U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

A TEST OF LENS RESOLUTION FOR THE PHOTOGRAPHER

CIRCULAR C428

U. S. DEPARTMENT OF COMMERCE
JESSE H. JONES, Secretary
NATIONAL BUREAU OF STANDARDS
LYMAN J. BRIGGS, Director

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By Irvine C. Gardner

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PREFACE

The purchase of materials on the basis of precise performance specifications is an important step toward providing the consumer with satisfactory products at a reasonable cost. It has long been recognized that the writing of performance specifications for optical instruments is a problem of peculiar difficulty. As a contribution toward the solution of this problem, this circular presents an objective test for obtaining a quantitative measure of the performance of a lens. This test can be made by means of the charts accompanying this circular and material ordinarily available to the photographer, either professional or amateur. The test described is a development from a method of test applied by the National Bureau of Standards to the testing of airplane-camera lenses during the past 20 years.

LYMAN J. BRIGGS, *Director*.

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ABSTRACT

This Circular provides the photographer with a set of charts by which the resolving power of a photographic lens may be numerically measured with respect to a definite scale of values. A detailed description is given of the procedure and technique to be followed in order that comparable values may be obtained by different observers. The test provides an objective method of testing a photographic lens.

CONTENTS

I. INTRODUCTION

1. CHOICE OF CRITERION FOR JUDGING A LENS

The interest in pictorial photography and in the technique of photography has created a desire for some general method of rating different photographic lenses according to their merit. Before such a rating can be made, it is necessary to give some consideration to the relative importance of the different characteristics of a lens, and it is not surprising that these characteristics assume differing degrees of importance, as the lens is to be used for different purposes. For airplane mapping, absence of distortion is a most important feature, and for architectural photography reasonable freedom from distortion is desirable, but for general photography considerable distortion can be tolerated if the other characteristics can thereby be improved. For most photographic purposes the most important criteria by which a lens is judged are speed and the quality of definition.

2. SPEED OF A LENS AS A CRITERION

The speed of a lens, as determined by the maximum relative aperture,[1] receives the most emphasis in sales literature. This is probably because the speed is one of the few characteristics of a lens for which a definite numerical system of measurement has been employed.

It should be noted that the maximum relative aperture of a lens does not completely determine the effective speed.

For lenses of the same maximum relative aperture, and consequently of the same nominal speed, an important variation of the effective speed may arise from differences in the number of glass-air surfaces. The Tessar type of lens has three separated components, and consequently three pairs of glass-air surfaces. The modern *f*/2 lens may have five separated components with five pairs of glass-air surfaces. Each pair of such surfaces entails a loss of from 8 to 10 percent of the light. Consequently, for a given exposure time, if the Tessar lens and the *f*/2 lens are stopped down to the same relative aperture, the Tessar lens will transmit approximately 20 percent more light than the *f*/2 lens. Even this difference is not in itself of great importance to the photographer because an error of 20 percent in the exposure carries no serious consequences; but by multiple reflection some of this reflected light eventually passes through the lens and reaches the emulsion. This light does not contribute to the image but is out of focus and tends to reduce the contrast or, in extreme cases, it produces ghosts. This result, arising from multiple reflection, is probably more serious in its effect upon the performance of the lens than is the decrease in effective speed arising from the loss of light.[2]

The speed is further affected by the absorption of the glass of which the lens is made; but even in the most unfavorable cases the loss of light by absorption in a photographic lens will scarcely exceed 5 percent, and with so small a total loss it is evident that there can be no important variation, arising from light absorption, in the performance of photographic lenses of different types or makes.

Lenses of different types or makes may show important differences in performance arising from differences in the vignetting. For a given setting of the diaphragm the effective exposure is necessarily less at the corners of the photographic plate than at the center.[3] However, in some instances, in order to produce a compact lens suitable for a hand camera of reduced size, or in order to lessen the cost of production, the outer components of the lens are unduly reduced in diameter. This can be done to such an extent that the speed of the

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[1] The maximum aperture of a lens is customarily expressed in terms of the focal length, the expression *f*/4.5 signifying that the diameter of the effective aperture is equal to the equivalent focal length divided by 4.5. (In German publications this is usually written *f*:4.5, the colon being the symbol for division.) The aperture of a lens, expressed in terms of the focal length in this manner, is referred to as the relative aperture. The number in the denominator, appearing to the right of the shilling mark or colon, is sometimes referred to as the *f*-number. The required exposure is commonly considered to be inversely proportional to the square of the *f*-number.

[2] Recently a process has been developed for depositing very thin layers of calcium fluoride or other materials on the surfaces of a photographic lens to reduce the loss by reflection. This should give more contrasty images because of the reduction of the effects of multiple reflection to which allusion has been made. One of the modern fast lenses with 10 glass-air surfaces, will transmit approximately 50 percent more light with a corresponding increase in effective speed, when all the surfaces are treated with calcium fluoride. For a lens with fewer glass-air surfaces the increase in speed is less. These lenses are now available for experimental purposes and, if no disadvantages develop, they should soon be available on the open market.

[3] An exception to this may occur when an elaborate diaphragm system is employed which selectively masks the center of the field of view in order to reduce the illumination received by the center to approximately the same as that received by the corners. A diaphragm system approximating this condition and consisting of an iris between the components, and a whirling disk mounted some distance in front of the lens is provided on the Hypergon wide angle lens.

lens, so far as the center of the plate is concerned, is not reduced, but there is excessive vignetting and the exposure received by the corners of the plate is much less than for a lens of the same nominal speed, but with the outer components of more generous diameter. With black-and-white film the latitude [4] of the emulsion, in most cases, masks the effect of the excessive vignetting and the performance of the lens is reasonably satisfactory.

However, the color films from which positive transparencies are produced by reversal are usually lacking in latitude. Consequently, transparencies produced with such films exposed through a lens having excessive vignetting, will often have dark corners and be unsatisfactory in appearance because the corners are noticeably underexposed when the center portion is properly exposed.

3. QUALITY OF DEFINITION AS A CRITERION

For most purposes it appears that the production of a sharp, crisp image is the indispensable attribute of a lens. The present prevalent practice of making enlargements of several diameters from the original negative has created a general demand for lenses giving sharper and better defined images than were considered satisfactory some years ago. A great variety of photographic lenses are now available and lenses identical in focal length and speed but of different makes and qualities sell at widely different prices. When such a series of lenses is tested, the most marked difference in performance is found to lie in the varying sharpness of the image produced; and this one characteristic is probably the best single criterion for determining the quality of a lens. In advertising literature the lens makers have not yet adopted a method of specifying the quality of their lenses that is helpful to the purchaser. This is not surprising because a precise specification of lens quality is attended with many difficulties. It is common practice to describe a lens as being free or sensibly free from the different aberrations such as chromatic and spherical aberration, coma, astigmatism, curvature, and distortion. No lens can be entirely free from these aberrations. Furthermore, in any lens that covers an extended field of view some of the aberrations are always present to such an extent that they are sensible at some part of the field, either on a contact print or on an enlargement of four or five diameters. Even if the engineering procedure of giving graphs showing the magnitudes of the aberrations at all points of the field were adopted, it would still be difficult to formulate an opinion of the relative quality of two lenses having different aberrations. Lenses are sometimes characterized by a statement that the diameter of the circle of confusion is 1/100th or 1/250th of an inch. This method of description appears to be a quantitative one, but it does not give complete information. A measurement of the circle of confusion offers peculiar difficulties. If the measurement be made on the photographic image of a star, real or artificial, the diameter of the recorded image is so largely a function of the brightness of the star and the duration of the exposure that it tells little about the performance of the lens. In fact, the astronomer customarily measures

[4] When the characteristics of a photographic emulsion are such that the exposure may be varied over a large range of values and result in negatives from which satisfactory prints may be made, the emulsion is said to possess latitude. When the exposure must be correct within narrow limits in order to produce satisfactory results, such a film is said to lack latitude.

the diameter of a star image in order to determine the brightness of the star. Definite statements regarding the method by which the diameter of the circle of confusion is measured are not generally made, but it appears probable that the values listed are commonly based upon the results of ray tracing by mathematical computations that are required for the development of the design of the lens. If this is the case, the diameter of the circle of confusion is a test of the excellence of the lens design and does not fully indicate the performance of the finished lens. It will be readily appreciated that a good design is a prerequisite for the construction of a good lens, but it will also be appreciated that good workmanship and careful control during the making of the lens are equally important. A method of specifying a lens that does not give weight to the quality of workmanship is not a suitable criterion of the excellence of a lens.

In connection with the testing of airplane camera lenses over a period of years, the National Bureau of Standards has had the opportunity of studying the suitability of a measurement of the resolving power of a lens as a method of specifying its quality of definition. An elaborate testing device [5] for measuring the resolving power has been built and all airplane camera lenses that are to be used on Government mapping projects must be tested upon this instrument. Because it does not appear practicable for the National Bureau of Standards to undertake the general testing of hand cameras for the public or to publish comparative ratings of the different lenses, a modified method of making a resolving-power test has been developed. This simplified test can be made by means of apparatus which the camera user can readily improvise, and can be conducted by one skilled in photographic technique to the extent that is required for the successful operation of a miniature camera.

II. SIGNIFICANCE OF A RESOLVING-POWER TEST

The test comprises a measure of the resolving power of the lens and camera combination, a characteristic that determines the sharpness of the image and the degree to which it can be enlarged. If one attempts to photograph a pattern of parallel lines, it will be found that the lines, if too close together, will photograph as a gray patch and the individual lines cannot be distinguished. If, however, the lines in the object are so far apart that the lens records them as distinct lines, the lens is said, in optical parlance, to resolve the lines. We can, therefore, give considerable information regarding the quality of definition of a lens by a statement regarding the finest pattern of lines that it resolves. A given pattern of lines will appear finer and be more difficult to resolve as it is placed more distant from the lens. Consequently, if the distance between the just resolvable lines on the test chart is measured, this tells nothing of the performance of the lens unless the distance from lens to chart is also measured. This introduces a certain amount of complication, which could be lessened somewhat if the separations of the lines were given in angular instead of linear measure. Actually, however, one is usually concerned, not with the fineness of detail in the object but with the fineness of detail upon the negative or the finished print. A large picture, or a small

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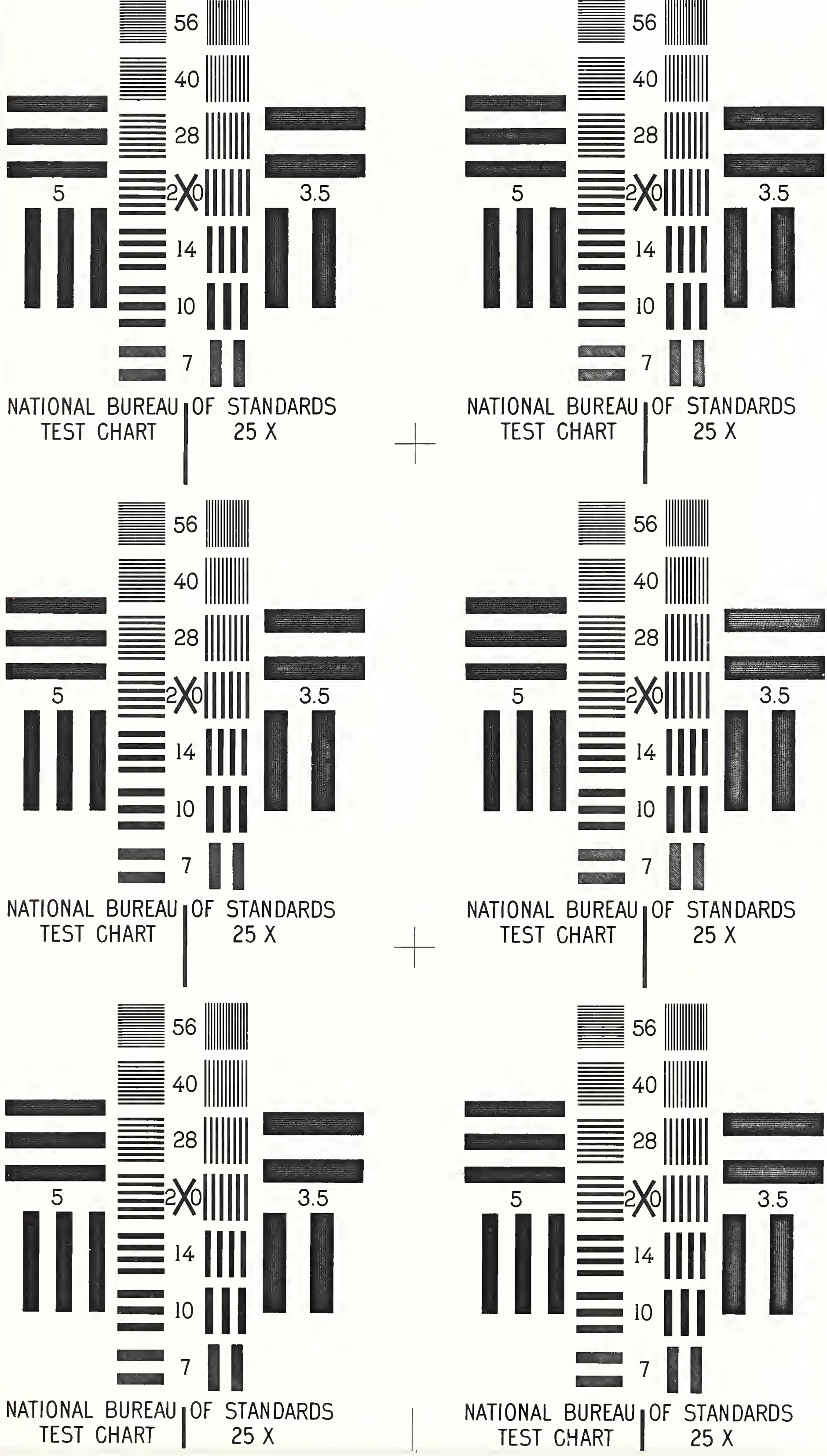
[5] Irvine C. Gardner and Frank A. Case, *Precision camera for testing lenses*, J. Research NBS **18**, 449–460, (1937) RP984. Obtainable from the Superintendent of Documents, U. S. Government Printing Office Washington, D. C., for 5 cents (stamps not accepted).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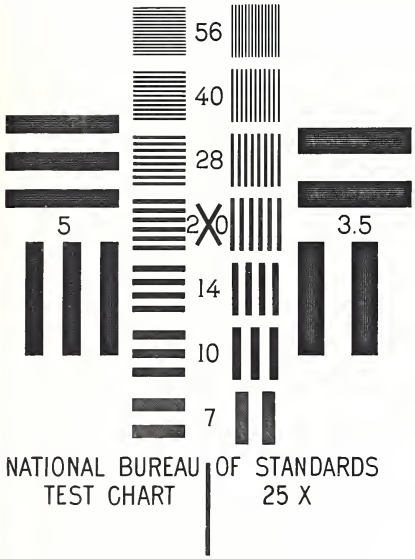
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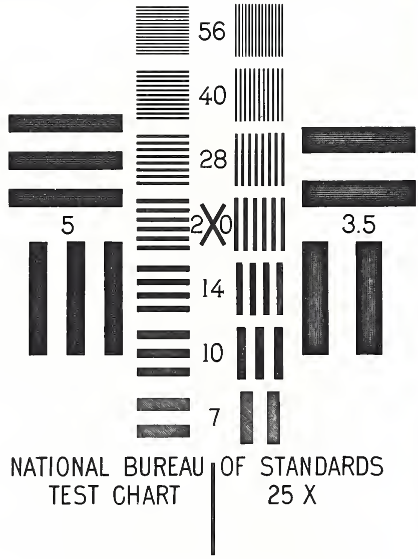
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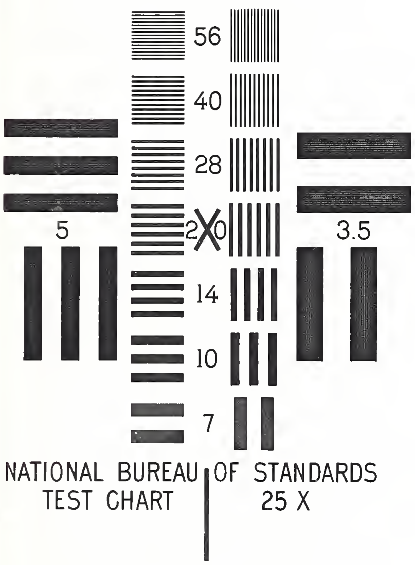
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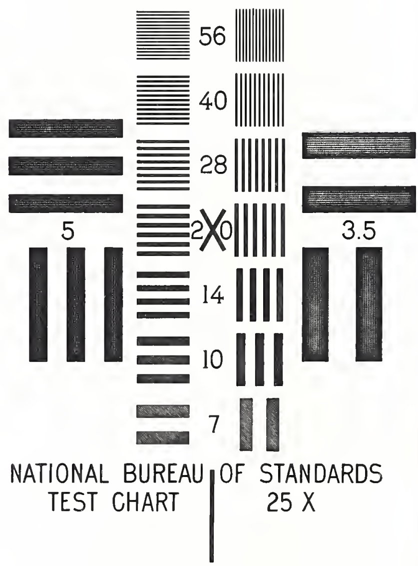
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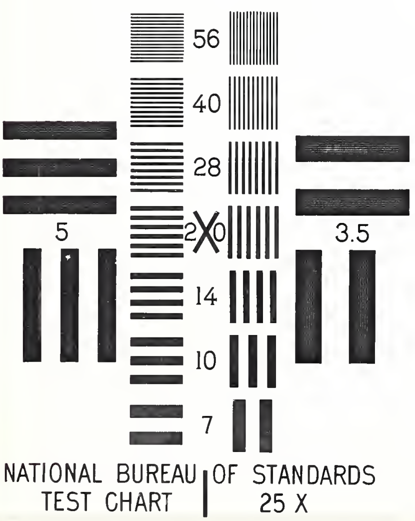
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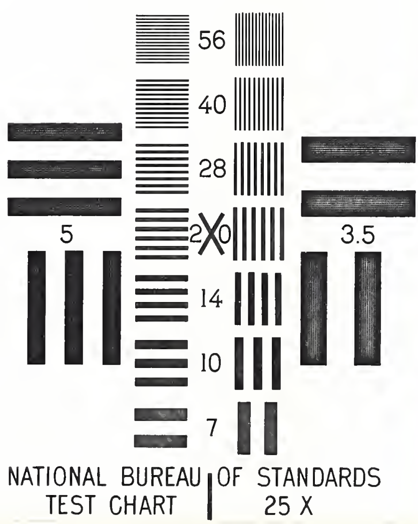
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picture, when examined for quality of definition is scrutinized from the distance of best seeing or perhaps examined with a hand lens, and it is commonly desired that the pictures be equally sharp regardless of size. From an artistic standpoint, there may be much to be said against this criterion, but nevertheless the user of a lens commonly expects the negative to be of approximately the same sharpness regardless of its size or the focal length of the lens. In view of this, it is desirable to base the determination of resolving power upon a measurement of the image. In accordance with the established practice, the number of lines per millimeter, measured on the negative, of the finest pattern resolved will be used as a measure of the resolving power. As an illustration, if the resolving power is given as 40, lines spaced 40 to the millimeter (the distance between the centers of the adjacent lines in such a case, is one-thousandth of an inch, or 25 microns) upon the negative are distinguishable as separate and distinct lines.

It should be mentioned that the resolution test, when conducted as described, is dependent not only upon the lens but also upon the camera construction and the characteristics of the photographic film. A lens cannot be expected to produce negatives of the first quality unless it is mounted in a camera that holds the film, free from curvature, in a plane normal to the axis of the lens. Furthermore, consistently good negatives cannot be produced unless the camera movements are sufficiently free from lost motion to permit a given adjustment to be repeated with certainty. Even with an excellent lens and camera, the resolution may be limited by the type of film that is used. With the better lenses, the limiting resolution in the center of the field is usually determined by the film rather than by the lens. Consequently, when testing a lens, the use of the finest grained film that is commercially available is recommended in order that the potential resolution of the lens may be more closely approximated.

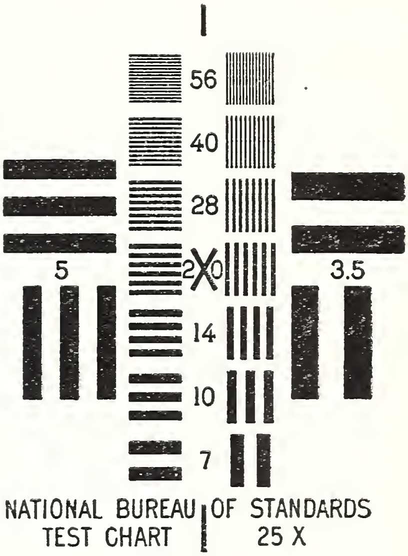

FIGURE 1.—*Chart for testing resolving power.*

If this chart is photographed from a distance of 26*f*, where *f* is the focal length of the lens, the spacing of the lines on the negative will correspond approximately to 56, 40, 28, 20, 14, 10, 7, 5, and 3.5 lines to the millimeter.

III. CHARTS FOR TESTING RESOLVING POWER

The patterns shown in figure 1 form a convenient test chart for use in the measurement of resolving power. In order that a pattern may be always recorded to the same scale on the negative, regardless of the focal length of the lens to be tested, it is necessary to have the distance of the chart from the lens proportional to the focal length.

If this chart, as reproduced, is photographed from a distance of 26*f*, where *f* is the focal length of the lens, the spacing of the lines on the negative will correspond approximately to 56, 40, 28, 20, 14, 10, 7, 5, and 3.5 lines to the millimeter. Of this series the choice of 40, 20, 10, and 5 was suggested by the decimal system. As the intervals between successive values in this simpler series are too great, the intermediate values were selected to form a series that is approximately geometric. It will be noted that the ratio between any two successive values of the complete series is 1.4 ($=\sqrt{2}$), and that the ratio of the spacings for any two patterns separated by an intermediate pattern is 2.

For each pattern there are two groups of lines, one vertical and one horizontal. For most lenses it will be found that the resolving power at points not near the center of the negative is noticeably different for lines of the same spacing when the lines are oriented differently in the field. A consideration of the symmetry present at such a point indicates that the greatest and least resolving powers will be found for patterns of lines directed toward the center of the negative and at right angles to this direction, although one cannot say in advance which of the directions will correspond to the greater resolving power. If several test charts are arranged in a horizontal row for photographing at such a height that the line of images passes through the center of the negative, the horizontal lines will be directed toward the center of the field and are accordingly designated *radial*. The vertical lines are designated *tangential*. These terms will be used to designate the two different resolving powers for lines in the two characteristic directions. If these two resolving powers have different values at a point, it indicates the presence of coma [6] or astigmatism.

Cases may arise in which one wishes to test resolving powers higher than 56 lines per millimeter. With cameras employed for reproducing printed material to a reduced scale on 35-mm film the fine-grained slow emulsion that is regularly employed enables one to advantageously utilize higher resolving powers than can be recorded on the faster types of film. When one desires to determine higher resolving powers than 56 lines to the millimeter, it is suggested that the same targets be used at a distance of 51*f* instead of 26*f*. The spacings of the patterns upon the negative then become 112, 80, 56, 40, 28, 20, 14, 10, and 7 lines per millimeter. This procedure is not recommended for regular use because, with the lenses of longer focal length, the increased distances require greater space than is commonly available indoors.

In order that the reader may test his camera lenses in accordance with the directions contained in this Circular, it is accompanied by a two-page insert containing 12 charts similar in design to that shown in figure 1. Charts of this nature are difficult to prepare by the usual method of printing from relief because the ink spreads on the paper and tends to fill the spaces between the lines, thus making the widths of lines and spaces unequal. To avoid this difficulty, plates for these charts have been ruled by means of a dividing engine by the Bureau of Engraving and Printing. By a process identical with that em-

[6] Coma and astigmatism are optical aberrations, which do not affect the images of axial points of a well-constructed lens but may be present in the images of points not lying on the axis of the lens. If coma is present, the image of a point will have a blurred extension extending toward or from the center of the field. If astigmatism is present, the image of a point cannot be focused into a sharply defined point image, but, for one setting of the lens it will be represented by a relatively sharp line segment lying along a radius passing through the center of the field, whereas for a second position, the image will be a relatively well-defined line segment perpendicular to the radius.

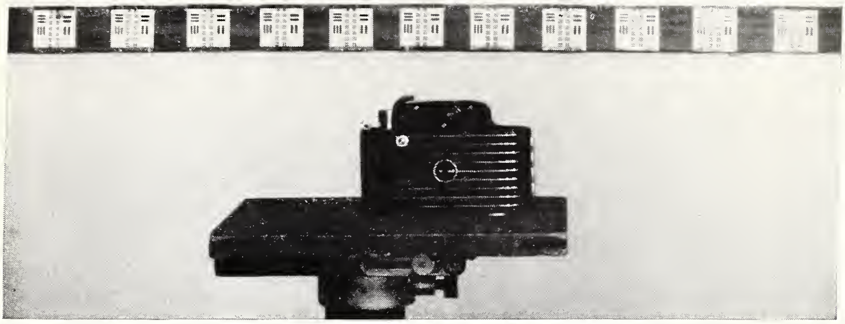

FIGURE 2.—*Arrangement of camera and charts for test.*

The charts are conveniently mounted on a 1- by 4-inch board. The spacings of the individual charts are such that the angle between any two successive charts, measured at the camera lens, is 5 degrees.

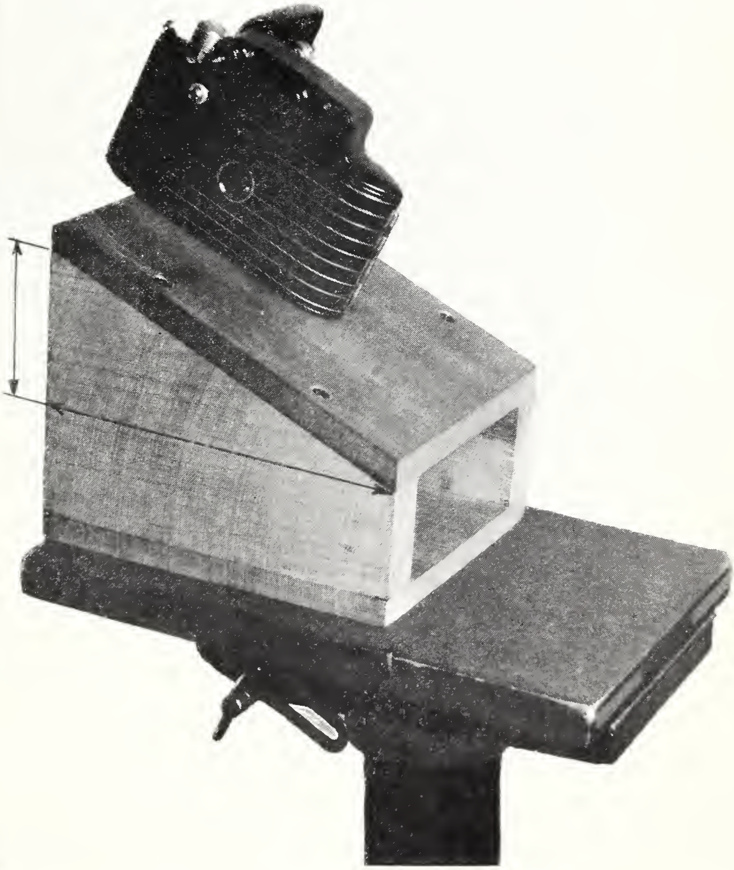

FIGURE 5.—*Camera mounted on special support.*

If a support of this form is interposed, as shown, between the tripod and the camera, the row of images will lie along the diagonal of the plate, as illustrated in the lower diagram of fig. 4. This enables the test to be extended to the corners of the negative.

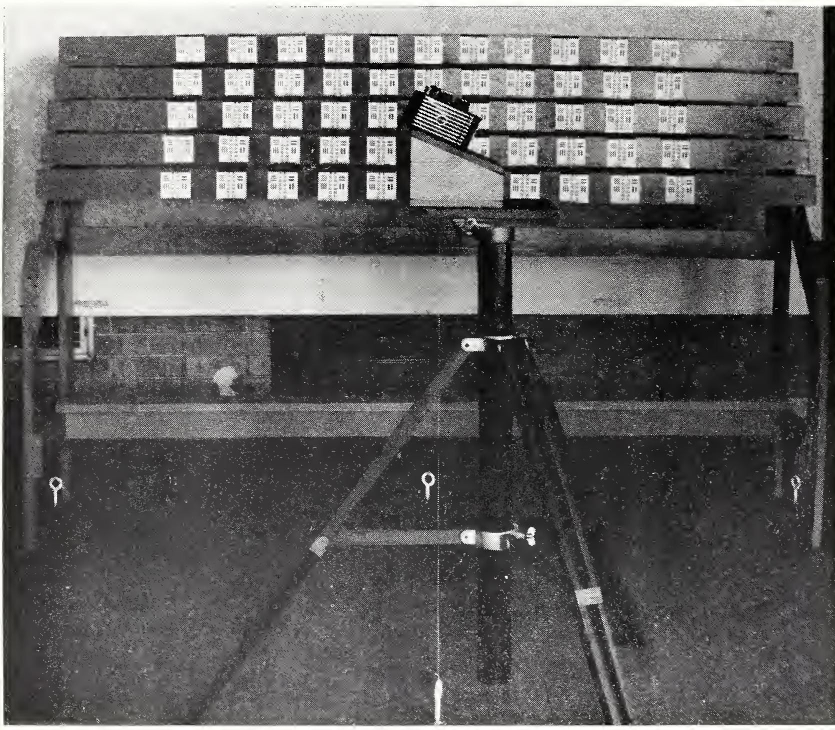

Figure 6.—*Test rack with multiple rows of charts.*

A very convenient form of mounting the charts if many lenses are to be tested. This arrangement of charts also enables one to test the adjustment of a coupled range finder.

ployed in the production of postage stamps, additional plates have been copied from the master plate, and the printing of the charts has been done from an intaglio surface. At the edges of the pages of the insert, marks will be found to serve as a guide for cutting the individual charts apart.

IV. DETAILS OF TEST

1. ARRANGEMENT OF CHARTS

The resolving power is not the same across the entire negative but is usually greatest at the center and decreases along any radius. It is commonly considered that a lens is perfectly symmetrical about its axis, and that in accordance with this symmetry the performance of

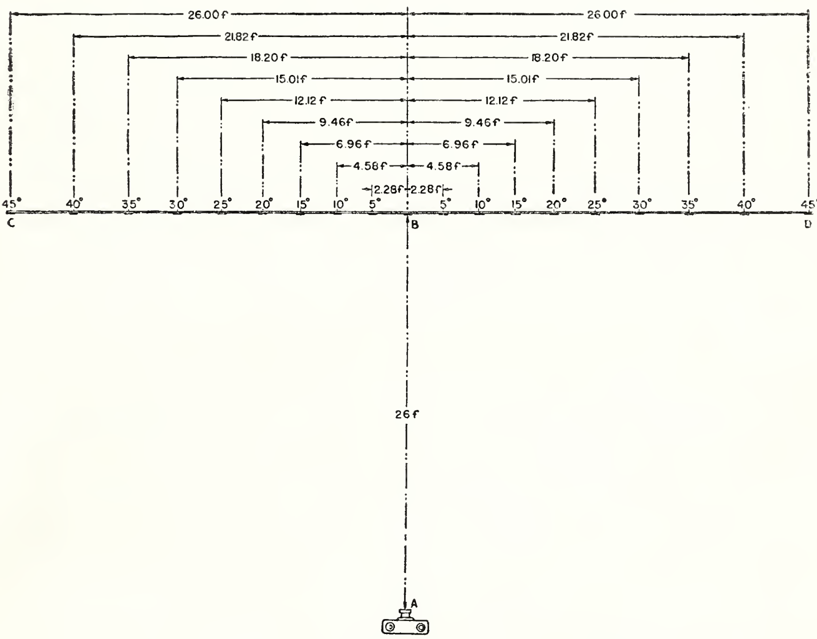

FIGURE 3.—*Plan view of arrangement of camera and charts for test.*

This is a plan view of the arrangement of charts and camera, as shown in fig. 2. The distances are given in terms of *f*, the focal length of the camera lens. If the distances *AC* and *AD* are made equal, the camera is located on the perpendicular bisector of the length *CD* and is, therefore, directly opposite the central chart.

the lens will be identical on all straight lines passing through the center of the field. A perfectly symmetrical lens is probably never realized because of the unavoidable errors of workmanship but, except for the most exacting purposes, it is satisfactory to treat the field as symmetrical. It is accordingly convenient to measure the resolving power at 5-degree intervals by a system of charts arranged in a horizontal row, as shown in figure 2. Figure 3 is a plan showing the spacing of the charts and the position of the camera. The distances are given in terms of *f*, so each coefficient must be multiplied by the focal length of the lens to determine the required spacing for intervals of 5 degrees. As an illustration, if the lens to be tested has a focal length of 50 mm, the distance from the lens to the central chart will be 1,300 mm (51.2 in), and the distances from this chart to the others on the two sides will be 114, 229, 348, 473, 606, 750, 910, 1,091, and 1,300 mm (4.5, 9.0, 13.7, 18.6, 23.9, 29.5, 35.8, 43.0, and 51.2 inches, respectively) for 5, 10, 15, 20, 25, 30, 35, 40, and 45 degrees respectively. The larger values of the angles are given in order to provide complete data for the testing of lenses of extremely wide angle. The field of a lens of 50-mm focal length used with a 35-mm film (24- by 36-mm negative) extends only 23.4 degrees when measured from the center to the extreme corner.

2. SPECIAL SUPPORT FOR CAMERA

If the camera is attached to the tripod in the usual manner and levelled, the row of images will extend across the negative, as shown on the upper diagram of figure 4, and the resolving powers near the corners will not be determined. An attachment similar to that shown in figure 5 can be made to support the camera in a position rotated about the axis of the lens to bring the recorded images upon a diagonal of the negative as shown in the lower diagram of figure 4. When designing this attachment, the base and altitude of the right triangle forming a portion of the mount (indicated by dimension lines on fig. 5), should be respectively proportional to the width and height of the negative. The same result can of course be obtained by having the camera levelled on the tripod in the usual manner and rotating the board, upon which the charts are mounted, through the proper angle.

3. USE OF MULTIPLE ROWS OF CHARTS[7]

It will be readily understood that the correct resolving power for a lens will not be obtained unless it is correctly focused. If many lenses are to be tested, it is advantageous to have the arrangement of charts shown in figure 6, as it largely eliminates the making of several exposures in order to make sure that good focus is obtained. There are five rows of charts, placed one above the other, all at different distances from the lens, but not far from the horizontal plane containing the camera axis. The lens to be tested is placed at a perpendicular distance, $26f$, from the center of the middle row and the camera is focused upon the central chart of this row. If the focus is correct, the central row of charts will be the sharpest on the resulting negative. If an error has been made in the setting, one of the nearer or farther rows of images will be sharper than the central one, and if the error in focusing is not too great, one row will be in good focus and the resolving powers can be read from it without making an additional exposure. If the different rows of charts on the test rack are spaced at distances in the line of sight of 62.5 mm (2.5 in.), the planes of best images of the different rows, measured in a direction perpendicular to the film, will be spaced 0.1 mm. This relation holds, regardless of the focal length of the lens under test, provided the charts are photographed from an axial distance of 26 focal lengths. As an illustration, if the lens is focused upon the central row of the series of charts, and

[7] Additional charts, in sets of 48 (8 pp.), may be obtained from the Superintendent of Documents, Washington, D. C., for $1.25. When ordering, they should be referred to as Charts for Testing Lens Resolution, NBS Miscellaneous Publication M166.

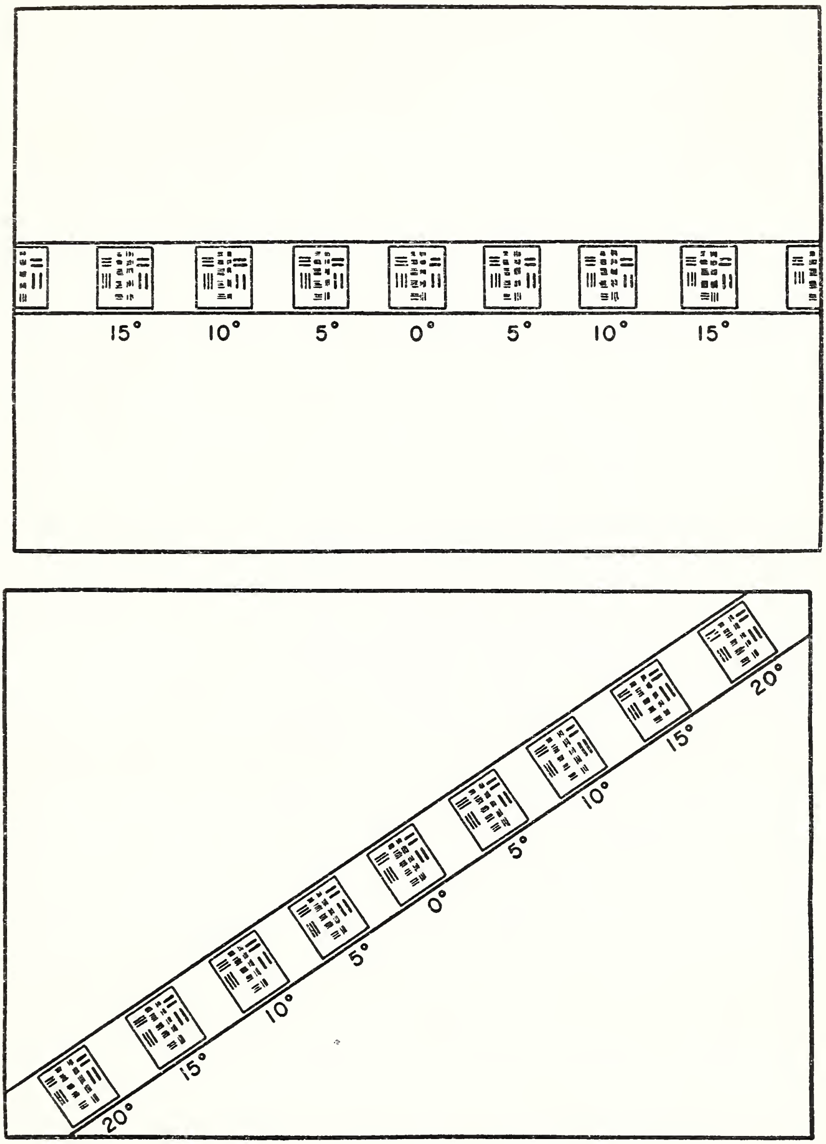

FIGURE 4.—*Two diagrams of resulting negatives.*

For the upper diagram the camera was mounted directly on the tripod and the row of charts was horizontal. The line of charts does not extend to the corners. For the lower diagram the camera has been mounted as shown in fig. 5, and the line of charts lies along a diagonal. If only one or two cameras are to be tested, it may be more convenient to mount the camera directly on the tripod and rotate the board carrying the charts in order to place them along the diagonal of the negative.

if the farthest row, spaced 125 mm back of the central row is in best focus, it indicates that the lens was 0.2 mm nearer the plane of the film than it should have been in order to focus the central row of the series upon the film.

In setting up the charts and camera, care must be taken that the distances are exact and that the axis of the camera is perpendicular to the row of charts, with the lens opposite the central target. For a camera of short focal length it is convenient to do the work indoors. The charts and the camera can then be adjusted to the same height by measuring upward from the floor. The distance from the camera to the central chart should be measured from the first principal point [8] of the lens. In general, the location of this point will not be known, but it will be sufficiently accurate to measure from the front surface of the lens. It will be found most convenient to measure all horizontal distances on the floor and to use plumb bobs to properly locate the parts above the measured points. If plumb bobs are not conveniently available, large screw eyes hung with the pointed ends downward are a satisfactory substitute. Four plumb bobs are desirable, one to locate the front surface of the lens, one to locate the center of the central chart, and one each at the corners of the two outermost charts. The projections of these points are located at A, B, C, and D on figure 3. The distance AB should be $26f$. In order to be sure that the camera is directly opposite the central target, AC and AD must be equal. This condition locates the camera on the perpendicular bisector of CD. With the camera over A, it must be so oriented by means of the view finder, or ground glass, that the central chart appears in the center of the photograph. If these adjustments are all accomplished as described, the camera will be directed squarely at the central chart. If many cameras are to be tested, it is convenient to lay off the distances on the floor and indicate the significant points by tacks. If plumb bobs are permanently attached to the strip that carries the charts and to the tripod, it is a simple matter to restore the correct adjustment by adjusting the plumb bobs over the tacks. A rack, such as is shown in figure 6, equipped with plumb bobs and used in this manner with a system of tacks indicating the positions for the commoner focal lengths will be found to be an especially convenient piece of testing equipment for photographic clubs, as it will enable each member to acquire for himself valuable and useful information about the performance of his lenses.

4. ILLUMINATION OF CHARTS

Satisfactory negatives cannot be obtained unless the charts are uniformly illuminated. If lenses of the shorter focal lengths, such as are used in miniature cameras, are to be tested, it is convenient to make the exposures indoors. Windows directly behind the camera are certain to produce unsatisfactory illumination because of specular reflection from the charts. In the usual home, a room is seldom found with the windows so arranged that none of the charts will reflect light directly into the lens with consequent overexposure of such charts. It is advisable to make the test at night or with shades drawn and to

[8] The principal points are two points, designated as first and second, on the axis of the lens. In order to simplify the mathematical equations defining object and image positions, it is convenient to measure object and image distances, respectively, from these points. Their properties are discussed in most books on optics. See chapter 4 of "The Principles of Optics," by Hardy and Perrin (McGraw-Hill Book Co., Inc., New York, N. Y.).

depend upon photoflood lights for the illumination. Two photoflood lights placed, one at either side, 3 or 4 feet in front of the plane of the charts (that is, toward the camera) and 4 or 5 feet beyond either end of the group of charts, will give satisfactory illumination. For lenses of longer focal length, the distance 26*f* becomes so great that it is usually more convenient to make the exposure outdoors.

5. METHODS OF FOCUSING

(a) FOCUSING BY MEANS OF COUPLED RANGE FINDER

If the camera is equipped with a range finder coupled to the lens, it may be advisable in order to attain greater precision, to focus with the help of a low-power telescope, focused to view distant objects. A three- or four-power telescope can be held directly behind the range finder so that the light passes from the object through the range finder, then through the telescope, and then to the eye. With this arrangement, the images are magnified and their coincidence can be more exactly determined. If a suitable telescope is not available, one barrel of an opera glass may be alined with the eye aperture of the range finder and satisfactory results obtained. A prism field glass is not recommended, as the higher magnification and the loss of light by the extra reflections at the prism surfaces make it less desirable for this purpose. If the multiple rows of charts shown in figure 6 are available, the range-finder setting is made on the middle row. If one of the other rows is sharpest on the negative, it indicates that the reading through the range finder has not been accurately made or that the range finder is out of adjustment. The truth of this latter conclusion should not be assumed unless the experiment is repeated several times and a consistent failure to focus on the central row is established.

(b) FOCUSING BY MEANS OF FOCUSING BACK

If the camera has no range finder but is equipped with a focusing back, it is advisable to use it for securing the correct focus. The grain of the ground glass is apt to introduce some uncertainty in deciding upon the best focus. Focusing may be done more precisely if the ground glass is temporarily replaced by a piece of clear glass of the same thickness. Marks should be made near the center of the surface of the glass that corresponds to the ground surface. A wax pencil or a wax crayon, such as comes in children's color sets, is convenient for this purpose. When looking squarely at the clear glass, the image can be seen only in the center of the field. Focusing must be done with a magnifying lens. The highest power available in a simple magnifier is recommended, and focusing is correct when the wax-pencil marks and the image are *simultaneously in focus* in the field of the magnifying lens.

(c) FOCUSING BY MEANS OF FOCUSING SCALE

If the camera has no range finder or ground glass but is provided with a focusing scale, it is probable that no indicated value on the scale will correspond exactly to the required distance of 26*f*. In such a case the distance from the chart to the lens may be altered to correspond exactly to the nearest indicated value. If this is done the nominal resolving power read directly from the negative will not be correct, because it will not give the actual number of lines per millimeter. The true resolving power can be found by the following proportion: The actual number of lines per millimeter is to the value read from the chart as the distance from the chart as the distance from the camera to the chart is to 26 focal lengths. When the test is conducted in this manner, results unfavorable to the lens will be obtained if the focusing scale is not accurate, because the lens will have been incorrectly focused for the indicated distance.

Another and perhaps better method of testing a lens on a camera equipped with a focusing scale is available. The camera is set up 26 focal lengths from the chart in the usual manner, and the corresponding setting on the focusing scale is estimated from the nearest indicated values. With this setting, if the resulting negative is not satisfactorily sharp, the setting on the scale is left fixed and the distance from the camera to the chart is altered by small steps until an exposure is obtained of satisfactory quality. If the alteration of the distance from 26 focal lengths is not greater than 10 percent, the readings of resolving power will be satisfactorily accurate. If the alteration of the distance has been more than 10 percent, the setting on the focusing scale should be appropriately altered and another series of exposures made, starting again at the distance of 26*f*.

6. PHOTOGRAPHIC TECHNIQUE

The fast or moderately fast film that is commonly used for pictorial photography will resolve from 40 to 50 lines per millimeter. A high-grade photographic lens will do considerably better than this at the center of the field, and consequently it is desirable to use one of the slower films of high resolving power when testing a lens. Even when this is done the upper limit of resolution that can be observed may be set by the film but at least the limit will be higher than that which can be recorded on the more commonly used films. Of the domestic films in motion picture sizes, Eastman Panchromatic Micro-file, or Agfa Minipan are suggested. With these films more than 100 lines per millimeter can be clearly resolved if the photographic lens produces an image of the requisite sharpness. For cameras not using motion-picture film, Panatomic *X*, Finopan, or other fine-grain film should be employed. The films giving the highest resolution are of the photo-mechanical type, such as Reprolith or Kodalith.

It is self-evident that there must be no vibration of the camera or charts when the exposures are made. The camera should be on a very rigid tripod or clamped to a table of the proper height, and the charts should be rigidly supported. When there is any doubt about the rigidity of the camera support, the following corrective procedure has been found advantageous to overcome the difficulty. The general illumination is reduced to such an extent that the exposure with the largest diaphram opening is not less than 3 or 4 seconds. When making an exposure the shutter is set at "time", a black card is held immediately in front of the lens but not touching it, and the shutter is opened either by the cable or finger release. After all tremor from opening the shutter has subsided, the card is taken from in front of the lens for the duration of the exposure, then replaced, and the shutter closed. By this procedure there is very little likelihood that making the exposure will cause harmful vibrations to the camera.

If one is already familiar with the use of one of the fine-grain developers, it is probably advisable that it should be used, although a fine-grain developer will not increase the resolving power of the emulsion. Most tests of lens resolution at this Bureau have been conducted with buffered *D76* [9] and *DK*20.[10] The film should be exposed and developed to yield a film of medium density. Exposures should be repeated until a negative, well-focused and of good technical quality, is obtained.

7. EXAMINATION OF NEGATIVE

On a satisfactory test negative the images should lie on a diagonal of the negative, with the central chart very close to the exact center of the negative. Furthermore, the negative should be of medium density and of first quality, photographically. No attempt should be made to read the value of the resolving power until such a negative is obtained. To properly interpret such a negative, it should preferably be examined with a compound microscope magnifying 30 or 40 diameters, although a good magnifying glass, magnifying 10 or 15 diameters, can be used on the coarser patterns. One may also examine the negative indirectly by making a 10 or 15 diameter bromide enlargement from the negative and then using the magnifying glass on the enlargement. When this method is used there is danger that the lens will not be judged fairly, because faults originating in the enlarging may be attributed to the lens under test.

As has been mentioned, the resolving powers for the vertical and horizontal lines are referred to as the tangential and radial resolving powers, respectively. On each chart (of the row in best focus, if multiple rows are used) the finest patterns of vertical and horizontal lines that are resolved are read and counted. A pattern of lines is resolved if the individual lines can be clearly distinguished and if the number of lines is the same as the number of lines in the test chart. This checking of the number of lines is important because diffraction effects sometimes produce a spurious resolution in which the lines are apparently clearly distinguishable on the negative but the total number of lines does not check with the number in the original pattern. The number of lines per millimeter in each pattern is given in the legend of figure 1. Typical results of the tests on lenses of miniature cameras are given in the following section.

V. INTERPRETATION OF RESULTS

For the central chart (0°) the tangential and radial resolving powers should be the same. If this is not the case, it probably indicates that the camera has not been pointed squarely at the central chart. When charts other than the central one are examined, it will usually be found that the vertical (tangential) and horizontal (radial) lines are not resolved equally well. This indicates the presence of coma or of astigmatism. This departure from perfection of imagery as one considers the definition near the margin of the field, is to be expected because no lens is entirely free from aberrations. A large relative aperture or a large angular field of view tends to accentuate this unequal quality of performance for central as compared with marginal parts of the field.

[9] J. I. Crabtree, Trans. Soc. Motion Picture Engrs. **11**, 77–87 (1927).
[10] J. I. Crabtree and B. W. Henn, Am. Phot. **33**, 78 (1939).

A photographic objective of first quality may not possess its maximum resolving power at its maximum aperture but at one or two stop numbers below the maximum. An $f/2$ lens may, for example, show its maximum resolving power at $f/2.8$ or $f/3.5$. A lens can be stopped down to such an extent that its resolving power again decreases, although this is perhaps not generally appreciated. Stopping a lens down increases the depth of focus and therefore increases the average sharpness of the usual photograph representing objects at various distances from the lens or, if the image surface is curved, it sharpens definition at the corners but it does not necessarily increase the sharpness of objects that happen to lie in the plane of best focus of a lens with a flat field. When copying a plane object, such as a drawing, the sharpest reproduction will be obtained with a setting considerably larger than the smallest aperture usually provided on a copying lens. These considerations suggest that it is interesting and desirable to test the resolving power of a lens at several different apertures if complete information about its performance is desired.

One may obtain better average definition over the entire field with lenses of 50-mm. focal length used with 35-mm. film (the typical focal length for cameras using 35-mm. film) than with lenses of hand cameras using a larger film, because the angular field of view, including the extreme corners, is only 23.4 degrees, an angular field of view smaller than that of the larger cameras. As an illustration, a 3½ by 4¾-inch (9 by 12 cm.) camera equipped with a lens of 5¼ in focal length has a field of view for which the extreme angle is 29.3 degrees. A rule sometimes quoted is that the focal length of the lens should be equal to the diagonal of the negative. When such a rule is followed, the extreme angle of the field of view is 26.5 degrees.

The significance of the measured resolution and its bearing upon the final photograph that one obtains can be best illustrated by an example. Suppose that one photographs an object containing details so fine that it is recorded on the negative with a fineness of structure corresponding to 40 lines per millimeter. If an enlargement of 10 diameters is made, this same detail will then correspond to 4 lines per millimeter or, according to the English system of measurement, 100 lines per inch. At a distance of 14 inches, the eye, under the most favorable conditions, resolves approximately 250 lines per inch. There is, however, no serious lack of sharpness when a finished enlargement shows detail corresponding to 100 lines per inch. Experience, in fact, will show that a much greater coarseness of detail is entirely satisfactory for the majority of pictorial subjects.

Table 1 gives tabulated values of resolving powers as determined by the test that has been described. These values are the results of isolated tests on lenses and should not be generalized as characteristics of any particular make or type of lens. The lenses tested were of domestic and foreign manufacture, lens *A* being the most expensive of the four, and lens *D* the least expensive. All of the lenses were of short focal length, such as are used in miniature cameras. The negatives from which these measurements were made have been much enlarged and are reproduced in figure 7. It is unlikely that the finer patterns of the charts will be resolved in the halftone reproduction as they were on the original negatives. However, an examination

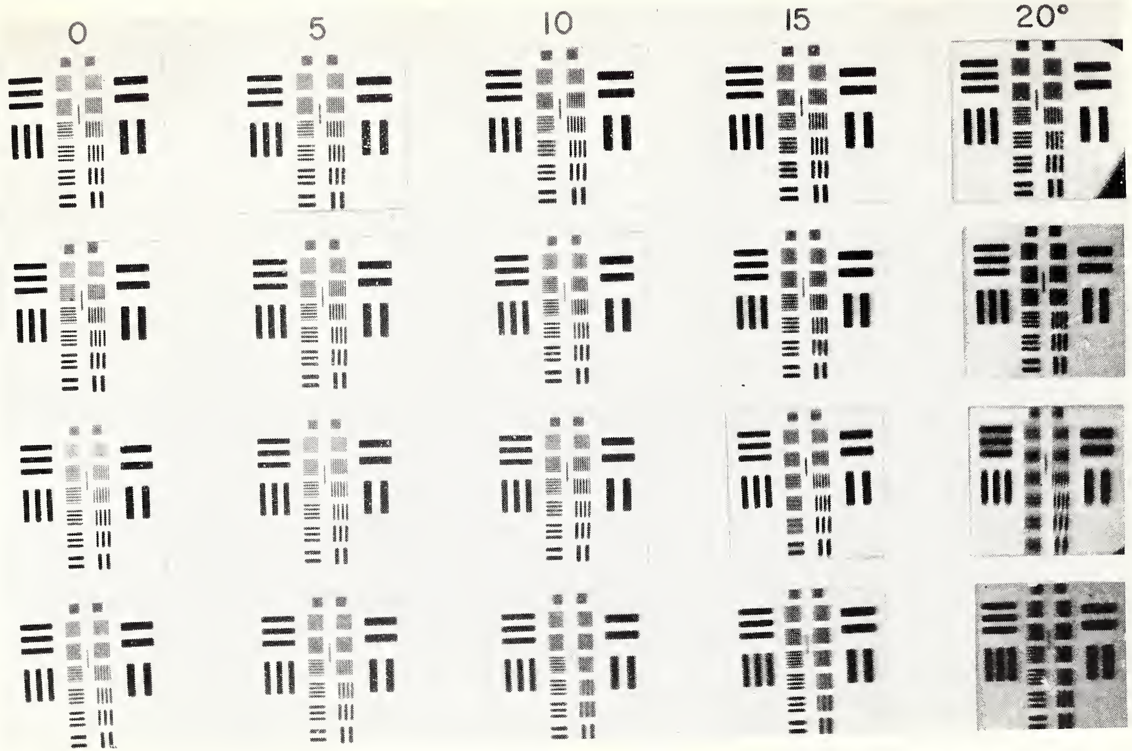

Figure 7.—*Results of tests of resolving power.*

Halftone reproductions of enlarged prints made from the negatives corresponding to the tests recorded in table 1. The horizontal rows, beginning with the upper one, correspond to lenses *A*, *B*, *C*, and *D*, respectively, of table 1.

of the coarser patterns will show the difference of quality of definition, rounded corners appearing on the lines in the coarse patterns when they are photographed with the lenses of low resolving power.

TABLE 1.—*Resolving power of four lenses of miniature cameras*

Lens	Aperture		20°	15°	10°	5°	0°	5°	10°	15°	20°
A	*f*/2	Tangential	40	56	56	56	56	56	56	56	40
		Radial	40	40	40	56	56	56	40	40	40
B	*f*/2	Tangential	20	28	40	56	56	56	56	56	28
		Radial	14	20	40	56	56	56	56	40	20
C	*f*/2.8	Tangential	28	56	40	40	40	40	56	28	28
		Radial	10	28	56	40	40	40	56	10	5
D	*f*/3.5	Tangential	14	20	28	20	40	20	10	10	10
		Radial	56	56	40	28	40	28	28	56	56

In table 1 it will be noted that the variation in resolving power is not always symmetrical with respect to the center of the field. Care was taken to insure that this difference did not arise from differences in the illumination of the charts. Differences may arise from poor centration of the different elements of a lens or from an imperfect camera back which fails to hold the film flat and in the focal plane.

Lenses of longer focal lengths, such as are supplied on $3\frac{1}{4}$- by $4\frac{1}{4}$- or 4- by 5-inch cameras, do not show as good resolution over the entire field as do the lenses for the miniature cameras. It is a more difficult problem to secure the same correction for the longer focal length as for the shorter focal length. In fact, it is quite impossible to achieve the same perfection of chromatic correction because of the limitations of the optical materials available. Furthermore, the lenses supplied with the cameras of larger size are usually of such focal length that a greater angular field is covered. For such equipment the resolving power at the center of the field may be 40 or 56 but near the corners it may be as low as 10 and, occasionally even lower at the extreme corner. For most work this still gives satisfactory performance, because photographs of this size are seldom enlarged more than four or five diameters.

WASHINGTON, May 21, 1940.

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