TRANSIT TIME CHARACTERISTICS OF MULTIPLIER PHOTOTUBES UNDER PULSE CONDITIONS

by

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INTRODUCTION

A phototube is a photosensitive or light actuated electron tube. It consists of a photocathode for emitting photoelectrons when it is illuminated and an anode for collecting the electrons emitted by the cathode. Since the electrons must be drawn from the cathode to the anode, an external source of voltage is required for the operation of the tube.

If a phototube is to be used for amplification, structures called dynodes are inserted into the phototube and it then becomes a multiplier phototube. The light falling on the light sensitive photocathode causes it to emit free electrons, which are focused into a beam and drawn to the first dynode. This dynode is at a more positive potential due to an external source of voltage. Each primary electron that strikes the dynode will free more electrons. The ratio of the number of electrons leaving the dynode surface to the number incident is called the secondary emission ratio. The secondary emission ratio is dependent upon the energy of the primary electrons. This process is then repeated, as each stage or dynode has a more positive potential than the previous one. The combined photoelectron emission and secondary electron emission can give a current multiplication of several million.

To achieve the large values of amplification, it is necessary that the materials for the photocathode and the dynodes be very efficient. The efficiency of interaction between photons and electrons varies with the wavelength of the incident radiation, and for any given photocathode material there will be a wavelength of incident radiation giving the largest current amplification.

This thesis in no way attempts to pass judgment on manufacturers or their tubes, for a given tube can be suitable for one application and yet not suitable for another. In many applications transit time through a phototube is unimportant; in other applications it may have a negligible effect upon the results required; in still other applications the transit time may conceivably have a value of the same order of magnitude as the time one is working with, therefore, having a real significance and requiring consideration.

In the past five years there has been an increased interest in phototube transit time analysis. R. V. Smith at the Westinghouse Research Laboratories, Quentin Kerns and Frederick Kirsten at the University of California Radiation Laboratory, W. J. McNamara at the Bell Telephone Laboratories, and George Morton at the RCA Laboratories have done considerable work in the areas covered by this thesis.

EXPERIMENTAL CONSIDERATIONS

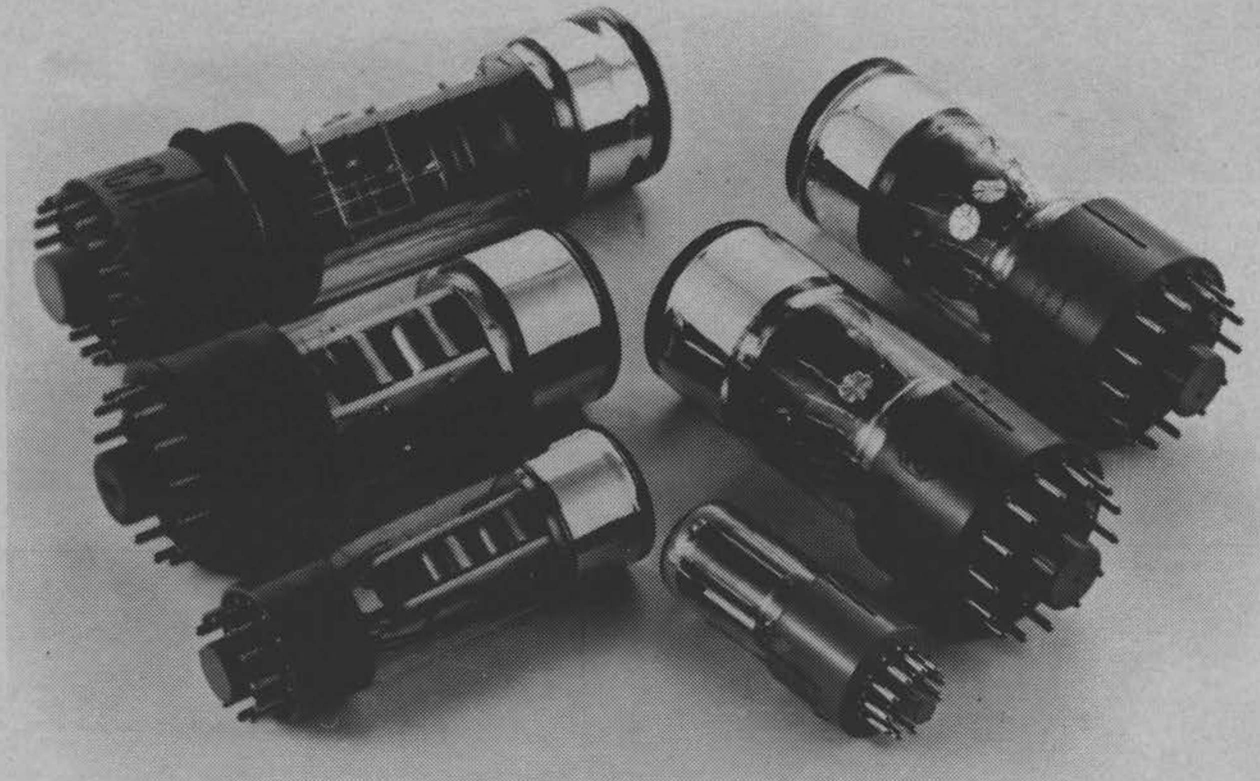
Nine commercial multiplier phototubes were tested to determine their transit times and the factors contributing to variations in the transit times. Figure 1 on page 4 shows six of the multiplier phototubes considered in this thesis. The 6935 and the 6362 are not shown in figure 1, but their appearance is about the same as the 6291, except that they have only a one-half inch diameter end-window as compared to the one and one-half inch diameter for the 6291. Both the 6935 and the 6362 are designed for use in printed circuits. The 6365 appears the same as the 6935, only it has a height of two inches as compared to four and three-quarters for the 6935.

The 6292, 6291, 6935, and the 6362 are 10-dynode box structures; the 6365 is a 6-dynode box structure, and are manufactured by Du Mont. The 2020 and 6655-A are 10-dynode shielded squirrel cage structures; the 931-A is a 9-dynode unshielded squirrel cage structure; the 6810 (17, p.137-140) is a 14-dynode linear structure, and are manufactured by RCA. All of the phototubes are end-window types except for the 931-A which is a side-window tube. The sample of tubes tested is small; of the 54 tubes, there were six 931-A's, four 6292's, four 2020's, two 6810's, eight 6291's, six 6935's, six 6362's, two 6655-A's, and sixteen 6365's.

A

B

C



D

E

F

Figure 1. Phototubes

A - RCA 6810
B - Du Mont 6292
C - Du Mont 6291

D - RCA 6655-A
E - RCA 2020
F - RCA 931-A

<u>LRL Mercury-Capsule Light Pulser</u>

Accurate transit-time measurement requires:

1. A time reference signal of known accuracy.

2. A light pulse with a fast-rise time.

3. Equipment that will accurately measure short time intervals and fast-rise time pulses.

4. An environment which will not affect the multiplier phototube response.

The most direct method of achieving the first two objectives was determined to be a mercury-capsule light pulser (figure 2, page 6), developed at the University of California Ernest O. Lawrence Radiation Laboratory (LRL) (5, p.1-35 and 6, p.31-36). This pulser's most important feature for transit time measurement, is that electrical pulses and light pulses are generated simultaneously in an arc discharge. In this way the electrical pulse can be used as a time reference. According to LRL, the 10 percent to 90 percent rise time for both pulses in the mercury pulser is less than 0.5 nanoseconds (1 nanosecond = 10^{-9} seconds = 1 millimicrosecond), and the light pulse width at the 50 percent points ($\frac{a}{2}$, where 'a' is the pulse amplitude) is less than 1.0 nanosecond. The light comes from a region of small diameter and can be considered a point source.

The reason for a fast rise time requirement becomes apparent when transit time is defined. It is the interval between the breakaway point on the input light pulse and

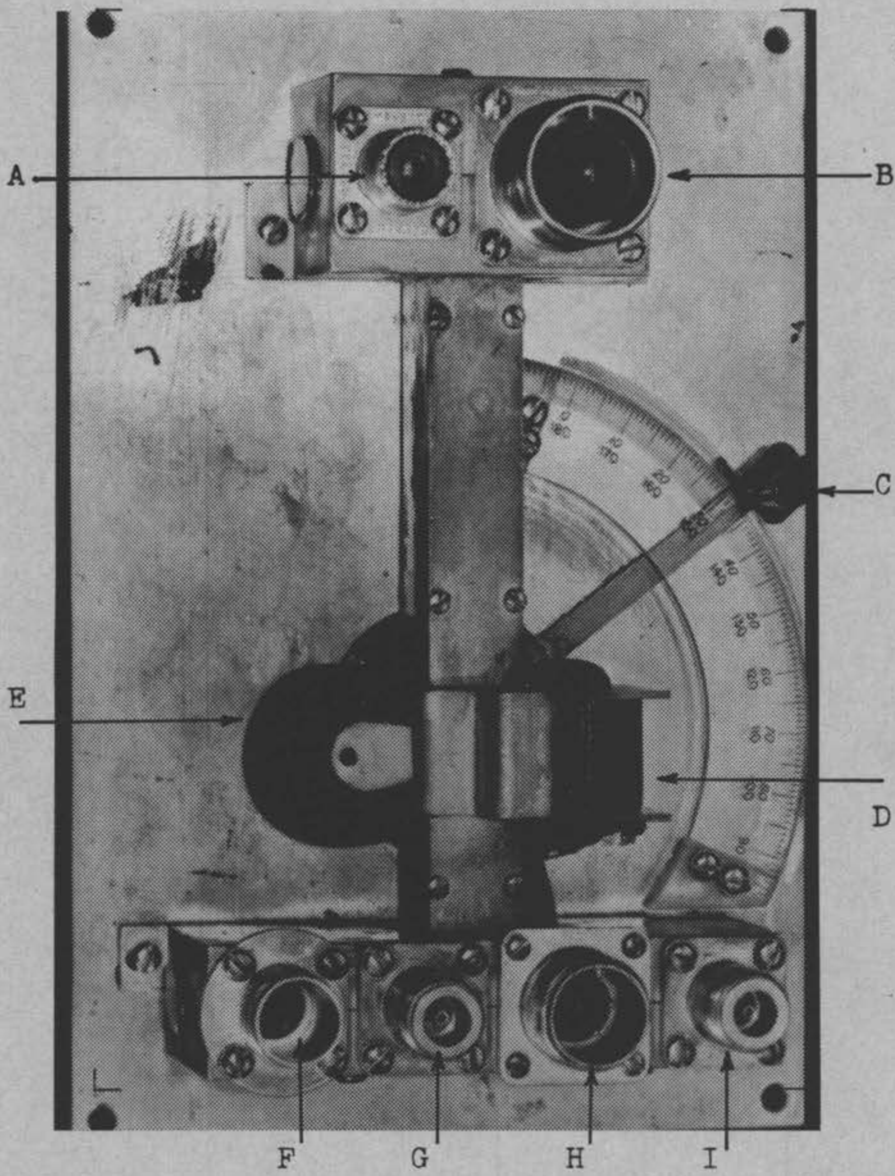


Figure 2. LRL Mercury-Capsule Light Pulser
(Light pulses are emitted from the back of the pulser.)

A - PG-5 monitor signal output

B - PG-6 high voltage input

C - Polaroid attenuator (varies light intensity by factor of 100)

D - Mercury-capsule driving coil

E - Permanent magnet

F - PG-1 125 ohm Trigger output

G - PG-4 51 ohm Trigger output

H - PG-3 driving coil input

I - PG-2 51 ohm trigger output

the 50 percent point on the resulting multiplier phototube output pulse (2, p. CC5-8 (3)). If some other point is used, the results will vary by some small amount. This can be a source of difference between the results obtained by different observers.

To find equipment that will measure rise times in the 1.0 nanosecond range is difficult, but it can be achieved by modifying a Tektronix 517-A oscilloscope. The oscilloscope rise time through the vertical amplifier is 7.0 nanoseconds; by going directly to the vertical deflection plates one can achieve approximately a 1.0 nanosecond rise time. By doing this one has to sacrifice sensitivity, for going to the vertical plates gives a sensitivity of approximately 15 volts per cm. Both the reference pulse and the output signal pulse are displayed on the same sweep of the oscilloscope.

Multiplier Phototube Environment

The restrictions on the multiplier phototube environment should be such that no external signal can affect the results. An obvious solution to this is to mount the phototube in a dark enclosure. Figure 3 on page 8 shows the light enclosure with the light pulser mounted on the end. The enclosure has a microswitch and high-voltage relay which cuts off the phototube high voltage when the door is opened. The high-voltage leads and the signal cables are terminated at the enclosure walls to make for

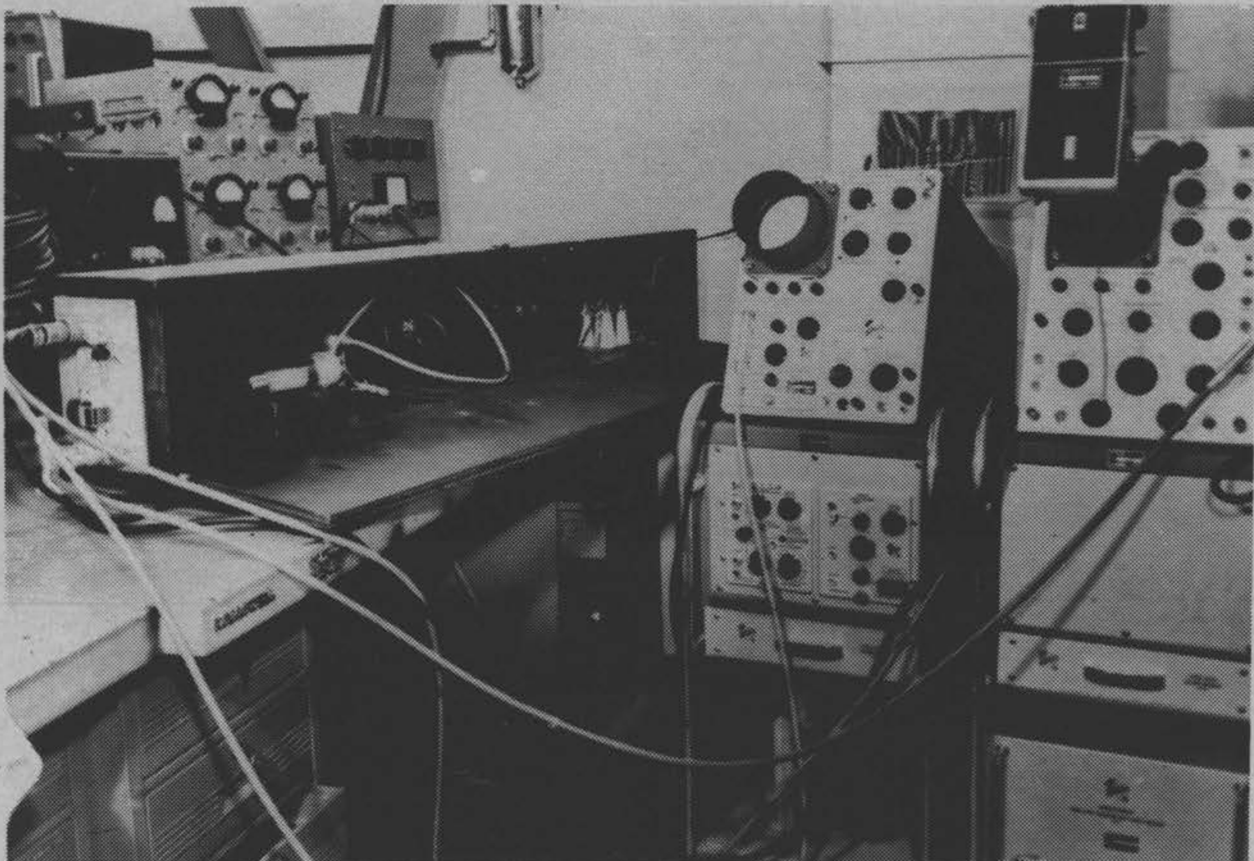


Figure 3. Transit Time Measurement Apparatus

Dark enclosure, cables, power supplies, and Tektronix Oscilloscopes use for transit time determination.

mobility, as well as to insure that the structure is light-tight. The door is inset and has a felt seal around the edges. A Polaroid camera with 3000 -speed film at an aperture of f 4.7 was inserted in the enclosure and the film was exposed for five minutes; no light leaks were detectable. In figure 3 on the shelf above the dark enclosure are the power supplies for the mercury pulser driving coil, the mercury pulser high voltage, and the phototube high voltage. The 541-A Tektronix Oscilloscope is used to monitor the mercury pulser, and the 517-A Tektronix Oscilloscope is used for observation of the output signal and marker signal.

Block Diagram for Transit Time Measurement

Figure 4 on page 10 shows the block diagram for the transit time measurement. It is the same system as shown in figure 3.

The multiplier phototube output signal pulse cable and the time marker cable have delays which are known to within 0.2 nanoseconds. These cables were measured using a SKL pulse generator and a 517-A Tektronix oscilloscope. When using the Tektronix oscilloscope with a direct connection to the vertical deflection plates, the delay through the signal cable and the time marker cable must be 100 nanoseconds longer than that through the cable that triggers the oscilloscope. This allows the sweep to be triggered and under way before the signal is applied to

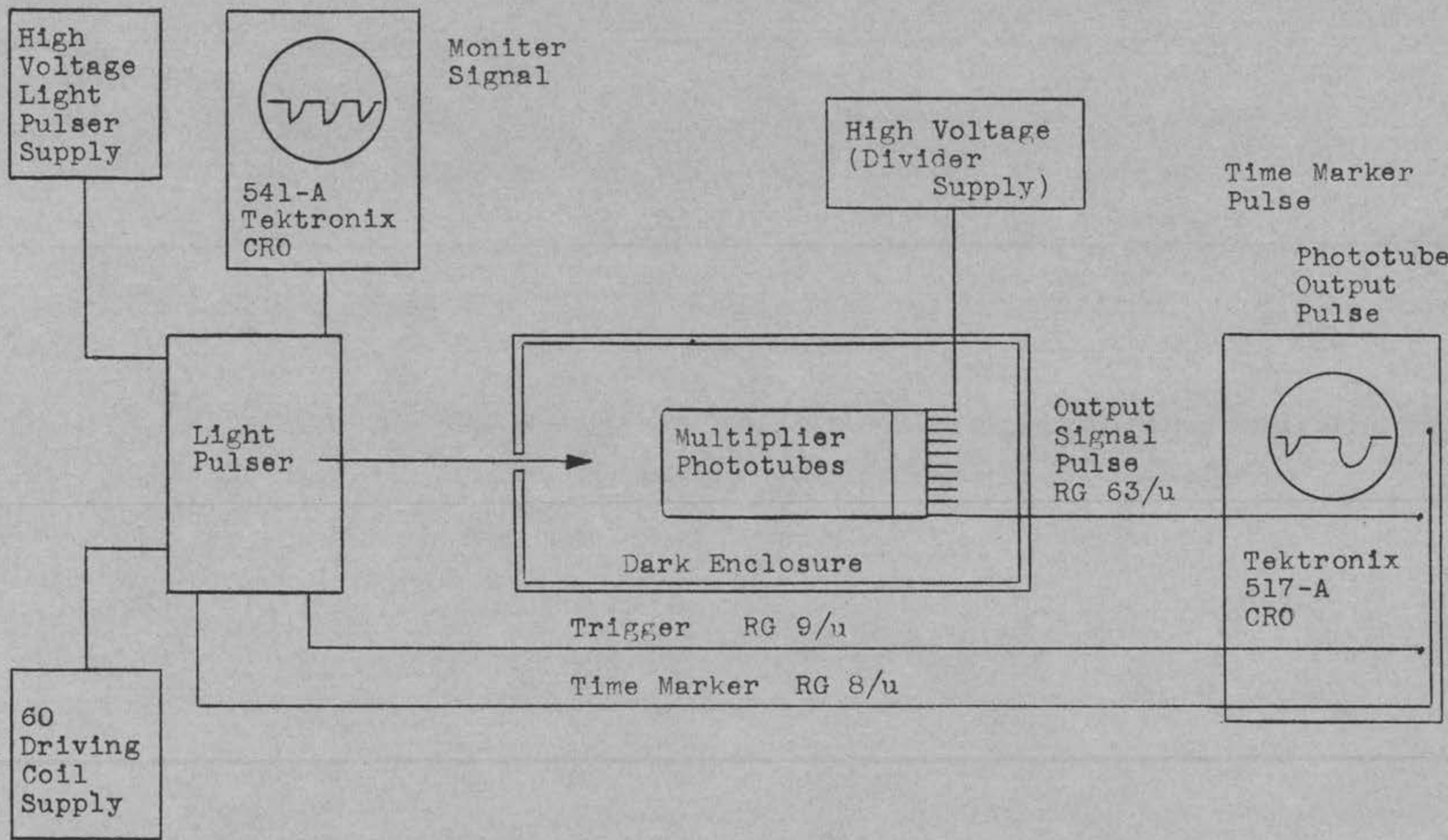


Figure 4. Block Diagram for Multiplier Phototube Transit Time Measurements

the vertical deflection plates. The distance between the light pulser and the multiplier phototube is one inch. The velocity of light in air is 1.0 foot per nanosecond, so this transit time is negligible.

TRANSIT TIME VALUES

The transit time in a multiplier phototube depends upon several factors. It varies with the cathode to anode voltage, the voltage distribution along the dynode structure, the place on the cathode in which the light is incident, the use of a fluor in the optical path, and the construction of the multiplier phototube.

Transit Time Variation With Overall Divider Voltage

The transit time as a function of the anode to cathode voltage is shown in figure 5 on page 12. The transit times shown here are the averages measured for each sample of multiplier tubes. The transit time is not as accurate as that which could be obtained with larger samples; however, the transit time does not vary by more than 4.0 nanoseconds from tube to tube.

It is noted that figure 5 is log log paper and therefore the relation between the transit time and the anode to cathode voltage is not linear. The relation can be found by examining the slope of each curve, and the derivation on pages 30 and 31 shows the relation that the transit time is proportional to the inverse square root of

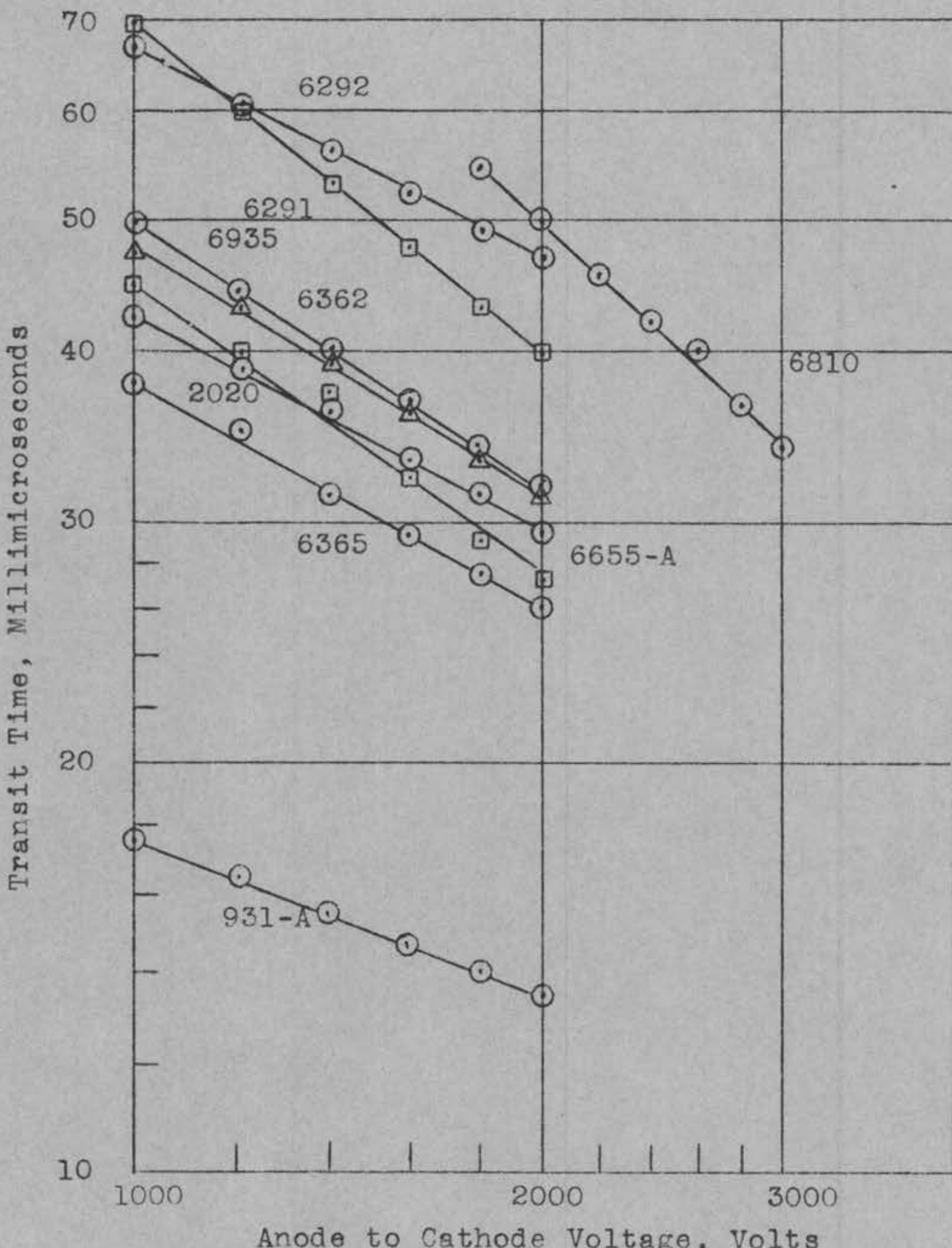


Figure 5. Multiplier Phototube Transit Time as a Function of Divider Voltage

the applied voltage. The constant of proportionality will, of course, change from tube type to tube type. Also, it should be noted that the slopes are not all exactly one-half, but the variations appear to be random, and no systematic departure is observed.

The voltage ranges which are used are typical of what might be used in any given application. The upper limit is where regeneration occurs, and the lower limit is where the output signal is too small to give accurate transit times. The manufacturer's rated voltage falls in approximately the middle of each voltage range. The input signal was always maintained at a constant value for each tube, and at a value for which the output was never saturated. The reason for this becomes apparent, when it is remembered that the transit time measurement depended upon measuring to the 50 percent point on the output pulse, and if a saturated pulse output was used the amplitude would be down, and consequently a transit time shorter than the actual transit time would be accepted. Using such measurements will lead to errors of from 1-5 nanoseconds in the true transit time value.

The values as found in figure 5 are in substantial agreement with those found by Smith (15, p. 121), Kerns (4, p. 114), and Kirsten (7, p. 3) for the 6292, 6655-A, 931-A, and the 6810. The 6291, 2020, 6935, 6362, and the 6365 were not determined in these studies and to the author's knowledge, values of transit time for these tubes have never before been published.

Figure 6 shows the oscilloscope trace of the transit time. The first pulse is the marker or reference pulse, and the second pulse is the multiplier phototube output pulse. Figure 6 shows two things quite clearly. The first, being of primary interest, is the decrease in the transit time with the increase of voltage. The other point of interest is the marked increase in amplification as the anode to cathode voltage increases.

A point of interest is the method of getting the transit time from the photographs such as figure 6. The method used was to put the photograph on a comparator, which is a much more accurate method than trying to measure directly off the oscilloscope face. Possibly a better way to have made the measurements would have been to superimpose timing markers upon the output signal with a frequency of 500 megacycles.

Photocathode Influences Transit Time

Photons striking on various portions of the photocathode actually liberate photoelectrons which take different times to reach the first dynode. It can be seen readily that the shape of the photocathode, the focusing shield, and the electric field within the tube determine the time required for the electron to travel the distance between the cathode and the first dynode. The effects of

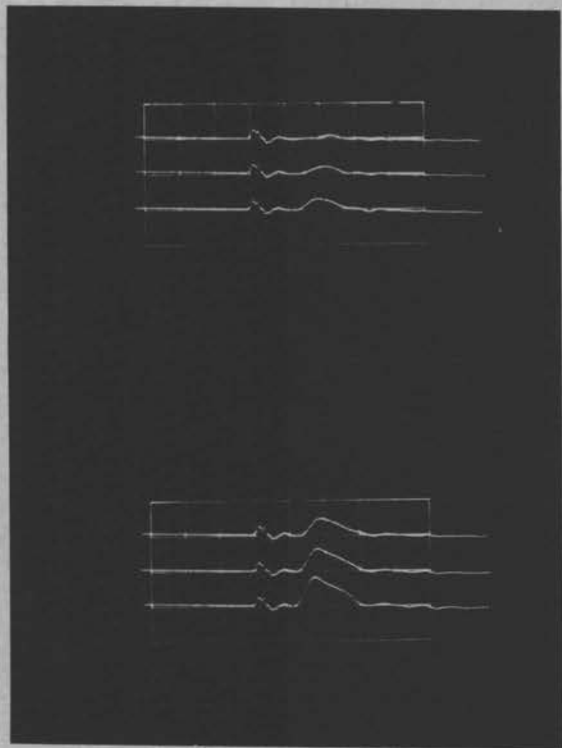


Figure 6. Delay between Trigger Pulse and Marker Pulse for Various Divider Voltages.

Tube Type 931-A
Horizontal 10mus/cm
Vertical 13 volts/cm
Voltage Distribution #2

Anode-cathode voltage from top to bottom:
1000v
1200v
1400v
1600v
1800v
2000v

this variation of time of travel for the electrons shows up at the anode pulse in the form of a spreading effect. Figure 6 on page 15 shows this effect quite forcefully, for the input pulse to the phototube is 1.0 nanoseconds wide at the 50 percent points, and at a divider voltage of 2000 volts, the output pulse is approximately 15 nanoseconds wide at the 50 percent points. It is evident that this spreading effect will tend to increase the transit time of the tube.

In order to get a qualitative analysis of this effect, a 6810 multiplier phototube was used, and the effect was studied by masking off a small portion of the cathode and then noting the transit time for this portion. Figure 7 on page 17 shows the transit time difference in millimicroseconds as a function of the distance of the exposed portion from the center of the 6810, which has a 2-inch diameter photocathode. When the light is incident on the extreme edge portion of the tube it will increase the transit time of those electrons by approximately 10 nanoseconds. If the whole cathode is illuminated, there will be a very definite spreading effect at the anode. As the electron travels through the tube there will also be an additional spreading due to the dynode shape and structure. The shape of the photocathode has much to do with the spread: the flat cathode, the partially curved cathode,

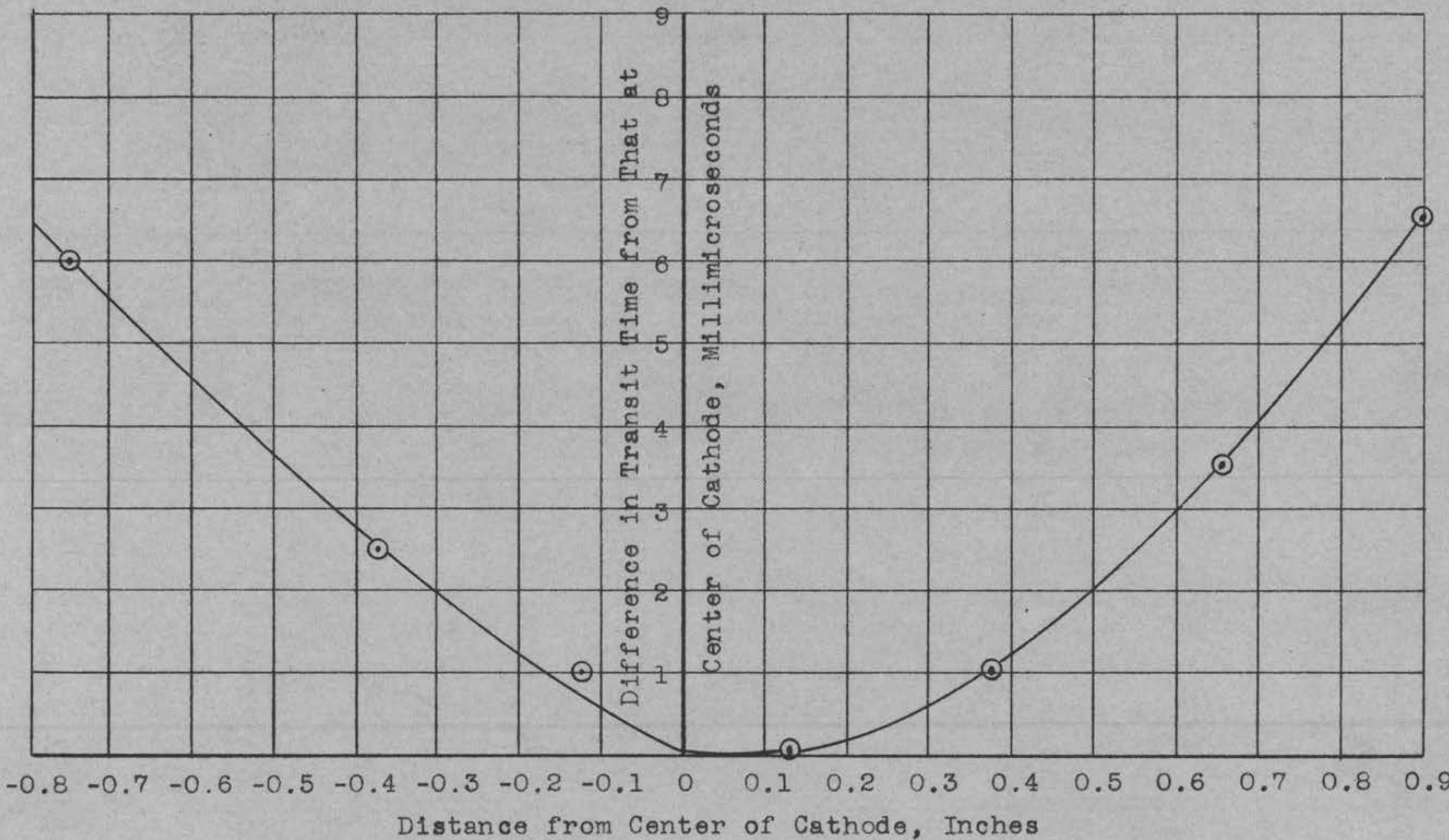


Figure 7. Difference in Transit Times for Photoelectrons
Emitted from Various Parts of Cathode for RCA 6810 PMT

and the fully curved cathode having less transit time spread in that order.

The larger dynode structures such as the 6810 and the 6292 will also display a larger spread effect than will the smaller dynode structures such as the 931-A. Some figures (13, p. 82-85) are available for time spread in various tubes for different manufacturers, but the method used to find these values is not mentioned. Smith (15, p. 122) has also found this spread for a limited number of tubes, and he gives his method as well as his results.

Voltage Distribution Influences Transit Time

Of great interest is the fact that the transit time will vary with the voltage distribution on the voltage divider. The voltage divider's overall voltage is a given value, but it can be distributed in a saddle distribution, a linearly increasing or decreasing distribution, or a constant distribution. The merits of these various distribution are discussed elsewhere (2, p. CC8-4 7-14); this study is concerned with the effects of the distribution on the transit time.

Figure 8 on page 19 shows the transit time as a function of divider voltage of a 931-A for two different voltage distributions. For figure 8 distribution #1 is a saddle distribution and distribution #2 is a constant distribution. At any given anode to cathode voltage, it is apparent that the transit time can be improved by the

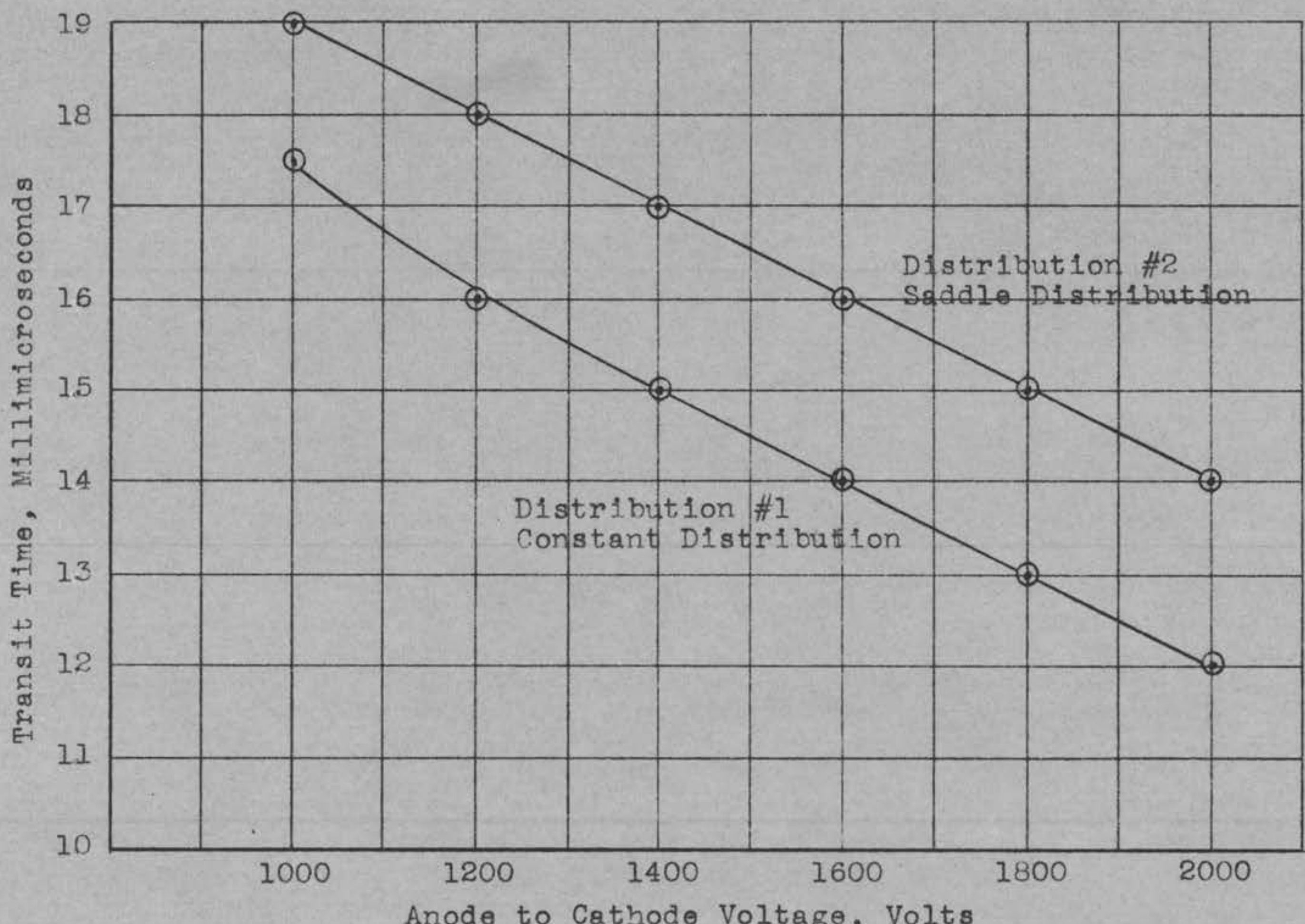


Figure 8. Transit Times for Two Voltage Distributions in the 931-A PMT

choice of the distribution. In this particular case, the transit time is improved by only 2.0 nanoseconds for any given voltage, but in the larger tubes this will be somewhat greater. If the transit time was extremely critical, it would appear that optimization of divider networks would be essential. The maximum current output or maximum gain is essentially the same regardless of the divider network used (2, p. CC8-4 7-14). This is advantageous for, if both gain and transit time should be critical for a specific application, one could improve the transit time by changing the divider network without appreciably affecting the maximum gain of the tube; however, the voltage at which this gain occurs would be altered. The saddle distribution appears to give the fastest transit time in a given tube. It is assumed that the divider networks used for this report are characteristic of those normally used.

The latter stages of the multiplier phototube had to be capacitively by-passed for with the peak pulse outputs drawn from the tubes, the bleeder current momentarily decreases and therefore there was a resultant voltage fall. In the output you then see what appears to be a second pulse, but is actually the same pulse much distorted. This type action is highly nonlinear as far as the response is concerned. The difficulty is overcome by by-passing the last few dynode bleeder resistors. The value of the capacitor is not critical, but should be chosen so that the

RC time constant will be at least ten times larger than the longest pulse to be detected.

Fluor Improves Transit Time

A fluor (18, p. 2-5) acts as a wavelength shifter (scintillator); for it consists of a photofluorescent compound used with a scintillator material to absorb photons and emit related photons of a longer wavelength. A fluor was inserted between the light source and the 6810 multiplier phototube. Figure 9 on page 22 shows in the top trace the pulse output with no fluor in the optical path. The bottom trace shows the output pulse with a fluor in the optical path. As can be seen, the gain does not appear to be altered, but the rise time of the pulse is somewhat improved.

The mercury pulser has an S-4 spectral response and the 6810 phototube has an S-11 spectral response. Therefore, the light from the pulser of about 3000 angstroms is absorbed by the fluor and re-emitted as light of approximately 4500 angstroms. The light pulse on the output of the fluor will thus have a much faster rise time and a slightly higher amplitude. This sharp-rise time pulse will strike the S-11 photocathode, which is very sensitive to 4500 angstrom light, and then the output pulse will also display a sharper rise time. Since the transit time is to the 50 percent point on the output pulse, it is interesting to note that the transit time is decreased by having the

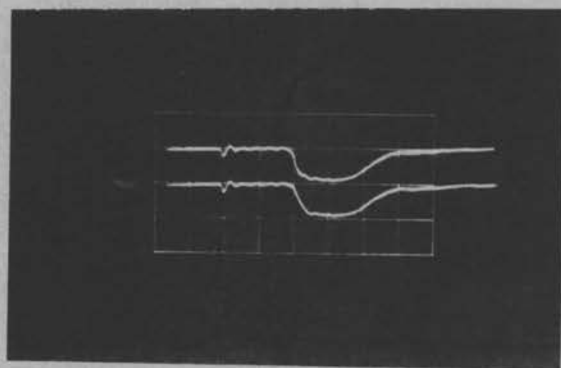


Figure 9.

Tube Type 6810

Horizontal 20mus/cm

Vertical 13 volts/cm

TOP: 6810 without fluor

BOTTOM: 6810 with fluor

fluor in the optical path. It should be borne in mind that the improvement in the transit time comes about by improving the rise time of the input pulse. The reason the output is not attenuated with the fluor is that it has 98 percent transmission.

Transit Time As a Function of Dynode Structure

The electron transit time in a multiplier phototube structure has been shown to be inversely proportional to the square root of the divider voltage (14, p. 16-21 and 15, p. 121-122). The validity of this statement depends upon three basic assumptions: (1) zero emission velocity at each surface, (2) instantaneous secondary emission, (3) a unique electron trajectory and potential distribution function within each gap, and independent of the overall voltage. For the case of the multiplier phototube, these assumptions prove to be essentially correct, although they do not represent the full physical picture.

The data of figure 5 is plotted as a function of the inverse square root of the overall voltage in figure 10 on page 24. The data falls along straight lines from the origin which verifies that the assumptions made form an adequate picture of the physical process.

Of extreme interest in figure 10 is the fact that the tubes fall within six groupings, which are the four geometric shapes mentioned, represented by the 54 tubes. It should be noted that the box dynode structures fall in

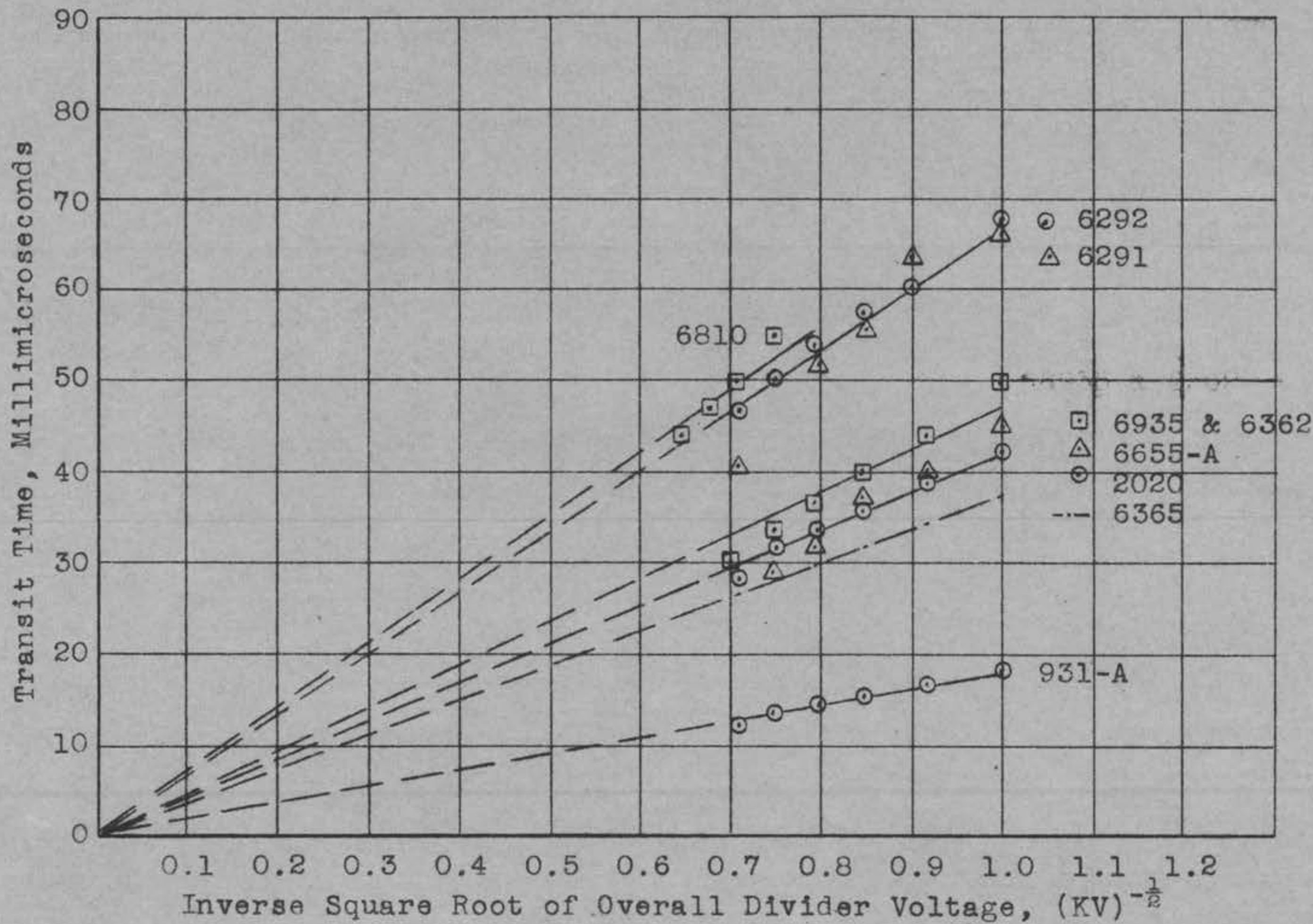


Figure 10. Multiplier Phototube Transit Time as a Function of the Inverse Square Root of the Divider Voltage

three groups depending upon the size of the dynodes, the distance between dynodes and other geometrical considerations. Thus, it would appear possible that given a tube with a known type of construction and size it would be very possible to predict the transit time for a given voltage. The variations in figure 10 appear to be of a random nature, and no departure of a systematic nature is observed.

It is difficult to make too many conclusions about the multiplier phototubes, but it is evident that transit times for the tube types increase with the number of dynodes, the gap between the dynodes, and with the length of the cathode-to-dynode-1 gap. If it is desirable to have both a short transit time and a high gain, the squirrel cage or the shielded squirrel cage structures would be the most desirable. If it is desirable to have both a short transit time and a small size, the shielded squirrel cage structure would be the most desirable. Most of the tubes are end-window type so that this is generally not a factor in consideration.

CALCULATED TRANSIT TIME

In order to determine if the measured values for the transit time for the various tubes are correct, it would be desirable to be able to calculate the transit time for a tube. In calculating the transit time there are two possibilities: (1) the use of the dimensions, geometry, and voltages, of a specific multiplier tube and the necessary approximations, (2) the use of an exact general method which is good for any geometry. The usefulness of each method depends upon the validity of the assumptions, and from a practical standpoint the ease of using the method for other than the most simple geometries.

Approximate Calculated Transit Time for the 6291

In order to calculate the transit time, it is necessary to have the dynode structure of a multiplier phototube available. Figure 11 on page 27 shows such a structure for the 6291 with the dimensions indicated in the figure. It will also be noted that a path has been assumed for a photoelectron to the first dynode, and also a path is assumed for a secondary electron traveling through the box dynode structure. The 6291 was a convenient tube to use, as the dynode structure has a quarter circle geometry that is easily described mathematically.

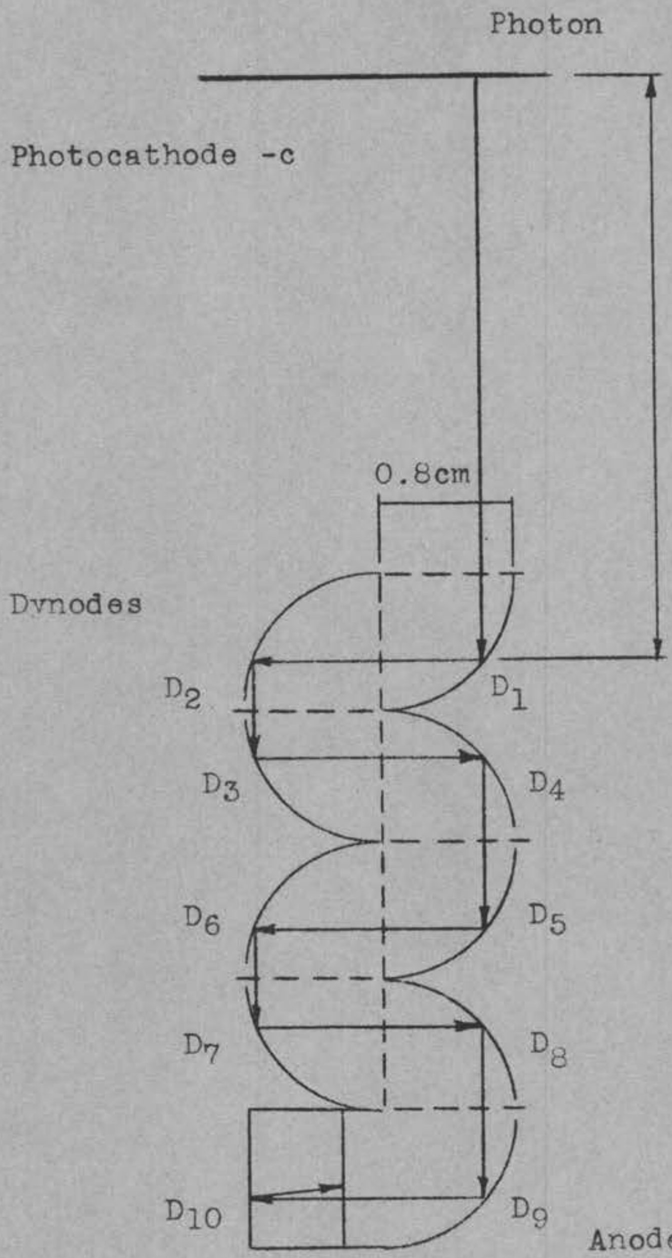
The electron will be assumed to be emitted from each dynode with zero initial velocity. The following energy relationship will then be true:

$$\frac{1}{2} m v^2 = e V \qquad (1)$$

m = mass of electron, kilograms

e = charge on electron, coulombs

v = velocity of electron, meters/second



Voltage Distribution Along Phototube

C	D_1	300v.
D_1	D_2	150v.
D_2	D_3	150v.
D_3	D_4	150v.
D_4	D_5	150v.
D_5	D_6	150v.
D_6	D_7	150v.
D_7	D_8	200v.
D_8	D_9	200v.
D_9	D_{10}	200v.
D_{10}	A	200v.
Total		2000v.

Figure 11. Cross Section through Dynodes of 6291 Showing Assumed Path an Electron Travels

V = voltage between dynodes, volts

d = distance, meters

t = time of travel, seconds

Equation (1) can be rewritten as:

$$\frac{1}{2} m \left(\frac{d}{t} \right)^2 = e V \qquad (2)$$

Rewriting equation (2) yields:

$$t = \sqrt{\frac{md^2}{2eV}} \qquad (3)$$

Equation (3) is interesting for it shows clearly that the transit time could be represented by a constant times the inverse square root of the applied voltage for a given dynode spacing. The total transit time will be the sum of the transit times along the length of the tube and is represented by equation (4).

$$T_T = \sum_{cath}^{Anode} t \qquad (4)$$

With the aid of equations (3) and (4) the transit time for the 6291 phototube can be calculated using the saddle voltage distribution indicated in figure 11 for an anode to cathode voltage of 2000 volts, and using one-half the voltage distribution values of figure 11 for an anode to cathode voltage of 1000 volts.

The results of this calculation yield a transit time of 30 nanoseconds for the 1000 volt distribution, and 22 nanoseconds for the 2000 volt distribution. These values are approximately one-half the measured values of 67 nanoseconds at 1000 volts and 40 nanoseconds at 2000 volts.

The calculations would be expected to be less than the measured values, for instantaneous secondary emission is assumed, as well as the fact that the chosen path is greatly idealized by its straight line distances. Of great interest is the fact that the calculated transit time is in the same order of magnitude as the measured value. However, the measured values of transit time are more accurate than the calculated values of transit time.

Exact Relation for Transit Time

The exact relationship for the transit time has been rigorously worked out (14, p. 16-21 and 16, p. 185-207), and only the assumptions and results will be presented here.

The equations consider an electron in the ith gap of a multiplier phototube, having left an arbitrarily shaped dynode surface with zero velocity, and being accelerated in an arbitrary electrostatic field toward another dynode at a potential more positive by an amount V_i. When along its trajectory Z_i, it has reached a position which is at potential $V(z)$ with respect to the preceding dynode, its velocity can be written:

$$\frac{1}{2} mv^2 = e\ V(z) \qquad (5)$$

$$v = \frac{dz}{dt} = \sqrt{\frac{2e}{m}} \sqrt{V(z)} \tag{6}$$

$$t_i = \sqrt{\frac{m}{2e}} \int_{z_i} \frac{dz}{\sqrt{V(z)}} \tag{7}$$

If we assume that the spatial potential distribution between dynodes and the resultant trajectory, are depenent only on the geometry and not on the actual value of V_i, of the voltage between dynodes, we can get another relation:

$$V(z) = f_i\ (z)\ V_i \tag{8}$$

let

$$A_i = \sqrt{\frac{m}{2e}} \int_{z_i} \frac{dz}{\sqrt{f_i(z)}} \tag{9}$$

then

$$t_i = \frac{A_i}{\sqrt{V_i}} \tag{10}$$

Here the $f_i(z)$ is the voltage distribution function along the trajectory z_i. It is now necessary to take the sum of a number of such accelerations (secondary emission is again considered instantaneous) assuming that the divider maintains constant ratios on all electrodes:

$$V_i = B_i\ V \tag{11}$$

B_i is the ratio of the voltage across the i<u>th</u> gap to the overall voltage, and these B_i's are constants and therefore independent of the overall voltage.

$$T = \sum_i t_i = \frac{1}{\sqrt{V}} \sum_i \frac{A_i}{\sqrt{B_i}} \tag{12}$$

let

$$A = \sum_i \frac{A_i}{\sqrt{B_i}} = \sqrt{\frac{m}{2e}} \sum_i \frac{1}{\sqrt{B_i}} \int_{z_i} \frac{dz}{\sqrt{f_i(z)}} \tag{13}$$

then

$$T = \frac{A}{\sqrt{V}} \tag{14}$$

Equation (14) is misleadingly simple, but when the value of "A" is taken into consideration the complexity of the problem is apparent. It is evident that, even for the simplest of geometries, the A_i coefficients are impossible to calculate other than by numerical methods.

The author has made no attempt to evaluate the value for the transit time from the exact method pursued in this section. I believe that it adds little to the transit time measurement picture, except to make it quite apparent why a laboratory method would generally be preferred.

It would appear that the transit time expression for 'A', as given by equation (13), could be minimized. To do this would require that the ratio of the voltage across the ith gap to the overall voltage be as large as possible. Also, it is desirable that the value of the voltage distribution function along the trajectory z_i be such that the integral along the path would make 'A' very small.

CONCLUSION

In order to accurately measure transit time in multiplier phototubes, it is necessary to have a fast rise time light pulse source, an accurate time reference, and an environment which will not introduce stray signals into the phototube.

(1) The transit time varies as the inverse square root of the anode to cathode voltage.

(2) The transit time varies with the point on the photocathode where the light is incident. The center of the photocathode gives the shortest transit time.

(3) The transit time is a minimum when a saddle voltage distribution is used.

(4) The fluor improves the transit time measurement by acting as a wavelength shifter and thus giving a faster rise time to the input pulse.

(5) The transit time appears to be predictable, for the various geometries fall into groupings as a function of the inverse square root of the voltage, so that a tube with a known geometry would have its transit time predicted for a given voltage.

The approximate calculated transit time is in close agreement with the measured value, however, the latter are more accurate. A rigorous mathematical approach can give a qualitative picture on designing a phototube for a minimum transit time.

Other factors influencing the values of transit times are controlled by the methods used in performing the measurements. These include:

(1) If some value other than the 50 percent point on the output pulse is used for the time of occurrence, either a longer or shorter transit time will be obtained.

(2) A saturated output current gives a shorter transit time than an unsaturated output current.

(3) The transit time can be measured directly off the scope or it can be measured on a comparator or with a marker signal. The latter methods give more accurate results.

It becomes apparent that when large transit times are prohibitive, care should be taken in choosing the specific multiplier phototube to use. If it is desired to have the gain a maximum and the transit time a minimum, the squirrel cage structures would be the choice.

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APPENDIX

LIGHT FEEDBACK EFFECT

One of the more important aspects of this thesis does not relate directly to the measurement of transit time, but rather to a phenomenon which was observed in the pursuit of the major objective. This is a phenomenon which has been seen by other observers and has been given the name "light feedback effect". The light feedback effect is actually of a great deal of interest because it is the phenomenon behind an unwanted effect known as the after-pulse.

After-Pulse Phenomenon

The first indication of the light feedback effect was noted when using the 6810 multiplier phototube near its regeneration voltage. The top trace in figure A1 on page 37 shows the after-pulse as observed. The bottom trace shows the output after the divider voltage has been reduced, so that the operation is no longer near the regeneration point. Initially, the hypothesis can be made that the after-pulse is created by light being generated in the anode region of the tube. The anode light travels back to the photocathode, causing the emission of photoelectrons which travel through the tube, and appear as a second signal pulse of decreased amplitude at the anode. The light goes from the anode region to the cathode region in a fraction of a nanosecond. Therefore, the after-pulse is

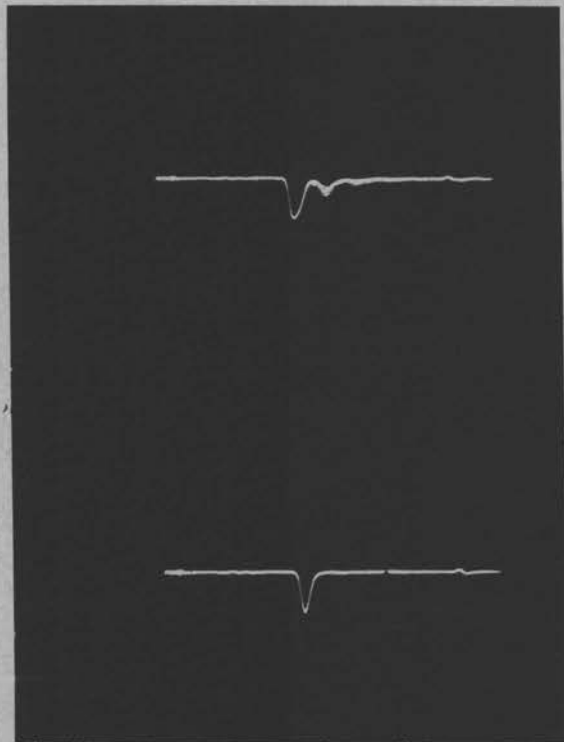

Figure A1

Tube Type 6810

Horizontal 50 mus/cm

TOP: After-pulse in 6810 at 2800 volts divider voltage.

BOTTOM: No after-pulse in 6810 at 2400 volts divider voltage.

displaced from the primary pulse by nearly the transit time of the tube. Referring back to figure 5 on page 12, the transit time for the 6810 at a divider voltage of 2800 volts is approximately 35 nanoseconds. The top trace of figure A1 shows that the after-pulse is displaced from the primary pulse by approximately 35 nanoseconds. This would tend to verify the initial hypothesis that the light is generated in the anode region of the tube.

System to Detect Light at Anode

To make certain that light feedback was the actual phenomenon taking place in the anode region, two tests were performed:

(1) A faint glow in the anode region of the 6810 phototube was photographed (7, p. 3) using Polaroid 3000-speed film with an f 4.7 aperture and a time exposure of five minutes.

(2) A second multiplier phototube (a 931-A side-window type because of the ease of mounting in the dark enclosure and its high gain characteristics) was used to detect and display the results on another oscilloscope.

A block diagram of the second system, using the 931-A as a detector is shown in figure A2 on page 39. If the light does originate at the anode region, it would take a path equal electrically to the transit time of the 6810, the transit time of the 931-A, the pulse output cable

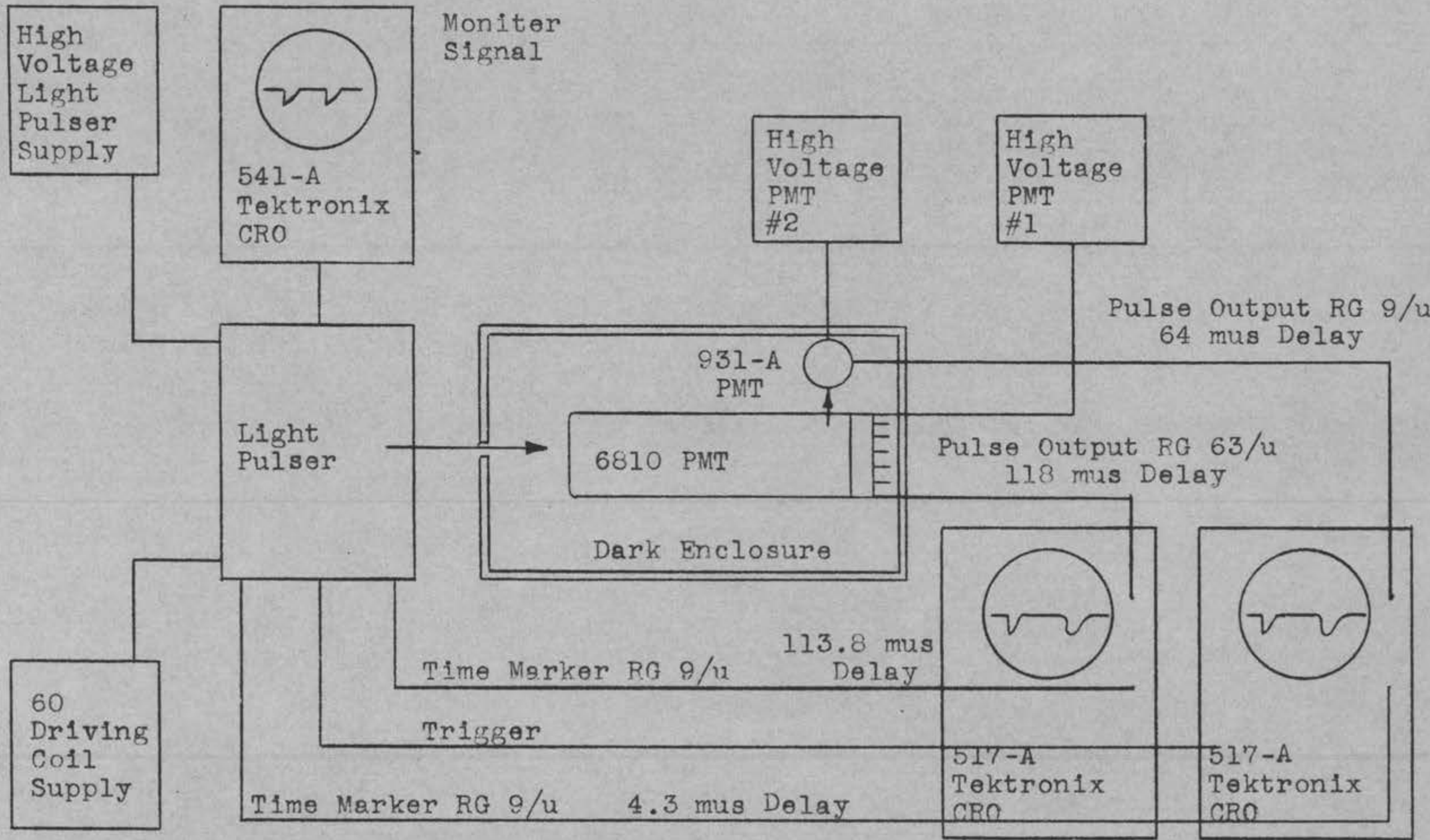

Figure A2. Block Diagram for Detecting Light Pulses at Anode delay to the oscilloscope, and less the time marker cable delay to the oscilloscope. Again from figure 5, the 6810 has a transit time of 40 nanoseconds at 2000 volts; figure 8 on page 19 shows that the 931-A has a 14 nanosecond delay at 2000 volts for distribution #2.

The computed delay between the time marker and the output signal is 113.8 nanoseconds. The delay between the time marker and the output signal as measured from a photograph on a comparator was 115.5 nanoseconds. These results are in close enough correlation to denote that the light feedback signal is actually emitted in the anode region. When the 931-A was varied along the length of the 6810, the only detectable signal as read on the output of the 931-A was that from the anode region of the 6810 phototube.

Figure A3 on page 41 shows the output signal from the 931-A phototube when it is mounted over the anode of the 6810. Figure A4 on page 41 shows the actual physical arrangement which was used in determining the light feedback effect. To make certain that some of the light from the light pulser was not coming directly to the 931-A phototube, the 6810's high voltage was removed. When this was done, no output was obtained from the 931-A which verified that there was definitely a light being generated in the anode region of the 6810. Figure A3 shows the 931-A output for two different divider voltages on the 6810,

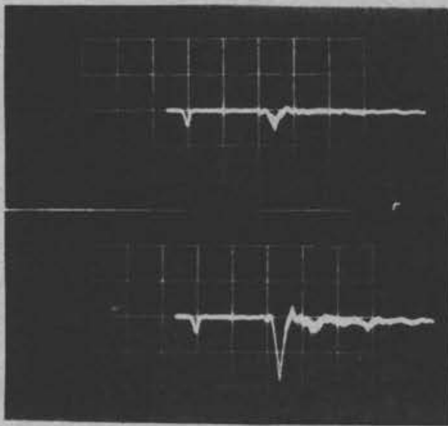

Figure A3. Light feedback Signal at Anode of 6810 PMT

TOP: Anode-Cathode 2400 v.
Horizontal 50 mus/cm
Vertical 4 volts/cm

BOTTOM: Anode-Cathode 2800 v.
Horizontal 50 mus/cm
Vertical 4 volts/cm

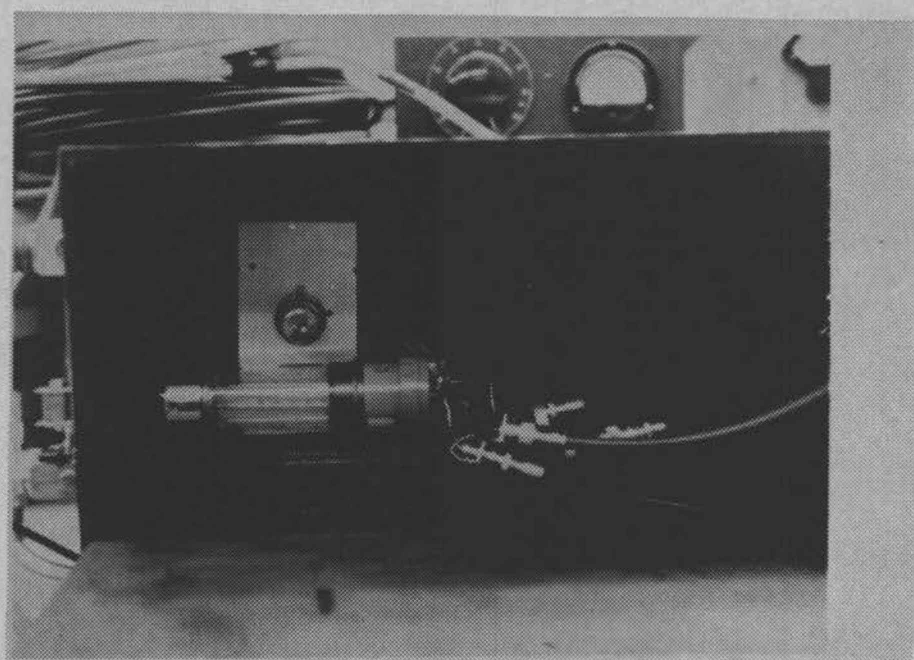

Figure A4. Physical Relation Between 6810 and 931-A for Detection of Light Feedback

Top tube is the 931-A.

and immediately suggests that a relation between the generated light and the divider voltage can be found.

Anode Light Variation with Divider Voltage

By using the 931-A phototube as a detector, the light signal at the anode of the 6810 was observed as the anode-to-cathode voltage on the 6810 was varied. Figure A5 on page 43 shows that the light intensity in the anode region of the 6810 varies linearly with the applied voltage. Most phototubes have the light generated in the anode region, but anode structures such as the squirrel cage, shielded squirrel cage, and the box structure are so constructed that the anode light cannot be fed back to the cathode. The 6810 has a linear dynode structure so that it is very easy for light to go directly back to the photocathode. If a given tube displays the feed-back phenomenon, it should be worked below the regeneration voltage, for the first after-pulse can be a significant percent of the primary pulse as is demonstrated in figure A1.

The intensity of the light generated in the anode region is nearly proportional to the current in the multiplier phototube. Several effects probably cause the light to be generated in the anode region. Among the possible causes are ionization of residual gases, the fluorescence of the mica supports, the fluorescence of the glass envelope, or some combination of all of these. This

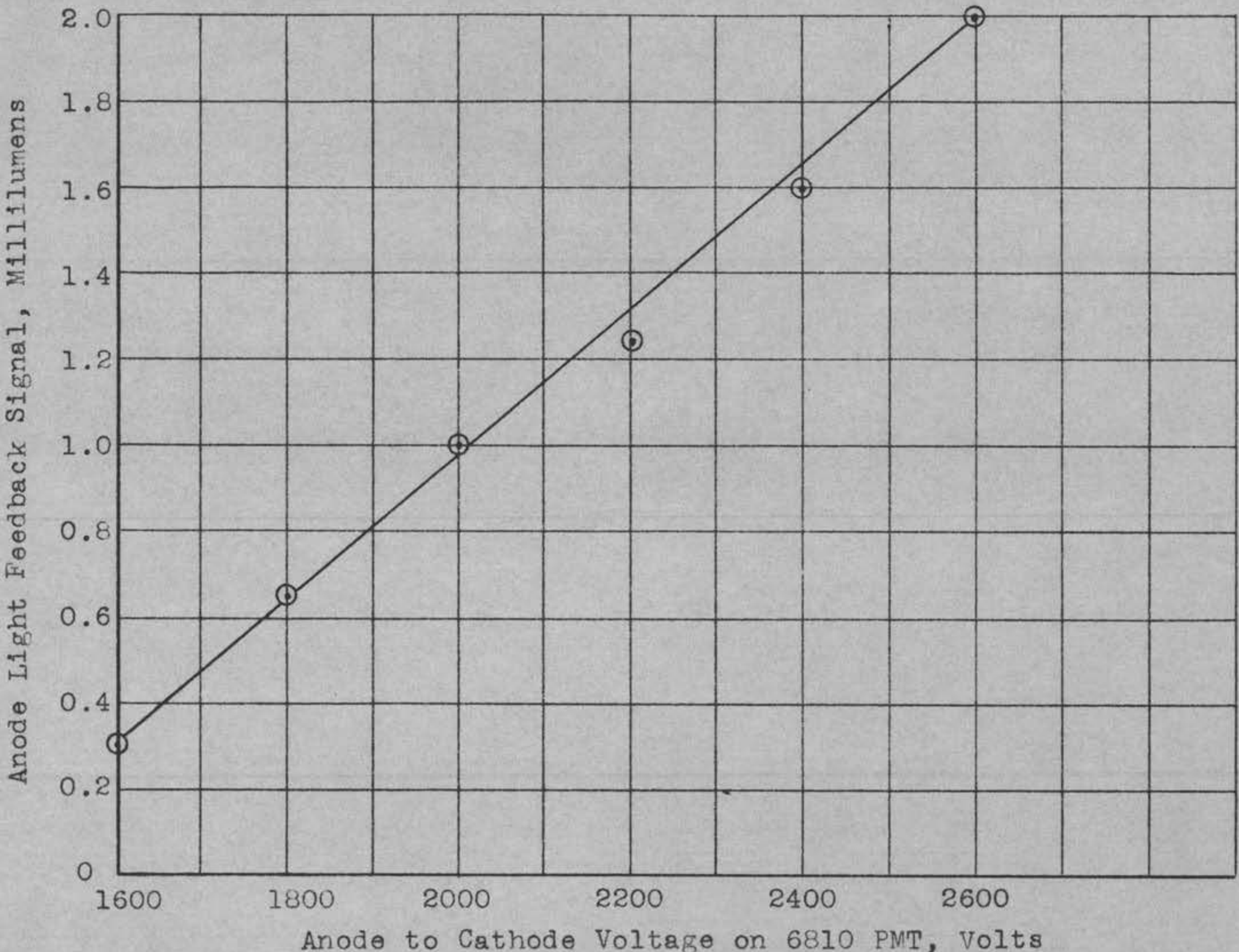

Figure A5. Variation of Light Feedback Signal with 6810 Divider Voltage explanation would also account, in part, for a much smaller feedback signal in squirrel cage structures, where there are no mica supports and where the electron path cannot reach the glass envelope.

Light feedback could be an extremely disturbing effect in certain application, such as where you would want to use the pulse width, or where you are integrating the output pulse to yield specific information. The adverse effects which this phenomenon suggests are completely avoidable if the tube is not used near the regeneration voltage. This voltage can be below or above the rated voltage of the tube, for the voltage where regeneration occurs depends a great deal upon the divider network distribution.