THE ROTATING SECTOR DISK AS USED IN AN OPTICAL PYROMETER

by

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I. INTRODUCTION

The rotating sector disk when used in place of a filter to reduce the intensity of a beam of light seems to have the advantage of reducing the intensities of all wavelengths present in the beam by the same fraction. However, this apparent advantage is offset to some extent by certain peculiarities that have not all been satisfactorily explained heretofore. The object of this investigation is to establish the causes of some of these peculiar effects.

As these effects cannot be stated in detail without having clearly in mind the construction, adjustments, and calibration of an optical pyrometer, this thesis contains first a description of the particular laboratory form of the Holborn-Kurlbaum optical pyrometer constructed for this investigation. This is followed by a statement of the particular problems investigated, and finally by the solutions found. Since the complete calibration of optical pyrometers has not been summarized in the literature, such a summary is included in connection with the description of the instrument.

II. THE HOLBORN-KURLBAUM OPTICAL PYROMETER

A. Description of the Instrument as Built

The essential parts of a Holborn-Kurlbaum optical pyrometer are shown in Fig. 1. The source or "background", A, and the pyrometer filament D are at conjugate foci of the highly corrected lens B. The image of the source and the pyrometer filament are viewed simultaneously by an eyepiece or telescope F. The current through the pyrometer filament is varied until the filament disappears against the image of the source, when a "brightness match" is said to exist. The appearance of the field with the pyrometer filament current too low correct, and too high is shown in Fig. 3. This figure also includes a view of a particularly sensitive criterion for establishing the brightness match.

At brightness match, the temperature of the background can be expressed in terms of the temperature of the pyrometer filament, but in order to do this the pyrometer filament must be calibrated and the instrument itself must be made somewhat more complicated.

To prevent injury to the eye, the intensity at the eye is reduced, usually by red glass filters. Since a pyrometer filament cannot be operated at high current values and maintain its calibration for a reasonable period of use, some sort of a device must be inserted between the background and the filament to reduce the intensity of the radiation from the background by a known factor. This device may be either a filter or a rotating sector disk.

A photograph of the pyrometer built is reproduced in Fig. 6. Reference letters in the following description all pertain to Fig. 1.

The sources used included a carbon arc, an iron arc, a sodium vapor lamp, and several flat or ribbon filament tungsten lamps. Most of the work was done with the latter. The ribbon was mounted in a vacuum, was approximately 3 cm long and 0.15 cm wide, and was operated at from 8 to 24 amperes furnished by a 24 volt storage battery.

The objective lens, B, was a Bausch and Lomb Zeiss Tessar of 22 cm focal length, provided with an iris diaphragm and mounted in a board that served also as a light shield. The diameter of the diaphragm could be varied from 5 to 40.5 mm. The diaphragm represented diagrammatically at C. A test of the lens by the Hartmann method (See Appendix) showed the spherical aberration curve to be practically a vertical line up to full aperture, F 4.5.

The pyrometer lamps used at D were all vacuum tungsten lamps provided with spherical bulbs of selected glass. The filaments were 0.025 mm in diameter and were provided with a U bend at the center to enable all measurements to be made at the same part of the filament. The pyrometer lamp was mounted on a pair of crossed micrometer slides;

provision was also made for vertical adjustment. The longitudinal motion necessary in focusing was controlled from the observing position.

The telescope F that served as an eyepiece magnifier was an ordinary reading telescope with a rack and pinion focusing device. It gave a somewhat sharper image when the objective was slightly reduced by the diaphragm E. The two diaphragms C and E give definite values to angles α and β. β must of course always be less than α, for if α should be made smaller than β, C and not E would be the limiting diaphragm. The effect of varying α will be discussed later.

On account of the high brightness of the eyepiece image, a filter of some sort must be supplied. The eyepiece filter, G, used throughout the experiments consisted of either one or two pieces, each 5.2 mm thick, of Corning high transmission red glass. This glass has a very sharp cut-off at 6240 A and transmits out to 7600 A. Its effective wavelength is 6596 A for the temperature interval used in the experiments, namely 1300°K to 2400°K.

For use as a filter, red has several advantages over other colors. When dealing with comparatively low temperature sources, red is the first color to become visible. Red does not fatigue the eye as rapidly as some other colors do. Red glass can be made that holds its transmission more nearly constant as the temperature of the glass rises due to the radiation it absorbs. Red glass can be made of more nearly monochromatic transmission. This is important as it is a great aid in making accurate brightness matches to have no color difference even though the background and the pyrometer filament differ 1000° or more in temperature. For a given change in wavelength the color change in the red is less perceptible than in some other parts of the spectrum. For use with a sector disk, as will be discussed later, red has the additional advantage of permitting a larger transmission through the disk due to decreased diffraction.

The photograph, Fig. 6, shows that the optical bench on which the pyrometer is mounted is of exceptionally heavy construction. This was found necessary in order to prevent vibrations. The stand consists of 3 inch iron pipe electrically welded. The bench proper is a piece of 6 inch channel iron 7/16 inch thick and 9 feet long. It is bolted unsymmetrically to the stand. The stand is separated from the concrete floor by hair felt an inch thick after compression. All standards that carry the pyrometer parts such as lens, lamp and telescope are made of 1.25 inch cold rolled steel rod.

To eliminate stray light an elaborate set of screens with different sized circular openings was made of plywood and painted black. It was soon found that these screens, due to their flexibility, caused vibrations of the pyrometer filament when struck by air currents made by the rotating sector disk. They were therefore replaced by the device shown in Fig. 6, consisting of three sections of heavy cardboard tubing, 5 inches in diameter, provided with numerous internal diaphragms having graded circular openings, all painted black with lampblack moistened with shellac.

As already mentioned, a rotating sector disk may be used to reduce the intensity of the background so that it will not be too bright for the eye. To allow for different background brightnesses, several disks with different openings were prepared. Each was made from an aluminum phonograph record, by cutting (generally) two radial openings, diametrically opposite each other. The edges of these openings were provided with safety razor blades held securely in place by pins and machine screws. Since the disks must be used at high speed, dynamic balance is important. It was found that a more accurate balance could be obtained by weighing the parts before assembly rather than by balancing the finished disk. For large sector openings, two equal disks, not furnished with razor blades, were used; by rotating one disk with respect to the other, and clamping, any desired opening could be obtained from zero to 12°.

The speed of the disks must be such that no flicker is observable even with the smallest sector openings; with two one degree slits this was found to be 2800 RPM. For a single one degree opening the speed of course had to be doubled.

Considerable time was spent in developing a suitable motor. Because it was available, a 3500 RPM quarter horse power induction motor was first tried. This happened to be the critical speed of some of the disks and therefore caused excessive vibration.

In the routine use of the pyrometer, a direct current motor is to be preferred because it makes possible any slight change of speed that may be necessary to avoid a critical period for a particular sector. Most of the disks had critical vibration speeds between 3000 RPM and 3600 RPM. For some of the measurements that were found to be necessary, a very constant speed was needed. Hence a 3600 RPM 3 phase quarter horse power synchronous motor was tried. This was made from an ordinary squirrel cage induction motor by rewinding the stator for two poles, 3 phase, and constructing a two pole slip ring rotor. It was brought into synchronism by means of an auxiliary direct current motor.

Speeds in the neighborhood of 6000 RPM, for a single small opening, were obtained by belting a one horse power direct current motor to the shaft carrying the disk. The round belt had a carefully glued joint and ran in grooved pulleys semi-circular in section.

To avoid vibrations, and also to facilitate changing the position of the disk in the beam, the rotating sector was carried on a separate massive stand made from an old barber chair base. This was found very handy as it permitted convenient adjustment of the height. The motor was bolted to a horizontal iron plate welded to a vertical six inch pipe carried by the base. The stand rested upon a layer of hairfelt one inch thick.

B. Auxiliary Apparatus

All direct current for the background and pyrometer filaments was furnished by storage batteries. When alternating current arcs were used, the voltage was reduced by transformers; line fluctuations were avoided by working late at night.

The current through the background was read by use of a precision Siemens and Halske Electrodynamometer type ammeter, range 0-25 amperes, the pointer being observed through a telescope.

The pyrometer filament current was determined by a potentiometer; as a precaution against appreciable changes in the value of the standard resistance or in the connections due to temperature variation, an ammeter was kept in the circuit. For comfort and speed in taking readings, the potentiometer should have no greater sensitivity than is necessary to determine accurately the minimum detectable change of current when matching the pyrometer filament and the background.

The flat filament lamp generally used as background did not have a uniform temperature throughout its length due to the usual end losses. All measurements were made on light from the central portion of the filament, care being taken to view the same small area throughout any series of readings. One of the lamps was provided with a minute notch in the edge of the filament to indicate this area.

Since the observer must be shielded from the background light and since with a constant current through the background filament its brightness is constant, precautions must be taken to have no reflected radiation returning to the filament and thus increasing its temperature. The walls and ceiling of the room were covered with corrugated paper which was painted black and then sprinkled with additional lamp black.

C. Adjustment of Apparatus

Good alignment of the area of the background used, the image of the background, the pyrometer filament, and the telescope is essential for high sensitivity. These parts are set approximately at the same height above the optical bench. With the objective lens and the pyrometer lamp removed, the cross hairs of the telescope are brought over the image of the desired area on the background. After again placing the pyrometer lamp in approximate position, it is moved about until the middle of its filament (usually indicated by a U dent) is in the line of sight.

Finally the objective lens is replaced, and its aperture reduced to a minimum. By moving nothing but this lens, the image of the notch of the background filament is brought into the center of the field and into line with the pyrometer filament and the cross hairs.

All of the parts are now in line; certain of them must yet be moved along the optical bench to bring them into focus when viewed through the telescope. With the lens diaphragm at its maximum opening, a sight is taken through the telescope and the pyrometer lamp is moved to and fro longitudinally until its filament and the image of the source are both in sharp focus for the same setting of the eyepiece. There must of course be no parallax between the pyrometer filament and the image of the notch of the background.

If this longitudinal adjustment has raised or lowered the pyrometer filament with respect to the notch in the background filament, the correction is made by moving the pyrometer lamp. If the entire length of the pyrometer filament that overlaps the background cannot be brought to the same color as the background, the pyrometer filament is not perpendicular to the line of sight and can be made so by a combination of a rotation about a vertical axis and a slight lateral shift. A slight apparent bending of the pyrometer filament as the eye is moved up or down in front of the eyepiece is sometimes noticed with pyrometer filaments mounted in small bulbs. This is due to a lens action of the bulb. The best that can be done is to have the pyrometer filament perpendicular to the background filament for the normal position of the eye. A pyrometer lamp that is to be calibrated and removed from the optical bench for future use should have a bulb sufficiently large not to show this effect.

It may be mentioned that the pyrometer lamp bulb often causes one or more images of the filament. These are less noticeable if the bulb is large. If the images interfere with making settings, they may be shielded out. In the final form of the apparatus this is easily done by inserting a slide in a slot cut in the shielding tube. Such a slide must remain in place permanently as the calibration curve of the instrument will be changed if it is moved.

D. Criteria for Matching

As has been indicated in making temperature measurements of the background, the current through the pyrometer filament is varied until it disappears against the background. When this condition has been obtained, a brightness match exists. The accuracy with which temperature can be measured depends upon the change in pyrometer filament current necessary to give a detectable departure from a brightness match. This in turn depends on the magnification of the eyepiece.

A magnification of 12 diameters is too low; it shows the pyrometer filament very small and uniform. A relatively large change in current is required to make it noticeably brighter or darker than the background. With a magnification that is too high, black or bright lines run along the edge of the filament and make it very difficult to judge when the equality of brightness exists. These lines will be discussed later.

An eyepiece having the proper magnification for maximum sensitivity shows a brightness match between the center line of the background and the pyrometer filament when the latter appears too dark near the edges of the background. See Fig. 3. This condition is due to the temperature gradient of the pyrometer filament.

Usually the accuracy required in making temperature measurements is not such as to necessitate maximum sensitivity. In view of this and the fact that fatigue of the observer must be considered, an eyepiece of such magnification as to give a match across the entire width of the background is used in commercial pyrometers and in ordinary laboratory work.

For a given eyepiece the condition of maximum sensitivity can be obtained by choosing the proper distance between the background filament and the objective lens (distance AB, Fig. 1). In any case this distance should be small enough so that the width of the background image is much larger than that of the pyrometer filament.

E. Calibration

Forsythe (9) states "To make a completely independent calibration of any pyrometer would be a great undertaking". This is obvious from the following brief considerations of the scientific background on which this type of temperature determination rests.

The pyrometer compares experimentally the brightnesses of two objects seen through the same red glass in the eyepiece of a telescope. Spectral brightness is a desirable quantity from which to compute temperature, since for certain wavelengths and temperatures, brightness varies several times as rapidly as temperature. For example, in the neighborhood of 2000°K, using an effective wavelength of 0.665μ the brightness varies more than ten times as rapidly as the temperature.

The light from the pyrometer lamp comes directly to the telescope whereas that from the background is reduced in intensity before it reaches the telescope by being passed through a filter or a sector disk. The problem is to determine the temperature of the background from the value of the pyrometer filament current.

Evidently, if the temperature of a body that can serve as a background is known for several different conditions, the pyrometer filament currents can be determined for these conditions, and a calibration curve giving the relation of temperature to filament current can be drawn. But this curve can be employed only when using the same filter or disk and when looking at a body that has the same spectral distribution of radiation as the original background.

There is only one type of body for which the spectral distribution of power radiated is known theoretically. That is the uniformly heated enclosure commonly called a blackbody. The blackbody can be conveniently held at particular temperatures represented by the melting points of metals, preferably non-oxidising metals.

The metals chosen are generally gold and palladium, whose melting points are taken as 1336°K and 1828°K respectively. The gold point has been established by measurements with a platinum resistance thermometer. The palladium point has been determined from the gold point and the radiation laws of the blackbody.

The power-temperature relation of a blackbody is most accurately expressed by Planck's equation:

$$J_\lambda = \frac{Ac_1\lambda^{-5}}{e^{c_2/\lambda T}-1}$$

where J_λ is the spectral radiant intensity, i.e. the power radiated per unit solid angle in a narrow region near the wavelength λ and is expressed in watts/steradian · cm; A is the total radiating area at temperature T°K, expressed in cm²; c_1 and c_2 are constants having the following values: $c_1 = 1.77 \times 10^{-12}$ watts cm²; $c_2 = 1.4320$ cm degrees. The constants c_1 and c_2 are determined by other means than temperature measurements.

If a blackbody background be held successively at the gold and the palladium points, the pyrometer filament current can be held constant and brightness matches for both points obtained by changing the sector openings. These sector openings will give the ratio $J_{\lambda An}/J_{\lambda Pd}$. But this ratio can be formed by applying Planck's law twice. The factors A and c_1 cancel out; c_2 is known; λ is the effective wavelength of the red glass; T, the Kelvin temperature, is known for the gold point and can therefore be computed for the palladium point. Other points can be determined in a similar manner, or can be computed from the law, and a so-called blackbody calibration curve can be drawn for the pyrometer filament. Lamps thus calibrated can be purchased; they must of course be used with the same kind of red glass with which they were calibrated.

The effective wavelength of a piece of glass is a very narrow wavelength interval for which the energy varies at the same rate with temperature as does the entire band transmitted by the glass. Since the eye is the comparison instrument, the visibility curve must be taken into account in determining the effective wavelength. Since the temperature of the glass rises due to the absorbed radiation, a glass is desired that will not change its effective wavelength with temperature.

Planck's law was mentioned in connection with the calibration computations. As a matter of fact, computations involving Planck's law are tedious. Labor can be saved without sacrificing accuracy in regions for which λT is less than 2000, by using Wien's law, which is older than Planck's and differs from it only in the omission of the term (-1) in the denominator. This equation is used in practically all optical pyrometry that does not involve temperatures above 2000°K.

In the present work, the background is not a blackbody but a tungsten filament. The use of the calibrated lamp therefore gives what is known as blackbody temperatures of the tungsten, that is the temperature of a blackbody that emits in the effective wavelength the same power that the tungsten does. To convert this into the true temperature of tungsten necessitates a comparison of the emission of a blackbody and of tungsten. This was done by Worthing (17) who used a hollow tungsten filament with needle holes in its surface; the radiation from the holes was blackbody radiation, which the surface of the filament gave tungsten radiation at the same temperature. There are only a few substances for which such studies have been made and for which true temperatures can be determined. The usual temperature obtained with an optical pyrometer is the blackbody temperature.

III. THE PROBLEM

Brightnesses at high temperatures cannot be accurately compared directly by the eye. It is necessary to reduce the intensity of the background beam by the use of sector disks or absorbing glasses. Glasses, as already mentioned, generally change their absorption characteristics with temperature, and when two or more are used at the same time, reflection troubles result. The transmission factor must be determined for each combination of filters in place, since it depends upon the direction of light through the glass and upon the relative order in which the absorbers are placed.

The sector disk has a constant transmission; however, it introduces other experimental difficulties, chief among which are strong air currents and diffraction effects. These diffraction effects were the immediate cause of undertaking the present investigation.

Certain discrepancies in measurements due to changing the position of the sector in the beam are mentioned by Forsythe (4) and by Forsythe and Worthing (18).

Quoting from Forsythe (4, p. 27)

> "If the rotating sector is used to cut down the apparent intensity of the background, care must be taken as to the location of the sector. There is a very marked difference in the results of temperature measurements, depending upon whether the sector is located near the objective lens or as near as possible to the pyrometer lamp. There is also a difference depending upon the relative

position of the openings in the sector and the source, providing the source is a lamp filament. If a sector of small transmission is mounted near the lens and so placed that the openings of the sector are parallel to the axis of the background filament when the sector is passing across the centre of the lens, the definition will be very bad, while if the openings of the sector are turned through 90° so that they are perpendicular to the axis of the filament, the definition will be quite good, but not so good as if the sector is located near the pyrometer lamp. When the rotating sector is located near the pyrometer lamp, the definition is good and practically independent of the position of the opening of the sector. If a very large source is used no such effect is noted. Using a pyrometer calibrated against such a large background and thus independent of the position of the sector to measure the brightness temperature of a small tungsten filament, large variations in temperature were found when different sectors were used near the objective lens. No such differences were found when the sector was located near the pyrometer filament."

Further, in attempting to determine the temperature of a certain tungsten lamp filament, first using an ordinary commercial Holborn-Kurlbaum pyrometer provided with absorbing glass filters and then a form with a rotating sector, Worthing and Forsythe found a discrepancy of about 40°K, the filament temperature being in the neighborhood of 2300°K. Since this difference was too great to ascribe to errors in measurement, the authors undertook the researches published in reference 18. They examine six possible causes of the discrepancy:

"1st. The lens and mirror actions of the pyrometer lamp bulb.
2d. The heating of the pyrometer filament by radiation from the background.
3d. The reflection into the eyepiece of light from the background at the edges of the pyrometer filament.

4th. A possible transmission by the pyrometer filament of light from the background incident on it.
5th. A possible change in the emissive properties of the pyrometer filament due to incident radiation from the background.
6th. The diffraction of light from the background at the edges of the pyrometer filament."

They eliminate all but the sixth, make the general statement that the disk should be placed as near the pyrometer filament as possible and state that: "This type of diffraction, in which the diffraction fringes are located in the plane of the diffracting edge, so far as the writers know has not been studied heretofore, seems to be an important type and to be well worth further study."

Worthing and Forsythe ascribe the entire effect, or difficulty, to this type of diffraction and do not study it beyond the point of finding out what to do about it in a practical way, namely to place the sector disk in a narrow part of the beam. In the present investigation a study is made of the general causes of this effect; several other experimental difficulties are traced to their sources, and optimum conditions are found governing the use of a filter and a disk in optical pyrometry.

IV. THE INVESTIGATION

A Striae

The first step in the experimental study of the problem was that of becoming thoroughly acquainted with all the effects due to changing the positions and sizes of the instrument parts shown in Fig. 1. Different backgrounds, auxiliary reflectors, lenses, slits, etc. were used as dictated by the progress of the experimentation. Unless otherwise indicated, the background was a ribbon filament tungsten lamp.

It was mentioned when describing the apparatus that vibrations, especially of the pyrometer filament, must be avoided. The critical speeds, at which a sector vibrates badly, do not permit brightness matches to be made even when the sector is near the pyrometer. Minute vibrations, too small to be noticed in the telescope, reduce the accuracy of setting; this point was studied by means of a microscope clamped to the bench of the optical pyrometer. Minute vibrations were found to cause dark lines along the edges of the pyrometer filament that look very much like diffraction fringes.

Accuracy of construction was noted by the fact that the direction of the rotation of the sector could be reversed without changing the reading of a brightness match. With the disk near the pyrometer lamp, any sector speed could be used that did not show flicker.

If sectors with slits varying from 1° to 5° are held stationary (non-rotating) in a horizontal position near C, Fig. 1, and a plaster of Paris screen is placed in the beam of light between D and E (from 8 to 12 inches from d) striae are observed on the screen. Their general appearance is shown in Fig. 7 (a). As the sector is gradually shifted toward the pyrometer lamp, the striae become less and less distinct until finally with the sector near D, Fig. 1, their appearance is as shown in Fig. 8. These striae are not caused by the pyrometer filament, for their appearance is the same for any position of the slit no matter whether the pyrometer filament is bright, dim, or non-luminous.

A slit of variable width was constructed and used in place of the slit in the sector disk. This slit was mounted so that it could be rotated about the axis of the light beam, and thus turned into the horizontal, vertical or any other angular position. Fig. 7 (b) shows the result when the slit is horizontal, i.e. perpendicular to the background filament. The striae do not change their appearance so long as the iris diaphragm at C, Fig. 1, is of either medium or large aperture. When the slit is made vertical, i.e. parallel to the background filament, and the diaphragm opening is large, the striae disappear, giving the image on the screen the appearance of Fig. 9.

Substituting a 1/16 inch sharp edged circular opening for the slit, striae are again formed on the screen as sown in Fig. 7 (c). If the slit is returned to its former position, very close to the circular hole, the appearance on the screen is not changed while the slit is given a complete turn.

With the slit in the horizontal position, the pyrometer lamp was replaced by several other lamps and also by spherical and cylindrical pieces of glass; in all cases the effect on the screen is similar to Fig. 7, but of course the widths and locations of the striae are not identical. No striae are observed when there is no bulb at D, Fig. 1, nor when a piece of plane glass occupies this position.

When two concentric cylinders are substituted for the pyrometer lamp, many more striae are produced; due to the form of the irregularities in the glass, a relative rotation of the cylinders often causes the striae to move up or down over the screen.

Between crossed Nicols the lamp bulbs and other glassware showed no strains.

The light passing through the slit is polarized to about the same extent as the light in Young's double slit experiment. This polarization probably contributes to the formation of striae. At least, when a stationary horizontal slit is illuminated by polarized light vibrating in the plane of the slit, the striae become noticeable more distinct.

Any hollow sphere through which light is passing shows internal reflections (similar to flare) and also acts as a divergent lens, Fig. 10. This divergence is shown experimentally by moving a small opaque shutter downward along the side of the bulb near the source. When this shutter covers only the top of the bulb, the bright section near the top in Fig. 7, is darkened, but above this region of the screen no change occurs. If the shutter is moved down on the other side of the bulb, the image is darkened from the top down.

Further, the thickness of the bulb is not uniform due to mould marks. These cause contiguous portions of the bulb to act alternately like convergent and divergent lenses. However, bulbs not blown in a mould sometimes give similar effects, but these are not so regular. To show the effect of ridges, some were made in a piece of flat glass, 1/16 inch thick, by heating it with a torch along parallel lines 1/8 inch apart and then pressing it in a direction at right angles to the lateral lines. Since the cylindrical ridges thus produced have a very short focal length, a long focus (1 meter) divergent lens was used in conjunction with the glass. The two together, when substituted for the lamp, showed striae very plainly.

The striae, therefore, are caused at least in part by irregularities in the glass of the pyrometer bulb. It is evident that a horizontally striated background is particularly bad for the purpose of making brightness matches between this background and a horizontal filament. The usual procedure is to reduce the magnification of the telescope until the striae are no longer visible.

One other experimental procedure will help, and that is to put the rotating sector disk near the pyrometer lamp. The light that forms the striae travels from the slit in layers or beams of unequal intensities, and these are separated still more by reflection and refraction at the uneven bulb. These effects are much less promounced when the slit is near the bulb because the parts of the beam that would produce striae have not yet become widely separated. They still overlap and hence do not produce marked striae. The telescope can therefore for this position of the disk be used with a somewhat higher magnification than when the disk is near the lens.

The fact that these component parts of the beam separate more and more as the distance from the sector increases make it evident that less light from the background enters the telescope when the slit is near the lens than when near the pyrometer filament. Consequently this explains, in part, why the pyrometer filament must be supplied with more current to produce a brightness match when the disk is near the filament than when near the objective lens.

The striae of course are not visible while the disk is in motion. It is a matter of common experience that it is much more difficult to make a brightness match when the disk is near the lens than when near the pyrometer lamp. It seems likely that this difficulty is due to the greater unevenness of the beam when the slit is far from the pyrometer lamp.

B. Diffraction at a Moving Slit

The question arose as to whether the diffraction pattern given by a moving slit at the speeds used may not be different from that at a stationary slit. No theoretical reason could be advanced, and no effect was found. However, as the special apparatus developed was used again in another part of this investigation, it will be described here. It is evident that no diffraction effects due to a moving object can be detected with a steady source. The source must be intermittent so as to illuminate the slit at a definite point in each revolution. Hence the background used was either a sodium vapor lamp or a carbon arc, operated on 60 cycle alternating current. A disk provided with a single slit was mounted on the shaft of a synchronous motor operated at 3600 R.P.M. When the slit was horizontal, current was admitted to the background lamp for about one five hundredth of a second by means of a special transformer.

This transformer, Fig. 28, was of the magnetic shunt type. Its primary was connected to the same 60 cycle line as the synchronous driving motor. The section of the core upon which the secondary was wound was saturated by a current slightly less than that required to operate the sodium lamp. Hence as the current in any particular cycle rises in the primary, the current also rises in the secondary and therefore in the lamp. The field due to this current opposes the flux through the secondary leg and demagnetizes it, thus compelling the flux to travel through the shunt. The current in the secondary therefore falls to zero in a small fraction of a period. The current wave of this transformer is shown in Fig. 11 (b). The voltage of the secondary was of course slightly larger than the ionizing potential of the lamp. It was found possible to photograph (Fig. 12) the diffraction pattern when a circular hole 3/16 inch in diameter was used in place of the slit, and rotated in a beam of light which had passed through a 1/8 inch stationary hole located near the focus of the objective lens. This does not show much except that the speed of the rotor is negligible in comparison with that of light.

C. Diffraction at the Pyrometer Filament

Diffraction of the light from the background, at the edges of the pyrometer filament, as already mentioned, was studied by Worthing and Forsythe. They showed it to be the cause of a rather spectacular effect. Consider a thin disk about three centimeters in diameter, placed on the axis of the light beam near to and on the emergent side of the objective lens. If this be viewed through the telescope in the usual manner, the pyrometer filament will appear to burn brightly even though no current is flowing through it. This illusion occurs whether the sector is rotating or stationary and even without the sector. A filament not enclosed in a bulb will show the same effect. The explanation is that the disk blocks out the central portion of the beam and thus permits diffraction effects to be observed that are normally not capable of observation on account of the high intensity of the entire visual field. Light from the background is diffracted at the edges of the wire in the usual manner and is thereby directed into the region in which the wire ordinarily casts a shadow. The result is that the wire itself appears to be hot.

This effect can also be produced by disks of other sizes, but the nearer a disk is to the pyrometer filament the larger must be its area relative to the cross section of the beam.

The diffraction fringes at the edge of the pyrometer filament can, however, also be shown without the use of the disk and while the pyrometer filament itself is hot, by using synchronous monochromatic illumination. A sodium vapor lamp energized by the special transformer already described forms the background, and is synchronized with the rotating sector disk. When the disk is near the objective lens, the telescope shows well-defined diffraction lines on either side of and parallel to the edges of the pyrometer filament. The diffracted light is plane polarized, vibrating parallel to the filament. This can also be shown with a carbon arc, but of course the bands are then colored.

D. Effects of Changing the Angle of the Cone of Rays Leaving the Objective Lens

From the standpoint of geometrical optics, a variation in the exit cone α should make no difference in the reading for a brightness match. Thus if the angle α is decreased, the image of I at I', Fig. 13, should decrease in intensity but not in size. The part of I seen at BB', however, for the same change in α should become smaller, but the central portion of I' when observed through the telescope (objective E) should not change in brightness until α becomes less than β.

The magnitude of a minimum permissible value of α can be determined from Fig. 13. Let P' represent the image of P formed by lens B. The apparent intensity of P' as observed through the telescope is determined by the cone of light B'P'B. Changes in the diaphragm opening of lens B can make no change in the intensity of P' as observed through the telescope until the diaphragm opening becomes less than AA'. If the beam does become less than AA', the cone of light passing through P' into the telescope will decrease and thus reduce the intensity of P'.

To make a brightness match, it is evident that the field at D as seen through the telescope objective BB' must at least be large enough to enable the U bend of the pyrometer filament to be seen easily. The image of the background must be of uniform intensity in this field; in other words, O' and P', Fig. 13, must have the same intensity. The length O'P' is known from the dimensions of the pyrometer filament. The telescope aperture BB' is fixed by the apparatus. The distances BD and DE are measurable. Hence the minimum value AA' is determined by drawing straight lines from B and B' through the end points of the image at D and extending them to the position of A, as is done in Fig. 14. The dimensions of the present apparatus are: BB' = 26 mm; O'I' = 1 mm; BD = 60 cm; DE = 120 cm. AA' is therefore 19 mm. $\alpha = \frac{19}{600} = 0.0316$ radian; $\beta = \frac{26}{120} = 0.0216$ radian . $\frac{\alpha}{\beta} = \frac{0.0316}{0.0216} = 1.46$. In the apparatus α was increased slightly so that $\alpha/\beta = 1.54$. Experiment shows that at a brightness match, α can be decreased to 0.0316 radian without affecting the value of the pyrometer current, but that when α is reduced below this value, the pyrometer current must be reduced to maintain the brightness match.

The preceding discussion shows very plainly that α cannot have less than a certain minimum value without affecting the condition at a brightness match. The question that arises immediately is whether any value of α above this minimum is as good as any other, or whether there is, possibly, a certain optimum value that is particularly convenient. A long series of experiments was undertaken to establish the relation between α and pyrometer current for different background brightnesses. From these experiments the existence of a definite optimum value of α has been established.

It was decided to study this problem first without the complication of diffraction and polarization introduced by the disk. Consequently the disk was replaced by each of five Wratten filters (No. 96) of different densities and a 76.5 per cent transmission filter made up of

Layers of photographic film together with a 50 per cent transmission Wratten filter. For each a series of brightness matches was made using different values of α. The data are summarized in Table 1 and in the curves of Figs. 15 to 19.

The curves are plotted with α as abscissas and pyrometer currents as ordinates. They fall away from the region of high brightness and small α fairly rapidly, flatten out, and fall off again slightly in the region of low brightness and large α. This second falling off, however, is not found in the curves for high intensities.

It was thought that the second downward trend of the curves might be due to light reflected from the surface of the filter. To verify this, a concave mirror was placed at one side of the beam in the path of a portion of the reflected light so as to throw it on a white screen at the focus of the mirror. When the central part of the beam was thus sent to the white screen, the lens opening could be changed from F 8 to F 5.6 without producing any noticeable change in brightness. However, when the peripheral rays were also sent to the screen by opening the diaphragm from F 5.6 to F 4.5, the change in brightness was easily noticed. More of the light from the background is reflected at the front surface of a filter when the aperture is large. As this light will not reach the plane of the pyrometer filament, the intensity match will be made with a current that is smaller than it would be if all of the light remained in the beam. This will cause the curve to deflect downward. Hence the final downward slope of the experimental curve is probably due to reflection of the background light from the surface of the filter.

The light that has passed through the filter was also examined for possible losses, for the direction of the light is changed by refraction and possibly by scattering. Whatever loss there was, was too small to be detected by reflection from mirrors. Consequently it was decided to test its presence by refraction. A 3 cm hole was ground at the center of a converging lens of 50 cm focal length and 10 cm diameter. This was placed near the emergent side of the filter, mounted on hinges so that it could be thrown into the beam at will or moved longitudinally toward the pyrometer lamp.

The lens was placed in the beam so that no part of the beam struck the edge of the hole. Then a filter whose transmission factor had been measured in situ was inserted in the beam. The lens was moved longitudinally until a difference in brightness was noticed upon throwing the lens in and out of the beam. At this point the average value of the reading without the lens was 0.3388 and with the lens 0.3390. These readings are so nearly equal as to show that the light lost from the beam by this means is negligible. The difference is noticeable because the observer can keep his eye on the match and flip the lens in and out of the beam.

The adjustable sector was set very carefully by means of a microscope so as to have the same transmission as the filter, on the assumption that Talbot's law holds. This sector replaced the filter. The current through the source, 22 amperes, and the diaphragm setting, $\alpha = 0.0614$ radians, $\alpha/\beta = 2.86$ were the same as used with the filter. The match readings were 0.3155 without the lens and 0.3164 with the lens, but a better match was obtained without the lens. It was necessary to move the lens nearer the sector for maximum difference than was the case with the filter.

This large difference shows that there is considerable diffraction of light at the sector edges into the geometrical shadow. It is to be noted that the transmission through the sector is less than that through the stationary filter.

From curves 16 to 19 values of the percent transmission, P, and the pyrometer filament current, I_{pf}, can be read for any desired values of α. This has been done; the values of a background filament current of 20 amperes are recorded in tables II and III. Fig. 20 contains the plots of these values and also corresponding curves for background filament currents of 12.5, 15.0 and 17.5 amperes, drawn for maximum and minimum values of α. All of these curves are seen to intersect the axis of ordinates at a definite point corresponding to a definite pyrometer current, called C in the discussions that follow.

These curves as well as those of Fig. 15 to Fig. 18 show that the value of α has very little effect upon the position of the curves for sources of low intensity. For higher intensities however, (I_s = 20 amperes or 2115°K), the change in the pyrometer filament current due to a change in α is more pronounced.

To study the effect of α, especially in this region, Tables II and III were expanded by adding columns containing log P, I_{Pf}-c, and log (I_{Pf}-c). Plotting log P against log (I_{Pf}-c) a family of curves results, of which all members start as straight lines for low values, and curve up slightly or down slightly for high values. One particular curve is straight throughout the entire range of the data taken. Samples of these curves are given in Figs. 21, 22, and 23, Fig. 22 showing the one that is entirely straight. This curve, as shown in the tables, is drawn for a background current of 20 amperes (2115°K) and a diaphragm opening, α, of 0.0656 radian (F/5.6)

The existence of the straight line evidently answers the question as to the existence of an optimum value of α; using this curve, the determination of temperature involves the least work and results in the greatest accuracy. Its equation is evidently log $(I_{Pf}-c)$ = log a + b log P, or $I_{Pf} = aP^b + c$, where log a is the intercept on the axis of ordinates, b is the slope, and c is the intercept on the axis of ordinates in Fig. 20; c is evidently the pyrometer current for zero transmission through the filter, and can be verified directly by experiment.

For the particular background used in this set of observations, the constants in the equation are readily determined; log a = 0.27; a = 1.339; b = 0.25; c = 2.25.

Substituting these values, the equation becomes

$$I_{Pf} = 0.1339\ P^{0.25} + 0.225 \text{ amperes}$$

This equation applies to a tungsten pyrometer filament 0.05 mm in diameter used at the optimum angle α. It is of use in determining the per cent transmission, P, of any filter for measured values of the pyrometer filament current I_{Pf}.

The question immediately arises as to whether this equation applies to a rotating sector disk as well as to filters, if not, why not, and whether there is a similar equation which does apply when using the sector near the pyrometer lamp.

Data taken in a manner similar to that described for the filter, lead to the curves shown in Fig. 25. These curves have been plotted with different ordinate scales merely for the convenience of having them all on one page.

They have the same general shape as those for the filter, even to the extent of showing a falling off for large values of α and low pyrometer filament currents. The chief difference is that for approximately equal reduction of intensities, the variations in the filament current due to a change in α are larger for the disk than for the filter. For example, a 10° sector opening is approximately the equivalent of a 3 per cent filter; a comparison of the curve for a 10° slit, Fig. 25, with that for a 4.18 per cent filter (no 3 per cent filter having been used) Fig. 15, shows that the variations of the filament current with α are larger for the sector. The filter functions mainly by absorption, but also produces a considerable weakening of the beam by reflection from the front surface. The sector disk of course prevents light from proceeding through its opaque part, but further, does not pass in the original direction all that comes through the slit, because some leaves this direction due to diffraction. On the other hand, some light may also by diffraction be brought into the beam. Since a change in α has more effect on the sector, it seems that the change in the angle of incidence (near the perpendicular incidence) has more effect on diffraction than on reflection.

Assuming that the optimum value of α is on the nearly horizontal portion of the curves of Fig. 25, as was the case with filters, the values $\alpha = 0.0614$ radian, $\alpha/\beta = 2.816$, are indicated. These values were used for experiments with sectors of different openings. The results are shown in Table VI, Fig. 25 and Fig. 27. An adjustable sector with sharp edged openings was used. Its edges were not made of razor blades, but were straighter throughout their length than are the edges of safety razor blades. The openings were set by the use of gauges whose thicknesses were measured accurately both singly and in groups. The gauges were inserted and held at the end of the slit nearest the center. For this purpose about one eighth of an inch of the slit edges were left perpendicular to the face. The inner edge of the slit was 104 mm from the center of the disk, and was not in the light beam. By the construction of the disks, two slits diametrically opposite, were presented to the light beam. The smallest slits for which readings were attempted, 0.08° each, were too small to permit reliable readings, the prominence of diffraction fringes making brightness matching very difficult. Hence only total openings larger than 0.1765° were used. Data were taken for two pyrometer lamps having filament diameters of 0.05 mm and 0.045 mm respectively. The sector disk was placed near the pyrometer lamp.

The data on the former were plotted in Fig. 26, the total opening in degrees being the abscissae and the pyrometer current the ordinates. The curve is definitely more complex than that for the filter, Fig. 22. Following the former procedure and plotting the logarithms of the coordinates produced three more or less straight lines. Due to the fact that not all of the original points lie accurately on the curve drawn in Fig. 26, the curve was redrawn with an expanded scale of abscissae in Fig. 27, giving rise to the parts A, B, C and D. E and F apply to the pyrometer filament 0.045 mm in diameter. Part A is approximately a straight line between 0.1765° and 1.05°. At point a, there is a comparatively sharp bend. Part B between 1.05° and 3.6° is also a straight line. There is a third straight line section, part C from 10.6° to 30°. Between 3.6° and 10.6° there is a gradual transition from one of these lines to the other. Beyond 30°, part D, the curve is smooth, but with no indications of straight line conditions.

These straight line sections can be definitely correlated with different physical conditions existing in the beam of light. Part A represents the combined results of diffraction at the slit and at the filament when the sector openings are small. Narrow slits cause large angles of diffraction. Thus light is lost from the main beam, making the background as seen in the telescope, too dim. At a brightness match, the filament current will therefore be too small.

Further, diffraction of the background light at the filament, bends some light into what would be the filament shadow and thus makes the filament appear too bright. Consequently too small a current flows in it. The pyrometer filament current is therefore low due to both diffraction at the slit and at the filament.

Part B represents a condition in which the filament current is still low, but not so much as in part A. The slit is wider and the loss by diffraction at the slit therefore probably negligible. Diffraction at the filament is almost the same as before. The filament current is therefore more nearly of proper value, meaning by proper, a value determined by the geometrical dimensions of the slit.

Part C represents conditions under which diffraction of both kinds is practically negligible. The increase in the brightness of the filament due to diffraction at the filament is so small as to cause only a negligible diminution in filament current at a brightness match; this difference is not noticeable at the existing brightnesses. Light passing through the slit is proportional to the sector opening.

Reference to the point f, Fig. 27, representing the 7° opening (two 3.5° slits) shows an experimental point not on either of the straight lines B and C. The indication is that a 3° slit offers no diffraction difficulties when used. If light intensity must be reduced to 1/120th of its original brightness it should be done with one 3° slit rotating with the proper speed. These statements are true for the present apparatus, i.e. for the focal length of the lens and the angle α used. With a smaller angle α, it may be possible to use somewhat smaller sectors without reference to diffraction at the slit. Diffraction at the filament always exists, but becomes negligible for moderate intensities.

V. TABLES

TABLE I

I_{pf} in amperes

0.98 Per Cent Transmission

α in Radians	I_s = 12.5	I_s = 15	I_s = 17.5	I_s = 20
0.0815	0.2445	0.2764	0.3192	0.3574
0.0735	0.2447	0.2767	0.3195	0.3576
0.0655	0.2449	0.2768	0.3197	0.3577
0.0556	0.2450	0.2771	0.3199	0.3579
0.0458	0.2450	0.2773	0.3200	0.3581
0.0395	0.2451	0.2774	0.3201	0.3584
0.0333	0.2452	0.2777	0.3204	0.3590
4.18 Per Cent Transmission				
0.0815	0.2681	0.3197	0.3697	0.4161
0.0735	0.2681	0.3198	0.3698	0.4163
0.0655	0.2681	0.3199	0.3699	0.4164
0.0556	0.2681	0.3201	0.3699	0.4164
0.0458	0.2683	0.3203	0.3699	0.4166
0.0395	0.2685	0.3205	0.3699	0.4167
0.0333	0.2686	0.3209	0.3708	0.4168

TABLE I Cont'd

I_{pf} in amperes

10 Per Cent Transmission

α in Radians	I_s = 12.5	I_s = 15	I_s = 17.5	I_s = 20
0.0815	0.2850	0.3475	0.4055	0.4618
0.0735	0.2854	0.3479	0.4058	0.4619
0.0655	0.2856	0.3482	0.4059	0.4620
0.0556	0.2858	0.3484	0.4061	0.4622
0.0458	0.2860	0.3485	0.4064	0.4624
0.0395	0.2863	0.3487	0.4068	0.4626
0.0333	0.2869	0.3492	0.4071	0.4629

31 Per Cent Transmission

α in Radians	I_s = 12.5	I_s = 15	I_s = 17.5	I_s = 20
0.0815	0.3150	0.4007	0.4743	0.5395
0.0735	0.3157	0.4008	0.4744	0.5397
0.0655	0.3158	0.4008	0.4740	0.5400
0.0556	0.3158	0.4008	0.4744	0.5404
0.0458	0.3160	0.4010	0.4744	0.5410
0.0395	0.3166	0.4018	0.4749	0.5414
0.0333	0.3180	0.4035	0.4760	0.5421

52.5 Per Cent Transmission

α in Radians	I_s = 12.5	I_s = 15	I_s = 17.5	I_s = 20
0.0815	0.3356	0.4290	0.5101	0.5874
0.0735	0.3360	0.4293	0.5104	0.5874
0.0655	0.3363	0.4294	0.5107	0.5874
0.0556	0.3364	0.4297	0.5110	0.5876
0.0458	0.3369	0.4300	0.5115	0.5881
0.0395	0.3378	0.4310	0.5120	0.5886
0.0333	0.3409	0.4330	0.5132	0.5897

TABLE I Cont'd

I_{pf} in amperes

76.5 Per Cent Transmission

α in Radians	I_s = 12.5	I_s = 15	I_s = 17.5	I_s = 20
0.0815	0.3544	0.4547	0.5439	0.6181
0.0735	0.3545	0.4547	0.5439	0.6195
0.0655	0.3545	0.4548	0.5439	0.6215
0.0556	0.3547	0.4549	0.5439	0.6220
0.0458	0.3550	0.4550	0.5440	0.6250
0.0395	0.3560	0.4556	0.5446	0.6275
0.0333	0.3582	0.4575	0.5461	0.6331

100 Per Cent Transmission

α in Radians	I_s = 12.5	I_s = 15	I_s = 17.5	I_s = 20
0.0815	0.3701	0.4732	0.5695	0.6455
0.0735	0.3701	0.4733	0.5698	0.6480
0.0655	0.3704	0.4736	0.5705	0.6501
0.0556	0.3708	0.4740	0.5710	0.6530
0.0458	0.3715	0.4747	0.5718	0.6575
0.0395	0.3722	0.4752	0.5726	0.6625
0.0333	0.3734	0.4761	0.5736	0.6725

TABLE II

I_s = 20 amperes

c = 2.25

α	P	log P	I_{pf} Deci-amperes	I_{pf} - c	log(I_{pf} - c)
0.0333	0	- ∞	2.25	0	- ∞
	0.98	-0.008774	3.59	1.34	0.127105
	4.18	0.621176	4.168	1.93	0.285557
	10.	1.0	4.629	2.379	0.376394
	31.	1.491,362	5.421	3.171	0.501196
	52.5	1.720159	5.897	3.649	0.562174
	76.5	1.883661	6.331	4.081	0.610767
	100.0	2.0	6.725	4.475	0.650793
0.0395	0	- ∞	2.25	0	- ∞
	0.98		3.584	1.334	0.124187
	4.18		4.167	1.917	0.282622
	10.		4.626	2.376	0.375846
	31.		5.414	3.164	0.500236
	52.5		5.886	3.636	0.560624
	76.5		6.275	4.025	0.604766
	100.		6.625	4.375	0.650793
0.0458	0		2.25	0	- ∞
	.98		3.581	1.331	0.124178
	4.18		4.166	1.916	0.282396
	10.		4.624	2.374	0.375481
	31.		5.410	3.160	0.499687
	52.5		5.881	3.631	0.560026
	76.5		6.250	4.000	0.602060
	100.		6.575	4.325	0.635986

TABLE III

I_s = 20 amperes

c = 2.25

α	P	log P	I_{pf} Deci-amperes	I_{pf} -c	$\log(I_{pf} - c)$
0.0556	0	$-\infty$	2.25	0	$-\infty$
	0.98	-0.008774	3.579	1.329	0.123525
	4.18	0.621176	4.165	1.915	0.282169
	10.	1.0	4.622	2.372	0.375115
	31.	1.491362	5.404	3.154	0.498862
	52.5	1.720159	5.876	3.626	0.559428
	76.5	1.883661	6.220	3.970	0.598791
	100.	2.0	6.530	4.280	0.631444
0.0655	0		2.25	0	$-\infty$
	0.98		3.577	1.327	0.122871
	4.18	0.62	4.164	1.914	0.281942
	10.	1.0	4.620	2.370	0.377748
	31.	1.49	5.400	3.140	0.498391
	52.5	1.72	5.874	3.624	0.559188
	76.5	1.88	6.215	3.965	0.598243
	100.	2.0	6.501	4.251	0.628491
0.0735	0		2.25	0	$-\infty$
	0.98		3.576	1.326	0.122544
	4.18		4.163	1.913	0.281715
	10.		4.619	2.369	0.374565
	31.		5.397	3.147	0.497897
	52.5		5.874	3.624	0.559188
	76.5		6.195	3.945	0.596047
	100.		6.480	4.230	0.626340

TABLE III Cont'd

α	P	log P	I_{pf} Deci-amperes	I_{pf} - c	log(I_{pf} - c)
0.0814	0		2.25	0	$-\infty$
	0.98		3.574	1.324	0.121888
	4.18		4.161	1.911	0.281261
	10.		4.618	2.368	0.374382
	31.		5.395	3.145	0.497621
	52.5		5.874	3.624	0.559188
	76.5		6.181	3.931	0.594503
	100.		6.455	4.205	0.623776

TABLE IV

I_s = 22 amperes

ß = 0.02148

α	1/4° Slit: Near Pyrometer Lamp I_{pf}	1/4° Slit: Near Objective	1/2° Slit: Near Pyrometer Filament	1/2° Slit: Near Objective
0.0764	0.2706	0.2704	0.2910	0.2906
0.0689	0.2707	0.2705	0.2913	0.2908
0.0614	0.2708	0.2706	0.2915	0.2911
0.0622	0.2708	0.2708	0.2917	0.2912
0.0430	0.2709	0.708	0.2918	0.2914
0.0372	0.2709	0.2709	0.2919	0.2914
0.0313	0.2710	0.2710	0.2920	0.2915
	1° Slit		1.5° Slit	
0.0764	0.3167	0.3160	0.3337	0.3334
0.0689	0.3169	0.3161	0.3339	0.3334
0.0614	0.3171	0.3162	0.3340	0.3336
0.0622	0.3172	0.3165	0.3342	0.3338
0.0430	0.3174	0.3168	0.3345	0.3340
0.0372	0.3176	0.3170	0.3348	0.3340
0.0313	0.3178	0.3172	0.3352	0.3345
	2° Slit		10° Slit	
0.0764	0.3472		0.4568	0.4565
0.0689	0.3473		0.4568	0.4557
0.0614	0.3474		0.4570	0.4570
0.0622	0.3476		0.4571	0.4572
0.0430	0.3480		0.4574	0.4574
0.0372	0.3484		0.4579	0.4576
0.0313	0.3490		0.4590	0.4589

TABLE V

Temperature By Leeds and Northrup Portable Pyrometer

$$\alpha = 0.0614 \cdot \frac{\alpha}{\beta} = 2.85$$

Reading I_s	I_s Amperes	Photometer ma	°F	°C	I_{pf} Amperes	°K °C + 273
26	13	407	2457	1348	0.3894	1621
28	14	428	2612	1434	0.4301	1707
30	15	448	2745	1508	0.4714	1781
32	16	467	2858	1570	0.5075	1850
34	17	490	2980	1638	0.5480	1920
36	18	516	3112	1710	0.5809	1983
38	19	532	3190	1754	0.6250	2047
39	19.5	544	3282	1805	0.6450	2078

TABLE VI

No. of Blades Inserted	mm	I_{pf} Amps	T Total Opening Degrees	C = 0.234 $(I_{pf} - c)$ I_{pf} = centi-amperes	Log $(I_{pf} - c)$	Log T
1	.16	.2430	.1765	0.9	-0.045757	-0.753255
2	.32	.2508	.3530	1.68	0.225309	-0.452225
3	.48	.2591	.5300	2.51	0.399674	-0.275724
4	.64	.2685	.7060	3.45	0.537819	-0.151195
5	.80	.2750	.8825	4.10	0.621784	-0.054285
6	.96	.2845	1.0590	5.05	0.703291	0.24898
7	1.13	.2854	1.248	5.14	0.710693	0.096215
8	1.30	.2880	1.434	5.40	0.732394	0.144943
9	1.46	.2924	1.610	5.84	0.766413	0.206826
10	1.62	.2957	1.790	6.17	0.790285	0.252853
15	2.45	.3052	2.70	7.12	0.852480	0.431364
20	3.25	.3198	3.59	8.58	0.933487	0.555094

TABLE VI (Cont'd)

Plates 1-320	mm	I_{pf} Amps	T Total Opening Degrees	C = 0.234 $(I_{pf} - c)$ I_{pf} = centi-amperes	Log $(I_{pf} - c)$	Log T
1-320	3.20	0.3195	3.53	8.55	0.031966	0.547775
1-2	6.41	0.3505	7.07	12.55	1.066326	0.849419
1-3	9.62	0.3732	10.60	14.82	1.143639	1.025306
1-4	12.83	0.3875	14.18	16.25	1.186108	1.141676
1-5	16.20	0.3965	17.88	17.15	1.210853	1.252368
1-6	19.09	0.4059	21.00	18.09	1.235276	1.322219
1-7	22.20	0.4198	24.50	19.48	1.269046	1.389166
1-8	25.38	0.4350	28.00	20.50	1.292256	1.447158
1-9	28.42	0.4420	31.40	21.02	1.322633	1.496930
		0.4670	45.00	23.30	1.367356	1.653213
		0.4871	60.00	25.31	1.403292	1.778151
		0.5413	120.00	30.73	1.487563	2.079181
		0.6080	240.00	37.40	1.572872	2.380211
		0.6582	360.00	42.42	1.627571	2.556303

Distance to inner end of opening 104 mm.

TABLE VII

No. of Blades Inserted	mm	T Total Opening Degrees	I_{pf} Amperes
1	0.16	0.1765	0.1915
2	0.32	0.3530	0.1970
3	0.48	0.5300	0.2012
4	0.64	0.7060	0.2045
5	0.80	0.8825	0.2074
6	0.96	1.059	0.2100
7	1.13	1.248	0.2122
8	1.30	1.434	0.2140
9	1.46	1.610	0.2157
10	1.62	1.790	0.2175
15	2.45	2.700	0.2260
20	3.25	3.59	0.2304
Plates			
1	3.20	3.53	0.2300
1-2	6.41	7.07	0.2454
1-3	9.62	10.60	0.2555
1-4	12.83	14.18	0.2630
1-5	16.20	17.88	0.2700
1-6	19.09	21.00	0.2750
1-7	22.20	24.50	0.2809
1-8	25.28	28.00	0.2860
1-9	28.42	31.40	

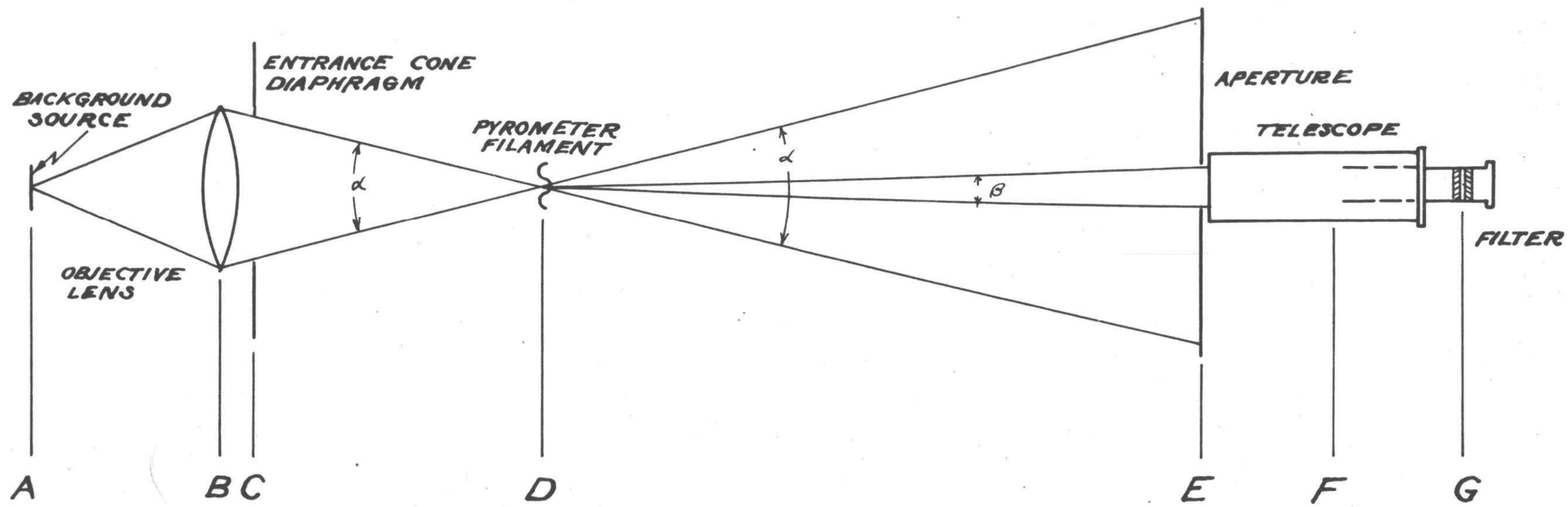


Figure 1

Diagram of Arrangement of Pyrometer
AB = 40 cm. BD = 46 cm DE = 120 cm.

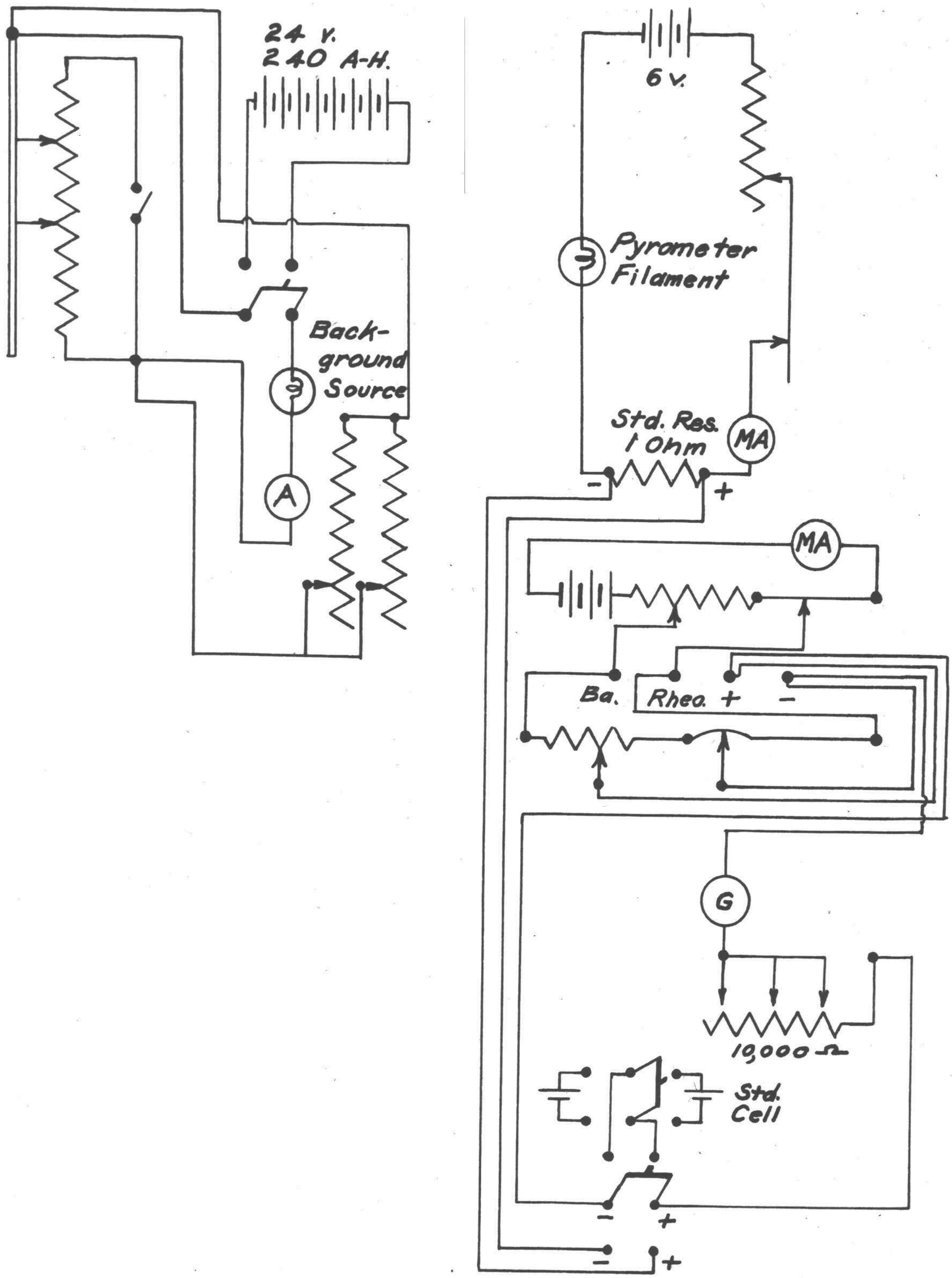
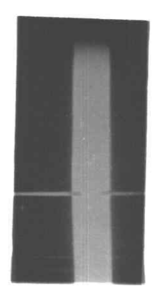


Figure 2

Diagram of Electrical Connections

a b c

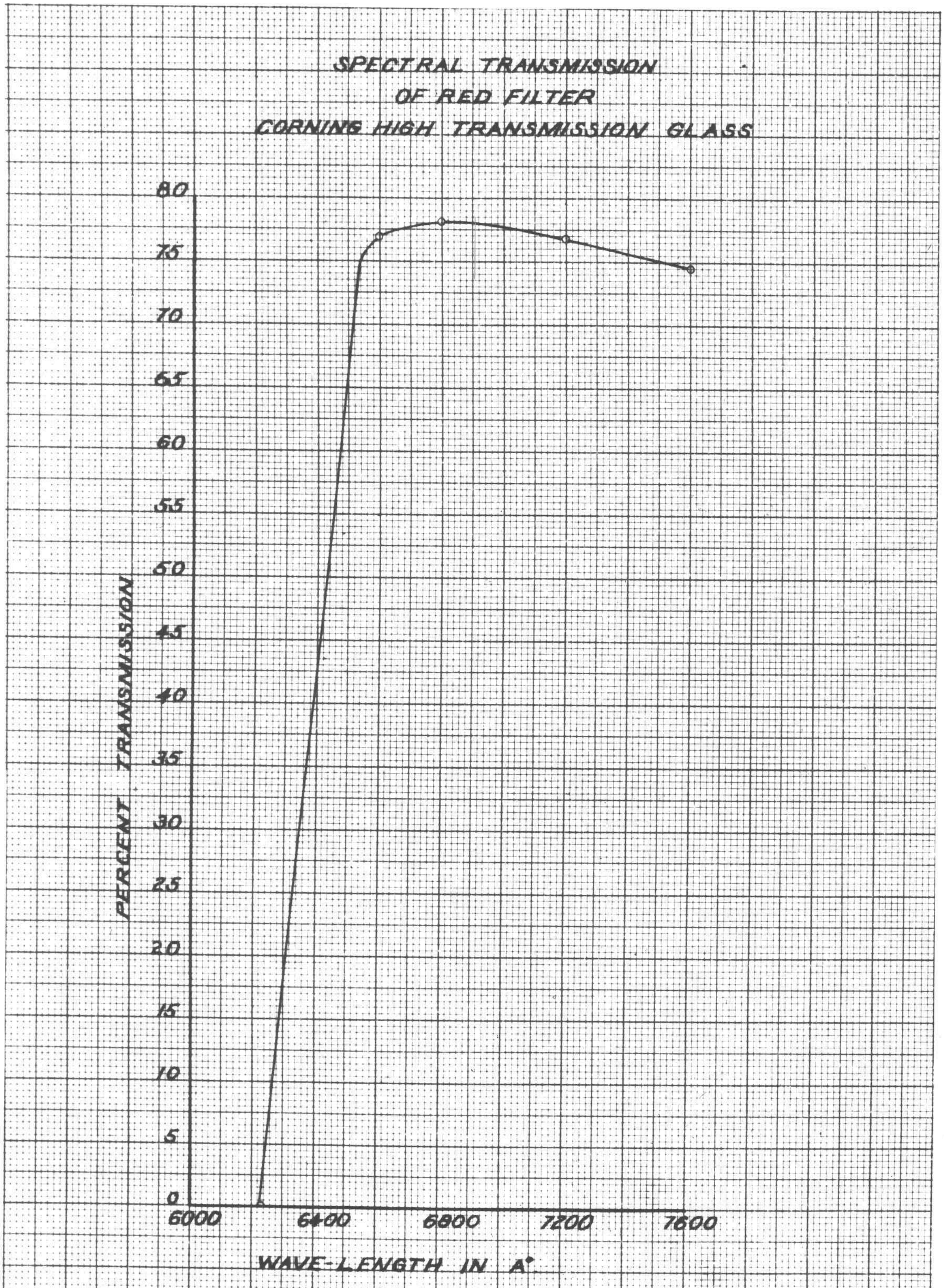
Eyepiece magnification, 14 diameters.
For usual measurements.



d

Eyepiece magnification, 17 diameters.
For wide sources, 4 mm. or more, maximum sensitivity is obtained at a match between the pyrometer filament and the center of the source only. The unmatched part of the pyrometer filament is slightly darker than it appears under observation, as, due to the difficulty in photographing, d was retouched.

Figure 3



SPECTRAL TRANSMISSION
OF RED FILTER
CORNING HIGH TRANSMISSION GLASS
PERCENT TRANSMISSION
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
6000
6400
6800
7200
7600
WAVE-LENGTH IN A°

Figure 4

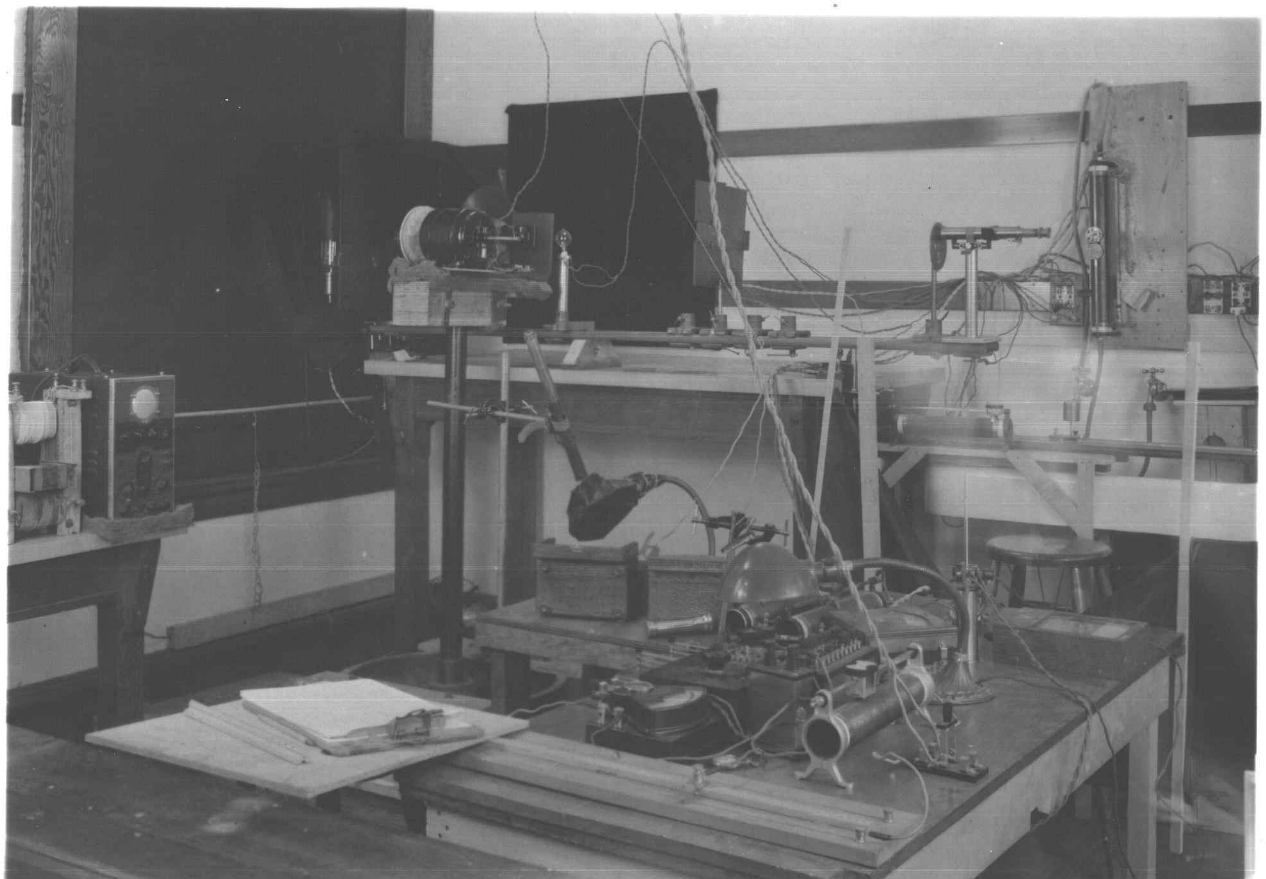


Figure 5

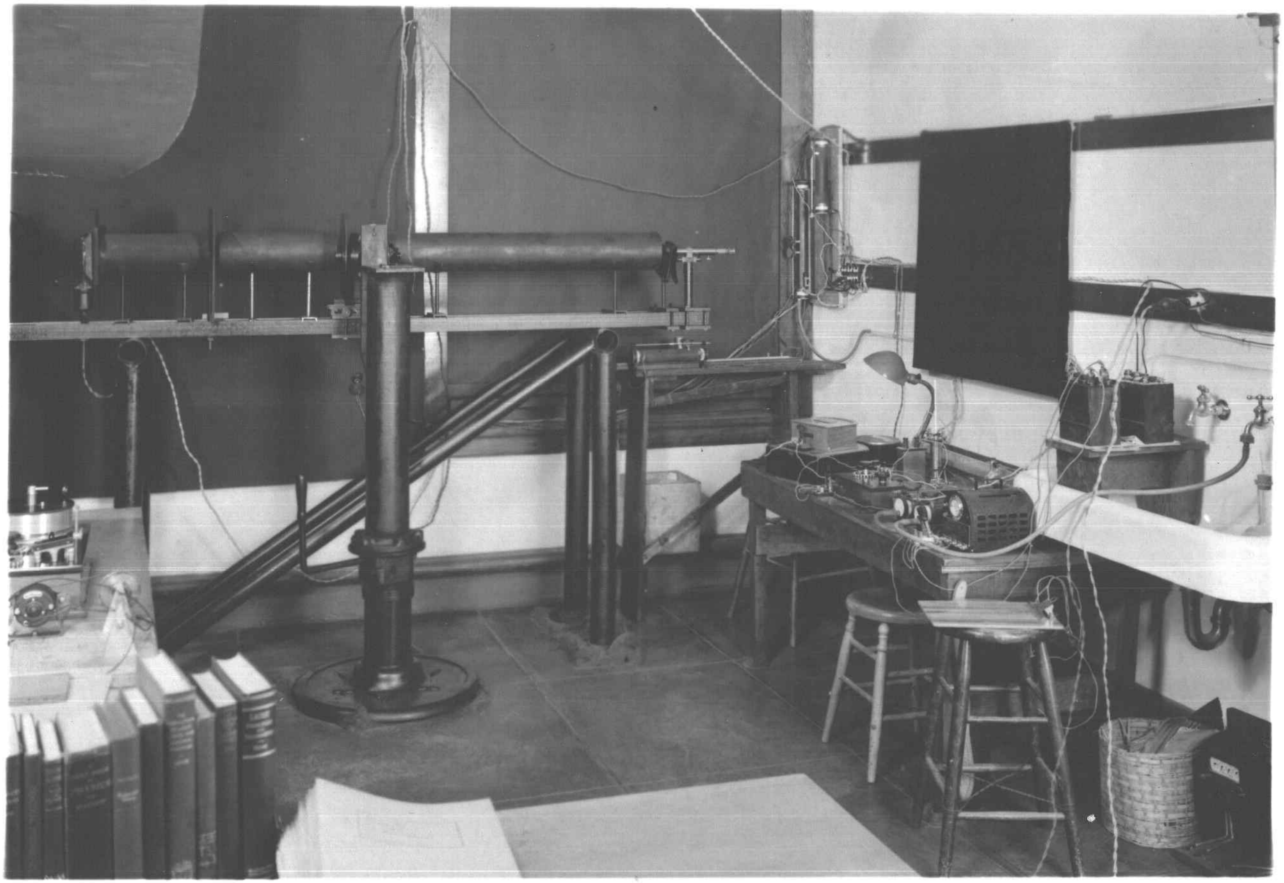
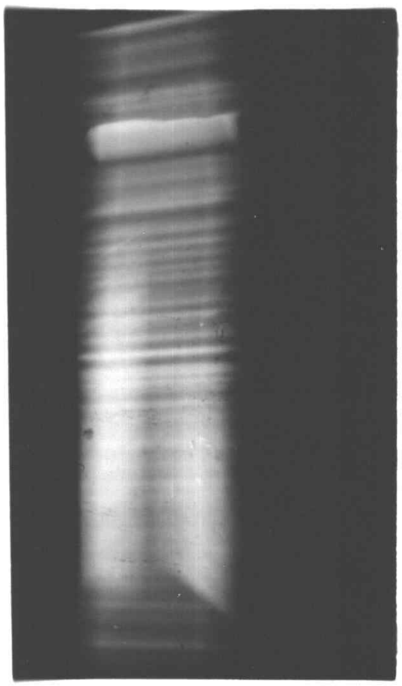
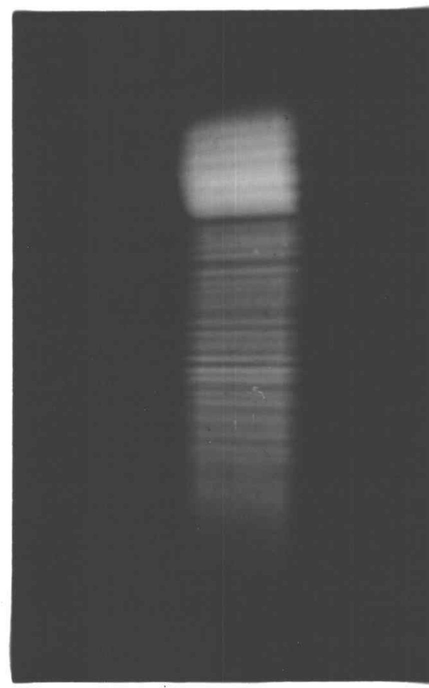


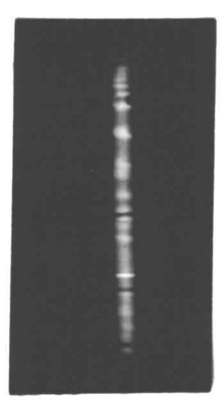
Figure 6



a



b



c

Figure 7

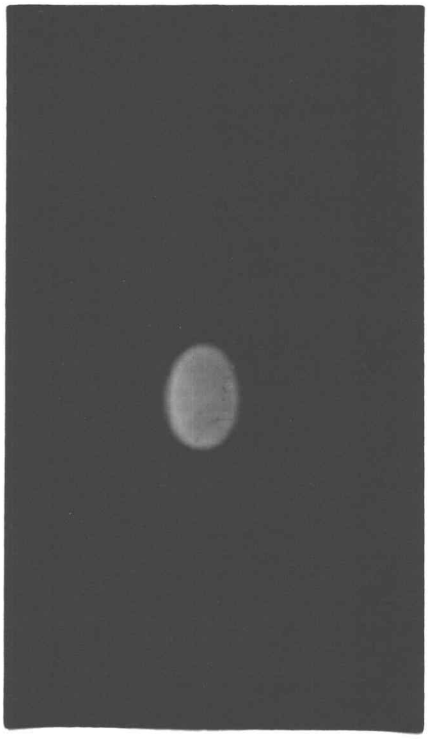


Figure 8

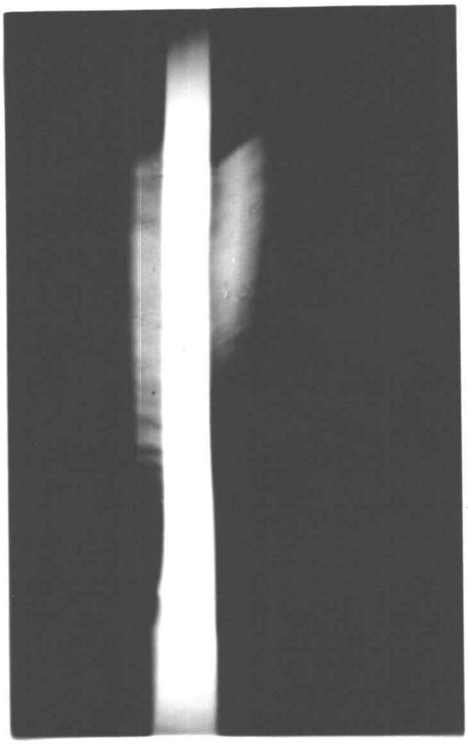


Figure 9

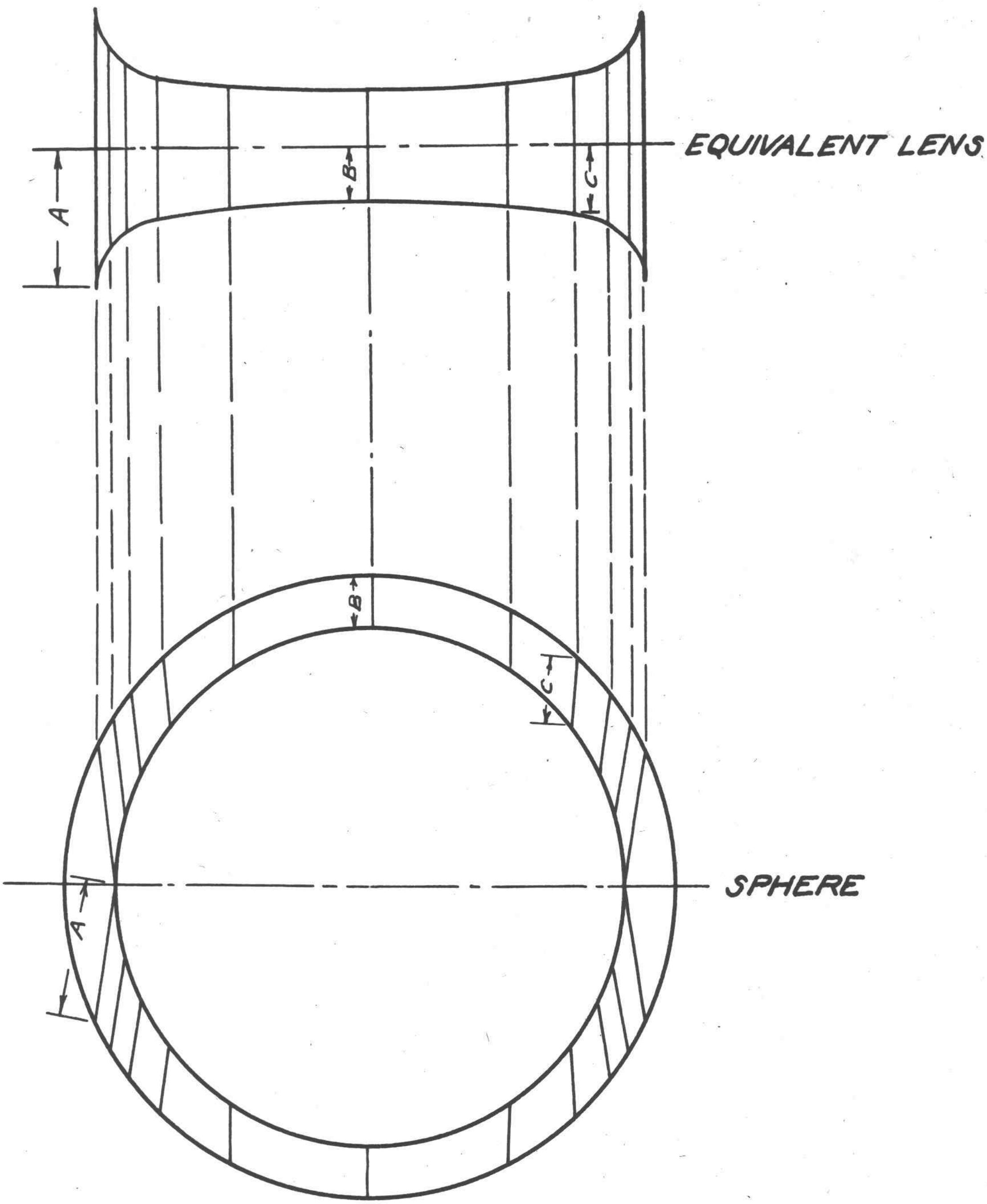
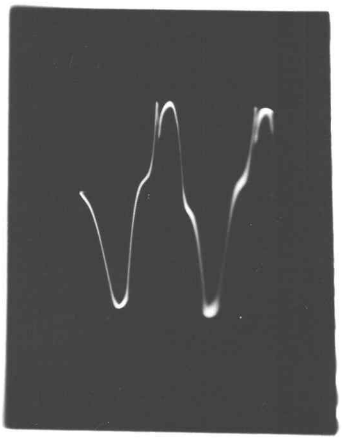
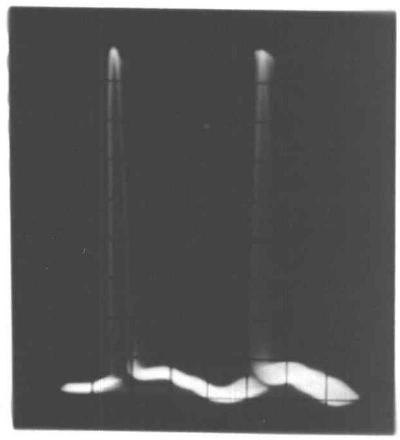


Figure 10

Lens Equivalent of a Hollow Sphere



a



b

Figure 11
Oscillograph of the source voltage wave, (a), and the current wave, (b), furnished by a specially constructed transformer used in synchronizing the source light with the sector disk.

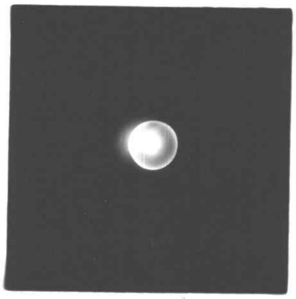


Figure 12

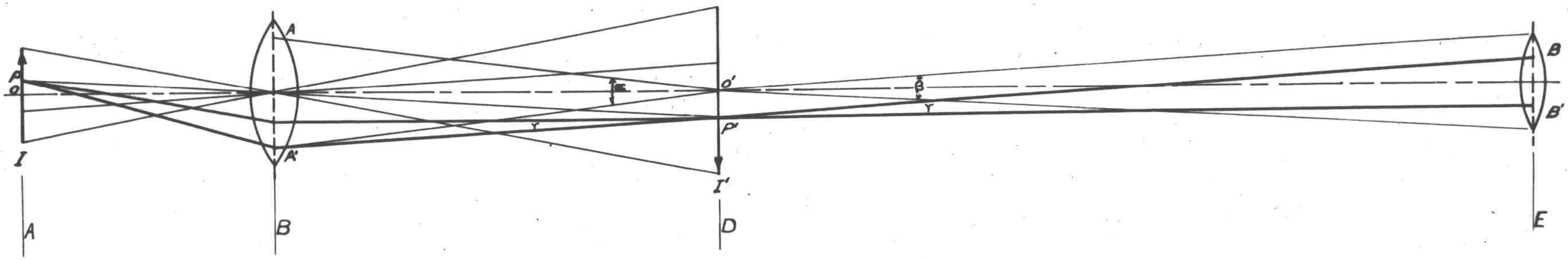


Figure 13

A, B, D, E have the same dimensions as in
Figure 1

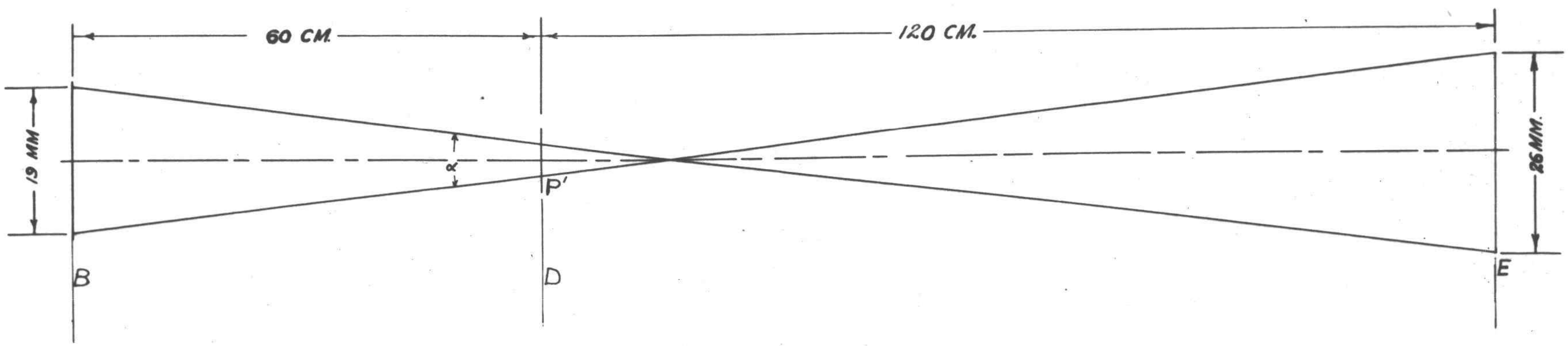


Figure 14

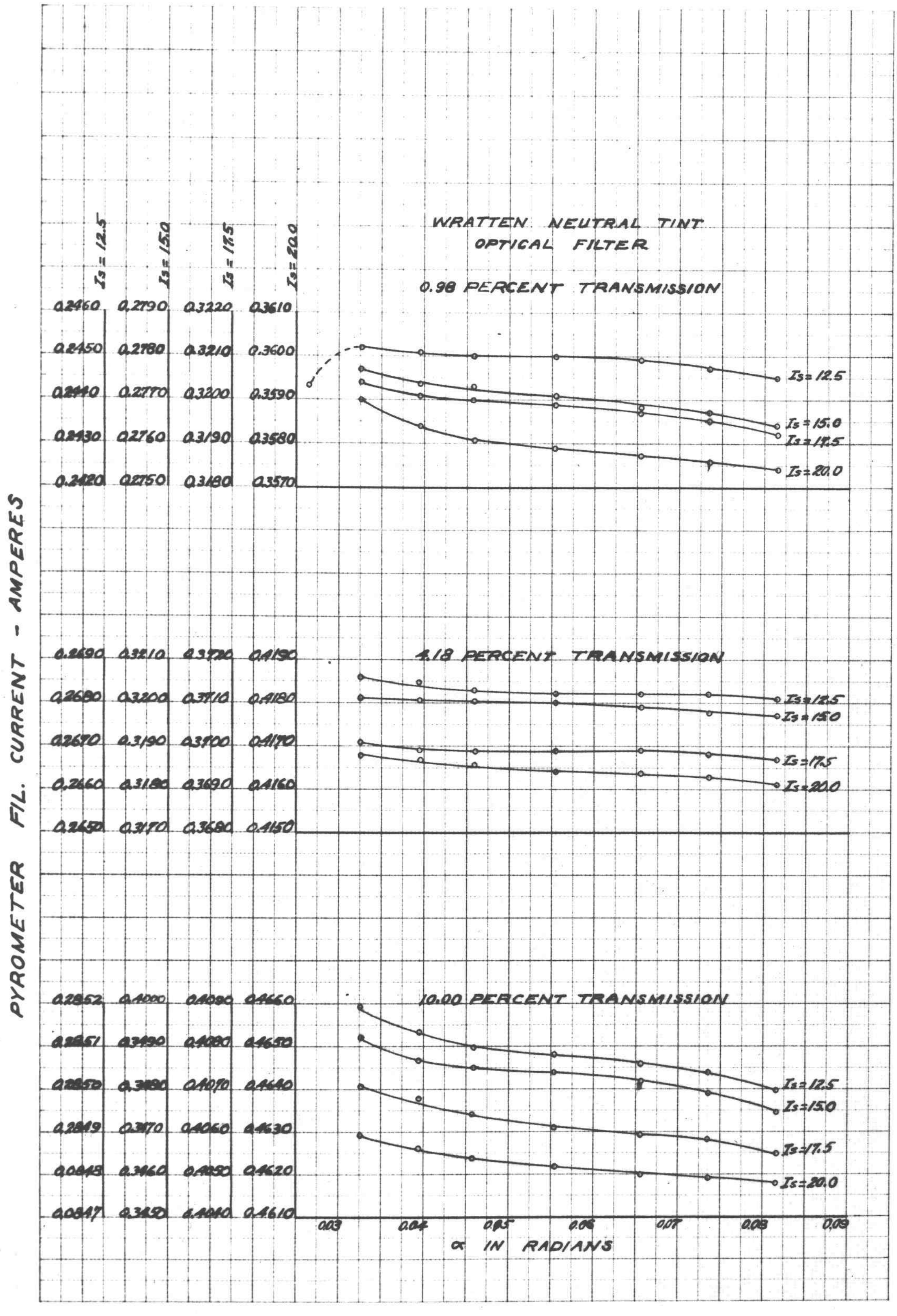

WRATTEN NEUTRAL TINT
OPTICAL FILTER
0.98 PERCENT TRANSMISSION
4.18 PERCENT TRANSMISSION
10.00 PERCENT TRANSMISSION
PYROMETER FIL. CURRENT - AMPERES
α IN RADIANS
Is = 12.5
Is = 15.0
Is = 17.5
Is = 20.0
0.03
0.04
0.05
0.06
0.07
0.08
0.09

Figure 15

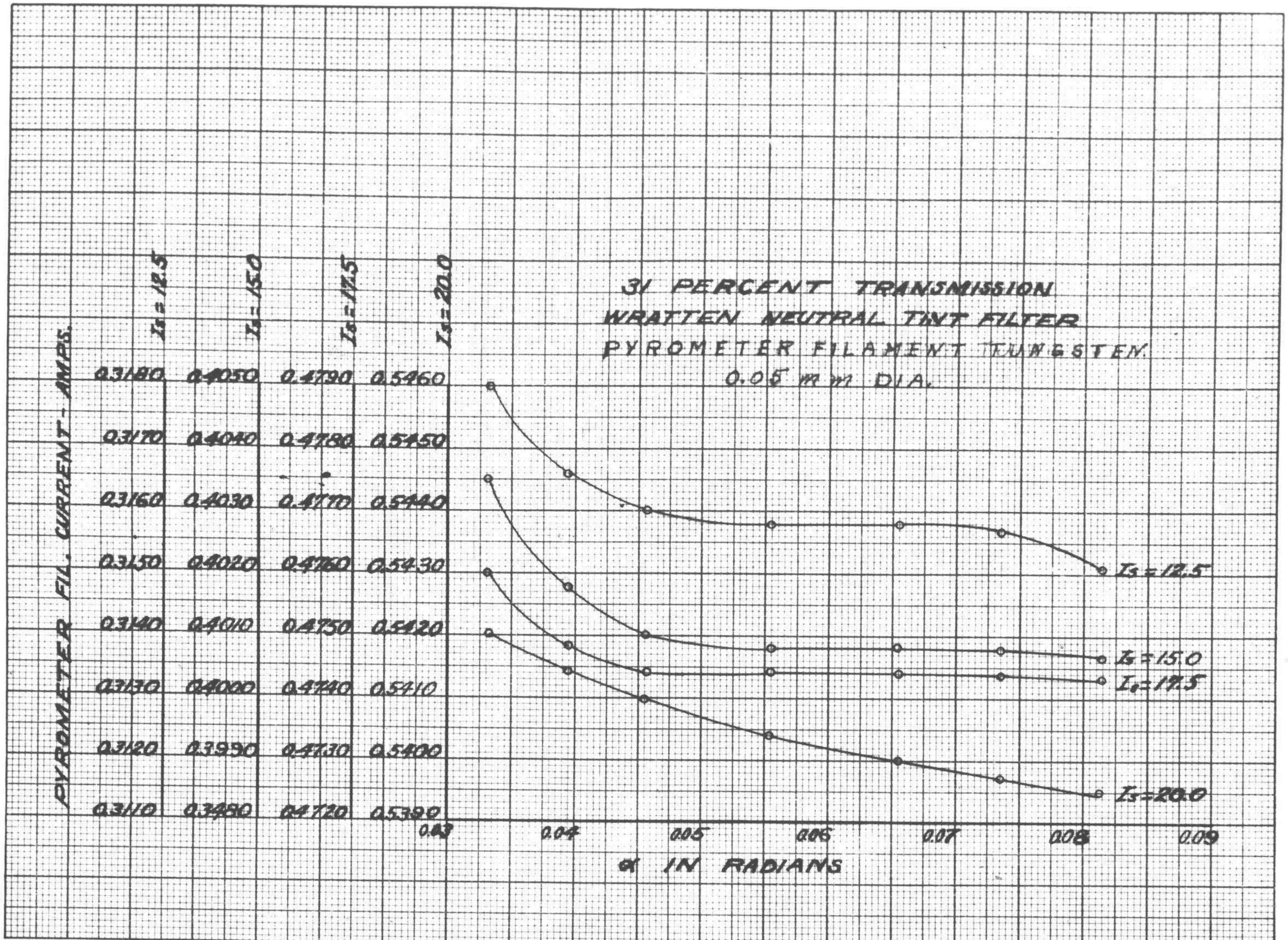

31 PERCENT TRANSMISSION
WRATTEN NEUTRAL TINT FILTER
PYROMETER FILAMENT TUNGSTEN
0.05 mm DIA.
PYROMETER FIL. CURRENT - AMPS.
Is = 12.5
Is = 15.0
Is = 17.5
Is = 20.0
0.3180 0.4050 0.4790 0.5460
0.3170 0.4040 0.4780 0.5450
0.3160 0.4030 0.4770 0.5440
0.3150 0.4020 0.4760 0.5430
0.3140 0.4010 0.4750 0.5420
0.3130 0.4000 0.4740 0.5410
0.3120 0.3990 0.4730 0.5400
0.3110 0.3980 0.4720 0.5390
0.03
0.04
0.05
0.06
0.07
0.08
0.09
α IN RADIANS

Figure 16

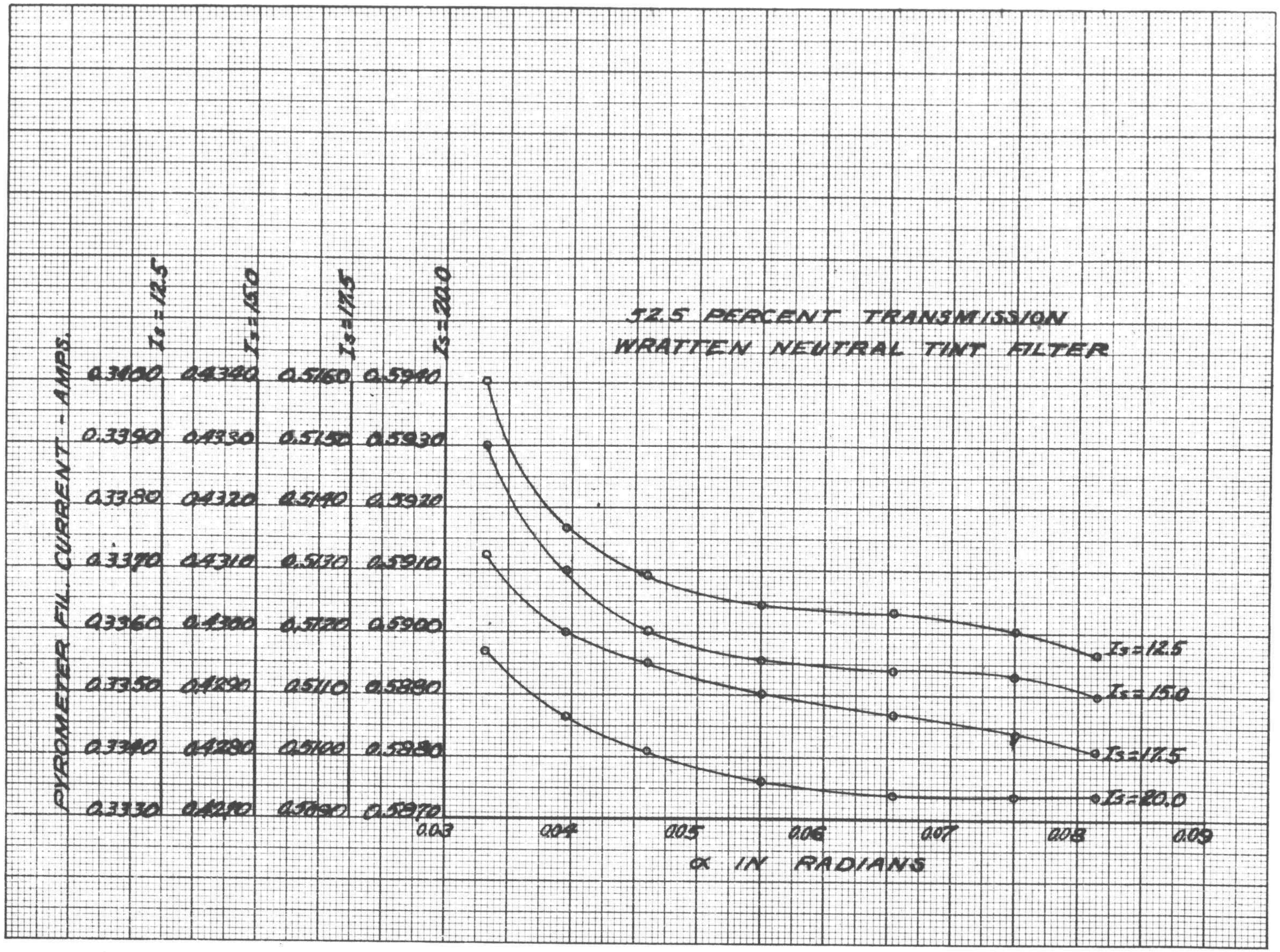

52.5 PERCENT TRANSMISSION
WRATTEN NEUTRAL TINT FILTER
PYROMETER FIL. CURRENT - AMPS.
Is = 12.5
Is = 15.0
Is = 17.5
Is = 20.0
0.3400 0.4340 0.5160 0.5940
0.3390 0.4330 0.5150 0.5930
0.3380 0.4320 0.5140 0.5920
0.3370 0.4310 0.5130 0.5910
0.3360 0.4300 0.5120 0.5900
0.3350 0.4290 0.5110 0.5890
0.3340 0.4280 0.5100 0.5880
0.3330 0.4270 0.5090 0.5870
0.03
0.04
0.05
0.06
0.07
0.08
0.09
α IN RADIANS
Is = 12.5
Is = 15.0
Is = 17.5
Is = 20.0

Figure 17

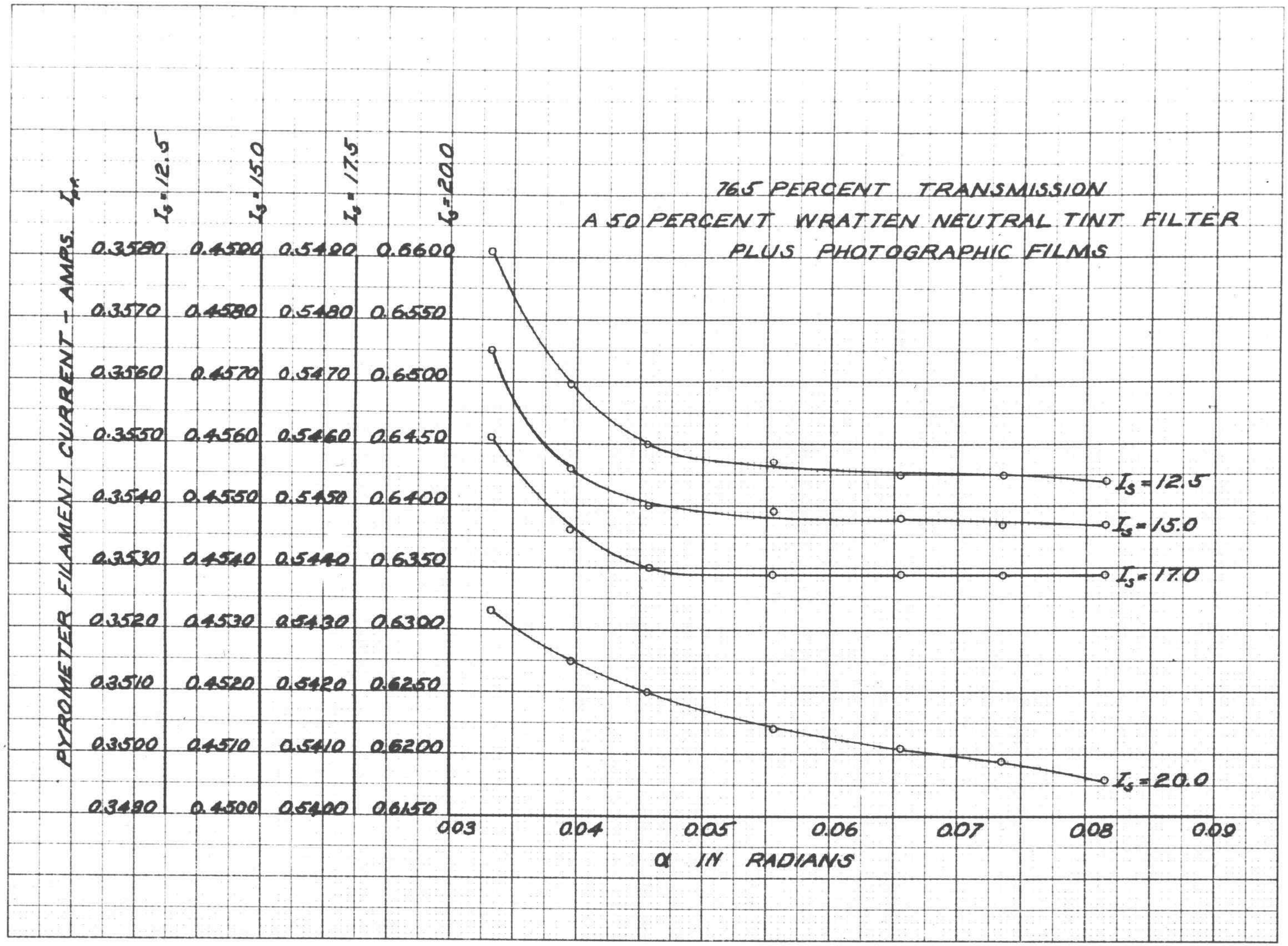

76.5 PERCENT TRANSMISSION
A 50 PERCENT WRATTEN NEUTRAL TINT FILTER
PLUS PHOTOGRAPHIC FILMS
PYROMETER FILAMENT CURRENT - AMPS. I_{pr}
$I_s = 12.5$
$I_s = 15.0$
$I_s = 17.5$
$I_s = 20.0$
0.3580 0.4590 0.5490 0.6600
0.3570 0.4580 0.5480 0.6550
0.3560 0.4570 0.5470 0.6500
0.3550 0.4560 0.5460 0.6450
0.3540 0.4550 0.5450 0.6400
0.3530 0.4540 0.5440 0.6350
0.3520 0.4530 0.5430 0.6300
0.3510 0.4520 0.5420 0.6250
0.3500 0.4510 0.5410 0.6200
0.3490 0.4500 0.5400 0.6150
$I_s = 12.5$
$I_s = 15.0$
$I_s = 17.0$
$I_s = 20.0$
0.03 0.04 0.05 0.06 0.07 0.08 0.09
α IN RADIANS

Figure 18

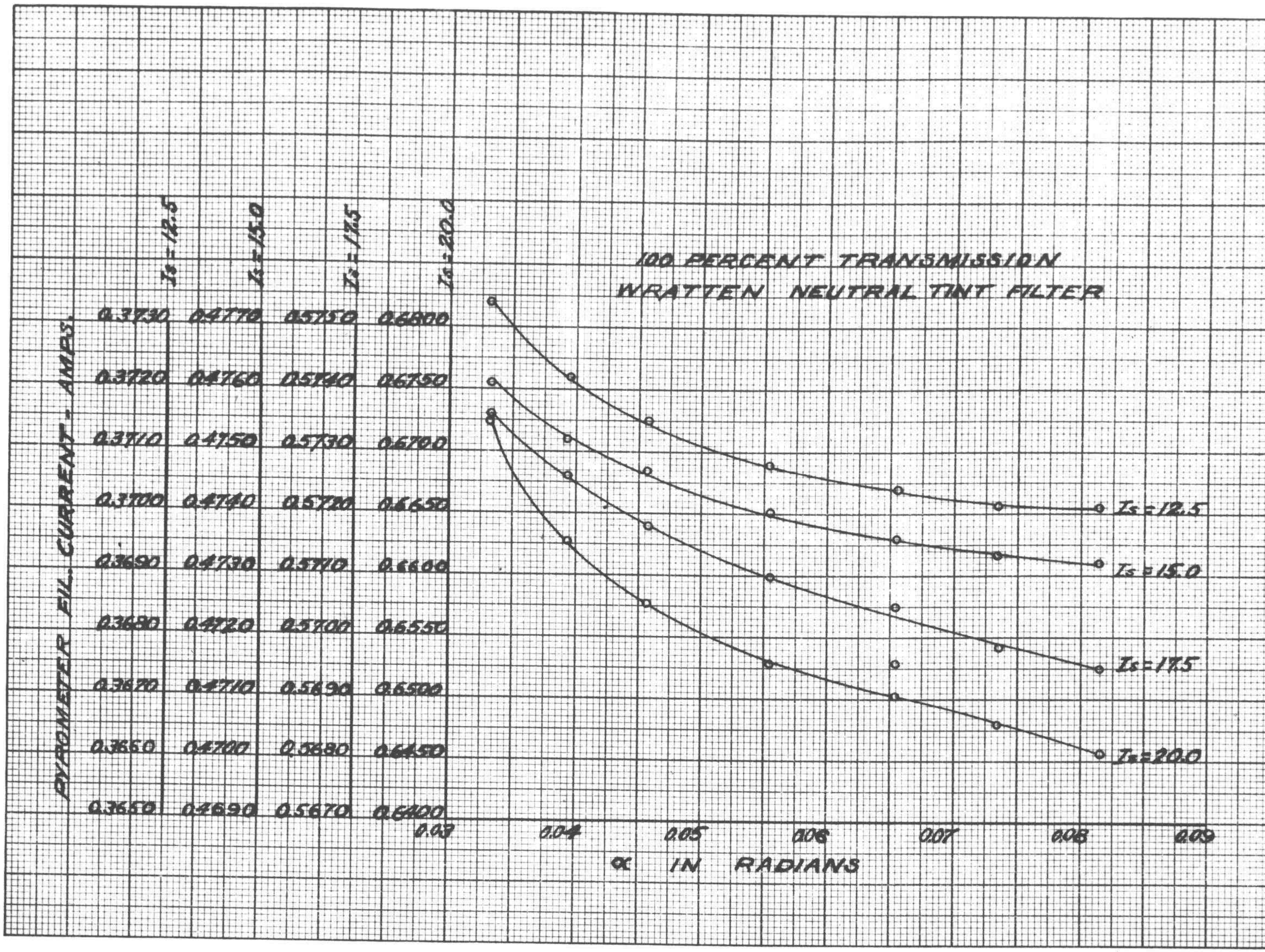

100 PERCENT TRANSMISSION
WRATTEN NEUTRAL TINT FILTER
PYROMETER FIL. CURRENT - AMPS.
Is = 12.5
Is = 15.0
Is = 17.5
Is = 20.0
0.3730 0.4770 0.5750 0.6800
0.3720 0.4760 0.5740 0.6750
0.3710 0.4750 0.5730 0.6700
0.3700 0.4740 0.5720 0.6650
0.3690 0.4730 0.5710 0.6600
0.3680 0.4720 0.5700 0.6550
0.3670 0.4710 0.5690 0.6500
0.3660 0.4700 0.5680 0.6450
0.3650 0.4690 0.5670 0.6400
0.03
0.04
0.05
0.06
0.07
0.08
0.09
α IN RADIANS

Figure 19

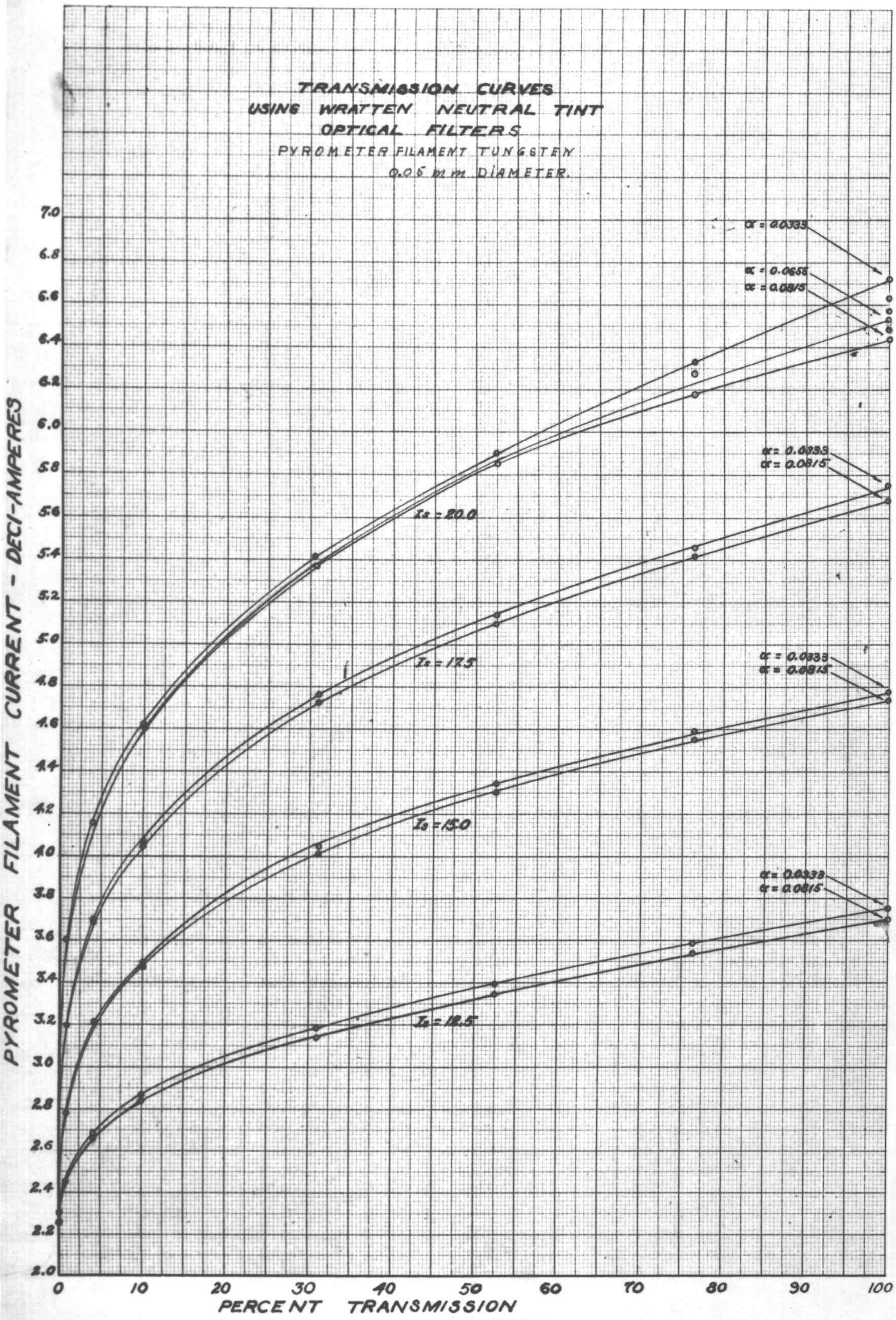

TRANSMISSION CURVES
USING WRATTEN NEUTRAL TINT
OPTICAL FILTERS
PYROMETER FILAMENT TUNGSTEN
0.05 mm DIAMETER.
α = 0.0333
α = 0.0655
α = 0.0815
α = 0.0333
α = 0.0815
α = 0.0333
α = 0.0815
α = 0.0333
α = 0.0815
Is = 20.0
Is = 17.5
Is = 15.0
Is = 12.5
PYROMETER FILAMENT CURRENT - DECI-AMPERES
PERCENT TRANSMISSION
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
6.6
6.8
7.0
0
10
20
30
40
50
60
70
80
90
100

Figure 20

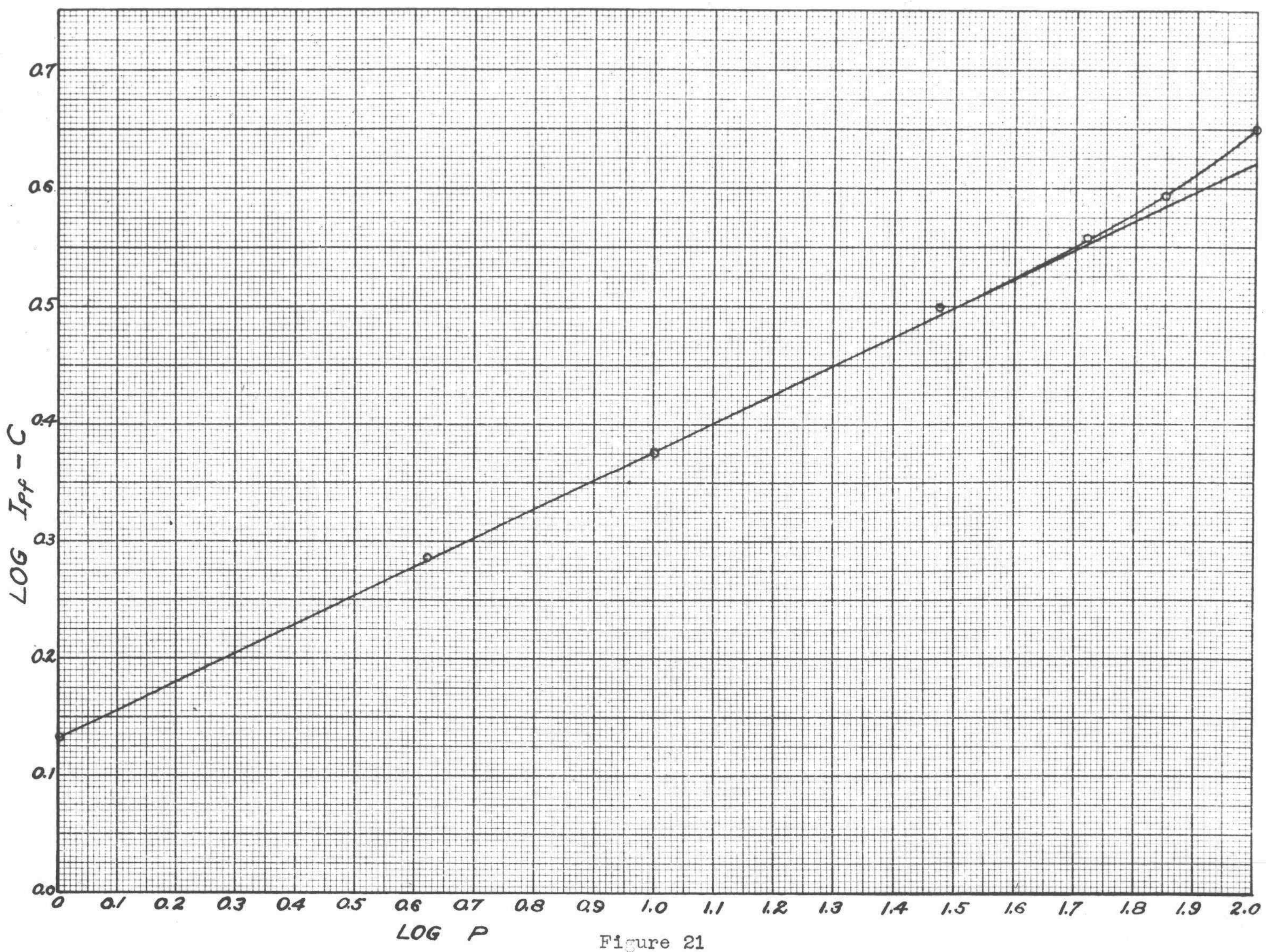

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
LOG I_{pf} - C
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
LOG P

Figure 21

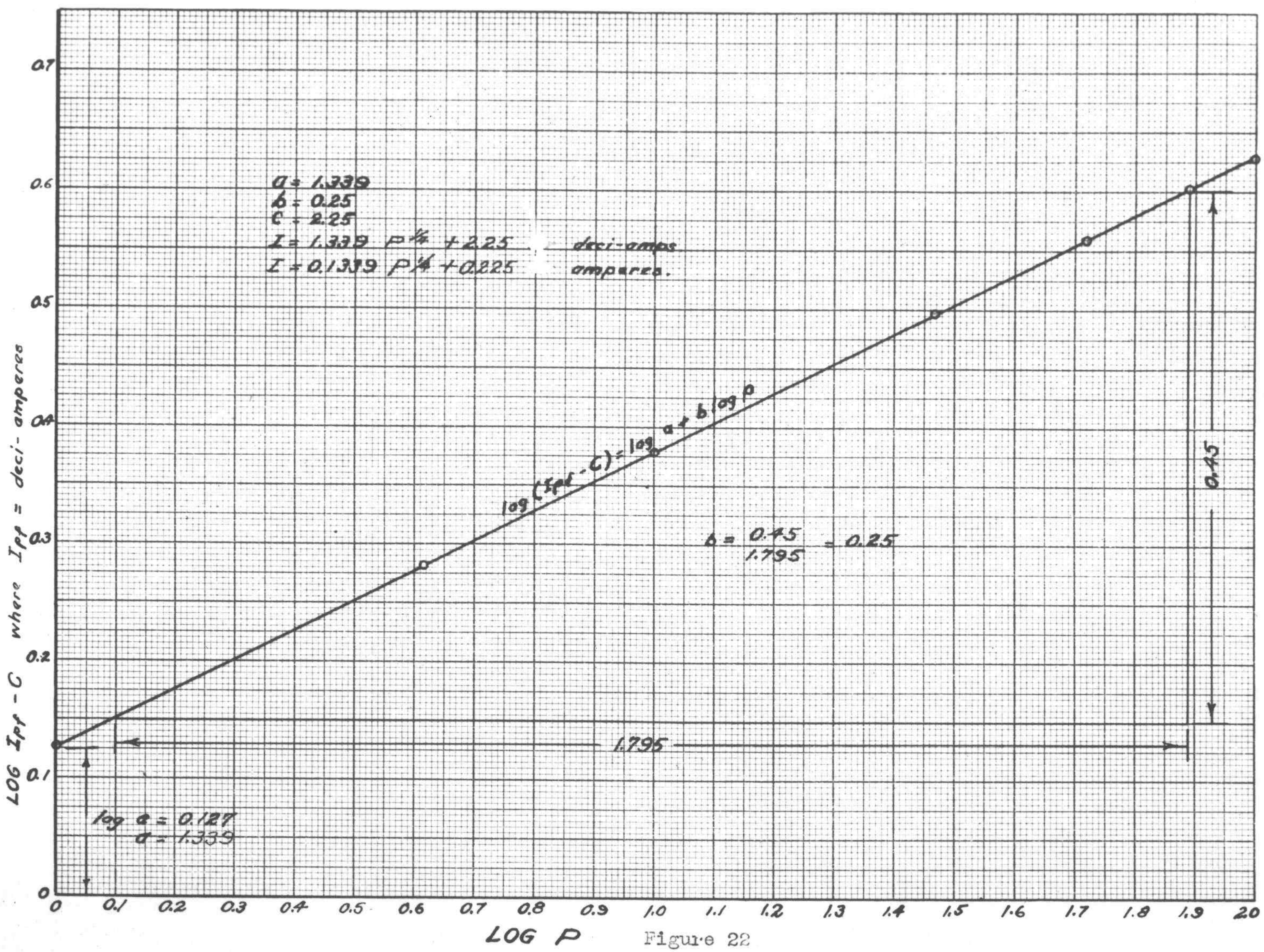
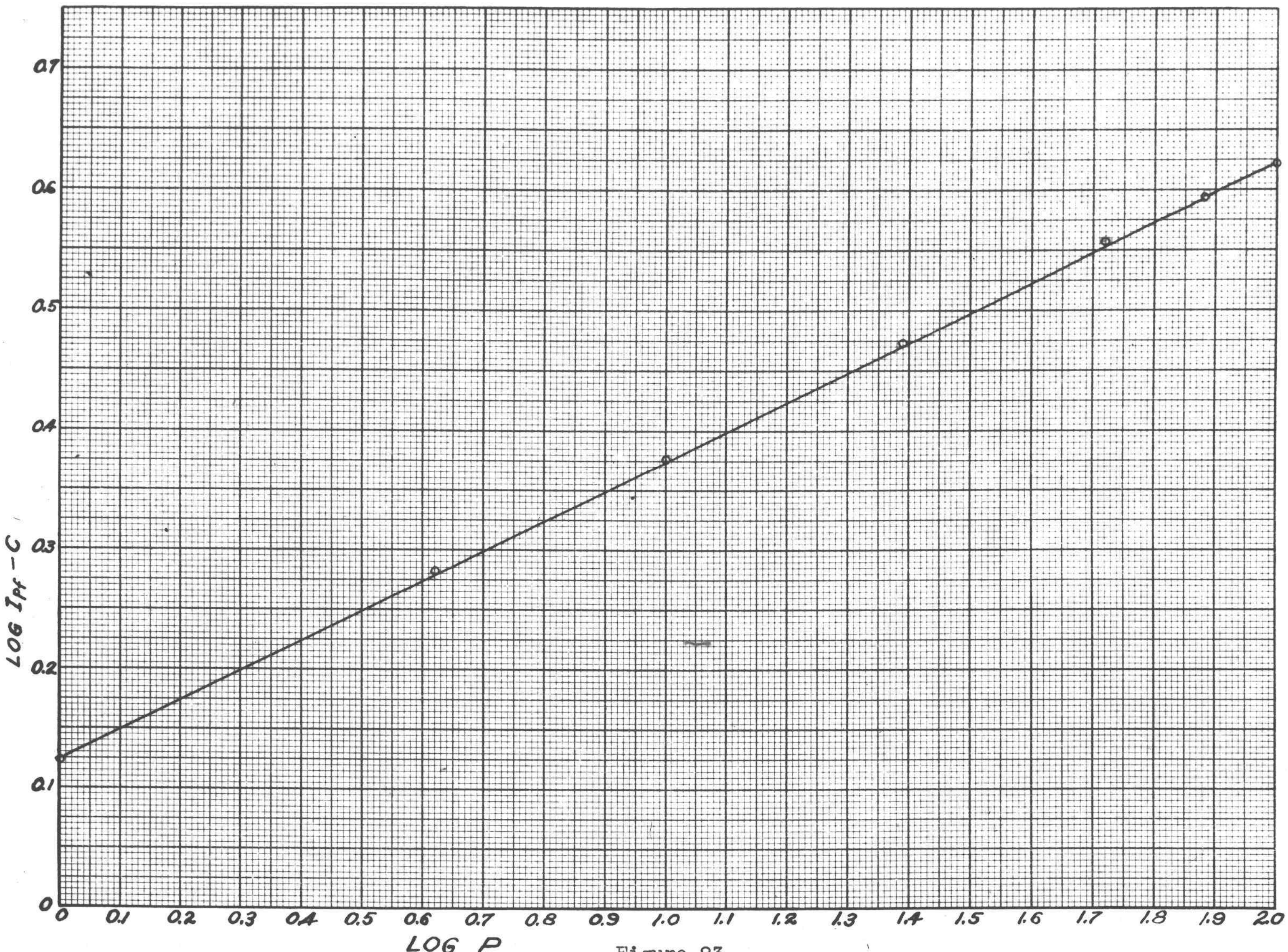

a = 1.339
b = 0.25
C = 2.25
I = 1.339 P^1/4 + 2.25 deci-amps
I = 0.1339 P^1/4 + 0.225 amperes.
log (Ipf - C) = log a + b log P
b = 0.45 / 1.795 = 0.25
0.45
1.795
log a = 0.127
a = 1.339
LOG Ipf - C where Ipf = deci-amperes
LOG P
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0

Figure 22



0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
LOG I_{Pf} - C
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
LOG P

Figure 23

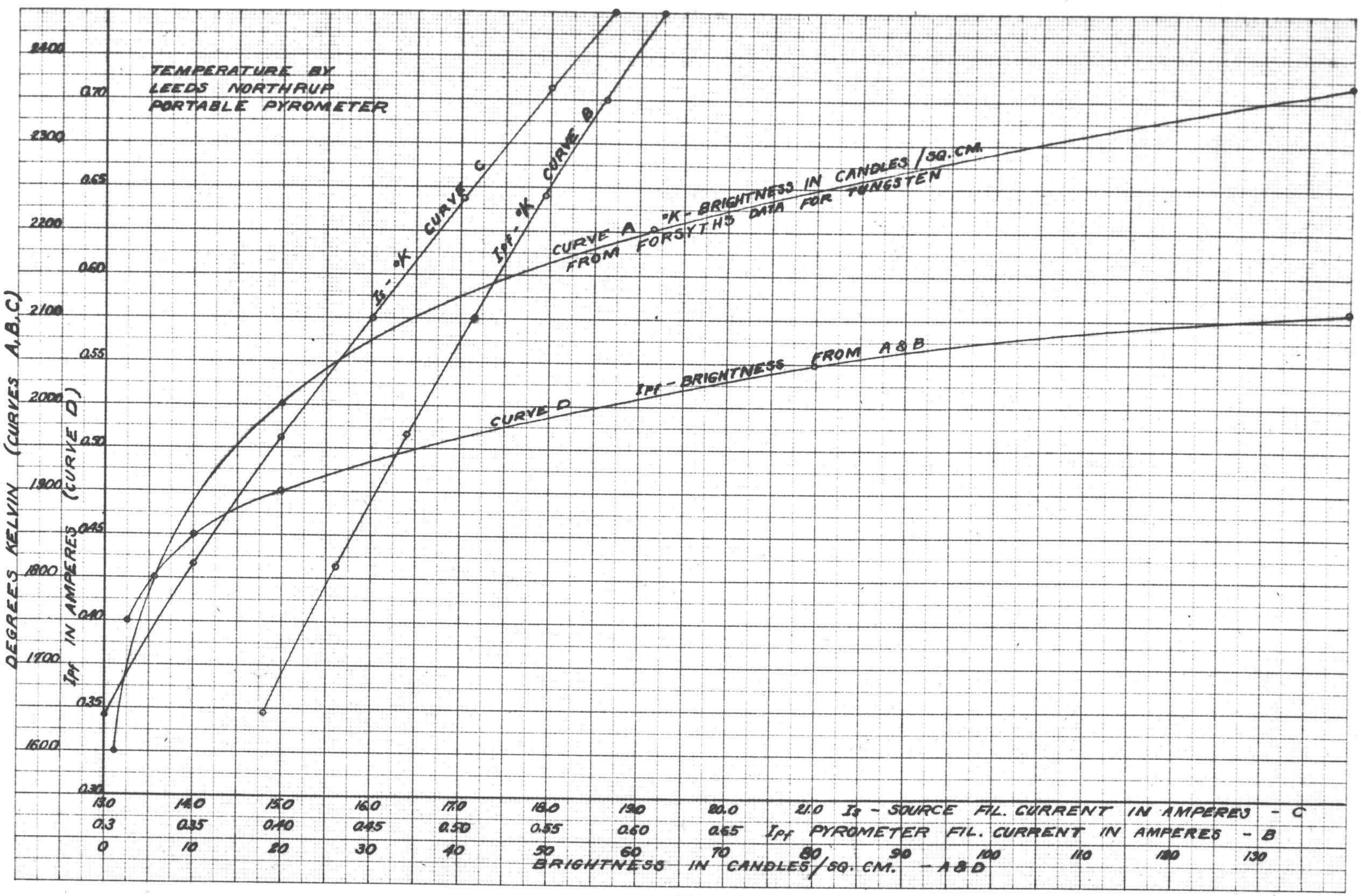

TEMPERATURE BY
LEEDS NORTHRUP
PORTABLE PYROMETER
DEGREES KELVIN (CURVES A,B,C)
Ipf IN AMPERES (CURVE D)
2400
2300
2200
2100
2000
1900
1800
1700
1600
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
Is - °K CURVE C
Ipf - °K CURVE B
CURVE A °K - BRIGHTNESS IN CANDLES / SQ.CM.
FROM FORSYTHS DATA FOR TUNGSTEN
CURVE D Ipf - BRIGHTNESS FROM A & B
13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0 21.0 Is - SOURCE FIL. CURRENT IN AMPERES - C
0.3 0.35 0.40 0.45 0.50 0.55 0.60 0.65 Ipf PYROMETER FIL. CURRENT IN AMPERES - B
0 10 20 30 40 50 60 70 80 90 100 110 120 130
BRIGHTNESS IN CANDLES/SQ. CM. - A & D

Figure 24

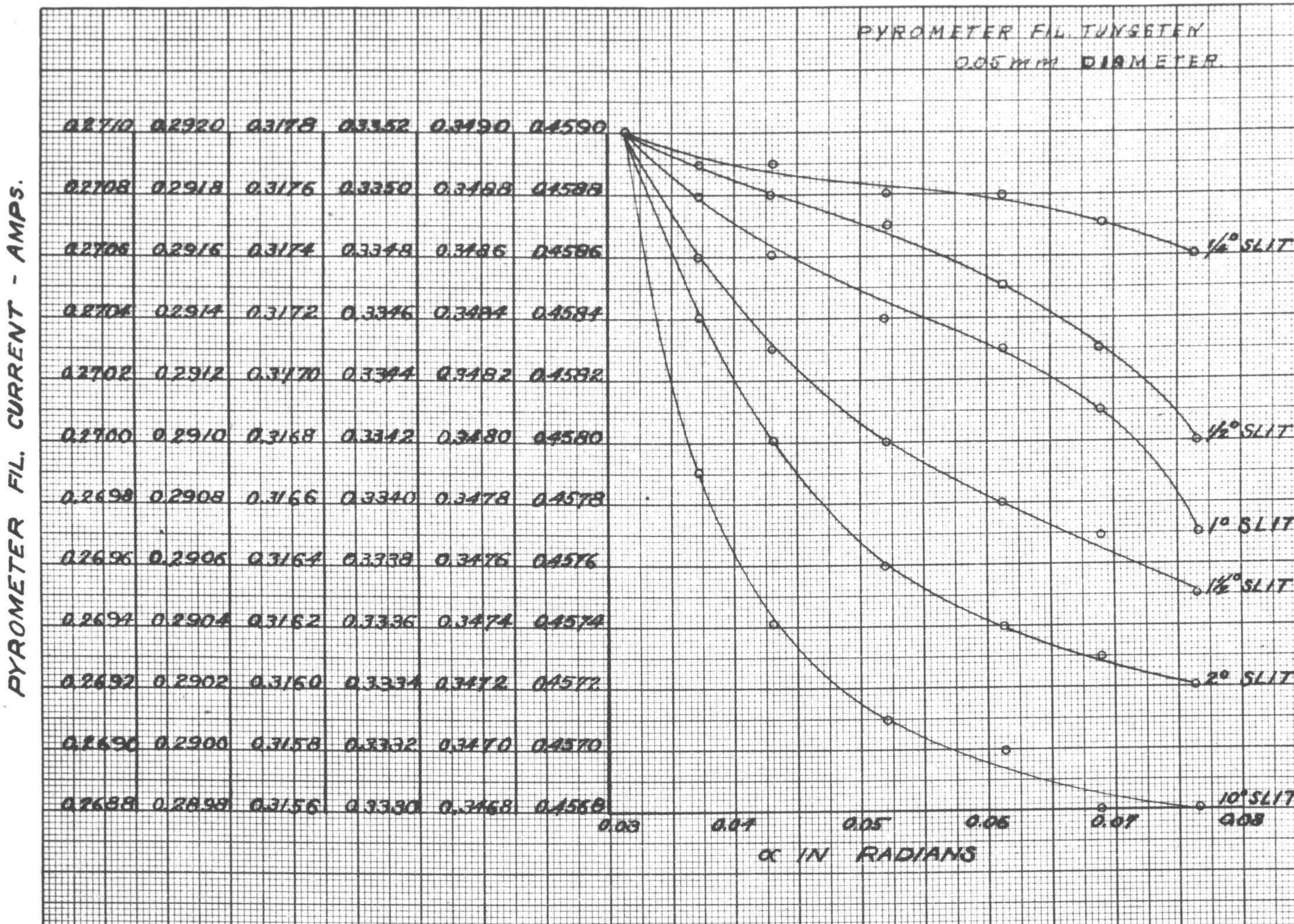


Figure 25

Variation in Pyrometer Filament Current for Changes in α and Different Openings in the Sectored Disk.

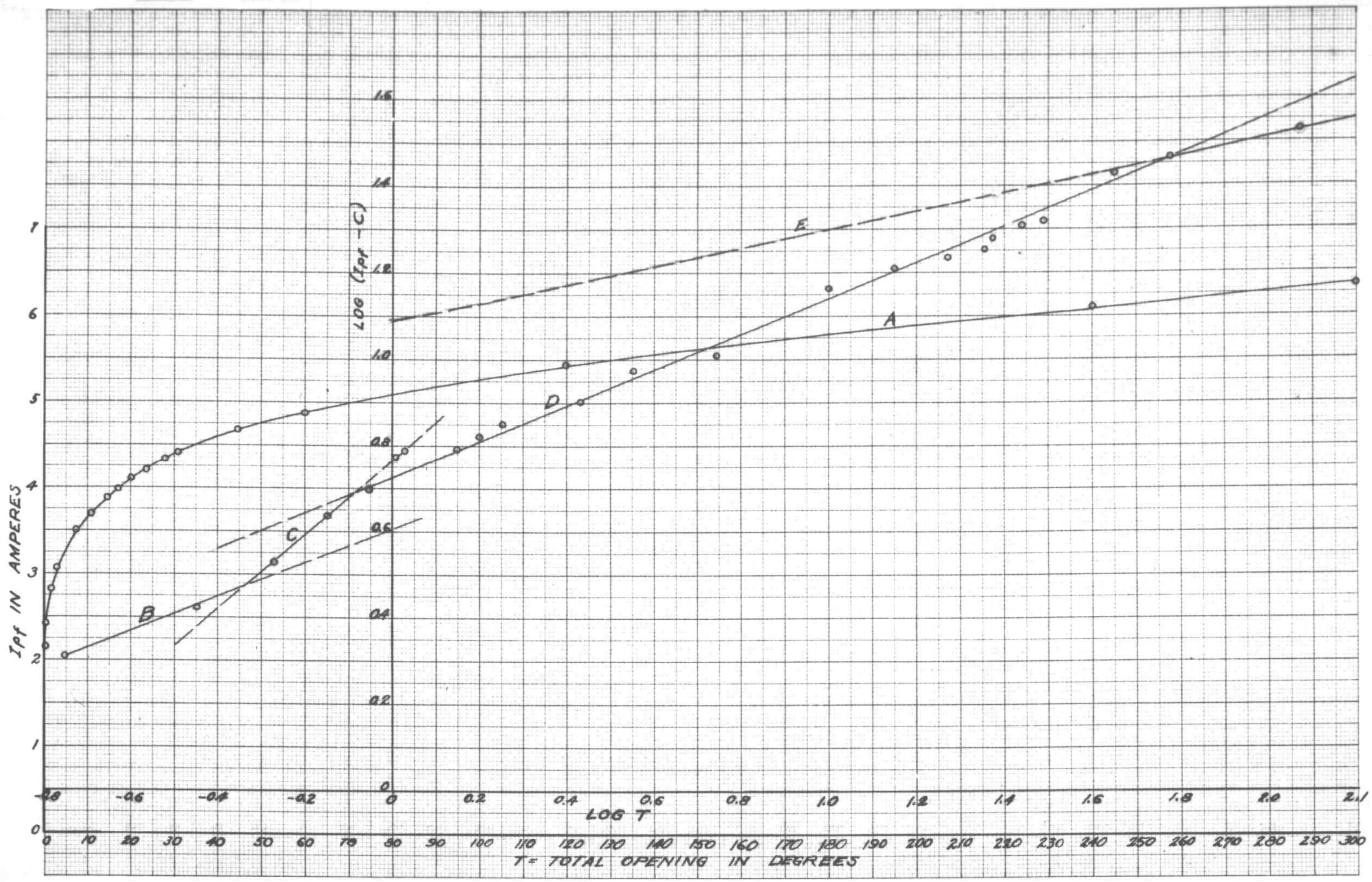


Figure 26.

Curve A is plotted from the same data as curves A, B, C, Figure 27. Curves B, C, D, E show the changes in slope of the log-log curves.

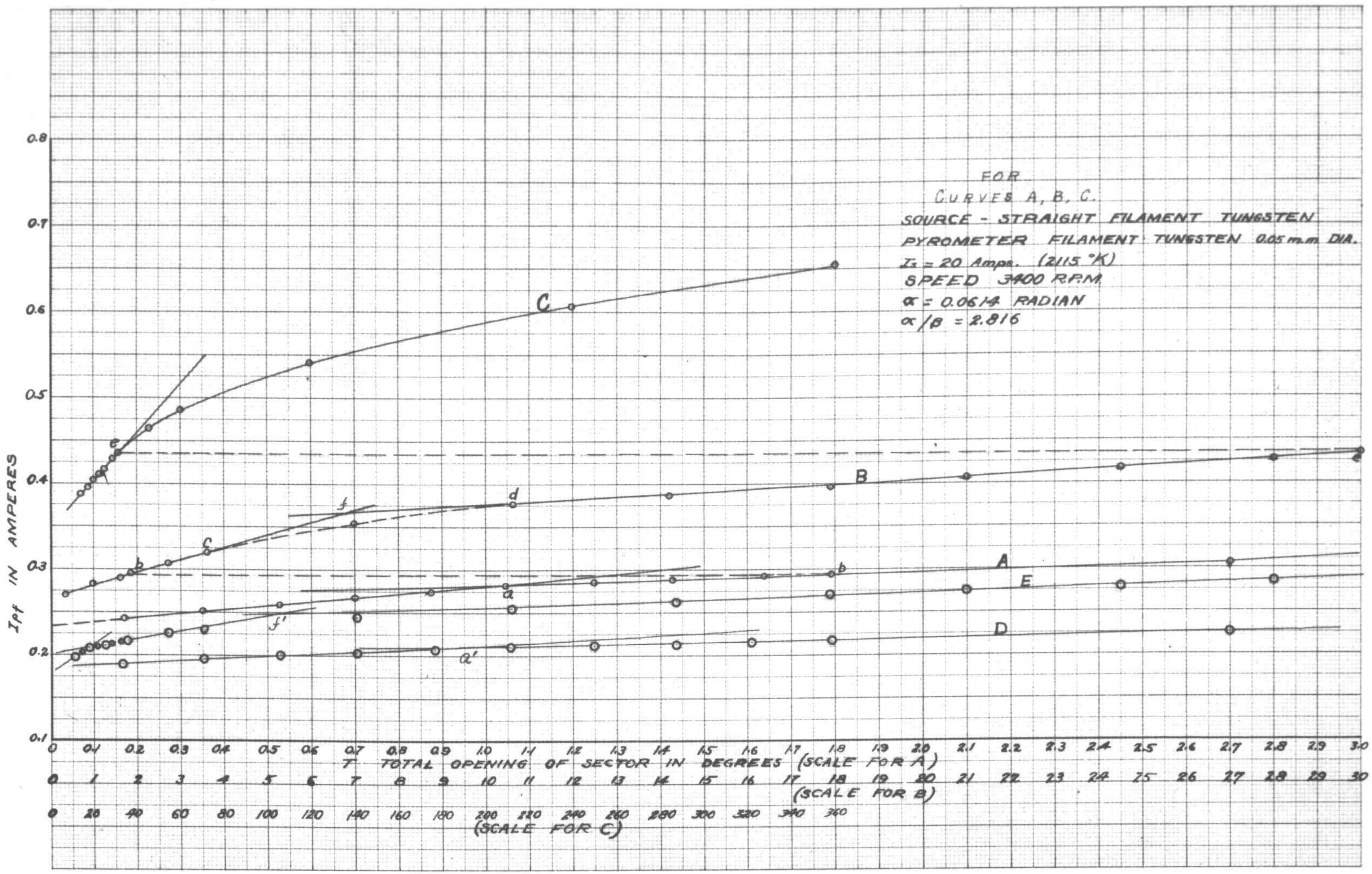


Figure 27

Curves Showing the Relation Between Pyrometer Filament Current in Amperes, I_{pf} and the Total Sector Opening in Degrees, T. Curves A, B and C were taken with a pyrometer filament 0.05 mm diameter and curves D and E with a 0.045 mm diameter filament.

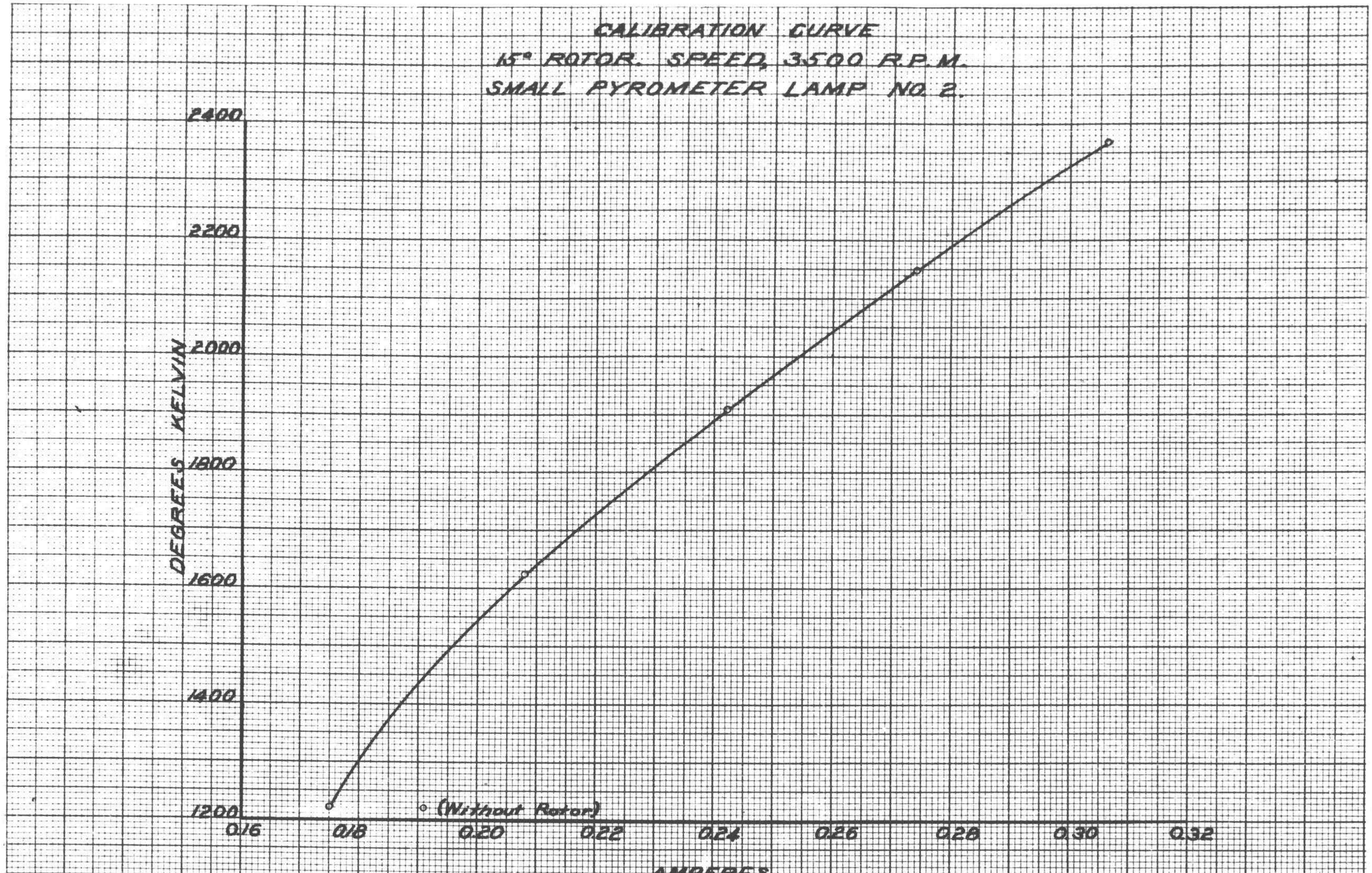

CALIBRATION CURVE
15° ROTOR. SPEED, 3500 R.P.M.
SMALL PYROMETER LAMP NO. 2.
DEGREES KELVIN
2400
2200
2000
1800
1600
1400
1200
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
(Without Rotor)
AMPERES

Figure 28

VII. SUMMARY

The use of a rotating sector disk to diminish the intensity of a beam of light involves several obscure phenomena that can be studied by means of a Holborn-Kurlbaum optical pyrometer. A very rigid laboratory form of this instrument was therefore designed and built.

The two chief phenomena investigated, and their causes are summarized herewith:

1. There is great difficulty in making a brightness match when the sector disk is near the objective lens. This was found to be due to (a) vibrations, particularly of the pyrometer filament caused in part by air currents from the rotating sector; (b) lack of exact alignment of the edges of two narrow slits along two diameters of the disk; (c) irregularities in the beam (striae) caused by slight irregularities in the bulb of the pyrometer lamp augmented by diffraction and probably polarization effects; (d) diffraction of light from the background at the rotating sector. These effects except (a) and (b), are all smaller when the sector is put into the narrow part of the beam near the pyrometer lamp.

2. When the pyrometer filament is at a brightness match with a constant background, the current in the pyrometer filament is small or large, indicating a lower or a higher temperature, depending on whether the sector disk

is placed near the objective lens or near the pyrometer lamp. That this is in part due to diffraction of light from the background at the pyrometer filament had already been established when this investigation was begun. Other factors involved were found to be (a) diffraction at the sector slit; (b) angle of convergence of the cone of rays leaving the objective lens.

Some other results of this investigation are:

1. The photography of diffraction fringes due to a circular opening in a rapidly rotating disk.

2. The establishment of criteria for higher sensitivity in the operation of the instrument: the selection of eyepiece magnification that will give complete disappearance of the pyrometer filament at the center of the background but not at its edges.

3. The establishment of the fact that when a filter is used instead of the rotating disk, there is for any particular instrument, an optimum angle of convergence of the cone of rays leaving the objective lens, and the derivation of an equation for determining the transmission of the filter in terms of pyrometer filament current (and therefore of temperature) at the angle.

4. The establishment for a rotating sector, of a most desirable angle of convergence of the beam leaving the objective lens, and the determination for this angle

of a set of three straight lines for obtaining temperature in terms of pyrometer filament current.

5. The determination of the fact that diffraction effects at the slit are negligible for sector openings of 3° and larger.

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