Nuclear Instruments and Methods in Physics Research A269 (1988) 237–245
North-Holland, Amsterdam

THE PERFORMANCE OF PHOTOMULTIPLIERS EXPOSED TO HELIUM

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Received 20 August 1987 and in revised form 14 December 1987

We report results of a study to determine how the performance of photomultipliers is affected by exposure to He. In our tests we monitor two 5 in. diameter EMI hemispherical photomultipliers while they are operated in He environments. Initially we observe He^+ afterpulses, at an approximately constant delay relative to the primary anode pulse. As the He gas pressure in the tubes increases however, strings of pulses typical of Townsend discharges occur. For the glass composition and geometry of the photomultipliers used in our tests, the internal gas concentration as a function of exposure to He is calculated using Fick's law for the permeation of solids by gases. The He permeation constant for the photomultiplier glass is obtained from a semiempirical formula developed by Altemose. We calculate the internal He concentration resulting from the He exposure which is observed to cause the regular occurrence of discharges and find that it is consistent with that required for production of discharges in the Townsend model. Guidelines are presented for using our results to estimate lifetimes of photomultiplier's of different geometries and glass types when operated in He environments.

1. Introduction

Small concentrations of gases inside a photomultiplier (PM) are known to cause afterpulses [1]. In new PMs, afterpulses can be associated with H_2, N_2, CO, He, and other gases found in air or produced from water vapor. When PMs have been exposed to air for as little as 2 years however, it has been reported that afterpulses associated with He increase dramatically as compared with those caused by heavier ions [2]. The reason for this is the relatively high permeability of glass to He.

In this paper we report results of tests we have done to determine the performance of PMs as a function of exposure to He. As we had anticipated, the afterpulse rate is observed to increase with exposure. In addition, as suggested by Paske [3], the concentration of He inside the PM eventually reaches a level sufficient to cause the sustained production of free electrons typical of Townsend discharges [4]. These discharges, which are manifested as strings of pulses at the anode, occur with increasing frequency and duration as exposure to He increases. Ultimately, strings lasting as long as ≈ 10–50 μs are observed for most instances in which a primary electron is emitted from the photocathode.

We begin with a brief discussion of afterpulsing in PMs and of the Townsend model for discharges in gases. We then summarize the results of Norton [5] and Altemose [6] regarding the permeation of glass by He. Using Fick's law for the permeation of solids by gases [7], together with the He permeation constant for the PM glass as obtained from Altemose's semiempirical formula, we estimate the He exposure required for Townsend discharges to occur. In particular, the Townsend discharge model predicts that sustained dark currents between electrodes are the result of ionization of neutral gas molecules by ions. The ionic contribution to the production of free electrons will become significant when the mean free path for ionization of neutral gas molecules by collision with gas ions becomes comparable to the photocathode–first dynode spacing.

Finally we discuss the two tests that we performed. In one test a PM is directly exposed to He and operated with a first stage voltage $V_0 \approx 400$ V, while in the other, the PM is submerged in mineral oil during exposure and operated with $V_0 \approx 600$ V. (The mineral oil has no appreciable effect upon the results while the difference in operating voltage is found to account for a factor of 2 or so difference in the He exposure required for discharges to occur.) We find that after a time lag of 1.9 d (consistent with that predicted by the time-dependent form of Fick's law), the occurrence of afterpulses begins to rise. Townsend discharge effects are then observed at subsequent He exposures consistent with those anticipated by our calculations.

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2. Afterpulses and discharges: the effect of gases in photomultipliers

Let $V(s)$ be the electric potential at a distance s from the photocathode along the direction of the field lines which are focused to the first dynode [8]. If an ion of charge Ze and mass m is produced at $s = s_0$, then the time it will take to reach a distance $s \leq s_0$ from the cathode is:

$$\tau(s_0, s) = -(m/2Ze)^{1/2} \int_{s_0}^{s} \mathrm{d}s \left(V(s_0) - V(s)\right)^{-1/2}. \tag{1}$$

For hemispherical phototubes the electric field increases with increasing s. Approximating the potential as $V(s) \approx V_0(s/d)^2$, where V_0 is the voltage difference between the cathode and first dynode, $\tau(s_0, s)$ is then:

$$\tau(s_0, s) = \left(md^2/2eZV_0\right)^{1/2} \left(\pi/2 - \sin^{-1}(s/s_0)\right). \tag{2}$$

Thus the time required to reach the photocathode at $s = 0$ is;

$$\tau_0 = \pi/2 \times \left(md^2/2ZeV_0\right)^{1/2}, \tag{3}$$

which is independent of s_0 [9].

Townsend [4] studied the effects of gases between electrodes and found that for low gas concentrations, the number n of electrons arriving at the anode is related to the number of electrons emitted from the cathode, n_0, by a simple exponential; $n = n_0\, \mathrm{e}^{\alpha d}$, where d is the electrode spacing and α is the mean number of gas ions produced per cm per electron traversing the gap. Townsend also observed that for fixed pressure and electric field, the number of electrons reaching the anode increases more rapidly than exponentially when the gap size d is made large [10]. The added electrons are the result of the ions themselves contributing to the production of free electrons by collision with – and ionization of – neutral gas molecules.

For these circumstances Townsend derives the following expression for the total number n of electrons at the anode:

$$n = n_0 \frac{(\alpha - \beta)\, \mathrm{e}^{(\alpha-\beta)d}}{\alpha - \beta\, \mathrm{e}^{(\alpha-\beta)d}}, \tag{4}$$

where β is the number of ions produced per cm by a positive ion in the gas as it is accelerated to the cathode [11]. This expression is singular at $\alpha = \beta\, \mathrm{e}^{(\alpha-\beta)d}$. The singularity corresponds to conditions for which full breakdown of the gas occurs – manifested as a spark [12]. As singularity conditions are approached, increasing numbers of electrons are produced regeneratively so that a current is observed to flow between the electrodes even after the source of photoelectrons emitted from the cathode is removed.

One expects ions to contribute significantly to the production of free electrons when the mean free path l for collision *and* ionization of a neutral gas molecule by an ion is comparable to the electrode spacing d. For a kinetic energy of 50 eV to 1 keV, the ionization cross section for He^+ ions on He atoms [13] is $\sigma \approx (1\text{–}4) \times 10^{-17}\,\mathrm{cm}^2$. The number density N of He atoms at room temperature and at pressure p μm Hg is $N = 3.54 \times 10^{13}\, p\ \mathrm{cm}^{-3}$. The mean free path l is then

$$l = (\sigma N)^{-1} = 2.8 \times 10^3 p^{-1} \left[\frac{\sigma}{10^{-17}}\right]^{-1}. \tag{5}$$

Thus l is comparable to d at a pressure p_0 given by $p_0 \approx 10^3 d^{-1}$. (Note that the ionization cross section in e^-–He collisions is $\sigma_e = (1.6\text{–}3.5) \times 10^{-17}\,\mathrm{cm}^2$ above 50 eV so that He ions will have roughly the same probability of ionizing He atoms as will electrons [14].) For the 5 in. diameter PMs used in our tests, $d \approx 10$ cm so that $p_0 \approx 100$ μm Hg. Thus, we estimate that Townsend discharges will occur regularly at a He pressure inside the phototube of ≈ 100 μm Hg.

When the ions produce free electrons by ionizing neutral gas molecules, these electrons proceed through the PM to produce an afterpulse which is delayed relative to the primary pulse by a time $\tau(s_0, s)$ where $s > 0$ is the point at which the He–He^+ collision occurs. For a mean free path l for this process, the probability that the ionization occurs before the ion has travelled a distance $s_0 - s$ is:

$$P = 1 - \mathrm{e}^{-(s_0 - s)/l}. \tag{6}$$

Thus the pulses initiated by electrons freed in these collisions will not necessarily occur at a constant delay relative to the primary pulse and will typically occur sooner than what is expected for a standard afterpulse (in which He^+ ions strike the photocathode to cause the emission of electrons). The occurrence of afterpulses at arbitrary times less than the time at which He afterpulses normally occur is thus characteristic of the production of free electrons via ionization of gas atoms by ions.

3. The permeability of glass to helium

For a plane membrane with pressure gradient Δp, cross sectional area A and thickness z, the quantity of gas passing through the membrane in time t is calculated from the steady state form of Fick's law [7] to be:

$$q = kAt\ \Delta p/z \quad \text{(plane membrane)}. \tag{7}$$

For a sphere, q is given by:

$$q = 4\pi a^2 kt\ \Delta p b/a(b - a) \quad \text{(spherical membrane)}, \tag{8}$$

where a and b are the inside and outside radii, respec-

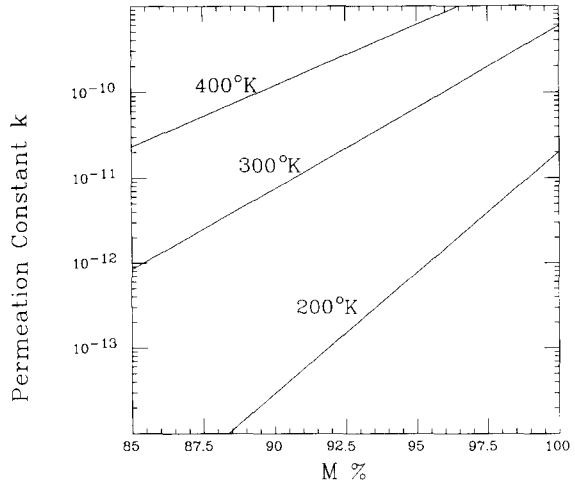

Fig. 1. Permeation constant k, eq. (10), as a function of %mol network-forming oxides M, at 200, 300 and 400 K.

tively, of the sphere. The permeation constant k depends upon temperature T as [5,6]:

$$k = k_0 \, e^{-Q/RT}, \tag{9}$$

where Q is the activation energy per gram atom, R is the gas constant ($R = 1.986$ cal/mol K), and k_0 is a constant. Altemose [6] has shown for glass that Q is proportional to the %mol concentration M of network-forming oxides; SiO_2, B_2O_3, and P_2O_5. He finds the following semiempirical formula for the permeation constant:

$$k = 4.8 \times 10^{-7} \, e^{(260M - 3.0\times 10^4)/RT}, \tag{10}$$

where M is in percent, R is cal/mol K, T is in K, and the units of k are cm^3 gas (NTP) per sec per cm^2 area per mm thickness per cm Hg gas pressure difference. Fig. 1 shows a plot of k vs %mol M of the network-forming oxides at various temperatures.

When our tests with the 5 in. EMI PMs were completed, the PMs were shattered to measure the glass thickness. The glass composition was obtained from Thorn–EMI corporation [15]. It turned out that the bulb and shaft were manufactured separately from different types of glass and joined with three further glass types over a span of 1 cm to avoid an abrupt change in the coefficient of thermal expansion. The shaft thickness is ≈ 1.0 mm and the bulb thickness is ≈ 2.0 mm. The %mol of network-forming oxides in the bulb and shaft are $M_{\text{bulb}} = 93.1$ and $M_{\text{shaft}} = 90.0$, respectively. The permeation constant for the bulb at $T = 300$ K is then [16]:

$$k \approx (2.9 \pm 1.0) \times 10^{-11} \quad \text{(bulb)}. \tag{11}$$

For the remainder of the tube, the permeation constant is:

$$k \approx (6.2 \pm 2.1) \times 10^{-12} \quad \text{(shaft and joint)}. \tag{12}$$

The bulb has an area of 410 cm^2 and the rest of the tube has an area of 110 cm^2. Thus the bulb accounts for 92% of the steady flow of He into the photomultiplier. The volume of the PM is $V = 810$ cm^3 so that from eq. (7) the pressure of gas accumulated in the PM as a function of He exposure, $t\Delta p$, is calculated to be:

$$p_{\text{tube}} = 7.6 \times 10^5 \frac{q}{V} \approx (36.8 \pm 12.5) t\Delta p, \tag{13}$$

where the units of $t\Delta p$ are d atm, and the units of p_{tube} are μm Hg. Thus the internal pressure will reach ≈ 100 μm Hg (for which we expect to see Townsend discharges as discussed in the last section) after an exposure of $t\Delta p \approx 3$ d atm.

So far we have only considered the steady-state form of Fick's law. It turns out that the time-dependent form of this law predicts that there is a finite time required for gas to diffuse through the glass membrane and begin the steady state flow given by eqs. (7) and (8). This time lag L depends upon the initial concentrations of gas C_0, C_1 and C_2, inside, and in the low and high pressure regions, on either side of the glass membrane, respectively. It also depends upon the diffusion constant D and the thickness z of the membrane [17]:

$$L = \frac{z^2}{D(C_2 - C_1)} \left[\frac{C_2}{6} + \frac{C_1}{3} + \frac{C_0}{2} \right]. \tag{14}$$

C_0 and C_1 are negligible compared with C_2 so that the lag is given by:

$$L_0 = \frac{z^2}{6D}, \tag{15}$$

independent of C_2. The diffusion constant D has units of cm^2 s^{-1} and has a numerical value which is related to the permeation constant k as $D \approx (500\text{–}2000)k$ [18]. Thus for $z = 0.2$ cm, we estimate a time lag L_0 on the order of 1–3 d for the PMs used in our tests [19]. For PMs operated in regions which have very high He concentrations, this time can correspond to a considerable He exposure.

In our tests, the He pressure outside the PM was initially 5 psi in the case where the PM was directly exposed to He, and 24 psi in the case where the PM was submerged in mineral oil. A delay of one day thus corresponds to exposures of 0.3 d atm and 1.6 d atm, respectively. The time lag L_0 should therefore have a very pronounced effect in the mineral oil test in particular. In the next section it will be seen that this is in fact the case.

Up to now we have not mentioned anything about the effect of the mineral oil in our second test. Our group is currently involved in the MACRO experiment at Gran Sasso (see the MACRO Technical Proposal, November 1984, unpublished), which will use a large quantity of liquid scintillator having a mineral oil base. We are particularly concerned about the effects of He

on PMs in this experiment because a major part of the experiment will comprise streamer tubes in which He will be the primary chamber gas. The PMs in this experiment will be immersed in mineral oil in order to match the index of refraction of the material in the immediate vicinity of the PMs to that of the liquid scintillator. The oil could conceivably add to the time lag L_0 and also reduce the permeation rate. For solid organic polymers having composition similar to that of mineral oil, Norton [5] states values for the permeation constant on the order of $\approx 10^{-8}$, corresponding to a diffusion constant $D \approx 10^{-5}$. For liquids, the diffusion constant of even heavy gases, such as nitrogen, at room temperature [20] is as high as 4.0×10^{-5} and so we expect D for He to be at least this large. Thus the mineral oil in our tests, which had a depth of several cm, is not expected to add more than $\approx 10\%$ to L_0 and should have negligible effect upon the permeation rate in the steady state.

4. Tests performed with 5 in. EMI photomultipliers

In the first test, a 5 in. EMI PM was placed in a chamber that was initially filled to a partial pressure of 5 psi with He [21]. In the second test a 5 in. PM was immersed in a mineral-oil-filled pyrex beaker before placement in the chamber. The He pressure in the second test was 24 psi. The PMs were powered at $\approx +1350$ V and $\approx +2000$ V respectively (cathode at ground). The PM bases used a resistor network that divided the voltage between stages such that the first stage (photocathode–first dynode) had roughly 4 times the voltage drop of the 10 successive multiplier stages, all of which had the same potential drop. Thus the first stage voltages were ≈ 400 V and ≈ 600 V in the two tests.For both tests, dark noise and afterpulsing were monitored. Primary electrons were produced in the PMs by flashing a green LED near the photocathode. The LED pulse was such that ≈ 1–3 photoelectrons were produced for each flash. A 100 MHz trace recorder with 32 kbyte memory unit was stopped when the LED was flashed to allow the subsequent anode signals, occurring up to ≈ 150 μs after the LED flash, to be digitized and written to minidisk for storage. In the mineral oil test, strings of $n \geq 2$ afterpulses were also monitored. For overnight monitoring, a scaler/timer was used in conjunction with a gate generator to produce triggers for the LED pulser and stop signals for the trace recorder every 1000 s. The events were stored on minidisks (these have a capacity of 39 trace recordings and so the 1000 s spacing of triggers insured that data was taken throughout the night). Dark noise and afterpulse rates were measured in the daytime only.

From eq. (3), the voltage across the cathode and first dynode in the 5 in. EMI PMs leads to an expected

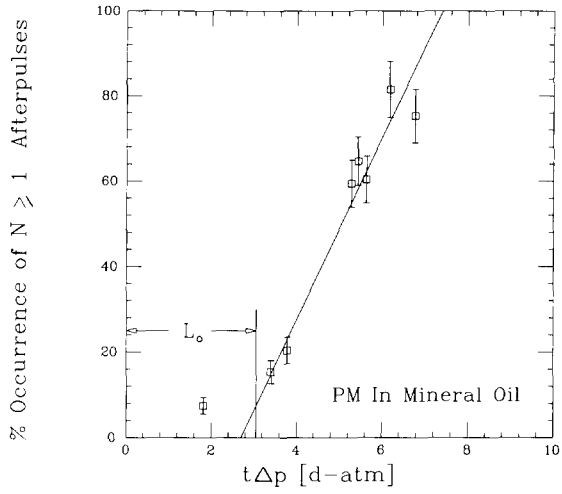

Fig. 2. The % of LED flashes which are followed by an afterpulse at $t \geq 500$ ns, as a function of exposure to He in the second test (PM in mineral oil and $V_0 = 600$ V). The first data point is taken to represent the initial noise level in the PM prior to exposure to He. The remaining points are fit to a line, as shown, to determine the time lag L_0 before the steady-state flow of He into the PM begins, as predicted by eq. (15).

afterpulse delay of $\approx 1.2 \pm 0.3$ μs for singly ionized He. For this reason the occurrence of afterpulses later than 500 ns after the primary pulse were monitored as one measure of He contamination. Fig. 2 shows a plot of data from the second test, in which the fraction of primary pulses followed by an afterpulse at $0.5\ \mu\text{s} < t < 10.0\ \mu\text{s}$ relative to the primary pulse is counted. After several d atm of He exposure the occurrence rate begins to rise roughly linearly. The data were least-squares-fit to a line. We find that if the first data point is included in the sample, the fit has a χ^2 value of 25.0 for 6 degrees of freedom. If the first point is not included, the fit has $\chi^2 = 4.0$ for 5 degrees of freedom. We conclude therefore that the first data point represents the rate of occurrence of afterpulses in the PM due to gases which were trapped in the PM before it was exposed to He, and the subsequent linear rise is due to the linear accumulation of He (see eqs. (7) and (8)) with exposure. The line which best fits the sample (fig. 2) intersects the initial noise rate at an exposure of $t\Delta p = 3.1 \pm 0.1$ d atm. For $\Delta p = 24$ psi, this means that the time lag required for He to diffuse through the glass and commence steady state flow into the PM is $L_0 = 1.9 \pm 0.1$ d. This is consistent with the time lag that we estimated using eq. (15) (see the discussion above).

In most uses of PMs, the ambient partial pressure of He is $\Delta p \ll 1$ atm so that the time lag L_0 will correspond to a very small exposure (unless the diffusion constant D is very small so that $L_0 \gg 1$ d). For this reason we will subtract the He exposures during the

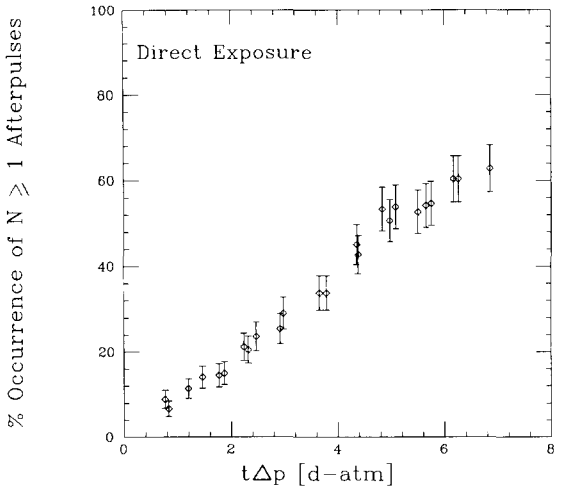

Fig. 3. The % of LED flashes which are followed by an afterpulse at $t \geq 500$ ns as a function of exposure to He in the first test after correcting for the time lag L_0.

delay time in order to present our results as a function of He exposure during which steady-state flow of He into the PM takes place [22]. Henceforth, "exposure" will thus be understood to mean exposure after subtraction of the time lag L_0.

Fig. 3 shows the measured percent of LED flashes followed by $n \geq 1$ afterpulse at $t \geq 500$ ns for the first test after subtraction of L_0 as measured in the second test. A line fit to the data in the figure has y-intercept consistent (within uncertainty) with a rate of 1–2% as measured in the pm prior to exposure to He. The delay time L_0 is calculated to be the same for the PMs used in the two tests to within an overall measurement uncertainty of $\approx 20\%$. It follows that the He diffusion and permeation properties of the tube glass in the two PMs is also the same to within this level of uncertainty.

In each test, the mean single-photoelectron pulse height was crudely measured to $\pm 50\%$. Thus a factor of 2 difference in the mean number of primary electrons (n_0 in eq. (4)) in the two tests is not unlikely and would explain the factor of 2 difference in the slopes of the rates presented in figs. 2 and 3.

In fig. 4 data are shown in which the fraction of LED flashes followed by strings of $n \geq 2$ afterpulses of duration $\Delta t > 500$ ns were counted in the second test. The rate of occurrence of these strings is seen to increase as $(t\Delta p)^m$, where $m = 1.8 \pm 0.4$. Initially the strings are due to a combination of the recurrence of standard afterpulses, and afterpulses resulting from electrons freed in He^+–He collisions. This is evidenced by the fact that the delay between some, but not all, of the pulses in the string is roughly constant at about 1–1.5 μs (see fig. 5a). At greater He exposures, the delay between pulses is more frequently shorter than that expected for standard afterpulses, indicating that He^+ ions are contributing more to the ionization of He atoms [23] (see fig. 5b). As expected, the duration of the strings was observed to grow. Ultimately strings as long as ≈ 10–50 μs, like that seen in fig. 5c, were seen for the majority of LED flashes. The mean number of afterpulses per primary pulse was monitored by using a discriminator and scaler to count the number of times the anode signal crossed a threshold of 30 mV, ($\approx 1/2$ photoelectron), in 10 μs after the LED was flashed. (A coincidence unit was used to produce an enable signal for the scaler only when *both* an LED pulse trigger *and* a primary pulse above 30 mV occurred.) Fig. 6 shows plots of data from these measurements. In the first test we see that the multiplicity of afterpulses increases exponentially with exposure. In the second test the number of data points is insufficient to say whether the increase here is also exponential [24].

Strong evidence for the occurrence of Townsend discharges is seen in the plots shown in fig. 7 of the dark noise in the PMs. The dark noise initially rises exponentially with exposure. With further exposure the rise becomes faster than exponential. This type of behavior is characteristic of the approach to breakdown predicted by Townsend. The exposure required for this to happen in the tests is seen to be ≈ 2 and 5 d atm, in rough agreement with our estimate of 3 d atm as discussed in the last section. The difference of ≈ 2–3 in the exposure required for discharges in the two tests is most likely attributable to the difference in the first stage voltages, V_0, used in the two tests.

In particular, for a given electrode gap size d, the singularity condition of eq. (4) is determined by the

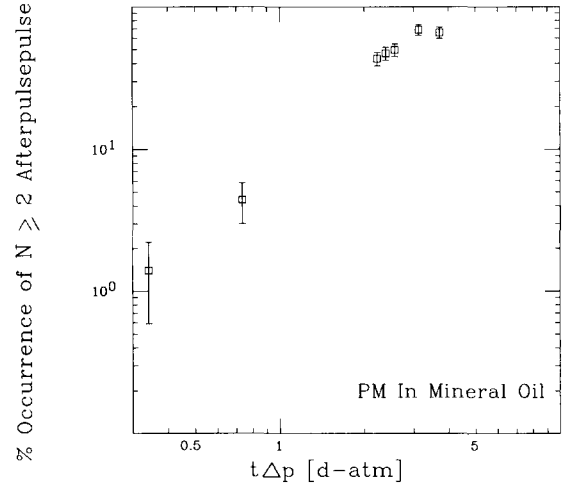

Fig. 4. The % occurrence of LED flashes followed by at least two afterpulses in the second test. Only strings of pulses of duration $\Delta t \geq 500$ ns were counted. The data rise roughly as a power of the exposure, $(t\Delta p)^m$, where $m = 1.8 \pm 0.4$.

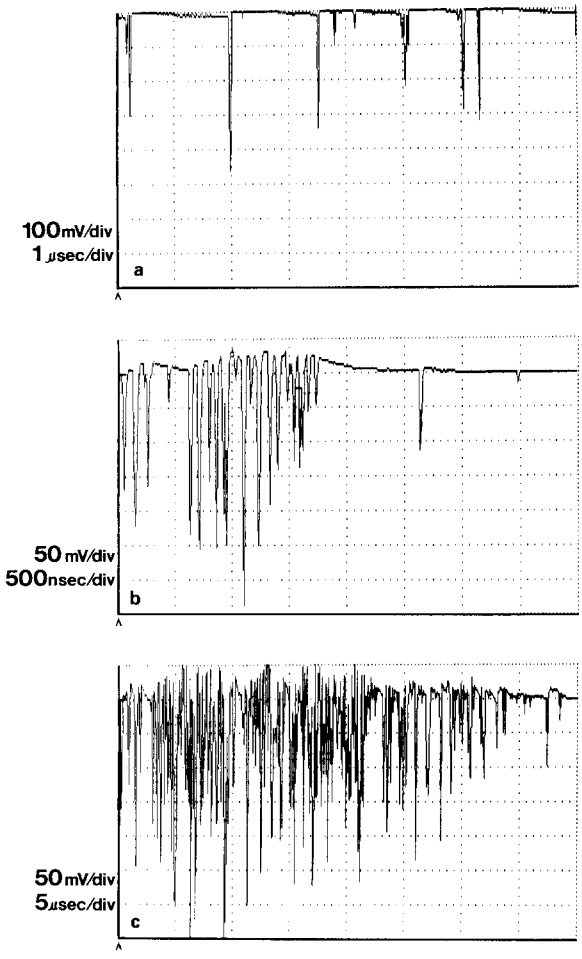

Fig. 5. (a) Primary pulse followed by standard He afterpulses mixed with afterpulses initiated by electrons freed in He^+–He collisions. (b) An early Townsend discharge occurring after an exposure of ≈ 2 d atm in the second test. In this case it is seen that the afterpulses are almost always separated by times significantly less than 1 μs. (c) Townsend discharge of duration $\Delta t = 40$ μs after an exposure of ≈ 3 d atm in the second test. The amplitude and time scales are marked at the left side of the signal traces.

Townsend coefficients α and β. These in turn depend upon the pressure of the He gas in the pm and the field strength (see ref. [11]). In the discussion above regarding the measurement of the time lag L_0, we concluded that the permeation properties of the tube glass in the PMs differed by less than $\approx 20\%$. The amount of He in the tubes as a function of exposure will therefore be very nearly the same as well. On the other hand, the complexity of the discharge process makes it difficult to calculate the effect of varying the gap voltage V_0. Some simple calculations we have performed do, however, indicate that the different voltages used in the two tests

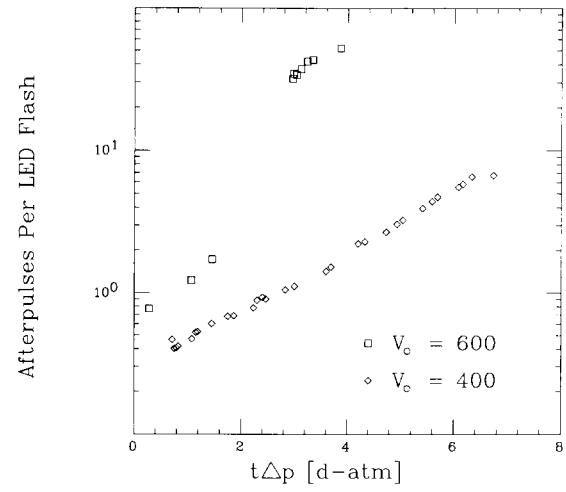

Fig. 6. The mean number of afterpulses counted in the time period, 500 ns $\leq t \leq 10$ μs after the primary pulse occurs, as a function of exposure to He in both tests.

could affect the exposure required for discharges to occur by a factor of 2 or so [25].

The dark noise rates are also seen to begin to plateau after roughly 3 and 7 d atm exposures. This is partly due to the fact that as the mean free path for inelastic collisions of He^+ with He becomes much smaller than the gap size d, the kinetic energy gained by the ions between collisions is more likely to be below 100 eV in which case the ionization cross sections are small. Another contribution to this effect may be the capture of photoelectrons by positive ions which accumulate in increasing numbers near the photocathode.

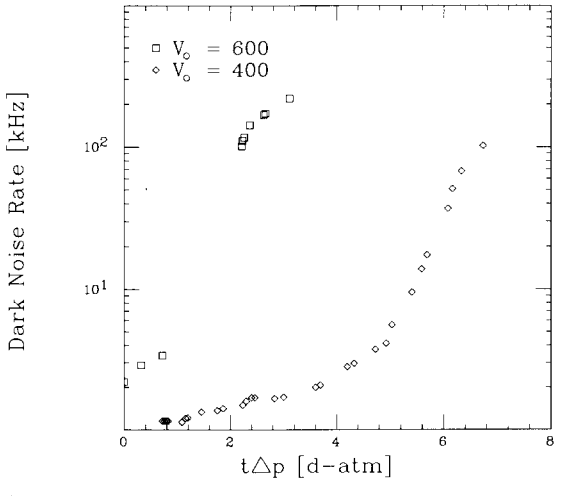

Fig. 7. Dark noise rates as a function of exposure in both tests. The dark noise is seen to initially rise exponentially and later to rise at a faster than exponential rate as expected for the occurrence of discharges.

5. Conclusions

From our tests we can conclude that He permeating into photomultipliers can represent a serious source of degradation of performance. For tubes in which the %mol concentration of network-forming oxides in the glass walls is high, even relatively low ambient He concentrations can cause serious damage to the PMs over periods of several years. The noise level resulting from Townsend discharges render PMs effectively useless for most applications. The exposure required for discharges to occur can therefore be interpreted as the lifetime of the pm scaled by the ambient He pressure Δp.

It has been seen in the analysis above that the important variables for determining the lifetime of a PM exposed to He are (a) the %mol concentration M of network-forming oxides in the tube glass, (b) the ambient He pressure Δp, (c) the mean ionization cross section σ for He^+ collisions with He, and (d) the geometry of the PM (surface area A, volume V, thickness z and photocathode–first dynode gap size d). Given this information, the He exposure required for Townsend discharges to begin to occur regularly, can be estimated by combining eqs. (5), (7) or (8), (10), and (13), i.e.:

$$t\Delta p \approx 1.2\times 10^{-3}\left[\frac{10^{-17}}{\sigma}\right]\left(\frac{zV}{Ad}\right) e^{-(260M-3.0\times 10^4)/RT}. \tag{16}$$

As seen in our tests, the gap voltage V_0 may be responsible for a factor of 2 or so difference in the PM lifetime. Fig. 8 shows plots of the *linearized exposure*, $t\Delta p(Ad/zV)$, calculated from eq. (16) as a function of %mol concentration of network-forming oxides, where we have extrapolated from our measurements to indicate the possible variation to be expected for PMs operated with $V_0 = 400$ and 600 V.

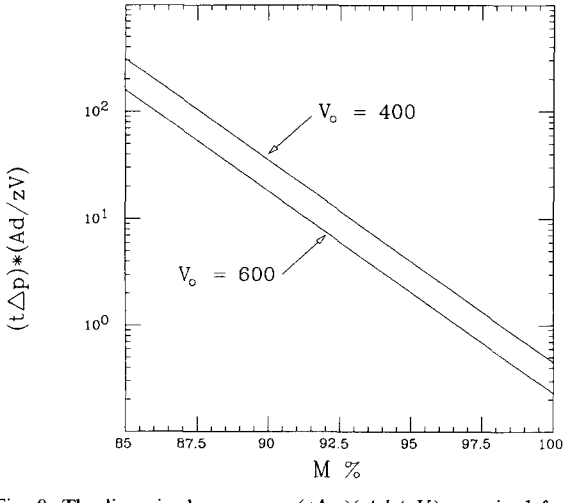

Fig. 8. The linearized exposure, $(t\Delta p)(Ad/zV)$, required for the regular occurrence of Townsend discharges to occur in PMs as a function of the %mol of network-forming oxides in the tube glass and for first stage voltages V_0 of 400 V and 600 V.

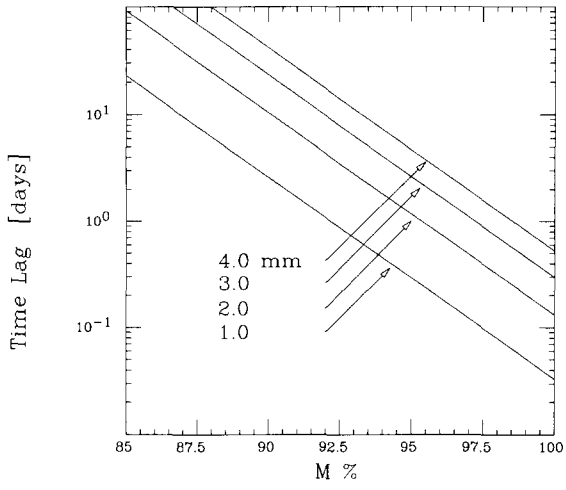

Fig. 9. The calculated time lag L_0 as a function of the %mol network-forming oxides for four typical PM glass thicknesses, $z = 1$, 2, 3, and 4 mm. (We assume that the diffusion constant is given by $D \approx 10^3\ k$ so that actual time lags could differ by a factor of 2 from those indicated by the plot – see the discussion following eq. (15)).

Fig. 9 plots the lag time L_0 (eq. (15)) also as a function of M, for various typical PM glass thicknesses $z = 1$, 2, 3, and 4 mm. For applications in which the ambient He pressure is expected to be high, the time lag can correspond to a significant exposure, as was the case in our tests. In such instances, the time lag must be included to obtain a more accurate estimate of the lifetime of the photomultiplier.

Acknowledgements

We like to thank R.A. Phaneuf of the Oak Ridge National Laboratory and J. Cuevas of the University of Chicago for their assistance in locating low energy ionization cross section data for He and for their insights in regard to the techniques used to measure these cross sections. We also thank S. Osaka for her assistance in preparing the figures for this paper. This research was made possibly by grant number 6973-5 from the US National Science Foundation and grant number 7098-7 from the US Department of Energy.

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[2] P.B. Coates, J. Phys. D, Appl. Phys. 6 (1973) 1159. Coates refers specifically to O_2. Morton et al. [1] however, used a valved glass tube system that allowed them to fill the PM with various gases in controlled amounts and found that O_2 did not cause afterpulsing even at concentrations as high as 10^{-5} Torr (for which other gases showed significant afterpulse rates). The afterpulses to which Coates refers are therefore probably the result of N_2 which has mass similar to O_2 and therefore will have roughly the same afterpulse delay time τ_0.

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[8] Ions which are produced in later stages are captured by dynodes and do not contribute substantially to afterpulse production. See ref. [2].

[9] For a uniform field: $V = V_0(s/d)$; $\tau = (2md/ZeV_0)^{1/2}(s_0 - s)^{1/2}$ and $\tau_0 \approx s_0^{1/2}$. In this case, τ_0 varies little with s_0 for $s_0 \gg 0$. Furthermore, the probability that an electron produces an ion upon collision with a neutral gas molecule increases at larger values of s_0 since it will have more likely attained a kinetic energy above 100 eV at which point the cross section for ionizing He is relatively large (see ref. [14]). Thus, for this potential also, afterpulse times for a given species of ion will be peaked about a fixed value of τ_0.

[10] For a fixed pressure p and, consequently, a fixed mean free path l for ionization of a gas molecule by collision, the number of ionizing collisions per charged particle as it traverses the gap will increase as the gap size d is made larger. The same increase in ionizing collisions can be obtained by decreasing the mean free path as a result of increasing the pressure so long as the cross section for ionization does not decrease appreciably with the decrease in l. This is the case, for instance, in PMs which are initially He free as they are exposed to He since the He pressure in the tube is then sufficiently low that $l \geq d$. Thus, as PMs are exposed to He we expect dark noise to rise with He exposure in the same way that Townsend observes currents to rise between electrodes filled with gas at constant pressure as d is increased.

[11] The strength of the electric field E will determine the ionization efficiency of the electron–molecule and ion–molecule collisions. The Townsend coefficient α depends upon E and p as $\alpha/p = f(E/p)$. This can be understood by the following simple argument (see ref. [4]). The chance of producing an ion by collision will depend upon the energy of the charged particle, i.e. the electric field E and mean free path l, which is inversely proportional to the pressure p. For an increase in pressure, $p \to cp$ $(c > 1)$, the mean free path is reduced, $l \to l/c$. If E is unchanged, the energy of the electron at collision is then reduced. If $E \to cE$, then the energy is restored but the situation is not as it was to begin with because the increase in p means that the number of gas molecules present is now larger by a factor of c. Thus α has increased by this factor. A similar argument can of course be made for the coefficient β. The argument has to be modified somewhat at very low pressures (see ref. [10]). Furthermore, in the above discussion a constant electric field E has been assumed. When the field varies with distance s from the cathode as in the PMs used in our tests, it follows that the Townsend coefficients will also depend on s.

[12] The Townsend theory does not hold for all conditions, e.g. appreciable overvoltages etc. This led to the development of the streamer theory of breakdown. Both theories have singularity conditions. See, Electrical Breakdown in Gases, ed. J.A. Rees (Wiley, New York, 1973).

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[16] The error in k is estimated from the variance of data points with respect to the empirical formula (see fig. 6 of ref. [6]).

[17] See ref. [7], pp. 18, 19.

[18] Compare tables 2 and 3 on p. 1312 of ref. [6].

[19] In general, L_0 is determined by the region with the highest value of D/z^2. In the PMs used in our tests, the values differ by $\approx 25\%$ in the two regions, with the larger value corresponding to the bulb region for which $M = 93\%$. Note that the lag time L_0 also corresponds to the amount of time it takes for the flow of He through the membrane to cease once the PM is removed from the region containing He. This explains the observation by S.P. Ahlen of Boston University and by R. McAlpine of Thorn–EMI Corp. of continued increases in noise currents after exposure to He has stopped. S.P. Ahlen and R. McAlpine, private communications.

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[21] In our first test, the pressure of the He in the containment vessel was changed twice – to 8 psi and then to 10 psi. In each case a time lag occurs before the increased steady state flow into the pm is established. This has been taken into account in presenting the data from this test.

[22] Thus if our data, presented in this manner, indicate a certain noise level after an exposure of x d atm, it can be stated that the same tube exposed to He at a partial pressure $\Delta p \ll 1$ atm will have noise at this level after $x/\Delta p$ d. E.g. for $\Delta p = 10^{-3}$ atm and $x = 1$ d atm, $x/\Delta p = 1000$ d $= 2.7$ yr.

[23] Afterpulses therefore occur in most instances in which a He^+ is formed – whether as a result of an electron freed from the cathode or from a He atom as a result of the impact of a He^+ ion. The probability that an afterpulse occurs at low internal gas pressures therefore depends upon whether or not an electron ionizes a He atom en route to the first dynode. The probability that at least two afterpulses occur in a string is then expected to be roughly

the square of the probability for the occurrence of a single afterpulse. Note that the exponent m calculated from the data in fig. 4 is consistent with a value of 2.0.

[24] Because the He pressure and high voltage were greater in the second test, the effects of He after the lag time L_0 were observed much more rapidly than in the first test. As a consequence there were, in general, fewer data points obtained in the mineral oil test. Furthermore, the most dramatic changes in the performance of the PM in this test look place over an eight hour period in one night when careful pulse counting measurements were not being performed. Nevertheless, the data are sufficient to confirm that the effects of the He are as expected.

[25] We used the e–He and He^+–He ionization cross sections (refs. [13] and [14]), in a Monte Carlo calculation of the rate at which a He ion produced by collision with a primary electron goes on to produce an additional He ion by collision with a neutral He atom. With $V_0 = 600$ V, we calculate a rate of $\approx 10\%$ when the partial pressure of He in the tube is chosen so that the mean free path for ionization of He by He^+ is comparable to the gap size d. For $V_0 = 400$ V, we do not calculate a similar rate until the He pressure in the tube is doubled. The calculation does not take into account the effect of inelastic collisions of He^+ with He (in which the ion will give up half of its kinetic energy to the He atom on average), or other details of the discharge process (e.g. electron–ion recombination, space charge effects etc.). The results of the calculation are thus only interpreted as an indication that the voltage V_0 may play a role at the "factor of 2" level in determining the exposure required for discharges to occur. In hindsight it would have been useful to vary the operating voltage in an individual test to better understand its effect on discharging.