DEPARTMENT OF COMMERCE AND LABOR

CIRCULAR

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 27

THE TESTING AND PROPERTIES OF OPTICAL INSTRUMENTS

[1st Edition]
Issued December 15, 1910

WASHINGTON
GOVERNMENT PRINTING OFFICE
1911

DEPARTMENT OF COMMERCE AND LABOR

CIRCULAR

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 27

THE TESTING AND PROPERTIES OF OPTICAL INSTRUMENTS

[1st Edition]
Issued December 15, 1910

WASHINGTON
GOVERNMENT PRINTING OFFICE
1911

THE TESTING AND PROPERTIES OF OPTICAL INSTRUMENTS

CONTENTS

Optical instruments fall into two general classes: (1) those used as an aid to vision (telescope, microscope, field glass), including those by which, with slight modification, photographic records may be obtained, and (2) those used for special purposes (spectroscope, photometer, polariscope), chiefly in optical laboratories. The properties of all optical instruments depend partly upon their general design and partly upon the degree of correction attained in the lenses and prisms used in their construction. The latter are discussed under *corrected lenses*, and in a third section the *optical properties of materials* are treated.

61419°—11

I. OPTICAL INSTRUMENTS

A. PROPERTIES OF INSTRUMENTS FOR AIDING VISION

All optical instruments used to aid vision may be classified and rated according to the degree of attainment of

1. Definition.
2. Magnification.
3. Illumination.
4. Angle of view.

in the image presented by them to the eye. Within limits, these should all be as great as possible, but since the attainment of any one of these properties requires the sacrifice of others, the design of all optical instruments is a compromise giving a maximum of those properties most desirable for the use to which the instrument is to be put. In some instruments (e. g., opera glass, reading telescope, spectacles, hand magnifier) the requirements are not severe and are easily met, in others the severest demands on the principles of construction are made.

1. **Definition.**—In securing high definition, three classes of limitations are encountered (1) the resolving power of the objective, (2) the incomplete elimination of aberrations in objective and ocular or compensation of aberrations between these, and (3) the granular structure of the retina and photographic plate.

No instrument can possibly present to the eye finer detail of object (microscope) or image (telescope) than corresponds to the aperature ratio of the objective and the wave length of light used for illumination. The formula for resolving power usually given is

$$\varphi = a\frac{\lambda}{r}$$

where φ is the angular distance between the objects to be resolved (e. g., double stars or diatom markings), λ the wave length of the illuminating light, r the radius of the objective, and a the resolving power constant. This constant varies from 0.5 for an image just recognizable to 1 for an image of sharp definition.

Since φ is (in general) the same for both object and image, we may substitute $\varphi = {}^{\delta}/_{F}$ (F, equivalent focal length of objective, δ size of detail to be observed) when either object or image is near a principal focal plane. Hence, putting $a = 0.5$ (limit of resolution)

$$\varphi = {}^{\delta}/_{F} = 0.5\frac{\lambda}{r} = \frac{\lambda}{D} \text{ or } \frac{\delta}{\lambda} = \frac{F}{D} = \text{Aperture ratio}$$

D being the diameter of the effective aperture of the objective. Hence the smallest observable detail, measured in wave lengths of the light used, is equal to the aperture ratio of the objective. An ultra-violet microscope using waves of length 0.250 μ should show details one-third the size of those given by the same instrument using red light of wave length 0.750 μ.

A microscope objective with numerical aperture 1.50 gives details one-third the size given by an $F/2$ or one-thirtieth the size given by an $F/20$ telescope objective. Good objectives intended to cover but a small field should give (by test) their full theoretical resolving power. If required to cover a wider field (for photographic work for example), slight axial aberrations must be left in the objective in order to secure oblique corrections and the definition falls to half or a third of the resolving power, i. e., the definition is improved by stopping down the lens aperture to half its diameter at full opening.

Lack of definition due to residual aberrations in objective and ocular depends on properties discussed under corrected lenses.

The third limitation on securing high definition, the granular structure of the photographic plate and of the retina, must be avoided by suitable magnification. The silver plate grains vary from 0.5 to 3.0 μ in greatest dimension and the so-called resolving power of plates is 5 to 10 times this distance according to the definition required. In the retina, the distance between centers of adjacent rods is 3 to 4 μ, which corresponds to 50 to 70 μ at 25 cm from the eye. In an image to be viewed by the eye therefore, the best definition must involve a shading off within a minimum distance of 50 to 70 μ. It may be noted that the retinal grain (3 μ) is just the resolving power of the eye (pupil 3 mm, equivalent focal length 15 mm, wave length 0.5 μ).

An instrument for visual observation is of normal defining power throughout if both resolving power and correction of aberrations give as high definition as the eye. This standard of perfection is sufficient for all practical purposes.

2. **Magnification.**—The size of image produced by magnification is the chief consideration in the use of optical instruments. Comfortable seeing requires an angular size of detail to be observed of about 0.008 (this type at 10 inches), but details to one-tenth or ten times this size may be observed without strain. The normal eye can accommodate itself to rays divergent from a point as near as 25 cm, parallel, or convergent toward a point a meter behind the eye. There is little to choose between divergent and parallel light so long as the angular size of image is unaltered.

When a *single lens* is interposed between the eye and an object, the lens increases the apparent size of the object in the ratio m (the magnification) given by

$$\frac{1}{m} - 1 = \frac{e}{f}\left(\frac{e}{d} - 1\right)$$

where f is the focal length of the lens, e is the distance of the lens and d of the object, from the eye. When e, f, and d are small in comparison with the visual accommodation distance (25 cm to ∞), the above expression reduces to the approximation $m = d/f$ commonly quoted.

In *hand magnifiers* a flat, wide field, free from color and distortion at the edges is required. Spherical aberration, astigmatism, and axial chromatism are of minor importance.

In telescopes, field glasses and similar instruments which the light enters and leaves in parallel rays (called *telescopic systems*) the magnifying power is simply the ratio of focal lengths of objective and ocular, $m = F/f$. Normal magnification is such that the cone of light leaving the ocular is at the eye point (position of the image of the objective formed by the ocular) of the same diameter as the pupil of the eye. A lower power ocular does not utilize the full power of the objective, a higher power ocular produces an image of lower intrinsic brightness than the object itself. Similarly every ocular should equal the objective in resolving power, hence should be of equal aperture ratio. A higher aperture ratio is useless because the cone of light would not fill the whole aperture of the ocular.

Combining the conditions for normal magnification ($m = D/P$) and normal resolving power of ocular in telescopic systems gives for the equivalent focal length of ocular

$$f = P\frac{F}{D},$$

P being the diameter of the pupil of the eye and F/D the aperture ratio of the objective. In other words, this is the condition that a central light cone just fills both ocular and eye pupil.

No telescopic system can, with advantage, give greater magnification than this even in the center of the field and with aberrations reduced to below the limits of definition set by the resolving power of the objective. In practice lower powers are generally used in order to secure a larger field angle or in photographic work to secure a larger field sensibly free from aberrations, higher powers when position not definition is required.

In the *miscroscope*, magnifications nearly as high as the resolving power of the objective will permit are freely used, the illumination being under control and the minutest details subject to observation. The smallest detail resolvable in green light with an objective of aperture ratio 0.6 is ($\delta = \lambda A$) 0.3 μ. The resolving power of the ocular may be less than that of the objective in the ratio of tube length to focal length of objective. Lower magnifications give better illumination and larger field.

3. **Illumination.**—The illumination of the visual field is of great importance in all optical instruments particularly in those of high power. The quality of the illumination, its direction, its intensity at the center of the visual field, its variations (producing contrast) in different parts of the image and the falling off in intensity from the center of the field outward have all to be considered.

For visual observation white light (daylight or its equivalent) is generally preferable but with badly achromatized instruments, monochromatic light may be best. The higher resolving power obtained by using blue light is counterbalanced by low luminosity and great retinal fatigue in visual work but for photographic work the use of monochromatic blue light may be decidedly advantageous.

Self-luminous objects of course completely fill the objective cone with light. The illumination of objects not self-luminous should be such as to fill the objective cone, otherwise both resolving power and image illumination will, of course, be reduced as though the aperture of the objective had been cut down. The brightness of an image observed visually is constant and equal to that of the object observed directly as long as the light cone at the eye point is as large or larger in diameter than the pupil of the eye. Other things being equal, the apparent brightness varies as the square of the diameter of the pupil of the eye. A mat field viewed through a blackened tube appears several times as bright as when viewed directly with the unshielded eye, for screening the eye from stray side light causes a maximum dilation of the pupil. Hence the value of effective eye shields on optical instruments, particularly field glasses and microscopes.

When the cone of light at the eye point is smaller than the pupil of the eye the brightness falls off as the square of the ratio of their diameters. Since the radius of the exit pupil is δ/Am for the microscope and r/m for the telescope (δ = visual distance 25 cm, A = aperture ratio, m = magnification, r = radius of objective), the relative brightness of object and image

$$B : B_0 = (\delta/Am)^2 : p^2 \text{ or } r^2/m^2 : p^2$$

where p is the radius of the pupil of the eye. $B = B_0$ gives the value of the normal magnification mentioned above.

When the object is very small (subtending less than one minute of arc) diffraction at the eye pupil fixes the size of the image, hence its brightness depends only upon the amount of light entering the objective—that is, upon the area of the objective.

When an image is projected on a screen or photographic plate the relative illumination of light per unit area of image and object is $TS/\cancel{uv}$ v^2 where S is the area of the objective, u object distance, v image distance, and $1 - T$ is the percentage loss of light by absorption and reflection within the lens. Hence, other things being equal, the brightness of the image is proportional to the area of the objective.

Contrast in the image is, of course, independent of magnification and aperture ratio except as regards details (points or lines), subtending less than a minute of arc. Bright details on a darker background (e. g., stars in the sky), gain in contrast, while dark details on a light ground (canals on Mars) lose in contrast by increasing the aperture of the objective.

No falling off in intensity of illumination of image from the center outward should be perceptible in an instrument for visual observation. Photographic instruments of wide angle may show a slight falling off but a large variation in either form of instrument indicates defective design.

4. **Field.**—The extent of the field of view covered by an optical instrument is found by projecting all stops (including lens rims and the pupil of the eye if a visual instrument) into the space between the objective and the object. The *field angle* is twice the angle between the axis and a line drawn through center of the objective and that stop image which is the least angular distance from the axis (the entrance pupil). The *visual angle* is the field angle multiplied by the magnification. A simpler method is to take

the angular opening of the ocular from the eye point as the visual angle, but this does not give a correct result when the eye pupil is a stop, as is commonly the case.

A large field of view is of most importance in field, marine, and opera glasses. The erection of the image requires the use of a negative ocular, a terrestrial ocular or else of erecting prisms. The negative ocular gives a small field (since the ocular cone is much larger than the eye pupil) but abundant illumination. The terrestrial ocular necessitates a cumbersome length of instrument and is little used. Erecting prisms give a large field but are heavy and if far apart require the use of small objectives with consequent loss of illumination, while if near together and near the ocular they require a considerable length of instrument.

In certain recent terrestrial (so-called wide angle) telescopes, the ocular is made of very wide aperture so that the eye can be moved about to view different parts of the image. The actual field angle is not increased but the entrance pupil is in effect movable, the net result being that a linear motion of the eye may be substituted for an angular displacement of the instrument.

B. SPECIAL LABORATORY INSTRUMENTS

Special optical instruments involve the principles above discussed as regards definition, magnification, illumination, and field angle, together with the properties of special pieces, such as prisms, polarizing plates, and the like, requiring extended discussion in detail.

C. TESTING OPTICAL INSTRUMENTS

The following optical instruments will be received for test:

- Field glasses.
- Opera glasses.
- Laboratory telescopes.
- Field telescopes (up to 10 cm objective).
- Telemeters and range finders.
- Telephoto combinations.
- Projection lenses.
- Magnifiers.
- Microscopes.

The testing of other special optical instruments may be arranged for by special request. The component lenses or lens systems or prisms of any optical instruments will be subjected to separate tests if desired (see Lens Testing and Refractometry). The instrument as a whole will be subjected to any or all of the following tests as desired:

- Magnifying power.
- Maximum field angle and visual angle.
- Relative illumination of image center and field at 2 to 5 angles.
- Lateral diffusion of image or
- Resolving power and residual aberrations (see Lens Testing).

II. CORRECTED LENSES

A. PROPERTIES OF LENSES

An image formed by a single simple lens contains gross imperfections of seven different kinds called *aberrations*. By combining two or more simple lenses these aberrations may be to some extent neutralized, giving a *corrected lens*. A residual aberration is *positive* if in the same direction from a perfect (plane, sharp, and undistorted) image as in an image formed by a single lens. Similarly it is said to be *under-corrected* or over-corrected as to any one aberration according to whether the residual of that aberration is positive or negative. The amount of any *residual aberration* may be expressed in terms of (*a*) focal length, (*b*) the aberration of an equivalent single lens, or (*c*) in actual lengths, in different cases.

It is impossible to free a lens completely from all aberrations. A lens may be practically (to the fifth order) freed from aberrations for two different *distances of object* or for two different *angles* (from the axis) or for light two (or more by careful choice of glass) different *wave lengths* or for two different *zones* of the lens. With a lens at full opening and an extended object emitting, reflecting, or transmitting light of many wave lengths, it is possible to secure an image of fair perfection near the axis only. Corrected lenses differ in their properties according to which set of corrections have been best attained.

Telescope objectives are very carefully corrected for very small zones ($F/20$) and objects near the axis (3°), microscope objectives for wide zones ($F/0.7 = N.A. 1.4$) and objects near the axis (2°). Photographic objectives vary from about $F/3$ covering 30° (portrait or high-speed lenses) to $F/20$ covering 120° (wide angle). Ordinary photographic lenses for general use are about $F/7$ and cover 70°. Oculars do not require as high corrections as objectives but must take account of the positions and properties of both the eye and the objective.

Telescope and microscope objectives should give, near the axis, a definition equal to their theoretical resolving power at full aperture, but the image falls off very rapidly in quality not far from the axis. The best photographic objectives give, at full aperture, about half their theoretical resolving power on the axis and nearly as much at some distance from the axis. The perfection of the corrections required in any case depends upon the work to be done and is limited by the size of image and the resolving power of the eye or photographic plate.

B. ABERRATIONS

1. **Spherical Aberration.**—Rays from a point on the axis, passing through different zones of a lens, come to a focus at different distances from the lens. This longitudinal spreading of the image is the spherical aberration. In a simple converging lens, the image is nearer for rays through the outer zones, hence such spherical aberration is considered positive. Spherical aberration may be eliminated by using other than spherical surfaces on

a lens, but since such surfaces would not assist in eliminating the six remaining aberrations they are not used. In practice the positive spherical aberration of one lens is balanced by negative in another, and since this balance depends on the divergence of the rays incident on the first lens spherical aberration can be eliminated for but one distance in front and one distance behind the lens. The limits of tolerance for residual spherical aberration range from 0.01 to 0.001 of the image distance. Its complete specification must be in terms of all distances of object and all zones of the lens.

2. **Coma.**—Coma is a one-sided blur occurring in images not on the axis, due (roughly speaking) to one side of the lens being nearer the object than the other. The elimination of coma is of prime importance in all wide angle lenses. It is positive when the blur is directed away from the axis; negative when toward the axis. Since it depends upon the divergence of the light entering the lens and upon the distance from the axis, it may be eliminated for objects at one distance from the lens and one angle from the axis, but not for all distances or all angles. In general, an extended image will show negative coma within and positive coma without a given circle. Coma is largely (not entirely) eliminated by making a lens symmetrical, as is done in many photographic objectives. Coma is specified in terms of angle and distance of object.

3 and 4. **Curvature of Field and Astigmatism.**—The image of a plane object normal to the axis formed by a simple lens lies on two coaxial egg-shaped surfaces. Radial (from axis) lines in the object will be in focus on the outer surface; tangential lines (or circles about the axis) on the inner surface. In other words, the image of a point in the object plane will be a short radial line on the outer image surface and a tangential line on the inner image surface.

Correcting a lens for astigmatism consists in bringing the two image surfaces together; correcting a lens for curvature of field consists in lengthening out the oblique pencils until the useful portion of the image surface is plane. These aberrations, like coma, may be eliminated for one angle and one distance of object, but not for all angles nor for all object distances. The angle for which astigmatism is eliminated is, in general, different from (and less than) that for which either image surface cuts the focal plane. Since rays lying in the plane of a point object and the lens axis (the primary plane) are largely screened off by the lens rim at large angles from the axis while rays in the secondary plane are not, the latter rays are given chief consideration in lens correction.

The limits of tolerance for field curvature and astigmatism depend, of course, on the aperture ratio of the lens, since both aberrations produce less diffuseness in the image the narrower the pencil of rays forming the image.

5. **Distortion.**—Distortion is essentially a variation in the magnification produced by a lens. This varies both with distance from the axis and, at any point, varies in different (e. g., radial or tangential) directions. Two different definitions of distortion are commonly quoted: (1) the

ratio of tangential to radial magnification (distortion positive or negative, as this ratio is greater or less than unity), and (2) the radial magnification of a radial length relative to magnification near the axis (distortion positive or negative, as this ratio is greater or less than unity). Obviously distortion can be logically specified only by reference to two curves of magnification as a function of distance from the axis, one for radial and one for tangential magnifications.

Lenses from which spherical aberration, coma, and field curvature have been largely eliminated give very little distortion, but the less highly corrected oculars in common use may give considerable distortion, particularly if used by near-sighted persons or if used as photographic oculars. A small form of well-corrected photographic objective best meets the severe requirements of an ocular to be used to produce distortion-free images at varying distances. Like the four previous aberrations, distortion can be eliminated for but two distances of object and two angles from the axis.

6. **Axial Chromatism.**—Axial chromatism is a variation in the image distance with wave length. Lenses are ordinarily corrected to make the focal-length the same for two different wave lengths—orange and blue if for visual observation; blue and extreme violet if for photographic work. Except when the glass used is carefully chosen, a lens is achromatic only for the two wave lengths for which the focal lengths are made equal, the residual color error being called its secondary spectrum. Axial chromatism is specified in terms of wave length and distance of object.

7. **Lateral Chromatism.**—Lateral chromatism is a variation of the size of image with wave length. Its elimination requires other corrections than those upon which the elimination of axial chromatism depends. Erecting oculars and lenses for three-color photography must be carefully corrected for lateral chromatism. This aberration is commonly eliminated, not near the axis where it would be of less consequence, but for some distant zone of the image.

Besides these seven third-order aberrations there are nine of the fifth order and others of still higher order, but these are too small to be sensible to the eye or photographic plate except for large angles and apertures. The same may be said of the chromatic differences of the first five third-order aberrations.

C. LENS TESTING

1. **Single Lenses.**—Special single lenses, including the unmounted components of compound lenses. Any or all of the following tests will be made as desired:

    Principal focal length.
    Location of equivalent planes.
    Radii of curvature of surfaces.
    Uniformity of curvature of surfaces.
    Centering of surfaces.
    Homogeneity and freedom from strain of glass.

Refractive index for wave length 5893 (*D*).
Refractive indices for wave lengths 6563 (*C*), 5893 (*D*), and 4861 (*F*).
Astigmatism.
Axis of astigmatism.

2. **Compound Lenses.**—Photographic objectives, objectives and oculars of optical instruments. Any or all of the following tests will be made as desired:

(a) *General tests*—

Equivalent focal length.
Location of equivalent planes.
Effective aperture and numerical aperture.
Loss of light by transmission.
Percentage of scattered light in image.
Relative illumination of image, oblique rays, 2 to 5 angles.

(b) *Definition tests* of actual performance in image plane—

Lateral diffusion of image near the axis.
Lateral diffusion of image outward.
Lateral diffusion of image inward.
Lateral diffusion of image tangentially.
} For 2 to 5 angles and 2 to 5 stop openings.

(c) *Residual aberrations* in actual value—

Spherical aberration by zones and distances (2 to 5 zones and 2 to 5 distances of object).
Coma for rays of 2 to 5 angles of obliquity, and for 2 to 5 distances of object.
Astigmatism, 2 to 5 distances of object, 2 to 5 angles.
Curvature of field, 2 to 5 distances of object, 2 to 5 angles.
Distortion, 2 to 5 distances of object, 2 to 5 angles.
Axial chromatism, 2 to 5 zones, 2 to 10 wave lengths, 2 to 5 distances of object.
Lateral chromatism, 2 to 5 angles of obliquity, 2 to 10 wave lengths, 2 to 5 distances of object.

The definition tests are intended for buyers and users of lenses, the measured aberrations for manufacturers and designers of lenses. Those desiring tests should state either the use to which the lens is to be put or else the precision required, for the labor and expense of the tests increase greatly with the number and precision of the tests made. Lenses for visual observation may have larger focal residual errors than those for photographic records owing to the accommodation of the eye. Further information may be had on request relating to the calculation of numerical aperture, "speed," depth of focus, the various aberrations, limits of tolerance for the different kinds of lenses for different classes of work, and descriptions of simple practical tests for common defects.

3. **Shutter Speed.**—Equivalent full opening and time of effective opening or any other function of the rate of change of area of shutter opening.

III. OPTICAL MATERIALS

A. REFRACTOMETRY

For the *identification* of optical glass, fluids, crystals, and the like a determination of the refractive index for yellow light to the fourth decimal place is often sufficient. Such tests are easily made with a simple refractometer of the total reflection type requiring but a few square millimeters of plane face or but a few drops of fluid.

For computing lenses and prisms it is necessary to know the refractive indices for a number of wave lengths to the fifth decimal place. The following wave lengths are the ones generally used:

Color	Line	Source	Wave length	
Red	A′	Potassium	0.7682	(Middle of double line)
Red	C	Hydrogen	0.6563	
Yellow	D	Sodium	0.5893	(Middle of double line)
Blue	F	Hydrogen	0.4861	
Violet	G′	Hydrogen	0.4341	

These determinations are made on small 60° prisms with a spectrometer.

Refractive indices may be determined to the sixth decimal place with a spectrometer of high precision provided with means of temperature control, monochromatic slit illumination, ocular slit (or slit wire), a divided circle reading to 2″ and very plane prism faces. This degree of precision is required for determining temperature coefficients of refractive index (which are of the order of 0.000002 per degree C) and indices of standard check samples of glass. Inhomogeneity of the glass generally occurs in the sixth or seventh decimal place and uncertainties in determining deviations and circle errors are of about the same order. Temperature coefficients from −10° to 50° C should be known for glass to be used for telescope objectives, from 10° to 300° C, for investigating the properties of glasses.

The following tests of optical materials will be made as desired:

1. *Identification* of glasses, crystals, and fluids by a determination of the refractive index to the fourth decimal place. A polished plane surface of 20 mm^2 on a solid or a few drops of a fluid are sufficient.

2. *Refractive index* and dispersion of glasses and fluids through the visible and ultra-violet spectra to the fifth decimal place. A 60° prism of the glass with two well-worked plane surfaces at least 5 mm across or 10 cc of the fluid are required.

3. *Refractive indices of gases* in the visible spectrum.

4. *Temperature coefficients* of refractive index, $-10°$ to $50°$ C, or $10°$ to $300°$ C for C, D, and F lines.

5. Prism *angles* and goniometry of crystals.

6. *Curvature* of lens, prism, and other surfaces.

7. *Parallelism* or flatness of surfaces.

8. *Homogeneity* of glass and freedom from strain of prisms.

Other tests of a similar nature will be undertaken by special arrangement.

B. ABSORPTOMETRY

Optical glass is tested for percentage absorption per 10 cm thickness, usually for 1, 3, or 5 wave lengths. Samples for test should be in brick-shaped blocks with ends ground and polished and with ends nearly but not quite parallel.

IV. REGULATIONS CONCERNING TESTS

(*a*) **Application for Test.**—The request for verification of any instrument should state explicitly the points at which test is to be made and the temperature or any other conditions which it is desired should be observed.

(*b*) **Identification Marks.**—Instruments and the packages in which they are shipped should both be plainly marked to facilitate identification, preferably with the name of the manufacturer or shipper, and a special reference number given to the article.

(*c*) **Shipping Directions.**—Instruments should be securely packed in cases or packages which may be used in returning them to the owner. Tops of cases should be screwed down whenever possible. Transportation charges are payable by the party desiring the test, and should be prepaid. Unless otherwise arranged, articles will be returned by express "collect."

(*d*) **Address.**—Articles should be addressed simply, "Bureau of Standards, Department of Commerce and Labor, Washington, D. C." Delays incident to other forms of address will thus be avoided.

Articles delivered in person or by messenger should be left at the office of the bureau and should be accompanied by a written request for the verification.

(*e*) **Remittances.**—Fees my be remitted by money order or check drawn to the order of the "Bureau of Standards." Delays in forwarding fees will involve corresponding delay in the completion of tests, as the articles are not returned until all fees due thereon have been received.

(*f*) **Breakage.**—Since all possible care is taken in testing and packing, the bureau does not assume any responsibility for breakage or other damage to instruments or materials submitted for test.

(*g*) **Fees.**—A reasonable fee will be charged for each test made. For testing *optical instruments*, the fee will be from $2 to $10, depending upon the instrument, the nature of the test, and the precision desired.

SCHEDULE 46.—OPTICAL INSTRUMENTS.

(a) Testing *compound lenses*—	
General tests as listed, each	$1. 00
Definition tests, each	$1. 00 to 5. 00
Measurement of aberrations, each	2. 00 to 20. 00
(b) Testing single lenses, each listed test	. 25
(c) Determination of *refractive indices* to the fourth decimal place	. 50
(d) Determination of *refractive indices* to the fifth decimal place	1. 00
(e) Determination of *temperature coefficient* of refractive index	$2. 00 to 10. 00
(f) Determination of indices of standard samples to the sixth decimal place	. 50 to 2. 00
(g) Color tests	. 50 to 5. 00

Fees for special tests and tests of the same kind in large number given upon request.

S. W. STRATTON,
Director.

Approved:
BENJ. S. CABLE,
Acting Secretary.