CHAPTER 13

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. 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.

13.1 Effects of Ambient Temperature

13.1.1 Temperature characteristics

The photomultiplier tube is more susceptible to ambient temperature than ordinary electronic components (such as resistors and capacitors). Therefore in precision measurement, 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 that heat conducts 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 13-1 shows temperature coefficients of major photomultiplier tubes as a function of wavelength.

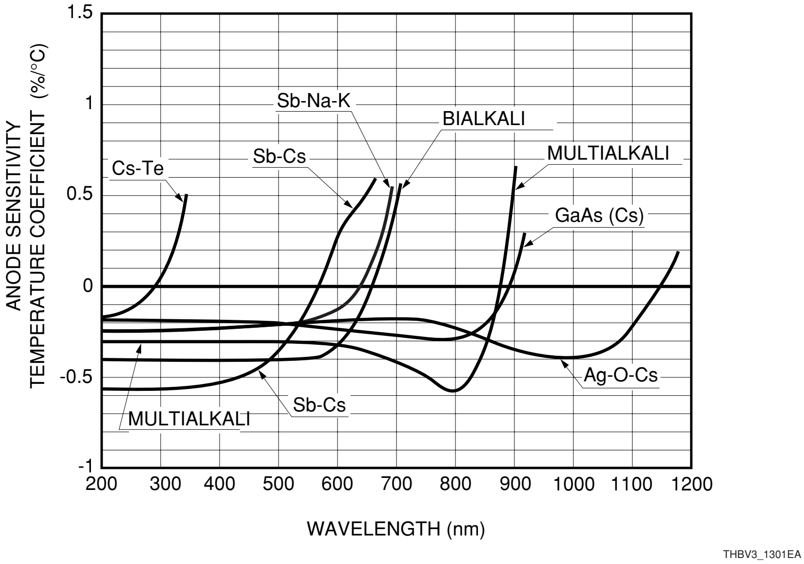

Figure 13-1: Temperature coefficients of photomultiplier tube photocathodes

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, so care is required when using such photomultiplier tubes.

Figure 13-2 shows typical cathode saturation current versus temperature for transmission type bialkali and multialkali photocathodes.

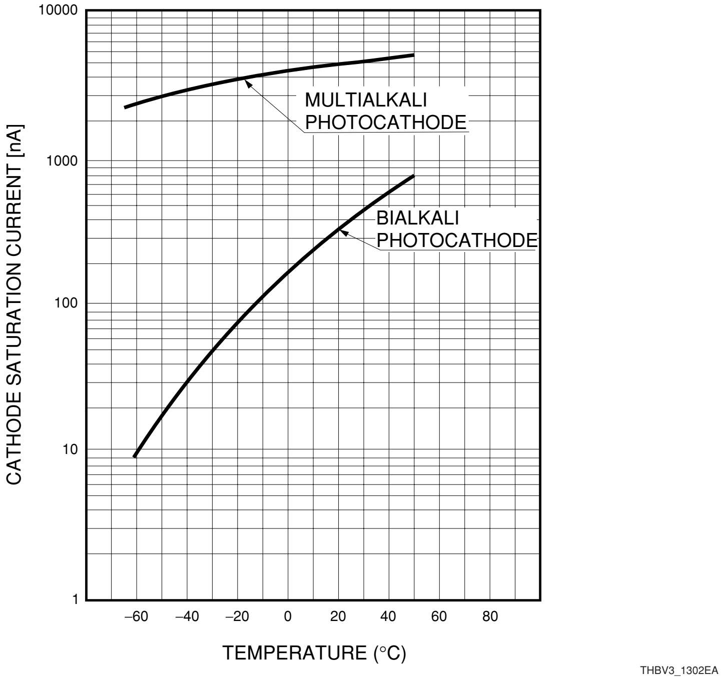

Figure 13-2: Cathode saturation current vs. temperature for transmission type photocathodes

(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. In low-light-level detection, this effect of the ambient temperature on the dark current is an important factor to consider. For example, 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 reduces the signal-to-noise ratio. If a photomultiplier tube must be operated at a high temperature, use of a special photocathode (Sb-Na-K) is recommended. Figure 13-3 shows dark current versus temperature characteristics of the major photocathode types. For details on dark current, refer to 4.3.6 in Chapter 4.

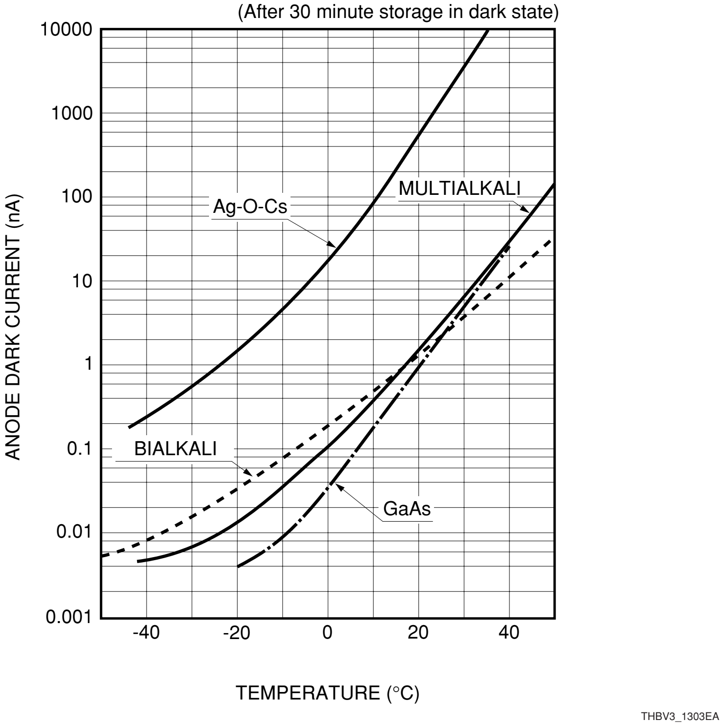

Figure 13-3: Anode dark current vs. temperature

13.1.2 High temperature photomultiplier tubes

Although the guaranteed operating temperature range for general photomultiplier tubes is up to 50°C, high temperature photomultiplier tubes can operate at high temperatures up to 175°C. These tubes use a specially processed bialkali photocathode that exhibits very low dark current even at high temperatures. The multiplier section employs copper-beryllium (CuBe) dynodes designed and optimized for use at high temperatures.

Typical characteristics for high temperature photomultiplier tubes are shown below. Anode dark current versus temperature characteristics are plotted in Figure 13-4, anode output current change over time at different temperatures in Figure 13-5, gain and energy resolution (pulse height resolution or PHR) versus temperature in Figure 13-6, and plateau characteristics at different temperatures in Figure 13-7.

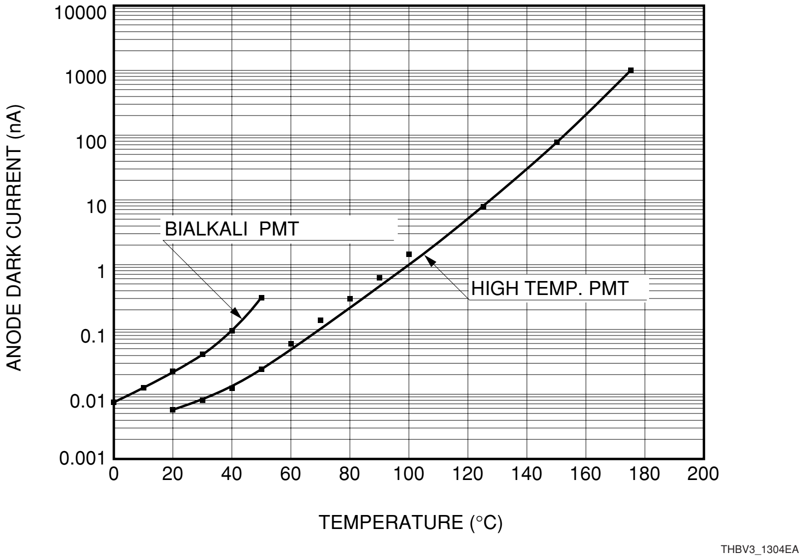

Figure 13-4: Anode dark current vs. temperature

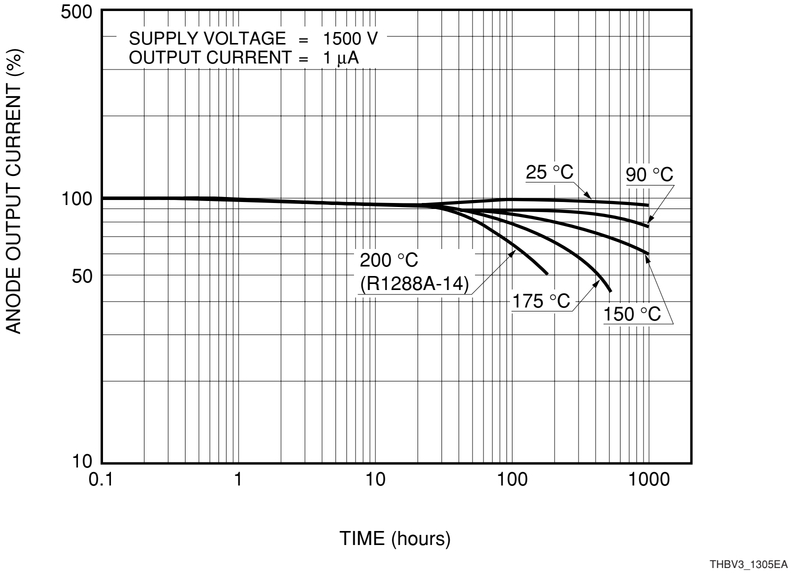

Figure 13-5: Anode current change over time at different temperatures

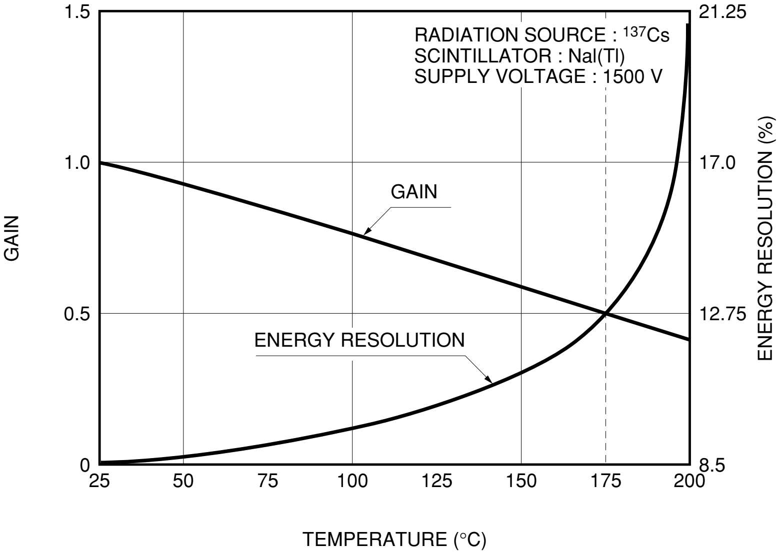

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Figure 13-6: Gain and energy resolution vs. temperature

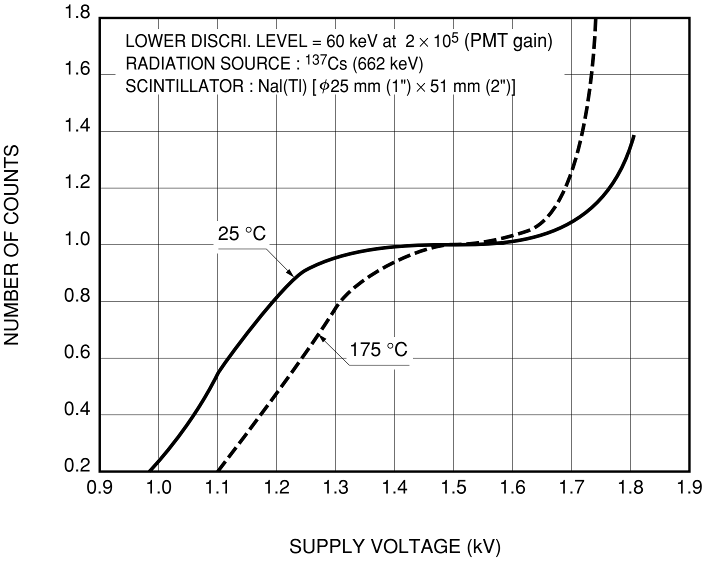

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Figure 13-7: Plateau characteristics at different temperatures

13.1.3 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.

As explained in section 13.1.1 (dark current), 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 glass bulb, base 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.

13.2 Effects of Humidity

13.2.1 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.

13.2.2 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. The photomultiplier tube must therefore be stored in locations of low humidity. 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.

13.3 Effects of External Magnetic Fields

13.3.1 Magnetic characteristics

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 (28 mm) side-on types. Metal-package type photomultiplier tubes (R7400 series) offer excellent immunity to magnetic fields because they have a short distance from the photocathode to the first dynode. Figure 13-8 shows the effects of magnetic fields on typical photomultiplier tubes. Also note that the higher the supply voltage to a photomultiplier tube, the less the effects of magnetic fields.

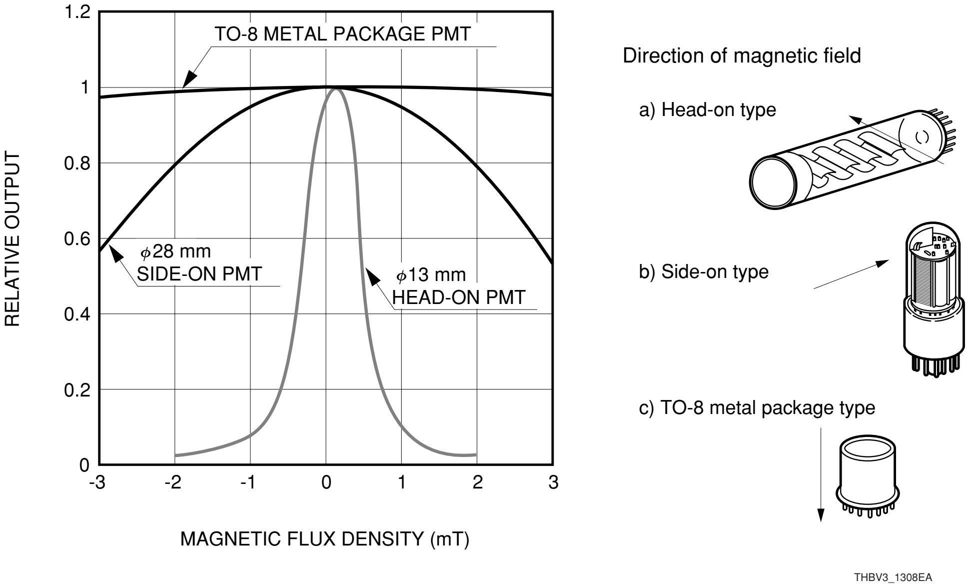

Figure 13-8: Magnetic characteristics of typical photomultiplier tubes

As can be seen from Figure 13-8, 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 5.4 of Chapter 5 for more details and specific usage of magnetic shield cases.

13.3.2 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 (19 stages).1) The structure of this photomultiplier tube is illustrated in Figure 13-9. Figure 13-10 shows current gain versus magnetic field perpendicular to the photocathode (tube axis) for a tetrode and triode types, and relative output of a 19-stage photomultiplier tube versus magnetic field at different angles.

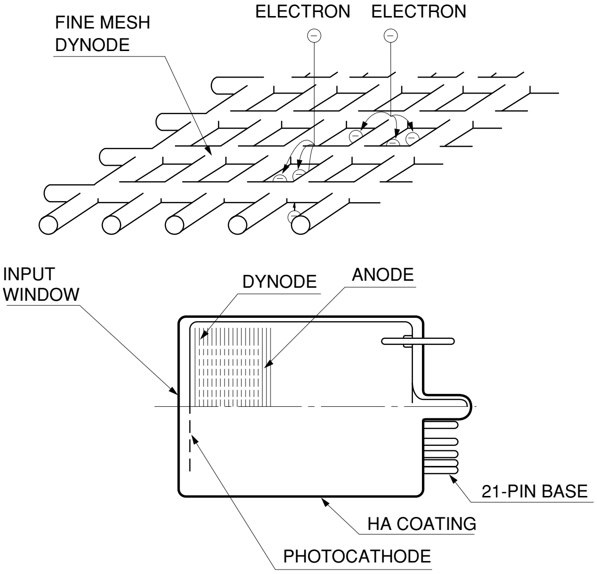

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Figure 13-9: Structure of a photomultiplier tube designed for use in highly magnetic fields

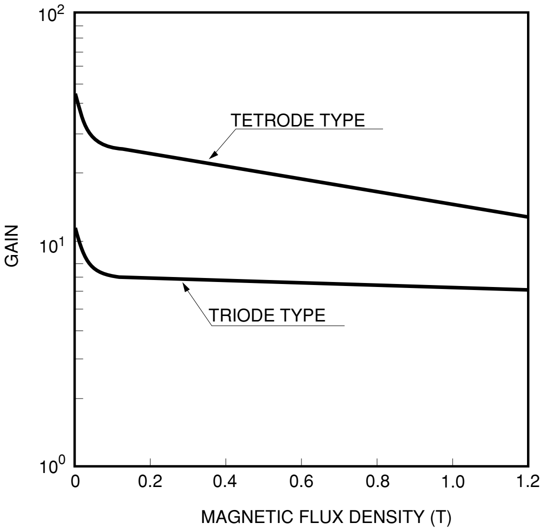

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Figure 13-10: Magnetic characteristics of photomultiplier tubes for highly magnetic fields (1)

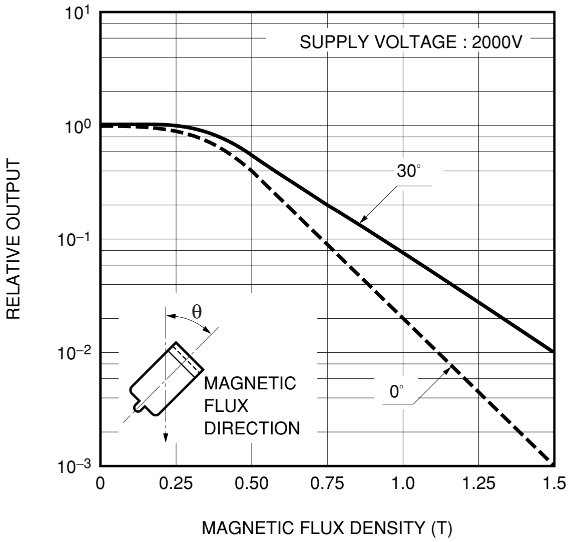

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Figure 13-10: Magnetic characteristics of photomultiplier tubes for highly magnetic fields (2)

13.3.3 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). 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.

13.3.4 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 with nonmagnetic materials for the dynode substrate. However, the stem pins and hermetically-sealed portions still must be made from magnetic materials.

13.4 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.

13.4.1 Resistance to vibration and shock during non-operation

Photomultiplier tubes are designed to withstand tens of m/s^2 of vibration and several thousand m/s^2 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 (m/s^2)	Maximum Shock (m/s^2)
1/2 inch side-on	150 (10 to 2000 Hz)	2000 (6 ms)
1-1/8 inch side-on	100 (10 to 500 Hz)	1000 (11ms)
Metal package TO-8 type	100 (10 to 500 Hz)	1000 (11 ms)
1/2 inch head-on	100 (10 to 500 Hz)	1000 (11 ms)
1-1/8 inch head-on	50 (10 to 500 Hz)	1000 (11 ms)
2 inch head-on	50 (10 to 500 Hz)	750 (11 ms)
3 inch head-on	50 (10 to 500 Hz)	750 (11 ms)

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 that is 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. Precautions are required, especially in handling a large diameter tube of more than 8 inches (204 millimeters).

13.4.2 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 13-11 shows the variations in the frequency spectrum of photomultiplier tube output subjected to vibration, along with the measurement block diagram.

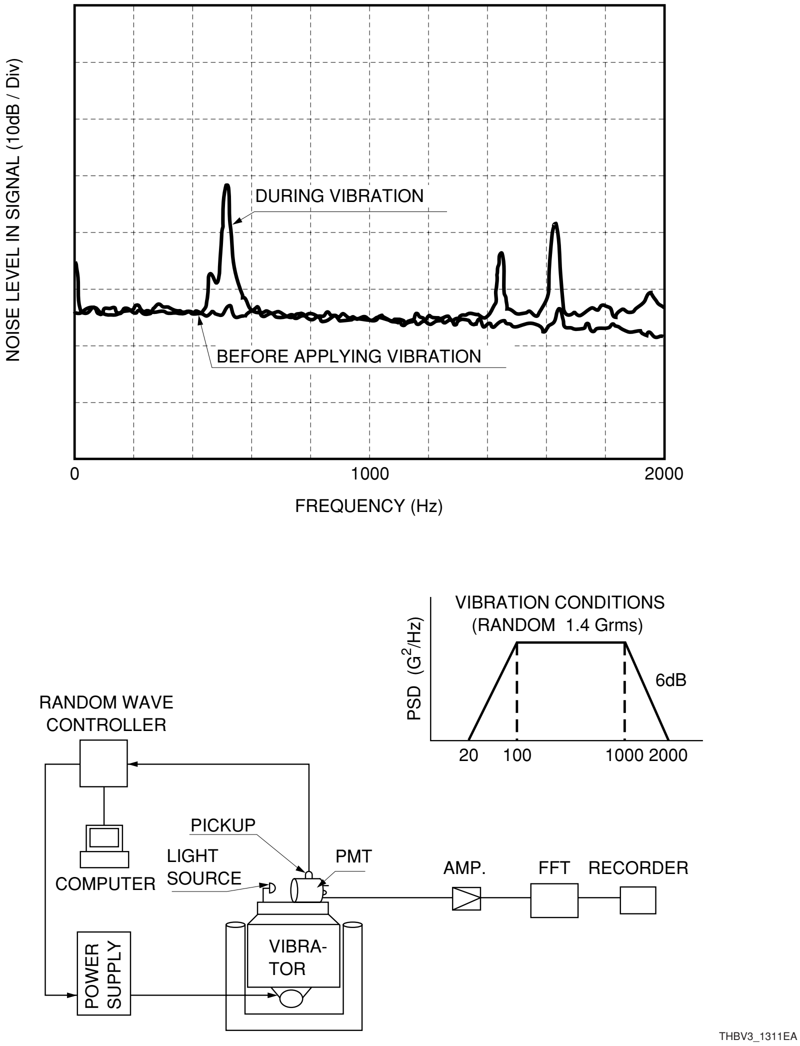


Figure 13-11: Resonance noise in the output signal of a photomultiplier tube subjected to vibration

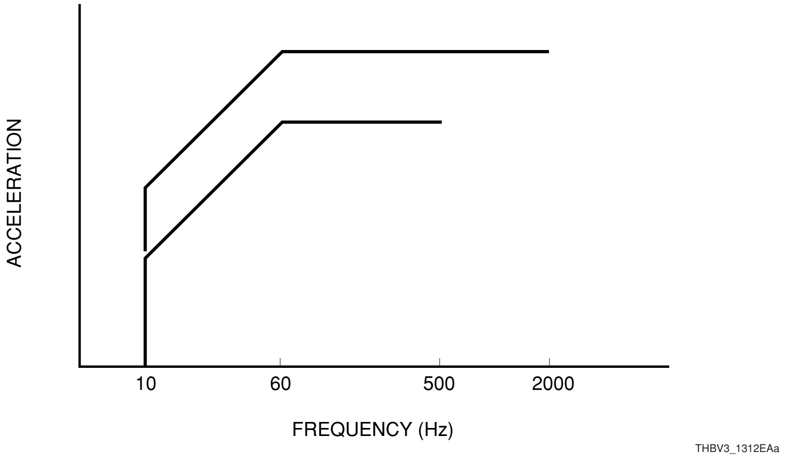
In this experiment, the photomultiplier tube is subjected to random vibration (1.4 Grms) from 20 Hz to 2000 Hz and its output signal is frequency-analyzed using a FFT (fast fourier transform). It is obvious from Figure 13-11 that the noise sharply increases at frequencies near 0.5 kHz, 1.45 kHz and 1.6 kHz.

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.

13.4.3 Testing methods and conditions

There are two vibration test methods[2): sinusoidal-wave and random-wave application tests. In the first method, 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. In the second 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 conditions close to the actual environment. In Figures 13-12 (A) and (B), vibration waveform examples created by sinusoidal wave and random wave are shown.

(A): Sinusoidal wave vibration pattern example



(B) Random vibration pattern example

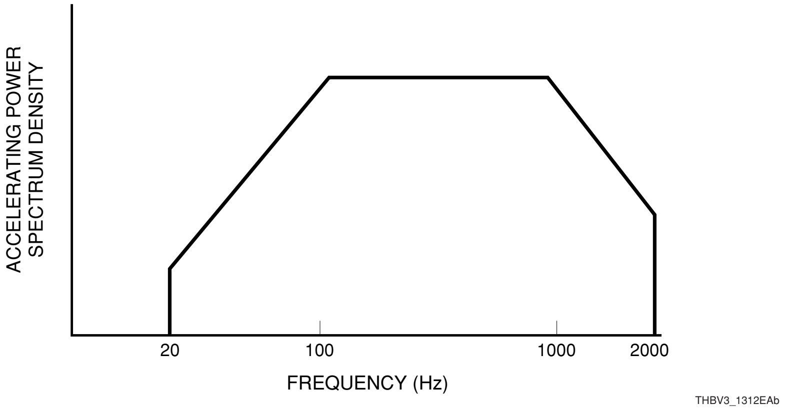


Figure 13-12: Vibration and shock pattern curves (1)

(C) Shock-application pattern (half-wave sinusoidal pulse)

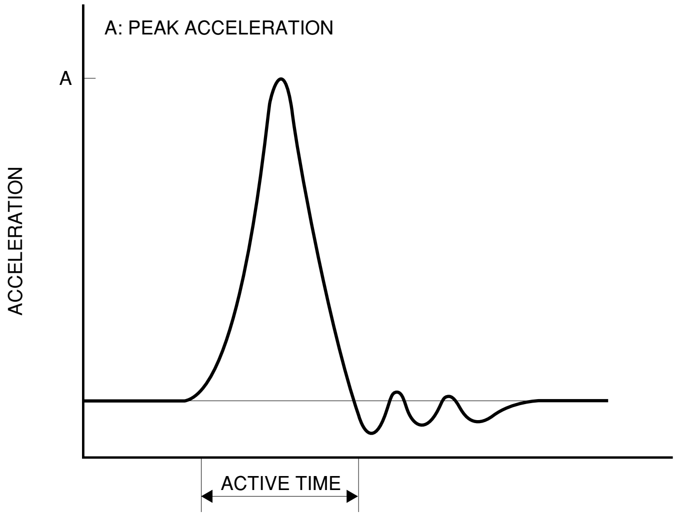


Figure 13-12: Vibration and shock pattern curves (2)

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 13-12 (C).

Official standards for vibration and shock test methods include IEC 60068, JIS-C0040 (vibration), JIS-C0041 (shock), MIL STD-810E and MIL STD-202F.[3)] 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, so that shocks were applied a total of 18 times. Accordingly, even if the test proves that a photomultiplier tube withstands a shock of 1000 m/s^2, this does not mean that it will survive such shocks dozens or hundreds of times.

13.4.4 Ruggedized photomultiplier tubes[4)]

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.[5)] To meet these applications, ruggedized photomultiplier tubes have been developed, which can operate reliably during periods of 200 m/s^2 to 500 m/s^2 vibration and 1000 m/s^2 to 10000 m/s^2 shock. A variety of ruggedized types are available ranging in diameter from 1/2 to 2 inches (13 to 51 millimeters) and are also available with different dynode structures. Most ruggedized photomultiplier tubes are based on conventional glass-envelope photomultiplier tubes, but feature improvements to their electrode supports, lead pins and dynode structure so that they will withstand severe shock and vibration. These ruggedized photomultiplier tubes have a diameter of 2 inches (51 millimeters) or less, and can withstand vibrations up to 200 m/s^2. If even higher performance is required, specially-designed ruggedized photomultiplier tubes having a stacked ceramic bulb are used. Figure 13-13 shows the cross section of this type of ruggedized photomultiplier tube.

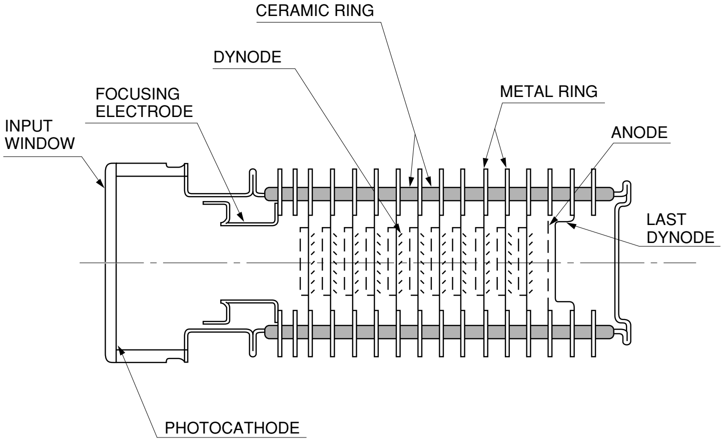


Figure 13-13: Cross section of a ruggedized photomultiplier tube using a stacked ceramic bulb.

As illustrated in Figure 13-9, 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 1-3/8 inch (34 mm) stacked-ceramic photomultiplier tube using a high-temperature bialkali photocathode and a 12-stage dynode multiplier is as follows:

Resistance to vibration	500 m/s^2 (50 to 2000 Hz)
Resistance to shock	10000 m/s^2 (0.5 ms)

13.5 Effects of Helium Gas

It is well known that helium gas permeates through glass.$^{6)}$ 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. This will cause permanent damage to the tube and must be avoided. To reduce the effects of helium gas, it is best to use alternatives to helium such as argon gas and nitrogen gas.

Helium gas exists on the earth at a partial pressure of about 0.5 Pa. 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 1.013×10^5 Pa) 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 1-1/8 inch (28 mm) diameter side-on photomultiplier tube with a silica bulb is left in the atmosphere, the helium partial-pressure inside the tube will increase to 9×10^{-2} Pa after one year. (Refer to Figure 13-14.)

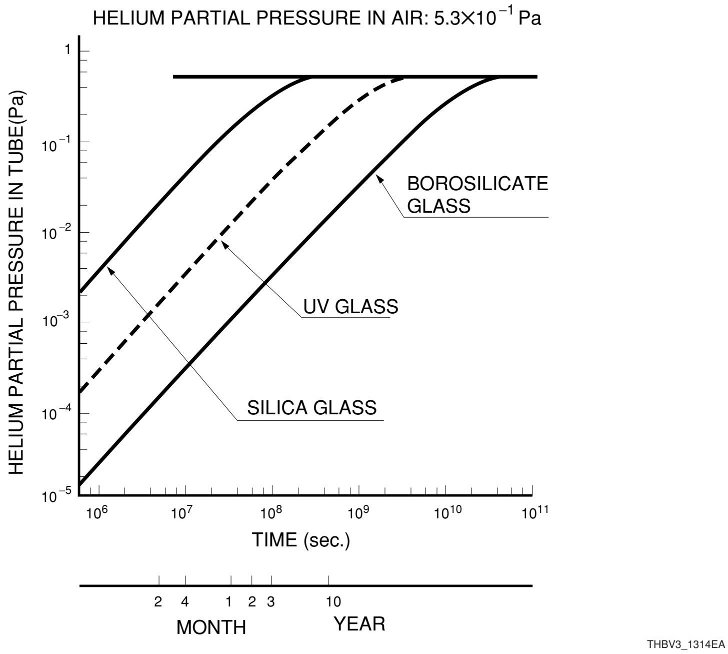


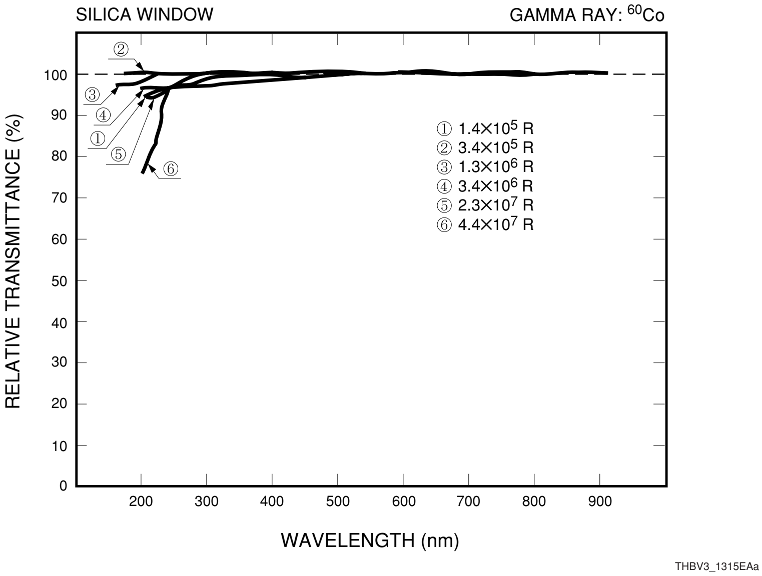
Figure 13-14: Bulb materials and variations in helium partial-pressure inside a tube

13.6 Effects of Radiation

Photomultiplier tube applications are constantly expanding, as stated previously, to such fields as high energy physics, nuclear medicine, X-ray 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.7) For example, radiation causes deterioration of the glass envelope, metals, insulators, and materials used to construct the photomultiplier tube.

13.6.1 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.8) Figures 13-15 to 13-17 show variations in the window transmittance when photomultiplier tubes are irradiated by gamma rays from a ^{60}Co radiation source and also by neutrons (14 MeV). (The windows are 2 mm thick.)



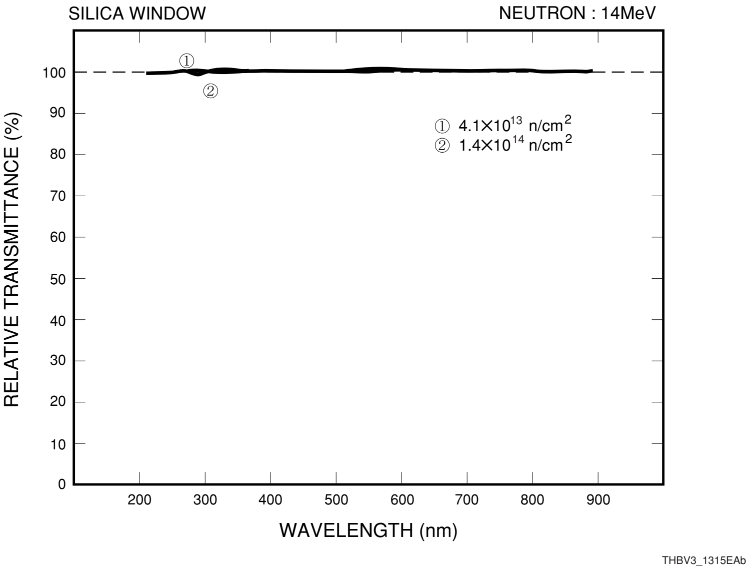
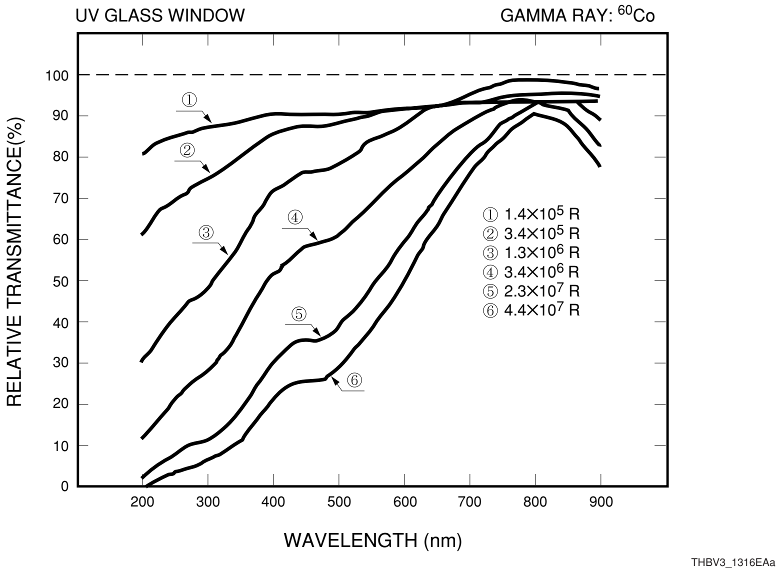


Figure 13-15: Transmittance change of silica window irradiated by gamma rays/neutrons



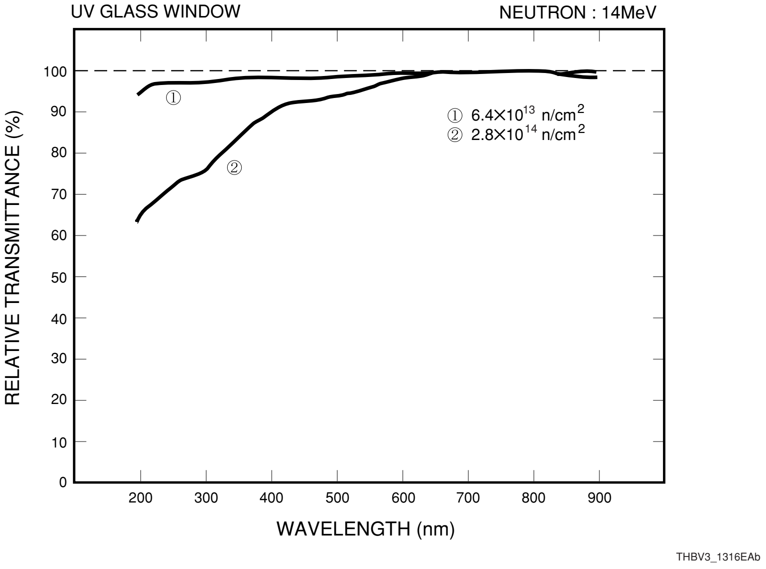
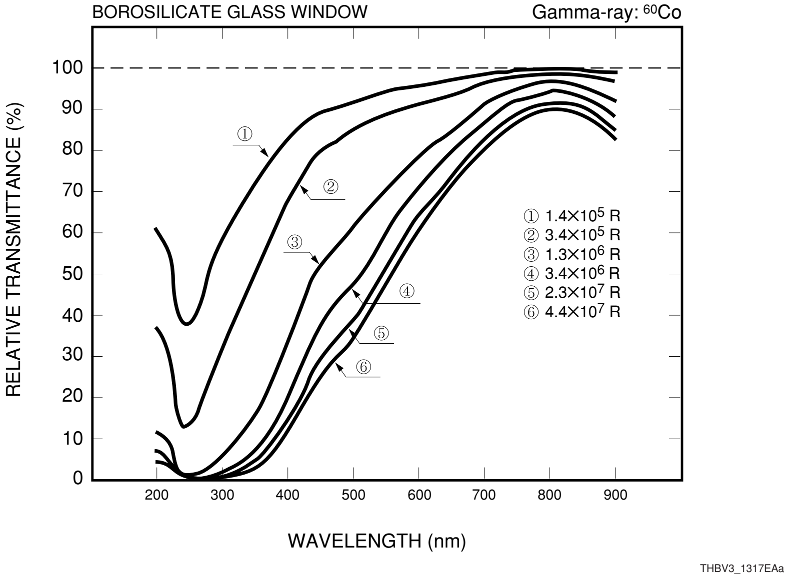


Figure 13-16: Transmittance change of UV glass window irradiated by gamma rays/neutrons



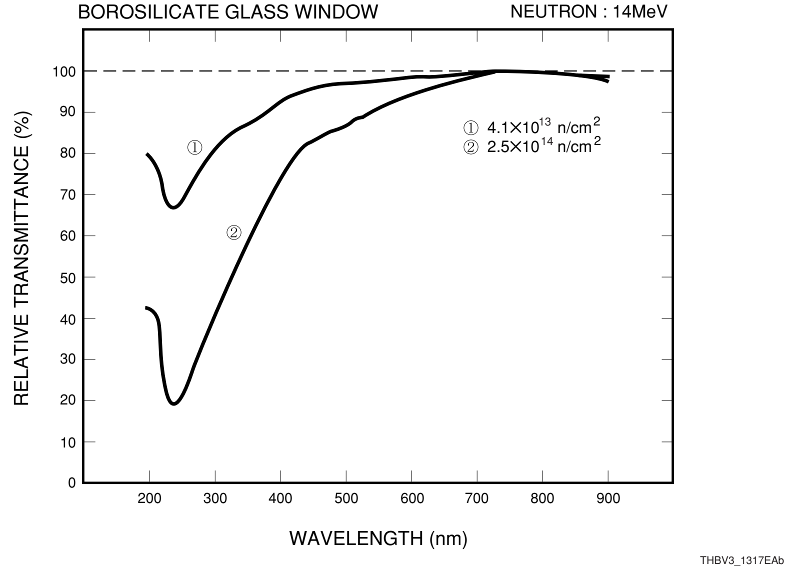


Figure 13-17: Transmittance change of borosilicate glass window irradiated by gamma rays/neutrons

As can be seen from these figures showing the data on a synthetic silica, UV glass and borosilicate glass respectively, a loss of 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 4.4×10^7 roentgens and neutrons of 1.4×10^{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 5×10^4 roentgens for the UV glass, and near 1×10^4 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 best with silica, followed by UV glass and borosilicate glass. If 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.

13.6.2 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.[9)]

Of these, the scintillation of the glass window likely has the largest contribution to noise, but 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 13-18 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).

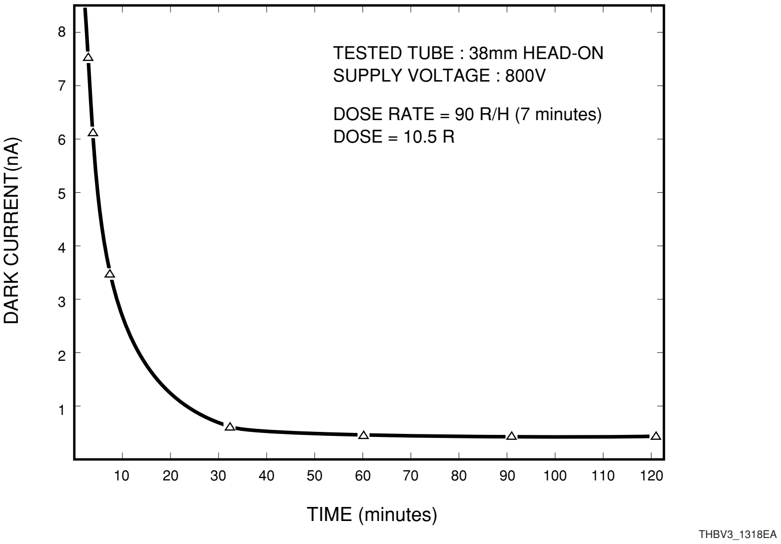


Figure 13-18: Dark current variation after exposure to gamma ray

13.7 Effects of Atmosphere

The photomultiplier tube may be used in environments not only at one atmosphere (1×10^5 Pa) but also at very low pressures or in depressurized areas such as in aircraft or an artificial satellite.

When there is a pressure drop from the atmospheric pressure down to a near vacuum in outer space, there is a possibility of a discharge occurring between the leads in the photomultiplier tube base. This phenomenon is known as 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 Pa to 1000 Pa*. If the photomultiplier tube is to be operated in this pressure range, sufficient precautions must be taken in the design and wiring of the parts to which a high voltage is applied. (* 133 Pa = 1 torr.)

Take the following precautions when using photomultiplier tubes in a vacuum.

(1) After making sure that a sufficient vacuum level is obtained, apply high voltage to the tube (gradually from low to high voltage).

(2) When the photomultiplier tube has a plastic base, it will take a long time until the inside of the base is evacuated to a specified vacuum. Drilling a small hole in the base is needed.

(3) A change from 1 to 0.1 Pa may increase the dark current and cause fluctuations in the signal output. Precaution must be taken to maintain the optimal installation conditions.

In high-energy physics applications such as proton decay experiments and neutrino observation, photomultiplier tubes are sometimes operated while underwater or in the sea. In this case, a pressure higher than the atmospheric pressure 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 higher pressure. However, 8-inch (204 mm) and 20-inch (508 mm) diameter photomultiplier tubes, specifically developed for high energy physics experiments, have a hemispherical shape capable of withstanding a high pressure. For example, 8-inch (204 mm) diameter tubes can withstand up to 7×10^5 Pa and 20-inch (508 mm) diameter tubes up to 6×10^5 Pa.

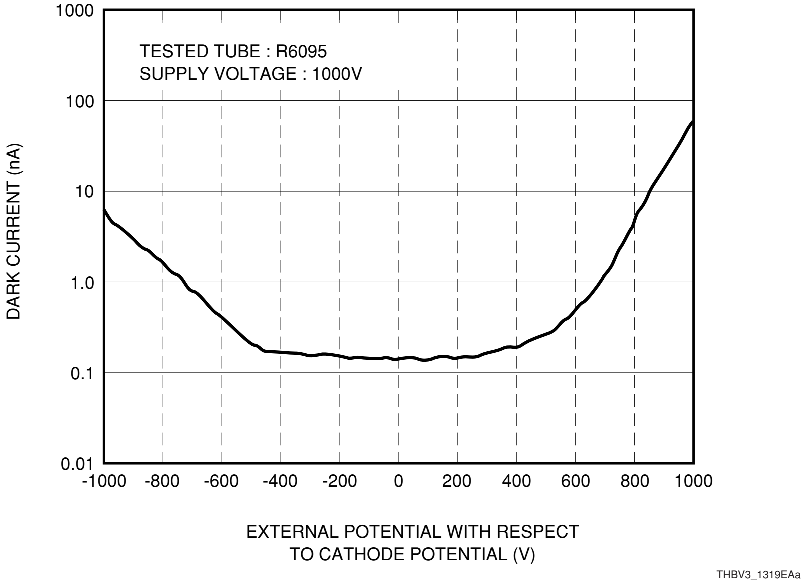
As for the bulb materials, photomultiplier tubes using a silica bulb provide lower pressure-resistance due to the graded seal. There are various shapes of input windows used for head-on photomultiplier tubes, including a plano-plano type (both the faceplate and photocathode are flat), a plano-concave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

13.8 Effects of External Electric Potential

Glass scintillation occurs by exposure to radioactive rays or UV light as explained in section 13.6.2. It also occurs when a strong electric field is applied to the glass. These types of glass scintillations will cause the dark current to increase.

13.8.1 Experiment

Figure 13-19 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 conductive coating with respect to the cathode potential.



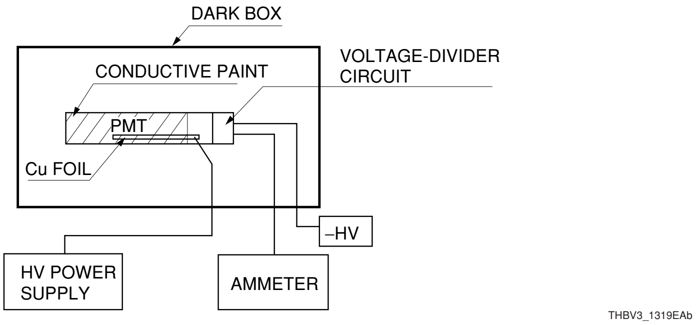


Figure 13-19: Dark current vs. external electric potential

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, and if the outside of the bulb has a large potential difference with respect to the cathode, scintillation will occur in the glass between the two surfaces. This scintillation light will reflect into the photocathode, causing an increase in the dark current.

The housing for photomultiplier tubes is usually made of metal and is grounded. This means that a grounded conductive material is around the photomultiplier tube and may cause the dark current to increase. This problem can be solved by allowing an adequate distance between the photomultiplier tube and the inside of the housing. Figure 13-20 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.

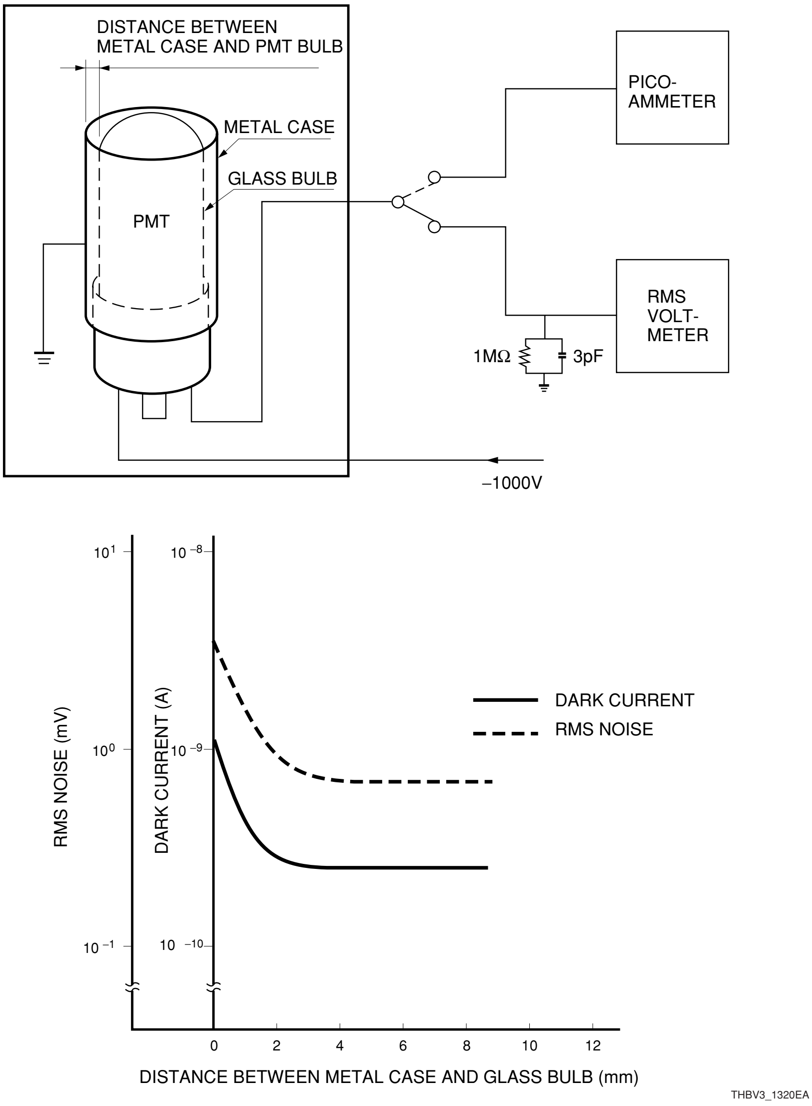


Figure 13-20: Dark current vs. distance to grounded case

13.8.2 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 13-21.

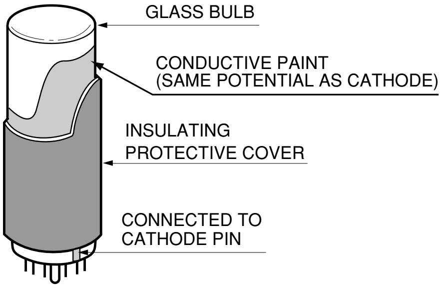


Figure 13-21: HA coating

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 surrounding 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 as shown in Figure 13-22, minute amounts of noise may still occur. 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. Therefore, when using the photomultiplier tube with a negative high voltage, do not allow the metal case or housing to make contact with the tube even if it is an HA coating type.

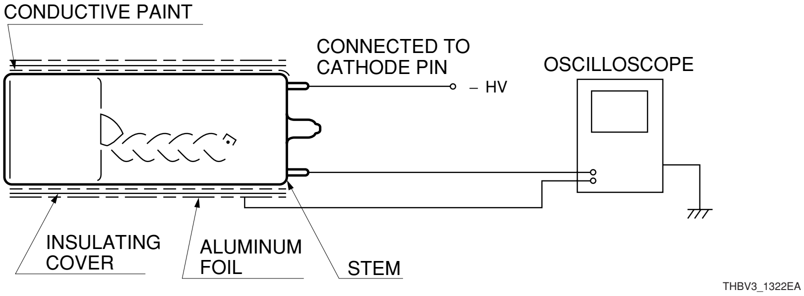


Figure 13-22: Observing the effect of external electric potential on HA coating

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, glass scintillation occurring in the faceplate has a larger influence on the noise. Any grounded object, even insulating materials, should not make contact with the faceplate. If such an object must make contact with the faceplate, use teflon or similar materials with high insulating properties. 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. Take precautions for the mounting method of the photomultiplier tube, so that no object makes contact with the photocathode faceplate and peripheral portions.

Taking account of the above, operating the photomultiplier tube in the cathode grounding scheme with the anode at a positive high voltage is recommended if possible.

13.9 Reliability

13.9.1 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 within 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 13-23 shows typical data for time stability when photomultiplier tubes are operated under harsh conditions at an anode current of 100 µA.

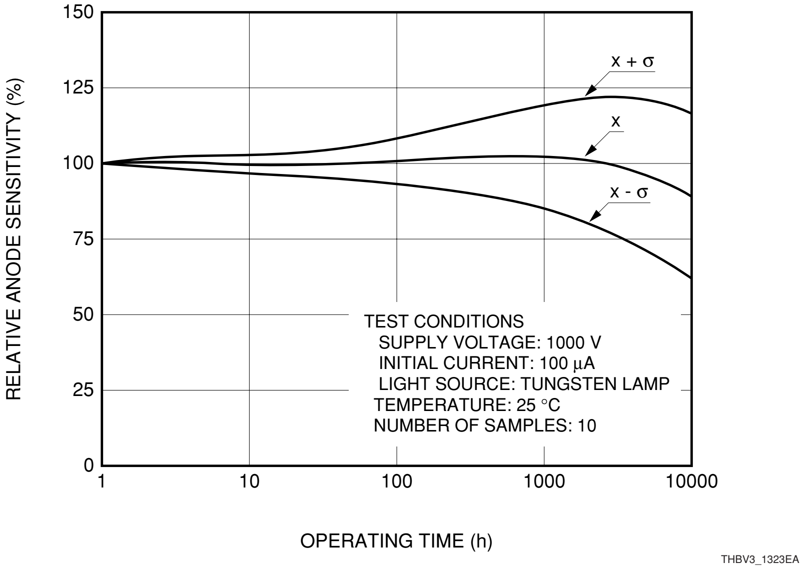
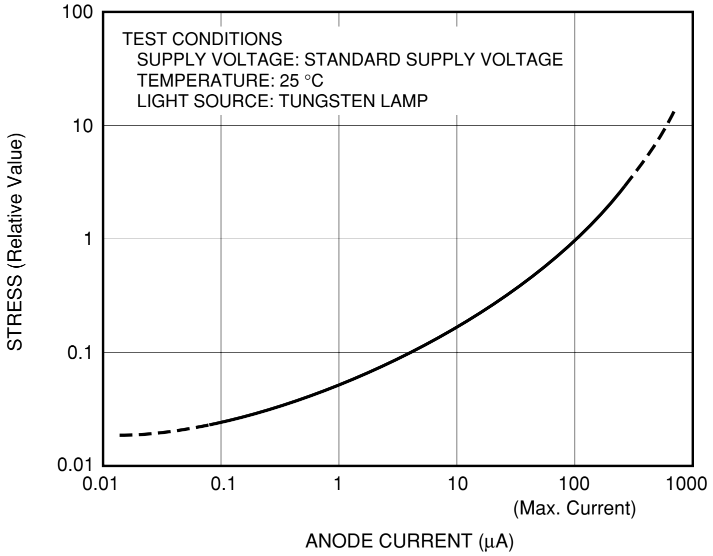


Figure 13-23: Stability over time

13.9.2 Current stress and stability

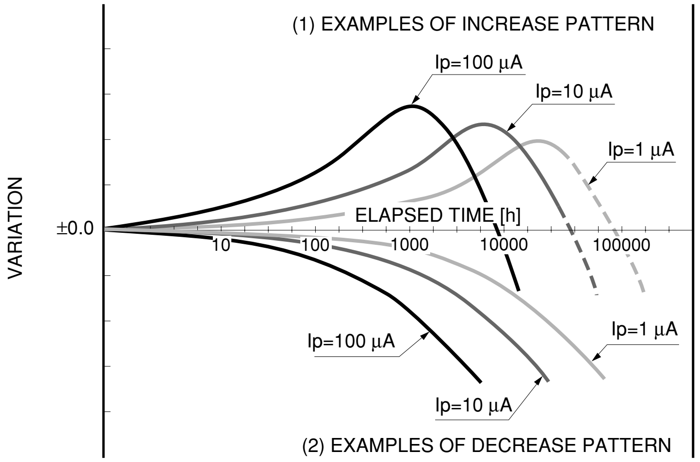
As mentioned in the preceding section, time stability of a photomultiplier tube varies with the operating conditions. In general, the larger the current stress, the earlier and more significant the variation that occurs. Typical stress on photomultiplier tube anode current is shown in Figure 13-24.



THBV3_1324EA

Figure 13-24: Current stress on photomultiplier tubes (at different anode currents)

Figure 13-25 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.



TEST CONDITIONS
SUPPLY VOLTAGE: STANDARD SUPPLY VOLTAGE
TEMPERATURE: ROOM TEMP.
LIGHT SOURCE: TUNGSTEN LAMP

THBV3_1325EA

Figure 13-25: Typical time stability of photomultiplier tubes (at different anode currents)

Stability over time can be improved to some extent by aging the tube. Figure 13-26 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 unused 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.

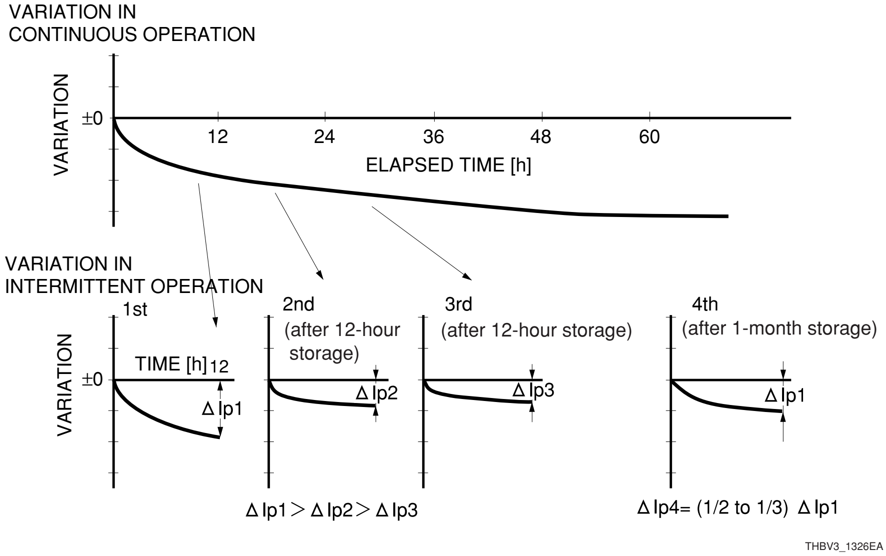


Figure 13-26: Effects of intermittent operation (aging effect)

13.9.3 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. In these applications, predicting and verifying the photomultiplier tube reliability are very important.

(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 rate11) 12) 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 2×10^{-7} to 2×10^{-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 5×10^{-7} failures/hour.

(3) Mean life

There is a measure of reliability which is commonly referred to as MTBF11) 12) (mean time between failure) or MTTF (mean time to failure). Stated simply, this is the average hours of time until any failure occurs or, in other words, mean life.

Since the definitions and fundamental calculations 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:11) 12)

$$\theta = 1 / \lambda$$

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 5×10^{5} to 5×10^{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 2×10^{6} hours.

(4) Reliability

Based on the fundamental calculation for stability data, reliability R is defined as follows.[11) 12)]

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

t: operating time in hours

λ: failure rate

Therefore, using a typical failure rate λ of photomultiplier tubes of 2×10^{-6} to 2×10^{-7} failures/hours, reliability R becomes as follows:

Elapsed time in operation	Reliability R(t)	
	at $\lambda = 2\times10^{-6}$	at $\lambda = 2\times10^{-7}$
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 when operated under favorable conditions.

13.9.4 Reliability tests and criteria used by 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 (55°C) (5°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 1250 V
   Anode output current: catalog-listed maximum rating, 10 to 100 μA

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 1×10^{-3} to 1×10^{-4} failures/hour and 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 temperature and current (50°C , 10 to 100 microamperes) will be approximately 400 times. This means that our in-house test conditions have an acceleration factor approximately 400 times that of the field data.

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