Final Report

for

INVESTIGATION OF DARK CURRENT IN ASCOP 541F MULTIPLIER PHOTOTUBES AFTER EXPOSURE TO HIGH LIGHT LEVEL

(23 October 1964 - 23 December 1964)

Contract No.: NAS5-9089

Prepared by

Electro-Mechanical Research, Inc.
Princeton Division

for

Goddard Space Flight Center
Greenbelt, Maryland

ABSTRACT

21763

Tests have been performed on eight ASCOP 541F multiplier phototubes over a wide range of high light-level exposure conditions to determine the time-dependent behavior of the dark current after such an exposure. The mechanism proposed for this misbehavior of the dark current is the thin-film field emission (Malter effect). Several methods for suppressing this effect have been proposed. Author

TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

It is a well-known (although little understood) fact that the dark current of a multiplier phototube rises to a level much higher than the quiescent level after even a very brief operation at high light levels. The recovery time for such an exposed tube varies from milliseconds to days depending on the conditions of exposure. This effect has been encountered by Dr. K. Hallum of NASA for his OSO experiments using ASCOP 541F multiplier phototubes. The 541F tubes were exposed to a high light level (earth albedo) and were driven into saturation at 5×10^{-5} amperes (limited by the bleeder resistor of 10 MΩ/stage). The resultant dark current was unable to recover quickly enough to the level required by Dr. Hallum, 5×10^{-9} amperes at a gain of 10^7 within 0.1 seconds (the quiescent level is more than an order of magnitude lower).

The principal objectives of this investigation are two-fold: (1) to study and understand the nature of the dark current behavior in ASCOP 541F tubes after exposure to high level light;

camera shutter (Konica focal-plane), with a rise and fall time of 200 microseconds was used to control the exposure. The bleeder chain had a value of 1 MΩ/stage so that the anode current was not limited until 3×10^{-4} amperes. A special bias control was used to cut off the cathode when necessary. The usual bias voltage was +8 volts with respect to the first dynode. Higher bias voltages were found to be unsatisfactory because the cathode would start to collect the electrons emitted by the first dynode. The set-up was so constructed that any number of stages (starting from the cathode) could be biased off to determine the contribution due to the remaining stages. The anode current was measured with a Keithley Model 410 Micromicroammeter.

The second series of tests to which these tubes were subjected was the investigation of the short-term component (from 1 millisecond to several seconds) of the time-dependent dark current behavior after exposure to high level light. The set-up, shown in Figure 2, is essentially the same as that used for the long-component studies except that a Tektronix type 535 oscilloscope is used in place of the Keithley meter.

and (2) to recommend a method to minimize this effect with emphasis on intrinsic changes.

EXPERIMENTAL

Eight ASCOP 541F multiplier phototubes were selected for this study, one with a special coaxial-type anode. Several other types of ASCOP tubes (541A, 541D, 541E, 641E, and 541G) were also selected for comparison purposes.

The first series of tests to which these tubes were subjected was the investigation of the long-term component (greater than 5 seconds) of the time-dependent dark current behavior after an exposure to high level light. The set-up is shown in Figure 1. The light used in the investigation was always monochromatic, provided by a mercury discharge lamp and Perkin-Elmer monochromator. The 2537 Å line of mercury was the most often used. The absolute level of the light was measured by the calibrated thermocouple during each run. An extremely fast

The exposure varied from 1 millisecond to several minutes, and the absolute light level was varied from 10^7 photons/sec to 10^{16} photons/sec at 2537 Å.

RESULTS AND DISCUSSION

Time Characteristics

Figure 4 represents a composite summary of long- and short-components of the time dependent dark current on five 541F tubes. Exposure level was 3×10^{-5} amperes anode current at 2537 Å (approximately 2 to 6×10^9 photons/sec incident on the cathode) for a duration of 1 second. Tube gain was 10^7. The lower boundary of the shaded region represents the time characteristics of the best 541F tested; the upper boundary represents that of the poorest 541F tested. The time characteristic curve for any one individual tube has been found to be reproducible, provided that adequate dark conditioning is allowed before each run.

The shape of the time characteristic curve resembles that of a simple exponential for the millisecond region, but for longer rest time (time after an exposure) the shape is almost t^{-1}. The best-fit single equation for all regions of the curve is $(1 + t/\tau)^{-1}$ where τ is a constant of the order of several milliseconds. The physical significance of the expression is not clearly evident. This t^{-1} shape appears to be general for different exposure conditions.

Results of experiments on other ASCOP tube types also show similar time characteristic curves. When normalized to the same exposure conditions these curves fall around the shaded band in Figure 4. These other tube types may have similar time characteristic curves but different quiescent levels depending on the photocathode used. For tubes with very high quiescent levels, such as 541A (with S-11 cathode) and 543C (with S-1 cathode), the dark current rise problem is not so obvious, because the quiescent level is attained in a fraction of a second after termination of exposure. For 541F and 541G tubes with quiescent levels around 10^{-11} to 10^{-13} amperes, the dark current rise problem is quite easily observed.

A polaroid camera was used to record the traces. The oscilloscope was triggered by either the flash synchronism of the camera shutter or the rising (or falling) edge of the light pulse, as required for the exposure duration.

An RCL 256-channel pulse-height analyzer in conjunction with a Tennelec TC150 preamplifier were used to obtain pulse-height spectra of the dark current after high light level exposures. The set-up is shown in Figure 3.

The 541F phototubes were all thoroughly dark conditioned before each investigation since the dark current characteristics were found to depend on its previous history. The dark conditioning consisted of storage in the dark for up to a week and operation under full voltage in the dark for at least several hours, sometimes overnight or over a weekend. When tubes had to be tested at different light levels and different exposure durations, the procedure followed was to start first with the lowest light level and the shortest exposure duration.

It is of interest to note that the extrapolated dark current at zero rest time is the non-signal component during exposure. This quantity may very well have been the extra sensitivity or gain shift reported by some users of multiplier phototubes(1). If this is so, then this dark current effect should be present in all multiplier phototubes. The absolute value of the "extra sensitivity" from Figure 4 is shown to fall in the range of 0.1 to about 20% for a 1 second high light exposure resulting in an anode current of 3×10^{-5} amperes.

Dependence On Exposure Duration and Light Level

The dependence of the dark current for five 541F tubes on exposure duration is shown in Figure 5. Rest time is constant at 0.1 seconds, exposure level is equivalent to 3×10^{-5} amperes anode current at 2537 Å (approximately 2 to 6×10^{9} photons/sec). The lower and upper boundaries of the shaded area again represent the best and poorest tubes, respectively. It is seen that the dark current at 0.1 seconds rest time is linearly proportional to exposure duration for exposures of less than 1 second. For higher exposure durations the dependence is sublinear. For shorter rest times the shaded band has a flatter slope.

The dependence on the light level (at 2537 Å) at an exposure duration of 1 second and a rest time of 0.1 seconds is given in Figure 6. The horizontal line represents the reported tolerance level of Dr. Hallum's experiments. The best tube shows a tolerance level of 10^{10} photons/sec while the poorest tube shows 10^8 photons/sec. For any arbitrary wavelength the dependence on the light level can be obtained from Figure 6 by using the inverse relationship between light level and effective quantum efficiency.

For different exposure durations and light levels the dark current after any given rest time is approximately proportional to the product of exposure duration and light level. Current amplification and wavelength of illumination are taken as constant.

Possible Mechanisms of Dark Current Rise

There are several possible mechanisms which can cause a rise in the dark current after an exposure to high light level. These are: (1) charging of the walls adjacent to the anode and the subsequent leaking off through the anode; (2) thin-film field emission (or tunneling) induced by the charges on the thin insulating secondary emissive dynode films (Malter effect); (3) various types of light feedback due to electron bombardment: gas ionization, and from dynodes and walls — cathodoluminescence, soft bremsstrahlung and plasmon re-emission; or due to photoluminescence from dynodes and walls; and (4) ion feedback.

Due to the very low quantum efficiency of the dynodes (and walls) any significant feedback mechanism must of necessity involve the photocathode. That is, biasing off the cathode after exposure to high light levels should result in a substantial change in dark current. Therefore, the first experiment we did was to study the time characteristics while alternately biasing off the cathode. Only a very small difference was observed, hence the various feedback mechanisms did not appear to be involved. This conclusion was reinforced by the pulse-height data. It was observed that the pulse-height spectrum of the dark current had a different shape (lower pulse height average) than the true cathode photoelectrons (weak light illumination). Furthermore, it seems hard to explain the prolonged time-dependent behavior by any other than some sort of charging mechanism.

Again, from the pulse-height data it became clear that it would be extremely difficult to account for the pulse-heights (which look like electrons emitted by the front-end dynodes) by the wall-charging mechanism. The net effect of the evidence showed that the Malter effect was the most probable mechanism. This contention was substantiated as discussed in the following.

Thin-Film Field Emission (Malter Effect)

The phenomenon of enhanced secondary emission from a thin-film insulator on a metal base by the thin-film field emission effect was first reported by L. Malter[2] in 1936. He also observed that when the primary beam was switched off, the emission current persisted for many hours. This effect was interpreted as follows: the positive charges formed at the surface of the insulator due to a secondary electron yield larger than unity produce a large enough field to cause field emission from the metal base. The field, once it has been established, remains for an extended period due to the slow process of charge neutralization and high resistivity. This effect has been rediscovered recently by workers in the semiconductor device field and has been given a new name: tunnel emission[3]. They report that when a voltage above a certain threshold is applied across a metal-insulator-metal thin-film sandwich high currents result; if the anode side of the metal film is thin enough high electron emission into the vacuum is observed.

The test of dynode charging as the major mechanism was shown in the following experiments.

First we compared the dark current decay data from a 541F tube with a special coaxial anode with that from standard 541F tubes. The tube with the coaxial anode has no wall between the anode and the thirteenth dynode and a wall unexposed to electrons between the anode and the last dynode. This tube should exhibit very little wall charging effects, if any. It was found that the difference in dark current decay between this and standard tubes was very small.

Next we investigated the dark current contributed by each individual dynode after a high-light exposure. This was done by biasing off dynodes in succession from the cathode end. After an exposure resulting in the order of 3×10^{-5} amperes anode current each dynode, on the average, seemed to contribute about equally. At higher exposure levels the front-end dynodes seemed to contribute somewhat more. Therefore, if there were any wall charging it could not be more than the contribution from the last dynode, which was less than 7%. The best estimates are that wall charging contributes no more than a few percent of the total dark current rise.

The last experiment we did was to excite selectively one particular dynode and observe its emission decay with time. This was done by negatively biasing off all the dynodes below the dynode under test during the light exposure; after exposure the dynodes preceding the one under test are positively biased off (so that they do not contribute to the measured emission) and the normal voltages restored to the succeeding dynodes. It was found that indeed whichever dynode was excited was the primary emission source. A typical result is presented in Figures 7 and 8. Figure 7 shows time characteristic curves after the first dynode had been subjected to a current of 3×10^{-10} amperes for 30 seconds. The upper curves represent the time characteristic for normal tube operation with the cathode on and with the cathode biased off, respectively. The lower curve shows the contribution from the rest of the tube after both the cathode and the first dynode are biased off. Figure 7 shows that the emission is practically all due to the bombarded first dynode resulting from surface charging during exposure.

Figure 8 gives the pulse-height spectra of the identical tube after the first dynode was subjected to the same exposure conditions. It is seen that practically all the dark current pulses are due to the first dynode emission. Furthermore, it takes about 10^5 seconds for the first dynode to decay to the quiescent level of the tube as set by the cathode dark current. The effect of dynode charging is obvious. To a first approximation the data from single dynode exposure experiments are consistent with those from the whole tube exposure experiments. The dark current rise due to a single dynode multiplied by the number of dynodes in a whole tube equals approximately that due to a whole tube under same exposure conditions.

An interesting side light of Figure 8 is that after one minute of rest time the field emitted electrons are mostly emitted singly in a random fashion.

SUPPRESSION OF DARK CURRENT RISE

Intrinsic Methods

Methods which can suppress the dark current rise by reducing the dynode charging effect (without resorting to external electronic bias systems or shutter mechanisms) are regarded as being intrinsic. The best of such methods is to construct tubes with dynodes which have little charging effects and fast charge neutralization rate. Studies conducted on other types of dynodes used in ASCOP tubes indicate that: (a) untreated Ag-MgO dynodes are somewhat better than cesium-treated Ag-MgO dynodes (used in 541F); and (b) multi-alkali treated Ag-MgO and Cu-BeO dynodes are similar to cesium-treated Ag-MgO dynodes.

Suggested approaches for an investigation to obtain dynodes with minimum thin-film charging effect are to: (1) vary the oxide layer thickness and subsequent alkali and heat treatments of present dynodes; (2) coat the dynodes with an extremely thin but highly conductive metallic film to neutralize charging; and

(3) test new materials with good conductivity as well as good secondary yield (plausible starting materials are CaO and SnO_2).

Extrinsic Methods

A simple extrinsic method used by Dr. Hallum, is to bias off the cathode during exposure. This procedure is not completely effective because the photoemission from the first dynode still results in charging. Figure 9 shows the effectiveness of this procedure at different wavelengths. For wavelengths shorter than 2500 Å this method can improve the tolerance level by three orders of magnitude; for wavelengths much longer than 2500 Å the quantum efficiency of the dynodes becomes comparable to that of the cathode and the effectiveness of this method drops off.

By combining this biasing method with a new tube configuration the tolerance level can be greatly improved. This design is illustrated in Figure 10, which is an outline of a proposed phototube with a reflective type cathode. In this case the cathode is the sole photo-emitter at all wavelengths because neither the incident nor the reflected beam will strike any other part of the phototube. If the cathode is biased off the remaining portion of the tube will not be distured. The tolerance level is theoretically unlimited.

Other extrinsic methods such as charge neutralization procedures by subjecting successive dynodes with electrons of energy causing secondary yield below unity may be effective but seem cumbersome. Results of a preliminay experiment on this procedure indicate that the effectiveness may be less than that of the simple cathode biasing procedure.

It should be pointed out here that there are some obvious advantages in using pulse counting instead of d.c. In this method the charging contribution of at least the lower dynodes may be eliminated by the discriminator setting.

CONCLUSION

The evidence is strong that the observed dark current behavior after a high light exposure in ASCOP 541F phototubes results from dynode charging effect. On the average each dynode contributes equally to the dark current. Ion and light feedback mechanisms have been eliminated on account of the negligible role played by the cathode and the prolonged time-dependent behavior exhibited by the dark current. Estimated contribution due to wall charging effects is a few percent at the most.

The dark current after a high light exposure has been found to vary, in a rough and empirical manner, (a) inversely with rest time and (b) linearly with the product of exposure duration and light. At 10^7 gain some 541F tubes can withstand a 1 second exposure of 10^{10} photons/sec at 2537 Å and still recover to a dark current level below 5×10^{-9} amperes after 0.1 seconds of rest time.

For the suppression of the dark current rise two approaches have been proposed: (a) new dynodes with minimum charging effects, and (b) a new phototube configuration with a reflective type photocathode used in conjunction with cathode biasing.

S.P. Wang.

S. P. Wang
Project Engineer

M. Rome

M. Rome, Director
Research & Development

SPW/pam

1/20/65

EMR POA 3746

REFERENCES

1. I. Cantarell - IEEE Trans. Nu. Sci., NS-11, 152 (1964 June) and references cited therein.

2. (a) L. Malter, Phys. Rev. 50, 48 (1936).

   (b) References and brief descriptions of subsequent work can be found in review articles on secondary emission by K. G. McKay (Adv. Electronics 1 (1948), H. Bruining (Pergamon Press 1954), and A. J. Dekker (Solid State Phys. 6, (1958).

3. (a) C. A. Mead, Phys. Rev. 128, 2088 (1962), and references cited therein.

   (b) H. Kanter and W. A. Feibelman, J. Appl. Phys. 33, 3580 (1962), and references cited therein.

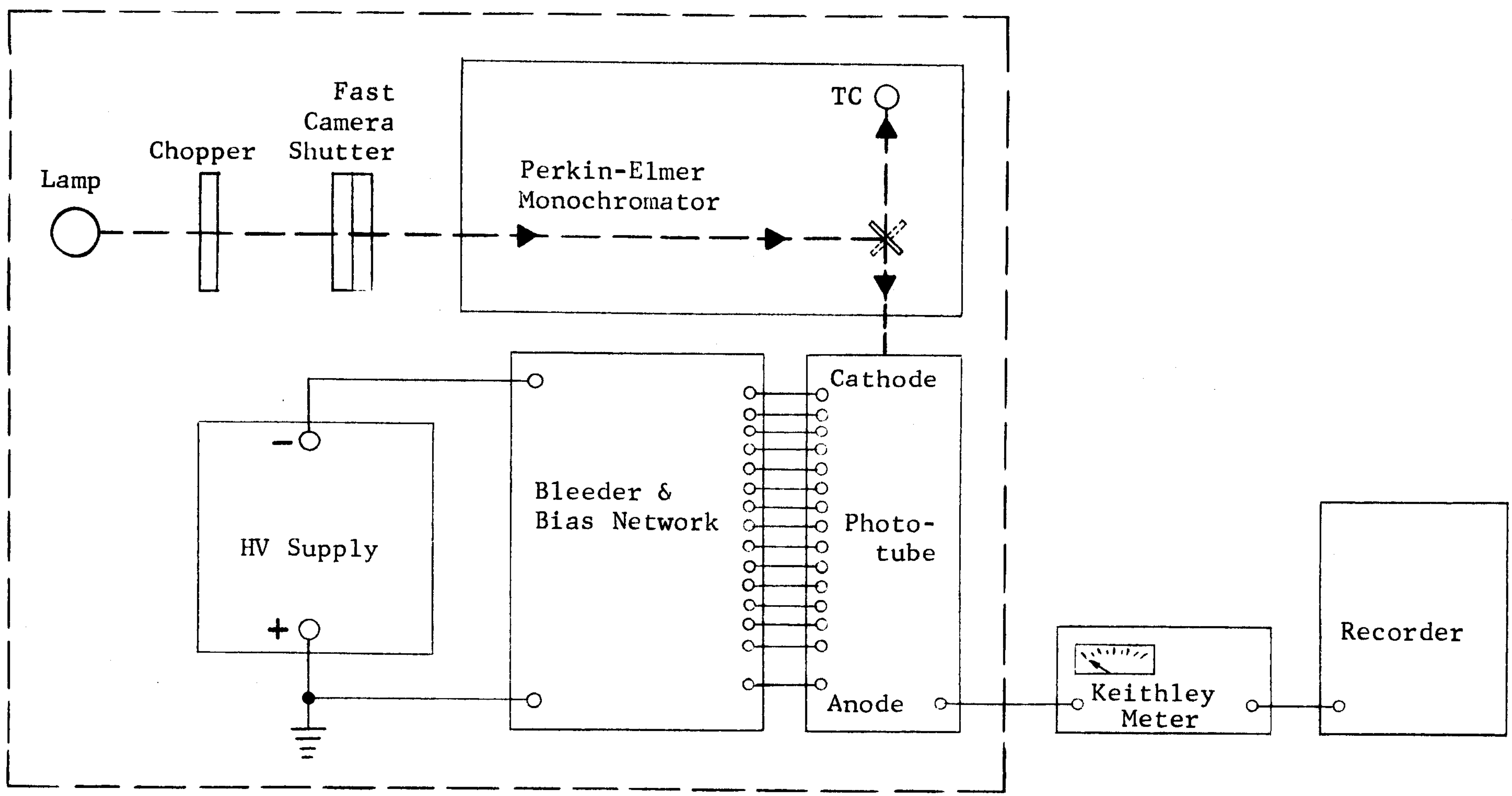


Figure 1. Set-up for long-term component studies.

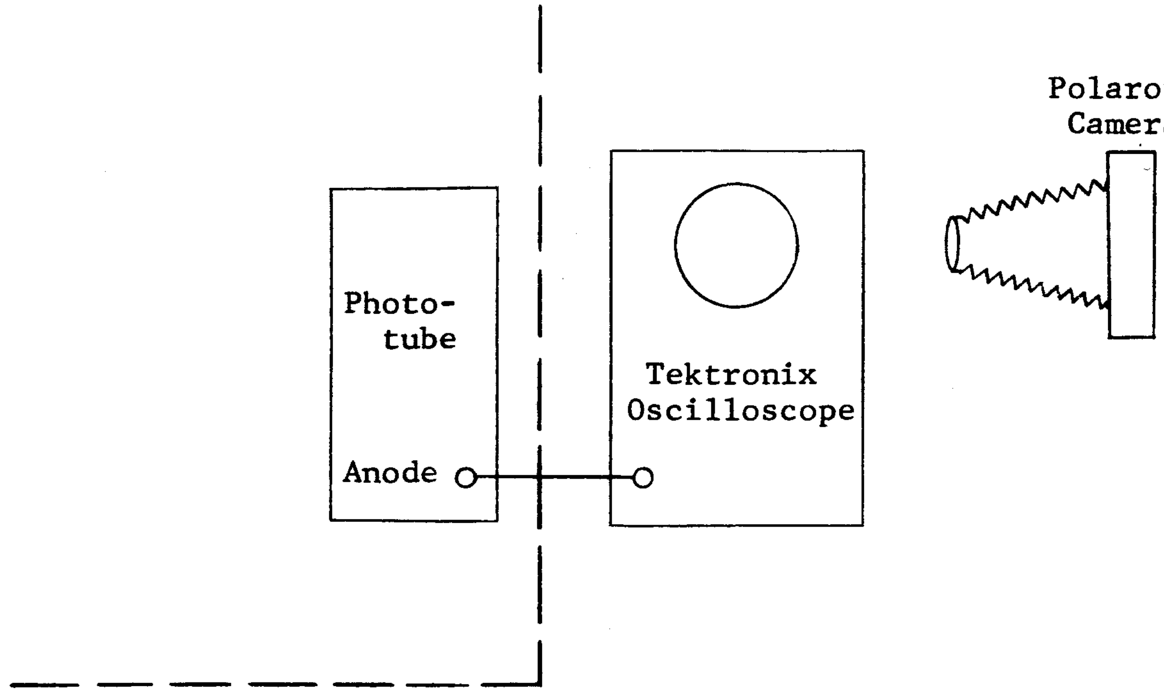


Figure 2. Set-up for short-term component studies.

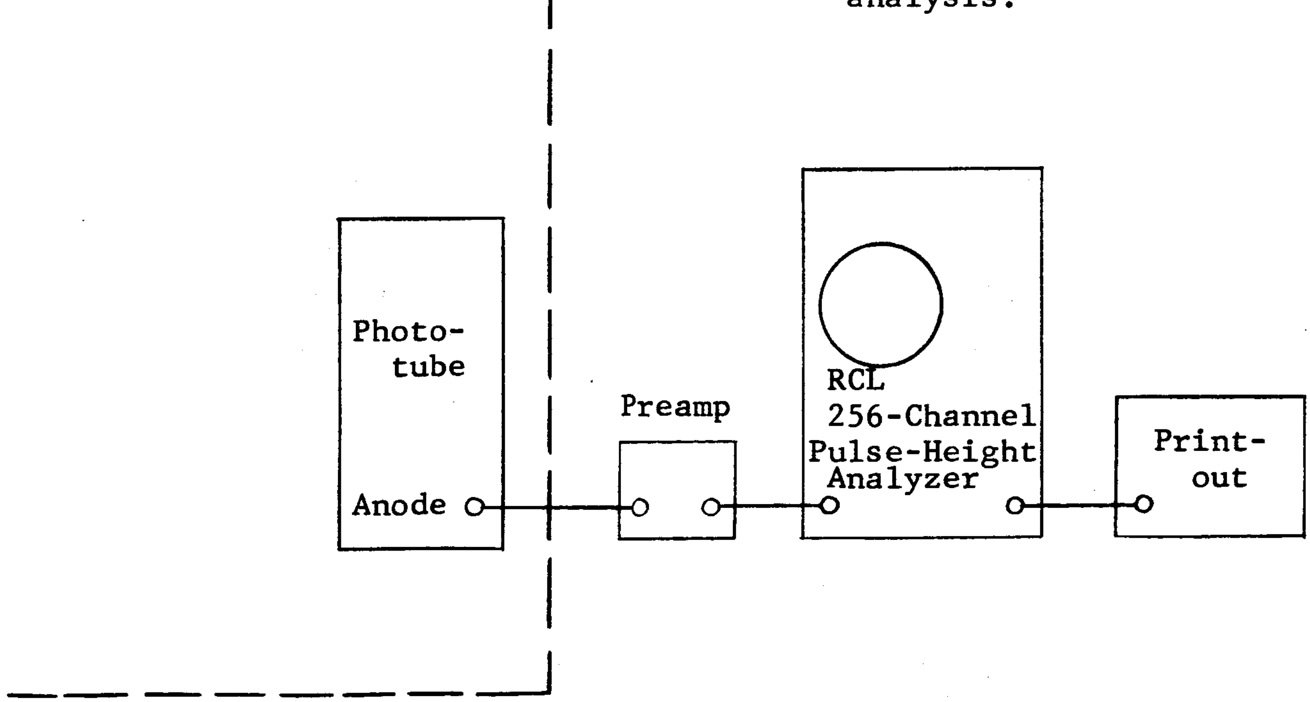


Figure 3. Set-up for pulse-height analysis.

Figure 4. Time-dependent behavior of dark current of ASCOP 541F multiplier phototubes after a high light level exposure.

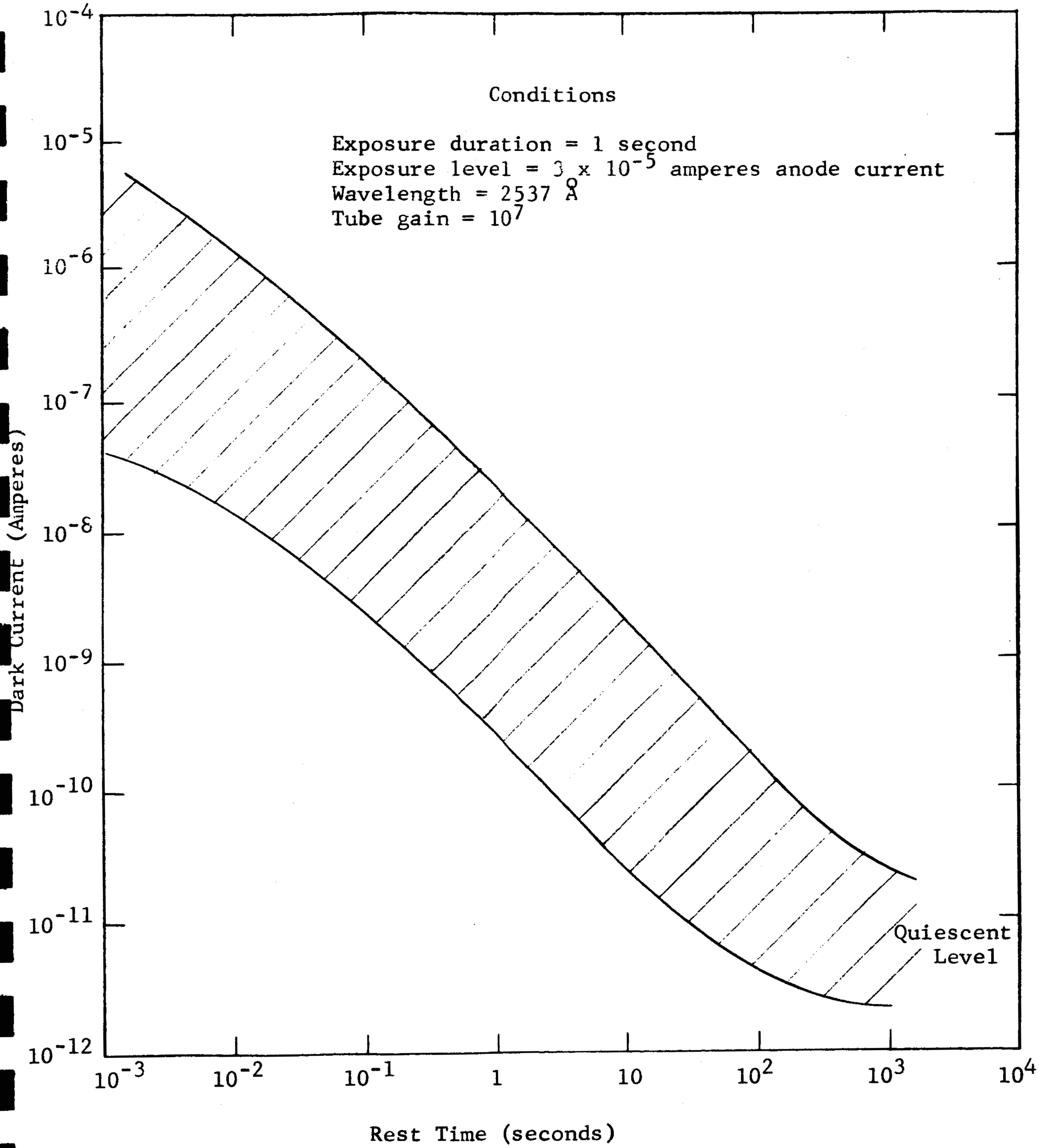


Figure 5. Dependence of dark current on exposure duration after 0.1 seconds of Rest Time.

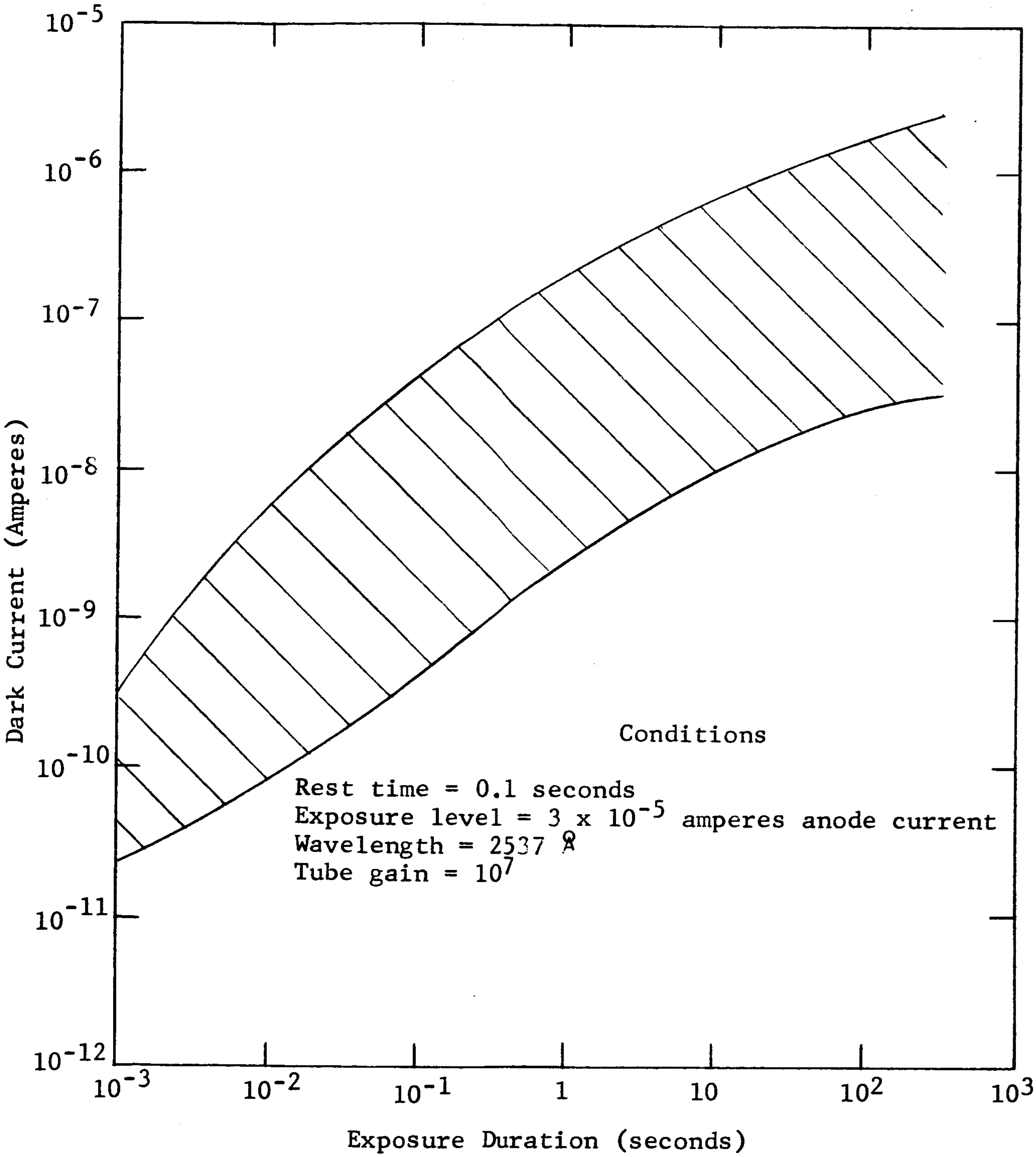


Figure 6. Dependence of dark current on light level after 0.1 seconds of rest time and an exposure of 1 second.

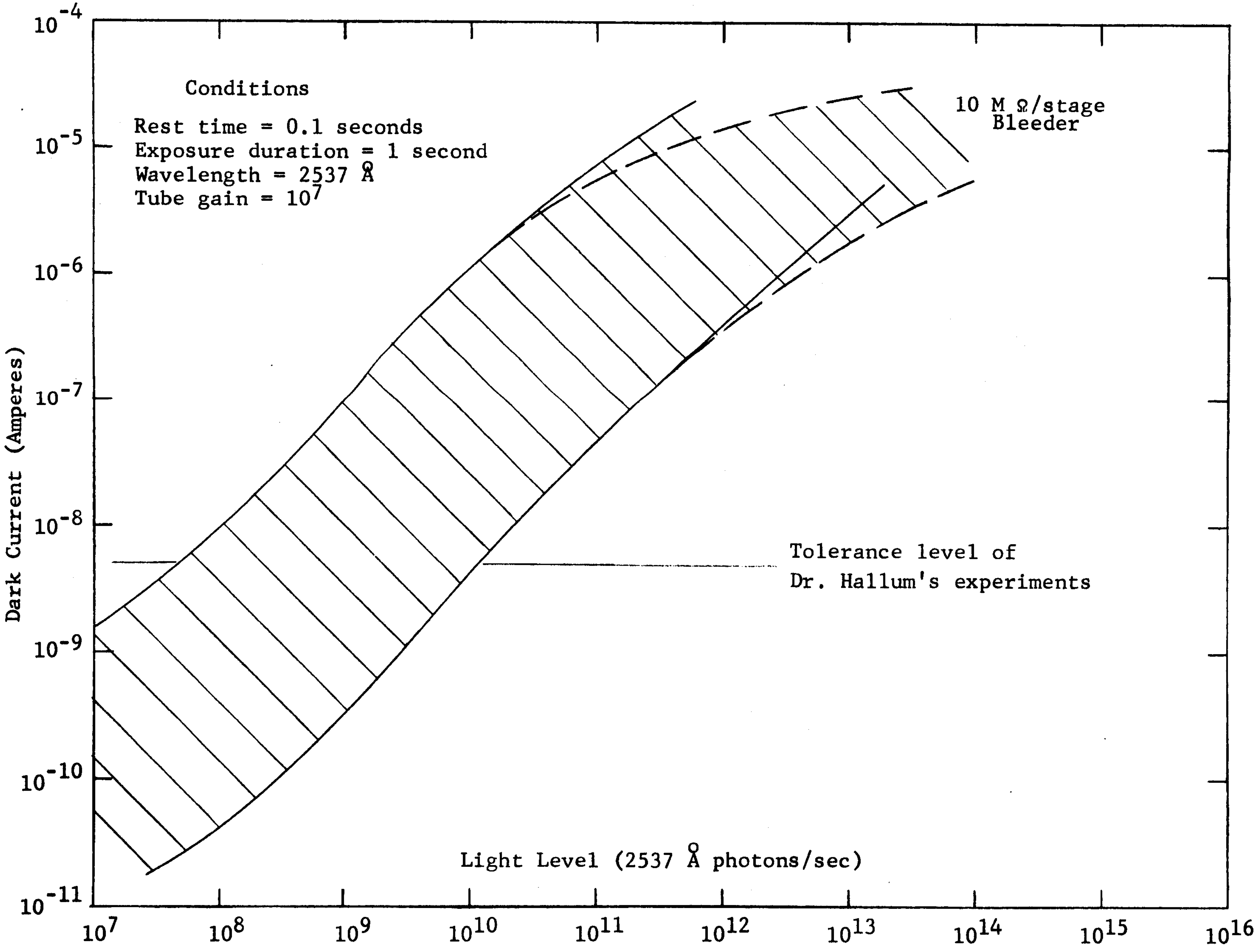
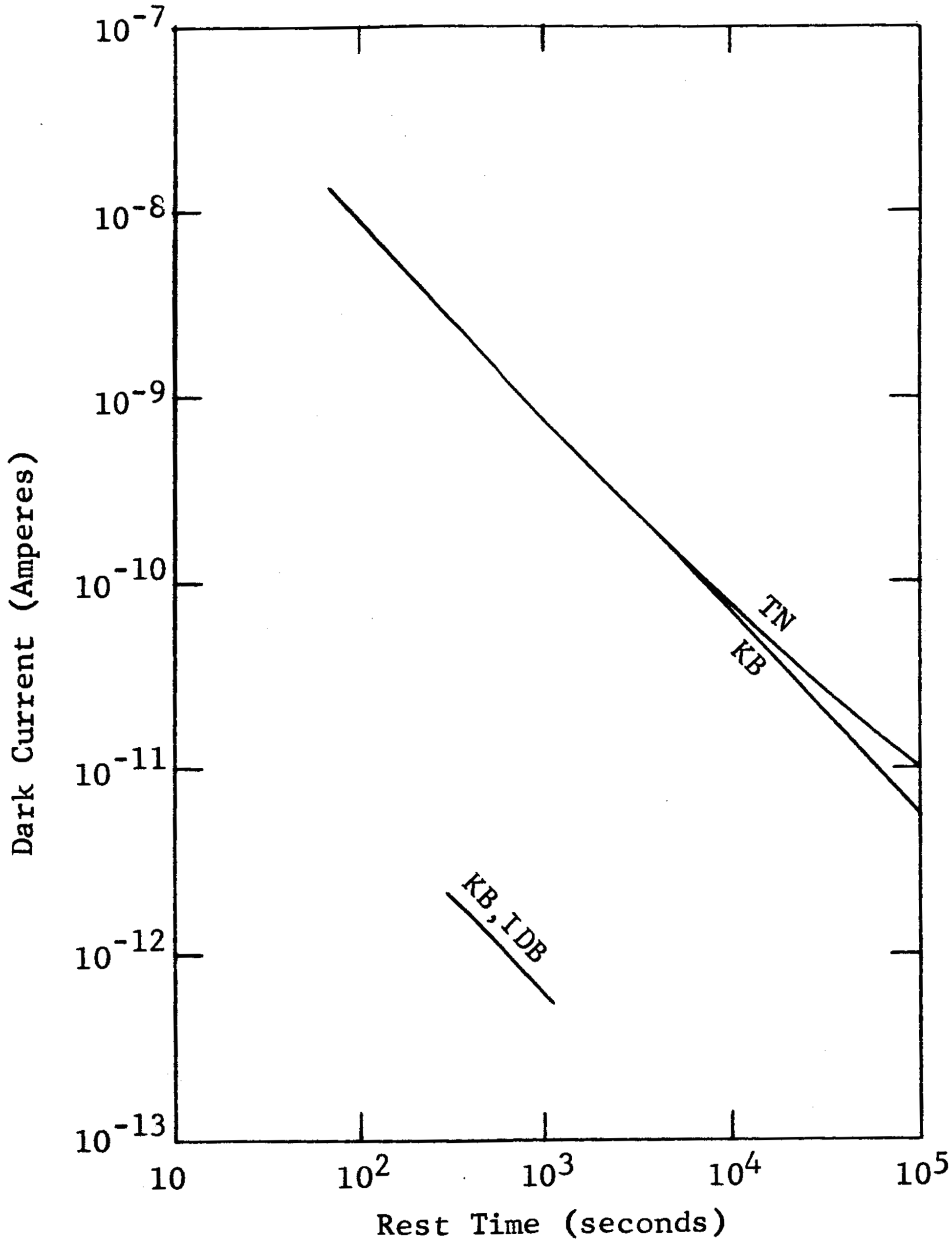
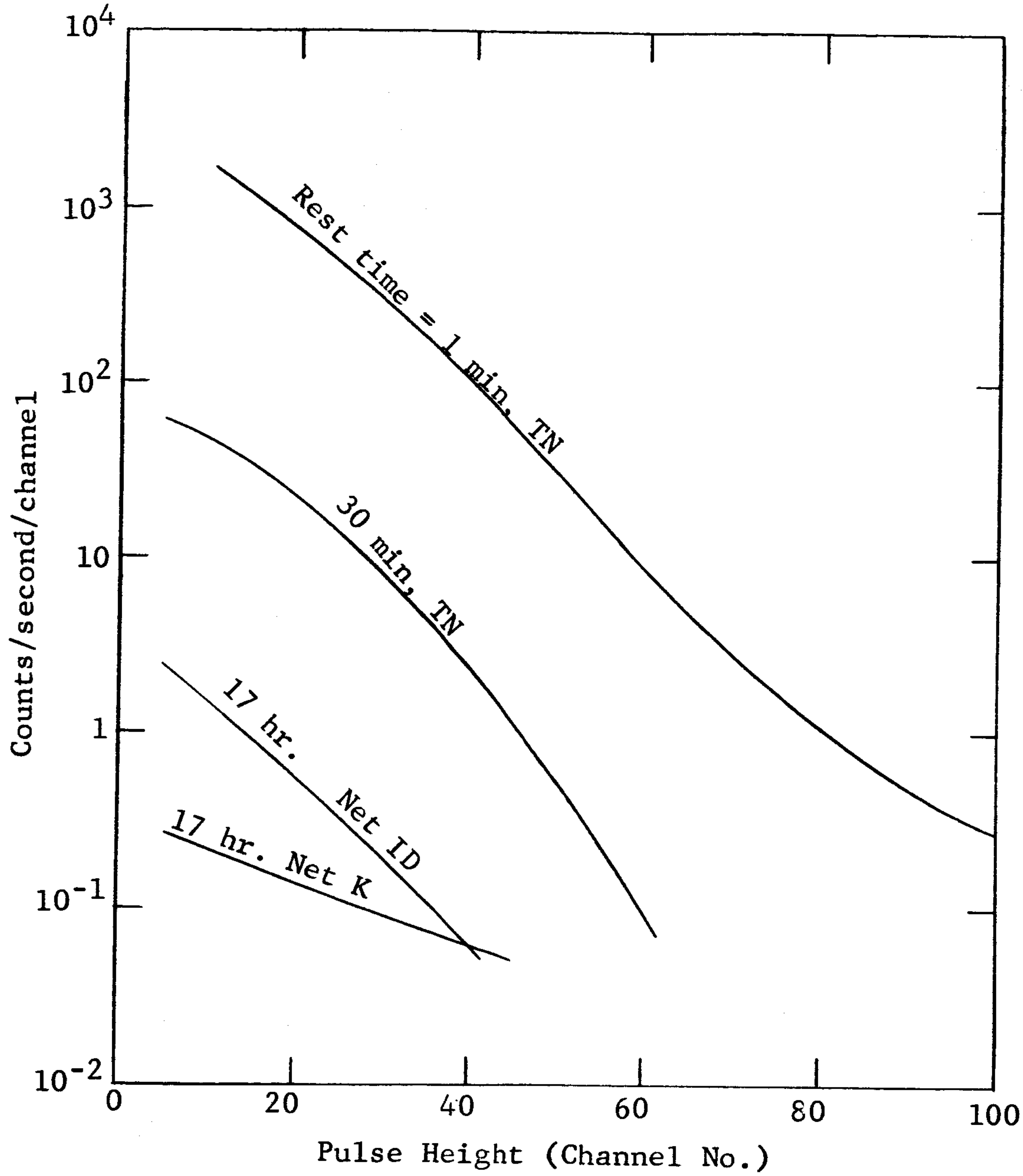


Figure 7. Time-dependent behavior of dark current after an exposure on the first dynode alone.



Legend: TN = tube normal, no bias
KB = cathode biased off
KB,IDB = both cathode and first dynode biased off
Exposure level = 3×10^{-10} amperes on first dynode
Exposure duration = 30 seconds
Tube gain = 10^7
Wavelength = 2357 Å

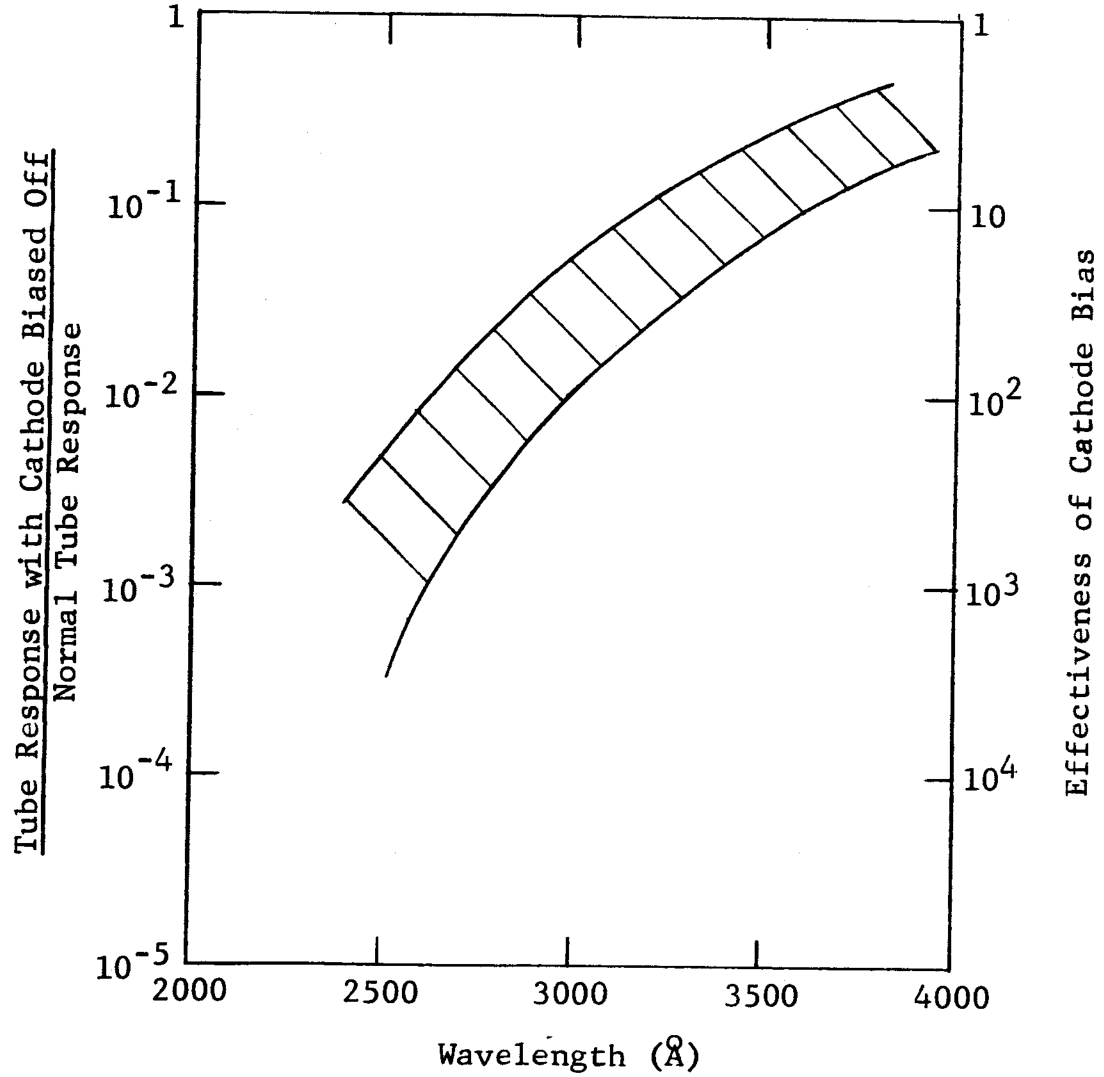
Figure 8. Pulse height spectrum at several rest times after an exposure on first dynode alone.



Legend: TN = tube normal, no bias
Net ID = net first dynode contribution
Net K = net cathode contribution

Same exposure conditions as in Figure 7.

Figure 9. Effectiveness of cathode bias versus wavelength for ASCOP 541F phototubes.



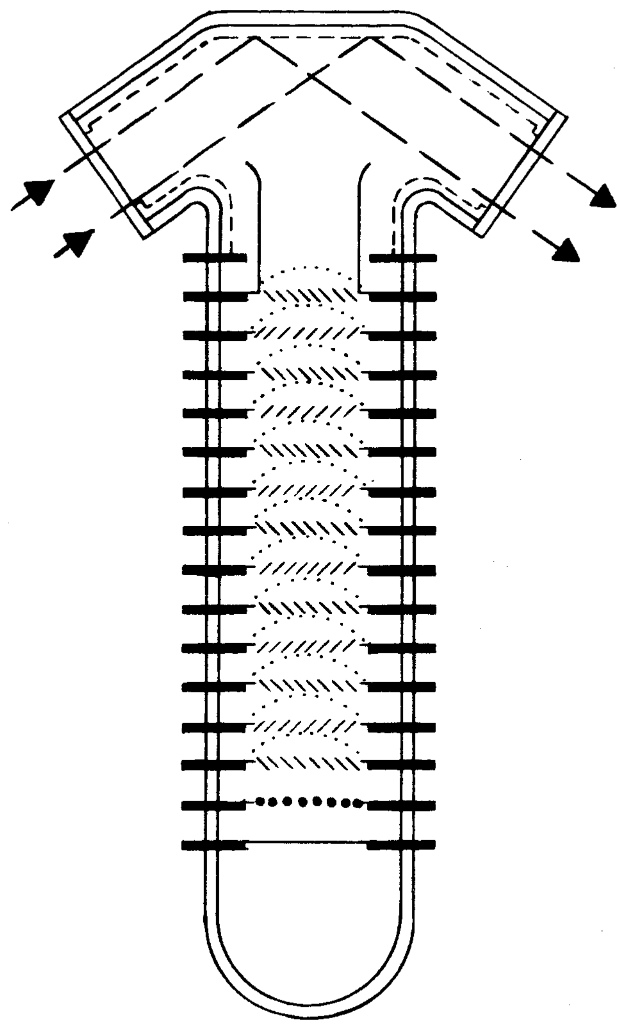


Figure 10. A phototube with reflective type cathode.