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Report on

Experiments with Sensitive Detectors of Ultra-Violet and Infra-Red Radiations.

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
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ABSTRACT

Signalling range experiments in a clear atmosphere gave the following results:

A. Near ultra-violet, wave-length 3660A. Source H-3 mercury lamp, 75 watts, screened by Corning "Violet Ultra" glass, 1 cm. thick, unfocussed;

(a) Receiver, fluorescent telescope, range 780 yards,
(b) Receiver, phototube counter, Locher "Li", unfocussed, range 1340 yards.

Calculate that with H-3 lamp and phototube each focussed into 30° cone, range would be 2700 yards, and into 10° cone range would be 6500 yards.

B. Far ultra-violet, wave-length around 2500A. Source H-3 mercury lamp, 75 watts, unscreened, unfocussed; receiver phototube counter, Locher "B", unfocussed; range 1500 yards. Calculate that with H-3 lamp and phototube each focussed into 30° or 10° cone, range would not be above 5000 yards because of limitation by atmospheric absorption.

C. Modulated visible light, wave-lengths 4000 to 7000A. Source 1000 watt tungsten lamp flashing 950 per second, unfocussed; receiver photoelectric cell unfocussed, with high gain amplifier;

photocell	SR-50	range	800 yards
	Photronic		600
	Photox		700
	Thalofide		900

Calculate that with lamp and photocell each focussed into 30° cone the ranges would be increased by a factor of 2, and into 10° cone by a factor of 5.

D. Modulated near infra-red light, wave-lengths 8000 to 11000A. Source 1000 watt tungsten lamp, screened by Corning "Heat Transmitting" class, 6 mm thick, unfocussed, flashing 950 per second; receiver photoelectric cell unfocussed with high gain amplifier;

photocell	SR-50	range	300 yards
	Photronic		10
	Photox		0
	Thalofide		300

Calculate that with lamp and photocell each focussed into 30° cone the ranges would be increased by a factor of 2, and into 10° cone by a factor of 5.

CHAPTER 1

INTRODUCTION

AUTHORIZATION

1. The experiments were authorized by Bureau of Engineering secret letter S-S64-5(6-4-W9) Serial No. 87 of 7 July 1937 to Director, Naval Research Laboratory.

REFERENCES

2. References pertinent to this report are:

Reference: (a) NRL Report No. H-1467 of 12 August 1938, "Ultra-Violet Signalling Equipment, Tests of January 1938".

SCOPE OF THE REPORT

3. This report presents, (1) discussion of experiments with fluorescent telescope reception of ultra-violet radiation, described in reference (a); (2) experiments with new photoelectric tube counter receivers of ultra-violet radiations; (3) experiments with photoelectric cell receivers of ultra-violet, visible and infra-red radiations. The report is therefore a preliminary experimental survey of modern methods of detecting the various radiations for the purpose of determining adaptability to signalling, recognition, etc. All of the methods and devices investigated were electrically and mechanically stable, and in this respect possessed the primary characteristics essential to shipboard installation. The conclusion is reached that under conditions at sea, ranges greater than a few miles appear difficult to achieve, and projected adaptation of the devices must contemplate such a limitation.

CHAPTER 2

FLUORESCENT TELESCOPE EXPERIMENTS

4. In reference (a) were described range tests of ultra-violet signalling equipment. The receivers were small telescopes, four power, with a fluorescent film at the focus of the objective lens. The transmitter consisted of a small high intensity quartz mercury lamp, General Electric Company Type H-3, 75 watts, in a housing with an ultra-violet filter of Corning "Violet Ultra" black glass which was transparent to the strong ultra-violet mercury line 3660A and was opaque to visible light. The energy distribution[1]

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1 L.B. Johnson and S.B. Webster, Rev.Sci.Inst. 9, 325 (1938); E.O. Hulburt, Phys.Rev. 32, 593 (1928).

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in the spectral lines of the lamp is given in Plate 1, and the transmission curve of the "Violet Ultra" glass in Plate 2; the slight transparency of the glass in the near infra-red was of no consequence. The range tests brought out two facts: (a) when the light was focussed into a 10° beam the ultra-violet signals could be seen with the fluorescent telescopes to a distance of about 4800 yards; (b) that the signals were not invisible to the unaided eye and could be seen by a youthful observer with ordinary binoculars to a distance of about 3500 yards. (The ultra-violet sensitivity of the normal eye decreases with age.) The conclusion was reached that the ratio of the fluorescent telescope range to binocular range was too small to give desired security and therefore that the ultra-violet equipment was not suitable for Service application.

5. A recent paper[2] is of academic interest; the author had lost the crystalline lens of one of his eyes in an accident. Being in scientific

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2 A.G. Gaydon, Proceedings Physical Society London, Vol. 50, page 714, September 1938.

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pursuits, he had had occasion to measure his vision before the accident and had found it to be normal in all respects. After the loss of the lens he found that the eye was abnormally sensitive to ultra-violet light, the increase in sensitiveness being about a thousand fold for wave-length 3660A due to the absorbing power of the lens for this wave-length. The result was that the author, if provided with a suitable glass lens for focussing on the retina, would be a much more sensitive detector of ultra-violet signals than an ordinary observer with the fluorescent telescope.

6. In the ultra-violet signalling experiments three intensities of projected beam were provided by means of three lenses. The maximum ranges obtained with the fluorescent telescopes are given in Table 1; lens #3 was actually no lens. The flux of energy at one yard from the transmitter was

<u>Table 1</u>

Lens	Fluorescent telescope, max. range, yards	Energy at 1 yard, erg cm^{-2} sec^{-1}	Energy at max. range, erg cm^{-2} sec^{-1}
#1	4800	330	1.5×10^{-5}
#2	3100	170	1.8
#3 (no lens)	780	40	1.4

measured with a calibrated thermocouple and galvanometer, the values for the three lenses being given in the third column of Table 1. By means of the inverse square law the flux of energy at the maximum signalling ranges were calculated and are in the fourth column of Table 1. Atmospheric absorption of the 3660A line is known[3] to be small for relatively short distances, less

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3 L.H. Dawson, L.P. Granath and E.O. Hulburt, Phys.Rev. 34, 136 (1929)

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than 5 miles, in a clear atmosphere and may be neglected. The numbers of the fourth column of Table 1 are the minimum energy of signalling under the conditions of the three experiments; the numbers should be, and probably are, the same within the error of observation. The average is

$$1.6 \times 10^{-5} \text{ erg cm}^{-2} \text{ sec}^{-1},$$

which is the minimum intensity of 3660A radiation necessary at the ultraviolet fluorescent telescope for signalling.

CHAPTER 3

PHOTOTUBE COUNTER APPARATUS

7. The photoelectric tube counter, originated by Geiger and Müller[4], is essentially a photoelectric cell. It consists of a photo-sensitive surface,

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4 Geiger and Müller, Phys.Zeit. 30, 533 (1929); G.L. Locher, Phys.Rev. 47, 326 (1935), Radiology 27, 149 (1936), and references <u>infra</u>.

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the cathode, in a glass or quartz bulb filled with a suitable gas, as helium or argon, at a pressure about 1/10 atmosphere; there must be present also a trace of an electronegative gas, as oxygen. The photo-sensitive surface is usually a film of an alkali metal, as sodium, lithium, etc., or a mixture of metals, or metallic oxides or hydrides, deposited on a metal support. In front of the photo-sensitive surface is a wire or grid, the anode, which is maintained at a suitable positive potential, usually over 100 volts. Light of suitable frequency, as ultra-violet light, falling on the photo-sensitive surface causes the emission of electrons which are accelerated toward the anode by the positive potential. They ionize by collision the gas in the tube, the ions and electrons thus formed giving rise to others, so that each photo-electron produces a measureable pulse of electrical current through the tube and auxiliary circuit. The current is further amplified to give a desired response, as a click in a pair of telephones. Thus the tube counter is a photoelectric cell and amplifier combined. By varying the design it can be arranged, and is being widely used, to detect or measure the intensity of light, x, β and γ rays, cosmic rays, neutrons, and any radiation which is absorbed by, and produces ionization in, the tube counter.

8. The tube counter and auxiliary circuit responds to, or records, each electron produced by the radiation in the tube, and in this respect the electrical response is perfect and is not susceptible of improvement. The device is several orders of magnitude more sensitive than the usual photoelectric cell with conventional high sensitivity electrometer or galvanometer, the sensitivity of which can not be extended to each a single electron. In another respect the tube counter falls short of theoretical perfection. In theory the emission of one photoelectron requires the absorption of only one quantum of light. Measurements show, however, that even in the case of the most sensitive photoelectric surfaces several thousand quanta of radiation on an average must fall on the surface before an electron is liberated. What actually happens to all of the quanta is not known in detail; evidently most of them are absorbed in the surface, either without ejecting electrons from the atoms of the surface, or if electrons are ejected they are caught in the surface and are not liberated. Actually, the quantum efficiency of a surface can be increased by making the surface so thin that it absorbs very little of the impingent radiation; in so doing the over-all efficiency of the surface as a detector of the radiation is uselessly low, although the quantum efficiency of the surface for the light which it does absorb may be relatively high.

9. Two phototube counters and auxiliary electrical amplifying equipment were obtained from Dr. G.L. Locher, Bartol Research Laboratory, Franklin Institute, Philadelphia. Dr. Locher is among the recognized authorities in this country in the development of tube counter devices. The two tube counters, denoted by "Li" and "B" had special characteristics described below. In Plate 3 is shown one of the phototubes; externally they had the same appearance. The phototube was of glass with a quartz window. The photo-sensitive surface was formed on the interior of the cathode which was an open metal cylinder; the anode was a small wire along the axis of the cylinder. The area of the photo-sensitive cathode was about 1 square cm.

10. Plate 4 is a photograph of the amplifier for use with the Locher phototubes. The small box on the right of Plate 4 was a light-tight container for the phototube with a hole over the quartz window of the phototube. The amplifier operated on 110 volt, 60 cycle A.C., taking about 200 watts. It contains dry cells and has functioned without attention for about six months. Its output passes either to a pair of telephones or to an automatic counter of the electrical pulses of the phototube. It is provided with a conventional "scaling" circuit of 1, 2, 4, 8 and 16. With the scaling circuit in position "1", each phototube pulse makes 1 click in the telephones or 1 count on the automatic counter. With the scaling circuit in position "2", two phototube pulses make 1 click in the telephones or 1 count on the automatic counter. Similarly for the scaling circuit at positions "4", "8" and "16". When the telephones are used the device is a "detector" of the radiation; when the automatic counter is used the device is a "measurer" of the relative intensity of the radiation, for the average number of pulses per unit time is proportional to the intensity of the radiation. The dimensions of the amplifier of Plate 4 were about twice as great as necessary; the amplifier was designed for laboratory use and not as field equipment.

11. In using the phototube counter apparatus for detecting radiation, as in Naval signalling, we assume that the "minimum counting rate for detection" is about 100 clicks per minute. The assumption requires explanation. The clicks from a tube counter exposed to a steady source of radiation are not regularly spaced in time but are distributed according to a probability law, and hence are irregular; in fact, they may be said to be "random" or "perfectly irregular". In illustration, a rate of 60 clicks per minute means an average of 60 clicks per minute, which is quite different from 1 click a second. Actually, for 10 seconds there may be no clicks at all, then in the next second a group of clicks may occur, being followed by groupings of silences and clicks in every possible manner; obeying, however, the rule that on an average there will occur 60 clicks per minute. To say that 100 clicks per minute is the "minimum rate for detection" requires that the receiver and transmitter be trained steadily on each other for 10 or 20 seconds, which may be difficult to do under certain conditions at sea. In the laboratory the fact that the radiation may fall steadily on the tube counter for as long a time as desired, together with inherent high sensitivity, permits the tube counter to be effective in measuring extremely weak radiations. In a contemplated Naval use at sea because of the relatively short time element involved the full sensitivity of the tube counter system can not always be utilized. However, in spite of the fact that the tube counter system may not be worked at complete efficiency it is the most sensitive detector known today of the radiations appropriate to it.

12. The clicks of the phototube counter are of a very poor quality for the purpose of Morse code signalling; in fact they are practically useless unless the counting rate is above, say, 600 per minute or 10 per second. Even in this case the audible note produced by the succession of erratically spaced clicks is very rough compared to the customary signal in a radio receiver.

Range with Locher Phototube Li.

13. The photosensitive cathode of the phototube Li contained lithium. Its spectral sensitivity curve, given in Plate 5, shows that the sensitivity extends well in to the blue part of the spectrum at 4500A. Therefore the phototube can not be used in daylight, but only at night. It is fairly sensitive at 3660A. A range test was made at night using the H-3 mercury lamp screened by Corning "Violet Ultra" glass as a source of 3660A radiation. There was no focussing on the lamp or phototube. At 370 yards there were 1310 clicks per minute. From this and the inverse square law the range for 100 clicks per minute was calculated to be 1340 yards, which was taken to be the maximum range. The number is entered in Table 2 together with the range for the fluorescent telescope.

Table 2. Ultra-violet 3660A range.

Ranges with H-3 lamp soreened by "Violet Ultra" Glass, no focussing on lamp or phototube.

Fluorescent telescope.	Phototube Li	Photocell SR-50
780 yards	1340 yards	100 yards

14. If a well designed lens or mirror were used at the phototube for focussing, the counting rate may be increased by a factor of about 9 and the range by a factor of 3. The range would then be 4000 yards for the unfocussed H-3 lamp, which is greater than the 780 yard range of the fluorescent telescope, which is of course a focussed receiver. On the whole the phototube counter apparatus as a receiver of 3660A radiation is several times as sensitive as the fluorescent telescope. It is more complicated than the fluorescent telescope, and whether it would be of use in a Naval signalling system is not known.

Discussion of a 3660A concealed communication system.

15. In the light of present knowledge let us visualize a 3660A concealed communication system and estimate its expected performance in a particular case. Suppose it were to be used for night recognition. Assume at the masthead of a ship a source of 3660A radiation made of a 500 watt mercury lamp surrounded by a cylinder of "Violet Ultra" glass 1 cm. thick. (Lamps similar to H-3 up to 1000 watts are made by the General Electric Company.) The source distributes its radiation equally in all directions in the horizontal plane. It will be visible to youthful observers with ordinary binoculars to a distance of about 2000 yards. It can be seen by anyone with

the fluorescent telescope to about 3000 yards. A clear atmosphere is assumed. Consider a Locher "Li" phototube receiver consisting of the phototube mounted at the focus of a 5 inch diameter, 16 inch focal length, glass lens; the receiver, then, is a cylinder about 6 inches in diameter, 24 inches long, weighing perhaps 6 pounds. The field of view is about 2^o, that is, it must be directed toward the source (which is supposedly invisible) within 2^o and be maintained in that direction for, say, 5 to 10 seconds. The operator probably holds the receiver in his hands. The receiver is connected by a wire to the nearby amplifier; out of the amplifier comes another wire to telephones worn by the observer. He points the receiver at the source and listens for the signal which is a series of clicks. The range may be about 8000 yards. The apparatus is about as delicate and fragile as normal radio equipment. Questions of upkeep enter.

16. The foregoing description is partly for the purpose of emphasizing the essential difference between the visual method, i.e. the fluorescent telescope, and the instrumental method, i.e. the phototube telescope, of detecting the presence of a distant, invisible, moving source of radiation. In the fluorescent telescope the invisible point source is seen as a visible point of light in the fluorescent field. If due to motion of the ship and wavering of the telescope the visible point of light moves out of the field, a simple instinctive reaction on the part of the observer is required to move the telescope to bring the point of light back again into the field. In the phototube telescope there is a small sensitive area about 1 square cm, the cathode of the phototube, in the focal plane of the objective lens. When the telescope is aimed at the source the image of the source falls on the sensitive area and causes a noise in the telephones. When the image moves off of the sensitive area the noise ceases, and random search with telescope aim is required to bring it back. All of this is so obvious that it is hardly worth the number of words which have been used.

Quantum efficiency of phototube Li.

17. From measurements with a calibrated thermo-couple and galvanometer the flux of energy of wave-length 3660A at 1 yard from the H-3 lamp through "Violet Ultra" glass, 1 cm thick, was 41 erg cm^{-2} sec^{-1}. At a distance of 370 yards the flux was 3.0×10^{-4} erg cm^{-2} sec^{-1}, or 5.7×10^7 quanta cm^{-2} sec^{-1} of 3660A radiation. The area of the cathode was 1.12 cm^2; hence the number of quanta falling per second into phototube Li was 6.4×10^7. These produced 1310 clicks per minute or 22 clicks per second. Therefore the quantum efficiency, or the average number of impingent quanta per click, was

$$2.9 \times 10^6 \text{ quanta per click.}$$

CHAPTER 4

EXPERIMENTS WITH LOCHER PHOTOTUBE B

Miscellaneous experiments.

18. The spectral sensitivity curve of the Locher phototube B, given in Plate 5, shows that the phototube is sensitive only to wave-lengths shorter than about 2600A. Therefore the tube does not respond to daylight or sunlight, that contains no wave-lengths shorter than about 2900A in appreciable intensity, and can be used even when exposed to direct sunlight. Such a characteristic is unusual; the materials in the tube and the method of manufacture are known only to Locher. Dr. Locher stated, and it is undoubtedly true, that the existence of such a tube, and even the possibility of the existence of such a tube, is not a matter of common suspection. The sensitivity of the tube is high, some years ago it would have been characterized as "extraordinary" or "impossible". The ultra-violet light from the flare of a match at 20 yards, from a bunsen flame at 5 yards, from a 25 watt tungsten lamp at 5 yards, produces roughly 30 clicks a minute, thereby demonstrating the existence of radiations below 2600A in these sources; such radiations from the sources have never been detected before, although there is no difficulty in acquiescing to their relatively weak existence.

Experiment with airplane engine exhaust.

19. It was thought that the luminous exhaust of an airplane engine might emit sufficient short wave ultra-violet radiations to be detectable with phototube B. The phototube apparatus was placed on the roof of the Laboratory in full daylight (11 A.M., September 1, 1938); there was a "stray count" of about 8 clicks per minute due probably to radio-active contamination in the atmosphere or possibly to secondary radiation of cosmic rays. A Naval scout plane made several flights on a course that brought it within about 200 yards of the Laboratory roof. No increase in the counting rate of the clicks occurred, and it was concluded that the plane emitted no radiations below 2600A of sufficient intensity to be detected at 200 yards. At this distance visible flashes of light from the exhaust could occasionally be seen.

Range experiment with phototube B.

20. The H-3 quartz mercury lamp with the glass bulb removed served as a source of ultra-violet light. From the energy distribution of the spectral lines, given in Plate 1, it is seen that the energy of the lamp in radiations below wave-length 2600A was mostly in the group of lines at 2537A and below. The lamp unfocussed at a distance of 400 yards produced in phototube B, also unfocussed, about 2700 clicks per minute.

21. A range test was carried out in full daylight in clear weather with the phototube B equipment on the roof of the Laboratory and with the mercury lamp on a boat on the Potomac River; the lamp and phototube were unfocussed. The observed clicks per minute are plotted as dots in Plate 6 after subtraction of a stray count of about 14 per minute. The counting rate

decreased with increasing range; at a range of about 1500 yards the counting rate was about 100 per minute which was roughly the minimum rate for detection. It was concluded that the maximum range was about 1500 yards.

22. Two theoretical curves were adjusted to pass through the observed value of 1200 clicks per minute at a range of 600 yards, Plate 6, each curve being based on the assumption that the number of clicks per minute was inversely proportional to the square of the range, one curve assuming no atmospheric absorption and one curve assuming atmospheric absorption. The value used for the absorption coefficient α was that measured[3] for a clear atmosphere at wave-length 2537A, namely, $\alpha = 4.5 \times 10^{-6}$, where α is defined by

$$i = i_0 \, 10^{-\alpha x} \quad , \qquad (1)$$

i_0 being the original intensity of the radiation, and i the intensity after passage through x cms of a clear atmosphere. It is seen that the curve which includes atmospheric absorption is in fair agreement with the observed points of Plate 6.

Phototube B as a concealed communication system.

23. The combination of phototube B as a receiver and the mercury lamp as a source of wave-lengths below 2600A possesses the elements of a concealed communication system. For example, by using a piece of glass or mica as a shutter, which are relatively opaque to wave-lengths below 2600A, signals may be transmitted which would be undetected by one who did not have phototube B. The system would be inoperative in fog. It has the disadvantage that intense visible light is radiated by the source. This could be eliminated by a filter which is opaque to the visible light and transparent to wave-lengths below 2600A; no such filter is known, and the chance of discovering such a filter is speculative. The range of the system may be increased by using a more intense source and by focussing, but atmospheric absorption introduces serious limitations to the range. For example, the range with the 75 watt lamp was about 1500 yards. For a 1000 watt lamp the range would be $1500\,(1000/75)^{1/2} = 5500$ yards, if there were no atmospheric absorption; however, because of an absorption of $\alpha = 4.5 \times 10^{-6}$, the range is about 3000 yards. Focussing will increase the range by an amount which increases with the sharpness of focus; a very sharply focussed system can not be operated between ships at sea. Due to this and to atmospheric absorption a range greater than 6000 yards appears difficult to achieve.

24. It is concluded that the system based on phototube B, which possesses at present the very rare virtues of being known to very few persons and of being manufactured by only one person, possesses important disadvantages.

Quantum efficiency of phototube B.

25. The flux of energy in wave-lengths below 2600A at a distance of 1 yard from the H-3 lamp was 63 erg cm^{-2} sec^{-1}, as measured with a calibrated thermo-couple and galvanometer. At a distance of 400 yards the flux

the flux was 3.6×10^{-4} erg cm^{-2} sec^{-1}, or 4.7×10^{7} quanta cm^{-2} sec^{-1} of wave-length 2537A. The area of the cathode was 1.25 cm^2; hence the number of quanta falling per second into phototube B was 5.9×10^{7}. These produced 2700 clicks per minute or 45 clicks per second. Therefore the quantum efficiency, or the average number of impingent quanta per click, was

$$1.3 \times 10^{6} \text{ quanta per click.}$$

CHAPTER 5

EXPERIMENTS WITH PHOTOELECTRIC CELL AMPLIFICATION

26. A source of radiation was modulated at audio-frequency by means of a rotating perforated disk, shown in Plate 7; the frequency was adjusted to 950 flashes per second. A photoelectric cell connected to an audio-frequency amplifier of high amplification was used to detect the radiation. Four photoelectric cells were tested that differed greatly in electrical and spectral characteristics. The photoelectric cells were "SR-50" and "Photox" of Westinghouse Company, "Photronic" of Weston Electrical Instrument Company, and "Thalofide" of T.W. Case. SR-50 is a vacuum type cell with a caesium silver oxide cathode. Photox is copper oxide and Photronic is selenium oxide; they are of the photo-voltaic type, that is, an e.m.f. is developed under illumination. Thalofide is of the type in which the resistance changes under illumination. SR-50, Photox and Photronic are available commercially at present. Thalofide was invented[5] in 1917, and is

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5 T.W. Case, Phys.Rev. 15, 289 (1920)

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not manufactured now. The one used in the present experiments had been carefully kept at this Laboratory in the dark for about 15 years and had not deteriorated appreciably.

27. The spectral sensitivity curves of the four cells are given in Plates 8 and 9; the ordinate scale of sensitivity for the various curves is not the same, and therefore the curves can not be used to discover the relative effectiveness of the photocells.

28. Amplification of the photoelectric cell response was obtained with the electrical circuits of Plates 10 and 11. Esentially, the circuit consisted of an introductory circuit, a first amplifier and a second amplifier. The introductory circuits are given in Plate 10. As shown in the lower portion of Plate 11 the photocell introductory circuit and first amplifier were in one box and the second amplifier was in another box. Plate 12 is a photograph of the complete assembly. A cylindrical tube was placed in front of the photocell to shield from stray light, but no focussing was used. The second amplifier was a three stage, resistance capacity coupled, audio-frequency amplifier, General Radio Company Type 719-AS2. The voltage amplification between A,B and the telephones, Plate 11, was about 50,000; to increase the amplification much above this value will be a matter of some difficulty.

29. From the curves of Plates 8 and 9 it is seen that SR-50 is the only photocell with appreciable sensitivity for ultra-violet radiation at 3660A. With no focussing of either the H-3 lamp or the cell, and with the "Violet Ultra" filter over the lamp, the range was about 100 yards; the number is entered in Table 2. The range is much less than that obtainable with the fluorescent telescope and phototube Li.

Ranges with visible and near infra-red radiation.

30. Range experiments were made with a tungsten lamp, 1000 watt airway beacon type, as a source of visible light, and with the same lamp screened by a filter of Corning "Heat Transmitting" glass, 6 mm thick, as a source of near infra-red light. The spectral energy curve of the lamp is in Plate 13, and the transmission of the Heat Transmitting glass in Plate 14. The results are summarized in Table 3, and show that SR-50 is the best of the four photocells. The slight superiority of the Thalofide cell for visible light is illusory and is more than overbalanced by its optical fragility and electrical unsteadiness.

Table 3. Visible and infra-red ranges.

Visible ranges: source, 1000 watt tungsten lamp, airway beacon type; no filter; no focussing of source or photocell,

SR-50	Photronic	Photox	Thalofide
800 yards	600 yards	700 yards	900 yards

Infra-red ranges: source, 1000 watt tungsten lamp, airway beacon type; "Heat Transmitting" glass filter 6 mm thick; no focussing of source or photocell,.

SR-50	Photronic	Photox	Thalofide
300 yards	10 yards	0 yards	300 yards

31. With one exception the ranges of Table 3 refer to full daylight conditions; ranges at night are not less, and may be slightly greater, than the values of Table 3. The exception is the 900 yard range for the Thalofide cell with visible light; the entry refers only to night conditions, since the Thalofide cell is ruined by exposure to full daylight and can be used in daylight only with a protecting filter of Heat Transmitting glass.

32. The range of 800 yards with SR-50 for visible light permits an estimate of ranges of telephony over a beam of visible light. If the power of the lamp were increased to 2000 watts and if efficient focussing with optically good, and sizable, mirrors and lenses were introduced at the lamp and photocell, the range could be increased perhaps 10 times, to 8000 yards or 4 miles. The estimate assumes complete modulation of the light beam. Or, put in another way, to telephone 5 miles over a light beam requires approximately a 2 kilowatt arc, efficiently modulated, focussed by a 30 inch diameter mirror into a 3^{o} beam, received by an SR-50 photocell at the focus of a well designed lens or mirror and connected with an amplifier of high amplification.

Concealed communication system with near infra-red radiation.

33. The SR-50 photocell receiver and the tungsten lamp with a Heat

Transmitting glass filter possess the elements of a system of secret communication based on the use of near infra-red radiations in the wave-length region from about 8000 to 10000A. The radiation is similar to visible light in regard to atmospheric absorption, that is, it does not penetrate fog, and passes through a clear atmosphere without noticeable attenuation in distances up to a few miles. As shown in Table 3 a 1000 watt lamp gives a range of 300 yards with no focussing. The range can be increased by increasing the power of the lamp and by providing focussing. Although no exact experiments have yet been made, it may be estimated that a range of 5 miles can be achieved only by sharp focussing, so sharp perhaps that the system would be difficult of operation between darkened ships at sea at night. The matter remains vague, however, until one decides what ranges are desirable and what sharpness of focussing is useful.

34. Dr. Locher is attempting to make phototube counters which are sensitive to near infra-red radiation, and plans to keep this Laboratory informed of his progress. Such a device might be more sensitive than any yet investigated.

35. In connection with possible development of a near infra-red communication system it should be mentioned that the Corning "Heat Transmitting" glass, 6 mm thick, is not completely opaque to visible light, but transmits a small amount of red light. Hence the tungsten lamp with the Heat Transmitting glass screen is slightly visible. Before giving serious consideration to the development of this type of system the visibility should be carefully investigated to discover how harmful it is and whether it can be, or should be, effectively eliminated. Increasing the thickness of the Heat Transmitting glass reduces the visibility but also reduces the infra-red range.

36. A night test of the visibility was carried out at this Laboratory. A 500 watt tungsten lamp was sharply focussed into a 3^{o} beam and was screened by Heat Transmitting glass 6 mm thick. The dim reddish light could be seen by an observer in the beam with unaided eye to about 60 yards, and with binoculars to about 200 yards but not at 300 yards. It was concluded that the range of visibility was about 300 yards. However, although the night was overcast and dark, with a clear lower atmosphere, there were many lights in the near distance of the countryside, and it is probable that under dark night conditions at sea with no disturbing artificial illumination, the visible range may be greater than 300 yards. The nocturnal conditions of the surroundings of this Laboratory are not suitable for investigating such questions.

37. It is seen from the curve of Plate 14 that the "Heat Transmitting" glass is of only moderate efficiency in its transmission of near **infra-red** radiations; for example, it passes only about 13, 40 and 41 percent at wave-lengths 9000, 10000 and 11000A, respectively. Recently much more efficient near infra-red filters have been described[6]; for example, one

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6 A.H. Pfund, Journal of the Optical Society of America, 29, 59 (1939).

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made of a solution of vanadyl sulphate with Corning "Signal Red" glass transmits about 1, 50 and 90 percent at 9000, 10000 and 11000A, respectively.

Such a filter contains a liquid and therefore is not well adapted to field use. However, it permits the suggestion that it might be possible to make a more efficient filter than the Corning "Heat Transmitting" glass.

Electron multiplier phototube.

38. The electron multiplier phototube is an ingenious combination of photocell and amplifier. It was developed by the Radio Corporation of America primarily for amplification of wide ranges of frequencies, such as occur in television. Its qualities in this respect are of no particular value to signalling. A brief description is included here for the sake of completeness. In Plate 15 is a photograph of a six stage electron multiplier phototube mounted between the pole pieces of an electromagnetic; six metal plates inside of the tube may be seen in the picture. The upper plate is a cathode with a small photosensitive area, 12 sq. mm., of caesium-silver-oxide. The other plates are treated in manufacture to have a good secondary electron emission characteristic. Crossed electric and magnetic fields are imposed on the tube. Photoelectrons from the cathode are accelerated under the action of the crossed fields and move in curved paths. They strike the next plate and give rise to many secondary electrons. These in turn travel to the next plate and an increasing number of electrons is released at each successive plate; this amounts to amplification of the original photocurrent.

39. The amplification obtainable in the electron multiplier tube is that expected from its design, and does not exceed that of conventional methods. The electron multiplier tube requires relatively high potentials and, for the type of Plate 15, a magnetic field; such requirements are not always convenient.

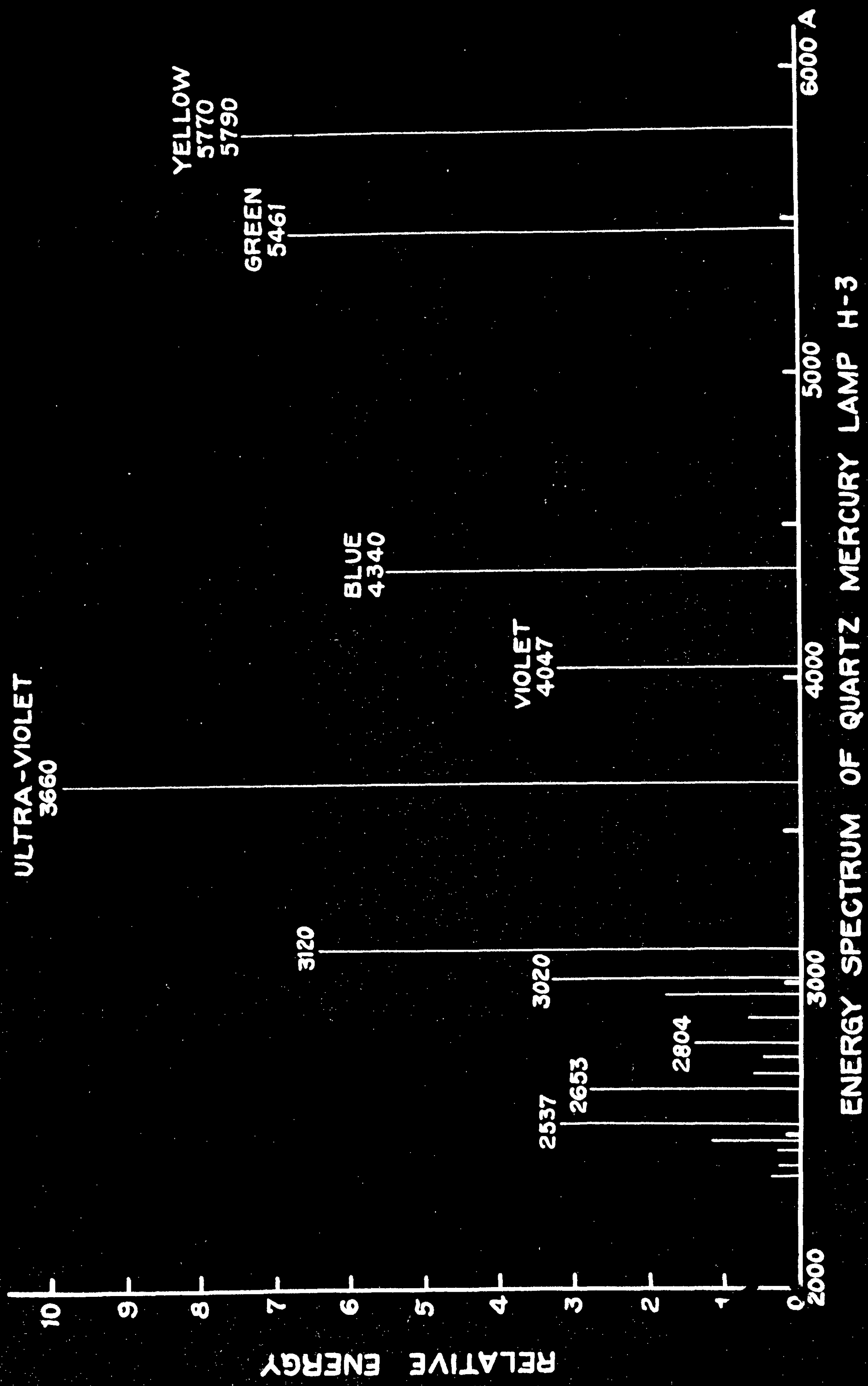
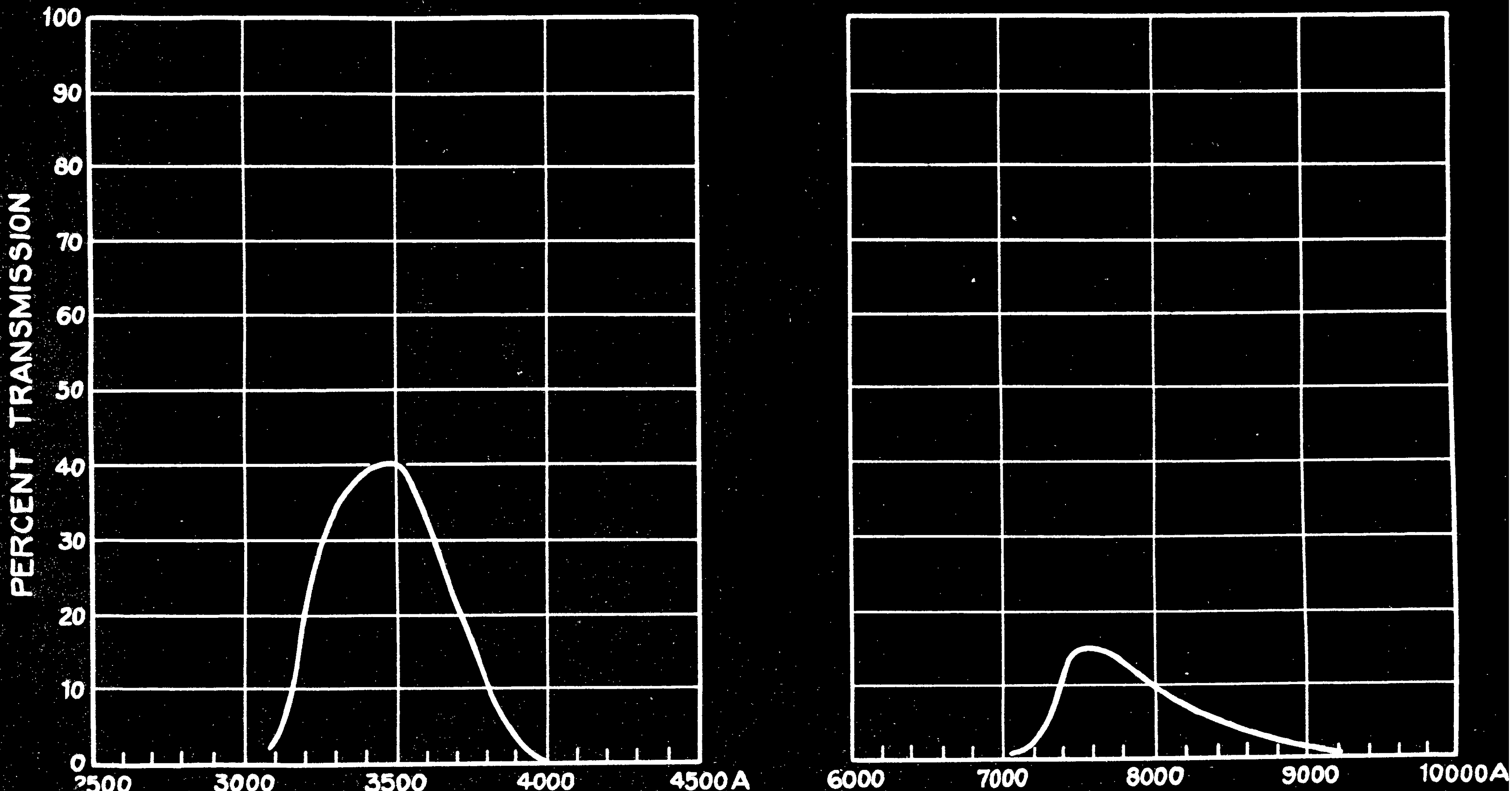
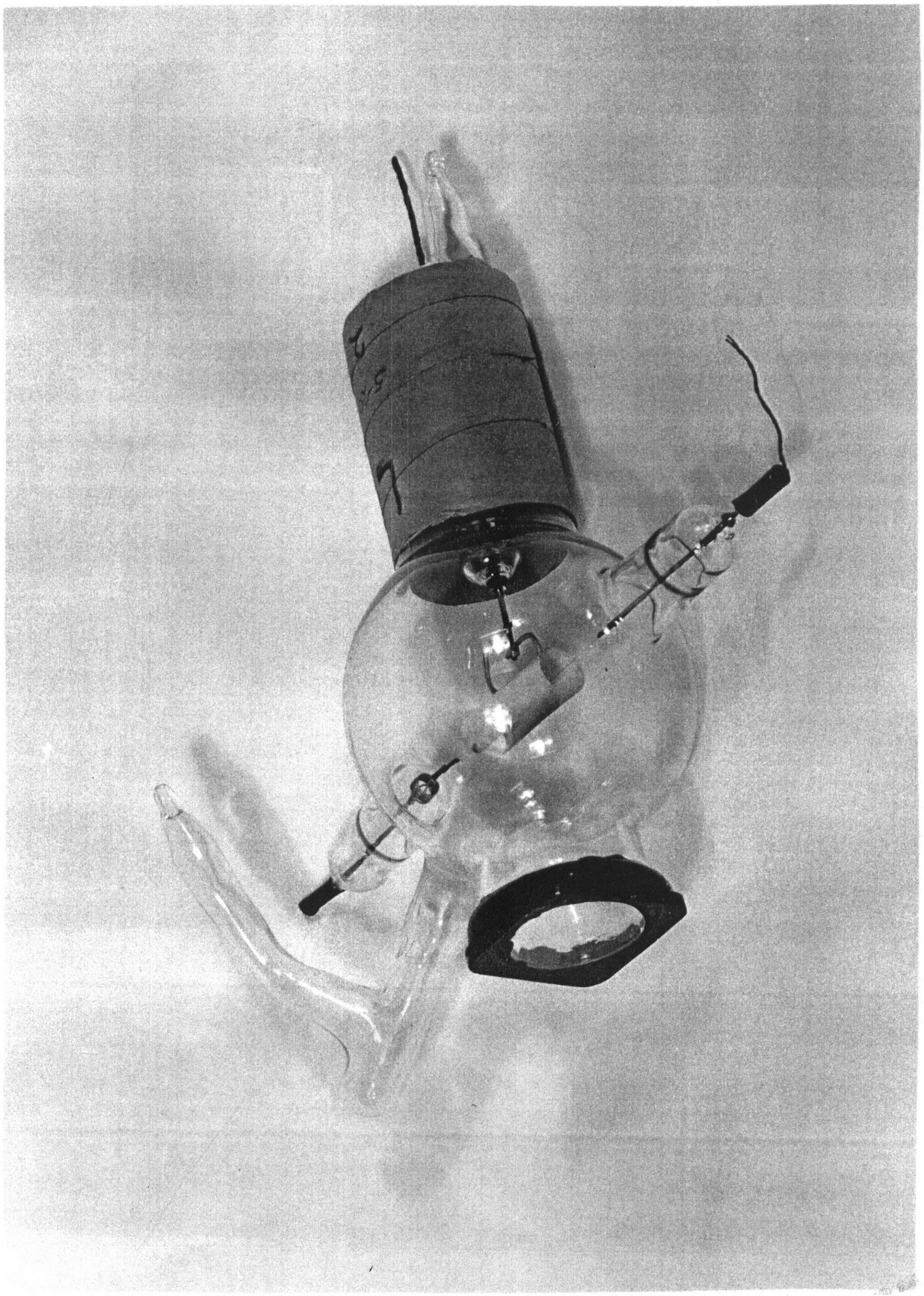

ENERGY SPECTRUM OF QUARTZ MERCURY LAMP H-3
RELATIVE ENERGY
0
1
2
3
4
5
6
7
8
9
10
2000
3000
4000
5000
6000 A
2537
2653
2804
3020
3120
ULTRA-VIOLET
3660
VIOLET
4047
BLUE
4340
GREEN
5461
YELLOW
5770
5790

PLATE 1



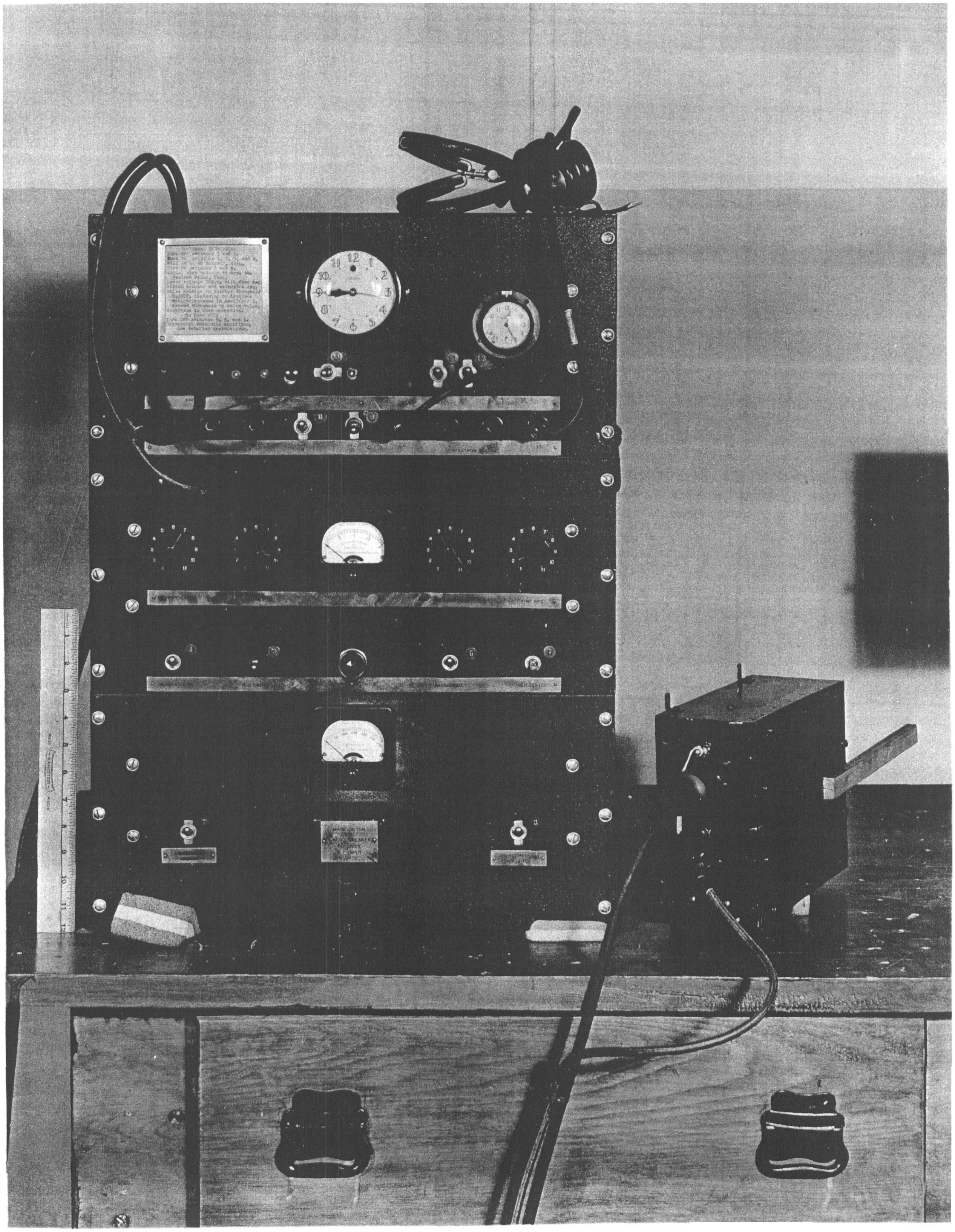
TRANSMISSION OF CORNING "VIOLET ULTRA" GLASS, 10 MILLIMETERS THICK

PLATE 2



LOCHER PHOTOTUBE

PLATE 3



AMPLIFIER FOR LOCHER PHOTOTUBE

PLATE 4

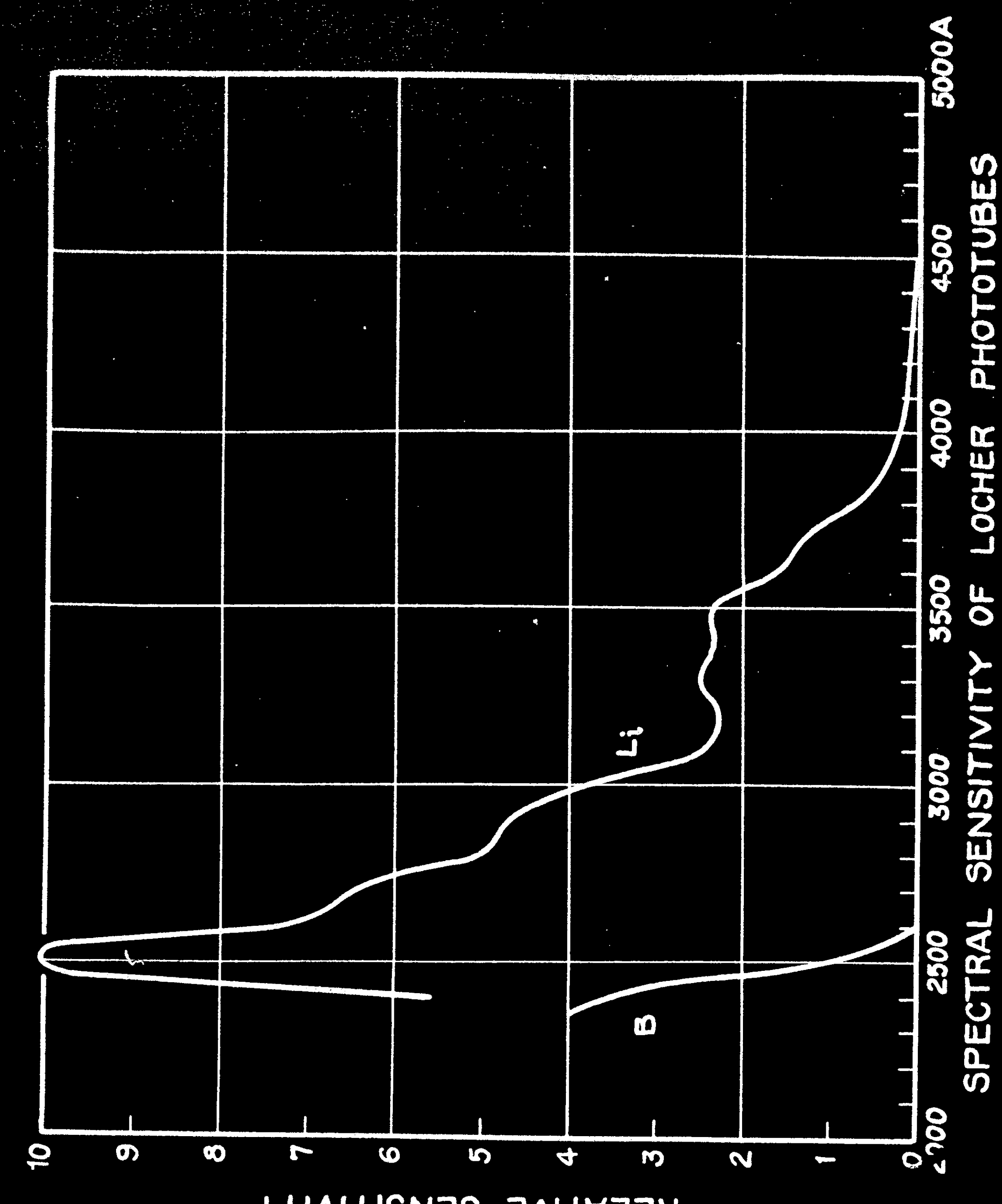
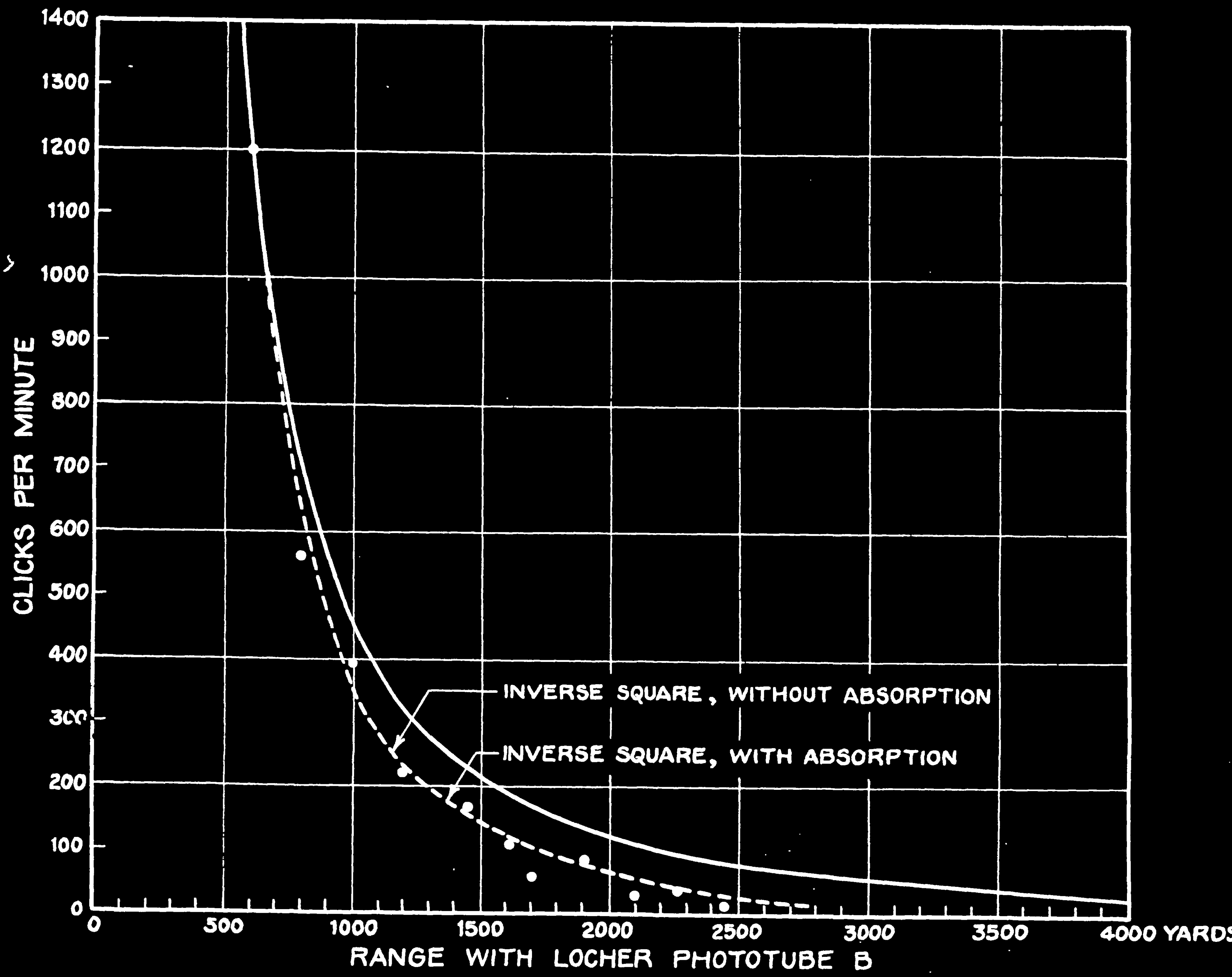
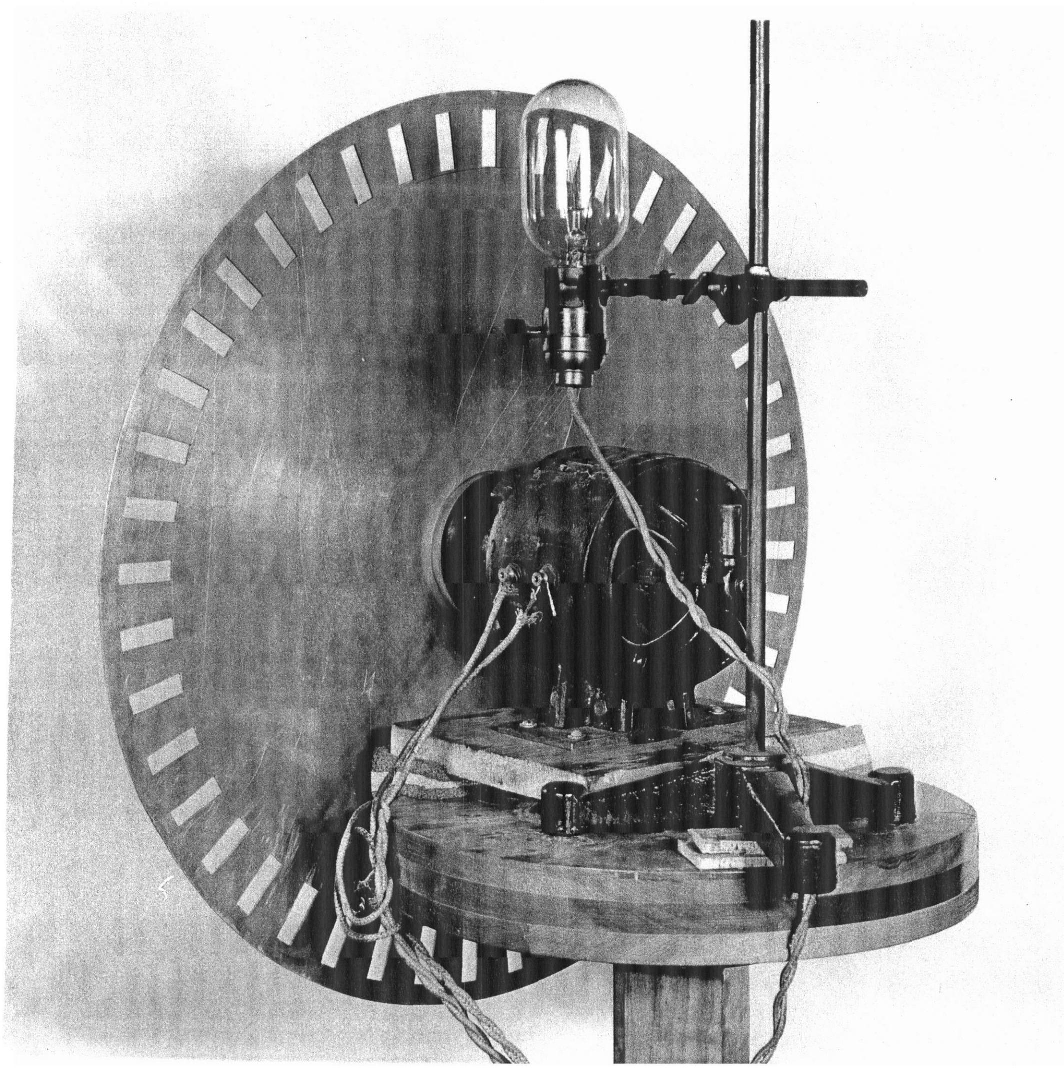

SPECTRAL SENSITIVITY OF LOCHER PHOTOTUBES
RELATIVE SENSITIVITY
0
1
2
3
4
5
6
7
8
9
10
2000
2500
3000
3500
4000
4500
5000A
Li
B

PLATE 5



CLICKS PER MINUTE
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000 YARDS
RANGE WITH LOCHER PHOTOTUBE B
INVERSE SQUARE, WITHOUT ABSORPTION
INVERSE SQUARE, WITH ABSORPTION

PLATE 6



FLASHING LIGHT

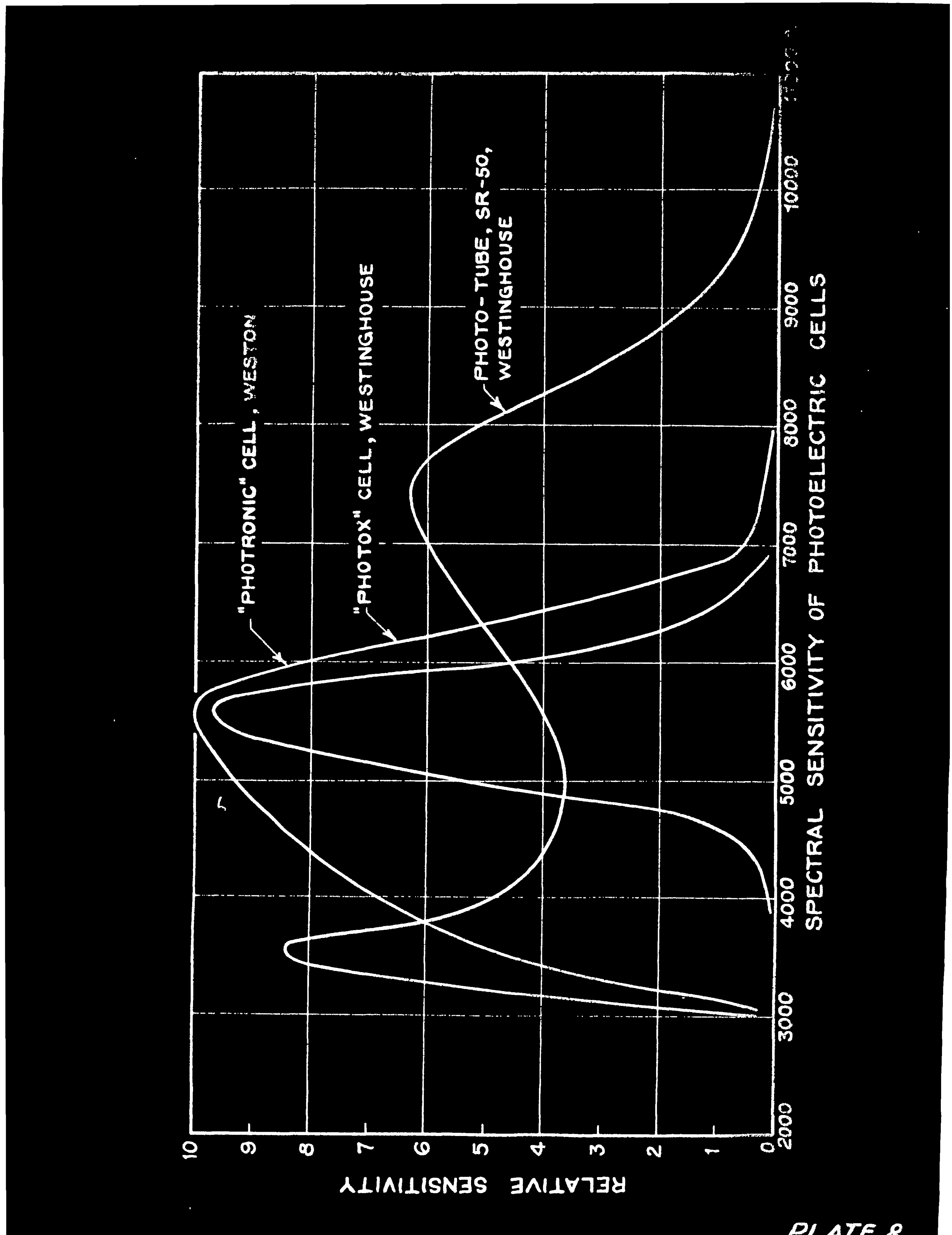
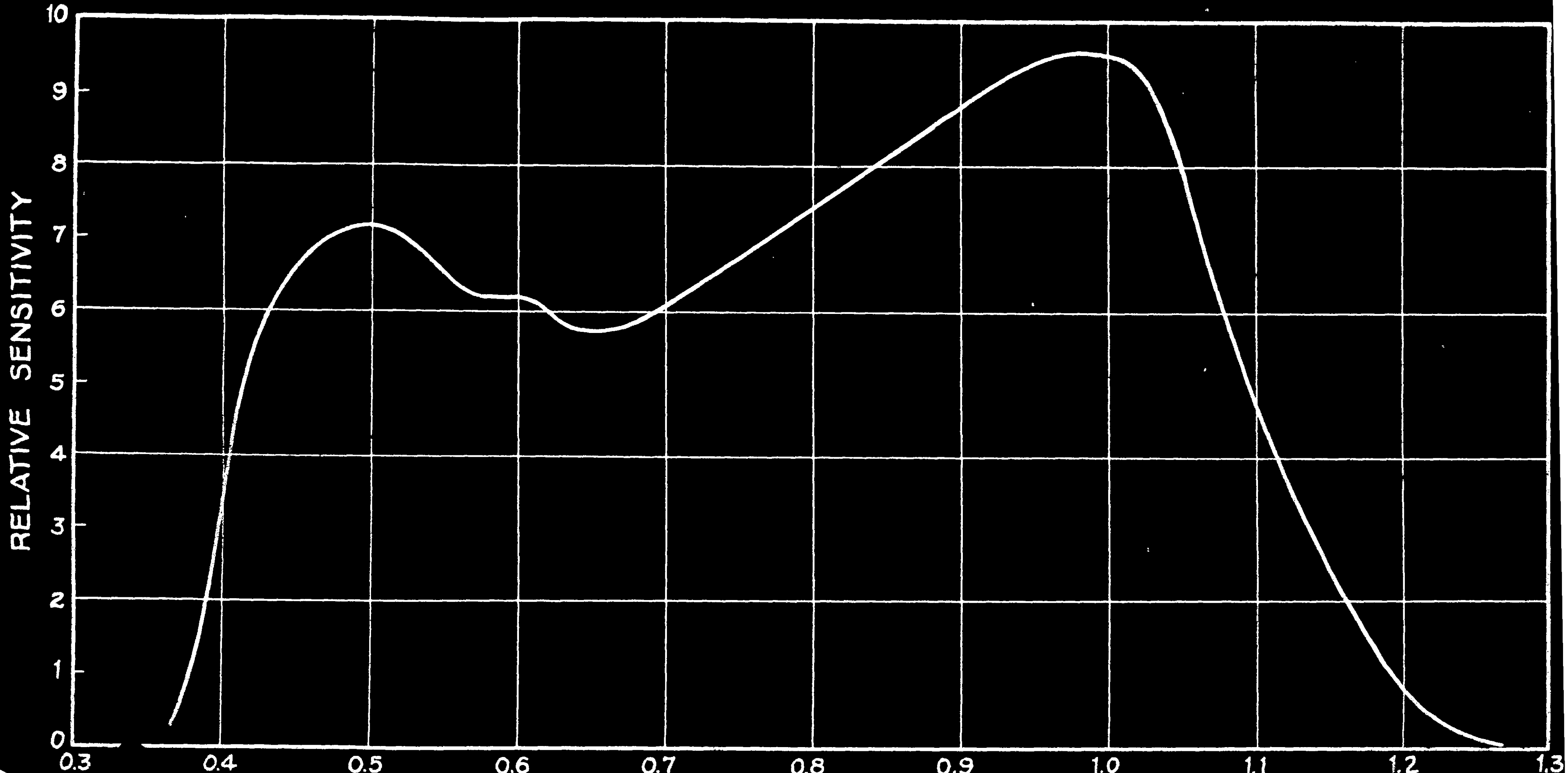
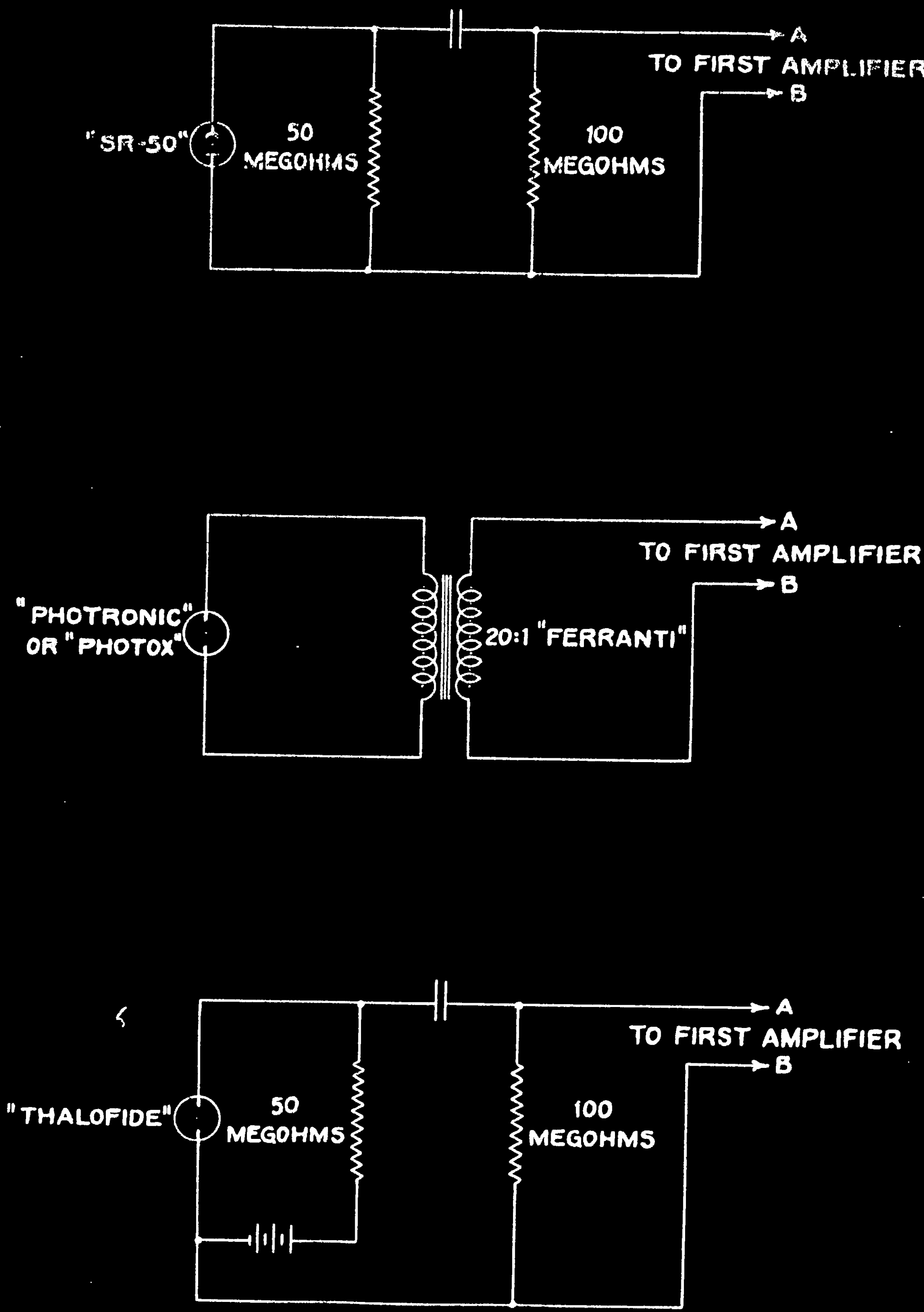

SPECTRAL SENSITIVITY OF PHOTOELECTRIC CELLS
RELATIVE SENSITIVITY
"PHOTRONIC" CELL, WESTON
"PHOTOX" CELL, WESTINGHOUSE
PHOTO-TUBE, SR-50, WESTINGHOUSE
0
1
2
3
4
5
6
7
8
9
10
2000
3000
4000
5000
6000
7000
8000
9000
10000

PLATE 8



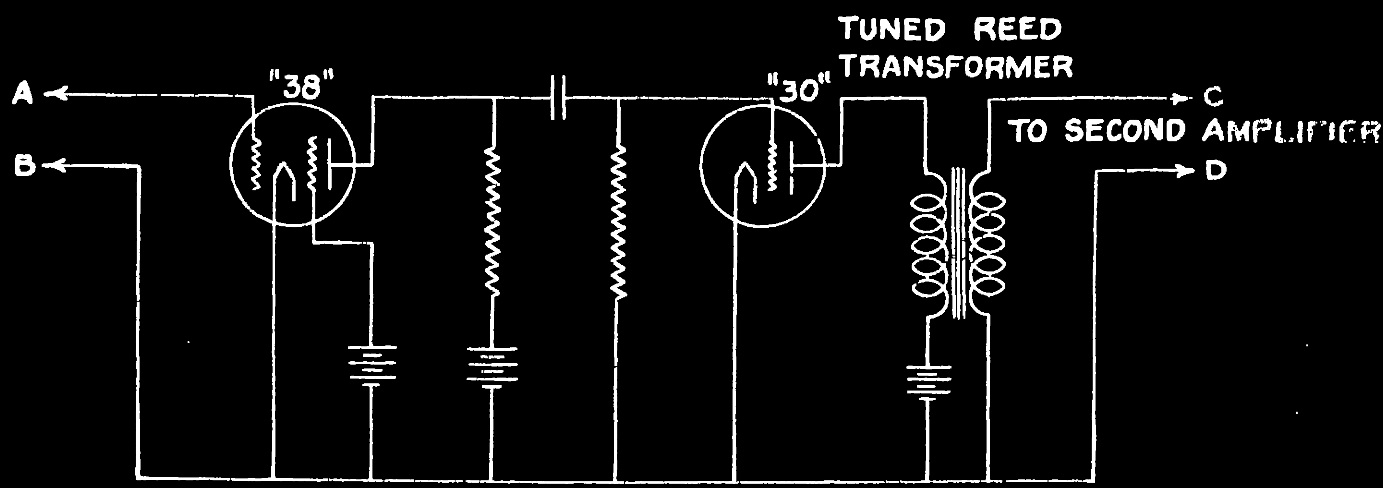
SPECTRAL SENSITIVITY OF THALOFIDE PHOTOELECTRIC CELL

PLATE 9

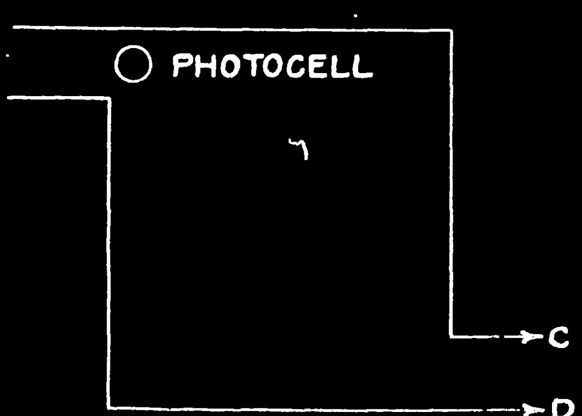


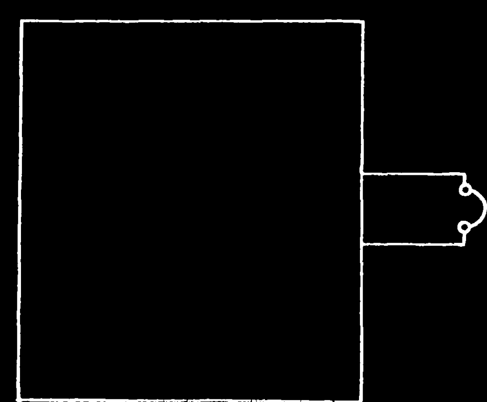
INTRODUCTORY CIRCUITS

PLATE 10



FIRST AMPLIFIER



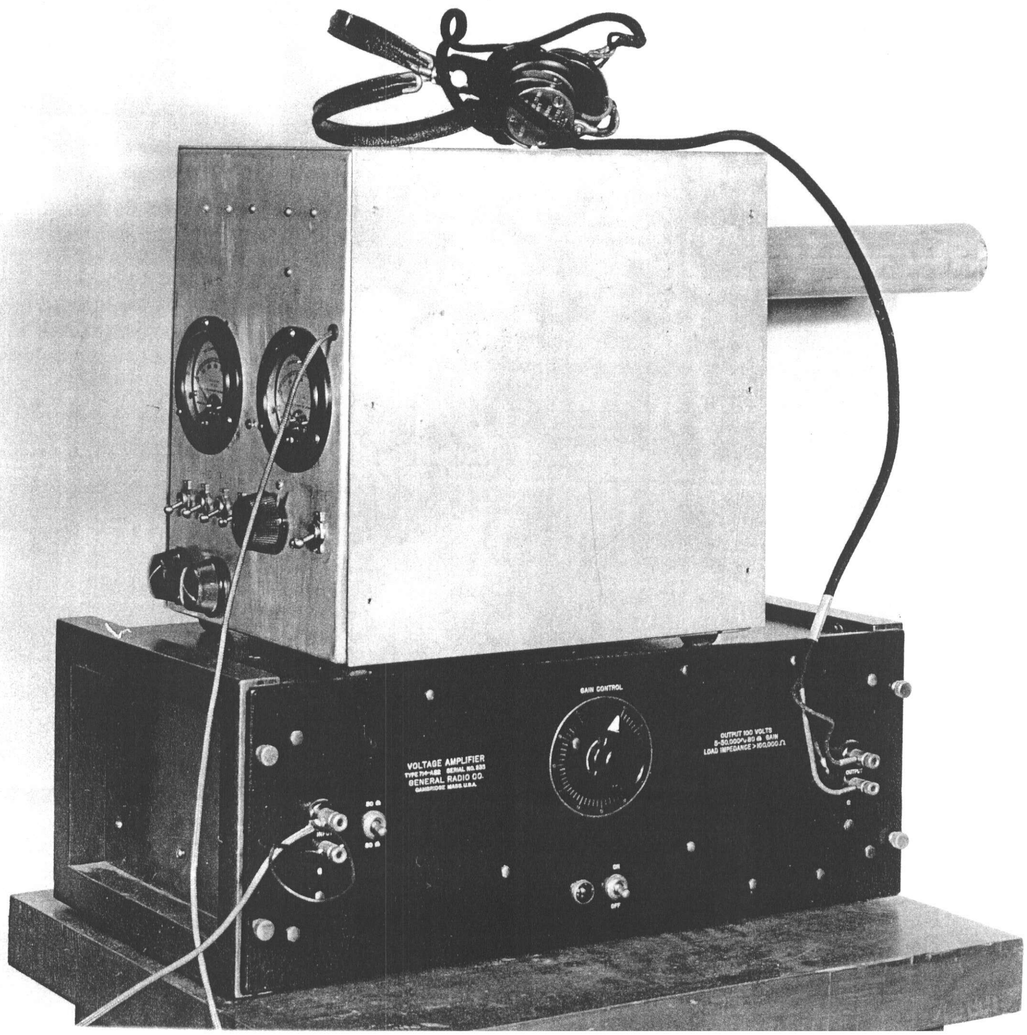


INTRODUCTORY CIRCUIT
AND FIRST AMPLIFIER

SECOND AMPLIFIER
G.R. TYPE 719-AS2

PHOTOCELL AMPLIFIER CIRCUITS

PLATE 11



PHOTOCELL AMPLIFIER

PLATE 12

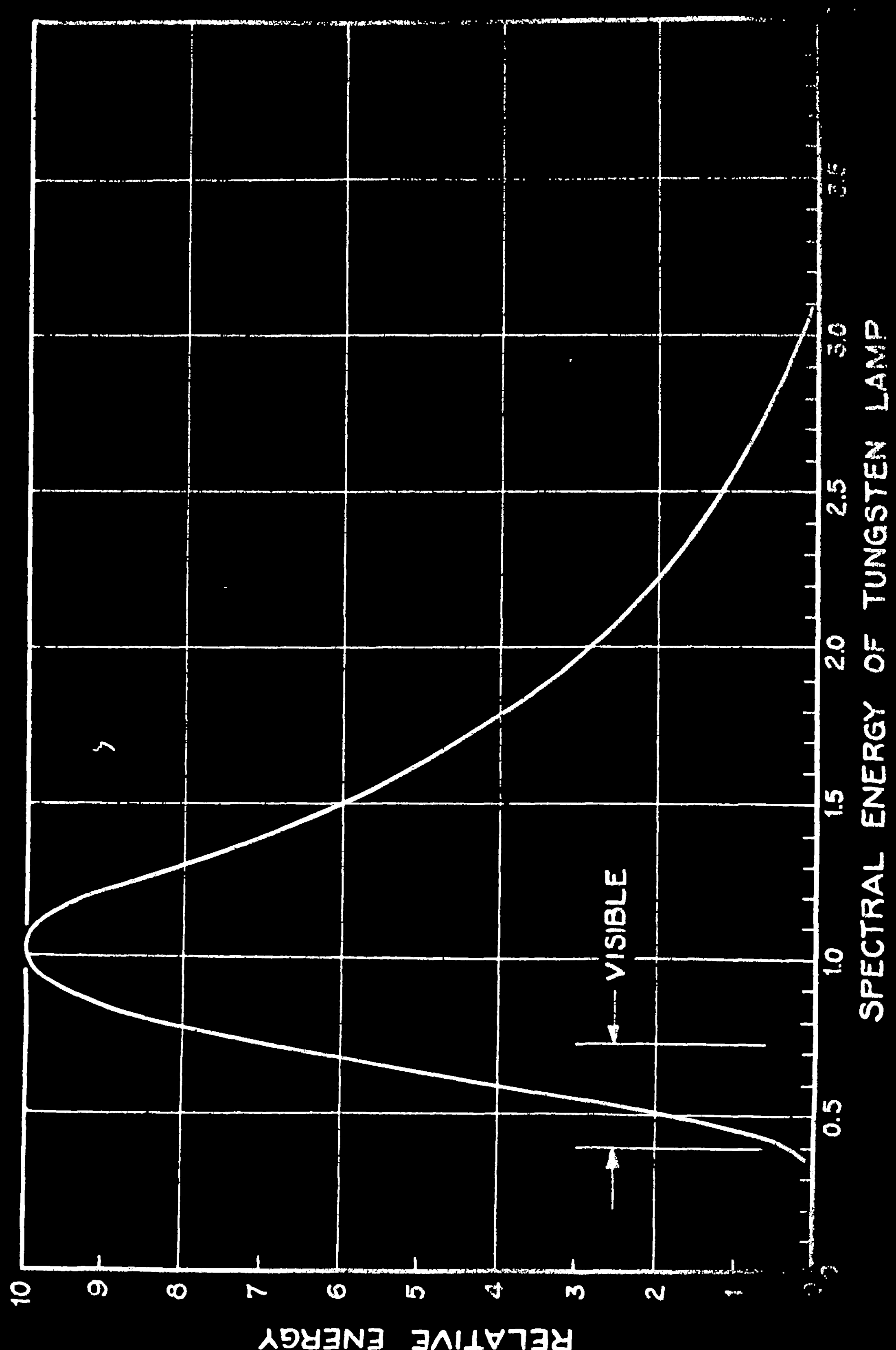
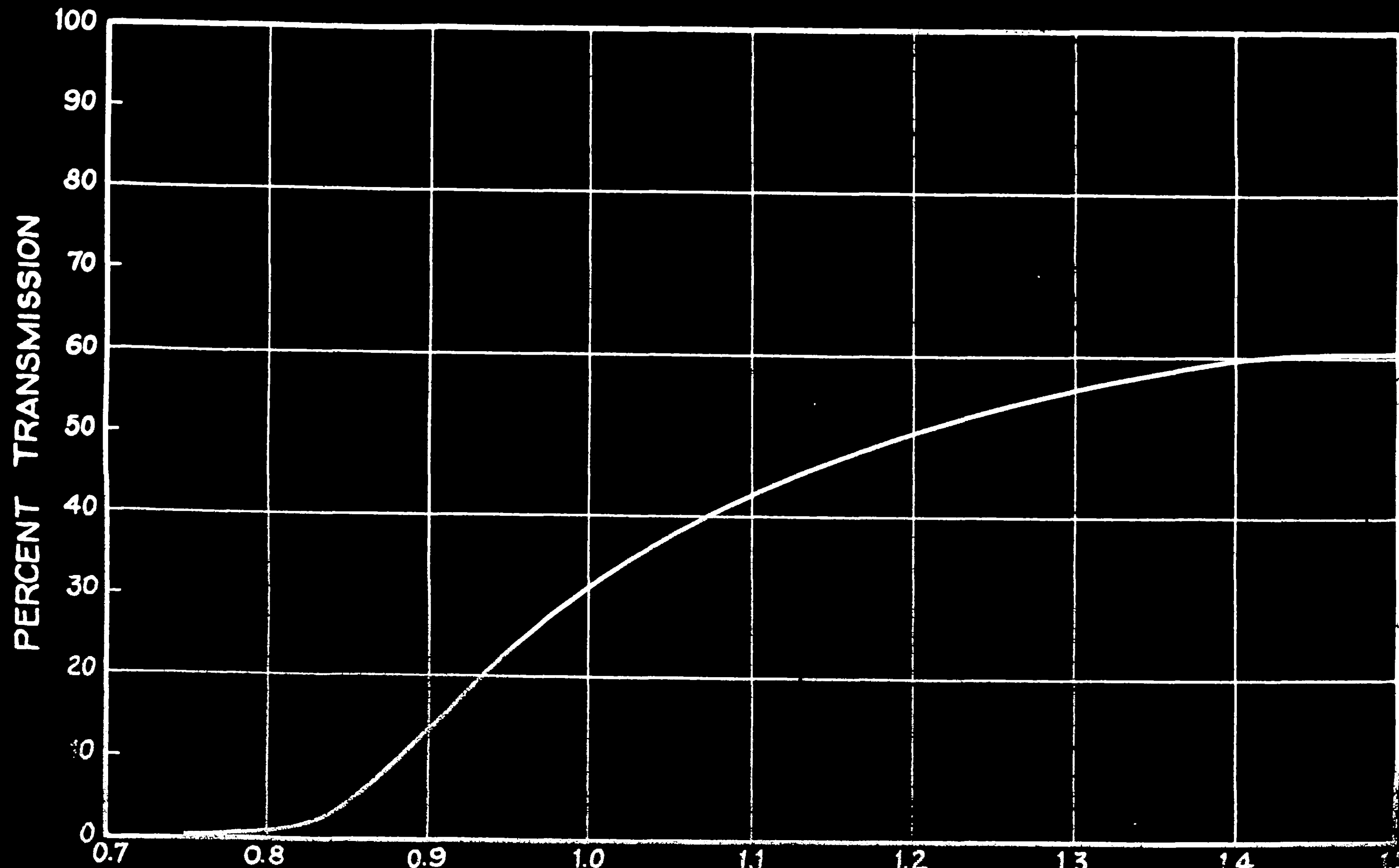
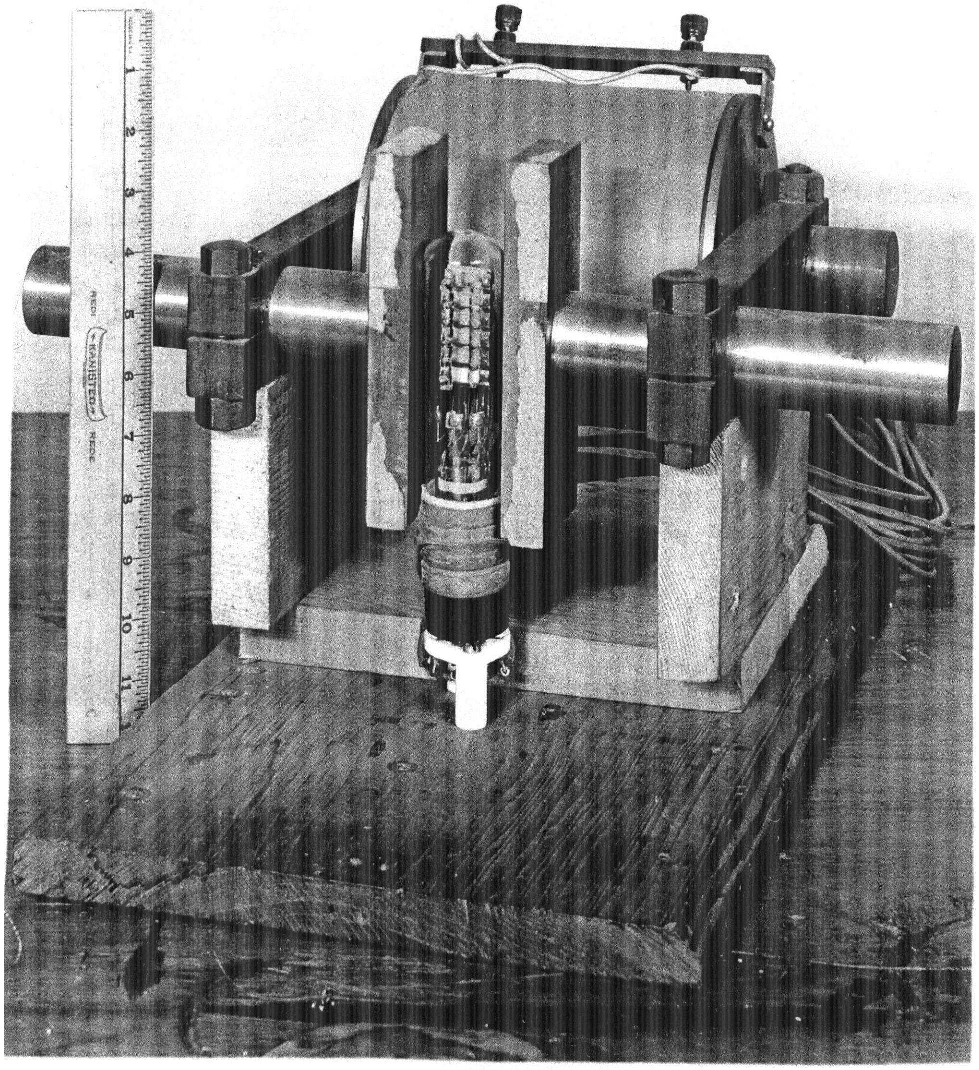

RELATIVE ENERGY
10
9
8
7
6
5
4
3
2
1
0.5
1.0
1.5
2.0
2.5
3.0
3.5
VISIBLE
SPECTRAL ENERGY OF TUNGSTEN LAMP

PLATE 13



TRANSMISSION OF CORNING "HEAT TRANSMITTING" GLASS, 6 MILLIMETERS THICK

PLATE 14



ELECTRON MULTIPLIER PHOTOTUBE

PLATE 15