LENSES FOR INDUSTRIAL AUTOMATION

PART THREE: CAMERA LENSES WITH FOUR AIR-SPACED ELEMENTS

Technical Note 218

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ABSTRACT

In Part Two, we offered a specification for a low-cost general-purpose lens for use with silicon photocell array cameras. In this report, we investigate the development of the all air-spaced, four-element lens from the patents that relate to the Goerz Celor, Goerz Dogmar, Cooke Aviar, and 100 mm Kodak Ektar (U.S. Patent No. 2,338,614). The design in the latter patent is compatible with our specification. Spherical aberration and OSC' curves are given for each of the designs and are used as the basis for evaluating suitability for our particular purpose.
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I  INTRODUCTION:  THE SPECIFICATION AND CANDIDATE DESIGNS

In Part One and Part Two, we have reviewed the requirements for lenses to be used with the high-resolution silicon array cameras that are now being applied to industrial automation. A standard for a low-cost, general-purpose lens for use with 1024-element linear arrays was proposed in Part Two; it has the following performance characteristics:

* Achromatic for 0.5461 micron and 0.8521 micron
* Spherical aberration corrected for 0.6563 micron
* Petzval sum, < 0.30
* Spherical aberration, < 0.005
* Offense against sine condition (OSC'), < 0.005
* Distortion (over 12 inch - 30 inch object distance), < 0.2%
* Focal length, 35-50 mm
* Aperture, f/4.5
* Field Semi-angle, 15 degrees.

This moderately stiff specification is mollified by the limited field angle. We have previously postulated that the most practical type of lens configuration would be the Celor all-air-spaced symmetrical form containing four elements; this opinion is supported by the following commercial products that demonstrate the usefulness of the Celor configuration:

(1) The 203 mm f/7.7 Kodak Ektar is rated excellent for use on a 4 X 5 view camera, at full aperture and at all magnifications. This lens is the modern version of the 203 mm f/7.7 Kodak Anastigmat; Figure 1 presents its specifications.

(2) The same configuration is commonly used for process lenses, e.g., Apo Artar, where low distortion is an essential requirement.

(3) The 100 mm f/4.5 Kodak Enlarging Ektar, the specifications of which are in Figure 2, is highly regarded. Kodak makes the following statement in one of

* For an explanation of the physical significance of these special technical terms, see Section II.
its brochures: "It is suitable for making color-separation negatives, matrices and color prints... These lenses are especially designed to meet the most rigid requirements in definition and color correction. Their correction for lateral chromatic aberration is extremely high" [1].

![Lens Diagram]

LENS SPEED: f/7.7, marked apertures—f/7.7, f/11, f/16, f/22, f/32, and f/45


FIGURE 1 SPECIFICATION FOR KODAK 203 mm f/7.7 ANASTIGMAT

We shall follow the development of the Color design from its inception in terms of two criteria: (1) the improvement achieved and (2) the additional cost. A ray-tracing program has been written for the purpose of evaluating designs that have been patented [2]. A patent specification is required to be a tutorial text, and a condition of granting the patent is that anyone skilled in the art should be able to achieve the improvements that are claimed,* otherwise, the patent does
not have good legal standing. The early patented designs are likely to produce results that are typical of moderate-cost efforts, and conceivably by using the latest glass types some improvement over the patent performance is likely to be obtainable. Even so, one very important parameter, OSC', is quite resilient and it is an open question whether new glasses will permit it to be decreased spectacularly. The general nature of the OSC' curve is an inherent property of the design.

* Unfortunately, the majority of patents contain errors, the resolution of which takes a lot of time for the reader. For example, the diagrams may be mislabeled, the sign of a radius may be incorrect, the word "negative" should read "positive," refractive indices have numbers transposed (1.62210 in place of 1.61120), values of refractive index are truncated (1.744 in place of 1.74450). Usually the focal length is given (100.0 mm), and this information alone may be sufficient to confirm the validity of the correct choice. Equally, if the back focal distance does not agree, there must be something inaccurate about the initial data. The coincidence of the visual and photographic foci for the Zeiss Ortho-Protar (Figure 4) is a good indication of the credibility of the computed curves.
II THE PARAMETERS DEFINING LENs PERFORMANCE

The performance of a camera lens can be conveniently discussed by subdividing the image plane into three regions: (1) close to the axis, (2) the near field, and (3) the far field. The various types of lens defects vary in significance greatly according to the part of the image plane that is being considered; thus, in the vicinity of the axis spherical aberration is the defect of greatest consequence, while astigmatism considerations may be neglected. On the other hand, in the outer part of the field, the influence of astigmatism is dominant. In the middle region, the strongest defect is coma; and because we are considering lenses that will be used only as far as 15 degrees off-axis, coma considerations are of rather more concern to us than the effects of astigmatism. The lenses we are dealing with are all anastigmats, i.e., lens designs in which the astigmatism may be reduced essentially to zero at a given off-axis angle. If we make this angle say 13 degrees, astigmatism is not likely to reach a level at which it becomes the controlling factor. For this reason, the main emphasis will be on the performance of the lens designs with respect to coma, or more particularly with "offense against the sine condition", OSC', which is a measure of coma.

The physical interpretation of the various technical terms has been discussed in Part One, but we will recapitulate very briefly.

We are analyzing the image of a point source and may first of all divide the defects (aberrations) into two classes--those concerned with light of various colors (i.e., chromatic) and those concerned with light of a specific wavelength (monochromatic). In all the lens designs under consideration, color defects can be compensated for to a sufficient degree, and we shall here be dealing primarily with the monochromatic defects.
The controlling error close to the axis is spherical aberration. If we subdivide the lens into a set of annuli, we desire that each annulus should form an image of a luminous point on the axis in precisely the same position. The measured imperfections in the axial intercept are defined as the longitudinal spherical aberration.

If we now move the luminous point away from the axis, the image point will move off axis in sympathy. However, the various annuli show slight differences in magnification factor, so that the image spreads out into a small radial line. The length of the line is called the coma, and the ratio of the length of the line to the distance of the image from the axis is called the "offense against the sine condition."

We now change the luminous point for a small luminous cross, where the lines are oriented so as to be radial and tangential. In the outer part of the image field, the radial and tangential lines do not focus in the same plane. If we shrink the luminous cross down to a point, in the radial and tangential focus conditions we are left with residual tangential and radial lines that are a measure of the astigmatism. The surfaces of radial (sagittal) and tangential focus can be brought into coincidence at some particular off-axis angle in the class of lenses called anastigmats. All modern lenses are anastigmats.

The other parameter of significance is the "Petzval Sum,

\[ \sum \frac{n_1 - n_2}{n_1 n_2 r} \]

where the sum is over all radii. The Petzval Sum determines the intrinsic curvature of the image field, i.e., close to the axis before astigmatism has flattened the field. The number quoted is the ratio of the focal length of the lens to the radius of the Petzval surface, and the smaller the Petzval Sum the flatter the image plane. Further, the smaller the Petzval Sum the less the astigmatism needed to flatten the field, i.e., the slower the definition is degraded. For a simple lens, the ratio is \(-1/n \sim -0.65\).
III  PATENTED DESIGNS

A.  Quotations from Hans Harting on the Celor

"Quality of Corrections" [3]

"Noteworthy are the simple construction of this objective, consisting of only four lenses, and its compactness because of the small vertex distance of the refracting surfaces. The anastigmatic flatness of field covers a large angle with small zonal errors, and this angle can be satisfactorily used because of the small amount of vignetting. The zones of spherical aberration are also small; but here, for the first time in the case of a double objective, we find a not inconsiderable coma."

"Coma of the Double Objectives" [4]

"While in the case of double objectives whose elements are cemented, we can discover no coma with a relative aperture of f/5.4, and can even increase the effective aperture to f/4.5 without detecting too serious a loss of brilliance in the image, in the case of a symmetrical objective composed of four single lenses coma is already noticeable at f/6.3, and is so strong at f/4.5 that these objectives cannot be compared for fineness of detail and resolving power with the unsymmetrical anastigmats* which are corrected for coma. Whether the quality of the picture suffers from this lack depends on the purpose for which it is intended."

These two quotations from Hans Harting carry a great deal of weight; Harting was one of the great designers of the period 1900-1910 and was the originator of the Voigtlander Heliar and Dynar. The lenses we need for the industrial automation work will frequently be used at maximum aperture, because this reduces the electrical load for illumination. On the basis of Harting's remarks, we might conclude that the 203 mm Kodak f/7.7 Ektar was deliberately made with aperture f/7.7 in order that it could never be used in a way that would yield inadequate performance. For the same reason, process lenses of Celor

* e.g., Cooke Triplet.
configuration are made to an aperture of f/9. Although the new lanthanum crown glasses are certainly capable of providing improved performance compared with the standards of 60 years ago, it seems evident that coma is the Achilles heel of the Celor design. It remains to be determined whether the design can be refined to yield full performance at f/6.3, the minimum aperture calculated in Part Two.

B. The Zeiss Ortho-Protar

In the light of Harting's strong statements about the residual coma in lenses of the Celor configuration, and especially in view of his favorable comments on designs based on cemented triplets, it was thought desirable to offer the Zeiss Ortho-Protar as a contemporary reference standard. Figure 3 presents its specifications. This lens is very compact—as compared with the superb Double Protar with aperture f/6.3, which is rather long and therefore vignettes—and was designed for photogrammetry. Thus, it has the extremely low distortion that we desire. The design specification is to be found in British Patent No. 4692 (1893). Because there are only four air-to-glass surfaces, even in its uncoated form the contrast would be quite high. The Zeiss Ortho-Protar was designed to be used at f/8, whereas wide-angle lenses of similar vintage, such as the Goerz Dagor (also cemented triplets), were intended to be used at f/11 or f/16. One may perhaps speculate that with modern glasses the aperture of the Ortho-Protar could be raised to f/7 or even f/6.3, while it should perform uniformly well out to at least 25 degrees from the lens axis. On the other hand, cemented triplets are difficult to center and are not favored by the glass shop; thus, the Ortho-Protar is inherently much more costly to make than the Celor.

The spherical aberration and OSC' curves for the Ortho-Protar for wavelengths of 0.5893 micron and 0.4340 micron are shown in Figures 4 and 5. To make a fair evaluation of the design, we must relate its construction to the conditions at the time the patent was granted—1893, when cameras used large plates and enlargers did not exist. If a lens
DOUBLE ANASTIGMAT: EACH HALF, f = 400 mm
MAXIMUM APERTURE = 0.063 (f/8)
PETZVAL SUM = -0.274

SOURCE: P. Rudolph, British Patent No. 4692 (1893), Figure 1

FIGURE 3 ZEISS ORTHO-PROTAR: SPECIFICATION

FIGURE 4  ZEISS ORTHO-PROTAR: SPHERICAL ABERRATION
(0.5893 microns and 0.434 microns)

FIGURE 5  ZEISS ORTHO-PROTAR: OSC' (0.5893 microns and 0.4358 microns)
is diffraction limited, the resolving power depends only on the lens aperture and not at all on the focal length. Thus, the number of resolvable elements increases linearly with the focal length. Lenses of the 1900 period were commonly made with focal lengths of 8 inches or more, and even by today's standards give very crisp images on 5 inch X 7 inch contact prints.

The computed curvoss for spherical aberration and OSC' for an Ortho-Protar designed according to the patent specification are given in Figures 4 and 5 for the D line (0.5893 micron) and for the G' line (0.4340 micron). In 1900, the only type of photographic emulsion available was the "ordinary," i.e., blue sensitive, with no sensitivity to either red or green light. Thus, it was important that the lens design should be optimized for the violet end of the spectrum.

Regarding Figures 4 and 5, we can make the following statements:

(1) The visual and photographic foci superimpose exactly. This is quite difficult to achieve and deserves special mention.
(2) The photographic compensation has received priority over the visual performance.
(3) The photographic OSC' at -0.0090 is well within the -0.01 standard that was usual for long-focal-length camera lenses.
(4) The spherical aberration of 0.9 % is also entirely satisfactory for a lens of this type.
(5) The lens holds its performance right up to full aperture.
(6) The Petzval Sum (-0.274) implies a moderately well-flattened field.

C. The Goerz Celor

The design specification of the Celor lens described in U.S. Patent No. 635,472, issued in 1899 to C. P. Goerz and E. von Hoegh, is given in Figure 6, and the calculated curves for spherical aberration and OSC' are shown in Figures 7 and 8, respectively. This lens is fully symmetrical in the sense that the radii, refractive indices, and
thicknesses of the front and rear halves are the same; however, the
diameter of the rear half is increased so that vignetting occurs at the
rim of the front element when the lens is used over a semi-field of +35
degrees. The vignetting is quite intentional and beneficial for
photographic purposes (see Conrady [5]).

The focal length of the lens described in the patent is 243 mm, and
the yellow focus is about 2 mm beyond the violet focus.

The patent contains the following statement:

"If, for instance, the achromatism of the two systems of
lenses can only be approximately obtained with the available
species of glass, we are able to cancel the still remaining
error without any difficulty by composing one of the lenses
of two lenses of approximately equal refraction, but of
different dispersion cemented together."

This would add considerably to the cost of manufacture, and there
is no indication that lenses labeled "Celor" were ever made this way.
The design would then take the form of the Planar, which was initially
made as described.

For apertures of f/8 and smaller, the photographic performance is
excellent, with spherical aberration < 0.005 and OSC' < 0.0035.
Although made to an aperture of f/4.5, the degradation for apertures
above f/7 is very rapid. In view of the displacement between the visual
and photographic foci, the user would need to stop the lens down to f/8
or smaller in any event. (See earlier comment by Harting on "coma of
double objectives.")

D. The Goerz Dogmar

In 1914, U.S. Patent 1,108,307 was granted to W. Zschokke for an
improved design that was produced by Goerz as the Dogmar. As Figure 9
indicates, the front and rear halves are no longer identical. The
yellow and violet focal planes have been made coincident, and the lens
has been modified so that it has improved performance at wider
apertures. The curves for spherical aberration and OSC' for 0.5893
\[ r_1 = +59.309 \text{ mm} \quad d_2 = 4.934 \text{ mm} \quad N_D = 1.000 \quad N_G = 1.000 \]

\[ r_2 = -130.924 \quad d_3 = 1.813 \quad 1.6112 \quad 1.62445 \]

\[ r_3 = -88.944 \quad d_4 = 2.246 \quad 1.000 \quad 1.000 \]

\[ r_4 = +71.973 \quad d_5 = 12.043 \quad 1.5356 \quad 1.54893 \]

\[ r_5 = -71.973 \quad d_6 = 2.246 \quad 1.000 \quad 1.000 \]

\[ r_6 = +88.944 \quad d_7 = 1.813 \quad 1.5356 \quad 1.54893 \]

\[ r_7 = +130.924 \quad d_8 = 4.934 \quad 1.6112 \quad 1.62445 \]

\[ r_8 = -59.309 \quad f = 243.1 \text{ mm} \]

\[ \text{PETZVAL SUM} = 0.256 \]


FIGURE 6  GOERZ CELOR: SPECIFICATION

13
$f = 243.1 \text{ mm}$

PETZVAL SUM $= 0.256$

$L_0 = -1,000,000 \text{ mm}$

**SOURCE:** E. von Höegh, U.S. Patent No. 635,472 (1899)

**FIGURE 7** GOERZ CELOR: SPHERICAL ABERRATION (0.5893 microns and 0.4358 microns)
FIGURE 8  GOERZ CELOR: OSC' (0.5893 microns and 0.4358 microns)

microns and 0.4340 microns are shown in Figures 10 and 11, respectively. This design is actually usable at f/4.5 whereas the original Celor was not. In the violet image plane, the spherical aberration is very small (< 0.005) up to f/5.0, and the maximum OSC' is < 0.006. Because the eight radii are now all different, and three kinds of glass are used rather than two, the manufacturing cost would be substantially increased over the Celor. Otherwise, this design comes very close to satisfying our specification for the general-purpose lens. The spectral correction in the infrared is comparable in difficulty with the correction in the violet.

E. The Cooke Aviar

The Cooke Aviar is described in the British Patents Nos 113,590 (1918) and 312,536 (1929). The dense barium crown glasses specified in the earlier patent were apparently not chemically stable and discolored under the influence of the atmosphere. According to the patent:

"The symmetrical type has obvious advantages from the manufacturer's point of view, but calculation shows that it will not yield a first-class objective of large field and wide aperture."
"Recent investigators of objectives of four simple lenses have discarded the symmetrical type." "Objectives made according to the above numerical specification give well-corrected definition over a field of semi-angle 26 degrees."

The performance of the Cooke Aviar, according to the specification in British Patent No. 312,536 and given in Figure 12, is shown by the spherical aberration curve Figure 13 and the OSC' curve in Figure 14 for illumination of a wavelength of 0.5893 micron. Computations for other wavelengths would require information from a Chance glass catalog of 1929 vintage.

The spherical aberration, which amounts to $9.338 - 9.242 = 0.096$ inch for a focal length of 10 inches, is 0.0096, and the OSC' is 0.0114, whereas our specification calls for a maximum of 0.005 for each. The reputation of the Cooke Aviar is excellent. These calculations
\[ r_1 = +27.701 \text{ mm} \quad d_1 = 4.2 \text{ mm} \]
\[ r_2 = -103.093 \]
\[ r_3 = -53.909 \]
\[ r_4 = +37.736 \]
\[ r_5 = -63.291 \]
\[ r_6 = +35.088 \]
\[ r_7 = -53.191 \]
\[ r_8 = -35.890 \]

\[ \begin{array}{ll}
\text{ND} & \text{NCl} \\
1.000 & 1.000 \\
1.61412 & 1.62803 \\
1.000 & 1.000 \\
1.56890 & 1.58637 \\
1.000 & 1.000 \\
1.54820 & 1.56364 \\
1.000 & 1.000 \\
1.61412 & 1.62803 \\
1.000 & 1.000 \\
\end{array} \]

\[ f = 100 \text{ mm} \quad \text{APERTURE} = f/4.5 \]


FIGURE 9  GOERZ DOGMAR: SPECIFICATION
FIGURE 10  Goerz Dogmar: Spherical Aberration (0.5893 microns and 0.4340 microns)
FIGURE 11  GOERZ DOGMAR: OSC' (0.5893 microns and 0.4340 microns)

demonstrate that a price must be paid if a usable wide aperture is
demanded in addition to a wide field. The Aviar was designed for
somewhat changed circumstances compared with the Dogmar, because by 1929
the use of panchromatic film was well established. It is possible to
achieve superior correction for achromatism with this type of lens
configuration.


The 100 mm Kodak Ektar described in U.S. Patent No. 2,338,614 of
1944 is essentially a revision of the Warmisham design, usable at f/4.5
and covering a semi-field of 25 degrees at f/4.5. The increment in
performance claimed in the patent is attributable to the use of the new
lanthanum crown glass of index 1.744 that had just been invented by
Kodak (1940).

Unfortunately, the numerical values given in the patent are not
self-consistent. The back focal distance of 89.2 mm given in the
listing (Figure 15) may well be true of the original design, but it does
not agree with the curve computed from the specification. The value
90.2 mm given by Cox [6] agrees with the paraxial value shown in Figure
17. The spherical aberration of 0.35 mm shown in Figure 3 of the patent
(Figure 16) is less than the 0.50 mm in Figure 17. Where does the error
come from? On looking through old literature, we find that the
refractive index of the lanthanum crown glass, EK-2, was really 1.74450;
if we lower the other index to 1.6285, we can produce a combination with
a back focus of 89.2 mm (Figure 17). However, this does not reduce the
spherical aberration. There is obviously at least one more inaccuracy
in the specification, and it may be merely a transposition of numbers,
e.g., 33.2 mm in place of 32.3 mm. It is quite remarkable how prevalent
this type of "accidental" error is in lens specifications; mostly the
errors are just a nuisance and can be easily resolved. In this case,
the inaccuracy is not simple to identify, and thus we shall use the
performance data computed from the values given in the patent.
$\lambda = 0.5893 \mu$

$r_1 = 2.9328 \quad t_1 = 0.4047 \quad n_1 = 1.57380$
$r_2 = -9.7348 \quad t_2 = 0.1736 \quad n_2 = 1.54997$
$r_3 = -4.9270 \quad t_3 = 0.1473 \quad n_3 = 1.54997$
$r_4 = +4.4527 \quad t_4 = 0.4097 \quad n_4 = 1.62340$
$r_5 = -5.3427 \quad t_5 = 0.1473$
$r_6 = +3.8188 \quad t_6 = 0.1736$
$r_7 = +5.9775 \quad t_7 = 0.4541$
$r_8 = -3.2063$

SOURCE: A. Warmisham, British Patent No. 312,536 (1929)

FIGURE 12 COOKE AVIAR: SPECIFICATION
FIGURE 13  COOKE AVIAR: SPHERICAL ABERRATION (0.5893 microns)
$L_0 = -1,000,000$

PETZVAL SUM = -0.347

$\lambda = 0.5893 \mu$

$f = 10.0$ inches

$\frac{f}{4.5}$

SOURCE: A. Warmsham, British Patent No. 312,636 (1929)

FIGURE 14  COOKE AVIAR: OSC' (0.5893 microns)
**F = 100 mm**

<table>
<thead>
<tr>
<th>LENS</th>
<th>ND</th>
<th>V</th>
<th>RADII</th>
<th>THICKNESSES</th>
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<tr>
<td>I</td>
<td>1.744</td>
<td>45.8</td>
<td>$R_1 = +33.2 \text{ mm}$</td>
<td>$t_1 = 5.8 \text{ mm}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$R_2 = -133.7$</td>
<td>$t_2 = 1.5$</td>
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<tr>
<td>II</td>
<td>1.629</td>
<td>35.3</td>
<td>$R_3 = -64.9$</td>
<td>$t_3 = 1.5$</td>
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<td></td>
<td></td>
<td></td>
<td>$R_4 = +38.6$</td>
<td>$t_4 = 5.8$</td>
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<tr>
<td>III</td>
<td>1.629</td>
<td>35.3</td>
<td>$R_5 = -60.3$</td>
<td>$t_5 = 1.5$</td>
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<td>$R_6 = +48.0$</td>
<td>$t_6 = 5.8$</td>
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<td>1.744</td>
<td>45.8</td>
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<td></td>
<td></td>
<td></td>
<td>$R_8 = -39.8$</td>
<td>$t_8 = 5.8$</td>
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</table>

**APERTURE = f/4.5**

**Source:** U.S. Patent No. 2,338,614

**FIGURE 15** KODAK 100 mm EKTAR: SPECIFICATION (PATENT)

FIGURE 16  KODAK 100 mm EKTAR: AUXILIARY INFORMATION (PATENT)
The computed value for the spherical aberration is 0.0050, and the corresponding value for OSC' is 0.0067 (Figure 18). The equivalent measurements for the Cooke Aviar were 0.0094 and 0.0114, so that the improvement produced by the use of the lanthanum crown glass is very substantial. The Petzval sum is excellent, implying a flat field. Clearly, this design comes very close to or exceeds our recommendations for a general-purpose lens for industrial automation.

One question remains: How rapidly does the performance deteriorate with distance? The design, as given in the patent, relates to an object at infinity. By suitable adjustment of the radii, the design can be modified to optimize performance at any distance we choose, e.g., 0.5 meter. We can derive an estimate of how the performance varies with distance by calculating the spherical aberration and OSC' of a 100 mm lens according to the patent specification for a distance of 1 meter. The industrial lens would have a focal length of 50 mm, so the 1 meter for the 100 mm lens would be equivalent to 0.5 meter, since the patent design is computed for infinity. At 1 meter distance there is a modest fall-off in performance, the spherical aberration increasing from 0.50 mm to 0.63 mm and the OSC' increasing from 0.0067 to 0.0073 (Figure 19).

IV CONCLUSIONS

On the evidence, we may conclude that the lens design given in the Aklin patent (U.S. Patent No. 2,338,614) could provide the basis for a general-purpose lens to be used with silicon photocell array cameras. Its optical performance would approximate our suggested specification; on the other hand, with eight different radii it would not be particularly low in cost, and the lanthanum crown glass used for the outer elements is vulnerable to chemical attack.

The important characteristics of the various lens designs are summarized in Table 1.
FIGURE 17  KODAK 100 mm EKTAR: SPHERICAL ABERRATION ($L_o = -10^6$ mm)
FIGURE 18  KODAK 100 mm EKTAR: OSC' (L₀ = -10⁶ mm)
FIGURE 19  KODAK 100 mm EKTAR: OSC' (L₀ = -10^3 mm)
Table 1

Summary of Results

<table>
<thead>
<tr>
<th>Maker</th>
<th>Patent No.</th>
<th>Useful Aperture</th>
<th>Spherical Aberration</th>
<th>OSC'</th>
<th>Petzval Sum</th>
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<td>Suggested specification</td>
<td></td>
<td>f/4.5</td>
<td>&lt; 0.005</td>
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<td>Ortho-</td>
<td>(1893)</td>
<td>f/8.0</td>
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<td>Goerz</td>
<td>635,472</td>
<td>f/70</td>
<td>At f/8</td>
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<td>(1929)</td>
<td>(wide angle)</td>
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<td>(wide angle)</td>
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REFERENCES


4. H. Harting, ibid, p. 163.


PATENTS


