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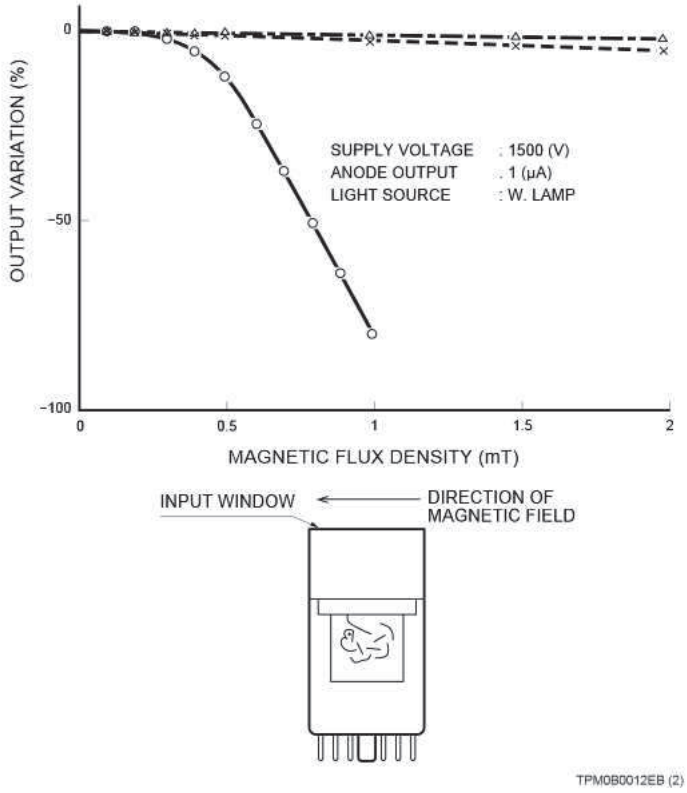


Figure 7-44 (3): Magnetic characteristics of a photomultiplier tube

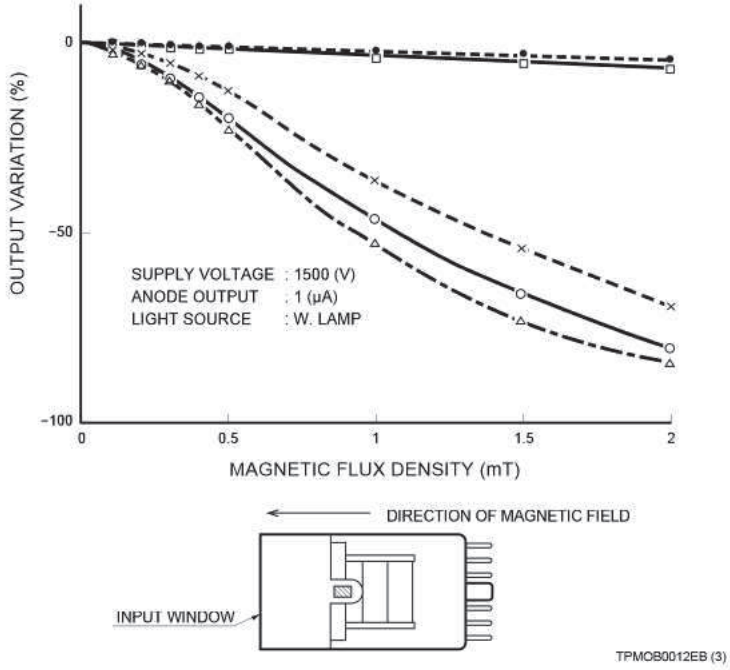


Figure 7-44 (4): Magnetic characteristics of a photomultiplier tube

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(5) Photomultiplier tube magnetic characteristics and shielding effect

Figures 7-45 (a) to (e) show magnetic characteristics of typical photomultiplier tubes (anode output variations versus magnetic flux density characteristics) and the shielding effects [7] of magnetic shield cases (Hamamatsu E989 series). It can be seen from these figures that use of a shield case can greatly reduce the influence of magnetic fields of less than one hundred milliteslas.

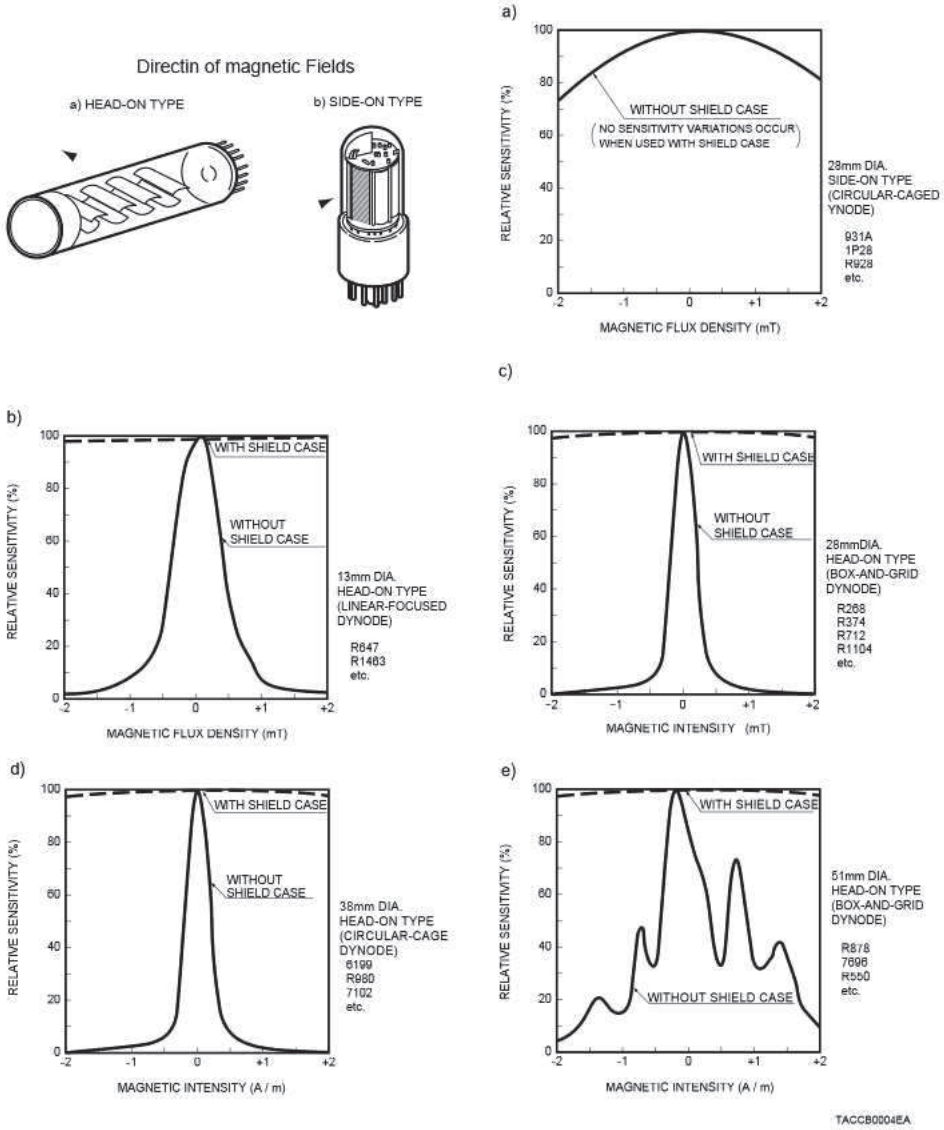


Figure 7-45: Effect of magnetic shield case

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(6) Handling the magnetic shield case

Magnetic shield cases are subject to deterioration in performance due to mechanical shock and deformation therefore sufficient care must be exercised during handling. Once the performance has deteriorated, a special annealing process is required to effect a recovery. In particular, since the permeability characteristics are more susceptible to external shock and stress, avoid any alteration, for example such as drilling and machining the shield case.

As stated in Chapter 3, if any object at ground potential is brought close to the bulb of a photomultiplier tube, the photomultiplier tube noise increases considerably. Therefore, it is advisable to use a magnetic shield case larger than the photomultiplier tube diameter. In this case, positioning the photomultiplier tube in the center of the shield case is important, otherwise an electrical problem may occur. Foam rubber or similar materials with good buffering and insulating properties can be used to hold the photomultiplier tube in the shield case.

It is recommended for safety and also for noise suppression measures that the magnetic shield case be grounded via a resistor of 5 to 10 megohms, although this is not mandatory when a HA-coating photomultiplier tube or a photomultiplier tube with the cathode at ground potential and the anode at a positive high voltage is used. In this case, sufficient care must be taken with regards to the insulation of the magnetic shield case.

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7. 5 Detector Head Assemblies

A compact detector head assembly can be configured, by integrating a voltage-divider circuit, signal processing amplifier and high-voltage power supply into a housing along with a photomultiplier tube. As examples, this section explains the Hamamatsu H6180-01 and H5784 detector head assemblies and their circuit configurations.

As Figure 7-46 shows, the H6180-01 incorporates a signal processing amplifier and circuit components designed for photon counting. Since a comparator and pulse shaper are included, measurement can be easily performed by simply connecting the output to a commercially available pulse counter. In addition, the built-in high-voltage power supply generates a high voltage inside the housing by input of +5 volts in order to operate the photomultiplier tube and signal processing amplifier.

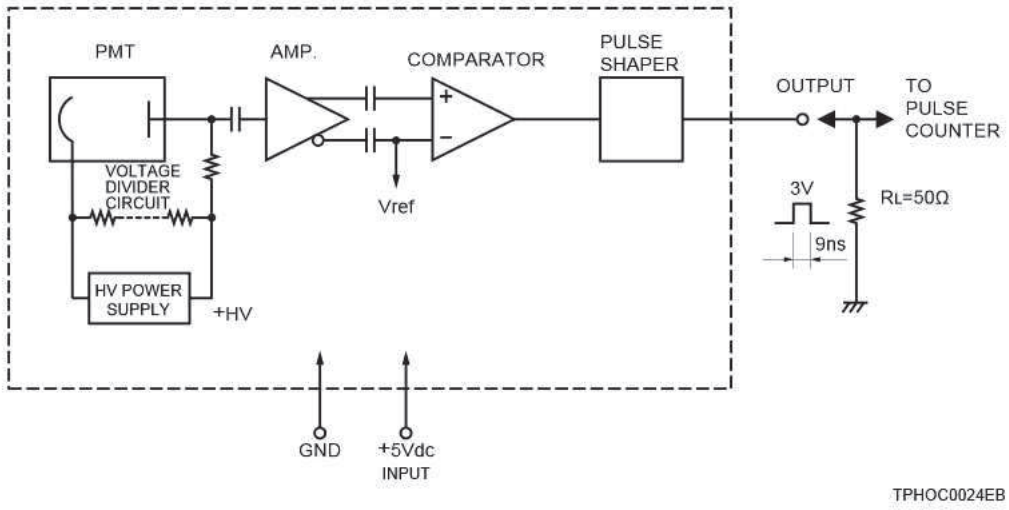


Figure 7-46: Internal circuit diagram of the H6180-01

In the H5784, a low-noise current-to-voltage conversion amplifier is used as a signal processing amplifier. To make this assembly as compact as possible, a metal package photomultiplier tube connected to a Cockcroft-Walton circuit as a high-voltage power supply is used. By simply supplying +12 volts, a high voltage is internally generated allowing operation of the photomultiplier tube and signal processing amplifier.

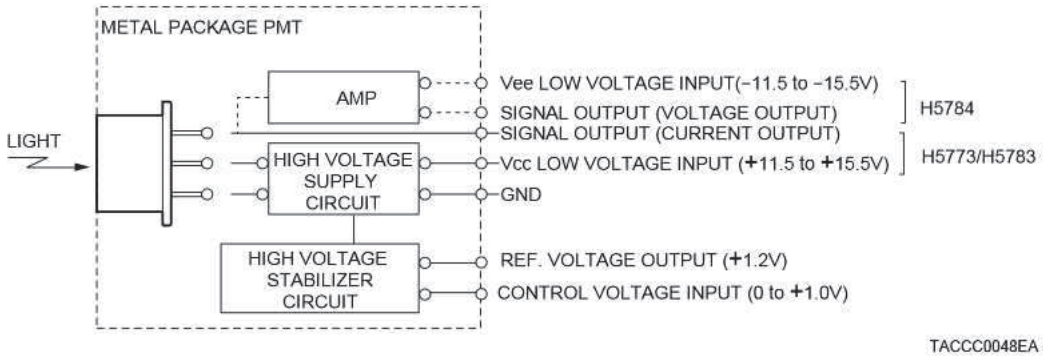


Figure 7-47: Internal circuit diagram of the H5784

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7. 6 Cooling

As described in Section 3.6 of Chapter 3, thermionic emission of electrons is a major cause of dark current. It is especially predominant when the photomultiplier tube is operated in a normal supply voltage range. Because of this, cooling the photomultiplier tube can effectively reduce the dark current and the resulting noise pulses, thus improving the signal-to-noise ratio and enhancing the lower detection limit. However, the following precautions are required for cooling a photomultiplier tube.

Photomultiplier tube cooling is usually performed in the range from 0°C to –30°C according to the temperature characteristic of the dark current. When a photomultiplier tube is cooled to such a temperature level, moisture condensation may occur at the input window, bulb stem or voltage-divider circuit. This condensation may cause a loss of light at the input window and an increase in the leakage current at the bulb stem or voltage-divider circuit. To prevent this condensation, circulating dry nitrogen gas is recommended, but the equipment configuration or application often limits the use of liquid nitrogen gas. For efficient cooling, Hamamatsu provides thermoelectric coolers having an evacuated double-pane quartz window with a defogger and also air-tight socket assemblies.[8] An example of thermoelectric coolers is shown in Figure 7-48, along with a suitable socket assembly.

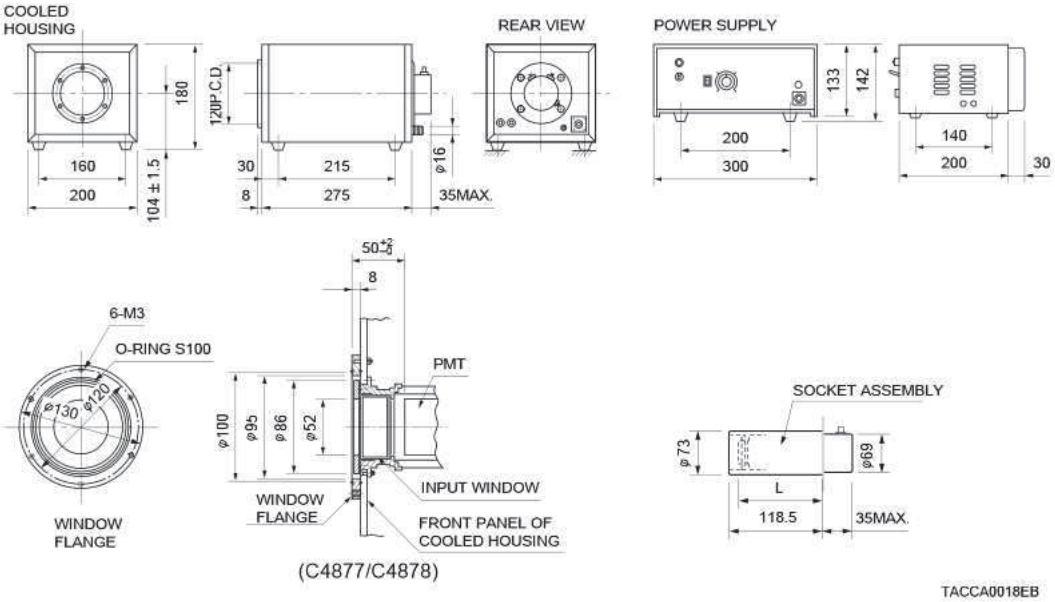


Figure 7-48: Thermoelectric cooler (manufactured by Hamamatsu Photonics)

The cooler shown in Figure 7-48 is identical with the Hamamatsu C4877 and C4848 coolers. The C4877 is designed for 2-inch or 1.5-inch diameter head-on photomultiplier tubes, while the C4848 is for MCP-PMTs. Either model can be cooled down to -30°C by thermoelectric cooling.

If a socket made by other manufacturers is used with a Hamamatsu photomultiplier tube, the bulb stem of the photomultiplier tube may possibly crack during cooling. This is due to the difference in the thermal expansion coefficient between the socket and the bulb stem. Be sure to use the mating socket available from Hamamatsu. Stem cracks may also occur from other causes, for example, a distortion of the stem. When the bulb stem is to be cooled below –50°C, the socket should not be used, instead, the lead pins of the photomultiplier tube should be directly connected to wiring leads. To facilitate this, use of socket contacts, as illustrated

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in Figure 7-49, will prove helpful. (The socket contact shown in the figure is Winchester 100-2520S.)

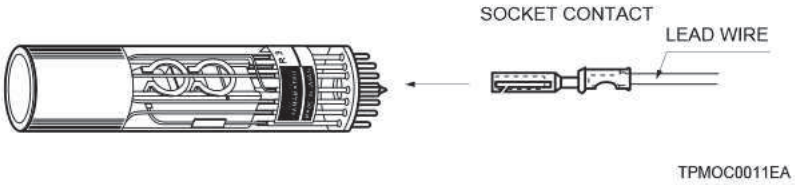


Figure 7-49: Connecting the lead pins to the socket contacts

Thermionic electrons are emitted not only from the photocathode but also from the dynodes. Of these, thermionic emissions that actually affect the dark current are those from the photocathode, Dy_1 and Dy_2, because the latter-stage dynodes contribute less to the current amplification. Therefore cooling the photocathode, Dy1, and Dy2 proves effective in reducing dark current and besides, this is advantageous in view of possible leakage currents which may occur due to moisture condensation on the bulb stem, base or socket.

The interior of a photomultiplier tube is a vacuum and thus heat is conducted through it very slowly. Therefore, it is recommended that the photomultiplier tube be left for one hour or longer after the ambient temperature has reached a constant level, so that the dark current and noise pulses will become constant. Another point to be observed is that, since heat generated from the voltage-divider resistors may heat the dynodes, the voltage-divider resistor values should not be made any smaller than necessary.

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1) Hamamatsu Photonics Catalog: Accessories for Photomultiplier Tubes.
2) McGRAW-HILL: Electronic Circuits Discrete and Integrated, International Student Edition.
3) Ref. to "Kerns-type PM base" Produced by R.L. McCarthy.
4) Hamamatsu Photonics Catalog: Accessories for Photomultiplier Tubes.
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CHAPTER 8
ENVIRONMENTAL RESISTANCE AND RELIABILITY

Photomultiplier tube characteristics, for example, sensitivity and dark current, are susceptible to environmental conditions such as ambient temperature, humidity and magnetic fields.[1)] To obtain the fullest capabilities from a photomultiplier tube, it is necessary to know how environmental conditions affect the photomultiplier tube and to take corrective action. This chapter discusses these points and also describes operating stability over time and reliability.

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8. 1 Effects of Ambient Temperature

8. 1. 1 Temperature characteristics

The photomultiplier tube is more susceptible to ambient temperature than ordinary electronic components (such as resistors and capacitors). In precision measurement therefore, the photomultiplier tube must be operated with temperature control or comparative photometric techniques so that the effects of ambient temperature are minimized. When performing temperature control, note that the interior of a photomultiplier tube is a vacuum and thereby heat is conducted through it very slowly. The photomultiplier tube should be left for one hour or longer until the photomultiplier tube reaches the same level as the ambient temperature and its characteristics become stable.

(1) Sensitivity

Temperature characteristics of anode sensitivity can be divided into those for cathode sensitivity (photocathode) and gain (dynode). Temperature characteristics for cathode sensitivity are dependent on the wavelength. In general, the temperature coefficient of cathode sensitivity varies significantly from a negative value to a positive value near the long wavelength limit. In contrast, temperature characteristics of gain have virtually no dependence on wavelength or on supply voltage. Figure 8-1 shows temperature coefficients of major photomultiplier tubes as a function of wavelength, with the abscissa representing wavelength and the ordinate expressing temperature coefficients of anode sensitivity.

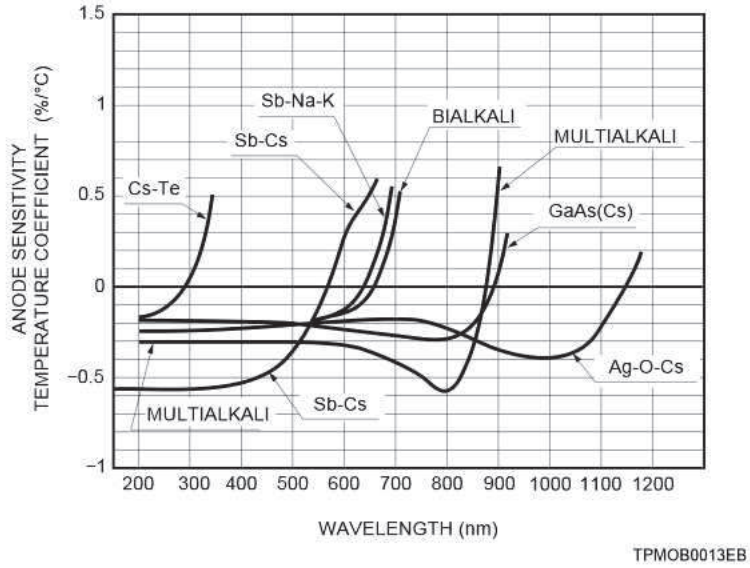


Figure 8-1: Photocathode types and temperature coefficients

When a photomultiplier tube with a transmission mode photocathode is used at very low temperatures, the subsequent increase in the photocathode surface resistance may cause a cathode current saturation effect, resulting in a loss of output linearity with respect to the incident light level. This effect appears drastically with certain types of bialkali photocathodes and thus care is required when using such photomultiplier tubes.

Typical cathode saturation currents for bialkali and multialkali photocathodes are shown in Figure 8-2.

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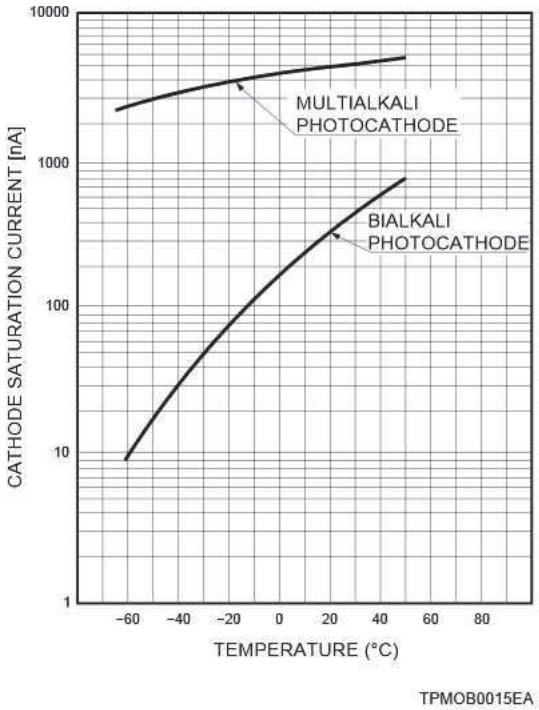


Figure 8-2: Cathode saturation current vs. temperature

(2) Dark current

A photocathode consists of materials having small energy gap and electron affinity so that photoelectrons can be released efficiently. This means that dark current is very sensitive to the ambient temperature. It greatly increases with temperature as shown in Figure 8-3. In low-light-level detection, this effect of the ambient temperature on the dark current is an important factor to consider.

Cooling a photomultiplier tube is most effective in reducing the dark current and improving the signal-to-noise ratio, especially for photomultiplier tubes with high sensitivity in the red to near infrared region. Conversely, using a photomultiplier tube at a high temperature invites signal-to-noise ratio deterioration. If a photomultiplier tube must be operated at a high temperature, use of a special photocathode (Sb-Na-K) is recommended. Figure 8-3 shows dark current versus temperature characteristics of photomultiplier tubes having major photocathodes.

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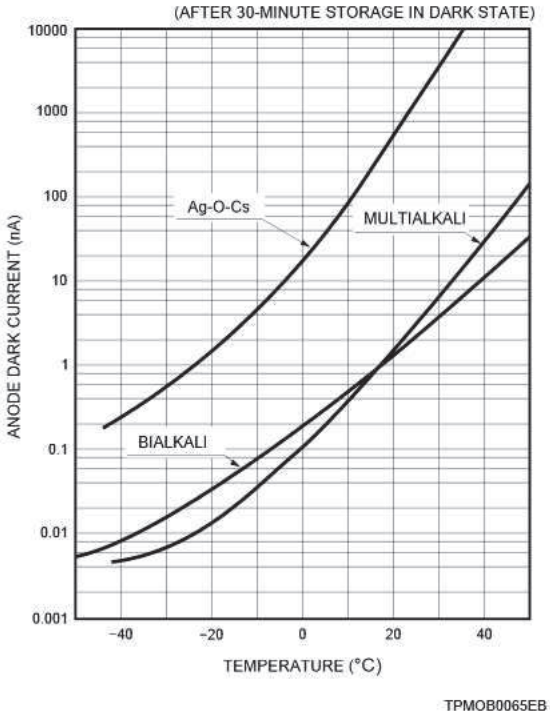


Figure 8-3: Temperature characteristics of anode dark current

8. 1. 2 Storage temperature and cooling precautions

Photomultiplier tube sensitivity varies somewhat during storage, even at room temperatures. This is probably due to the movement of alkali elements activating the photocathode and dynode surfaces. If a photomultiplier tube is left at a high temperature, this sensitivity variation will be accelerated. It is therefore recommended that the photomultiplier tube be stored at or below room temperatures.

In the case of PMT assemblies, do not store them in a place where the temperature falls below the specified storage temperature (generally -20°C).

As explained in (2), "Dark current" in the preceding section "8.1.1", photomultiplier tubes using a photocathode with high red-to-white sensitivity such as multialkali, GaAs(Cs), InGaAs and Ag-O-Cs are often cooled during operation to reduce the dark current. In this case, the following precautions should be observed, otherwise the difference in thermal expansion coefficient between the photomultiplier tube bulb, socket and adhesive (epoxy resin) may cause bulb rupture.

1. Avoid using a photomultiplier tube with a plastic base when cooling to -30°C or below.
2. Assemble a voltage-divider circuit on a PC board and connect it to the socket using thin, soft wires, so that excessive force is not applied to the lead pins.
3. Avoid subjecting a photomultiplier tube to drastic temperature changes.

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8. 2 Effects of Humidity

8. 2. 1 Operating humidity

Since the photomultiplier tube is operated at high voltages and handles very low current in the order of micro to picoamperes, leakage current between the lead pins may create a significant problem. This leakage current sometimes increases by several orders of magnitude due to a rise in the ambient humidity. It is advisable that the photomultiplier tube be operated at a humidity below 60 percent.

8. 2. 2 Storage humidity

If a photomultiplier tube is left at a high humidity for a long period of time, the following problems may occur: an increase in the leakage current on the bulb stem surface, contact failure due to rust formed on the lead pin surface and, for UV glass, a loss of transmittance. Therefore, the photomultiplier tube must be stored in locations of low humidity. In addition, since dirt on the photomultiplier tube surface may be a cause of increased leakage current and rust formation on the leads, avoid touching the bulb stem, lead pins and especially around the anode pin of a plastic base with bare hands. These portions must be kept clean but, if they become contaminated, use anhydrous alcohol for cleaning.

8. 3 Effects of External Magnetic Fields

8. 3. 1 Magnetic characteristics[2)]

In photomultiplier tube operation, because low-energy electrons travel along a long path in a vacuum, their trajectories are affected by even a slight magnetic field such as terrestrial magnetism, causing an anode sensitivity variation. A prime reason for this sensitivity variation is that the electron trajectories influenced by the magnetic fields cannot precisely focus the photoelectrons onto the first dynode. This means that photomultiplier tubes having a long distance between the photocathode and the first dynode or a small first-dynode opening in comparison with the photocathode area are more vulnerable to effects of a magnetic field.

For most head-on photomultiplier tubes, the anode sensitivity will be reduced by as much as 50 percent by a magnetic flux density of below 0.1 to several milliteslas. The sensitivity is most vulnerable to a magnetic flux in the direction parallel to the photocathode surface (X axis). Side-on photomultiplier tubes exhibit less sensitivity variations since the distance from the photocathode to the first dynode is short. The magnetic flux density at which the anode sensitivity reduces 50 percent is approximately 3.5 milliteslas for 1-1/8 inch side-on types. Recently developed metal-can type photomultiplier tubes (R5600 series) offer excellent immunity to magnetic fields because they have a short distance from the photocathode to the first dynode. Figure 8-4 shows the effects of magnetic fields on typical photomultiplier tubes.[3)] Note that the higher the supply voltage to a photomultiplier tube, the less the effects of magnetic fields.

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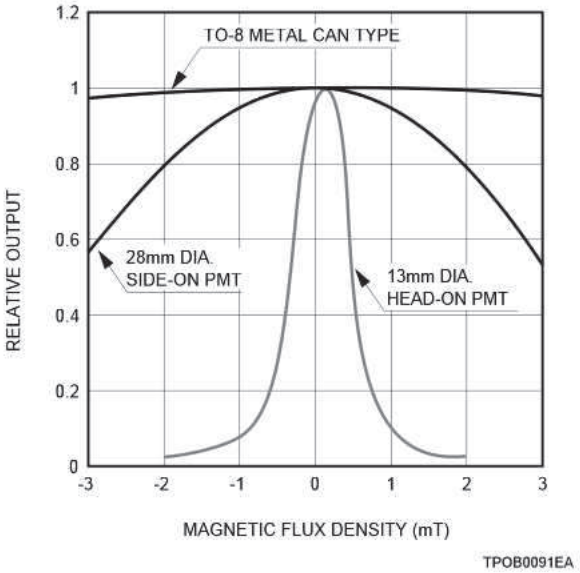


Figure 8-4: Magnetic characteristics of typical photomultiplier tubes

As can be seen from Figure 8-4, photomultiplier tubes are susceptible to magnetic fields. It is advisable that the photomultiplier tube be used in locations where no magnetic source is present. In particular, avoid using the photomultiplier tube near such devices as transformers and magnets. If the photomultiplier tube must be operated in a magnetic field, be sure to use a magnetic shield case. Refer to Section 7.4 of Chapter 7 for more details and specific usage of magnetic shield cases.

8. 3. 2 Photomultiplier tubes for use in highly magnetic fields

As stated previously, normal photomultiplier tubes exhibit a large variation in a magnetic field, for example, sensitivity reduces at least one order of magnitude in a magnetic field of 10 milliteslas. In high-energy physics applications, however, photomultiplier tubes capable of operating in a magnetic field of more than one tesla are demanded. To meet these demands, special photomultiplier tubes with fine-mesh dynodes have been developed and put into use. These photomultiplier tubes include a "triode" type using a single stage dynode, a "tetrode" type using a two-stage dynode and a high-gain type using multiple dynode stages (8 to 19 stages).[4] The structure of this photomultiplier tube is illustrated in Figure 8-5. Figure 8-6 shows (1) current gain versus magnetic field perpendicular to the photocathode (tube axis) for a tetrode and triode types, and (2) relative output of a 19-stage photomultiplier tube versus magnetic field at different angles.

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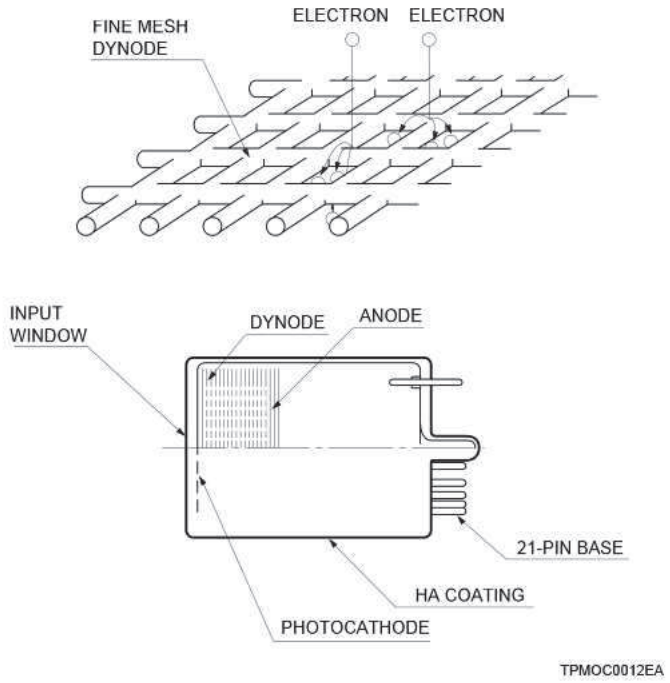


Figure 8-5: Structure of a photomultiplier tube designed for use in highly magnetic fields

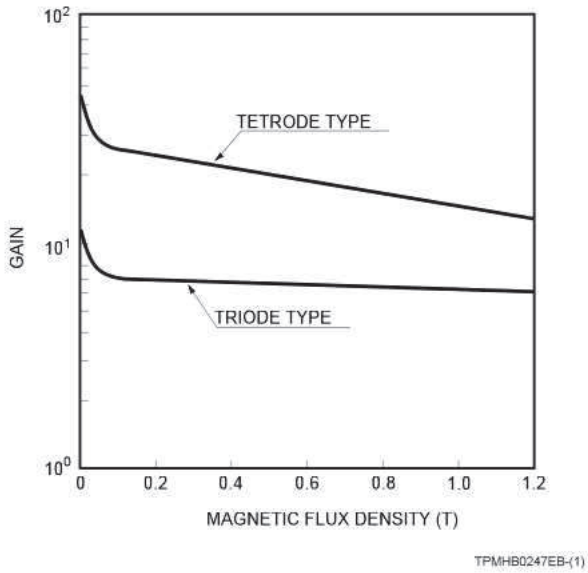


Figure 8-6 (1): Magnetic characteristics of photomultiplier tubes for highly magnetic fields

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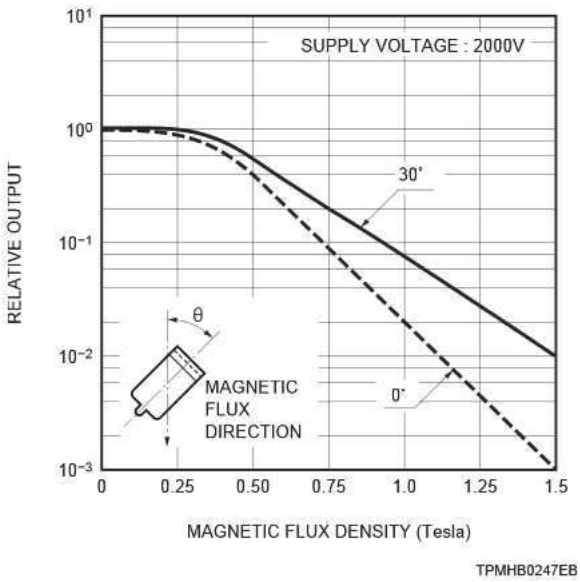


Figure 8-6 (2): Magnetic characteristics of photomultiplier tubes for highly magnetic fields

8. 3. 3 Magnetization

The dynode substrate is commonly made from nickel with magnetic properties, and the photomultiplier tube leads and electrodes are also made from similar metals which can be magnetized. There will be no problem as long as the photomultiplier tube is operated in a weak magnetic field such as from terrestrial magnetism. If the magnetic field strength increases and exceeds the initial permeability of the dynode substrate and electrode materials, they will remain magnetized even after the magnetic field has been removed (residual magnetism). Thus the gain after the magnetic field has once been applied will differ from that before the magnetic field is applied. If magnetized, they can be demagnetized by applying an AC magnetic field to the photomultiplier tube and gradually attenuating it.

8. 3. 4 Photomultiplier tubes made of nonmagnetic materials

In applications where a photomultiplier tube must be used in a highly magnetic field or magnetization of the tube is unwanted, photomultiplier tubes made of nonmagnetic materials are sometimes required. Hamamatsu Photonics offers photomultiplier tubes assembled using nonmagnetic materials for the dynode substrate. However, the stem pins and hermetically-sealed portions still must be made from magnetic materials. Fortunately, stems made of a nonmagnetic material has been developed recently for use in special applications. It will soon become possible to manufacture a whole photomultiplier tube with nonmagnetic materials.

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8. 4 Vibration and Shock

Resistance to vibration and shock can be categorized into two conditions: one is under non-operating conditions, for example, during transportation or storage and the other is under conditions when the tube is actually installed and operated in equipment. Except for special tubes designed for such applications as rocket-borne space research and geological surveys, photomultiplier tubes should not be exposed to vibration and shock during operation.

8. 4. 1 Resistance to vibration and shock during non-operation

Most photomultiplier tubes are designed to withstand several G of vibration and several hundred G of shock. However, if excessive vibration and shock are applied to a photomultiplier tube, its characteristics may vary and the bulb envelope may break.

In general, photomultiplier tubes with a smaller size, lighter weight and shorter overall length exhibit better resistance to vibration and shock. Even so, sufficient care must be exercised when handling. The following table shows the maximum vibration and shock values which photomultiplier tubes can withstand.

PMT Type	Maximum Vibration	Maximum Shock
1/2 inch side-on	15G (10 to 2000Hz)	200G (6ms)
1-1/8 inch side-on	10G (10 to 500Hz)	100G (11ms)
1/2 inch head-on	10G (10 to 500Hz)	100G (11ms)
1-1/8 inch head-on	5G (10 to 500Hz)	100G (11ms)
2 inch head-on type	5G (10 to 500Hz)	75G (11ms)
3 inch head-on type	5G (10 to 500Hz)	75G (11ms)

The photomultiplier tube envelope is made of glass, so it is vulnerable to direct mechanical shock. Envelopes with silica windows are especially vulnerable to shock on the bulb side because of a graded glass seal. Sufficient care must be taken in handling this type of tube. Furthermore, photomultiplier tubes designed for liquid scintillation counting use a very thin faceplate of 0.5 millimeters thick. Some of them may be broken even by a slight shock. Since the photomultiplier tube is a vacuum tube, if the envelope is broken, implosion may cause it to fly apart in fragments. Thus care is required, especially in handling a large diameter tube of more than 8 inches.

8. 4. 2 Resistance to vibration and shock during operation (resonance)

The photomultiplier tube is not normally designed to receive vibration and shocks during operation, except for specially-designed ruggedized tubes. If a photomultiplier tube suffers vibration or shocks during operation, problems such as variations of the signal level and an increase in the microphonic noise may occur. Attention should be given to the mounting method and arrangement of the tube. Moreover, the photomultiplier tube may have a resonance at a certain frequency, but this resonant frequency differs from tube to tube. If vibration is increased at this resonance, the above problems will be more noticeable, leading to the breakage of the envelope. Figure 8-7 shows the variations in the frequency spectrum of photomultiplier tube output subjected to vibration, along with the measurement block diagram.

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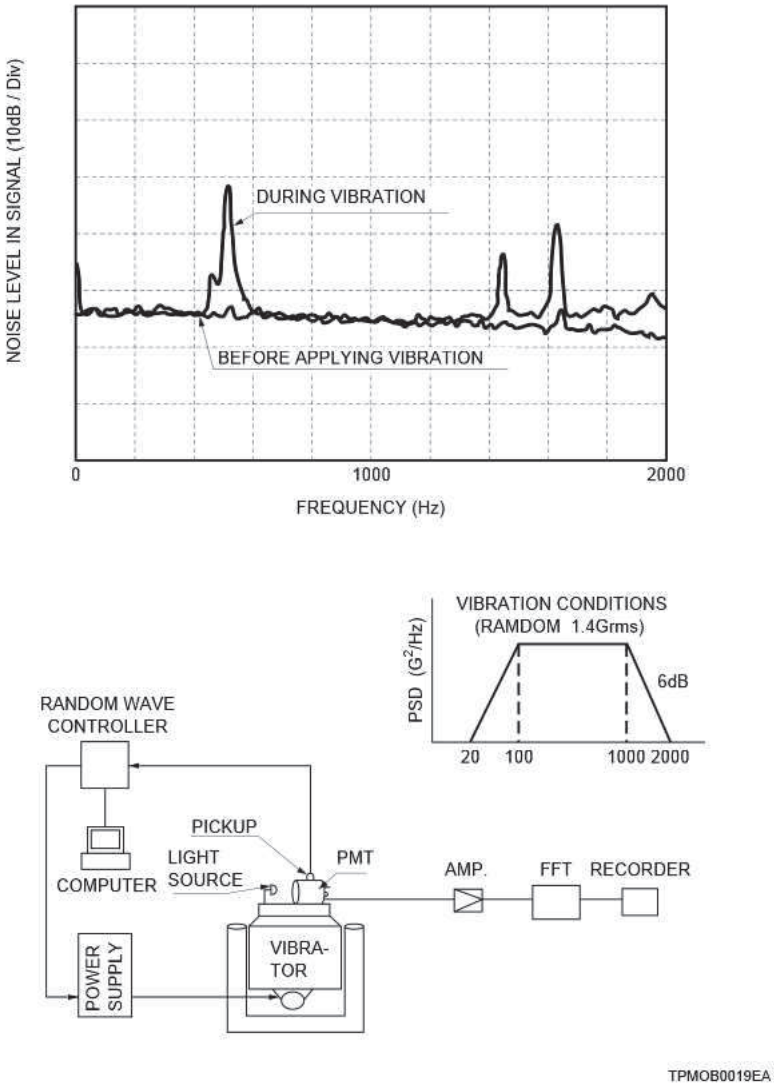


Figure 8-7: Resonance noise of photomultiplier tube output subjected to vibration

In this experiment, the photomultiplier tube is subjected to random vibration (1.4G rms) from 20Hz to 2000Hz and its output signal is frequency-analyzed using a FFT (fast fourier transform). It is obvious from Figure 8-7 that the noise sharply increases at frequencies near 500Hz, 1450Hz and 1600Hz.

When measurement is made at extremely low light levels, even a slight vibration caused by the table on which the equipment is placed may be a source of noise. Precautions should be taken to ensure the equipment is installed securely and also the cable length to the preamplifier should be checked.

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8. 4. 3 Testing methods and conditions

There are two vibration test methods[5]: sinusoidal-wave and random-wave application tests. The sinusoidal wave used for vibration tests is determined by the frequency range, displacement (amplitude), acceleration, vibration duration and sweep time. The frequency sweep method commonly employed is a logarithmic sweep method. The random wave is determined by the acceleration, power spectrum density (G^2/Hz), and the vibration duration, and is expressed in terms of the RMS value. This method allows tests to be performed under the conditions close to the actual environment. In Figure 8-8 (A) and (B), vibration waveform examples created by sinusoidal wave and random wave are shown.

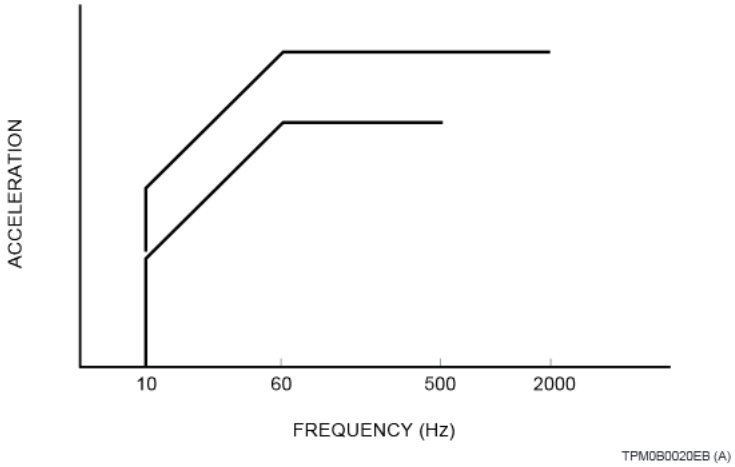


Figure 8-8 (A): Sinusoidal wave vibration pattern example

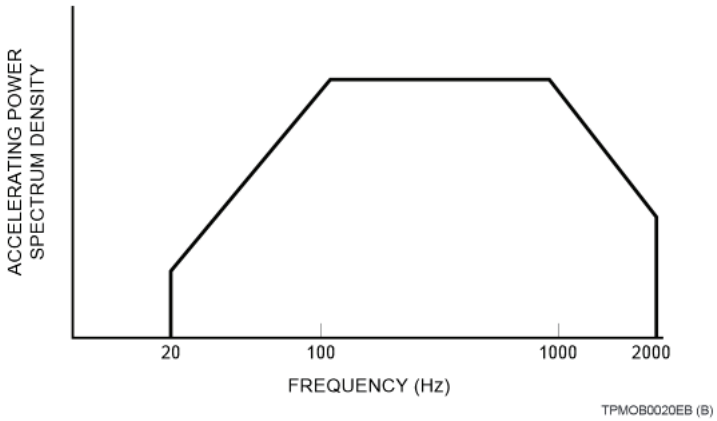


Figure 8-8 (B): Random vibration pattern example

Various methods are used in shock tests such as half-wave sinusoidal pulses, sawtooth wave pulses, and trapezoidal wave pulses. Hamamatsu Photonics performs shock tests using half-wave sinusoidal pulses. The test conditions are determined by the peak acceleration, shock duration, and the number of shocks applied. A typical shock-application pattern is shown in Figure 8-8 (C).

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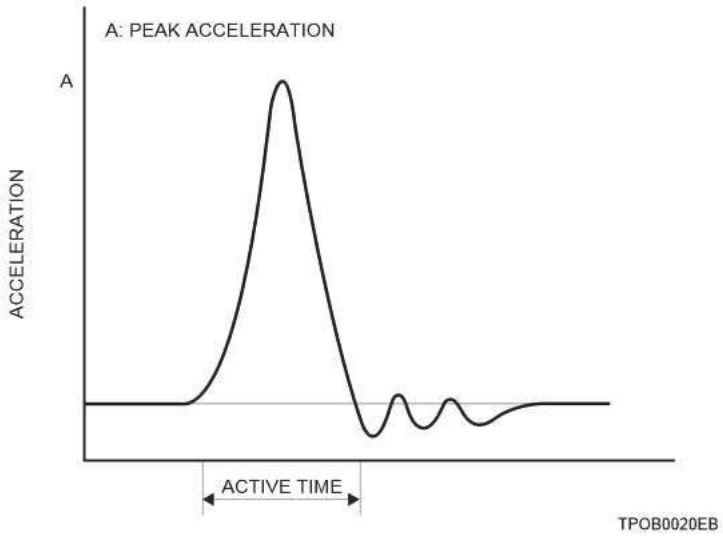


Figure 8-8 (C): Shock-application pattern (half-wave sinusoidal pulse)

Official standards for vibration and shock test methods include IEC Pub. 68, JIS-C0040 (vibration), JIS-C0041 (shock), MIL STD-810E and MIL STD-202F.[6] Hamamatsu Photonics performs the vibration and shock tests in conformance to these official standards. The above data for vibration and shock tests were measured under these official conditions. For instance, the shock tests were carried out along three orthogonal axes for a shock duration period of 11 milliseconds, three times each in the plus and minus directions, and thus shocks were applied a total of 18 times. Accordingly, even if the test proves that a photomultiplier tube withstands a shock of 100G, this does not mean that it will survive such shocks dozens or hundreds of times.

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8. 4. 4 Ruggedized photomultiplier tubes[7)]

In geological surveys such as oil well logging or in space research in which photomultiplier tubes are launched in a rocket, extremely high resistance to vibration and shock is required.[8)] To meet these applications, ruggedized photomultiplier tubes have been developed, which can operate reliably during periods of 20G to 50G vibration and 100G to 1000G shock. A variety of ruggedized types are available ranging in diameter from 1/2 to 2 inches and are also available with different dynode structures. Most ruggedized photomultiplier tubes have been devised based on conventional glass-envelope photomultiplier tubes by improving their electrode supports, lead pins and dynode structure so that they will withstand severe shock and vibration. These ruggedized photomultiplier tubes with a diameter of 2 inches or less can withstand vibrations up to 20G. If even higher performance is required, specially-designed ruggedized photomultiplier tubes having a stacked ceramic bulb are used. Figure 8-9 shows the cross section of this type of ruggedized photomultiplier tube.

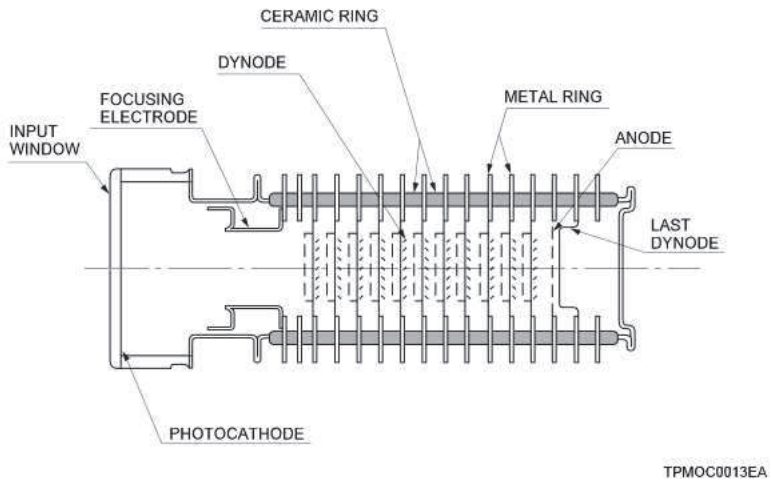


Figure 8-9: Cross section of a ruggedized photomultiplier tube using a stacked ceramic bulb.

As illustrated in Figure 8-9, each dynode electrode of this ruggedized photomultiplier tube is securely welded to a ceramic ring. This structure resists electrical discontinuity, contact failure and envelope rupture even under severe vibration and shock. This is because the dynodes resist deformation and peeling. No lead wires, ceramic spacers or cathode contacts are required, and few fragile glass parts need to be used. The voltage-divider resistors can be soldered on the outside of the metal rings which are fused to the ceramic rings, assuring high ruggedness even after the voltage-divider circuit has been assembled on the tube. The typical maximum vibration and shock for a stacked-ceramic photomultiplier tube using a high-temperature bialkali photocathode and a 12-stage dynode multiplier is as follows:

Resistance to vibration	50G	(50 to 2000Hz)
Resistance to shock	1000G	(0.5ms)

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8. 5 Effects of Helium Gas

It is well known that helium gas permeates through glass.[9] The extent of helium permeation through glass depends on the glass materials, their composition and ambient temperature. Photomultiplier tubes designed for UV light detection usually employ silica glass for the input window. Helium gas permeates through silica glass more than through other window materials. So if such a photomultiplier tube is stored or operated in environments where helium gas is present, a gas increase occurs inside the tube, leading to an increase in dark current and promoting a degradation of the breakdown voltage level. This eventually results in breakdown and end of the tube service life. For example, if a photomultiplier tube with a silica bulb is placed in helium gas at one atmosphere, a drastic increase of afterpulse due to helium gas will be seen in about 30 minutes, making the tube unusable. Thus this must be avoided. To reduce the effects of helium gas, it is best to store the tube in helium-free environments such as argon gas and nitrogen gas.

Helium gas exists on the earth at a partial pressure of about 0.5 pascals. As stated above, the permeability of helium through silica glass is extremely high, as much as 10^{-19}cm^2/s (at a pressure difference of 1.013 5 10^5 pascals) at room temperatures. Because of this, the helium pressure inside the photomultiplier tube gradually increases and finally reaches a level close to the helium partial-pressure in the atmosphere. The time needed to reach that level depends on the surface area and thickness of the silica glass. For instance, if a side-on photomultiplier tube (1-1/8 inch diameter type) with a silica bulb is left in the atmosphere, the helium partial-pressure inside the tube will increase to 95 10^{-2} pascals after one year. (Refer to Figure 8-10.) In practice however, if the helium partial-pressure inside the tube increases to a level equal to the helium partial-pressure in the atmosphere, no significant problem will immediately occur and the tube is still usable.

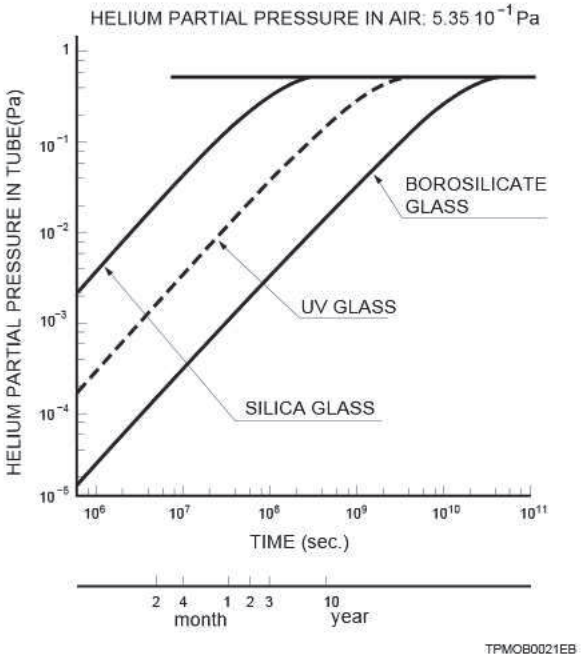


Figure 8-10: Bulb materials and variations in helium partial-pressure inside a tube

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8. 6 Effects of Radiation

Photomultiplier tube applications are constantly expanding, as stated previously, to such fields as high energy physics, nuclear medicine, X-ray applied instrumentation, and space research. In these environments, photomultiplier tubes are usually exposed to radiation (X-rays, alpha rays, beta rays, gamma rays, neutrons, etc.) which somewhat affect the performance characteristics of photomultiplier tubes.[10] Such radiation is detected by the photomultiplier tube photocathode and converted into useful signals, but it also causes deterioration of the glass envelope, metals, insulators, and materials used to construct the photomultiplier tube. The following sections describe the effects of radiation.

8. 6. 1 Deterioration of window transmittance

Even when a photomultiplier tube is exposed to radiation, the cathode sensitivity and secondary emission ratio exhibit very little variation. Sensitivity variation chiefly results from a loss of transmittance through the window due to coloring of the glass, which is an essential part of the photodetector.[11] Figures 8-11 to 8-13 show variations in the window transmittance when photomultiplier tubes are irradiated by gamma rays from a ^{60}Co radiation source and also by neutrons (14MeV).

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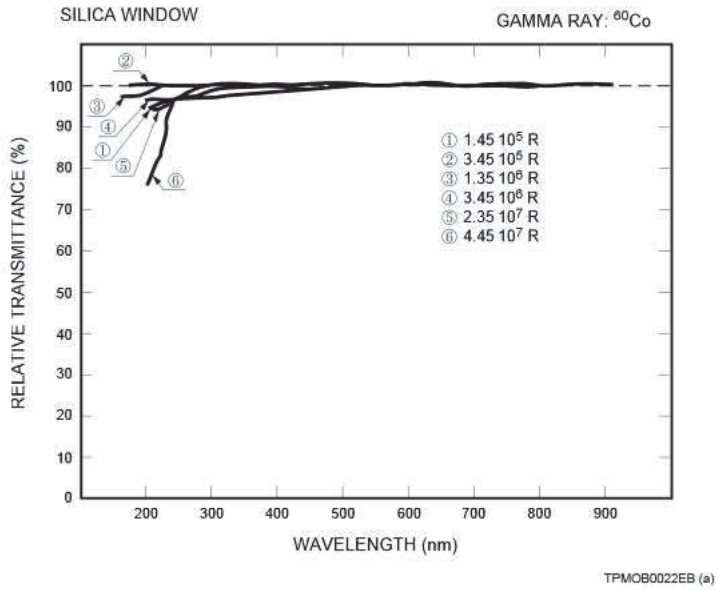


Figure 8-11 (a): Transmittance variations of synthetic silica window when irradiated by gamma rays

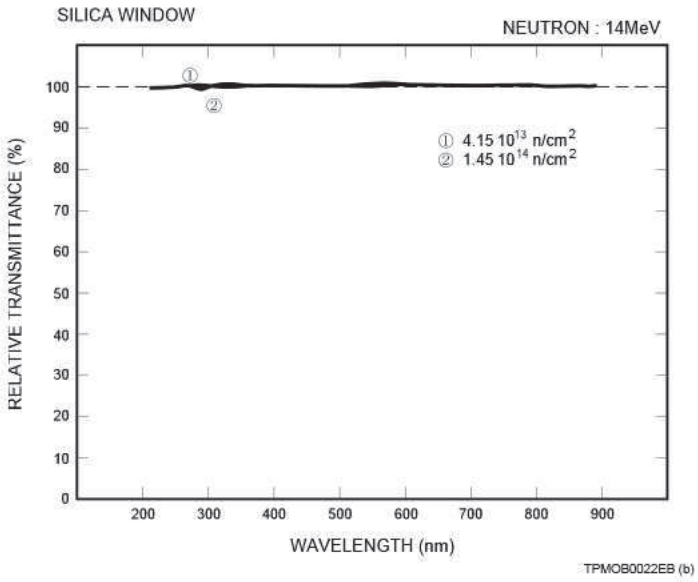


Figure 8-11 (b): Transmittance variations of synthetic silica window when irradiated by neutrons

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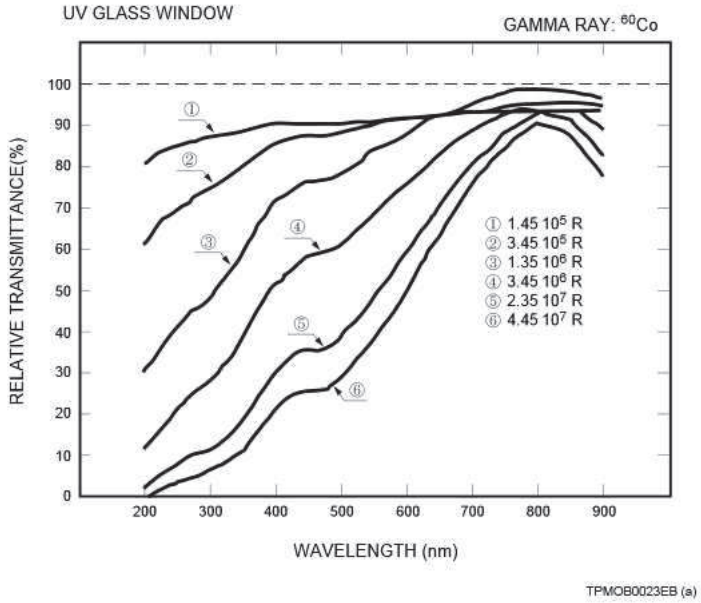


Figure 8-12 (a): Transmittance variations of UV glass window when irradiated by gamma rays

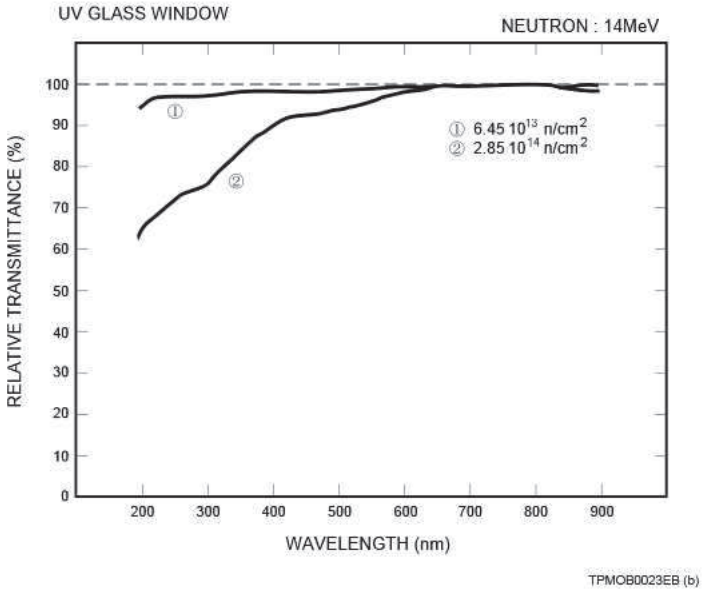


Figure 8-12 (b): Transmittance variations of UV glass window when irradiated by neutrons

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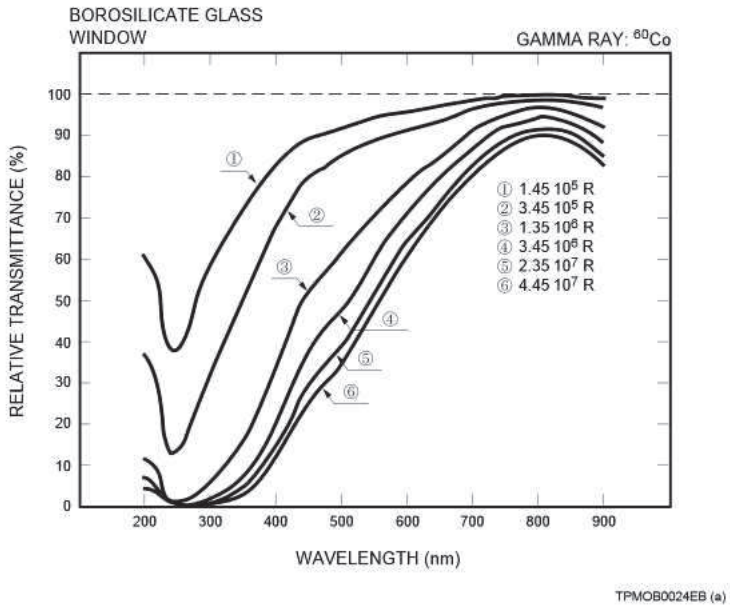


Figure 8-13 (a): Transmittance variations of borosilicate glass window when irradiated by gamma rays

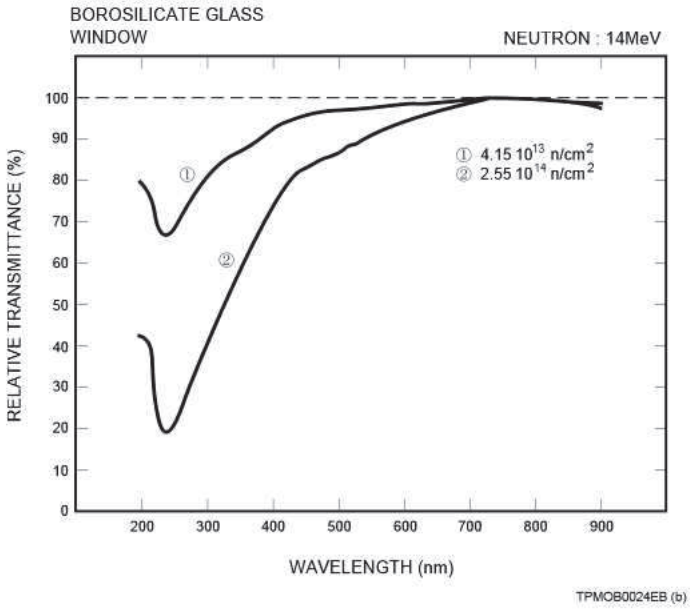


Figure 8-13(b): Transmittance variations of a borosilicate glass window when irradiated by neutrons

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As can be seen from these figures showing the data on a synthetic silica, UV glass and borosilicate glass respectively, a loss of the transmittance occurs more noticeably in the UV region. The synthetic silica glass is least affected by radiation and virtually no variation is seen after irradiation of gamma rays of 4.45 10^7 roentgens and neutrons of 1.45 10^{14}n/cm^2. There are two types of silica glass: synthetic silica and fused silica. The synthetic silica exhibits a higher resistance to radiation than the fused silica. A loss of transmittance begins to occur from near 55 10^4 roentgens for the UV glass, and near 15 10^4 roentgens for the borosilicate glass. However, this tendency is not constant even for the same type of glass, because the composition differs depending on the fabrication method. In general, the radiation-resistance characteristic is superior in the order of silica, UV glass and borosilicate glass. When the transmittance has dropped due to exposure to radiation, it will recover to some extent after storage. This recovery is more effective when the tube is stored at higher temperatures.

8. 6. 2 Glass scintillation

The photomultiplier tube is slightly sensitive to radiation and produces a resultant noise. This is primarily due to unwanted scintillation of the glass window caused by beta and alpha rays or scintillation of the glass window and electron emission from the photocathode and dynodes caused by gamma rays and neutrons.[12)]

Of these, the scintillation of the glass window likely has the largest contribution to noise, but, as described in Section 3.11 of Chapter 3, the amount of scintillation differs depending on the type of glass. Glass scintillation further causes a continual fluorescence or phosphorescence to occur even after radiation has been removed, resulting in yet another source of noise. Figure 8-14 shows a variation in the dark current when a tube is irradiated by gamma rays, indicating that it takes 40 to 60 minutes to reach a steady level. In the case of neutron irradiation, it has been confirmed that the dynode materials are made radioactive through nuclear reaction (n, p) (n, n, p).

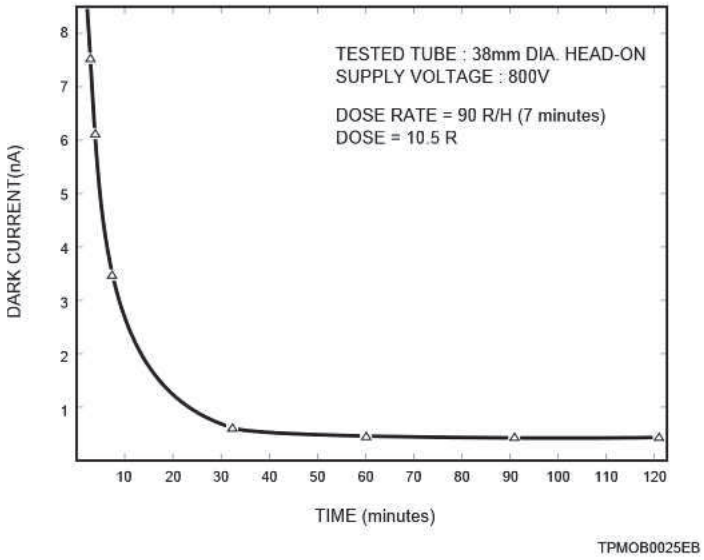


Figure 8-14: Dark current variation after gamma-ray irradiation

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8. 7 Effects of Atmosphere

The photomultiplier tube may be used in environments not only at one atmosphere but also at very low pressures or in depressurized areas such as in aircraft and scientific satellite.

When there is a pressure drop from the atmospheric pressure down to a near vacuum, there is a possibility of a discharge occurring in the photomultiplier tube. This phenomenon is known as the Paschen's law. The law states that the minimum sparking potential between two electrodes in a gas is a function of the product of the distance between the electrodes and the gas pressure, if the electric field is uniform and the ambient temperature is constant.

The distance between the leads on the outside base and on the socket is set to an interval so that no discharge occurs in environments at one atmosphere or in vacuum. However, these structures tend to discharge most frequently at pressures from 100 to 1000 pascals*. If the tube is to be operated in this pressure range, sufficient precautions must be taken in the designing and wiring of the parts to which a high voltage is applied.

(* 133 pascals equal one torr.)

In high-energy physics applications such as proton decay experiments and cosmic ray detection, photomultiplier tubes are sometimes operated while underwater or in the sea. In this case, a pressure higher than one atmosphere is applied to the photomultiplier tube. The breaking pressure depends on the configuration, size and bulb material of the photomultiplier tube. In most cases, smaller tubes can withstand a higher pressure. However, large diameter (8 to 20 inches) photomultiplier tubes, specifically developed for high energy physics experiments, have a hemispherical shape capable of withstanding a high pressure. For example, 8-inch diameter tubes can withstand up to 7 atmospheres and 20-inch diameter tubes up to 6 atmospheres.

As for the bulb materials, photomultiplier tubes using a silica bulb provide lower pressure-resistance due to the graded seal. There are various shapes of input windows used for head-on photomultiplier tubes, including a plano-plano type (both the faceplate and photocathode are flat), a plano-concave type (the faceplate is flat but the photocathode is concave) and a convex-concave type (the faceplate is convex but the photocathode is concave). Compared to the plano-plano type, the plano-concave and convex-concave types offer higher pressure-resistance.

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8. 8 Effects of External Electric Potential

Glass scintillation occurs upon exposure to radioactive rays or UV light, as explained in Section 8.6.2 of Chapter 8. It also occurs when a strong electric field is inside the glass. These glass scintillations cause the dark current to increase.

8. 8. 1 Experiment

Figure 8-15 shows the dark current variations of a photomultiplier tube whose side bulb is coated with conductive paint, measured while changing the electric potential of this coating with respect to the cathode potential.

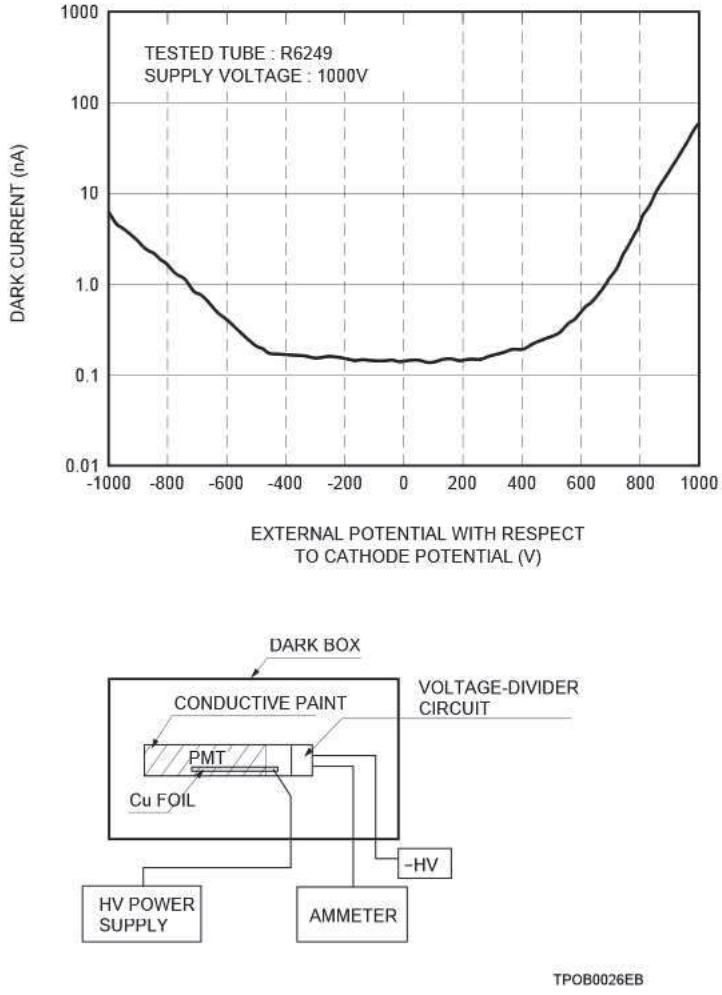


Figure 8-15: Dark current vs. external electric potential

It is clear that the larger the potential difference with respect to the cathode, the higher the dark current. The reason for this effect is that the inner surface of the bulb near the cathode is aluminum-coated and maintained at the cathode potential as explained in Chapter 2, and if the outside of the bulb has a large potential difference with respect to the cathode, glass scintillation occurs there. This scintillation light is reflected into the photocathode, causing an increase in the dark current.

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The housing in which the photomultiplier tube is installed is usually grounded. If the photomultiplier tube is operated in the anode grounding scheme with the cathode at a negative high voltage and is installed close to the wall of the housing, the dark current may increase for the same reason. This problem can be solved by allowing an adequate distance between the photomultiplier tube and the inside of the housing. Figure 8-16 shows the dark current variations while the distance between the photomultiplier tube and the grounded case is changed, proving that there is no increase in the dark current when the separation is 4 millimeters or more.

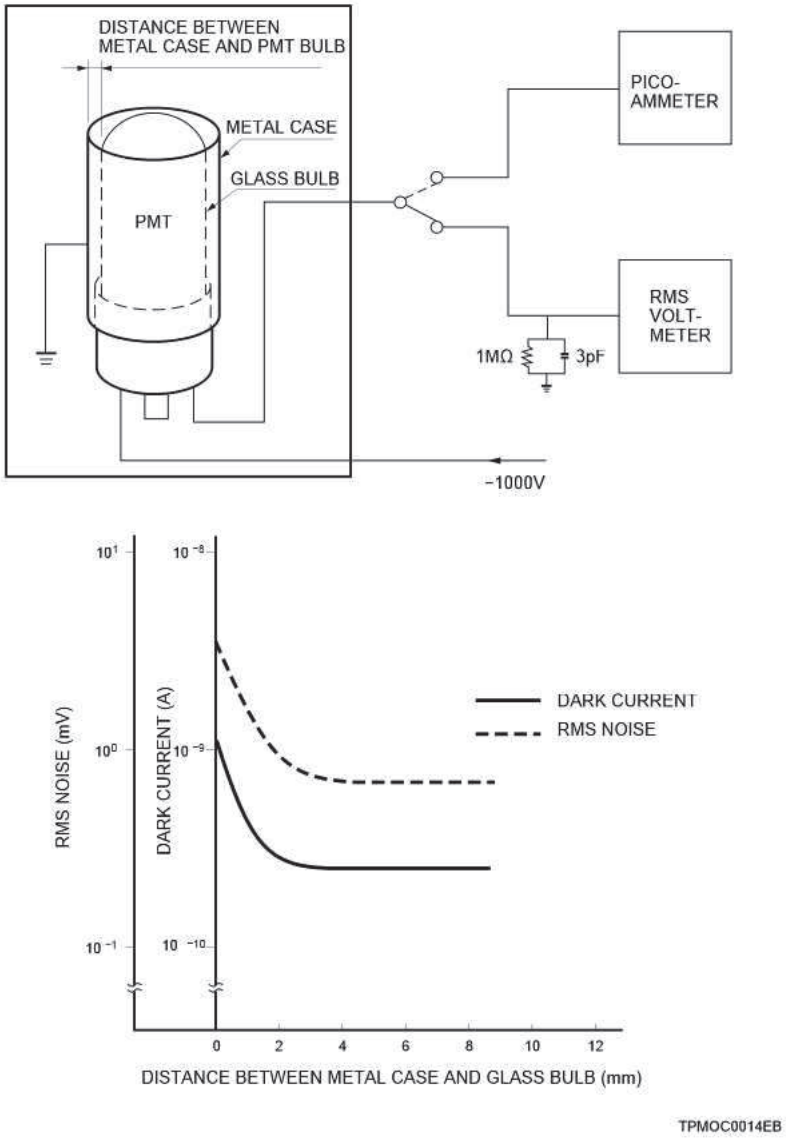


Figure 8-16: Dark current vs. distance to the grounded case

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8. 8. 2 Taking corrective action

The above effects of external electric potential can be eliminated by use of the cathode grounding scheme with the anode at a positive high voltage, but photomultiplier tubes are frequently operated in the anode grounding scheme with the cathode at a negative high voltage. In this case, a technique of applying a conductive paint around the outside of the bulb and connecting it to the cathode potential can be used, as illustrated in Figure 8-17.[13)]

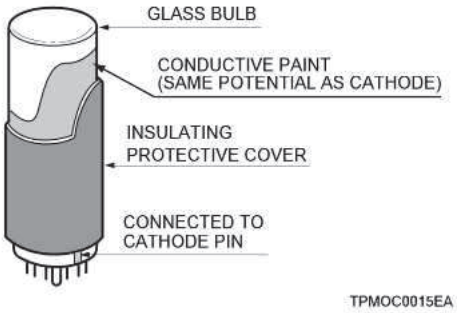


Figure 8-17: HA coating

This technique is called "HA coating" by Hamamatsu Photonics and, since a negative high voltage is applied to the outside of the bulb, the whole bulb is covered with an insulating cover (heat-shrinkable tube) for safety. The noise problem caused by the external electric potential can be minimized by use of an HA coating. Even so, in cases where a metal foil at ground potential is wrapped around the tube, minute amounts of noise may still occur. This effect can be observed using a setup like that shown in Figure 8-18. This noise is probably caused by a small discharge which may sometimes occur due to dielectric breakdown in the insulating cover, which then produces a glass scintillation reaching the photocathode. This problem can be reduced by shifting the metal foil wrapped around the HA coating away from the photocathode toward the bulb stem.

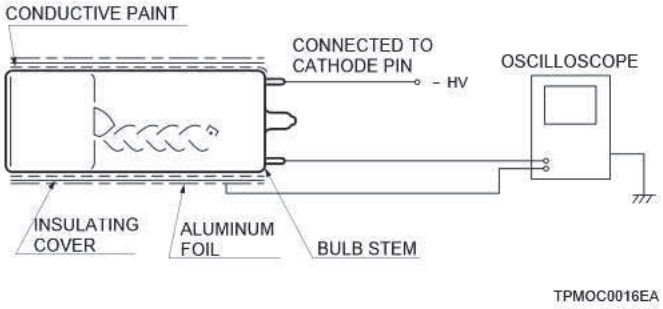


Figure 8-18: Observing the effect of external electric potential on HA coating

As mentioned above, the HA coating can be effectively used to eliminate the effects of external potential on the side of the bulb. However, if a grounded conductive object is located on the photocathode faceplate, there are no effective countermeasures and what is worse, scintillation occurring in the faceplate has a larger influence on the noise. Therefore, any grounded object, even insulating materials, should not make contact with the faceplate. If such an object must make contact with the faceplate, it is necessary to select one with high insulating properties such as teflon. Another point to be observed is that a grounded object located on the faceplate can cause not only a noise increase but also deterioration of the photocathode sensitivity. Once deteriorated, the sensitivity will never recover to the original level. Thus, particular care must be exercised with regard to the mounting method of the photomultiplier tube. Taking account of the above effects of external electric potential it is recommended, if possible, that the photomultiplier tube be operated in the cathode grounding scheme with the anode at a positive high voltage.

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8. 9 Reliability

8. 9. 1 Stability over time (life characteristic)

Stability over time of a photomultiplier tube exhibits a somewhat specific pattern according to the type of photocathode and the dynode materials, but greatly depends on the operating conditions (especially on the output current) and the fabrication process. Also, stability over time widely varies from tube to tube even among the same tube family. In normal operation, the cathode current flowing through the photocathode is on the order of picoamperes, and the photocathode fatigue can virtually be ignored. Accordingly, the operating stability of the dynodes is an important factor that largely affects the stability over time of the photomultiplier tube. Figure 8-19 shows typical data for time stability when photomultiplier tubes are operated at an anode current of 10μA.

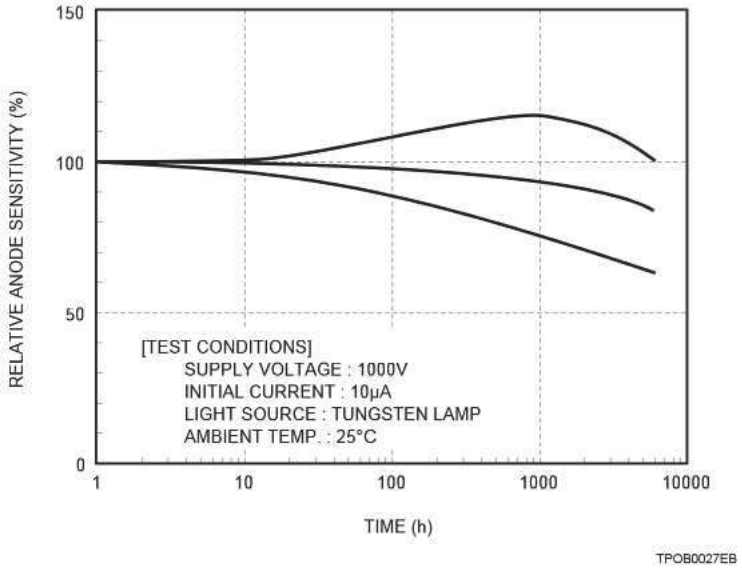


Figure 8-19: Typical time stability of photomultiplier tubes

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8. 9. 2 Current stress and stability

As mentioned in the preceding section, time stability of a photomultiplier tube varies with the operating conditions. In general, the larger the current stress, the earlier and more significant the variation that occurs. Figure 8-20 shows typical time stability of photomultiplier tubes when their operating anode currents Ip are set to 1, 10 and 100 microamperes, indicating both increasing and decreasing patterns.

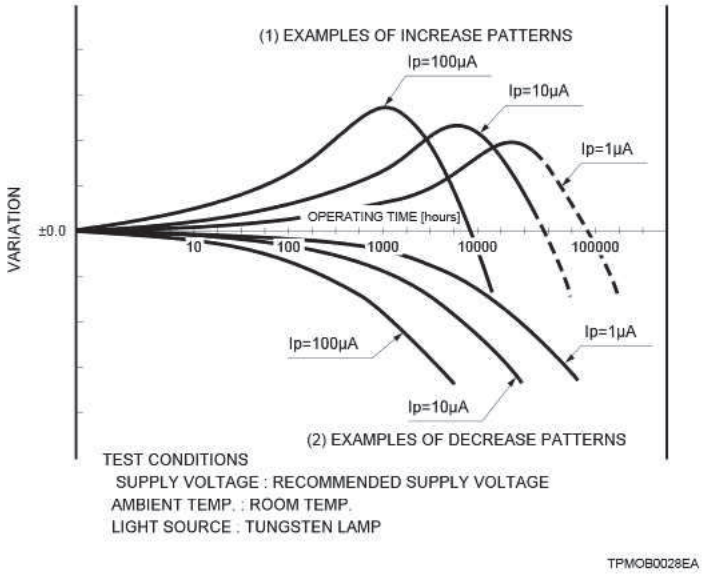


Figure 8-20: Typical time stability of photomultiplier tubes (at different anode currents)

Figure 8-21 shows a typical acceleration factor over time with respect to the anode current. Stability over time can be improved to some extent by aging the tube. Figure 8-22 shows the initial output variations when a photomultiplier tube is intermittently operated. It is obvious from the figure that a large variation during the initial operation can be reduced to nearly half, during the second or later operations.

When the photomultiplier tube is left for long periods of time, stability will return to its original values. In applications where high stability is prerequisite, we recommend the tube be aged before use.

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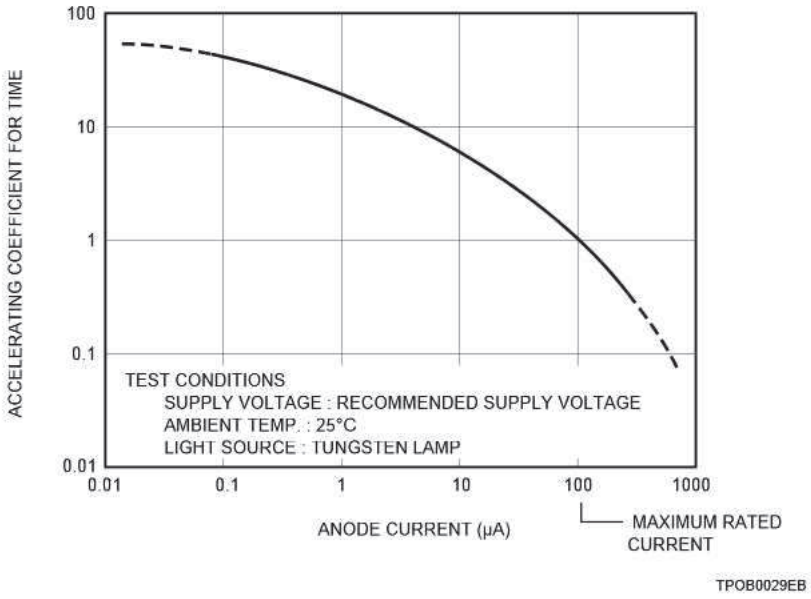


Figure 8-21: Typical acceleration factor over time with respect to anode current

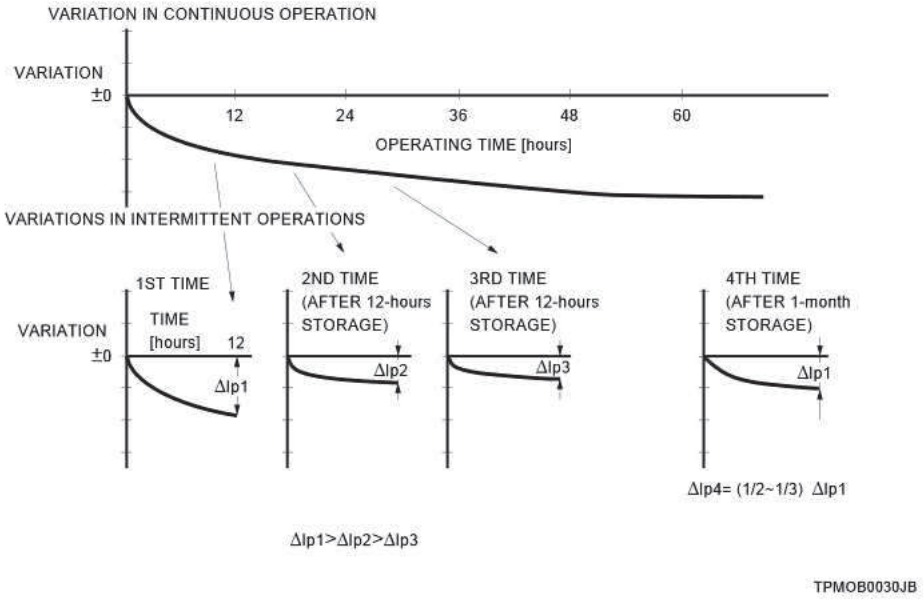


Figure 8-22: Effects of intermittent operation (aging effect)

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8. 9. 3 Reliability

Photomultiplier tube applications are constantly expanding to such fields as scintillation counting, high energy physics, nuclear medicine, X-ray applied instrumentation, and aerospace fields. In these application fields, a large number of photomultiplier tubes (sometimes hundreds or occasionally even thousands of tubes) are used in one instrument. It is therefore extremely important in these applications to predict and verify the reliability of the photomultiplier tubes.

(1) Failure mode

Failure mode for photomultiplier tubes is roughly classified into gradual failure and breakdown failure. The main failure mode is gradual failure, which includes cathode sensitivity degradation, a loss of gain, an increase in dark current and a decrease in dielectric resistance. Breakdown failure includes cracks in the faceplate, bulb envelope and stem portion, and also air leakage through microscopic cracks. Breakdown failure fatally damages the photomultiplier tube, making it permanently unusable.

Since Hamamatsu photomultiplier tubes undergo stringent screening both in the manufacturing and inspection process, most possible failures and their causes are eliminated before shipping. As a result of in-house reliability tests, we have found most of the failure mode causes lie in a loss (or variation) of gain. This means that the photomultiplier tube can still be properly used by adjusting the operating voltage.

(2) Failure rate

Failure rate[15) 16)] is defined as the probability of failure per unit time. Failure rate is generally estimated by using the following two kinds of data:

1. In-house reliability test data
2. Field data

Actual results obtained from field data prove that the photomultiplier tube failure rate is at a level of $25\ 10^{-7}$ to $25\ 10^{-6}$ failures/hour with operating conditions at room temperatures, a rated supply voltage and an anode output current of 100 nanoamperes. In particular, it is predicted that those tubes which have undergone screening provide a failure rate as small as $55\ 10^{-7}$ failures/hour.

(3) Mean life

There is a measure of reliability which is commonly referred to as MTBF[15) 16)] (mean time between failure) or MTTF (mean time to failure). Stated simply, this is the average hours of time until any failure occurs, in other words, mean life.

Since the definition and fundamental calculation of these terms are described in detail in various papers, this section only briefly explains these terms.

The relation between the failure rate (λ) and the mean life (θ) can be expressed on the assumption that it has failure distribution in accordance with exponential distribution, as follows:[15) 16)]

$$\theta\Delta = 1 / \lambda$$

Therefore, the reciprocal of the failure rate is the mean life.

As an example, when a photomultiplier tube is operated in room environments with the anode output current of about 100 nanoamperes, a mean life of $55\ 10^{3}$ to $55\ 10^{6}$ hours can be predicted based on the failure rate explained above. For those tube which have passed screening, the mean life would be more than $25\ 10^{6}$ hours.

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(4) Reliability

Based on the fundamental calculation for stability data, reliability R is defined as follows.[15) 16)]

$R(t) = e^{-t\lambda}$

t: operating time in hours

λ: failure rate

Therefore, using a typical failure rate λ of photomultiplier tubes of $25\ 10^{-6}$ to $25\ 10^{-7}$ failures/time, reliability R becomes as follows:

Elapsed time in operation	Reliability R(t)	
	at $\lambda = 25\ 10^{-6}$	at $\lambda = 25\ 10^{-7}$
One year (8760 hours)	98.3%	99.8%
2 years (17520 hours)	96.6%	99.7%
3 years (26280 hours)	94.9%	99.5%
4 years (35040 hours)	93.2%	99.3%
5 years (43800 hours)	91.6%	99.1%

The above results can be used as a reference in determining reliability levels of photomultiplier tubes, and prove that the photomultiplier tube provides considerably high reliability levels tube when operated under favorable conditions.

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8. 9. 4 Reliability tests and criteria used in Hamamatsu Photonics

Hamamatsu Photonics performs in-house reliability tests by setting the following test conditions and failure criteria to obtain the failure rate.

Reliability test conditions

1) Environmental stress conditions
   Room temperature (25°C) and high temperature (60°C) (10°C above the maximum rating)
2) Test procedures
   Storage and operating life
3) Operating conditions (photomultiplier tubes)
   Supply voltage: catalog-listed standard operating voltage 1000 to 1250V
   Anode output current: catalog-listed maximum rating 10 to 100μA

Failure criteria

1) Anode sensitivity judged as the end of life: ±50% variation
2) Anode sensitivity during non-operation (storage): ±25% variation
3) Cathode sensitivity: ±25% variation
4) Anode dark current (DC): more than 500 times increase, faulty dielectric-resistance
5) Breakdown failure: discharge, crack, anode leakage current, etc.

Notice that the above criteria are specified by Hamamatsu Photonics for evaluation and do not necessarily indicate that a tube outside these standards is unusable.

Hamamatsu Photonics has continually performed reliability tests under the above conditions over extended periods of time and has collected large amounts of data. Our evaluation results show that the failure rate of photomultiplier tubes ranges from 15 10^{-3} to 15 10^{-4} failures/hour and thus the mean time is from 1000 up to 10000 hours. Based on these results, the ratio of the failure rate at room temperatures and an anode output current of 100 nanoamperes, to the failure rate under operating conditions at a maximum rating (10 to 100 microamperes) will be approximately 500 times. This means that our in-house test conditions have an acceleration factor approximately 500 times that of the field data.

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CHAPTER 9

APPLICATIONS

Photomultiplier tubes (PMTs) are extensively used as photodetectors in various measuring equipment in fields such as chemical analysis, medical diagnosis, scientific research and industrial measurement. This chapter introduces major applications of photomultiplier tubes and describes the principle and detection methods of each application.

This chapter also explains the types of photomultiplier tubes which are most suited for each application as well as the major performance characteristics required of the photomultiplier tubes and their measurement methods.

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9. 1 Spectrophotometry

9. 1. 1 Overview

Spectrophotometry is a study of the transmission and reflection properties of material samples as a function of wavelength, but the term commonly means chemical analysis of various substances utilizing photometry. Photometric instruments used in this field are broadly divided into two methods: one utilizes light absorption, reflection or polarization at specific wavelengths and the other uses external energy to excite a sample and measures the subsequent light emission. Photomultiplier tubes have been most widely used in this field for years. Major principles used in spectrophotometry are classified as illustrated in Figure 9-1 below.

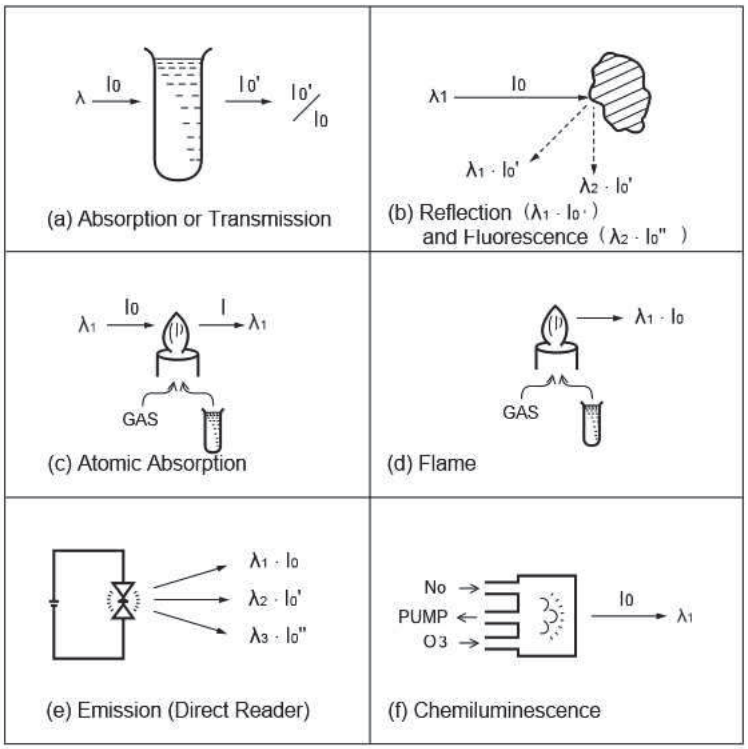


Figure 9-1: Major principles of spectrophotometry

Specific photometric instruments currently used are:

1) Visible to UV spectrophotometers (absorption, reflection)
2) Infrared spectrophotometers (absorption, reflection)
3) Far UV spectrophotometers (absorption, reflection)
4) Emission spectrophotometers
5) Fluorescence spectrophotometers
6) Atomic absorption spectrophotometers
7) Azimuthal, circular dichroism meters
8) Raman spectrophotometers
9) Densitometers, colorimeters and color analyzers
etc.

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9. 1 .2 Specific applications

The following paragraphs explain major, specific applications of spectrophotometers, divided into two methods utilizing absorption or emission.

(1) Utilizing Absorption

A. UV, visible and infrared spectrophotometers

When light passes through a substance, the light energy causes changes in the electronic state of the substance (electron transition) or induces characteristic vibration of the molecules, resulting in a loss of partial energy. This is referred to as absorption, and quantitative analysis can be performed by measuring the extent of absorption.

The principle and simplified block diagram[1)] of an absorption spectrophotometer are shown in Figure 9-2.

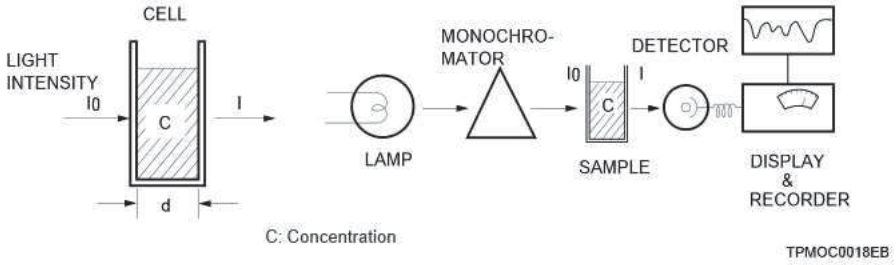


Figure 9-2: Principle and block diagram of a absorption spectrophotometer

There are various optical systems in use today for spectrophotometers. Figure 9-3 illustrates the optical system[2)] of a spectrophotometer using sequential plasma emission as the light source for covering from the ultraviolet to visible and infrared range.

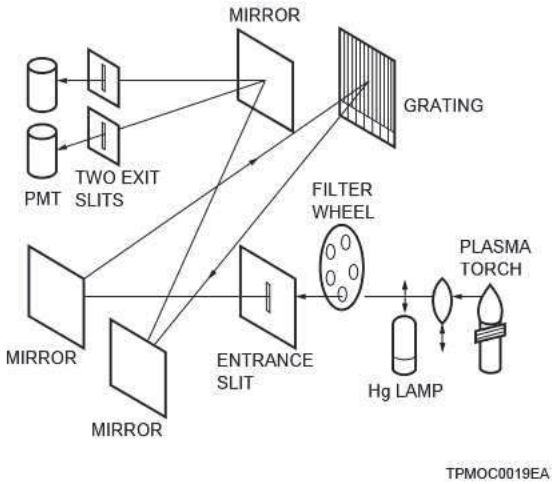


Figure 9-3: Optical system of a UV to visible spectrophotometer

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B. Atomic absorption spectrophotometers

The atomic absorption spectrophotometer employs special light sources (hollow cathode lamps) constructed for the respective elements to be analyzed. A sample is dissolved in solvent and burned for atomization, and light from the specific hollow cathode lamp is passed through the flame. The amount of light that is absorbed is proportional to the concentration of the sample material. Therefore, by comparing the extent of absorption between the sample to be analyzed and a standard sample measured in advance, it is possible to know the concentration of the specific element contained in the sample. A typical optical system[3] used for atomic absorption spectrophotometers is shown in Figure 9-4.

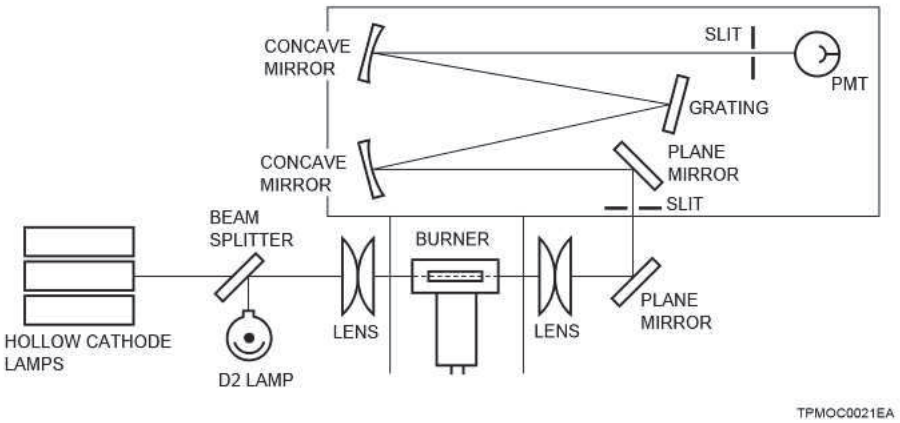


Figure 9-4: Optical system used for atomic absorption spectrophotometers

(2) Utilizing Emission

A. Photoelectric emission spectrophotometers (direct readers)

When external energy is applied to a sample, light emission occurs from the sample. Dispersing this emission using a monochromator, into characteristic spectral lines of elements and measuring their presence and intensity simultaneously, enables rapid qualitative and quantitative analysis of the elements contained in the sample. Figure 9-5 illustrates the block diagram[4] of a photoelectric emission spectrophotometer in which multiple photomultiplier tubes are used.

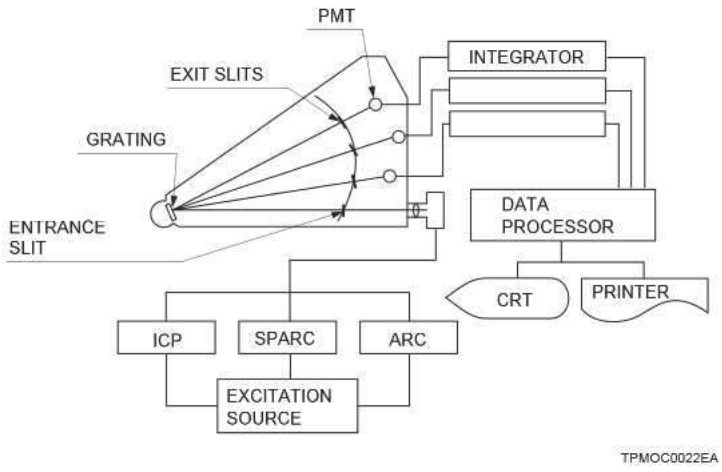


Figure 9-5: Block diagram illustrating a photoelectric emission spectrophotometer

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B. Fluorospectrophotometers

The fluorospectrophotometer is mainly used for chemical analysis in biochemistry, especially in molecular biology. When a substance is illuminated and excited by visible or ultraviolet light, it may emit light with a wavelength longer than that of the excitation light. This light emission is known as fluorescence and its emission process[5] is shown in Figure 9-6. Measuring the fluorescent intensity and spectra allows quantitative and qualitative analysis of the elements contained in the substance.

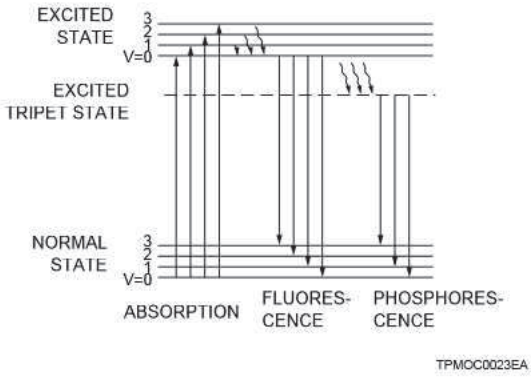


Figure 9-6: Fluorescent molecular energy levels

Figure 9-7 shows the structure[6] of a fluorospectrophotometer using photomultiplier tubes as the detectors. This instrument roughly consists of a light source, excitation monochromator, fluorescence monochromator and fluorescence detector. A xenon lamp is commonly used as the light source because it provides a continuous spectrum output over a wide spectral range. The excitation and fluorescence monochromators use the same diffraction grating or prism, as are used in general-purpose monochromators.

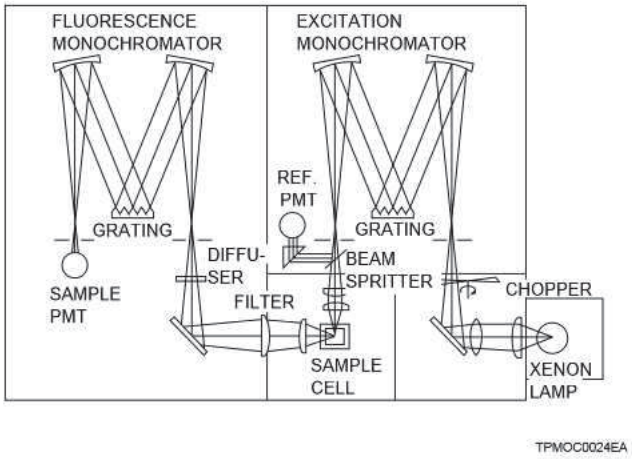


Figure 9-7: Fluorospectrophotometer structure

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9. 1. 3 Characteristics required of photomultiplier tubes

The following photomultiplier tube characteristics are required in this application.

a) High stability

b) Low dark current

c) High signal-to-noise ratio

d) Wide spectral response (ultraviolet to infrared)

e) Low hysteresis

f) Excellent polarization properties

Side-on and head-on photomultiplier tubes having a multialkali photocathode and silica window are most frequently used in these applications.

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9. 2 Gamma Cameras

9. 2. 1 Overview

Imaging equipment utilizing a radioactive isotope (RI) first appeared as a scintillation scanner before undergoing successive improvements leading to the currently used gamma camera developed by Anger (U.S.A.). Recently, even more sophisticated equipment called SPECT (single photon emission computed tomography) utilizing the principle of the gamma camera, has been developed and is now coming into wide use. An external view of a gamma camera is shown in Figure 9-8.

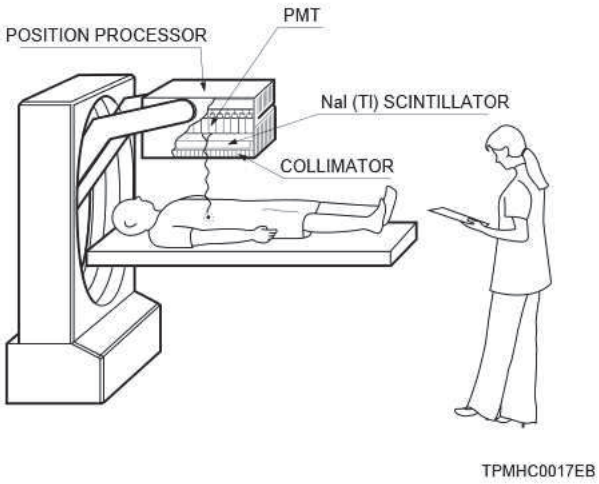


Figure 9-8: External view of a gamma camera

Figure 9-9 shows sectional views of a detector used in gamma cameras, in which dozens of photomultiplier tubes are installed in a honeycomb arrangement. Each photomultiplier tube is coupled, via a light-guide, to a large-diameter scintillator made from a thallium-activated sodium-iodide (NaI(Tl) scintillator), serving as a gamma-ray detector.

Three prime features of gamma cameras are:

1. High sensitivity
2. Broad, static field-of-view
3. High spatial resolution

These features lead to advantages such that rapid changes in the RI distribution can be measured and the length of diagnostic time shortened.

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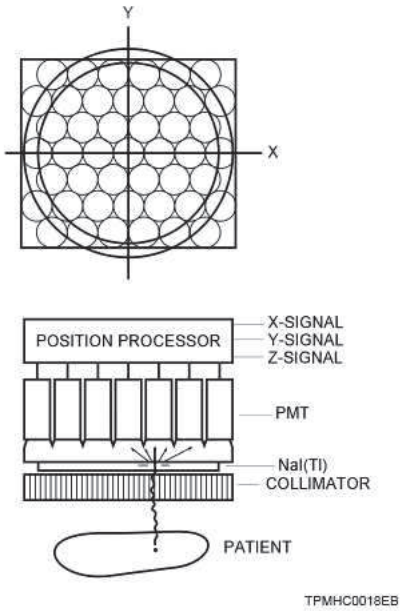


Figure 9-9: Sectional views of a detector used in gamma cameras

To make more effective use of these advantages, a variety of gamma-ray nuclide drugs have been developed for use with the gamma cameras. In addition, improvements in the position processing circuit have achieved higher resolution, making gamma cameras more popular in medical diagnosis. Major nuclides used for nuclear medical imaging are listed in Table 9-1 and the principle of SPECT equipment utilizing gamma cameras is shown in Figure 9-10.

Recently, a SPECT equipped with two or three camera heads is often used to improve sensitivity. Moreover, a PET-SPECT with two camera heads has now been developed which is capable of simultaneous counting of gamma-ray pairs released from a positron-emitting nuclide.

Nuclide	Gamma-ray energy (keV)	Half-life
^{99m}Tc	141(no β)	6.01h
^{133}Xe	81(β:346)	5.243d
^{67}Ga	93(37%), 185(20%), 300(17%)	78.3h
^{201}Tl	70.8(Hg-X), 16.7(11%), 135(2.8%)	72.91h
^{131}I	364(81%)(β.606)	8.04d
^{123}I	159(83%)	13.2h
^{81m}Kr	190(67%)	13s
^{111}In	245(94%), 171(90%)	2.83d

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Table 9-1: Major nuclides used for nuclear medical imaging

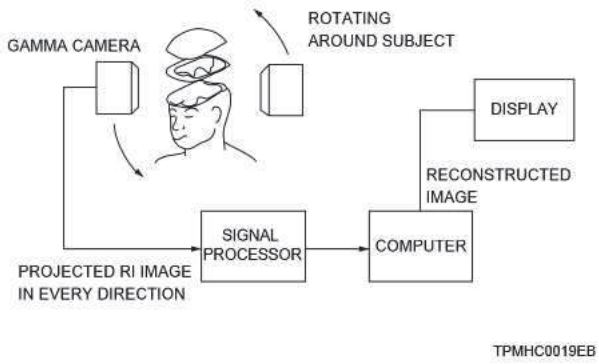


Figure 9-10: Principle of SPECT

9. 2. 2 Major characteristics required of photomultiplier tubes

The following characteristics are required particularly for photomultiplier tubes used in gamma cameras and SPECT equipment.

a) High energy resolution or pulse height resolution (PHR)

b) Excellent uniformity (especially azimuth uniformity; refer to Section 3.5.2)

c) High stability

d) Uniform RPH (relative pulse height) gain between each tube

Energy resolution is one of the most important characteristics required of photomultiplier tubes used in gamma cameras. As explained in (1) in 3-5-2, the photomultiplier tube photocathode must have a high quantum efficiency in the spectral range where NaI(Tl) scintillator emission occurs and high collection efficiency of photoelectrons onto the first dynode. Since these photomultiplier tube characteristics greatly affect the spatial resolution of gamma cameras, the use of photomultiplier tubes with good energy resolution usually improves the spatial resolution of gamma cameras. Photomultiplier tube uniformity also has an effect on the position linearity and uniformity which are computed by a gamma camera.

With the recent progress in digital technology using computers, it is becoming possible to correct the position linearity and uniformity of gamma cameras. Even so, these are still important characteristics for concern. The most important factor that affects gamma camera performance is photomultiplier tube stability. Because the position and energy information is obtained from the pulse height of photomultiplier tube output, if the output pulse height varies due to the amount of input gamma-rays or extended operating time, this may cause problems with output pulse height measurement. (Refer to Section 3.3.4, "Stability") Figure 9-11 shows typical long-term stability characteristics for the Hamamatsu R1306 photomultiplier tube specifically devel-

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oped for gamma cameras.

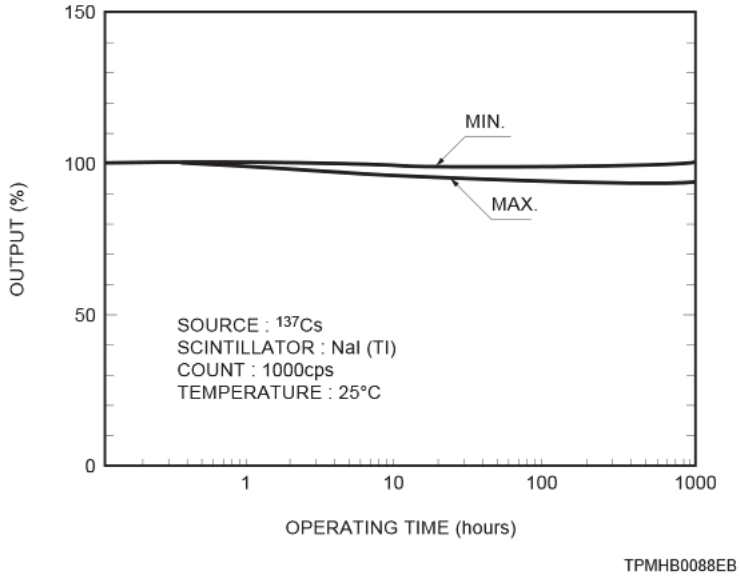


Figure 9-11: Typical long-term stability of a photomultiplier tube

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9. 3 Positron Emission Tomography (PET)

9. 3. 1 Overview

In addition to gamma cameras and SPECT described previously, much attention has recently been focused on positron emission tomography (PET) as an application of nuclear medical diagnosis using photomultiplier tubes. This section explains specific examples of PET. The schematic diagram[7] of a PET system is illustrated in Figure 9-12, the external view in Figure 9-13, and the cutaway view of the detector section in Figure 9-14.

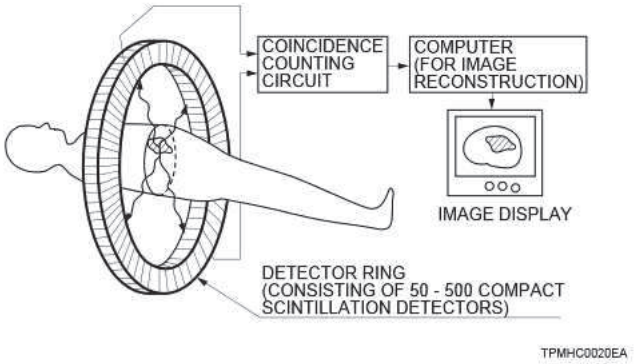


Figure 9-12: Concept view of a PET system



Figure 9-13: External view of a PET system

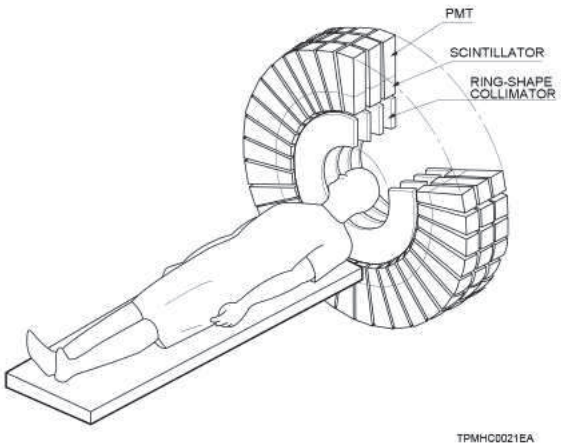


Figure 9-14: Cutaway view of a PET system

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PET provides tomographic images of a living body in the active state, by injecting pharmaceuticals labeled with positron-emitting radioisotope into the body and measuring their concentrations Typical positron-emitting radioisotopes used in PET are ^{11}C, ^{13}N, ^{15}O and ^{18}F.

When positrons are emitted within the body, they combine with the electrons in the neighboring tissues, releasing a pair of gamma-rays at 180 degrees opposite each other. Multiple rings of detectors surrounding the subject detect and measure these gamma rays by coincidence technique. The principle of this measurement is shown in Figure 9-15. By arranging the acquired transaxial data at each angle, the PET system then creates a tomographic image by image reconstruction technique in the same manner as used in X-ray computed tomography (X-ray CT).

A prime feature of PET is that quantitative measurement of physiological or biochemical information such as metabolism, blood flow and neural transmission within the body can be performed. Up until now, PET has been chiefly used in research and study on brain functions and other organ mechanisms. Recently, PET is gradually being put to active use in medical diagnosis, proving effective in diagnosing cardiac diseases and cancer.

A detector used in PET consists of a compact photomultiplier coupled to a scintillator. To efficiently detect gamma-rays of high energy (511keV) released from inside the body, scintillators with high stopping power versus gamma-rays, such as BGO crystals are commonly used.

Another type of measurement technique is now being studied, which utilizes TOF (time-of-flight) of gamma-rays generated by positron annihilation. This measurement uses high-speed photomultiplier tubes and scintillators with a short emission decay.

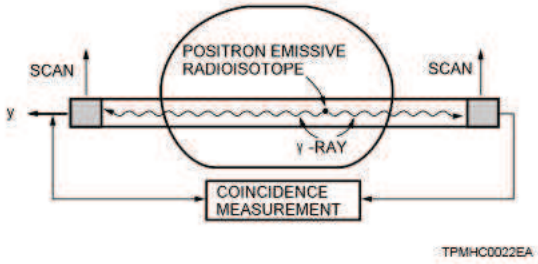


Figure 9-15: Principles of PET measurement

Scintillator	Density (g/cm^3)	Relative Emission Intensity	Emission Time (ns)	Wavelength of Peak Emission (nm)
BaF_2	4.89	5/26	0.8/620	220/320
BGO	7.13	20	60/300	480
LSO	7.35	72	40	420
GSO	6.71	20	60/600	430
NaI(Tl)	3.67	100	230	410

Table 9-2: Characteristics of major scintillators

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9. 3. 2 Major characteristics required of photomultiplier tubes

Photomultiplier tubes used in PET systems must have the following characteristics.

a) High energy resolution or pulse height resolution (PHR)

b) High gain and minimal variations between individual tubes

c) Excellent CRT (coincidence resolving time)

d) High level of stability

e) Compact size

(1) Photomultiplier tubes coupled to BGO ($Bi_4Ge_3O_{12}$) scintillators

This application requires high energy resolution of the photomultiplier tube. For this purpose, the photomultiplier tube must have high photocathode quantum efficiency at the emission wavelength (480 nanometers) of the BGO scintillator (See Figure 9-16), high secondary emission ratio (δ) of the first dynode and excellent photoelectron collection efficiency (α). Moreover, because many photomultiplier tubes are used at the same time in one system, it is also important that the photomultiplier tubes be compact and have adequate gain in order to improve position resolution.

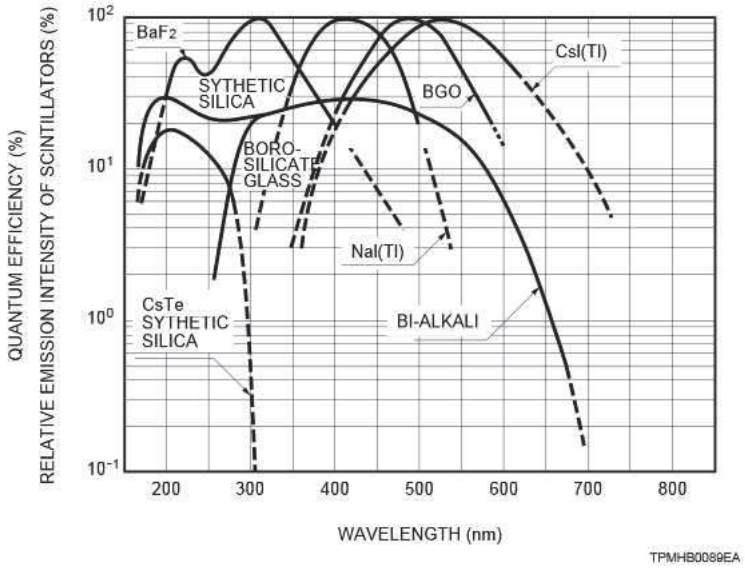


Figure 9-16: Scintillator emission spectra and photocathode spectral response of photomultiplier tubes

Figure 9-17 shows a cutaway view of the structure of a low-profile photomultiplier tube (R5900-c8) recently developed for PET. This tube has a unique structure of cross plate anode intended to improve position resolution. Position is identified with this anode by calculating the center of gravity, making it compatible with small scintillator segments. Its compact configuration allows increasing the installation density of scintillators, thus reducing the dead space and leading to high sensitivity in PET.

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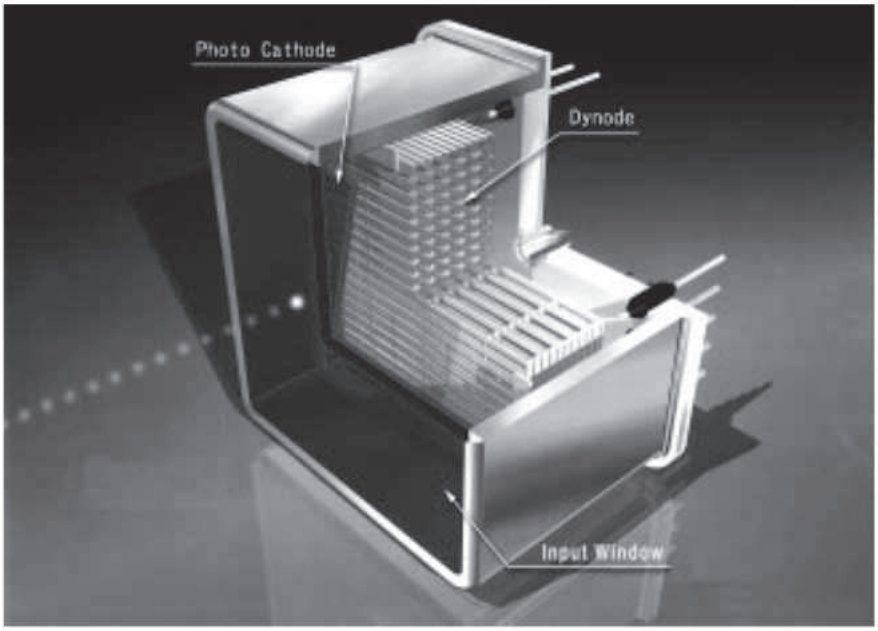


Figure 9-17: Cutaway view of R5900-c8 photomultiplier tube developed for positron CT

(2) Photomultiplier tubes coupled to barium fluoride (BaF_2) scintillators

Barium fluoride (BaF_2) scintillators offer an extremely short emission decay compared to other scintillators and are used particularly for radiation detectors requiring high speeds. One application is positron imaging that utilizes TOF (time of flight) of gamma-rays. Photomultiplier tubes in this application should have characteristics equivalent to those used with BGO scintillators. In addition, the photocathode quantum efficiency must be high at the peak wavelength of fast emission components (220 nanometers) of BaF_2 scintillators (see Figure 9-16) and the CRT (coincidence resolving time) as fast as possible. (See Figure 9-18 and 3.3.1, "Time characteristics".) Better CRT provides more accurate TOF information to acquire high-quality tomographic images, making it possible to perform dynamic studies. Another characteristic required of photomultiplier tubes is high gain.

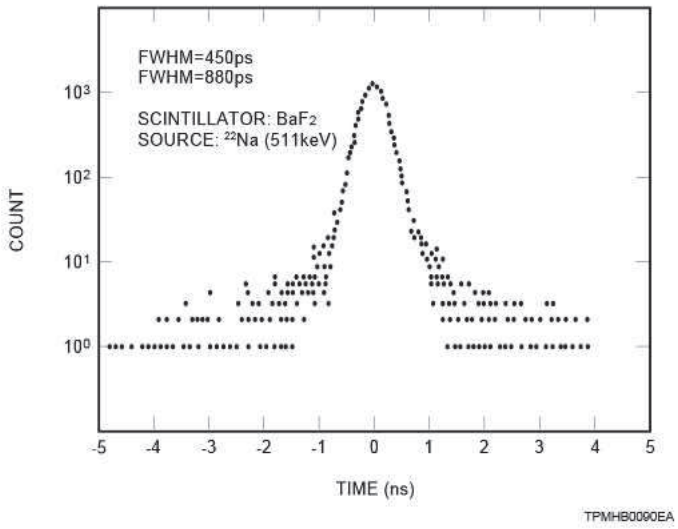


Figure 9-18: CRT spectrum of R2496 obtained at energy threshold of 140keV

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9. 4 In-vitro Assay

The analysis and inspection of blood or urine samples collected out of a living body is referred to as in-vitro assay. It is used for physical checkups, diagnosis, and evaluation of drug potency. The in-vitro assay can be classified as shown in Table 9-3. Of these, the concentrations of most tumor markers, hormones, drugs and viruses which are classified under immunological assay are exceedingly low. This requires extremely high-sensitivity inspection equipment for frequently requiring use of photomultiplier tubes.

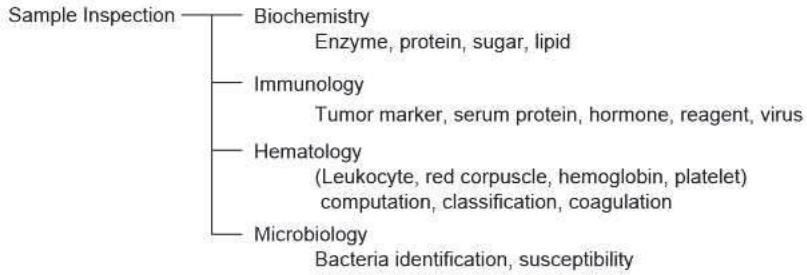


Table 9-3: Classification of in-vitro inspection

Immunoassay, a measurement technique making use of specificity of the antigen-antibody reaction, is widely used. The principles of immunoassay[9] are illustrated in Figure 9-19 below, and the procedures of each method are explained in the subsequent paragraphs.

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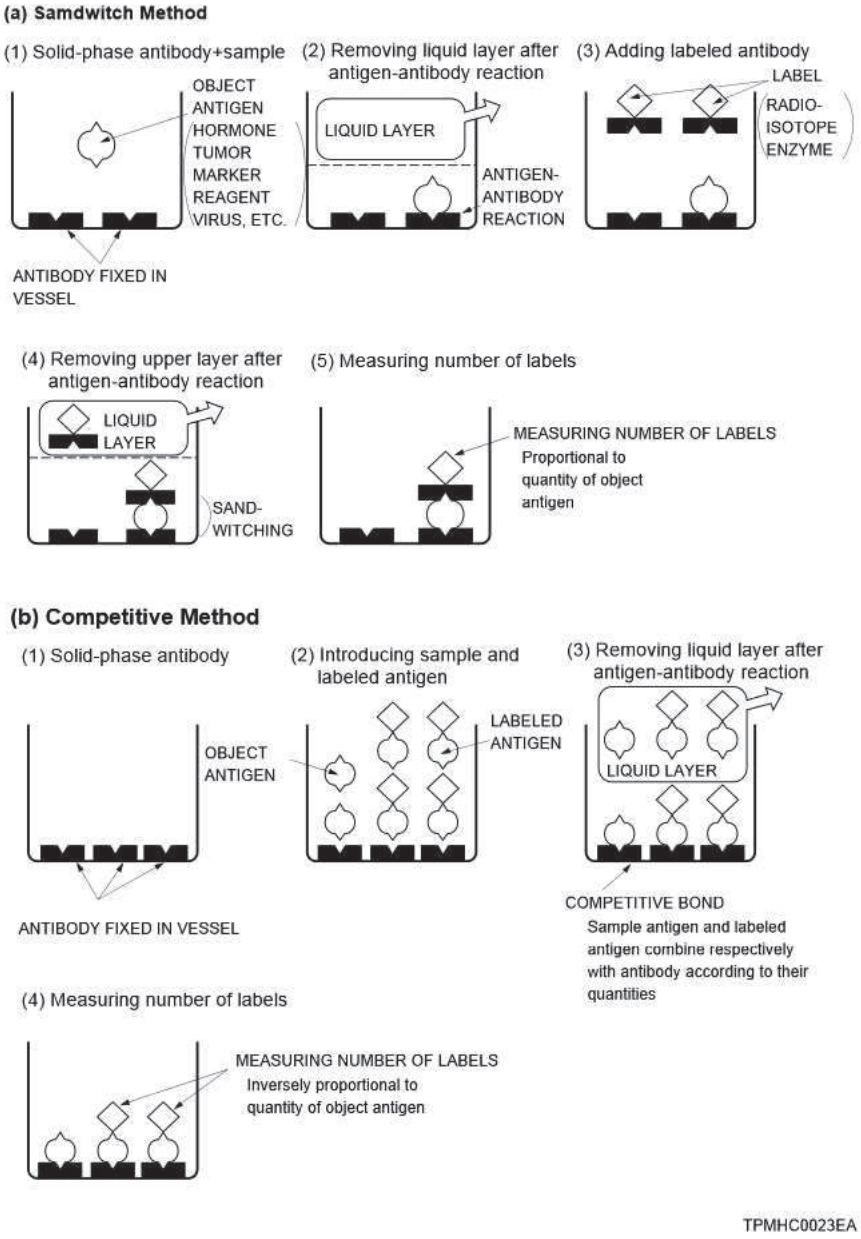


Figure 9-19: Principles of immunoassay

Figure 9-19 (a) is a technique known as the sandwich method. Step (1): Samples are introduced into a vessel in which antibodies responding to object antigens (hormones, tumor markers, etc.) are fixed (solid-phase antibody). Step (2): Antigen-antibody reaction occurs, and each object antigen combines with a solid-phase antibody. This reaction has an extremely high singularity and hardly ever occurs with a different antigen. After antigen-antibody reaction, the liquid layer is removed leaving the combined antigen and antibody. Step (3): Labeled antibodies are added, which combine with object antigens. Step (4): Antigen-antibody reaction occurs again so that the object antigen is sandwiched between the antibodies. Then the liquid layer is removed. Step (5): The quantity of labels is optically measured using a photomultiplier tube.

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Figure 9-19 (b) is another technique called the competitive method. Step (1): Antibodies responding to object antigens are fixed on the bottom of a vessel. Step (2): Samples are added along with the labeled object antigens. Step (3): Competitive reaction in which object antigens and labeled antigens combine with labeled antibodies in proportional to their concentration, reaching a state of equilibrium. After the antigen-antibody reaction, the unnecessary upper layer is removed. Step (4): The quantity of labels is measured using a photomultiplier tube. In the sandwich method, the higher the concentration of object antigens, the larger the signal. Conversely, in the competitive method, the higher the concentration of the object antigens, the lower the signal.

Immunoassay can be further categorized according to the material used for labeling as follows

(1) Using radioactive isotopes for labeling
(Radioimmunoassay)

(2) Using enzymes for labeling
(Enzymeimmunoassay)

9. 4. 1 RIA (Radioimmunoassay) method

(1) Overview

Radioactive isotope (RI) is used for the labeling as was explained above, and radiation (gamma or beta rays) emitting from the RI labels is detected by the combination of a scintillator and a photomultiplier tube, so that the object antigen can be quantitatively measured. Radioactive isotopes most frequently used for labeling are ^{3}H, ^{14}C, ^{57}Co, ^{75}Se, ^{125}I and ^{131}I. (See Table 9-4.)[10] Of these, ^{125}I offers useful characteristics for labeling and is very widely used. Because radioactive isotopes other than ^{3}H and ^{14}C emit gamma rays, sodium iodide crystals are used as a scintillator, providing a high conversion efficiency.

Radioisotope	Half-life	Energy	Detection Method
^{3}H	12.26 years	β	Liquid scintillation
^{14}C	5730 years	β	Liquid scintillation
^{57}Co	270 days	γ	Scintillation crystal
^{75}Se	120.4 days	γ	Scintillation crystal
^{125}I	60 days	γ	Scintillation crystal
^{137}I	8 days	β, γ	Scintillation crystal

Table 9-4: Radioactive isotopes used for labeling in radioimmunoassay

Recently, for in-vitro assays, the quantity of samples and the number of items to be measured are rapidly increasing. To meet this trend, the equipment for radioimmunoassay has been automated. A typical piece of automated equipment in use today is the well scintillation counter[11] that makes use of sodium iodide scintillators having a well-like hole to enhance the conversion efficiency of the radiation into light. Measurements are made by automatically inserting test tubes, which contain a mixture of antigens and antibodies including labels, into each hole in the scintillator. (See Figure 9-20.) Each detector section including a scintillator is covered by lead shield to block extraneous radiation.

Isotopes ^{3}H and ^{14}C can be used for labeling; however, because they emit extremely low-energy beta rays, a liquid scintillation counter explained in Section 9.5, is used to make measurements with these two isotopes.

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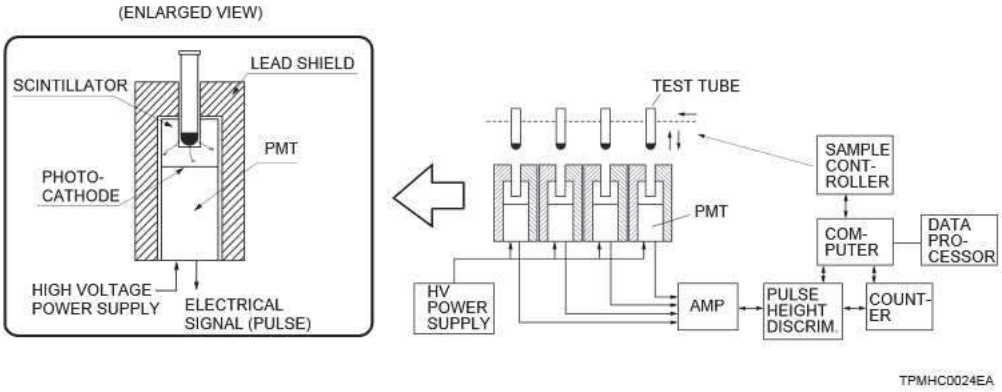


Figure 9-20: Schematic block diagram illustrating a well scintillation counter

(2) Major characteristics required of photomultiplier tubes

Photomultiplier tubes used in RIA must have the following characteristics.

a) High energy resolution or pulse height resolution (PHR)

b) High level of stability

c) Low noise

To obtain high energy resolution, the photomultiplier tube should have high quantum efficiency at the peak emission wavelength (410 nanometers) of the sodium iodide (NaI(Tl)) scintillator. (See Figure 9-16.) In addition, because this application field deals with quite a few samples that emit extremely small amounts of radiation, it is also very important that the photomultiplier tube exhibits sufficiently low noise.

9. 4. 2 EIA (Enzymeimmunoassay) method

(1) Overview

An enzyme is used as a label utilizing the antigen-antibody reaction. As Figure 9-21[12] shows, RIA offers exceptionally high sensitivity among various immunoassay techniques. However, because it uses radioactive isotopes, various restrictions are imposed on its use. On the other hand, though its sensitivity is inferior to RIA, EIA is more popular because of its easy use. EIA sensitivity is gradually increasing due to improvements in reagents and detection method.

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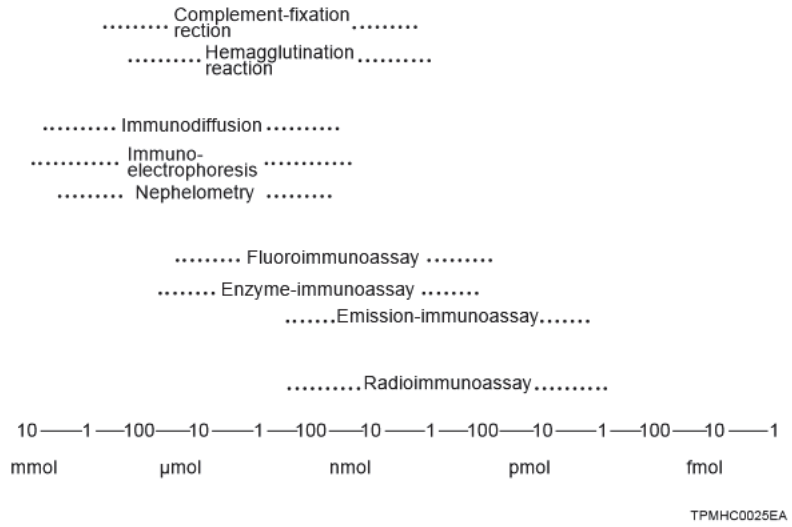


Figure 9-21: Comparison of various immunoassay techniques and measurable concentration range (Use this comparison data just for a general guide.)

In the EIA procedure, an enzyme used as a label in the antigen-antibody mixture in the last step in Figure 9-19 is activated to create a product. Then, color or fluorescence emitted from the product is detected by a photomultiplier tube. (See Figure 9-22.)[13] The extent of color or fluorescent intensity is proportional to the quantity of enzyme (enzyme concentration).

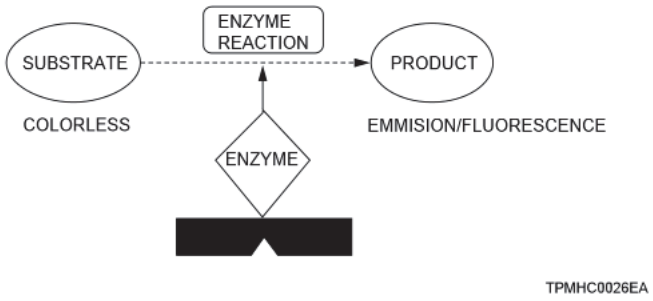


Figure 9-22: Label enzyme reaction

(2) Major characteristics required of photomultiplier tubes

a) High sensitivity at the wavelength of color or fluorescence emitted from the product of the enzyme reaction

b) Low dark current

c) High signal-to-noise ratio

d) Compact size

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9. 4. 3 Other immunoassay methods

(1) Overview

Besides EIA, several non radioactive immunoassay techniques not using radioisotopes are under research and development.

One of these is fluoroimmunoassay in which a fluorescent substance is used for labeling. The final remaining mixture of antigens and antibodies is irradiated by an excitation light and the resulting fluorescence is measured with regard to the intensity, wavelength shift and polarization. This technique offers slightly higher sensitivity than that of EIA. Figure 9-23 shows the schematic of a fluorescence-polarization photometer,[14] which is used for fluoroimmunoassay.

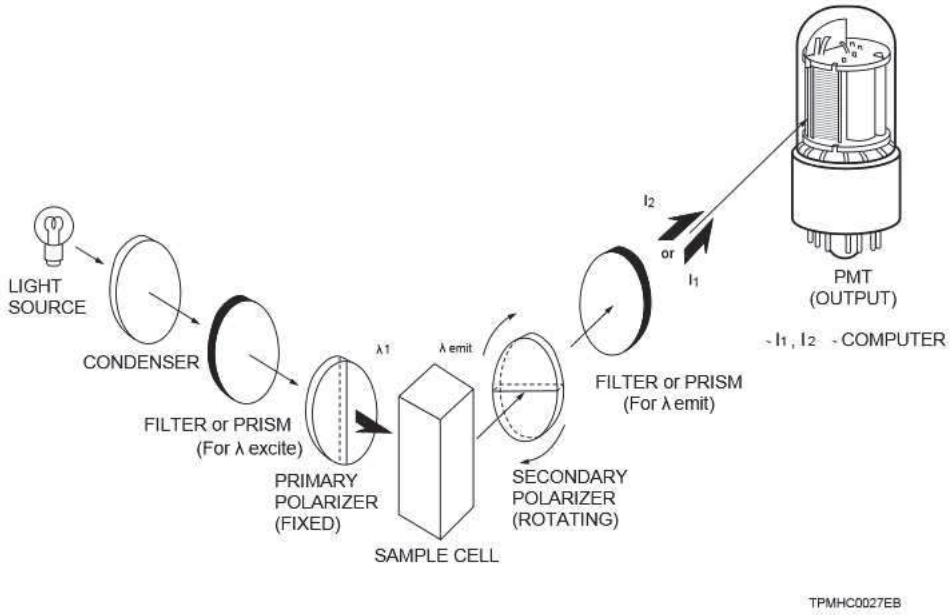


Figure 9-23: Schematic presentation of a fluorescence-polarization photometer

To achieve high sensitivity equal to RIA by using non-radioactive immunoassay, intensive research and development of emission-immunoassay has been carried out. This immunoassay uses a chemiluminous substance or bioluminous substance for labeling and allows the final remaining mixture of antigens and antibodies to emit light, which is detected by a photomultiplier tube. There are three types of emission-immunoassay methods, as follows:

1) Use of a chemiluminous substance such as luminol and acridinium for labeling

2) Use of chemiluminescence or bioluminescence for activation of the label enzyme used in EIA

3) Use of a catalyst for the bioluminescence reaction

Methods 2) and 3) can be thought of as kinds of EIA techniques. As shown in Figure 9-21 previously, emission-immunoassay is a high sensitivity equivalent to RIA.

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(2) Major characteristics required of photomultiplier tubes

Fluoroimmunoassay

a) High sensitivity at fluorescent wavelengths

b) High level of stability

c) Low dark current

d) High signal-to-noise ratio

e) Compact size

Emission-immunoassay

a) High sensitivity at emission wavelengths

b) Excellent single-photoelectron pulse height distribution

c) Low dark current pulse

d) High gain

e) Compact size

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9. 5 Liquid Scintillation Counting Systems

9. 5. 1 Overview

Among the various radiation detecting methods, the liquid scintillation counting system is primarily used for detection of alpha and beta rays. This is because this system provides higher sensitivity to alpha and beta rays compared to other methods and also offers low background, enabling highly accurate measurement. Photomultiplier tubes are essential for detecting exceptionally low level light resulting from low-energy alpha and beta rays.

Liquid scintillation counting systems are used in diverse applications. One of their major applications is in tracer analysis using radioactive isotopes such as ^{3}H and ^{14}C as a label, which is referred to in Section 9.4.1, "RIA (Radioimmunoassay)". This tracer analysis is effectively used for diagnosis of biofunctions and diseases. The schematic block diagram of a liquid scintillation counting system is shown in Figure 9-24.

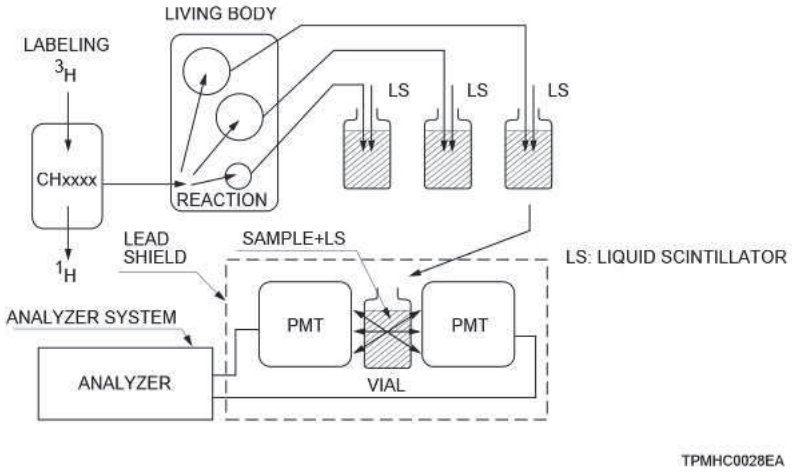


Figure 9-24: Schematic construction of the tracer analysis (liquid scintillation counting system)

There are many other applications of liquid scintillation counting, including Cherenkov radiation detection, age measurement and rock analysis. Beta energy released from ^{3}H or ^{14}C is very low and, moreover, the corresponding emission from the liquid scintillator is also extremely low in comparison with those from crystal scintillators. For this reason, photomultiplier tube background noise has a large influence on the measurement accuracy. A coincidence counting circuit is used to eliminate this background noise. As Figure 9-25[13] shows, the coincident outputs from a pair of photomultiplier tubes are counted as a signal from the sample. Because the possibility that noise from individual photomultiplier tubes will simultaneously enter the coincidence counting circuit is extremely low, the signal can be separated from the noise with a high degree of accuracy.

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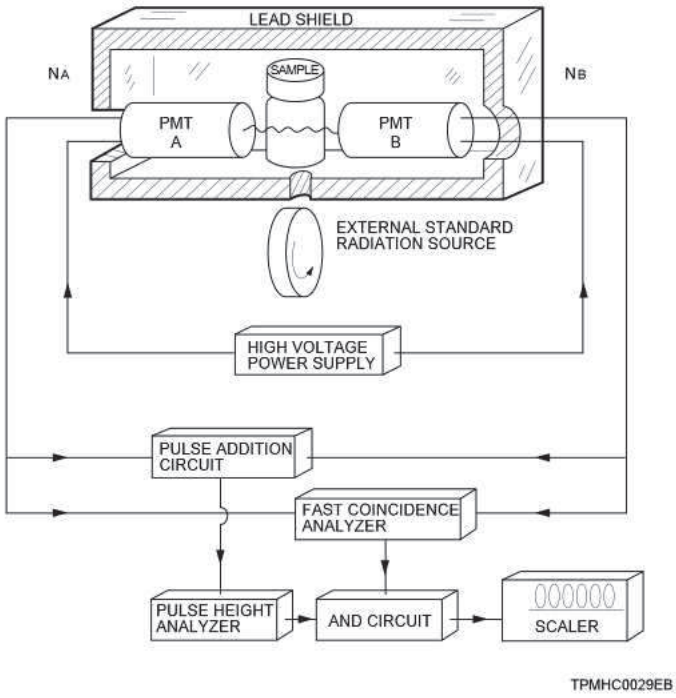


Figure 9-25: Basic construction of a liquid scintillation counting system

9. 5. 2 Major characteristics required of photomultiplier tubes

The following photomultiplier tube characteristics are important in liquid scintillation counting systems.

a) Low thermionic emission noise

b) Low scintillation of the faceplate or side bulb of a photomultiplier tube

c) High-speed time response

d) High quantum efficiency

e) Excellent linearity

f) High gain

Liquid scintillation counting places even more stringent demands on photomultiplier tube characteristics in comparison with other applications. For instance, item b) above, is not so severe in other applications but is extremely important for liquid scintillation counting as it determines the system performance. As shown in Figure 9-25, the pulse counting technique known as the coincidence counting is effectively used to reduce noise to as low a level as 15cpm (counts per minute). Even so, if glass scintillation occurs and a resulting noise of several cpm is generated, the signal-to-noise ratio will significantly deteriorate. Therefore, glass bulbs causing minimum scintillation are selected. Because such scintillation from the glass is mainly caused by radioisotope elements contained in the glass, these glass bulbs must contain very small amounts of such elements. For this purpose, silica glass bulbs which basically contain no impurities are often used.

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9. 6 Biotechnology

In life science applications, photomultiplier tubes are mainly used for detection of fluorescence and scattered light. Major equipment used for life science includes cell sorters, fluorometers and DNA sequencers.

9. 6. 1 Overview

(1) Cell sorters

When light is irradiated onto a rapidly flowing solution which contains cells or chromosomes, a scattered light or fluorescence is released from the cells or chromosomes. By analyzing this scattered light or fluorescence, it is possible to elucidate cell properties and structures and separate the cells based on these properties. This field is known as flow cytometry. A cell sorter like the one illustrated in Figure 9-26 is most frequently used. The cell sorter is an instrument that selects and collects only specific cells labeled by a fluorescent substance from a mixture of cells in a solution.

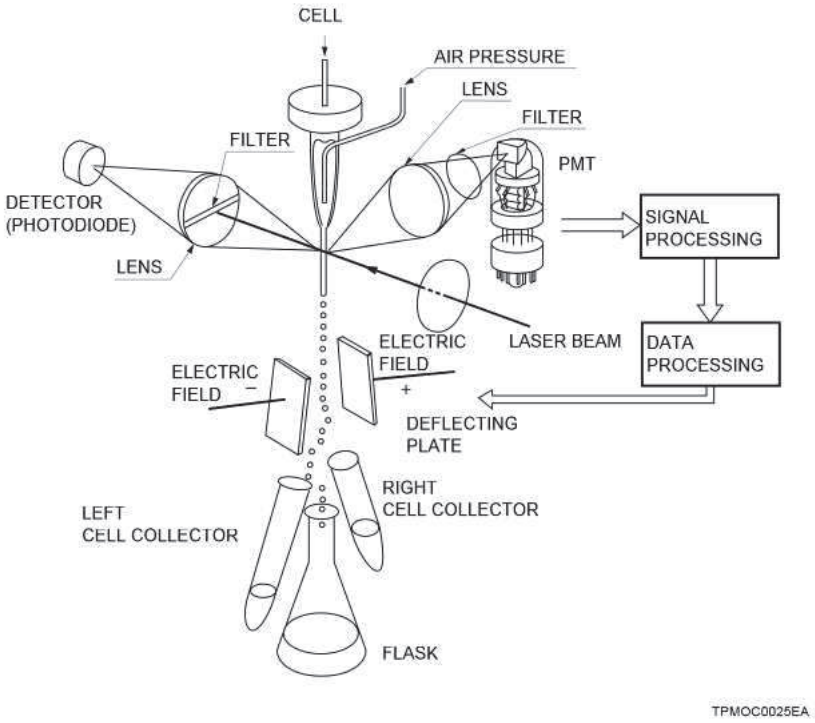


Figure 9-26: Major components for a cell sorter

In a cell sorter, a fluorescent probe is first attached to the cells. The cells pass through a thin tube at a fixed velocity. When each cell passes through a small area onto which an intense laser beam is focused, the fluorescence is emitted from the cell and is detected by a photomultiplier tube. The photomultiplier tube outputs an electrical signal in proportion to the number of fluorescent molecules attached to each cell. At the same time, the laser beam light is scattered forward by the cell, and detecting this scattered light gives information on the cell volume. After processing these two signals, the cell sorter creates an electrical pulse that deflects a drop of liquid, containing the desired cell into one of the collection tubes.

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(2) Fluorometers

While the ultimate purpose of the cell sorter explained above is to separate cells, the fluorometer[16] is used to analyze cells and chemical substances by measuring the fluorescence or scattered light from a cell or chromosome with regard to such factors as the fluorescence spectrum, fluorescence quantum efficiency, fluorescence anisotropy (polarization) and fluorescence lifetime. (See Figure 9-27.)

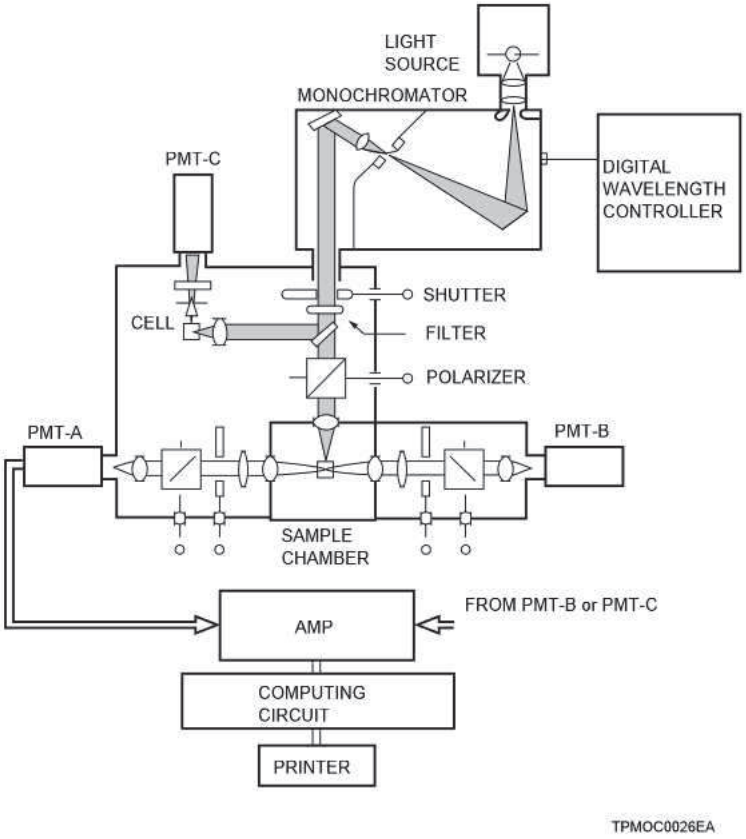


Figure 9-27: Automatic fluorescence-depolarization photometer

The basic configuration of the fluorometer is nearly identical with that of the fluorospectrophotometer and thus a description is omitted here. There are a variety of models of fluorometers which are roughly categorized into: filtering fluorescence photometers, spectrofluorescence photometers, compensated-spectrofluorescence photometers, fluoroanisotropy analyzers, and phase fluorescence lifetime measurement systems. Of these, the fluoroanisotropy analyzer is an instrument specially dedicated to measurement of fluorescence-depolarization.

When performing research on biological samples such as proteins, nucleic acid and lipid membranes, rotational relaxation of a fluorescent molecule takes place only slowly and the fluorescence is polarized in most cases. It is still necessary to compensate for the effect of fluorescence depolarization when measuring quantum efficiency and spectrum. For this purpose, the automatic fluorescence-depolarization photometer uses a pair of photomultiplier tubes which detect the two polarized components at the same time.

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(3) DNA sequencers

This is an instrument used to decode the base arrangement of DNA extracted from a cell. The principle of a DNA sequencer is shown in Figure 9-28. An extracted DNA segment is injected onto gel electrophoresis plate along with a fluorescent label which combines with the DNA. When an electric potential is applied across the gel, the DNA begins to migrate and separate based on size and charge. When the DNA segment reaches the position of the scanning line, it is excited by a laser, causing only the portion with the labeling pigment to give off fluorescence. This fluorescent light is passed through monochromatic filters and detected by photomultiplier tubes. Computer-processing of the position at which the fluorescence has occurred gives information on where the specific bases are located. The DNA sequencer is used for the genetic study of living organisms, research into the cause and treatment of genetic diseases and decoding of human genes.

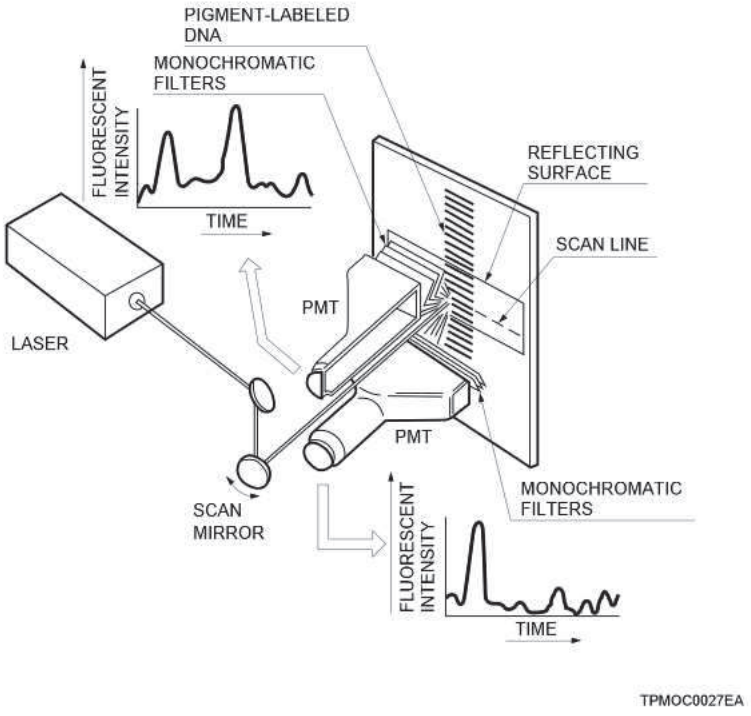


Figure 9-28 Principle of a DNA sequencer

9. 6. 2 Major characteristics required of photomultiplier tubes

Because the photomultiplier tube detects very-low fluorescence emitted from a cell or DNA, the following characteristics are required as in the case of spectrophotometry.

a) High stability

b) Low dark current

c) High signal-to-noise ratio

d) Wide spectral response

e) Low hysteresis

f) Excellent polarization properties

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9. 7 High-Energy Physics Experiments

Photomultiplier tubes are widely used as detectors in high-energy physics experiments. For example, when a charged particle passes through a scintillator, a light flash is given off in accordance with the particle energy. Detecting this light flash makes it possible to measure the energy, speed and direction of the charged particle. This technique is absolutely essential in high-energy physics research which is constantly aiming for the ultimate in scientific technology.

9. 7. 1 Overview

Photomultiplier tubes are used in a variety of equipment for high-energy particle detection such as a hodoscopes, TOF (time of flight) counters, Cherenkov counters and calorimeters. Photomultiplier tubes are also used in proton decay and neutrino detection where a great number of large-diameter tubes are required.

Figure 9-29 shows a simplified diagram[1/] of a hodoscope. Plastic scintillators are arrayed in two orthogonal layers followed by photomultiplier tubes. The position and time at which a charged particle passes through certain scintillators are detected by the corresponding photomultiplier tubes.

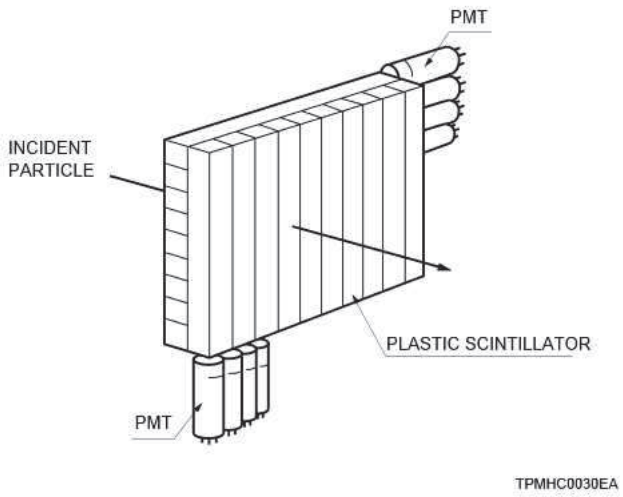


Figure 9-29: Simplified diagram of a hodoscope

Figure 9-30 illustrates a cutaway view of a CDF detector installed in a high energy accelerator. The CDF detector is used to measure the amount of photons, electrons and other elementary particles (π mesons, etc.) which are created by collision of protons and positrons.

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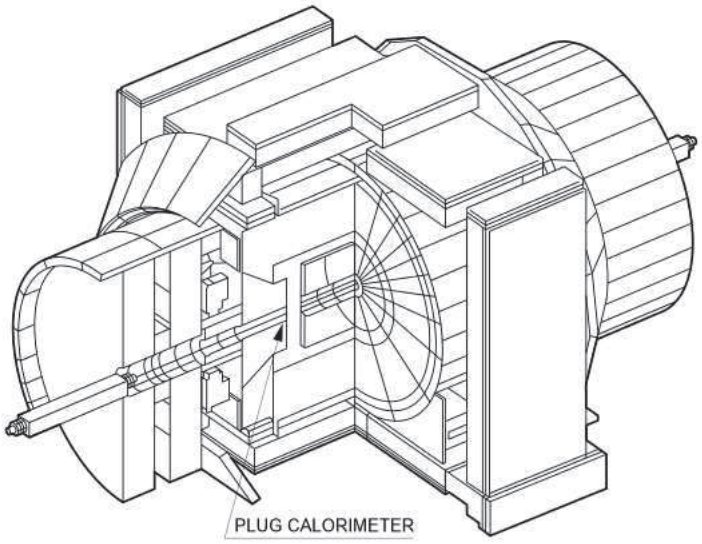


Figure 9-30: Cutaway view of a CDF detector

Figure 9-31 shows end views of a calorimeter with three detecting layers designed for different targets to be measured. From the inner position near the collision reaction point, a PSD (Preshower detector for identifying photons and pi mesons), an EM (Electromagnetic calorimeter for measuring the energy of photons) and a HAD (Hadronic calorimeter for measuring the energy of π mesons) are radially installed. Among these, a detailed view of the PSD is shown Figure 9-32. When a particle beam passes through the scintillators, a series of scintillations are produced and detected by the respective photomultiplier tubes.

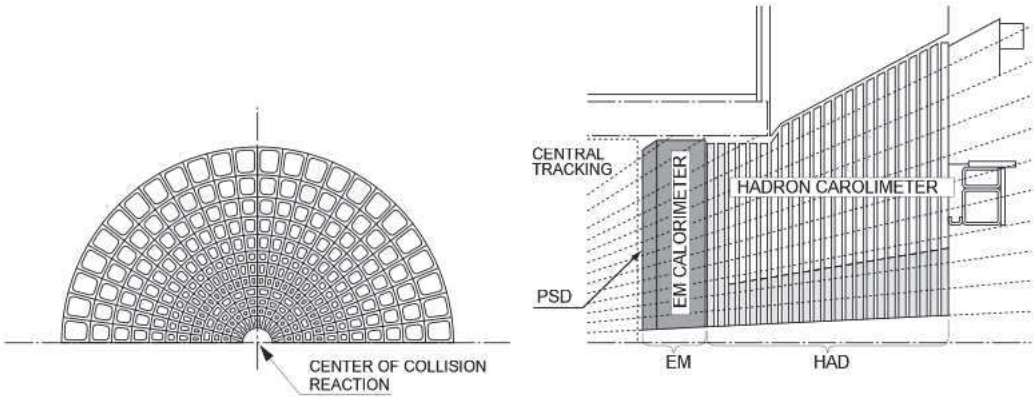


Figure 9-31: End view of a calorimeter

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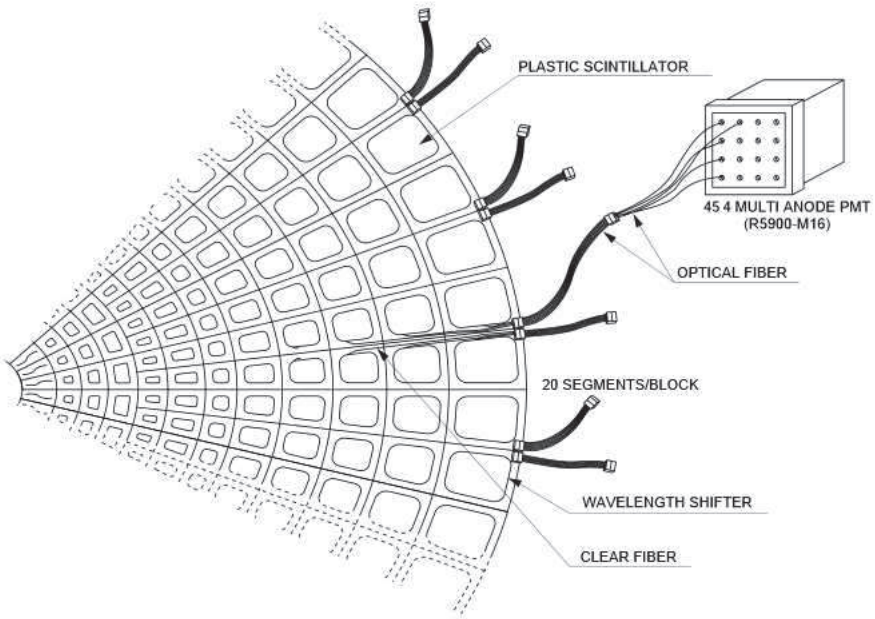


Figure 9-32: Layout of a PSD (Preshower detector)

In the PSD, photons detected with each of a 20-segmented plastic scintillator are guided to optical fibers by way of wavelength-shifting fibers and then collected into each channel of a multianode photomultiplier tube (R5900-M16). Since the PSD handles a great deal of signals up to a total of 960 channels, multianode photomultiplier tubes play an important role in reducing the cost per channel.

Figure 9-33 shows a schematic view of proton decay experiment presently being performed in Kamioka, Japan. Here, a 50,000-ton tank of super-purified water has been surrounded by more than ten-thousand, 20-inch diameter, hemispherical photomultiplier tubes. The photomultiplier tubes are used to constantly detect Cherenkov radiation that is supposedly emitted when proton decay occurs in water. In this experiment, neutrinos released from the sun or a supernova as it bursts have been successively detected.

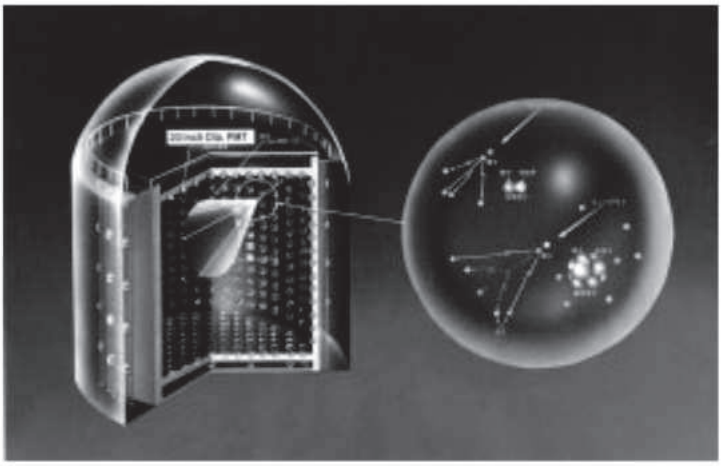


Figure 9-33: Proton decay experiment SUPER-KAMIOKANDE, Japan

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9. 7. 2 Major characteristics required of photomultiplier tubes

The following characteristics are required of photomultiplier tubes used in the vicinity of an accelerator.

a) High energy resolution or pulse height resolution (PHR)

b) Good pulse linearity

c) Excellent time characteristics

d) High magnetic immunity

e) Long life and high stability

For photomultiplier tubes used in proton decay and neutrino detection, the following characteristics are essential.

f) Large diameter (wide effective field-of-view)

g) Low noise

To obtain high energy resolution, it is important that the photomultiplier tube must have high absolute sensitivity in the emission wavelength range of the scintillator to be used. Moreover, because a wide range of light levels need to be measured at the same time in high-energy physics experiments, pulse linearity characteristics are also important. (Refer to Section 3.3.2, "Linearity" and Section 7.1.3, "Divider current and output linearity".)

In TOF counters in which the traveling time of a particle is measured, time characteristics are very important factors to consider. (Refer to Section 3.3.1, "Timing properties".) In general, photomultiplier tubes using a linear-focused dynode structure are frequently used in TOF counters because of superior time characteristics as compared to photomultiplier tubes using other dynodes.

When photomultiplier tubes are used in the vicinity of an accelerator, their magnetic characteristics are significant because stray magnetic fields may be generated there. As discussed in the section on magnetic characteristics, photomultiplier tubes using fine-mesh dynodes display high immunity to magnetic fields, thus making them suitable for use in environments where magnetic fields are present.

In proton decay and neutrino detection, because the frequency of signal occurrence is very low, exceptionally low noise qualities are required of photomultiplier tubes. Furthermore, each photomultiplier tube should cover a wide detection area, so large-diameter tubes with a wide field-of-view are required. Hemispherical photomultiplier tubes with a large diameter from 5, 8, 15 up to 20 inches are available from Hamamatsu Photonics.

Cherenkov radiation provides higher intensity at short wavelengths, thus photomultiplier tubes used for this application must have high ultraviolet sensitivity. Also, since Cherenkov radiation is very low, a photon counting technique is usually used.

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9. 8 Oil Well Logging

9. 8. 1 Overview

Special photomultiplier tubes capable of operating reliably in harsh environments including high temperature and severe vibration and shock have been developed. This section explains oil well exploration (oil well logging) as a sample application of these special tubes.

To locate an oil deposit and to determine its size, oil well logging is used. This technique makes use of photomultiplier tubes as detectors for density well logging using radiation, neutron well logging and natural gamma-ray-spectrum well logging. In these well loggings. A probe containing a neutron or gamma ray source is lowered into a well as it is being drilled. The radiation or the neutrons that are scattered by the rock surrounding the well are detected by a scintillator/photomultiplier. The amount of scattered radiation detected is indicative of the density of the rock that surrounds the well. The scattered neutrons indicate the porosity of the rock which is required to ascertain if the oil can be removed. Naturally occurring gamma rays are detected to locate shale which indicates the presence of oil or gas. Figure 9-34 shows the measurement method[18] for oil well logging using radiation, and Figure 9-35 shows the cross sectional view[19] of the strata layers around an oil well site.

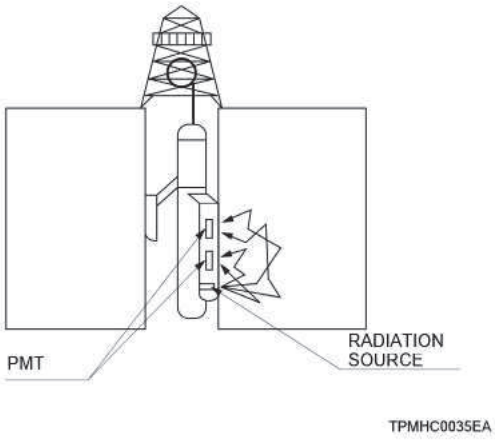


Figure 9-34: Measurement method for oil well logging using radiation

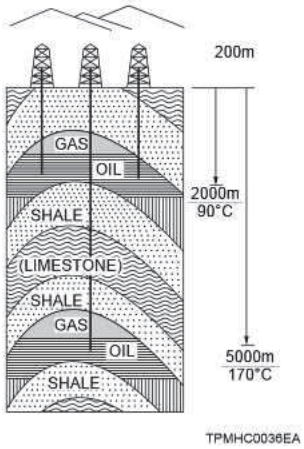


Figure 9-35: Cross sectional view of strata layers around an oil well

9. 8. 2 Major characteristics required of photomultiplier tubes

The depth of a trial hole may be as deep as several thousand meters where the ambient temperature reaches as high as 150 to 200°C. In addition, shock and vibration are also applied to the photomultiplier tubes, imposing an extremely severe environment on the photomultiplier tubes. Normal photomultiplier tubes cannot survive under these conditions and therefore custom-designed photomultiplier tubes are required.

To meet these requirements, various types of ruggedized, high-temperature photomultiplier tubes have been developed which ensure adequate performance even under these severe environments. These photomultiplier tubes have a special photocathode that exhibits a minimal increase in dark current even at high temperatures and, in the multiplier section, copper-beryllium (Cu-Be) dynodes capable of withstanding high temperatures are employed. Furthermore, the electrode structures are designed with careful consideration given to the effects of thermal expansion and vibration.

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As typical characteristics, gain and energy resolution (pulse height resolution)[20] with respect to temperature are plotted in Figure 9-36 and plateau characteristics[21] at different temperatures are shown in Figure 9-37. Also, typical stability data[22] of anode output current at different temperatures is shown in Figure 9-38.

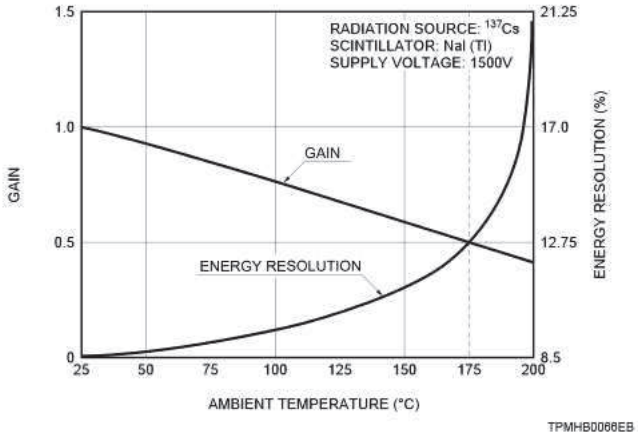


Figure 9-36: Gain and energy resolution vs. temperature

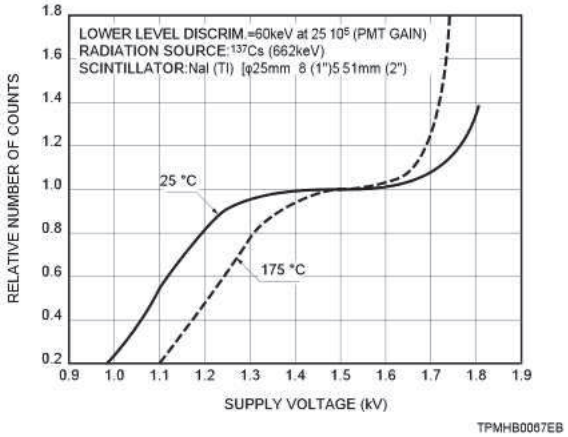


Figure 9-37: Plateau characteristics at different temperatures

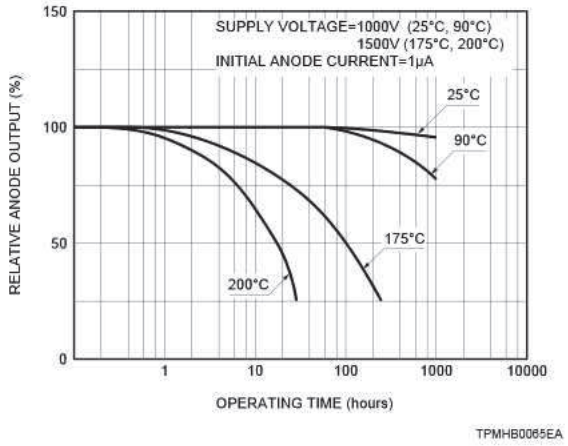


Figure 9-38: Anode current stability at different temperatures

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9. 9 Mass Spectrometry/Solid Surface Analysis

Mass spectrometry is a technique used to identify and analyze the mass, makeup and minute quantity of a sample through the measurement of the difference in mass and movement of ions by exerting electric or magnetic energy on the sample which is ionized.

Solid state surface analysis is used to examine the surface state of a sample through the measurement of photoelectrons, secondary electrons, reflected electrons, transmitting electrons, Auger electrons or X-rays which are generated as a result of interactions of incident electrons with atoms composing the sample, which take place when an electron beam or X-ray irradiates the sample.

9. 9. 1 Mass spectrometers

(1) Overview[23) 24)]

Mass spectrometers are broadly classified into two groups: one using magnetic force (magnet) and one not using magnetic force. Currently used mass spectrometers fall under one of the following four types.

- Time of flight (TOF) type
- Quadrupole (Q-Pole) or ion trap type
- Magnetic field type
- Ion cyclotron (FTICR) type

Among these, the quadrupole (Q-Pole) type mass spectrometer is most widely used and its block diagram is shown in Figure 9-39.

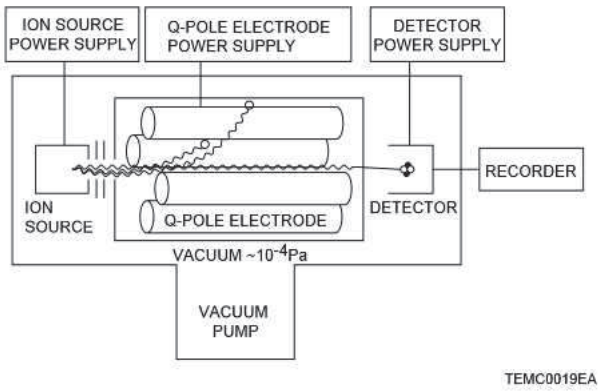


Figure 9-39: Block diagram of a quadrupole (Q-Pole) type mass spectrometer

When a sample is guided into the ionizer, it is ionized through the electronic ionization (EI method), chemical ionization (CI method), fast atomic bombardment (FAB method), electro-spray ionization (ESI method) or atmospheric pressure chemical ionization (APCI method). The ionized sample is sent to the analyzer section (quadrupolar electrodes) in which the sample is separated depending on the mass per charge count (m/z) by the DC voltage and high-frequency voltage applied to the quadrupolar electrodes. After passing through the analyzer section, the ions then reach the detector section where they are detected by an electron multiplier tube.

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Mass spectrometers are often combined with a gas chromatograph or liquid chromatograph to build a gas chromatograph mass spectrometer (GC-MS) or liquid chromatograph mass spectrometer (LC-MS). Mass spectrometers are used to identify, measure and analyze the composition of various samples such as petrochemicals, fragrance materials, medicines, biogenic components and substances causing environmental pollution. Figure 9-40 shows the schematic drawing of a gas chromatograph mass spectrometer.

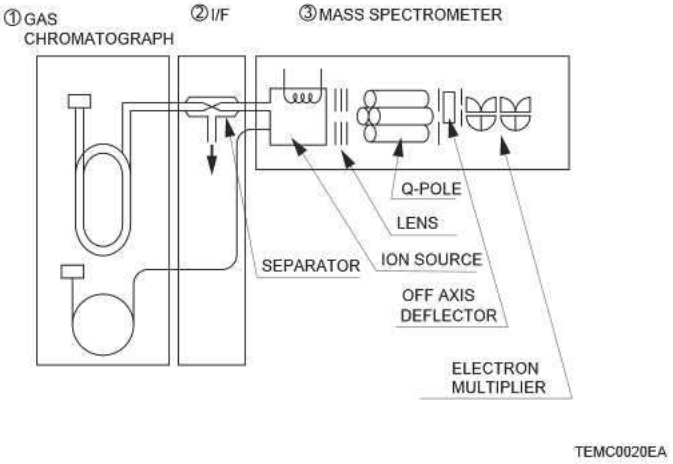


Figure 9-40: Schematic drawing of a gas chromatograph mass spectrometer.

(2) Major characteristics required of electron multiplier tubes

Since the mass spectrometer measures and analyzes the sample in minute amounts, electron multiplier tubes should have the following characteristics.

a) High gain

b) Low noise

c) Long operating life

9. 9. 2 Solid surface analyzers

(1) Overview[25)]

Solid surface analyzers are broadly divided into two groups: one using electron beams to irradiate a sample and the other using X-rays. Major solid surface analyzers presently used are as follows.

- Scanning electron microscope (SEM)
- Transmission electron microscope (TEM)
- Auger electron spectrometer (AES)
- Electron spectrometer for chemical analysis (ESCA)

When a sample is irradiated by electron beams, interactions of the incident electrons with atoms which compose the sample occur and generate various kinds of signals characterized by the particular atom. Figure 9-41 shows the kinds of signals obtained and the approximate depth at which each signal is generated on the surface of the sample.

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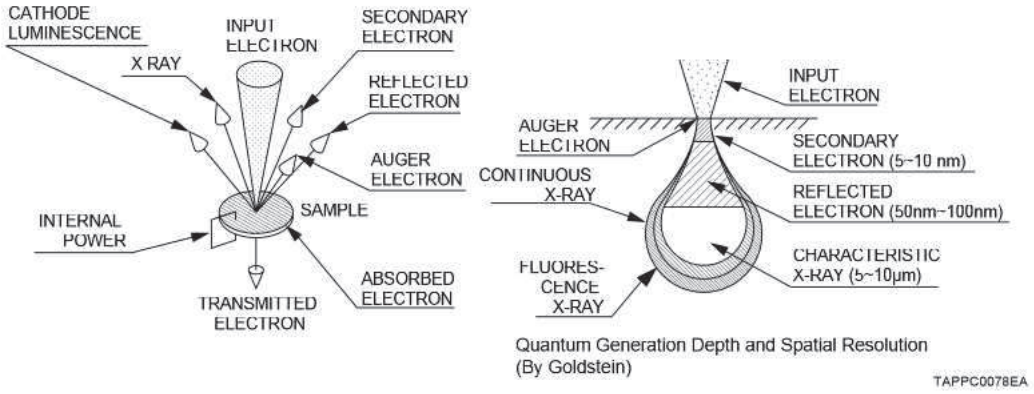


Figure 9-41: Interactions of incident electrons with sample

Obtained signals are chosen to extract necessary information according to measurement purpose, which is then used for analyzing the surface of the sample.

Among the four types of surface analyzers, the scanning electron microscope (SEM) is the most widely used and its structure and principle are illustrated in Figure 9-42.[26)]

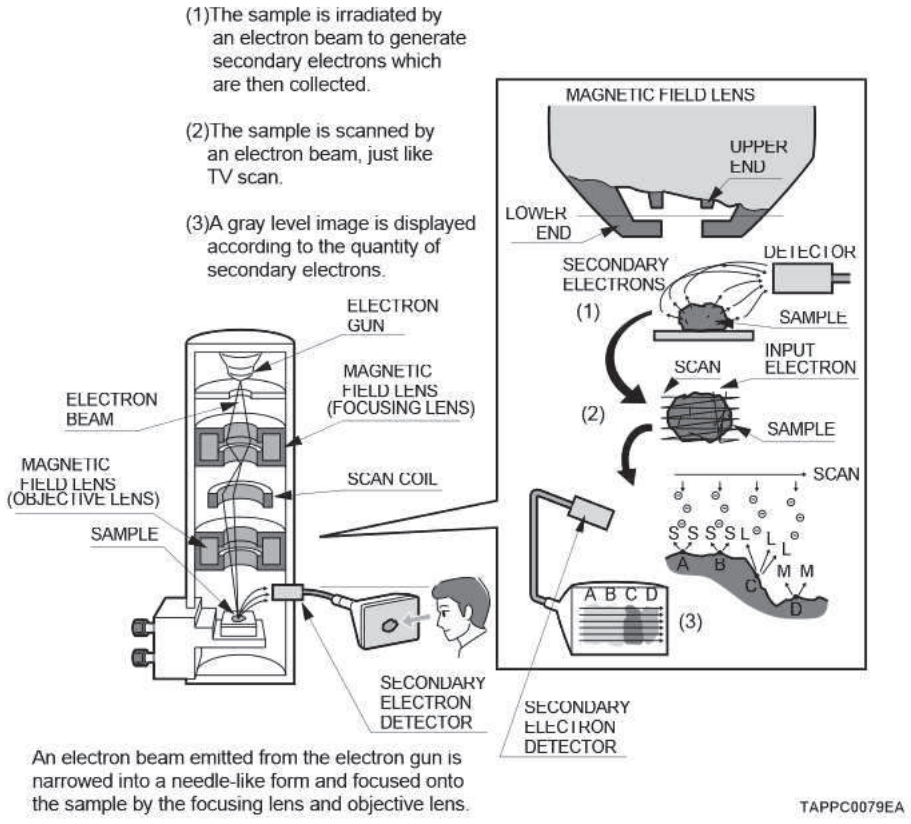


Figure 9-42: Structure and principle of a scanning electron microscope

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An electron beam emitted from the electron gun is accelerated at a voltage of 0.5 to 30kV. This accelerated electron beam is then condensed by electromagnetic lens action of the focusing lens and objective lens, and finally formed into a very narrow beam of 3 to 100nm in diameter, irradiating on the surface of a sample. Secondary electrons are then produced from the surface of the sample where the electron beam landed, and detected with a secondary electron detector. The electron beam can be scanned in the XY directions across the predetermined area on the surface of the sample by scanning the electromagnetic lens. A magnified image can be displayed on the CRT in synchronization with the signals of the secondary electron detector. Figure 9-43 shows the structure and operation of the secondary electron detector.

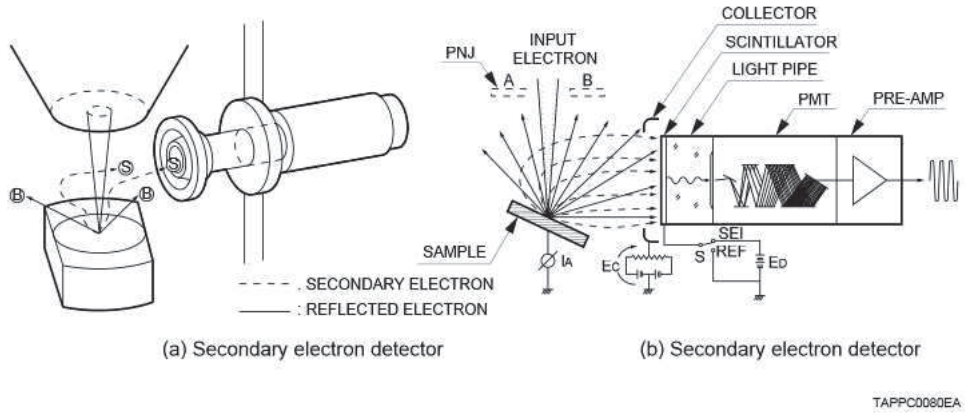


Figure 9-43: Structure and operation of a secondary electron detector

A typical secondary electron detector consists of a collector electrode, scintillator, light pipe, photomultiplier tube and preamplifier. Voltage is applied to the collector electrode and scintillator at a level required to collect secondary electrons efficiently. Most of the secondary electrons produced from the sample enter the scintillator and are converted into light. This converted light then passes through the light pipe and is detected with the photomultiplier tube. Figure 9-44 shows the images of a broken surface of ceramic, observed with a scanning electron microscope.[27)]

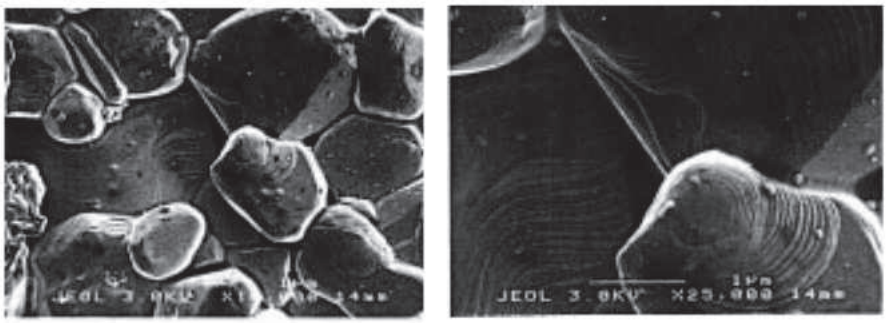


Figure 9-44: Photographs of broken ceramic material taken with a scanning electron microscope

(2) Major characteristics required of photomultiplier tubes

To detect low level light emitted from the scintillator, photomultiplier tubes must have the following characteristics.

a) High stability

b) Low dark current

c) High quantum efficiency

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9.10 Environmental Measurement

Photomultiplier tubes are also used as detectors in environmental measurement equipment, for example, in dust counters used to detect dust contained in air or liquids, and radiation survey monitors used in nuclear power plants. This section explains some of these applications.

9.10.1 Dust counters

(1) Overview

A dust counter measures the concentration of floating dust in the atmosphere or inside a room by making use of principles such as light scattering and absorption of beta rays. Figure 9-45[28] shows the principle of a dust counter using light scattering. If dust is present in the light path, light is scattered by the dust. The quantity of this scattered light is proportional to the quantity of dust. The scattered light is detected by a photomultiplier tube and after being integrated, the output signal is converted into a pulse signal, which then corresponds to the mass concentration. This method offers an advantage that the output signal can immediately follow changes in the concentration, making it suitable for continuous operation to monitor the change over time. However, this method has a disadvantage in that even if the mass concentration is constant, the quantity of scattered light varies with such factors as particle shape and the refractive index.

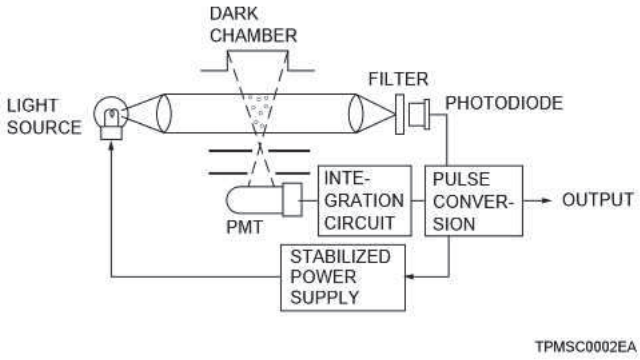


Figure 9-45: Block diagram of a dust counter using light scattering

Another dust counter makes use of the absorption of beta rays which is proportional to the mass of a substance through which the beta rays are transmitted. A filter paper is used to collect the dust, and the difference in the amount of beta-ray absorption before and after collecting the dust are compared to determine the mass.

(2) Major characteristics required of photomultiplier tubes

Since dust counters measure low levels of light, the following characteristics are required of photomultiplier tubes.

a) Less spike noise

b) High quantum efficiency

c) High gain

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9.10.2 NOx analyzers

(1) Overview

These instruments are used to measure nitrogen oxide (NOx), an air-polluting gas contained in exhaust gases from automobiles and other internal combustion engines. NOx is a general term indicating nitrogen monoxide (NO) and nitrogen dioxide (NO_2) and, in many countries, the concentration of NOx is limited by air pollution regulations so that it shall not exceed a certain level.

Figure 9-46 shows the configuration of an NOx analyzer making use of chemiluminescence.[29] When NO gas reacts with ozone (O_3) to become NO_2 gas, chemiluminescence is released. The intensity of this chemiluminescence is proportional to the concentration of NOx. Since other gases contained in the exhaust gas do not produce such luminescence, the NOx concentration can be selectively measured by detecting the intensity of this chemiluminescence.

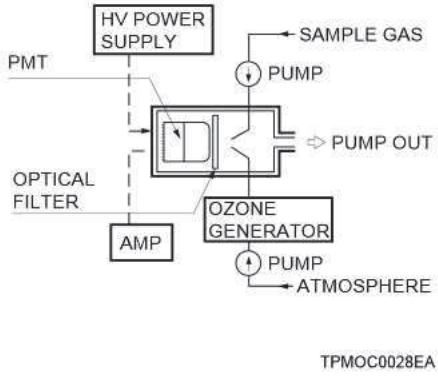


Figure 9-46: NOx analyzer utilizing chemiluminescence

(2) Major characteristics required of photomultiplier tubes

The following characteristics are required because this chemiluminescence increases at 600 nanometers and extends into the infrared region.

a) High quantum efficiency in the infrared region

b) Low noise

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9.10.3 Turbidimeters

(1) Overview

When floating particles are contained in a liquid, light incident on the liquid is absorbed, scattered or refracted by these particles. It looks cloudy or hazy to the human eye. To express the clarity of such liquid, the term "turbidity" is used. A turbidimeter is a device that numerically measures the turbidity by using light transmission or scattering. There are various methods as explained below:

1) Transmitted-light method
   a) Transmitted-light method
   b) Transmitted/scattered-light method
2) Scattered-light method
   a) Forward scattered-light method
   b) Backward scattered-light method
   c) Surface scattered-light method

The principles of the surface scattered-light method[30] and the transmitted/scattered-light method[31] are shown in Figures 9-47 and 9-48, respectively. Either method uses a photomultiplier tube as the photodetector. In the surface scattered-light method, a light beam illuminates the surface of the liquid and the intensity of the light scattered from near the surface is measured. This method facilitates a wide range of measurement points by changing the position at which the light beam is incident. Since the light beam directly strikes the liquid surface, there will be less measurement errors which may otherwise be caused by reflective objects such as a window. However, errors may occur when measuring a colored liquid. The transmitted/scattered-light method measures the ratio between the transmitted and scattered light. No error occurs even when measuring a colored liquid, but dirt or stains on the window may affect the measurement accuracy.

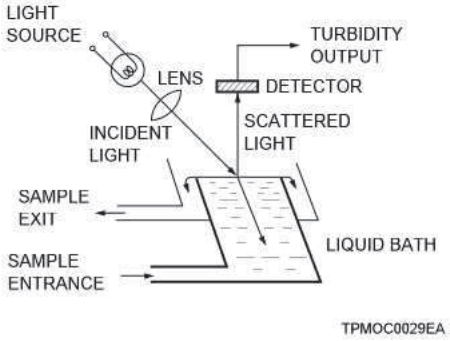


Figure 9-47: Turbidimeter using the surface scattered-light method

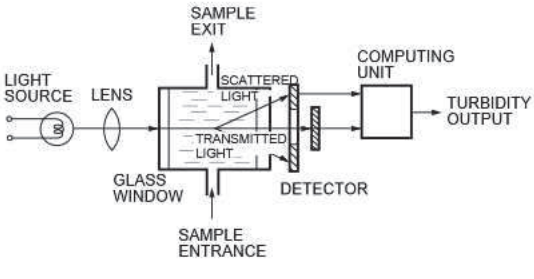


Figure 9-48: Turbidimeter using the transmitted/scattered-light method

(2) Major characteristics required of photomultiplier tubes

Photomultiplier tubes used for turbidimeters must provide the following factors.

a) Low noise

b) High quantum efficiency

c) High gain

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9.10.4 Door monitors

(1) Overview

As the name implies, the door monitor is installed near the exit door in the monitored area of a nuclear power plant, in order to check the personnel going out of this area for contamination by radioactive material. A photomultiplier tube is used in conjunction with a scintillator to detect radiation released from the radioactive material. An example[32] of a door monitor is shown in Figure 9-49. The detector section consists of an array of scintillators coupled to photomultiplier tubes, enabling simultaneous measurement of the location and extent of contamination. Since the number of signals to be detected is usually very low, a coincidence counting circuit is used as in the case of scintillation counting to minimize erroneous signal counting.

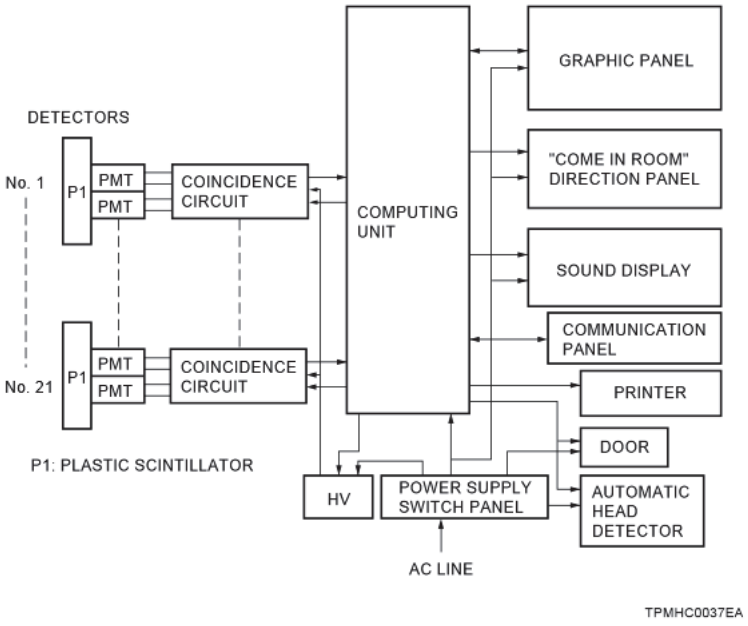


Figure 9-49: Block diagram of a door monitor

(2) Major characteristics required of photomultiplier tubes

Because the number of signals to be detected is very low and, further, the amount of light detected by one photomultiplier tube is small, the following characteristics are required of each photomultiplier tube:

a) High quantum efficiency

b) Low noise

c) High energy resolution or pulse height resolution (PHR)

d) High gain

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9.11 Applications to Laser Measurement

Recently, lasers are being applied to a wide range of measurement and processing applications owing to their superior advantages such as spatial or temporal coherency and high optical power.

Applications utilizing lasers can be classified as follows:

1) Measurement
Rangefinder, laser radar, holography, laser chemistry, medical measurement

2) Data processing
Optical communications, optical data processing

3) Energy sources
Laser processing, laser fusion, laser scalpel

This section explains typical applications of photomultiplier tubes used in laser measurements and major characteristics required.

9.11.1 Overview

Laser measurement applications using photomultiplier tubes include laser radars for rangefinding and atmospheric observation and laser spectroscopy such as fluorescence lifetime measurement. For signal processing in these measurements, the photon counting mode is widely used rather than analog mode, in order to improve the signal-to-noise ratio and enhance the detection limit. Furthermore, time correlated photon counting (TCPC) technique is employed in picosecond measurements such as fluorescence lifetime determination. Figure 9-50 illustrates the block diagram of a laser radar used for atmospheric observation,[33] installed at the National Environmental Pollution Laboratory, Tsukuba, Japan.

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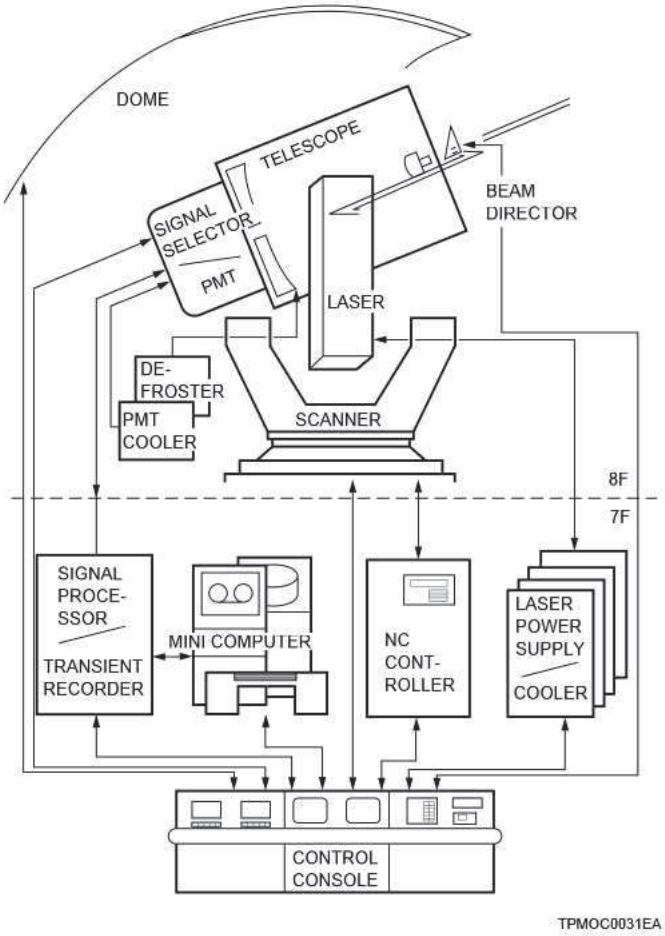


Figure 9-50: Schematic construction of a laser radar for atmospheric observation

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9.11.2 Major characteristics required of photomultiplier tubes

The following photomultiplier tube characteristics are essential in this field.

a) Fast time response

b) Low noise

c) High gain

Of these, time response is the most important factor. With the development of laser technology, photomultiplier tubes with faster time response are in greater demand. In particular, electron transit time spread (TTS) is important for picosecond resolution in measuring fluorescence lifetime.

The TTS (transit time spread) is greatly affected by CTTD (cathode transit time difference) and wavelength effects (Refer to Section 3.3.1, "Time characteristics".) These effects sometimes cause significant problems in normal photomultiplier tubes using discrete dynodes, but create very few problems with an MCP-PMT. Normally, noise should be as low as possible to achieve a high signal-to-noise ratio and especially, the dark count must be small.

The gain should be high enough to obtain a good pulse height distribution in single photon events, in other words, a distinct valley should exist in the single-photoelectron pulse height distribution. Typically, gain of 55 10^6 is necessary.

Figures 9-51[34] and 9-52[35] show a system setup for fluorescence lifetime measurement and typical results that were measured. The photomultiplier tube used for this measurement is a high-speed MCT-PMT (Hamamatsu R3809U).

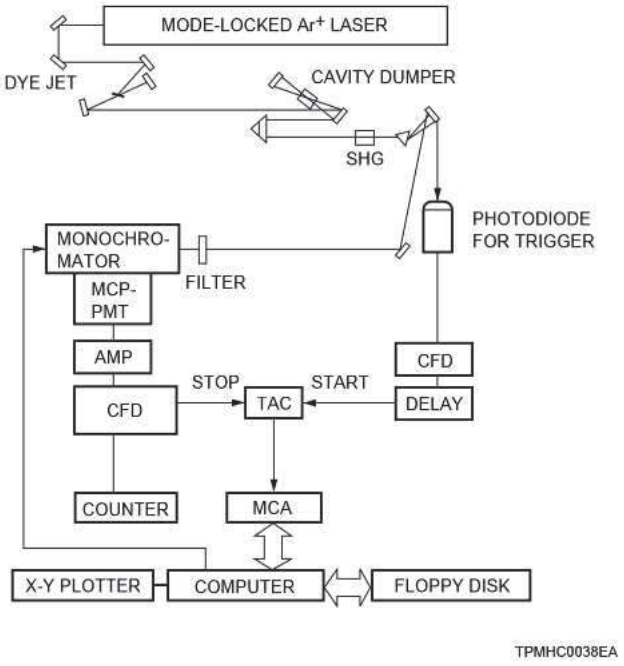


Figure 9-51: TCPC system for fluorescence lifetime measurement

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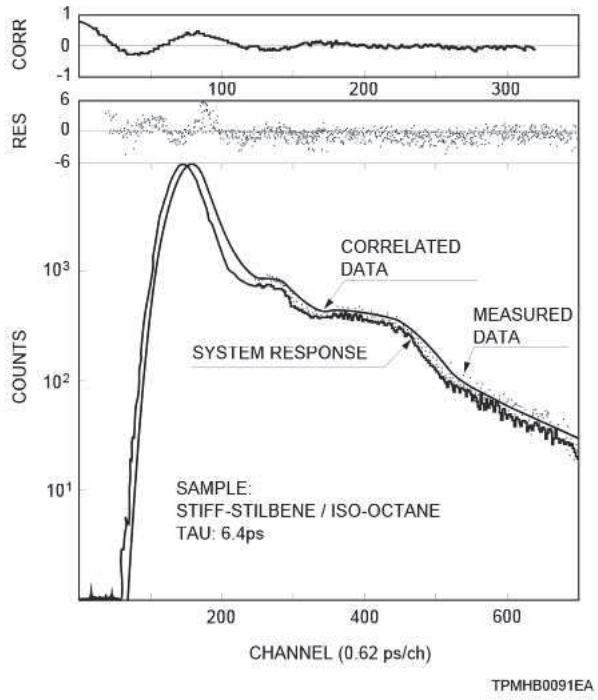


Figure 9-52: Fluorescence lifetime data of stiff-stilbene (courtesy of Prof. Yamazaki, Hokkaido University, Japan)

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9.12 Plasma Applications

Photomultiplier tubes and MCPs (microchannel plates) are used in plasma measurements, such as plasma electron-density and electron-temperature measurement applications utilizing Thomson scattering or the Doppler effect, plasma spatial-distribution observation and plasma impurity measurements intended for controlling impurities and ions in plasma.

9.12.1 Overview

Figure 9-53 shows the construction of a plasma electron-density and electron-temperature measuring system,[36] actually used in a Japanese tokamak-type nuclear fusion reactor "JFT-2". The detector and signal processing units used in this system are also shown in Figure 9-54[37], example of a scattered-light measuring system[38] using a high-power ruby laser designed for plasma diagnosis is shown in Figure 9-55. In both systems, photomultiplier tubes are used as detectors in the ultraviolet to visible region, while multichannel spectrophotometry using an MCP is performed in the soft X-ray region.

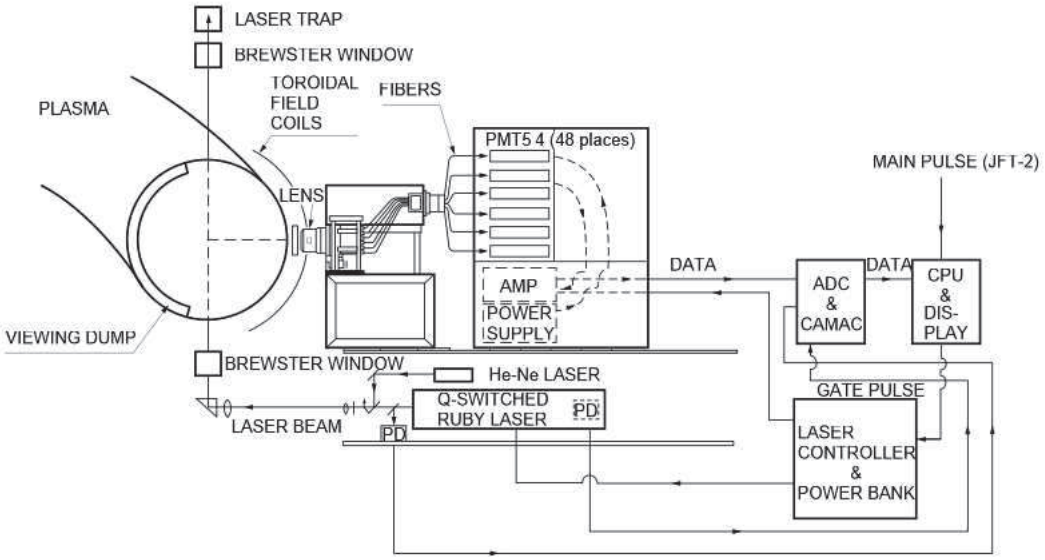


Figure 9-53: Schematic construction of a plasma electron-density and electron-temperature measuring system

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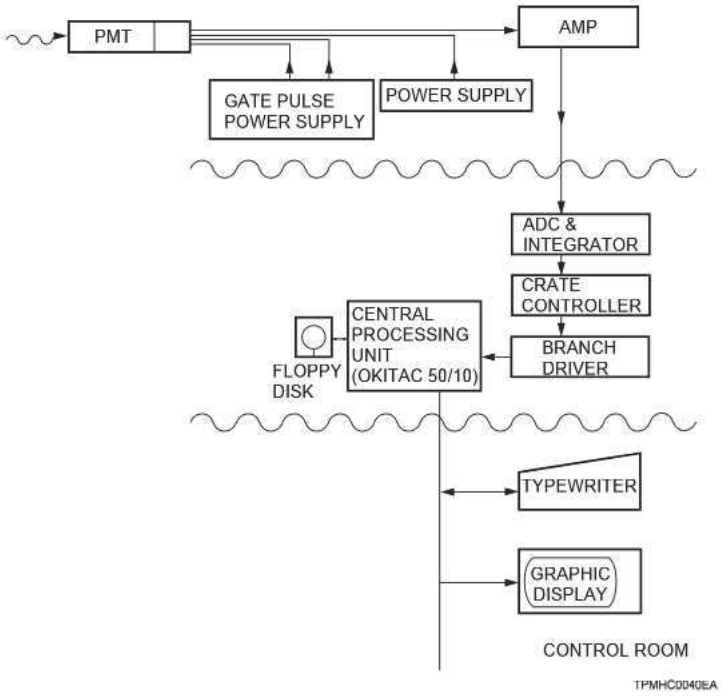


Figure 9-54: Block diagram of the detector and signal processing units used in the above system

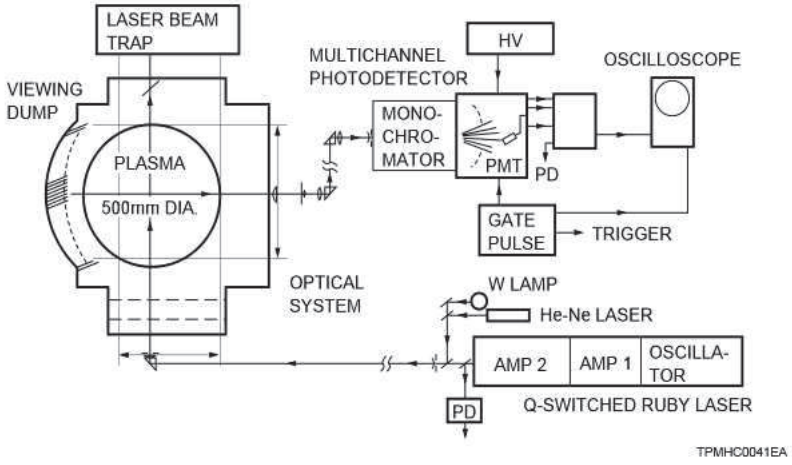


Figure 9-55: Example of a scattered-light measuring system using a ruby laser

9.12.2 Major characteristics required of photomultiplier tubes

a) High photocathode sensitivity

b) Gate operation

Photomultiplier tubes used in this field must provide gate operation to avoid damage caused by input of intense light from the excitation laser, as well as high sensitivity for detecting low light levels.

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9.13 Color Scanners

Photomultiplier tubes are used in color scanners in photographic printing applications. The color scanner is a high-precision instrument designed to produce color-analyzed film by photoelectrically scanning an original color film or reflective print and analyzing its color balance.

9.13.1 Overview

Figure 9-56 shows the block diagram of a color scanner using a photomultiplier tube for each of three primary (red, green, blue) colors and black. There is another type of color scanner that uses a single photomultiplier tube for analyzing and controlling RGB colors by rotating the drum 3 times faster.

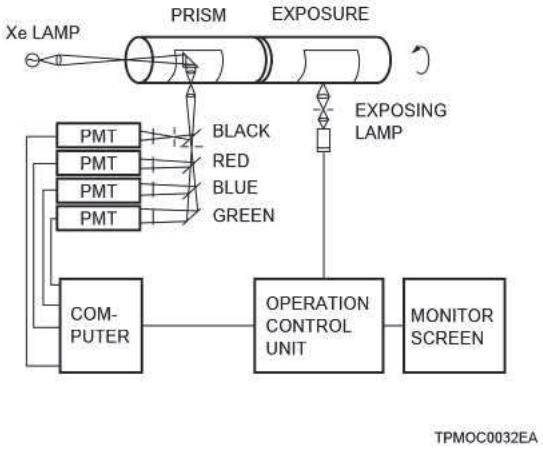


Figure 9-56: Block diagram of a color scanner

9.13.2 Major characteristics required of photomultiplier tubes

The following characteristics are required of photomultiplier tubes used in these applications.

a) High quantum efficiency at each wavelength of RGB

b) Low noise, especially no microphonic noise

c) Fast signal-waveform fall time

d) Good reproducibility with respect to changes in input signal

e) High stability

Among these, fall time and reproducibility are very important factors that affect color shading and resolution of color scanners.

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9.14 Industrial Measurement Applications

For non-contact measurement on a production line and other industrial measurement applications where rapid measurement with a high degree of accuracy and quality is essential, extensive use is made of various devices having photomultiplier tubes as detectors. These devices include thickness gauges, laser scanners and flying spot scanners, which are briefly discussed in the following paragraphs.

9.14.1 Thickness gauges

(1) Overview

To measure the thickness of paper, plastics and steel plates on a production line, non-contact measurement techniques that use radiation such as beta rays, X rays or gamma rays are favored.

These techniques can be roughly divided into two methods: one measures the amount of beta or gamma rays transmitted through an object[39] (Figure 9-57) and the other measures the amount of fluorescent X-rays[40] (Figure 9-58).

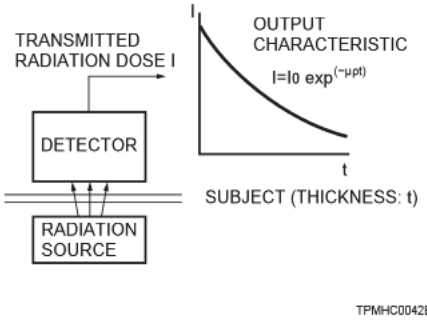


Figure 9-57: Principle of a transmission-mode thickness gauge

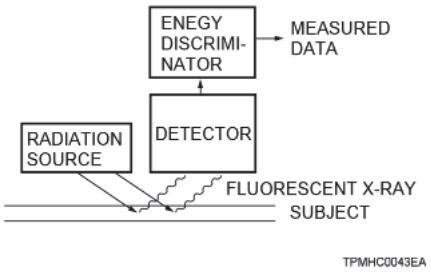


Figure 9-58: Principle of a fluorescent X-ray thickness gauge

When the intensity of radiation incident on a material is I_O, the transmitted radiation intensity I can be expressed in the following relation:

$$I = -I_0 e^{(-\mu\rho t)}$$

t : thickness (m)
ρ : density (g/m^3)
μ : mass absorption coefficient (m^2/g)

Since the transmitted radiation intensity is proportional to the count rate, the thickness of the material can be obtained by calculating the count rate. In general, beta rays are used to measure rubber, plastics and paper which have a small surface density (thickness5 density), while gamma rays are used to measure material with a large density such as metals. In addition, infrared radiation is also used for measurement of films, plastics and other similar materials.

Fluorescent X-rays are used to measure the film thickness of plating and deposition layers. Fluorescent X-rays are secondary X-rays generated when a material is excited by radiation and have characteristic energy of the material. By detecting and discriminating this energy, the quantitative measurement of the object material can be made.

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There are a variety of detectors used in these applications, such as proportional counter tubes, GM counter tubes, photomultiplier tubes and semiconductor detectors. Photomultiplier tubes are used in conjunction with scintillators, mainly for detection of gamma rays and X-rays.

(2) Characteristics required of photomultiplier tubes

Major characteristics required of photomultiplier tubes in these applications are as follows:

a) Superior linearity characteristics

b) Low hysteresis

c) High energy resolution or pulse height resolution (PHR)

d) Stability

9.14.2 Laser scanners

(1) Overview

Laser scanners are widely used in pattern recognition such as defect inspection and mask alignment of semiconductor wafers.

In semiconductor wafer inspection systems,[41] a laser beam is scanned over the wafer surface or the wafer itself is scanned while a laser beam is focused onto a fixed point. In either case, photomultiplier tubes are commonly used to detect scattered light caused by dirt, stain and defects on the wafer surface. (See Figure 9-59.)

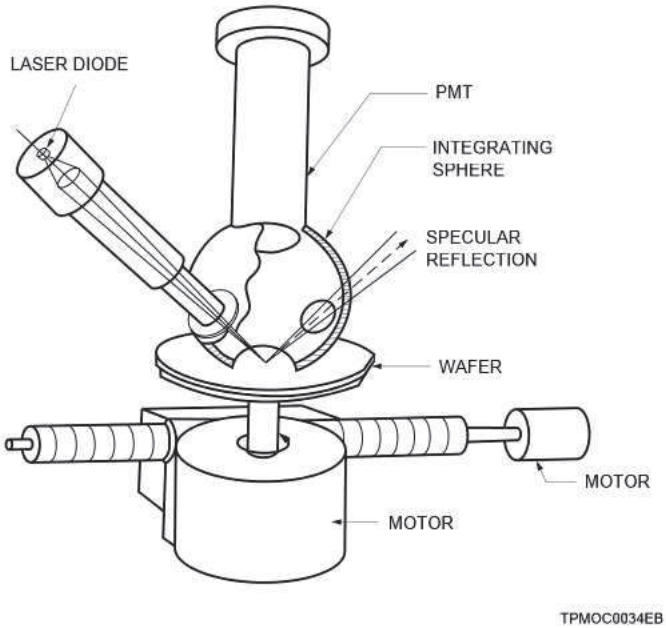


Figure 9-59: Construction of the optical system for a semiconductor wafer inspection system

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(2) Characteristics required of photomultiplier tubes

The following characteristics are required of photomultiplier tubes used in laser scanners.

a) Low dark current and spike noise

b) High quantum efficiency at wavelengths to be measured

c) Superior uniformity

d) Superior linearity

e) Resistance to relatively large current and good stability

9.14.3 Flying spot scanners

(1) Overview

There are several methods for converting the information recorded on photographic film into electrical signals, for example, methods using a camera tube, CCD linear image sensor or flying spot scanning. Of these, flying spot scanning using photomultiplier tubes as detectors has been extensively used thanks to its advantages in processing speed, sensitivity and image quality including resolution and signal-to-noise ratio.

In a typical flying spot scanner, a special low-lag CRT (cathode-ray tube) called a flying spot tube provides a small light spot to form a raster. The raster is focused onto the film, and the transmitted or reflected light is detected by photomultiplier tubes. The block diagram[42] of a typical flying spot scanner is shown in Figure 9-60. The flying spot scanner is used not only in image processing but also inspection of photolithographic masks used for fabrication of semiconductor devices. Figure 9-61 shows an example of this application.[43]

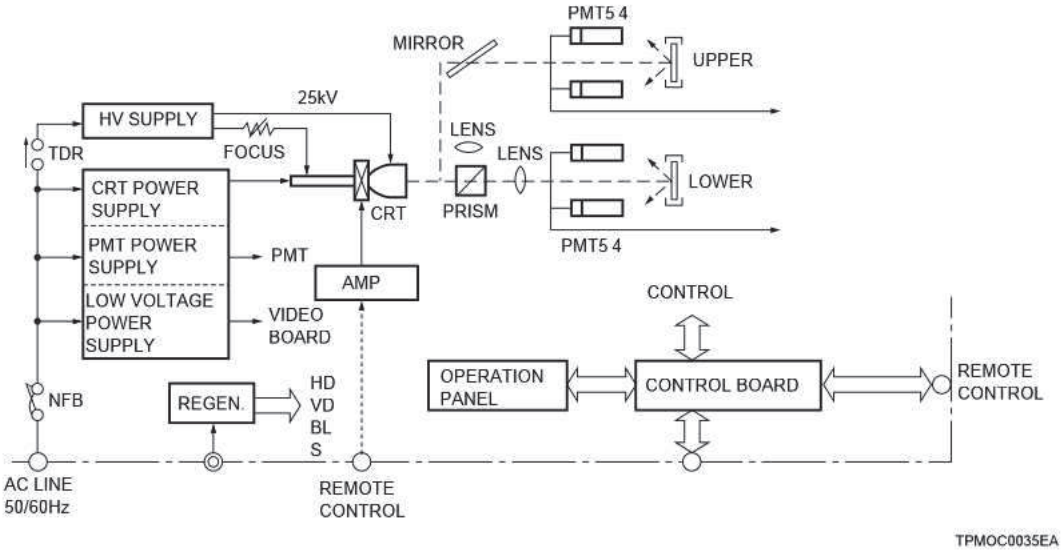


Figure 9-60: Block diagram of a flying spot scanner

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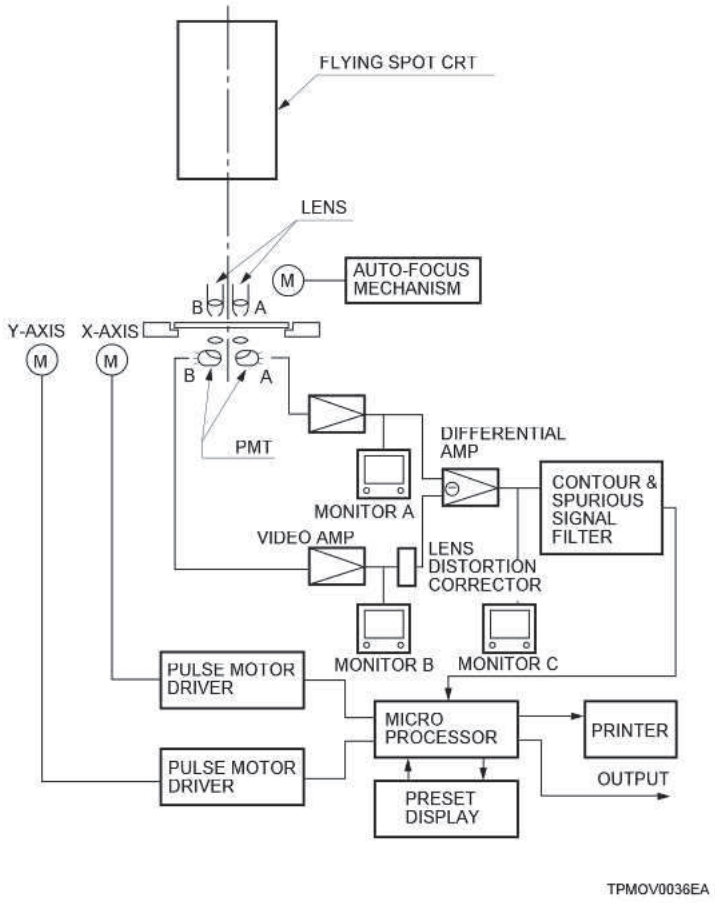


Figure 9-61: Semiconductor mask inspection system utilizing a flying spot scanner

(2) Characteristics required of photomultiplier tubes

Photomultiplier tubes used in flying spot scanners should have the following characteristics.

a) Low dark current and spike noise

b) High quantum efficiency (at RGB wavelengths in the case of color operation)

c) Wide dynamic range

Spike noise may be a cause of a spot-like noise, and low quantum efficiency may result in an increase in shot noise, leading to deterioration of the signal-to-noise ratio.

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9.15 Space Research Applications

Photomultiplier tubes are widely used in space research applications, for example, detection of X-rays from space, planetary observation, solar observation, environmental measurement in inner or outer space and aurora observation. In addition, photomultiplier tubes are also used for spectral measurements of various radiation in the atmosphere or outer space and measurement of X-rays from supernovas.

9.15.1 Overview

Figure 9-62 illustrates the structure of ASUKA launched and placed in its orbit in February 1993, as the fourth astronomical satellite for X-ray observation in Japan. A gas imaging spectrometer (GIS) is used as the detector, which consists of a gas-scintillation proportional counter coupled to a photomultiplier tube (Hamamatsu R2486X).

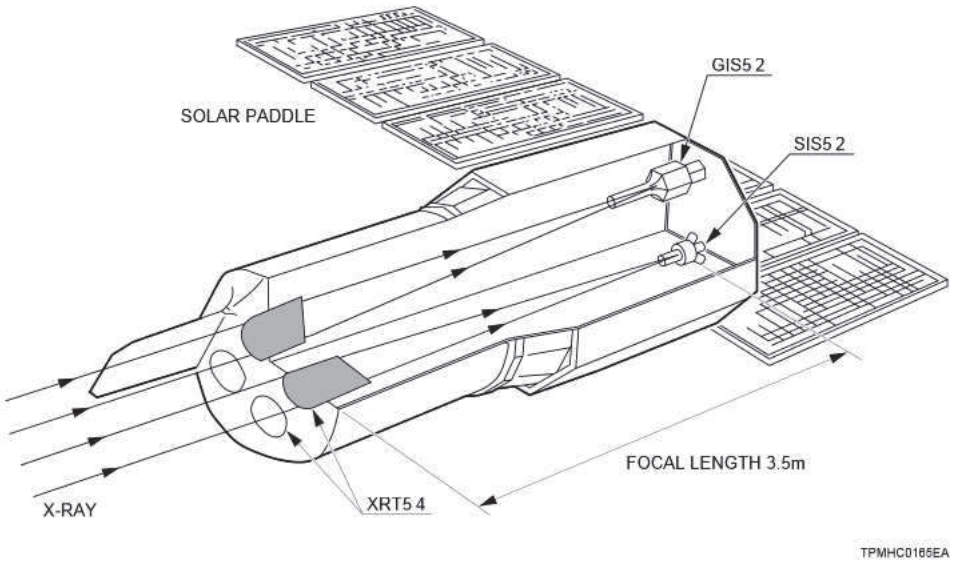


Figure 9-62: Astronomical satellite ASUKA for X-ray observation

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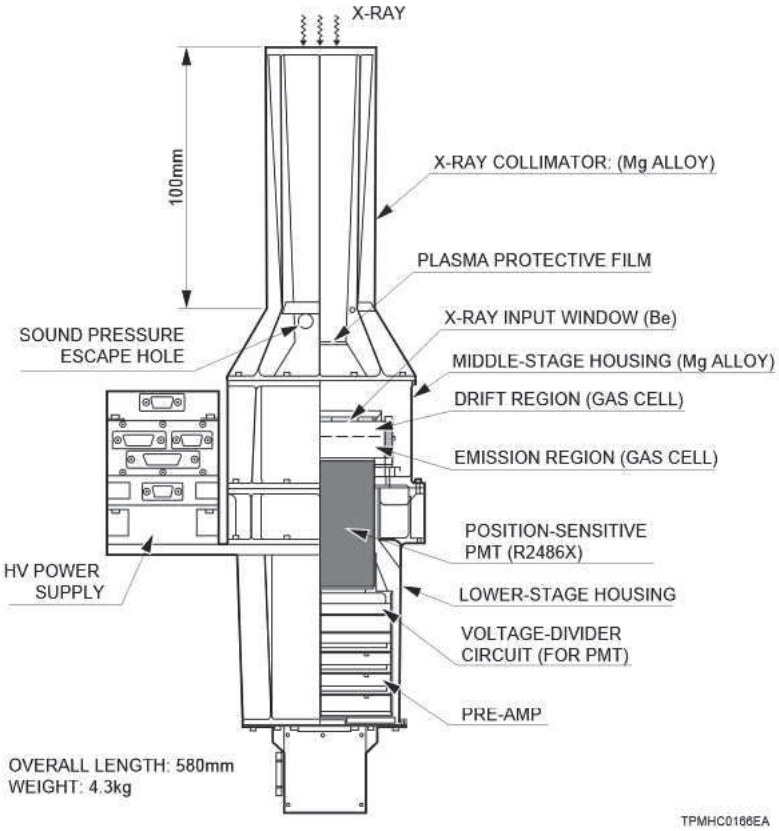


Figure 9-63: X-ray detector (GIS detector) mounted in the ASUKA

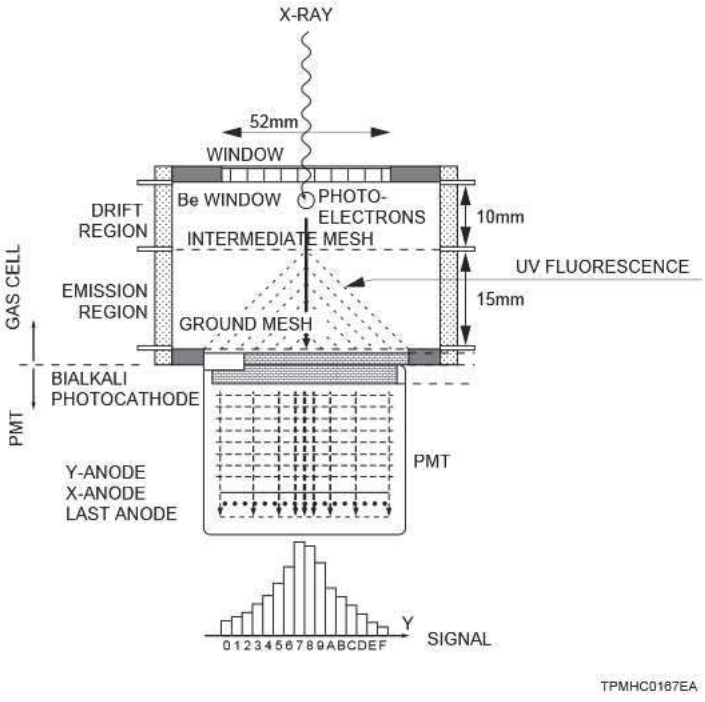


Figure 9-64: Principle of detection in the GIS detector

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The ASUKA has succeeded in discovering various interesting facts, beginning from the detection of X-rays travelling from the supernova named "SN19993J", discovery of low-luminosity nucleus in the center of ordinary galaxy, and world's first detection of inverse Compton X-rays coming from a radio galaxy. Furthermore, the ASUKA successfully revealed that the low energy spectrum of CXB (cosmic X-ray background) is extending to 1keV as single photon fingers. This discovery is expected to elucidate the CXB, which is the primary object of the ASUKA.

9.15.2 Characteristics required of photomultiplier tubes

Photomultiplier tubes used in these applications must provide the following characteristics.

a) High energy resolution

b) Resistance to vibration and shock

c) Solar blind response (in the case of vacuum UV to UV detection)

As discussed in Chapter 8, photomultiplier tube resistance to vibration and shock differs depending on the tube size and dynode structure. Normal photomultiplier tubes are resistant to a vibration of 5 to 10G, while ruggedized tubes can endure up to 15 to 30G. Table 9-5 classifies the grades of measurement conditions. Note that these grades are based on the sinusoidal vibration test, so random vibration tests should also be taken into account as well. Hamamatsu Photonics performs vibration tests according to the user's needs in order to design and manufacture vibration-proof, ruggedized photomultiplier tubes.

Grade	Acceleration G	Frequency	Photomultiplier Tube
A	5.0	10 to 55	Normal type
B	5.0	10 to 500	Normal type
C	7.5	10 to 500	Normal type
D	10	10 to 1000	Normal type
E	15	10 to 2000	Ruggedized type
F	20	10 to 2000	Ruggedized type
G	25	10 to 2000	Ruggedized type
H	30	10 to 2000	Ruggedized type

Table 9-5: Vibration test conditions

In the measurement of radiation traveling from space, photomultiplier tubes must have high sensitivity in the vacuum UV to UV range but also have a solar blind response. Since the detection limit on the short wavelength side is determined by the transmittance of the window material used for the photomultiplier tube, proper selection of window material is also important. Figure 9-65 shows transmittance characteristics of various window materials and Figure 9-66 shows spectral response characteristics of solar blind photocathodes specifically intended for UV detection.

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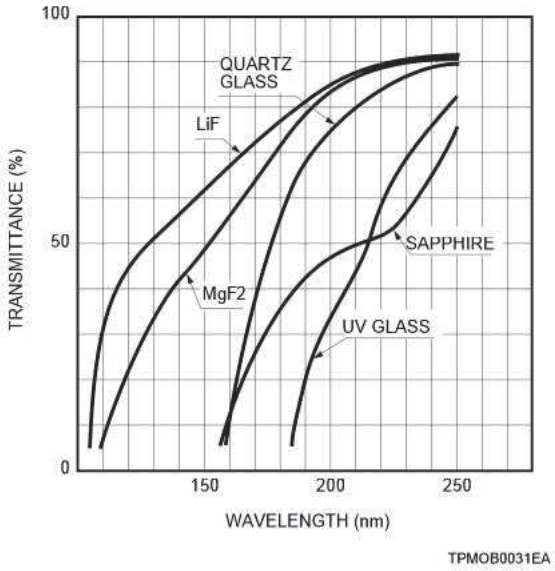


Figure 9-65: Transmittance characteristics of various window materials

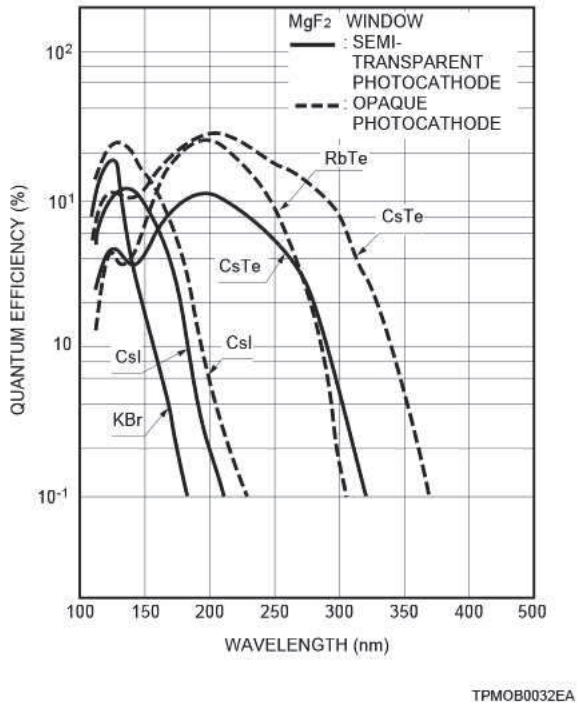


Figure 9-66: Spectral response characteristics of solar blind photocathodes

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9.16 Low-Light-Level Detection

Lately, low-light-level detection is becoming increasingly important in various scientific fields. In particular, low-light-level detection techniques are in greater demand in such studies as Raman scattering, Rayleigh scattering, biology, analytical chemistry, astronomy and fluorescence analysis, The detection techniques using photomultiplier tubes include the analog DC method, analog pulse method and digital method (photon counting). Of these, the photon counting is extremely effective in low-light-level detection. The excellent characteristics of photomultiplier tubes such as high gain and low noise can be fully utilized in this field.

9.16.1 Overview

Low-light-level detection utilizing the superior signal-to-noise ratio of photomultiplier tubes is being applied to diverse fields including Raman scattering, biology, chemical analysis and astronomy. Figure 9-67 shows the block diagram of a laser Raman spectrophotometer.[44)]

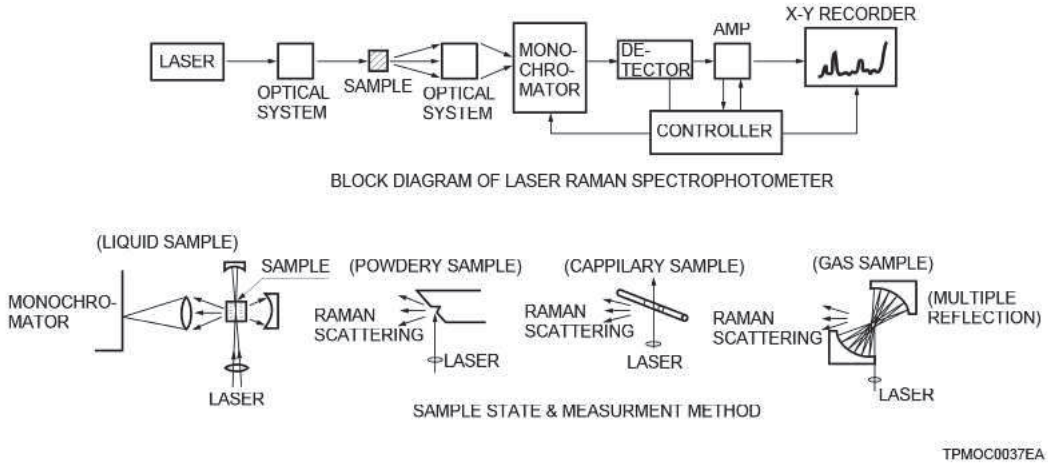


Figure 9-67: Block diagram of a laser Raman spectrophotometer

With recent advancements in laser technology, life science research such as a study of local protein structures utilizing Raman scattering is rapidly progressing. Because Raman scattering has an extremely low light level as compared to Rayleigh scattering (with the same wavelength as that of the excitation light), a high-quality monochromator with minimum stray light and a high-sensitivity detector must be used to separate the Raman scattering from extraneous light. A common monochromator used in Raman spectrophotometry is a double-monochromator equipped with a holographic grating or, in some cases a triple-monochromator with filter mechanism. Raman spectrophotometry requires such a complicated optical system that the incident light on the photomultiplier tube will be exceptionally low. For this reason, the photon counting method which ensures excellent signal-to-noise ratio and stability is frequently used. The monochromator and optical system used in Raman spectrophotometry must provide "minimum stray light", "high resolution" and "good light-collection efficiency". Figure 9-68 shows the optical layout[45)] of a laser Raman spectrophotometer. This instrument usually uses a photomultiplier tube specially selected for photon counting.

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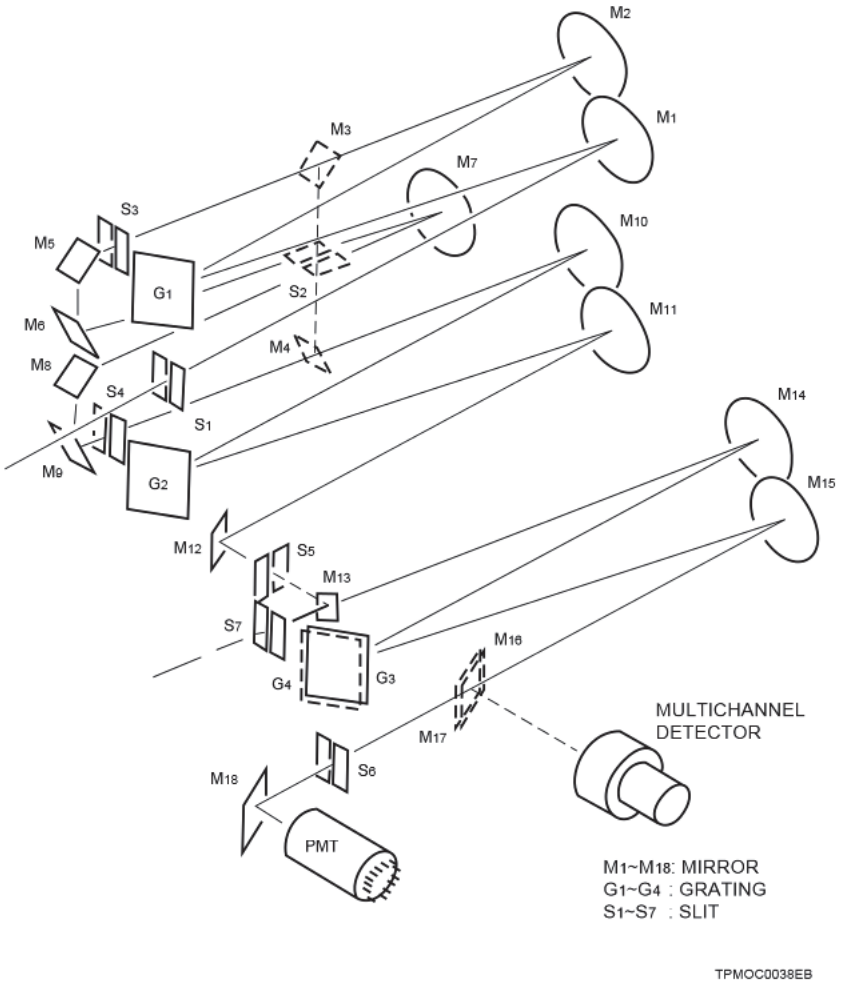


Figure 9-68: Optical layout of a laser Raman spectrophotometer

9.16.2 Characteristics required of photomultiplier tubes

The following characteristics are required of photomultiplier tubes used in photon counting.

a) Less broadening of pulse height distribution, in other words, superior single photoelectron resolution (a sharp valley should exist so that the effects of photomultiplier tube sensitivity drift and supply voltage fluctuation can be reduced when the tube is operated over extended time periods.

b) Less dark current pulse

c) High gain

If linear counting is essential up to a high light level, a fast-response photomultiplier tube must be used. In this case, it is recommended that photomultiplier tubes with a linear-focused dynode or circular-cage dynode be used.

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