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This down-loadable chapter is an excerpt from Optical System Design by Robert E. Fischer and Biljana Tadic-Galeb, published by SPIE Press and McGraw-Hill. It is titled ‘Optical Design Considerations for Optics Fabrication.’

Bob Wiederhold and I were grateful for the opportunity to contribute our manufacturing expertise to this ‘down to earth’ text about optical design. This book is a useful desk reference for everyone involved with optical systems.

There are several software programs that are available to enable design an optical system. But the software can’t give the designer all of the practical considerations with regard to making the lenses. Chapter 17 addresses the most common manufacturing issues that push out delivery or drive up cost. Some effort to deal with these issues at the design phase will save time and money.

We hope that this chapter is informative and helpful. Please send us your comments at info@optimaxsi.com. Thank you.

Best of luck with your project,

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Chapter 17 Optical Design Considerations for Optics Fabrication

From the point of view of a lens manufacturer, what design attributes have the most influence on manufacturing efficiency? The primary design considerations are optical material, component size, shape, and manufacturing tolerances. All of these attributes are variable at the design phase and can have significant impact on lens manufacturing costs.

In order to narrow the scope of this chapter, the text assumes the manufacture of a precision glass lens of approximately 50mm diameter using grinding and polishing techniques. The information is presented in the following order:

1. *Material* — a summary of manufacturing considerations for optical glasses
2. *Manufacturing* — an overview of conventional and advanced process technologies
3. *Special Fabrication Considerations* — a review of tolerancing trade-offs and finishing options
4. *Relative Manufacturing Cost* — an analysis of manufacturing variables
5. *Sourcing Considerations* — suggestions for achieving project goals
6. *Conclusion* — summary table for quick reference.

While this analysis is based on a 50mm diameter glass lens, it can also be adapted to include specific market niches such as micro-optics (diameters smaller than 5mm), macro-optics (diameters larger than 300mm), prisms and flats, molded glass and plastic optics, diamond turned crystal and metal optics, and diffractive optical elements. These niches are addressed in additional chapters of this book.

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17.1 Material

There are more than 100 different optical glasses available worldwide, and each has a unique set of optical, chemical, and thermal characteristics. Only a few glass manufacturers in the world produce these optical glasses, and each manufacturer has a company-specific glass naming convention. Cross-referencing the glasses is possible via a six-digit glass code (ABCXYZ) that is derived from the index of refraction (n_d = 1.ABC) and the Abbe value (ν_d = XY.Z). For the vast majority of optical applications, glasses from differing manufacturers can be direct substitutes. Lens designers should be aware, however, that equivalent glasses having the same six-digit glass code might not have exactly the same optical, chemical, and mechanical properties. For example, Schott's SK-16 (620603) has slightly different characteristics than Ohara's S-BSM-16 (620603). Be aware: optical design software will define glasses that can achieve a desired optical performance, but it cannot determine the glasses' current availability in the market. Nor will the software give consideration for the glasses' chemical and thermal properties. For example, it may be important to consider that the index of refraction of a glass changes with temperature at a known rate. Other parameters that are important to consider are spectral transmission, dispersion, material quality, mechanical, chemical, and thermal properties.

Design Considerations

Material quality is defined by tolerances of optical properties, striae grades, homogeneity, and birefringence. Optical properties include spectral transmission, index of refraction, and dispersion. Data for each glass type is available from its manufacturer. If tighter than standard optical properties are required, then additional cost and time are usually associated with obtaining the material. Specification of glass based on material quality is provided in the

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International Standard ISO 10110 and the U.S. military specification MIL-G-174B. A brief summary of glass material specifications using nomenclature from Schott Optical Glass is shown in Figure #1.

Before finalizing an optical design, some consideration should be given to glass cost and availability. Glass prices vary from a few dollars per pound to several hundred dollars per pound. In some cases, it may be more economical to add a lens to the design in order to avoid expensive glasses. In addition, many glasses are not regularly stocked. Instead they are melted to order, which can take several months. Pricing and melt frequencies are available from glass manufacturers. Each manufacturer has a list of "Preferred" glasses that are most frequently melted and usually available from stock. It's important to note that "Preferred" does not imply "best glass type available." From a manufacturing perspective, "Preferred" refers only to the availability of the glass in stock. For example, BK-7 is readily available from stock and is among the most economical of glass types. On the other hand, a glass like SF-59 is not made as frequently and may not be as readily available. If delivery is a concern, the designer may want to use only glasses from the frequently melted glass list.

<u>Striae</u> Grade AA (P) is classified as "precision striae" and has no visible striae. Grade A only has striae that are light and scattered when viewed in the direction of maximum visibility. Grade B has only striae that are light when viewed in direction of maximum visibility and parallel to the face of the plate.

<u>Birefringence</u> is the amount of residual stress in the glass and depends on annealing conditions, type of glass, and dimensions. The birefringence is stated as nm/cm difference in optical path measured at a distance from the edge equaling 5% of the diameter or width of the blank. Normal quality is defined as (except for diameters larger than 600mm and thicker than 100mm):

i. Standard is less than or equal to 10 nm/cm
ii. Special Annealing (NSK) or Precision Annealing is less than or equal to 6 nm/cm
iii. Special Annealing (NSSK) or Precision Quality after Special Annealing (PSSK) is less than or equal to 4 nm/cm.

<u>Homogeneity</u> is the degree to which refractive index varies within a piece of glass. The smaller the variation, the better the homogeneity. Each block of glass is tested for homogeneity grade.

Normal Grade	$\pm 1 \times 10^{-4}$
H1 Grade	$\pm 2 \times 10^{-5}$
H2 Grade	$\pm 5 \times 10^{-6}$
H3 Grade	$\pm 2 \times 10^{-6}$
H4 Grade	$\pm 1 \times 10^{-6}$

Tolerances of Optical Properties consist of deviations of refractive index for a melt from values stated in the catalog. Normal tolerance is ±0.001 for most glass types. Glasses with n_d greater than 1.83 may vary by as much as ±0.002 from catalog values. Tolerances for n_d are ±0.0002 for Grade 1, ±0.0003 for Grade 2 and ±0.0005 for Grade 3.

The dispersion of a melt may vary from catalog values by ±0.8%. Tolerances for v_d are ±0.2% for Grade 1, ±0.3% for Grade 2 and ±0.5% for Grade 3.

<<Figure #1: Glass Material Specifications >>

Fabrication Considerations

Because the mechanical, chemical, and thermal properties of glass are what determine the ease or difficulty of making optics from the material, these properties are of particular interest to the optical fabricator.

Mechanical properties include hardness and abrasion resistance. These properties determine the rate at which material is removed, and should be among the first to consider.

Hardness is measured in accordance with ISO 9385. It is measured with a micro-hardness tester that utilizes a precision diamond point applied with a specific amount of force. This probe contacts and penetrates the polished glass sample at room temperature. Carefully measuring the resultant indentation yields a calculation known as the “Knoop hardness” of the material. Knoop hardness ranges from 300 to 700 for most optical glasses, where 300 represents a soft glass and 700 harder glasses. In general, the harder the glass the longer the time required to grind and polish the lens.

Abrasion resistance affects how fast the glass will process. Abrasion resistance is the ratio of material removed on a test piece of glass to the material removed from a BK-7 sample. The abrasion resistance of BK-7 is set to equal 100. The higher the number, the faster material will be removed. The values range from about 60 to 400. Compared to BK-7, a glass with a value of 60 will take almost twice as long to process. Conversely, glass with a value of 400 will take only one-quarter the time. The process time seems to imply that softer glasses are cheaper to fabricate. One must remember, however, that other factors such as cosmetic finish may offset potential savings. Soft glasses are more difficult to polish to achieve very good cosmetics and low RMS surface roughness. As a general rule of thumb, for lenses with identical specifications except for material, a BK-7 lens will be cheaper to produce. The cost of a lens increases as the abrasion resistance value moves away from that of BK-7. For example, glasses that have high abrasion resistance can require significantly longer grinding and polishing times. On the other hand, glasses with a low abrasion resistance are more difficult to achieve tight thickness tolerance, especially when good cosmetics are required.

Relative cost and density are also important factors to consider. The density of glass is described as gm/cm^3. Multiplying this number by the blank volume (including cutting allowances), and cost yields the approximate cost of a blank. It is important to remember dollars per pound of glass is not the only factor determining the cost of the optic. For example, SF6 and SFL6 are virtually identical optically. SFL6 costs 63% more per pound, but its density is only 65% the density of SF6, offsetting the higher per pound cost. In addition, SFL6 is much easier to process, which ultimately yields lower manufacturing costs.

Chemical properties are also of interest to the optician. There are several tests that characterize the chemical behavior of glass with regard to humidity, acid, alkali, and phosphate stainability. The values reported from these tests reflect the degree of processing difficulty and special handling a glass will require. Designers should therefore refer to chemical property test values when making lens design decisions. The chemical properties tests for glass are explained in more detail in Figure #2.

<u>Climate resistance (CR)</u> is a test that evaluates the material's resistance to water vapor. Glasses are rated and segregated into classes, CR 1 to CR 4. The higher the class, the more likely the material will be affected by high relative humidity. In general, all optically polished surfaces should be properly protected before storing. Class 4 glasses should be processed and handled with extra care.

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Resistance to acid (SR) is a test that measures the time taken to dissolve a 0.1µm layer in an aggressive acidic solution. Classes range from SR 1 to SR 53. Glasses of classes SR 51 to SR 53 are especially susceptible to staining during processing and require special consideration.

Resistance to alkali (AR) is similar to resistance to acid because it also measures the time taken to dissolve a 0.1µm layer, in this case, in an aggressive alkaline solution. Classes range from SR 1 to SR 4 with SR 4 being most susceptible to stain from exposure to alkalis. This is of particular interest to the optician because most grinding and polishing solutions become increasingly alkaline due to the chemical reaction between the water and the abraded glass particle. For this reason most optical shops monitor the pH of their slurries and adjust them to neutral as needed.

Resistance to staining (FR) is a test that measures the stain resistance to slightly acidic water. The classes range from FR 0 to FR 5 with the higher classes being less resistant. The resultant stain from this type of exposure is a bluish-brown discoloration of the polished surface. FR 5 class lenses need to be processed with particular care since the stain will form in less than 12 minutes of exposure. Hence, any perspiration or acid condensation must be removed from the polished surface immediately to avoid staining. The surface should be protected from the environment during processing and storage.

<<Figure #2: Chemical Property Tests for Glass >>

To summarize the chemical properties listed in Figure #2, if a glass is low in all categories, then it is stable and unlikely to stain during standard manufacturing processes and storage. If a glass is high in one or more categories, it is very likely to cause problems *if* special care is not taken. As a general rule, any glass with a stain coefficient of 3 or more must be handled with special care. Glasses with stain designations in the 50's (e.g., SK-55, S-FPL53) tend to be very troublesome. The poor chemical properties of these glasses can lead to residual stain from deblocking, cleaning and/or handling of the lens. If stained, the lens may require repolishing to remove the stain. This causes more risk to the part, either from handling or missing the mechanical tolerances. For example, if tight thickness control is required and the glass is prone to staining, it is more difficult to achieve a stain-free surface within the desired thickness tolerance.

Thermal properties of glass may also affect optimal process methods. Thermal expansion coefficients range from 4 to 16 * 10^{-6}/°K. Glasses with a coefficient over 10 must be handled very carefully during any operation involving rapid thermal change. In fact, even body heat that is transferred by touching the glass may cause subsurface micro-fractures. Glasses with high thermal coefficients of expansion are more susceptible to surface distortion and catastrophic

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fractures during blocking and handling. If the coefficient is over 10, then the process should not include any rapid thermal processes. Because of the difficulty in handling these glasses, they should be avoided whenever possible.

Optical glasses can be segregated into groups by their material properties. It may be helpful to contact the preferred glass manufacturer for a particular material to get summary data. As an example, Figure #3 is a quick reference chart to select the more favorable glasses.

Stable Glasses	Climate Stainable	Alkaline Stainable	Acid Stainable	Heat Sensitive	Soft Material
BK7	PSK50	LaK11	FK3	FK52	FK3
BaK2	SK16	LaK21	PSK52	PSK53A	PSK54
SFL6	LaK21	All KzFS	SK16	SF59	SF6
SF11	KzFS1	SK16	SSKN5	TiF6	TiF6

<<Figure #3: Optical Glasses Categorized by Material Properties>>

Glass material is available in various forms of supply. It can be in block, rod, or slab form requiring sawing or core drilling operations to make it into disks; or it can be purchased as a disk. In any case, the desired form is defined by a diameter and a thickness—or in other words, a cylinder that totally contains the final lens geometry with some oversize allowance for processing. This approach is the quickest, but not the most cost-effective. Buying the glass as a molded blank provides the lowest cost. Material efficiency is achieved by taking a piece of glass of the appropriate weight, heating it and pressing it into a metal mold to make the shape (slightly larger) of the final lens. This approach requires several weeks for the glass to be delivered, however it minimizes glass cost for higher volume projects.

17.2 Manufacturing

For more than 100 years, the manufacture of lenses has remained essentially unchanged. While these conventional methods utilize relatively low cost machinery, they are also very labor intensive and require highly skilled craftsmen. With recent innovations in computer numerically controlled (CNC) machines, faster and less labor intensive manufacturing methods are now viable options to conventional methods. From prototyping to high volume production, automated grinding and polishing technologies are now available for lens fabrication.

Although these new technologies are more efficient and provide more reliable production, they require significant initial capital investment. In addition, there are some situations where conventional methods are simpler to use and more cost-effective. To understand practical applications and benefits of each type of lens fabrication, brief descriptions of the manufacturing methods follow.

Conventional Lens Fabrication begins with a plano–plano disk of glass or a near form molded lens blank. The blank is placed into a chuck that rotates around the mechanical center of the glass disk. A ring tool with embedded diamonds removes bulk material and grinds down the top surface of the blank. This process gives the lens blank a spherical shape and a coarse surface finish. This surface has significant subsurface micro-fractures, which must be removed by loose abrasive lapping at a later stage in the manufacturing process. The lens blank can then be flipped and its second side ground to near net shape using the same process. This overall process is called generating because the end result is the generation of a blank in the shape of the final lens.

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<<Figure #4: Conventional Generation>>

To prepare for the fine grinding and polishing process, the perimeter of the lens blank is wrapped with tape to create a reservoir. Molten pitch is poured onto the surface of the lens, filling the reservoir. The pitch is allowed to cool at room temperature until a solidified pitch layer, called a "pitch button," is developed.

The next step is to arrange the lenses in a circular pattern to be processed as a group called a multiple block. Multiple blocks are assembled by laying the buttoned lenses into a tool, which has a radius approximately equal to the design radius. Now, with the generated spherical surface down and the pitch button side facing up, the array of lenses is ready to receive the blocking tool. This heated metal tool is placed in contact with the pitch buttons, allowed to melt into the pitch, and then quickly cooled to room temperature. The resultant "block of lenses" is then ready for loose abrasive lapping.

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The purpose of loose abrasive lapping, often referred to as grinding, is to remove the residual sub-surface damage that was incurred during the generating process. The block of lenses is fine ground with loose abrasive grains mixed with water. Grinding is a step-down process that begins with large grains and continues with sequentially smaller and smaller grains. Grain sizes typically range from 30 microns to 5 microns. At this point in the manufacturing process, the operator is trying to achieve two goals: a spherical surface very close to the design radius, and no sub-surface damage. It is important for the optician to be aware of the abrasion resistance of the glass in order to control center thickness while minimizing sub-surface damage. To achieve a thickness within the center thickness tolerance, a certain amount of material (on the order of tens of microns) is left on the lens for removal during polishing.

<<Figure #5: A Block of Lenses>>

The lens is polished to the specified radius of curvature, spherical irregularity, and cosmetic finish by using a soft pitch lap pressed to the desired radius and rotated about the spherical lens surface while a cerium oxide polishing slurry is applied. The radius of the lens is controlled with a test glass or test plate of known radius. The lens is compared to the test plate by direct contact and/or evaluating the fringes of the Fizeau interferometric test. This test also gives the optician the ability to measure spherical irregularity, which is the maximum allowable perturbation of the spherical wavefront. The cosmetic requirements for the lens dictate the maximum allowable surface imperfections such as scratches, digs, and chips.

Once both sides of the lens are polished, the lens is centered by precision grinding the edge of the lens on a special lathe. This process accomplishes two tasks. First, the lens is ground to its final diameter. Second, the optical and mechanical axes of the lens are made coaxial with one another. This is also the point at which any flats or special mounting bevels are ground onto the lens.

<<Figure #6: Conventional Centering>>

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Once the lens is centered, manufacturing is complete. The lens is cleaned and inspected for workmanship. If it is satisfactory, the lens will be delivered either uncoated or with an antireflection coating. If the lens is not satisfactory, it is returned to one or more of the steps in the process to be corrected. If the lens cannot be reworked to meet the required specifications, it is scrapped.

Recent advancements spearheaded by the Center for Optics Manufacturing (COM) at the University of Rochester in Rochester, New York, have led to the development of equipment and processes that enable the optician to perform a variety of operations on computer controlled machines—processes called *CNC Lens Fabrication*.

The equipment combines the accuracy of multi-axis CNC motion control with robust machine designs that are faster, more versatile, and more precise than conventional machines. This automated process minimizes part handling and transfer errors, which are prone to happen with the more manual conventional process. It also enables the optician to generate precision surfaces that are pre-centered to final diameter and ready to polish. The precision spindles yield little sub-surface damage, which reduces polishing time and shortens overall production time. An added benefit of using this equipment is that the lens can be shaped to precise complex dimensions during the generation sequence.

Once the lens has been precision generated, it is polished to meet all the requirements for surface accuracy and cosmetics. Polishing may be done utilizing the conventional process described earlier in the Conventional Manufacturing section of this chapter, or with a new CNC polishing machine. Determining which polishing method is most appropriate depends on geometry of the lens, as well as the quantity being produced. For example, if the lens has a

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relatively long radius of curvature then conventional polishing of a multiple block may be most cost-effective.

<<Figure #7: Deterministic Grinding with CNC Machine>>

It is important to note that this is a two-machine process with very good process control. For most applications the lens fabrication is complete. However, for high precision applications COM has developed a complementary machining technology that can significantly improve the surface figure of the lens.

This new technology uses a unique fluid that is magnetically manipulated to deterministically remove material from the lens. The process is called magnetorheological finishing (MRF). The magnetorheological (MR) fluid stiffens as it passes through a magnetic field thus forming a temporary finishing surface or polishing pad. The MR fluid carries polishing slurry that is presented to the lens surface in a precisely controlled pattern by varying the magnetic field's strength and direction. Because fresh abrasive is continuously delivered to the polishing zone, heat and debris are constantly removed. This process reduces cycle times and is capable of producing fractional wave surface irregularity.

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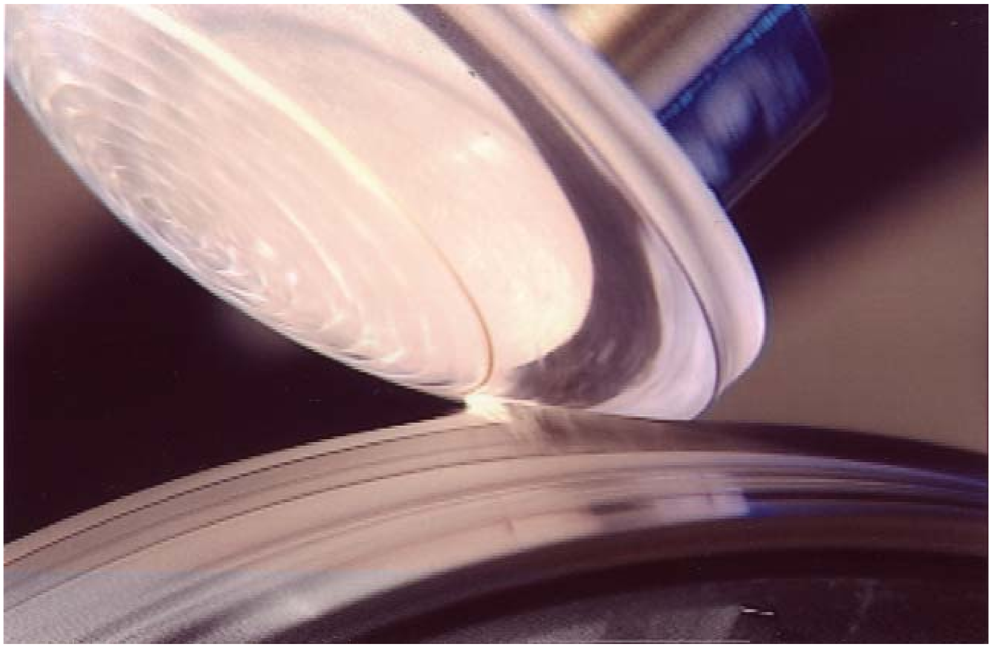
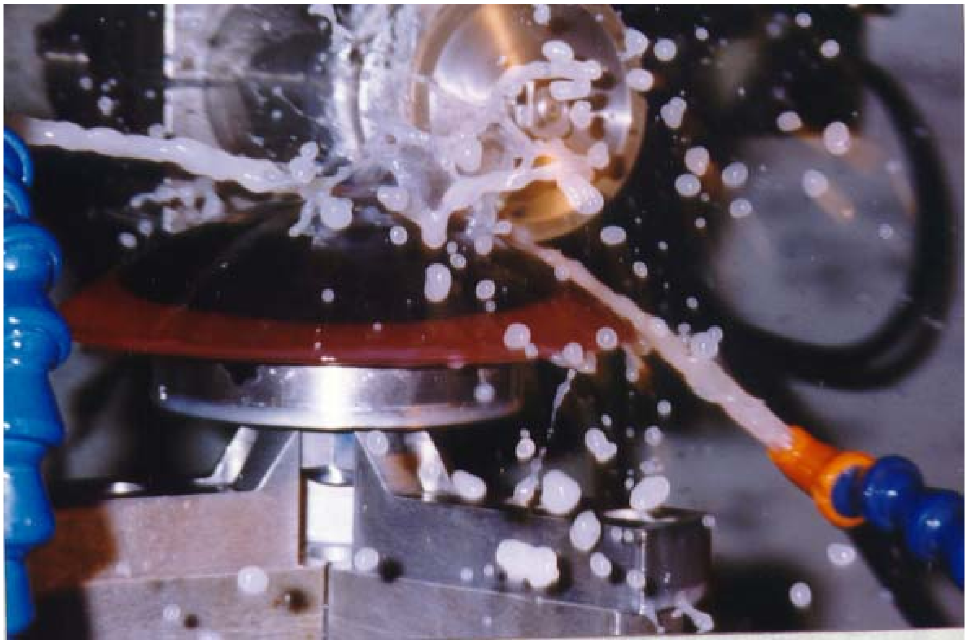


<<Figure #8: Magnetorheological Finishing (MRF)>>

The development of CNC machine technologies led directly to the capability to fabricate precision aspheric lenses in brittle materials, e.g., optical glass. Robust CNC machines are able to profile grind complex rotationally symmetric shapes defined by polynomial equations. This development effort continues today. Commercially viable processing methods are being developed for conformal optics. Conformal optics is loosely defined as non-rotationally symmetric, such as a saddle or a toroid. In fact, processing methods for conformal topics have progressed so far, that testing the finished optic is often more challenging than making it.



<<Figure #9: Precision Fabrication of Aspheric Lenses via CNC Machining >>

For more information regarding these new technologies please visit one or more of the following Web sites:

www.Optipro.com

www.QED.com

www.opticam..Rochester.edu

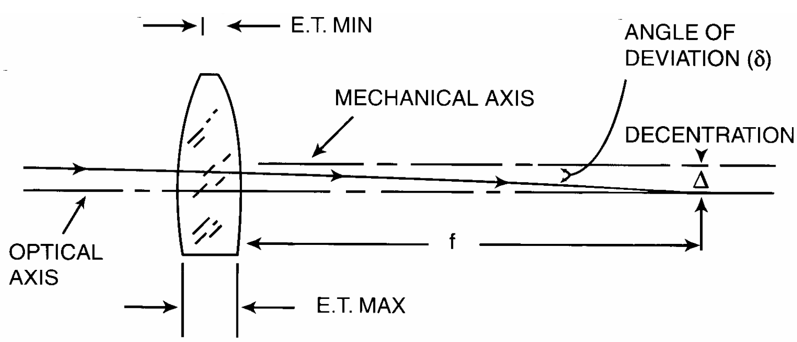
www.photonicsonline.com

17. 3 Special Fabrication Considerations

Centering tolerance is a complex opto-mechanical parameter that is frequently misinterpreted. For example, 1arc min edge thickness difference (ETD) may be reasonable for a 50mm diameter lens, but a 6mm diameter lens with this tolerance requires centering to 0.003mm ETD, which is extremely difficult. Figure #10 demonstrates the relationships between different wedge specifications. These equations provide conversions from one tolerance designation to another. The equations work well for most lenses, but lose accuracy with meniscus lenses as they approach concentricity.

	Deviation (Dv)	Edge Runout (ERO)	Surface Runout (ETD)
Deviation (Dv)		Dv = 1720*ERO/f	DV = 3440*(n-1)*ETD/D
Edge Runout (ERO)	ERO = D*Dv/3440*(n-1)		ERO = 2*f(n-1)*ETD/Dv
Surface Runout (ETD)	ETD = D*DV/3440*(n-1)	ETD = D*ERO/2*f(n-1)	

Where: Dv = deviation (in minutes)
ERO = edge runout
ETD = edge thickness difference
D = diameter
F = focal length
n = material index of refraction (same value used to calculate focal length)



Showing the relationships between the optical and mechanical axes, and the decentration and angle of deviation in a decentered lens.

<<Figure #10: Centering Tolerance Specifications>>

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If the tolerance analysis indicates that surfaces must be controlled to a few microns, then precision potting of the finished components should be considered. Precision potting refers to active alignment of the optic axis to the mechanical axis within the mounting cell. Because of the difficulty to center lenses to ETD's of less than 10 microns, assembly techniques have been developed to provide sub-micron alignment. For most optical systems, it is not beneficial to put unusually tight constraints on the lens because the housing in which it will be mounted typically will have more error than the lens.

Clear aperture is a specification dimension. It should provide enough aperture for light rays to pass through, however, many problems can result from the clear aperture being specified too close to the outside diameter of the lens. For example, achieving fractional wavelength surface quality will be difficult due to edge roll-off in polishing. In addition, during coating, the lens is held mechanically in a fixture above the coating source. Therefore, it is important to have sufficient clearance between physical diameter of the optic and clear aperture. Ideally, a clear aperture to diameter difference should be at least 2.0mm or 5% of the aperture, whichever measurement is greater.

There is an alternative when the clearance is not adequate for the coating tooling: the lens may be coated before edging. This option is not desirable, however, because the coating will be at risk during the edging process.

Thickness tolerances are more difficult to achieve on softer glasses that are less resistant to abrasion. When tight thickness tolerance is required along with very stringent cosmetics and fractional wavelength irregularity, the optician must allow the right amount of excess material to accommodate for grinding and polishing of the lens. This causes a wider range of center thickness, which may produce lower production yields. As a result, it may be necessary to start more pieces to account for the expected losses.

Sag tolerances are sometimes specified as the desired clear aperture. This is a difficult feature to measure. A better method is to compute the sag as a function of the clear aperture and the radius. This yields an axial height—the on-axis distance from the plane of the sag face to the spherical surface—which can be easily and accurately measured. If the sag face is used as a mounting surface, then the tolerances for the sag and center thickness are cumulative. If the sag is not a mounting surface, then it should be identified as a reference (Ref) surface in order to reduce cost.

Radius tolerance is used to specify the allowable radius measurement deviation from nominal for the test plate (i.e., spherical reference tool) that will be used for lens production. For precision optics this measurement is typically 0.1% of the nominal radius and not less than 10 microns for short radii. The optical designer should be aware there are no industry standards for radius measurement and that absolute radius measurement is not possible. If five different optics manufacturers measure a test plate, then there will be five different readings. For radii less than 1000mm, the variation will be on the order of a few microns. For radii over 1000mm the variation could be several millimeters. Researchers at The National Institute for Standards and Technology are working toward a solution to this problem.

Power tolerance is a measure of the deviation from the chosen test plate. This ensures consistency among a group of lenses. In other words, each lens will match the test plate within the power tolerance. From the designer's perspective, the radius tolerance and the power tolerance are cumulative. The original purpose of the power tolerance was to indicate the maximum number of power fringes for which the irregularity fringes could be counted. For example, in order to see 2 fringes of irregularity, the maximum number of power fringes is 10 fringes; for 1 fringe irregularity the maximum is 5 fringes. However, automated interferometric metrology is reducing the need to rely on traditional test plates.

Surface irregularity is a measure of the deviation from a perfect sphere. It is not only a function of the operator's skill and expertise, but also a function of the process geometry. As a general rule, multiple blocks with more pieces will have less irregularity than three spots or singles. The irregularity of lenses processed on multiple blocks will have a tendency to be cylindrical in nature while lenses processed as singles will have a symmetric aspheric profile shape, usually like a sombrero. There are certainly exceptions to this rule, but the general shape of the irregularity will follow these tendencies. Irregularity is defined very well by ISO 10110. See Figure #11 for more information.

<<Figure #11: ISO 10110-5 Surface Form Tolerances>>

Aspheric lens manufacturing technology has progressed rapidly over the past few years. The pace of this progress is limited somewhat by the difficulty in measuring aspheric profiles that include up to 16^{th} order terms. Using bonded diamond-tool generation for brittle materials (e.g., glass), convex aspheres are usually easier to fabricate than concave surfaces. The computer-controlled machines can process complex shapes irrespective of best-fit sphere. In contrast, single point diamond-turning machines can produce convex and concave surfaces on plastic and crystalline materials. However, small departures from best-fit sphere are preferred. The manufacturing cost for aspheres is typically 2 to 5 times that of spherical lenses with short radii. The generally accepted method for metrology is surface profiling to an accuracy of ±0.1

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micron. Aspheric form error on the order of 50 microns may be good enough for a condenser lens, while a precision quality focusing lens would require ±1 micron tolerance. Greater precision is possible with interferometric testing, which often requires the fabrication of a special null lens.

Bevels, chamfers, and break edges are machining features utilized at the corners of a lens to help prevent edge chipping. Bevels should be specified whenever the included angle of two surfaces on an optic is less than 155^{o}.

Cosmetic tolerances are well defined in MIL-O-13830 and ISO 10110. Most cosmetic inspection of lenses is still done visually by comparing the lenses to scratch-dig reference pieces. Alternatively, defects can be evaluated and categorized using a measuring microscope.

Anti-reflection coatings are a significant cost driver and can be reduced with minimal design effort. The most economical solution is to coat all surfaces with a single layer MgF_2 coating. This enables the lenses to be coated all in one run (depending on size and quantity). Single-layer MgF_2 coating will yield about 1.5% reflection for each low index surface and less than 1.0% reflection for each high index surface. For multi-element systems, specifying different coatings within the system can minimize coating costs. For example, the high index glasses may be coated with MgF_2 while a broad band anti-reflection (BBAR) coating is applied to the low index material. As a result, coating cost may be reduced because only the low index glasses are receiving multi-layer BBAR coatings, which are more expensive than MgF_2 coating. When using this approach, the designer should consider that BBAR coatings are index dependent. The coater will batch lenses by index, less than 1.60, 1.60 to 1.70, and greater than 1.70. Using glasses within two of these ranges instead of all three will reduce coating costs.

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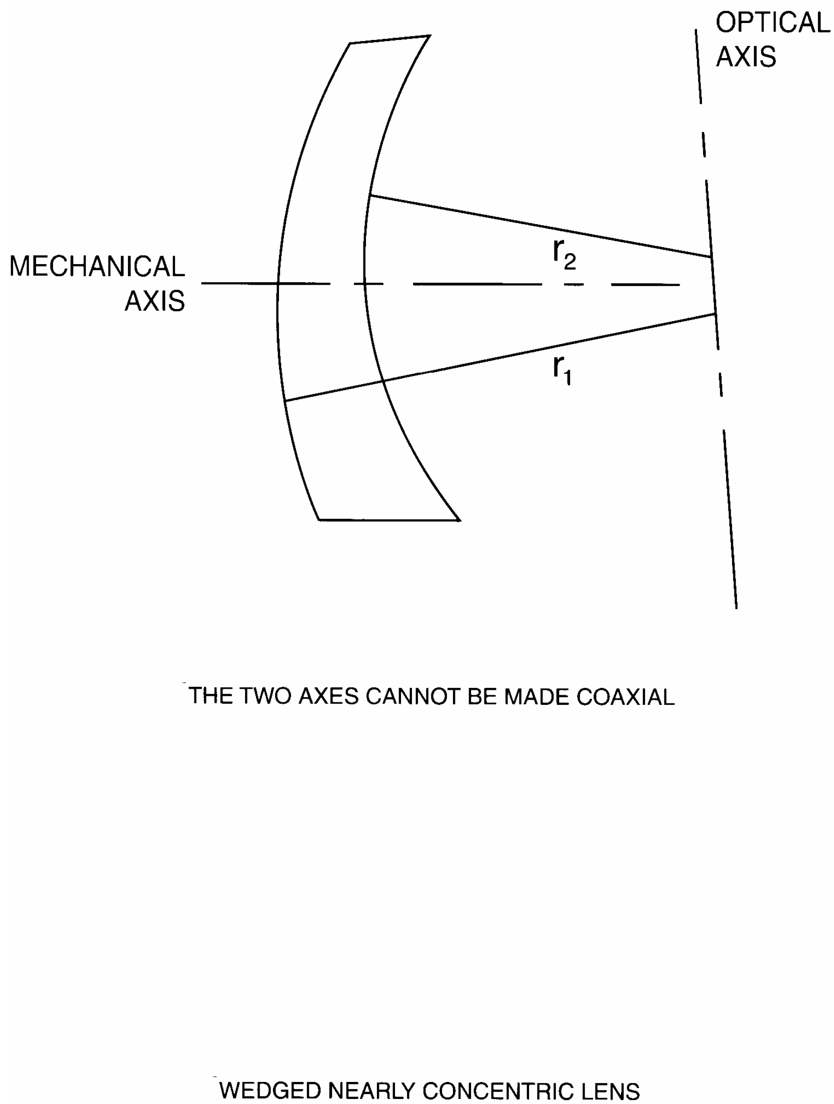
Blocking quantities are a function of the relationship between the radius and the diameter of a lens. The graph in Figure #12 reveals the relationship between radius, diameter, and blocking quantity. For example, lenses with a radius to diameter ratio of less than 0.84 will process as a single, a ratio of 0.84 to 1.04 will run three pieces to a block, and so on. The more surfaces per block, the lower the cost per lens to process it. The diameter of the parts and the capabilities of the manufacturer put additional parameters around the number of pieces that can be produced at one time.

<<Figure #12: Blocking Graph>>

Concentric lenses create a problem with centering accuracy. Because the centers of curvature for both surfaces are close to one another, the optician is not able to remove much residual wedge in the centering process. When the concentric lenses have weak curves and the lenses are processed as a multiple block, special care must be taken during blocking and grinding to prevent wedge in the part. In general, it is best to process concentric lenses individually on CNC equipment where the tolerances can be well controlled.



<<Figure #13: Concentric Lens>>

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Hemispheres and hyper-hemispheres are difficult to process because the polishing tool must rotate beyond the waist of the lens. This requires specialized machines and tooling. Small convex hemispheres are often made by modifying spheres to the desired shape. The use of concave hemispheres should be avoided whenever possible due to manufacturing difficulties associated with these shapes. It is important to note that designing and applying an antireflective coating for all angles of incidence presents another set of challenges, such as special coating textures to apply uniform antireflection coatings.

Aspect ratio is the relationship of center thickness to diameter. The higher the ratio, the higher the probability that the glass will distort during processing. The distortion is a function of thermal stress caused by the application of heated pitch and its subsequent cooling. After polishing, the lens is deblocked from the pitch and the stress is relieved. Lenses with extremely thin centers or thin edges are prone to develop surface irregularities during processing. Ideal aspect ratios are less than 6:1 for precision optics with one half-fringe irregularity. Aspect ratios greater than 10:1 will be more problematic and therefore more costly. There is also a greater likelihood for surface deformation from mounting and the assembly process.

Thin edges can occur when there is a strong convex surface on at least one side of the lens. When the edge is thin (< 1mm), it is more fragile and prone to chipping, and the optician is able to protect only the edge with a minimal bevel. Thin edges cause flaking out of glass particles during polishing, which leads to difficulty in achieving good cosmetic surfaces. A thin edge lens is also difficult to hold in place for testing on an interferometer because the slightest amount of pressure causes the lens to distort.

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Segmenting refers to special mechanical shaping. It is difficult to polish lenses of non-circular geometries. Therefore, if segmenting is required, the manufacturer will usually perform this step last. Unfortunately, all of the value (material and labor) has already been invested in the lens, which inherently makes this a high-risk process.

Edge blackening of the lens helps reduce scattered light and often improves contrast and signal to noise ratio. Permanent black ink that is water and alcohol resistant is easy to apply and does not cause mechanical build up on the surface. Lacquers and epoxies are more opaque, however, they are more difficult to apply and add tens of microns to the diameter of the lens. Epoxy is the most durable option, and if factored in during the design of the lens, it will not negatively impact the finished diameter of the lens.

An important consideration before manufacturing begins is component testing, which verifies that all parameters of the lens can be measured to the desired accuracy. Inspection data should be provided with all prototype components. In the event that an optical system does not perform as predicted by its design, the system can be computer modeled using the actual test data. In production, it may be helpful to perform inspection in compliance with the military specification MIL-PRF-13830B for a pre-specified Acceptable Quality Level (AQL).

Cemented doublets can enhance optical system performance without decreasing light throughput. There are many methods for making doublets and the optimal choice will require some design consideration, including thickness tolerance, surface irregularity and assembly.

Doublets yield some thickness flexibility for the designer. Most doublets are made from a flint and crown lens and have optical adhesive indices of about 1.5, similar to the crown glass. When tight thickness control is needed on a doublet, rather than give half the tolerance to each half of the doublet, the designer may be able to give the whole tolerance to each half and then

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have the optician match the thickness of each half before cementing them to make the doublet fall within the tolerance band. This can be a cost-effective solution to controlling doublet thickness.

All optical adhesives have some amount of shrinkage due to curing. This shrinkage can cause deformation of the lens elements and compromise the irregularity of the polished surfaces. Avoiding thin lenses in doublets and selecting a low shrinkage adhesive help minimize this effect.

The assembly method for a doublet will depend on the wedge tolerance. The simplest approach is to center each half of the doublet to the same diameter and use the edges of the lens for alignment. This method is best suited for lenses greater than 15mm in diameter. Another method is to center one half, the base lens, to a precision diameter and center the other half, the floater, to a smaller and less precise diameter. Then, referencing on the base lens, the optic axis of the floater can be aligned. In special cases the doublet can be built and centered as the final process. This is a very high-risk process and should be avoided when possible.

Alignment Method	**Mechanical Consideration**	**Precision (arc min)**
V-block – aligns the diameters of the two lenses to be co-cylindrical	Precision center the lenses to the same diameter and desired wedge tolerance.	6
Bell clamping – aligns the polished surfaces to be coaxial by mechanical positioning	Precision center the base lens and center the floater to a smaller diameter	3
Active alignment - aligns the polished surfaces to be coaxial by visual interactive positioning	Precision center the base lens and center the floater to a smaller diameter	< 1

<<Figure #14: Centered Doublet Guidelines>>

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17.4 Relative Manufacturing Cost

In addition to design considerations already described in this chapter, there are several other variables that can significantly impact the relative manufacturing cost of lenses. For example, the tolerances given to manufacturing specifications can lead to additional costs being incurred during manufacture of the lens. Other variables that may influence cost are the aspect ratio and the preferred delivery time.

In the mid-1970's, J. Plummer and W. Lagger wrote an article for *Photonics Spectra®* entitled "Cost Effective Design." The article contrasted the effect of manufacturing tolerance on the cost to make a lens. The chart from that article, represented in Figure #15, has been updated to detail the cost impact of several variables for a manufacturing process that utilizes the newer deterministic microgrinding technology.

Variable	➔ More Difficult ➔ ➔				
Diameter (mm)	±0.10	±0.05	±0.025	±0.0125	±0.0075
	100	100	102	105	125
Thickness (mm)	±0.20	±0.10	±0.05	±0.025	±0.0125
	100	103	115	140	200
Stain	<2	2	3	4	5
	100	103	110	140	175
Cosmetics (Scr-Dig)	80-50	60-40	40-20	20-10	10-5
	100	100	120	150	250
Test (fringes)	5-2	3-1	2-½	1-¼	½-1/8
	100	105	125	175	250
Wedge (arc minutes)	3	2	1	½	¼
	100	105	110	125	150
Doublets (arc minutes)	6	3	2	1	< ½
	100	105	110	150	200
Aspect Ratio	<10:1	15:1	20:1	30:1	50:1
	100	120	175	250	350
Delivery Time (weeks)	8	6	4	2	1
	100	100	130	170	200

<<Figure #15: 1999 Relative Manufacturing Costs using Deterministic CNC Processing>>

These relative costs are not cumulative, but are clearly interrelated as previous comments in this chapter discussion have indicated. The total cost impact of several factors would be a complex mathematical function, and would vary from shop to shop depending on the capabilities and strengths of each shop.

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17.5 Sourcing Considerations

Every project has specific goals, such as to bring a new product to market before the competition, to develop a new capability, or to reduce manufacturing cost. In order to be successful, the project manager must determine the priorities among price, quality, and timeliness. The manager must then communicate those priorities to everyone involved with completing the project. The following guidelines are offered for consideration in achieving cost, quality, and delivery goals.

- To minimize cost and delivery time, buy from a catalog whenever possible. At the same time, keep in mind that custom lenses are often required in order to achieve a desired optical performance.
- To minimize risk on a project (i.e., maximize the potential for good quality and on-time delivery) use domestic manufacturers for prototyping and pre-production. Optics manufacturers in the United States have superior manufacturing capabilities for rapid prototyping, high precision optics, computer generated holographic (CGH) and diffractive optical elements (DOE), laser optics, precision glass aspheres, polarizers, complex optical coatings, and much more.
- Rapid prototyping can significantly minimize cost and delivery time. Some projects are very time sensitive and optical components become the pacing item. Typical delivery time for rapid prototyping is 8 to 10 weeks. Seek a manufacturer with a proven track record. Several manufacturers have developed the ability to expedite the manufacturing process to achieve shipment of coated optics within a few days. This service may require a premium on the standard price.

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- To reduce cost with relatively low risk, seek a domestic importer with an established offshore facility that has the ability to test and certify product quality. Or for the lowest price, consider working directly with an offshore supplier. However, this is quite risky if you don't have the appropriate metrology to verify the product quality.

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17.6 Conclusion

This chapter presents a great deal of information that helps the designer select attributes and tolerances based on manufacturing considerations. Perhaps the most useful summary is a reference chart that provides a list of reasonable or typical manufacturing tolerances for commercial quality and precision quality lenses (see Figure #16). This chart is intended as a guideline and assumes a 50mm diameter BK-7 lens. The manufacturing limits are not absolute, but represent a pain and/or cost threshold. Job specific tolerances may vary depending on component size, shape, glass material, and preferred delivery time.

OPTIMAX	**Commercial Quality**	**Precision Quality**	**Manufacturing Limits**
Glass Quality (n_d)	± 0.001	± 0.0005	Melt Controlled
Diameter (mm)	+ 0.00 / - 0.10	+ 0.000 / - 0.025	+ 0.000 / - 0.010
Center Thickness (mm)	± 0.150	± 0.050	± 0.010
Sag (mm)	± 0.050	± 0.025	± 0.010
Radius	± 0.2 %	± 0.1 %	± 0.025 %
Power - Irregularity (fringe)	5 - 2	3 - 0.5	1 - 0.1
Aspheric Profile (microns)	± 25	± 2	±0.5
Wedge Lens (TIR, mm)	0.050	0.010	0.005
Prism Angles (TIA, arc min)	± 3	± 0.5	± 0.1
Bevels (max face width @ 45°, mm)	1.0	0.5	No Bevel
SCR - DIG	80 - 50	60 - 40	10 - 5
AR Coating (Ave R)	MgF2 R<1.5%	BBAR, R< 0.5 %	Custom design

<<Figure #16: Typical Manufacturing Tolerances>>

Once a lens has been designed and toleranced, manufacturing drawings are utilized to convey the lens requirements to the optician. Examples of a conventional manufacturing print and a drawing that complies with ISO standards follow. For more information, see Part 10, "Table Representing Data of a Lens Element," within ISO 10110 (Optics and Optical Instruments: Preparation of Drawings for Optical Elements and Systems).

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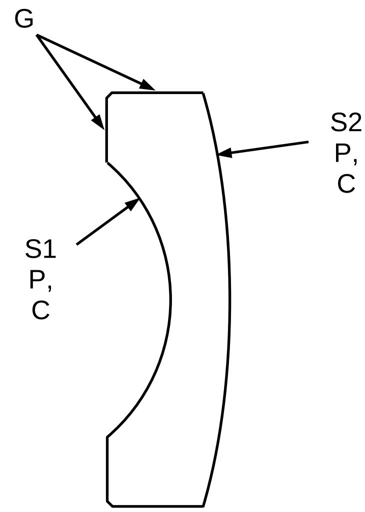
	Radius	Radius tolerance	Power/ Irreg.	Clear aper. diameter.
S	13.589	TPF	5/3	20.6
S	64.643	TPF	5/3	29.0

Edge diameter	Diameter tolerance	CT	Thickness tolerance	Wedge
31.18	±0.05	4.45	±0.05	0.05

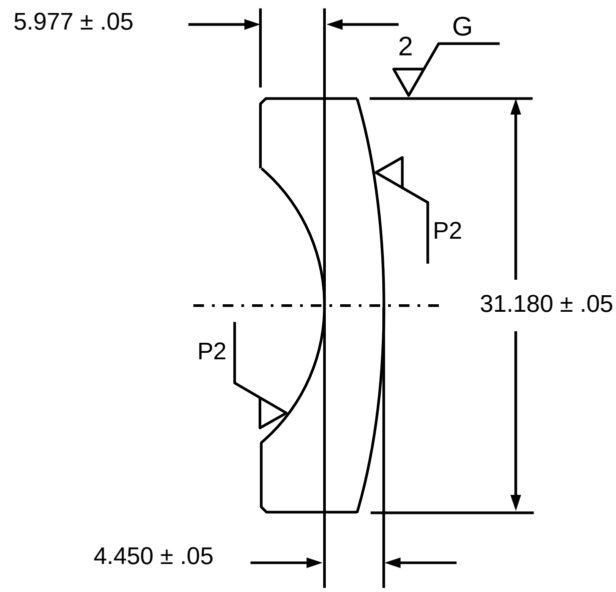


Notes:

1. All dimensions in inches.
2. Material: Optical glass per MIL-G-174 type BK7 Schott No. 517642
   nd = 1.5168 ± 0.0005 V = 64.2 ± 0.8% striae Grade A, fine anneal
3. Surfaces marked “P” polish to power / irregularity indicated
4. Manufacturer per mil-0-13830
5. Surface quality 60 - 40
6. Surfaces marked “C” coat with high efficiency coating with average reflectance per surface ≤ 0.5% from 420 - 680 nm
7. Surface marked “G” fine grind and blacken with no buildup
8. Bevel edges at 45 degrees to 0.5 max face width
9. Diameter to flat is 19.952 (REF) with surface sag of 5.977 ±0.05 on surface S1

	DR	
	CHK	
	APP	
Sample Element	SCALE -	

<<Figure #17a: Conventional Lens Manufacturing Print>>



Left Surface	Material Spec.	Right Surface
R 13.589 CC øe 20.6 Prot Chamfer .5 max Ave R < .5% from λ 430-670nm, AOI<40° 3/ 5(3) 4/ 8.34' 5/ 3 x .040,L 3 x .016 C 3 x .25 6/ -	Schott BK7 Nd 1.5168 ±.0005 Vd 64.2 ± .8% 0/ 10 1/ 5 x .016 2/ 0 ; 2	R 64.643 CX øe 29.0 Prot Chamfer .5 max Ave R < .5% from λ 430-670nm, AOI<40° 3/ 5(3) 4/ 5/ 3 x .040,L 3 x .016 C 3 x .25 6/ -
Indications according To ISO 10110	PN: Sample Element Print	

<<Figure #17b: ISO Lens Manufacturing Print>>