Design and use of mass-produced aspheres at Kodak

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Aspheric surfaces provide both performance and cost advantages for large-quantity lens production. Aspheres are reviewed from their early application in viewfinders to their use in camera lenses and, most recently, to applications in laser focusing lenses. There are restrictions imposed on the shape or strength of aspheres by either the manufacturing processes or testing techniques that the designer must recognize.

I. Introduction

The spherical aberration of a condenser lens can be reduced if a hyperbolic rather than a spherical surface is used. Recognizing this, Eastman Kodak Co. began the pressing of aspheric glass condenser elements. These elements were part of the Kodascope B 16-mm motion picture projector shown in Fig. 1, which, when introduced in 1927, marked the beginning of over a half-century of large-volume production of aspheres.

The use of millions of aspheres a year is now an accepted practice. To understand why, several critical applications of aspheres will be reviewed. The benefits they provide to the design and their preferred method of testing will be discussed. A description will be given of the population distribution of aspheres that have appeared in Kodak's designs. The current manufacturing limits for mass-produced aspheres will be presented, and, finally, some future applications will be anticipated.

II. Viewfinders

Let us first consider the aspheres found in camera viewfinders. In 1957, the Signet 30 and Signet 50 cameras were introduced, two years later the Automatic 35 Camera (Fig. 1). They all had the same finder, a reversed Galilean-type consisting of a negative objective lens and a positive eye lens (Fig. 2). Similar finders are found in today's cameras. There are compelling reasons for using aspheres in these finders. In fact, all Kodak's still cameras now have aspheres, with good reason. There are two aberrations which limit a finder's performance: lateral color and distortion. Both are controlled by the negative objective element. To reduce lateral color, a material of low dispersion is required. To reduce distortion, a high index of refraction is needed. These characteristics are available only in costly rare-earth lanthanum crown glasses. If we instead choose acrylic, an inexpensive plastic, it has the low dispersion which reduces color but also has low refractive index, which causes excessive distortion. However, if an asphere is added to the element, distortion may be reduced easily. An aspheric curve may be polished into the mold and thousands of surfaces replicated accurately and inexpensively.

How are the aspheres used in viewfinders tested? Recognize that the surface quality required for finder systems is not as stringent as the quality required for photographic lenses. When the asphere was first used on the Signet 30 camera, the aspheric mold insert was tested by gauge fit. A brass gauge was cut having the correct profile, placed against the mold-insert surface, and, if they matched so that no light could be seen through the interface, the insert was thought to be satisfactory. The surfaces of the plastic parts were not measured but only tested visually as part of the finder system. Today testing is more rigorous. During production start-up, both mold and finished part are tested to within one wavelength with an optical profilometer or specially designed refractive null correctors. Gauge fits remains a backup test technique. Day-to-day variability in the parts caused by variations in the molding process is visually inspected for complete filling, then monitored as any plastic lens is, by checking flange focus. No special concern is needed for aspheric variations.

How strong are the aspheres used in viewfinders? To provide direction for future manufacturing technology development, a population survey was made looking for potential trends.[1] Among 83 surfaces from 70 different viewfinder designs, the majority were found to depart from a best-fit spheres with <550 waves (Fig. 3). These surfaces were distributed very evenly out to 400 waves

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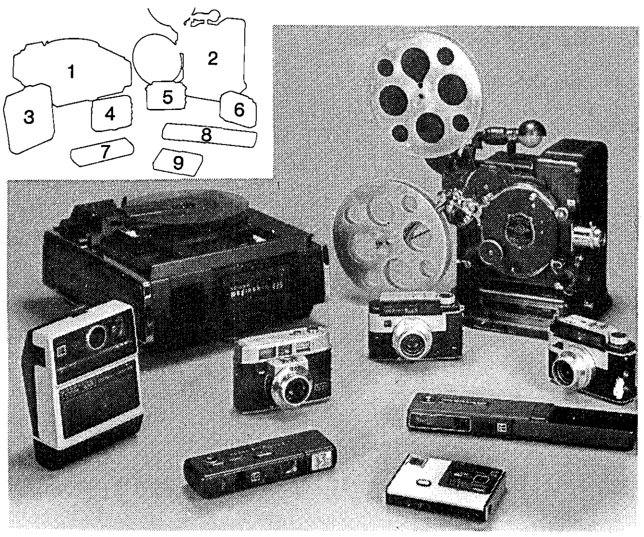

Fig. 1. Eastman Kodak products that contained significant advances in the company's ability to design and fabricate aspheres include (1) the Moviedeck 425 projector, (2) the Kodascope B projector, (3) the EK6 instant camera, (4) the Automatic 35 camera, (5) the Signet 30 camera, (6) the Signet 50 camera, (7) the Ektramax camera, (8) the Ektralite 500 camera, and (9) the Disc 4000 camera.

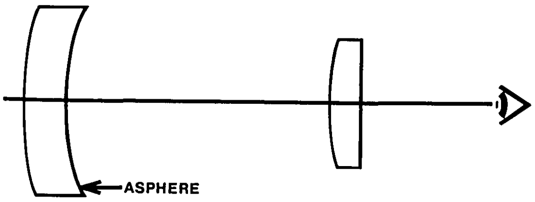

Fig. 2. This optical schematic drawing depicts the single Galilean viewfinder that was used in the Signet 30, Signet 50, and Automatic 35 cameras. The negative element of the finder was acrylic with an asphere on its second surface.

of departure with lower frequency beyond this level (Fig. 4). There is virtually no limit to how strong an asphere may be molded of plastic. The distribution of surface numerical aperture vs frequency was even (Fig. 5), as was the distribution of surface numerical aperture vs departure (Fig. 6).

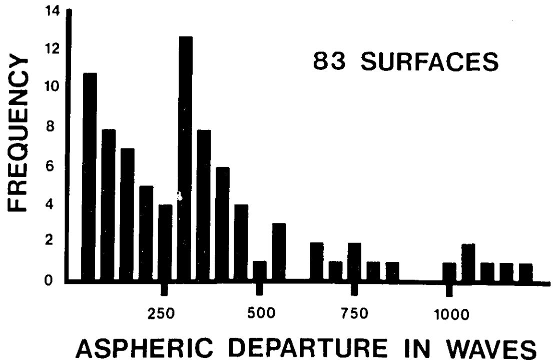

Fig. 3. In an analysis of 83 surfaces from 70 different viewfinder designs, the aspheric departure from a best-fit sphere ranged from 0.3 waves to more than 1000 waves.

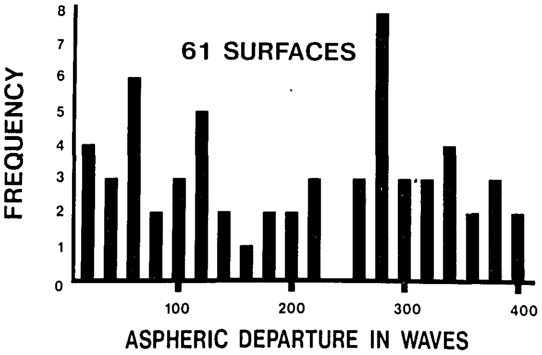

Fig. 4. Among viewfinder aspheres studied, 61 surfaces, or 73.5% of the total, were evenly distributed between 0.3 waves and 400 waves departure from a best-fit sphere.

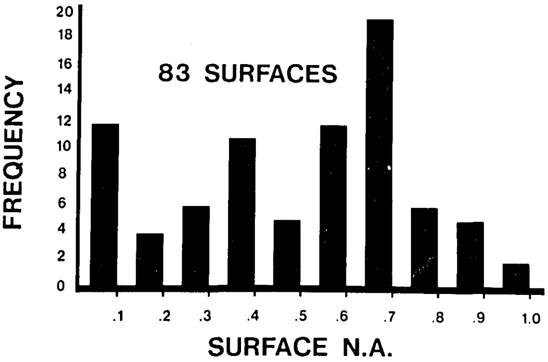

Fig. 5. Seventy-four viewfinder aspheres, or 89% of the total analyzed, had surface numerical apertures of 0.74 or less. The distribution of these surfaces is fairly even over the range of surface numerical apertures.

Before concluding this discussion of aspheres in viewfinders, let us review a system that employed three aspheres and could not have been possible without them. In 1976 the company unveiled it first line of instant cameras. The top of the line, the Kodak EK6 instant camera (Fig. 1), featured a unique focusing aid in the finder called the zooming circle. The finder was a reversed Galilean (Fig. 7) using an aspheric surface on the negative objective lens to reduce distortion, as previously described. Introduced into the line of sight by means of a beam splitter was the zooming circle. As the user focused the camera, a circle in the finder would change size. By encircling the subject's head (Fig. 8), the user was measuring an object of fairly constant size. The closer the head, the larger the circle. By linking the circle and lens focus mechanism, matching circle size to head size focused the camera at the correct distance. Inside the camera, the circle was a physically clear area on opaque film. The circle was moved fore and aft to change its apparent size. A stationary plastic element with two aspheric surfaces was required to keep the circle sharply defined through its range of travel. Testing of the mold to produce this double asphere was accomplished by gauge fits. The element was tested visually as part of the system, crudely but adequately.

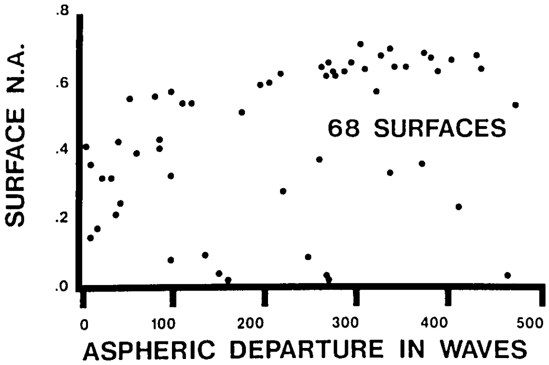

Fig. 6. Comparing surface numerical aperture vs aspheric departure, 68 viewfinder aspheres, or 82% of those reviewed, failed to reveal significant trends. These surfaces all had surface numerical apertures of <0.8 and aspheric departure of <500 waves.

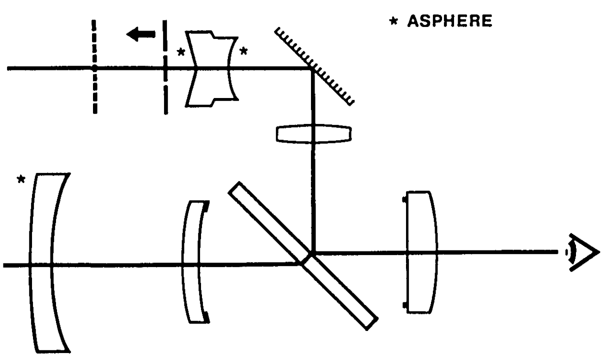

Fig. 7. Novel focusing aid, the zooming circle, was introduced in Kodak's EK6 instant camera. It employed three aspheres, one in the straightthrough finder and two on a single element in the portion containing a clear circle on an opaque piece of film. The stationary double asphere kept the circle in sharp focus as the circle moved transversely, changing apparent size. The motion of the circle was linked to the camera's focusing mechanism.

III. Projection and Camera Lenses

After developing confidence in the ability to manufacture aspheres for viewfinders, the company next developed a super 8 movie projection lens with an asphere. The lens was an $f/1.8$ plastic–glass triplet (Fig. 9) introduced in 1974 in the Kodak Moviedeck projector (Fig. 1). The second surface of the lens was hyperbolic with a 16-wave departure from the best-fit sphere. The first two elements were plastic, and the rear element was glass to act as a heat absorber. The lens replaced a four-element glass lens of comparable performance originally designed at $f/1.4$ at about half of the cost.

Following this success, a mass-produced camera lens with an asphere was found in the Kodak Ektramax camera (Fig. 1) introduced in 1978. It was a 26-mm $f/1.9$ lens consisting of four elements, one glass and three plastic. It's performance was comparable with that of a conventional five-element glass lens at less than two-thirds of the cost.

Fig. 8. By matching the size of the zooming circle to the size of the subject's head, the user of an EK6 instant camera could achieve proper focus.

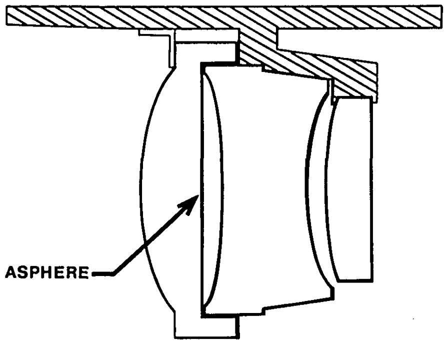

Fig. 9. This schematic cross section depicts the $f/1.8$ plastic–glass triplet projection lens introduced in 1974. The first two elements were plastic. The second surface of the first element was hyperbolic.

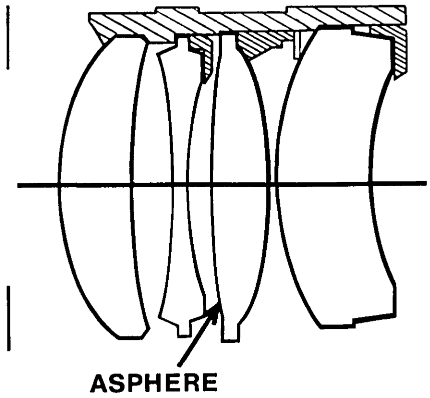

Fig. 10. This 26-mm $f/1.9$ lens made low-light photography available for users of the 110 film format. The first element was glass, the remaining three elements were plastic. A multiterm asphere was placed on the fifth surface.

The Ektramax Camera lens, first reported on in 1979,[2] was a modified triplet with the rear positive element split (Fig. 10). The glass element was in front followed by three plastic elements. The rear element was at thick meniscus having almost no power that effectively flattened the field. The asphere was on the fifth surface.

Low cost and high performance were two good reasons for choosing to use an asphere in the Ektramax camera. There were factors, however, which inhibited what form the asphere could take. An asphere could not be approved in a design unless it could be tested. Accordingly, the lens designer was also responsible for designing a manufacturable null corrector for the surface. Since a molded plastic aspheric lens also required an aspheric mold insert, the designer had to provide a second null corrector for the insert. There are, in turn, restrictions on what constitutes a manufacturable null corrector addressed previously.[3] The camera lens designer also recognized that when possible aspheres should be applied to weak rather than strong surfaces, where they tend to be less sensitive to tilt and decentration.

The asphere in the Ektramax camera met these criteria. It was on a weak surface with 81 waves of asphericity. Null correctors were successfully designed and fabricated for both the mold insert and the aspheric lens surface.

If an aspheric surface had not been used, the spherical aberration of the *f*/1.9 lens could not have been controlled adequately with the remaining lens parameters. Acceptable image quality without the asphere was unachievable. More than a half million lenses were eventually produced.

Encouraged by the success of the Ektramax Camera lens, another aspheric camera lens soon evolved. It was produced for the Kodak Ektralite 500 camera (Fig. 1) first sold in 1980.

Although the company has used plastic triplets in their cameras for many years, there were unique requirements for the Ektralite 500 Camera that made consideration of an asphere necessary. To develop a more compact camera the lens focal length was reduced by 15% over earlier models. The resultant increase in angular field coverage required either glass optics or an aspheric surface applied to plastic optics. With hundreds of thousands of cameras scheduled to be built, the plastic lens was chosen because it was less expensive to reproduce. The lens was a 22-mm *f*/8 compact all-plastic triplet (Fig. 11). To help control distortion and off-axis performance, the designer placed a 15-wave asphere on the weak fifth surface. Null correctors to test both the mold insert and lens surface were designed and fabricated.

In 1982 the company's disk camera lens was introduced. Each camera produced had a lens with a glass aspheric surface. It was the first high-precision glass asphere ever produced by the millions.

The lens, first reported in 1982,[4] had a focal length of 12.5 mm with a relative aperture of *f*/2.8 and a semiangular field of view of 29° (Fig. 12). The lens consisted of four glass elements with the asphere on the first surface of the second element. This surface was nearly plano with ~9.5 waves of aspheric departure from a best-fit sphere.

To appreciate the advantages an asphere provided to the disk camera program, consider the alternative. A nonaspheric design required a fifth element for comparable computed optical performance. The diaphragm and shutter were placed in front of the lens in the nonaspheric design, the only space available. Using an asphere, there was an immediate cost advantage of requiring one less element and fewer assembly operations. Also, by combining the third and fourth elements of the five-element design into a single positive element, space became available to place the shutter and diaphragm between elements reducing the thickness of the camera. The asphere was chosen to counteract the additional negative spherical aberration introduced when the two positive elements were combined into one.

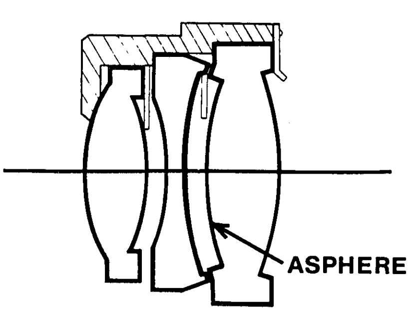

Fig. 11. A 22-mm *f*/8 all-plastic triplet was designed for use in the Ektralite 500 camera. Because it was also used in the Ektralite 600 camera which featured dual-lens capability, it used the same shutter as the telephoto lens. This required an entrance pupil located close to the shutter to avoid vignetting. An asphere on the fifth lens surface helped control astigmatism and distortion.

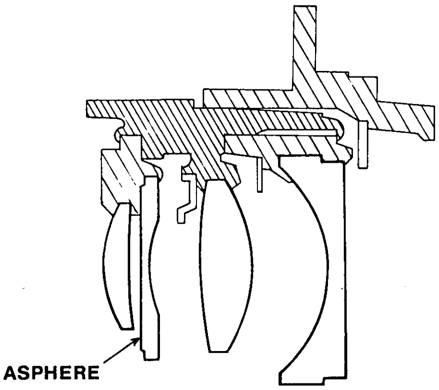

Fig. 12. Millions of glass aspheres have been produced for the lens in the Kodak disk camera. With an asphere on the third surface, the 12.5-mm *f*/2.8 all-glass lens provides the high-quality imagery required for the small format.

Because the maximum departure of the asphere from a best-fit sphere was only ~9.5 waves, it was possible to test it interferometrically using a computer-generated hologram. In production, testing was done on an audit or sampling basis.

Just as was done for viewfinders, a survey was conducted to determine the strength of the aspheres used in the company's camera and projector lenses.[1] A total of 175 aspheric surfaces from 116 lens designs was explored (Fig. 13). Most of these aspheres were found to have surfaces departing from a best-fit sphere with <300 waves (Fig. 14). These same surfaces showed an even distribution of surface numerical aperture between 0 and 1.0 (Fig. 15). Plotting the departure from best-fit sphere vs the surface numerical aperture, approximately two-thirds of the surfaces are evenly distributed with

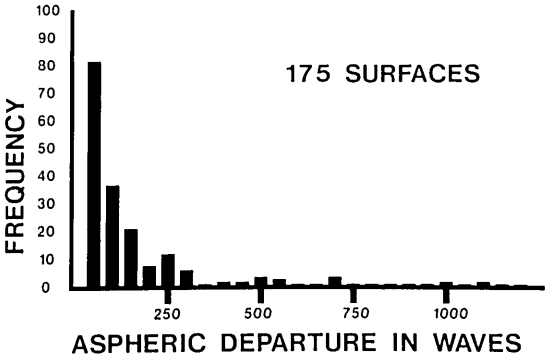

Fig. 13. In a study that reviewed 175 surfaces from 116 different nonviewfinder lens designs, the aspheric departure from a best-fit sphere varied from 0.7 waves to more than 1000 waves. Only 7.5% of the surfaces had departures in excess of 300 waves.

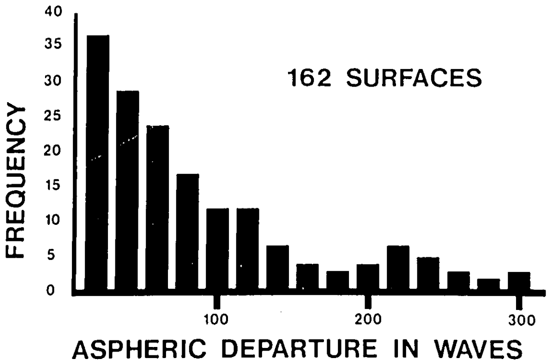

Fig. 14. Frequency of occurrence of projection and photographic lens aspheric surfaces decreases sharply as the aspheric departure from the best-fit sphere increases. Eighty percent of the surfaces studied had departures of <160 waves.

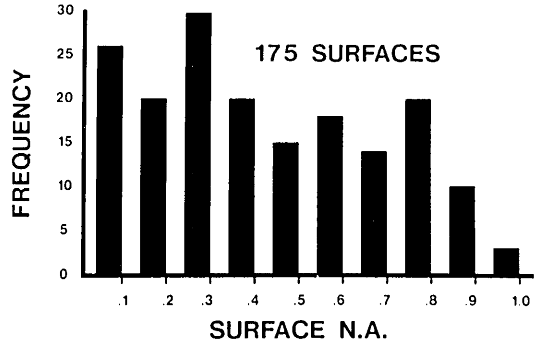

Fig. 15. When the surface numerical apertures of aspheres found in projection and photographic lens designs were plotted as a function of their frequency of occurrence, they were found to be evenly distributed out to 0.9.

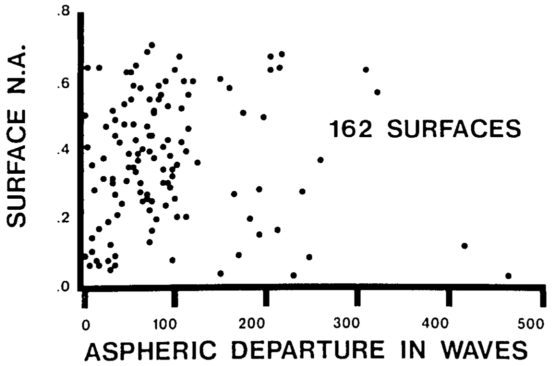

Fig. 16. For aspheres in projection and photographic lens designs, the surface numerical aperture was plotted against aspheric departure. Two-thirds of the surfaces had <100 waves of departure and numerical apertures of <0.9.

100 waves of departure or less and a surface numerical aperture of <0.9 (Fig. 16).

IV. Limitations

Widespread use of aspheres in mass production is inhibited by two factors, the ability to test and the ability to fabricate. Plastic aspheres chosen for production because of their strength are usually limited by testing considerations. Glass aspheres frequently encounter process restrictions before testing becomes a concern.

A very reliable and precise way of testing aspheres is interferometrically with the aid of either a specially designed null corrector, a computer-generated hologram, or both. As described in an earlier paper,[3] a null corrector is a lens designed with spherical aberration so that its emerging wave front will match the shape of the desired aspheric surface. The asphere, if placed at a specified position along the optical axis, would then reflect light back through the lens—free from aberration. The null corrector and test surface are usually placed in one arm of a Twyman-Green interferometer. If the test surface is in error, interference fringes will appear which will describe the departure from the desired asphere.

Some aspheric surfaces cannot be matched by the wave front created by a null corrector. Then a computer-generated hologram, either alone or with an auxiliary null corrector, is required to provide the appropriate wave front. Although we are describing surface testing, it should be recognized that element testing by transmission is also possible with a null corrector or hologram.

Another useful aspheric surface test utilizes a Williams interferometer. The asphere being tested is placed in one arm of the interferometer and compared against a perfect asphere in the other arm. The trick, of course, is to fabricate one perfect asphere to serve as the reference surface. As asphere sufficiently near perfection is considered feasible, so the Williams interferometer is an attractive choice.

Process capabilities have dictated which glass aspheres are attempted for mass production. The ability to fabricate glass aspheres has produced an ever-changing list of guidelines for such parameters as radii, thickness, and aspheric departure. Lens designers and optical engineers must constantly review these guidelines to take advantage of the latest process developments. As a practical matter, prospective customers should expect to work with company engineers during early design stages to insure that their glass aspheric lens will meet these guidelines. They should also be prepared to discuss their systems specifications. This permits a timely evaluation of our manufacturing competence and tolerance trade-offs.

To appreciate the variety of limitations for not only the aspheric surface, but for all parameters of the glass aspheric lens element, these guidelines will now be reviewed.

Recognize that these capabilities and limitations are flexible and changing for two reasons. First, the process technology is expanding rapidly. Glass lenses once thought impossible to fabricate are now planned for production. Second, and most important, the guidelines are not independent of each other; they are interactive. Certainly all the limits of the process are not simultaneously attainable in a single element. For example, a surface test possible in one configuration may be unattainable in another. A strong asphere may be feasible on a shallow curve but not on a strong radius. While extraordinary results may be achieved in a laboratory run they sometimes cannot be economically repeated in production.

Consider first the process limitations on lens diameters. Because of an established preference for insert molding and mounting techniques, diameter control of the glass element is not a significant concern. Insert molding refers to the process of taking an uncentered element, aligning both optical surfaces to establish an optical axis, and then injection molding plastic around the glass. The outer diameter of the plastic mount is then concentric to the optical axis.

The diameter of the largest glass aspheric lens made in the laboratory exceeds 80 mm. Because large lenses are historically required in smaller quantities, the cost advantage quickly disappears. More expensive tooling may be required. Lenses ~15 mm in diameter are preferred, 30 mm possible. Diameter tolerances of ±0.10 mm including runout are frequently specified.

As part of a glass aspheric element, radii of <5 mm, convex or concave, and as large as plano, have been successfully fabricated. Radii are limited by either surface strength or testing requirements.

Glass element thickness tolerances can be held to ±0.015 mm, a difficult tolerance to achieve by conventional processes. For negative elements, a minimum center thickness of 0.4 is reasonable. A negative element must have an edge thickness of at least 0.7 mm. The edge thickness of positive elements may be as small as 0.3 mm. Large elements require proportionally larger edge thicknesses.

A surface quality, in terms of scratch and dig tolerances, of 80–50 is adequate for most applications. Smaller-diameter elements or more-critical lenses may require a specification of 60–40 or 40–20 resulting in increased production costs.

Surface figure has been defined as a tolerance on fringe deviation from nominal, as measured in an interferometric test. A four-number specification is used describing allowable fringes of power, irregularity (cylindricity), asphericity (aspheric departure at full aperture), and zonal error (aspheric departure at an intermediate aperture). A test of 3–1–1–½ is readily achievable in production. A test of 2–½–½–¼ is possible at increased expense.

More than 50 glasses from a variety of manufacturers have been approved for use in the process for mass-producing glass aspheres. Because of this, customers should recognize the importance of discussing their glass choice with company engineers before finalizing their design.

There are several process limitations that are unique to the specification of aspheric surfaces. Axial alignment of an asphere to the center of curvature of the opposing side of the lens (or the axis of another asphere) can be maintained to within 15 min of arc. This angle is defined as between the aspheric axis and the line joining the center of curvature of the opposing side and the vertex of the asphere. For small lenses, 10 min of arc are feasible.

The strength of the aspheric surface is a major concern both in fabrication and testing. The stronger the curve the more difficult the aspheric element is to fabricate. The lens designer must attempt to place the asphere on a weak surface, one which has a radius of the best-fit sphere larger than, say, 75 mm. It is preferred that the aspheric departure from the best-fit sphere not exceed 25 wavelengths, although a 100-wave departure is possible. It is desired that surface slope, measured in waves per millimeter, should not exceed 30, although a maximum of 40 is thought possible. Recognize that aspheric departure and surface slope are primarily concerns of metrology rather than process limitations. What limits the ability to measure aspheres? Frequently, it depends on the precision of the null corrector, the accuracy of the hologram, or the quality of the reference surface.

In the past, it was unlikely that the lens designer heeded all these process and testing limitations. In practice, the designer began the effort with a list of approved glasses and attempted to place the necessary asphere on a weak surface. The manufacturing engineer, consulting with the process development engineer, determined aspheric fabrication feasibility. Today the designer is learning these limitations, understands them, and incorporates them in the design. If the design is feasible, work on sample lenses begins. If not feasible, other design solutions must be sought. If the feasibility is in question and the designer believes the design has strong merit, additional process development may result, or test techniques may be refined further.

V. New Applications

The availability of low-cost glass aspheric elements has created several evolutionary trends in optical design. Customers, both within Kodak's corporate structure and from other companies, have optical requirements which can be enhanced by use of this aspheric technology. It has been obvious for generations that many lenses can be simplified by using aspheres. This is a task any competent lens designer can accomplish. Only now, with the availability of mass-produced glass as-

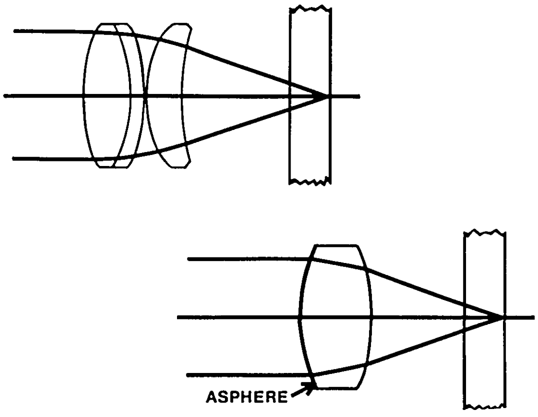

Fig. 17. Three-element lens now found in many audiodisk players may soon be replaced by a single-element high-index lens with an aspheric surface. A singlet with a low index of refraction was found to require a second nonspherical surface to provide satisfactory image quality.

pheres, does it become practical. Here are some examples, some cases where aspheres may provide tangible benefits.

Just as an asphere reduced the complexity of the disk camera lens, it can simplify the designs found on today's compact 35-mm cameras. The asphere represents an additional degree of freedom to the designer. With it, he can choose to improve performance, reduce the number of elements compared to a nonaspheric design, increase the relative aperture without adding elements, or cover a wide angular field, which implies a shorter focal length and more compact camera. For example, by using an asphere in one design investigation, a full stop was gained from *f*/5.6 to *f*/4 in a 38-mm glass triplet camera lens. Performance of the two designs was comparable.

Another attractive application of aspheres is in the design and fabrication of digital videodisk and audiodisk lenses. These lenses focus a laser beam onto an optical disk. In one application, they work in the near IR at numerical apertures of 0.45–0.50. Early designs for this application were reminiscent of microscope objectives comprised of two or more elements (Fig. 17). Unlike microscope objectives, these lenses are expected to become as plentiful as the phonograph needles they are designed to supplant. They cover very small angular fields. Now, by using an asphere, a one-element design is feasible (Fig. 17). Aspheres can control and correct an axial wave front over large numerical apertures, so aspheric singlets become the obvious choice to replace the earlier multielement all-spherical designs. There is another benefit of using aspheres for audiodisk lenses. The simpler lenses made possible by aspheres have less mass, an important consideration when developing the tracking mechanism which is part of the assembly.

VI. Conclusion

When designing with aspheres, one must consider more than just where to place the asphere for best image correction. One must consider the practical process limitations, the fabrication feasibility. Finally, the designer must be sensitized to the expected testing technique.

Camera lenses and digital audiodisk lenses are just two potential applications for mass-produced precision glass aspheres. The creative designer will identify others.

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