Free-form technology

In the first part of a series on free-form lenses, **Professor Mo Jalie** defines free-form lenses and looks at the manufacturing technology behind them. **One CET point C7882, suitable for optometrists and dispensing opticians**

Free-form is one of the buzzwords in the optometric world today. The term fundamentally describes a surface which normally defies simple mathematical description, in the sense that no single equation can be used to define the surface. Instead, the surface is described by its sag measurements at thousands of points.

Typically, a progressive surface is a free-form surface. Thus one could describe any progressive lens as a free-form lens. However, a laboratory which finishes a convex side semi-finished progressive blank with traditional surfacing equipment (toric or spherical generator, followed by traditional smoothing and polishing) would be foolish to claim that they are manufacturing a free-form lens.

The real advantage of free-form technology is that it allows the designer to better compensate for the aberrations of the lens when working the concave side of the semi-finished blank. This, of course, demands software which can calculate the optimum form of the surface upon receipt of individual prescriptions from the eye care practitioner. Only the major manufacturers, with their in-house design teams, really have the ability to produce these 'double free-form surface' lenses.

The term, 'free-form', is a relatively new addition to ophthalmic literature and, at present, is being used to describe several different things. The basic meaning of the term is a description of a surface which usually cannot be specified by means of an algebraic equation and instead, is described numerically by listing the *x,y,z* co-ordinates for thousands of points on the surface. Use of this method enables non-rotationally symmetrical surfaces to be specified in such a fashion that they can be both analysed and manufactured accurately. Thus, the term, 'free-form', really applies to the surface itself. However, the ability to design and produce state-of-the-art lens designs after receipt of the prescription order, has opened up a new vista of possibilities which major manufacturers have been quick to exploit. For example, personalised lenses, which are custom designed to the wearer's needs, are now a possibility. In this paper, the author explores the origin of the term 'free-form' and its significance for both the manufacturer and the eye care practitioner.

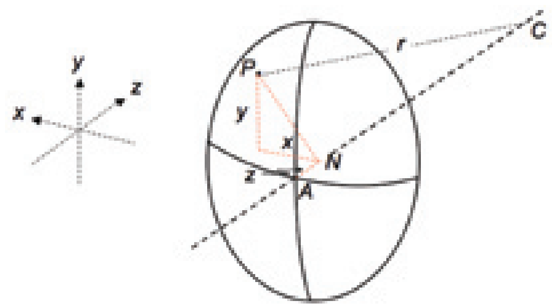

Figure 1 Equation to the spherical surface
Note that $r^2 = PN^2 + (r - z)^2$
and that $PN = \sqrt{(x^2 + y^2)}$, so $x^2 + y^2 + z^2 - 2rz = 0$
from which $z = r - \sqrt{(r^2 - x^2 - y^2)}$

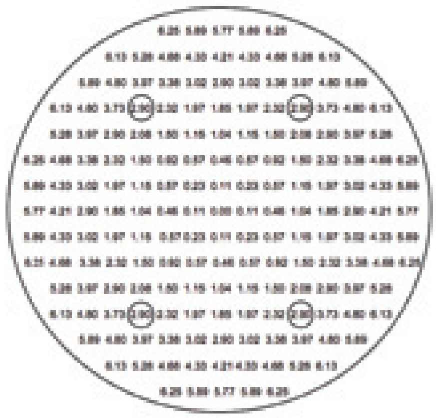

Figure 2 Free-form description of a spherical surface of power -5.50D worked on a material of refractive index 1.60. The z-values listed are the sags of the surface for the x,y coordinates which are given in 5mm intervals from the centre out to 35mm. In order to fully describe and subsequently generate the surface, x and y would need to step in 0.25mm intervals. The four circled values represent the coordinates (±15, ±20, 2.90)

Free-form description of a surface

The dictionary definition of the term 'free-form' is 'of an irregular shape or structure'.[1] At first sight, this may not be too apt a description of an optical surface whose curvature is supposed to vary smoothly without discontinuities.

To understand the basic concepts underlying the free-form description of a surface, we look first at the simplest surface employed on spectacle lenses, the spherical surface (Figure 1).

A spherical surface is formed by the locus of a point in three dimensions (*x,y,z*) moving at a fixed distance from a fixed point (the centre of curvature of the surface, *C*). Assuming the origin to lie at the vertex, *A*, of the surface the equation to the spherical surface is:

$$x^2 + y^2 + z^2 - 2rz = 0$$

Note in Figure 1 that the axes have been chosen such that z is the optical axis of the surface and the sag of the surface for point *P* which lies on the surface is *z*.

Solving for z produces:

$$z = r - \sqrt{\{r^2 - x^2 - y^2\}}.$$

If a computer numerical control (CNC) generator is programmed with this equation for a given value of *r* and values of *x* and *y* ranging from, for example, -35 to +35, the on-board computer will evaluate *z* for these variables and the point cutter will generate a sphere of radius *r* and diameter 70mm.

By way of example, consider a 5.50D surface worked on a material of refractive index 1.60. The surface has a radius of curvature of 600/5.50 = 109.091mm.

Suppose the co-ordinates of the point P in Figure 1 are *x* = 15mm and *y* = 20mm, then the sag *z*, for this point on the surface is:

$$z = 109.091 - \sqrt{\{109.091^2 - 15^2 - 20^2\}}$$

$$= 2.903\text{mm}.$$

In generating this surface, when the effective cutting point of the generator lies at the point *x* = 15, *y* = 20, the *z*

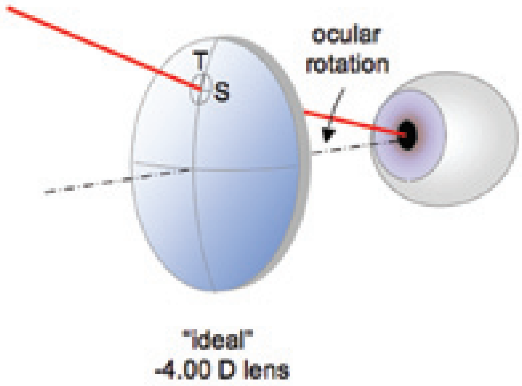

Figure 3 Illustrating the tangential and sagittal planes of refraction when the eye has rotated upwards (along the 90 meridian) behind a -4.00 D lens

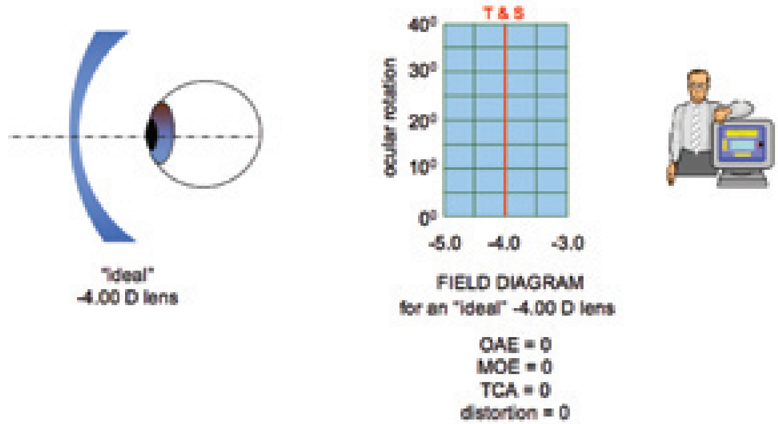

Figure 4 The ideal optical performance for a -4.00 D lens. the four significant aberrations are all zero. The field diagram indicates that the tangential (T) and sagittal (S) oblique vertex sphere powers remain -4.00 D for all zones of the lens

coordinate will lie 2.903mm above the vertex of the curve, in other words, its instantaneous *x, y, z* coordinates will be (15, 20, 2.903).

Figure 2 represents a free-form description of this spherical surface. At the centre of the surface (co-ordinates 0, 0, 0), the sag (or *z*-value) of the surface is zero. The *z*-values of the surface are then given in 5mm intervals ($x = 5$, $y = 5$) out to 35mm in the *x* and *y* meridians.

Since the surface is rotationally symmetrical, there are four points on the surface where $x = \pm15$, $y = \pm20$ and $z = 2.903$mm, and these four *z*-values have been circled. Needless to say, the CNC data file will contain intervals as close as 0.25mm for the *x* and *y* co-ordinates with many thousands of values for *z*, which will normally be given to an accuracy of one micrometre (0.001mm).

To understand how this information is related to the design of a lens, it is necessary to consider how lens aberrations are controlled and how the best form for a given power is determined.

Consider a lens of power -4.00D, made in a material of refractive index 1.60 and designed to be worn 27mm in front of the eye's centre of rotation. Figure 3 depicts an eye viewing through this -4.00D lens. The eye has rotated upwards to view through a point above the optical centre. A line drawn from the visual point to the optical centre represents the tangential plane of the refraction which the ray undergoes on its passage through the lens. The vergence imparted by the lens in this plane represents the tangential oblique vertex sphere power of the lens.

The plane at right angles to the tangential plane is the sagittal plane of refraction and the vergence imparted by the lens in this plane represents the sagittal oblique vertex sphere power of the lens. The oblique vertex sphere powers represent the vergences in the refracted pencils where they meet the vertex sphere, an imaginary spherical surface concentric with the eye's centre of rotation which just touches the back vertex of the lens.

Ideally, the tangential and sagittal oblique vertex sphere powers should be the same as the back vertex power of the lens which in this case, is -4.00D.

The aberration data for an ideal -4.00D lens is shown in Figure 4. As the eye rotates away from the optical centre the four significant aberrations, oblique astigmatic error (OAE), mean oblique error (MOE), transverse chromatic aberration (TCA) and distortion should all remain zero. TCA is primarily a function of the Abbe number for the material and the lens designer has little control over this aberration when the lens material has been chosen. Distortion varies with the form of the lens, but cannot be significantly altered if the usual Ostwalt bending is chosen for the lens.

The significance of the remaining two aberrations, OAE and MOE is most easily studied with the aid of the field diagram illustrated in Figure 4 which shows how the tangential and sagittal oblique vertex sphere powers vary as the eye rotates away from the optical centre of the lens. With an ideal lens, these two powers would remain -4.00D for all zones of the lens, which

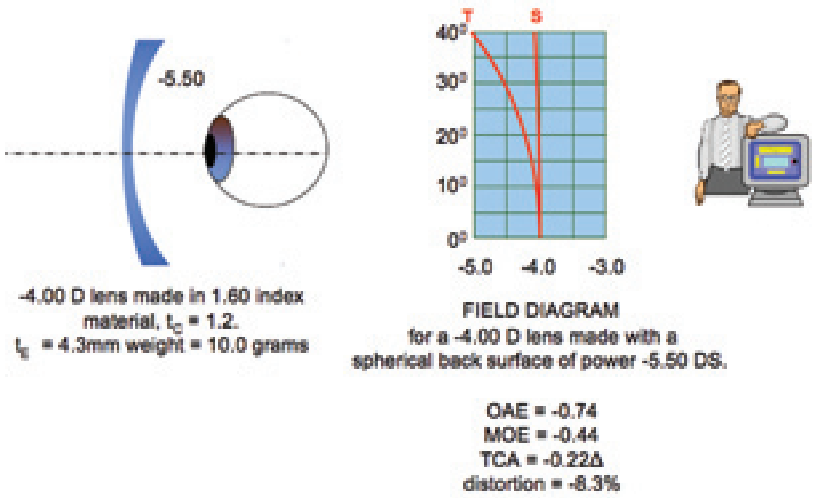

Figure 5 The performance of a -4.00 D lens made in 1.60 index material with a concave spherical surface of power -5.50 D. Note that the performance for the 35° zone is quite poor, the aberrational astigmatism is found to be -0.74D. The Abbe number for this material was assumed to be 42 and the TCA for the 35° zone is seen to be -0.22Δ

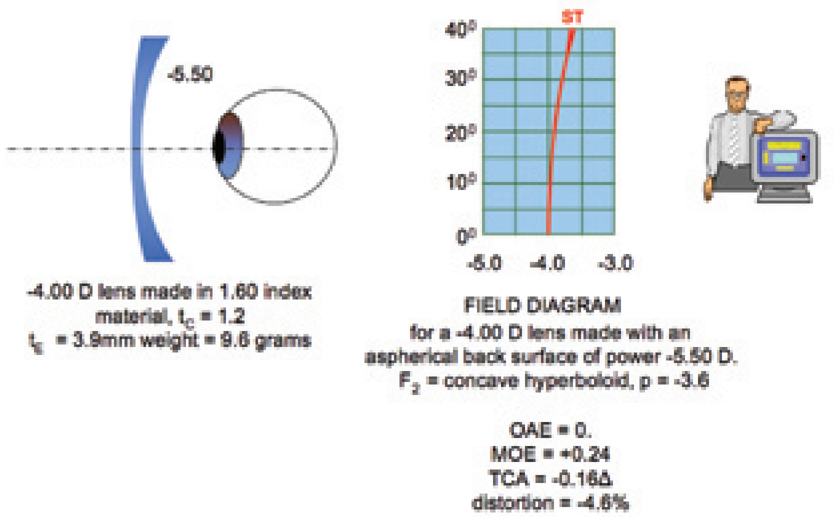

Figure 6 The performance for a -4.00D lens made in 1.60 index material with a concave hyperboloidal surface with p-value -3.6, whose power at the vertex is -5.50D. The use of an aspherical surface has restored the optical performance of the design to match that of a spherical best form lens. Note that the lens is somewhat thinner and lighter than the spherical design illustrated in Figure 5

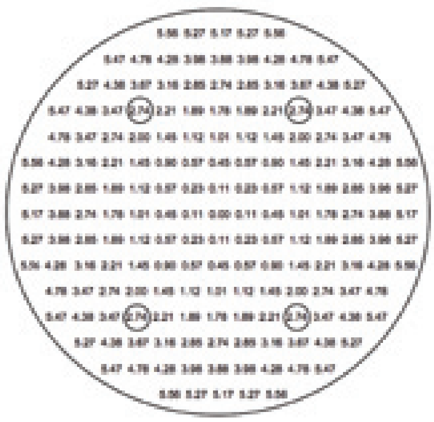

Figure 7 Free-form description of a hyperboloidal surface of power -5.50D and p-value -3.6, worked on a material of refractive index 1.60. The z-values listed are the sags of the surface for the x,y coordinates which are given in 5mm intervals from the centre out to 35mm. The four circled values represent the coordinates (±15, ±20, 2.74)

is illustrated by the fact that as the eye rotates away from the optical centre of the lens, the plot of these two powers remains -4.00D.

Suppose the lens is made with a +1.50D base curve. The concave spherical surface would have a power of -5.50D. This is the surface for which a free-form description was given in Figure 2. The optical performance of this lens is illustrated in Figure 5 and is seen to be quite poor. When the eye has rotated through 35° from the optical centre of the lens, the tangential and sagittal oblique vertex sphere powers are -4.81D and -4.07D, respectively.

The OAE is -0.74D, (T – S), the MOE is -0.44D, the TCA is -0.22Δ and the distortion is -8.3 per cent. Only the T and S values can be read from the field diagram in Figure 5.

If the -5.50D concave spherical surface is replaced by a hyperboloid of the same power (at the vertex) the positive surface astigmatism will neutralize the aberrational astigmatism of oblique incidence.[2,3] The result is illustrated in Figure 6 where the field diagram confirms that the poor off-axis performance of the flat form lens with spherical surfaces which was illustrated in Figure 5, has been restored by asphering the concave surface. In practice, either the convex or the concave surface could be aspherised to eliminate the aberrational astigmatism, but here, the concave surface has been chosen to demonstrate how free-form surfacing can be employed to produce the surface.

A free-form description of the -5.50D hyperboloidal surface, whose aspheric-

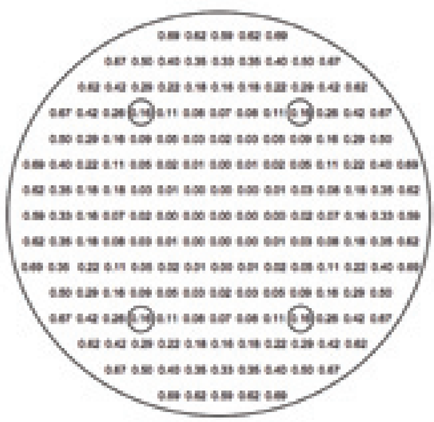

Figure 8 Aberration filter expressed in digital form. The four circled values represent the coordinates (±15, ±20, 0.16) where the value, 0.16, represents the adjustment to the z-coordinate (aberration filter) applied to this point

ity is described by its p-value (here, p = -3.6), is illustrated in Figure 7 and it can be seen by comparing the z-values given in Figure 7 with those in Figure 2 that the hyperboloidal surface starts to flatten when compared with the spherical surface just 5mm away from the vertex of the curve (at 0,0,0).

The hyperboloidal surface is also rotationally symmetrical and so there are four points on the surface where $x = \pm15$, $y = \pm20$ and z = 2.74mm, and once again, these four z-values have been circled.

Nikon have pointed out that differences in the z-values between the spherical surface on a lens with poor optical performance and the z-values for the aspherical surface which corrects the aberrations, can be looked upon as an aberration filter, a phrase which is most apt in describing the difference between the surfaces in free-form terms.

Figure 8 illustrates the aberration filter for the hyperboloidal surface which has been used to 'filter' the aberrations for the -4.00D lens whose performance has been discussed in the text.

It could be stated that for the points where $x = \pm15$ and $y = \pm20$ the z filter at each point is the difference between the spherical and hyperboloidal sags for this coordinate, 2.90 - 2.74 = 0.16mm.

Although the equations to spherical, toroidal and conicoidal surfaces are well known and may be programmed to generate these three commonly used surfaces, the equations to atoroidal and progressive surfaces are usually not known and such surfaces are described numerically rather than by a mathematical equation. The numeric description of a non-rotationally symmetrical, progressive power surface is given in Figure 9 which illustrates the free-form description of a convex progressive surface of power +4.00 Add +2.00 taken from US Patent 6 019 470, for a Progressive Multifocal Lens.[4] Study of the z-coordinates immediately reveals the asymmetric nature of the surface.

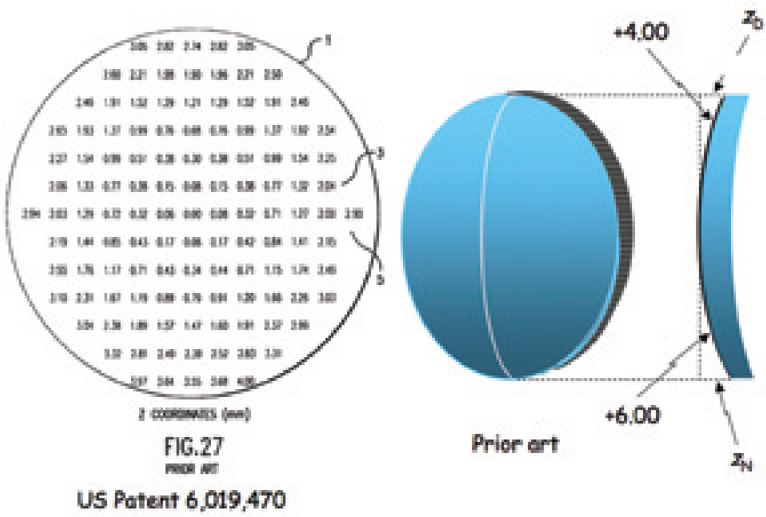

Figure 9 Free-form description of a progressive power surface, +4.00 Add +2.00

Figure 10 Free-form manufacturing system (courtesy of OptoTech)

Free-form technology in manufacture

Over the last few years, there has been a revolution in lens surfacing methods and machinery. It is now possible to directly surface multifocal lenses without the need for semi-finished blanks with progressive surfaces which have been worked to a standard design. Several machinery manufacturers offer CNC generators which produce free-form surfaces (Figures 10 and 11). The surface finish is such that there is no need for smoothing, the generated curve is ready to polish. This method of working removes the necessity for a large range of smoothing and polishing tools as well as the need for different sets of tools for working materials of different refractive indices. This is just one of the attractions of free-form technology to the ophthalmic prescription industry. The ability to use semi-finished sphere blanks, already finished and hard-coated on the convex side, to produce single vision lenses in any form, spherical, or aspheric, toric or atoric, and progressive lenses of any prescription and near addition combination, just by working the concave side of the lens implies an enormous saving in inventory costs.

It is with this goal in sight that the major machinery manufacturers have invested so much in research and development of today's CNC, free-form generators. Over the last three years, CNC polishing machines have been perfected which, when linked to the generator, allow robotic passage of the generated surface to the polisher which will accept output from the generator without the need to handle the lens between each process. The HSC smart-P all-in-one generator and polisher from Schneider uses just 15 square feet of floor space and combines the latest state-of-the-art generator and polishing technology in a single machine. Lenses are generated with a ready-to-polish surface finish and, without the need to unclamp the blank, then polished using Schneider's proprietary adaptive tool polishing technology.

Figure 12 illustrates the three main steps in the working cycle of the HSC smart-P free-form machine. The surface is first brought to rough curve ▶

by a high speed cutting process (Figure 12a), then the ready-to-polish surface completed with a single point cutter (Figure 12b). This is followed by the integrated adaptive polishing system for the surface Figure 12c).

Almost in step with the developments which have taken place in new machinery has been the revolution in computing methods which have become available in recent years. More powerful processors have enabled the very lengthy and complex calculations required to compute the lens form and digitize the surface to take place at the prescription laboratory in real time, at the point of receipt of the order from the individual eye care practitioners. Software development has also needed to keep up with modern hardware. Several skills are needed in the production of suitable software for free-form machinery. The lens surface is calculated by means of state-of-the-art lens design calculation software that not only controls the generating and polishing processes enabling them to follow precisely the algorithm which describes the shape of the surface but also the speed and position of the lens with respect to the cutting or polishing tool. It will be appreciated that both lens design expertise and experience in engineering science is required to support all stages in the CNC production routine. Free-form machinery without the necessary software, of course, cannot produce lenses.

It should be apparent that for the smaller surfacing laboratory, just installing free-form production machinery is not sufficient to be able produce any lens design. Software support is paramount and this has been recognised by several major lens manufacturers who are prepared to offer their own in-house expertise and design software to the smaller laboratory to enable them to produce atoroidal and progressive surfaces to the major manufacturer's design. Naturally, the software supplier has no other control over the finished lens, the responsibility for retaining quality of product as well as optical quality remains with the laboratory that processes the lens. ●

● The next instalment will look at free form technology from a practitioner perspective.

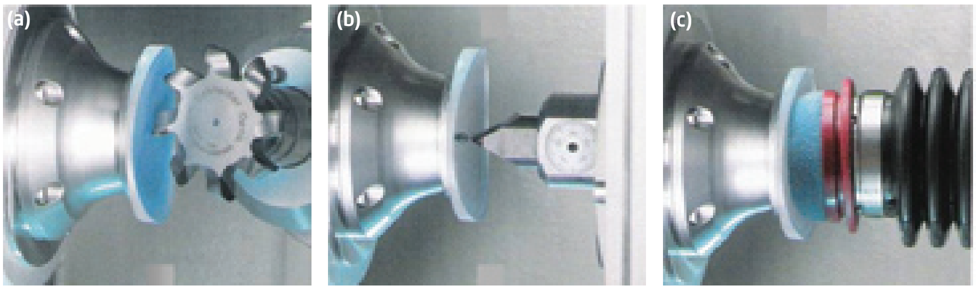

Figure 12 Schneider HSC smart-P generating and polishing cycles (a) high speed cutting (b) single point truing (c) adaptive polishing (Courtesy of Schneider)

Figure 11 Schneider HSC smart-P free-form all-in-one generator and polisher with footprint of just 15ft² (courtesy of Schneider Machines)

References

1 *The Concise Oxford Dictionary of Current English* – 9th Ed. 1995. Edited by DellaThompson, (Oxford: OUP)

2 Jalie M. (1984). *Principles of Ophthalmic Lenses.* (London: ABDO)

3 Jalie M (2003). *Ophthalmic Lenses & Dispensing.* (London: Butterworth-Heinemann)

4 Mukaiyama H & Kato K (2000) US Patent 6 019 470 Progressive multifocal lens and manufacturing method of eyeglass lens and progressive multifocal lens.

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MULTIPLE-CHOICE QUESTIONS

1 Which of the following could be described as a 'free form'?

A A lens surface defined by an algebraic equation
B A surface with axial symmetry
C A non-rotational surface defined by 3 linear co-ordinates for each point on its surface
D A lens that may be moulded into any shape

2 Which of the statements regarding tangential and sagittal sphere powers is correct?

A Ideally they should be the same as the back vertex powers
B They dictate vergence from two parallel planes
C The sagittal plane runs from any point viewed on a lens to the optical centre of a lens
D The tangential plane influences aberration on upgaze only

3 As the eye rotates away from the optical centre, which of the following is not a significant aberration?

A Oblique astigmatic error
B Mean oblique error
C Transverse chromatic aberration
D Axial spherical aberration

4 Which of the following is a function of the Abbe number?

A Oblique astigmatic error
B Mean oblique error
C Transverse chromatic aberration
D Axial spherical aberration

5 Which of the following might be termed an 'aberration filter'?

A Differences between the x and y values on a spherical lens
B Differences between the z values on a poor optical performance spherical lens and those on an aberration free aspheric lens
C A coating of specific thickness to filter out aberrant light
D The difference between the aberration profiles at any specific z value on a free form lens surface

6 Which of the following is true about free form lens manufacture?

A Surface finishes need no further smoothing and are ready for polishing
B The convex side of the blank cannot be coated
C Only the convex surface needs to be worked on
D The process allows significant inventory cost savings

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