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SUBJECT

Report on

Signalling with Pulses of Light

by

John [illegible]
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Report on

Signalling with Pulses of Light

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ABSTRACT

A system of light pulse signalling was developed and tested. The source consisted of high intensity flashes of light produced by the discharge of a 112 micro-farad condenser at 2000 volts through a tube of argon gas. The receiver was a six stage electron multiplier phototube with high gain pulse amplifier. With both source and receiver unfocussed the signalling ranges were 800, 7000 and 500 yards, respectively, for the infra-red, visible and ultra-violet portions of the spectrum. With the source focussed into a 12° cone and with the receiver sharply focussed it was estimated that the above ranges would be increased about ten times.

It was concluded that the ranges were too short to be of much use for secret signalling, quite apart from the disadvantages (1) that the system is inoperative in daylight and in fog, (2) that, since the system transmits only a few flashes per minute, its use for conveying information is limited.

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APPENDICES

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Chapter 1

INTRODUCTION

Authorization

1. The present work was authorized by Eng.let. S-A13-2(4-12-R) Serial #348 of 4/15/39.

References

2. Pertinent references are:

(a) Conf.let. from Lt.Comdr. B.G. Lake, USN, of 8 March 1939, to SecNav., Subject "Infra-red signalling", and third endorsement thereto.
(b) NRL Report H-1519 of 28 February 1939, "Experiments with Sensitive Detectors of Ultra-violet and Infra-red Radiations".

Historical

3. Reference (a) proposed a signalling system composed of a source or transmitter and a receiver of near infra-red radiations. The transmitter is a glass discharge tube filled with argon at a moderate pressure and made to flash by the discharge of a condenser. The receiver is a photo-electric cell connected to a high gain amplifier of appropriate design. The third endorsement of reference (a) remarked that the feature of a short intense pulse of light emitted and received was novel and that no data were available on the range achievable by a light pulse system. The efficiency of the condenser discharge through argon, or through any gas for that matter, as a source of near infra-red radiation was not known. The system brought up another unknown point, the visibility of flashes of short duration. It seemed clear that present data were not sufficient to permit a reliable estimate of the effectiveness of the system.

Scope of the Present Experiments

4. The use of very short flashes of light for naval signalling purposes required the development of means for producing these lights and means for receiving the signals advantageously. The conventional method of producing an intense flash of light is by means of the discharge of a condenser through a tube containing a gas at a pressure about 1/10 atmospheric. Edgerton (1) has used such a method to illuminate rapidly moving bodies for short time intervals for photographic and visual observation purposes. This means of production of light flashes appears

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(1) H.E. Edgerton and J.R. Killian, "Flash", and references therein, published 1939 by Hale, Cushman and Flint, Boston.

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with great advantage against all others, such as mechanical shutters, Kerr cells, and exploded wires. An investigation, Chapter 2, was therefore made of the character of the phenomena exhibited by high-energy condensed discharges, and of the technique of making the tubes for the discharge. The light produced by the discharge was studied with a spectrograph to determine its spectral quality and usefulness as an infra-red, an ultra-violet, and a visible signal. The intensity-time function of the lights was studied by means of a photo-cell receiver with oscillograph and with a specially designed electronic ballistic device, and by photographic means on a rapidly moving film.

5. Two means were used for receiving the signal, consisting of a photo-cell of the electron-multiplier type with (1) a cathode-ray oscillograph, and (2) a trigger circuit. Range experiments were carried out, Chapter 3.

6. Experiments were performed, Chapter 4, to determine how bright a single flash of light appears as a function of the time of duration of the flash, for duration times from 1/5 second to 1/23000 second.

Summary of the Present Results

7. The present experiments led to the conclusion that light flashes of the order 10^{-4} to 10^{-6} seconds duration have no foreseeable practical use for secret light signalling at sea. The advantages in principle are: (1) a light of very short duration, although having great maximum radiation, might be so quick that physiological lag in the eye would make it nearly invisible, although an electronic device with less lag would be affected; (2) the sharpness of the light pulse offers an advantage in designing an electrical receiver, because ordinary slow variations in the light reaching the photo-sensitive element may be profoundly attenuated by electrical wave filters, and thus the background of light and electrical "noise" against which the desired signal must stand out can be lowered without simultaneously reducing the level of the signal itself.

8. It was found that advantage (1) is not real, as the experiments described in Chapter 4 show, at least for a duration of the flash as short as 1/23000 second. Advantage (2) is real, but is not great enough, with practical electrical design, to send a useful invisible signal using visible light. An infra-red signal may be sent and received over a range of several miles if ordinary focussing is employed at the light source and the receiver. Since the speed of signalling at this range would be slow (several seconds between flashes), it is not likely that this method of infra-red signalling would serve naval purposes of secret signalling.

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Chapter 2

EXPERIMENTAL ARRANGEMENTS

Electron Multiplier Phototube.

9. The photocell tube used in these experiments was a developmental model by RCA of the electron multiplier type. This consists of a series of six co-planar electron emitting plates and a parallel opposed series of non-emitting plates in an evacuated tube.

10. An electric field is produced in the tube by applying a potential difference of 150 volts between successive emitting plates, and also between successive non-emitting plates, the non-emitting plate opposite any emitter being connected to the next in the series of emitters. An electro-magnet maintains a magnetic field in the tube parallel to the planes of the plates and normal to the electric field. These two fields in the tube are then such that an electron leaving one emitting surface travels to the next in the series. The first in the series of emitting plates is photo-electron emitting, and the rest are secondary-electron emitters, emitting about six electrons per 150 volt incident electron. The action of the tube is therefore to deliver to the last plate in the series about 8,000 electrons when one electron is ejected from the first plate by a light quantum. These 8000 electrons are collected on a plate maintained 300 volts positive with respect to the last electron emitter; the charge thus delivered runs through a resistor in the circuit of the collector and produces a potential difference across this resistance, which is the signal used.

11. Plate 1 is a picture of the electron multiplier phototube mounted between the poles of the electromagnet. Plate 2 shows the spectral sensitivity of the first plate of the phototube. The curve is characteristic of the caesium silver-oxide surface, with considerable sensitivity in the near ultra-violet and near infra-red regions of the spectrum.

Thyratron Receiver

12. In the experiments to determine the signalling range of the flashing lights, the receiving apparatus was the electron-multiplier phototube connected to a thyratron relay. The circuit used is diagrammed in Plate 3. A pulse from the electron multiplier tube, amplified about 50 times by the acorn type 954 tube, causes a momentary positive voltage to be applied to the grid of the Type 2050 thyratron. If this pulse is greater than a chosen value, the thyratron, initially non-conducting, will ionize and conduct a current limited by the plate resistor of 1/2 megohm; the millimeter in the plate circuit indicates this and shows that a pulse has been received. The plate current is shut off and the tube made non-conducting again by opening and closing the switch Sw; the receiver is then ready for another pulse. The threshold for conduction of the thyratron is determined by its plate voltage; at the specified voltage, the grid voltage of the 2050 must be at least 1.8 volts less than that of the cathode for the tube to be non-conductive. As used in

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our range tests, the steady grid bias voltage (adjusted by potentiometer P) was set 1/20 volt more negative than the threshold voltage; this determines that the device respond to a pulse of 1/20 volt on the thyratron grid, or 1/20 x 1/50 = 1/1,000 volt on the grid of the 954 tube, or to a current of 10^{-8} amperes in the electron multiplier tube anode. It was judged that this sensitivity approached the maximum which could be realized in practical design.

Electronic Pulse Analyzer

13. The electronic ballistic device is designed to measure the time interval during which the signal pulse from the light source through the photo-electric multiplier tube is greater than a fixed value, which is determined by the operator. It will be described with reference to the circuit diagram given in Plate 4.

14. The pulse of electrons from the multiplier tube plate goes through the little diode and causes the plate current of tube (2) to stop. Tube (2) unblocks after the electron pulse stops and the charge on its grid leaks off; by choosing the grid resistor sufficiently small, the time for the charge to leak off is made small compared to the total duration of the electron pulse from the phototube. The plate of tube (2) then suffers a nearly square voltage pulse of controlled magnitude and of length equal to the time (T) of the electron pulse. This square pulse, impressed on the screen grid of tube (3), unblocks (3) and permits cathode current to flow to its plate and into the condenser C, resulting in a charge on this condenser equal to the unblocked cathode current times T, and therefore a potential difference equal to this charge divided by the capacity C. This voltage change is impressed on the nominal suppressor grid of the tube (4), and causes a decrease of plate current in (4), which is read on a microammeter in the plate circuit. (This use of the 954 as a sensitive electrometer tube with this arrangement was suggested by Dr. G.L. Locher of this Laboratory.) This decrease of plate current is then proportional to the time of the pulse. By adjusting the potentiometer P the diode (1) is biased, so that the electron pulse from the phototube is passed only after a certain voltage V (equal to the reading of the meter) has been developed by the pulse across the resistor R; and so that the tube (2) then remains blocked only so long as the electron pulse develops a voltage across R exceeding V. The whole action of this circuit then is that the change in the reading of the final microammeter is proportional (with a calculable constant of proportionality) to the time during which the rate of arrival of electrons at the final plate of the phototube exceeds a preset value. Thus an intensity-time relation for the flashing tube being studied can be deduced by operating the set for a series of values of the potentiometer setting.

Photographic Pulse Analyzer

15. A moving-film camera developed by the Mechanics and Electricity Division of this Laboratory was used in order to study the intensity-time function of the lamps without the limitations of the electronic analyzer, which measures only the duration of a given light intensity (not the sharpness of the beginning of the pulse).

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16. The essential optical arrangement is shown in Plate 5. The slit S, 0.005 inch wide, is focussed by lens Z on a strip of film at F, bent into a cylinder and rotated 2,000 times a second. The linear speed of the film at the focus is 5,000 inches per second; since the magnification of Z is 1/10, the width of the image of the slit on the film (0.0005 inch) is passed over in 1/10 microsecond, providing ample resolution. The lamp at L is arranged with its axis parallel to the slit and at such a distance that the lens Z is filled with light and light from each point of the source can enter the lens. This arrangement gives on the developed film a very fair representation of the march of the light intensity of the flash.

17. The moving film camera pictures of the flashes are shown in Plate 6.

Power Supply for the Flashing Tubes

18. The tubes were flashed by allowing a condenser of 112 microfarads charged to 2,000 volts to pass through the tubes. The condenser was a bank of four 28 microfarad pyranol condensers, nominally rated at 500 volts; most condensers tried withstood the 300 per cent overvoltage. They were charged by two radio power transformers connected in series, through a Type 1616 rectifier tube used almost within its nominal rating. The condensers could be fully charged within about three seconds when the rectifier was new. It should be noted that the speed of signalling will be limited to this speed if the tube can be kept cool.

19. Since 2,000 volts is not sufficient to break down the gas in the tube at the pressure and dimensions used, the discharge was initiated by means of a high-frequency discharge in the tube produced by a Tesla coil leak tester.

Construction of the Flashing Lamps.

20. A commercial flashing lamp was available manufactured by H.E. Edgerton, 69 Massachusetts Avenue, Cambridge, Massachusetts. This contained krypton gas at an unknown pressure. It was called the Edgerton "Speedlight".

21. A successful endeavor was made to construct lamps which gave a more intense flash than the Edgerton lamp. Because of the high current of the electrical discharge through the lamps, rugged electrode structure was of primary importance in design. All lamps made were about 15 cm long and 3/4 inch diameter, of pyrex tubing, with one electrode at each end. In some lamps, the electrodes were aluminum cylinders screwed tightly onto the molybdenum ends of "Koolgrid" 50 mil leads. In later lamps, a simple construction using a copper-glass seal was used: a copper spinning, in the form of a thin-edged cylindrical cup 1/2 inch long and 1/2 inch in diameter, sealed into the end of a pyrex tube, served as vacuum seal and as electrode. Both methods gave usable lamps. The gas used in the lamps was argon, at pressures of about 10 cm of mercury, introduced by conventional high-vacuum technique.

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Result of Measurements of the Light Flashes

22. The evidence of the electronic intensity-duration meter, and of the moving film camera, Plate 6, shows that the main part of the flash occurs in an interval of 20 microseconds, followed by weaker radiation which decays in the next 200 microseconds. The initial rise of intensity is very rapid, the peak occurring about 10 microseconds after initiation of the discharge; for the Edgerton lamp and typical NRL argon lamps this peak is about 2 million candles, and the surface brightness about 0.1 million candles/cm^2, one-half the sun's brightness. The intensity of the Copper Spark was about 1/5 that of the rare gas lamps.

23. The discharge in all lights except the Copper Spark was non-oscillatory, signifying a fairly efficient transfer of energy to the gas. The damping resistance of the Copper Spark was so low that six complete oscillations took place during luminescence; this arrangement did not produce maximum luminous intensity.

Spectra of the Light Flashes

24. In Plate 8 are shown the spectra of the condensed discharges through the Edgerton tube, a typical home-made argon tube, and the spark between copper electrodes in air. It is seen that all the flashes emitted much visible light and that the rare gas tubes emitted relatively more infra-red light than the copper spark. The upper spectra of Plate 8 also show the difference between a continuous low-current (d.c.) discharge and the impulsive, high-current condensed spark discharge. The difference is that the impulsive discharge enhances the shorter wave-lengths more than it does the longer wave-lengths.

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Chapter 3

RANGE EXPERIMENTS

25. Range experiments were carried out over a distance of 260 feet through a laboratory corridor. The source and receiving phototube were unfocussed. The source was attenuated accurately by known amounts by means of Nicol prisms and absorbing screens until the least practical signal was received. The attenuation was determined for each of three sources for three cases: (1) with no filter over the source and hence the source visible, (2) with Corning infra-red transmitting black glass (6 mm thick) over the source, (3) with Corning ultra-violet transmitting black glass (10 mm thick) over the source. In cases (2) and (3) the source was nearly invisible. The attenuation values are given as fractions in Table 1. The range was then calculated from the inverse square law and the known attenuation by means of the relation,

range = 260 feet times the square root of the reciprocal of the attenuation.

26. The ranges in yards are given in Table 2. These ranges are the essential results of the present investigation.

27. From Table 2 we see that for invisible or secret signalling the best range was obtained with the argon tube with the infra-red filter; for this case the range was about 800 yards with no focussing. Apart from focussing, which is discussed in the next paragraph, it is doubtful that the range can be increased very much. The amount of electrical energy put into the flash cannot be increased without shortening the life of the lamp too greatly. With the energy used, the lamp would survive only about 100 flashes before cracking to pieces. The limit of receiver sensitivity was approached, and there appears to be no method of surmounting this limit.

TABLE 1

Attenuation for 260 feet, source and receiver unfocussed.

Source	(1) visible	(2) infra-red	(3) ultra-violet
Edgerton lamp	1/2,560	1/40	1/16
Argon lamp	1/6,400	1/80	1/40
Copper spark	1/640	1/4	1/2

[redacted]

TABLE 2

Calculated ranges, source and receiver unfocussed.

Source	(1) visible	(2) infra-red	(3) ultra-violet
Edgerton lamp	4,000 yards	500 yards	300 yards
Argon lamp	7,000 yards	800 yards	500 yards
Copper spark	2,000 yards	200 yards	100 yards

28. Focussing will increase the range. Consider first a focussed source and an unfocussed receiver. An 8-inch diameter Fresnel lens, which focusses the light into a circular ring about 7° wide will increase the intensity four times, and hence the range twice; the 800 yard range of the infra-red argon tube would be increased to 1600 yards. With a 12-inch signalling searchlight mirror, which focusses the light into a 12° cone, the intensity would be increased 25 times and the range 5 times; the 800 yard range becomes 4,000 yards. Now suppose a lens or mirror is used to focus the light on the receiver, this may increase the intensity by at least 9 and the range by 3; the 4,000 yards will become 12,000 yards, or 6 miles. Such a focussed receiver will have a very narrow field of view; it must be pointed at the source within at least 5 degrees. Thus the increased range is secured by narrowing the field of view, and a too narrow field of view is not practicable for ships at sea.

29. The general conclusion appears to be that the light pulse system does not offer ranges great enough to be of practical naval use at sea. It is of interest to remark that the above ranges are about the same as the ranges achieved with modulated light sources and photo-electric cell reception with low frequency amplification, reference (b).

30. The character of the light pulse system should be made entirely clear. Since several seconds are required for the condensers to become charged, only a small number of flashes per minute can be transmitted. Therefore the system can not be used to transmit messages; only by an impracticable stretch of the imagination could the system be multiplied or amplified to the point of message transmission. Thus the system could only be used to indicate direction, as a lighthouse. And, being inoperative during the day and in fog, it could only be used at night in a clear atmosphere.

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Chapter 4

BRIGHTNESS OF A FLASH OF LIGHT

31. Experiments were performed to find out how bright a single flash of light appears as a function of the time of duration of the flash. This was accomplished by determining the ratio of the minimum perceptible intensity for a constant light and a flash of light for various duration of the flash. Blondel and Rey (2) made observations

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(2) Blondel and Rey, Trans.I.E.S. 7, 625 (1912)

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for duration times from 3 seconds to 1/100 second, and the present experiments covered the range from 1/10 second to 1/23,000 second. In the experiment of Blondel and Rey a steady light at a fixed distance was decreased to b_o, the brightness at which it was barely perceptible. The light was then occulted by a shutter to give a single flash of duration Δt seconds and its brightness b again adjusted to bare perceptibility. The ratio b/b_o was determined, and the experiment repeated for various values of Δt. Since Blondel and Rey were interested in flashes of light for navigational aids, as lighthouses, no observations were made for Δt less than 1/100 second. Their results are given in the first two columns of Table 3 and show that b/b_o increased rapidly as Δt decreased.

32. The total luminous energy in the flash is $b \Delta t$. The values of $b \Delta t/b_o$ are proportional to the luminous energy in the flash; they are in the third column of Table 3 and are plotted in the dotted curve BR, Plate 10. It appears that $b \Delta t/b_o$ decreases rapidly as Δt decreases with indications of reaching a constant value for Δt less than about 1/30 second. The meaning of this is discussed later.

33. To carry out observations for values of Δt below 1/100 second, the apparatus of Plate 9 was used. S_1 and S_2, about 4 inches apart, were sources of light. They consisted of small holes in the ends of photometer boxes backed by small pieces of ground glass and illuminated by lights L_1 and L_2, respectively. The brightness of S_1 was adjustable in known amounts over a range of 200,000 by varying the distance L_1 from S_1 and by placing neutral filters at F. In front of S_1 was a shutter S by means of which could be produced flashes of duration times Δt from several seconds to 1/23,000 second. For Δt greater than 1/1,250 second a focal place camera shutter was used; for Δt less than 1/1,250 second a rotating disk with a small hole in conjunction with the camera shutter was used. The shortest flash which the apparatus could give was 1/23,000 second; to produce flashes of shorter duration and of known intensity would require more elaborate experimental arrangements. The source of light S_2 was used for fixation or comparison; its brightness was adjusted by the current through the lamp L_2.

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34. The experimental procedure was as follows: Sources S_1 and S_2 were approximately white in color and were observed in a dark room with dark adapted eyes at a distance of about 10 feet. The sources were circular, of diameter about 1 mm, and subtended an angle of 1 minute of arc at the eyes of the observer. They thus appeared as stars. S_2 was adjusted to a low intensity, about that of a second magnitude star, as the North Star, and merely served as a fixation point to indicate where the observer should look. S_1 was shined steadily and was reduced to the minimum perceptible intensity; this gave b_o. S_1 was then flashed with a duration time Δt seconds and its intensity again adjusted to minimum perceptibility; this gave b. The values of $b \Delta t/b_o$, determined by six observers are plotted in the crooked lines of Plate 10 as ordinates against Δt as abscissa.

35. The curves of the six observers are not very smooth; the irregularities arise mainly from the fact that the adjustment of a light to minimum perceptible intensity demands a judgment of the observer which is not very definite and which can not be repeated with exactness. The fact that some of the curves were considerably above the others is of no consequence here, and is to be ascribed to differing judgment criteria as well as to eye functioning of the several observers.

36. The important fact to be derived from the curves of Plate 10 is that the value of $b \Delta t/b_o$ is approximately constant for Δt throughout the range from about 1/10 to 1/23,000 second. The lower three curves indicate a slight increase of $b \Delta t/b_o$ as Δt decreases from 1/1,250 to 1/23,000 second. This departure from constancy is less than a 100 per cent increase, and may not be real. The values of b/b and $b \Delta t/b_o$ from a smoothed average of the lower three curves T, D, and E of Plate 10 are tabulated in Table 4.

37. The experiment was repeated with blue lights and with red lights, and with holes S_1 and S_2 8 mm in diameter which subtended an angle of 8' at the eye and appeared as small round disks. In all these cases the curves were similar to those of Plate 10, which refer to small white lights, in that $b \Delta t/b_o$ fell to an approximately constant value for Δt below 1/25 second. The experiment with 1 mm white lights was repeated with the difference that measurements were made at a fixed low brightness instead of at the minimum perceptible brightness. In this experiment S_2 was set at about the brightness of the North Star and S_1 was adjusted to an apparent equal brightness for various values of Δt. Again results similar to those of Plate 10 were obtained.

38. Now the quantity $b \Delta t/b_o$ is proportional to the total luminous energy in the flash of light. Therefore the experimental fact that $b \Delta t/b_o$ is approximately constant for Δt below about 1/25 second means that the apparent brightness of the flash depended only on the luminous energy of the flash; it means, for example, that a flash 1/1,000 second in length appears equally as bright (or can be seen equally as as far) as a flash 10 times as long and 1/10 as intense, or as a flash 1/10 as long and 10 times as intense. Therefore, within the range of the experiments, the eye is approximately a true integrator of the received luminous energy. The slight observed increase in $b \Delta t/b_o$ for Δt below 1/1,250 second would mean that the eye response is not quite proportional to the received energy, but becomes less efficient at the

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higher values of Δt. The effect is small and, being barely outside the irregularities of experiment, may not be real. If real, it is too small to be of practical importance in the present connection, but may be of some academic interest. Extension of the observations to flashes of duration below 1/23,000 second might be of interest, but was considered to be beyond the scope of the present investigation.

39. The rise of the $b \Delta t/b_0$ curve with Δt increasing above about 1/25 second comes about from the persistence of vision of the eye. For, when Δt is greater than the time of persistence of vision, which is roughly 1/3 to 1/30 second depending on the intensity of the light and other factors, then increasing Δt to greater values does not increase the apparent brightness of the flash. Hence, as Δt increases b/b_0 descends asymptotically to unity and the product $b \Delta t/b_0$ increases proportionally with Δt. In fact the curves of Plate 10 provide a means of measuring certain aspects of the phenomena of the persistence of vision.

40. The fact that the apparent brightness of a flash of light has been found to be proportional to the total luminous energy in the flash for durations of flash down to 1/23,000 second shows that the supposition is erroneous that the eye brilliancy of the flash might fall off with decreasing time of duration to such an extent that by means of instrumental reception as the photoelectric cell, which is known to respond faithfully to the total energy down to durations of 10^{-8} second, it might be possible to detect a flash so short that it was invisible. The realm of tenability of the supposition is thus relegated to speculation concerning flashes shorter than 1/23,000 second.

[redacted]

TABLE 3

Flash of light data. Blondel and Rey

Duration of flash Δt	b/b_o	$b \Delta t/b_o$
3.00 second	1.07	3.3
2.00	1.10	2.2
1.00	1.21	1.2
0.80	1.26	1.0
0.60	1.35	0.81
0.40	1.52	0.61
0.30	1.70	0.51
0.20	2.05	0.41
0.10	3.1	0.31
0.05	5.2	0.26
0.025	9.4	0.23
0.01	22	0.22

TABLE 4

Flash of light data. Present experiments.

Duration of flash Δt	b/b_o	$b \Delta t/b_o$
1/5 second	2.2	0.44
1/10	3.2	.32
1/25	6.0	.24
1/50	11	.22
1/125	28	.22
1/250	56	.22
1/500	120	.24
1/1250	320	.26
1/7000	2200	.32
1/13500	4800	.36
1/23000	8800	.38

[redacted]

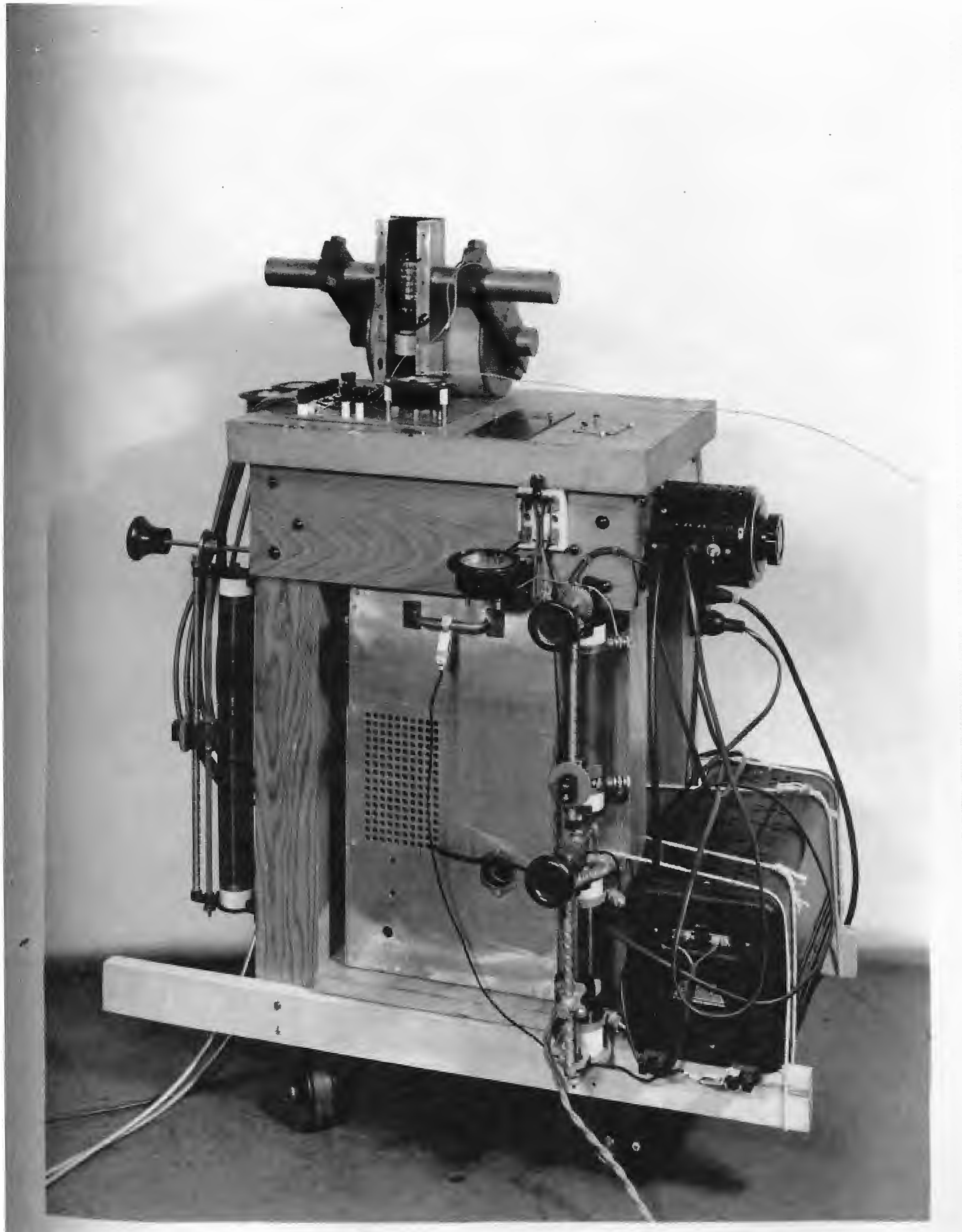

Plate 1

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SPECTRAL SENSITIVITY CURVE OF
R.C.A. ELECTRON TUBE MULTIPLIER

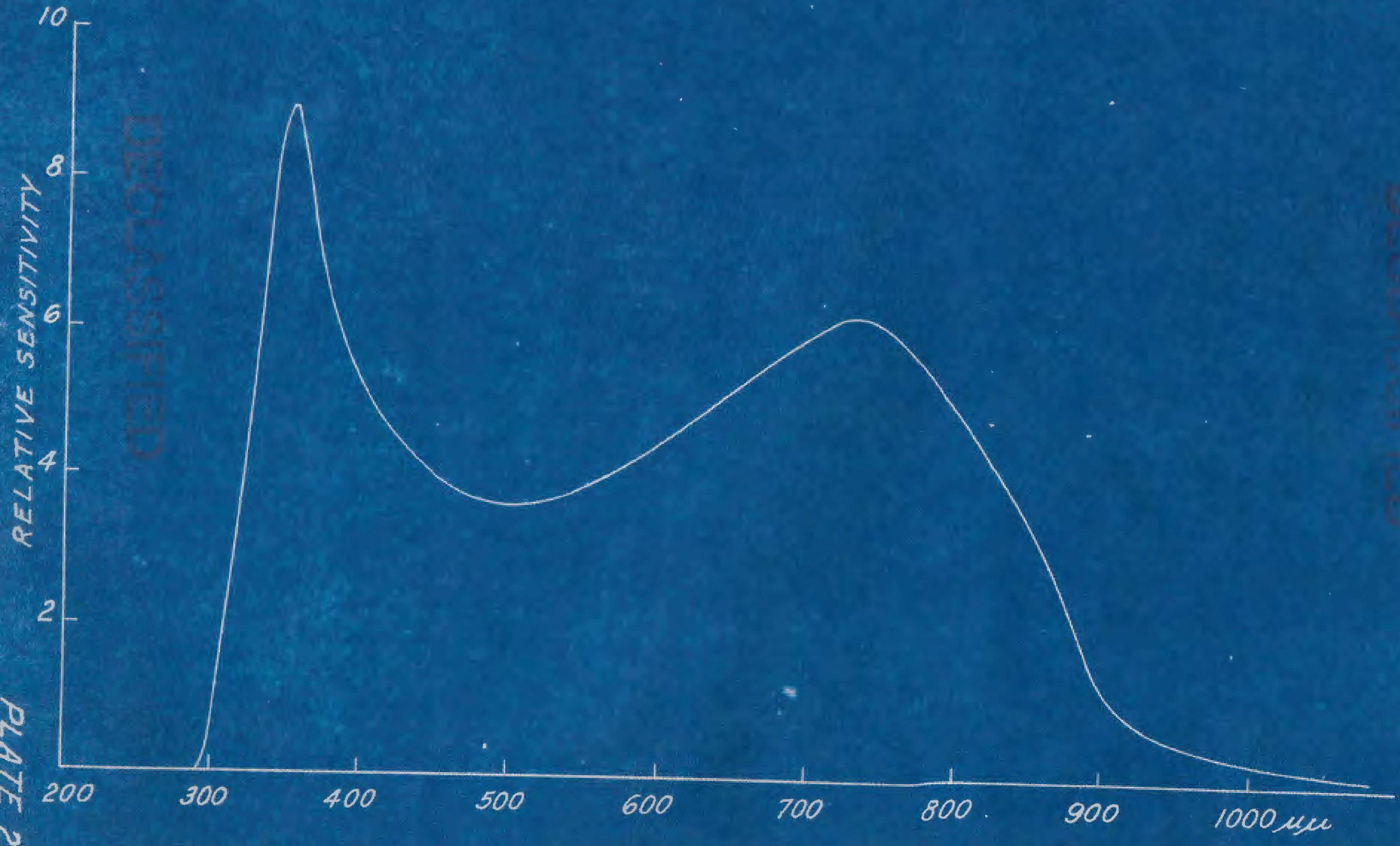
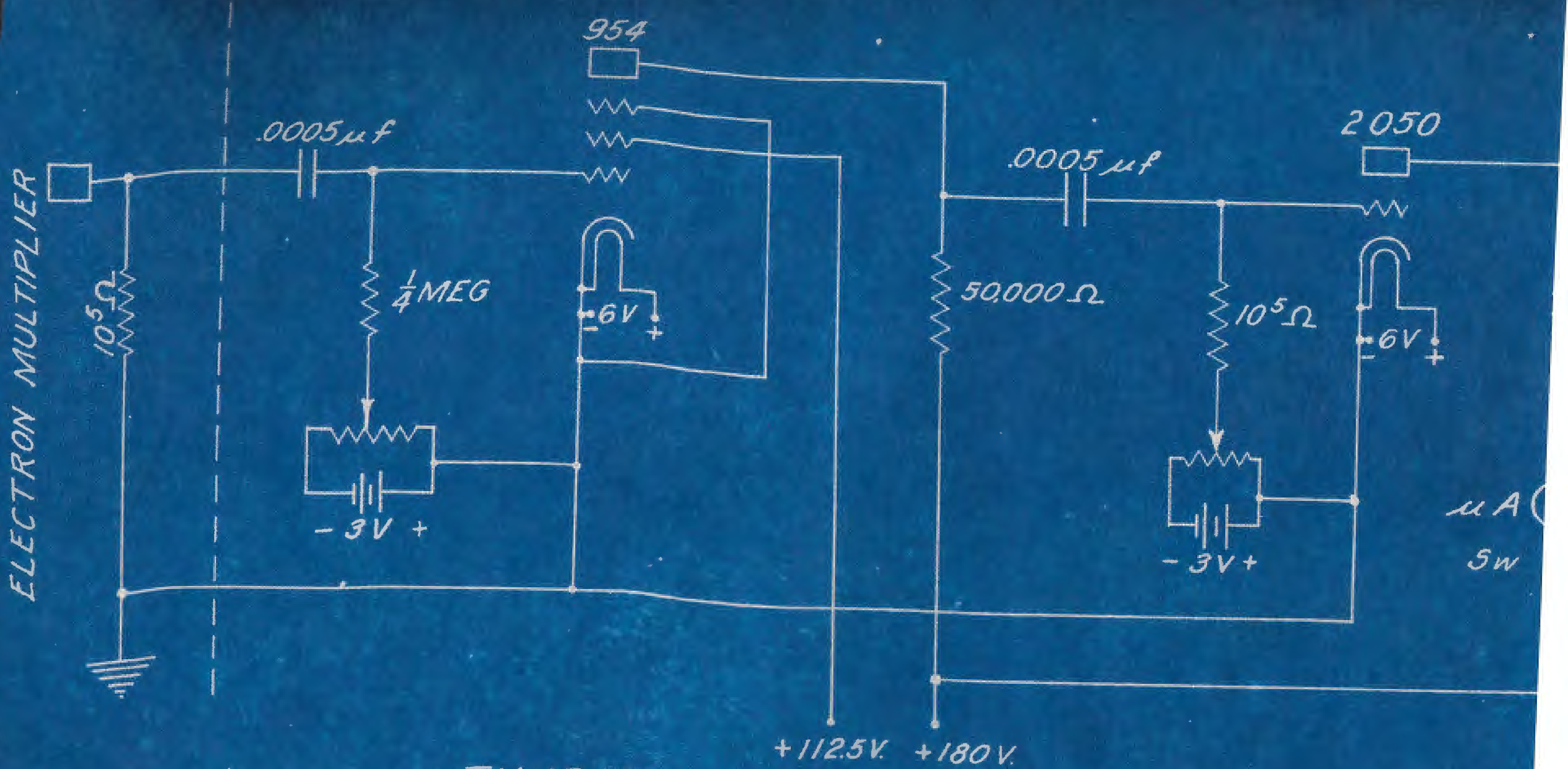
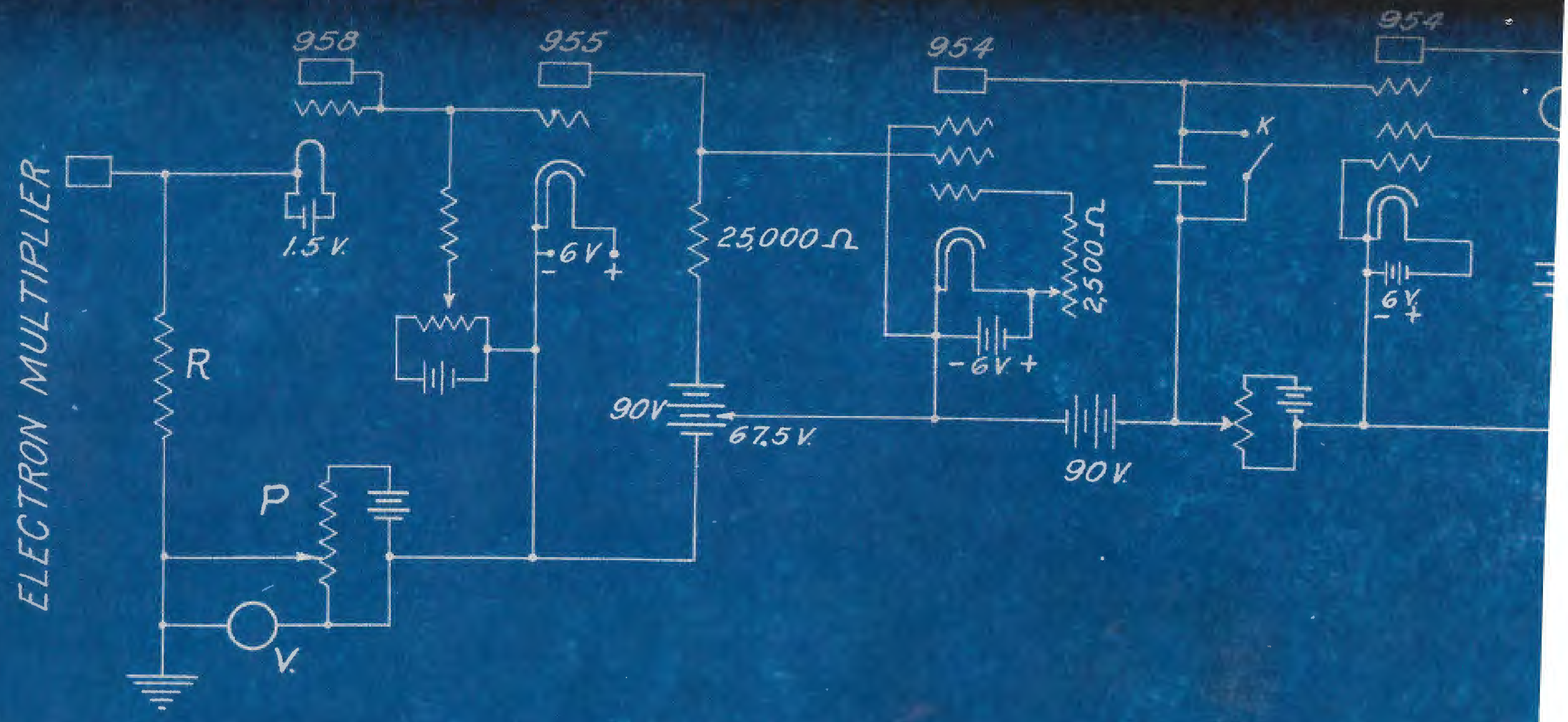


PLATE 2



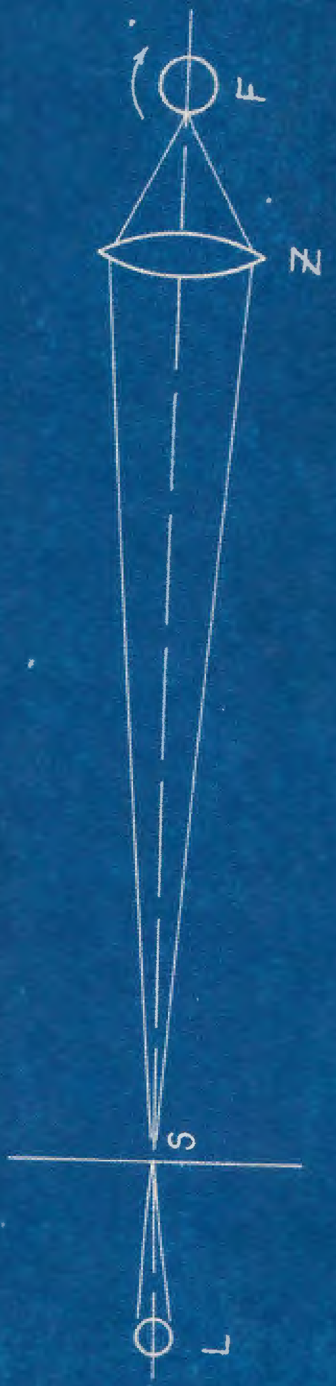
THYRATRON RECEIVER CIRCUIT

PLATE 3



ELECTRONIC PULSE ANALYZER

PLATE 4



OPTICAL SYSTEM OF MOVING-FILM CAMERA

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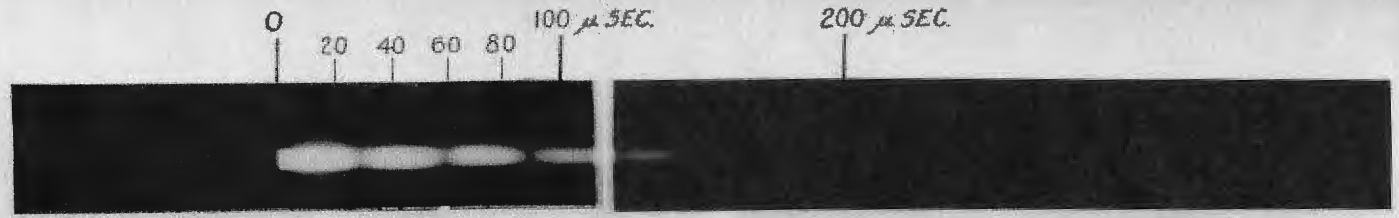
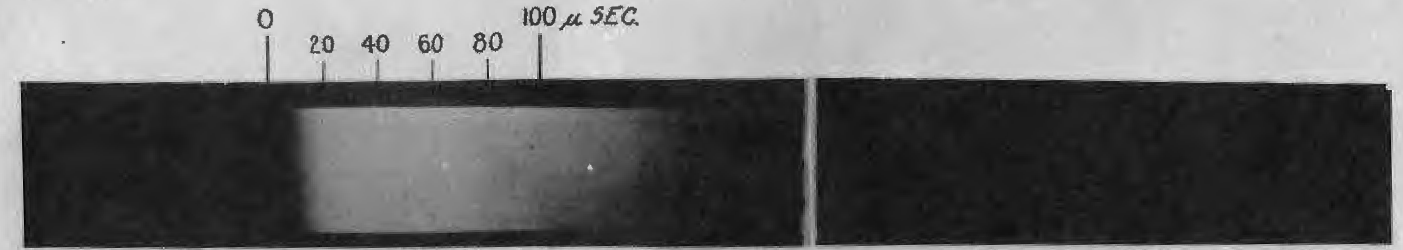
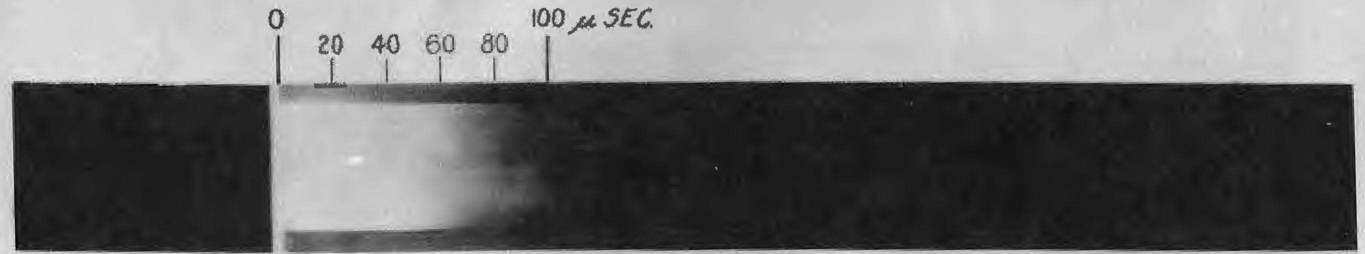
PLATE 5



COPPER SPARK IN AIR $\frac{1}{4}''$ DIAM. CU. RODS, $\frac{3}{32}''$ SEPARATION



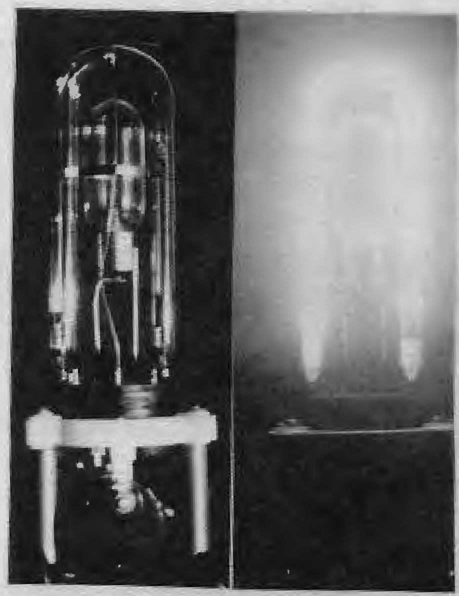
EDGERTON "SPEEDLIGHT"



NRL ARGON TUBE

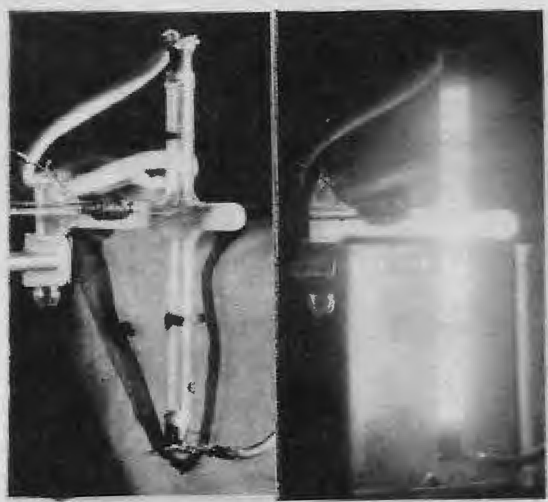
MOVING FILM PICTURES OF FLASHES

PLATE 6



EDGERTON "SPEEDLIGHT"

CU. SPARK

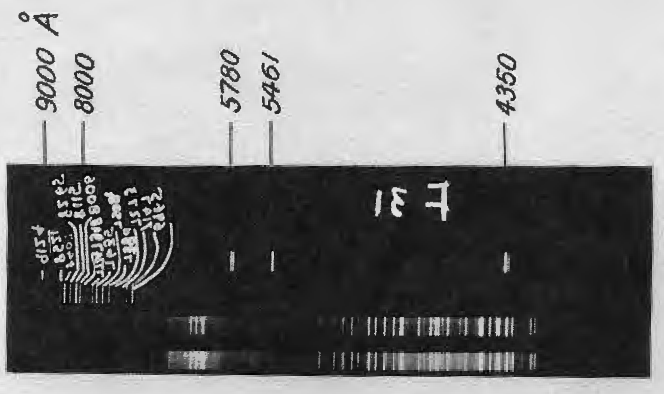


NRL ARGON TUBE

TYPICAL FLASHING LAMPS

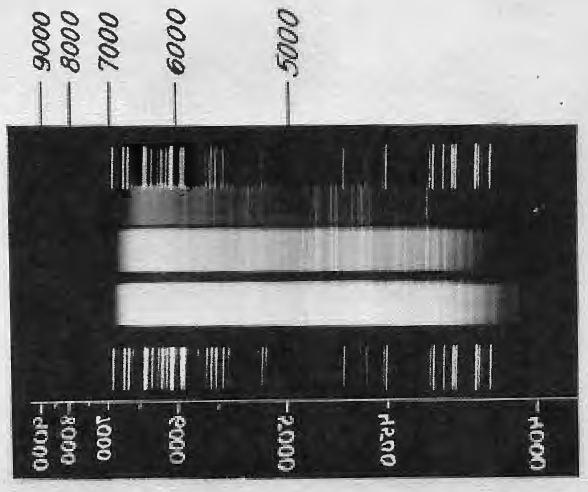
PLATE 7

[redacted]



HG.
ARGON, D.C. DISCH.
} ARGON, CONDENSED

HG
COPPER SPARK

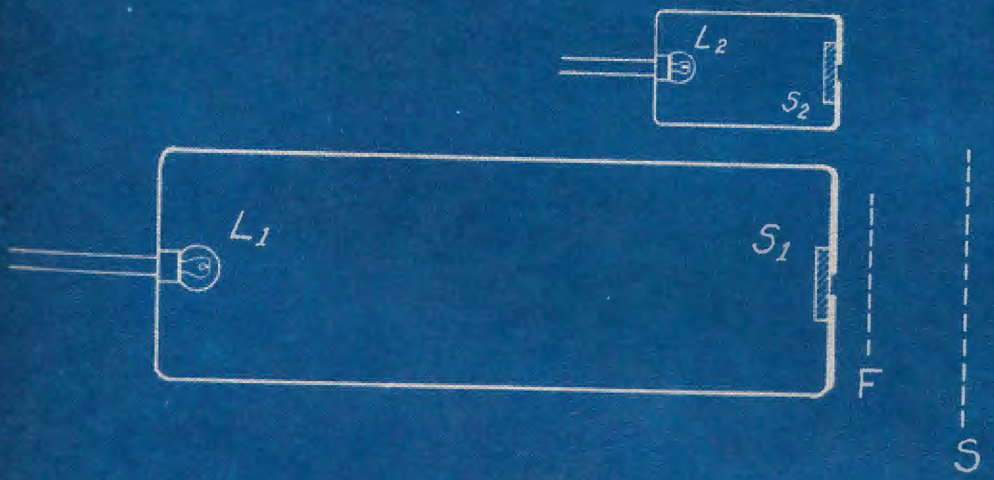


ARGON
} EDGERTON "SPEEDLIGHT"

SPECTRA OF THE VARIOUS LIGHTS STUDIED

PLATE 8

[redacted] DECLASSIFIED



FLASH OF LIGHT APPARATUS

[redacted]

PLATE 9

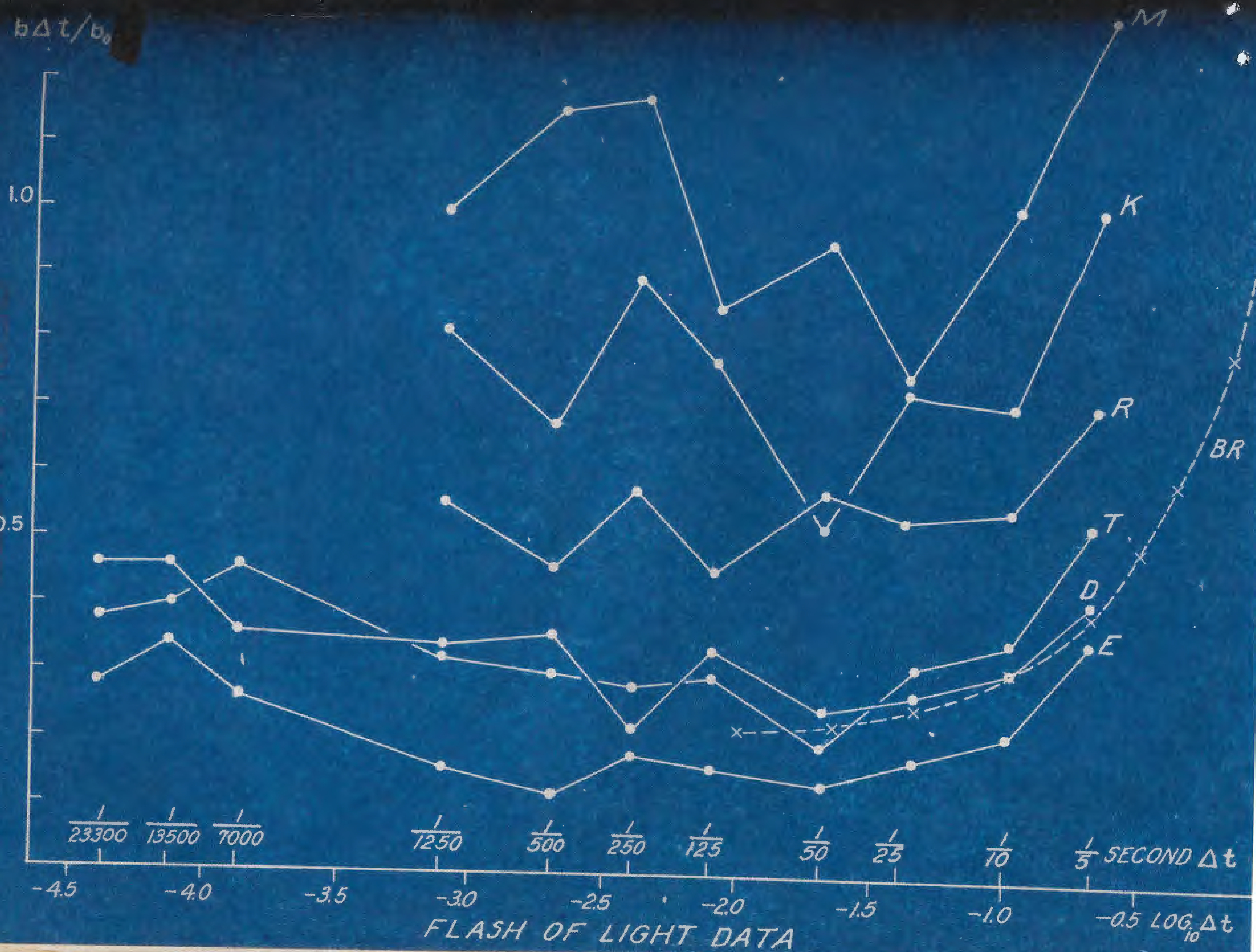

b∆t/b₀
1.0
0.5
M
K
R
T
D
E
BR
1/23300
1/13500
1/7000
1/1250
1/500
1/250
1/125
1/50
1/25
1/10
1/5 SECOND ∆t
-4.5
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5 LOG10 ∆t
FLASH OF LIGHT DATA

PLATE 10