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Title Reconstruction and Calibration of a Small Grating Spectrograph

Abstract Approved Redacted for privacy
(Major Professor)

The object of this investigation was to redesign and put into workable shape a certain grating spectrometer. A new grating holder was designed and constructed that permits of making all of the necessary adjustments step by step. An auxiliary telescope mounting was designed and built to permit all preliminary adjustments to be made visually and rapidly. A safe method of supplying sources with high tension current was designed and constructed.

Tests were made to establish the limits of the usable first order spectrum and to determine the fact that the departures from a normal spectrum are practically negligible.

A spectral calibration chart was obtained by use of six different sources.

A study was made of the absorption curves of six different samples of dyed cellophane.

The spectrometer has been converted into a usable instrument convenient to use.

RECONSTRUCTION AND CALIBRATION OF A
SMALL GRATING SPECTROGRAPH

by

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To Professor J. C. Garman, I wish to express my thanks for suggesting the determination of absorption of dyed cellophane as one of the problems considered.

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RECONSTRUCTION AND CALIBRATION OF A SMALL GRATING SPECTROGRAPH

Introduction

The present thesis problem had its origin in the failure of a commercial grating holder to function properly. It was impossible in a reasonable time to place the grating in a recently purchased spectrograph so as to obtain a sharply focused spectrogram.

An attempt was made, during the summer of 1939, to mount the grating permanently in a usable position. All attempts, however, were futile, as the holder could not be shifted gradually from one position to another and since, further, its position was shifted by the act of tightening the clamp screw.

In order to make the necessary adjustments, the holder must be capable of independent rotation about three mutually perpendicular axes. With the grating perpendicular to the floor of the spectrograph, let us consider the X axis perpendicular to the face of the grating at its central point, the Y axis vertical and the Z axis horizontal.

The design of the new grating holder permits independent rotation by means of spring controlled set screws. The holder is movable along a track on the floor of the spectrograph, the track being in the direction of the center of the photographic film. By the use of this holder, a perfect adjustment can be made in a few minutes. This holder has made the spectrograph a very useful piece of apparatus.

Tests were made to show the upper and lower usable wave-length limits. Test photographs were taken with the holder at different distances from the film to check the sharpness of focus. The dispersion was measured for different positions of the grating with respect to the Y axis. For calibration purposes, a film was exposed giving known lines of mercury, helium, argon, neon, sodium and iron.

Theory of the Grating Spectrograph

As is well known, if the source of radiation of a grating spectrograph is placed on the Rowland circle, whose diameter is equal to the radius of curvature of the grating, the spectra of the various orders will be in focus on an arc of the same circle.

In Fig. 1, let PQ be a grating with C as its center of curvature. For a first approximation, (5) let the width of the grating be so small compared to its radius of curvature that its surface may be considered to deviate a negligible amount from the Rowland circle. With a monochromatic source at A, let one ray, AP, strike the grating at an angle of incidence i. This gives rise to a diffracted ray, PB, in the first order at angle θ. Similarly, let AQ be another ray incident at angle i at another point on the grating. Its first order diffraction image will also leave at an angle θ and therefore reinforce ray PB at B. This is true because angles APB and AQB, being subtended by the same arc, must be equal. What is true for points P and Q will also be true for all other points of the grating. If the source is not monochromatic, lines corresponding to other wave-lengths will be formed on the arc of the circle in the neighborhood of B.

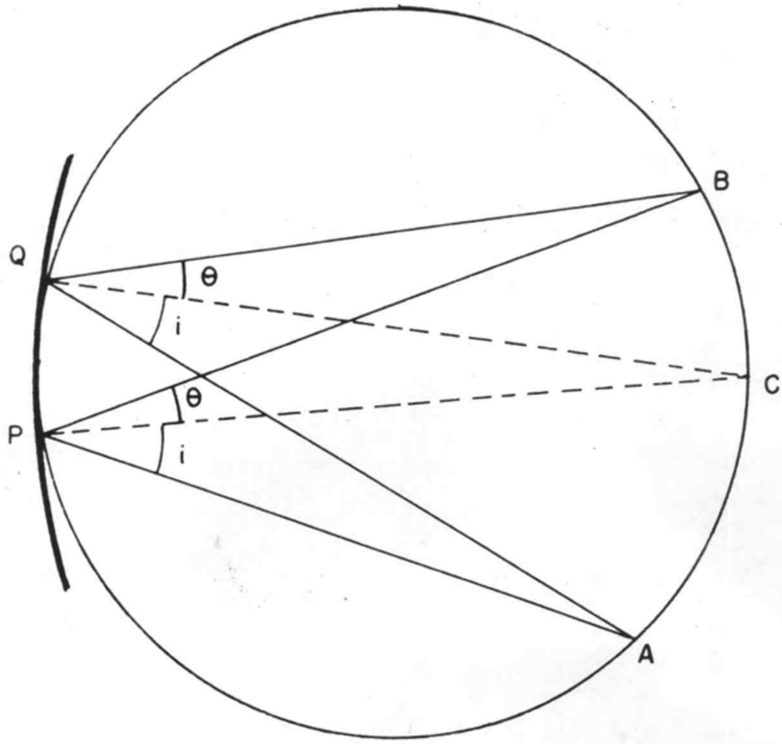


Figure (1)

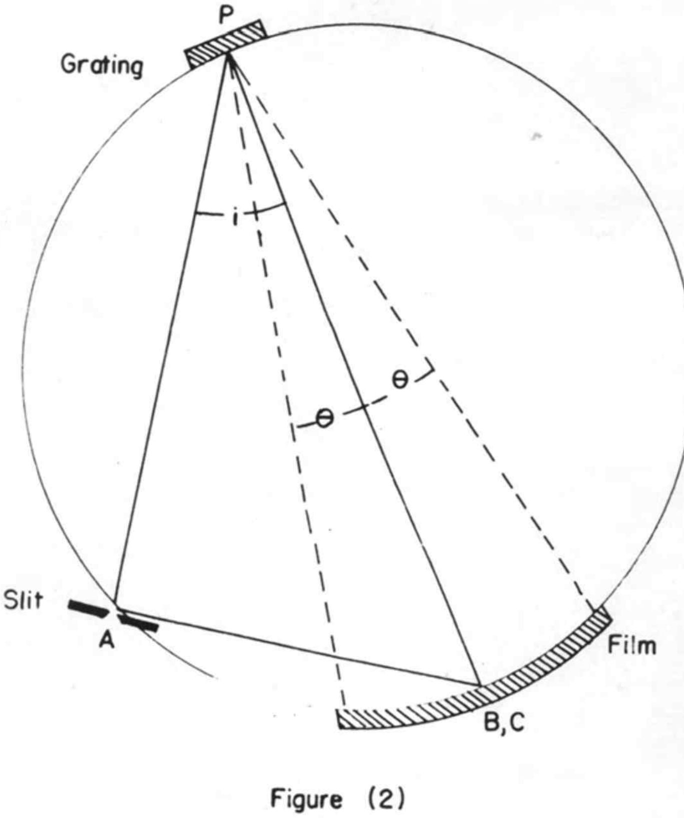


Figure (2)

The Cenco Concave Grating Spectrograph used in this investigation is designed to focus the first order spectrum (range 4000 A) with its central line at 4800 A. In other words, angle θ is zero at this wave-length so that points B and C will coincide. The points P, A, and BC will lie at the vertices of a right triangle as shown in Fig. 2.

Since the grating face does not actually lie in the Rowland circle, it will be necessary to determine more closely the location of the lines of the spectrum. The position of the lines and orders of the spectra can be shown in the following manner. From a very elementary point of view, (1) let A, B, C and D in Fig. 3 represent the smooth parts of the grating from which reflection takes place. If a parallel beam is incident at angle i, consider the radiation diffracted at angle θ. The two rays striking the smooth parts A and B are in phase at A and F and at B and G, if the lines AF and BG are perpendicular respectively to the incident and diffracted beams. If two crests of a wave front start from B and G simultaneously, they will arrive at the same time at the focus of a lens whose axis makes an angle θ with the normal to the grating and will, therefore, reinforce one another. Hence the path difference between the rays falling on successive smooth parts of the grating is

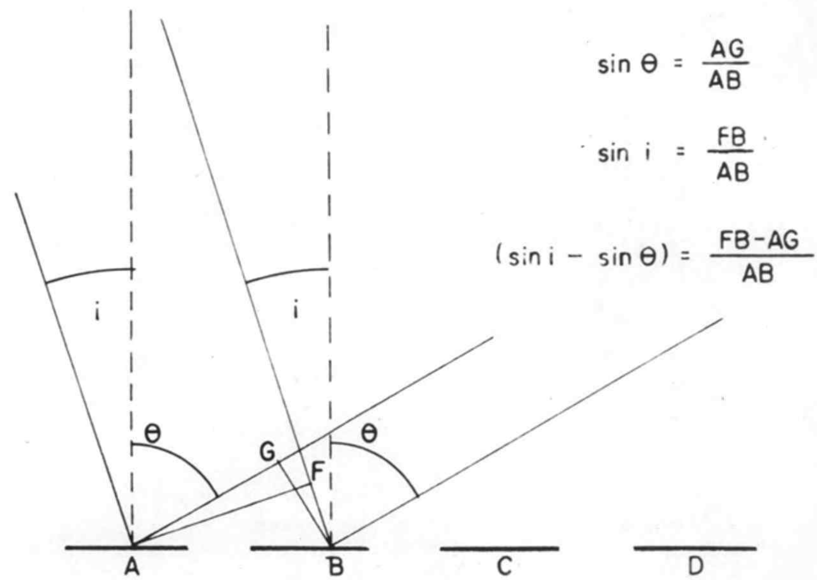


Figure (3)

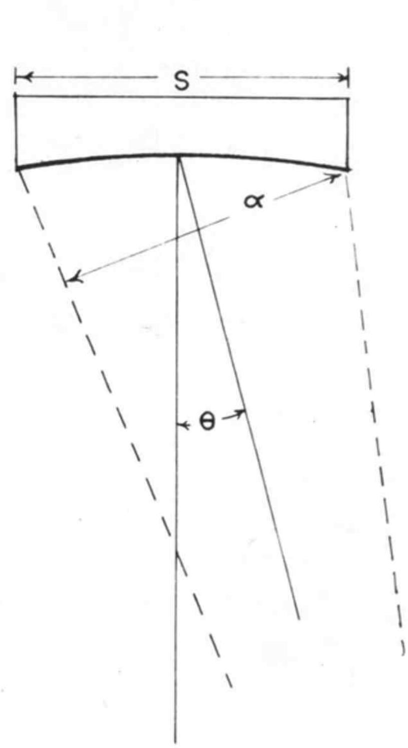


Figure (4)

AG - BF. If AB, the grating space, is denoted by m, and if the case under consideration is that in which the difference AG - BF is an integral number n of wave-lengths λ, the equation (1) is readily derived from Fig. 3:

$$m(\sin \theta - \sin i) = n\lambda \qquad (1)$$

It is of interest to calculate the angle i for the present spectrograph when $n = 1$, $\theta = 0$, $\lambda = 4800 \times 10^{-8}$, and $m = 2.54/15160 = 1.675 \times 10^{-4}$ cm.

$$4800 \times 10^{-8} = 1.675 \times 1.675 \times 10^{-4}(\sin i) \qquad (2)$$

$$16° \; 22' = i \qquad (3)$$

The dispersion may be obtained by differentiating equation (1) considering i constant:

$$D = \frac{d\theta}{d\lambda} = \frac{n}{m \cos \theta} \qquad (4)$$

The values of θ for first order lines at extreme positions on the film are obtained by making $\theta = 0$, and giving the value 16° 22' to i, and respectively 2800×10^{-8} and 6800×10^{-8} to λ. The two values of θ are found to be ± 6° 34'; that is, the shortest and longest wave-lengths photographed lie 6° 34' to either side of the 4800 A position. Equation (4) shows that the dispersion depends on $\cos \theta$; as cos 6° 34' = 0.9934, which is nearly unity, the dispersion is seen to be approximately constant throughout the entire spectrum, deviating only sixty-six parts in a thousand at each extreme.

Although there is apt to be a slight variation in the number of lines per inch on a grating replica, the dispersion of the grating may be calculated from (4). The radius of curvature of the grating is 106 cm. Hence:

$$\frac{d\theta}{d\lambda} = \frac{dx}{d\lambda} \cdot \frac{1}{106} = \frac{1}{1.675 \times 10^{-4}\text{cm} \cdot 1} = \frac{10^{-4}}{1.675}\ \text{A} \qquad (5)$$

where dx is the distance in centimeters on the film at 4800 A corresponding to a spectral width of $d\lambda$.

Since it is customary to express the dispersion of a spectrograph in Angstroms per millimeter, the result may be written:

$$\frac{d\lambda}{dx} = \frac{1.675}{106 \times 10^{-4}} = 157.5\ \text{A/cm or } 15.8\ \text{A/mm.} \qquad (6)$$

This is very nearly 400 Angstroms per inch, so that a scale divided into fortieths of an inch may be used as an approximate wave-length scale. Such a scale enables measurements to be made to within a few Angstroms. For more accurate measurements, comparison spectra must be exposed on the same film as the unknown.

The limit of resolution of an optical instrument is $\Delta\lambda/\lambda$, and the resolving power is the reciprocal of this quantity:

$$R = \lambda/\Delta\lambda \qquad (7)$$

where $\Delta\lambda$ is the wave-length difference which is just detectable. Under these conditions, the diffraction pattern of two lines λ_1 and λ_2 where ($\lambda_1 - \lambda_2 = \Delta\lambda$) is such that the central maximum of one falls on the first minimum of the other:

$$\Delta\lambda = \frac{d\lambda}{d\theta} \cdot \Delta\theta \qquad (8)$$

But $$\Delta\theta = \lambda/\alpha \qquad (9)$$

where α is the effective aperture, S cos θ, Fig. 4, S being the grating width. Hence:

$$\Delta\theta = \frac{\lambda}{S \cos \theta} \qquad (10)$$

Substituting equations (10) and (4) in equation (8):

$$\Delta\lambda = \frac{m \cos \theta}{n} \cdot \frac{\lambda}{S \cos \theta} = \frac{m\lambda}{nx} \qquad (11)$$

Substituting equation (11) in equation (7):

$$R = \frac{\lambda \cdot ns}{m\lambda} = \frac{ns}{m} = nN \qquad (12)$$

where N is the total number of lines on the grating.

This shows that the resolving power is directly proportional to the total number of lines of the grating. In general, therefore, the wider the grating, the better the resolution of the spectral lines. However, as it is extremely difficult to transfer a large replica film without damage or distortion, the grating used in this instrument is masked down to a small portion of its total surface. Longer exposures are of course necessary, but the spectra obtained are of a better quality than those that would be given by the entire grating.

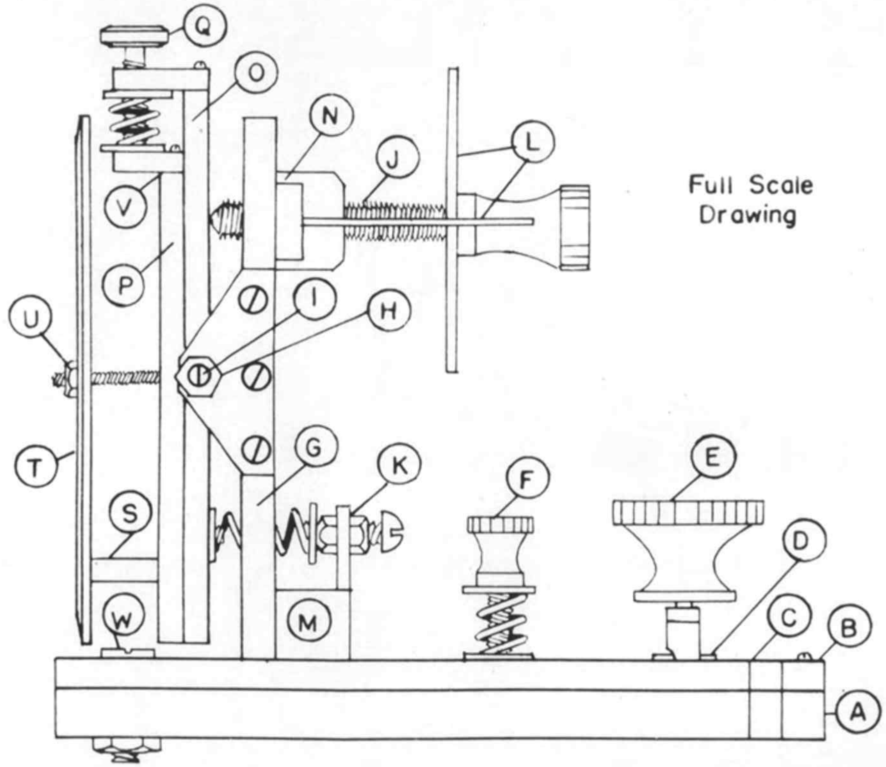
Construction

The main part of the newly designed grating holder was constructed of brass. The letters in the following discussion refer to Fig. 5.

The base-plate A was cut from a three-inch piece of quarter-inch sheet brass. One end was drilled for the Y axis pivot screw W while the other end was cut to a 3 3/16 inch arc; scale B was affixed by two machine screws. The turntable C for the Y axis pivot was cut from three-sixteenths inch stock. It was drilled for the pivot screw W and shaped to the same arc as the base-plate A. The turntable was provided with an index mark to locate its position with respect to scale B. The turntable may be rotated by means of the rack and pinion D, actuated by turning knob E. The knurled knob and spring at F control the friction between the turntable and the base-plate. The rack used at D has twelve teeth per inch; the pinion has ten teeth and was the smallest commercially stocked one available.

The Z axis pivot support G was made of three-sixteenths sheet brass. The end supports H were made of the same material and were fastened to G by six machine screws. The Z axis pivot pins I were made by tapering the ends of machine screws, leaving enough thread to permit the

SPECTROGRAPH GRATING HOLDER



Full Scale
Drawing

Figure (5)

use of a lock nut to hold them in position in H. The set screw J is used to tilt the holder about the Z axis against the pressure produced by spring K. The scale on the head L is divided into fifty divisions, the pitch of the thread being one millimeter. The supports at M and N were made respectively of three-eighths and half inch square stock.

The X axis base-plate O and turntable P were formed from eighth inch brass stock. The base-plate was drilled for both the Z axis and X axis pivot screws. The set screw Q and spring R are used to rotate the turntable P about the X axis. The brass shelf S is the support for the grating and enables accurate replacement if the grating is removed for any reason. The clamp ring T was made from a piece of one-sixteenth inch sheet brass; it is secured by tightening the nuts at U. A scale was placed at V so that changes of rotation about the X axis can be noted. The pivot screw W is placed so that its projection passes through the pole of the grating.

Two more motions are necessary to focus the grating. One is a sliding motion of the grating in the direction of the center of the film. The other is a rotation of the optical bench that carries the source of light and other equipment so as to keep the grating in the center of the cone of light admitted by the slit. The first of these motions is accomplished by fastening the grating holder to an iron sled that can slide along a cast iron track, Fig. 8, bolted to the floor of the spectrograph case. The sled is held against the track by a spring A, Fig. 8, and is moved along the track by the micrometer screw B, similar to the screw J, Fig. 5. The entire mounting is also shown in Fig. 7.

For visual observation of the spectrum and for testing whether the curvature of the film holder as made by the manufacturer is correct or not, a track, Fig. 6, consisting of two quarter-inch brass rods bent into arcs of concentric circles was mounted beyond the film holder; a short focus telescope mounted on a cart could be moved from place to place along the track to determine the sharpness of focus in all parts of the spectrum. Tipping of the telescope was prevented by a spring friction clamp on the cart applied to the track. This device saved both time and film. Fortunately the film holder was found to be constructed accurately.

One type of source used with the spectrograph is a gas discharge tube operated from a neon sign lamp transformer. To eliminate the chance of a shock, a high tension safety feed system A, Fig. 6, was designed. Brass rods E, serving as bus bars, are supported by insulators in a U shaped channel so that they cannot be touched accidentally. The channels are attached to the wall by means of

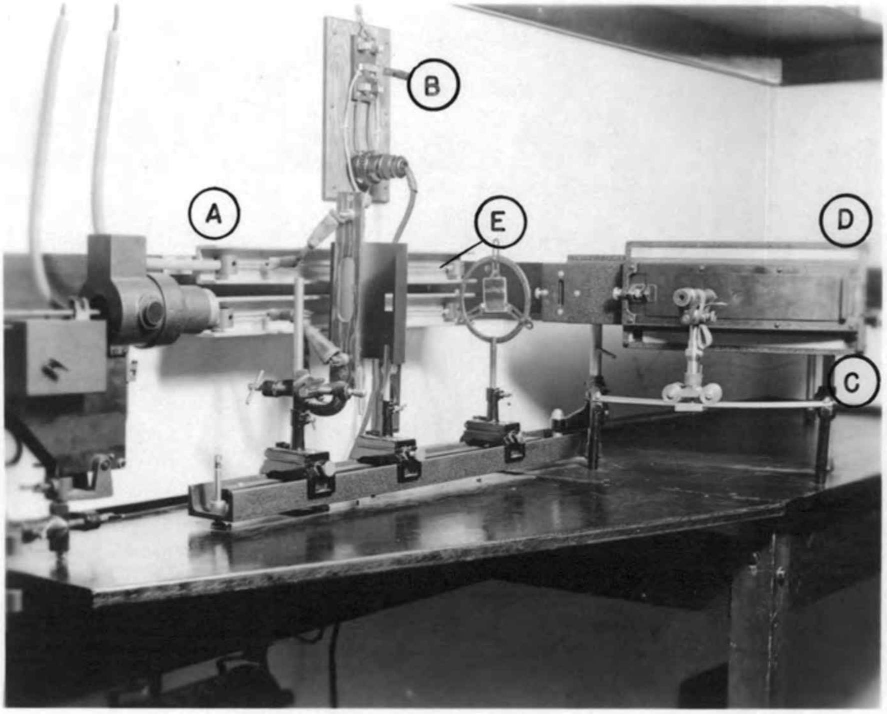


Figure (6)

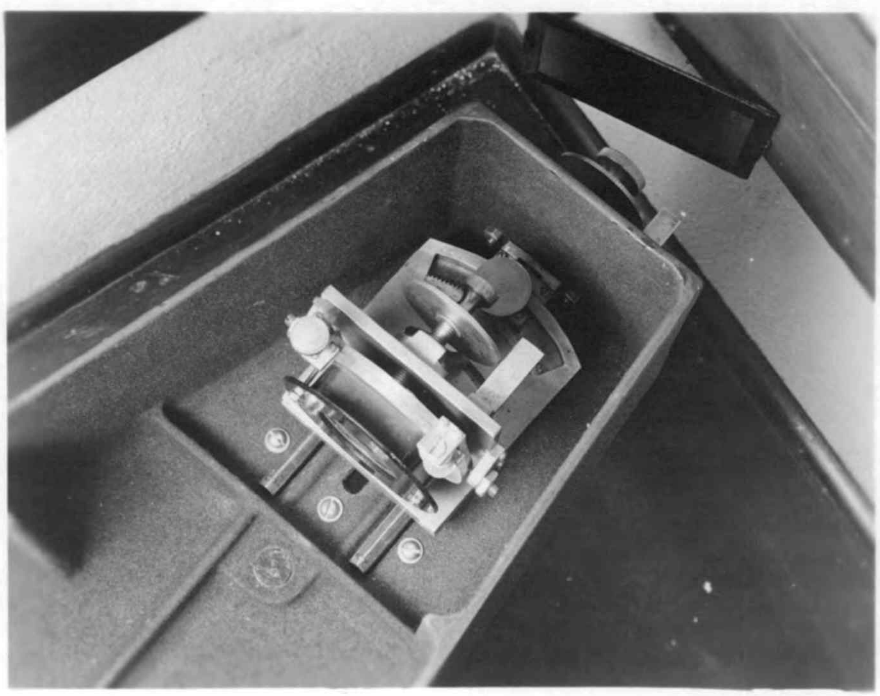


Figure (7)

HORIZONTAL TRACK AND GRATING HOLDER BED

The sliding base plate A is lapped to fit the track B. The grating holder proper is bolted securely to A.

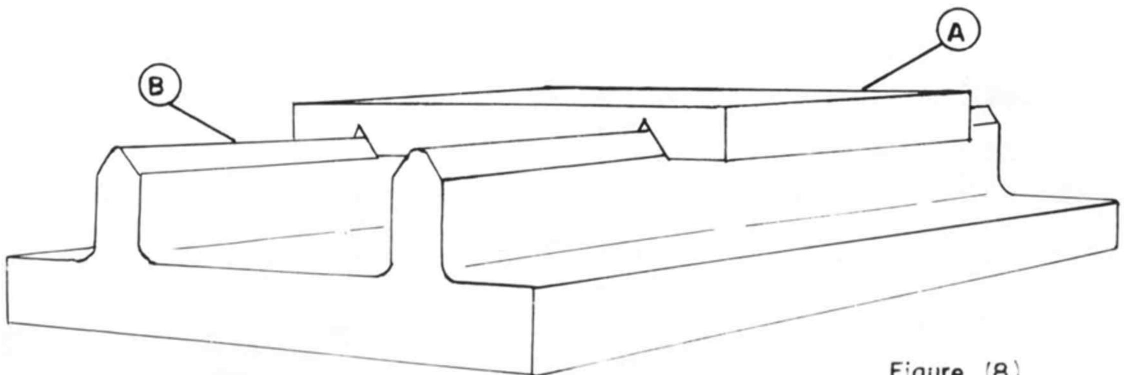


Figure (8)

GRATING HOLDER AND TRACK MOUNT

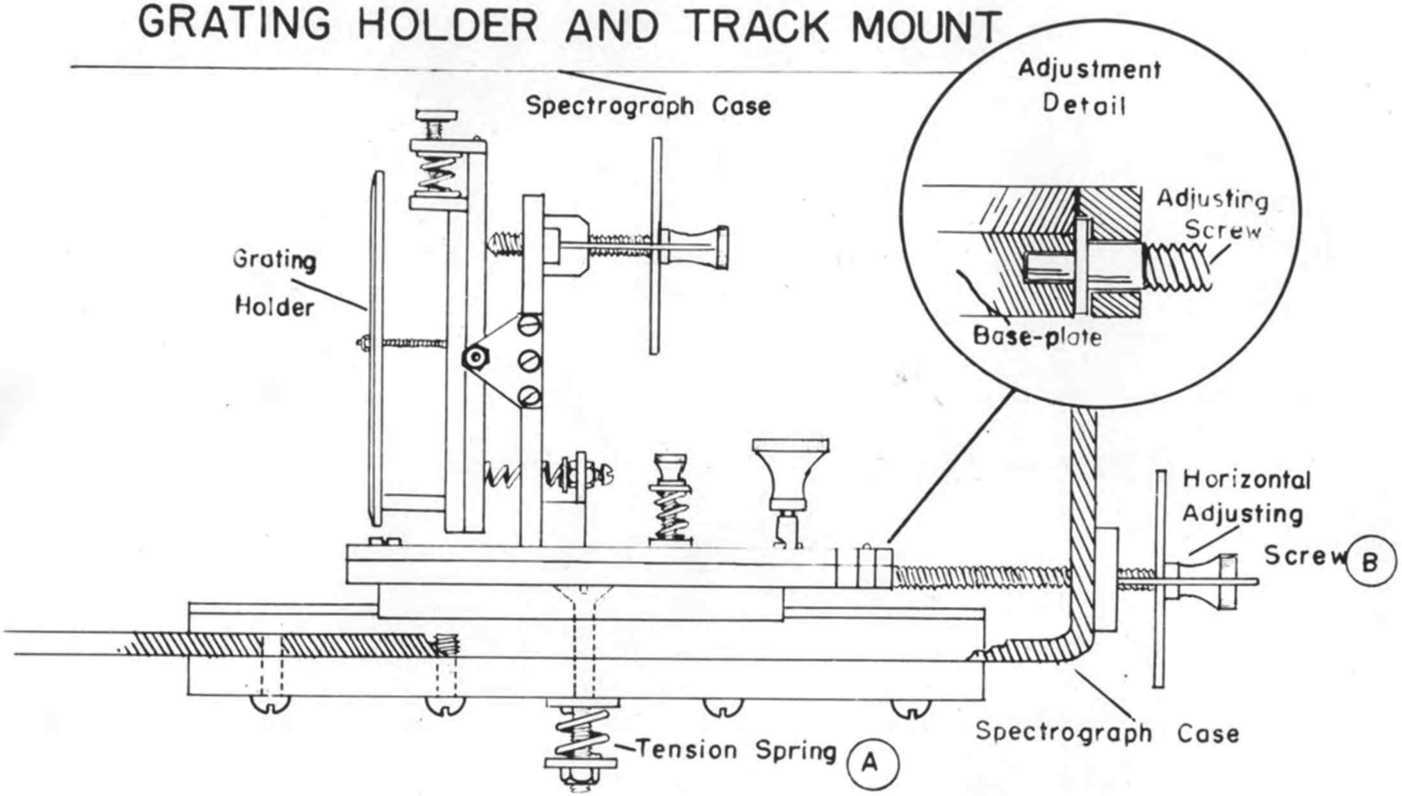


Figure (9)

stand-off rods. The transformer is mounted on the wall at such a height that contact with its terminals is impossible. The high tension leads for the transformer run down to the brass rods; the leads consist of insulated wires which are surrounded by rubber tubing. As the U channels are mounted just above and to the rear of the optical bench, a tube holder can be operated in any position along the bench, the connection to the high tension leads being made by short wires with spring clips at each end.

A carbon arc mounted near the end of the optical bench serves as an alternate light source.

For convenience, a photographic dark room was equipped adjacent to the spectrometer room. As the films were of two by ten-inch non-standard dimensions and as the cost of the developer had to be considered, a special film tank 3 by 5 by 10.5 inches of one-half gallon capacity was constructed from three-ply fir veneer. It was lined with celluloid and rendered leak proof at the joints by celluloid dissolved in acetone.

A ten-inch pyrex baking dish serves as a very good hypo tank.

The film washer, Fig. 10, was designed so as to afford maximum water circulation. It was constructed of one-sixteenth galvanized iron. Overflow is allowed to

CUT-AWAY VIEW OF FILM WASHER

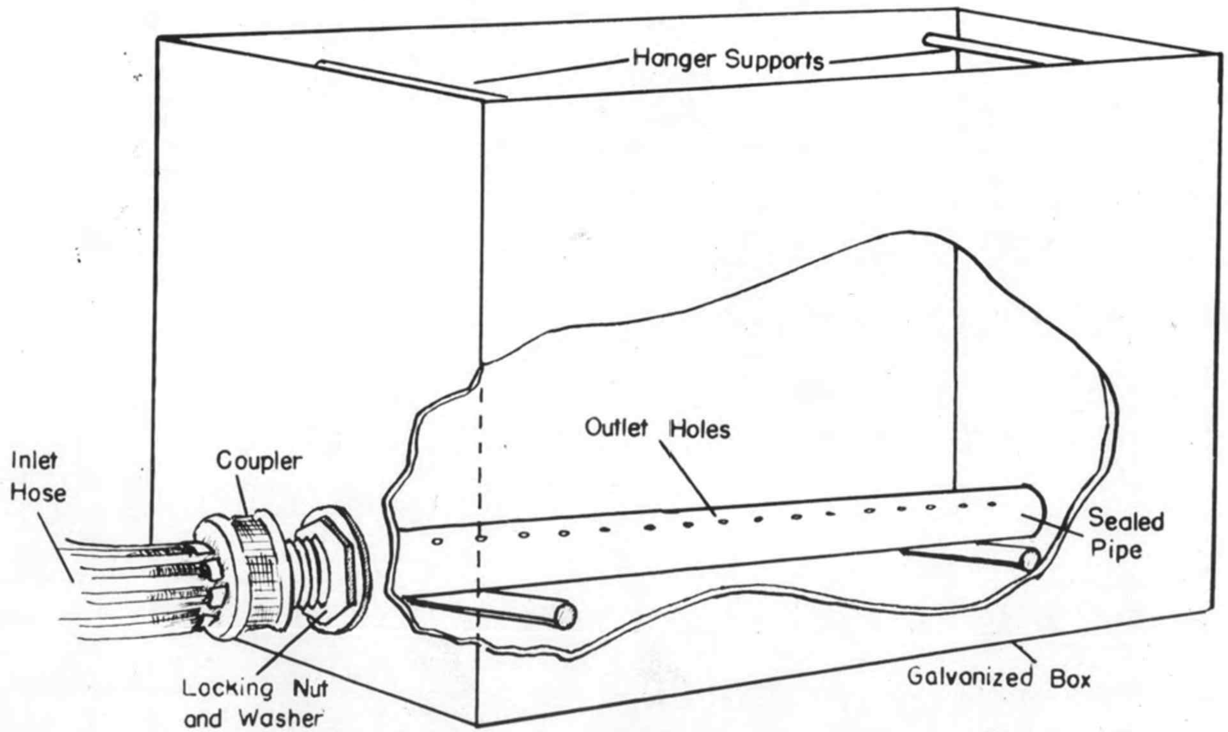


Figure (10)

escape over the sides as the entire unit is placed in the sink.

Film hangers were specially made; each is ten and one-half inches long and is provided with three film clips.

The dark room arrangements are shown in Fig. 11.

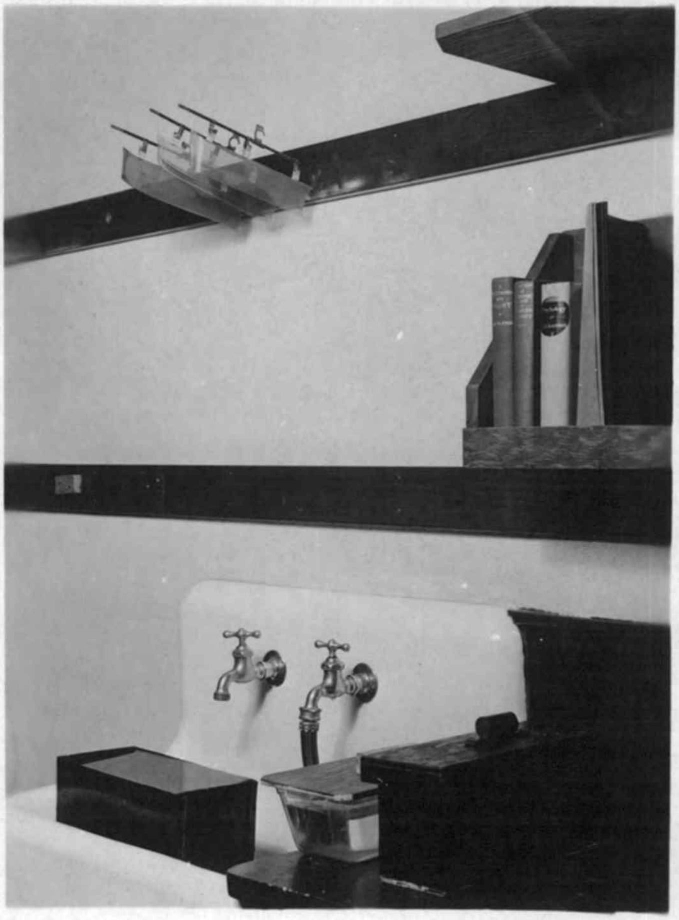


Figure (11)

Operation

The grating spectrograph, as it is now set up, is a very simple instrument to operate and yields excellent results with moderate care.

Before taking a spectrogram it is well to make a preliminary calibration to see that everything is in adjustment. This is most easily done visually by setting the telescope on the mark indicating the proper position of the 5461 A line and seeing that the cross hair actually locates the position of the green line given by a mercury discharge tube. If it is necessary to make adjustments, bring the green line on the cross hair, center the spectrum on the slit in the film mask and then bring the spectrum into the sharpest focus by moving the grating holder along the track. The slit must be parallel to the grating lines and has an adjustment for this purpose as well as for width. (Fig. 12)

The film holder must of course be loaded in the dark room. It is advisable to back the film with black paper as an additional precaution against halation. Do not withdraw the slide from the film holder without making sure that the spectrograph shutter is in the closed position. This shutter is operated by an easily accessible knob (Fig. 13).

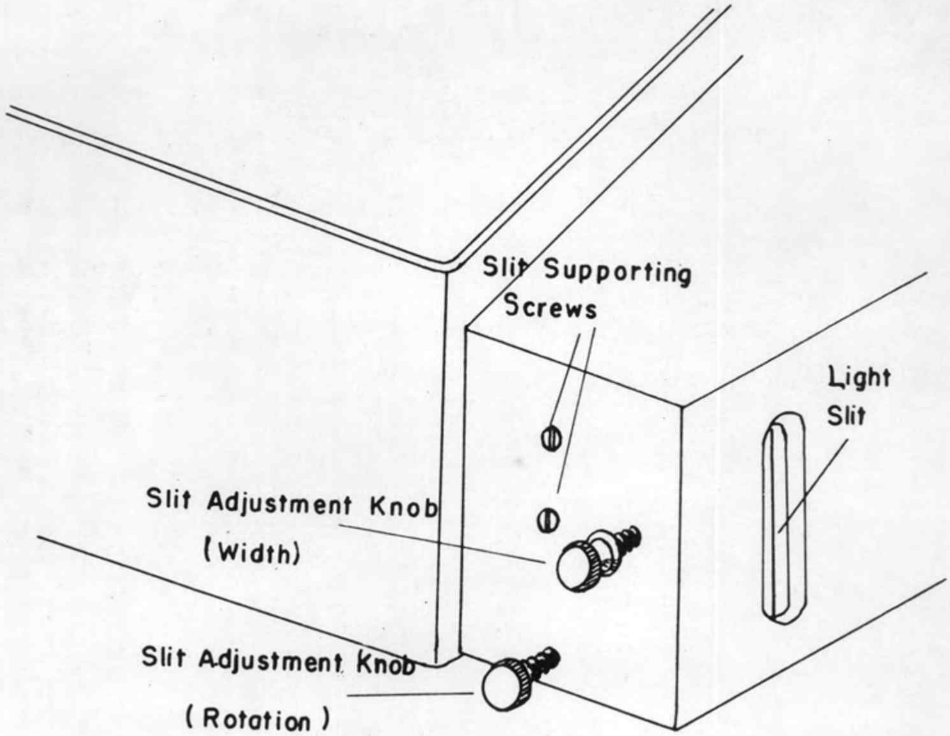


Figure (12)

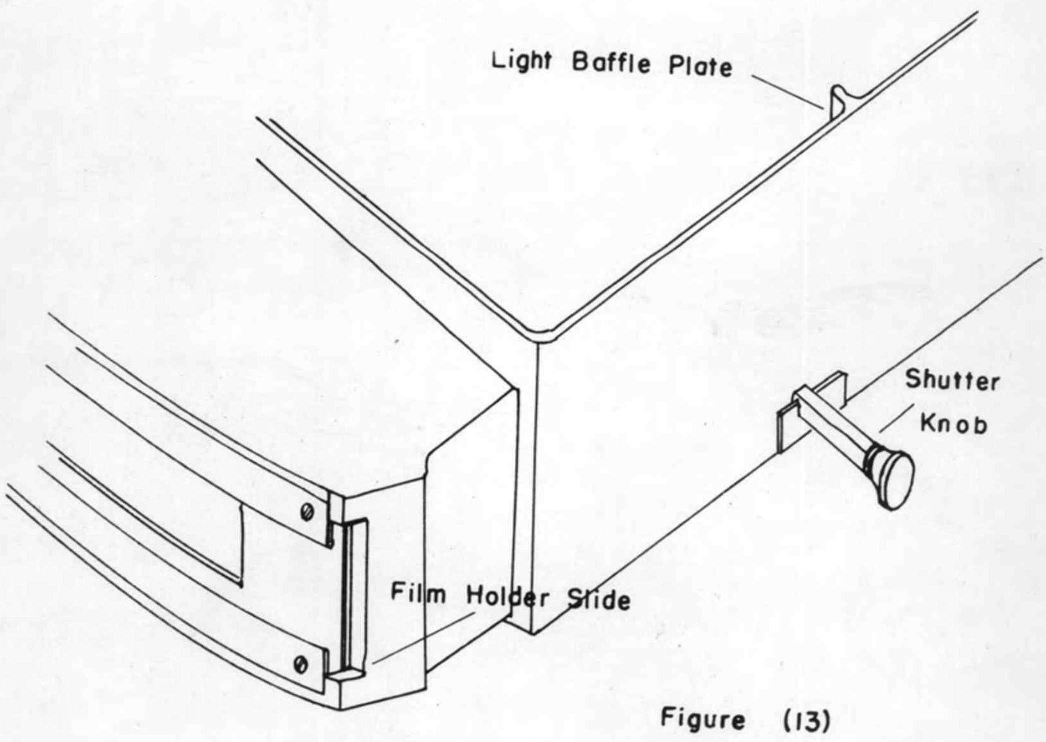


Figure (13)

Two masks are provided, one allowing 7 exposures vertically above each other and the other 13. The former is to be used when comparison spectra are taken. Exposures vary from one second with the carbon arc to several minutes with some of the gas-filled tubes.

The best developer is the popular Eastman DK-76. In fresh developer the film should be developed for about twelve minutes.

The spectrogram can be viewed by transmitted light and a low power magnifier. Contact prints or enlargements can of course be made "if desired". Lines can be identified roughly as already indicated by an engineer's scale divided into fortieths of an inch. More accurate wave length measurement requires the use of a comparison spectrum or a "standard" film viewed by the aid of a traveling microscope or a traveling film carrier.

For quantitative data upon the relative intensities of lines the spectrogram can be measured by a densitometer.

The film used should be of a good color response type. Triax Pan was found satisfactory, but any fairly fast panchromatic or panatomic film can be used.

It is wise to make several exposures with slightly different settings of the grating holder on the track (Fig. 9) in order to obtain a sharper film than is usually obtained by visual focusing. The scale along the track makes it possible to return to the exact position that gave the sharpest image.

Plate 2, Fig. 14, shows the results of moving the horizontal adjusting screw to obtain perfect focus of the instrument. The film itself shows a little more definitely that the fourth spectrum from the top is in most perfect focus.

Test Data

A number of spectra were taken, largely to test the adjustment of the apparatus.

Emission Spectra. Plate 1, Fig. 14, shows from bottom to top various types of emission spectra using as sources, carbon arc; iron arc; arc with one electrode carbon and one electrode iron; discharge tubes containing mercury, argon, helium, and neon and argon combined. This film has been calibrated for use as a calibration standard.

Spectral Limits. Plate 3, Fig. 14, shows the upper and lower limits of the spectrum as obtained by rotating the grating about the Y axis. The lower limit is determined by the response of the film and occurs at approximately 3300 A. The upper limit is approximately 6800 A and is established by the appearance of the second order spectrum.

Dispersion. The films taken to determine the spectral limits were also used to detect deviations from normal dispersion. These deviations were found to be too small to measure accurately with the apparatus available.

Absorption Spectra. Plates 1, 2, 3, Fig. 15, show several absorption spectra of samples of dyed cellophane. For these films the mask was omitted, the cellophane being placed in a jig covering the upper half of the slit.

The films were examined in a specially built photoelectric densitometer. Light from a 500 watt mazda projection lamp was passed through the spectrogram. The beam was then limited by a slit 1/4 mm x 4 mm and allowed to impinge on the Weston photronic cell. Deflections of a wall galvanometer were recorded for successive shifts of the film corresponding to 100 A. At each of these wave lengths, readings were taken on the spectra formed by the upper and lower parts of the slit. The ratio of these readings yields the absorption factor directly.

The data are shown in the form of curves in Figs. 16 to 21.

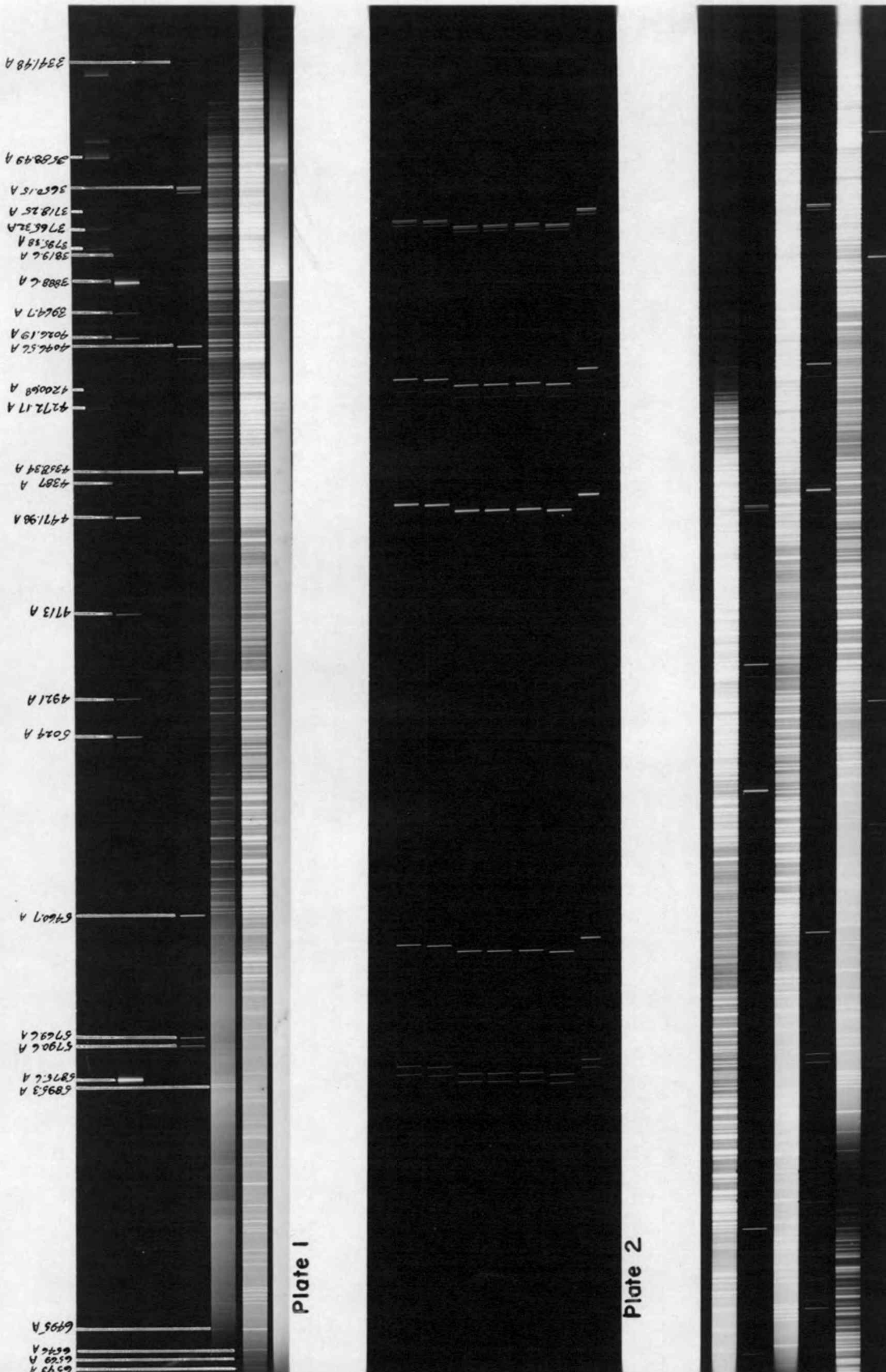


Figure (14)

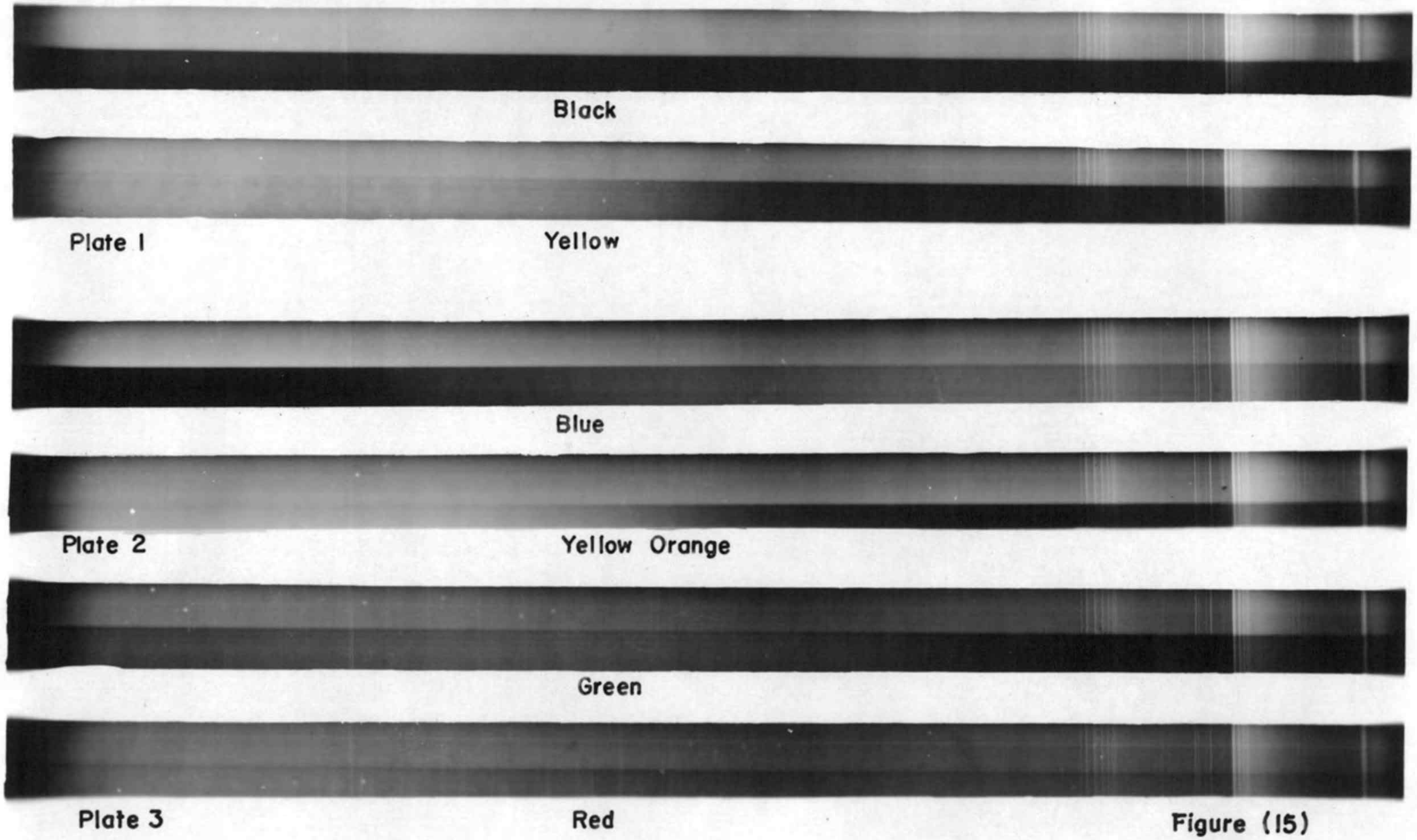

Black
Plate 1
Yellow
Blue
Plate 2
Yellow Orange
Green
Plate 3
Red

Figure (15)

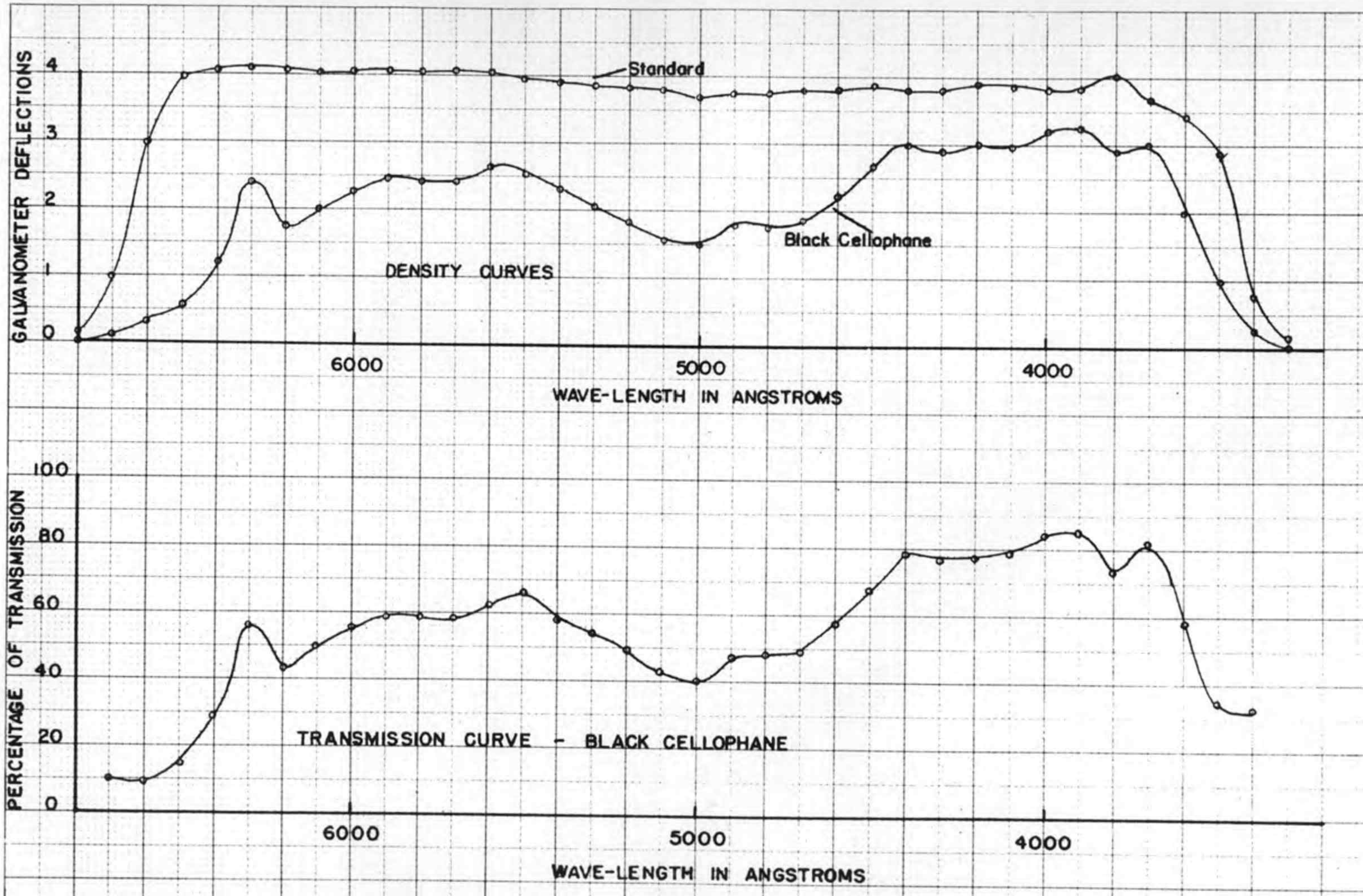

GALVANOMETER DEFLECTIONS
4
3
2
1
0
Standard
Black Cellophane
DENSITY CURVES
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS
PERCENTAGE OF TRANSMISSION
100
80
60
40
20
0
TRANSMISSION CURVE - BLACK CELLOPHANE
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS

Figure 16

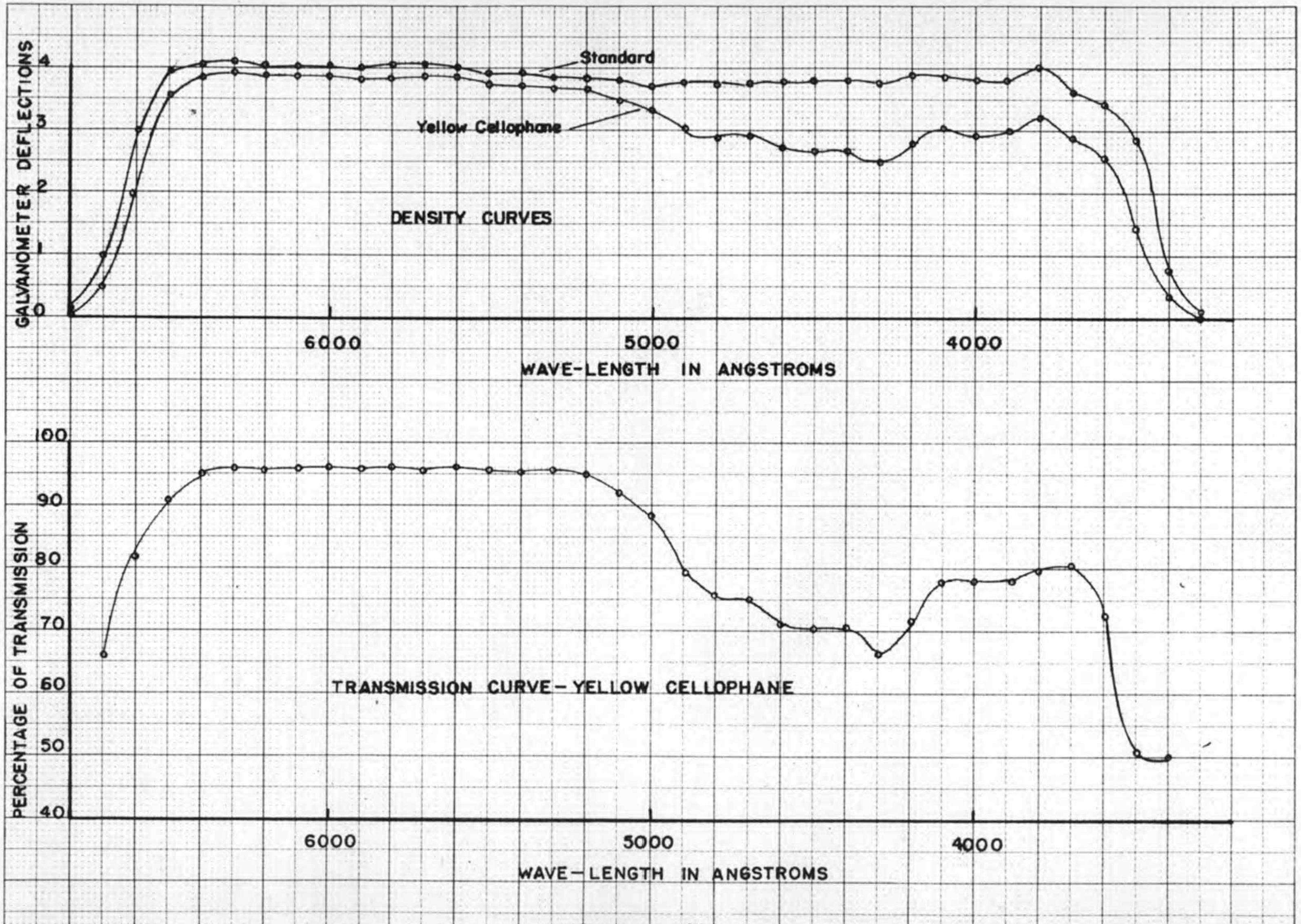

Standard
Yellow Cellophane
GALVANOMETER DEFLECTIONS
0
1
2
3
4
DENSITY CURVES
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS
PERCENTAGE OF TRANSMISSION
40
50
60
70
80
90
100
TRANSMISSION CURVE - YELLOW CELLOPHANE
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS

Figure 17

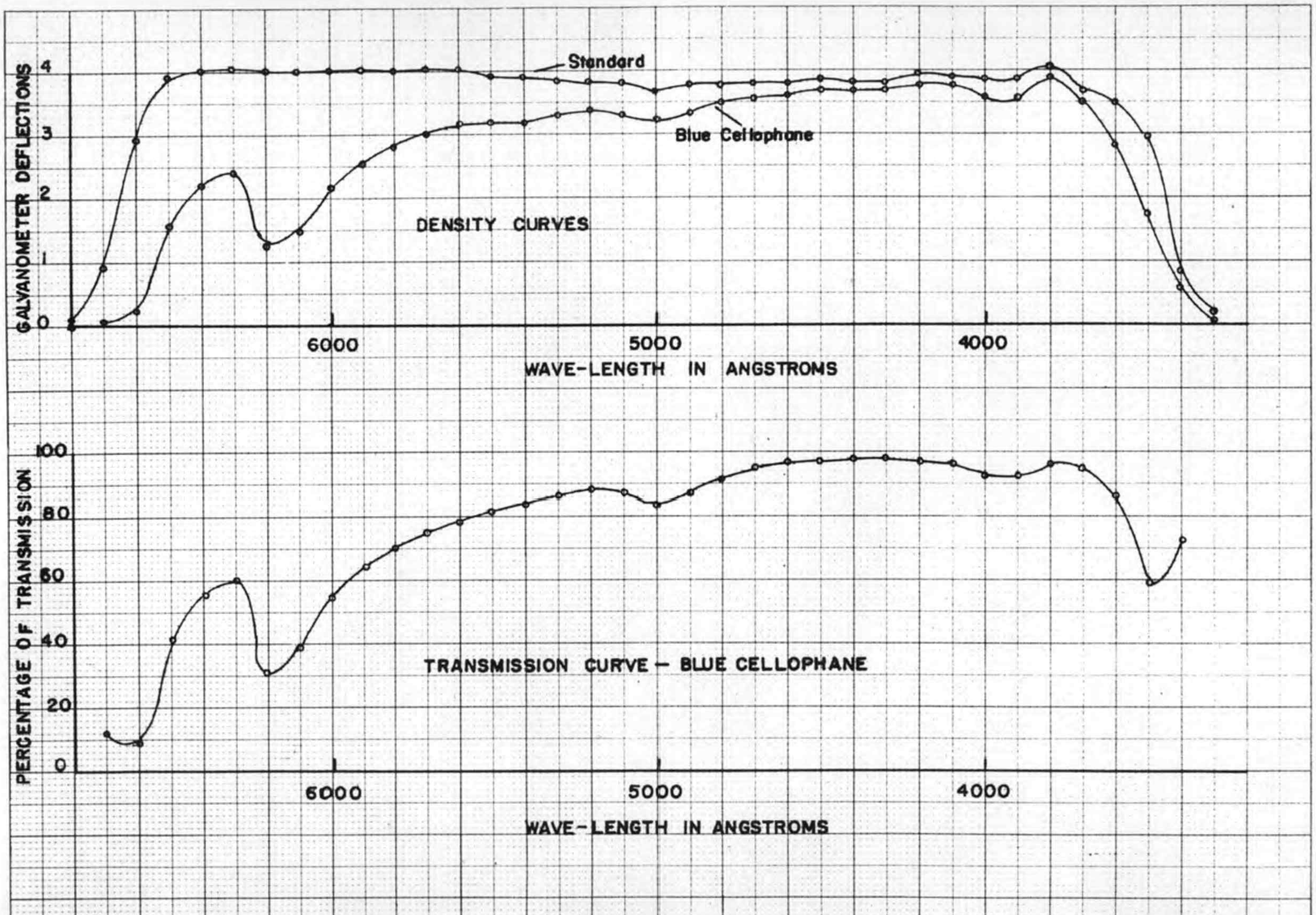

Standard
Blue Cellophane
GALVANOMETER DEFLECTIONS
4
3
2
1
0
DENSITY CURVES
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS
PERCENTAGE OF TRANSMISSION
100
80
60
40
20
0
TRANSMISSION CURVE – BLUE CELLOPHANE
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS

Figure 18

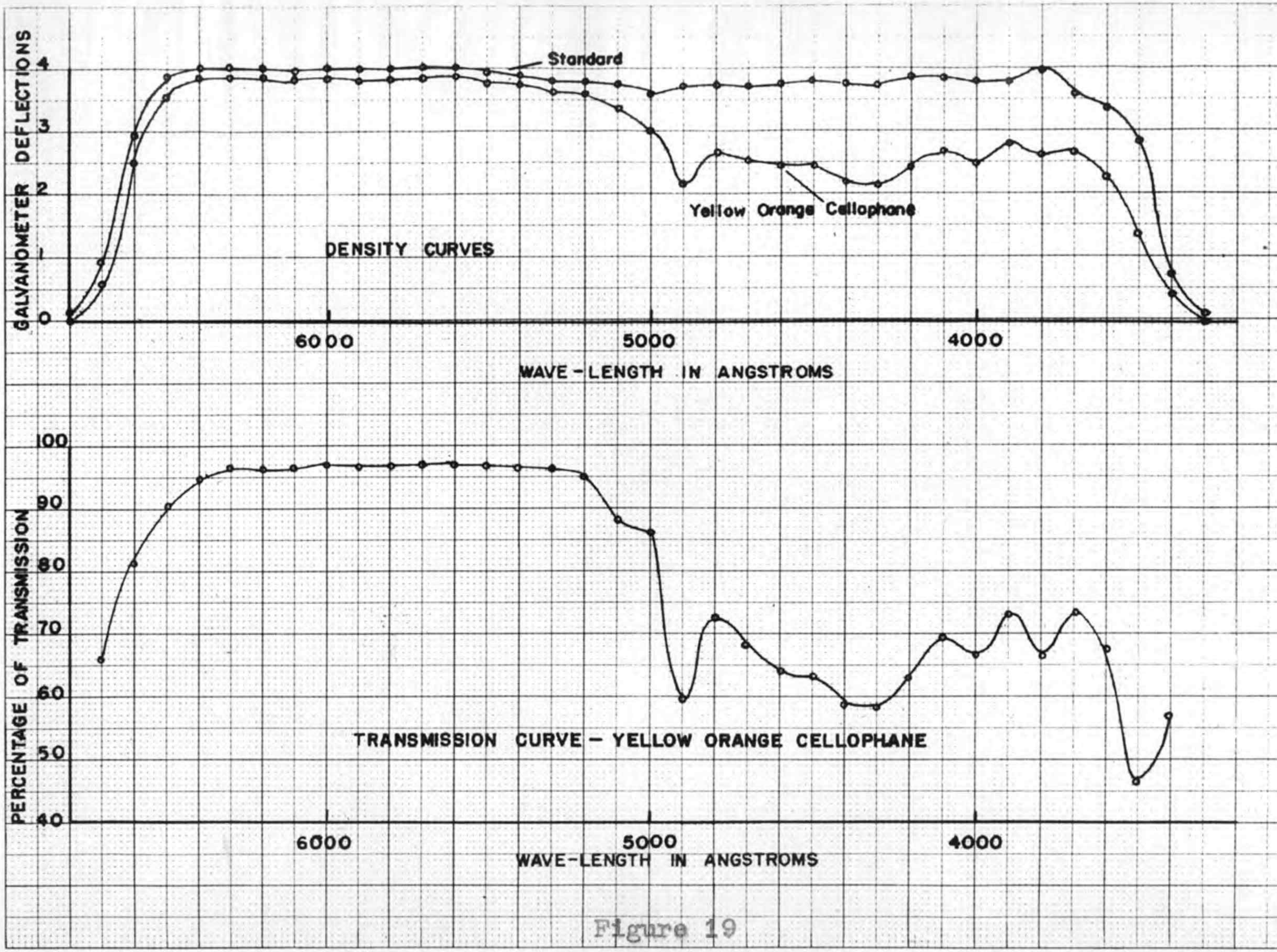

Standard
GALVANOMETER DEFLECTIONS
Yellow Orange Cellophane
DENSITY CURVES
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS
PERCENTAGE OF TRANSMISSION
TRANSMISSION CURVE - YELLOW ORANGE CELLOPHANE
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS

Figure 19

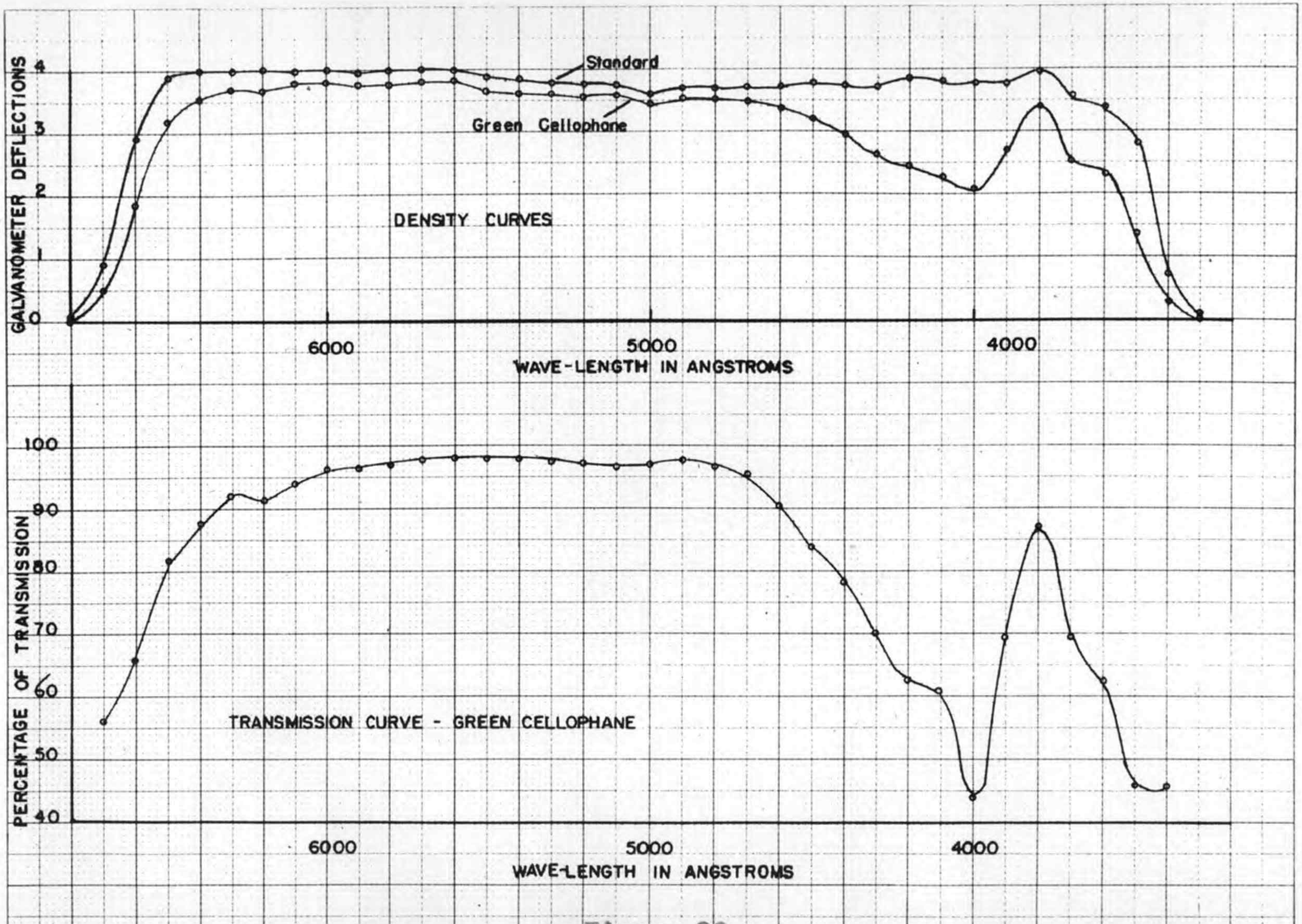

Standard
Green Cellophane
GALVANOMETER DEFLECTIONS
4
3
2
1
0
DENSITY CURVES
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS
100
90
80
70
60
50
40
PERCENTAGE OF TRANSMISSION
TRANSMISSION CURVE - GREEN CELLOPHANE
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS

Figure 20

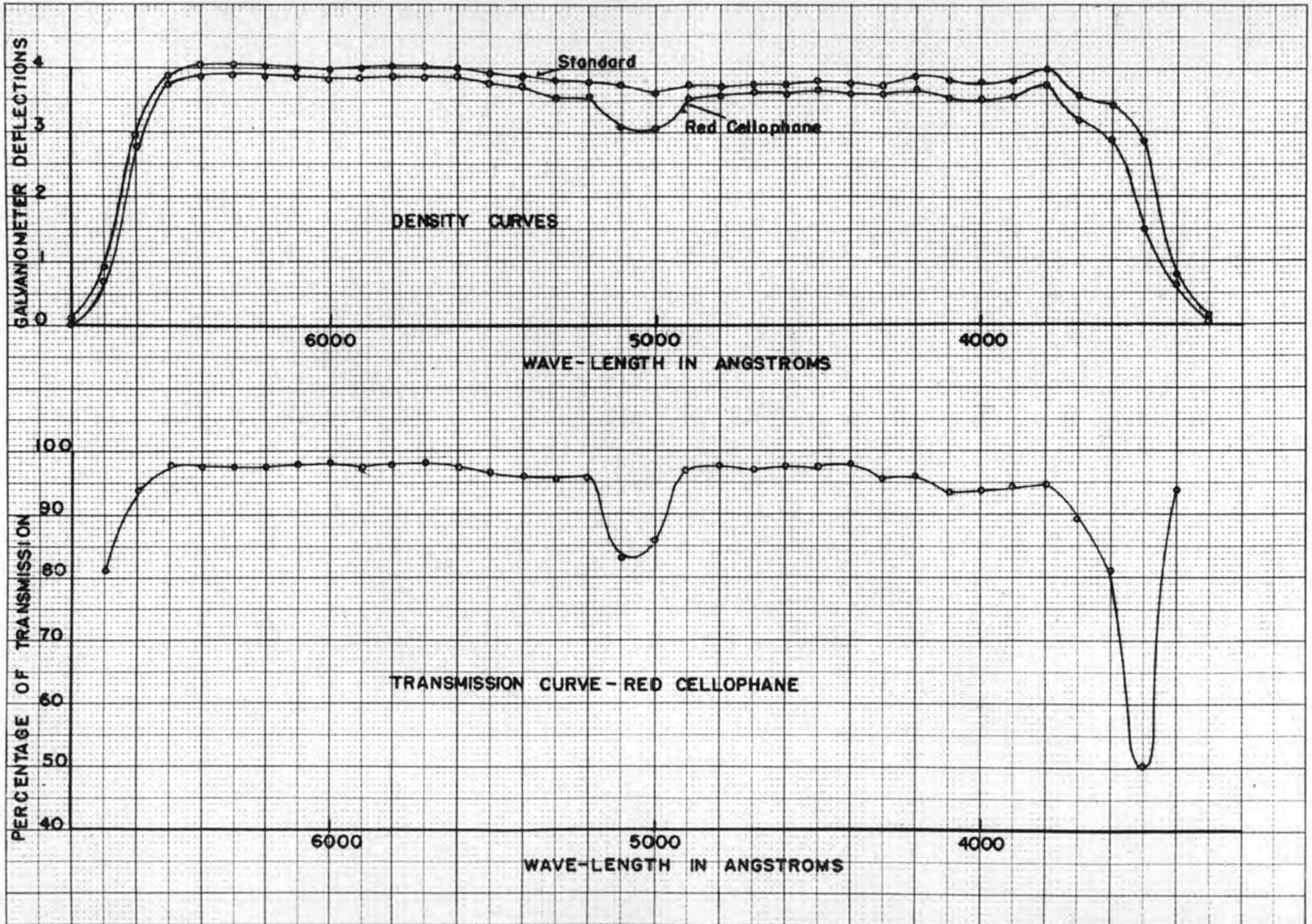

GALVANOMETER DEFLECTIONS
0
1
2
3
4
Standard
Red Cellophane
DENSITY CURVES
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS
PERCENTAGE OF TRANSMISSION
40
50
60
70
80
90
100
TRANSMISSION CURVE - RED CELLOPHANE
6000
5000
4000
WAVE-LENGTH IN ANGSTROMS

Figure 21

Summary

The object of this investigation was to redesign and put into workable shape a certain grating spectrometer. A new grating holder was designed and constructed that permits of making all of the necessary adjustments step by step. An auxiliary telescope mounting was designed and built to permit all preliminary adjustments to be made visually and rapidly. A safe method of supplying sources with high tension current was designed and constructed.

Tests were made to establish the limits of the usable first order spectrum and to determine the fact that the departures from a normal spectrum are practically negligible.

A spectral calibration chart was obtained by use of six different sources.

A study was made of the absorption curves of six different samples of dyed cellophane.

The spectrometer has been converted into a usable instrument convenient to use.

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