DESIGN AND CONSTRUCTION
OF A
NEW SPECTROPHOTOMETER

by

JOHN FRANCIS JOYCE

Submitted in Partial Fulfillment of the
Requirement for the Degree of
Master of Science
from the
Massachusetts Institute of Technology
1930

Signature of writer
Certification by Dep't of Electrical Engineering
Instructor in Charge of Research..

TABLE OF CONTENTS

CHAPTER I

OBJECT OF THESIS

For some time the Illumination Laboratory at the Massachusetts Institute of Technology has felt the need of a spectrophotometer. The present photometric equipment of the laboratory includes:

A bar photometer, using a Lummer-Brodhun photometer head, for the measurement of candlepower of ordinary incandescent lamps.

An Ulbricht integrating sphere for measuring the luminous output of lamps.

One Macbeth illuminometer and two foot-candle meters, for use in measuring the illumination at various points in a room.

This equipment has been more or less adequate in the past, but the widespread use of colored lamps has made necessary a photometer which would be better adapted for measuring the candlepower of colored lamps than either the bar photometer or the integrating sphere.

The limitations of the above equipment are well known to anybody who has tried balancing a colored lamp against a white standard. At best the work is tedious and inaccurate, even though the operator be experienced.

At the suggestion of Mr. Moon, the design and construction was undertaken of a spectrophotometer especially adapted for the measurement of candlepower of colored lamps.

CHAPTER II

SPECTROPHOTOMETRY AND SPECTROPHOTOMETERS

Spectrophotometry may be defined as the visual measurement of relative radiant energy as a function of wavelength or frequency. This energy may be that emitted by incandescent or other light sources, or it may be that transmitted, absorbed, or reflected by transparent or absorbing materials. There are, however, other than visual methods, such as photographic, photoelectric, and radiometric. These are often used in the visible region of the spectrum, but of necessity in the ultra-violet and infra-red where the eye can no longer be used.

The general purposes of spectrophotometry are the determination of spectral emissive, transmissive, and reflective characteristics. Such determinations furnish a basis for color specification which is unique and fundamental, in that the stimulus of the color may thus be completely specified. Such specification is independent of material color standards and of abnormalities of the observer's color vision, - to which limitations all so-called colorimetric methods are more or less subject.

Every spectrophotometric apparatus consists essentially of two parts: (a) the spectral dispersing system, and (b) the photometric system. Spectral dispersion is usually effected by a prism system, although grating systems have also been used. The photometric system consists ordinarily of a uniformly illuminated two-part photometric field with means available for varying the brightness of one or both parts in a continuous manner.

G. Govi, in 1860, was apparently the first to use what might be called a spectrophotometer. He projected two spectra, each from a different source and dispersed by the same prism, on to a white diffusing surface. These contiguous spectra were then examined through a diaphragm by which any small region could be selected at will. Brightnesses were varied by changing the distances of the light sources.

K. Vierordt, in 1874, replaced the usual collimator slit with a divided slit, the width of each part of which was independently controlled by a separate micrometer. This resulted in the formation of two spectra, one directly above the other which could be seen through the eyepiece. The brightness in either half of the field could be varied by varying the width of the respective part of the collimator slit. This method had two serious faults, - one, that unilateral slits were used, and another in the fact that, because of the small separation of the collimator slits, the two spectra were separated by a small dark space sufficient to decidedly reduce the precision.

Later improvements consisted in using bi-lateral instead of lateral slits, replacing the variable slit method of varying brightness by other methods, and in devising means for eliminating the space between the two spectra. A bilateral slit is one which moves in both directions from the zero point.

Polarization methods of varying the brightness have been used by Glan, Crova, Hüfer, Nutting and others. Nutting also designed a photometer (Fig. 1) for use in conjunction with a spectrometer. Glan, in 1877, by means of a rochon prism within the instrument, obtained two beams of light, polarized mutually at right angles, which, after passing through a nicol prism, formed the two continguous spectra. Rotation of the nicol prism would, in general, increase the brightness of one part of the field while decreasing the

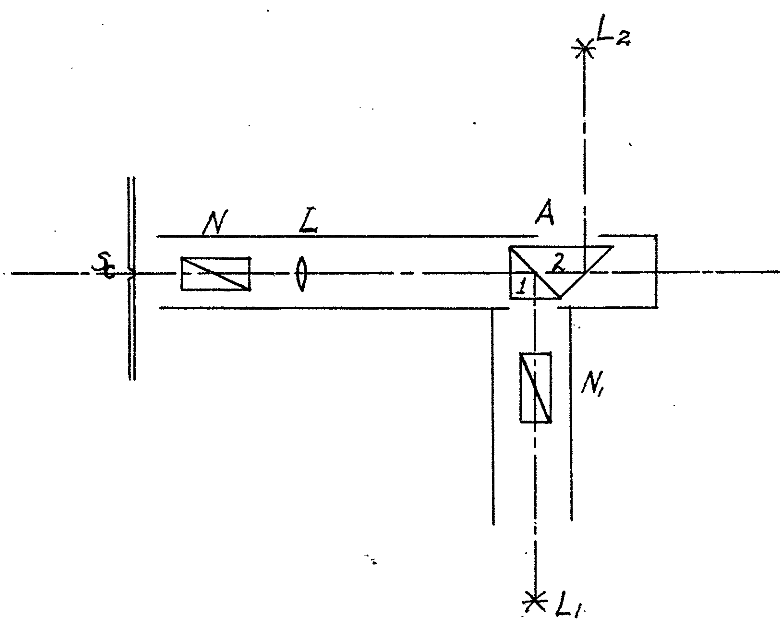


Fig. 1
Nutting's original polarization photometer
S_c - Collimator Slit. N, N_1 Nicol Prisms.
L - Lens, $A_{(1,2)}$ - Total reflection prisms.

brightness of the other.

In Crova's instrument (1883) the light in one half the field only is polarized. This is accomplished by means of two nicol prisms in series. The brightness is varied by rotating one.

Hüfner's spectrophotometer (1887) is similar to Crova's except that the nicols are separated, one being placed before part of the collimator slit so as to polarize one beam, the other is placed in the telescope. While both beams pass through the latter nicol its rotation will change the brightness only in the beam already polarized.

The König-Martens (1899) and Brace-Lemon (1914) spectrophotometers were monochromatic-field instruments employing polarization methods of varying brightness, and were well adapted to the measurement of relative energy distribution of light sources.

Non-polarization monochromatic-field spectrophotometers have been developed by Lummer and Brodhun in 1892, and Keuffel and Esser in 1923. Several others of this type were made, but of lesser importance. The Lummer-Brodhun instrument uses a unique cube to show the two sources in contrast. The cube is made up of two right prisms (Fig. 2a), having part of the contacting surface of one ground away. The brightness is varied by interposing a suitable clear glass plate before the cube. The field obtained by the use of this prism is of the type shown in Fig. (2) b,.

The spectrophotometer is widely used for measurement of relative radiant energy.

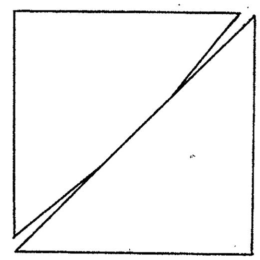


Fig. 2a Lummer-Brodhun Cube.

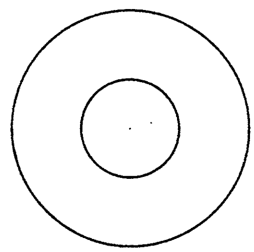


Fig. 2b Form of Comparison Field.

The Keuffel and Esser color analyser is designed for the measurement of the transmissive and reflective properties of materials. A variable sector is used to alter the brightness of one beam. A biprism is employed to give two fields for comparison.

There are at present several different types available commercially both in this country and abroad. These include the juxtaposed spectra instruments of Hüfner and Nutting ; the Martens photometer with spectrometer and polarization attachments; the monochromatic-field instruments of König-Martens, Lummer-Brodhun, and Brace-Lemon; and the Keuffel & Esser color analyser including spectrometer variable sector and illuminating sphere.

The instruments mentioned in this chapter can not be readily adapted to candlepower measurement. They are inherently limited, as mentioned before, to measurement of relative radiant energy in connection with the determination of transmission, absorption and reflection factors of materials.

CHAPTER III

GENERAL CONSIDERATIONS

Before the design could be definitely decided upon, it was necessary to make several preliminary tests. By using a prism and a single lens the spectrum obtained is larger and apparently better than when two lenses are used. When convergent light from the lens is passed through the prism, each component color is treated by the prism according to its refrangibility. There are, however, objections to allowing a convergent beam to fall upon a prism since the definition of the image of the slit is best only for that single color which passes symmetrically through the prism; that is, in such a way that the angle of incidence is equal to the angle of emergence, and the beam in the prism is parallel to the base. (Fig. 3).

It is therefore necessary, where best results are required, to use two lenses arranged in such a way that the beam between them is parallel. The lens nearest the slit is placed so that the divergent rays from the slit are rendered parallel in passing through. When the parallel beam falls upon the prism, the rays of each color pass in a parallel beam through the prism, and

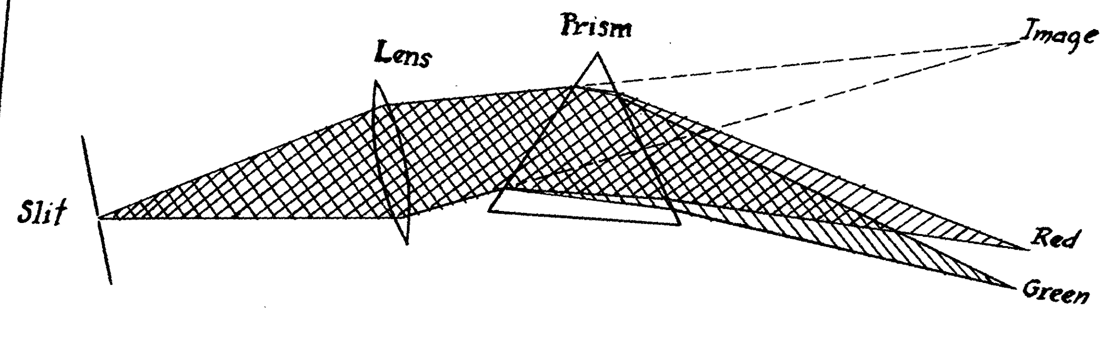

Prism
Image
Lens
Slit
Red
Green

Fig. 3a.

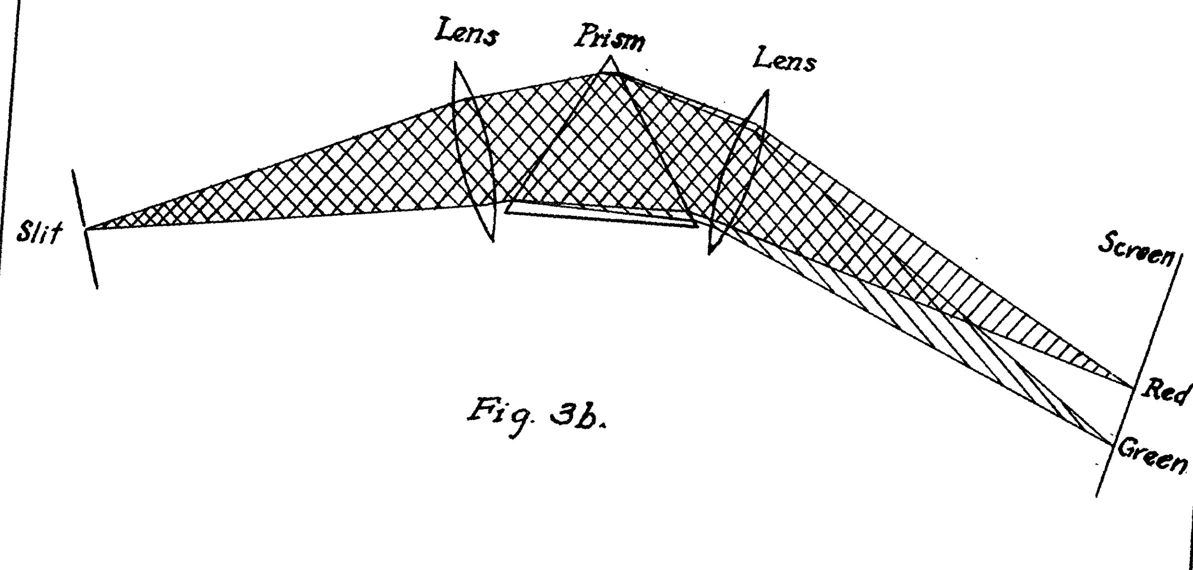

Lens
Prism
Lens
Slit
Screen
Red
Green

Fig. 3b.

emerge from it still a parallel beam, although each colored beam emerges at a slightly different angle. Each parallel beam falls upon the second lens and is thereby converted into a converging beam which converges on a focus and forms there an image of the slit. In this way the images for the colors are set side by side in the focal plane of the lens where they are thrown on a screen. With the refracting edge of the prism parallel to the slit, the images of the slit are parallel to each other and to the slit.

Unless care is taken in the choice of lenses, errors are sure to creep in for several reasons. When a pencil of white light is refracted through a lens it suffers dispersion just as in refraction through a prism. Thus if a pencil of light, (Fig. 4)

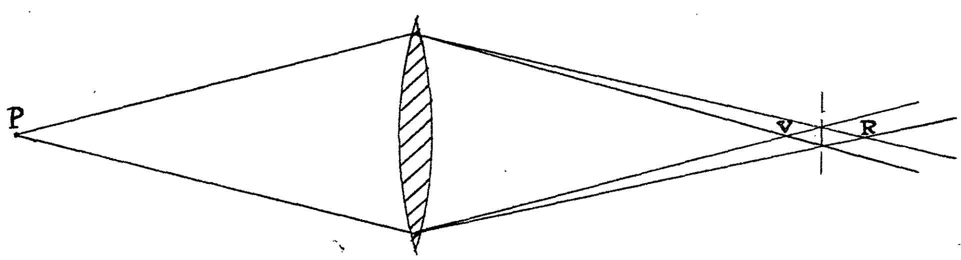


Fig. 4.

diverging from point P, be incident on the convex lens L, then the red rays, being the least refrangible, are brought to a focus at R; while the violet rays converge to a focus V nearer the lens. The orange, yellow, green, and blue rays converge to points intermediate between R and V, so that the image formed on a screen anywhere near R or V will be colored at its edges.

This effect of dispersion of light when refracted through a lens is called chromatic aberration, and was a great source of trouble in the construction of optical instruments until it was shown that deviation could be obtained without dispersion; that is, it was possible to make the rays converge to a focus without obtaining a colored image. This result, as in the case of prisms, is achieved by combining two lenses, a convex lens of crown glass, and a concave lens of smaller curvature made of flint glass. The possibility of constructing an achromatic lens depends upon the fact that the dispersive power of flint-glass is greater than that for crown-glass in proportion to the deviation produced.

Another error found in lenses is called spherical aberration. This is evident where the pencil of rays is not a small one, for after refraction, all the rays will not go accurately to one point, and those furthest from the axis will show the most deviation from the true focus. This defect may be remedied by the use of a stop, but at the loss of light. Spherical aberration is extremely complicated and depends on the relative curvatures of the two surfaces of the lens and upon the refractive index of the substances of which the lens is made. Spherical aberration can be compensated by following certain steps, but the lens designer must still work very largely by trial because of the infinite number of possible combinations of differently shaped lenses, of different kinds of glass with different distances between surfaces.

Media usually employed for prisms are: Carbon disulphide, glass, quartz, Iceland spar, fluorite, sylvin and rock-salt. Of these, glass is, of course, the most common, owing to its cheapness and also the great variety in dispersive power which may be obtained.

Quartz, Iceland spar, and fluorite are used on account of their great transparency to the ultra-violet rays. Rock-salt and sylvin are useful for their transparency to the infra-red portion of the spectrum. Carbon bisulphide has a very high dispersive power, but is very inconvenient owing to its being a liquid. Whenever used it must be enclosed in a hollow prism, which must be kept well closed on account of the great volatility of the liquid.

Generally speaking, glass is the best material to use for prisms. The advantage of glass lies in its cheapness and its toughness.

It is always found that the spectrum lines as seen in a prism spectrum are curved, with the convex sides turned toward the red end. This is due to the fact that only the rays from the center of the slit pass through a principal plane of the prism. By a principal plane is meant a plane perpendicular to the plane of the refracting edge of the prism. In order that the deviation be a minimum, two conditions must be satisfied: first, that the rays pass through a principal plane, and second, that the angles of incidence and emergence be equal. The collimator lens is only able to render parallel the rays it receives from the center of the slit, and therefore these rays only traverse principal planes of the prism; the rays from the other portions of the slit thus do not traverse a principal plane, and therefore suffer a greater amount of deviation, an amount which increases the further from the center of the slit the rays start. Therefore, the closer the slit approaches a line, the straighter the spectrum lines become, and also the more well-defined the lines become.

When the kind of glass to be used for the prism has been chosen, the resolving power of a spectroscope depends only on what may be called the effective length of the base of the prism or prisms, and not on the way in which the base is arranged. (Base, as used above, refers to the base of one prism or the effective base of a series of prisms). When a beam of light passes through a prism the "effective base of the prism" is the difference in thickness of glass traversed by the two rays which form the extreme flanks of the beam. This principle, first pointed out by Lord Rayleigh, should be used when wishing to push a spectroscope to the the limit of its power. From this fact it is seen that the results are the same whether one large prism is used (Fig. 5) or several small ones, (Fig. 6) so long as the total length of the base is the same.

The multiple prism spectroscope is used where a direct vision, portable and rigid instrument is required. They are also used where an instrument of high dispersive power is required, yet only small prisms are available.

Since it was intended that a photoelectric cell would be used in the spectrophotometer, it was deemed advisable to conduct a test of the photo-cell to determine the constancy of current readings from day to day.

The photoelectric cell was placed at one end of a long blackened box, and an incandescent lamp at the other end. To make the test more complete, it was decided to test the photoelectric response to different colors of light. To this end a box was built, just large enough to fit over the photo-cell. A hole was

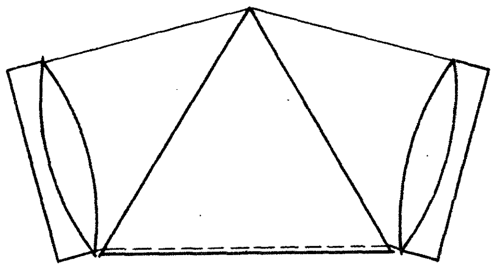


Fig. 5.

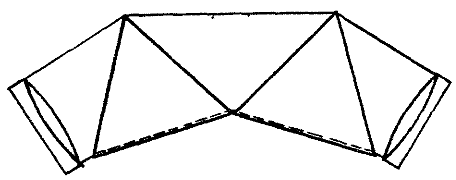


Fig. 6.

made in the side facing the incandescent lamp, and a frame was made about the hole to receive color filters. By this means the color of the light reaching the cell could be changed.

The voltage on the incandescent lamp was kept constant at 110^{v}, while the voltage on the photo-cell was kept constant at 170^{v}. The photoelectric current was measured by a galvanometer. Tests were made on two different photo-cells, a General Electric cell and a Westinghouse cell. The readings of current obtained from the Westinghouse cell were very much smaller than those from the General Electric cell, and only the results obtained from the latter cell are given. (Table 1)

Date of Readings	Galvanometer Deflection (Cm.)			
	Light Filters Used			
	#8*	#25	#50	#62
March 8	9.60	6.70	1.90	2.80
March 10	9.75	6.90	1.70	2.60
March 11	9.45	6.70	1.67	2.50
March 13	9.50	6.70	1.67	2.50
March 14	9.50	6.70	1.65	2.50
March 20	9.50	6.70	1.65	2.50

Table 1 - Showing Constancy of Photoelectric Response

The erratic readings of March 8, 10 and 11 are due to the fact that the box over the cell was removed each day in order to test both cells. When the box was

*Wratten Filters --Made by Eastman Kodak Co.

replaced over the cell it was given a slightly different position with respect to the cell, which resulted in erratic readings. After the third day the Westinghouse cell was eliminated from the test, and the box was left stationary about the G. E. cell. Constant readings were obtained thereafter, which justifies the use of a photo-cell in the spectrophotometer.

The information set forth in this chapter was later found to be of considerable assistance not only in the design, but also in setting up and adjusting the optical system of the spectrophotometer.

CHAPTER IV

DESIGN

The spectrophometers described in Chapter II are not well adapted for candlepower measurement. It would be necessary to balance each band of color against the corresponding color of the standard. This method is indeed highly accurate, but for practical purposes the time required to make such measurements would be excessive. It is therefore intended (a) that the instrument to be built shall give an instantaneous reading of candle-power of an accuracy comparable to that obtainable on the bar photometer, and (b) that the operation of the instrument shall be as foolproof as possible. With this in mind, the design was worked out so that only one adjustment is necessary, that being the adjustment of the potentiometer used to balance the bridge amplifier.

As in all spectrophotometers there is a light dispersing system, and a photometric system. The light dispersing system is composed of a collimator, to render parallel the rays from the sourse; a prism, to disperse the parallel rays into their respective colors, and a condensing lens to produce an image of the slit for each color. At the focal plane of the condensing lens a template is placed, and behind the template a photoelectric cell. The shape of the template is such that the light which passes through will cause a current to flow which is proportional to the candlepower of the source. The photoelectric current is then passed through a Wynn-Williams bridge amplifier circuit which is balanced while the cell is dark. When light falls upon the cell, the balance is disturbed causing an unbalance current to flow in the meter which may be calibrated to read directly in candlepower.

In the following paragraphs a more detailed account is given of the design features of the instrument. Figures and dimensions are given in the chapter devoted to construction of the instrument.

THE SLIT

The slit is formed between two metal jaws which move in parallel grooves. This plan is adopted to insure the parallelism of the slit opening. The grooves are screwed to a back plate in which a hole is bored to admit light to the slit.

The edges of the jaws are bevelled with the bevelled edges away from the light source. The reasons for this are first, because it is very much easier in this way to obtain edges which are true, and second, because if the edges were not bevelled but cut square, a certain quantity of light would be reflected from these edges tending to produce fuzziness in the spectrum lines. A very ingenious suggestion came from Crookes (1895) in the way of quartz jaws. These jaws are cut the same way as metal jaws, and therefore the edges form prisms which refract away all the light which falls upon them. They have the advantage of being able to take a finer edge than metal jaws, and are capable of giving better definition.

The back plate and grooves are of brass, while the movable jaws are of steel. Steel was chosen rather than brass since the bevelled edges of the jaws are extremely delicate and very easily damaged.

THE LENSES

Compound lenses are used in order to correct for chromatic aberration. Each lens is two inches in diameter and has a focal length of ten inches. They are equivalent to lenses of larger diameter, which are stopped down to reduce spherical aberration. The collimating lens is placed at a distance from the slit equal to its focal length. The diverging rays from the slit are therefore rendered parallel in passing through the lens. The parallel rays pass through the prism and on emerging are passed through the condensing lens. This lens receives the parallel rays of each color and forms a converging beam which is brought to focus at the template.

THE PRISM

An equilateral glass prism is used to disperse the light. Glass is employed because it transmits all of the visible portion of the spectrum and also because of its cheapness. The prism is placed between the collimating and condensing lenses, at the angle of minimum deviation of the yellow sodium line.

THE TEMPLATE

The template is employed so that the response of the response of the photoelectric cell to the incident light will be comparable to the response of the human eye. The shape will depend on two things; first, the manner in which the photoelectric cell responds to each unit of energy radiated by the source at the different wavelengths, and second, on the visual response curve of the human eye. To get the curve of photoelectric current versus wavelength it is necessary to make a second slit and place it at the focal plane of the condensing lens. This slit is mounted on a screw and can be moved horizontally by means of a knob. In this way the slit can be moved along the spectrum thus allowing any color to fall on the photoelectric cell. By making the slit very narrow the energy falling on the cell can be limited to a very narrow band of wavelengths.

The curve of radiant energy versus wavelength of the calibrating lamp must also be obtained. This is given for a black body by Planck's formula:

$$E = \frac{C_1}{\lambda^5} \frac{1}{\epsilon^{\frac{C_2}{\lambda T}} - 1} \text{ watts/cm}^2\text{/micron}$$

$C_1 = 37,200$

$C_2 = 14,330$

λ = wavelength in microns.

T = temperature in degrees Kelvin.

A tungsten filament radiates in a manner very nearly the same as a black body, but with approximately one-half the energy. Multiplying Planck's formula by e_T, we get the radiation formula for tungsten.

The quantity e_T is known as the spectral emissivity of tungsten and is approximately equal to 0.50.

Taking the curve of photoelectric current vs. wavelength and dividing each ordinate by the corresponding ordinate of the radiation curve, a resulting curve is obtained of current per unit of radiant energy against wavelength.

If the template were made from this curve, the photo-cell stationed directly in the path of the light passing through the template would give a current which would depend on the energy distribution of the source. However, this current would not be a true measure of the candlepower of the lamp as seen by the eye. Photo-cells usually have their point of maximum sensitivity at a wavelength other than that at which the eye is most sensitive. In order to make the photo-cell respond in a manner comparable to the response of the human eye, it is necessary to apply the visual response curve of the eye to the template. Therefore, the final shape of the template is determined of three curves, the response curve of the photo-cell, the radiation curve of the source and the response curve of the human eye.

THE AMPLIFIER

As a result of the small quantity of light available, the photoelectric current is likewise very small, and must be amplified in order to get a current which will be readable on a micro-ammeter.

A bridge amplifier is used in which equal resistances are placed in two arms of the bridge, and a vacuum tube in each of the other arms. The bridge can be balanced by altering the grid bias on one of the tubes. The photoelectric current is passed through a resistance in the grid circuit, thus causing the bridge to go out of balance, and causing an unbalance current to go through the meter. The unbalance current is directly proportional to the amount of change in the grid potential and is therefore a measure of the current from the photoelectric cell, which in turn is a measure of the candlepower of the lamp being tested.

The scale of the meter indicating the unbalance current can be calibrated directly in candlepower, by noting the deflection due to several different standard lamps.

Calibrating the meter in this manner takes account of absorption and scattering of light by the optical system. It also takes into account the relation existing between grid potential and unbalance current.

CHAPTER V

CONSTRUCTION

The construction progressed in a series of steps, many of which were entirely independent of others. The steps or separate assemblies were:

(1) Construction of the slit which is placed before the light source.

(2) Mounting the prism and lenses in their proper positions with respect to the slit, and to each other.

(3) Construction of the movable slit for use in calibrating the instrument.

(4) Setting up the photo-electric cell back of the movable slit.

(5) Construction of amplifier unit to amplify the photo-electric currents.

(6) Construction of the template.

THE SLIT

The back plate is made of 1/8" flat brass stock 6" x 8". A 3/4" hole is drilled 5 7/8" from the bottom allowing light from the test lamp to pass through the slit. Each of the jaws of the slit are of 1/8" steel 1" wide and 2 1/2" long. These jaws are set in brass

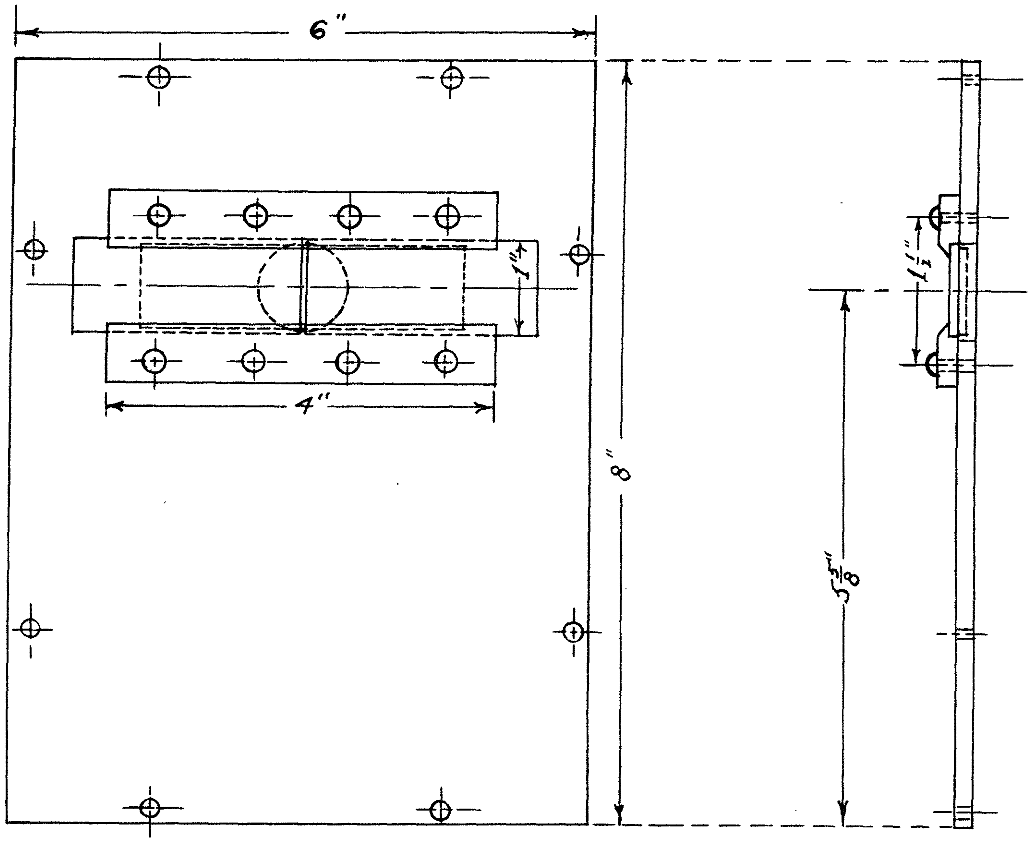


Fig 7. Collimator Slit Mounted on Brass Back-plate
One-half full size.

grooves which are bolted on to the back plate. Fig. (7) The edges of the jaws are bevelled at 45 degree angles, with the bevelled edges away from the light source. The edges are ground and lapped to parallelism in order that the image of the slit be straight and well defined. A slot 3 1/2" long, 7/8" wide, and 1/16" deep, is milled just back of the jaws to allow for inserting a thin metal strip for adjusting the length of the slit. This strip was made such that the slit was 5/8" long.

The test lamp is inserted in a socket which is mounted back of the slit.

PRISM AND LENSES

The lenses used are plano-convex and are corrected for chromatic aberration. They are 2" in diameter and are mounted in wooden frames as shown in Fig. (8). The focal length of each lens was determined by allowing the rays from a distant arc light (parallel rays) to pass through the lens and then measuring the distance from the base to the focal plane, at which distance the arc lamp was sharply focused. The focal length of the lens depends on which side is facing the distant object. This is due to the unsymmetrical nature of a compound lens.

The collimating lens was found to have a focal length of 8 3/8" measured to base of mounting, when the convex face was towards the arc lamp, and 8 5/8" when the other face was towards the lamp. The condensing lens was found to have corresponding focal lengths of 8 1/2" and 8 3/4" respectively. Since the center of the slit was about 5 7/8" above the base board, it was necessary to set the bases and prism on a platform 3 1/2" above the base, so that the center line of the lenses would be exactly in a line with the center of the slit.

The first lens is placed parallel to and 8 3/8" from the back plate on which the slit is mounted. The lens is held in this position by screwing the base firmly to the platform.

The refracting edge of the prism is 1 3/4" long (Fig. 9) and in order that the prism be lined up properly with the lens it is necessary to set it upon a block which is securely fastened to the platform. The prism is held fast by means of a set screw which screws down on the top. A flat metal triangle covered with black velvet is placed between the screw and the prism to distribute the pressure over the top. The second lens is set in the path of the rays leaving the prism. The rays of each color are parallel, but the rays of different colors have a slight angular displacement. The exact position for the lens is determined by taking a white card and placing it in that position which gives the smallest pattern. This amounts to placing the lens

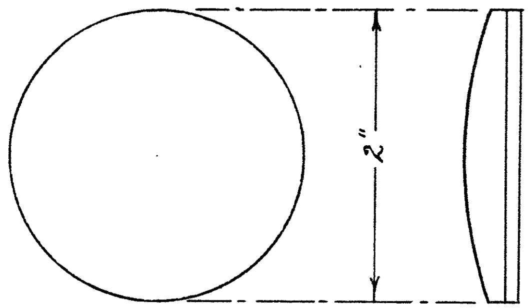


Fig. 8(a) Lens before being mounted.

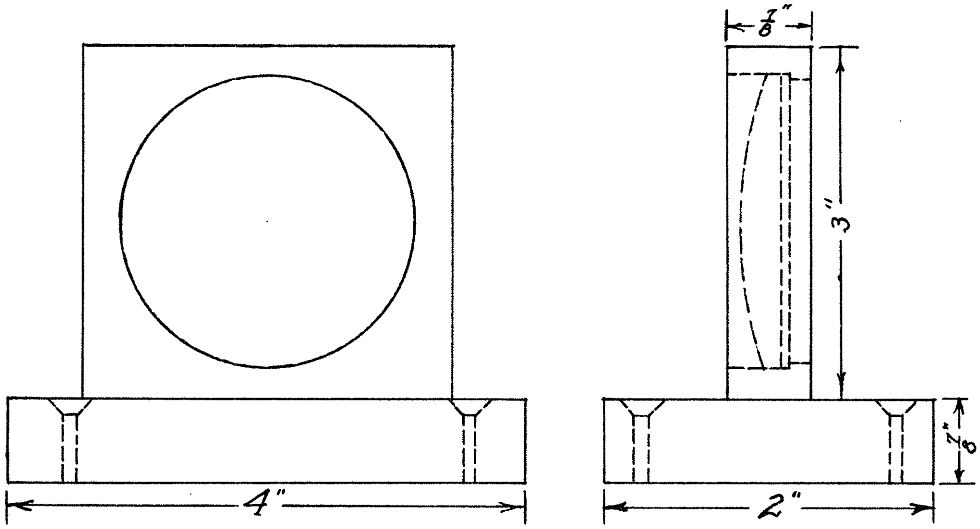


Fig. 8(b) Lens in wooden frame.

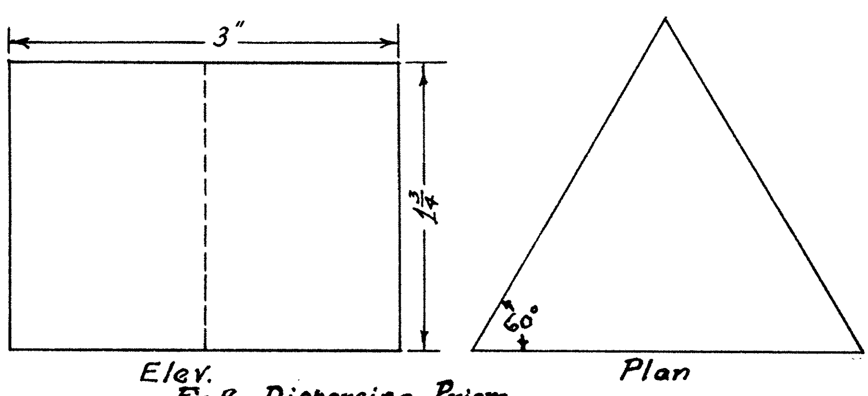


Fig. 9 Dispersing Prism.

as near perpendicular to all rays as is possible. At the focal distance of this lens the screen is placed Fig. (18). The spectrum was thrown on a white screen while the optical system was being adjusted.

ADJUSTMENT OF THE PRISM

The prism is turned about a vertical axis until the light from the collimating lens falls upon the first polished surface with such an angle of incidence that the light emerges from the second polished surface with an angle of emergence about equal to the angle of incidence. Now by turning the prism slightly about the vertical axis, the spectrum will move to one side or other. When in turning the prism the spectrum moves to a position from which with further turning it appears to turn back and move in the opposite direction, the prism is said to pass through the position of minimum deviation. However, since there are many rays of different refrangibilities passing through the prism, each with a different angle of minimum deviation, it is necessary to set the prism for a color near the center of the spectrum. A color very commonly used is the yellow sodium line, which occupies a prominent position in the spectrum and for which the adjustment can be made with the greatest simplicity.

The apparatus is now set up to produce a continuous spectrum which can be focused on a screen

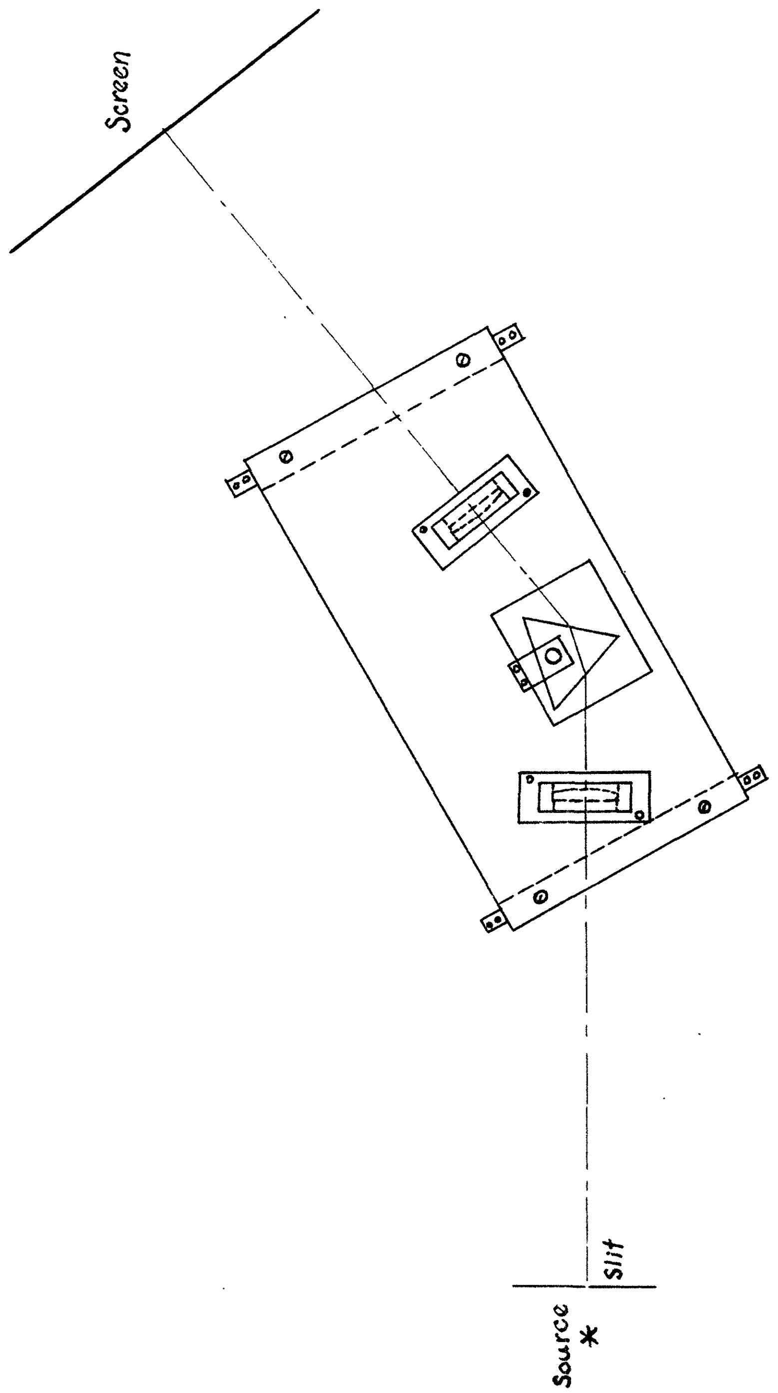


Fig. 10 OPTICAL LAYOUT

located 8 1/2" from the second lens. The next step is to make the template. As stated in a previous chapter the curve of the template represents the photoelectric current per unit of energy of the calibration lamp against wavelength, each wavelength ordinate being corrected by the corresponding visibility factor of the eye.

It is therefore necessary to obtain two curves, one of energy radiated by the calibration lamp against wavelength, and second, of photoelectric current against wavelength of the energy from the calibration lamp. The first curve may be calculated from Planck's equation, the temperature used being that of the filament of an ordinary 100 watt, 115 volt incandescent lamp. This size of lamp is operated at 2755°Kelvin. However, due to possible deviation from this temperature, curves are also plotted for 15° above and below 2755°K. The curves are shown in Fig. 11. The three curves are made pass through a common point at 5600 Å, and the other points at each wavelength are averaged. This is done to get the average slope of the energy distribution curve at a temperature near 2755°. The result is shown in Fig. 12. The second curve is obtained by allowing a small band of wavelengths to pass through the movable slit and fall on the photoelectric cell. By moving the slit along

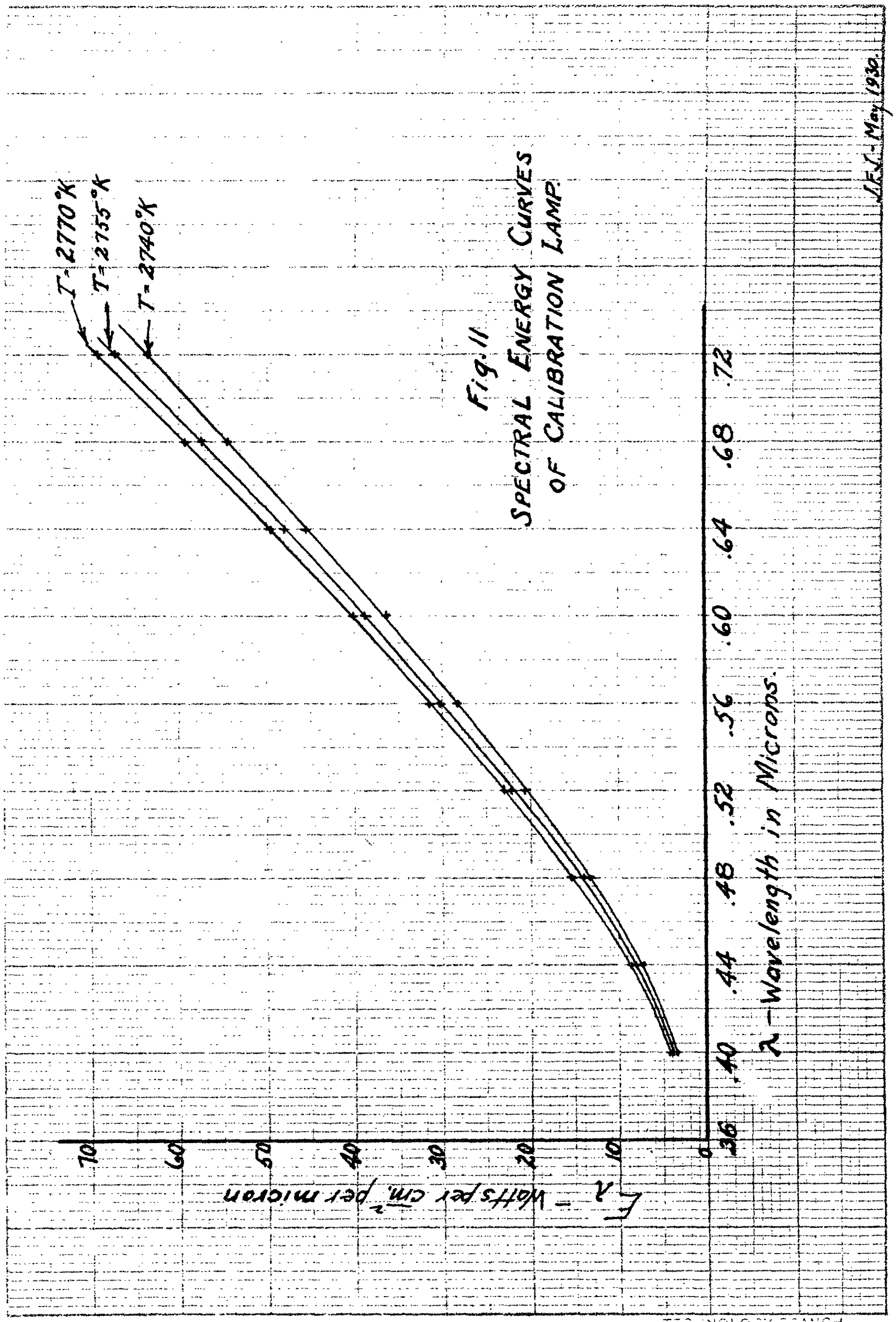


Fig. 11
SPECTRAL ENERGY CURVES
OF CALIBRATION LAMP.

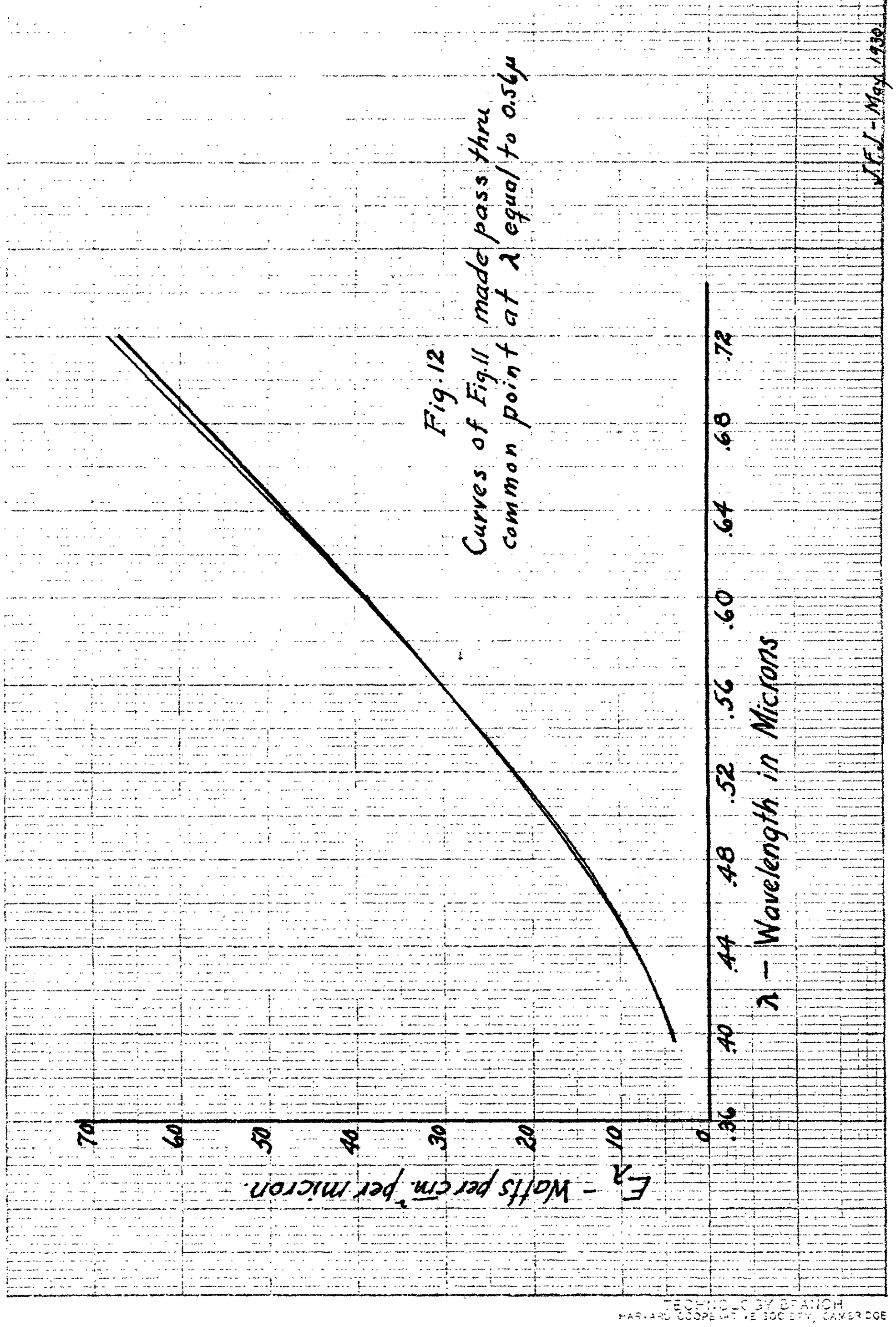
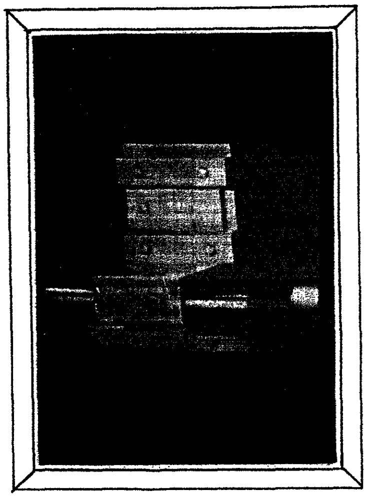


Fig. 12
Curves of Fig. 11 made pass thru common point at λ equal to 0.56μ

the spectrum a curve is obtained of photoelectric response versus wavelengths. The photoelectric current must be amplified in order to get a current large enough to be readable on a micro-ammeter.

The movable slit is shown on Plate I and is mounted on a screw which turns in a brass base. The base is made of 1/4" stock, 2 1/2" x 6". The end pieces are 1" high, in each of which three holes are drilled, a 1/2" hole for the screw and 2 1/4" holes for the rods to guide the movable block. The block is built up of brass, since it was very difficult to machine a solid block so that it would fit snugly on the screw. The back plate supporting the jaws of the slit is screwed to the block. The movable jaws, as on the collimator slit, move in grooves which are screwed to the back plate. One of the jaws is held by a screw, and adjustments are made by moving the other jaw.

The height of the center of the slit is 2 5/16" above the base, so that a platform is required to raise the center of the slit, to the center of the collimator slit. There is a graduated scale on the base and a pointer to indicate the position of the slit. Each division represents 1/20", so that when the knob is turned through 360° the pointer moves over one division. The knob has 100 divisions on its circumference, each



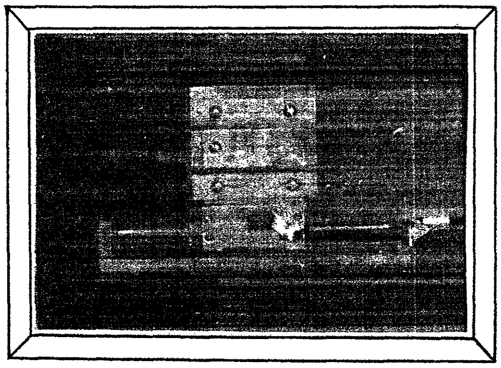


Plate I   Two views of movable slit.

division representing .0005" horizontal motion of the slit.

The curve obtained is shown in Fig. 13 and is given as photoelectric current versus position of slit on graduated scale. The visibility curve of the human eye is given in Fig. 14 . Combining the three curves as explained earlier, the curve of the template is obtained. (Fig. 15.)

The template is made from a strip of aluminum 1" wide, 2 1/2" long, and 1/16" thick. The curve is plotted on the aluminum and the area under the curve removed. Small holes were first drilled, the remainder being filed away. The maximum ordinate of the curve was reduced to 15/32", in order that the area would be well within the upper and lower boundary lines of the spectrum.

By locating on the template the yellow sodium line, it is then easy to locate the template in its proper position in the spectrum. Since the jaws of the movable slit are 1/8" thick, the template is backed up by another similar aluminum strip which is cut away in back of the template opening. The two strips are pinned together and placed in the position of the steel jaws of the movable slit. The template is bolted in place after it is adjusted with the aid of the sodium line.

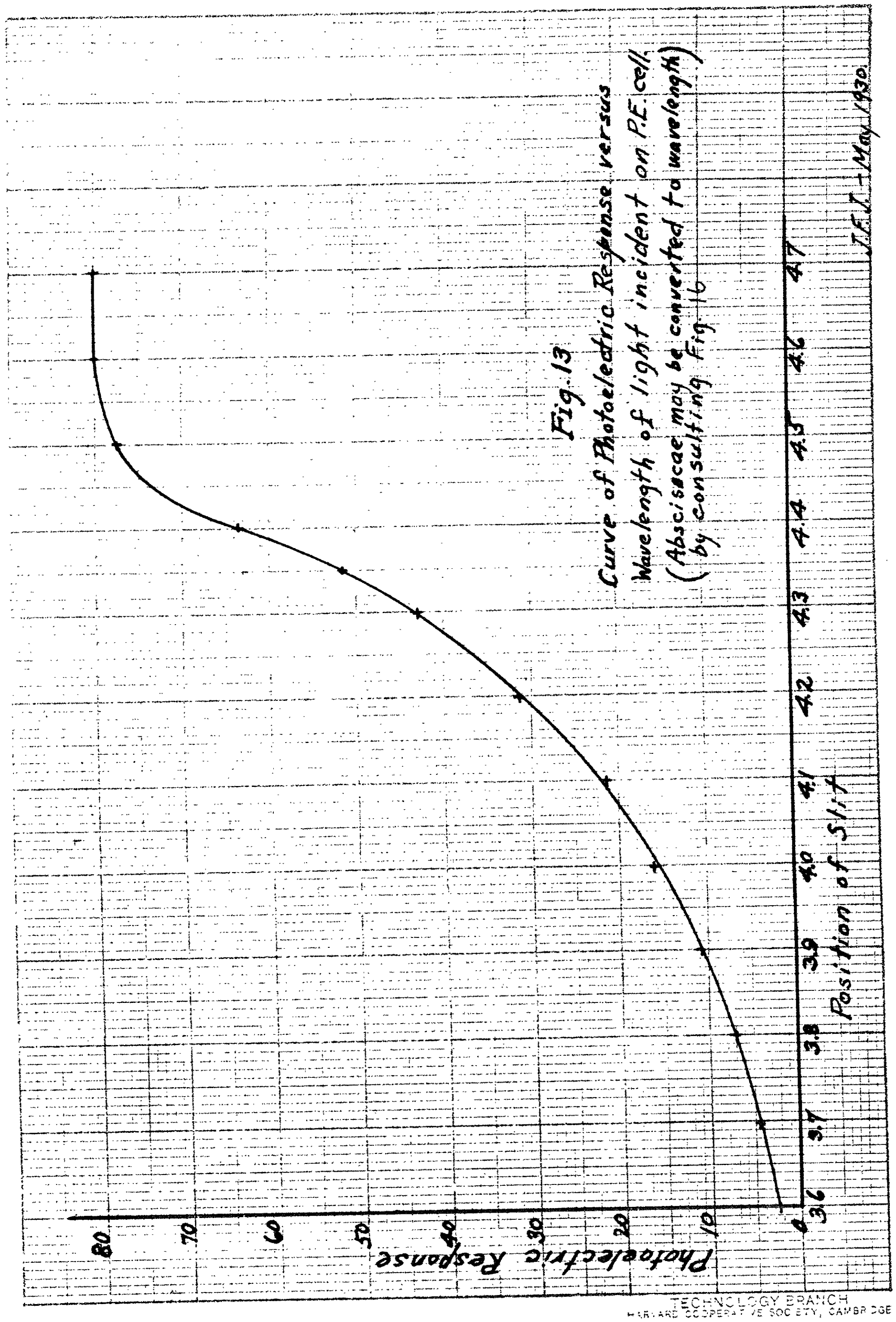


Fig. 13
Curve of Photoelectric Response versus Wavelength of light incident on P.E. cell
(Abscissae may be converted to wavelength by consulting Fig. 16)
May 1930
Position of Slit
3.6
3.7
3.8
3.9
4.0
4.1
4.2
4.3
4.4
4.5
4.6
4.7
Photoelectric Response
0
10
20
30
40
50
60
70
80

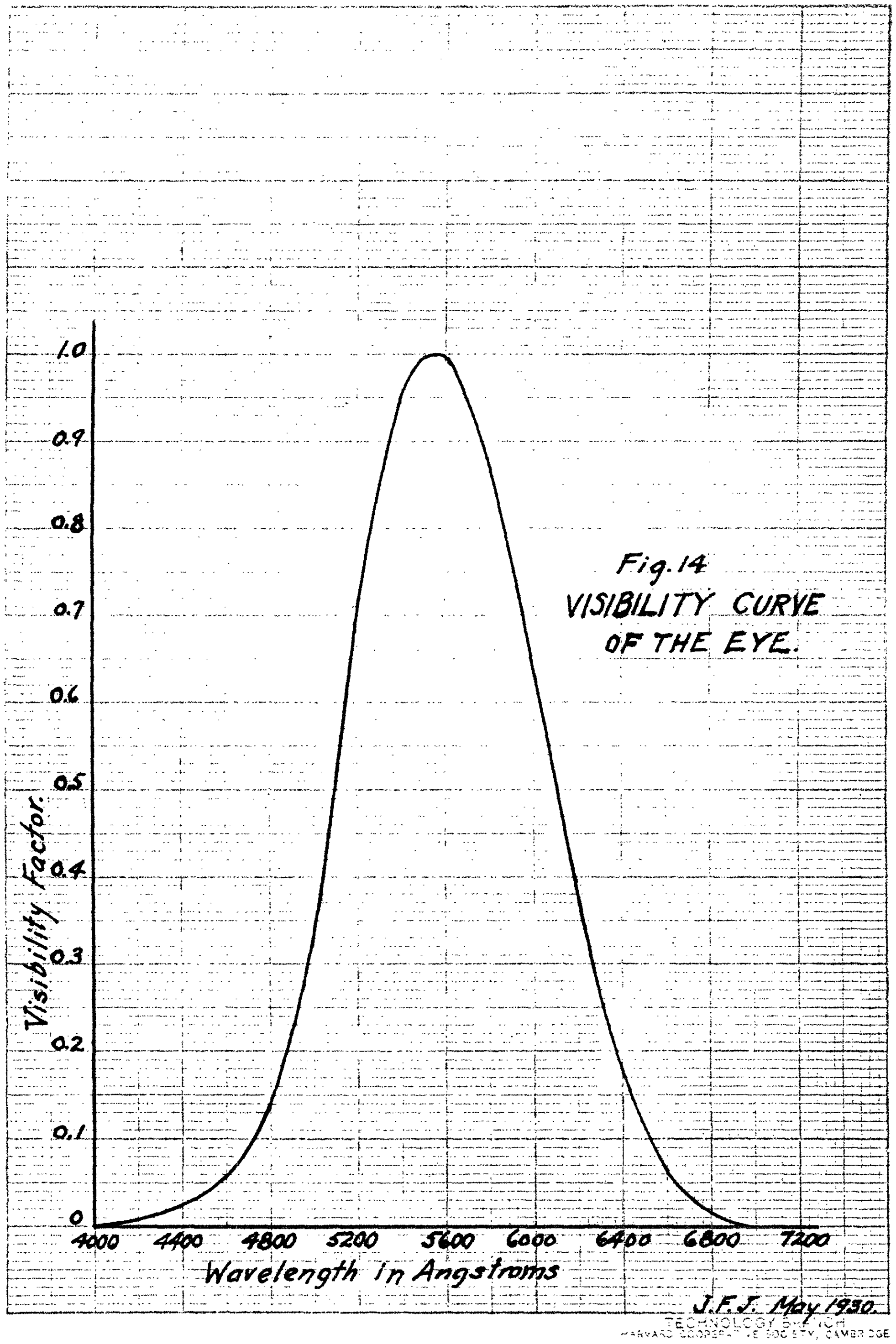


Fig. 14
VISIBILITY CURVE
OF THE EYE.

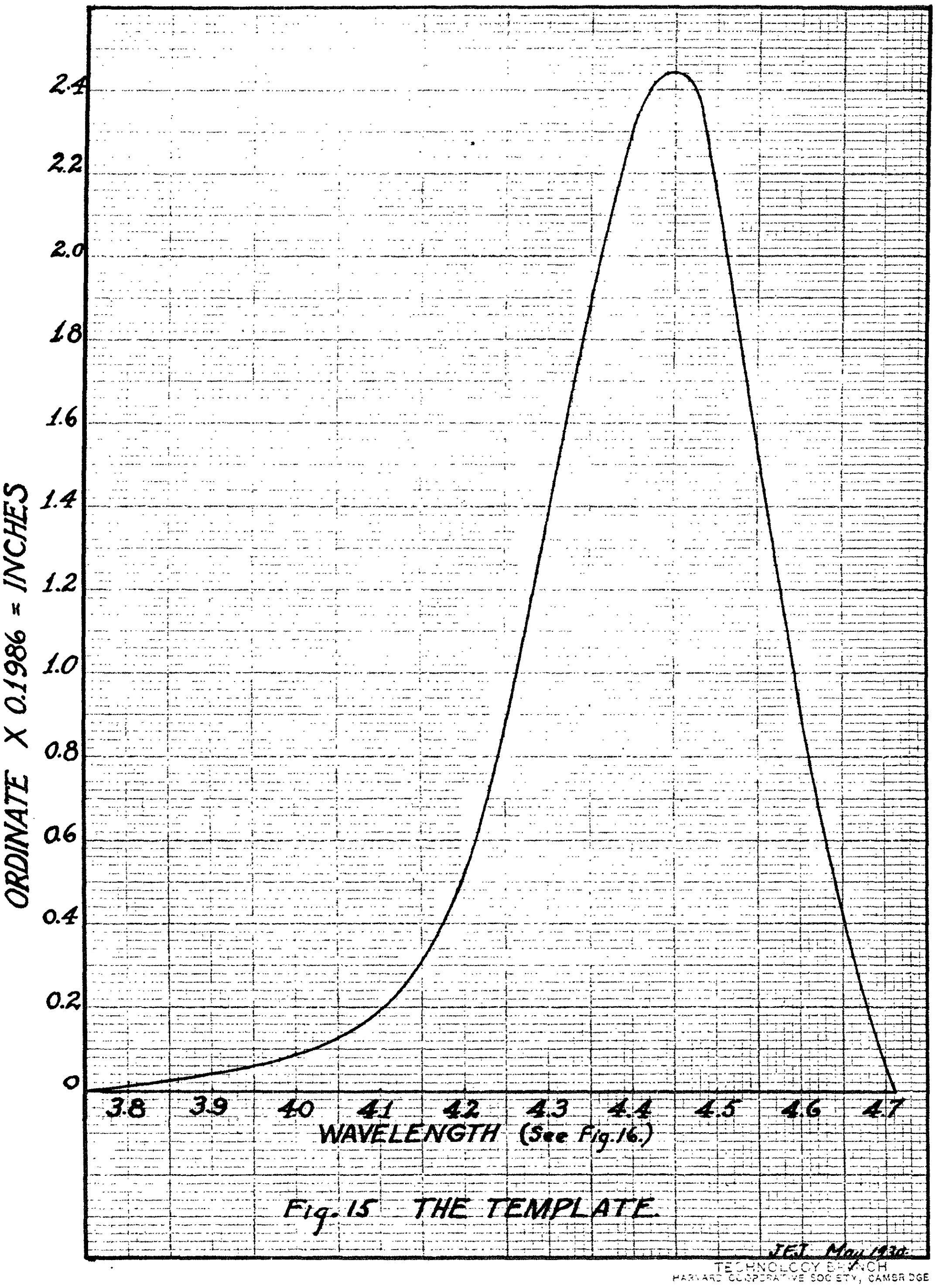


Fig. 15 THE TEMPLATE.

In order to know the wavelength corresponding to a given setting of the slit, it was necessary to calibrate the graduated scale on the base. This was accomplished by means of a mercury lamp, a hydrogen tube, and the yellow sodium line obtained by inserting common salt in the flame of an alcohol lamp.

The mercury lamp gave four very distinct lines and one which was much fainter. These lines were well spread out but did not include the red portion of the

Color	Wavelength (Å)
Yellow	5780
Yellow-Green	5461
Faint Green	4916
Blue-Violet	4358
Violet	4065

Table 2. Lines of mercury arc spectrum.

spectrum. (Table 2.) The hydrogen tube provided the necessary line in the red portion of the spectrum. A high-voltage transformer was used to excite the tube, and a line was obtained having a wavelength of 6563Å. From these points a curve was obtained of position of slit versus wavelength which is shown in Fig. 16.

The yellow sodium line (5890Å) was found to fall very conveniently on the curve. This line, owing to the ease with which it can be obtained, was employed

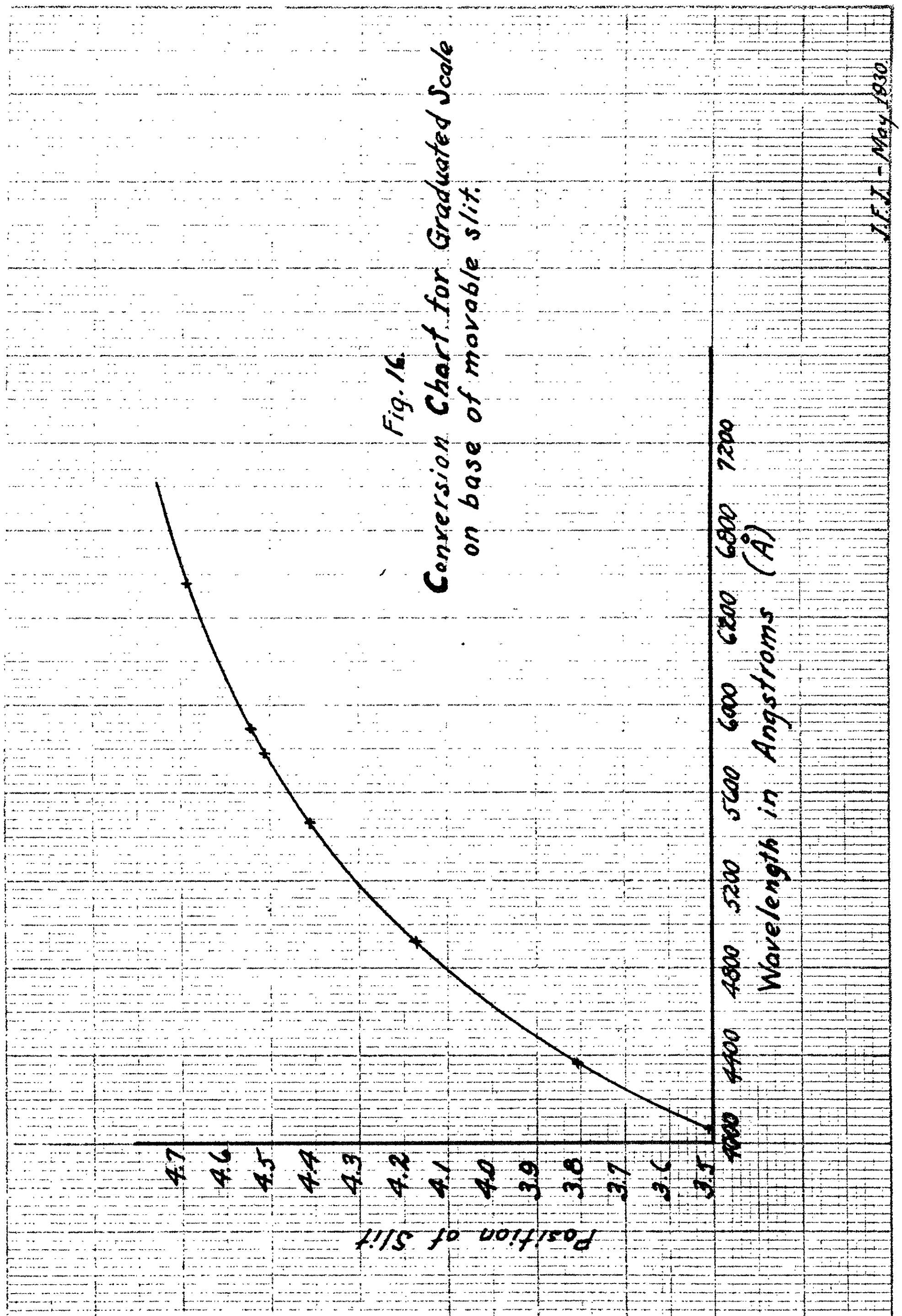


Fig. 16
Conversion Chart for Graduated Scale on base of movable slit.

especially to locate the template in place, a mark having been made on the template corresponding to 5890Å.

A small amount of backlash was found to exist between the screw and the moving block. To eliminate errors from this source, readings were made only on clockwise rotation of the graduated knob, after the backlash was taken up.

THE AMPLIFIER

A diagram of the bridge amplifier used is given in Fig. 17. Two 10,000 obm resistances are employed in the upper arms of the bridge, and two Cunningham C-324 screen grid tubes are used in the other arms. A B-battery of 157 volts is employed as the source of current. When operating normally, with a plate current of 4 mils, there are approximately 120 volts on the plate of each tube. The tubes are heater--type tubes and are rated at 1.75 amperes filament current. The screen grids are rated at 75 volts. In the grid circuit six 10-megohm resistances are placed in series with the grid bias. The photoelectric cell is placed between the control grid and the junction of the 10,000 ohm resistances. A potentiometer is placed across the grid voltage in order to adjust the grid potential of one tube.

When the photoelectric cell is dark, it acts as an open circuit, but when exposed to light it conducts, thus altering the grid potential of the left hand tube. The balance of the bridge is obtained by varying the grid potential across the right hand tube by means of the potentiometer.

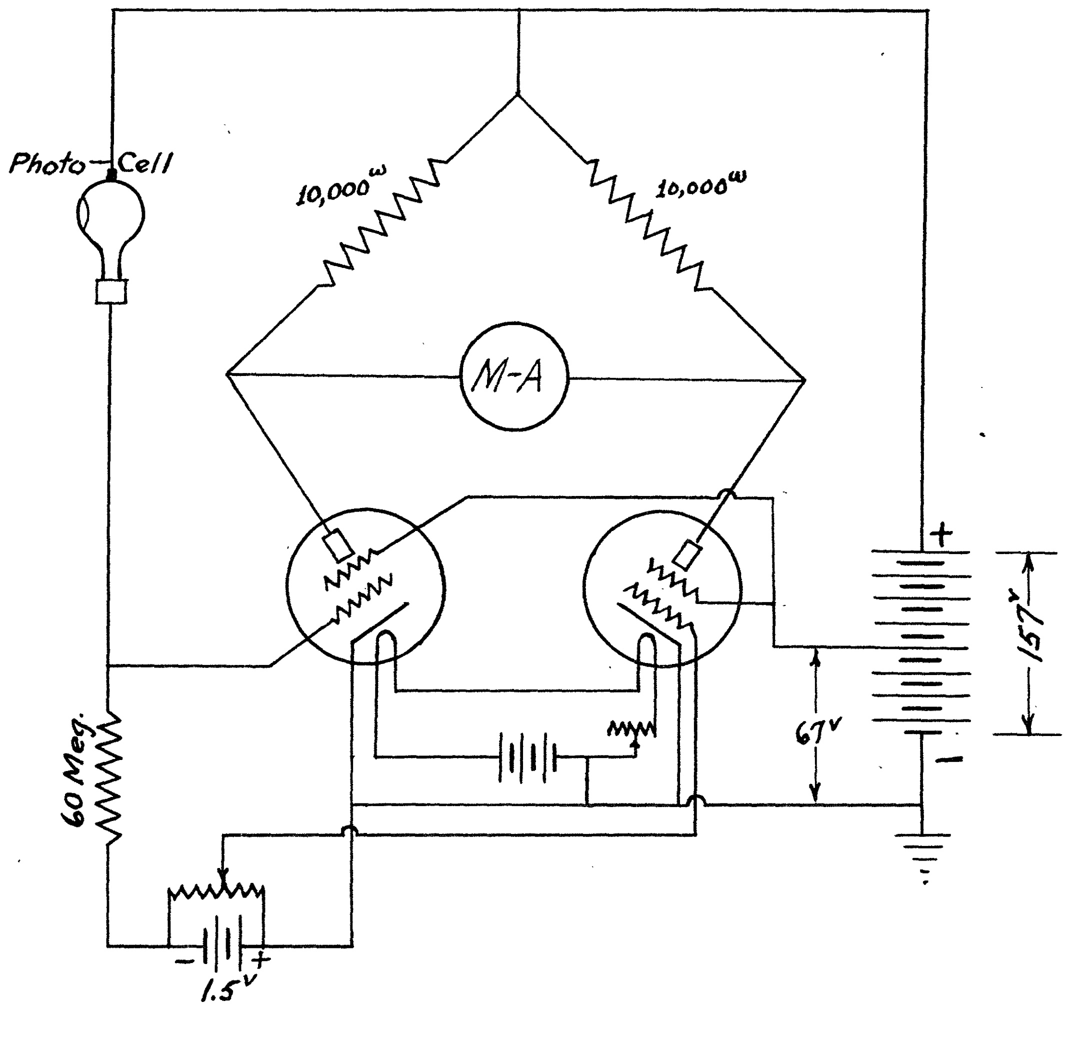


Fig.17 BRIDGE AMPLIFIER.

CHAPTER VI

CALIBRATION and OPERATION

The calibration of the instrument is very simply made. By means of the bar photometer, the candlepower of several lamps were compared with a standard lamp. Before calibration the bridge is brought to balance while the photoelectric cell is dark. By inserting each lamp in turn in the socket back of the slit, and noting the deflection of the needle, the scale is calibrated to read directly in candlepower. The calibration curve obtained is shown in Fig. 18.

As explained before, the operation of the instrument consists merely of first balancing the bridge with the photoelectric cell dark, and then closing the switch on the unknown lamp. From the deflection of the meter the candlepower of the unknown lamp can be read from the calibration chart.

In Plate II a view is given of the optical system with the cover of the instrument removed. Baffles are used within the cover to absorb scattered and reflected light.

Plate III shows both the optical system and the bridge amplifier

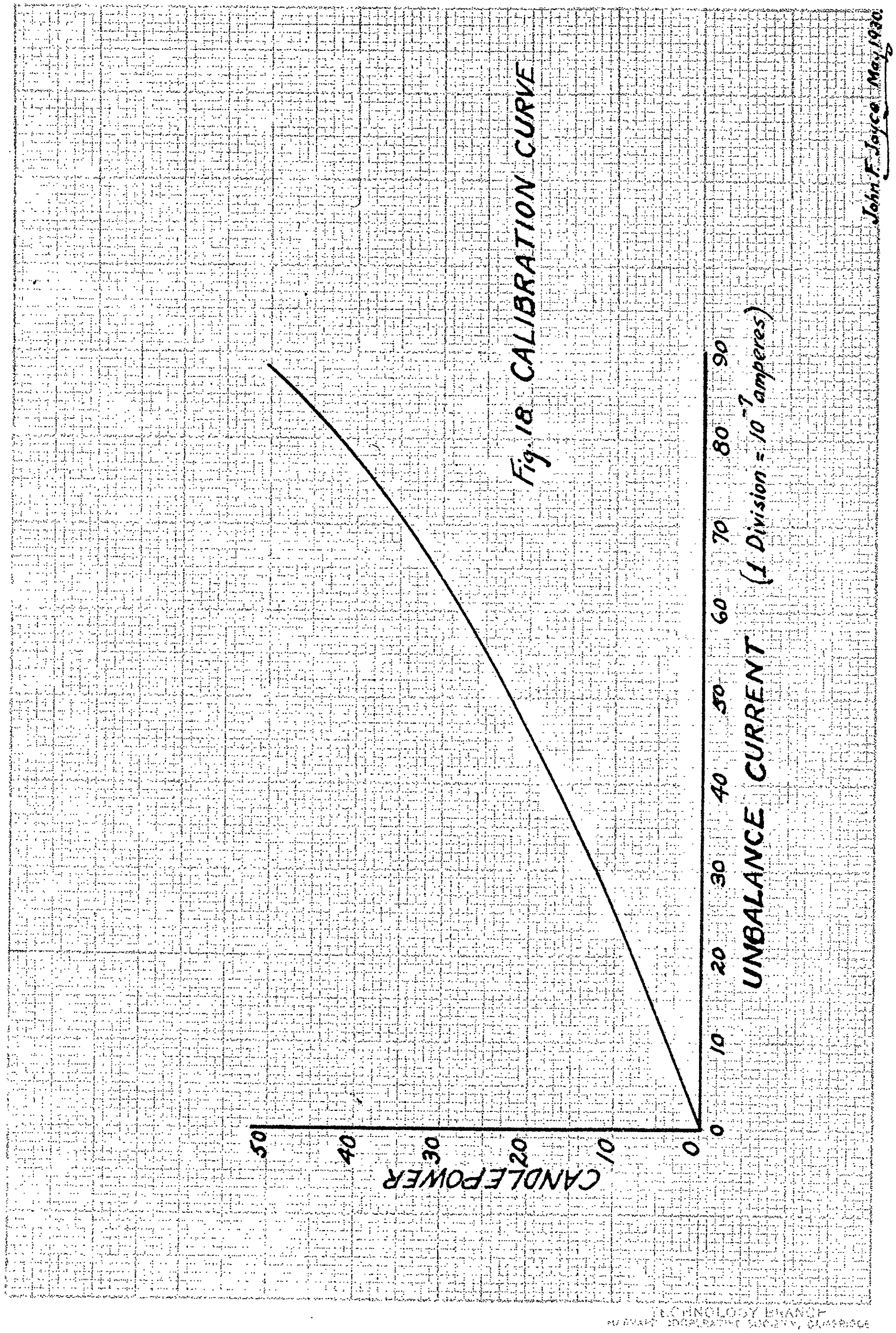


Fig. 18 CALIBRATION CURVE

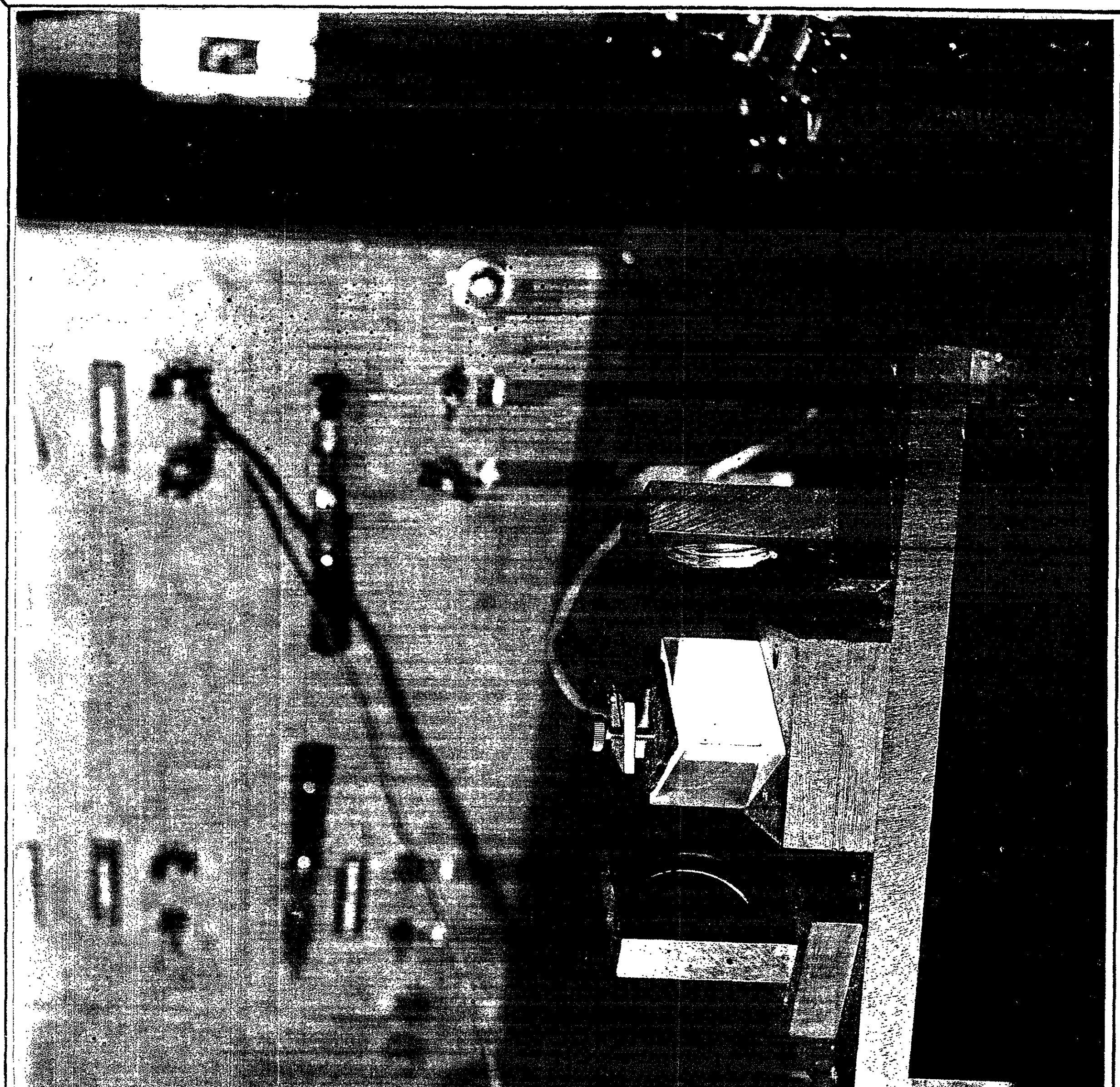


PLATE II

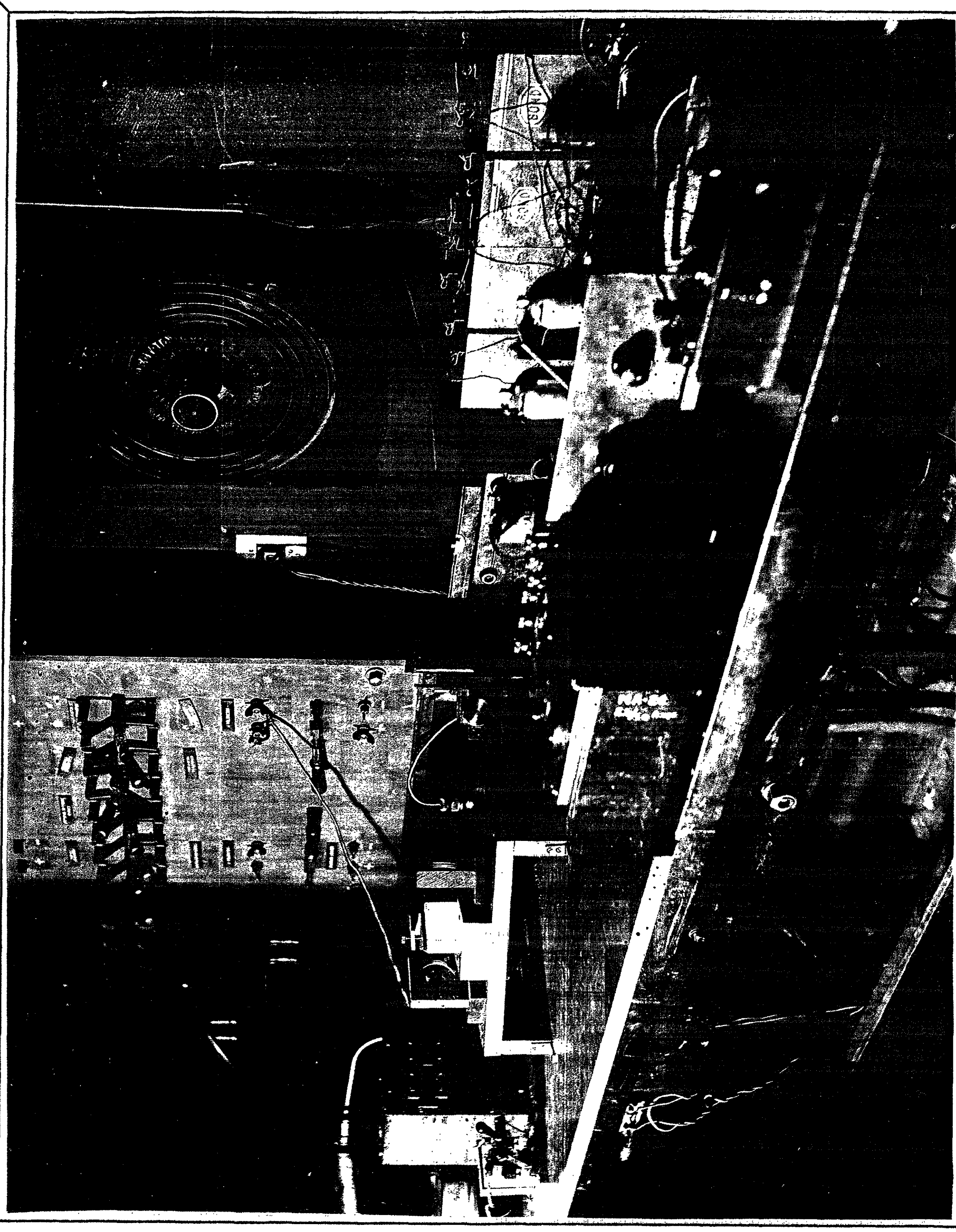


PLATE III

CHAPTER VII

CONCLUSIONS and RECOMMENDATIONS

The instrument as completed will give a reading proportional to candlepower for that size of lamp for which the meter is calibrated. If a lamp having the same candlepower but a larger globe was to be measured, a smaller reading would be obtained due to the fact that the larger globe would cause a decrease in brightness per unit area of the globe. The larger globe would tend to produce a larger reading since the globe would be nearer to the slit. These difficulties could easily be remedied by mounting the socket on a rack which would allow moving the socket away from the slit by an amount sufficient to make the brightness of the slit equal to that made by the smaller lamp.

However, since colored lamps are usually made in 25 and 50 watt sizes, only one additional socket position would be necessary.

To make the instrument more versatile, socket adjustments might be determined for the more common sizes of ordinary incandescent lamps. Further study could profitably be made in determining the brightness of the slit, the quantity of light reaching the photocell, and the sensitivity of the amplifier.

It was hoped that the above would be determined in this thesis, but it was not possible in the time available.

BIBLIOGRAPHY

Nichols, J. -- Manual of Applied Physics. Vol. II

Wood, R. --Physical Optics --1911

Robertson, J. K. -- Introduction to Physical Optics-1929

Newall, H. F. -- The Spectroscope- 1910

Baly, E. C. C. -- Spectroscopy-1912

Gibson, K. S. -- Photoelectric Spectrophotometry
Bur. of Standards Scientific Papers 349 1919

Keuffel, C. W. -- A Direct Reading Spectrophotometer
J. O. S. A. 11, 1925 p403

Taylor, L. -- A Comparison of Three Spectrophotometric
Methods. J. O. S. A. 14 1927 p332.

Report on Spectrophotometry
J. O. S. A. 10, 1925 p169.
J. O. S. A. 11, 1925 p357.