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A LOGARITHMIC RECORDER FOR MEASURING LIGHT DOWN TO LOW INTENSITIES

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ABSTRACT

Ordinarily, photomultiplier tubes are used in photometers which have a linear response, with a consequent need for switching from high to low sensitivity ranges. To prevent injury to the multiplier tube and to avoid switching to various sensitivity levels, another electronic instrument has been developed and tested. It covers an extremely wide range on a single logarithmic scale, and intensity recordings can be made directly on an ordinary Esterline-Angus 0-1 ma recorder. A multiplier feedback circuit is combined with a zero balancing circuit and two pentode tubes that automatically cut in at higher intensities to correct for deviations from a true logarithmic response. With a fairly good 1P21 tube and the constants as computed, a range of brightness of 10^6 can be covered with the lowest brightness at approximately 4×10^{-4} microlamberts.

PROBLEM STATUS

This is an interim report on a portion of the problem. Work involving the described equipment is still in progress.

AUTHORIZATION

NRL Problem N06-19R.
NR 476-190

A LOGARITHMIC RECORDER FOR MEASURING LIGHT DOWN TO LOW INTENSITIES

INTRODUCTION

In the normal process of "seeing" the human eye has the important advantage of covering very wide ranges of light intensities with comparative ease. From the classical work of Weber and Fechner in earlier times it was shown that, within certain limitations, the eye is a logarithmic detector of light. Or, more specifically, the sensation produced by light flux varies directly as the logarithm of the stimulus or flux involved. Such a characteristic enables the observer to do photometric work even down to fairly low levels without noticing any great change in the eyes themselves.

Photometers using photoelectric or photovoltaic cells as detectors generally have output meter deflections that vary linearly with the incident light. This means that wide variation in the intensity cannot be measured on a single scale. Then too, with sensitive instruments, damage is liable to occur when a sudden change from low intensity to high intensity takes place.

A low-level light detector using a photomultiplier tube was described in a recent paper [1]. A five-position switch enables the operator to cover a wide range of light values to very low levels, but for sudden changes and very wide variations this linear instrument has disadvantages. For example, the range of intensities produced by a phosphorescent material during the total period of decay cannot be adequately recorded on a single scale. Since a sensitivity setting for the instrument for higher brightnesses will show a graphical result practically zero while the phosphor is still luminous, no accurate determination can be made of the brightness at lower levels unless an operator resorts to switch adjustments.

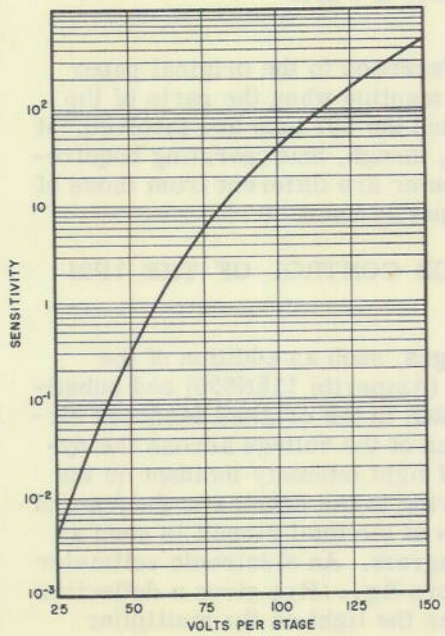


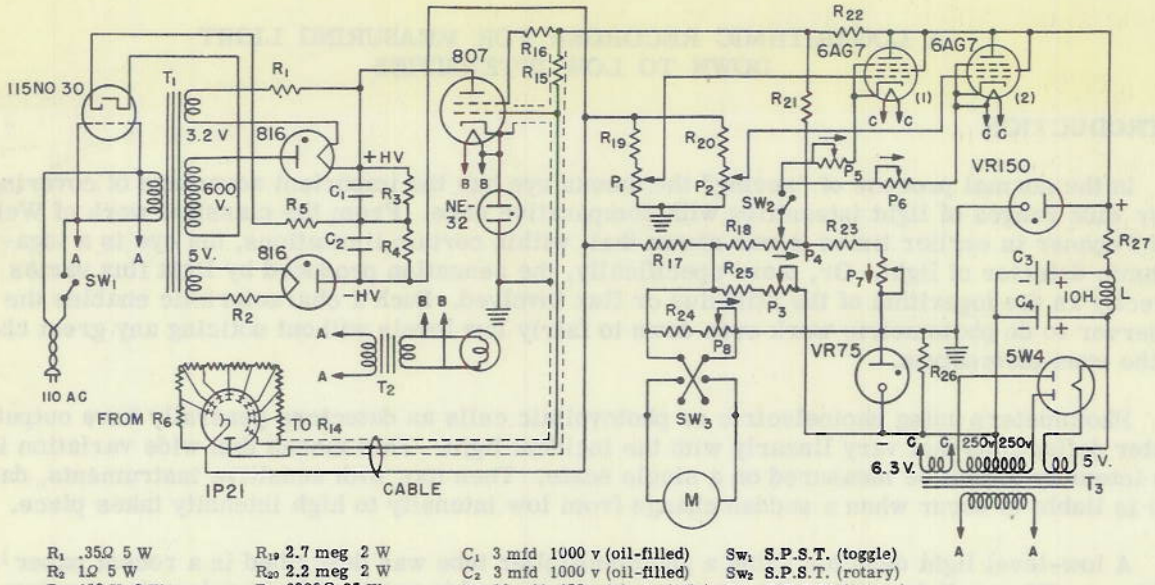
Figure 1. Dynode Voltage vs Sensitivity for an Average 1P21 Tube

Circuits with a logarithmic output scale of limited range have been described, and some of them use a basic principle in the multiplier tube to get a logarithmic deflection. This is made possible by the fact that an approximate logarithmic relation exists between the tube sensitivity and the dynode voltage, as illustrated in Figure 1. A densitometer using such a principle in a feedback circuit has been developed by Sweet [2] for commercial purposes, but the range of linearity on a semilog graph is only about 10^3 and the balancing circuits are not suitable for general photometric uses.

In initial experiments, an exact duplicate was made of the instrument described by Sweet, and tests showed it to be sensitive with a high degree of stability. Much work was spent on trying to adapt the circuit for wide-range photometry, particularly by changing the automatic meter-shunt arrangement, but all efforts led to the conclusion that some new circuit was desirable. The 807 tube and the high-voltage power supply for the photomultiplier tube, however, were found very satisfactory for limited voltage control on the dynodes, and even the constants from the original circuit were used to good advantage in this part of the circuit.

A description of basic circuit elements is given in Sweet's article, and it is therefore possible to omit these discussions

[1] Plymale, W. S., Jr. and Hansen, D. F., "A Stabilized Voltage Supply and Linear Amplifier for Photomultiplier Tubes," NRL Report No. 3555, Oct. 12, 1949.
[2] Sweet, M. H., "Logarithmic Photometer," Electronics, 19: 105-109, November 1946.



R_1 .35Ω 5 W	R_{19} 2.7 meg 2 W	C_1 3 mfd 1000 v (oil-filled)	Sw_1 S.P.S.T. (toggle)
R_2 1Ω 5 W	R_{20} 2.2 meg 2 W	C_2 3 mfd 1000 v (oil-filled)	Sw_2 S.P.S.T. (rotary)
R_3 100 K 2 W	R_{21} 6000Ω 25 W	C_3 20 mfd 450 v (electrolytic)	Sw_3 D.P.D.T. (rotary)
R_4 100 K 2 W	R_{22} 1,250Ω 10 W	C_4 20 mfd 450 v (electrolytic)	
R_5 400Ω 5 W	R_{23} 220Ω 1 W		T_1 Thordarson T-22R02
R_6..R_{14} 15 K 1 W each	R_{24} 500Ω 1 W	P_1 .1 meg 1 W	T_2 Thordarson T-22R00
R_{15} 100 meg 2 W	R_{25} 22 K 1 W	P_2 .2 meg 1 W	
R_{16} 1 K 1 W	R_{26} 3,800Ω 10 W	P_3 .1 meg 1 W	L Thordarson T-14C04
R_{17} 330 K 8 W	R_{27} 1,000Ω 10 W	P_4 500Ω 2 W	
R_{18} 620Ω 1 W		P_5 5 K 1 W	
		P_6 1 K 1 W	
		P_7 200Ω 1 W	
		P_8 4 K 1 W	

Figure 2. The Complete Circuit with Table of Parts

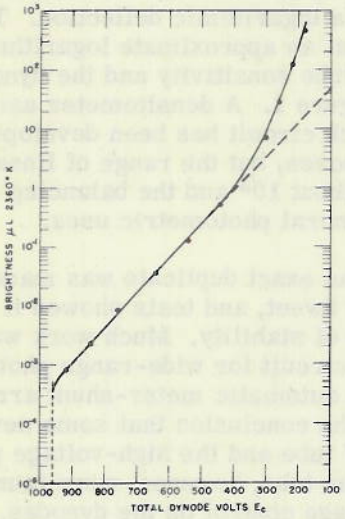


Figure 3. Dynode Voltage vs Light Input for Feedback Circuit

here. Subsequent references to the original paper are confined to brief mention when the parts of the circuit centered around the 807 tube are involved. It is to be remembered, though, that operating requirements for a densitometer are different from those of a photometer as ordinarily used.

FEEDBACK VOLTAGE CONTROL OF THE 1P21 TUBE

With minor changes, such as addition of the thermal delay switch (Amperite 115N030) and substistution of the 1P21 tube, in the original feedback circuit[3], curves were run of the voltage across the dynodes as a function of light intensity incident on the photocathode. Referring to the schematic diagram of Figure 2, this portion of the total circuit is seen as the left half of the diagram. An electronic voltmeter placed across resistors R6...R14 gives a deflection which becomes less as the light on the multiplier photocathode is increased. For a certain limited range no further circuits are needed to produce a fairly logarithmic photometer, but correction features are necessary if the indicated voltage is to be used over an extended range. A plot of brightness vs dynode voltage is shown in Figure 3. Any multiplier tube giving a curve similar to this may be used with the circuit constants given in Figure 2. The ordinates on the graph of Figure 3 represent the brightness

[3]Sweet, op. cit.

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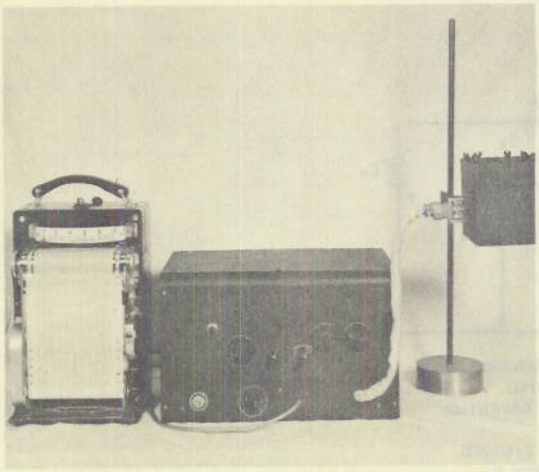


Figure 4. Front View of Apparatus

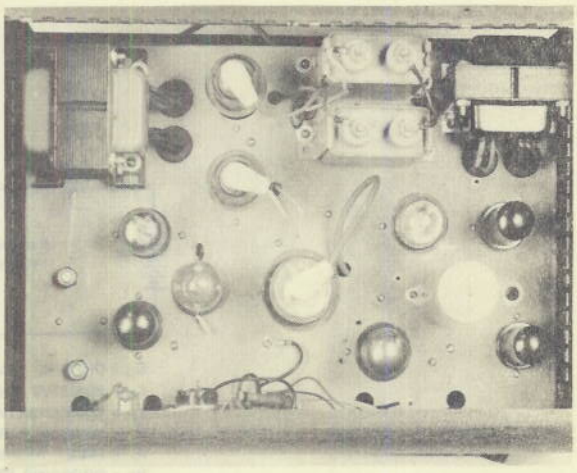


Figure 5. Top View of Apparatus

of an ideal reflector when placed in the position of the photocathode. That is to say, they represent the illumination on the phototube.

From darkness to an illumination value of about 0.5 μL the voltage curve is essentially linear for good 1P21 tubes with desirable saturation characteristics. Some tubes showed appreciable curvature below this point and were discarded even though their noise and sensitivity characteristics were good for many purposes. If early saturation takes place in the multiplier, the range is too limited for effective correction circuits.

A full discussion of the 807 control tube is given in the original paper[4]. Apparently, any 807 tube of standard characteristics may be used, but of course any peculiarities in the grid-voltage vs plate-resistance curves will affect the curve of Figure 3.

Finally, there are certain construction precautions to be observed in mounting and wiring the feedback circuit. The multiplier anode and control grid circuits are returned to ground through a resistor of very high value (100 megs.); and such features as good tube sockets, polyethylene insulation, and proper leakage paths are essential.

THE COMPLETE PHOTOMETER CIRCUIT

A front view of the instrument is shown in Figure 4, a top view (chassis) being shown in Figure 5. For convenience in bench work, the phototube has been placed in a pick-up box separate from the main instrument. The recorder, which requires only a small two-wire cable from the main unit, is also shown.

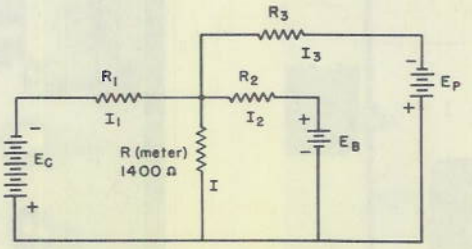
As mentioned before, the left-hand side of the diagram (Figure 2) is the feedback part of the circuit and the voltage output from this arrangement may be considered as the driving voltage (E_C) for a combination balancing-correcting-recording circuit.

By the use of Kirchhoff equations it was possible to set up conditions and evaluate the circuit constants for preliminary trials. Consider the circuit of Figure 6. For full deflection of the recorder meter,

E_C = 150 volts (approximately) E_P = 75 volts

I = 1 ma and RI = 1.4 volts

[4] Sweet, op. cit.



E_C = DRIVING VOLTAGE FROM DYNODES
E_B = POSITIVE BUCKING POTENTIAL
E_P = COMPENSATING NEGATIVE POTENTIAL
R = RECORDER RESISTANCE
R_1 = INPUT RESISTANCE FROM DYNODES
R_2 = DROPPING RESISTANCE FROM E_B
R_3 = DROPPING RESISTANCE FROM NEGATIVE SUPPLY

Figure 6. Basic Balancing Circuits for Recorder in Output

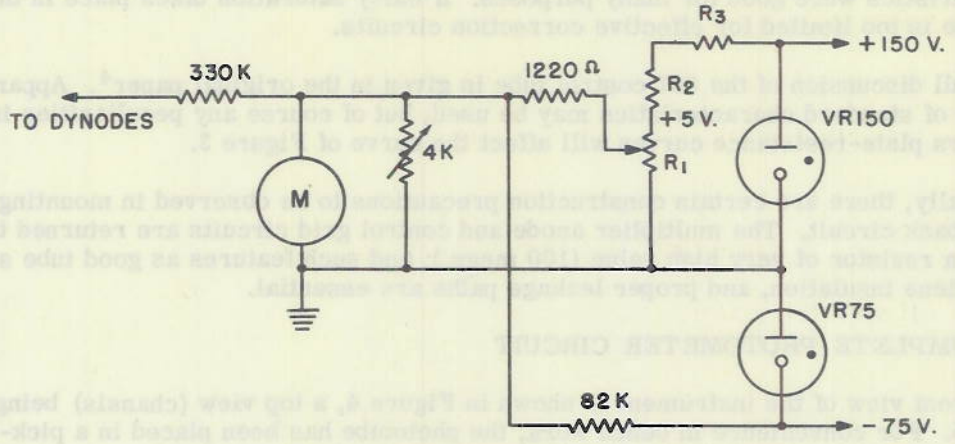


Figure 7. Experimental Balancing Circuit

For no deflection (null balance),

$$E_C = 820 \text{ volts (approximately)} \qquad E_p = 75 \text{ volts}$$

$$I = 0 \text{ and } RI = 0$$

With a value of 83K assigned to R_3 and an arbitrary value of 4.4 volts given to E_B, it was found possible to effect a solution whereby R_1 = 315K ohms and R_2 = 1220 ohms.

After some experimentation, the circuit of Figure 7 was found to be satisfactory as a balancing circuit where the resistors R_1, R_2, and R_3 were merely divider resistors for the +150 volts. With such a circuit it was possible to run brightness-vs-deflection curves. As indicated

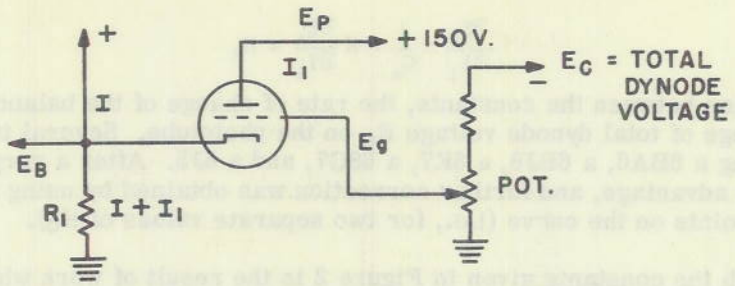


Figure 8. Automatic Corrector Circuit

in the graph of Figure 3, the instrument was linear up to about 0.5 μL, but above that point some kind of correction circuit was needed.

After several experiments, it was decided that an automatic increase in the voltage E_B, after the dynode voltage E_c dropped to the vicinity of 440 volts, seemed the best method to correct for non-linearity. A simplified circuit for such an arrangement is given in Figure 8. When the negative voltage E_c drops to a certain value, a proportional drop in E_g, the grid bias on the tube, occurs and the tube becomes conducting. This causes an additional current I_1 to flow in the resistor R_1 which produces an increase in E_B, the bucking voltage.

The relation between E_B and E_c may be illustrated by considering first that

$$I_1 = f(E_c) \tag{1}$$

for a given tube and

$$E_B = (I + I_1)R_1 \tag{2}$$

where I is essentially constant.

Now,

$$E_g = (I + I_1)R_1 + KE_c \tag{3}$$

where K = fixed ratio. Then

$$\frac{\partial E_B}{\partial I_1} = R_1 \tag{4}$$

and

$$\frac{\partial E_g}{\partial I_1} = R_1 + K\frac{\partial E_c}{\partial I_1}, \tag{5}$$

and substituting,

$$\frac{\partial E_B}{\partial I_1} = \frac{\partial E_g}{\partial I_1} - K\frac{\partial E_c}{\partial I_1}. \tag{6}$$

In equation (6) the term $\frac{\partial E_g}{\partial I_1}$ is defined as $\frac{1}{G_m}$, where G_m is the mutual conductance of the tube.

Therefore,

$$\frac{\partial E_B}{\partial I_1} = \frac{1}{G_m} - K\frac{\partial E_c}{\partial I_1} = R_1$$

which gives a relation between the constants, the rate of change of the balancing voltage E_B, and the rate of change of total dynode voltage E_c on the phototube. Several tubes were tried in the circuit, including a 6BA6, a 6BJ6, a 6K7, a 6SG7, and a 6J5. After a very extensive search, a 6AC7 was used to advantage, and further correction was obtained by using two 6AG7 tubes to cut in at different points on the curve (i.e., for two separate values of E_c).

The circuit with the constants given in Figure 2 is the result of work which actually involved purely experimental methods using a photometer bench. It was found that a variable component of voltage obtained from the negative side of the supply and controlled by the rheostat P7 gave a smooth zero adjustment. The automatic cut-in points could be adjusted by the potentiometers P1 and P2 with the rheostats P5 and P6 controlling the current through each 6AG7 tube. A shunting rheostat P8 across the output gave a sensitivity control over the instrument so that a given calibration could be maintained with a slight touch-up adjustment. It was found that a potentiometer P4 enabled the operator to vary the effect of the 6AG7 tubes in the circuit for values of E_g low enough to cause appreciable tube conduction.

From the standpoint of constructing an instrument to utilize somewhat different 1P21 tubes, it is evident that a number of controls are necessary. Operating convenience, nevertheless, is a factor, and any simplification in control manipulation is a further improvement. Referring to Figure 2, the potentiometers P1, P2, P7, and P8 are operated from the control panel. The remaining adjustments can be made with a screwdriver, and no additional adjustment of these chassis-mounted potentiometers should be necessary after a given multiplier tube has been incorporated into the instrument. This requires that an initial calibration be run using a photometer bench. Actually, the control potentiometers on the panel are needed only for touch-up adjustments after the final calibration is made.

SENSITIVITY AND STABILITY

Since the instrument covers such a vast range on a single scale, it is of interest to see how stable it is under actual operating conditions. The photomultiplier tube itself is subject to well-known vagaries, and any circuit incorporating this tube may be expected to undergo some change with use. Stability tests, however, show that once the instrument has warmed up it holds a calibration remarkably well.

Noise effects in a multiplier tube, which ordinarily are troublesome, do not show up to the extent they do in linear photometers. Most of the effects noticed are due to fatigue effects in the 1P21 tube and to the fact that the normal dark current changes slightly after the tube is subjected to appreciable light. Fatigue effects, though, tend to be minimized by the fact that the total dynode voltage is automatically reduced when the multiplier tube is exposed to light. A high impedance in the 1P21 tube anode circuit also prevents excessive current to be drawn from the tube at any time.

Insofar as tests show, the action of the 6AG7 corrector tubes is stable, and only slight warm-up effects are noticed when these tubes are brought into play by sudden illumination of the photocathode.

A calibration of the instrument is shown in Figure 9. At the lower limit a brightness value of $4\times10^{-4}\,\mu$L is easily read, and the maximum value for full deflection is $400\,\mu$L. The corrector circuit does not operate over the curve below $0.5\,\mu$L, and adjustment to the point A was made with the variable meter shunt P8.

With the switch Sw_2 open, the curve would assume a more vertical slope from point A upward, so that about $8000\,\mu$L would be needed for full deflection. By closing switch Sw_2 and successively adjusting the controls for the 6AG7 tubes, it is possible to obtain an essentially

linear graph. The main adjustment to point B is made with the potentiometer P1, and the curve is pulled onto point C by setting the potentiometer P2 so that the second 6AG7 draws sufficient current. It was found that occasional touch-up adjustments to the points A, B, and C were necessary if the instrument was used to make precise measurements. Curve FF′ is the calibration curve with a spectral correction filter over the multiplier tube.

To illustrate the performance of the photometer under actual operating conditions a record was made on the Esterline-Angus over a period of nearly five hours (Figure 10). The chart was run at the rate of two horizontal divisions per hour and the shutter left open and closed for periods of a half-hour each. Touch-up adjustments were made at the points 1, 2, 3, 4, and 5, in that order. Only two intensities, 28 and 0.5 μL, were used for the run, but more were used in the initial adjustment period.

It may be noticed on the graph that the recorder pen tends to fall below zero after the photocathode of the multiplier has been illuminated and then darkened. Such an effect seems to indicate that the tube dark current is reduced during a cycle of illumination and that recovery is rather slow. Furthermore, after a dark period the pen tends to over-shoot the original position slightly, but after a few minutes the instrument tends to correct itself. From these points it is evident, however, that the circuit can maintain a steady deflection over a half-hour period with very little loss in sensitivity.

The five-hour run of Figure 10 was made under ideal laboratory conditions in a dark room with practically no temperature fluctuations. No light intensities higher than a few hundred microlamberts were allowed with the pick-up box shutter open, and care was used to keep the tungsten calibration lamp at a

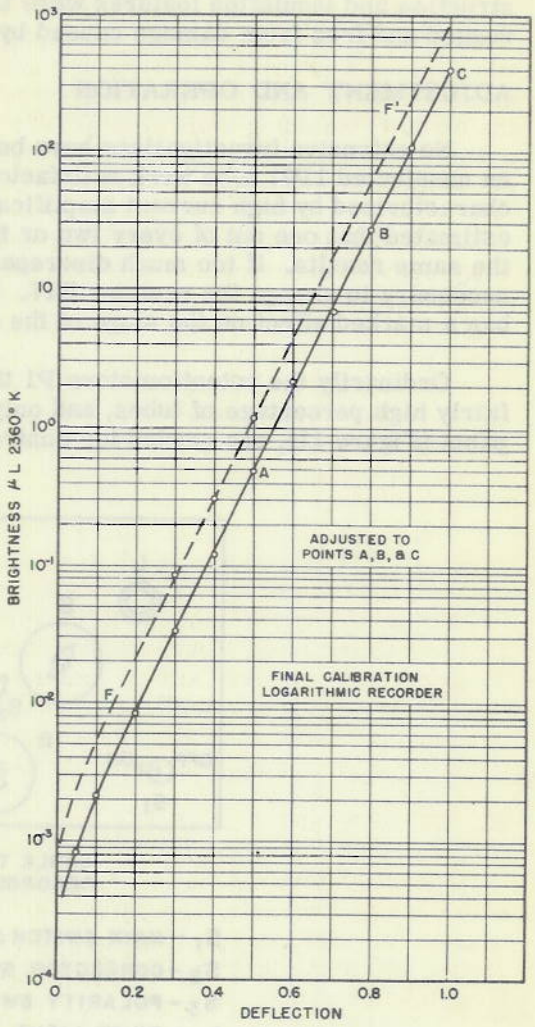


Figure 9. Calibration Curve

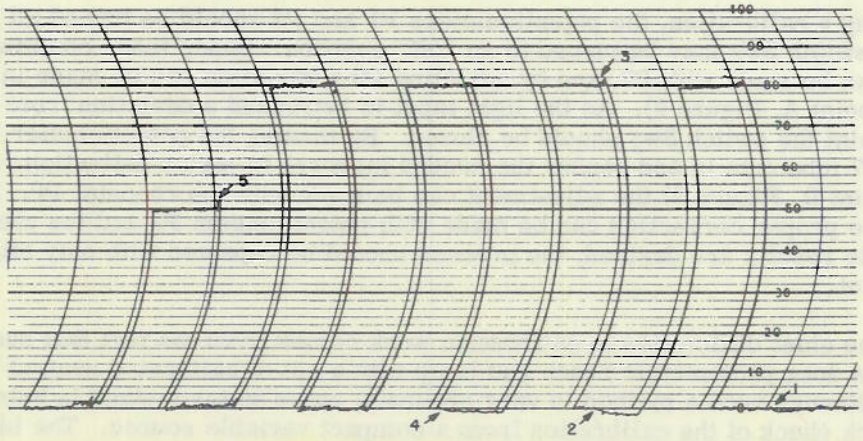


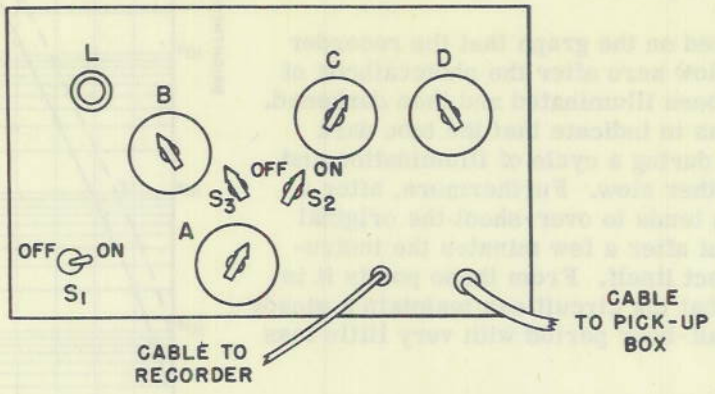
Figure 10. Test Recording with Two Light Intensities

steady emissive level. In practice, it may not be possible to have these conditions, but it seems that the instrument would be quite stable under more severe service. If special construction and insulation features were incorporated in the apparatus, it could be made unusually rugged and free from damage caused by every-day handling.

ADJUSTMENT AND OPERATION

No extensive investigations have been made to determine exactly the probability of having an unselected 1P21 tube work satisfactorily in the circuit of Figure 5. The one chosen was characterized by high current amplification and appreciable dark current. Nevertheless, it is estimated that one out of every two or three could be adjusted into the circuit to give essentially the same results. If too much discrepancy exists, or if a narrower range is desired, it may be necessary to change the resistor R17. This is the input resistor into the deflection circuit and has a marked effect on the slope of the curve of Figure 9.

Ordinarily the potentiometers P1 through P8 should afford sufficient adjustment for a fairly high percentage of tubes, and only the potentiometers P1, P2, P7, and P8, located on the panel (Figure 11), are needed for control of the instrument.



S_1 – MAIN SWITCH (SW_1)
S_2 – CORRECTOR SWITCH (SW_2)
S_3 – POLARITY SWITCH (SW_3)
L – PILOT LIGHT
A – ZERO CONTROL (P_7)
B – SENSITIVITY (P_8)
C – 1st CORRECTOR (P_1)
D – 2nd CORRECTOR (P_2)

Figure 11. Control Panel

In starting a calibration, the potentiometers P1 and P2 should be turned all the way to the left, and the switch Sw2 may be turned to an "off" position. Under these conditions the zero adjustment can be made with P7, and by adjusting P8 a variation can be made in the gain of the instrument (point A, Figure 9). As the light input is increased a deviation from linearity begins, and at this point the switch Sw_2 should be closed. By turning the potentiometer P1 to the right, the first 6AG7 tube cuts in and causes the needed increase in meter deflection. Further up on the curve (point B, Figure 9) the adjustment can be made with the rheostat P5. For full-scale deflection, the proper correction can be made with potentiometer P2 and the rheostat P6. If more accurate results are desired, the process should be repeated with only slight adjustments to each control.

One of the chief difficulties in calibration work comes from the fact that such a wide range is covered. A long photometric bench and lamp with a set of calibrated neutral Wratten filters was used. Although such a method is very accurate, some better method is being sought to permit a quick check of the calibration from a compact variable source. The idea of using a small lamp turret or a 35 mm strip of film with a steep density curve seems more practical.

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At present, a compact source using a simple film-wind and lamp-aperture arrangement is being developed.

CONCLUSION

A developmental program involving the construction and testing of several instruments using the circuit described above has not been attempted. It is evident, however, that the performance of such apparatus should be satisfactory and comparatively free from operational difficulties.

The constants given for the circuit were computed primarily with the aim of using the instrument in the photometric measurement of phosphorescent material. For example, the range is ideally suited to measure and record the decay of brightness in luminous paints and plastics. Here the brightness range is quite extensive and the time of decay ranges up to several hours.

Other uses, of course, suggest themselves, such as recording the fluctuations of light due to atmospheric effects over comparatively long periods of time, direct measurement of brightness in a photometry laboratory, and perhaps communication experiments with ultraviolet or infrared light.

The apparatus as presently developed is part of a program to invent and organize newer methods for reliable evaluation tests on phosphorescent materials. Many of these materials are used by the Navy, and reliable equipment is being developed to enable operators of limited experience to make consistent and accurate photometric tests at low brightness.

* * *

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