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PATENT SPECIFICATION

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PROVISIONAL SPECIFICATION

Improvements in or relating to Objectives

We, TAYLOR, TAYLOR & HOBSON LIMITED, a Company registered under the Laws of Great Britain, and ARTHUR WARMISHAM, British Subject, both of 104, Stoughton Street, Leicester, do hereby declare the nature of this invention to be as follows:—

This invention relates to objectives for photographic or like purposes, in which use is made of aspherical surfaces in order to obtain improved correction more especially for spherical aberration.

Various objectives of this kind have been proposed and in most cases the aspherical surfaces have been convex surfaces and usually the outermost surfaces of the objective. Thus for example in one proposal a meniscus doublet, which may itself constitute a complete objective with its air-exposed concave surface next to a diaphragm or may be combined with another similar doublet with the two air-exposed concave surfaces facing the diaphragm, has had its air-exposed convex surface aspherical and in the form of a prolate spheroid. Again British Patent Specification No. 435,149 describes an objective of the kind comprising two dispersive meniscus components located between two collective components and enclosing a diaphragm with their air-exposed concave surfaces facing the diaphragm, in which correction for spherical aberration at a wide aperture such as F/1.1 is obtained by the use of one or more aspherical surfaces, preferably one or more of the convex surfaces of the collective components.

According to the present invention, in an objective having the air-exposed surface or surfaces immediately next to the diaphragm position concave, such concave surface or one or each of such concave surfaces is aspherical, whilst the remaining surfaces of the objective are all spherical, the aspherical surface or each aspherical surface being in the form of a surface of revolution which is less shallow than the spherical surface which osculates it at its vertex on the optical axis. Thus the meridian section of such surface may be represented in polar coordinates (with respect to an origin at the centre of curvature at the vertex and to an axis of reference through the origin and the vertex) of the form

$r = r_0 + a\,\theta^4 + b\,\theta^6 + \ldots$ (higher powers of θ)

where r_0 is the numerical value of the radius of curvature at the vertex (so that r and r_0 are positive whether the surface is concave or convex towards the incident light) and a and b are constants of which a is negative. Such surface may conveniently have approximately the form of the polar cap of an oblate spheroid.

It is to be understood that the phrase "diaphragm position" herein used, is to be interpreted as meaning either the actual position of the diaphragm or, in cases where no diaphragm is provided (as for example may be the case when the objective is used for projection purposes), the position which would be occupied by the diaphragm if there were one.

The invention is applicable to objectives of various types, and generally gives improved correction not only for spherical aberration but also for the other errors such as coma, astigmatism and distortion, thus making it possible to obtain correction with higher apertures than have hitherto been attainable in objectives of the same type. Another advantage of the invention is that it materially assists in enabling good correction, especially for spherical aberration, to be obtained simultaneously for axial pencils and for oblique pencils.

In one simple arrangement, the objective comprises a single compound meniscus lens having at least three elements cemented together and having its air-exposed concave surface, which faces the diaphragm position, aspherical. In this case the aspherical surface preferably has such a form that the coefficient a in the polar equation has a numerical value greater than $1\frac{1}{2}$ per cent. of the equivalent focal length of the lens. The axial thickness of the lens is preferably greater than 6 per cent. of the equivalent focal length, and the radius of curvature (at the vertex) of each of the air-exposed surfaces of the lens is greater than 15 per cent. of the equivalent focal length of the lens. With such an

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arrangement good correction can be obtained with an aperture F/8 or even higher.

The invention is equally applicable to the modified form of such objective in which the lens is split up into two components, consisting respectively of a compound divergent meniscus component having its air-exposed concave surface aspherical and facing the diaphragm position and of a convergent component facing the air-exposed convex surface of the first component.

As is well-known, good correction for higher apertures can be obtained by providing a further component or components on the other side of the diaphragm position. The objective may be symmetrical about the diaphragm position with each half self-corrected, such an arrangement having the advantage that, by making one half of the objective removable, two alternative objectives of different focal length are readily available for use as may be required. It is often preferable, however, to employ an asymmetrical arrangement, and in some instances only one of the two concave surfaces immediately next to the diaphragm is made aspherical.

Thus the objective may comprise two compound convergent meniscus components enclosing the diaphragm position between them, one or each of the two air-exposed concave surfaces which face the diaphragm position being aspherical. One or each of the two components may consist of at least three elements cemented together. Preferably in at least one of the components the radius of curvature (at the axis) of each of the two air-exposed surfaces is greater than 25 per cent. of the equivalent focal length of the objective. Preferably at least one of the components has an axial thickness greater than 10 per cent. of the equivalent focal length of the objective. Thus in one convenient arrangement at least one of the two components has an aspherical concave surface in combination with an axial thickness greater than 12 per cent. of the equivalent focal length. In the case of an asymmetrical objective, the air-exposed concave surface of the front component conveniently has a radius of curvature at the axis smaller than that of the air-exposed convex surface thereof, whilst in the back component the radius of curvature at the axis of the air-exposed concave surface is greater than that of the air-exposed convex surface. In the case of a symmetrical objective the aspherical surface of each component preferably has such a form that the coefficient a in the polar equation is numerically greater than $2\frac{1}{2}$ per cent. of the equivalent focal length of the objective.

In another arrangement, giving good correction for the highest apertures usually required, the objective comprises two compound divergent meniscus components located between two convergent components and enclosing the diaphragm position between them, one or each of the two air-exposed concave surfaces next to the diaphragm position being aspherical. In one variant of this arrangement, which may be regarded as a modification of the objective of the prior Patent No. 435,149 above mentioned giving improved correction with a very wide aperture such as F/1.1, both the air-exposed concave surfaces adjacent to the diaphragm position are aspherical. The sum of the numerical values of the radii of the air-exposed convex surfaces of the two dispersive components should preferably be not less than 90 per cent. of the equivalent focal length of the objective, and similarly the sum of the numerical values of the radii of curvature at their vertices of the air-exposed concave surfaces of these components should preferably be not less than 55 per cent. of the equivalent focal length. In another variant, intended more especially to improve the correction for oblique pencils as well as axial pencils with a somewhat smaller aperture such as F/2, the coefficient a in the polar equation above set out has a numerical value less than one per cent. of the equivalent focal length of the objective. Although in this case satisfactory results can usually be obtained with one aspherical surface only, it may sometimes be convenient to distribute the asphericity between the two concave surfaces next to the diaphragm position. The sum of the numerical values of the radii of the air-exposed convex surfaces of the two dispersive components should preferably be not less than 75 per cent. of the equivalent focal length of the objective, and similarly the sum of the numerical values of the radii of curvature at their vertices of the air-exposed concave surfaces of these components should preferably be not less than 52 per cent. of the equivalent focal length of the objective.

Numerical data for some convenient practical examples of photographic objective according to the invention are given in the tables below. In these tables the radii of the successive surfaces of the elements of the objective counting from the front, that is the side facing the incident light, are indicated respectively by R_1 R_2 . . . . . (the radius given for an aspherical surface being the radius of curvature at the vertex thereof) the radii being indicated as positive or negative in accordance with whether the surfaces are convex or concave to the incident light, and the axial thicknesses of the individual elements are indicated respectively by D_1 D_2. . . . The axial air separations between the various components, where the objective has more than a single component, are indicated by S_1 S_2. . . . . , whilst in cases where the objective consists of a single meniscus lens the tables give the stop distance, that is the axial distance of the diaphragm from the front surface of the lens. The tables also give the refractive indices (for the D-line) and the Abbé V numbers of the glasses used for the individual elements.

In the first two examples the objective consists of a single meniscus lens having its concave air-exposed surface facing the incident light with a diaphragm in front of such surface, and consisting of three elements cemented together.

EXAMPLE 1.

Equivalent focal length 1.000. Relative aperture F/8.

Radius	Thickness	Stop distance	Refractive index n_D	Abbé V number.
		.033		
R_1 − .1988				
	D_1 .031		1.5163	64.0
R_2 − .2237				
	D_2 .016		1.5174	52.2
R_3 + .4587				
	D_3 .026		1.6204	60.2
R_4 − .2065				

EXAMPLE 2.

Equivalent focal length 1.000. Relative aperture F/7.3.

Radius	Thickness	Stop distance	Refractive index n_D	Abbé V number.
		.033		
R_1 − .1873				
	D_1 .022		1.6204	60.2
R_2 − .1471				
	D_2 .016		1.5174	52.2
R_3 + .4587				
	D_3 .026		1.6204	60.2
R_4 − .2059				

The first surface in each example is aspherical and approximates to the polar cap of an oblate spheroid generated by revolution of an ellipse about its minor axis, the generating ellipse in Example 1 having minor axis .1000 and eccentricity .7050, and in Example 2 having minor axis .1110 and eccentricity .6384. Thus the surface may have a meridian section defined in polar coordinates in Example 1 by the equation

$$r = .1988 - .02455\ \theta^4 - .008037\ \theta^6$$

and in Example 2 by the equation

$$r = .1873 - .01609\ \theta^4 - .002849\ \theta^6.$$

These two examples are corrected for higher apertures than the prior known meniscus lenses, and generally they differ from such lenses in having shallower curves in relation to the focal length and, in order to retain a flat field, much larger axial thickness. Thus in both examples the radius of each external surface is considerably greater than 15 per cent. of the equivalent focal length as contrasted with, for example, 11 or 12½ per cent. for the known lenses, whilst the overall thickness is greater than 6 per cent. (7.3 per cent. in Example 1 and 6.4 per cent. in Example 2) as contrasted with, say, 3 per cent. for the known lenses.

Although the monochromatic correction can be obtained with two refractive indices (as will be evident from Example 1), a third element is required to secure achromatism in this example since glasses do not exist with refractive indices 1.620 and 1.517 in combination with the necessary ratio of dispersions. In Example 2 the necessity for this third element is turned to advantage by making the element nearest the diaphragm of high refractive index, thereby reducing the Airy Petzval sum in comparison with Example 1. Alternatively, the presence of the third element may be utilised to reduce further the curvatures of the air-exposed surfaces, which reacts to increase the Airy Petzval sum.

In the third example, the objective consists of two components both located behind the diaphragm, the front component consisting of a divergent meniscus doublet and the back component of a simple convergent element.

EXAMPLE 3.

Equivalent focal length 1.000. Relative aperture F/4.

Radius	Thickness or Separation	Stop Distance	Refractive index n_D	Abbé V number.
		.0506		
R_1 – .2079				
	D_1 .0253		1.6132	36.9
R_2 ∞				
	D_2 .0651		1.6129	59.4
R_3 – .2700				
	S_1 .0051			
R_4 – 2.730				
	D_3 .0325		1.6437	48.2
R_5 – .4810				

The front surface R_1 is aspherical and approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse whose minor axis is .1988 and whose eccentricity is .2086. The polar equation of the meridian section of the surface is

$$r = .2079 - .001181\ \theta^4 + .000166\ \theta^6.$$

In the fourth example, the objective consists of two similar meniscus triplets symmetrically arranged on opposite sides of the diaphragm.

EXAMPLE 4.

Equivalent focal length 1.000. Relative aperture F/4.2.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number
R_1 + .3471			
	D_1 .0438	1.6204	60.2
R_2 – .7731			
	D_2 .0270	1.5174	52.2
R_3 + .2480			
	D_3 .0371	1.6204	60.2
R_4 + .3158			
	S_1 .1112		
R_5 – .3158			
	D_4 .0371	1.6204	60.2
R_6 – .2480			
	D_5 .0270	1.5174	52.2
R_7 + .7731			
	D_6 .0438	1.6204	60.2
R_8 – .3471			

In this example the two surfaces R_4 R_5 are aspherical, each approximating to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .1871 and eccentricity .6383, the polar equation of the meridian section being

$$r = .3158 - .02713\ \theta^4 - .01690\ \theta^6.$$

The thickness of each component is .1079, and each of the air-exposed surfaces has a radius considerably greater than 25 per cent. of the equivalent focal length. This example has the advantage, since each component is self-corrected, of providing two alternative objectives of different focal length, namely the complete double objective and the single objective obtained by removing the front component completely from the double objective.

This example may be modified, with the advantage of somewhat improving the correction of the double objective but sacrificing the advantage of having each half self-corrected, by making the objective asymmetrical as regards asphericity, for example by confining the asphericity wholly to one only of the two concave surfaces, say the surface R_5. In this modification the aspherical surface R_5 approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .1233 and eccentricity .7811, the polar equation of the meridian section being

$$r = .3158 - .06163\ \theta^4 - .03789\ \theta^6.$$

Still better results as regards correction of the double objective can be obtained by making the two halves dissimilar not only in asphericity but also in other respects, as indicated in the following example.

EXAMPLE 5.

Equivalent focal length 1.000. Relative aperture F/3.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .3642			
	D_1 .095	1.6204	60.2
R_2 − 1.111			
	D_2 .130	1.5174	52.2
R_3 + .1100			
	D_3 .094	1.5174	64.2
R_4 + .2778			
	S_1 .108		
R_5 − .4167			
	D_4 .097	1.5174	64.2
R_6 − .1100			
	D_5 .093	1.5174	52.2
R_7 + .4546			
	D_6 .050	1.6440	48.3
R_8 − .4003			

In this example the surfaces R_4 R_5 are both aspherical and each approximates to the polar cap of an oblate spheroid, of which the generating ellipse has minor axis .1116 and eccentricity .7735 in the case of the surface R_4 and minor axis .1390 and eccentricity .8163 in the case of the surface R_5. The polar equation of the meridian section for R_4 is

$$r = .2778 - .05171\ \theta^4 - .01201\ \theta^6.$$

and the corresponding equation for R_5 is

$$r = .4167 - .10406\ \theta^4 - .02889\ \theta^6.$$

The surfaces R_2 R_7 are both convergent surfaces and it will be noticed that the axial thicknesses of the two components are respectively .319 and .240. It will also be noticed that radius of curvature at the axis of surface R_4 is less than the radius of R_1, whilst that of R_5 is greater than the radius of R_8, and that all four radii are greater than 25 per cent. of the equivalent focal length.

In each of the remaining four examples, the objective comprises two divergent meniscus doublets enclosing the diaphragm and located between two convergent components each consisting of a single element.

EXAMPLE 6.

Equivalent focal length 1.000. Relative aperture F/1.8.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .7120			
	D_1 .100	1.6130	59.3
R_2 +3.333			
	S_1 .012		
R_3 + .4415			
	D_2 .110	1.6138	59.4
R_4 ∞			
	D_3 .050	1.6048	38.0
R_5 + .2889			
	S_2 .160		
R_6 − .2974			
	D_4 .050	1.5781	40.5
R_7 +3.333			
	D_5 .110	1.6252	56.1
R_8 − .3922			
	S_3 .012		
R_9 +2.439			
	D_6 .090	1.6130	59.3
R_{10} − .9652			

In this example the surface R_6 is spherical, whilst the surface R_5 approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .2820 and eccentricity .1546, the polar equation of the meridian section being $r = .2889 - .0008850\ \theta^4 + .0001366\ \theta^6$.

EXAMPLE 7.

Equivalent focal length 1.000. Relative aperture F/2.0.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .67049			
	D_1 .0711	1.6130	59.3
R_2 +2.8211			
	S_1 .0122		
R_3 + .45542			
	D_2 .1117	1.6138	59.4
R_4 ∞			
	D_3 .0508	1.6048	38.0
R_5 + .29342			
	S_2 .1625		
R_6 − .30205			
	D_4 .0508	1.5781	40.5
R_7 +3.3852			
	D_5 .1117	1.6252	56.1
R_8 − .38330			
	S_3 .0122		
R_9 +2.4771			
	D_6 .0609	1.6130	59.3
R_{10} −1.0948			

In this example the surface R_5 is spherical, whilst the surface R_6 approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .2723 and eccentricity .2674, the polar equation of the meridian section being $r = .29342 - .002825\ \theta^4 + .0003620\ \theta^6$.

EXAMPLE 8.

Equivalent focal length 1.000. Relative aperture F/1.8.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .7120			
	D_1 .100	1.6130	59.3
R_2 + 3.333			
	S_1 .012		
R_3 + .4415			
	D_2 .110	1.6138	59.4
R_4 ∞			
	D_3 .050	1.5760	40.5
R_5 + .2825			
	S_2 .160		
R_6 − .2991			
	D_4 .050	1.6210	36.3
R_7 +10.00			
	D_5 .110	1.6250	56.1
R_8 + .3846			
	S_3 .012		
R_9 + 2.439			
	D_6 .090	1.6130	59.3
R_{10} − .9009			

In this example the surface R_5 is spherical and the surface R_6 approximates to the polar cap of an oblate spheroid generated by an ellipse having minor axis .2920 and eccentricity .1549, the polar equation of the meridian section being

$$r = .2991 - .000920\ \theta^4 + .000142\ \theta^6.$$

The foregoing examples 6—8, which have one aspherical surface only, show considerable improvement over known objectives of the same general type, in respect more particularly of affording good correction (more especially in respect of spherical aberration) not only for axial pencils but also for oblique pencils. The following example, in which the asphericity is distributed between the two concave surfaces next to the diaphragm, is well corrected, at least as far as axial pencils are concerned, for a still higher aperture of F/1.1.

EXAMPLE 9.

Equivalent focal length 1.000. Relative aperture F/1.1.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .9390			
	D_1 .120	1.613	59.3
R_2 +19.23			
	S_1 .003		
R_3 + .5000			
	D_2 .290	1.653	46.3
R_4 − 1.250			
	D_3 .030	1.650	33.6
R_5 + .2857			
	S_2 .230		
R_6 − .3846			
	D_4 .030	1.672	32.3
R_7 + .4545			
	D_5 .215	1.653	46.3
R_8 − .5000			
	S_3 .003		
R_9 + 1.053			
	D_6 .080	1.653	46.3
R_{10} − .9921			

The surface R_5 in this example approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .2592 and eccentricity .3050, and the surface may consist of a surface of revolution having a meridian section defined in polar coordinates by the equation

$$r = .2857 - .003665\ \theta^4 + .000423\ \theta^6.$$

The surface R_6 may likewise approximate to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .3047 and eccentricity .4560, the polar equation of the meridian section being

$$r = .3846 - .01262\ \theta^4 + .000447\ \theta^6.$$

It will be appreciated that, although described primarily with respect to objectives for photographic purposes, the invention is also applicable to projection objectives and in such case it may often be unnecessary to provide the diaphragm at all. Thus for instance most of the examples of objective above described can be employed without the diaphragm for projection purposes.

Dated this 5th day of May, 1938.

A. F. PULLINGER,
Agent for the Applicants.

COMPLETE SPECIFICATION

Improvements in or relating to Objectives

We, TAYLOR, TAYLOR & HOBSON LIMITED, a Company registered under the Laws of Great Britain, and ARTHUR WARMISHAM, British Subject, both of 104, Stoughton Street, Leicester, do hereby declare the nature of this invention and in what manner the same is to be performed, to be particularly described and ascertained in and by the following statement:—

This invention relates to objectives for photographic or like purposes, in which use is made of aspherical surfaces in order to obtain improved correction more especially for spherical aberration.

Various objectives of this kind have been proposed and in most cases the aspherical surfaces have been convex surfaces and usually the outermost surfaces of the objective. Thus for example in one proposal a meniscus doublet, which may itself constitute a complete objective with its air-exposed concave surface next to a diaphragm or may be combined with another similar doublet with the two air-exposed concave surfaces facing the diaphragm, has had its air-exposed convex surface aspherical and in the form of a prolate spheroid. Again British Patent Specification No. 435,149 describes an objective of the kind comprising two dispersive meniscus components located between two collective components and enclosing a diaphragm with their air-exposed concave surfaces facing the diaphragm, in which correction for spherical aberration at a wide aperture such as F/1.1 is obtained by the use of one or more aspherical surfaces, preferably one or more of the convex surfaces of the collective components.

According to the present invention, in an objective having the air-exposed surface or surfaces immediately next to the diaphragm position concave, such concave surface or one or each of such concave surfaces is aspherical, whilst the remaining surfaces of the objective are all spherical, the aspherical surface or each aspherical surface being in the form of a surface of revolution which is less shallow than the spherical surface which osculates it at its vertex on the optical axis. Thus the meridian section of such surface may be represented in polar coordinates (with respect to an origin at the centre of curvature at the vertex and to an axis of reference through the origin and the vertex) by an equation of the form $r = r_0 + a\ \theta^4 + b\ \theta^6 + \ldots$ (higher powers of θ) where r_0 is the numerical value of the radius of curvature at the vertex (so that r and r_0 are positive whether the surface is concave or convex towards the incident light) and a and b are constants of which a is negative. Such surface may conveniently have approximately the form of the polar cap of an oblate spheroid.

It is to be understood that the phrase "diaphragm position" herein used, is to be interpreted as meaning either the actual position of the diaphragm or, in cases where no diaphragm is provided (as for example may be the case when the objective is used for projection purposes), the position which would be occupied by the diaphragm if there were one.

The invention is applicable to objectives of various types, and generally gives improved correction not only for spherical aberration but also for the other errors such as coma, astigmatism and distortion, thus making it possible to obtain correction with higher apertures than have hitherto been attainable in objectives of the same type. Another advantage of the invention is that it materially assists in enabling good correction, especially for spherical aberration, to be obtained simultaneously for axial pencils and for oblique pencils.

In one simple arrangement, the objective comprises a single compound meniscus lens having at least three elements cemented together and having its air-exposed concave surface, which faces the diaphragm position, aspherical. In this case the aspherical surface preferably has such a form that the coefficient a in the polar equation has a numerical value greater than $1\frac{1}{2}$ per cent. of the equivalent focal length of the lens. The axial thickness of the lens is preferably greater than 6 per cent. of the equivalent focal length, and the radius of curvature (at the vertex) of each of the air-exposed surfaces of the lens is greater than 15 per cent. of the equivalent focal length of the lens. With such an arrangement good correction can be obtained with an aperture F/8 or even higher.

The invention is equally applicable to the modified form of such objective in which the lens is split up into two components, consisting respectively of a compound divergent meniscus component having its air-exposed concave surface aspherical and facing the diaphragm position and of a convergent component facing the air-exposed convex surface of the first component.

As is well-known, good correction for higher apertures can be obtained by providing a further component or components on the other side of the diaphragm position. The objective may be symmetrical about the diaphragm position with each half self-corrected, such an arrangement having the advantage that, by making one half of the objective removable, two alternative objectives of different focal length are readily available for use as may be required. It is often preferable, however, to employ an asymmetrical arrangement, and in some instances only one of the two concave surfaces immediately next to the diaphragm is made aspherical.

Thus the objective may comprise two compound convergent meniscus components enclosing the diaphragm position between them, one or each of the two air-exposed concave surfaces which face the diaphragm position being aspherical. One or each of the two components may consist of at least three elements cemented together. Preferably in at least one of the components the radius of curvature (at the axis) of each of the two air-exposed surfaces is greater than 25 per cent. of the equivalent focal length of the objective. Preferably at least one of the components has an axial thickness greater than 10 per cent. of the equivalent focal length of the objective. Thus in one convenient arrangement at least one of the two components has an aspherical concave surface in combination with an axial thickness greater than 12 per cent. of the equivalent focal length. In the case of an asymmetrical objective, the air-exposed concave surface of the front component conveniently has a radius of curvature at the axis smaller than that of the air-exposed convex surface thereof, whilst in the back component the radius of curvature at the axis of the air-exposed concave surface is greater than that of the air-exposed convex surface. In the case of a symmetrical objective the aspherical surface of each component preferably has such a form that the coefficient a in the polar equation is numerically greater than $2\frac{1}{2}$ per cent. of the equivalent focal length of the objective.

In another arrangement, giving good correction for the highest apertures usually required, the objective comprises two compound divergent meniscus components located between two convergent components and enclosing the diaphragm position between them, one or each of the two air-exposed concave surfaces next to the diaphragm position being aspherical. In one variant of this arrangement, which may be regarded as a modification of the objective of the prior Patent No. 435,149 above mentioned giving improved correction with a very wide aperture such as F/1.1, both the air-exposed concave surfaces adjacent to the diaphragm position are aspherical. The sum of the numerical values of the radii of the air-exposed convex surfaces of the two dispersive components should preferably be not less than 90 per cent. of the equivalent focal length of the objective, and similarly the sum of the numerical values of the radii of curvature at their vertices of the air-exposed concave surfaces of these components should preferably be not less than 55 per cent. of the equivalent focal length. In another variant, intended more especially to improve the correction for oblique pencils as well as axial pencils with a somewhat smaller aperture such as F/2, the coefficient a in the polar equation above set out has a numerical value less than one per cent. of the equivalent focal length of the objective. Although in this case satisfactory results can usually be obtained with one aspherical surface only, it may sometimes be convenient to distribute the asphericity between the two concave surfaces next to the diaphragm position. The sum of the numerical values of the radii of the air-exposed convex surfaces of the two dispersive components should preferably be not less than 75 per cent. of the equivalent focal length of the objective, and similarly the sum of the numerical values of the radii of curvature at their vertices of the air-exposed concave surfaces of these components should preferably be not less than 52 per cent. of the equivalent focal length of the objective.

The invention may be carried into practice in various ways, but some convenient practical arrangements of photographic objective according thereto are described below by way of example with reference to the accompanying drawings, in which

Figure 1 shows diagrammatically one type of objective of which two numerical examples according to the invention are given,

Figure 2 illustrates another type of objective of which one example according to the invention is given,

Figure 3 illustrates a further type of objective of which three examples according to the invention are given, and

Figure 4 shows yet another type of objective of which four examples according to the invention are given.

Numerical data for the ten examples are given in the tables below. In these tables the radii of the successive surfaces of the elements of the objective counting from the front, that is the side facing the incident light, are indicated respectively at R_1 R_2 . . . . . (the radius given for an aspherical surface being the radius of curvature at the vertex thereof) the radii being indicated as positive or negative in accordance with whether the surfaces are convex or concave to the incident light, and the axial thicknesses of the individual elements are indicated respectively by D_1 D_2 . . . . The axial air separations between the various components, where the objective has more than a single component, are indicated by S_1 S_2 . . . . , whilst in cases where the objective consists of a single meniscus lens the tables give the stop distance, that is the axial distance of the diaphragm from the front surface of the lens. The tables also give the refractive indices (for the D-line) and the Abbé V numbers of the glasses used for the individual elements.

In the first two examples the objective is of the type shown in Figure 1 and comprises a single meniscus lens having its concave air-exposed surface facing the incident light with a diaphragm indicated at A in front of such surface and consisting of three elements cemented together.

EXAMPLE 1.

Equivalent focal length 1.000. Relative aperture F/8.

Radius	Thickness	Refractive index n_D	Abbé V number.
R_1 −.1988			
	D_1 .031	1.5163	64.0
R_2 −.2237			
	D_2 .016	1.5174	52.2
R_3 +.4587			
	D_3 .026	1.6204	60.2
R_4 −.2065			

In this example the axial distance B from the diaphragm A to the first surface is .033. This first surface is aspherical and approximates to the polar cap of an oblate spheroid generated by revolution about its minor axis of an ellipse having minor axis .1000 and eccentricity .7050. Thus the surface may have a meridian section defined in polar coordinates by the equation

$$r = .1988 - .02455\ \theta^4 - .008037\ \theta^6$$

EXAMPLE 2.

Equivalent focal length 1.000. Relative aperture F/7.3.

Radius	Thickness	Refractive index n_D	Abbé V number.
R_1 − .1873			
	D_1 .022	1.6204	60.2
R_2 − .1471			
	D_2 .016	1.5174	52.2
R_3 + .4587			
	D_3 .026	1.6204	60.2
R_4 − .2059			

In this example the axial distance B from the diaphragm A to the first surface is again .033. This first surface is aspherical and approximates to the polar cap of an oblate spheroid generated by revolution about its minor axis of an ellipse having minor axis .1110 and eccentricity .6384, the corresponding polar equation of the meridian section being

$$r = .1873 - .01609\ \theta^4 - .002849\ \theta^6.$$

These two examples are corrected for higher apertures than the prior known meniscus lenses, and generally they differ from such lenses in having shallower curves in relation to the focal length and, in order to retain a flat field, much larger axial thickness. Thus in both examples the radius of each external surface is considerably greater than 15 per cent. of the equivalent focal length as contrasted with, for example, 11 or 12½ per cent. for the known lenses, whilst the overall thickness is greater than 6 per cent. (7.3 per cent. in Example 1 and 6.4 per cent. in Example 2) as contrasted with, say, 3 per cent. for the known lenses.

Although the monochromatic correction could be obtained with two refractive indices only the third element in Example 1 is required to secure achromatism since glasses do not exist with refractive indices 1.620 and 1.517 in combination with the necessary ratio of dispersions. In Example 2 the necessity for this third element is turned to advantage by making the element nearest the diaphragm of high refractive index, thereby reducing the Airy Petzval sum in comparison with Example 1. Alternatively, the presence of the third element may be utilised to reduce further the curvatures of the air-exposed surfaces, which reacts to increase the Airy Petzval sum.

In the third example, shown in Figure 2, the objective consists of two components both located behind the diaphragm A, the front component consisting of a divergent meniscus doublet and the back component of a simple convergent element.

EXAMPLE 3.

Equivalent focal length 1.000. Relative aperture F/4.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 − .2079			
	D_1 .0253	1.6132	36.9
R_2 ∞			
	D_2 .0651	1.6129	59.4
R_3 − .2700			
	S_1 .0051		
R_4 − 2.730			
	D_3 .0325	1.6437	48.2
R_5 − .4810			

In this example the axial distance B from the diaphragm A to the first surface is .0506. This first surface is aspherical and approximates to the polar cap of an oblate spheroid generated by revolution about its minor axis of an ellipse having minor axis .1988 and eccentricity .2086, the polar equation of the meridian section being

$$r = .2079 - .001181\ \theta^4 + .000166\ \theta^6.$$

In the fourth example, the objective is of the type shown in Figure 3 and consists of two similar meniscus triplets symmetrically arranged on opposite sides of the diaphragm A.

EXAMPLE 4.

Equivalent focal length 1.000. Relative aperture F/4.2.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number
R_1 + .3471			
	D_1 .0438	1.6204	60.2
R_2 − .7731			
	D_2 .0270	1.5174	52.2
R_3 + .2480			
	D_3 .0371	1.6204	60.2
R_4 + .3158			
	S_1 .1112		
R_5 − .3158			
	D_4 .0371	1.6204	60.2
R_6 − .2480			
	D_5 .0270	1.5174	52.2
R_7 + .7731			
	D_6 .0438	1.6204	60.2
R_8 − .3471			

In this example the two surfaces R_4 R_5 are aspherical, each approximating to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .1871 and eccentricity .6383, the polar equation of the meridian section being

$$r = .3158 - .02713\ \theta^4 - .01690\ \theta^6.$$

The thickness of each component is .1079, and each of the air-exposed surfaces has a radius considerably greater than 25 per cent. of the equivalent focal length. This example has the advantage, since each component is self-corrected, of providing two alternative objectives of different focal length, namely the complete double objective and the single objective obtained by removing the front component completely from the double objective.

This example may be modified, with the advantage of somewhat improving the correction of the double objective but sacrificing the advantage of having each half self-corrected, by making the objective asymmetrical as regards asphericity, for example by confining the asphericity wholly to one only of the two concave surfaces, say the surface R_5. In this modification the aspherical surface R_5 approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .1233 and eccentricity .7811, the polar equation of the meridian section being

$$r = .3158 - .06163\ \theta^4 - .03789\ \theta^6.$$

Still better results as regards correction of the double objective can be obtained by making the two halves dissimilar not only in asphericity but also in other respects, as indicated in the following example.

EXAMPLE 5.

Equivalent focal length 1.000. Relative aperture F/3.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .3642			
	D_1 095	1.6204	60.2
R_2 − 1.111			
	D_2 .130	1.5174	52.2
R_3 + .1100			
	D_3 .094	1.5174	64.2
R_4 + .2778			
	S_1 .108		
R_5 − .4167			
	D_4 .097	1.5174	64.2
R_6 − .1100			
	D_5 .093	1.5174	52.2
R_7 + .4546			
	D_6 .050	1.6440	48.3
R_8 − .4003			

In this example the surfaces R_4 R_5 are both aspherical and each approximates to the polar cap of an oblate spheroid, of which the generating ellipse has minor axis .1116 and eccentricity .7735 in the case of the surface R_4 and minor axis .1390 and eccentricity .8163 in the case of a surface R_5. The polar equation of the meridian section for R_4 is

$$r = .2778 - .05171\ \theta^4 - .01201\ \theta^6.$$

and the corresponding equation for R_5 is

$$r = .4167 - .10406\ \theta^4 - .02889\ \theta^6.$$

The surfaces R_2 R_7 are both convergent surfaces and it will be noticed that the axial thicknesses of the two components are respectively .319 and .240. It will also be noticed that radius of curvature at the axis of surface R_4 is less than the radius of R_1, whilst that of R_5 is greater than the radius of R_8, and that all four radii are greater than 25 per cent. of the equivalent focal length.

In each of the remaining four examples, the objective is of the type shown in Figure 4, and comprises two divergent meniscus doublets enclosing the diaphragm A and located between two convergent components each consisting of a single element.

EXAMPLE 6.

Equivalent focal length 1.000. Relative aperture F/1.8.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .7120			
	D_1 .100	1.6130	59.3
R_2 +3.333			
	S_1 .012		
R_3 + .4415			
	D_2 .110	1.6138	59.4
R_4 ∞			
	D_3 .050	1.6048	38.0
R_5 + .2889			
	S_2 .160		
R_6 − .2974			
	D_4 .050	1.5781	40.5
R_7 +3.333			
	D_5 .110	1.6252	56.1
R_8 − .3922			
	S_3 .012		
R_9 +2.439			
	D_6 .090	1.6130	59.3
R_{10} − .9652			

In this example the surface R_6 is spherical, whilst the surface R_5 approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .2820 and eccentricity .1546, the polar equation of the meridian section being

$$r = .2889 - .0008850\ \theta^4 + .0001366\ \theta^6.$$

EXAMPLE 7.

Equivalent focal length 1.000. Relative aperture F/2.0.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .67049			
	D_1 .0711	1.6130	59.3
R_2 +2.8211			
	S_1 .0122		
R_3 + .45542			
	D_2 .1117	1.6138	59.4
R_4 ∞			
	D_3 .0508	1.6048	38.0
R_5 + .29342			
	S_2 .1625		
R_6 − .30205			
	D_4 .0508	1.5781	40.5
R_7 +3.3852			
	D_5 .1117	1.6252	56.1
R_8 − .38330			
	S_3 .0122		
R_9 +2.4771			
	D_6 .0609	1.6130	59.3
R_{10} −1.0948			

In this example the surface R_5 is spherical, whilst the surface R_6 approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .2723 and eccentricity .2674, the polar equation of the meridian section being

$$r = .29342 - .002825\ \theta^4 + .0003620\ \theta^6.$$

EXAMPLE 8.

Equivalent focal length 1.000. Relative aperture F/1.8.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .7120			
	D_1 .100	1.6130	59.3
R_2 + 3.333			
	S_1 .012		
R_3 + .4415			
	D_2 .110	1.6138	59.4
R_4 ∞			
	D_3 .050	1.5760	40.5
R_5 + .2825			
	S_2 .160		
R_6 − .2991			
	D_4 .050	1.6210	36.3
R_7 +10.00			
	D_5 .110	1.6250	56.1
R_8 − .3846			
	S_3 .012		
R_9 + 2.439			
	D_6 .090	1.6130	59.3
R_{10} − .9009			

In this example the surface R_5 is spherical and the surface R_6 approximates to the polar cap of an oblate spheroid generated by an ellipse having minor axis .2920 and eccentricity .1549, the polar equation of the meridian section being

$$r = .2991 - .000920\ \theta^4 + .000142\ \theta^6.$$

The foregoing examples 6—8, which have one aspherical surface only, show considerable improvement over known objectives of the same general type, in respect more particularly of affording good correction (more especially in respect of spherical aberration) not only for axial pencils but also for oblique pencils. The following example, in which the asphericity is distributed between the two concave surfaces next to the diaphragm, is well corrected, at least as far as axial pencils are concerned, for a still higher aperture of F/1.1.

EXAMPLE 9.

Equivalent focal length 1.000. Relative aperture F/1.1.

Radius	Thickness or Separation	Refractive index n_D	Abbé V number.
R_1 + .9390			
	D_1 .120	1.613	59.3
R_2 +19.23			
	S_1 .003		
R_3 + .5000			
	D_2 .290	1.653	46.3
R_4 − 1.250			
	D_3 .030	1.650	33.6
R_5 + .2857			
	S_2 .230		
R_6 − .3846			
	D_4 .030	1.672	32.3
R_7 + .4545			
	D_5 .215	1.653	46.3
R_8 − .5000			
	S_3 .003		
R_9 + 1.053			
	D_6 .080	1.653	46.3
R_{10} − .9921			

The surface R_5 in this example approximates to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .2592 and eccentricity .3050, and the surface may consist of a surface of revolution having a meridian section defined in polar coordinates by the equation.

$$r = .2857 - .003665\ \theta^4 + .000423\ \theta^6.$$

The surface R_6 may likewise approximate to the polar cap of an oblate spheroid formed by rotation about its minor axis of an ellipse having minor axis .3047 and eccentricity .4560, the polar equation of the meridian section being

$$r = .3846 - .01262\ \theta^4 + .000447\ \theta^6.$$

It will be appreciated that, although described primarily with respect to objectives for photographic purposes, the invention is also applicable to projection objectives and in such case it may often be unnecessary to provide the diaphragm at all. Thus for instance most of the examples of objective above described can be employed without the diaphragm for projection purposes.

Having now particularly described and ascertained the nature of our said invention and in what manner the same is to be performed, we declare that what we claim is:—

1. An objective for photographic or like purposes having the air-exposed surface or surfaces immediately next to the diaphragm position concave, in which such concave surface or one or each of such concave surfaces is in the form of a surface of revolution, whose meridian section is represented in polar coordinates (with respect to an origin at the centre of curvature at the vertex and to an axis of reference through the origin and the vertex) by an equation of the form $r = r_0 + a\ \theta^4 + b\ \theta^6 + \ldots$ (higher powers of θ) where r_0 is the numerical value of the radius of curvature at the vertex and a and b are constants of which a is negative, the remaining surfaces of the objective all being spherical.

2. An objective as claimed in Claim 1, in which the aspherical surface or each aspherical surface has approximately the

form of the polar cap of an oblate spheroid.

3. An objective as claimed in Claim 1 or Claim 2, comprising a single compound meniscus lens having at least three elements cemented together and having its air-exposed concave surface which faces the diaphragm position aspherical.

4. An objective as claimed in Claim 3, in which the aspherical surface has such a form that the coefficient a in the polar equation has a numerical value greater than $1\frac{1}{2}$ per cent. of the equivalent focal length of the lens.

5. An objective as claimed in Claim 3 or Claim 4, in which the axial thickness of the lens is greater than 6 per cent. of the equivalent focal length of the lens.

6. An objective as claimed in Claim 3 or Claim 4 or Claim 5, in which the radius of curvature (at the vertex) of each of the air-exposed surfaces of the lens is greater than 15 per cent. of the equivalent focal length of the lens.

7. An objective as claimed in Claim 1 or Claim 2, comprising a compound divergent meniscus component having its air-exposed concave surface aspherical and facing the diaphragm position, and its air-exposed convex surface facing a convergent component.

8. An objective as claimed in Claim 1 or Claim 2, comprising two compound convergent meniscus components enclosing the diaphragm position between them, one or each of the two air-exposed concave surfaces which face the diaphragm position being aspherical.

9. An objective as claimed in Claim 8, in which one or each of the two components consists of at least three elements cemented together.

10. An objective as claimed in Claim 8 or Claim 9, in which in at least one of the components the radius of curvature (at the axis) of each of the two air-exposed surfaces is greater than 25 per cent. of the equivalent focal length of the objective.

11. An objective as claimed in Claim 8 or Claim 9 or Claim 10, in which at least one of the components has an axial thickness greater than 10 per cent. of the equivalent focal length of the objective.

12. An objective as claimed in Claim 11, in which at least one of the components has an aspherical concave surface in combination with an axial thickness greater than 12 per cent. of the equivalent focal length of the objective.

13. An objective as claimed in any one of Claims 8—12, in which in the front component the air-exposed concave surface has a radius of curvature at the axis smaller than that of the air-exposed convex surface, whilst in the back component the air-exposed concave surface has a radius of curvature at the axis greater than that of the air-exposed convex surface.

14. An objective as claimed in any one of Claims 8—11, in which the objective is symmetrical with respect to the diaphragm position, the aspherical surface of each component having a form such that the coefficient a in the polar equation is numerically greater than $2\frac{1}{2}$ per cent. of the equivalent focal length of the objective.

15. An objective as claimed in Claim 1 or Claim 2, comprising two compound divergent meniscus components located between two convergent components and enclosing the diaphragm position between them, one or each of the air-exposed concave surfaces which face the diaphragm position being aspherical.

16. An objective as claimed in Claim 15, in which the sum of the numerical values of the radii of the air-exposed convex surfaces of the divergent components is not less than 75 per cent. of the equivalent focal length of the objective.

17. An objective as claimed in Claim 15 or Claim 16, in which the sum of the numerical values of the radii of curvature at the axis of the air-exposed concave surfaces of the divergent components is not less than 52 per cent. of the equivalent focal length of the objective.

18. An objective as claimed in Claim 15 or Claim 16 or Claim 17, in which the aspherical surface or each aspherical surface has a form such that the coefficient a in the polar equation has numerical value less than one per cent. of the equivalent focal length of the objective.

19. An objective as claimed in Claim 16, in which the air-exposed concave surfaces facing the diaphragm position are both aspherical and the sum of the numerical values of the radii of the air-exposed convex surfaces of the divergent components is not less than 90 per cent. of the equivalent focal length of the objective.

20. An objective as claimed in Claim 17, in which the air-exposed concave surfaces facing the diaphragm position are both aspherical and the sum of the numerical values of the radii of curvature at the axis of such surfaces is not less than 55 per cent. of the equivalent focal length of the objective.

21. The photographic or like objective in any one of the practical embodiments herein described having numerical data substantially as set forth.

Dated this 26th day of April, 1939.

A. F. PULLINGER,
Agent for the Applicants.

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Fig. 1.

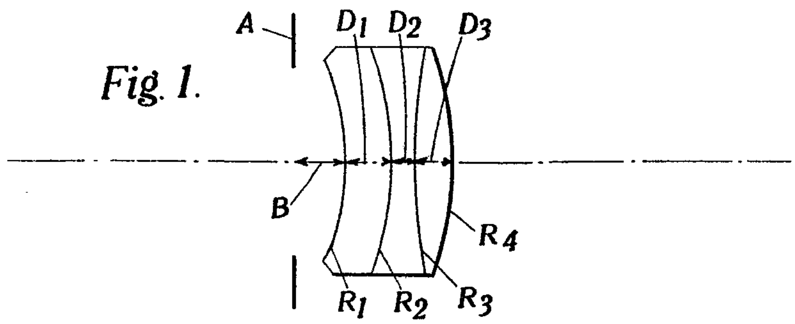

Fig. 2.

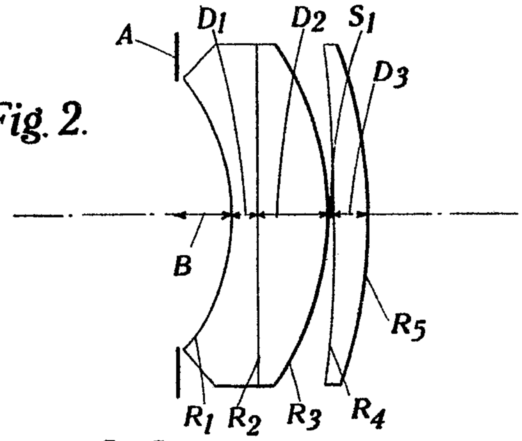

Fig. 3.

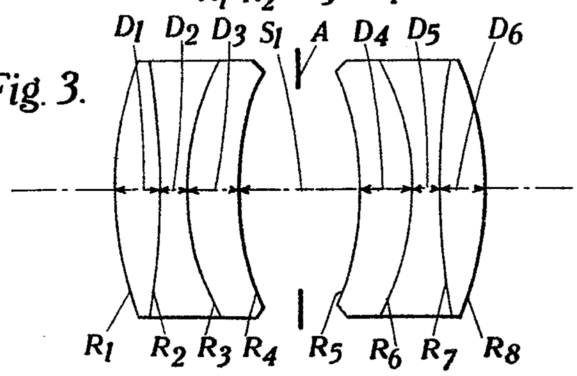

Fig. 4.