.25)	340 1000	30	150	-20	3.0	
	15 (3/5), head-on	R7400P-01	300~850	8 dia.	19 (0.19)	370 800	500	1000	25	0.78	Metal package type
UV to Near IR	13 (1/2), head-on	R1463P	185~850	10 dia.	22 (0.3)	270 800	900	1000	25	2.5	
	28 (1-1/8), head-on	R1104P	185~850	25 dia.	23 (0.3)	270 800	4500	7000	25	15.0	High gain
	51 (2), head-on	R943-02	160~930	105 10	22 (12)	300 800	20	50	-20	3.0	
	13 (1/2), side-on	R6358P	185~850	45 13	24 (13)	240 600	20	50	25	1.4	
	28 (1-1/8), side-on	R928P	185~900	85 24	25 (2.7)	260 800	500	1000	25	2.2	
	28 (1-1/8), side-on	R2949	185~900	85 6	25 (2.7)	260 800	300 (3)	500 —	25 -20	2.2	UV to near IR Low dark count
	28 (1-1/8), side-on	R2658P	185~1010	35 12	14 (0.13)	330 1000	50	300	-20	2.0	InGaAs photocathode
	28 (1-1/8), side-on	R4632	185~850	85 24	26 (11)	270 600	50	100	25	2.2	Low dark count in near IR
	15 (3/5), head-on	R7400P-04	185~850	8 dia.	20 (0.19)	280 300	500	1000	25	0.78	Metal package type

Table 3-6: Typical characteristics of photomultiplier tubes for photon counting

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3. 5 Scintillation Counting

Radiation of various types is widely utilized for non-destructive inspection and testing such as in medical diagnosis, industrial inspection, material analysis and other diverse fields. In such applications, radiation detectors play an important role. There are various methods for detecting radiation.[34) 53) 54)] For example, typical detectors include proportional counters, semiconductor detectors that make use of gas and solid ionization respectively, radiation-sensitive films, cloud chambers, and scintillation counters.

In scintillation counting, the combination of a scintillator and photomultiplier tube is one of the most commonly used detectors for practical applications.[55) 56)] Scintillation counting has many advantages over other detection methods, for example, a wide choice of scintillator materials, fast time response, high detection efficiency, and a large detection area. This section gives definitions of photomultiplier tube characteristics required for scintillation counting and explains their measurement methods and typical data.

3. 5. 1 Scintillators and photomultiplier tubes[28)]

When ionizing radiation enters a scintillator, it produces a fluorescent flash with a short decay time. This is known as scintillation. In the case of gamma rays, this scintillation occurs as a result of excitation of the bound electrons by means of free electrons inside the scintillator. These free electrons are generated by the following three mutual interactions: the photoelectric effect, Compton effect, and pair production. The probability of occurrence of these interactions depends on the type of scintillators and the energy level of the gamma rays. Figure 3-55 shows the extent of these interactions when gamma-ray energy is absorbed by a NaI(Tl) scintillator.

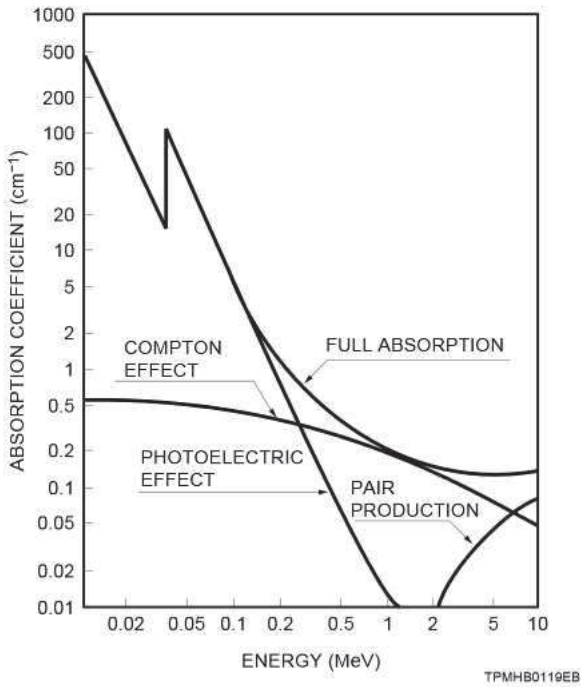


Figure 3-55: Gamma-ray absorption characteristics of NaI(Tl) scintillator

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From Figure 3-55, it is clear that the photoelectric effect predominates at low energy levels of gamma rays, but pair production increases at high energy levels. Of these three interactions, the amount of scintillation produced by the photoelectric effect is proportional to gamma-ray energy because all the energy of the gamma ray is given to the orbital electrons. The photomultiplier tube outputs an electrical charge in proportion to the amount of this scintillation, as a result, the output pulse height from the photomultiplier tube is essentially proportional to the incident radiation energy. Accordingly, a scintillation counter consisting of a scintillator and a photomultiplier tube provides accurate radiation energy distribution and its dose rate by measuring the photomultiplier tube output pulse height and count rate. To carry out energy analysis, the current output from the photomultiplier tube is converted into a voltage output by an integrating preamplifier and fed to a PHA (pulse height analyzer) for analyzing the pulse height.[53] A typical block diagram for scintillation counting is shown in Figure 3-56.

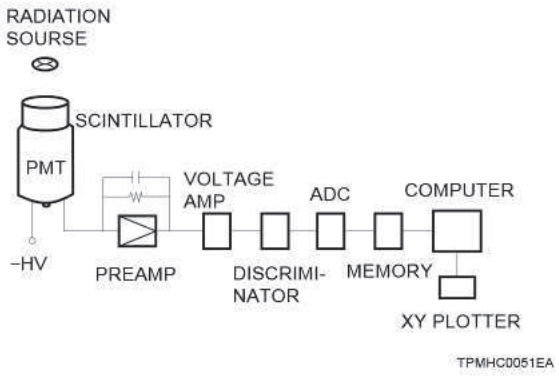


Figure 3-56: Block diagram for scintillation counting

Scintillators are divided into inorganic scintillators and organic scintillators. Most inorganic scintillators are made of a halogen compound such as NaI(Tl), BGO, BaF_2, CsI(Tl) and ZnS. Of these, the NaI(Tl) scintillator is most commonly used. These inorganic scintillators offer advantages of excellent energy conversion efficiency, high absorption efficiency and a good probability for the photoelectric effect compared to organic scintillators. Unfortunately however, they are not easy to handle because of deliquescence and vulnerability to shock and impact.

Organic scintillators include plastic scintillators, liquid scintillators and anthracene, an organic crystal. These scintillators display a short decay time and have no deliquescence. In addition, plastic scintillators are easy to handle and available in various types varying from small or thin sizes to large sizes with special configurations. In the detection of gamma rays, however, organic scintillators have a low absorption coefficient and exhibit less probability for the photoelectric effect. Accordingly, they are not suited for energy analysis applications. Table 3-7 lists typical characteristics and applications of major scintillators which have been developed up to the present.[56]

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Scinti-llators	Density (g/cm^3)	Emission Intensity (NaI(Tl) normalized at 100)	Emission Time (ns)	Peak Emission Wavelength (nm)	Applications
NaI(Tl)	3.67	100	230	410	Surveymeter, area monitor, gamma camera, SPECT
BGO	7.13	15	300	480	PET, X-ray CT
CsI(Tl)	4.51	45 to 50	1000	530	Surveymeter, area monitor, X-ray CT
Pure CsI	4.51	<10	10	310	High energy physics
BaF2	4.88	20	0.9/630	220/325	TOF, PET
GSO:Ce	6.71	20	30	310/430	Area monitor, oil well logging
Plastic	1.03	25	2	400	Area monitor, neutron detection
LSO	7.35	70	40	420	PET
PWO	8.28	0.7	15	470	High energy physics
YAP	5.55	40	30	380	Surveymeter, compact gamma camera

Table 3-7: Typical characteristics and applications of scintillators

A scintillator is attached to a photomultiplier tube with coupling material as shown in Figure 3-57. The coupling material is used in place of an air layer in order to minimize optical loss between the scintillator and the photocathode faceplate. Silicon oil having an index of refraction close to that of the glass faceplate is most widely used as a coupling material. However, selecting the proper material which provides good transmittance over the emission spectrum of the scintillator is necessary. Figure 3-58 indicates typical emission spectra of major scintillators and photocathode spectral responses of various photomultiplier tubes.

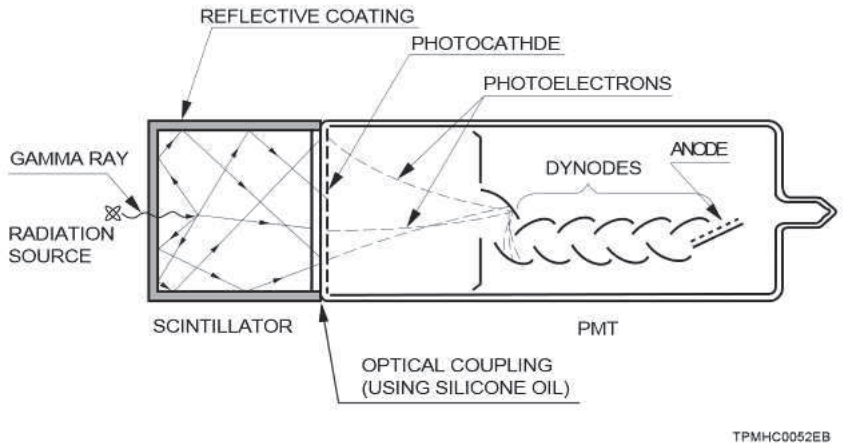


Figure 3-57: Gamma-ray detection using a NaI(Tl) scintillator and a photomultiplier tube

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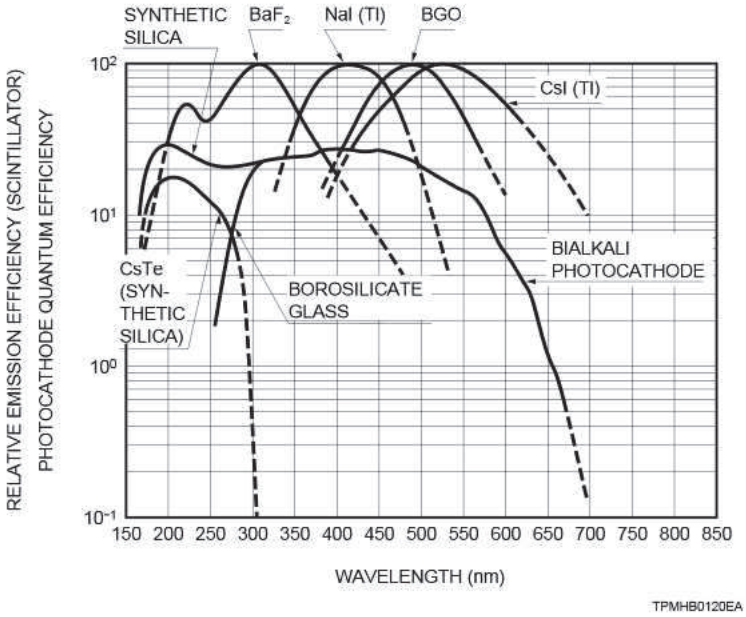


Figure 3-58: Photocathode quantum efficiency and emission spectra of major scintillators

3. 5. 2 Various characteristics

(1) Energy resolution

Figure 3-56 shows typical pulse height distributions for various kinds of gamma ray sources (^{55}Fe, ^{57}Co, ^{137}Cs, ^{60}Co) taken with a photomultiplier tube coupled to an NaI(Tl) crystal. (The same measurement method as shown in Figure 3-56 is used.)

When gamma-ray energy incident on the scintillator increases and the average number of resultant photons per unit disintegration becomes large, the shape of the photopeak distribution closely approximates a Gaussian distribution, which is expressed by the following equation:

$$P(X)= \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(X-\bar{X})^2}{2\sigma^2}\right) \quad \text{(Eq. 3-43)}$$

where σ is the standard deviation (σ= FWHM/2.35) and X is the average number of photons produced. The energy resolution or pulse height resolution (PHR) R is defined as the ratio of the FWHM (ΔP) to the pulse height (P) at the peak count rate, as follows. R is usually stated in percent.

$$R = \frac{\Delta P}{P} \quad \text{(Eq. 3-44)}$$

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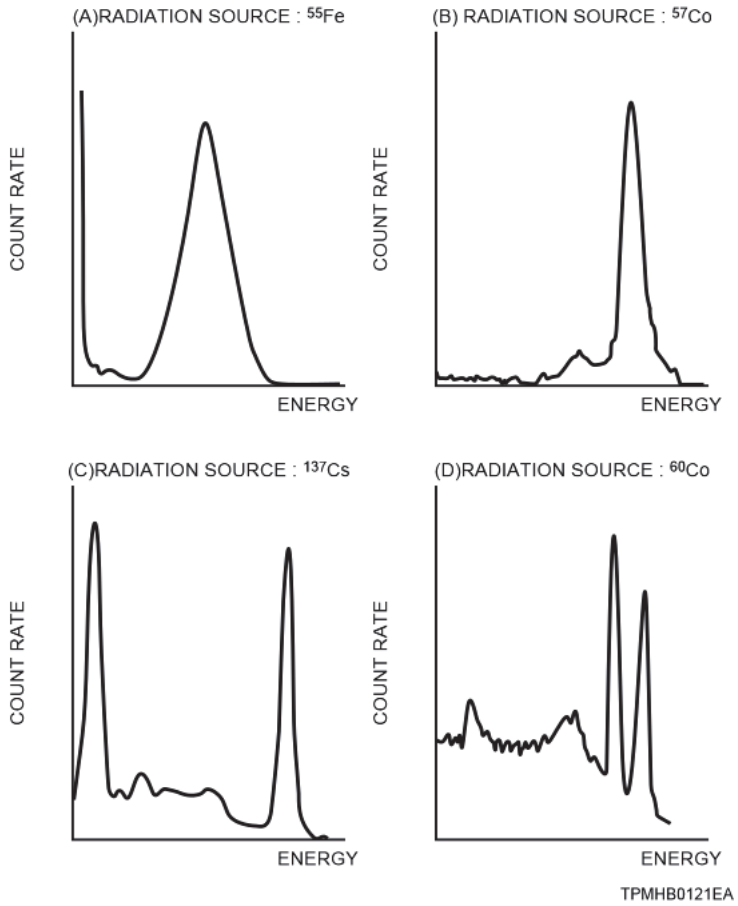


Figure 3-59: Typical pulse height distributions

The following factors affect the energy resolution.

(1) Energy conversion efficiency of the scintillator

(2) Intrinsic energy resolution of the scintillator

(3) Light collection efficiency of the photomultiplier tube photocathode

(4) Quantum efficiency (η) of the photomultiplier tube photocathode

(5) Collection efficiency (α) at first dynode and gain

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Generally, energy resolution is given by

$$R^2(E) = R_s^2(E) + Rp^2(E) \quad \text{(Eq. 3-45)}$$

where

$$R_P^2(E) = \frac{5.56}{N\eta\alpha}\left(\frac{\delta}{\delta-1}\right) \quad \text{(Eq. 3-46)}$$

in which N is the average number of photons incident on the photocathode per unit disintegration and σ is the secondary emission yield at each dynode (assumed to be constant here).

In the above equations, Rs(E) is the energy resolution of the scintillator and Rp(E) is that of the photomultiplier tube, both of which depend on the energy (E) of the incident gamma ray. $Rp^2(E)$ is inversely proportional to E.

When a 2-inch diameter by 2-inch length NaI(Tl) scintillator and a 2-inch diameter photomultiplier tube (Hamamatsu R878) are used, the following values will typically be obtained for R, Rs and Rp:

With E=122keV (^{57}Co), R ≈ 10%, Rs≈7 or 8%, Rp ≈ 7%

With E=662keV (^{137}Cs), R ≈ 7%, Rs ≈ 6%, Rp ≈ 3.5%

Along with using a scintillator with high conversion efficiency and good inherent energy resolution, to obtain higher energy resolution, good optical coupling should be provided to reduce optical loss. For this purpose, as mentioned previously it is helpful to couple the scintillator and the photomultiplier tube using silicon oil having an index of refraction close to that of the faceplate of the photomultiplier tube.

When the intensity distribution of light entering the photomultiplier tube is always constant over the photocathode, the photomultiplier tube uniformity has no effect on the energy resolution. However, if the light flash from the scintillator fluctuates with respect to the incident position on the photocathode, the photomultiplier tube uniformity may degrade the energy resolution. To avoid this problem, a light-guide is sometimes placed between the scintillator and the photomultiplier tube so that the light flash from the scintillator is diffused and allowed to enter uniformly over the photocathode. But this technique is not necessary when using a photomultiplier tube with normal uniformity.

γ-ray source	Energy (keV)	NaI(Tl) + PMT	BGO + PMT
^{55}Fe	5.9	40 to 50%	–
^{241}Am	59.5	12 to 15%	70 to 150%
^{57}Co	122	8.5 to 10%	35 to 50%
^{22}Na	511	7.5 to 9.0%	13 to 25%
^{137}Cs	662	6.5 to 8.5%	11 to 20%
^{60}Co	1,170	5 to 6.5%	8.5 to 11%
	1,330	4.5 to 5.5%	8.0 to 9.5%

Table 3-8: Energy resolution for typical gamma-ray sources, obtained with a NaI(Tl) or BGO scintillator

Energy resolution is one of the most important characteristics in radiation measurement such as gamma cameras and gamma counters. Therefore photomultiplier tubes used in these applications are usually tested for energy resolution. Table 3-8 summarizes energy resolution for typical gamma rays measured with a NaI(Tl)/photomultiplier tube or a BGO/photomultiplier tube combination device. As shown in the table, each of the data exhibits a certain variation in energy resolution. This is due to the non-uniformity of the physical size of the scintillator or photomultiplier tube and also the performance variations between individual photomultiplier tubes. If necessary, it is possible to select only those photomultiplier tubes that meet specific specifications.

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(2) Relative pulse height

In scintillation counting, when a photomultiplier tube is operated at a constant supply voltage and the gain of the measuring circuit is fixed, the pulse height that gives the peak of the pulse height distribution is referred to as the relative pulse height (RPH). This is commonly stated in terms of the channel number at which the maximum count rate of the pulse height distribution is obtained with a pulse height analyzer.[28] The same measurement setup is used as shown in Figure 3-56. This relative pulse height essentially means the collective gain of a photomultiplier tube used in scintillation counting. It usually shows a good correlation with measurement data taken by users (instrument manufacturers) and thus is often used for simple evaluation of a photomultiplier tube.

When measured with a NaI(Tl) scintillator, the relative pulse height provides a close correlation with blue sensitivity because the emission spectrum of the NaI(Tl) resembles the spectral transmittance of the Corning filter CS No.5-58 which is used for the blue sensitivity measurement. (Refer to Section 3.1.5.)

(3) Linearity

Output current linearity of a photomultiplier tube with respect to the amount of scintillation flash is another important parameter to discuss. Since linearity of general-purpose photomultiplier tubes has already been described earlier, this section explains how to measure linearity related to scintillation counting. Figure 3-60 shows a typical pulse height distribution for the ^{226}Ra taken with a NaI(Tl) and Figure 3-61 indicates the relationship between each peak channel and the gamma-ray energy. Because ^{226}Ra releases various kinds of radiation ranging in energy from 10.8keV to 2.2MeV, it is used for linearity measurements over a wide energy range.

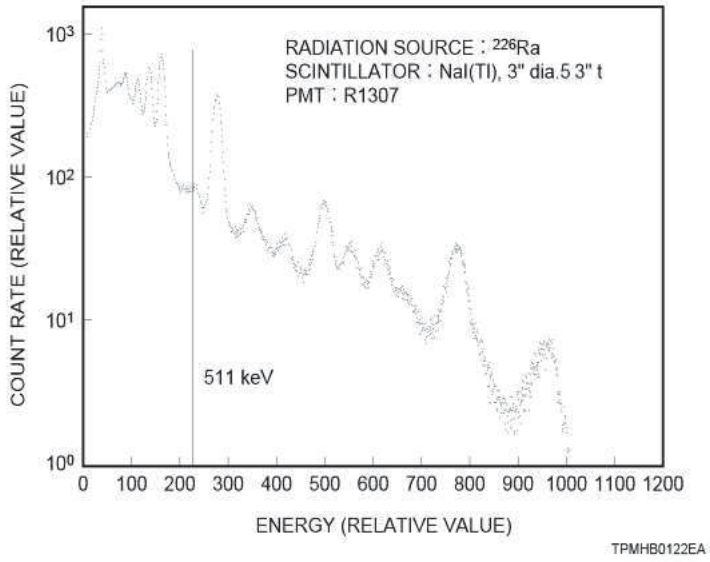


Figure 3-60: Pulse height distribution for the ^{226}Ra taken with a NaI(Tl)

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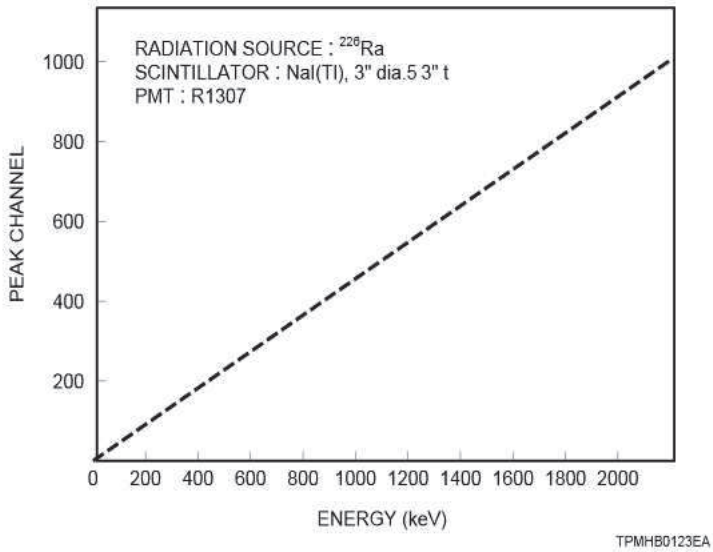


Figure 3-61: Relation between peak channel and gamma-ray energy

Amount of emission from a NaI(Tl) scintillator equals about 30 photons per 1keV of gamma-ray energy. Accordingly, some 20,000 photons (662keV5 30) are generated with ^{137}Cs and some 40,000 photons (1330keV 5 30) are generated with ^{60}Co. Photomultiplier tube linearity and measurement methods using normal light sources have been discussed in Section 3.3.2. When ^{60}Co is used for linearity measurements under the conditions that the photomultiplier tube gain is at 10^6 and the decay constant (τ s) of the NaI(Tl) scintillator is 250 nanoseconds at room temperature, the photomultiplier tube output current Ip is given by

$$Ip = \frac{N5\,h5\,m5\,e}{\tau s}$$

$$= 45\ 10^{4}5\ 0.255\ 10^{6}5\ \frac{1.65\ 10^{-19}}{2505\ 10^{-9}} \quad \text{(Eq. 3-47)}$$

$$= 6.45\ 10^{-3}(A)$$

where

μ: gain of photomultiplier tube
N: amount of light flash per event produced from scintillator
e: electron charge
η: quantum efficiency of photocathode (assumed to be 25%)

Thus in this measurement the photomultiplier tube must have a pulse linearity over 6.4 milliamperes. In particular, care should be taken with respect to the linearity range when measuring radiation at higher energy levels as the photomultiplier tube produces a large amount of light flash.

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(4) Uniformity

The uniformity of a photomultiplier tube affects the performance of systems utilizing scintillation counting, especially in such equipment as Anger cameras used to detect the incident position of radiation. Uniformity of a photomultiplier tube is commonly defined as the variation in the output current with respect to the photocathode position on which a light spot is scanned.

However, another evaluation method like that illustrated in Figure 3-62[28] provides more useful data which allows users to predict the direct effects of uniformity on the equipment.

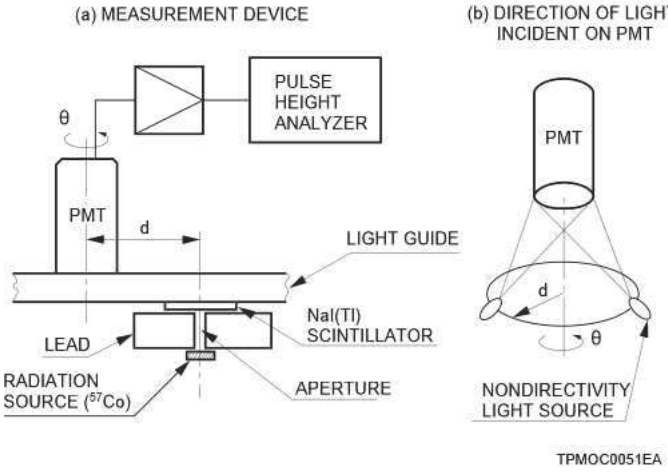


Figure 3-62: Measurement method for azimuth uniformity

In Figure 3-62, the photomultiplier tube is set at a distance (d) from a light source. The output variations of the photomultiplier tube are measured as the light source is rotated around the tube (by changing angle θ). The same procedure is repeated at different values of d. Then plotting the positions (d,θ) of the light source providing equal output gives a graph similar to a contour map (Figure 3-63).

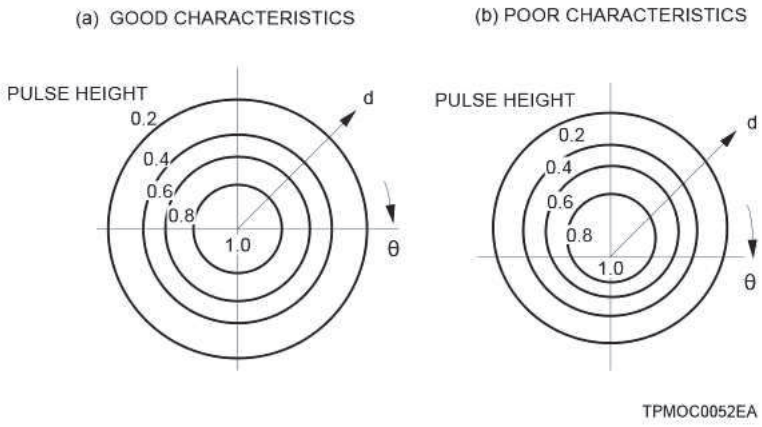


Figure 3-63: Examples of azimuth uniformity data

Uniformity data evaluated by this method is called the azimuth uniformity. If photomultiplier tubes with poor azimuth uniformity are installed in an Anger camera, position distortion may occur in the detection area, degrading spatial resolution. Since the azimuth uniformity requires a long time to test, it is not practical to measure this data for every photomultiplier tube. Usually, only a sample of photomultiplier tubes are measured to provide reference data.

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(5) Stability

There are two types of stability tests used in scintillation counting: long term stability[28] and short term stability.[28] Both stability tests employ a ^{137}Cs radiation source and a NaI(Tl) scintillator. The variation in the photopeak obtained from a photomultiplier tube is measured with a pulse height analyzer (PHA). These stability tests differ slightly from those applied to the general-purpose photomultiplier tubes which were discussed in the previous section.

a) Long term stability

The long term stability is also referred to as the photopeak drift. In this stability test, the photomultiplier tube is allowed to warm up for one hour with the photopeak count rate maintained at 1kcps. After this, the variation rate of the photopeak pulse height (channel number) is measured for a period of 16 hours.

The same measurement setup shown in Figure 3-56 is used and the variation occurring in the peak channel is recorded as the time elapses. Typical photomultiplier tube data is shown in Figure 3-64 below.

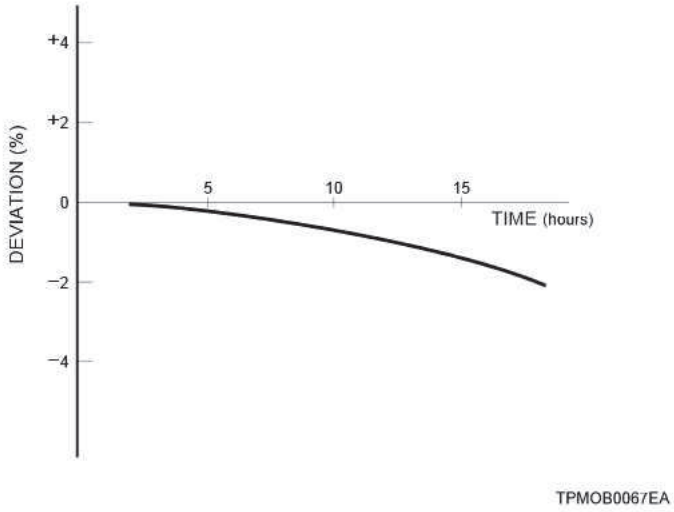


Figure 3-64: Long term stability of a typical photomultiplier tube

There are a few tube types that exhibit somewhat a tendency to increase during the period of 16 hours. However, most photomultiplier tubes tend to show decreasing values, with a variation rate within plus or minus several percent. This tendency is analogous to the drift characteristic explained earlier, but this test method is more practical for scintillation applications. Numerically, the long term stability DLTS is defined as the mean deviation of the peak pulse height (or mean gain deviation) with respect to the mean pulse height, expressed in percent as given by the equation below. It usually has a value of 1 or 2 percent.

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$$D_{LTS} = \frac{\sum_{n=1}^{n} |Pi-\bar{P}|}{n} \cdot \frac{100}{\bar{P}} \quad \text{(Eq. 3-48)}$$

where

$\bar{P}$: mean value of photopeak pulse height (channel)
Pi: peak pulse height at the i-th reading
n: total number of readings for 16 hours

b) Short term stability

The short term stability is also referred to as the count rate stability. The variation in the photopeak pulse height is measured when the photopeak count rate is increased from 10kcps to 1kcps. If the photopeak pulse height at a count rate of 10kcps is given by A and that at 1kcps by B, the short term stability DSTS is stated by the following relationship. This value is expected to be about ±1 percent.

$$D_{STS} = (1-\frac{B}{A})5\ 100(\%) \quad \text{(Eq. 3-49)}$$

This instability is caused by the abrupt change in output current resulting from the changing count rate, and is closely related to the hysteresis effect in photomultiplier tubes.

(6) Noise

In scintillation counting, a signal pulse is usually produced by multiple photoelectrons simultaneously emitted from the photocathode, which create a higher pulse height than most dark current pulses do. Use of a discriminator effectively eliminates most dark current pulses with lower amplitudes. Accordingly, only noise pulses with higher amplitudes will be a problem in scintillation counting. To remove this type of noise pulse, the coincident counting technique is commonly used.

Noise pulses with higher amplitudes may be caused by radiation released from natural radioactive elements contained in a reinforced concrete building or in the atmosphere. These noise pulses may be a significant problem, particularly in low-level-radiation measurements. Concrete used to construct a building usually contains Rn, Th and ^{40}Fe, and steel contains U, Th and ^{60}Co. Radioactive floating dust and Rn or Th gases may be present in the atmosphere, and a scintillator may also contain minute amounts of ^{40}K and ^{208}Tl. Furthermore, borosilicate glass used to fabricate the faceplate of a photomultiplier tube contains potassium of which ^{40}K comprises 0.118 percent. The ^{40}K releases gamma rays of 1.46MeV.

Figure 3-65 shows background noise measured with a Hamamatsu R877 photomultiplier tube (5-inch diameter, borosilicate glass, bialkali photocathode) coupled to a NaI(Tl) scintillator (5-inch diameter 5 2-inch length), (1) n Figure 3-65 is measured without taking any countermeasures, while (2) is measured by shielding the tube with two lead blocks of 100 and 50 millimeter thickness, each being placed respectively in the lower section and upper section. (3) is data taken with an R877-01 that employs a so-called K-free glass containing a very minute amount of potassium for its faceplate and side bulb envelope.

Since these measurements were made using the setup in which the peak of ^{13}/Cs (662keV) becomes 300 channels, the energy range measured covers from about several thousand keV to 2.2MeV. In this energy range, the background noise that is as high as 470cps during normal measurement, can be drastically reduced to 26cps (about 1/20) by shielding the tube with lead blocks. Consequently, it has been proven that most background noise originate from environmental radiation. In addition, use of the R877-01 with K-free glass (Refer to Section 3.1.2.) further reduces the total noise counts down to about 16cps. Particularly, in the energy range from 1.2 to 1.6MeV where noise counts mainly result from the ^{40}K (1.46MeV), the noise count of 3.3cps measured with the R877 (normal borosilicate glass) is reduced to 0.9cps with the R877-01 (K-free glass).

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The external parts of a photomultiplier tube and the scintillator, are usually maintained at ground potential. Therefore, a cathode ground scheme with the high voltage applied to the anode is often used in scintillation counting.

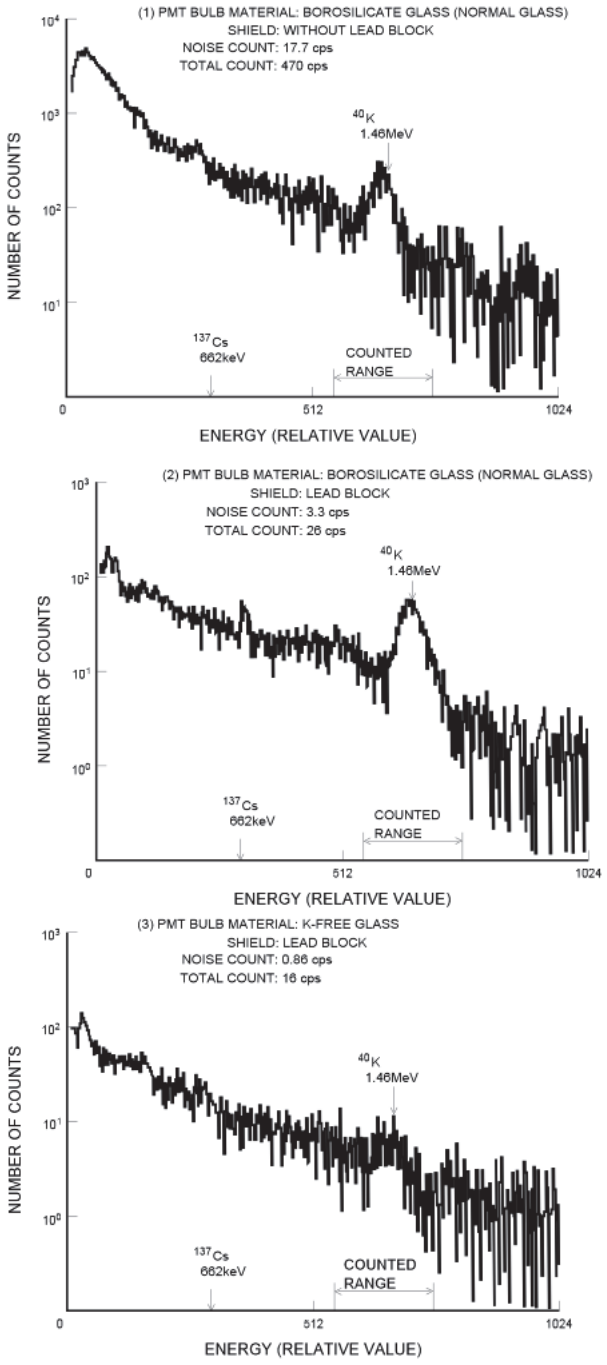


Figure 3-65: Background noise

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